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Neutron fluence spectrometry using disk activation

Göran Lövestam [a,*], Mikael Hult [a], Andreas Fessler [a], Joël Gasparro [a], Pierre Kockerols [a], Klaas Okkinga [a], Hamid Tagziria [b], Filip Vanhavere [c], J.S. Elisabeth Wieslander [a,d]

[a] EC-JRC-Institute for Reference Materials and Measurements (IRMM), Retieseweg 111, B-2440 Geel, Belgium
[b] EC-JRC-Institute for the Protection and the Security of the Citizen (IPSC), Via E. Fermi 1, I-21020 Ispra (VA), Italy
[c] SCK•CEN, Boeretang, 2400 Mol, Belgium
[d] Department of Physics, P.O. Box 35 (YFL), FIN-40014, University of Jyväskylä, Finland

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ABSTRACT

A simple and robust detector for spectrometry of environmental neutrons has been developed. The technique is based on neutron activation of a series of different metal disks followed by low-level gamma-ray spectrometry of the activated disks and subsequent neutron spectrum unfolding. The technique is similar to foil activation but here the applied neutron fluence rates are much lower than usually in the case of foil activation. The detector has been tested in quasi mono-energetic neutron fields with fluence rates in the order of 1000–10000 cm^{-2} s^{-1}, where the obtained spectra showed good agreement with spectra measured using a Bonner sphere spectrometer. The detector has also been tested using an AmBe source and at a neutron fluence rate of about 40 cm^{-2} s^{-1}, again, a good agreement with the assumed spectrum was achieved.

1. Introduction

Considering the increasing number of nuclear installations world-wide it is imperative to ensure that adequate techniques to monitor environmental neutron radiation and doses are available. Important issues like environmental and personal safety, safety at work, benchmarking of existing monitoring techniques and unveiling of terrorist threats are sometimes directly linked to whether neutron spectrometry is possible. The techniques used today for measurement of environmental neutron energy spectra include Bonner sphere spectrometry (Bramblett et al., 1960) which is rather accurate but bulky and time consuming to carry out, and bubble detectors (Roy et al., 1987) which suffer from high uncertainties for spectrometry.

In this work, a novel approach is tested. It is based on measuring the neutron activity induced in a series of small metal disks followed by spectrum unfolding to obtain a neutron energy spectrum from the measurement site. A similar technique, usually referred to as the foil activation technique, is widely used for the characterisation of high neutron fluence rates, for example inside nuclear reactors and at neutron research institutes, see for example Negoita (2004). The detector discussed here, however, is aimed for the measurement of much lower fluxes which is facilitated by using thicker disks and low-background gamma-ray detectors for measuring the activation products. Due to the more complex geometry (a ring with several thick disks) neutron scattering corrections and thick target gamma measurement efficiencies need to be determined. This gives a slightly higher uncertainty compared to the foil activation technique but the contribution to the total uncertainty is limited to about 1% for a typical measurement.

As an environmental neutron-flux detector, the proposed detector possesses a number of distinct advantages. The detector

- is practically only sensitive to neutron radiation,
- is small and robust,
- requires no electrical power at the measurement site,
- can be placed at remote locations or locations with difficult access and/or in hazardous environments,
- sensitivity can be increased by using more and bigger disks and by using underground gamma-ray detectors for measuring the induced activity in the disks,
- is energy sensitive over a large neutron energy region, and
- is of relatively low cost.

A few limitations should, however, also be noted:

- The measurement of the activation products can be time consuming, especially if low detection limits are sought.
- The necessary time between the end of an activation and the start of gamma-ray measurements limits the possible disk materials to isotopes with long half-lives relative to the transport time.

* Corresponding author. Tel.: +32 (0) 14 571373; fax: +32 (0) 14 571376.
E-mail address: goeran.loevestam@ec.europa.eu (G. Lövestam).

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- Only constant neutron fields can be accurately measured, no information about flux-changes in the spectrum during the irradiation time is obtained.

For applications there are numerous situations where a better knowledge of the neutron spectrum would give a better understanding of the origin of the neutrons, scattering effects, possible shielding effects, etc. Although in this study, the detector is designed as a neutron spectrometer, its extension to neutron dosimetry using a different design is anticipated.

2. Materials and methods

The main concept of the technique consists of three parts: 1) the neutron sensitive device consisting of a number of metal disks arranged in a holder, 2) a low-background gamma-ray measurement station and 3) a spectrum unfolding procedure.

2.1. Materials for the detector device

For the actual detector device a number of different metals are chosen depending on the prospected irradiation time and the expected neutron energy distribution. To generate adequate data for spectrum unfolding at least 6 neutron activation reactions are necessary and about 8–10 are recommended. The detector used for the measurements discussed here comprised 8 disks and the elements Mg, Al, Ti, Fe, Ni, Co, Cu and In. Each disk was 5 mm thick and 20 mm in diameter and had been analysed for possible prior activation by means of low-background gamma-ray spectrometry. The disks were geometrically arranged in a circle as in Fig. 1 on a circular piece of sticky hard paper.

The detector disk materials must be chemically stable, robust and not hygroscopic so as to facilitate the placement of the detector in rough, hostile environments. The mass as well as the isotopic and chemical composition must be well known and with high purity, which is critical. As an example, a manganese impurity in an iron disk produces via the ^{55}Mn(n,γ)^{56}Mn reaction the same reaction product as the ^{56}Fe(n,p)^{56}Mn reaction.

Activated pure metal disks are highly suited for gamma-ray measurements due to the well defined sample geometry, easy sample preparation and clean gamma-ray spectra that are relatively easy to analyse. Using pure metals eases the peak identification as well as minimises the background contribution from the sample itself. This results in a technique with low detection limits that can benefit from using low-background (or even ultra low-background) gamma-ray detection systems in order to further reduce the detection limits. An alternative to pure elemental metals is the use of alloys. By using several elements in each disk, fewer disks have to be used and measured by gamma-ray spectrometry, giving a faster technique with fewer detectors. The disadvantages are (i) the activation can lead to decay products with similar or overlapping gamma lines, (ii) the less material of each metal results in a lower activity and higher detection limits and (iii) each gamma-ray spectrum will have more peaks which could give higher detection limits.

It should be noted that the re-use of disks is, of course, only possible after an elapsed time corresponding to a number of half-lives for the produced radionuclides, depending on the sensitivity sought. For all measurements in this study, the disks were irradiated only once.

The neutron cross sections for the disk materials must be well known and large enough in order to produce sufficient activation products for gamma-ray measurements with appropriate statistics. The excitation functions should have different thresholds and together cover the full energy interval of interest in order to allow for the spectrum unfolding. It is desirable to avoid disk materials where different reactions produce the same radionuclide in one disk. Data for the activation reactions used in this study are given in Table 1.

A general requirement of an activation product is that its decay should be followed by at least one gamma-ray with energy between about 50 keV and 2 MeV and with a precisely known high emission probability. In addition, it is essential that the corresponding half-lives are short enough for all disks to be measured in a reasonable time span after the irradiation, but also long enough to transport the disks from the activation site to the gamma-ray detector. If several gamma-ray detectors are available and the disks can be retrieved and measured shortly after the neutron irradiation, radionuclides with shorter half-lives can be used. If the fluence rate varies during the irradiation the half-lives must be chosen long with respect to the irradiation time in order to not to reach the saturation activity. For a constant neutron field this is not the case. Furthermore, if the neutron fluence varies but the variations are known, reactions with shorter half-lives can be used since a correction can be applied to account for the variations.

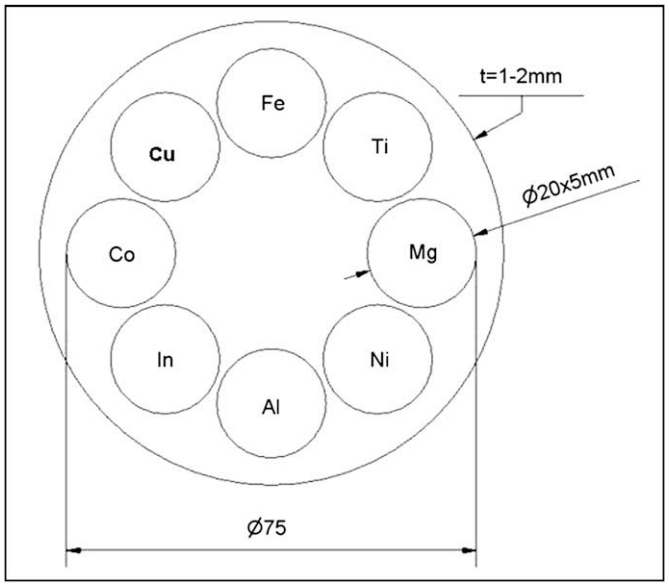

Fig. 1. Schematic drawing of the detector arrangement as viewed from the front. The disks are arranged in a circle on a sticky paper holder with a thickness of about 1–2 mm.

Table 1
Nuclear reactions used for the tested detector units. $T_{1/2}$ is the half-life, E_g is the gamma-ray energy, P_γ is the intensity of the most prominent gamma-ray, and I_{ab} is the natural isotopic abundance.

Reaction	Threshold (MeV)	$T_{1/2}$ (d)	E_g (keV)	P_γ (%)	I_{ab} (%)
^{24}Mg(n,p)^{24}Na	5.70	0.62	1368 (and 2753)	100.0	78.99
^{27}Al(n,p)^{27}Mg	2.00	0.0066	844 (and 1014)	71.80	100
^{27}Al(n,α)^{24}Na	5.10	0.62	1368 (and 2753)	100.00	100
^{46}Ti(n,p)^{46}Sc	3.00	83.79	889 (and 1021)	100.0	8.25
^{47}Ti(n,p)^{47}Sc	0.80	3.35	159	68.30	7.44
^{48}Ti(n,p)^{48}Sc	3.60	1.82	983 (and 1037, 1312)	100.0	73.72
^{54}Fe(n,p)^{54}Mn	1.10	312.30	835	99.97	5.845
^{56}Fe(n,p)^{56}Mn	3.20	0.11	847 (and 1810, 2113)	98.9	91.754
^{58}Ni(n,p)^{58}Co	0.80	70.78	811	99.49	68.27
^{58}Ni(n,d + np)^{57}Co	6.10	271.77	122	85.5	68.27
^{59}Co(n,α)^{56}Mn	4.00	0.11	847 (and 1810, 2113)	98.9	100
^{59}Co(n,2n)^{58}Co	10.70	70.78	811	99.45	100
^{59}Co(n,p)^{59}Fe	1.60	44.5	1099	56.59	100
^{63}Cu(n,γ)^{64}Cu	0.00	0.529	1346	0.5	69.17
^{115}In(n,n′)^{115}In	0.40	0.19	336.2 (and X-ray at 24)	45.8	95.7
^{115}In(n,γ)^{116m}In	0.00	0.03764	1293.5	84.4	95.7