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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Evaluation and test of the response matrix of a multisphere neutron spectrometer in a wide energy range *
Part II. Simulation

A. Aroua [a], M. Grecescu [a], M. Lanfranchi [a,1], P. Lerch [a], S. Prêtre [b] and J.-F. Valley [a]

[a] *Institute for Applied Radiophysics, CH-1015 Lausanne, Switzerland*
[b] *Swiss Nuclear Safety Inspectorate, CH-5232 Villigen-HSK, Switzerland*
[1] *Present address: LPN, CP8, CH-1042 Assens, Switzerland*

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The response matrix of a multisphere neutron spectrometer has been calculated using the ANISN particles transport code and a recent condensed cross-section library. The matrix has then been extended up to 400 MeV. A detailed investigation of several calculation parameters led to the establishment of an improved model of the system. The adjustment of the calculated response functions to the experimental calibration points (8 keV–14.8 MeV) has given coherent results, the deviation of the calculated values from the measured ones being less than 10% for the maximum sensitivity regions. The calculated response functions have been compared to others reported in the literature. Finally the effect of a cadmium shell on the spheres' response has been studied.

1. Introduction

A major step in the development of a multisphere spectrometer is the evaluation of its response between the limited number of available calibration energies. This is particularly necessary over a wide energy interval in the intermediate range covering five decades (from thermal energies up to the keV region) where there is a lack of monoenergetic neutron sources [1].

The response functions are established over the whole useful energy range using several methods:

- interpolation and extrapolation techniques [2,3];
- fit of the experimental data by an algebraic expression [4];
- numerical computation of the response functions [5,6].

In order to determine the response functions between the experimental points we adopted the last method which is the most commonly used. It consists in simulating the system, computing its response and adjusting the results to the experimental calibration points.

The calculation of the Bonner spheres' response functions is performed through the investigation of all possible neutron interactions with the detection system. One possible way to achieve this task is to follow the path of each neutron entering the system, by applying the well-known neutron interaction laws; such an approach is used in the Monte Carlo method. In this statistical method a large number of neutron tracks (histories) are followed in order to obtain statistically significant results. Very recently Mares et al. [7] reported a set of response functions for Bonner spheres calculated with the MCNP Monte Carlo code. Monte Carlo codes have the advantage to solve any three-dimensional geometry problem, but they require a great amount of computer time.

A second approach, similar to that used in gas kinetics, considers the average particle behaviour; a neutron population is then seen as a statistical entity. A neutron balance is drawn up by expressing in a particle transport equation (Boltzmann equation) the production and loss of neutrons in terms of probabilities. The discrete ordinates method is frequently used for solving the neutron transport equation and has been applied for the calculation of the spheres' responses. A large number of computer codes [8] are based on this method which is described in detail by Carlson and Lathrop [9]. The adjoint mode, first applied by Hansen and Sandmeier [5] to establish the response of a thermal neutron detector surrounded by a spherical moderator, allows the calculation of the whole response function in a single run.

This paper presents the evaluation of the response matrix of a multisphere spectrometer described in the

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preceding paper [1], using the discrete ordinates method and the adjoint technique.

2. Method of calculation

2.1. The ANISN code

The one-dimensional ANISN transport code [10,11] for neutrons and gammas is used in the present work. It allows multigroup calculations, considers the scattering anisotropy and accounts for the angular dependance of the transfer cross sections by expanding them in Legendre polynomials. ANISN has been used in conjunction with MELANIE [12], a user-friendly interface program which allows to introduce the input data in a free format, easy to handle, in contrast with the rigid input format of the original ANISN code.

2.2. Microscopic cross-section libraries

2.2.1. BUGLE-80 cross-section library
BUGLE-80 [13], is a recent version (1980) of the BUGLE cross-section library [14,15]. It is condensed from VITAMIN-C [16] which is built upon ENDF/B and LENDL files. BUGLE-80 contains 47 neutron groups with two of them in the thermal region. This library has been used very recently by Wang and Blue [17] for the calculation of the response of a similar spectrometric system.

2.2.2. HILO cross-section library
The multisphere spectrometer may be used near high energy accelerators, or radiotherapy electron accelerators. Around these installations, neutrons with an energy up to several tens of MeV are produced. The unfolding of neutron spectra extending to these energies is not possible since the response matrix established using the BUGLE-80 cross-section library is limited to 17.3 MeV.

In the literature only Sanna [6] presented calculations extending from thermal energies to 400 MeV. The calculations were performed by means of the DTF-IV code on a set of seven spheres of diameters from 2 to 18 in. with a lithium-6 iodide scintillator at the center. The library used comprises 31 energetic groups only. From the results obtained by Sanna and which showed no irregularities in the response functions at high energies, several authors extended their systems' response matrices to high energies either by hand extrapolation or by normalising the results of Sanna to theirs.

In our case the response functions calculation above 17.3 MeV has been undertaken using the HILO library from Oak Ridge [18] which has 66 neutron groups and covers a range extending from thermal energies to 400 MeV. HILO presents a broad energy structure at low energies.

2.3. Optimization of the calculation

The steps in the space discretization should not be lower than 10 intervals per decade of attenuation [19] which corresponds to 16 mm for the polyethylene and for thermal neutrons.

The experience showed [19] that for most practical problems the scattering anisotropy is well treated if the scattering differential cross section is expanded in low-order Legendre polynomials (P2 or P3 approximations). It is reported also [19] that for most cases the discretization of the angular domain into 16 intervals is adequate.

In our case a sensitivity analysis has been undertaken in order to determine the optimum set of parameters. It showed that passing from P3 to P2 expansion leads to a variation of the result of 0.01% which is negligible. It showed also that the modification of the calculation parameters within a reasonable range leads to an overall variation of 2–3% in the response of the 6 in. sphere which is considered representative both for the dimensions and for the response function.

After these preliminary calculations the P2 approximation has been chosen. The angular domain has been discretised into 64 intervals. Concerning the space discretization, the interval width has been established as follows: 2 mm for helium (counter gas), 0.2 mm for Monel (counter wall), 1.25 mm for polyethylene (Bonner sphere) and 10 cm for air (medium between the source and the sphere).

2.4. Computer model of the Bonner spheres system

2.4.1. Neutron detector representation
The thermal neutron counter which does not have a spherical geometry must be replaced by an equivalent sphere in order to perform a one-dimensional calculation. Sanna who made calculations with a cylindrical lithium-6 iodide detector [6] has adjusted the ^{6}Li(n, α) cross sections in order to maintain the same collision probability when passing from a cylindrical to a spherical shape for every energy group. Other authors have suggested a variety of basic criteria for the determination of the radius of the equivalent spherical detector: the mean chord equality criterion [20] and the equivolume hypothesis [21] for detectors translucent for thermal neutrons and where the whole detector volume participates in their absorption; the equisurface hypothesis [5,22,23] for detectors opaque for thermal neutrons and where the neutron absorption occurs rather at the surface. The Monte Carlo calculations performed by Dhairyawan [24] on a variety of thermal detectors placed at the centre of Bonner spheres have

shown that depending on the type of detector, the system's response varies with either the square or the cube of the detector's radius.

In our case the helium-3 counter which has a quasi orthocylindric volume (∅ 0.9 cm × 1.0 cm) has been replaced by an equivalent sphere of equal volume. This is justified by the quasi-transparency of the sensitive volume to thermal neutrons [20]; the evaluation of the mean path of thermal neutrons for the operating helium pressure showed that it is of the order of the counter's diameter (0.9 cm). Preliminary calculations indicated that a slight variation (a few %) of the equivalent sphere's diameter does not affect the computed response if the helium quantity is maintained constant.

2.4.2. Density effects

A nominal value of 8 bar (8×10^5 Pa) for the helium filling pressure was considered, according to the manufacturer's specifications. The first calculations revealed that an increase of 10% in the helium pressure leads to a 4.5% increase in the reaction rate within the sensitive area. The results reported by Uwamino et al. [25] show that the counter's efficiency increases with the helium pressure until the appearance of a saturation due to screening effects, an increase of the recombination rate in the gas and the formation of negative ions [26]. A deviation of the effective pressure from the nominal value is implicitly corrected by the adjustment of the calculated responses to the experimental calibration points (section 3).

The counter wall is made of monel with a density of 8.4–8.8 g cm^{-3} (according to the manufacturer). Calculations on the 6 in. sphere with these two values gave 0.2% difference in the result. Finally a mean density of 8.6 g cm^{-3} has been adopted.

The influence of the polyethylene density on the shape of the spheres' response functions has been investigated by many authors [25,27–29]. The work reported recently by Mares et al. [7] has shown that the variation of the polyethylene density from 0.92 to 1.00 g cm^{-3} leads to a considerable change in the shape of the spheres' response functions. If the neutron attenuation in polyethylene is considered to be proportional to the product of the density and the mean chord of the sphere, it follows that a given variation in the polyethylene density is equivalent to a variation of the same order in the sphere diameter (with constant density).

In our case the spheres are made of polyethylene with a density of 0.916–0.918 g cm^{-3} (according to the manufacturer). The measurements performed on a couple of samples revealed a density of 0.916 g cm^{-3}. This value has been adopted for the calculations. In a comparative computing test with the 6 in. sphere, a density of 0.918 g cm^{-3} gave a difference of 0.5% in the result.

2.4.3. Effect of the counter's duct

The principal deviation of our system from an ideal spherical geometry is due to the presence of a local inhomogeneity created by the radial duct that houses the counter and the high voltage cable. This channel induces several effects such as a local decrease in the neutron moderation, a free access to the sensitive volume of some nonmoderated neutrons and leakage of moderated neutrons to the outside. The higher the ratio of the channel volume to the sphere volume, the more pronounced these effects are. Similar effects have been investigated by Rohloff and Heinzelmann [30] who evaluated experimentally the influence on the system's response of different light pipes used with a lithium iodide crystal. The results of this study have shown that the inhomogeneity produces a loss of sensitivity which is more important for small spheres and for thermal neutrons.

In our simulation of the Bonner spheres system, a correction for the loss of thermalization has been attempted. This is in our opinion the dominant effect for the irradiation geometries used in practice. The lack of polyethylene in the duct has been simulated by a variable weighting of the polyethylene density. This has been done in steps of 1 mm over the first 20 intervals. The weighting factor applied at a distance d from the detector's centre is given by the ratio of the polyethylene quantity that remains after boring the channel in a spherical shell of radius d, to the total quantity in this shell in the absence of the channel. This ratio becomes greater than 0.99 beyond a distance of 20 mm.

Fig. 1 illustrates the effect of a cylindrical channel on the response functions of the Bonner spheres. The results show once again that the effect is pronounced mainly for small spheres at low energies. It can be seen that from the 4.2 in. sphere upwards, the changes of

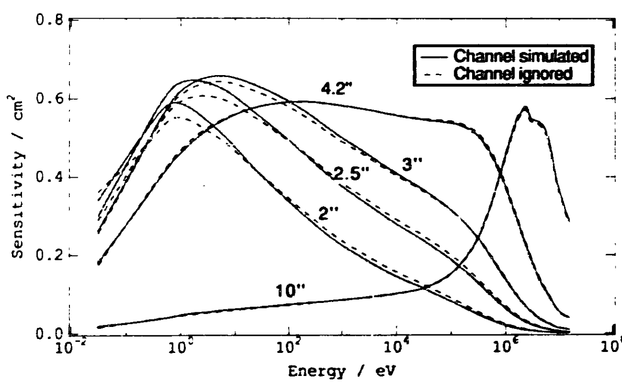

Fig. 1. Effect of the cylindrical channel simulation on the Bonner spheres response functions.

the response functions due to the channel are so small that they can be neglected.

For a low diameter sphere the lack of polyethylene leads to a decrease of thermal neutron capture in the sphere and favours the access of a higher number of these neutron to the sensitive volume. This produces an increase of the detector's sensitivity at low energies. On the other hand the lack of polyethylene reduces the thermalization of fast neutrons in the sphere and induces therefore a slight fall in the detector's sensitivity at high energies as it is shown in fig. 1. This behaviour is in contradiction with the experimental results of ref. [30]. The difference may be due to the fact that our computation simulates a lack of moderating material, while the experimental results concern merely a change of material.

2.4.4. Source–detector distance

For the calculation of the response functions a distance of one meter has been considered, for two reasons:

- even if theoretically a point source produces a plane parallel beam only at an infinite distance, the results reported in the literature and the international recommendations [5,31–35] indicate that in practice at source–detector distances greater than five to six times the detector's radius, the irradiation can be considered as plane parallel. In our case the choice of the distance was determined by the diameter of the biggest sphere (15 in.).
- for all the measurements performed with point sources the source–detector distance has been equal or greater than one meter.

Calculations of the response functions have been made with different source–detector distances, from 20 cm to 50 cm by steps of 5 cm and up to 100 cm by steps of 10 cm. Fig. 2 presents the results obtained for the 12 in. sphere at four distances. Beyond 50 cm the distance effect becomes negligible even for a sphere of such a large diameter.

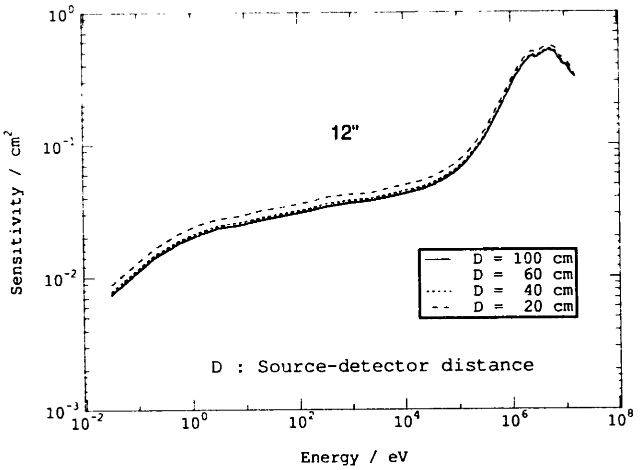

Fig. 2. Influence of the source–detector distance on the 12 in. sphere response function.

3. Results and discussion

The adjustment of the calculation to the calibration points is made by multiplication of the computed curves with a scaling factor. Its value is adjusted until the average quadratic difference between calculated and measured sphere responses reaches a minimum. In an ideal situation one should find a common multiplying factor for all the curves.

Other adjustment methods have been suggested in the literature; some of them modify even the shape of the response functions in order to bring them closer to the experimental points. Thomas et al. [36] have used an unfolding code which performs a nonlinear adjustment of the calculated response functions. These methods assume an accurate estimation of the errors associated with both the calculated functions and the experimental results. The independent deformation of each response function raises questions about the coherence of the simulation model adopted for the calculation and excludes any intercomparison of calculation methods.

Fig. 3 shows the response functions of the 2.5, 4.2 and 8 in. spheres, adjusted individually to the monoenergetic beams calibration points. It permits the comparison with the results obtained by other authors who used the same type of counter.

The main difference between the matrix calculated in the present work and that established by Vylet [37] is an increase of the sensitivity of the small spheres at low energies. The present results are in good agreement with those reported by several authors such as Zaborowski [4], Sanna [6] and Hertel and Davidson [23] and especially with the calculation made by Caizergues [21] who used the same type of counter as ours.

The individual adjustment of the response functions which mainly accounts for the maximum sensitivity region, has given the results presented in table 1. The variance of the individual adjustment factors is relatively low and this justifies to take a mean value for all the spheres. The use of a mean adjustment factor has given for all the spheres deviations less than 30% between the calculation and the measurement. For the regions of maximum sensitivity these deviations are less than 10%.

Because the thermal neutron beams employed for the calibration of the Bonner spheres are not truly monoenergetic, the corresponding results are used only for verification of the response functions [38]. They

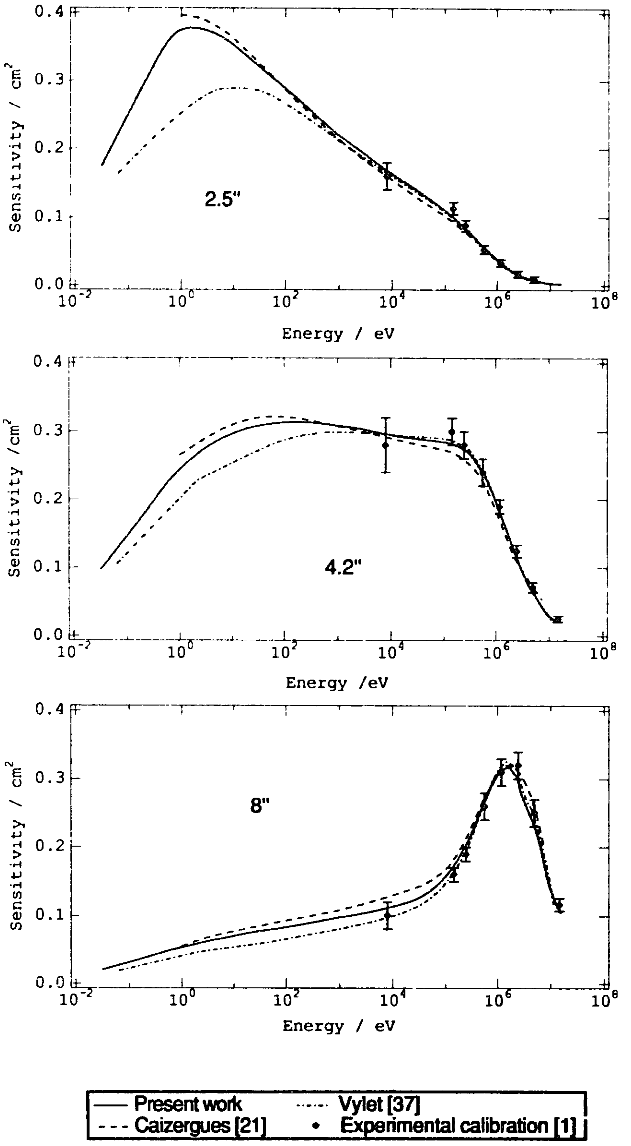

Fig. 3. Individual adjustment of the 2.5, 4.2 and 8 in. spheres response functions.

Table 1
Individual adjustment factors for the Bonner spheres response functions

Sphere diameter [in.]	Adjustment factor
4.2	0.53
5	0.52
6	0.50
8	0.49
9	0.48
10	0.47
12	0.49
15	0.50
Mean	0.50
Standard deviation	2%

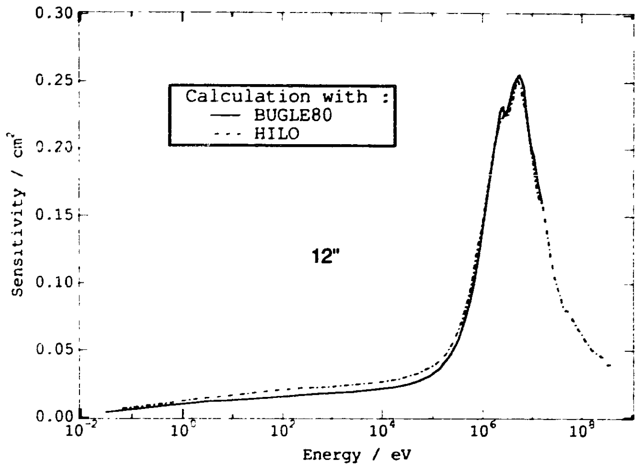

Fig. 4. The 12 in. sphere response function obtained with two different cross-section libraries.

have not been considered in the adjustment of the calculated response functions to the calibration points.

Fig. 4 presents the 12 in. sphere response function extended to 400 MeV (obtained with HILO) and compares it to that obtained with BUGLE-80. Even if the energetic structure of HILO is very broad at low energies, the agreement between the two results is very good especially beyond 1 MeV.

Fig. 5 shows the main result of the present work, i.e. the set of response functions of our Bonner spheres system, obtained by calculation with the ANISN code, adjustment to the calibration points and extension up to 400 MeV. The response matrix in numerical form may be obtained from the authors on request.

The response functions accounting for the effect of a cadmium cover of 8.6 g cm^{-3} density and 1.4 mm thickness have been calculated for the bare counter and for spheres with diameters from 2 to 6 in. Fig. 6 presents the ratios of cadmium-covered spheres re-

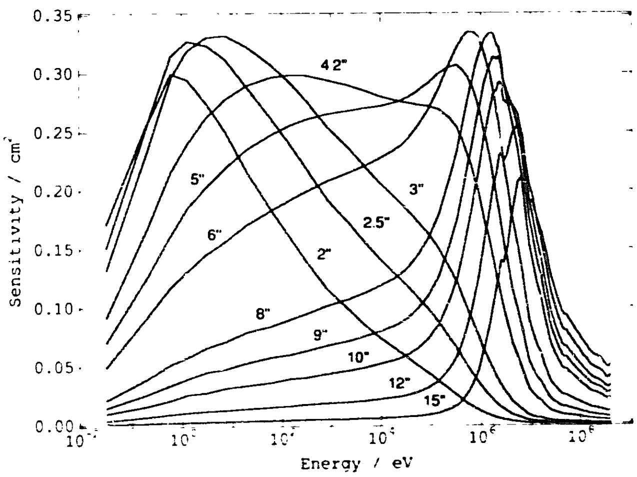

Fig. 5. Response matrix of the multisphere spectrometer.

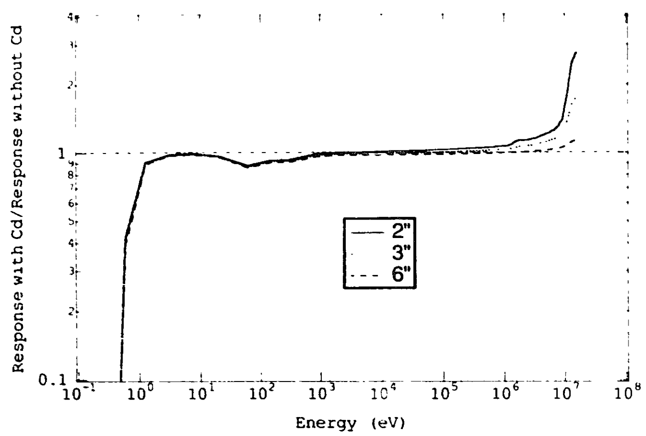

Fig. 6. Effect of the cadmium shielding on the Bonner spheres response functions.

sponses to bare spheres responses. The cadmium cutoff is clearly shown. Moreover a slight loss of sensitivity with cadmium can be seen in the energy region around 100 eV. This is due to the presence in this region of resonance peaks in the cadmium absorption cross section. The broadening of these peaks is caused by the energetic structure used in the calculation.

The figure shows also an increase of the response above 1 MeV when cadmium is used. This effect, more pronounced for small spheres, has been reported also by Hertel and Davidson [23] who associated it to inelastic interactions and (n, 2n) nuclear reactions in cadmium, whose cross section increases with energy. Consequently, when measurements are performed with the cadmium cover in hard spectra such as the americium–beryllium, a slight increase in the small spheres count rates should be expected. In practice the count rates of small spheres are so low in hard spectra that the effect is hidden by statistical errors.

4. Conclusion

The response matrix of a multisphere spectrometer has been calculated using a recent cross section library, and extended up to 400 MeV. Different factors affecting the spheres' response functions have been simulated and studied, such as the counter's filling pressure, the polyethylene density and the counter's duct. After adjusting the calculation to the experimental points, the overall observed deviations are less than 30%; for the maximum sensitivity region the deviations are less than 10%. Considering the errors on both the experimental calibration and the calculation, the present results can be considered as fully satisfactory.

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