Radiation Physics Note 59

The Neutron Spectrum from a Pu-Be Source

Alex Elwyn June 24, 1986

I. Introduction

A multisphere system is used at Fermilab to characterize neutron spectra in the stray fields outside of shielding at various locations around the site. It is of interest, therefore, as a check on the measurement and analysis procedures, to apply the same methods to a source of neutrons whose properties are reasonably well-known. This report describes the results of the measurement of the neutron fluence from a ²³⁸Pu-Be source by use of an 8 mm x 8 mm ⁶LiI crystal embedded in a plastic scintillator (phoswich), and a set of eight polyethylene moderating spheres with diameters of 5.1, 7.6, 12.7, 20.3, 25.4, 30.5, and 45.7 cm. The measurements were carried out in the second floor calibration room at Site 68. Some properties of the room scattered neutrons to which the spherical detectors also respond are discussed.

II. Procedures

The ²³⁸Pu-Be source (FNAL# 238Be-7.2-1) was placed on an Al support structure at the center (approximately) of the upstairs calibration room

[†]The room is about 11 feet by 14 feet with an 8 foot high ceiling.

at Site 68 at a height of ~64 cm above the floor. The phoswich detector (Aw73) was placed at the center of each moderating sphere[†] in turn, and located so that the sphere center was ~1 m. from the source at the same height above the floor. A measurement was also made with a bare (unmoderated) phoswich detector. The source strength corrected for the decay of ²³⁸Pu was 1.66 x 10⁷ neut-sec⁻¹, which for an isotropic point source corresponds to a neutron flux at 1 m. of 132 neut-cm⁻²-sec⁻¹. Standard electronics techniques, as described previously (Co85), were used to accumulate a pulse height spectrum (for time intervals of 275-800 sec) in which the peak associated with neutrons was well separated from background events. The measured sphere responses are listed in Co1. 2 of Table 1; the values normalized so that their sum is unity are shown as the solid points in Fig. 1.

III. Backgrounds

The total measured response of each spherically-moderated detector is subject to small geometric corrections, and includes contributions that arise from both air and room scattered neutrons as well as those that come directly from the source (Hu84, Ei85). Geometric effects associated with source

[†]The fluence measurement with the 45.7 cm diameter sphere was actually performed outside the building at Site 68. Neutron counts were obtained relative to those from the 20.3 cm diameter sphere, so that normalization to the indoor results could be accomplished in a straightforward manner.

anisotropies (e.g., due to the source's cylindrical rather than spherical shape) as well as with the finite size of the spherical moderator are estimated (Ei85) to be less than a few percent. The air in-scattering component has been shown (see discussion in Na72) to be proportional to r^{-1} , where r is the source-to-detector distance. Its magnitude, however, although approximately twice as large (McC81) as out-scattering (or air attenuation), has been found (Ei85) to be less than 2% per meter for the 7.6 cm and larger-sized spheres, under circumstances similar to the present situation. These effects have therefore been neglected in the analysis that follows.

The contribution of room scattered neutrons to the total detector response should be significant since the ratio of reflected-to-incident neutron current densities (albedo) from surfaces that have high hydrogen content is greater than 0.5 for fast neutrons (Ei82). This contribution to the detector response is approximately constant over the central volume of the room (Ei82), and since the direct response to source neutrons falls off as r^{-2} the total detector counting rate can be written as $C_T = C_0/r^2 + C_1$, or equivalently,

$$C_T r^2 = C_0 (1 + Sr^2),$$
 (1)
where $S = C_1/C_0$.

We have measured the neutron flux for the 7.6, 20.3, 30.5 cm, and bare detectors as a function of source-to-detector distances r of 0.6 to 1.9 m. The detector responses multiplied by r^2 and plotted as a function of r^2 are shown in Fig. 2. The smooth lines represent a best-fit to Eq.(1) from the results of a least-squares analysis; numerical values of the coefficients are given in Table 2. The fact that the data are well represented by a linear fit provides

justification for the neglect of the air in-scattering component; a sizeable contribution from air scattering to the measured response would lead to the existence of an additional term, linear in r, in Eq.(1).

From the fits to the data the fraction of the measured response due to both direct (C_0/C_T) and room-scattered (C_1/C_T) neutrons are obtained at a source-to-detector distance of 1 m., and shown in Table 2 in Cols. 4 and 5. Note that particularly for the bare and 7.6 cm detector the room-scattered neutrons represent a significant fraction of the total response for the Site 68 calibration room. Although not directly comparable, an estimate of room scattering based on both single-surface reflection and a completely enclosed (six-surface) concrete room having the same surface area as the Site 68 room was obtained from data for a $^{252}{\rm Cf}$ source presented by Eisenhauer et al (Ei85) (see also Ei65). The results for both a 3-inch (7.6 cm) sphere and a 9-inch (22.9 cm) spherical remmeter are listed in Table 2 , and provide some feeling for the expected size of the room-scattered background.

Fig. 3 shows the fraction of the measured response that arises from source neutrons directly, plotted as a function of sphere diameter. Multiplication of the measured PuBe responses for each sphere by these ratios (taken from the smooth curve on Fig. 3 for those spheres for which room scattering measurements were not made) gives the sphere response for the source neutrons alone. These room-scattering corrected values are listed in Table 1, and when normalized so that their sum is unity are shown as X's in Fig. 1. The fraction of direct neutrons to be associated with the 45.7 cm sphere was taken as ~0.96 in the subsequent discussion (Sect. IV).

IV. Neutron Spectra

The neutron spectra associated with the data of Table 1 were unfolded by use of the BUNKI (Lo84) computer program. The code makes use of the SPUNIT (Br84) interactive recursion method but allows a choice of starting solutions as well. The response functions used were those of Sanna (Sa73) appropriate to an 8 mm diam. by 8 mm long 6 LiI crystal. The unfolded spectra, based on a starting solution with a Maxwellian peak at 4-MeV superimposed on an 1/E slowing-down shape, for the total and direct source neutrons are shown in Fig. 4a and 4b. Since the abscissa is logarithmic and the ordinate is $N(E)/\Delta(\log E)$, the area under the curves for each energy bin is proportional to the neutron fluence within that bin. The smooth curves of Fig. 1 represent fits to the measured sphere responses for the spectra shown in Fig. 4a and 4b.

Although the characteristic feature of the spectra (in Figs. 4a and 4b) is the peak near 4 MeV, more detailed observation reveals quantitative differences in the two cases. For the "true" Pu-Be data (i.e., the room-scattering corrected responses) 93% of the total fluence compared to 77% for the uncorrected data arises from neutrons with energies between -0.1 and 15 MeV. The corrected spectrum shows less than 0.5% of the neutron fluence in the thermal bin compared to about 12% for the uncorrected data. Furthermore, a small peak (6% of the total fluence) is observed in the region between 0.5 eV and 1-keV on the direct source spectrum. Fig. 5 shows the spectra of Fig. 4a and 4b replotted with a logarithmic scale on the y-axis to more clearly display the low-energy characteristics and the differences in the two cases. The lower spectrum in Fig. 5 is qualitatively similar to a multisphere Pu-Be source

measurement reported in Thorngate and Griffin (Th85), although the present results show a lot fewer thermal neutrons.

The Bonner multisphere spectrometer is a low resolution (although broad dynamic range) detector system. Thus, previously observed structure in the Pu-Be source spectrum (see, e.g., An63 and An72), characterized by maxima at 3.2, 4.7, 7.7, and 9.6 MeV, was not seen in the present studies. Even so, the present results show the spectral endpoint to be in the 8-15 MeV energy bin in agreement with the previously known value of about 12 MeV. And furthermore, the average neutron energy is ~3.5 MeV which agrees to ~12% with the accepted average value of 4-4.1 MeV (Pa73, Na67).

The peaks at 4.7 MeV and higher energies observed in measurements done with better resolution can be understood in terms of the primary ^9Be (α , n) reaction to the known ^{12}C final states (An63). At lower energies, however, the shape of the spectrum depends on the amount of Pu and the kind of source encapsulation. It is largely influenced by secondary processes, such as elastic scattering, (n, 2n), and (n, fission) reactions, in the source materials. As observed in the literature (see, e.g., An63) the spectral shapes at energies between ~0.5 and 2 MeV vary greatly from experiment to experiment. No previous measurements of the neutron yield below about 0.5 MeV, and particularly below 1 keV, have been reported.

The differences in the sphere responses for the total and direct-source contributions can be attributed to room scattered neutrons. Numerical values are listed in Table 1, and the neutron spectrum unfolded from this data is shown

in Fig. 4c. Unfortunately the fit to the sphere responses for this case was not very good. Usually under such circumstances, the difficulties inherent in spectrum unfolding procedures (e.g., underdetermination problems, ill-conditioned nature, etc., see Co85) can lead to spurious results; the spectral peak at 5-10 MeV (in Fig.4c) may fall into this category. For the rest, 41% of the room scattered neutron flux falls into the thermal bin and 53% occurs at energies between -.005 and 0.5 MeV.

Other properties of the unfolded spectra are listed in Table 3, and compared to previous information as appropriate. Both the average energy and to a lesser extent the QF obtained in the present analysis (Cols. 3 and 4) are in reasonable agreement with the values (Col. 6) from the literature. The flux-to-dose equivalent conversion factor for the Pu-Be source neutrons (Col. 4) is in excellent agreement with the average value from the compilation of Nachtigall (Na67) but lower by about 11% than the value quoted by Hofert and Raffnsoe (Ho80).

The flux of neutrons coming directly from the source as obtained in the analysis is about a factor of two lower than the value calculated from the "known" properties of the Pu-Be source. This could mean that the source strength and calibration date are not as well known as expected. However,

 $^{^{\}dagger}$ It should be noted that previous reports usually refer to 239 Pu rather than 238 Pu, which is the appropriate isotope in the present case.

results from the unfolding analysis depend strongly on the particular set of response matrices employed; and since, of the many such sets that exist, it is not known which if any is the correct one, the flux calculated with the Sanna matrices (Sa73) could in in error. It is planned to further study the effects of different sets of response matrices in neutron spectrum unfolding.

Finally, spectra for both the total and direct source responses were unfolded without use of the 45.2 cm (18 inch) sphere. The results for direct source neutrons are shown in Col. 4 of Table 3. While the fits to the sphere responses were still very good, there were small spectral shape and magnitude changes (-a few percent at any energy). Differences in total flux, dose, dose-equivalent, etc., were less than ~10%, as seen in the Table. The 45.7 cm sphere therefore does not contribute significantly to the characterization of a neutron field like that from a Pu-Be source, and its unwieldy use could be avoided.

I want to thank Chuck Salsbury for his considerable help with the measurments. He was particularly effective in handling the 45.7 cm (18 inch) diameter sphere!

References

- (An63) Anderson M.E. and Bond W.H., 1963, "Neutron spectrum of a Plutonium-Beryllium source," Nucl. Phys. 43, 330.
- (An72) Anderson M.E. and Neff R.A., 1972, "Neutron energy spectra of different size 239 Pu-Be (α ,n) sources," Nucl. Instr. and Meth. 99, 231.
- (Aw71) Awschalom M., Borak T., and Howe H., 1971, A Study of Spherical,

 Pseudospherical, and Cylindrical Moderators for a Neutron Dose

 Equivalent Rate Meter, Fermi Nat. Acc. Lab. TM-291.
- (Aw73) Awschalom M. and Coulson L., 1973, "A new technique in environmental neutron spectroscopy," in: Proc. of IRPA, pp. 1464-1469, U.S. AEC Conf-730907-P2 (Oak Ridge, TN: U.S. Dept. of Energy, Technical Information Center).
- (Br84) Brackenbush L.W. and Scherpelz R.I., 1984, "SPUNIT, a computer code to multisphere unfolding," in: Computer Applications in Health Physics (Edited by R.L. Kathren, D.P. Higby, M.A. McKinney), pp. 4.1-4.6 (Richland, WA.).
- (Co85) Cossairt J.D., Couch J.G., Elwyn A.J. and Freeman W.S., 1985,

 "Radiation measurements in a labyrinth penetration at a high-energy
 proton accelerator," Health Phys. 49, 907.

- (Ei65) Eisenhauer C.M., 1965, "An image source technique for calculating reflection of gamma rays or neutrons," Health Phys. 11, 1145.
- (Ei82) Eisenhauer C.M., Schwartz R.B., and Johnson T., 1982, "Measurement of neutrons reflected from the surfaces of a calibration room," Health

 Phys. 42, 489.
- (Ei85) Eisenhauer C.M., Hunt J.B. and Schwartz R.B., 1985, "Calibration techniques for neutron personal dosimetry," Rad. Prot. Dos. 10, 43.
- (Ho80) Hofert M. and Raffnsoe Ch., 1980, "Measurement of absolute absorbed dose and dose-equivalent response for instruments used around high-energy proton accelerators," Nucl. Instr. and Meth 176, 443.
- (Hu84) Hunt J.B., 1984, "The calibration of neutron sensitive spherical devices," Rad. Prot. Dos. 8, 239.
- (Lo84) Lowry K.A. and Johnson T.L., 1984, "Modifications to Interactive

 Recursion Unfolding Algorithms and Computer Codes to Find More

 Appropriate Neutron Spectra," Naval Research Lab., Washington, D.C.

 20375, NRL Memo Report 5340.
- (McC81) McCall R.C., 1981, Private communication as quoted in Ei85.

- (Na67) Nachtigall D., 1967, "Average and effective energies, fluence-dose conversion factors and quality factors of the neutron spectra of some (α,n) sources," Health Phys. 13, 213.
- (Na72) Nachtigall D. and Burger G., 1972, "Dose equivalent determination in neutron fields by means of moderator techniques," in: Topics In

 Radiation Dosimetry, Supplement 1 (edited by F.H. Attix), pp. 385-459

 (New York, N.Y.: Academic Press, Inc.).
- (Pa73) Patterson H.W. and Thomas R.H., 1973, Accelerator Health Physics (New York, N.Y.: Academic Press, Inc.).
- (Sa73) Sanna R.S., 1973, Thirty One Group Response Matrices for the

 Multisphere Neutron Spectrometer Over the Energy Range Thermal to 400

 MeV, U.S. Atomic Energy Commission, Report HASL-267.
- (Th85) Thorngate J.H. and Griffith R.V., 1985, "Neutron spectrometers for radiation monitoring at Lawrence Livermore National Laboratory," Rad.

 Prot. Dos. 10, 125.

TABLE 1

Measured sphere responses, sphere responses corrected for room scattered neutrons, and responses due to room scattered neutrons. The corrected responses correspond to direct Pu-Be source neutrons.

DETECTOR	TOTAL RESPONSE (C _T)	RESPONSE CORRECTED FOR ROOM SCAT. (Pu-Be SOURCE)	ROOM SCAT. RESPONSE
	(neut-sec ⁻¹)	(neut-sec ⁻¹)	(neut-sec ⁻¹)
Bare	8.99 ± .14	1.35 ± .70	7.64 ± .84
5.08 cm	12.37 ± .17	4.95 ± 1.43	7.42 ± .67
7.62 cm	24.11 ± .27	12.18 ± .79	11.93 ± .78
12.7 cm	54.75 ± .55	37.50 ± 1.95	17.25 ± 2.07
20.32 cm	63.08 ± .63	56.52 ± 2.66	6.56 ± 1.15
25.4 cm	54.19 ± .54	50.94 ± 2.6	3.25 ± .91
30.5 cm	42.11 ± .42	39.96 ± 2.04	2.15 ± .82
45.72 cm	15.42 ± .27	14.8 ± 1.48	0.62 ± .07

Room scattered neutrons. Results of fits to Eq. 1 in Text.

TABLE 2

		Present Results (Pu-Be Source)	(Pu-Be Source)		From 1	Ref. E185	From Ref. E185 (252-Cf Source)	ource)
•					Single Concrete	mcrete	Enclosed Concrete	Concrete
	S	Site 68 Calibration Room	on Room		Surface		Room	
DETECTOR	c _o	s = C ₁	000	$\frac{c_1}{c}$	ဂ _ါ ့င	ဂြိုင	<u>-</u>	င္း
Bare	1.26 ± .65	5.8 ± 3.0	$0.15 \pm .08$	0.85 ± .09		· Marie		
7.6 cm	10.96 ± .56	0.98 ± .07	0.51 ± .03	0.50 ± .03	0.24 ^{a)}	0.76 ^{a)}	0.21 ^{b)}	0.79 ^{b)}
20.3 cm	52.71 ± 1.65	0.116 ± .02	$0.90 \pm .04$	0.10 ± .02	0.89 ^{c)}	0.11 ^{c)}	0.60 ^{c)}	0.40 ^{c)}
30.5 сш	39.42 ± 1.31	0.054±.02	0.95 ± .05	0.05 ± .02		.		

<sup>a) 3" (7.6 cm) sphere
b) 3" (7.6 cm) Cadmium covered sphere
c) 9" (22.9 cm) spherical remmeter</sup>

m laboration (6) below

TABLE 3

Characteristics of various data sets. The data set in column (4) below represents the properties of the direct Pu-Be source neutrons.

(1)	(2)	(3)		4) ECTED	(5) ROOM	(6) PuBe
QUANTITY	UNITS	TOTAL	FOR	ROOM SCAT	SCAT	PROPERTIES
			ALL SPHERES	NO 45.7 cm SPHERE		
Flux	n-cm ⁻² -sec ⁻¹	89.20	63.32	64.63	24.98	132 +
Ē	MeV	3.38	3.54	3.97	0.76	4.0 *
Dose	mrad/hr	1,17	1.03	1.08	0.091	2.2 **
Dose-Equiv- alent (DE)	mrem/hr	9.32	8.48	8.64	0.52	16.7 **
QF		8.00	8.24	8.02	5,68	7.48 *
Flux-to-DE Conversion	$\frac{n-cm^{-2}-sec^{-1}}{mrem/hr}$	9.57	7.47	7.48	48.0	7.89 *

^{*}For source 238Be-7.2-1 at 1 meter. Source strength was decay-corrected to 5/1/86 from its value of 1.89 x 10^7 neut-sec⁻¹ on 11/1/69. See text.

^{*}These are average values for 239 Pu only, based on calculations. The values for QF and Flux-to-DE conversion factors are very closely equal to those calculated for Am-Be. From Na67.

^{**}See Aw 71.

Figure Captions

- Normalized detector response as a function of spherical moderator diameter.
 The smooth curves are calculated results for spectra unfolded by BUNKI.
- 2. Detector response C_T multiplied by r^2 as a function of r^2 , where r is the source to detector distance, for various detectors as indicated. The straight lines represent least-squares fits, as discussed in the text.
- 3. Fraction of the measured sphere response that arises directly from the Pu-Be source neutrons as a function of sphere diameter.
- 4. Unfolded spectra based on (a) total measured sphere responses, (b) direct Pu-Be source neutrons, and (c) room scattered neutrons. The spectra were unfolded using BUNKI.
- 5. Unfolded spectra based on total measured sphere responses (top) and direct Pu-Be source neutrons (bottom). These are the same spectra shown with a linear ordinate scale in Figs. 4a and 4b. D on ordinate should be interpreted as Δ . See Figs. 4a and 4b.









