

## Provisional Report

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# On the discovery of new elements (IUPAC/IUPAP Provisional Report)

Provisional Report of the 2017 Joint Working Group of IUPAC and IUPAP

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**Abstract:** Almost thirty years ago the criteria that are currently used to verify claims for the discovery of a new element were set down by the comprehensive work of a Transfermium Working Group, TWG, jointly established by IUPAC and IUPAP. The recent completion of the naming of the 118 elements in the first seven periods of the Periodic Table of the Elements was considered as an opportunity for a review of these criteria in the light of the experimental and theoretical advances in the field. In late 2016 the Unions decided to establish a new Joint Working Group, JWG, consisting of six members determined by the Unions. A first meeting of the JWG was in May 2017. One year later this report was finished. In a first part the works and conclusions of the TWG and the Joint Working Parties, JWP, deciding on the discovery of the now named elements are summarized. Possible experimental developments for production and identification of new elements beyond the presently known ones are estimated. Criteria and guidelines for establishing priority of discovery of these potential new elements are presented. Special emphasis is given to a description for the application of the criteria and the limits for their applicability.

**Keywords:** discovery; IUPAC Commission for Nuclear Physics; IUPAC Inorganic Chemistry Division; naming process; new elements; periodic table; superheavy elements; superheavy nuclei; Transfermium Working Group; trans-organesson.

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## Preface

*Prepared by Bruce McKellar, past president of IUPAP and approved by Kennedy Reed, President of IUPAP and Qifeng Zhou, President of IUPAC*

The proposal that the criteria for the discovery of new elements, established 25 years ago by the Transfermium Working Group (TWG) established by IUPAP and IUPAC, be reviewed grew out of discussions started by

Natalia Tarasova and Bruce McKellar, the Presidents of IUPAC and IUPAP in 2016. These discussions were driven by a desire to revise the procedures for the Joint Working Parties (JWPs) set up by the Unions for determining claims for the discovery of new elements before any new claims were made. In the course of these discussions it became clear that the criteria for discovery set out previously related to discovery methods which were being replaced by newer methods, and that it would be useful also to revise those criteria before new claims were made.

As a result, the Unions set up a Joint Working Group (JWG) on the criteria for discovery of new elements. The decision was made in late 2016, and its Terms of Reference were approved by the Executive Council of IUPAP and the Executive Committee of IUPAC. Although the Terms of Reference are available on the websites of the Unions, for the convenience of the readers they are provided as Attachment 1 of this publication. The first meeting of the JWG was in May 2017 and this, its report, was received on May 25, 2018. Each Union appointed three of the members of the JWG, and each Union appointed two nuclear physicists and one nuclear chemist.

The Unions greatly appreciate the difficult work undertaken by the JWG. In the 1990s the TWG had to distill the criteria they set down from experiments which had already been done, identifying possible new elements. In contrast, the JWG was now asked to set down criteria which could be applied to experiments which were yet to be done. They have provided the scientific community with an insightful review of the past discovery experiments, and of the related discovery determinations by a succession of JWPs, emphasizing that, after occasional controversy, the determinations were accepted by the Unions, and the competing laboratories. Based on the recent successful experiments they identified likely experiments searching for elements beyond oganesson and devised appropriate criteria for the identification of those elements. They follow this up with advice to experimentalists making claims for new elements, and to the next Joint Working Party judging those claims. We note that the Unions have approved the IUPAC and IUPAP Procedures for Validating Claims for the Discovery of New Elements and Naming those Elements, setting out how the next JWP will operate, and these are available on the websites of the Unions and as Attachment 2 of this paper.

We thank the Chair, Sigurd Hofmann, GSI, the Vice-Chair, Hideyuki Sakai, RIKEN, and the other JWG members Sergey N. Dmitriev, JINR, Claes Fahlander, Lund University, Jacklyn M. Gates, LBNL, and James B. Roberto, ORNL, for their dedication to the task entrusted to them and for the very helpful report they have produced which will not only guide those who will be tasked with determining the validity and the priority of claims of discovery of new elements, but also the experimentalists making those claims.

In accordance with the Terms of Reference under which the JWG was established, this report has been provisionally accepted by us, and is open for comment for 5 months. Comments should be directed to us, and will be accepted up to 31 March 2019.

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24 August 2018

*The report was submitted to the Presidents of IUPAC and IUPAP on May 25, 2018*

## 1 Introduction

Criteria and rules related to assigning priority of discovery of a new element were set up by the Transfermium Working Group, TWG, in 1991 [1]. At that time, elements up to element number 109 had been discovered. However, not all of them could be named because in some cases priority of discovery could not be clearly established. It was the task of the TWG jointly set-up by IUPAC and IUPAP to work out appropriate criteria and rules so that existing claims for discovery could be settled and that, for the future, the priority of discovery of new elements could be decided timely and unambiguously.

New elements from 110 to 118 were synthesized since that time. Discovery of those elements was assigned using the criteria and rules set up in the 1991 TWG report, and all of the elements were named, from darmstadtium for element 110 to oganesson for element 118.

The most significant result on research of isotopes of elements beyond rutherfordium having proton number  $Z=104$  was the observation that most of these nuclei decay by  $\alpha$ -emission and not by spontaneous fission (SF), as expected earlier. Some of the measured half-lives extended up to values of several tens of seconds even for the heaviest observed nuclei with mass numbers at  $A=285$  of element copernicium,  $Z=112$ .

The observations are in line with shell-model predictions of the existence of two regions of increased stability. The theoretical results are based on macroscopic-microscopic (MM) shell-model calculations which were developed in the second half of the 1960s. One region of increased stability was calculated for deformed nuclei located around the isotope  $^{270}\text{Hs}$ ,  $Z=108$ , and the other for spherical nuclei at the doubly magic nucleus having closed shells for protons of  $Z=114$  and for neutrons of  $N=184$ .

Most isotopes in the region of the deformed nuclei from bohrium,  $Z=107$ , to nihonium,  $Z=113$ , were produced in heavy ion fusion reactions using  $^{208}\text{Pb}$  and  $^{209}\text{Bi}$  as targets. Due to the exceptional low excitation energy of the compound nucleus these reactions are known as ‘cold fusion’ reactions. For more reliable identification of the isotopes, the new method of in-flight separation of the reaction products using electromagnetic devices and of their implantation into position sensitive silicon detectors was developed at the end of the 1970s.

At the end of the 1990s, similar separation and detection systems were used for study of ‘hot fusion’ reactions using beams of  $^{48}\text{Ca}$  and targets of radioactive isotopes of actinide elements. These reactions produce more neutron rich compound nuclei being located closer to the double magic nucleus at  $Z=114$  and  $N=184$ . The experiments revealed the high stability of those superheavy nuclei so that isotopes of elements as heavy as 118 could be produced, despite the significantly higher excitation energy of the compound nuclei compared to that in cold fusion reactions.

Chemically, the now heaviest known element with proton number 118 terminates in column 18, as element oganesson, the seventh row in the Periodic Table of the Elements.

The identification of the new elements produced in hot fusion reactions with  $^{48}\text{Ca}$  beams was challenged in two ways. Firstly, only few atoms of the new elements could be produced and, secondly, the new superheavy nuclei, SHN, were located in an area of the chart of nuclei, which, via decay chains, was not connected to any known nucleus. Nevertheless, the measured results provided sufficient information so that the discovery of the new elements up to  $Z=118$  could be successfully assigned by a number of subsequently installed Joint Working Parties, JWP. The JWPs, a group of independent physicists and chemists, were set up by IUPAC and IUPAP, when decisions on claims for discovery of new elements became necessary. The task of these groups of experts was to scrutinise the published data to assess whether the new material adequately met the requirements of the TWG [1], to report back to IUPAC and IUPAP, and to publish a report about their findings in the journal *Pure and Applied Chemistry*.

The remarkable growth of superheavy element research based on the development of intensive beams of rare but stable isotopes, the use of neutron rich radioactive targets of actinides, and highly sensitive detection methods was difficult to envisage at the time when criteria and rules for assigning priority of discovery of new elements were set up in 1991. Therefore, not all criteria could take into account specific advantages or any problems and difficulties inherent to the production and identification methods being in use now.

A new Joint Working Group, JWG, was installed by IUPAC and IUPAP at the beginning of 2017. It consists of six members. Three were suggested by IUPAC and three by IUPAP. Two members are nuclear chemists and four nuclear physicists which considers the circumstance that all of the last eighteen elements were identified using physical methods and that future new elements will most likely be identified also by physical methods. The restriction excluding the appointment of members from a claimant laboratory which applies to JWPs does not apply to this JWG, which is not evaluating any claims.

A first meeting of the new JWG with participation of the Presidents of IUPAC and IUPAP took place in Egelsbach near GSI in Darmstadt, Germany, from May 20 to 22, 2017. After election of a chairman and a vice chairman, both Presidents communicated the Terms of Reference for JWG to review the criteria and rules worked out by the 1991 TWG in the light of the experimental and theoretical advances in the field. A second four hour meeting was arranged during the 3rd International Symposium on Super-Heavy Elements in Kazimierz Dolny, Poland, on September 11, 2017.

**Table 1:** List of agreed recommendations for names and symbols of elements with atomic numbers 101 to 118.

Element	Name	Symbol	IUPAC Recommendations
101	mendelevium	Md	<i>Pure Appl. Chem.</i> <b>69</b> , 2471–2473, (1997) [2]
102	nobelium	No	<i>Pure Appl. Chem.</i> <b>69</b> , 2471–2473, (1997) [2]
103	lawrencium	Lr	<i>Pure Appl. Chem.</i> <b>69</b> , 2471–2473, (1997) [2]
104	rutherfordium	Rf	<i>Pure Appl. Chem.</i> <b>69</b> , 2471–2473, (1997) [2]
105	dubnium	Db	<i>Pure Appl. Chem.</i> <b>69</b> , 2471–2473, (1997) [2]
106	seaborgium	Sg	<i>Pure Appl. Chem.</i> <b>69</b> , 2471–2473, (1997) [2]
107	bohrium	Bh	<i>Pure Appl. Chem.</i> <b>69</b> , 2471–2473, (1997) [2]
108	hassium	Hs	<i>Pure Appl. Chem.</i> <b>69</b> , 2471–2473, (1997) [2]
109	meitnerium	Mt	<i>Pure Appl. Chem.</i> <b>69</b> , 2471–2473, (1997) [2]
110	darmstadtium	Ds	<i>Pure Appl. Chem.</i> <b>75</b> , 1613–1615, (2003) [3]
111	roentgenium	Rg	<i>Pure Appl. Chem.</i> <b>76</b> , 2101–2103, (2004) [4]
112	copernicium	Cn	<i>Pure Appl. Chem.</i> <b>82</b> , 753–755, (2010) [5]
113	nihonium	Nh	<i>Pure Appl. Chem.</i> <b>88</b> , 1225–1229, (2016) [6]
114	flerovium	Fl	<i>Pure Appl. Chem.</i> <b>84</b> , 1669–1672, (2012) [7]
115	moscovium	Mc	<i>Pure Appl. Chem.</i> <b>88</b> , 1225–1229, (2016) [6]
116	livermorium	Lv	<i>Pure Appl. Chem.</i> <b>84</b> , 1669–1672, (2012) [7]
117	tennessine	Ts	<i>Pure Appl. Chem.</i> <b>88</b> , 1225–1229, (2016) [6]
118	oganesson	Og	<i>Pure Appl. Chem.</i> <b>88</b> , 1225–1229, (2016) [6]

The results of our investigation are presented in this report.

In a first part, Sect. 2, we summarize the works and conclusions of TWG and previous JWPs on discovery of elements 101 to 118. The accepted names of these elements are listed in Table 1 together with references to the corresponding publications in *Pure and Applied Chemistry*.

The achievement for physical and chemical properties resulting from the discovery of the new nuclei and elements is presented in Sect. 4. On the basis of this information and considering theoretical predictions, we estimate possible experimental developments and results for production and identification of new isotopes of new elements beyond oganesson, element 118, in Sect. 5.

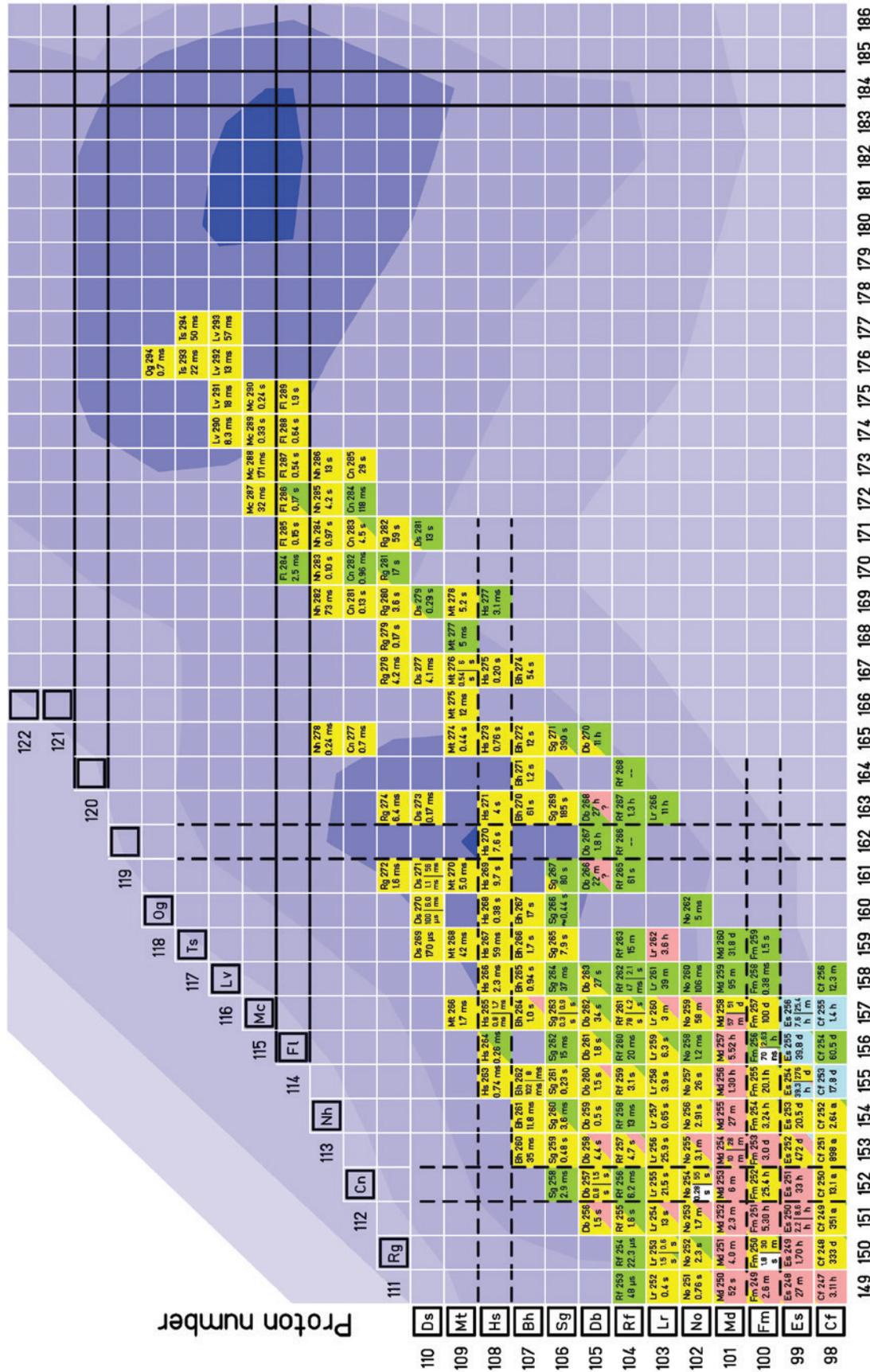
Criteria and guidelines for establishing priority of discovery of those potential new elements are presented in Sect. 6. During the work on this section we revealed that a list of criteria most of which were in shorter form already listed in the 1991 TWG report, is not sufficient to resolve many problems that can arise from the sometimes complicated matter. We felt it necessary to add certain guidelines for application of the criteria.

This main part of our work is followed by requests and guidelines to experimentalists and JWPs, Sect. 7, which should allow for a timely and unambiguous decision on assigning priority of discovery.

We also make a remark to the use of the terms ‘superheavy nuclei, SHN’, ‘superheavy elements, SHE’, and the ‘island of stability’. These terms are not well defined in the scientific literature. Our suggestion for use of these terms is presented in Sect. 3.

A summary and concluding remarks are given in Sect. 8 followed by the lists of abbreviations and references. In the list of abbreviations we summarize most of the relevant abbreviations which are in use in the literature. Not all of them were used in this article. We avoid overloading the article with too many abbreviations. Abbreviations are used only in cases where they are almost self-explaining.

We do not consider our work as a review of all experimental and theoretical studies performed in the field since 1991. References are made only to publications when needed for better understanding of the presented text. In particular, we are not presenting references to all of the claims for discovery of the new elements up to 118. These references can be found in the articles of JWPs listed in Table 1. For general overview of experimental and theoretical investigations and for further reading we refer to review articles presented, *e.g.* in [8–12] and to the references given therein. In particular we point to a recent Special Issue on Superheavy Elements published in [13].



Neutron number

**Fig. 1:** Upper end of the chart of nuclei showing the presently (2018) known nuclei. For each known isotope the element name, mass number, and half-life are given. Colours are attributed to their decay mode:  $\alpha$ -decay (yellow),  $\beta^-$ - or electron-capture decay (red),  $\beta^-$ -decay (blue), spontaneous fission (green), and  $\gamma$ -decaying isomers (white). The elements from proton number 107 to 113 were discovered in fusion reactions after evaporation of one neutron from the compound nucleus (cold fusion reactions based on  $^{208}\text{Pb}$  and  $^{209}\text{Bi}$  targets). The corresponding isotopes are located on the more neutron deficient side and cover the region of deformed superheavy nuclei with the centre at  $Z=108$  and  $N=162$ . The more neutron rich isotopes of elements 112 and 113 were produced in reactions using a  $^{48}\text{Ca}$  beam and targets of  $^{238}\text{U}$  and  $^{237}\text{Np}$  and the new elements from 114 to 118 were produced with targets of  $^{242}\text{Pu}$ ,  $^{244}\text{Pu}$ ,  $^{243}\text{Am}$ ,  $^{245}\text{Cm}$ ,  $^{248}\text{Cm}$ ,  $^{249}\text{Bk}$ , and  $^{249}\text{Cf}$ . Many of the neutron rich isotopes down to Db and Rf are produced as decay products in  $\alpha$ -decay chains. So far not confirmed are the electron-capture decays of the isotopes  $^{266}\text{Db}$  and  $^{268}\text{Db}$  and the subsequently populated spontaneously fissioning nuclei. These isotopes are indicated with question marks. Proton numbers  $Z=114$  and  $120$  and neutron number  $N=184$  are emphasized. At these numbers the shell model predicts closed spherical shells or subshells, respectively. The bold dashed lines mark proton numbers 100 and 108 and neutron numbers 152 and 162. Nuclei with that number of protons or neutrons have increased stability. However, they are deformed contrary to the spherical SHN. The crossing at  $Z=114$  and  $N=162$  reflects the uncertainty, whether nuclei in that region are deformed or spherical. The background structure shows the calculated ground-state shell-correction energy in steps of 1 MeV from  $-7$  MeV (dark blue) to  $-3$  MeV (light blue) according to the macroscopic-microscopic model [27–29]. The two regions of deformed and spherical superheavy nuclei are clearly visible.

## 2 Discovery and names of elements 101 to 118

### 2.1 Elements 101 to 109

Over a period of four years from 1988 to 91 the TWG worked out criteria in several meetings carried out also in the three laboratories of chief concern at LBNL in Berkeley, JINR in Dubna, and GSI in Darmstadt. The criteria were published in 1991 [1] and the analysis of the discovery of the transfermium elements was published in 1992 [14]. The identical text related to the analysis was published again in 1993 [15] but now with a subsequent response of the three laboratories to the work of the TWG, and, eventually, with a response of TWG to criticism from those laboratories [16]. A common agreement between TWG and the three laboratories was not achieved.

The following years saw a number of consultations and exchange of letters in order to find agreement with IUPAC, IUPAP, and the laboratories on discovery and naming of the elements from 101 to 109. A final IUPAC Recommendation for the names and symbols of the transfermium elements with atomic number 101 to 109 was published in 1997 [4]. It was accepted also by IUPAP and the scientists of the involved laboratories. The agreed names are listed in Table 1.

In these 1997 recommendations the 1994 recommendations [17] were adopted as provisional. The 1994 decision that an element should not be named after a living person was changed. This rule was not regarded ‘as an important issue and many thought it irrelevant’. The Commission agreed to the use of appropriate names derived from (a) mythical concepts or characters, (b) place, area or country, (c) a property of the element, and (d) a scientist.

### 2.2 Elements 110 to 118

After the work of the TWG on discovery of the elements 101 to 109 finished in 1997, four Joint Working Parties were subsequently launched by IUPAC and IUPAP for assigning priority of discovery of elements from 110 to 118. The work of these JWPs is documented in the following:

1999 – 2001: P. J. Karol, H. Nakahara, B. W. Petley, E. Vogt.

‘*On the Discovery of the Elements 110–112*’ [18].

2001 – 2003: P. J. Karol, H. Nakahara, B. W. Petley, E. Vogt.

‘*On the Claims for Discovery of Elements 110, 111, 112, 114, 116, and 118*’ [19].

2005 – 2009: R. C. Barber, H. W. Gäggeler, P. J. Karol, H. Nakahara, E. Vardaci, E. Vogt.

‘*Discovery of the Element with Atomic Number 112*’ [20].

2007 – 2011: R. C. Barber, P. J. Karol, H. Nakahara, E. Vardaci, E. W. Vogt.

*'Discovery of the Elements with Atomic Numbers greater than or equal to 113'* [21, 22].

2012 – 2016: P. J. Karol, R. C. Barber, B. M. Sherrill, E. Vardaci, T. Yamazaki.

*'Discovery of the Elements with Atomic Numbers  $Z=113, 115$  and  $117$ '* [23].

2012 – 2016: P. J. Karol, R. C. Barber, B. M. Sherrill, E. Vardaci, T. Yamazaki.

*'Discovery of the Element with Atomic Number 118 completing the 7<sup>th</sup> Row of the Periodic Table'*[24].

In these six IUPAC Technical Reports, the JWPs assigned priority of discovery of the elements from 110 to 118 on the basis of the criteria published by the TWG in 1991. The decisions were accepted by IUPAC, IUPAP, and, in particular, by the involved laboratories, although some of the details of the report [23] were the subject of additional discussion in the scientific community.

Rules for the 'Naming of New Elements' were published in an IUPAC Recommendation in 2002 [25]. An update followed in 2016 considering the special ending of names in group 17 and 18 of the Periodic Table [26]. It was decided that the names of all new elements should have an ending that reflects and maintains historical and chemical consistency. This would be in general '-ium' for elements belonging to groups 1 to 16, '-ine' for elements of group 17 and '-on' for elements of group 18. It was also substantiated, if and when the priority of discovery of an already named element is successfully challenged, then this element will not be renamed, which was the case of element 102 (nobelium). In that 2002 report [25] also the procedure is outlined which has to be applied for achieving a final recommendation for the name of a new element.

The accepted names of the elements from 110 to 118 are listed in Table 1 together with the references of IUPAC's recommendations for using these names. The presently known isotopes of these elements are shown in Fig. 1.

### 3 Definition of the terms 'superheavy elements', 'superheavy nuclei', and 'island of stability'

In the original sense, the term 'superheavy nuclei', SHN, characterized spherical nuclei for which higher stability was expected due to the anticipated existence of a next double shell closure beyond the known double shell closure at  $^{208}\text{Pb}$ . Early nuclear shell-model calculations predicted the next closed shell for the protons at  $Z=126$  in analogy to the closed neutron shell at  $N=126$  and as a next shell for the neutrons  $N=184$ . Subsequent refined calculations suggest  $Z=114$  as a more pronounced shell closure. Proton number 126 and also 120 were obtained as closures of subshells. As in the case of  $^{208}\text{Pb}$  these shells and subshells are valid for spherical nuclei.

It was expected that the surrounding nuclei at a distance from the double magic nucleus would not exist due to low fission barriers so that the SHN in the vicinity of the double magic nucleus would form an island of stability in a sea of unstable nuclei. The extension of the island into the direction of lower and higher proton and neutron numbers was uncertain. In particular, also the location of the nucleus with highest stability or longest half-life, *i.e.* the centre of the island of stability was subject of theoretical investigations.

Later, it became more commonplace, in particular in comprehensible articles for a broader public, to speak of elements instead of nuclei, and the term superheavy elements, SHE, came in use. Furthermore, the application of the term SHE was extended to lighter elements, and it is now often used for all elements from rutherfordium, element 104, upwards. Such a definition of SHE is reasonable because rutherfordium is the first element after closure of the actinide series. However, for characterization of the properties of nuclei, such as *e.g.* their lifetimes, the term elements cannot be used. It is meaningless to speak of long or short-lived elements, only isotopes of elements can have short or long lifetimes.

The presently existing data on nuclei of elements up to oganesson reveal that the island character of spherical SHN is less pronounced than expected earlier. The spherical SHN are not completely surrounded by a sea unstable nuclei. Due to the existence of the region of nuclei of increased stability around  $^{270}\text{Hs}$ ,  $Z=108$  and  $N=162$ , the originally isolated region of spherical SHN can be connected via  $\alpha$ -decay chains with the

mainland of known nuclei. Therefore, it seems reasonable to extend the term SHN so that also the deformed nuclei in the area around  $^{270}\text{Hs}$  are included. These nuclei owe the increased stability from the arrangement of single particle energy levels at large deformation. The term ‘shell closure’ for these deformed nuclei is not an adequate expression. It should be reserved for closed shells of spherical nuclei.

Experimental data as well as theoretical arguments reveal a reduced stabilizing effect of the arrangement of single particle energy levels at deformation for isotopes of rutherfordium. This finding suggests a natural lower limit of the region of SHN for isotopes of element rutherfordium,  $Z=104$ . The so determined definition of lightest SHN aligns SHN with SHE which also begin at rutherfordium, the first trans-actinide element.

Throughout this article we use the term SHE when properties of elements are discussed and the term SHN when properties of nuclei are in the focus. In particular cases related to the nuclear structure of SHN, we distinguish between ‘deformed SHN’ and ‘spherical SHN’. Both regions are separated by a transitional region of minimal stability, *i.e.* lowest fission barriers. This transitional region follows approximately the line of  $A=280$  isobars.

Nuclear structure and decay properties as well as production cross-sections reveal distinctive differences between deformed SHN and spherical SHN. These peculiarities have to be considered in discourses on superheavy nuclei, although both areas are combined under the common name SHN with the definition suggested here.

The properties deformed and spherical mean a rough classification of the two areas of nuclei. In reality the degree and shape of deformation is determined by minima of the negative binding energy for each individual nucleus. How quickly sphericity changes into deformation is subject of further experimental and theoretical studies.

The allegorical term ‘island of stability’ was brought up at a time when some calculations obtained half-lives of millions of years for nuclei on the island of spherical SHN. However, island of stability is not a synonym for island of spherical SHN although the existence of both is closely related to the existence of the double shell-closure at  $Z=114$  and  $N=184$ .

The important difference between both islands is the different location of the nucleus with strongest shell-correction energy in terms of the macroscopic-microscopic model and the nucleus with longest half-life. Both do not coincide with each other nor with the location of the double magic nucleus  $Z=114$  and  $N=184$ . In Sect. 4.1 we will present the reason for that difference.

How far the region of SHN extends in the direction of higher proton numbers will be the subject of further experimental and theoretical studies. It is reasonable that the influence of the shells or subshell at  $Z=114$ , 120 and 126 on the stability of nuclei will vanish with increasing number of protons. However, further shells at higher proton and neutron numbers and also nuclei of increased stability due to exotic shapes are theoretically predicted, which could form one or more further islands in a sea of instability. In order to keep the terms SHN and SHE for description of nuclei and elements whose existence is based on the shell closures  $Z=114$  and  $N=184$ , we suggest to label the nuclei and elements beyond  $Z=126$  with ‘beyond SHN’ and ‘beyond SHE’, respectively, as long as specific names are not existing. This naming would be almost aligned with the expectation of a ‘superactinide’ series which is expected to start at element  $Z=121$ .

## 4 Achieved knowledge about transfermium elements with respect to physics and chemistry

### 4.1 Physics

The most significant structure observed of nuclei of heavy elements up to nobelium was the systematically long SF half-lives for isotones with neutron numbers  $N=152$ . This regular behaviour changed at element 104. It was exhibited in 1974 that the SF half-life of  $^{256}\text{Rf}$  is four orders of magnitude less than expected from systematics [30]. The theoretical explanation that a second hump in the fission barrier drops below the ground-state at  $^{256}\text{Rf}$  and thus reduces significantly the width of the barrier, was given in [31]. It was a major success of the newly developed macroscopic-microscopic model.

This model is based on a suggestion of Vilen Mitrofanowitsch Strutinsky [32]. It was developed in the middle of the 1960s. Its application led to the prediction that the next closed shell for the protons beyond  $^{208}\text{Pb}$  may not be at  $Z=126$  as deduced from the harmonic oscillator potential with spin-orbit term, but at  $Z=114$  using a Woods-Saxon potential for the nucleons [33]. The next closed shell for the neutrons was left unchanged at  $N=184$ . Thus a region of spherical SHN of increased stability was predicted at those proton and neutron numbers.

An important additional prediction of the MM model was a region of increased stability also for nuclei in the vicinity of  $Z=108$  and  $N=162$ . However, in that region the nuclei were predicted to be deformed at deformation parameters  $\beta_2=+0.23$  and  $\beta_4=-0.09$  [34, 35]. The reason for their increased stability is a relatively large gap between single particle energy levels at  $Z=108$  and  $N=162$  resulting in a relatively high density of single particle energy levels below those numbers of protons and neutrons at the given deformation.

Results describing the stability and decay properties of nuclei in the heavy element region are shown in Fig. 2. Figure 2a shows the shell-correction energies. The regions of increased stability for deformed and spherical SHN are clearly visible. The same information is given also as coloured background in Fig. 1.

Partial SF half-lives [28, 29], Fig. 2c, reflect the landscape of shell-correction energies. Longest SF half-lives of  $10^{12}$  s (32 000 years) are predicted for spherical SHN, whereas the longest SF half-lives for deformed SHN are only at  $10^3$  s, although the shell-correction energy of  $-7$  MeV there is similar as for the spherical SHN. The main reason for this reduced SF half-life is the deformed shape of the ground-state, which results in more narrow fission barriers.

Partial  $\alpha$ -half-lives [27, 29], Fig. 2b, decrease gradually from about  $10^3$  s at the bottom of the stability valley to  $10^{-9}$  s for isotopes of element 124. The  $\beta$ -half-lives [36], Fig. 2d, decrease slowly with increasing distance on both sides from the bottom of the stability valley.

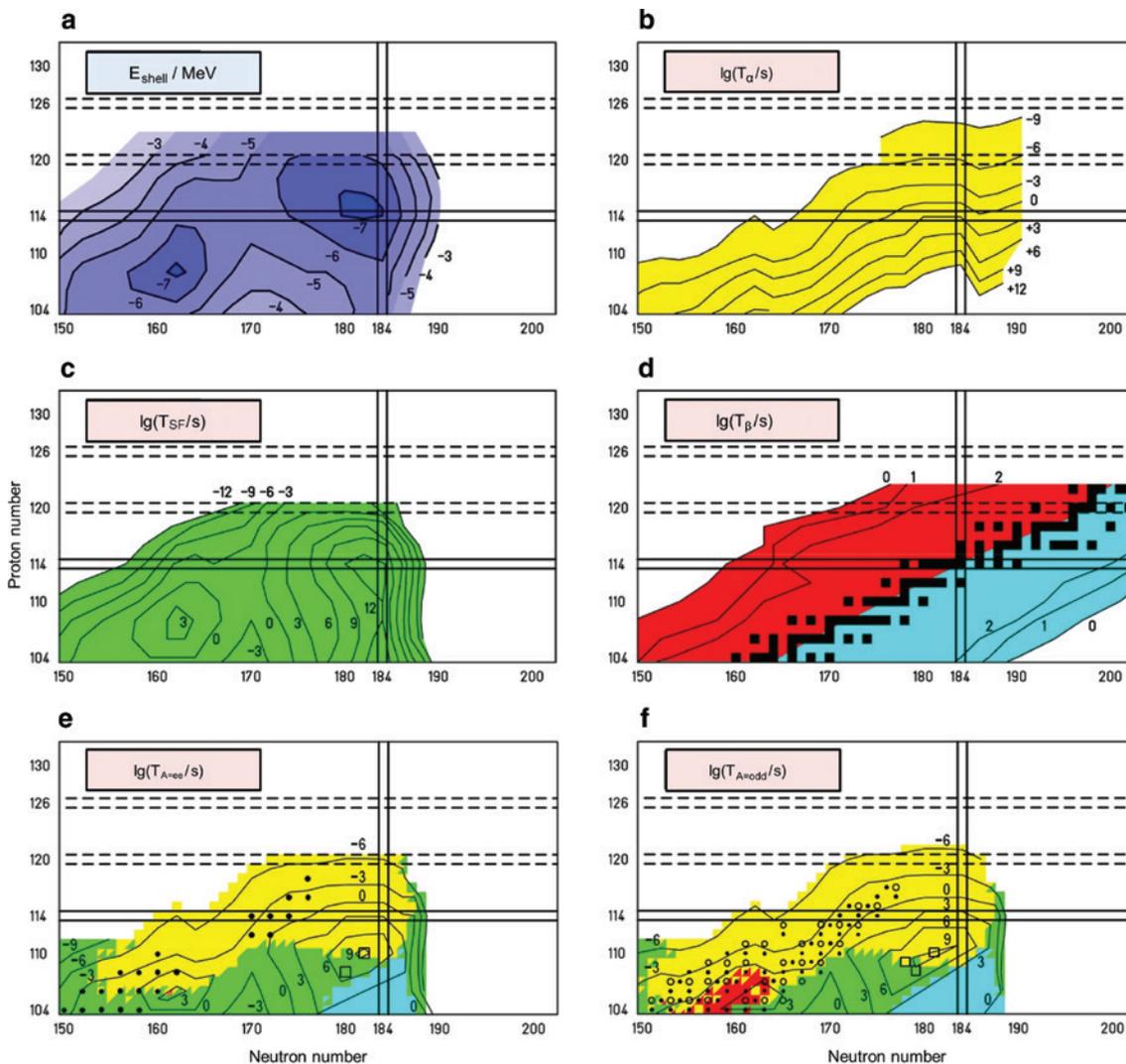
Alpha- and  $\beta$ -decay connect closely neighboured nuclei. The contour map of their half-lives is, therefore, less modulated by the shell-correction energy than the fission half-life. However, as it was measured from the  $\alpha$ -decay chain of  $^{277}\text{Cn}$ , the local binding energies of nuclei at  $N=162$  are such that the  $\alpha$ -half-life increases by five orders of magnitude when the nuclei of the chain pass neutron number  $N=162$ . This observation is in agreement with the theoretical predictions of the MM model [36, 37].

The dominating decay modes are shown in Fig. 2e for even-even nuclei and in Fig. 2f for odd- $A$  nuclei. For the even-even nuclei the two regions of deformed heavy nuclei and spherical SHN merge and form a region of  $\alpha$ -emitters surrounded by fissioning nuclei. The longest half-life predicted for deformed even-even SHN is about 1000 s for  $^{268}\text{Sg}$  having an SF/ $\alpha$ -branching ratio of about 1/1. Isotopes with longest half-lives predicted for even-even spherical SHN are  $^{290}\text{Ds}$  with  $T_{1/2,\text{SF}}=10^8$  s (3 years) and  $^{292}\text{Ds}$  with  $T_{1/2,\alpha}=10^9$  s (32 years). The regions of longest half-lives do not coincide with the regions of highest stability. These are at  $^{270}\text{Hs}$  for deformed SHN and at  $^{296}\text{Fl} - ^{298}\text{Lv}$  for spherical SHN. There, the total half-lives are short due to the high probability for  $\alpha$ -decay.

In the case of odd nuclei, Fig. 2f, the partial  $\alpha$ - and SF-half-lives were multiplied by a factor of 10 and 1000, respectively, thus making provisions for the odd particle hindrance factors. The  $\beta$ -half-lives were divided by 10, because first-forbidden transitions were not taken into account in the calculations (see discussion in [36]). For the odd nuclei the island character of  $\alpha$ -emitters disappeared and  $\alpha$ -decay propagates down to rutherfordium and beyond. Longest living odd- $A$  isotopes are located in the same region as the longest living even-even isotopes. In the region of spherical SHN, longest half-lives of about 30 years are expected for the spontaneously fissioning nucleus  $^{287}\text{Hs}$  and the  $\alpha$ -emitters  $^{287}\text{Mt}$  and  $^{291}\text{Ds}$ .

Experimentally observed isotopes are marked in Fig. 2e and f. Detailed comparisons of experimental results with theoretical data of the MM model were performed in review articles [9, 10, 38]. Concerning the basic decay modes of nuclei in the transfermium region up to the heaviest known isotopes on the island of SHN, a remarkably good agreement between experiment and theory is obvious. Although good agreement exists between measured half-lives and those predicted by the MM model for the known nuclei, there is still uncertainty for the predicted half-lives and decay modes for nuclei having a higher number of neutrons. Already small changes of the binding energy and deformation can considerably change the partial  $\alpha$ -half-life and in particular the partial SF half-lives. Therefore, the values of the predicted longest half-lives are rather uncertain.

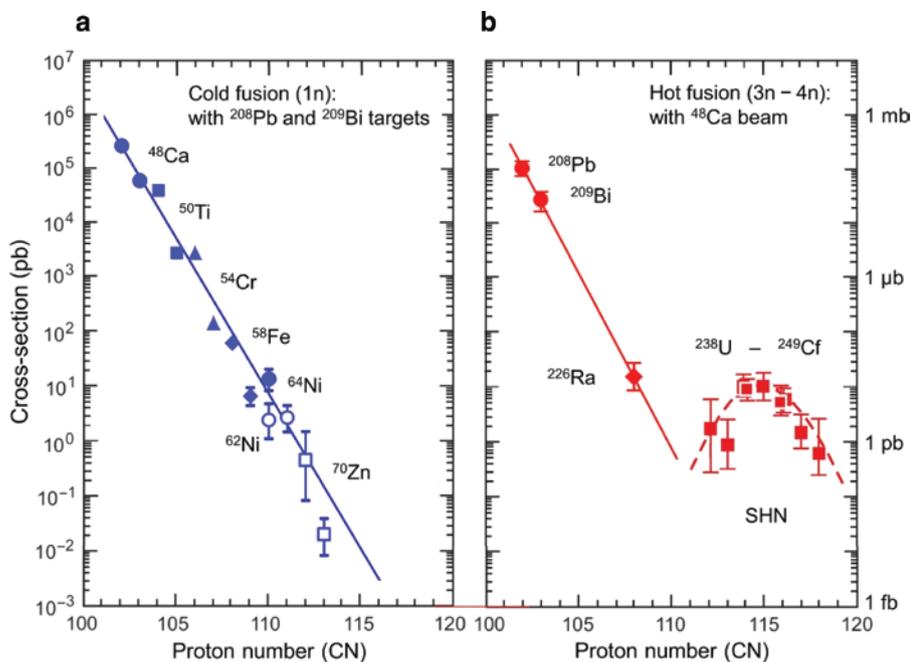
Eventually, it is important to mention that the regions of longest half-lives will probably not correspond to the regions of highest production cross-sections. A significant factor contributing to the cross-section is the



**Fig. 2:** The decay properties of superheavy nuclei according to macroscopic-microscopic calculations. Ground-state shell-correction energy (a); unhindered partial  $\alpha$ -decay half-life (b); unhindered partial spontaneous fission half-life (c);  $\beta^+$  or electron capture and  $\beta^-$ -decay half-life with  $\beta$ -stable nuclei marked by filled squares (d); dominating partial  $\alpha$ ,  $\beta$  or spontaneous fission half-lives for even-even nuclei (e) and odd- $A$  nuclei (f). Numbers at the level lines give the shell-correction energy in MeV (a), the logarithm of the partial half-lives in seconds for  $\alpha$ -decay (b), spontaneous fission (c),  $\beta^+$ - and  $\beta^-$ -decay (d), total half-life for even-even nuclei (e), and total half-life for odd- $A$  nuclei (f). The calculated data in a), b), and c) are from [27–29] and in d) from [36]. In the case of odd mass nuclei (f), the partial  $\alpha$  and spontaneous fission half-lives were multiplied by factors of 10 and 1000, respectively, in order to take the odd particle hindrance factors into account. The  $\beta$ -half-lives were divided by 10 (see text for details). The presently known even-even nuclei are marked by dots in e), those of odd- $A$  nuclei by smaller dots in f). Also shown in f) are the known odd-odd nuclei marked by open circles. Open squares in e) and f) mark the nuclei for which longest half-lives for dominating  $\alpha$ -decay and dominating spontaneous fission, respectively, are expected (see text).

fission probability of the CN, which is determined by the fission barrier. These barriers in turn are dominantly determined by the ground-state shell-correction energies in the region of SHN. It is obvious from the results of the calculations on fission barriers plotted in Fig. 2 that the highest cross-sections are expected for nuclei from  $Z=114$  to  $116$  and neutron numbers  $N=182$ , whereas the longest half-lives are expected for the lighter elements from  $Z=108$  to  $110$  and  $N=180$  to  $182$ .

Measured evaporation residue cross-sections are shown in Fig. 3. The increase of the cross-sections for hot fusion at element 112 up to a maximum value between elements 114 to 116 is explained by a strong reduction of the fission probability of the compound nuclei due to the increase of the fission barrier of nuclei in the



**Fig. 3:** Measured cross-sections for cold (a) and hot fusion reactions (b). Filled symbols in (a) mark the maximum of the 1n excitation function, open symbols mark the highest cross-sections in the case of incomplete excitation functions. Symbols are marked by the isotopes of the beam used in reactions with  $^{208}\text{Pb}$  and  $^{209}\text{Bi}$ . In (b) the cross-section of the 3n channel is plotted for reactions of  $^{48}\text{Ca}$  with  $^{208}\text{Pb}$  and  $^{209}\text{Bi}$  for synthesis of No and Lr [39], respectively. The isotope  $^{270}\text{Hs}$  was produced in a 4n channel in irradiations of  $^{226}\text{Ra}$  [40] with  $^{48}\text{Ca}$ . The dominating channels in the region of SHN are 3n and 4n. The maximum of the sum of both cross-sections at a certain excitation energy  $E^*$  of the compound nucleus is plotted. The corresponding compound nuclei were produced in reactions with targets of  $^{238}\text{U}$ ,  $^{237}\text{Np}$ ,  $^{242}\text{Pu}$ ,  $^{244}\text{Pu}$ ,  $^{243}\text{Am}$ ,  $^{245}\text{Cm}$ ,  $^{248}\text{Cm}$ ,  $^{249}\text{Bk}$ , and  $^{249}\text{Cf}$ . The cross-sections for production of spherical SHN for proton numbers from 112 to 118 in (b) were taken from [11]. The curves are drawn to guide the eye.

area of SHN. It represents, besides the increasing half-lives, another demonstration that the island of spherical SHN was reached experimentally.

In the following we summarize the achieved knowledge about superheavy nuclei obtained in physics experiments.

1. The systematics of long living  $N=152$  isotones is changed at  $Z=104$  due to the drop of the second hump in the fission barrier below the nuclear ground-state.
2. For isotopes of  $N=154$  to 165 and elements beyond rutherfordium up to nihonium, SF is not the dominating decay mode. Most of the nuclei decay by  $\alpha$ -emission with half-lives in the range from 0.1 ms to 100 s. These decay properties allow for measuring correlated  $\alpha$ -decays establishing decay chains ending in known nuclei for a reliable identification of the produced nuclei and elements by a genetic relationship.
3. The theoretically predicted region of increased stability of nuclei around  $Z=108$  and  $N=162$  is experimentally confirmed, both in location and extension.
4. The application of cold fusion based on  $^{208}\text{Pb}$  and  $^{209}\text{Bi}$  target and emission of only one neutron from the compound nuclei turned out to be successful up to the synthesis of  $^{278}\text{Nh}$ . The theoretically predicted extrapush energy [41] for synthesis of these nuclei was disproved. On the contrary, the measurement of excitation functions revealed that projectile and target nuclei fuse at low centre-of-mass energies so that maximum cross-sections are obtained when projectile and target nuclei are at rest when only the outer regions of the diffused surfaces are in contact. Transfer of protons from the projectile to the target initiates the fusion process and reduces the electric repulsions. Decreasing cross-sections with increasing proton number of the beam are mainly due to an increasing amount of quasifission, which is the term for the reparation of the reaction partners on the way from contact to the formation of a compound nucleus.
5. A number of quasiparticle isomers were observed in the region of deformed SHN. In the heaviest case known,  $^{270}\text{Ds}$ , the  $\alpha$ -decay half-life of 6.0 ms of the isomer at 1.13 MeV is longer than that of the ground-

state, 0.1 ms [42]. The production cross-section for the isomer and the ground-state in the reaction  $^{64}\text{Ni} + ^{207}\text{Pb}$  is comparable, 5 pb and 8 pb, respectively. Spin and parity values of  $9^-$ ,  $10^-$  or  $8^+$  are theoretically predicted for the isomer [43]. The observation of this isomer is an interesting example for a possible future production of SHN via isomers in the cases of too short half-lives of the ground-states or too high fission probability of the compound nucleus at too low fission barriers.

- Using beams of  $^{48}\text{Ca}$  and various actinide targets from  $^{238}\text{U}$  to  $^{249}\text{Cf}$  the predicted region of spherical SHN was reached. In these hot fusion reactions more neutron rich isotopes of copernicium and nihonium were directly produced and the new elements from flerovium ( $Z=114$ ) to oganesson (118) were synthesized.
- Properties of measured  $\alpha$ -decay chains are in agreement with predictions of the MM model. In particular, the termination of decay chains from even-even nuclei at element 104 in the case of deformed SHN and at element 112 in the case of spherical SHN is well understood due to the low fission barriers of these nuclei as predicted by the MM model. Also understood is the extension of the  $\alpha$ -decay chains of odd- $A$  and odd-odd nuclei down to isotopes of rutherfordium and dubnium due to the odd-nucleon hindrance of fission.
- Measured half-lives of the newly discovered SHN increase from a few milliseconds on the more neutron deficient side to some tens of seconds for the heaviest known isotopes. This result confirms the theoretical prediction of a region of increased stability of spherical SHN based on closed shells and subshells at  $Z=114, 120$  and  $126$  and  $N=184$ .
- Measured cross-sections reach values of about 10 pb for production of  $^{288}\text{Fl}$  in a  $4n$  and  $^{288}\text{Mc}$  in a  $3n$  evaporation channel at excitation energies of about 35 to 40 MeV. The relatively high cross-sections for these hot fusion reactions are another proof of existence of the region of SHN revealing increased stability and relatively high fission barriers. The data disprove predictions that shell effects of SHN vanish at excitation energies which characterize hot fusion reactions.
- The maxima of the cross-sections of hot fusion reactions are observed systematically at a few MeV higher beam energy than calculated for a configuration of zero centre-of-mass kinetic energy when the mean radii of beam and target nucleus are at contact in a central collision. In this model spherical projectile and target nuclei are assumed [44]. This observation differs from the case of cold fusion when spherical  $^{208}\text{Pb}$  or  $^{209}\text{Bi}$  targets are used and the cross-section maxima are measured at energies below the contact of the mean radii, see item 4. In the case of hot fusion the measured excitation functions reveal that maximum cross-sections are obtained in configurations when projectile and deformed target nucleus come to rest in a most compact configuration which can be reached considering both quadrupole and hexadecupole deformation of the target nucleus. However, also in this configuration only the outer orbits are touching when projectile and target are at rest. Elongated configurations do not significantly contribute to the fusion cross-section, although they would result in lowest excitation energies of the compound nuclei. In such configurations the system re-separates via quasifission before fusion.
- The extension of the island of SHN, in particular into the region of highest stability and longest half-lives located closer to neutron number  $N=184$ , is not yet explored.
- Still missing in most cases are experimental data on small branching ratios for SF,  $\alpha$ -decay, and electron capture decay. Such possibilities can be expected from theoretical investigations. They would provide important information on fission barriers in the case of nuclei for which only  $\alpha$ -decay is known or on relative masses obtained from  $\alpha$ -decay data in the case of nuclei for which only SF is known so far. In addition, as a critical circumstance, unknown branching ratios can result in misinterpretation of newly measured decay chains.

## 4.2 Chemistry

A major advance in the study of the chemistry of heavy elements was the proposal by Glenn Theodore Seaborg in 1945 that the elements beyond radium form a second group of elements, after the lanthanides, of similar chemical behaviour [45]. This series of elements received the name actinides from the element actinium after which the series starts. The similarity of the chemical behaviour of lanthanides and actinides is due to the

1 H hydrogen 1.008 [1.0078, 1.0082]																	2 He helium 4.0026
3 Li lithium 6.94 [6.938, 6.947]	4 Be beryllium 9.0122											5 B boron 10.81 [10.806, 10.821]	6 C carbon 12.01 [12.009, 12.012]	7 N nitrogen 14.007 [14.0064, 14.009]	8 O oxygen 15.999 [15.998, 15.999]	9 F fluorine 18.998 [18.998, 18.999]	10 Ne neon 20.180
11 Na sodium 22.990	12 Mg magnesium 24.305 [24.304, 24.307]											13 Al aluminum 26.982	14 Si silicon 28.086 [28.084, 28.088]	15 P phosphorus 30.974	16 S sulfur 32.06 [32.059, 32.074]	17 Cl chlorine 35.45 [35.446, 35.457]	18 Ar argon 39.948
19 K potassium 39.098 [40.078(4)]	20 Ca calcium 40.078(4)	21 Sc scandium 44.956 [47.867]	22 Ti titanium 47.867 [50.942]	23 V vanadium 50.942 [51.996]	24 Cr chromium 51.996 [54.938]	25 Mn manganese 54.938 [55.845(2)]	26 Fe iron 55.845(2)	27 Co cobalt 58.933 [58.933]	28 Ni nickel 58.693 [58.693]	29 Cu copper 63.546(3)	30 Zn zinc 65.38(2)	31 Ga gallium 69.723 [69.723]	32 Ge germanium 72.630(8)	33 As arsenic 74.922 [74.922]	34 Se selenium 78.971(8)	35 Br bromine 79.904 [79.901, 79.907]	36 Kr krypton 83.796(2)
37 Rb rubidium 85.468 [87.62]	38 Sr strontium 87.62 [88.906]	39 Y yttrium 88.906 [91.224(2)]	40 Zr zirconium 91.224(2)	41 Nb niobium 92.906 [95.95]	42 Mo molybdenum 95.95 [101.07(2)]	43 Tc technetium 101.07(2)	44 Ru ruthenium 101.07(2)	45 Rh rhodium 102.91 [106.42]	46 Pd palladium 106.42 [112.41]	47 Ag silver 107.87 [112.41]	48 Cd cadmium 112.41 [112.41]	49 In indium 114.82 [114.82]	50 Sn tin 118.71 [118.71]	51 Sb antimony 121.76 [127.80(2)]	52 Te tellurium 127.80(2)	53 I iodine 126.905 [126.905]	54 Xe xenon 131.29
55 Cs caesium 132.91 [137.33]	56 Ba barium 137.33 [137.33]	57-71 lanthanoids	72 Hf hafnium 178.49(2)	73 Ta tantalum 180.95 [183.84]	74 W tungsten 183.84 [186.21]	75 Re rhenium 186.21 [186.21]	76 Os osmium 190.23(3)	77 Ir iridium 192.22 [192.22]	78 Pt platinum 195.08 [195.08]	79 Au gold 196.97 [196.97]	80 Hg mercury 200.59 [200.59]	81 Tl thallium 204.38 [204.38, 204.39]	82 Pb lead 207.2 [207.2]	83 Bi bismuth 208.98 [208.98]	84 Po polonium 209	85 At astatine 210	86 Rn radon 222
87 Fr francium 223	88 Ra radium 226	89-103 actinoids	104 Rf rutherfordium 261	105 Db dubnium 262	106 Sg seaborgium 263	107 Bh bohrium 264	108 Hs hassium 265	109 Mt meitnerium 266	110 Ds darmstadtium 267	111 Rg roentgenium 268	112 Cn copernicium 269	113 Nh nihonium 270	114 Fl flerovium 271	115 Mc moscovium 272	116 Lv livermorium 273	117 Ts tennessine 274	118 Og oganesson 277
57 La lanthanum 138.91 [138.91]	58 Ce cerium 140.12 [140.12]	59 Pr praseodymium 140.91 [140.91]	60 Nd neodymium 144.24 [144.24]	61 Pm promethium 145	62 Sm samarium 150.36(2) [150.36(2)]	63 Eu europium 151.96 [151.96]	64 Gd gadolinium 157.25(3) [157.25(3)]	65 Tb terbium 158.93 [158.93]	66 Dy dysprosium 162.50 [162.50]	67 Ho holmium 164.93 [164.93]	68 Er erbium 167.26 [167.26]	69 Tm thulium 168.93 [168.93]	70 Yb ytterbium 173.05 [173.05]	71 Lu lutetium 174.97 [174.97]			
89 Ac actinium 227	90 Th thorium 232.04 [232.04]	91 Pa protactinium 231.04 [231.04]	92 U uranium 238.03 [238.03]	93 Np neptunium 237	94 Pu plutonium 244	95 Am americium 243	96 Cm curium 247	97 Bk berkelium 247	98 Cf californium 251	99 Es einsteinium 252	100 Fm fermium 257	101 Md mendelevium 258	102 No nobelium 259	103 Lr lawrencium 262			

Fig. 4: The IUPAC Periodic Table of the Elements dated from November 28, 2016. For each element the atomic number, the symbol, the element name, the conventional atomic weight, and the standard atomic weight are given. The figure was taken from [53].

stepwise filling of the 4f and 5f electron shells, respectively, so that the chemistry of these elements is mainly determined by the outer 5d, 6s and 6d, 7s electrons, respectively.

Only half of the group of actinide elements from thorium ( $Z=90$ ) to curium (96) was known in 1945. The group consisting of a total of 14 elements was completed with element lawrencium (103) in 1961. Subsequently, isotopes of the transactinides, beginning with rutherfordium in column 4 of the Periodic Table, were produced. The so far highest element, oganesson, has the atomic number  $Z=118$ . This element terminates the seventh row in the Periodic Table at column 18. Element 118 was discovered by Yuri Tsolakowich Oganessian and co-workers at FLNR in Dubna in 2006 [46]. The 2016 official Periodic Table of the Elements of IUPAC is shown in Fig. 4. All 118 elements from  $Z=1$ , hydrogen, to  $Z=118$ , oganesson, are known and have received a definite name according to the regulations of IUPAC and IUPAP.

Chemistry played an important role in the discovery of all transuranium elements up to nobelium either for separation or for identification. All heavier elements were identified by physical means, and the study of the chemical properties of those elements became the subject of scientific research on their own.

The most interesting subject influencing the atomic properties and the chemical behaviour of actinides and SHE is the so called ‘relativistic effect’. A simplified explanation of the term ‘relativistic effect’ is given by the radial shrinking of the inner spherical  $s_{1/2}$  and  $p_{1/2}$  electron wave functions which have large amplitudes at and near the location of the nucleus. This relativistic radial shrinking is caused by the strong Coulomb attraction by the high  $Z$  nucleus as consequence of the position-momentum uncertainty principle. The shrunken  $s_{1/2}$  and  $p_{1/2}$  wave functions screen the Coulomb potential of the nucleus more than in nonrelativistic cases, which influences the binding of the outer valence electrons. In the region of SHE these are the 5f, 6d, 7s, and 7p electrons which are close in energy and destabilized due to the shielding effect. However, also the  $7s_{1/2}$  and  $7p_{1/2}$  electron wave functions have large amplitudes at the nucleus which in turn causes a relativistic increase of the binding energy. This complicated interaction between the highly charged nucleus and up to 118 electrons makes accurate predictions of the atomic and chemical properties of SHE rather difficult.

On the other hand it is just this complexity which triggers experimental and theoretical investigations. Recent review articles present today’s status of research on the chemistry of SHE using liquid phase and gas phase methods [47, 48]. Physical methods for investigation of the atomic and ionic level structure of heavy

elements using laser spectroscopic methods are reviewed in [49]. An overview of theoretical attempts for reproduction and prediction of chemical and atomic properties of SHE is given in [50–52]. Criteria for assigning priority of a new element based on atomic and chemical methods are presented in Sects. 6.10 and 6.11, respectively.

## 5 Aspects related to the discovery of new elements beyond $Z=118$

The present task of the JWG of establishing criteria for assigning the discovery of new elements differs from that of the TWG functioning during the years 1988 to 1991. At that time, criteria were developed for assigning priority of discovery of elements for which discovery was already claimed up to meitnerium,  $Z=109$ . The present JWG is aiming to work out criteria for assigning discovery of new elements beyond oganesson,  $Z=118$ , which may be discovered in the future. Therefore, it is essential to estimate on the basis of known data and theoretical studies which new elements will most likely be searched for, what their decay properties may be, and which methods could be applied for production and identification using present and near future technology. In this context it is also of interest to which degree the 1991 criteria could be applied for assigning priority of elements from 110 to 118, which were not known in 1991, and if or how revised criteria would support the earlier made decisions.

Although criteria are principally based on definite physical laws, it is presently not possible to generally establish definite criteria on those laws that could be applied for all conceivable cases that may occur in the future. Three reasons prevent such an initiative. Firstly, the locations of regions of highest stability of prospective new elements are unknown. Secondly, the optimum production reactions for new elements are unknown. In addition, as it resulted from the discovery of the new spherical SHN, stability significantly influences the production cross-section due to a reduced fission probability of the generally excited newly produced nucleus. Thirdly, technical developments may considerably improve the methods for detection and identification of new elements in the future. In addition, methods may be improved, which presently seem to be not applicable. The possibilities for synthesis of new elements may be broadened by higher beam intensities, radioactive beams, secondary reactions using fragments from induced fission, and application of the heaviest beams up to uranium or even heavier with the use of more radioactive isotopes of actinide elements.

Eventually, technical developments may result in a revival of the search for new elements of long lifetime in nature, which have been produced in astrophysical processes. Search for those elements could be performed using terrestrial material or in objects brought to earth from the moon or via other extra-terrestrial objects from the universe, which have passed or arrive from a supernova explosion or a neutron star merger.

It is obvious that under these circumstances we can reliably develop criteria only for cases which most likely will find application in discovery of isotopes of new elements close to the heaviest presently known isotopes of SHN. For establishing those criteria we present in the following subsection expectations for results of experiments searching for new elements just above the known element  $Z=118$ . Such an investigation is a necessary prerequisite for establishing criteria for assigning priority of discovery of such elements in the future. Search experiments for some of those elements were already performed. However, the results were negative or inconclusive. Further experiments under improved conditions and at longer irradiation times are already planned at various laboratories.

In a second subsection we present more speculative cases of stability and production of new elements at larger distance from the known elements. Such cases were already considered in theoretical studies [54–58]. It is foreseeable that with longer accessible accelerator time and more efficient separation and more sensitive detection techniques also attempts will be continued to find and identify such objects. However, the nature of those experimental results is unpredictable. For such cases only general criteria can be established. Detailed *ad hoc* investigation will then become necessary in the case of results which indicate the discovery of a new element far from the presently known heaviest one.

## 5.1 Prospective new elements in the region of spherical SHN

The likely most successful reactions for production of isotopes of new elements just above the presently known isotope of oganesson will still profit from the increased stability of the island of SHN. Part of this island was experimentally explored using reactions of a  $^{48}\text{Ca}$  beam and targets of  $^{238}\text{U}$ ,  $^{237}\text{Np}$ ,  $^{242}\text{Pu}$ ,  $^{244}\text{Pu}$ ,  $^{243}\text{Am}$ ,  $^{245}\text{Cm}$ ,  $^{248}\text{Cm}$ ,  $^{249}\text{Bk}$ , and  $^{249}\text{Cf}$ . In continuation of this series of experiments, targets of  $^{254}\text{Es}$  for element 119 and  $^{257}\text{Fm}$  for element 120 have to be irradiated with a  $^{48}\text{Ca}$  beam. Although the half-lives of those exotic target isotopes of 276 and 100 days, respectively, are comparable to that of the already successfully used  $^{249}\text{Bk}$ , 327 days, their production in a high neutron flux reactor is extremely difficult. Maximum amounts of only a few tens of micrograms or nanograms, respectively, can be produced. For comparison, the amounts of  $^{249}\text{Bk}$ , which were produced at ORNL for recent studies on isotopes of tennessine, were 22 mg [59] and 25 mg [60]. Based on current capabilities, reactions using isotopes of lighter actinide targets combined with beams heavier than  $^{48}\text{Ca}$ , e.g.  $^{45}\text{Sc}$ ,  $^{50}\text{Ti}$ ,  $^{51}\text{V}$ ,  $^{54}\text{Cr}$ , etc., represent the most reasonable path forward.

Presently under investigation for possible production of heavy nuclei are fusion reactions using radioactive ion beams and multinucleon transfer reactions. Radioactive neutron rich ion beams will certainly broaden the possibilities for studying more neutron rich nuclei in regions where fragmentation reactions fail, *i.e.* above uranium. However, not yet sufficiently explored is the dependence of the fusion cross-section on neutron number, in particular, if an increase of the cross-section can compensate for part of the losses in yield due to the significantly lower beam intensities. Therefore, we presently do not consider radioactive ion beams as an option for producing new elements in a near future.

The use of secondary reactions of fragments from induced fission with the surrounding heavy nuclei was invented by Amnon Marinov *et al.* [61]. An experimental proof of those results and exploration of the application of the method for production of new isotopes and new elements is pending.

The situation is similar with the use of multinucleon transfer reactions for synthesis of new elements. This type of reaction was considered as promising in the past before reactions like  $^{238}\text{U} + ^{248}\text{Cm}$  could be studied experimentally. The theoretical background was that the flow of nucleons from the beam to the target will be into the direction of SHN having a locally increased stability. However, first experiments investigating the reaction products by chemical means revealed a rapid decrease of the cross-section with increasing element number. The heaviest nuclei identified in these reactions were from mendelevium ( $A=255$  to  $258$ ) with cross-sections of 60 nb [62].

More recent theoretical studies [63] obtain a nucleon flow such that nuclei near  $^{208}\text{Pb}$  are produced as one of the primary products in reactions like  $^{238}\text{U} + ^{248}\text{Cm}$ . The second primary fragments will then be nuclei near  $^{278}\text{Sg}$ . Therefore, this type of reaction is considered promising for synthesis of neutron rich isotopes of elements near seaborgium. It also may open a possibility to come closer to the region of nuclei with longest lifetimes expected at  $^{288}\text{Hs} - ^{292}\text{Ds}$ .

However, these heavy nuclei will be excited having a high probability for fission. In the present work we do not consider multinucleon transfer reactions as an option for producing new elements above the known element oganesson,  $Z=118$ , in the near future. Nevertheless, basic criteria can be established in order to judge possible claims for discovery of such elements using multinucleon transfer reactions and fusion reactions with radioactive ion beams or secondary reactions with fragments from induced fission.

A further reduction of the cross-section is expected for the production of new elements just beyond element 118 using the most promising fusion reactions based on actinide targets as discussed before. Measured cross-sections for production of tennessine ( $\sigma_{3n} = 3.6$  pb [60]) and oganesson ( $\sigma_{3n} = 0.5$  pb [60]) reveal a decrease after a maximum was reached at moscovium ( $\sigma_{3n} = 8.5$  pb [64]), see Fig. 3. A further decrease of the cross-sections for synthesis of elements 119 and 120 can be expected on the basis of decreasing fission barriers predicted by the MM model and due to an increasing quasifission process when beams of elements heavier than  $^{48}\text{Ca}$  are used. This means that for the production and identification of those elements only a few atoms can be expected even at increased beam intensity and long irradiation times of several months. These circumstances demand criteria that take into account the specific separation and detection methods of high efficiency.

Relatively optimistic perspectives are expected for identifying the produced nuclei by  $\alpha$ -decay chains even in the case of a low number of produced nuclei. So far the predictions of the MM models were well

**Table 2:** Expected decay chains of isotopes of elements 119 and 120 which could be produced in reactions with beams of the most neutron rich stable isotopes of elements from calcium to manganese and targets of  $^{244}\text{Pu}$ ,  $^{243}\text{Am}$ ,  $^{248}\text{Cm}$ ,  $^{249}\text{Bk}$ ,  $^{249}\text{Cf}$ ,  $^{250}\text{Cf}$ ,  $^{251}\text{Cf}$ , and  $^{254}\text{Es}$ .<sup>a)</sup>

${}^A_Z N$	odd/even	${}^A_Z$ new $\alpha$ -emitter; ${}^A_Z$ known $\alpha$ -emitter; ${}^A_Z$ new SF; ${}^A_Z$ known SF
$^{293}_{119}_{174}$	o_e	$^{293}_{119}_{289}\text{Ts}_{285}\text{Mc}_{281}\text{Nh}_{277}\text{Rg}_{273}\text{Mt}_{269}\text{Bh}_{265}\text{Db}_{261}\text{Lr}$
$^{295}_{119}_{176}$	o_e	$^{295}_{119}_{291}\text{Ts}_{287}\text{Mc}_{283}\text{Nh}_{279}\text{Rg}_{275}\text{Mt}_{271}\text{Bh}_{267}\text{Db}$
$^{297}_{119}_{178}$	o_e	$^{297}_{119}_{293}\text{Ts}_{289}\text{Mc}_{285}\text{Nh}_{281}\text{Rg}$
$^{299}_{119}_{180}$	o_e	$^{299}_{119}_{295}\text{Ts}_{291}\text{Mc}_{287}\text{Nh}_{283}\text{Rg}_{279}\text{Mt}$ (all isotopes new)
$^{294}_{119}_{175}$	o_o	$^{294}_{119}_{290}\text{Ts}_{286}\text{Mc}_{282}\text{Nh}_{278}\text{Rg}_{274}\text{Mt}_{270}\text{Bh}_{266}\text{Db}^{\text{b}}$
$^{296}_{119}_{177}$	o_o	$^{296}_{119}_{292}\text{Ts}_{288}\text{Mc}_{284}\text{Nh}_{280}\text{Rg}_{276}\text{Mt}_{272}\text{Bh}_{268}\text{Db}^{\text{b}}$
$^{298}_{119}_{179}$	o_o	$^{298}_{119}_{294}\text{Ts}_{290}\text{Mc}_{286}\text{Nh}_{282}\text{Rg}_{278}\text{Mt}_{274}\text{Bh}_{270}\text{Db}$
$^{300}_{119}_{181}$	o_o	$^{300}_{119}_{296}\text{Ts}_{292}\text{Mc}_{288}\text{Nh}_{284}\text{Rg}_{280}\text{Mt}_{276}\text{Bh}$ (all isotopes new)
$^{295}_{120}_{175}$	e_o	$^{295}_{120}_{291}\text{Og}_{287}\text{Lv}_{283}\text{Fl}_{279}\text{Cn}_{275}\text{Ds}_{271}\text{Hs}_{267}\text{Sg}$
$^{297}_{120}_{177}$	e_o	$^{297}_{120}_{293}\text{Og}_{289}\text{Lv}_{285}\text{Fl}_{281}\text{Cn}_{277}\text{Ds}_{273}\text{Hs}_{269}\text{Sg}_{265}\text{Rf}$
$^{299}_{120}_{179}$	e_o	$^{299}_{120}_{295}\text{Og}_{291}\text{Lv}_{287}\text{Fl}_{283}\text{Cn}_{279}\text{Ds}$
$^{296}_{120}_{176}$	e_e	$^{296}_{120}_{292}\text{Og}_{288}\text{Lv}_{284}\text{Fl}$
$^{298}_{120}_{178}$	e_e	$^{298}_{120}_{294}\text{Og}_{290}\text{Lv}_{286}\text{Fl}_{282}\text{Cn}$
$^{300}_{120}_{180}$	e_e	$^{300}_{120}_{296}\text{Og}_{292}\text{Lv}_{288}\text{Fl}_{284}\text{Cn}$

a) Evaporation of 2, 3, and 4 neutrons from the compound nucleus was considered. For the decays of the isotopes only the dominant decay branch was taken into account. All nuclei of the two most neutron rich decay chains emerging from the decay of  $^{299}\text{119}$  and  $^{300}\text{119}$  are unknown. Their decay modes were estimated on the basis of the decay data given in Fig. 2.

b) It is uncertain whether the isotopes  $^{266}\text{Db}$  and  $^{268}\text{Db}$  populated by  $\alpha$ -decay of  $^{270}\text{Bh}$  and  $^{272}\text{Bh}$ , respectively, decay by spontaneous fission (SF) or the isotopes  $^{266}\text{Rf}$  and  $^{268}\text{Rf}$  populated via an intermediate electron capture decay, see also Fig. 1.

confirmed by the experimental results on SHN up to element 118. An application of the results of those models for estimating the decay properties of isotopes of elements 119 and 120 seems justified. The graphs shown in Fig. 2, which are based on results of MM models, present a reasonable overview on calculated decay modes and half-lives of known and unknown isotopes in the region of SHN.

Considering evaporation of two to four neutrons from the compound nucleus of the before given fusion reactions, we expect for element 119 the production of isotopes with mass numbers  $A=293$  to 300 and for element 120 mass numbers  $A=295$  to 300. This is a total of eight new isotopes of element 119 and a total of six isotopes of element 120, for which detailed criteria can be worked out. Possible decay chains from these isotopes are listed in Table 2. The unknown and presently known nuclei are marked. On the basis of this compilation criteria can be established for discovery of elements 119 and 120 expected in the near future. Obviously, these criteria can be applied also for elements 121 and 122 if the produced isotopes will decay by  $\alpha$ -emission populating already known decay chains. Although fusion reactions and emission of a few neutrons are expected to be the most probable production mechanism of these SHN as well as  $\alpha$ -decay as a most probable decay mode, the criteria have to consider also the possibility of different evaporation and production channels and decay properties as, e.g. pxn and  $\alpha$ xn evaporation channels, isomeric states, electron capture, and SF.

## 5.2 Prospective new elements at a distance from the region of spherical SHN

Modern accelerators offer the possibilities for carrying out nuclear reactions with the heaviest beams like  $^{238}\text{U}$ , even heavier beams of more radioactive isotopes of actinides were already discussed. Beams of radioactive isotopes of lighter elements, both neutron rich and neutron deficient, will become available with increased intensity in the future. Experimental techniques are continuously refined with respect to efficiency, sensitivity, accuracy, and rapidity for the study of the physical and chemical properties of nuclei, ions, and atoms.

Theoretical models and their predictions initiated the experimental search for SHN. Several models, as e.g. the MM models, predicted well the properties of nuclei in the region of SHN. However, already a comparison of different MM models and even more a comparison with the results of self-consistent mean-field models reveal partly significant differences. Therefore, it seems reasonable to consider also possible future experimental results, which appear unlikely or even unrealistic presently.

Options which are closely related to the presently studied spherical SHN that obtain their stability from closed shells at  $Z=114$  and  $N=184$  are the predictions of relativistic mean field models that increased stability could exist also at proton numbers 120, 124 or 126 [65–70]. In terms of the shell model closed shells or subshells would exist at these proton numbers. For the neutrons the mean field models predict high stability at  $N=184$  similar as the shell models.

Present experimental data on  $\alpha$ -decay known up to element 118 do not rule out such possibilities. If these predictions are correct, the spherical SHN could extend up to element 120 or even up to 126. A considerable increase of the  $\alpha$ -decay half-life of the respective nuclei would be the consequence, compared to the predictions of the MM model as shown in Fig. 2b.

Possible claims of discovery of such elements could be in the most optimistic case the detection of an  $\alpha$ -decay chain populating already known nuclei in the region of spherical SHN. However, chains consisting only of new isotopes or observation of only SF may also be detected. To establish detailed criteria of discovery for all of these possibilities seems not very meaningful. However, general criteria could be established which could help to assign priority of discovery in the case of unforeseen observations. Which of the measured physical or chemical properties will deliver the most convincing argument for assigning priority of discovery is difficult to predict. Lifetime and the number of detected nuclei of a particular isotope will be the most important properties which will determine the identification methods.

Shell-model calculations predict further closed shells or subshells beyond  $Z=126$  and  $N=184$ , the heaviest shell closures being located at  $Z=164$  and  $N=318$  [54]. Also predicted are nuclei in the region of SHN being strongly deformed in the ground-state or in an isomeric state [71, 72]. Isomeric states were considered to explain the observation of long lived species which were assigned to SHN in [73], which, however, were not yet confirmed, could not be reproduced or were even disproved. In addition, some theoretical calculations suggest stability for exotic nuclear shapes. Bubble nuclei or toroidal shapes were investigated and predicted to exist for nuclei beyond  $Z=126$  [55–58]. Presently, it seems unlikely that such nuclei could exist in a stable configuration. Difficult to predict is also in which way these nuclei could decay. If future experimental results would indicate the existence of such exotic phenomena it will probably be necessary in an *ad hoc* JWP investigation to decide about the correctness of the interpretation of the measurements.

Eventually, we consider the identification of long lived heavy nuclei and elements which could have been produced in astrophysical processes. To date, from time to time, efforts are published describing the search for such species in nature [74]. With our current knowledge we expect the longest living nuclei in the region of neutron rich isotopes of the elements from 108 to 110, see Fig. 2. Although these isotopes do not belong to new elements their discovery would be extremely interesting. Methods for identification of such long-living isotopes could provide criteria which can be applied for assigning priority of discovery of long-living isotopes of new elements.

## 6 Criteria for establishing discovery of a new element

The criteria described in the 1991 TWG report [1] considered valid physical and chemical properties of elementary matter as well as production and identification methods which were known and applied at that time. Due to the generally valid character of the underlying physical and chemical laws, the application of these criteria is conclusive.

However, as it was already indicated by the synthesis of elements 107 to 109 in the beginning of the 1980s, the feasibility for producing new elements in the laboratory became more and more difficult. When in the past hundreds of atoms could be produced at cross-sections of microbarns to hundreds of nanobarns, the

investigations are dealing now with single or only few atoms produced with cross-sections of picobarns and even below. Only due to immense technical improvements of accelerators, separators, and detection systems and the admittedly well suited decay properties of the produced nuclei has it been possible to reliably identify isotopes of elements at these small cross-sections. The recent discoveries of new elements and the knowledge that we can extract for the synthesis and properties of further new elements, do not change the existing criteria for assigning priority of discovery, but they change the weights when and how they have to be applied.

All superheavy elements with proton number  $Z \geq 104$  were solely produced in heavy ion fusion reactions. The evaporation residues of elements  $Z \geq 107$  were separated with electromagnetic separators, and the nuclei were identified by decay chains starting with a signal from the implantation of an evaporation residue into a Si detector and subsequent signals from  $\alpha$ -decays and/or SF. In most cases the signals from the decay chains were preceded by time-of-flight signals from detectors in front of the Si detectors. For further discrimination of the background, position sensitive detectors were used. Details of the experimental set-ups can be found in the specific literature and in review articles [8, 10]. There, also options for further improvement of accelerators, separators, and detection systems are described.

It is expected that these or similar methods will be the major tools for producing new elements and their identification also in the future. Therefore, we will concentrate here on the presentation of criteria related to these techniques. Criteria which can be applied in other types of experiments will be also discussed as appropriate.

The term criterion as we use it here is mainly related to the experimental methods used for producing and identifying new elements. However, we use it also for characterizing the production methods and the properties of those elements and nuclei, as *e.g.* fusion-evaporation reactions, multinucleon transfer reactions, half-lives,  $\alpha$ -decay energies, and decay modes.

We do not use the term criterion as would be the case in mathematics, where it is a necessary and sufficient condition for proving the correctness of a mathematical law. In our case, two or more criteria often need to be applied in order to unambiguously assign discovery of a new element. It will be the task of a team of experts, the JWP, to evaluate the results of the particular experiments and to decide if those results and their quality are sufficient for assigning discovery of a new element. In this sense the elaborated criteria serve as a guideline for future JWPs. They cannot be used as a simple checklist where at the end the majority of fulfilled criteria decide on priority. This cannot be the case because most of the criteria need to be supplemented with a weight factor considering the amount of uncertainty attributed to the measurement and to the statistical relevance. In addition, new experimental developments and results may require future demand for extensions of the list and weighting factors of the criteria.

In the following Sects. 6.1 to 6.12, we will work out criteria for assigning priority of discovery of a new element which most likely will find application in a search of elements 119, 120 or slightly above in the future. However, criteria will also be discussed, which could be useful in cases of unexpected or unconventional experimental results so that such results can be characterized as sufficient or insufficient for assigning discovery of a new element. In Sect. 7 we present under the header ‘Guidelines to Experimentalists and Joint Working Parties’ the conditions which are necessary to objectively and sufficiently judge an experimental work or in the case of several claims to evaluate the priority of discovery.

## 6.1 Definition of what is a new element

Certainly, the most important criterion for the discovery is the characterization of a new element itself. In the 1991 TWG report [1] the following statement is given:

*‘Discovery of a chemical element is the experimental demonstration, beyond reasonable doubt, of the existence of a nuclide with an atomic number  $Z$  not identified before, existing for at least  $10^{-14}$  s.*

*Note 1. This lifetime is chosen as a reasonable estimate of the time it takes for a nucleus to acquire its outer electrons. It is not considered self-evident that talking about an ‘element’ makes sense if no outer electrons, bearers of the chemical properties, are present.*

*Note 2. Discovery of an element can be based on chemical or physical methods or on both.*

*Note 3. The exact value of  $Z$  need not be determined, only that it is different from all  $Z$ -values observed before, beyond reasonable doubt.*

*Note 4. Neither is it required that the exact value of the mass number  $A$  be known. Even if a value for  $A$  is suggested that is later proved incorrect (but if an isotope with a nearby value of  $A$ , which could also have been produced, has the reported properties), this does not necessarily invalidate discovery of the new element.'*

*Supplement to 'Discovery'.* In its original sense, the term 'discovery' means to find something in nature, in our case an element, which is stable or has a long enough lifetime so that it could be discovered on earth, as e.g. the rare-earth elements or isotopes of thorium and uranium. So far, none of the heavy elements in the transuranium region were discovered, beyond reasonable doubt, in this way. Several previous claims of this type are not yet confirmed or were disproven in later closer inspection.

Since the first attempts to produce new elements beyond uranium, the term discovery is also used for the two-step process of, firstly, producing the new element in a nuclear reaction and, secondly, identifying that element by physical or chemical means. In this sense the term discovery means substantially the discovery that such nuclei are sufficiently stable so that they can exist, which is proven by production and identification.

*Supplement to Note 1.* The lifetime of about  $10^{-14}$  s seems to be a reasonable lower limit for what we want to call an element. On one side it is short enough for the arrangement of most of the electrons in the electric field of the nucleus and on the other side it is long enough so that a nucleus can be formed in its ground-state or in an isomeric state. Determination of a lifetime limit of that magnitude excludes shorter living transitional nuclear configurations, compound nuclei and/or nuclear resonances from being called an element, although X-rays or conversion electrons could be emitted from that system.

Related to this item is the meaning of radioactivity. Radioactive decays are generally understood as emission of nucleons, clusters of nucleons or SF of nuclei in the ground-state or an isomeric state. Also understood as radioactivity is the emission of leptons in the case of the transmutation of a proton into a neutron and *vice versa* due to weak interaction. When the same emissions occur as part of a reaction these processes are characterized with the supplement 'reaction', e.g. neutron evaporation reaction or quasifission reaction. The time scale of these processes is much shorter than  $10^{-14}$  s, but tails of some of these processes may extend up to that value.

*Supplement to Note 2.* It seems reasonable to split the term 'physical methods' into methods of 'atomic physics' and 'nuclear physics'. Atomic physics represents then the link between chemical and physical methods.

*Supplement to Note 3.* A more precise formulation of the statement given in Note 3 is 'The exact value of  $Z$  need not be determined, it only has to be proven beyond reasonable doubt that it is different from all  $Z$ -values observed before.'

Fulfillment of the requested conditions is certainly sufficient for assigning priority of discovery of a new element. However, circumstances may arise to prevent a name for an element whose element number is not known.

Realistically, the most convincing proof that the  $Z$  value of an element differs from all  $Z$  values observed before is the determination of its  $Z$  value. The situation that an element exists without knowing its  $Z$  value is probably only temporary. In this very specific case it seems reasonable to start with the naming procedure of such an element only when also the element number is definitely established.

*Supplement to Note 4.* An example for a discovery where the mass number  $A$  can be completely disregarded is the identification by X-rays or an unambiguous chemical identification. Such methods can be applied for the new element itself or for the elemental properties of its radioactive decay products, if the radioactive decays can be retraced unambiguously back to the predecessors, ideally back to the originally produced isotope of the new element.

It also could occur in an experiment that the value of  $Z$  can be determined but the value of  $A$  remains uncertain and is, therefore, only ‘suggested’ or ‘tentatively’ assigned. In this case a later correction of  $A$  does not invalidate the discovery of the new element. However, if both  $Z$  and  $A$  are claimed to be unambiguously determined in a first experiment and if, in particular, the determination of  $A$  was essential for assigning  $Z$ , but the assignment of  $A$  turns out to be incorrect later, it has to be verified by careful inspection if the agreement of  $Z$  with a later corrected result could be by chance. If this is the case, the first claim cannot be accepted as the discovery of a new element.

## 6.2 Criterion of time for assigning priority of discovery

An important criterion for assigning priority of discovery is the time of the discovery. The only safely retraceable earliest date and time which can be associated with a discovery is the date of submission of the recorded research work for publication. This date is called ‘time of discovery’ in the following. Irrelevant is the date and time when the actual observation was made, which is described in the publication, and also irrelevant is the date of publication.

The time criterion presents a clear preference for assigning priority of discovery in the case of two or more claims which both or all are convincing. However, special consideration is needed when the observations of two or more experiments have to be combined for deducing an unambiguous discovery of a new element. In such cases, discovery profiles need to be established by weighting and combining the observations of the different experiments. In this evaluation the time of discovery is one of the important criteria. In a particular case, it is the task of a JWP to work out the appropriate discovery profiles.

In the case of submission to a refereed journal it often occurs that a revised version is published. In critical assessments of two or more almost simultaneous publications it may become necessary that not the submission date of the first version is decisive but that of the revised version if significant modifications of the manuscript were performed. In those cases the JWP has to be provided with the different versions of the research work. Requests to the contents of the publication and means of publication will be presented in Sect. 7.

The particular weight of time of discovery is also expressed by the possibility to publish important results in the form of a letter or short note. Its date of submission can be accepted as time of discovery when the letter or short note contains all necessary information for judging the value of the observation. If this is not possible in a short letter, a more complete longer publication has to be published within a reasonable short time not longer than approximately one year so that the date of submission of the letter can be accepted as time of the discovery.

Confirmation experiments are desirable and sometimes necessary for assigning priority of discovery when a first result was not completely convincing. With the knowledge of the experiment parameters of the first experiment as, *e.g.* type of reaction and beam energy, it is usually easier to improve the amount and quality of the measured data in a follow up experiment. However, when the breakthrough to new results was obtained in the first experiment and those results were not disproven in follow up experiments, but principally confirmed, then priority of discovery has to be assigned to the first experiment due to the earlier time of submission of the result for publication.

In several cases in the past, see, *e.g.* the discovery of elements 107 and 108, important contributions from a second laboratory were considered as co-discovery. However, in practice it was always the case that the laboratory announcing a discovery first and presenting convincing data, was respected with priority of discovery and was asked to suggest a name for that element. The establishing of discovery profiles on the basis of weighted criteria for production and identification of a new element with particular consideration of the time of discovery should result in a unique determination of the priority of discovery.

Progress in research which includes the search for new elements is based on collaboration and friendship, but also on competition between research laboratories and scientists. As such it is a motivation for the researchers to continuously improve techniques and knowledge for discovering the new. Being honoured

with the assignment of priority is the prize that a research team can win. It is the outstanding task of future JWPs to work out with the use of the criteria developed by JWG and own careful inquiries the basis for clear decisions on the priority of discovery with particular consideration of the time of discovery.

The importance of time of a discovery, in this case of an exploration, was demonstrated by a dramatic example from the past in a completely different field. On December 14<sup>th</sup>, 1911, Roald Amundsen and his four companions arrived at the South Pole. They arrived 33–34 days before Robert Falcon Scott's team of also five people. Scott's group reached the Pole on January 17<sup>th</sup>, 1912, only to find that Amundsen had preceded them. 'The worst has happened'; 'All the day dreams must go'; 'Great God! This is an awful place'. Scott wrote in his diary. He and his team perished on the way back.

Many other examples can be found in the history of mankind where the time aiming for a discovery or an exploration was the driving force for the aims to extend the borders of knowledge.

### 6.3 Criteria related to genetic relation

Discovery of an element by genetic relations is the identification of one or more unknown nuclei by establishing a unique relation between the radioactive decays of those nuclei to known properties of one or more known descendants. Usually, the known properties of the known nuclei are those of their radioactive decays, but can be also other unambiguous characteristics like masses, X-rays or chemical properties.

However, genetic relations can be established also between radioactive decays of nuclei which are all unknown. This can occur when decay chains terminate by SF before the region of known nuclei is reached or if too long lifetimes or difficult to measure  $\beta$ -decays prevent tracking of the decay chain down to the region of known nuclei. In such cases an established genetic relation alone does not deliver reliable information, if nuclei of new elements were produced, although the used reaction and the properties of the measured  $\alpha$ -decays can provide strong hints.

*A priori*, such chains, if produced in a fusion reaction, could be the result of various nucleon or particle evaporations from a compound nucleus, *e.g.* xn, pxn,  $\alpha$ xn, *etc.*, which prevents rigorous assignment of the element number. The origin of a measured  $\alpha$ -decay chain without connection to known nuclei is even more uncertain if observed in a multinucleon transfer reaction. It even cannot be ruled out that new, either neutron rich or neutron deficient isotopes of already known elements have been produced.

In such cases the identity of one or more members of the measured decay chain has to be established by other identification methods. That could also affect two or more neighbouring decay chains in a new region of unknown nuclei, as it was the case in the discovery of the spherical SHN.

A definite element assignment of at least one of the unknown observed nuclei could be achieved by measurement of X-rays or  $\alpha$ -X-ray coincidences, see Sect. 6.8. Alternatively, element specific chemical identification can be performed if unknown isotopes of known elements are populated in the decay chain, see Sect. 6.11. In certain cases also precision mass measurements could result in an element assignment, see Sect. 6.7.

An effective limitation of the possible region of produced nuclei is obtained by comparison of the yields measured in experiments with separators of different separation characteristics, as *e.g.* gas-filled separators and velocity filters, see Sect. 6.6. Qualitatively similar information is obtained by measurements of excitation functions, see Sect. 6.5., which can be combined with a study of the systematics of decay properties of, *e.g.* neighbouring even-even and even-odd nuclei, see Sect. 6.9 on 'Criteria related to systematics of experimental results and theoretical predictions'.

However, the population of a previously observed unknown decay chain in a reaction using a two protons and two neutrons heavier target and the same type of beam particles, does not fix the element numbers of the origins of either or both of the two chains. It only confirms the existence of genetically correlated decays of unknown nuclei, whose parent isotopes are produced in the same reaction channel, namely xn, pxn,  $\alpha$ xn or any other reaction channel.

In any case, to safely establish a genetic relationship requires a number of prerequisites which we discuss in the following subsections.

### 6.3.1 Technical criteria for establishing genetic relations

Prerequisite for an efficient measurement of decay chains is the separation of the reaction products, in fusion reactions these are the evaporation residues, from other unwanted reaction products and from the beam. Separators in use are gas-filled separators or vacuum velocity or energy filters. After having passed a time-of-flight detector, the evaporation residues are implanted into an array of position sensitive silicon detectors, which deliver signals from the implantation and the subsequent  $\alpha$ -decays or spontaneous fission.

A second silicon detector behind the stop detector serves as a veto detector for rejecting high energy light particles, usually from reactions with the target backing, with isotopes of elements like oxygen in a compound target, and, in the case of gas-filled separators, from collisions with the atoms of the gas filling.

The silicon detectors can be surrounded by an array of germanium detectors for measuring  $\gamma$ - or X-rays. Modern experimental set-ups use fast digitizing of the detector signals so that part of the noise and pile-up can be recognized and rejected, if necessary. Time information, relative or absolute, when a signal was measured with the detection system, can be deduced with an accuracy of about 10 to 100 ns.

The momentum which evaporation residues obtain in a fusion reaction with relatively light beams like  $^{48}\text{Ca}$  results in an implantation depth of only a few micrometers into the silicon stop detector. Therefore,  $\alpha$ -particles and one of the fission fragments can escape into the backward direction leaving, however, an energy-loss and a time signal from which the lifetime of the decaying nucleus can be deduced. For measuring the full energy of those escaping  $\alpha$ -particles or fission fragments, the stop detector is surrounded by an array of silicon detectors in the backward direction.

Position sensitive detectors deliver, firstly, information on the ion optical settings of the separator and, secondly, they reduce the effective background rate due to the reduction of the effective detector area to the size of the pixel in which the evaporation residue was implanted. A meaningful minimum pixel size is given by the range of the  $\alpha$ -particles of about 70 to 100  $\mu\text{m}$ . A low background rate is essential for unambiguously tracking the decay chains over long periods.

Further reduction of the background can be achieved by switching off the beam as soon as an implanted evaporation residue and/or the first decays of a chain are detected. Similar background reduction is achieved in the case of pulsed beams from the accelerator. Alternatively, a shuttle of two detectors or the deflection of the separated ions onto two independent detector systems could be used. The latter systems would also increase the efficiency of the measurement compared to the method of turning off the beam.

From time-of-flight and energy of the implanted evaporation residue, a rough mass value can be deduced. The accuracy is about 10 to 20 % FWHM. This is sufficient for distinguishing evaporation residues and background particles from the beam, from elastically scattered target nuclei, and from most of the nuclei produced in multinucleon transfer reactions. An improvement of the accuracy of the mass determination, which is mainly given by the energy resolution of the silicon detectors, would be highly desirable. It could be achieved by, *e.g.* bolometric detectors having a higher energy resolution and, additionally, using longer flight paths.

The time-of-flight detector or a simpler version of a thin foil transmission detector allows for distinguishing signals from ions which are implanted into the stop detector from signals from the radioactive decays. For an efficient discrimination a high efficiency of the time-of-flight or transmission detector is mandatory. In the future, ion tracking ionization chambers may be capable of discriminating even atomic numbers of recoils transmitted to the focal plane detector system [75].

The great advantage of the implantation method is the high efficiency for detecting implanted particles of almost 100 %. The efficiency only depends on the size of the detector relative to the distribution of particles in the focal plane of the separator. The limitations of the total efficiency are mainly due to the efficiency of the preceding separator of about 5 to 50 %.

Limitations for short lifetimes are given by the flight time of the produced nucleus through the separator of approximately 1  $\mu\text{s}$  and for the subsequent radioactive decays by the rise time of the detector signals of about 10 to 100 ns. The limits for long lifetimes are given by the rate and energy of background signals. It can

be considerably extended by switching off the beam or using two independent detector systems as discussed before. Then, lifetimes of single decays of up to several days can be measured.

The relatively high energy from an  $\alpha$ -particle completely stopped in the detector or a SF event deliver pronounced, easily detectable signals. Low energy signals emerge from  $\alpha$ -particles which escape in backward direction without being stopped in the backward detectors. Such low amplitude signals can be lost due to an insufficient sensitive detection device. Then, as it occurred several times in the past, it was not completely clear if a presumably unobserved  $\alpha$ -decay is due to an  $\alpha xn$  evaporation channel or due to an  $xn$  channel and lost  $\alpha$ -particle. Experimental efforts are needed in order to avoid such ambiguities.

Using low noise detectors and carefully designed electronic circuits and modern digital signal processing, such low energy signals can be measured. These may not only occur from  $\alpha$ -particles escaping in backward direction, but also from conversion electrons from the decay of an isomeric state or an excited level which was populated in an  $\alpha$ -decay. Also accessible for a sensitive measurement are Auger electrons or soft X-rays emitted after EC or, in the case of a  $\beta$ -decay, the  $\beta$ -particle itself. The more complete the genealogy of a decay chain is measured, the more safe is the  $A$  and  $Z$  assignment of the decaying parent nucleus and thus the identification of a new element.

The before described experimental conditions yield a number of criteria which have to be considered for judging the quality of an experimental result claiming the discovery of an element. In addition to the implementation of all or parts of the described ideal experimental set-up, the quality of the results with respect to background suppression, detector resolution, noise, *etc.*, must also be evaluated. In addition, of importance for the evaluation are the control and stability of beam intensity and energy as well as the quality of the target before and during irradiation. In Sect. 7 we will compile which experimental details need to be given in a publication so that a meaningful evaluation of the results can be performed by the JWP of independent scientists.

### 6.3.2 Physical criteria for establishing genetic relations

The second part after the discussion of the technical prerequisites for measuring genetic relations considers the physical properties of the detected isotopes. Although  $\alpha$ -decay (besides radioactive emission of protons or neutrons) is the simplest decay process, and for many nuclei there exists a strong correlation between  $\alpha$ -energy and lifetime, nuclear structure can significantly influence the  $\alpha$ -decay properties of individual nuclei. In addition, statistical fluctuations of the measured  $\alpha$ -energy which is determined by the detector resolution and of the lifetime which is a consequence of the radioactive decay process need to be considered as criteria when decay chains are used for assigning priority of discovery of an element.

A measured small spread of the  $\alpha$ -energies seems a convincing argument for an assignment to the decay of a certain nucleus. However, an unreasonably narrow distribution has the same low probability as a broad distribution relative to the energy resolution of the detector. The same argument holds for the distribution of measured lifetimes. In a comparison of measured decay data from different experiments, but also of data from a single experiment, which were assigned to a certain nucleus, a comprehensive statistical analysis has to be performed in order to decide on the level of agreement or disagreement of the measured data. The role of statistical fluctuations influencing the grade of plausibility in an assignment process will be further discussed in Sect. 6.12.

Apart from statistical fluctuations, nuclear structure can significantly modify the transition probabilities of  $\alpha$ -decay, in particular in the case of odd- $A$  or odd-odd nuclei. In the region of heavy elements, already measured were  $\alpha$ -transitions starting at one parent level, which spread with comparable intensity across an energy window of up to about 1 MeV.

The measurement of different  $\alpha$ -energies could raise doubts in the assignment of those transitions to a certain parent isotope. Subsequent measurements at higher yield could reveal the actual conditions. In the case of genetically linked decays, a plain and well established decay mode of at least one of the members of the chain could result in an unambiguous assignment of other members of the chain, which have more

complicated decay patterns. A common lifetime within statistical fluctuations measured for all those transitions is another supporting argument for the assignment.

Concerning the assignment of priority of discovery, the measurement of different  $\alpha$ -energies should not be an obstacle to recognition of discovery, in particular, if these are expected in odd- $A$  and odd-odd nuclei and if later repetition experiments performed at higher yield confirm the first results.

Similarly, the measured  $\alpha$ -decay properties in the case of isomeric states could complicate a clear assignment in a first attempt. Unexpected long lifetimes for a high energy transition from the decay of the isomer together with expected, possibly also observed decays of the ground-state could result in a difficult to understand decay pattern. The data could be such that additional experiments are required. Also in such a case it seems justified to assign priority of discovery to the first experiment if its results are confirmed at higher yield in follow up experiments.

It can occur that discovery of a new element is claimed on the basis of a measured decay chain of which one or more decays of the descendants agree with established data but, in addition, as a new result a new decay branch, *e.g.* electron capture or SF, of one of the descendants is observed. Such a new result could prevent recognition of the discovery. However, if the observation is confirmed in later experiments, the result of the first experiment has to be accepted as the discovery of a new element.

Conceivable is a situation that the beginning of a chain marking the decay of an isotope of a new element is genetically linked to one or more known daughters. However, a long lived decay at the end of the chain was erroneously assigned as found out in subsequent experiments. For such or similar more complicated situations strict rules cannot be meaningfully established in advance. A decision will depend on the weight that the first experiment has been given to that long lived terminating nucleus for identification of the whole decay chain. If the decay properties of this nucleus were essential for assigning the whole decay chain and later experiments reveal an erroneous assignment of this specific nucleus, then assignment of the whole decay chain must be questioned.

A relatively low weight should be given to the observation of the shortest thinkable genetic relation measured for an implanted evaporation residue and subsequent SF. A combination of criteria obtained from different measurements has to be applied for achieving a reliable discovery profile for a unique assignment.

It seems reasonable to expect that identification of new elements via genetic relations between decaying nuclei will be of major importance in future experiments. In those experiments the measurement of decay chains occurring between ground-states of even-even nuclei will deliver the least complicated results. Then, the observation of only one decay chain may be sufficient for assigning priority of discovery of an element. In the case of odd- $A$  or odd-odd nuclei, the decay paths can be more complicated, but also then, one chain should be sufficient for assigning discovery of an element. Confirmation can be waived if an investigation of all details of the experiment and analysis leaves no doubt on the correctness of the result. Such a 'one event rule' without confirmation for assigning priority of discovery of an element relies on the fact that the genetically linked daughter decays had been safely identified before in one or more other experiments.

The formation of the sum of  $\alpha$ -energies from the subsequent decays of nuclei within a chain has no significance in the case of odd- $A$  or odd-odd nuclei if the complete decay path including intermediate electromagnetic transitions is unknown. In the case of even-even nuclei already the individual  $\alpha$ -energies reveal agreement when the transitions occur between ground-states. Forming the sum of  $\alpha$ -energies is then superfluous. However, different  $\alpha$ -energies can occur also for decays of even-even nuclei when low energy rotational levels or isomeric states are involved. Observations of this kind do not constitute an obstacle for assigning priority of discovery.

The criterion of genetic relation between decays of nuclei of a decay chain, if used for assigning priority of discovery of an element, is unequivocally connected to established decay properties of one or more known nuclei of the descendants. Assigning a new element on the basis of such genetic relations has to be precise in both  $A$  and  $Z$ .

However, a correct assignment of the mass number  $A$  can be prevented if, *e.g.* the decay properties of the known nuclei of neighbouring chains are similar within detector resolution. Their mass numbers could have been determined, *e.g.* by additional measurement of excitation functions. In such a case an assignment of  $Z$  can be correctly given but the mass number  $A$  can be only suggested or tentatively given if no additional information, *e.g.* from the measurement of excitation functions is available. In these or similar cases a tentatively given mass number  $A$  does not prevent assigning priority of discovery of an element.

If the genetic relation is based on the decay of one or more isotopes of which the element affiliation is based on measurement of X-rays or unambiguous chemistry, then an assignment of the mass number  $A$  is irrelevant. It is not advisable to assign a mass number  $A$  to an isotope of a potential new element if  $A$  is not definitely determined.

### 6.3.3 Genetic relations used for identification of elements 107 to 118

The method for establishing genetic relations is highly efficient in experiments at recoil separators in studies of regions of the nuclear chart, where  $\alpha$ -decays are the dominant decay mode, and the lifetimes are within a time window from microseconds to some hundreds of seconds. These are the optimal decay properties of nuclei allowing for a safe identification of chains of correlated  $\alpha$ -decays using position sensitive silicon detectors. Such ideal conditions were the requirement for the successful identification of elements from 107 to 118.

In those experiments the decay chains assigned to the elements from 107 to 113, see Table 1 and Fig. 1, belong to the class of chains where the decay properties of nuclei at the end of the chain were already known. These known nuclei act as so called anchor nuclei for identification of the decays of unknown nuclei. In favourable cases only one measured decay chain was sufficient for discovery of a new element. To date the longest chains consisting of six subsequent  $\alpha$ -decays were measured for  $^{277}\text{Cn}$  and  $^{278}\text{Nh}$ .

Similarly long chains have been observed for elements 116 and 117 descending from  $^{291}\text{Lv}$  and  $^{294}\text{Ts}$ . However, all of the genetically related nuclei of decay chains measured in the discovery experiments of elements 114 to 118 do not end in the region of known nuclei, see Table 1 and Fig. 1. Applying the criteria which are compiled in this work to the results of the discovery experiments performed at FLNR and of the confirmation of those experiments and to new results obtained at other laboratories up to now, the following conclusion can be drawn.

Firstly, an assignment of the decay chains  $^{283}\text{Cn} - ^{279}\text{Ds}$  and  $^{292}\text{Lv} - ^{288}\text{Fl} - ^{284}\text{Cn}$  could be achieved due to the comparison of the yields measured at the gas-filled separator DGFRS and the velocity filter SHIP and due to the agreement of the decay data measured in both experiments. The usefulness of the different efficiencies for separation of fusion products from xn and pxn,  $\alpha$ xn reactions and products from multinucleon transfer reactions for distinguishing the products of these reactions will be presented in Sect. 6.6. The nuclei of the two decay chains given before were observed with the same yield at both separators. They served as anchor nuclei in the new region of SHN. The relevance of  $^{292}\text{Lv}$  and  $^{283}\text{Cn}$  and their descendants as anchor nuclei has been substantiated in independent work recently using the RIKEN gas-filled separators GARIS [76] and GARIS-II [77], respectively.

Secondly, discovery profiles based on genetic relations, excitation functions, cross reactions, systematics of odd-even effects of the decay properties, and the exclusion principle resulted in an unambiguous assignment of most of the other decay chains of SHN observed so far and, thus, of the new elements 115, 117, and 118.

In conclusion we state that genetic relations represent a safe criterion for assigning discovery of a new element in cases where the genealogy can be traced to at least one known descendant and the measured data are of sufficiently high quality that an unambiguous assignment is possible. In the case of decay chains consisting totally of unknown nuclei, additional investigations or measurements are

needed so that additional criteria can be applied for safely assigning priority of discovery. The comprehensive set of data measured for elements 114 to 118 allowed for determining priority of discovery of that elements.

### 6.3.4 Expectations for discovery of elements 119 and 120 based on genetic relations

Based on the present knowledge of nuclear reactions and stability of heavy elements, it is most likely that the next new elements that will be produced are elements 119 and 120. With a beam of  $^{48}\text{Ca}$  the needed targets would be  $^{254}\text{Es}$  and  $^{257}\text{Fm}$ , respectively. Those materials are not available in sufficient quantities. Therefore, heavier beams of isotopes of elements from scandium to manganese have to be used. The evaporation residues produced with those beams and targets of the most neutron rich actinides are listed in Table 2. The evaporation residues are located in a region where  $\alpha$ -decay is expected to be the main decay mode with high probability. Consequently, well established decay chains will be populated and a safe identification of the measured decay chains seems reasonable.

Most of the chains start with one, two or three unknown  $\alpha$ -decays. After that in most cases already known  $\alpha$ -decay chains are populated, which terminate by known fissioning nuclei. Exceptions are the two decay chains starting at  $^{293}\text{119}$  and  $^{296}\text{120}$  where only the terminating fissioning nuclei are known. In two cases, the expected decay chains starting at  $^{299}\text{119}$  and  $^{300}\text{119}$ , all the members are unknown.

According to the estimates given in Table 2, it seems likely that elements 119 and 120 can be safely identified by genetic relations to known nuclei. However, there still exists uncertainty related to nuclear structure. Difficult to predict are the currently unknown  $\alpha$ -transitions into excited levels, in particular in odd- $A$  and odd-odd nuclei, the existence of isomeric states, and unexpected high fission probabilities which could result in an early termination of the decay chains. Problematic could also be the insufficiently studied electron capture decay mode of some of the longer living isotopes.

Experiments using fusion reactions of beams just above  $^{48}\text{Ca}$  and available neutron rich actinide targets are a continuation of the experiments which led to the detection of isotopes on the island of stability and the discovery of elements from 114 to 118. Isotopes of the new elements 119 and 120 are expected to be located on the upper end of that island. They have a high probability to decay by  $\alpha$ -emission into now known nuclei, which probably will result in a safe identification of the new elements. However, so far unknown nuclear structure effects may complicate the decay characteristics so that for a safe identification of those elements several subsequent experiments may become necessary. In that case, in turn, it will be the task of a future JWP to assign priority of discovery on the basis of discovery profiles.

## 6.4 Criteria related to cross-reactions

Cross-reactions were considered as ‘*valuable assignment criteria*’ in the 1991 TWG report [1]. The definition is based on a ‘*comparison of the probability of production of a nucleus  $(A,Z)$  in different combinations of  $(A,Z)_{\text{target}}$  and  $(A,Z)_{\text{beam}}$* ’.

In the past and still in the 1991 TWG report the term ‘cross-bombardment’ was used. For understandable reasons we suggest to use the term ‘cross-reaction’ instead. For similar reasons, we prefer the notion ‘beam’ or ‘beam particle’ instead of ‘projectile’, whenever possible.

In the ideal case of cross-reactions the same compound nucleus is produced in at least two different combinations of beam and target resulting in the same evaporation residue. In these cases the lines in the chart of nuclei connecting the beam and the target nuclei are crossing which gave the name to these types of reactions. An example is  $^{22}\text{Ne} + ^{248}\text{Cm}$  and  $^{26}\text{Mg} + ^{244}\text{Pu}$ , both resulting in the compound nucleus  $^{270}\text{Sg}$ . Beam energies can be chosen so that also the same excitation energy is obtained. Only slight differences exist in the distributions of the angular momenta if similar beam-target combinations are used.

The main difference between the two constituents of a cross-reaction is related to differences in the entrance channel. At the time of the 1991 TWG report it was well known that in reactions with light beams the probability is relatively high for pre-compound  $\alpha$ -emission or even a more vigorous breakup of the beam particle followed by incomplete fusion. Nuclear structure of the beam particles as, *e.g.* cluster effects determine the probability for such break-ups. Therefore, one could expect that those break-up reactions occur with different probability when different light beams are used giving information on the reaction mechanism and thus the produced nuclei or elements. The quantity of information is enhanced when, in addition, angular and/or velocity distributions of the evaporation residues and excitation functions are measured. The results from such a complex of measurements will result in a valuable assignment criterion for the discovery of a new element. This means to experimentally distinguish xn, pxn,  $\alpha$ xn evaporation channels and pre-compound particle emission and incomplete fusion.

The before given definition of the term cross-reaction is very strictly related to the production of the same compound nucleus using different combinations of beams and targets. However, the definition can be extended so that it means the production of the same nucleus and its subsequent decay chain using any reaction, including the secondary production via radioactive decays. For all reactions and radioactive decays except  $\beta^-$ -decay, this has the simple consequence that the observation of a nucleus  $(A, Z)$  must have an atomic number  $Z$  less than or equal to the sum  $Z_{\text{beam}} + Z_{\text{target}}$ . If, *e.g.* a new nucleus  $(A, Z)$  is observed in a reaction with  $Z_{\text{beam}} + Z_{\text{target}} \leq 118$ , this nucleus cannot be an isotope of a new element, taking into account that the presently (2018) heaviest known element has the element number  $Z = 118$ .

The new definition is reasonable for two reasons. Firstly, new elements beyond  $Z = 118$  will not be produced in fusion reactions with light beams where pre-compound particle emission and incomplete fusion play a major role. So far, in cold fusion with beams from isotopes of calcium up to zinc and in hot fusion with beams of  $^{48}\text{Ca}$  strong components of such reactions were not observed. In these cases, beams in the vicinity of  $^{48}\text{Ca}$  and actinide targets, multinucleon transfer and quasifission have relatively high cross-sections but the products of those reactions were dominantly observed in the area close to the target nuclei and not in the region of elements beyond rutherfordium. Secondly, in possible future experiments using multinucleon transfer reactions with significantly heavier beams as, *e.g.*  $^{238}\text{U}$ , the assignment of the atomic number could be restricted using different combinations of beam and target with gradually decreasing sums of  $Z_{\text{beam}} + Z_{\text{target}}$ .

The following examples are intended to elucidate the new definition of cross-reactions and the resulting criteria which can be applied for assigning discovery of a new element.

Firstly, we consider two reactions with the same light beam but different targets, *e.g.*  $^{22}\text{Ne} + ^{244}\text{Pu}$  and  $^{22}\text{Ne} + ^{248}\text{Cm}$ , resulting in the compound nuclei  $^{266}\text{Rf}$  and  $^{270}\text{Sg}$ . In both cases the beam particle will contribute in a same way to the reaction. Information related to differences in the entrance channel like pre-compound  $\alpha$ -emission cannot be obtained. From the result the trivial conclusion is obtained that with the two protons heavier target a two protons heavier evaporation residue is produced, which must, in the case of  $\alpha$ -decay, populate the decay chain produced with the lighter target. This determines via genetic relation only the  $Z$  when the  $Z$  of at least one of the daughter products is already known.

In recent JWP reports the term cross-reaction was already used in the sense of our new definition. Reactions using a  $^{48}\text{Ca}$  beam and targets with atomic numbers differing by two units were called cross-reactions. It was considered as a strong criterion for assigning discovery of a new element when the decay chain produced with the lighter element target was populated by  $\alpha$ -decay of an isotope produced with the heavier element target. However, such a conclusion is only justified when the decay chain starting at the isotope of the lighter element is already well established. But then the criterion of genetic relations has to be applied.

Related to the item of cross-reaction is the production of the nucleus  $(A, Z)_{\text{ER}}$  with the same beam but different target isotopes, *e.g.*  $^{242}\text{Pu}$  and  $^{244}\text{Pu}$ , at different beam energies in different xn-evaporation channels. Also such a combination is not a cross-reaction in the old definition, but it is using the new definition given here. A closer inspection of the results which are obtained from the reactions using two different target isotopes reveals that the obtained information is closely related to the criterion of excitation function which is discussed in Sect. 6.5.

A similar but slightly more complicated scenario is given by the two reactions  $^{48}\text{Ca} + ^{242}\text{Pu}$  and  $^{48}\text{Ca} + ^{245}\text{Cm}$  resulting in the compound nuclei  $^{290}\text{Fl}$  and  $^{293}\text{Lv}$ , respectively. The nucleus  $^{287}\text{Fl}$  can be produced in a 3n evaporation channel from  $^{290}\text{Fl}$  or as  $\alpha$ -decay daughter of  $^{291}\text{Lv}$  which originates from a 2n channel in the reaction with the  $^{245}\text{Cm}$  target.

These two reactions are an example where the influential arguments for an element assignment are based on the different excitation energies of the compound nuclei in the two reactions, arguments which belong to the category of excitation function. Again, arguments for assigning discovery of the two protons heavier element are only due to genetic relations if at least one of the daughter products is known, but not from the fact that with the curium target a two protons heavier element is produced. In the given example the recognized anchor nucleus was  $^{283}\text{Cn}$ , the  $\alpha$ -decay daughter of  $^{287}\text{Fl}$  which resulted in the assignment of priority of discovery of, firstly, element 114 and, then, of element 116. Without that previously recognized nucleus  $^{283}\text{Cn}$  the application of the cross-reaction criterion alone would not contribute arguments for the discovery of the new element 116.

## 6.5 Criteria related to excitation functions or yield curves

Requirements for the measurement of high quality excitation functions are monoisotopic beams of well-defined energy, a reliable determination of the beam dose, a monoisotopic target material, homogeneous targets of known thickness resulting in energy loss less than the width of the excitation function, a precise control of possible changes of the target during irradiation at usually high beam intensities, and eventually, a detection technique of well-known efficiency. The knowledge of the efficiency is not needed for the measurement of yield curves. Yield curves compare the number of identified isotopes relative to each other as function of the beam energy or other properties, as, e.g. the ion optical settings of a separator. For the measurement of yield curves the stability of the whole measuring system is mandatory.

The greatest obstacle for measuring excitation functions of SHN is the low production yield. If only one or a few atoms are produced in measuring times of several weeks, the statistical error bars are large and the accuracy is usually insufficient for determining height, width, and position of an excitation function. Nevertheless, such measurements were performed in several cases of cold and hot fusion reactions, see review articles [8, 11, 78].

The results on hot fusion revealed that the excitation functions of the 3n and 4n channels have the highest maxima and a reasonable width of about 10 MeV as expected from many other measurements for lighter elements at comparable excitation energy. The positions of the maxima of the excitation functions at 35 to 40 MeV do not differ significantly so that the evaporation of three or four neutrons cannot definitively be determined. The physical reason for overlapping excitation functions is given by the energy of the fusion barrier, which cuts the fusion probability on the low energy side thus producing a maximum of the 3n channel at higher energy than expected without a barrier suppression of fusion. The same argument holds for the 2n channel which is even more significantly cut by the fusion barrier. At higher energies, only few values at excitation energies of 45 to 50 MeV were measured for the 5n channel.

Valuable for an isotopic assignment is a comparison of results measured, e.g. with a beam of  $^{48}\text{Ca}$  and targets of the same  $Z$  but different  $A$ , e.g.  $^{242}\text{Pu}$  and  $^{244}\text{Pu}$ . In that case an evaporation residue, in the example it could be the already known isotope  $^{287}\text{Fl}$ , can be produced in a 3n channel with  $^{242}\text{Pu}$  and it could be observed at higher beam energy with the  $^{244}\text{Pu}$  target in a 5n channel, but then at lower cross-section. If this turns out to be the case it is a strong criterion that in both reactions the evaporation residue was produced in xn or pxn evaporation channels. Energetically possible  $\alpha$ xn channels would reveal a different trend. Due to the higher Coulomb barrier for  $\alpha$ -emission the  $\alpha$ xn cross-section would increase with increasing beam energy in this range of excitation energies.

*A priori*,  $\alpha$ -evaporation is not an energetically forbidden evaporation channel in the region of SHN. When new regions in the chart of nuclei are being explored experimentally, also this option has to be considered. Then, the sole measurement of yield curves with expected low number of events is not sufficient to

unambiguously distinguish xn, pxn or  $\alpha$ xn channels. Therefore, additional criteria must be considered for assigning priority of discovery of a new element.

A prominent example is the discovery of the new elements flerovium and livermorium located in the, at that time, unexplored region of spherical SHN with no connection via decay chains to known nuclei. In these cases, the element numbers 114 and 116 were unambiguously determined applying the discovery profiles as outlined in [21, 22].

In follow up experiments using hot fusion with beams of  $^{48}\text{Ca}$ , a possible evaporation of  $\alpha$ -particles from the compound nucleus was not established. Failed observation of decay  $\alpha$ -particles from a parent nucleus produced in a supposed xn channel could be reasonably explained by technical deficiencies. Therefore, the stricter rules related to the application of the criterion of yield curves, which have to be applied on results exploring new regions in the chart of nuclei, can be relaxed when sufficient experimental results are already available. As recent examples we mention the discovery of new isotopes of elements flerovium and livermorium and the discovery of the new elements moscovium, tennessine, and oganesson after the production of the first isotopes of flerovium and livermorium was acknowledged.

Valuable information in relation to excitation functions can be obtained from experiments when the beam energy is deliberately chosen unusually high or low. The then obtained negative results can be considered as criterion for the production of observed nuclei in a fusion-evaporation process at the proper beam energy and that within the statistical relevance the positive result was not produced randomly. In particular, a production of isotopes in multinucleon transfer reactions could be excluded. Their excitation function differs considerably from that of a fusion-evaporation reaction. Prerequisite for the application of these arguments are the sufficiently high isotopic purity of beam and target and a mono-energetic beam.

The excitation functions of cold fusion reactions are located at excitation energies between 10 and 20 MeV for the 1n and 2n evaporation channel [11, 79]. Their width is only about 4.5 MeV. In future studies of cold fusion an interesting phenomenon would be the observation of a 0n channel, e.g. a radiative capture process. Although cold fusion may not be the choice for producing new elements, further studies are highly important for the understanding of the reaction mechanism in particular with beams of more neutron rich radioactive isotopes which will be available in the future.

## 6.6 Criteria related to properties of heavy ion separators

The sole method for separation and partly also for identification of the first transuranium elements was chemistry. Later, mechanical transport systems like wheels, tapes or gas transport systems were used to carry the activity in front of or between radiation detectors. This way the elements from lawrencium ( $Z=103$ ) to seaborgium (106) were discovered. Such systems were relatively slow. Already the measurement of lifetimes of a few milliseconds turned out to be problematic. For separation of products from different reactions only the range in the stopping material could be used. The criteria established in 1991 [1] took in particular into account those separation and identification methods for assigning priority of elements from 101 to 106.

A breakthrough in the direction of shorter lifetimes and efficient separation was achieved with the development of electromagnetic separators for in-flight separation of the reaction products in the middle of the 1970s. The first new elements which were discovered with the new technique were the elements from 107 to 109 measured at SHIP [8]. At that time, the 1993 TWG report called it a '*very sophisticated technique*'. The results were so convincing that TWG assigned priority of discovery of element 109 to the SHIP group '*even though originally only one event was observed*'.

Since that time, in-flight separation by electromagnetic devices, both vacuum and gas-filled separators are in use, and implantation into position sensitive detectors became the standard tool in research on new elements. All new elements from 107 to 118 were produced using this method. The sensitivity was improved not only with respect to measuring short lifetimes, but also with respect to measuring production yields with cross-section of about one picobarn and even below. It seems reasonable that the sensitivity can be

**Table 3:** In-flight separators used or under construction for SHN and SHE research.

Vacuum separators	$\Omega$ /msr	$\Phi_B$ /deg $\Phi_E$ /deg	$B\rho$ /T m	$F\rho$ /MV
Kinematic separators				
LISE-3 Wien filter [85] <sup>a)</sup>	–	Cross-fields	–	–
SHELS, FLNR [86] <sup>b)</sup>	5.5	–8 +16 –16 +8 +37	1	10
SHIP, GSI [87]	8	–6 +12 –12 +6 –7	1.2	20
VASSILISSA, FLNR [88] <sup>b)</sup>	15	–8 +16 –8 +37	1	26
Recoil mass separators				
FMA, ANL [89]	8	–20 +40 –20	1.0	18
MARA, JYFL [90]	10	–20 +40	1	14
S3, GANIL [91] <sup>c)</sup>	9	+22 +22 –25 –22	1.8	12
Gas-filled separators				
BGS, Berkeley [92]	45	–25 –45	2.5	
DGFRS-I, JINR [93]	10	–23	3.1	
DGFRS-II, JINR [94] <sup>c)</sup>	–	+30 +10	3.2	
GARIS, RIKEN [95]	12	–45 –10	2.16	
GARIS II, RIKEN [96]	18	–30 –7	2.43	
RITU, JYFL [97]	10	+25	2.2	
SHANS, LANZHOU [98]	25	+52	2.9	
TASCA, GSI [99]	13	–30	2.4	

a) Maximum electric tension is  $\pm 250$  kV, maximum magnetic flux density is 0.1 T.

b) The energy filter VASSILISSA was modified to the velocity filter SHELS in 2015.

c) Under construction.

The table displays the angular acceptance,  $\Omega$ , in msr and the dispersive elements listed with the deflection angles  $\Phi_B$  and  $\Phi_E$  in degrees. The subscripts B and E distinguish deflection in a magnetic field B and in an electric field E, respectively. Deflection by magnetic and electric fields is given in black and red, respectively. Plus and minus signs indicate deflection to the left and to the right, respectively, with respect to the beam direction. The first dispersive element of the separators is given to the left. The maximum beam rigidities  $B\rho$  in Teslameter (T m) and  $F\rho$  (red) in Megavolt (MV) are also given. The slightly modified table was taken from [84].

further improved, which recommends this method for heavy element research also in the future. Therefore, the presently used technique is described in more detail in the following. The description of the identification techniques at separators was presented in Sect. 6.3.1 on ‘Technical criteria for establishing genetic relations’.

In-flight separation by electromagnetic devices uses primarily the different momenta and ionic charge states of the ions participating in nuclear collisions or reactions. The main advantage is the fast separation time of approximately 1  $\mu$ s. In addition, the separation is independent from chemical properties of the produced species, except a weak dependence of the ionic charge state of low velocity ions in a gas filled separator [80]. Different research aims and other boundary conditions demanded different designs of in-flight electromagnetic separators. Table 3 lists those presently in operation or under construction.

In the case of fusion reactions, the momentum of the projectile is fully transferred to the momentum of the compound nucleus. During de-excitation of that excited compound nucleus, its momentum is changed by the recoil from the emitted neutrons, protons, and/or  $\alpha$ -particles. The momentum of the resulting evaporation residue being in the ground-state or in an isomeric state, is modified by energy loss and straggling in the remainder of the traversed target layer. Eventually, the mean electric charge state of the evaporation residue and the charge-state distribution is determined by its velocity and the properties of the material covering the target downstream.

A complication arises in the case that the evaporation residue leaves the target in an isomeric state having a lifetime less or comparable to the flight time of the evaporation residue through the separator. De-excitation of the isomer can result in a considerable increase of the charge state by emission of conversion and Auger electrons. A sudden change of the charge state inside the electromagnetic fields of a vacuum separator results in a change of the ion optical trajectory and, possibly, in complete loss of those evaporation residues. The effect is less critical in the case of gas-filled separators.

In the case of lifetimes of the isomer shorter than the time needed for entering the first ion optical element of the separator, which is generally about 10 to 100 ns, this phenomenon can be avoided by placing a charge reset foil, *e.g.* 20  $\mu\text{g}/\text{cm}^2$  carbon foil, between target and first ion optical element of the separator. A further advantage of such a foil is the increase of the charge state of the beam particles which could pass the thin target through pin holes. Without such a foil the relatively low charge state of the beam particles from the accelerator results in high electromagnetic rigidity and thus increased background behind the separator in the zero degree direction. Due to the relatively high velocity of the beam particles, this latter kind of background is effective also when gas-filled separators are used.

The main purpose of the separator is an efficient suppression of beam particles and of unwanted reaction products. In experiments searching for evaporation residues produced in complete fusion reactions, all other reaction products as those from multinucleon transfer reactions and fission of the compound nuclei appear as background. Unwanted background particles also arise from beam particles traversing the target without reaction and from elastically scattered target nuclei.

Basically two separator types can be distinguished, vacuum and gas-filled separators. The main differences are related to the different charge states of all ions entering the focusing and separating fields, which result in different properties for separation.

The arrangement of magnetic and/or electric fields in the case of vacuum separators allows for separation in velocity (SHIP, SHELS), energy (VASSILISSA) or mass (FMA, MARA, S3), see Table 3. The advantage of velocity filters for separation of evaporation residues is given by the fact that evaporation residues have a well-defined velocity which is different from all other reaction products and the beam particles. In the ideal case of combined electric and magnetic fields the separation is independent from charge and mass, which is a major advantage in the case of isomers decaying inside the separator by emission of conversion electrons or Auger electrons. At separated magnetic and electric fields such decaying isomeric evaporation residues which rapidly increase the charge state to a high value will most likely hit the walls of the vacuum chamber. The range of accepted velocities can be adjusted so that transmissions of 5 to 50 % are obtained.

Varying the fields of the filter allows for measuring the velocity distribution of reaction products. This way pre-compound emission of  $\alpha$ -particles from light beams, emission of  $\alpha$ 's from the compound nuclei or nuclei produced in multinucleon transfer reactions can be distinguished from evaporation residues produced in xn or pxn reactions. In the particular case of  $\alpha$ -emission from the compound nuclei, the yield of the evaporation residues as function of the velocity has a minimum at the velocity of the compound nucleus [81, 82]. The reason is that in the case of  $\alpha$ -emission perpendicular to the trajectory, the recoiling evaporation residue will not enter the acceptance angle of the separator. Alphas emitted in or opposite to the beam direction transfer momentum to the recoil nucleus so that its velocity is no longer within the accepted range if this is adjusted for velocities of the compound nucleus, *i.e.* evaporation residues from xn or pxn reactions.

The basic idea for developing gas-filled separators lies in the fact that in collisions of the reaction products with the atoms of the gas, the reaction products with velocity  $v$  continuously change the ionic charge state so that the ions of element number  $Z$  carry a mean charge state  $q$  proportional to  $v \times Z^{1/3}$  when traversing the gas volume. In general, helium or hydrogen is used as the gas filling at a pressure of 50 to 100 Pa (0.5 to 1 mbar).

Because the deflection of ions of mass number  $A$  in a magnetic field is proportional to  $v \times A/q$ , we obtain a velocity independent deflection in the magnetic dipole field of a gas-filled separator being proportional to  $A/Z^{1/3}$  [83]. As  $A/Z$  is roughly constant in the region of heavy isotopes, the deflection in a magnetic field is proportional to  $A^{2/3}$  and independent from velocity and ionic charge state. Therefore, the transmission through a gas-filled separator is high, particularly in reactions with light beam particles where the relative velocity spread and relative charge distribution of the evaporation residues escaping from the target is broad [82].

Another advantage is the simplicity and low cost of such a separator. Disadvantages of the  $A^{2/3}$  separation include the higher background in particular of target-like transfer products in irradiation of heavy target nuclei with light beam particles. Another drawback is given by the fact that gas-filled separators do not sufficiently discriminate between evaporation residues produced by evaporation of nucleons from  $\alpha$ xn channels or products of incomplete fusion.

At sufficiently high number of events, discrimination between xn or pxn and  $\alpha$ xn channels can be achieved with a velocity filter by measuring the velocity distribution of the reaction products. A comparison of the cross-sections measured with a kinematic separator with field settings appropriate for the velocity of xn channels with the cross-sections measured with a gas-filled separator may already be sufficient for discrimination. Measurement of the complete velocity distribution is not needed. However, pxn channels cannot be distinguished from pure xn evaporation channels, though the recoil from an emitted proton is too small to drive the recoiled nucleus out of the velocity window. Whether elements with odd or even proton numbers are produced in xn and/or pxn reactions could be determined using the criteria of genetic relations, systematics of odd particle hindrance, X-ray or high precision mass measurements.

Useful information for distinguishing xn, pxn channels from  $\alpha$ xn channels and multinucleon transfer reactions can be also obtained by a change of the separation properties of the separator. This procedure can be applied for vacuum as well as gas-filled separators. The separation and suppression properties of a separator can be modified mechanically by changing collimating elements within the separators or ion optically by modifying the field settings. At gas-filled separators, *e.g.* a high resolution mode and a high efficiency mode can be obtained using different settings of the focusing quadrupole elements.

Of essential importance for the quality of separation is the quality of the beam and the target. Particles in a beam halo will hit the target frame or beam diagnostic elements, where they are scattered and lose energy, both effects resulting in an increase of the background of beam particles behind the separator. Similar effects arise from admixtures to the beam of other isotopes or other beam energies than the nominal value.

Inhomogeneous targets or changes of the structure of the target during irradiation at high beam intensity results in unwanted and often uncontrolled changes of background and transmission. Essential is a continuous control of the target. Location of the target and size of the beam spot have to be adapted to the properties of the separator. *E.g.* high intensity beams demand a larger size of the beam spot whereas small beam spots result in better performance of the separator.

Other technical problems to be solved when using high intensity beams is the heating of the target which eventually could result in melting or evaporation of the target. The unavoidable sputtering of atoms or clusters of atoms from the target surfaces is another destructive phenomenon. The use of rotating target wheels was a step in the direction of using higher beam intensities.

Further improvement of the separators is possible. Larger sizes of the focusing elements and larger gaps of the deflecting fields will increase the transmission. The background can be reduced by installing additional ion optical elements or using a tandem of vacuum and gas-filled separators.

The efficiency or transmission is an important but difficult to determine property of a separator. It is essential for calculation of the cross-section, and high efficiencies simply save expensive beam time. In general, the efficiency must be determined for each specific experiment. It depends on the reaction and thickness and composition of the target. These items determine values and widths of velocity, charge, and angular distribution of the reaction products being ejected in the direction of the separator. Whereas the trajectories inside the separator of particles with known properties can be calculated safely, uncertainties arise from the properties of ions, in particular of those of isotopes of new elements, escaping from the target. All these items result sometimes in erroneous and misleading information on efficiency values of specific separators given in the literature. In addition, there has been a tendency to be optimistic when describing the efficiency of separators.

Most influential on momentum and charge state of ions and thus on efficiency calculations is the target thickness itself. Small widths of both momentum and charge state distribution of the ions and thus high efficiency values are obtained with thin targets ( $0.1 \mu\text{g}/\text{cm}^2$  or less). However, in this case the yield of produced nuclei is small. Optimum values for the target thickness are in the range from  $0.4$  to  $1.0 \text{ mg}/\text{cm}^2$ . Then, the angular acceptance is less due to scattering of reaction products in the thicker target layer, but the number of produced nuclei is significantly higher.

The measurement of efficiencies is difficult and time consuming in the case of small cross-sections. Accurate and systematic data were obtained for the gas-filled separator RITU in Jyväskylä [100]. Gamma rays from the de-excitation cascade of the evaporation residue were measured directly at the target with Ge detectors in

singles mode and in coincidence with evaporation residues behind the separator. In this case the efficiency of the detector system behind the separator is also included.

Other measurements of the efficiency used catcher foils or tape transport systems mounted directly behind the target. The caught and transported activity is measured off-line and is then compared with the activity measured behind the separator. However, these methods are applicable only for radioactive decays with relatively long lifetime ( $\geq 1$  s) and high production rates because all other reaction products contribute as background to the stopped and unseparated activity.

Finally, we mention isotope separators on-line, so called ISOL systems. In these systems the reaction products are stopped and escape at low charge states from the heated stopping device by evaporation or from an ECR-ion source as used in more recent devices. The ions are accelerated by a DC electric tension of about 30 to 100 kV and enter a separating magnetic dipole field with well-defined momentum which results in a mass resolution  $m/\Delta m$  of several thousand. Although these devices were very successful in discovery of many exotic isotopes, they were not used in recent discoveries of new elements. The main reasons are the relatively low efficiency, the relatively long time for extraction of the ions from the ion source, and the dependence on chemical properties.

Extensions to kinematic separators, which resulted in new applications in recent years, are devices for high resolution mass measurements like ion traps or multi reflection time-of-flight (MRTof) mass spectrometers. Before the reaction products enter the measuring devices, they need to be stopped in a gas catcher from which they are extracted by electric fields of a few Volts per centimetre. These gas filled chambers, which by themselves can be used for a number of physical and chemical investigations, unfortunately reduce the efficiency of these devices. More details related to the possibility for identification of the element number using precision mass measurements will be presented in the following Sect. 6.7.

## 6.7 Criteria related to precision mass measurement

The following text is taken from the 1991 TWG report [1]:

*'A well calibrated mass spectrometer with a resolution significantly better than 1/2 mass unit can yield an excellent criterion for assigning the mass number of the reaction products. One should, of course, be certain that one does not accidentally observe molecular fragments with the same  $\Sigma A$ .*

*Although in ion sources for mass spectrometry some chemical differentiation occurs, no useful information concerning  $Z$  can be drawn from  $A$ , except of course that an exceptionally high  $A$  would point strongly to a new (high) value for  $Z$ . Also, the value from evidence from other data might be strengthened by combination with mass spectroscopic evidence (e.g. when a possible daughter was observed.)*

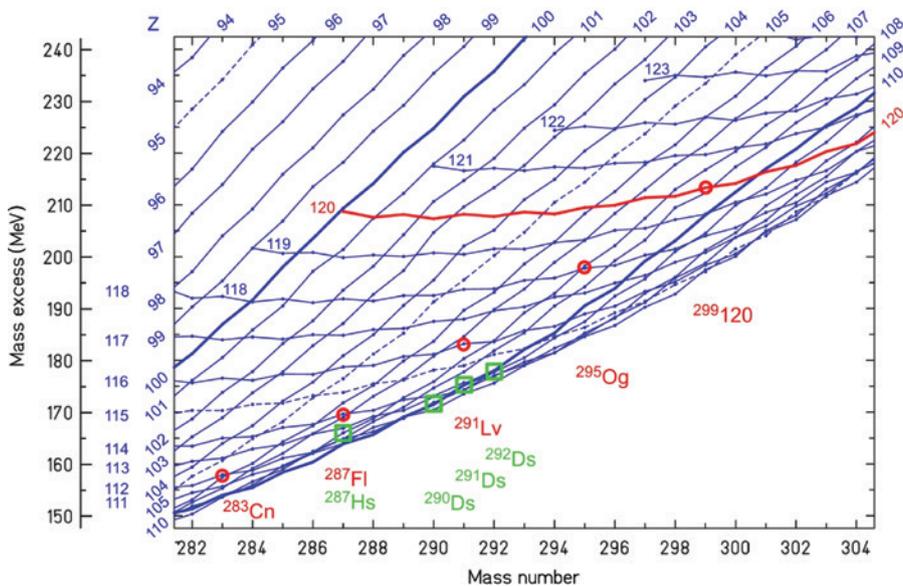
*Even with limited resolution, a mass ('isotope') separator can be used to suppress unwanted backgrounds.'*

Since that TWG report, devices for high precision mass measurements of isotopes became a standard tool in nuclear and atomic physics. Of interest for isotopes produced at accelerators are the devices mounted on-line behind recoil separators. As stand-alone systems they are of interest in experiments searching for long living SHN in nature, similar as isotope separators, but with significantly higher mass resolution.

Two spectrometer types were developed, Penning traps and multi reflection time-of-flight spectrometers (MRTof). Both types were already used for precision mass measurements of isotopes in the region of heavy elements [101–104].

The mass measurement is independent from the decay mode ( $\alpha$ -,  $\beta^+$ - and  $\beta^-$ -decay, SF) for both types. This predestines precision mass measurement for a direct identification of the mass number  $A$ , in particular in cases where genetic relations due to long lifetimes can no longer be established. The lower half-life limit for measuring masses is at a few hundreds and a few tens of milliseconds for Penning traps and MRTof systems, respectively.

The precision of the mass measurement using a Penning trap was  $\Delta m/m \approx 6 \times 10^{-8}$  for several isotopes of nobelium, which corresponds to an uncertainty  $\Delta m \times c^2$  of about 15 keV [102, 105]. The cyclotron resonance curve for determining the mass value was observed with a number of 100 to 200 nuclei [106]. At a number of



**Fig. 5:** Theoretical mass excesses [35] plotted for isobars from  $A = 282$  to  $304$ . The curves are labelled with the element number  $Z$ . Red circles mark the nuclei of the  $\alpha$ -decay chain starting at the possible candidate  $^{299}120$  of the new element 120 down to  $^{283}\text{Cn}$ . Already known are the nuclei from  $^{291}\text{Lv}$  to the spontaneously fissioning  $^{267}\text{Rf}$  of the  $\alpha$ -decay chain, though the isotope  $^{279}\text{Ds}$  has an SF branching of 90 % [10], not shown here. Squares in green mark the nuclei  $^{287}\text{Hs}$ ,  $^{290}\text{Ds}$ ,  $^{291}\text{Ds}$ , and  $^{292}\text{Ds}$ . For these superheavy nuclei longest half-lives are expected as discussed in Sect. 4.1. These nuclei are also emphasized in Fig. 2. Note that the masses of neighbouring isobars differ by about  $931 \text{ MeV}/c^2$  and are well separated by accurate mass measurements. See text for further explanation.

only 48 nuclei, which is at the lower limit for measuring a resonance curve, the mass of  $^{256}\text{Lr}$  ( $T_{1/2} = 27 \text{ s}$ ) was measured with an accuracy of  $\Delta m/m$  of  $3 \times 10^{-7}$  which corresponds to a  $\Delta m \times c^2$  value of  $83 \text{ keV}$  [102].

The limitation for measuring masses of isotopes with short half-life is shifted to values of some tens of milliseconds using MRToF mass measurement. *E.g.* the mass of  $^{213}\text{Rn}$  ( $T_{1/2} = 19.5 \text{ ms}$ ) was measured in [107]. In addition, accurate masses can be obtained already from a significantly smaller number of ions. The mass of  $^{249}\text{Md}$  ( $T_{1/2} = 24 \text{ s}$ ) was determined with an accuracy of  $\Delta m/m = 1 \times 10^{-7}$  which corresponds to a  $\Delta m \times c^2$  value of  $26 \text{ keV}$  from only 14 detected ions [104].

The efficiency of the systems, when used on-line, is mainly determined by the efficiency of the preceding gas-filled stopping chamber. It is at about 1 to 10 %, but continuous efforts are being made for improvement.

The high accuracy of the mass determination may also allow for a determination of the element number  $Z$  or at least a narrowing of  $Z$  in certain regions of the chart of nuclei. For many nuclei in the region of heavy elements the masses from one to the next heavier isobar, both having the same  $A$  but differing by one unit in  $Z$ , differ by more than  $1 \text{ MeV}/c^2$ . Therefore, at a mass resolving power of less than  $0.1 \text{ MeV}$ , information on  $Z$  is obtainable.

However, precision mass measurement does not offer an unambiguous criterion for  $Z$  identification. For demonstration we show in Fig. 5 mass-excess values for isobars of SHN from  $A = 282$  to  $304$ . The values were taken from the MM model calculations [35]. The range of  $Z$  values is determined by the tabulation given in [35]. For the comparison it is reasonable to use mass-excess values instead of masses. However, note that the masses of neighbouring isobars differ by about  $931 \text{ MeV}/c^2$  and are well separated by Penning-trap or MRToF systems.

Particularly difficult for  $Z$  identification are isobars close to the bottom of the valley of stability. Examples are the nuclei of SHE for which longest half-lives are expected, see explanation in the figure caption and Sect. 4.1. The mass-excess values of these four nuclei are marked by green squares in Fig. 5. Considering an uncertainty of the mass calculation of about  $\pm 2 \text{ MeV}$ , we obtain, *e.g.* near the expected mass for  $^{292}\text{Ds}$ ,  $Z$  values from 110 to 114. An unambiguous result would be obtained if such a mass would be measured in a fusion reaction with a compound nucleus of element 110. In that case the reaction restricts the  $Z$  values to 110. However, the observation of such a mass in a multinucleon transfer reaction using the reaction  $^{238}\text{U} + ^{238}\text{U}$ , *e.g.* would restrict the  $Z$  values from 110 to 114.

Less ambiguous results are obtained for nuclei at a distance from the bottom of the valley of stability. Examples are given by a possible decay chain starting from  $^{299}120$ . The nuclei of the chain are marked by red circles in Fig. 5. Due to the crossing of curves with different  $Z$ , an element assignment is not completely definite, but can be limited to only two elements, for  $^{299}120$  to  $Z=120$  and  $109$ , for  $^{295}\text{Og}$  to  $Z=118$  and  $108$ , and for  $^{291}\text{Lv}$  to  $116$  and  $107$ . In the case of fusion reactions the lower  $Z$  values can be excluded at the given  $A$  values due to the too high neutron numbers of  $N=190$ ,  $187$ , and  $184$ , respectively. In the case of multinucleon transfer reactions additional criteria must be applied for obtaining an unambiguous  $Z$  assignment. If, however, at least two subsequently correlated  $\alpha$ -decays are measured, the lower  $Z$  values are also excluded, because they differ by one unit in  $Z$  only.

In the given example, too short half-lives for  $^{299}120$  and  $^{295}\text{Og}$  could restrict the mass measurement to  $^{291}\text{Lv}$  and to nuclei further down in the decay chain. On the other hand, high spin isomers could result in longer half-lives of  $^{299}120$  and  $^{295}\text{Og}$ , which again could be accessible for a precision mass measurement. Also in these cases, a  $Z$  identification could become possible, if the excitation energy of the isomer is not too high, e.g. less than about  $2\text{ MeV}$ .

Other possibilities for mass measurements, but of less resolving power, are experiments at ISOL magnetic mass separators and accelerator mass spectrometry. Both systems were already used in search experiments for isotopes of SHE in nature [108, 109].

Problematic in all mass measurements is the possibility of the formation of heavy molecules, which could mimic the existence of a superheavy isotope. Repetition of experiments at different devices and under different conditions could help to avoid erroneous assignments. In the case of exclusion experiments it has to be demonstrated that the observation of possibly existing isotopes is not prevented by the experimental conditions.

We also point out the usefulness of time-of-flight energy measurements with detectors mounted directly behind recoil separators. Already in several experiments performed so far, such a ToF-energy measurement resulted in a coarse assignment of the mass number of the implanted nucleus with an uncertainty of about 10 to 20 %. In most cases this was sufficient for excluding most of the background events originating from scattered beam particles, scattered target-like nuclei, and multinucleon transfer reactions. Further improvement of these ToF-energy devices with respect to resolution and efficiency would be desirable.

## 6.8 Criteria related to characteristic X-rays and Auger electrons

The 1991 TWG report stated:

*'The energy of X-rays can be determined in the same way as those of  $\gamma$ -rays. They can be distinguished from  $\gamma$ -rays if observed with reasonable statistics, since X-rays (both K and L) show very characteristic patterns. Similarly, Auger electrons might be distinguished from conversion electrons. The presence of X-radiations of the correct energy is an unambiguous assignment property yielding the atomic number of the atom emitting those X-rays.'*

X-rays are the most direct characterization of an element and represent a most significant criterion for its discovery. The measurement of X-rays determines uniquely the element number. It is independent from the mass number  $A$ .

X-rays can be emitted from the originally produced isotope of an element during decay of an isomeric state when one or more electromagnetic transitions are converted and holes in the K or L electron shells are produced. Another possibility is the production of inner shell vacancies, with less probability in the K shell, when fast ions pass a converter foil, e.g. a  $1\text{ mg/cm}^2$  tin foil [110]. This process received the name collision induced X-rays. A third method which is of interest in particular in the case of larger samples of unknown material is proton-induced X-ray production [111].

As described above, an element must have a lifetime longer than approximately  $10^{-14}\text{ s}$ . This lifetime criterion is not fulfilled when, e.g. X-rays are observed in coincidence with fission fragments from the disintegration of a compound nucleus. Such X-rays attributed to element 120 were observed in coincidence with fission fragments in the reaction  $^{64}\text{Ni} + ^{238}\text{U}$  at the VAMOS spectrometer at GANIL [112]. In that experiment a

minimum mean fission lifetime of  $2.5 \times 10^{-18}$  s of the compound nucleus was deduced from the energy widths of the measured X-rays lines.

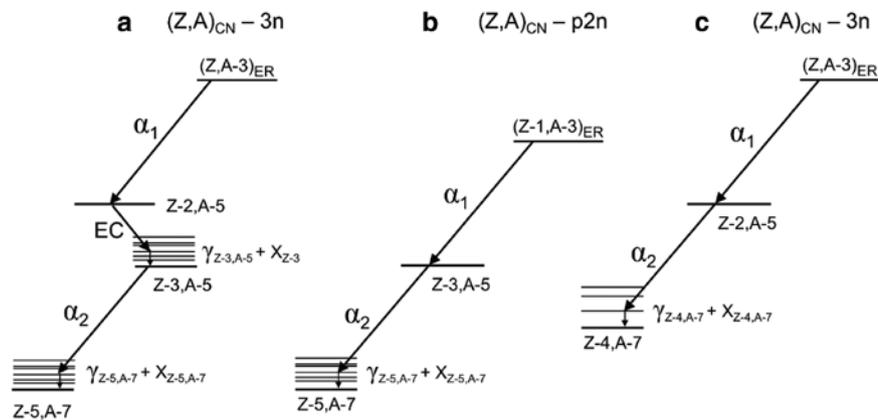
Radioactive decays are another source for a possible emission of X-rays if excited levels in the daughter nucleus are populated. Electron capture directly produces inner shell vacancies. Like in the case of X-ray emission during the decay of an isomeric state, these processes depend on the structure of the individual nuclei.

The emitted X-rays, when produced in  $\alpha$ - or  $\beta$ -decay including electron capture, are characteristic for the element number of the daughter product of the radioactive decay. In present day heavy element experiments these kind of X-rays are usually measured in coincidence with  $\alpha$ -particles, but also coincidences with conversion or Auger electrons or  $\gamma$ -rays would be possible if the daughter product de-excites in a cascade of electromagnetic transitions. The reason for the necessity of coincidence measurement is the rare number of produced nuclei at simultaneously high  $\gamma$  background.

It is not necessary that the  $\alpha$ -X-ray coincidence be measured for the  $\alpha$ -decay of the produced isotope of the new element. In the case of  $\alpha$ -decay chains, coincidences can be obtained also with  $\alpha$ -decays in later steps of the chain, sometimes even with higher yield which depends on the nuclear structure of the decay products. Such an experiment, where  $\alpha$ -particles in decay chains from  $^{288}\text{Mc}$  were measured in coincidence with photons, was recently performed at GSI. The statistics are not good enough to draw definite conclusions but the experiment proves that the principle of X-ray identification can be made to work [113].

However, these  $\alpha$ -X-ray coincidence measurements can give ambiguous results if pxn evaporation channels can occur and if electron-capture decays are possible decay modes of nuclei of the decay chain. An example is shown in Fig. 6. In both cases (a) and (b), the  $\alpha_2$ -particle is followed by X-rays of element  $(Z-5)$  where  $Z$  is the element number of the compound nucleus. However, the implanted residue can be element  $Z$  produced in a  $3n$  channel (a) or element  $Z-1$  produced in a  $p2n$  channel (b). The  $\alpha$ -X-ray coincidence measurement identifies unambiguously only the element number of the X-ray emitting nucleus and its  $\alpha$ -decaying parent, but not that of further predecessors. Considering unknown  $\alpha$ -decay hindrance factors and relatively high electron-capture decay probabilities, lifetime estimates will not be able to distinguish the two possibilities.

In the case of longer decay chains even more than one electron capture decay can occur, and various decay paths become possible. In conclusion we have to state that without additional assumptions an  $\alpha$ -X-ray coincidence measurement for one  $\alpha$ -decay of a chain does not result in general in an independent unambiguous assignment of the element number of all members of the decay chain. Unambiguously identified is only the element number of the  $\alpha$ -decaying nucleus and its X-ray emitting daughter.



**Fig. 6:** Schematic decay schemes of examples of  $\alpha$ -X-ray coincidence measurements. The assignment of the element number of the evaporation residues (ER) at the beginning of the  $\alpha$ -decay chains is ambiguous in (a) and (b). It is unambiguous in (c). Note, that a possible X-ray emitted from the nucleus  $(Z-3, A-5)$  in (a) is not in prompt coincidence with  $\alpha_1$  and, therefore, difficult to determine. In all three cases the compound nuclei (CN) have the same  $A$  and  $Z$  values.

Figure 6c shows an example for an unambiguous assignment by an  $\alpha$ -X-ray coincidence measurement in the case of a fusion evaporation reaction when the element number of the compound nucleus is known by the reaction and the total number of  $\alpha$ -decays was measured. In that case the X-ray of element ( $Z-4$ ) determines the element number of all members of the chain. If, however, the chain was produced in a reaction where the  $Z$  value of the reaction product is not defined, e.g. a multinucleon transfer reaction, then only the element numbers of the two nuclei involved in the  $\alpha$ -X-ray coincidence are defined when electron capture of the precursors cannot be excluded.

Delayed  $\alpha$ -X-ray, X-ray- $\alpha$  or X-ray-SF coincidences become possible at short enough lifetime of the decaying nucleus or isomer and correspondingly low background of the  $\gamma$ -spectrum. Intermediate emission of  $\gamma$ -rays or conversion electrons may complete the decay pattern. Prerequisite for the measurement of such a more complete decay pattern is a high sensitivity for low energy signals achievable only with a low noise electronic equipment and without signal losses due to dead time effects. With such ideal instrumentation the ambiguities related to intermediate electron capture decays or isomeric states could be significantly reduced. First promising results of measurements in the region of superheavy nuclei were published recently [114, 115].

In any case, identification via X-rays requires sufficient statistical accuracy so that the characteristic intensity distribution identifies the measured signals as X-rays and, secondly, that the X-ray lines are statistically significantly visible on top of a possibly also structured background.

## 6.9 Criteria related to systematics of experimental results and theoretical predictions

Chemical properties of elements and physical properties of nuclei and atoms reveal characteristic features which often appear periodically forming groups of elements, atoms or nuclei having similar characteristics. Responsible for these features are the quantum mechanical processes of how nucleons form nuclei and how these nuclei and electrons form atoms and molecules. These periodic structures are well understood within the framework of the shell models for nuclei and atoms. Comparative studies of experimental and theoretical results for trying to assign observed new phenomena of so far unknown nuclei or atoms is an important and useful method. Results of an extrapolation or interpolation of experimental data gain additional weight when the results are corroborated by theoretical predictions which consider these shell effects.

In the following we present some examples how systematic properties and theoretical calculations can be applied as convincing or useful criteria for determining priority of discovery of new elements.

The most convincing criterion for a correct element assignment besides the establishing of a genetic relation to known anchors is that of the agreement of measured X-ray energies and intensities with systematics and theoretical predictions. This was discussed in detail in the previous section.

Systematic difference of half-lives of SF between even-even, odd- $A$ , and odd-odd nuclei can be used as a confirmation criterion in regions of nuclei where a number of neighbours is available for comparison. So far, measured partial SF half-lives of odd- $A$  and odd-odd nuclei were always significantly larger than the geometrical mean of the partial SF half-lives of the even-even neighbours. An enhancement of the fission probability of odd- $A$  or odd-odd nuclei relative to the geometrical mean of the half-lives of the even-even neighbours was never observed.

Systematic trends were also observed for the total kinetic energy, TKE, of SF. For many nuclei TKE obeys a  $Z^2/A^{1/3}$  dependence. A high TKE value indicates a high element number due to the quadratic dependence on  $Z$ . However, the systematics of TKE values can usually be used only as a supporting criterion. Firstly, TKE has a wide distribution. A sufficiently accurate mean value can be determined only from a relatively high number of measured decays. Secondly, a particular energy calibration is needed for determining the energies of the fission fragments. And thirdly, the high TKE values of symmetrically fissioning nuclei known for isotopes

in the vicinity of  $^{258}\text{Fm}$  could mimic fission of a high  $Z$  nucleus. Symmetrically fissioning nuclei are likely produced in multinucleon transfer reactions and can contribute to the background in search experiments for new elements.

Similarly, the short half-lives of fission isomers reaching from nanoseconds to some tens of milliseconds could mimic fission of a high  $Z$  nucleus. Although their TKE values are smaller, 170 to 180 MeV, the energy measurement of such a fission event from a nucleus implanted only a few micrometers into the sensitive layer of a Si detector, is often not sufficiently accurate for a definitive discrimination. Also fission isomers are likely produced in multinucleon transfer reactions, in particular when isotopes of actinides are used as target material.

The background of symmetrically fissioning nuclei and fission isomers are examples where systematics cannot be applied as sole criterion for assigning priority of discovery of an element. Other reasons that systematics of fission properties is not always a reliable criterion is given by nuclear structure. As an example we mention the broken systematics of SF half-lives of  $N=152$  isotones at  $^{258}\text{Rf}$ . It occurs at  $^{258}\text{Rf}$  and the heavier isotones due to the lowering of the second hump of the barrier below the ground-state.

Similarly, but now into the direction of longer half-lives, is the increase of the fission barrier for spherical SHN due to shell effects. This effect breaks the systematic trend of decreasing cross-sections using hot fusion reactions with beams of  $^{48}\text{Ca}$  when the region of SHN is reached, see Fig. 3. In both cases, initial critical objections based on systematics were dispelled by further measurements and theoretical explanations of the measured phenomena.

The consequence of the increase of the fission barrier for SHN is the increase of the partial SF half-life. In the region of SHN, which was studied so far and which is accessible in hot fusion reactions with beams of stable ions, the SF half-lives are significantly longer than the partial  $\alpha$ -half-lives, see Fig. 2. This circumstance makes the consideration of the systematics of  $\alpha$ -decay particularly attractive for establishing criteria for assigning priority of discovery of new elements in the vicinity of the region of SHN.

The AME-2016 compilation of experimental data on  $\alpha$ -decay energies,  $Q_\alpha$ , between ground-states of parent and daughter nuclei reveals systematic trends [116]. For most nuclei in the SHN region, a systematic increase of the energies is observed with an increase of the proton number relative to the number of neutrons. Only near closed shells, but similar for protons and neutrons, the systematics is broken. However, this again reveals a systematic change in so far that the  $Q_\alpha$ -values are low just below a closed shell and they are highest just two protons or two neutrons, respectively, above a closed shell. These properties are well understood within the framework of nuclear shell models. A comparison of experimental and theoretical  $Q_\alpha$ -energies is considered as a supporting criterion, in particular when several measured data of neighbouring nuclei are available for comparison. It should be mentioned that it makes no difference if the  $Q_\alpha$ -values are determined from measured energies of  $\alpha$ -decaying nuclei or from mass measurements of nuclei which then can be also  $\alpha$ -stable or almost stable. For clarification we note that we use the term  $Q_\alpha$  in specific cases with a supplement, for the  $\alpha$ -decay of any nuclear state and not only for the mass difference of the corresponding nuclei in the ground-state. This definition is needed for distinguishing  $Q_\alpha$ -values and measured smaller  $\alpha$ -energies,  $E_\alpha$ , from and to any nuclear state, in particular also from isomeric states.

Complications with using systematics of  $Q_\alpha$ -values arise from the occurrence of isomeric states. A measured  $Q_\alpha$ -value higher or lower than systematics must not be used as an argument against an otherwise identified isotope or element as long as isomeric states cannot be excluded.

An impressive systematic relation exists between partial  $\alpha$ -decay half-lives and  $\alpha$ -energies. The relation was set-up by Hans Geiger and John Mitchell Nuttall already in 1911. The observation was theoretically explained in 1928 by George Gamov as a quantum mechanical tunnelling process of the  $\alpha$ -particle through the Coulomb barrier. The relation is experimentally proven over a span of 30 orders of magnitude for nuclei with half-lives from  $7 \times 10^{15}$  years ( $^{148}\text{Sm}$ ) to  $0.18 \mu\text{s}$  ( $^{216}\text{Ra}$ ).

In Fig. 7 we show the results of a WKB calculation drawn in the form of the well-known Geiger-Nuttall plot for  $\alpha$ -decays of even-even nuclei in the region of heavy elements for  $Z=100$  to 134. For details of the used WKB calculation, see [117]. Each line represents the dependence of the half-life on the  $\alpha$ -energy for fixed values of  $Z$  and  $A$ . The  $A$  values were chosen so that they agree approximately with the mean values of



by the observation that nuclear structure modifies the  $\alpha$ -decay probabilities for  $0^+$  ground-states by less than a factor of ten for all isotopes of elements above lead and neutron numbers greater 126. Maximum reduction of the  $\alpha$ -decay probability of a factor of ten was observed for  $^{210}\text{Po}$  at  $N=126$ , see discussion in [118].

In Fig. 7, the largest deviation of the measured half-lives from the WKB calculation exists for  $^{286}\text{Fl}$ . Due to the good agreement of all other measured data with the calculations it seems worthwhile to try to find an explanation for the deviation. A total of 25 decays were published in various papers of the DGFERS group. Two additional decays of  $^{286}\text{Fl}$  were measured at the Berkeley BGS separator [119, 120]. From the total of 27 decays 14 were  $\alpha$ -decays and 13 SF. The measured decay times result in a total half-life of  $(168^{+39}_{-27})$  ms and an  $\alpha$ -branching of 0.55 was deduced from the number of events. The data point in Fig. 7 was calculated with these values. From the 14  $\alpha$ -decays alone we get a half-life of  $(109^{+40}_{-23})$  ms, and from the 13 SF events it is  $(231^{+84}_{-49})$  ms. The errors are calculated for a confidence level of 68 % according to the procedure given in [121]. The deviating values indicate that probably some of the longer lived SF events do not belong to the decay of  $^{286}\text{Fl}$ , and the  $\alpha$ -branching is higher than 0.55. This example demonstrates that a comparison of measured data with theoretical calculations is not only a useful tool for establishing discovery of a new element, but can point out also inconsistencies in measured decay properties of known nuclei.

How well systematics can be used for excluding certain assignments will be demonstrated in the following example. The first decay chain assigned to a nucleus in the region of spherical SHN was observed in the reaction  $^{48}\text{Ca} + ^{244}\text{Pu}$  in [122]. The chain was characterized as candidate for  $^{289}114$  produced in a  $3n$  evaporation channel. Later measurements of excitation functions led to a correction of this assignment. A suggested possible alternative assignment was the  $2n$ -evaporation channel producing the even-even isotope  $^{290}114$ . A comparison with the calculated  $\alpha$ -half-lives reveals the decays of potential daughters  $^{286}\text{Cn}$  and  $^{282}\text{Ds}$  are well in agreement with the experiment, but the half-lives of the parent  $^{290}\text{Fl}$  and the terminating nucleus  $^{278}\text{Hs}$  are considerably longer than calculated. Considering in addition the presently known decay properties of the neighbouring decay chain starting at  $^{289}\text{Fl}$  and terminating at  $^{277}\text{Hs}$ , one can now make a tentative assignment of that first measured chain of a nucleus of a spherical superheavy element to an electron capture decay branch of  $^{290}\text{Fl}$  or the production of  $^{290}\text{Nh}$  in a  $pn$  evaporation channel. Interestingly, a decay chain with equally long half-lives was observed again in the reaction  $^{48}\text{Ca} + ^{248}\text{Cm}$  in 2000. The result was published in the laboratory report [123]. However, no definite conclusions were drawn.

We present this discussion in more detail here, because it reveals an interesting aspect related to determining priority of discovery of a new element. If the before given new interpretation turns out to be correct, an isotope of element 114 would have been produced at the FLNR-DGFERS in an experiment during November and December 1998. The paper [122] with tentative assignment of the chain to  $^{289}114$  was submitted on March 8, 1999 and published October 8, 1999. An also tentative alternative assignment to  $^{290}114$  was suggested in [124], submitted on December 1, 2003. On the basis of new experimental data available in 2016 supplementing the systematics the before given tentative interpretation was suggested in [12]. If this turns out to be correct, the decay of element 113 would have been observed already in 1998 but could have been assigned only tentatively due to the lack of sufficient information. In any case a definite assignment of this chain of isotopes with long lifetimes cannot be made now and was even more difficult to perform at the time of the experiment. With good reason this result could not be accepted as discovery whether of element 114 nor of element 113.

In subsequent years unambiguous data were measured and assigned to decays of isotopes of elements 113 and 114, which resulted in an assignment of discovery of these elements to research groups at RIKEN and JINR, respectively. In Sect. 7, ‘Guidelines to Experimentalists and Joint Working Parties’, we will consider this occurrence and similar events under the aspect of discovery of priority of an element.

## 6.10 Criteria related to atomic physics

Atomic physics covers an extremely large field of medium, low, and ultra-low energy physics. Consequently, the amount of information inherent from atomic physics is enormous. It covers systems like hydrogen- and

helium-like ions of high- $Z$  elements, the arrangement of electrons in the electric field of a nucleus including the interaction with different properties like spin and deformation of that nucleus, the emission of electromagnetic radiation or Auger electrons accompanying the arrangement process of the electrons, the interaction of ions and neutral atoms at rest or in motion with ions or atoms of the same species or with those of other elements. *Vice versa*, atoms, ions and their compounds from simple molecules to macroscopic formations can be stimulated by electromagnetic radiation or charged particles. Furthermore, the appearance of various atomic properties is related to the temperature and properties of the surrounding medium and electromagnetic fields so that special research fields emerged, from plasma physics at high temperature to, e.g. superconductivity at low and ultra-low temperatures.

Particularly important phenomena of atomic physics for identification of SHE are the emission of X-rays, of both K or L X-rays, and/or Auger electrons, the emission of collision induced X-rays, and the aspects of atomic physics for chemical properties. Due to their importance for identification of SHE, these two subjects are discussed in the dedicated Sects. 6.8 and 6.11, respectively. In this section recent atomic physics experiments on isotopes of heavy elements are presented. A possible application for identification of new elements is discussed.

Ionization potentials and atomic excitation schemes are in the center of interest both of experimental as well as theoretical studies. In the region of heavy and superheavy elements these properties are strongly influenced by the so called relativistic effects which were presented in Sect. 4.2 in connection with achievements obtained in chemistry. As in chemistry of SHE, the same theoretical calculations are used also for predictions of the ionization potentials and atomic levels. However, these calculations are not sufficiently accurate to be used for identification of new elements. Experimental data on known atoms and ions of SHE are needed for comparison and adjustment of the model parameters.

A review of recent atomic physics experiments in the region of heavy elements was presented in [125]. In that review the following methods are presented in detail: single-ion spectroscopy in Paul traps, laser-induced fluorescence spectroscopy, LIF, radiation-detected optical pumping, RADOP, radioactive decay-detected resonance ionization spectroscopy, RADRIS, and ion-guide-detected resonance ionization spectroscopy, IGRIS.

The principal difficulty of all of these methods when applied to isotopes in the region of heavy elements is the small number of atoms or ions available. For elements above fermium the ions have to be produced *in situ* in nuclear fusion reactions. After separation by a recoil separator, the evaporation residues are focused onto a gas-filled stopping chamber where the ions are collected, extracted, and subsequently guided into an ion trap. The total efficiency is composed of the efficiency of the separator, 5 to 50 %, and the collection and extraction efficiency of a gas-filled stopping chamber, 1 to 10 %.

The heaviest isotopes studied to date using atomic physics methods were investigated using RADRIS experiments. These were the isotopes  $^{254}\text{No}$  and  $^{252}\text{No}$  which were produced in reactions with a  $^{48}\text{Ca}$  beam and targets of  $^{208}\text{Pb}$  and  $^{206}\text{Pb}$ , respectively, at cross-sections of 2 and 0.5  $\mu\text{b}$  [126]. In a two-step laser ionization process the first step  $7s^2\ ^1S_0 \rightarrow 7s7p\ ^1P_1$  resonance of  $^{254}\text{No}$  atoms was measured at a wavelength of 333.76 nm. Theoretical predictions were in the range from 322 to 385 nm [127–129]. The measured resonance had a width of 0.01 nm FWHM. Several ten thousands of  $^{254}\text{No}$  isotopes had to be produced for measuring the resonance curve.

The measured results on atomic levels in  $^{254}\text{No}$  are certainly a great success for the developed experimental technique. The results are a promising first step into atomic spectroscopy of heavy ions and atoms opening a door for a multiplicity of investigations mentioned at the beginning of this section. In particular, further increases of beam intensities and efficiencies may increase sensitivities by factors of 10 to 100 allowing isotopes produced with cross-sections of some tens of nanobarns to be studied. However, these cross-sections are still several orders of magnitude away from the level of picobarns or below, at which SHE are presently produced or new elements may be produced in the future.

In addition, for an isotope identification using atomic spectroscopy the measured results have to be compared with systematic trends or theoretical calculations. These do not exist or they are too uncertain, respectively, for a reliable use for an identification of a new element. We do not consider atomic spectroscopy as a tool for assigning priority of discovery of a new element in a foreseeable future.

## 6.11 Criteria related to chemistry

Chemistry played an important role in the discovery of all transuranium elements up to nobelium as well for separation as for identification. All heavier elements were identified by physical means, and the study of the chemical properties of those elements became the subject of scientific research by its own. At increasing charge of the atomic nucleus the influence of the so called relativistic effects on chemical properties is the subject of those studies, see Sect. 4.2. Due to the unknown chemical properties of new elements their direct identification by chemical means remains unsatisfactory.

In addition, chemical studies of potential new elements are impeded by the low number of produced atoms. The results of all chemical investigations on restricted amounts of a few atoms require physical measurements of nuclear or atomic properties as, *e.g.* radioactive decays, mass-measurements or X-ray identification. In this respect criteria worked out for discovery of new elements by physical means are also valid when a sample of produced atoms undergoes a chemical treatment.

As discussed in Sect. 6.8, ‘Criteria related to characteristic X-rays and Auger electrons’, chemistry identifies only the element under investigation. The uncertainty of chemical properties of elements beyond oganesson related to the influence of relativistic effects, prevent application of chemical methods alone for directly identifying new elements.

What remains is the element identification of a decay chain by determining the chemical properties of a descendant member of that decay chain. This procedure could be a reliable criterion for identification of a new element if similar conditions can be applied as in the case of X-ray identification discussed before. Firstly, the chemical treatment has to be unambiguously specific for that element similar as in the case of an X-ray measurement, and, secondly, the decay chain must be unambiguously traced back to the decay of an isotope of the new element. Problems related with the identification of unknown decay chains due to  $xn$ ,  $pxn$ , and  $\alpha xn$  evaporation channels and possible electron capture decay of one or more members of a decay chain were discussed in Sect. 6.8. As outlined there, the identification of a new element is particularly challenging when production methods different from the established heavy ion fusion reactions, as *e.g.* multinucleon transfer reactions, are used.

The chemical identification of one or more potential long living isotopes of a new element in natural material is also confronted with the problem of unknown chemical properties of the highest  $Z$  elements. In these cases, unambiguous element identification is only possible in combination with other identification methods like precision mass measurements, X-ray identification or accelerator mass spectroscopy. So far claims for discovery of new elements in natural samples have either been disproved or were not or could not be confirmed.

## 6.12 Criteria related to statistical and experimental uncertainties

Ambiguities in assigning measured characteristics or decay properties of nuclei, atoms or elements often arise from too large errors. In nuclear physics experiments, errors emerge from the experimental setup used for the measurement, from the statistical distribution of reactions and decay processes, and from the quantum mechanical uncertainty principle.

Errors originating from the latter two processes can be influenced only by the number of measured events. Details of the properties of those errors will be discussed later in this section.

Errors emerging from the experimental equipment are determined by the accuracy of the applied instruments and by the design of the experimental setup. These errors can be minimized using the most advanced techniques and sophisticated planning of the experiment. In the following we will discuss items which are most important for establishing criteria related to the discovery of a new element. For judging the value of published experimental data, these or other items of importance in a particular experiment have to be given explicitly in a publication. Here we concentrate on experiments using fusion-evaporation or similar reactions

which most likely will be used for synthesis of further new elements. Similar standards are demanded in claims of new elements using other identification methods.

Given here are not procedures on how to determine errors in specific cases. Too many parameters can enter which influence the particular measurement. Instead, given are some recommended principles for presenting errors and probabilities in publications so that the quality of the measurement can be evaluated with respect to the claim of discovery of a new element. In addition, some examples from previous experiments are given.

### 6.12.1 Errors related to cross-sections

For the calculation of the cross-sections and their errors, uncertainties of the measured values of the beam dose, target thickness, and efficiency contribute. Errors from statistical fluctuation can be larger than those of the experiment parameters in the case of low numbers of events. Nevertheless, all errors have to be listed individually in a publication. This is a necessary condition for evaluating the quality of the experiment, for comparison with competing experiments, and, eventually, for a later formation of mean values of data from different experiments and of higher statistical relevance.

Particular attention has to be given to the indication of the efficiency. In experiments at recoil separators, the total efficiency is composed of the angular acceptance of the reaction products, their transmission through the separator, and the efficiency of the detection system. All three values depend on the type of the reaction,  $xn$ ,  $pxn$ ,  $\alpha xn$  evaporation reaction or multinucleon transfer reaction and the design of the separator. It is essential for the evaluation to know, how the values of the angular acceptance and the transmission were determined, by calculation, experimentally, by adjusting to literature values of cross-sections from other experiments or by crude estimation.

### 6.12.2 Errors related to the measurement of energies, in particular $\alpha$ -energies

Alpha energies and their errors are most important for the comparison of different measurements but also for data within a given publication. Usually, the energy value is derived from a calibration of the measured signal with known energies from  $\alpha$ -decays of known nuclei. The calibration procedure contributes a systematic error to the energy of the measured signal or the mean value of signals. A second contribution is due to the energy resolution of the detector. The value of the resolution as standard deviation has to be given explicitly together with the corresponding  $\alpha$ -energy and the information on the shape of the measured  $\alpha$ -lines used for calibration, if they are, e.g. symmetric or asymmetric.

For the evaluation of the quality of the measurement, the presentation of calibration and resolution is of importance including a listing of the used calibration lines. In the case of high  $\alpha$ -energy values, when a distant extrapolation becomes necessary, a detailed presentation of the calibration procedure has to be given. This is also the case for energies and their errors for escaping  $\alpha$ -particles which were stopped in the backward detectors. It has to be indicated how the energy value and its error were derived or if these data are the result of a crude estimation.

More difficult is the determination of the total kinetic energy of an SF process and its error. If such energies are used as an argument for assigning an SF event to a certain nucleus or element, a detailed description of the measuring and calibration procedure has to be given. Also important is what assumptions were made for the width of the TKE values. The phenomenon of bimodal fission reveals the problem of determining TKE values from a small number of SF events.

A Gaussian distribution is a good approximation to the line shape of a  $\gamma$ -line, similar as in the case of  $\alpha$ -lines. At low number of events the error is dominated by the resolution of the detector, which determines the line shape. A systematic error can also arise from the calibration procedure.

### 6.12.3 Errors related to the measurement of lifetimes

The lifetimes of known SHN are well above 1  $\mu\text{s}$ . The measurement of such lifetimes is technically unproblematic. Time periods between, *e.g.* two subsequent  $\alpha$ -decays, are generally measured with accuracy of the order of 100 ns or less. Uncertainties which can significantly distort the assignment of measurement of lifetimes arise from undetected intermediate decays or spurious signals which are erroneously interpreted as implanted reaction products or radioactive decays. In the first case an optimization of the electronic hardware helps to avoid losses of signals. The reason for the second type of event is too high background. If the background cannot be reduced, a careful statistical analysis has to be applied for determining the probability for the occurrence of spurious events. Particularly problematic is the measurement of unusually long lifetimes of hours or even days. As discussed before, the measurement of such long lifetimes is technically possible by a significant reduction of the background.

The dominant uncertainty in the case of only one or a few measured decays arises from the statistical distribution of the decay process. Up to five events, this uncertainty is larger than the difference between the lifetime  $\tau$  and half-life  $T_{1/2}$ . The lifetime and half-life must be clearly distinguished to ensure that later comparisons with different experiments are correct.

### 6.12.4 Probability of being true or false

One of the most difficult questions to answer is that if an announcement or an observation is true or false. This problem is not just limited to physical or chemical experiments. The problem range extends from careless behaviour to deliberate forgery.

The main reason for false results in physics experiments results from misinterpretation of background events. The demand to reduce or avoid background is a trivial but most important requirement in the performance of an experiment.

Often the origin of the background is unknown. It even can happen that the existence of a background is unknown. In those cases a correct interpretation of measured data is impossible. This means for the particular case of the assignment of discovery of an element that the experiment has to be repeated under improved conditions.

Various attempts were made and are applied in certain experiments to determine probability values if an observation is correct or false. Two studies which are specifically tailored to results from measurements on production and decay of atomic nuclei at low statistics were published by Schmidt *et al.* [121] and Schmidt [130].

In many experimental studies on SHN the Schmidt prescription is used for calculation of errors and probability values. If applied correctly, these recipes are extremely useful for ranking the quality of experimental results and for comparing results from different experiments. Furthermore, as an additional experimental test for the occurrence of randomly correlated decay chains, the number of such chains should be determined as function of increasing widths of time, energy, and position windows. Examples should be included in the publication claiming discovery of a new element.

Related to the information which has to be presented in a claim for discovery of a new element in order to judge the quality of the work, it is mandatory that sufficient information is presented how a certain probability value was calculated. This concerns in particular the specific background rate in an assumed energy window or detector area. See also criteria discussed in Sects. 6.3 and 6.6.

## 7 Guidelines to experimentalists and Joint Working Parties

The criteria that should be considered for a discovery of a new element to be accepted were outlined in Sect. 6. The complexity of the research work, experimental difficulties and corresponding results which

often need completion in further experiments do not always allow for an immediate and safe recognition for assigning a unique value to the element number  $Z$ . The identification must rely upon combinations of these criteria, and different groups may choose different combinations. The relative importance of the criteria will vary from case to case depending on the manner in which they are combined. In addition and for various reasons the presentation of the results in a publication may not always be complete or it may be even misleading.

In this section we will discuss requirements and guidelines for experimentalists dealing with the information which has to be provided in a publication so that the results can be correctly classified and, if necessary, the results of competing research groups can be appropriately assessed. Another issue is related to the procedure how and to whom claims of a new element should be presented so that the results can be accepted or rejected by the responsible bodies in a timely manner.

Similarly important are guidelines directed to these bodies responsible for evaluating claims or other issues related to the discovery of a new element. Since the elaborative work of TWG at the beginning of the 1990s these bodies are the Joint Working Parties (JWP) which were commonly installed by IUPAC and IUPAP.

## 7.1 Guidelines to experimentalists

Authors claiming discovery of a new element or any other issue related to the discovery of a new element should publish their results in a peer-reviewed scientific journal that maintains high standards of quality and thereby provides credibility. In exceptional cases other methods of publication as in Archive for Physics or Archive for Chemistry or by similar means of publication could be accepted. In any case, public access to the information is mandatory.

Subsequent to the publication or already at the date of acceptance of the paper, a copy has to be sent to the secretariat of IUPAC and/or IUPAP depending on the used identification method with the request for consideration as discovery of a new element.

To facilitate JWP validation of a claim or discovery, the claimant paper should clearly specify all steps taken in the experiment that the authors consider add confidence to their claim. They should state which specific criteria their particular experiment is addressing, how successful they are in fulfilling that particular criteria, and which of the criteria they consider is the most important and most accurate for the discovery. Finally, from the text should follow clearly that the authors are claiming the discovery of a new element. Publications providing a possible indication for the production of a new element or announcing a candidate for being an isotope of a new element cannot be considered as discovery. Statements of this type are too vague although very important for increasing the efforts aiming to settle those early results.

The elements produced and discovered since 1981 were solely identified by means of physical methods. Meanwhile several hundred atoms and decay chains of superheavy isotopes were measured. Based on the experience how these nuclei were produced and how the information was published, we will present a short compilation of information in addition to the more detailed requirements presented in the criteria section. We expect that this or similar informative material will be presented in publications claiming discovery of an element. Of course, possible are references to previous publications if, *e.g.* the used experimental methods were reported in detail earlier.

Having in mind the method of genetic relations to known nuclei, a unique identification of the chains is essential. A discussion of new results on the basis of mean values cannot be accepted, if the individual decay chains are not also presented. In specific cases the chronology of the measured events can be of importance. Therefore, each measured event or decay chain has to be marked by a time stamp or a period of time when it was registered in the apparatus when an exact time stamp cannot be given. The paper should also contain the dates of the experiment, including date and time of the observation of the events

which are important for the discovery. This information could be of value for an unambiguous identification of certain events and it could be used as a supporting argument for assigning priority in the case of unclear claims. Other requirements related to the time of submission and of publication of a paper were discussed in Sect. 6.2.

A proper and detailed treatment of experimental and statistical uncertainties is essential for assessment of the data and for comparison in the case of competitive claims. Basic requirements were presented in Sect. 6.12. Many of the measured quantities are composed of an experimental error like resolution, a systematic error due to the applied calibration procedure, and a statistical error. All three contributions have to be identified, although, as in the case of a small number of events, the statistical uncertainty could be overwhelming. The information is needed for data evaluation when over time the number of events increases and statistical uncertainties decrease.

The evaluation of the probability of an event or of an event chain being real or accidental is an essential step in the data analysis. The input values of these calculations have to be given in the publication as well as a reference to the applied statistical analysis method. Other aspects related to this item are discussed in Sect. 6.12.4.

It is recommended that the experimentalists publish as much of their data as possible. Currently unclear observations could find an explanation in later experiments. Otherwise, *e.g.* a later observation could be characterized as spurious and be questioned with the argument that it was not observed in a previous experiment by another group.

It is obvious that all of the detailed information cannot be included in a relatively short letter. Therefore and if necessary, a more comprehensive publication should follow in a reasonable time. In addition, as will be discussed below, an investigating JWP has to be provided with all experimental details on request. In appropriate form this information should also be available to the public.

The publication of all this information is to facilitate, for the JWP and for other research groups and scientists, the evaluation of the claim with sufficient detail that an independent scientific test of a specific experiment could in principle be performed.

## 7.2 Guidelines to the Joint Working Party, JWP

Previously, a Joint Working Party was installed or an existing one was reactivated by IUPAC and IUPAP when claims for discovery of a new element had been published and an assessment became necessary. The JWP then requested from the claiming parties all relevant information published up to an arbitrarily set deadline. Due to the volume of accumulated claims it could take several years before the JWP could conclude its work. In the meantime new experimental results could have been published which were not or only partially considered in the report. In the case of an eventually rejected claim due to insufficient experimental data, the experimentalists could have lost time for improving the results of their experiment.

In order to accelerate the process of recognition, we suggest that the experimentalists send a copy of their claimant paper to the Presidents of IUPAC and/or IUPAP for consideration after the paper had been published or was accepted for publication.

The Presidents of IUPAC and IUPAP will then forward the request to an already existing JWP or will appoint a new JWP by mutual agreement according to the rules published in [131]. This procedure has the advantage that the experimentalists receive relatively quickly the information if their work is sufficient or not for being accepted as a discovery. Additional research work can be provided in the case of rejection.

The future procedure of appointing a Joint IUPAC and IUPAP Working Party is presented in [131]. The JWP will consist of six members, three nominated by IUPAC and three by IUPAP. Their task is to analyse in detail the published data of a claimant paper and all other papers that are relevant to the discovery of a new element. They shall, with the aid of the criteria and guidelines presented in this report, make an assessment as to the validity of the claim or claims. In the case of results obtained with new methods not discussed here,

actions for assessing priority have to be performed which are equivalent and in the same deliberate spirit as discussed here for the known methods.

The main responsibility for a correct decision of the discovery of a new element is at the JWPs. Therefore, the new rules of IUPAC and IUPAP published in [131] foresee several control steps before the JWP report can be published, first, as a provisional report in *Pure and Applied Chemistry*, which becomes final after peer review.

Before the provisional report can be submitted, the draft report of the JWP will be peer reviewed using two to four referees. This peer review process will be jointly supervised by two co-editors, one from each Union. The so reviewed and conceivably revised provisional report will be sent to the editor of *Pure and Applied Chemistry*, including the referees' reports and all related correspondence. It is expected that the editor of *Pure and Applied Chemistry* will incorporate this material into the normal review process prior to publication of the provisional report.

The provisional report, as it is to be published shall be approved by the Presidents of IUPAC and IUPAP, on the advice of the Division of Inorganic Chemistry and the Commission for Nuclear Physics, respectively, and published in *Pure and Applied Chemistry*.

This provisional report is open for comments for five months. This period of five months presents to the involved laboratories or any other scientist or institution the possibility to critically comment on the decisions of JWP. No response, in particular from the directly involved laboratory or laboratories, is considered as agreement to the decisions of the JWP presented in the provisional report.

All comments received at the secretaries of IUPAC and/or IUPAP during the five months period will be forwarded to the Presidents of the Unions and to the referees. A summary of the comments or in particular cases also a complete text of one or more comments will be published in *Pure and Applied Chemistry*. Subsequently, the Presidents of IUPAC and IUPAP will, with advice from the Divisions of Inorganic Chemistry and the Commission for Nuclear Physics, respectively, decide whether to make the report final, or on what other actions should be taken.

To carry out this task, JWP has to be provided with the claimant paper and relevant references, in particular those which describe the experimental set-up or other experimental details. Beyond the access to published information, JWP has a right to receive and the duty to ask for additional information from the experimenters if needed. In direct discussion with the experimentalists it may become crucial to examine the original raw data. Upon request and in the course of complete transparency, it may become necessary that this additional information including the raw data is also provided to the public. This can be achieved via reference to a relevant file on the homepage of the institute or the scientists or by any other means.

JWP should clearly specify all the steps that were taken by the experimentalists that they consider add confidence to the claim, and also all the steps and criteria that they find are not of relevance for the claim. To facilitate the understanding of their assessment the JWP should be as specific as possible in the report, and refrain from including irrelevant paragraphs.

They should discuss which criteria were used, and assess what certainty a specific discovery reached. They should also discuss how successful they believe the experiment was in fulfilling that particular criterion, and they should indicate the importance of the different criteria used in the research work, and which criterion they consider is the most important for the discovery.

They should, with the help of the statistical method used in the research work and if necessary with additional investigation check the consistency of all experimental data being reported. In some experiments the consideration of background which could produce spurious events or event chains could be particularly important and needs special investigation.

The JWP does not need to restrict their source of information to only published papers. They are encouraged to discuss with the authors of the claimant papers, if they encounter problems with understanding the paper, if they find issues that are unclear, or if there otherwise is some need for clarification. They can also consult other experts in the field if they find that would be of value.

In conclusion, the main task of the JWP is to establish a discovery profile by collecting and weighting all information relevant for the discovery of an element. The more transparent and communicative the evaluation process is, the easier well-founded decisions will be achieved.

### 7.3 General remarks related to the approval of claims

An item of general importance is the reproducibility of experimental results. The 1991 TWG report [1] presented the following position:

*'Confirmation demands reproducibility, which is also related to setting up discovery profiles. All scientific data, other than those relating to unique events such as a supernova, must be susceptible of reproduction. In the case of the new elements the TWG attaches considerable importance to reproducibility and would indeed like to be able to suggest that no new element should be recognized officially until the data upon which the claim is based have been reproduced, preferably in another laboratory and preferably by a different technique. However, it cannot: given the immense labour and the time necessary to detect perhaps even a single atom of a new element, it would appear unreasonable to apply such a demand of demonstrated reproducibility in all rigidity. We do not believe that recognition of the discovery of a new element should always be held up until the experiment or its equivalent have been repeated, desirable in principle as this may be. However, we would waive this requirement only in cases where the data are of such a nature that no reasonable doubt is possible (for instance for data with a high degree of internal redundancy and of the highest quality), and under circumstances where a repetition of the experiment would imply an unreasonable burden.'*

The experience gained from the synthesis of new elements since that time reveals that the results of experiments, which received a positive assessment of discovery, were successfully reproduced, either before assessment or after priority of discovery had been assigned. Most of the confirmation experiments were performed at independent laboratories. Only in a few cases did these confirmation experiments fail. However, that results had been retraced before priority of discovery had been assigned. We conclude that by appropriate application of the discovery criteria and careful objective assessment of the experimental work, the decisions of the JWP have been extremely reliable.

The key statements of the 1991 TWG related to the subject of reproducibility are: *'Confirmation demands reproducibility'* and *'we would waive this requirement only in cases where the data are of such a nature that no reasonable doubt is possible'*. All eighteen elements discovered since 1991 and also the three ones discovered between 1981 and 1984, were produced in heavy ion fusion reactions and identified after separation of evaporation residues by electromagnetic devices. Most of these new elements were identified by genetic relations of correlated  $\alpha$ - or SF-decays. *Per se*, with each of these experiments the production and identification method was also corroborated. Thus, the almost identical method used and the basically similar results can, at least partially be considered as repetition. The systematics of the results gained over years can serve as a relatively strong argument for assigning priority, when new elements are discovered using those methods. The request for reproducibility is partially given by the established production and identification method. The request to exactly repeat a certain experiment or to confirm the results using different techniques can more easily be waived when well recognized methods are applied.

A different situation occurs when discovery of an element is claimed that was produced and identified with methods for which no or only limited experience exists for study of heavy nuclei. Such reactions are, e.g. multinucleon transfer reactions or secondary reactions with radioactive fragments. Another type of possible production of SHN is in astrophysical processes. Results of search experiments for long living surviving nuclei were announced from time to time but none of these claims could be confirmed or, as in some cases, they were even disproved. In some cases repetition was not yet performed.

In these or similar cases where no broad experience on production and identification exists, it is mandatory that the result of a claim has to be reproduced, *'preferably in another laboratory and preferably by a different'* or an improved *'technique'*. Confirmation is particularly called for in cases for which negative results were already obtained in experiments aiming to confirm the previous claim. This request takes into account the difficulty to clearly disprove an earlier questionable result.

We cannot consider here all possible situations with two or more not completely convincing claims which render a clear assignment but which could result in serious controversies among the claimants. In such cases it is good scientific habit to try to find a solution among the claimants with the help of the experienced members of a Joint Working Party. In the case of really equivalent results published simultaneously, a reasonable solution could be to discuss a shared discovery among the claimants and the members of the Joint Working Party. Such a solution would also demonstrate that in science the scientific result stands over particular individual interests.

Finally, we appeal to fairness among all research groups. Keeping scientific standards is the highest good that we can return to the general public as thanks for the support.

## 8 Summary and concluding remarks

The intention of this report was to update criteria which were elaborated by a Transfermium Working Group during the years 1988 to 1991 as a basis for assigning priority of the discovery of new elements having atomic numbers greater than 100.

Since that time the number of known elements extended up to element 118 which closes the seventh row in the Periodic Table of the Elements. Physical results revealed two regions of increased stability, one for deformed superheavy nuclei located at proton number 108 and neutron number 162 and the region of spherical superheavy nuclei gaining their stability from the closed shells for protons and neutrons at  $Z=114$  and  $N=184$ , respectively. Both regions and the probable decay modes and half-lives of the isotopes were theoretically predicted in the second half of the 1960s. Problematic remained the optimum method and related yield for production of these nuclei or elements.

Remarkable experimental efforts were necessary for producing and detecting these nuclei. These developments served as a basis for the presented update of the 1991 criteria for assigning priority of discovery of a new element. Therefore, in a first part we set forth the present status of research on superheavy nuclei or elements. Subsequently we present the knowledge on nuclear and chemical properties achieved from the produced isotopes of these elements and the methods how they were produced.

Detailed investigation of the experimental data presented as claims for discovery of a new element revealed that in general the nature of the experimental data is such that an absolutely secure identification in a first discovery experiment is rarely possible when new regions in the chart of nuclei are explored, as it was the case with the discovery of spherical superheavy nuclei at the end of the 1990s. However, combining the information from various irradiations and measurements, the new elements could be safely and relatively quickly identified. The term 'discovery profile' was already coined for this procedure in the 1991 TWG report.

Less problematic is the identification of new elements when the produced isotopes can be genetically connected to known daughter products via traceable decay chains and using known reactions as, *e.g.* fusion evaporation reactions, and established identification methods. In that case only one measured decay chain could be sufficient for safely assigning priority of discovery.

In this report we discuss various identification methods and point out in particular to the experimental problems which can arise and which can hamper the interpretation of the measurements. Also considered are physical properties of the reaction for production and properties of the nuclear decays. All this information is meant as hint for experimentalists and members of future Joint Working Parties to be considered. This report does and cannot present a list of criteria for checking fulfilled and failed criteria where the number of fulfilled criteria decides on the discovery. It rather reveals that for each criterion its weight and its applicability to a certain experimental result have to be carefully considered.

Finally, we suggest a procedure how experimentalists can claim the discovery of a new element. We present the recommendations for the contents of an experimental paper so that an evaluating group of experts, the Joint Working Party, is supplied with well founded information on the proposed discovery. Also provided are recommendations to the members of the Joint Working Parties for consideration in the preparation of their report.

## Abbreviations often used in the article and in the related literature

### Laboratories

ANL	Argonne National Laboratory, Argonne near Chicago, Illinois, USA
FLNR	Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia
GANIL	Grand Accélérateur National d'Ions Lourds, Accelerator Laboratory, Caen, France
GSI	Gesellschaft für Schwer-Ionen-Forschung, Accelerator Laboratory, Darmstadt, Germany
IMP	Institute of Modern Physics, Lanzhou, China
JINR	Joint Institute for Nuclear Research, Dubna, 130 km north from Moscow, Russia
JYFL	Jyväskylän Yliopiston Fysiikan Laitos, the Finish words for University of Jyväskylä, Department of Physics, Accelerator Laboratory in Jyväskylä, Finland
LBNL	Lawrence Berkeley National Laboratory, Berkeley, California, USA
LLNL	Lawrence Livermore National Laboratory, Livermore, California, USA
ORNL	Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
RIKEN	Institute of Physical and Chemical Research, Saitama, near Tokyo, Japan

### Accelerators and accelerator projects

88-inch cyclotron	Sector focused K = 140 cyclotron, LBNL, Berkeley, California, USA
ATLAS	Argonne Tandem Linac Accelerator System, superconducting accelerator, ANL, Argonne, Illinois, USA
DC-280	Dubna cyclotron as main part of the SHE factory, K factor = 280
HILAC	Heavy Ion Linear Accelerator, LBNL, Berkeley, California, USA
RIA	Rare Isotope Accelerator, accelerator project, USA
RILAC	RIKEN Heavy-ion Linac, RIKEN, Japan
SPIRAL	Système de Production d'Ions Radioactifs et d'Accélération en Ligne, an accelerator complex for the production and acceleration of radioactive ions under construction at GANIL in Caen, France
SPIRAL II	Superconducting Linear Accelerator, GANIL, Caen, France
U-400	400-cm diameter isochronous cyclotron, FLNR, Dubna, Russia
UNILAC	UNiversal Linear ACcelerator, an accelerator for heavy ions at GSI in Darmstadt, Germany
VERA	Vienna Environmental Research Accelerator, University of Vienna, Vienna, Austria

### Ion sources and related items

DECRIS	Dubna Electron Cyclotron Resonance Ion Source
ECR	Electron Cyclotron Resonance ion source
CAPRICE	Compact A Plusieurs Résonances Ionisantes Cyclotron, special type of ECR ion source
MIVOC	Metal Ions from Volatile Compounds, <i>e.g.</i> Fe(C <sub>5</sub> H <sub>5</sub> ) <sub>2</sub>
PIG	Penning Ion Gauge
VENUS ECR	Versatile ECR ion source for Nuclear Science, superconducting ECR ion source

### Separators and detection devices

AMS	Accelerator Mass Spectrometry
FMA	Fragment Mass Analyser, recoil mass spectrometer at ANL
BGS	Berkeley Gas-filled Separator, LBNL, Berkeley, California, USA
DGFRS	Dubna Gas-filled Recoil Separator at U-400, FLNR, Dubna, Russia
DGFRS II	Dubna Gas-filled Recoil Separator II at DC-280, FLNR, Dubna, Russia
DSSD	Double Sided silicon Strip detector
GARIS	Gas-filled Recoil Ion Separator, RIKEN, Saitama, Japan
GARIS II	Gas-filled Recoil Ion Separator, optimized for hot fusion reactions using actinide targets, RIKEN, Saitama, Japan

ICP-SFMS	Inductively Coupled Plasma Sector Field Mass Spectrometry
IGISOL	Ion Guide Isotope Separator On-Line
ISOL	Isotope Separator On-Line
PIPS	Passivated Implanted Planar Silicon detector
MARA	Mass Analysing Recoil Apparatus, vacuum-mode recoil mass separator, JYFL, Jyväskylä, Finland
MRTof	Multi Reflection Time-of-Flight mass spectrometers
NASE	NAch-SEparator, vacuum or gas-filled post separator at SHIP, now stand alone gas-filled separator TASCA, GSI, Darmstadt, Germany
OLGA	On-Line Gas chromatography Apparatus
RITU	Recoil Ion Transport Unit, gas-filled separator, JYFL, Jyväskylä, Finland
S3	Super Separator Spectrometer, GANIL, Caen, France
SHELS	Separator for Heavy Element Spectroscopy, FLNR, Dubna, Russia
SHIP	Separator for Heavy Ion reaction Products, velocity filter for fusion reaction products at GSI, Darmstadt, Germany
TASCA	Trans Actinide Separator and Chemistry Apparatus, gas-filled separator, former post-separator NASE at SHIP, GSI, Darmstadt, Germany
ToF	Time-of-flight detector device
SHANS	Spectrometer for Heavy Atom and Nuclear Structure, gas-filled recoil separator at IMP, Lanzhou
VASSILISSA	Energy filter, separator for fusion-reaction products named after a fairy in a Russian fairy tale, FLNR, Dubna, Russia

### Organizations, unions, groups, and parties

JWG	Joint Working Group, established in 2017, elaborates criteria and procedures to be applied in assigning priority of discovery of new elements beyond $Z = 118$
IUPAC	International Union of Pure and Applied Chemistry
IUPAP	International Union of Pure and Applied Physics
JWP	Joint Working Party, several JWPs of independent experts evaluated the claims of discovery of new elements in the years from 1999 to 2016.
NAO	National Adhering Organizations
TWG	Transfermium Working Group, evaluated the claims of discovery of element 101 to 109 on the basis of criteria of discovery in the years from 1987 to 1993

### Physical quantities

$A$	Mass number $A = Z + N$
$B\rho$	Magnetic rigidity: effect of a magnetic field on the motion of a charged particle
CN	Compound nucleus
$E_\alpha$	Laboratory energy of $\alpha$ -particle emitted during $\alpha$ -decay
ER	Evaporation residue
$F\rho$	Electric rigidity: effect of an electric field on the motion of a charged particle
$m(A, Z)$	Mass of the nucleus with mass number $A$ and proton number $Z$
$N$	Number of neutrons
$Q_\alpha(A, Z)$	$\alpha$ -decay energy for ground-state to ground-state decays $Q_\alpha(A, Z) = E_\alpha \times (m(A-4, Z-2) + m_\alpha) / m(A-4, Z-2) \approx E_\alpha \times A / (A-4)$
$\sigma$	Reaction cross-section (in barn, symbol b; $1 \text{ b} = 10^{-28} \text{ m}^2$ )
$T$ or $T_{1/2}$	Half-life, $T_{1/2} = \tau \times \ln 2$
$T_{\text{tot}}, T_\alpha, T_\beta, T_{\text{SF}}$	Total and partial half-life for $\alpha$ -, $\beta$ -decay, and spontaneous fission
$Z$	Number of protons
$\tau$	Lifetime, $\tau = T_{1/2} / \ln 2$
$\tau_{\text{tot}}, \tau_\alpha, \tau_\beta, \tau_{\text{SF}}$	Total and partial lifetime for $\alpha$ -, $\beta$ -decay, and spontaneous fission
$\lambda$	Decay probability, $\lambda = 1/\tau$

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## Attachments

### Attachment 1

Terms of Reference for a IUPAC/IUPAP Joint Working Group to Examine the Criteria used to Verify Claims for the Discovery of New Elements

*International Union of Pure and Applied Physics (IUPAP), 9 December 2016 and International Union of Pure and Applied Chemistry (IUPAC), 19 November 2016*

### Rationale and purpose

Some twenty-five years have now elapsed since the criteria that are currently used to verify claims for the discovery of a new element were set down. The recent completion of the naming of the one-hundred and eighteen elements in the first seven periods of the Periodic Table of the elements provides a natural opportunity for a necessary expert review of these criteria in the light of the experimental and theoretical advances in the field. It is proposed to set up a IUPAC/IUPAP Joint Working Group (JWG) to examine these criteria under the terms of reference set out below.

This JWG is set up for the specific task of reviewing and, if necessary, updating these criteria, and is distinct from the IUPAC/IUPAP Joint Working Parties (JWP) which have and which will evaluate claims to have discovered new elements. Should the JWG recommend any changes to these criteria it will include in its report a recommendation on whether a JWP needs to be appointed to re-examine priorities assigned to any of the recently discovered elements based on these new criteria.

If, and when, new claims for the discovery of new elements appear in the literature, a JWP will also be appointed; this later JWP should also examine any assignments made for earlier elements that may have been challenged.

### Composition and establishment of the JWG

The JWG will be established following the guidelines below:

1. The Presidents of IUPAC and IUPAP will appoint by mutual agreement a Joint IUPAC/IUPAP Working Group of six members with relevant expertise in the Discovery of New Elements, three to be nominated by the President of IUPAC, with advice from the Division of Inorganic Chemistry; three to be nominated by the President of IUPAP, with advice from the Commission for Nuclear Physics.
2. Appointments are made respecting the importance of continuity and new experience in the process of discovering new elements.
3. The Joint Working Group will elect a Chair and a Vice Chair, subject to the approval of the Presidents of IUPAC and IUPAP.

Clearly the restriction excluding the appointment of members from a claimant laboratory which applies to Joint Working Parties will not apply to this Joint Working Group, which is not evaluating any claims.

### Terms of reference

The JWG will review and, if necessary, make recommendations for the revision of the criteria originally set down for determining the discovery of a new element and given by the Transfermium Working Group in 1991 [Wapstra *et al.* "Discovery of the Transfermium Elements" (*Pure Appl. Chem.*, Vol. 63, No. 6, pp. 879–886 (1991))].

The JWG will report using the procedures laid down below:

1. The Joint Working Group shall report within 12 months on the progress of its work to the Presidents of IUPAC and IUPAP.

2. The Joint Working Group shall also report to the Presidents of IUPAC and IUPAP when there are new developments which it feels should be reported, when a report is requested by the President of one of the Unions.
3. A copy of the draft report as sent for technical review will be provided to Presidents of IUPAC and IUPAP.
4. A copy of the report of the Joint Working Group as submitted for publication will be provided to the Presidents of IUPAC and IUPAP.

The JWG report will be approved following the procedure laid down below:

1. The report, as it is to be published shall be approved by the Presidents of IUPAC and IUPAP, on the advice of the Division of Inorganic Chemistry and the Commission for Nuclear Physics respectively, and published as a provisional report in *Pure and Applied Chemistry*.
2. The provisional report is open for comment for five months. Comments will be forwarded to the Presidents of IUPAC and IUPAP, who will, with advice from the Division of Inorganic Chemistry and the Commission for Nuclear Physics, respectively, decide whether to make the report final, or on what other action should be taken.

The public release of the findings of this Joint Working Group shall be made jointly in the name of both Unions, by joint press release or by any other means.

## Attachment 2

IUPAC and IUPAP Procedures for Validating Claims for the Discovery of New Elements and Naming those Elements

*International Union of Pure and Applied Physics (IUPAP), 9 October 2017 and International Union of Pure and Applied Chemistry (IUPAC), 18 September 2017*

## Introduction

The procedures recently followed for validating claims for the discovery of new elements 113, 115, 117 and 118 and naming those elements had their origin in the IUPAC-IUPAP appointment of the Transfermium Working Group of IUPAC and IUPAP in 1986. It is now timely to re-establish these co-operative arrangements, both for the validation of the claims and for the naming of the elements. This process was initiated by IUPAP, also recognizing that the process of synthesizing or discovering a new element relies heavily on nuclear physics facilities and techniques, and is a complex process where chemists and physicists are often involved.

The validation of claims has been made by an IUPAC-IUPAP Joint Working Party (JWP). This document sets out the agreed procedures for the appointment of the Joint Working Party, for its operation, and for the reporting of its results.

The naming of the elements has been under the oversight of the IUPAC Division of Inorganic Chemistry, and this document also sets out the agreed procedures for determining and reporting the new names.

## IUPAC-IUPAP Joint Working Party for the validation of claims of new elements

### 1. Guidelines for the Appointment of Members

- 1.1 In the event of a claim for the discovery of new elements requiring investigation, or of the publication of results which call into question the results analysed by previous Joint Working Parties, the Presidents of IUPAC and IUPAP will appoint by mutual agreement a Joint IUPAC-IUPAP Working Party of six members with relevant expertise to validate claims and resolve disputes for the Discovery of New Elements,

- three to be nominated by the President of IUPAC, with advice from the Division of Inorganic Chemistry
  - three to be nominated by the President of IUPAP, with advice from the Commission for Nuclear Physics, such that:
    - all six members come from different countries, preferably and if possible not from those who are claiming new discoveries, or raised a dispute
    - appointments are made respecting the importance of both continuity and expertise in the process of evaluating discoveries of new elements.
- 1.2 The members must not come from a claimant institution, or from an institution whose earlier claims are questioned, or from an institution questioning those claims.
  - 1.3 The Joint Working Party will elect a Chair and a Vice Chair, subject to the approval of the Presidents of IUPAC and IUPAP.
  - 1.4 After the appointment of the Joint Working Party one of the Unions will provide the secretariat which invites and collects information from claimants and others, relevant to the claims made and passes that information to the Joint Working Party and to the other Union.
  - 1.5 The Joint Working Party will be appointed until it reports on the claims it was set up to validate, or resolve a dispute. It will be released from its responsibility and disbanded after the naming of elements is announced and ratified.
  - 1.6 Should the Joint Working Party not resolve the claims within two years, the Presidents of IUPAC and IUPAP will consult to decide whether, and in what form, it should continue to work.
  - 1.7 Should additional claims of the discovery of new elements or rebuttals of such claims be received while the Joint Working Party is in operation, the Presidents of IUPAC and IUPAP will consult on whether these claims should be referred to the existing Joint Working Party, whether the Joint Working Party be reconstituted to consider them, or whether a second Joint Working Party should be appointed to consider them.

## 2. Procedure for approval of claims by the Joint Working Party

- 2.1 The Joint Working Party shall evaluate claims against the criteria set out by the Transfermium Joint Working Group in 1991 (Wapstra *et al.* (1991) “Discovery of the Transfermium Elements”, *Pure Appl. Chem.*, Vol. 63, No. 6, pp. 879–886; <https://doi.org/10.1351/pac199163060879>), and in updates agreed to by both Unions.
- 2.2 The Joint Working Party shall report annually on the progress of its work to the Presidents of IUPAC and IUPAP.
- 2.3 The Joint Working Party shall also report to the Presidents of IUPAC and IUPAP
  - when there are new developments which it feels should be reported,
  - when a report is requested by the President of one the Unions.
- 2.4 A copy of the draft report as sent for technical review will be provided to the Presidents of IUPAC and IUPAP.
- 2.5 A copy of the report of the Joint Working Party to be submitted for publication will be provided to the Presidents of IUPAC and IUPAP.
- 2.6 It is intended that the full detailed report will be published in *Pure and Applied Chemistry*, and that, to publicise the verification of a new element, a short report be published in a widely read general scientific journal, such as *Science* or *Nature*.
- 2.7 The Presidents of IUPAC and IUPAP in consultation with the President of the IUPAC Division of Inorganic Chemistry and the Chair of the IUPAP Commission on Nuclear Physics will appoint two co-editors, one from each Union, who will jointly supervise the peer review of the report of the Joint Working Group, using at least two and up to four referees, and provide the reviewed and revised copy for publication to the editor of the journal *Pure and Applied Chemistry*, including the referees’

reports and all related correspondence. It is expected that the editor of *Pure and Applied Chemistry* will incorporate this material into the normal review process of the publication.

- 2.8 The report, as it is to be published shall be approved by the Presidents of IUPAC and IUPAP, on the advice of the Division of Inorganic Chemistry and the Commission for Nuclear Physics, respectively, and published as a provisional report in the journal *Pure and Applied Chemistry*.
- 2.9 Provisional announcements in the name of both Unions of the findings of the Joint Working Party shall be made on publication of the approved final report, by joint press release and by any other means. The announcement shall clearly state that the determination of claims for new elements is the work of a Joint Working Party of both Unions.
- 2.10 After publication and announcement of the findings of the Joint Working Party, the provisional report is open for comment for five months. Comments will be forwarded to the Presidents of IUPAC and IUPAP, who will, with advice from the Division of Inorganic Chemistry and the Commission for Nuclear Physics, respectively, decide whether to make the report final, or on what other actions should be taken.

### 3. Naming of New Elements

- 3.1 Once the report has been made final the President of the Inorganic Chemistry Division of IUPAC invites the laboratory or laboratories to which priority for discovery has been assigned to propose a name and symbol for the element in line with the established guidelines. After names and symbols have been proposed and the procedures of IUPAC set out in the paper “How to name new chemical elements (IUPAC Recommendations 2016)”, Koppenol *et al.* (2016), *Pure Appl. Chem.*, Vol. 88, No. 4, pp. 401–405; <https://doi.org:10.1515/pac-2015-0802>) for the approval of those names have been concluded, the provisional recommendation will be approved by the Presidents of both Unions before publication. The announcements of the provisional recommendation and the names and symbols of the new elements shall be made by both Unions, by joint press release and by any other means. The announcement will clearly state that the provisional names and symbols have been recommended by IUPAC, following the determination of claims for the discovery by a Joint Working Party of both Unions.
- 3.2 The provisional recommendations are open for public review for a period of five months. At the conclusion of this period the President of the Inorganic Chemistry Division forwards the Division’s final recommendation for the name and atomic symbol of a new element to the Council of the IUPAC for formal approval by the Union and publication in *Pure and Applied Chemistry*. At the time the final recommendation is provided to the Council of IUPAC it will be notified to the President of IUPAP.