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HIGH ENERGY PHOTON ACTIVATION

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SUMMARY

Interaction of high energy gamma photons with matter results in the formation of radionuclides, many of which have been made the basis for important applications in analysis. Of particular practical consequence is the possibility of sensitive and accurate determination of light elements, particularly beryllium, carbon, oxygen, nitrogen, and fluorine. Other important developments are nondestructive methods for a number of elements including strontium, zirconium, calcium and iron in complex matrices such as silicates and biological materials.

This survey includes general information on sources of photons, the character of their interactions with the sample, cross sections for the formation of radionuclides interesting in analysis, and data on sensitivities and possible interferences. Important data on recent applications are summarized in one of the Tables.

In the Table of Isotopes condensed information is given on 236 isotopes of significance in analysis, including their reactions, threshold values, characteristics of the isotopes produced and sensitivities for a set of irradiation conditions.

INTRODUCTION

Development of accelerators producing beams of high energy photons. such as betatrons, linear accelerators and microtrons, opened possibilities for the development of a new activation technique which is rapidly gaining in importance. Their interaction with matter results in the formation of radionuclides, many of which have suitable characteristics for applications in analysis. These reactions, as well as the isotopes produced, are with a few exceptions different from those obtained by irradiation with thermal neutrons, and, except for the (n, 2n) reaction, from those produced with fast neutrons. The technique therefore covers several elements and/or matrices not accessible by other activation methods.

The specific advantages of the activation principle, the most important of which is the essential freedom from contamination problems, resulting in better accuracy, as well as the wide applicability of the nondestructive approach in multielement analysis, apply also to photon activation analysis.

Gamma photons can be compared with neutrons with respect to ability to penetrate matter; self shielding, which can be a serious limitation in thermal neutron activation analysis. is less critical in phonon activation.

Another substantial feature offered by photon activation analysis is the unique possibility for determining with very high sensitivity the light elements, of which carbon as well as beryllium and deuterium are not covered by either fast neutron or thermal neutron activation. The technique is also advantageous in determining oxygen and fluorine and it can be used as an alternative

for a number of other elements, including the halogens, strontium, chromium, rubidium, thallium and lead.

Frequently its application is indicated by the nature of the sample. Elements like sodium and potassium are encountered in a number of mineral and biological samples as major components and interfere seriously in thermal neutron activation analysis because of their very large induced activities and the unfavourable distribution of peaks and complex nature of their spectra. They can be tolerated in relatively high concentrations when using non-destructive photon activation analysis of many natural and synthetic silicates, as well as of plant and animal tissues. Earlier work on photon activation analysis has been evaluated in the excellent reviews by Baker[4]. Lutz[61] and Engelmann[22]. A bibliography covering references up to the end of 1971 is also available as a publication of the US National Bureau of Standards[2]. In this survey emphasis will therefore be given to recent developments.

SOURCES OF HIGH ENERGY PHOTONS

Photons to be used for activation analysis must have an energy considerably higher than the threshold energy of the respective nuclear reaction. Isotopic sources emitting gamma photons in the energy range up to two MeV have therefore very limited application in photon activation analysis. Deuterium and beryllium have exceptionally low threshold energies for the (γ, n) reaction, 1.667 MeV, and 2.224 MeV respectively, and are thus two exceptional elements which may be conveniently determined by using ^{124}Sb or ^{24}Na gamma sources and counting directly the emitted neutrons. Several applications of this technique have been described[25, 26, 35, 95].

Gamma radiation from radioactive cobalt sources has also been studied from the point of view of its application to activation analysis. Its use is based on the measurement of the activity of the short lived metastable isomers produced by (γ, γ') excitation. In experimental conditions as used by Law and Iddings[52] who irradiated 13 elements (Sr, Rh, Cd, In, Ba, Lu, Ta, Hg, Pb, Os, Se, Ag, Br) using a 5000 Ci ^{60}Co source, they were able to measure induced activities only in indium, cadmium and strontium; overall activation cross sections as determined for ^{111}Cd, ^{113}In and ^{115}In are of the order of 10^{-32} cm^2.

Results by Veres and Pavlicsek[113] indicate that with a stronger source (80 kCi) and by taking large samples (50 g) selenium, bromine and indium could be detected in concentrations of the order of 10 ppm, while for silver, cadmium and strontium the detection limit is lower by a factor of ten (Ag, Cd) to twenty (Sr).

GENERATION OF GAMMA PHOTONS

From *Table 1*. which gives threshold values for the most important reactions induced by gamma photons in order of their importance, it follows that the energies involved are above 8 MeV for (γ, n) reactions and above 6 MeV for the (γ, p) reaction.

Curves representing effective cross sections for reactions induced by high

energy gamma photons have their maxima 6–7 MeV above the threshold energy and extend another 7 MeV beyond the maximum.

Three commercially available accelerators cover the required energy range: linear accelerators, betatrons and microtrons. Although they differ

Table 1. Threshold values for reaction of gamma photons with some isotopes

Isotope	γ, n	γ, p	γ, 2n	γ, 2p	γ, np	γ, ^{3}He	γ, t	γ, α
^{12}C	*18.72*	15.96	*31.80*	*27.18*	27.41	26.28	27.36	7.37
^{19}F	*10.43*	7.99	*19.58*	*23.93*	16.04	*22.10*	11.70	4.01
^{45}Sc	*11.32*	6.89	*21.03*	*19.06*	18.03	*20.97*	22.90	7.93
^{94}Zr	*8.20*	*10.31*	14.95	*18.93*	17.80	*18.52*	*15.86*	*3.76*
^{107}Ag	*9.53*	5.78	*17.42*	*15.12*	15.33	*16.39*	13.94	2.81
^{109}Ag	*9.18*	6.48	16.46	*15.44*	*15.71*	*13.76*	13.76	*3.28*
^{127}I	*9.15*	6.22	*16.24*	*15.28*	14.76	*16.33*	13.43	2.18
^{165}Ho	*8.04*	6.15	*14.60*	*14.71*	13.81	*14.36*	11.58	*0*
^{176}Hf	*8.11*	6.43	15.02	11.95	*14.23*	11.66	12.37	0
^{196}Hg	*8.81*	*6.57*	*16.12*	16.69	*14.99*	*12.36*	*13.48*	0

in the principle of acceleration, electrons are normally used as accelerated particles in all of them. Following acceleration to the selected energy, the electron beam is allowed to strike a platinum, tungsten, gold or tantalum converter in which the electrons are stopped. In the process of stopping the energy is dissipated by ionization and excitation processes and as heat, but in converters with high atomic numbers as much as 40–60 per cent can be released as a bremsstrahlung pulse having its maximum energy equal to that of the primary electron beam and its maximum intensity in the direction of the axis of the electron beam. Photon flux density at a given energy is dependent upon the mean current of the primary beam. In a linear accelerator mean currents are relatively large, typically 5–15 μA, although they can be as high as 100 μA[39] or even higher in some newer machines. The maximum energy of photons obtained from a linear accelerator is given by the length of the accelerating tube which is basically a waveguide in which the electrons are accelerated by the progressing electromagnetic waves (*Figure 1a*). The energy increase per meter length of the accelerator is of the order of 3–5 MeV; for analytical applications they are operated normally at energies of 20 to 40 MeV although irradiations at energies up to 80 MeV have been reported in recent papers.

Linear accelerators can be considered as photon sources of choice for photon activation analysis. The construction principle makes the access to the converter easy as it is mounted at the end of a linear tube (*Figure 1b*). They operate at relatively high currents, the energy of the beam can be easily varied and the sensitivites achieved for elements like oxygen, carbon or fluorine are in the range of micrograms or even nanograms.

Betatrons are commercially produced for energies of 22 MeV (Allis Chalmers), of 31 MeV (Brown Bowery) and of 42 MeV (Siemens). Maximum currents, however, are much lower compared to linear accelerators, typically between 0.01 and 0.1 μA. Electrons are accelerated in the magnetic field of an electromagnet and move in a circular orbit. Due to the relatively large diameter of the acceleration tube and its curvature it is not possible to

irradiate the samples in the immediate vicinity of the converter. The closest possible position is about 15 cm. Some betatrons allow the introduction of the sample inside the accelerating tube next to the converter[49–51]; this improves the intensity but on the other hand limits the size of the sample considerably. Another alternative is the extraction of the beam: this however is connected with considerable technical requirement (see *Figure 2*).

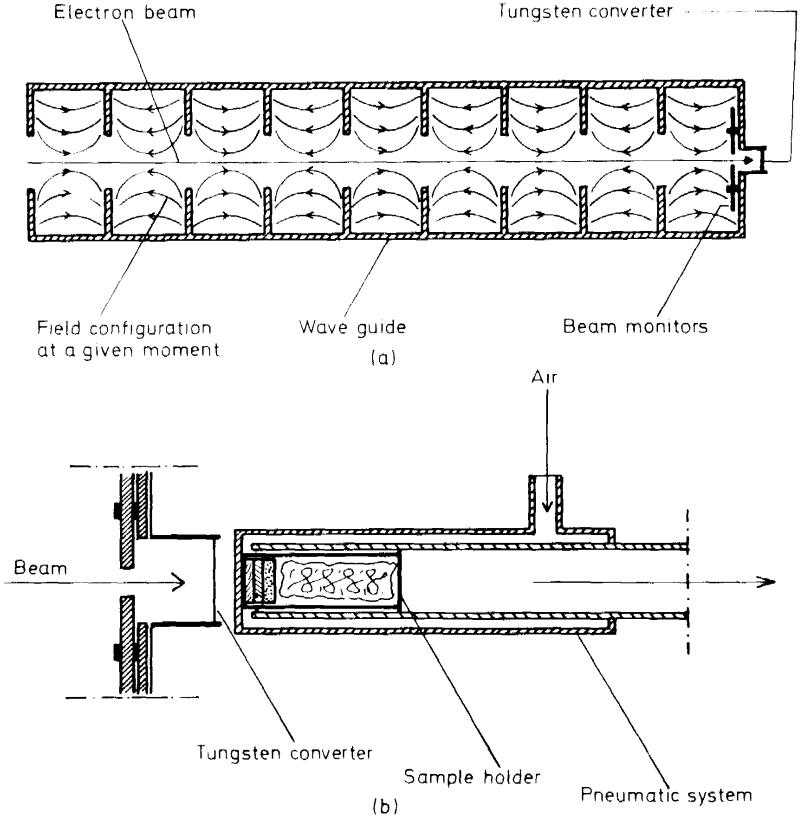

Figure 1. a Schematic diagram of a linear accelerator (not to scale). *b* Target assembly

Even when working outside the tube, the betatron still offers excellent possibilities for precise nondestructive analysis in the concentration range between a few percent and thousandths of a percent.

Microtrons, which combine certain features of the two accelerators just discussed and operate on the principle of oscillation in a single resonator cavity, have so far been little used in photon activation although they are suitable for the purpose from the point of view of energies as well as attainable currents. Reported work refers to energies of 29 MeV at 15 μA currents[12, 23, 40, 78].

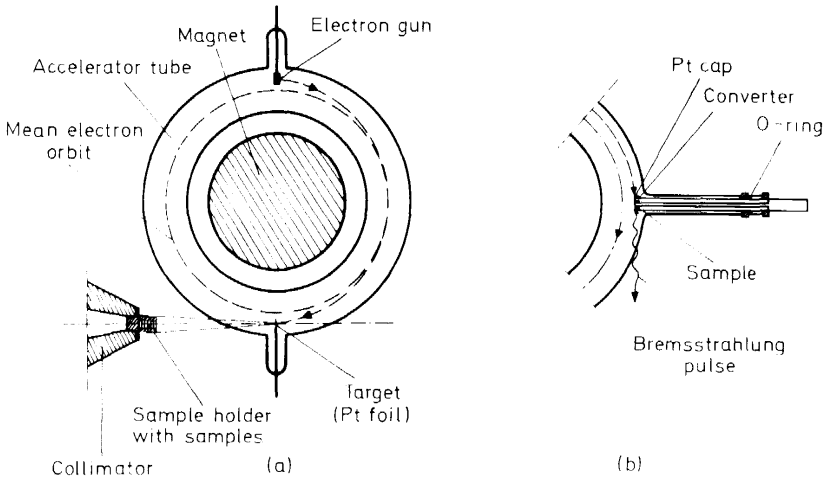

Figure 2. a Betatron accelerating tube with a target assembly. *b* Internal target arrangement

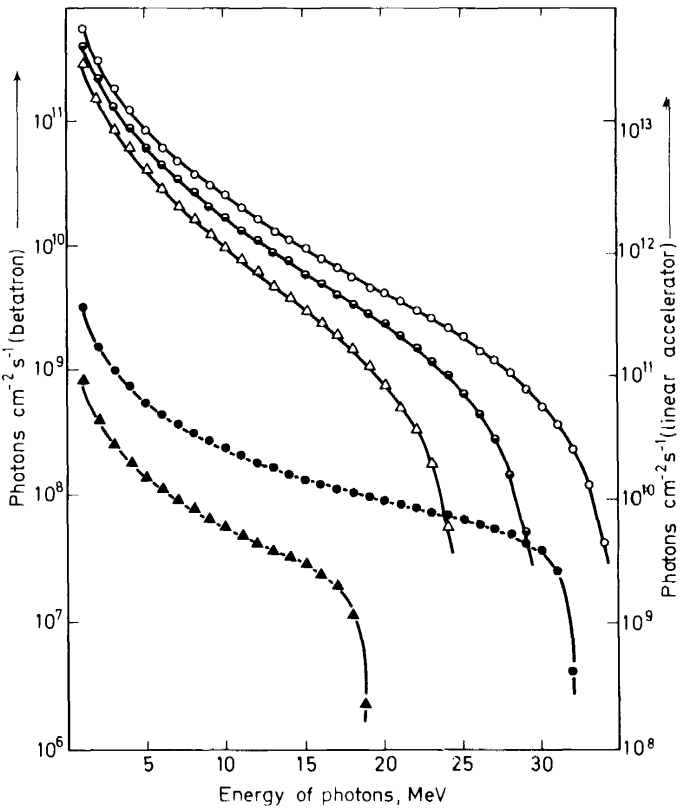

Figure 3. Photon flux of bremsstrahlung from linear accelerator (right scale) and from betatron (left scale). Linear accelerator operated at 100 μA mean current and at E_{max} of 35 MeV (○), 30 MeV (◒) and 25 MeV (△). Betatron mean electron current 0.1 μA at E_{max} of 32 MeV (●) and 19 MeV (▲).

This discussion will be limited primarily to work with accelerators as they cover the whole range of energies of interest and offer high flexibility with respect to the energies at which they are operated. This in turn is an important parameter in adjusting the selectivity of photon activation by exploiting differences in threshold values.

The intensity of the bremsstrahlung is a continuous function of the energy and therefore given as photons $cm^{-2}\ s^{-1}$ for an energy interval of 1 MeV. *Figure 3* illustrates this dependence for a linear accelerator and for a betatron. The diameter of the sample was 1 cm, but at different thicknesses of the converter, 6 mm and 0.5 mm respectively[43, 56]. In the case of a thicker target, there is a higher contribution of photons with lower energies, whereas in the case of a betatron with a target thickness of only 0.5 mm the curve approaches the theoretical form of Schiffs spectrum[8, 101].

ACTIVATION OF ELEMENTS BY HIGH ENERGY PHOTONS

The energy required for expulsion of a particle in the interaction of a nucleus with a photon is given by the binding energy of the nucleus. Threshold energies are generally lowest for (γ, α) interactions. However, because of the electric charge of the resulting particle, the effective cross sections for these reactions are small. Stable isotopes are formed in most interactions of this type. Next to (γ, α), the lowest threshold energies in most isotopes, and the largest effective cross sections, are found in (γ, n) reactions. There are only a few exceptions among light elements where the effective cross section can be larger for (γ, p). The reaction product of the lightest isotope of any element in (γ, n) reactions is a radionuclide with the exception of the very lightest elements. Radionuclides formed are identical to those obtained in $(n, 2n)$ reactions of fast neutrons. Apart from (γ, n) and (γ, p) reactions, other possible interactions are less important from the point of view of their use in actual determinations. Nevertheless they have to be considered because their occurrence, in particular when working at higher energies, can result in interferences which are by no means negligible. Some of them will be dealt with when discussing the application of the technique to actual samples. Also reactions of the type $(\gamma, 2n)$, $(\gamma, 3n)$, (γ, pn) and $(\gamma, \alpha n)$ appear promising in the determination of certain heavier elements e.g. bismuth.

CALCULATION OF THE INDUCED ACTIVITY

Cross sections in photon activation depend upon the energy typically as shown in *Figure 4*, for the case of copper. It has been measured by Jones and Terwillinger[36] up to an energy of 320 MeV. The part of the curve following the threshold energy is referred to as giant resonance. Because the method used was based on counting neutrons, all interactions are included in which neutrons are produced, i.e. $(\gamma, n) + (\gamma, np) + (\gamma, \alpha n) + (\gamma, 2n) + (\gamma, 3n)$ etc. The curve representing separately the cross section for the most interesting reaction, $^{63}Cu\ (\gamma, n)\ ^{62}Cu$, is drawn with a broken line. According

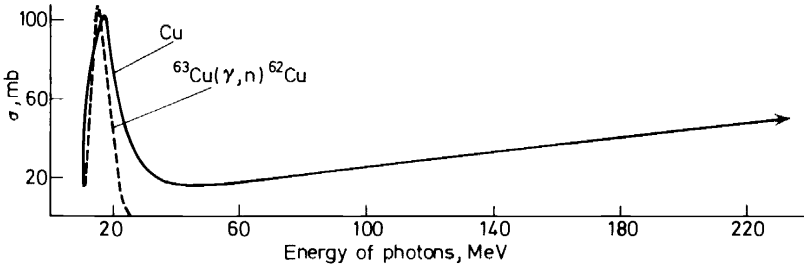

Figure 4. Dependence of cross section of copper on the photon energy up to 320 MeV The broken curve represents the cross section separately for $^{63}Cu(\gamma, n)^{62}Cu$ (Ref. 36).

to recent measurements[11], the cross section for this reaction is 70 mb at the energy of its maximum. The shapes of the curves for other elements are similar. Certain isotopes, however, have two maxima, and in a few light elements (^{12}C, ^{16}O) the curves characterizing cross sections are even more complicated (see *Figures 5* and *6*).

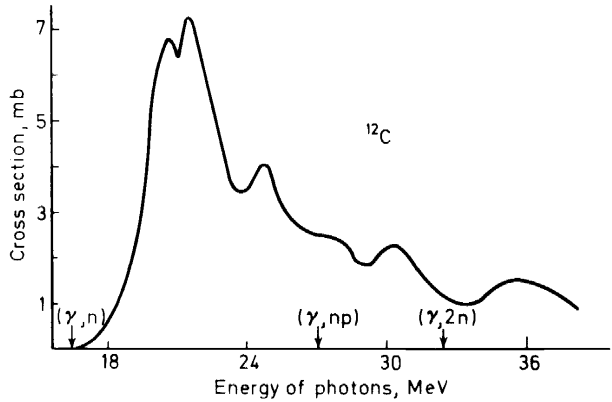

Figure 5. Energy dependence of cross section of ^{12}C for $[(\gamma, n) + (\gamma, np)]$ measured by Fultz *et al.*[24]

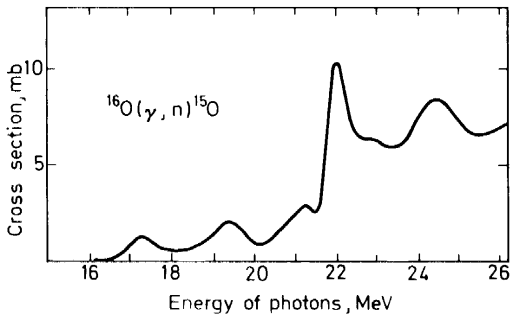

Figure 6. Energy dependence of cross section of oxygen (γ, n) as determined by Miller[67]

Data on cross sections, if known, are normally presented in tables as integrated cross sections, i.e. cross sections integrated over energy E.

$$\sigma_i = \int \sigma(E)\,dE. \qquad (\text{MeV} \cdot \text{b})$$

Approximate values can be calculated by the empirical formula of Jones and Terwillinger. It applies up to 27.5 MeV[36] and gives the peak area of the cross section σ_n for the production of photoneutrons

$$\int_0^{27.5} \sigma_n(E)\,dE = 5.2 \times 10^{-4} A^{1.8} \qquad (\text{MeV} \cdot \text{b})$$

where A is the atomic number of the isotope.

The basic formula as used for calculating the induced activity in thermal neutron, and fast neutron, activation analysis, is not directly applicable. In the interactions of thermal neutrons, and 14 MeV neutrons, the energy and the flux are defined and cross sections have discrete values. In photonuclear activation, the flux as well as cross section are energy dependent. Calculations have therefore to be carried out by replacing σ in the equation

$$A = N\phi\sigma(1 - e^{-\lambda t})$$

by the sum of products of cross sections by fluxes in the range of energies from the threshold over the area of the peak. For a rapid calculation of the activity to be expected it is possible to take into the equation the value of the number of photons per one MeV at the energy E_m, i.e. in the position of the maximum of the cross section, and to insert as σ the integrated cross section σ_i. Nomographs have also been prepared by Ricci[98] from which the respective values can simply be read off.

In curves representing cross sections (σ_{eff}) the difference between the threshold and the energy of the maximum is approximately 6.5 MeV[68] independently of the atomic number. Therefore if E_m is not available it can be obtained by simply adding 6.5 MeV to the threshold energy.

Values found by these calculation will be only approximate; nevertheless, they give some idea of the specific activity to be expected in the irradiation of a given element. Accurate values for specific samples can be obtained only by experiment under the given irradiation conditions.

Several papers have appeared recently quoting sensitivities for alternative sets of well defined conditions. In an article by Lutz[56], they are given for a linear accelerator operated at energies of 25, 30 and 35 MeV, respectively and based separately on four and ten minute irradiations in a defined target configuration. Another important reference as to the sensitivities is the paper by Engelmann[17] who determined (γ, n) activation curves for 17 elements in conditions comparable to those reported by Lutz. A table giving activities obtained from a 10 kW linear accelerator operated at 20 and 25 MeV was published in the work of McGregor[62].

Other references as to the maximum sensitivities or detection limits include the paper by Oka[76] for an energy of 20 MeV and a mean accelerated electron current of 40 μA. In the case of the betatron, extensive measurements have

been carried out by Kochevanov and Kuznetsov[41] who irradiated 2 mm thick pellets at a maximum energy of 24 MeV. Data from the last two papers are included in the Table of Useful Photon-induced Reactions in the Appendix.

In one of his latest papers[51] Kuznetsov grouped the elements according to the absolute minimum amount which can be detected, under given experimental conditions, with a precision better than 10 per cent. Among those with sensitivities better than 1 μg are carbon, phosphorus, copper, zinc, gallium, bromine, rubidium, silver, antimony and praseodymium. In terms of concentrations, referring to a two gram sample, the sensitivity in the first group corresponds approximately to 10^{-5} per cent, taking copper as an example. Specific activities are also given for irradiations at 15.6, 18.6, 23.0 and 26.3 MeV for the entire periodic table[49,50]. In the next group are elements with sensitivities between 1 and 10 μg, represented by nitrogen, oxygen, fluorine, magnesium, chlorine, potassium, iron, strontium, zirconium, samarium, tellurium, holmium and hafnium. These are also the elements which have recently attracted much interest in the application of photon activation analysis to real samples. However, by applying the nondestructive principle of analysis based on the use of high resolution Ge–Li detectors, a number of major components, i.e. Ca, Cr, Fe and Pb were also determined[15,32,102] in such complex samples as rocks or biological standard reference materials, although they belong to the fourth (10–1000 μg) or even fifth group (> 1000 μg) according to the above listing.

INTERFERENCES IN PHOTON ACTIVATION ANALYSIS

Interferences in photon activation analysis are inherent with the nature of the interactions of high energy photons. Most radionuclides produced by (γ, n) reactions are positron emitters. In the group of light elements there are no specific gamma rays emitted, and measurements are based on the 0.511 MeV positron annihilation radiation. In order to achieve the required selectivity there is the possibility of carrying out the irradiation at an energy below the threshold value of the interfering reaction. Nuclides with higher threshold energies are thus eliminated, but only at the expense of sensitivity, since by reducing the energy of the primary beam, there is a considerable decrease in the intensity of the bremsstrahlung. These losses are considerable; at an initial energy of about 25 MeV and for an energy decrease of 7–9 MeV, sensitivity is diminished approximately by a factor of five. This is due not only to the reduction in the photon flux but also to the less favourable energy distribution in the beam, in which there is a shift towards relatively higher yields of low energy photons. Therefore this approach is justified only if the available accelerator allows operation at high beam currents.

A better way of dealing with this problem is to apply decay curve analysis. If the number of components in the sample is low, and the half lives of the radionuclides produced not too close, high precision can still be retained, especially if the counting system is coupled with a computer for data processing[44].

With increasing energy, thresholds for certain other reactions can be exceeded and occasionally the same radionuclides can be produced from neighbouring isotopes if present in the sample. Furthermore, protons and

neutrons are produced in secondary reactions with components in the sample, accelerator and surrounding equipment. Contributions from these reactions can be either reduced or taken into consideration if the approximate composition is known. The problem is really very acute only in the determination of light elements; in elements with higher atomic numbers, the radionuclides produced also decay by x-rays and gamma emission other than annihilation radiation. Problems of interference will be dealt with by way of examples in the next section on practical applications.

PRACTICAL APPLICATIONS

The accuracy of photon activation analysis depends, as in other activation techniques, primarily on proper selection of standards and monitors as well as on careful observation of geometrical conditions during irradiation and during counting. Photons obtained from accelerators are concentrated into a beam of a relatively small angle and the space for accommodation of samples, standards and monitors is rather restricted. Samples are most frequently sandwiched sequentially between standards and monitors, and the number of the latter must be sufficient to ensure a reliable evaluation of the received dose. The position of samples with respect to the beam can be monitored by suitable arrangements at the target based e.g. on measurement of the current through a system of metal rods positioned in the beam path (*Figure 1*) or by the use of a phosphorescent screen and TV camera. Uniform and reproducible dose distribution may be achieved by rotating the sample container, (usually a rabbit connected to a pneumatic system) in a position close to the target[9, 32, 119]. It is also important to keep the thickness of the samples and associated standards and monitors as low as possible in order to avoid large differences[43] in the dose between the front and the rear part of the irradiated package (*Figure 7*). Expressions for evaluation of self shielding corrections have been derived and verified experimentally by Lutz[55]. Depending upon the type of samples, graphite discs, Teflon and lead foil have been used as monitors; their diameter is adjusted to that of the samples and is typically 10 mm.

It is understandable that the interest of photon activation analysts has been concentrated for a long time on oxygen, carbon and nitrogen, in view of the advantages offered by the technique on the one hand, and difficulties associated with conventional methods of their determination on the other, e.g. vacuum fusion and inert gas fusion, which are tedious and not applicable to all types of sample. From the point of view of possible alternatives the determination of fluorine also presents a problem. The Willard Winter procedure based on distillation of H_2SiF_6 from perchloric, sulphuric or phosphoric medium is lengthy and tedious and the subsequent titration with thorium nitrate is of limited sensitivity. Therefore a number of papers have been published recently on the determination of this element[30, 43, 44] by photon activation.

In *Table 2* are listed the four most important light elements with relevant data regarding the reactions, the radionuclides produced, their characteristics and the most important interferences.

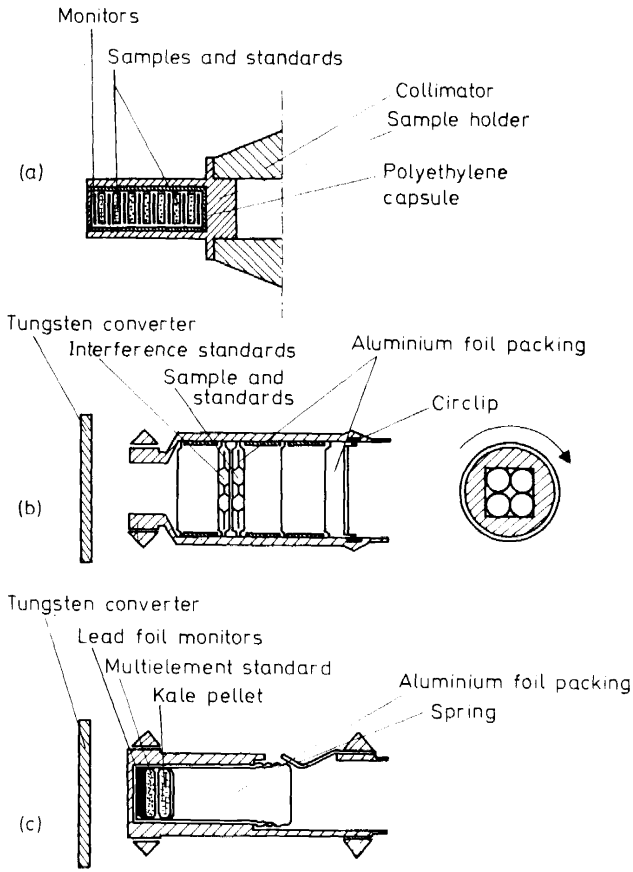

Figure 7. Alternative irradiation configurations for photon activation: *a* Stationary sample holder with samples and standards placed in a sequence behind each other in a polyethylene vial. *b* Rotating sample holder with samples and standards encapsuled in aluminium in planar arrangement inside an aluminium rabbit. *c* Stationary sample holder as used for larger samples and standards, encapsulated in aluminium and placed behind each other with monitors in front, in between and behind.

Figure 7. b and *c* reproduced by permission after the AERE *Report 6910*[32]

Table 2. Determination of important light elements by (γ, n) reactions

Element	Reaction	Half life min	Threshold energy, MeV	Interferences
O	$^{16}O(\gamma, n)\,^{15}O$	2.05	15.67	P, S[a]
N	$^{14}N(\gamma, n)\,^{13}N$	9.96	10.55	Cu, Fe[b]
C	$^{12}C(\gamma, n)\,^{11}C$	20.34	18.72	Ag[c]
F	$^{19}F(\gamma, n)\,^{18}F$	109.7	10.43	Na, Ti[d]

[a] 2.50 min ^{30}P is the product of both ^{31}P (γ, n) ^{30}P and ^{32}S (γ, pn) ^{30}P reactions.
[b] ^{53}Fe and ^{62}Cu have half lives of 8.5 and 9.76 min respectively.
[c] At higher energies ^{14}N and ^{16}O can also interfere by reactions $^{14}N(\gamma, t)^{11}C$, $^{16}O(\gamma, \alpha n)^{11}C$ respectively[17].
[d] Sodium interferes by giving ^{18}F through ^{23}Na (γ, γn); interference by titanium is due to the similar half life of ^{45}Ti, which is also a positron emitter.

From the last column in the Table, it is obvious that most frequently interferences do not result from nuclear reactions associated with the element to be determined, but from radionuclides having similar half lives produced from other elements in the sample. In complex matrices it is therefore only exceptionally possible to avoid chemical separations, particularly if concentrations are in the ppm range. Furthermore, oxygen, nitrogen and carbon bound or adsorbed on surfaces can contribute as much as an order of magnitude to the apparent concentration of these elements. In fast neutron determination of oxygen this is a major problem because the analysis is based on measurements of the ^{16}N activity produced by (n, p) reaction with ^{16}O. The half life of ^{16}N is only 7.3 s, and irradiation has to be carried out in argon or nitrogen. The half life of ^{15}O produced by (γ, n) reaction is long enough to allow etching of the sample prior to measurements of the activity. By etching, a sufficient amount of sample surface is dissolved to remove surface-bound oxygen contamination. Using 1 g samples of copper, iron, and low carbon steel, Chapyzhnikov *et al.* were able to determine oxygen in concentrations below 10^{-5} per cent. Following etching, the sample was ignited in graphite at 2800°C[12]. The resulting $C^{15}O$ was oxidized to carbon dioxide and absorbed in a trap filled with KOH powder, which was placed between two NaI crystals in coincidence[37]. Kh. Evzhanov *et al.*[23] studied in detail the determination of oxygen in the alkali metals and alkaline earths Li, K, Ca, Mg from the point of view of removal of surface contamination and found solvents which ensure dissolution of reproducible amounts of these metals from the surface, thus eliminating the need for weighing, and the associated loss of time.

A new very promising alternative involving neutron counting has been proposed by Scherle and Engelmann for the determination of oxygen, fluorine and boron[18, 100] based on the reactions

$$^{18}O(\gamma, p)^{17}N$$

$$^{19}F(\gamma, 2p)^{17}N$$

$$^{11}B(\gamma, 2p)^{9}Li$$

occurring at energies between 40 and 62 MeV. Radioactive ^{17}N produced from oxygen and fluorine respectively decays by delayed neutron emission according to the sequence

$$^{17}N \xrightarrow{\beta} {}^{17}O^* \begin{cases} \longrightarrow {}^{16}O^* + n \longrightarrow {}^{12}C + n + \alpha \\ \longrightarrow {}^{16}O + n \end{cases}$$

The half lives of ^{17}N and ^{9}Li are 4.14 s and 0.168 s respectively. Over 10^9 neutrons are emitted per gram of oxygen per second at 60 MeV and 50 μA mean current. The sensitivity is lower by a factor of a hundred for the other two isotopes.

Recently much effort has been devoted to the development of systems capable of determining simultaneously carbon, oxygen and possibly nitrogen, using the ignition principle. For certain matrices, this could be achieved nondestructively taking advantage of differences in half lives. Zadvorny *et al.*[120] used a linear accelerator operated at 22 MeV and 5 μA mean current in their nondestructive determination of carbon and oxygen in beryllium.

Hislop and Wood were able to demonstrate the feasibility of nondestructive carbon determination in pure vanadium[29]. They compared their nondestructive method with the one by chemical separation and found very good agreement. Electrical etching with a methanol solution of H_2SO_4 was used for removing the surface layer.

A new separation system for determining oxygen in presence of large excess of carbon was devised by Hislop and Williams[31]. They found that the mixed oxidant consisting of manganese dioxide containing 13 per cent copper oxide and 0.1 per cent silver oxide (hopcalite) retains ^{11}C and ^{15}O activity at room temperature but releases ^{11}C at 650°C. An absorption train made of copper turnings followed by hopcalite, soda lime and a molecular sieve, also retains nitrogen. Although the behaviour of the latter was not found to be consistent the proposed combination does represent a reliable system for quantitative separation and determination of carbon and oxygen at concentration levels well below 1 μg.

Another element very thoroughly studied is fluorine. Although it is possible to determine this element by thermal neutron activation, as well as by activation by 14 MeV neutrons, both techniques suffer from considerable disadvantages. The half life of ^{20}F produced in thermal activation is only 11.2 s, which excludes postirradiation treatment of the sample, and direct counting is subject to interferences. On irradiation with either 14 MeV neutrons or with photons, ^{18}F is formed since (n, 2n) and (γ, n) reactions result in the production of identical isotopes. However, the sensitivity attainable in irradiations with 14 MeV neutrons is lower by a few orders of magnitude than that obtainable with linear accelerators. The half life of ^{18}F is long enough to allow chemical treatment, although it is frequently possible, by optimization of the energy of the photons, irradiation time, of the period between the end of irradiation and counting, to use the method nondestructively. The resulting advantages are obvious.

Of the possible interferences resulting from photonuclear interactions these are mainly to be expected from the neon isotopes, as shown in *Table 3*. However, neon would be only exceptionally found in a sample together with fluorine. Furthermore, there is enough difference in the threshold energy of the $^{19}F(\gamma, n)^{18}F$ reaction and any other of those listed to allow acceptable sensitivity to be obtained by irradiating at energies just below the threshold of the interfering reactions. This also applies to the $^{23}Na(\gamma, \alpha n)^{18}F$ reaction which does have great practical implications due to the presence of sodium in almost every sample, frequently as the major component[118].

Table 3. Interference in the determination of fluorine

Reaction	Isotope abundance %	Threshold energy, MeV
$^{19}F(\gamma, n)^{18}F$	100	10.44
$^{20}Ne(\gamma, d)^{18}F$	90.92	21.06
$^{20}Ne(\gamma, np)^{18}F$	90.92	23.29
$^{21}Ne(\gamma, t)^{18}F$	0.257	21.56
$^{21}Ne(\gamma, nd)^{18}F$	0.257	27.82
$^{22}Ne(\gamma, nt)^{18}F$	8.82	31.95
$^{23}Na(\gamma, n\alpha)^{18}F$	100	20.93

Other interferences could arise from certain secondary reactions in materials rich in hydrogen and oxygen. In irradiations of aqueous solutions in reactors the reaction $^{18}O(p, n)^{18}F$ is frequently observed. Similarly protons are produced by the reaction $^{16}O(\gamma, p)^{15}N$. The former reaction has been studied in detail by Wilkniss[117] who used photon activation for determining fluorine in sea water: the chemical separation used for the isolation of fluorine activity was based on distillation of H_2SiF_6 and subsequent precipitation as $PbFCl$[116]. The distillation combined with coprecipitation with CaF_2 and $CaCO_3$ was applied by Hislop *et al.*[30]. The nondestructive approach has proved feasible in an investigation dealing with the determination of fluoride at somewhat higher concentrations in pharmaceutical products using a betatron[44]. In the application of this principle to the analysis of enamels with a high titanium content, interferences come from $^{46}Ti(\gamma, n)^{45}Ti$, decaying with a half life of 3.08 h. Results can be corrected by subtracting the titanium contribution, which can be evaluated from the simultaneous reaction $^{48}Ti(\gamma, p)^{47}Sc$ producing ^{47}Sc, with a gamma ray at 160 keV. Reactions involved are illustrated in the spectrum shown in *Figure 8*.

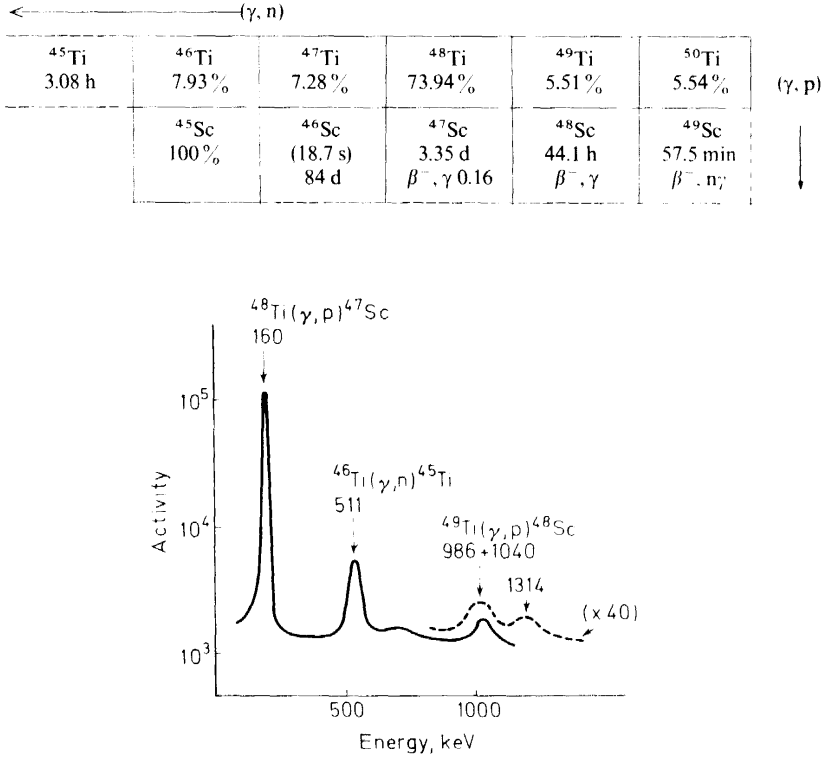

Figure 8. Diagram of Ti isotopes, their reactions with gamma photons and the resulting spectrum on irradiation of pure TiO_2 in the bremsstrahlung from a 32 MeV betatron[44]. Amount of sample: 500 mg; irradiation time: 1 h; time of the end of irradiation: 1 h; detector: NaI(Tl) 7.5 × 7.5 cm.

The resolution of the composite decay curves in this and similar systems can best be carried out by computer processing of data. Compared with the tedious and lengthy chemical methods for fluorine, photon activation offers a very elegant and precise approach for this element, in particular when it is desirable to recover the sample in the original form.

It is only very recently that the interest in photon activation analysis has shifted to many interesting possibilities offered for the analysis of heavier elements which have more complicated decay schemes and can be much more specifically characterized and determined by gamma ray spectrometry.

A series of papers of importance for analytical applications of photon activation analysis giving basic information on yields, and nuclides formed in (γ, p), (γ, α) and (γ, n) reactions respectively for 20 MeV bremsstrahlung has been published by Oka *et al.*[74, 77–79].

Determination of a number of elements including rare earths[75, 89], zirconium and hafnium in mixtures[82, 83], gallium, indium and thallium[84, 85], cobalt and nickel[86], arsenic[90], niobium[91], rubidium[110] and precious metals[87, 88] has been studied by the same group using gamma photons of energies up to 30 MeV.

Saito has recently investigated yields by (γ, n) reactions for 12 nuclides and for energies up to 68 MeV[99]. Activation analysis of rare earths[38], zirconium[94], iodine[108], cesium[111] and rubidium[109] was studied at these energies using mainly synthetic mixtures.

Separation schemes for radionuclides produced in activation of titanium and vanadium at four energies, 30, 45, 55 and 60 MeV respectively were devised by Oka *et al.*[80] in association with yields determinations. Production of ^{7}Be obtained in irradiation of beryllium, boron, carbon and oxygen targets was also studied and a separation of beryllium described[81].

Combining photon, thermal neutron, and fast neutron activation analysis, Schmitt *et al.* have analysed rock materials nondestructively by high resolution gamma spectrometry and were able to determine 17 elements[102]. Magnesium, calcium, titanium and nickel were determined by photon activation analysis using bremsstrahlung of 23 MeV for magnesium and 28 MeV for the other three elements. Reduction of energy in magnesium activation was necessary in order to minimize interferences by reactions $^{27}Al(n, \alpha)^{24}Na$ and $^{23}Na(n, \gamma)^{24}Na$ which all give the same isotope. In view of the high concentration of aluminium in basaltic rocks, a systematic error might result, in particular from the first reaction.

Hislop and Williams applied photon activation analysis to standard rocks, biological materials and lunar samples[32] and identified 20 elements in the resulting gamma spectra. Good precision has been achieved in the determinations of major components, calcium and iron, present in concentrations of from 1.3 to 11.1 per cent and 1.8 to 24 per cent respectively. Strontium, rubidium and zirconium were determined at the ppm level. As shown in *Table 4*, alternative reactions are available in the evaluation of calcium, iron and titanium concentrations. Other elements could be determined in terms of upper limits. A typical spectrum as obtained for kale after 30 min irradiation and 72 hours decay time is shown in *Figure 9* which is reproduced by permission after the A.E.R.E. Report R 6910[32].

A method for lead was described by Dutilk and Das[15], who applied photon

Table 4. Characteristics of radionuclides formed and sensitivities obtainable in the determination of Mg, Ca, Ti, Cr, Fe, Rb, Zr, Tl and Pb by photon activation analysis[32]

Element	Reaction	Half life	Measured peak, keV	Sensitivity* µg	Major interference
Mg	$^{25}Mg(\gamma, p)^{24}Na$	15.05 h	1368		$^{27}Al(n, \alpha)^{24}Na$
			1731		$^{23}Na(n, \gamma)^{24}Na$
Ca	$^{44}Ca(\gamma, p)^{43}K$	22 h	618	5	
	$^{48}Ca(\gamma, n)^{47}Ca$	4.5 d	1297	50	
Ti	$^{48}Ti(\gamma, p)^{47}Sc$	3.3 d	160	0.2	$^{48}Ca(\gamma, n)^{47}Ca, \beta^-$
	$^{49}Ti(\gamma, p)^{48}Sc$	1.83 d	984		
Cr	$^{52}Cr(\gamma, n)^{51}Cr$	27.8 d	320		$^{56}Fe(\gamma, \alpha n)^{51}Cr$
Fe	$^{56}Fe(\gamma, p)^{56}Mn$	2.64 h	847	5	$^{55}Mn(n, \gamma)^{56}Mn$
	$^{54}Fe(\gamma, np)^{52}Mn$	5.6 d	1433	500	
Rb	$^{85}Rb(\gamma, n)^{84}Rb$	33 d	882	0.5	
Sr	$^{88}Sr(\gamma, n)^{87m}Sr$	2.8 h	389	0.02	$^{89}Y(\gamma, 2n)^{88}Y, \beta^+$
Zr	$^{90}Zr(\gamma, n)^{89}Zr$	78 h	909	0.1	$^{93}Nb(\gamma, tn)^{89}Zr$
Tl	$^{203}Tl(\gamma, n)^{202}Tl$	12 d	440	0.2	
Pb	$^{204}Pb(\gamma, n)^{203}Pb$	52.4 h	279	1	$^{204}Hg(\gamma, n)^{203}Hg$
					$^{198}Hg(\gamma, n)^{197m}Hg$

* Based on: 1. 60 min irradiation, 40 MeV and 5 µA.
2. Counting period and decay = 1 half life or 12 h, whichever shorter..
3. 3 times stn. devn. detector Ge(Li) background at appropriate energy.

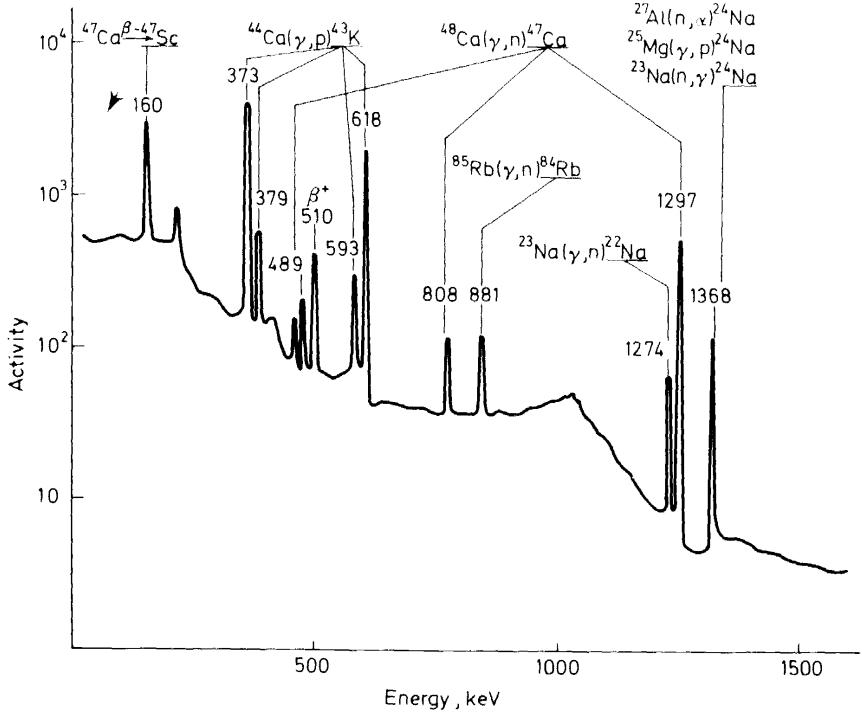

Figure 9. High resolution gamma spectrum of gamma activated kale 72 hours after the end of irradiation with linac[32]. Irradiation time: 30 m; energy: 35–40 MeV; current: 4–8 µA; counting time: 2 h 16 m; detector: 40 cm^3 Ge–Li; amount of sample: 400 mg

Table 5. Practical applications

Element determined	Matrix	Method	Source of photons and energy	Concentration level or detection limit*	Ref.
D	biological tissues	photoneutron	IS ^{24}Na, 25 Ci	1.5 μg	26
	water, crystals, minerals	photoneutron	IS ^{24}Na	150 ppm	35
Be	ores	photoneutron	IS ^{124}Sb, 1 Ci	50 ppm	25
	hydrometallurgical products	photoneutron	IS ^{124}Sb, 0.1 Ci		95
	ores	photoneutron	IS ^{124}Sb, 10 mCi	20 ppm BeO	121
B, C, O	silicon		LA, 40 MeV		20
C	steel, metals (Zn, Au, Ag, Mo, Cd, Fe, Cr, Ni)	separation as CO_2, absorption		1 ppm	58, 60, 96, 97
	sodium (reactor tech.)	separation, absorption		0.5 μg	54, 19
	biological tissue (tobacco mosaic virus)	irradiation by electrons		0.12 μg	47
	archeological sample (sword)	nondestructive			114
	vanadium	destructive and nondestructive	LA, 32–42 MeV 5–10 μA	10–15 ppm	29
	silicon	comparison and charged part. activation			21
C, N, O	Si, Fe, Nb	separation as O_2, N_2, CO_2			16
	Li, Na, Ca, Mg	etching for decontamination	MT, 29 MeV		23
	steel, Mo	separation, hopcalite			31
C, O	beryllium	nondestructive	LA, 22 MeV, 5 μA	5 ppm	120
	inorganic materials	separation as O_2 and CO_2		0.003 μgC 0.1 μgO	5

Table 5 (contd.)

Element determined	Matrix	Method	Source of photons and energy	Contamination level or detection limit*	Ref.
	alloy (Pb–Bi)	nondestructive			63
	cesium	nondestructive	BT, 20–30 MeV		92
N, O	Al, Be, Zr, Ti	destructive, nondestructive	LA, 24–40 MeV	0.2 ppm N 10 ppm O	64
O	sodium (reactor tech.)	separation NaOH as H_2O after exchange		20–160 ppm	59
	inorganic materials	separation as $C^{15}O_2$ impulse heating in graphite			112
	metals Cu, Fe	separation as CO_2	MT, 5 μA	0.07 ppm	12, 37
	metals Al, Be, Ti		BT, 29 MeV, 15 μA		40
	steels Nb, Ti, Sn				78
	Cu, Sn, steel	conduction atmosphere	29 MeV, 15 μA		69
	iodine oxides	nondestructive	BT, 23 MeV		48
O, P, Zr	inorg. ion exchangers		BT, 16.5 MeV		46
O, Zr, Sb	inorg. ion exchangers		BT, 25 MeV		45
F	sea water	chem. sep. (distill., PbFCl)	LA, 22 MeV, 30 μA	10 ppm	116
F	pharmaceutical, biological products	nondestructive	BT	100 μg	43, 73
F, Cl	PVC, Teflon	nondestructive	BT, 18 MeV		13
F, Cl, Br, I	geochemistry	chemical separation			115
F, Ti	enamels	nondestructive	BT		44
F, Sr, others	biological tissue				3
Ca, Ti, Cr, Fe, Rb, Sr, Zr	standard rocks, lunar samples, kale	nondestructive	LA, 35–40 MeV (25–30 MeV) 4–8 μA		32

Ti	iron, copper	chemical separation (oxinate extract. ^{45}Ti)	LA, 20–27 MeV, 30 μA	0.1–0.01 μg	103
Ni	copper	chem. sep. DMG	LA, 27 MeV	0.01–0.001 μg	103
Cu	synthetic sample. Zn	destructive ^{64}Cu:^{67}Cu ratio	LA, 20 MeV, 40 μA		1
Cu, Ag	copper ores	nondestructive	BT		93
Zn	Pb, Zn ores	nondestructive	BT		71
Ga	indium	nondestructive	LA, 20 MeV	200 ppm	84
As	selenium		20 MeV	80 ppm	90
Se, Br, Sr, Ag, Cd, In	alloys	nondestructive	IS ^{60}Co, 80 kCi	1000 μg Se. Br. Cd, In	113
Se, Sr, Y, Rh, Ag, Cd, In, Sn, Ba, Lu, Hf, Pt, Au, Hg	ores	nondestructive	Van de Graaf 4.2 MeV, 1 mA		42
Sr	sea water		LA, 30 MeV		27
Y	rare earths	nondestructive	LA, 20 MeV		57
Zr	hafnium	nondestructive, ^{89}Zr, 4.4 min.	LA, 20 MeV	1 ppm	103
Zr	hafnium	nondestructive, ^{89}Zr	LA, 20 MeV	10 ppm	83
Te	rocks	nondestructive	LA, 575 MeV, 600 μA	400 μg	10
I	biological materials	nondestructive	LA, 22 MeV, 250 μA	1.0 μg	70
Hg	ores		LA, 5 MeV		106
Tl	glass, Zn	separation	LA, 35 MeV, 30 μA	0.001 μg	65
Pb	milk powder		LA, 40 MeV, 30 μA	0.5 μg	15
Pb	kale, orchard leaves, human bone	radiochem. sep.	LA, 35–40 MeV, 5 μA	0.1 μg	33
Pb, Sn (Fe, Zn, Ni)	ancient bronze	nondestructive	LA, 15–45 MeV	0.15–1.21 % Pb 3.26–12.9 % Sn	107

Abbreviations: BT—Betatron. IS Isotopic source, LA – Linac, MT—Microtron.
* As defined in original paper.

activation to the determination of this element in milk powder by a destructive method following irradiation of the sample with linear accelerator at 40 MeV, and 30 μA mean current. Lutz and Masters have demonstrated the value of photon activation in the analysis of glass and pure zinc metal in determining thallium present in the ppm level[65]. Irradiation conditions were similar to those used by Dutilk for lead.

A survey of applications of photon activation analysis to real samples with condensed relevant data is given in *Table 5*.

The attached Table of isotopes gives condensed information on 236 isotopes of significance in analysis, including their reactions, threshold values, characteristics of the isotopes produced and sensitivities for a set of irradiation conditions. The Table is taken from a recent review by Slunečko and Kosta[105].

The basis for the selection of radionuclides in this Table was the catalogue by Baker, Hunter and Wood[6,7] but some other publications[41,56,62,76] were also taken into consideration. Sensitivity values for linear accelerator and betatron are those measured by Oka[76] and Kochevanov and Kuznetsov[41], respectively.

Apart from these sources tables by Seelmann-Eggebert *et al.*[104], Lederer *et al.*[53], Crouthamel[14] and Nuclear Data Sheets[72] were also used. Values for threshold energies are taken from the publications by Mattauch *et al.*[66] and Howerton *et al.*[34]. Values for effective cross sections are, with a few exceptions, taken from the compilation by Goryachev[28].

CONCLUSION

It appears that photon activation analysis by producing a different range of radionuclides, is ideally suited for samples rich in sodium, potassium, manganese and some other elements with high cross section for thermal neutrons, as they are not activated to the extent of introducing handling problems or serious interferences. Although in general somewhat less sensitive, by one or two orders of magnitude in comparison to thermal neutron activation, it covers some very important elements which cannot be determined nondestructively at all, or with difficulty, by any other technique. It also offers attractive alternatives to other approaches in combination with simple radiochemical separations.

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APPENDIX

Table of Useful Photon-induced Reactions

1. Reaction	2. Abundance in nature %	3. Half life of radionuclide	4. Type of decay	5. Energy of gamma radiation* MeV	6. Threshold energy Q, MeV	7. E_{max} MeV	8. σ_{int}† MeV · b	Sensitivity limits 9. Linac 20 MeV, 1 h µg	10. Betatron 24 MeV, 30 m mg	11. Remarks‡
$^{2}H(\gamma, n)^{1}H$	0.0149				2.224					neutrons measured
$^{9}Be(\gamma, n)^{8}Be$	100				1.665					
$^{12}C(\gamma, n)^{11}C$	98.89	20.3 m	β^+	*[0.511]*(200)	18.71	23.2	0.046 (37)	0.41	0.061	
$^{14}N(\gamma, n)^{13}N$	99.63	9.96 m	β^+	*[0.511]*(200)	10.55			0.17	0.43	
$^{16}O(\gamma, n)^{15}O$	99.76	2.03 m	β^+	*[0.511]*(200)	15.67	22.2	0.042 (26)	0.17	0.06	
$^{16}O(\gamma, n\alpha)^{11}C$	99.75	20.3 m	β^+	[0.511](200)	25.88					
$^{17}O(\gamma, p)^{16}N$	0.0374	7.1 s	β^-	6.13(69), 7.11(5), 2.75(1)	13.78					
$^{19}F(\gamma, n)^{18}F$	100	109.7 m	β^+ EC	*[0.511]*(194)	10.43	20	0.039 (26)	0.0030	0.055	
$^{20}Ne(\gamma, n)^{19}Ne$	99.92	17.4 s	β^+	[0.511](200)	16.86					
$^{20}Ne(\gamma, p)^{20}F$	0.257	11.2 s	β^-	1.63(100)	13.01					
$^{23}Na(\gamma, n)^{22}Na$	100	2.62 y	β^+ EC	*[0.511]*(180), 1.275(100)	12.42			43		
$^{23}Na(\gamma, 2n)^{21}Na$	100	22.8 s	β^+	[0.511](200), 0.350(2.3)	23.47	32				
$^{24}Mg(\gamma, n)^{23}Mg$	78.70	12.0 s	β^-	[0.511](200), 0.44(9)	16.53	19.5	0.058 (26)			
$^{24}Mg(\gamma, p)^{24}Na$	10.13	15.05 h	β^-	1.369(100), 2.754(100)	12.06	20.5	0.056 (24)	1.6		
$^{25}Mg(\gamma, p)^{25}Na$	11.17	59.6 s	β^-	0.98(15), 0.58(14), 0.39(14), 1.61	14.14	22	0.07 (20)		14	
$^{27}Al(\gamma, n)^{26m}Al$	100	6.4 s	β^+ EC	[0.511](170), 1.81(100), 1.12(4)	13.06	19.5	0.042 (25)			
$^{27}Si(\gamma, p)^{26}Al$	4.70	2.3 m	β^-	*1.780*(100)	12.33	20.5	0.26 (26)	1.5	12	
$^{28}Si(\gamma, p)^{27}Al$	3.09	6.6 m	β^-	*1.28*(94), 2.43(6)	13.51	21.5	0.19 (26)	33	10	
$^{30}P(\gamma, n)^{30}P$	100	2.50 m	β^+	*[0.511]*(200), 2.23(0.5)	12.31	19	0.12 (26)	0.018	0.06	
$^{30}P(\gamma, 2p)^{29}Al$	100	6.6 m	β^-	1.28(94), 2.43(6)	20.80					
$^{31}P(\gamma, d)^{30}P$	95.0	2.5 m	β^+	[0.511](200), 2.23(0.5)	18.95	26	0.028 (30)			
$^{31}P(\gamma, np)^{30}P$					21.17					
$^{32}S(\gamma, p)^{32}P$	0.76	14.3 d	β^-		9.57					
$^{33}S(\gamma, p)^{33}P$	4.22	25.3 d	β^-		10.89					
$^{35}Cl(\gamma, n)^{34m}Cl$	75.53	32 m	β^+ IT	*[0.511]*(100), 0.145(45), 2.12(38), *3.30*	12.63	19	0.125 (30)	0.069/4.5	0.15	^{34}Cl (1.6 s)
$^{37}Ar(\gamma, p)^{36}Cl$	99.6	56 m	β^-	1.27(50), 1.52(42), 0.246(44)	12.53		0.16 (28)			
$^{39}K(\gamma, n)^{38}K$	93.1	7.7 m	β^+	*[0.511]*(200), *2.170*(100)	13.09	18.2	0.04 (21)	0.052/0.41	0.31	
$^{40}Ca(\gamma, p)^{39}K$	0.145	12.36 h	β^-	1.524(18), 0.310(2)	10.67					
$^{42}Ca(\gamma, p)^{41}K$	2.06	22 h	β^-	*0.373*(85), 0.619(81), 0.39(18), m	12.17		0.125 (31)	9		
$^{43}Ca(\gamma, n)^{42}Ca$	0.185	4.54 d	β^-	*1.308*(74), 0.49(5), 0.815(5)	9.94			108		^{43}Sc (3.4 d)
$^{43}Ca(\gamma, p)^{42}K$	0.185	17.5 s	β^-	2.0(84), 2.6(15)	15.26					
$^{45}Sc(\gamma, n)^{44}Sc$	100	4 h	β^+ EC	[0.511](188), 1.159(100)	11.32			0.0027/0.0095	0.26	
$^{45}Sc(\gamma, n)^{44m}Sc$	100	2.4 d	IT EC	*0.271*(86), 1.14(2.7), 1.02	11.32			0.32		
$^{46}Ti(\gamma, n)^{45}Ti$	7.93	3.08 h	β^+ EC	*[0.511]*(170), 0.718(0.4), 1.408	13.19		0.26 (31)	0.051	0.39	
$^{46}Ti(\gamma, d)^{44}Sc$	7.93	4.0 h	β^+ EC	[0.511](188), 1.159(100)	19.45					
$^{46}Ti(\gamma, np)^{44}Sc$					21.67					
$^{47}Ti(\gamma, p)^{46m}Sc$	7.98	18.7 s	IT	0.142	10.46					
$^{47}Ti(\gamma, p)^{46}Sc$	73.94	3.35 d	β^-	*0.160*(73)	11.45		0.217 (31)	0.67		
$^{50}V(\gamma, \alpha)^{46}Sc$	99.76	3.35 d	β^-	*0.160*(73)	10.30		0.012 (32)	23		
$^{50}Cr(\gamma, n)^{49}Cr$	4.31	42 m	β^+ EC	*[0.511]*(186), 0.091(28), 0.063(14), 0.153(13)	12.93	19.0	0.25 (23)	0.30	0.37	
$^{50}Cr(\gamma, np)^{49}Ti$	4.31	3.08 h	β^+ EC	[0.511](170), 0.718(0.4), 1.408	21.74					

^{52}Cr(γ, n)^{51}Cr	83.76	27.8 d	EC	0.320(9)	12.03					
^{53}Cr(γ, p)^{52}V	9.95	3.75 m	β$^-$	1.434(100)	11.13	19.7	0.09 (23)			
^{54}Cr(γ, p)^{53}V	2.38	2.0 m	β$^-$	1.00(100)	12.04					
^{55}Mn(γ, n)^{54}Mn	100	303 d	EC	*0.835*(100)	10.22			7.3		
^{54}Fe(γ, n)^{53}Fe	5.82	8.51 m	β$^+$ EC	[*0.511*](196), *0.38*(32)	13.62	19	0.29 (3)	0.22/2.0	0.14	
^{54}Fe(γ, d)^{52m}Mn	5.82	21 m	β$^+$ IT	[0.511](193), 1.434(100), 0.383(2)	18.78					
^{54}Fe(γ, np)^{52m}Mn					20.90					
^{54}Fe(γ, d)^{52}Mn	5.82	5.7 d	EC β$^+$	1.434(100), 0.935(84), 0.744(82), [0.511](67)	18.78					
^{54}Fe(γ, np)^{52}Mn					20.90					
^{54}Fe(γ, 2n)^{52}Fe	5.82	8.2 h	β$^+$ EC	[0.511](112), 0.165(100)	24.06					
^{57}Fe(γ, p)^{56}Mn	2.19	2.57 h	β$^-$	0.847(99), 1.811(29), 2.110(15)	10.56					
^{58}Fe(γ, p)^{57}Mn	0.33	1.7 m	β$^-$	0.122, 0.136, 0.22, 0.353, 0.692	11.96					
^{59}Co(γ, n)^{58}Co	100	71 d	EC β$^+$	0.810(99), [0.511](30), 0.865(14), 1.67	10.47	17.5	0.45 (28)	11		
^{58}Ni(γ, n)^{57}Ni	67.88	36.0 h	EC β$^+$	[0.511](92), 1.37(86), 0.127(14), 1.89	12.19	19	0.22 (32)	1.0	7.4	
^{62}Ni(γ, p)^{61}Co	3.66	1.6 h	β$^-$	0.067(89)	11.11	22	0.13 (22)			
^{63}Cu(γ, n)^{62}Cu	69.09	9.76 m	β$^+$ EC	[0.511](195), 1.17(0.5), 0.88(0.3)	10.84	17	0.52 (28)	0.0010	0.02	
^{63}Cu(γ, 2n)^{61}Cu	69.09	3.3 h	β$^+$ EC	[0.511](120), 0.284(12), 1.19(5), 0.38, 0.067	19.74	25	0.08 (36)			^{52}Mn, ^{52}Mn
^{65}Cu(γ, n)^{64}Cu	30.91	12.8 h	EC β$^-$β$^+$	[0.511](38), 1.34(0.5)	9.91	17	0.44 (28)			
^{64}Zn(γ, n)^{63}Zn	48.89	38.4 m	β$^+$ EC	[0.511](186), 0.669(8), 0.962(6), 1.42	11.85	17.2	0.33 (23)	0.013	0.025	
^{70}Zn(γ, n)^{69m}Zn	0.62	13.9 h	IT	0.439(95)	9.29					
^{69}Ga(γ, n)^{68}Ga	60.4	68.3 m	β$^+$ EC	[*0.511*](176), 1.078(3.5), 0.80(0.4), m	10.32			0.00092	0.029	
^{71}Ga(γ, n)^{70}Ga	39.6	21.1 m	β$^-$	1.040(0.5), 0.173(0.16)	9.31					
^{70}Ge(γ, n)^{69}Ge	20.52	39 h	EC β$^+$	[*0.511*](68), 1.107(28), 0.573(13), m	11.53	20	0.59 (21)	0.29	0.31	
^{76}Ge(γ, n)^{75}Ge	7.76	83 m	β$^-$	*0.265*(11), 0.199(1.4), 0.427(0.3), m	9.45	18.9	1.5 (21)	0.12		
^{76}Ge(γ, n)^{75m}Ge	7.76	48 s	IT	0.139(39)	9.45					
^{75}As(γ, n)^{74}As	100	17.7 d	β$^+$ ECβ$^-$	*0.596*(61), [0.511](59), 0.635(14)	10.25			0.65	15	
^{75}As(γ, n)^{74m}As	100	8 s	IT	0.283	10.25					
^{74}Se(γ, n)^{73}Se	0.87	7.1 h	β$^+$ EC	[0.511](130), 0.359(99), 0.066(45)	12.11			0.60		
^{74}Se(γ, n)^{73m}Se	0.87	42 m	β$^+$ EC	[0.511](126), 0.251(14), 0.58(6), 0.088(6)	12.11					
^{77}Se(γ, γ')^{77m}Se	7.58	17.5 s	IT	[0.161](50)	10.49					
^{78}Se(γ, n)^{77m}Se	23.52									
^{82}Se(γ, n)^{81}Se	9.19	18 m	β$^-$	0.28(0.9), 0.56(0.3), 0.83(0.2) 0.030	9.26	16	0.87 (21)			
^{82}Se(γ, n)^{81m}Se	9.19	57 m	IT	0.103(8)	9.26					
^{79}Br(γ, n)^{78}Br	50.54	6.4 m	β$^+$ EC	[0.511](184), 0.614(14)	10.70	18	0.36 (24)		0.061	
^{79}Br(γ, 2n)^{77}Br	50.54	56 h	EC β$^+$	0.24(30), 0.52(24), 0.58(7), 0.300(6), m	18.98					
^{81}Br(γ, n)^{80}Br	49.46	17.6 m	β$^-$ECβ$^+$	0.618(7), [0.511](5), 0.666(1)	10.16	18	0.72 (24)	0.30		
^{81}Br(γ, n)^{80m}Br	49.46	4.4 h	IT	0.037(36)	10.16		0.36 (24)	0.39		^{80}Br (17.6 m), E *0.618*
^{86}Kr(γ, n)^{77}Kr	0.354	1.2 h	β$^+$ EC	[0.511], 0.108, 0.131, 0.149, 0.665	11.87				0.14	
^{82}Kr(γ, n)^{81m}Kr	11.56	13 s	IT	0.190(65)	10.99					
^{86}Kr(γ, n)^{85m}Kr	17.37	4.4 h	β$^-$ IT	0.150(74), 0.305(13)	9.85					
^{85}Rb(γ, n)^{84}Rb	72.15	33 d	EC β$^+$	0.88(74), [0.511](42), 1.90(0.8), 1.01	10.48					
^{85}Rb(γ, n)^{84m}Rb	72.15	21 m	IT EC	0.250(65), 0.216(37), *0.464*(32)	10.48			0.042	0.14	
^{87}Rb(γ, n)^{86m}Rb	27.85	1.0 m	IT	0.56	9.94	17.5				
^{88}Sr(γ, n)^{85m}Sr	9.86	70 m	IT EC	0.231(85), 0.150(14)	11.52				0.13	
^{88}Sr(γ, γ')^{87m}Sr	7.02	2.8 h	IT	*0.388*(80)	11.10				0.065	
^{88}Sr(γ, n)^{87m}Sr	82.56									

1. Reaction	2. Abundance in nature %	3. Half life of radionuclide	4. Type of decay	5. Energy of gamma radiation* MeV	6. Threshold energy Q, MeV	7. E_{max} MeV	8. σ_{int}† MeV·b	Sensitivity limits 9. Linac 20 MeV, 1 h µg	10. Betatron 24 MeV, 30 m mg	11. Remarks‡
^{89}Y(γ, n)^{88}Y	100	108 d	EC β⁻	1.836(100), *0.898*(91)	11.48	16.8	0.8 (23)	4.0		
^{89}Y(γ, 2n)^{87m}Y	100	14 h	IT	0.381(74)	17.66					
^{89}Y(γ, 2n)^{87}Y	100	80 h	EC β⁺	0.483	17.66					
^{89}Y(γ, p)^{88m}Y	100	16 s	IT	0.91(99)		10.5, 16				
^{90}Zr(γ, n)^{89}Zr	51.46	78.4 h	EC β⁺	0.91(99), 0.511(44), 1.71(1)	12.00	16.8	0.9 (23)	0.51		
^{90}Zr(γ, n)^{89m}Zr	51.46	4.2 m	IT EC β⁺	*0.588*(87), 1.51(6)	12.00			0.0073	0.31	
^{93}Nb(γ, n)^{92}Nb	100	10.2 d	EC	*0.934*(99)	8.84	17.0	1.25 (22)	0.34	3.2	
^{93}Nb(γ, 3n)^{90}Nb	100	14.6 h	β⁺ EC	1.14(97), 2.32(82), [0.511], 0.142, 2.18	28.75					
^{92}Mo(γ, n)^{91}Mo	15.84	15.5 m	β⁺	[0.511]	12.58	18.7	0.14 (25)	0.020	0.15	
^{92}Mo(γ, n)^{91m}Mo	15.84	65 s	IT β⁺ EC	[0.511](76), 0.658(54), 1.21(22), 1.53	12.58	18.7	0.71 (25)			
^{92}Mo(γ, n)^{91m}Mo	9.04	6.9 h	IT	0.685(100), 1.479(100), 0.264(58)	9.62					
^{92}Mo(γ, p)^{91}Nb	23.78	74 m	β⁻	0.665(98)	9.79			*0.10*		
^{100}Mo(γ, n)^{99}Mo	9.63	66.7 h	β⁻	0.740(12), 1.181(7), 0.780(4), m	8.30	16.5	1.5 (31)			
^{96}Ru(γ, n)^{95}Ru	5.51	1.65 h	EC β⁺	0.340(70), [0.511](30), 1.09(21), 0.625, m	10.12			0.065	0.2	^{95}Tc(20 h)
^{96}Ru(γ, p)^{95m}Tc	5.51	60 d	EC β⁺	0.204(70), 0.584(36), 0.838(27), 0.823, m	7.31					
^{103}Rh(γ, n)^{102}Rh	100	206 d	EC β⁻ β⁺	*0.475*(57), [0.511](25), 0.628(4), 1.103, m	9.31			3.7		
^{103}Rh(γ, 2n)^{101m}Rh	100	4.4 d	EC IT	*0.307*(83), 0.545(6)	16.76			0.68		
^{103}Rh(γ, 3n)^{100}Rh	100	20 h	EC β	0.540(88), 2.37(39), 0.820(25), 1.32(25), m	26.65					
^{103}Rh(γ, γ')^{103m}Rh	100	57 m	IT	0.040(0.4)		9.3, 20			1.2	
^{102}Pd(γ, n)^{101}Pd	0.96	8.3 h	EC β⁺	*0.296*(30), 0.590(24), 0.270(8), [0.511](5), m	10.36			0.19		
^{104}Pd(γ, n)^{103m}Pd	26.71	21 s	IT	0.21	9.23				4.0	
^{104}Pd(γ, n)^{103m}Pd	11.81	4.7 m	IT	*0.188*(58)	8.81			0.15		
^{107}Ag(γ, γ')^{107m}Ag	51.35	44 s	IT	0.094(5)		9.4				
^{107}Ag(γ, n)^{106}Ag	51.35	24 m	β⁺ EC	[*0.511*] + *0.512*(140)	9.53	14	2.48 (25)	0.023	0.071	
^{107}Ag(γ, n)^{106m}Ag	51.35	8.3 d	EC	0.512(86), 1.046(29), 0.616(23), 0.451, 0.221, m	9.53					
^{107}Ag(γ, 2n)^{105}Ag	51.35	41.2 d	EC	0.344(42), 0.280(32), 0.443(10), 0.62 – 0.68, m	17.42					
^{109}Ag(γ, n)^{108}Ag	48.65	2.3 m	β⁻ EC β⁺	[0.511](0.56), 0.434(0.45), 0.615, 0.632	9.18	16.5	1.65 (22)			
^{109}Ag(γ, γ')^{109m}Ag	48.65	40 s	EC IT	0.614(90), 0.722(90), 0.434(89), 0.080						
^{106}Cd(γ, n)^{105}Cd	1.215	55 m	EC β⁺	0.308, 0.320, 0.347, 0.433, [0.511], m	10.87					
^{111}Cd(γ, γ')^{111m}Cd	12.75	49 m	IT	0.247(94), 0.150(30)	9.40			0.16	0.41	
^{113}Cd(γ, n)^{113m}Cd	24.07									
^{113}Cd(γ, p)^{113}Ag	12.26	5.2 h	β⁻	0.617(41), 1.40(5), 1.63(3), 2.11(3), m	9.76					
^{114}Cd(γ, n)^{113}Cd	7.58	53.5 h	β⁻	0.53(26), 0.49(10), 0.262(2), 0.230	8.69					
^{113}In(γ, n)^{112}In	4.28	14.4 m	β⁻ EC β⁺	[*0.511*](44), 0.617(6)	9.43			0.074		
^{113}In(γ, n)^{112m}In	4.28	21 m	IT	*0.156*(9)	9.43			0.081	0.9	
^{113}In(γ, γ')^{113m}In	4.28	1.66 h	IT	0.393(64)						
^{115}In(γ, n)^{114}In	95.72	72 s	β⁻ EC	1.299(0.17)	9.03	15	2.7 (23)			
^{115}In(γ, n)^{114m}In	95.72	50 d	IT EC	0.192(17), 0.558(3.5), 0.724(3.5)	9.03					
^{115}In(γ, γ')^{115m}In	95.72	4.5 h	IT β⁻	0.335(50)		9	0.034 (23)			
^{120}Sn(γ, n)^{119}Sn	0.96	35 m	EC β⁺	[0.511](5), 1.14(1.8), 0.75(1.1), m	11.08	16	1.82 (30)			^{117}In(2.8 d)
^{120}Sn(γ, p)^{119m}In	7.61	54 m	β⁻	1.293(80), 1.09(53), 0.417(36), 2.111, 0.819, m	9.49					
^{120}Sn(γ, γ')^{119m}Sn	7.61	14 d	IT β⁻	0.158(87)	9.33					
^{120}Sn(γ, n)^{119m}Sn	24.03									

$^{118}_{50}$Sn(γ, p)^{117}In	24.03	45 m	β^-	0.565(100), 0.158(87)	10.08					
$^{124}_{50}$Sn(γ, n)^{123}Sn	5.94	40 m	β	0.160(84)	8.51	15.5	1.56 (30)	0.13	0.6	
$^{121}_{51}$Sb(γ, n)^{120}Sb	57.25	15.9 m	EC β^-	[0.511](87), 1.171(1.3)	9.25			0.019	0.027	
$^{121}_{51}$Sb(γ, n)^{120m}Sb	57.25	5.8 d	EC	[1.171](100), 1.03(99), 0.200(88), 0.090(81)	9.25	14.5	1.2 (24)			
$^{123}_{51}$Sb(γ, n)^{122}Sb	42.75	2.68 d	$\beta^-\beta^+$	0.564(66), 0.686(3.4), 1.140(0.7), 1.26	8.98	14.5	2.0 (24)	0.17		
$^{123}_{51}$Sb(γ, n)^{122m}Sb	42.75	4.2 m	IT β^-	0.061(50), 0.075(17)	8.98				0.58	
$^{120}_{52}$Te(γ, n)^{119}Te	0.089	16 h	EC β^+	0.645(85), 0.70(11), 1.76(3.6)	10.28					
$^{122}_{52}$Te(γ, n)^{121}Te	2.46	17 d	EC	0.573(80), 0.508(18)	10.06					
$^{130}_{52}$Te(γ, n)^{129}Te	34.48	69 m	β^-	0.027(19), 0.455(15), 0.275(1.7), 1.08(1.5), m	8.39			0.023		
$^{130}_{52}$Te(γ, n)^{129m}Te	34.48	34.1 d	IT β^-	0.69(6)	8.39					
$^{127}_{53}$I(γ, n)^{126}I	100	12.8 d	EC $\beta^-\beta^+$	0.386(34), 0.667(33)	9.15	15.2	1.79 (33)	0.22	3.6	
$^{128}_{54}$Xe(γ, n)^{127m}Xe	1.919	70 s	IT	0.125, 0.175	9.64					
$^{136}_{54}$Xe(γ, n)^{135}Xe	8.87	9.15 h	β^-	0.250(91), 0.61(3)	7.88					
$^{136}_{54}$Xe(γ, n)^{135m}Xe	8.87	15.6 m	IT	0.527(80)	7.88				0.5	
$^{133}_{55}$Cs(γ, n)^{132}Cs	100	6.6 d	EC $\beta^-\beta^+$	0.669(99), 0.48, 1.320(0.6), 1.138	9.04			0.087	1.1	
$^{133}_{55}$Cs(γ, 3n)^{130}Cs	100	29.1 m	β^+ ECβ^-	[0.511]	25.5					
$^{130}_{56}$Ba(γ, n)^{129}Ba	0.101	2.2 h	EC β^+	0.182(100R), 0.21(65R), [0.511], 1.45, m	10.26					
$^{132}_{56}$Ba(γ, n)^{131m}Ba	0.097	14.5 m	IT	0.107(40)	9.56					
$^{135}_{56}$Ba(γ, γ′)^{135m}Ba	6.95	28.7 h	IT	0.268(16)	9.23					
$^{135}_{56}$Ba(γ, n)^{135m}Ba	7.81									
$^{137}_{56}$Ba(γ, γ′)^{137m}Ba	11.32	2.55 m	IT	0.662(89)				0.039	0.14	
$^{138}_{56}$Ba(γ, n)^{137m}Ba	71.62									
$^{138}_{57}$La(γ, 2n)^{136}La	0.089	9.5 m	EC β^+	[0.511](66), 0.818(2.5)	16.58					
$^{139}_{57}$La(γ, 3n)^{136}La	99.911				25.37					
$^{136}_{58}$Ce(γ, n)^{135}Ce	0.193	17.0 h	EC	0.265(100R), 0.59(98R), 0.300(56R), m	9.99					^{135}La (19.4 h)
$^{136}_{58}$Ce(γ, n)^{135m}Ce	0.193	20 s	IT	0.08, 0.15, 0.21, 0.30	9.99					
$^{138}_{58}$Ce(γ, n)^{137m}Ce	0.250	34.4 h	IT EC	0.255(11), 0.825(0.5), 0.168(0.4), m	9.47					^{137}Ce (9 h)
$^{140}_{58}$Ce(γ, n)^{139}Ce	88.48	140 d	EC	*0.165*(80)	9.04	15.6	1.8 (21)	0.54		
$^{140}_{58}$Ce(γ, n)^{139m}Ce	88.48	56.5 s	IT	0.746(93)	9.04				5.0	
$^{141}_{59}$Pr(γ, n)^{140}Pr	100	3.4 m	β^+ EC	[*0.511*](100), 1.596(0.3)	7.67	15.2	2.1 (30)	0.0010	0.013	
$^{141}_{59}$Pr(γ, 2n)^{139}Pr	100	4.5 h		[0.511](18), 1.35(0.5), 1.61(0.3)	17.06	20	0.4 (31)			
$^{141}_{59}$Pr(γ, 3n)^{138}Pr	100	2.2 h	EC β^+	0.79(100), 1.04(100), 0.298(77), [0.511](46)	26.88					
$^{142}_{60}$Nd(γ, n)^{141}Nd	27.11	2.5 h	EC β^+	[*0.511*](6), 1.14(2), 1.30(1), 0.145	9.81	14.8	2.3 (33)	0.0087		
$^{142}_{60}$Nd(γ, n)^{141m}Nd	27.11	64 s	IT	0.755	9.81				23	
$^{150}_{60}$Nd(γ, n)^{149}Nd	5.62	1.73 h	β^-	*0.210*(27), 0.27(26), 0.114(18), m	7.33					
$^{144}_{62}$Sm(γ, n)^{143}Sm	3.09	8.83 m	EC β^+	[0.511](100)	10.46	17.25	0.91 (22)	0.086		
$^{144}_{62}$Sm(γ, n)^{143m}Sm	3.09	64 s	IT	0.748	10.46					
$^{144}_{62}$Sm(γ, 2n)^{142}Sm	3.09	72.4 m	EC β^-	[0.511](100), 0.15 – 0.35 (complex)						
$^{152}_{62}$Sm(γ, p)^{151}Pm	26.72	28 h	β^-	0.340(21), 0.17(18), 0.10(7), 0.45(5), m	8.63					
$^{154}_{62}$Sm(γ, n)^{153}Sm	22.71	46.8 h	β^-	*0.103*(28), 0.070(5.4), m	7.90			0.17		
$^{151}_{63}$Eu(γ, n)^{150m}Eu	47.82	12.6 h	β^- ECβ^+	*0.334*(4), 0.406(3), [0.511](0.8), m	7.93			0.18		
$^{153}_{63}$Eu(γ, n)^{152m}Eu	52.18	9.3 h	β^- EC	0.842(13), 0.963(12), 0.122(8), m	8.54			0.14		
$^{160}_{64}$Gd(γ, n)^{159}Gd	21.90	18.56 h	β^-	0.363(9), 0.058(3)	7.38	13.5	2.2 (33)	0.20		
$^{159}_{65}$Tb(γ, n)^{158m}Tb	100	10.5 s	IT	0.110(0.5)	8.18				0.45	
$^{159}_{65}$Tb(γ, 3n)^{156}Tb	100	5.1 d	EC β^-	*0.535*(70), 0.199(40), 1.22(29), 0.356(13), m	23.65					
$^{158}_{66}$Dy(γ, n)^{157}Dy	0.0902	8.06 h	EC	*0.326*(91)	8.84			3.2		
$^{163}_{66}$Dy(γ, p)^{162}Tb	24.97	7.5 m	β^-	0.258(100R), 0.89(54R), 0.81(44R), 0.180(26R), m	8.27					

1. Reaction	2. Abundance in nature a_0	3. Half life of radionuclide	4. Type of decay	5. Energy of gamma radiation* MeV	6. Threshold energy Q, MeV	7. E_{max} MeV	8. σ_{int}† MeV·b	Sensitivity limits 9. Linac 20 MeV, 1 h µg	10. Betatron 24 MeV, 30 m mg	11. Remarks
^{164}Dy(γ, p)^{163}Tb	28.18	6.5 h	β⁻	*0.330*, 0.510, 0.235, 0.025	8.55					
^{165}Ho(γ, n)^{164}Ho	100	36.7 m	β⁻ EC	*0.091*, 0.073	8.04			0.39	0.012	Dy Ex – *0.54*
^{165}Ho(γ, 3n)^{162}Ho	100	15 m	EC β⁺	[0.511](9), 0.081(8)	23.00					
^{165}Ho(γ, 3n)^{162m}Ho	100	68 m	IT EC	0.185(26), 1.224(24), 0.940(13), 0.283(12), m	23.00					
^{167}Er(γ, n)^{166}Er	0.136	3.1 h	EC	*0.826*(63), 0.211(9), 0.592(8), 1.37 m	9.20			1.1		^{166}Ho(2.5 h)
^{168}Er(γ, p)^{167}Ho	27.07	3.1 h	β⁻	0.079, 0.083, 0.208, 0.238, 0.321, *0.347*, 0.387	7.99					
^{169}Tm(γ, n)^{168}Tm	100	93.1 d	EC	*0.19*(77), 0.82(88), 0.448(27), m	8.06			0.56		
^{168}Yb(γ, n)^{167}Yb	0.135	17.7 m	EC β⁺	0.113(90), *0.176*(15)[0.511]	8.98			7.1		
^{170}Yb(γ, n)^{169}Yb	3.03	32 d	EC	0.198(35), 0.177(22), 0.110(18), 0.308(10), m	8.55					
^{170}Yb(γ, n)^{169m}Yb	3.03	46 s	IT	0.070	8.55					
^{171}Yb(γ, p)^{171}Tm	31.84	8.2 h	β⁻	0.399(89), 0.465(8), 0.066(1.1)	7.97					
^{176}Yb(γ, n)^{175}Yb	12.73	4.2 d	β⁻	0.396(6.0), 0.283(3.7), 0.114(1.9)	6.64					
^{176}Yb(γ, γ')^{176m}Yb	12.73	12 s	IT	0.094, 0.19, 0.29, 0.38						
^{175}Lu(γ, n)^{174m}Lu	97.41	175 d	IT EC	0.067, 0.176, 0.273, 0.994	7.80			4.10		^{174}Lu (3.6 y) E = 1.24
^{175}Lu(γ, 3n)^{172}Lu	97.41	6.7 d	EC	1.09(60), 0.90(45), 0.182(26), 0.81(21), m	22.92					
^{176}Lu(γ, γ')^{176m}Lu	2.59	3.68 h	β⁻	*0.088*(10)	6.19			0.64		
^{174}Hf(γ, n)^{173}Hf	0.18	23.6 h	EC	*0.13*(96), 0.30(52), 0.162(5), m	6.61			19		
^{176}Hf(γ, p)^{176}Lu	13.75	22 m	β⁻	0.089, 0.214, 0.326, 0.427	7.53					^{177}Hf m (4.3 s)
^{178}Hf(γ, γ')^{178m}Hf	13.75	18.6 s	IT	0.217(94)	7.33					
^{180}Hf(n, n')^{179m}Hf	35.24									
^{180}Hf(γ, γ')^{180m}Hf	35.24	5.5 h	IT	0.333(93), 0.215(82), 0.444(80), m						
^{181}Ta(γ, n)^{180m}Ta	99.99	8.1 h	β⁻	*0.093*(4), 0.103(0.6)	7.64	13.5	2.4 (33)	0.040/0.0015	0.077	Hf$_X$ = *0.065*
^{181}Ta(γ, p)^{180m}Hf	99.99	5.5 h	IT	0.333(93), 0.215(82), 0.444(80), 0.501(17), m	6.19					
^{180}W(γ, n)^{179m}W	0.135	5 m	IT	*0.222*						
^{183}W(γ, γ')^{183m}W	14.40	5.3 s	IT	0.108(19), 0.053(11), 0.160(6), m	7.42					
^{184}W(γ, n)^{183m}W	30.64									
^{186}W(γ, n)^{185m}W	28.41	1.6 m	IT	0.17(100R), 0.13(70R), 0.100(16R), m	7.21				8.1	
^{185}W(γ, p)^{185}Ta	30.64	49 m	β⁻	*0.175*(60), 0.100(6), 0.245(5), 0.075(5)	8.33	20.5, 28	0.05 (33)			
^{185}Re(γ, n)^{184}Re	37.07	38 d	EC	0.111, 0.78, *0.90*	7.81			1.8		
^{185}Re(γ, 3n)^{182m}Re	37.07	13 h	EC β⁻	0.068, 0.100, 1.122, 1.189, 1.23 [0.511], m	22.64					
^{187}Re(γ, n)^{186}Re	62.93	90 h	β⁻ EC	0.137(9), 0.768(0.035), 0.632	7.32			0.42	6	
^{184}Os(γ, n)^{183}Os	0.018	14 h	EC	0.382(90), 0.114(27), 0.168(10), 0.48(9), m	–					
^{184}Os(γ, n)^{183m}Os	0.018	10 h	EC IT	1.105(48), 1.035(6)	–					
^{186}Os(γ, n)^{185}Os	1.59	94 d	EC	0.646(80), 0.875(14)	8.30					
^{190}Os(γ, γ')^{190m}Os	26.4	10 m	IT	0.616(99), 0.502(98), 0.361(94), 0.187						
^{190}Os(γ, n)^{191}Os	41.0	15 d	β⁻	*0.129*(25)	7.63			2.7		
^{190}Os(γ, n)^{191m}Os	41.0	13 h	IT	0.074	7.63				4.3	
^{191}Ir(γ, n)^{190}Ir	37.3	11 d	EC	0.56(72), *0.187*(51), 0.37(39), m	8.25			0.18		
^{191}Ir(γ, n)^{190m}Ir	37.3	3.2 h	EC IT	0.616(93), 0.502(92), 0.361(98), 0.187	8.25					
^{192}Ir(γ, n)^{192}Ir	62.7	74 d	β⁻ EC	0.317(81), 0.468(49), 0.308(30), 0.296(29), m	7.79					
^{192}Pt(γ, n)^{191}Pt	0.78	3.0 d	EC	0.539(9), 0.36(5), 0.410(3), 0.129(2), m	8.36					
^{198}Pt(γ, n)^{197}Pt	7.21	18 h	β⁻	0.077(20), 0.191(6)	7.56					

$^{198}_{78}$(γ, n)^{197m}Pt	7.21	86 m	IT β⁻	*0.346*(13), 0.279(2.6)	7.56			0.92		
$^{197}_{79}$Au(γ, n)^{196}Au	100	6.2 d	EC β⁺	*0.356*(94), 0.333(25), 0.426(6), 1.09	8.08	13.6	2.14 (25)	0.033	0.13	
$^{197}_{79}$Au(γ, n)^{196m}Au	100	9.7 h	IT	0.148(42), 0.188(32), 0.285(5), 0.316	8.08					
$^{197}_{79}$Au(γ, γ')^{197m}Au	100	7.5 s	IT	0.279(75), 0.130(8)		7.8, 15				
$^{198}_{80}$Hg(γ, n)^{197}Hg	10.02	64.14 h	EC	0.077(18), 0.191(2), 0.268(0.15)	8.63					
$^{198}_{80}$Hg(γ, n)^{197m}Hg	10.02	23.8 h	IT EC	0.134(42), 0.279(7)	8.63					^{197}Hg(64, 14 h), ^{197m}Au (7.5 s)
$^{199}_{80}$Hg(γ, γ')^{199m}Hg	16.84	43 m	IT	*0.158*(53), *0.375*(15)				0.64	0.16	
$^{200}_{80}$Hg(γ, n)^{199m}Hg	23.13				8.03					
$^{204}_{80}$Hg(γ, n)^{203}Hg	6.85	46.9 d	β⁻	0.279(77)	7.50					
$^{203}_{81}$Tl(γ, n)^{202}Tl	29.50	12.4 d	EC	*0.439*(95), 0.522(0.1), 0.961	7.70			0.30	2.9	
$^{203}_{81}$Tl(γ, 2n)^{201}Tl	29.50	73.5 h	EC	0.167(8), 0.135(2)	14.65					
$^{203}_{81}$Tl(γ, 3n)^{200}Tl	29.50	26.1 h	EC β⁺	0.368(88), 1.21(35), 0.579(10), 0.829(8), m	22.92					
$^{204}_{82}$Pb(γ, n)^{203}Pb	1.48	52.1 h	EC	*0.279*(81), 0.40(5), 0.680(0.9)	8.24			1.0	8.8	
$^{204}_{82}$Pb(γ, n)^{203m}Pb	1.48	6 s	IT	0.825(70)	8.24					
$^{204}_{82}$Pb(γ, γ')^{204m}Pb	1.48	68 m	IT	*0.29*, 0.90				0.52		
$^{209}_{83}$Bi(γ, 2n)^{207}Bi	100	30 y	EC	0.570(98), 1.063(77), 1.771(9)	14.32			1.300		
$^{209}_{83}$Bi(γ, 3n)^{206}Bi	100	6.24 d	EC β⁺	0.803(99), 0.880(72), *0.516*(46), 0.343(26), m	22.35					

* Gamma rays in Column 5 are quoted in sequence of their abundances; R behind a figure in brackets indicates relative values, the other figures expressing percent; m behind the values for energy means that additional less abundant lines are emitted. X-rays and coincident-sum peaks are not included.

† Number in brackets, Column 8, represents the photon energy (in MeV) for which the value of σ_{int} applies.

‡ Radioactive decay products of some radionuclides, and their half lives, are given in Column 11.