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APPLICATIONS OF BONNER SPHERE DETECTORS IN NEUTRON FIELD DOSIMETRY

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I INTRODUCTION

Since the second world war, a number of neutron flux detectors have been developed to achieve neutron detection efficiencies that were approximately directionally isotropic and either that were independent of energy (flux detectors),[1-3] had energy dependence proportional to the recriprocal of the flux to dose equivalent (DE) conversion factors (rem meters)[4-6] or had energy dependence that maximized at some neutron energy (spectrometers).[4,7-9] One of the most famous of all such detectors is the Bonner sphere spectrometer (BSS).[4] In its original form it consisted of a 4 mm x 4 mm high ^{6}LiI(Eu) crystal which could be positioned at the center of five polyethylene spherical moderators 2 to 12 inches in diameter.

A large bibliography exists on the BSS attesting to the usefulness of this technique. The authors are citing only a part of these references considered representative of the literature.

II THEORY.

As they traverse matter, epithermal and fast neutrons undergo elastic and/or inelastic scattering losing energy until they reach thermal equilibrium or leave the moderator. This process is known as neutron slowing down or moderation. Moderators should have high scattering to absorbtion cross section ratios so that the largest number of incident neutrons will be thermalized before being absorbed. Good moderating materials are composed primarily of hydrogen, deuterium, beryllium, carbon and oxygen.

The energy dependence of a neutron detector is the result of convoluting the moderated neutron spectrum at the center of the sphere with the energy dependent detection efficiency of the neutron detector. The moderator shapes may be spherical,[4] pseudospherical,[10] cylindrical,[1,3,5,10-12] or cubical.[13,14] A number of such detection efficiencies have been calculated and/or measured (Tables 2 through 8, and Ref 15). Attempts have been made to enhance the low energy resolution by wrapping some of the moderators in cadmium[16,17] and/or boron.[18] Another response modification for better matching the reciprocal of the flux-to-DE energy curve was made by inserting a Cd-shell at an intermediate radius.[6]

If a neutron detector is placed at the center of a number 'r' of spherical moderators of various diameters each detector-moderator combination will have a different response to neutrons as a function of energy. The response of the BSS, as a function of energy, for one such set of moderator spheres, with a 4mm x 4mm ^{6}LiI(Eu) scintillator, is shown in Figure 1.[8]

The response of each detector of an array of 'r' elements to a neutron spectrum, N(E), may be written as a homogeneous Fredholm equation,

$$B_j = \int_0^\infty N(E) R_j(E)\, dE \qquad (j=1,r) \qquad (1)$$

where,

B_j is the response for the j-th detector in the array,

N(E) is the energy spectrum of the neutron field, and

$R_j(E)$ is the absolute response for j-th detector as a function of neutron energy.

When the detector responses are known for 'n' discrete energy groups, equation (1) may be rewritten:

$$B_j = \sum_{g=1}^{n} N_g \; R_{j,g} \; \Delta E_g \qquad (j=1,r) \qquad (2)$$

where,

N_g is the differential neutron energy flux for the g-th energy group,

$R_{j,g}$ is the response of j-th detector to neutrons of group 'g', and ΔE_g is the energy width of the group.

The response distributions were calculated for a 4mm x 4mm ^6Li detector (instead of $^6LiI(Eu)$) bare and at the center of polyethylene spheres 2, 3, 5, 8, 10, and 12 inch diameter, exposed to several neutron spectra using 31 group responses[8] (Fig. 1), for three realistic and three "monochromatic" spectra. The realistic spectra were: the leakage spectra of the Oak Ridge unreflected Health Physics Research Reactor (HPRR),[19] the atmospheric cosmic-ray neutron spectrum,[20] and the neutron spectrum of a bare ^{252}Cf fission source;[21] while the "monochromatic" spectra were energy groups 31, 20, and 7. Figure 2 shows the three realistic spectra while Figures 3 and 4 display the response distributions.

III MODERATORS

Spherical polyethylene moderators are the nearly universal choice of those using the BSS method of neutron detection.[16,22-25] The spherical symmetry, with the detector at the center of the sphere often results in an isotropic response.

Density of commercial polyethylene ranges between 0.91 and 0.96 g cm^{-3}.[26] In fact, one user[27] found that the densities of a set of seven spheres were all different and varied from 0.912 to 0.961 g cm^{-3}. Hence, density and proper response must be matched. The response ratio for 10 inch diameter polyethylene spheres having densities 0.90 and 0.95 g cm^{-3} is shown by curve 1,[8] Fig. 5. Such changes in polyethylene density may have serious effects on interpretation of measurements. Most commonly, the polyethylene used is the so called "linear" high density polyethylene (ρ = 0.96 g cm^{-3}).

Another source of errors is the use of polyethylene responses for a different moderating material. Curve II of Figure 5 shows the response ratio for a 0.5 inch x 0.5 inch scintillator at the center of 10 inch spheres of polyethylene (0.95 g cm^{-3}) (Table 6) and water (Table 7). Here, the effect on the results is even greater than for a mismatch in moderator densities for the same material.

There is no best BSS. In practice, there are compromises. In some situations, the classical BSS[4] may be augmented with additional spheres[28] and even with activation detectors[29] in an attempt to increase the energy resolution of the deconvoluted neutron energy spectrum. When an acceptable solution to the set of Fredholm equations is found, integral parameters such as fluence, absorbed dose and DE may be obtained with the largest practical precision. Attempting a large area survey with such an extensive multidetector system may be a task of mammoth proportions. Therefore, for expediency and portability the system has often been reduced to a few, one to five, detectors.[30-33] As the number of elements in a BSS decreases, the accuracy of the determination of the integral parameters may decrease. However, in many circumstances the DE determinations using a reduced set, even a single detector, may still be satisfactory for health physics purposes.[4-6]

IV INSTRUMENTATION AND MEASUREMENTS

The choice of the neutron detector is a compromise. The choice may be due to the user's experience, availability of suitable equipment, gamma ray discrimination, portability, absolute detection efficiency, information desired in real time or integrated over a period, DE rate and/or duty cycle of the neutron field.

Neutron detectors may be divided in two groups, active and passive. In either case, the gamma sensitivity of the neutron detector must be investigated and, in general, compensated by suitable means.

ACTIVE DETECTORS.

Active detectors may be either scintillators plus photomultipliers or gas filled counters operated in the proportional or Geiger-Muller mode. Their main advantage is real time data acquisition and, at times, good gamma ray discrimination. They may be used to monitor fields and set-off alarms. Data may be collected and displayed automatically.

Scintillators.

The most common scintillator used in BSS, is the ^{6}LiI(Eu).[4] In this detector the neutron-photon discrimination is achieved through the exoergic ^{6}LiI$(n,\alpha)^{3}$H, Q=4.8 MeV, reaction which causes a large light output due to the neutron capture. The dimensions of the crystal itself are chosen to limit the light output from electrons or external charged particles crossing it.[4] The consequence of using a suitably small crystal (4 mm x 4 mm) is that the absolute neutron detection efficiency is typically 0.1 percent.[4]

There are occasions when satisfactory discrimination against background charged particles cannot be achieved even with small crystals as in the evaluation of the weak neutron fields from cosmic rays. Various methods have been tried to overcome this problem. One uses large (0.50 inch x 0.50 inch) ^{6}LiI(Eu) and ^{7}LiI(Eu) crystals and the net neutron contribution is the difference of the two signals.[34] A second method is to use a single ^{6}LiI(Eu) crystal and collect the data on a multichannel analyser. Values for the background may be interpolated and subtracted from the (n,α) peak.[35,36] These two methods use small differences of two large signals. This causes large uncertainties in the net response. A third approach uses a phoswich[37,38] to reject external particles. The phoswich consists of a small ^{6}LiI(Eu) crystal inside a "cup" made of plastic scintillator

(Figure 6). Since the decay time constants of the two scintillators are about three orders of magnitude apart, a simple pulse shape discriminator permits excellent rejection of external particles.[38] Figures 7 and 8 show environmental data collected for 48.3 hours using a 4 mm x 4 mm crystal and for 70.8 hours using an 8 mm x 8 mm crystal, in both cases the moderator was a ten inch pseudosphere.[38] It may be seen that the phoswich dramatically reduces the background noise allowing the use of an 8mm x 8mm crystal which increased the sensitivity of the BSS by approximately a factor of four.

Just as with the moderator, care must be taken to use the appropriate response for the detector chosen. Curve III, of Figure 5, shows the ratio of the response of a 4 x 4 mm to that of a 12.7 mm x 12.7 mm ^{6}Li detector at the center of a 2 inch polyethylene sphere.[8]

LiI is an extremely hygroscopic substance and even well sealed crystals tend to degrade in time. Degradation is evidenced by a change in crystal color and energy resolution of the (n,α) peak. To avoid these problems ^{6}Li loaded glass could be used. However, no reference to their use in BSS has been found by the authors. UV lucite is recommended for light pipes between crystal and photomultipliers because it is much clearer and absorbs much less of the visible part of the spectrum than ordinary lucite. The light pipe should make a snug fit into the moderator to minimize neutron leakage from the environment to the detector.[39] This last recommendation also applies to the installation of any neutron detector holder in a sphere. Use of small diameter photomultipliers is also recommended to minimize interference with the polar angle neutron detection efficiency. The ambient environment in which measurements are made may dictate taking special precautions to protect the electronics. For example, in making measurements inside the containment of a PWR reactor, it was necessary to cool and dessicate the electronics.[35]

Gas Filled Detectors.

Proportional counters. Detectors filled with suitable gases and operated in the proportional mode may provide discrimination against photons. Two suitable gases are ^{3}He and $^{10}BF_3$. ^{3}He has been tried satisfactorily in a 3 cm diameter, spherical proportional counter at the center of a 20.8 cm sphere.[40] However, the $^{3}He(n,p)^{3}H$ has a Q of only 765 keV. Therefore, it does not furnish a strong neutron signal to simplify photon rejection. Elsewhere, a small cylindrical $^{10}BF_3$ counter was tried with some success in spheres 9 and 10 inches in diameter.[41] $^{10}BF_3$ counters have good photon discrimination via the $^{10}B(n,\alpha)^{7}Li$, Q = 2.8 MeV reaction, even though most of the transitions occur to the 0.48 MeV excited state of ^{7}Li decreasing somewhat the photon rejection. The signals from these gas filled counters are generally processed via charge integrating preamplifiers. However, fast current type instrumentation may be used such as the very fast signal processing 50 ohm systems. This yields not only better discrimination against background by reducing pulse pile-up, but also allows higher neutron counting rates and operations in smaller duty cycle neutron fields.

Due to the mechanisms for energy loss, incoming monochromatic neutrons collide different numbers of times with the nuclei of the moderator while slowing down, causing a spread in path lengths and slow down times. The neutron fluxes encountered in field applications have continuous energy spectra. Thus, the spread out in time for the arrival of slow neutrons at the detector location in a BSS, even from short neutron pulses should be of the order of a hundred or more microseconds for the larger spheres (six inches or more in diameter).[42] Thus, BSS with electronic counters may work well, using appropriate correction factors, in small duty cycle fields having fairly high dose equivalent rates.

Geiger-Muller Counters. These detectors have been used successfully in very short duty cycle neutron fields. A thin walled G-M tube wrapped in silver foil allows for the activation of the silver in a short time and then counting their activities during a relatively long time, $^{109}Ag(n,\gamma)$ $^{110}Ag(t_{1/2}=24.4$ sec) and $^{107}Ag(n,\gamma)$ $^{108}Ag(t_{1/2}=2.4$ min).[10,43-45] In cases where the duty cycle of the accompanying photon radiation is large, a dual system of identical G-M's tubes may be used, one wrapped in silver and the other in tin.[10,45] The output of the tin wrapped G-M is substracted from the silver wrapped one and the difference is the neutron component. The use of a low power microcomputer makes this differential system easy to calibrate and operate.[45]

PASSIVE DETECTORS.

Neutron interactions in the detectors may be recorded by the radioactivation or radioluminescence they produce. Passive detectors have some advantages over counters such as portability, lower unit cost and independence from neutron field duty cycle.

Radioactivation. Nuclear reactions in a number of elements may be used to record the thermal neutron flux. The actual choice of foil will depend on the length of time the neutron field is to be monitored and its intensity. In the past, such elements as indium,[46] gold (Table 8),[44] tantalum,[47] and cobalt[2] have been used successfully in moderated neutron flux integrators.

Thermoluminescent Dosimeters. These TLD dosimeters have been used as neutron detectors, usually ^{6}LiF and ^{7}LiF pairs, both in powder form[48] and extruded chips.[29,36,49] The photon response of these dosimeters is essentially the same, but the (n,α) reaction in ^{6}Li is orders of magnitude larger than in ^{7}Li. Hence, the difference between the responses of the ^{6}LiF and the ^{7}LiF is a measure of the neutron signals. Great care must be taken transporting the TLD detectors to protect them from unwanted exposure to neutrons.[36] Transport is that period between annealing and start of measurement plus that from the end of the measurement to readout. A successful manner to handle TLD pairs is to load them in typically polyethylene[50] inserts that go into the BSS moderators and put the inserts in Cd-cylinders. Then, upon reaching the measurement site the inserts are rapidly removed from the Cd-cylinders and inserted in the moderators. Upon completion of the measurement, the procedure is reversed.

V. SPECTRAL DECONVOLUTION

Spectral deconvolution is, simply, the solution of Eq. 1 for N(E). A very good review paper on the subject was presented at the 2nd ASTM-EURATOM Symposium on Reactor Dosimetry in 1977.[51] Deconvolution methods were grouped into four categories: derivative, parametric, quadrature, and Monte Carlo.

The primary application of the derivative method is with recoil particle detectors, and not for BSS.

The parametric procedure may be used if a functional representation of the spectrum exists, e.g., evaporation or fission spectra. The BSS responses are used to determine the parameters for the appropriate functional representation.[52,53]

The quadrature method involves the solution of Eq. 2 by linear estimation, least squares, iterative or mathematical programming techniques, or a combination thereof. The three most common deconvolution codes (BON,[54-56] LOUHI,[57,58] and SAND[59]) used with the BSS are found in this category. BON,[29,36,60-62] LOUHI[16,63-65] and SAND[66,67] have been used to deconvolute spectra ranging from PWR containment to accelerator shield leakage spectra from BSS measurements.

The Monte Carlo category uses Monte Carlo techniques to randomly chose a neutron spectrum. This spectrum is then convoluted with the BSS response functions to yield a response distribution. The process is repeated a great number of times and the response distributions, thus obtained, are compared with the measured one. The spectrum yielding the best agreement is said to be an adequate solution of Eq. 2 for N_g. The only known code using this technique is SWIFT.[68,69] SWIFT saves the four spectra whose response distributions best agree with the measured response distribution and averages them to yield the N_g.

A word of warning: since the systems dealt with here are usually underdetermined, a solution to Fredholm's equation is not unique. However, this has not been a serious problem in practice.

VI. CALIBRATION

In the field, the absolute neutron detection efficiencies of BSS elements are most often checked using ^{241}AmBe, ^{241}AmB, and ^{252}Cf sources.[42,70-73] In so doing, the effect of walls, floor, and ceiling scattering[74,75] as well as sphere to sphere scattering must be taken into account.

To check the energy response of BSS elements, one may want to use nearly monochromatic beams[73,76,77] if an accelerator is available, or a number of continuous energy spectra (α,n) and/or (γ,n) sources,[42,73,78] otherwise. The use of radioactive sources for detector calibration implies that the user has (1) a calibration for the total neutron emission into 4π; (2) knowledge of the source output as a function of polar and azimuthal angles, particularly in the case of the more massive sources, and (3) knowledge of the neutron energy spectrum for the source. Item (2) is very important if one uses a long half-life alpha emitter such as ^{239}Pu ($t_{1/2}$ = 24,000 years) since the outputs at 0^{o} and 90^{o} (polar angles) may be significantly different. For this reason, shorter lived alpha sources such as ^{241}Am ($t_{1/2}$ = 455 years) and ^{238}Pu ($t_{1/2}$ = 86.4 years) have become quite common. Mixtures or combinations of either ^{238}Pu or ^{241}Am with Be, B, F and Li are readily available commercially.[79] Prices ranges (August, 1983) for 5 Ci, sources are US$3000 (^{238}PuBe) to US$4800 (^{238}PuLi) and US$3600 (^{241}AmBe) to US$6500 (^{241}AmLi).[79]

The evaluation of the BSS output in terms of neutron flux, absorbed dose or dose equivalent per unit of response requires the evaluation of the constants C_j in equation 3, using a neutron source with known strength and energy spectrum.

$$B_j = \sum_{g=1}^{n} S\, C_j\, N'_{s,g}\, R'_{j,g}\, \Delta E_g \qquad (3)$$

where,

$N'_{s,g}$ is the normalized differential energy flux of source neutrons for the g-th energy group.

S is the source strength,

$R'_{j,g}$ is the average relative energy response of the j-th detector in the g-th energy interval, and other terms have the same definitions as in equations 2 & 3.

The C_j's are, then, given by

$$C_j = B_j / \, S \sum_{g=1}^{n} N'_{s,g}\, R'_{j,g}\, \Delta E_g \qquad (4)$$

Once the C_j's are known, the deconvolution techniques described in Section V may be used.

If dosimetry is to be done with a single detector 'j' and information exists on the energy spectrum of the field neutrons, the procedure that follows is preferrable to the use of average properties of neutron sources to calculate the detector response in terms of flux, absorbed dose or DE.

The flux, F, can be obtained from

$$F = B_j / \; C_j \sum_{g=1}^{n} N'_{f,g} \; R'_{j,g} \; \Delta E_g \tag{5}$$

and the specific dose equivalent, $\overline{DE}$, from

$$\overline{DE} = \sum_{g=1}^{n} DE_g \; N'_{f,g} \; \Delta E_g \qquad \sum_{g=1}^{n} N'_{f,g} \; \Delta E_g , \tag{6}$$

where,

$N'_{f,g}$ is the normalized field neutron energy spectrum ($F \; N'f,g$ is the neutron field energy spectrum).

and

DE_g = average flux-to-dose equivalent conversion factor for the g-th energy interval.

Finally, the dose equivalent is obtained from,

$DE = F \; \overline{DE}$

VII. SUMMARY

The major advantage of the BSS is that it covers an energy range from thermal to hundreds of MEV. No other spectrometer covers this entire energy range.

Among its disadvantages are its inherently low energy resolution and its weight (up to 47 kg). Another disadvantage is that if one uses a single detector alternating the moderators, one has to be concerned with time variations of the neutron field. On the other hand, if one uses multiple detectors, one for each moderator, and makes a simultaneous exposure of the entire system, the concern is about spatial variations of the neutron field and interactions between detectors.

Problems that should be studied in the future include:
(1) benchmarking for testing of spectral deconvolution codes;
(2) determination of what is an adequate BSS, i.e., how many and what size moderators should be used;
(3) development of deconvolution codes for use with microcomputers so that real time data reduction becomes a reality, and
(4) a study of moderator to moderator interactions.

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DETECTOR[1] (Dimens. in mm)	MODERATORS[2]	ENERGY RANGE[3]	METHOD	REF.	COMMENTS
4x4	2,3,5,8 & 12	Therm.-15	Exper.	4	Original BSS
4x4	Bare, Cd.,cvd. 2,3,5,8, & 12	Therm.-160	Extrap. Grp. av.	80	Used data of Ref. 4
4x4	2,3,5,8,10,18,16&18	Therm.-192	Theo.	7	DTK
4x4	2,3,5,8,10,12, 16 & 18	Therm.-192	Grp. av.	55	Used data of Ref.7
51 (diam.)BF_3	2,3,4,5,6,8,10&12	Therm.-14	Theo.	81	ANISN
51 (diam.)BF_3	Bare, 3 & 6	Therm.-15	Theo.	82	MORSE
4x4, 8x8, 12.7x12.7 & gold foil	Bare,2,3,5,8,10, 12 & 18	Therm.-100	Theo.	8	DTF-IV
12.7 x 12.7	Bare,2,3,5,8,10, 12 & 18, H_2O	Therm.-100	Theo.	8	DTF-IV
12.7 x 12.7	2,3,5,8,10,12&18	0.1-18 MeV	Exper.	27	Verification of Ref. 8 data
4x4	2,3,5,8,10&12	Therm.-15	Theo.	39	Monte Carlo
51 (diam.)BF_3	3,5,8,10 & 12	Therm.-15	Theo.	39	Monte Carlo
203 (long)BF_3	Bare,1.18 & 2.36 thick cyl.	Therm.-15	Theo.	83	ANISN-JR
4x4	Bare & 2 to 20 1/2 inch increm'ts.	Therm.-17	Theo.	28	ANISN

Grp.	ENERGY, MeV
1	2.312E+02 TO 4.000E+02
2	1.336E+02 TO 2.312E+02
3	7.725E+01 TO 1.336E+02
4	4.465E+01 TO 7.725E+01
5	2.581E+01 TO 4.465E+01
6	1.492E+01 TO 2.581E+01
7	7.408E+00 TO 1.492E+01
8	3.679E+00 TO 7.408E+00
9	1.827E+00 TO 3.679E+00
10	9.072E-01 TO 1.827E+00
11	4.508E-01 TO 9.072E-01
12	2.237E-01 TO 4.508E-01
13	1.111E-01 TO 2.237E-01
14	5.248E-02 TO 1.111E-01
15	2.479E-02 TO 5.248E-02
16	1.171E-02 TO 2.479E-02
17	5.531E-03 TO 1.171E-02
18	2.613E-03 TO 5.531E-03
19	1.234E-03 TO 2.613E-03
20	5.930E-04 TO 1.234E-03
21	2.754E-04 TO 5.930E-04
22	1.301E-04 TO 2.754E-04
23	6.144E-05 TO 1.301E-04
24	2.902E-05 TO 6.144E-05
25	1.371E-05 TO 2.902E-05
26	6.476E-06 TO 1.371E-05
27	3.059E-06 TO 6.476E-06
28	1.445E-06 TO 3.059E-06
29	6.826E-07 TO 1.445E-06
30	4.140E-07 TO 6.826E-07
31	THERMAL

Table 2

Energy structure for 31 group response functions.[8]

Table 3

Multisphere spectrometer response matrix for polyethylene

moderators (ρ=0.95 g cm^{-3}), 4 mm x 4 mm ^{6}Li detector.[8]

GRP.	BARE	2''	3''	5''	8''	10''	12''	18''
1	4.6976E-06	1.2274E-04	1.0990E-03	8.1887E-03	2.5791E-02	3.6530E-02	4.5101E-02	6.0432E-02
2	7.9545E-06	1.4230E-04	1.2418E-03	9.0718E-03	2.7837E-02	3.8754E-02	4.7023E-02	5.9752E-02
3	1.2187E-05	1.7340E-04	1.4579E-03	1.0216E-02	2.9912E-02	4.0501E-02	4.7852E-02	5.6262E-02
4	1.8732E-05	2.2399E-04	1.8495E-03	1.2700E-02	3.5823E-02	4.7160E-02	5.4066E-02	5.7515E-02
5	3.0015E-05	3.3619E-04	2.7406E-03	1.8369E-02	4.9672E-02	6.3345E-02	7.0151E-02	6.6262E-02
6	4.5946E-05	5.6625E-04	4.6141E-03	3.0087E-02	7.7386E-02	9.5157E-02	1.0138E-01	8.4305E-02
7	5.0065E-05	1.1240E-03	9.5620E-03	6.2602E-02	1.5676E-01	1.8753E-01	1.9337E-01	1.4300E-01
8	1.0212E-04	2.8111E-03	2.1791E-02	1.2033E-01	2.4234E-01	2.5271E-01	2.2732E-01	1.1088E-01
9	1.7899E-04	6.3270E-03	4.3506E-02	1.9417E-01	2.9716E-01	2.5929E-01	1.9443E-01	5.3320E-02
10	2.7026E-04	1.3117E-02	7.8327E-02	2.7672E-01	3.1410E-01	2.2464E-01	1.3709E-01	1.9273E-02
11	4.4492E-04	2.2515E-02	1.1167E-01	2.9930E-01	2.3996E-01	1.3148E-01	6.5539E-02	4.2358E-03
12	1.8542E-03	3.5256E-02	1.4577E-01	3.0607E-01	1.8344E-01	8.7274E-02	3.5767E-02	1.4869E-03
13	1.1751E-03	4.8106E-02	1.7119E-01	2.9329E-01	1.4143E-01	6.0500E-02	2.2973E-02	8.1618E-04
14	8.6945E-04	6.0893E-02	1.8931E-01	2.7627E-01	1.1537E-01	4.6842E-02	1.7308E-02	5.8120E-04
15	1.1018E-03	7.3447E-02	2.0392E-01	2.6292E-01	9.9956E-02	3.9555E-02	1.4468E-02	4.7145E-04
16	1.4500E-03	8.5947E-02	2.1740E-01	2.5440E-01	9.0743E-02	3.5413E-02	1.2893E-02	4.1165E-04
17	1.9348E-03	9.9158E-02	2.3095E-01	2.4873E-01	8.4475E-02	3.2668E-02	1.1862E-02	3.7243E-04
18	2.5755E-03	1.1357E-01	2.4477E-01	2.4427E-01	7.9611E-02	3.0582E-02	1.1083E-02	3.4271E-04
19	3.6579E-03	1.2949E-01	2.5862E-01	2.3989E-01	7.5388E-02	2.8809E-02	1.0425E-02	3.1762E-04
20	5.2735E-03	1.4707E-01	2.7216E-01	2.3497E-01	7.1450E-02	2.7190E-02	9.8278E-03	2.9500E-04
21	7.6454E-03	1.6634E-01	2.8493E-01	2.2916E-01	6.7632E-02	2.5652E-02	9.2632E-03	2.7387E-04
22	1.0811E-02	1.8717E-01	2.9629E-01	2.2211E-01	6.3817E-02	2.4144E-02	8.7115E-03	2.5357E-04
23	1.5240E-02	2.0928E-01	3.0564E-01	2.1382E-01	6.0000E-02	2.2657E-02	8.1696E-03	2.3401E-04
24	2.1592E-02	2.3206E-01	3.1219E-01	2.0421E-01	5.6152E-02	2.1176E-02	7.6313E-03	2.1502E-04
25	3.0286E-02	2.5451E-01	3.1486E-01	1.9308E-01	5.2201E-02	1.9669E-02	7.0849E-03	1.9626E-04
26	4.1793E-02	2.7498E-01	3.1239E-01	1.8023E-01	4.8075E-02	1.8107E-02	6.5193E-03	1.7746E-04
27	5.6322E-02	2.9081E-01	3.0303E-01	1.6529E-01	4.3653E-02	1.6441E-02	5.9170E-03	1.5819E-04
28	7.4135E-02	2.9784E-01	2.8439E-01	1.4762E-01	3.8738E-02	1.4594E-02	5.2508E-03	1.3778E-04
29	9.4778E-02	2.8930E-01	2.5294E-01	1.2606E-01	3.2995E-02	1.2442E-02	4.4758E-03	1.1514E-04
30	1.1327E-01	2.6279E-01	2.1168E-01	1.0261E-01	2.6903E-02	1.0161E-02	3.6564E-03	9.2207E-05
31	1.6854E-01	1.2852E-01	9.7515E-02	4.7543E-02	1.2653E-02	4.8054E-03	1.7332E-03	4.2525E-05

Table 4

Multisphere spectrometer response matrix for polyethylene moderators (ρ=0.95 g cm^{-3}), 8 mm x 8 mm ^{6}Li detector.[8]

GRP.	BARE	2''	3''	5''	8''	10''	12''	18''
1	3.7765E-05	5.2507E-04	4.0441E-03	2.8583E-02	8.8714E-02	1.2521E-01	1.5420E-01	2.0542E-01
2	6.3898E-05	6.1803E-04	4.5805E-03	3.1676E-02	9.5759E-02	1.3284E-01	1.6078E-01	2.0311E-01
3	9.7882E-05	7.6236E-04	5.3868E-03	3.5679E-02	1.0290E-01	1.3883E-01	1.6360E-01	1.9124E-01
4	1.5034E-04	9.9289E-04	6.8447E-03	4.4364E-02	1.2323E-01	1.6165E-01	1.8484E-01	1.9548E-01
5	2.4014E-04	1.4920E-03	1.0141E-02	6.4161E-02	1.7085E-01	2.1710E-01	2.3979E-01	2.2516E-01
6	3.6683E-04	2.4879E-03	1.7041E-02	1.0505E-01	2.6613E-01	3.2605E-01	3.4647E-01	2.8640E-01
7	4.0010E-04	4.8064E-03	3.5168E-02	2.1846E-01	5.3903E-01	6.4242E-01	6.6063E-01	4.8565E-01
8	8.1679E-04	1.1865E-02	7.9972E-02	4.1967E-01	8.3256E-01	8.6483E-01	7.7570E-01	3.7619E-01
9	1.4310E-03	2.6362E-02	1.5930E-01	6.7653E-01	1.0193E+00	8.8557E-01	6.6190E-01	1.8064E-01
10	2.1546E-03	5.4062E-02	2.8617E-01	9.6275E-01	1.0746E+00	7.6472E-01	4.6493E-01	6.5336E-03
11	3.5567E-03	9.2192E-02	4.0714E-01	1.0387E+00	8.1749E-01	4.6113E-01	2.2104E-01	1.4569E-03
12	1.4685E-02	1.4402E-01	5.3013E-01	1.0587E+00	6.2211E-01	2.9421E-01	1.2013E-01	5.3011E-03
13	9.3027E-03	1.9307E-01	6.1980E-01	1.0107E+00	4.7788E-01	2.0335E-01	7.7027E-02	3.0143E-03
14	6.9113E-03	2.4274E-01	6.8326E-01	9.4898E-01	3.8894E-01	1.5722E-01	5.8017E-02	2.1983E-03
15	8.7511E-03	2.9165E-01	7.3388E-01	9.0069E-01	3.3652E-01	1.3268E-01	4.8502E-02	1.8123E-03
16	1.1498E-02	3.4006E-01	7.8024E-01	8.6961E-01	3.0526E-01	1.1875E-01	4.3232E-02	1.6013E-03
17	1.5303E-02	3.9089E-01	8.2658E-01	8.4863E-01	2.8401E-01	1.0952E-01	3.9782E-02	1.4630E-03
18	2.0310E-02	4.4594E-01	8.7350E-01	8.3198E-01	2.6754E-01	1.0251E-01	3.7180E-02	1.3585E-03
19	2.8730E-02	5.0620E-01	9.2008E-01	8.1576E-01	2.5326E-01	9.6553E-02	3.4982E-02	1.2702E-03
20	4.1096E-02	5.7195E-01	9.6496E-01	7.9777E-01	2.3996E-01	9.1119E-02	3.2988E-02	1.1902E-03
21	5.8971E-02	6.4301E-01	1.0065E+00	7.7682E-01	2.2709E-01	8.5959E-02	3.1102E-02	1.1151E-03
22	8.2564E-02	7.1846E-01	1.0424E+00	7.5183E-01	2.1423E-01	8.0897E-02	2.9260E-02	1.0422E-03
23	1.1463E-01	7.9678E-01	1.0706E+00	7.2275E-01	2.0139E-01	7.5909E-02	2.7451E-02	9.7113E-04
24	1.5878E-01	8.7535E-01	1.0885E+00	6.8938E-01	1.8845E-01	7.0944E-02	2.5653E-02	9.0127E-04
25	2.1603E-01	9.4994E-01	1.0926E+00	6.5103E-01	1.7517E-01	6.5893E-02	2.3827E-02	8.3118E-04
26	2.8685E-01	1.0143E+00	1.0786E+00	6.0709E-01	1.6132E-01	6.0657E-02	2.1936E-02	7.5964E-04
27	3.8739E-01	1.0590E+00	1.0411E+00	5.5632E-01	1.4648E-01	5.5072E-02	1.9920E-02	6.8469E-04
28	4.5725E-01	1.0699E+00	9.7249E-01	4.9656E-01	1.2998E-01	4.8884E-02	1.7688E-02	6.0329E-04
29	5.4393E-01	1.0248E+00	8.6126E-01	4.2383E-01	1.1071E-01	4.1671E-02	1.5087E-02	5.1052E-04
30	6.0763E-01	9.1903E-01	7.1837E-01	3.4491E-01	9.0270E-02	3.4030E-02	1.2334E-02	4.1419E-04
31	7.2354E-01	4.4430E-01	3.3029E-01	1.5980E-01	4.2455E-02	1.6092E-02	5.8542E-03	1.9493E-04

Table 5

Multisphere spectrometer response matrix for polyethylene moderators (ρ=0.95 g cm^{-3}), 12.7 mm x 12.7 mm ^{6}Li detector.[8]

GRP.	BARE	2''	3''	5''	8''	10''	12''	18''
1	1.5104E-03	2.6322E-03	9.3415E-03	5.3314E-02	1.5879E-01	2.2232E-01	2.7255E-01	3.5990E-01
2	8.0742E-04	2.0846E-03	9.6389E-03	5.8179E-02	1.7054E-01	2.3501E-01	2.8335E-01	3.5509E-01
3	4.6054E-04	1.9979E-03	1.0811E-02	6.5046E-02	1.8279E-01	2.4516E-01	2.8790E-01	3.3396E-01
4	3.3241E-04	2.2982E-03	1.3459E-02	8.0626E-02	2.1868E-01	2.8522E-01	3.2503E-01	3.4113E-01
5	3.9104E-04	3.3305E-03	1.9862E-02	1.1650E-01	3.0308E-01	3.8293E-01	4.2152E-01	3.9275E-01
6	7.4214E-04	5.7175E-03	3.3449E-02	1.9084E-01	4.7209E-01	5.7504E-01	6.0890E-01	4.9932E-01
7	1.5989E-03	1.1802E-02	6.9598E-02	3.9724E-01	9.5633E-01	1.1329E+00	1.1608E+00	8.4621E-01
8	3.2678E-03	2.8593E-02	1.5759E-01	7.6214E-01	1.4749E+00	1.5224E+00	1.3601E+00	6.5352E-01
9	5.7206E-03	6.2287E-02	3.1238E-01	1.2262E+00	1.8007E+00	1.5534E+00	1.1558E+00	3.1182E-01
10	8.5852E-03	1.2550E-01	5.5859E-01	1.7400E+00	1.8897E+00	1.3339E+00	8.0668E-01	1.1141E-01
11	1.4210E-02	2.1165E-01	7.9128E-01	1.8685E+00	1.4269E+00	7.9741E-01	3.7993E-01	2.4143E-02
12	5.6420E-02	3.2835E-01	1.0251E+00	1.8928E+00	1.0774E+00	5.0486E-01	2.0499E-01	8.4538E-03
13	3.6809E-02	4.2943E-01	1.1886E+00	1.7949E+00	8.2257E-01	3.4731E-01	1.3099E-01	4.6589E-03
14	2.7451E-02	5.3390E-01	1.3024E+00	1.6756E+00	6.6698E-01	2.6797E-01	9.8543E-02	3.3292E-03
15	3.4721E-02	6.3689E-01	1.3912E+00	1.5829E+00	5.7586E-01	2.2594E-01	8.2341E-02	2.7071E-03
16	4.5538E-02	7.3752E-01	1.4713E+00	1.5227E+00	5.2170E-01	2.0214E-01	7.3374E-02	2.3681E-03
17	6.0466E-02	8.4181E-01	1.5506E+00	1.4813E+00	4.8497E-01	1.8639E-01	6.7503E-02	2.1457E-03
18	7.9981E-02	9.5311E-01	1.6299E+00	1.4481E+00	4.5656E-01	1.7444E-01	6.3073E-02	1.9772E-03
19	1.1246E-01	1.0728E+00	1.7071E+00	1.4161E+00	4.3196E-01	1.6429E-01	5.9332E-02	1.8350E-03
20	1.5998E-01	1.2005E+00	1.7794E+00	1.3814E+00	4.0911E-01	1.5503E-01	5.5938E-02	1.7067E-03
21	2.2750E-01	1.3347E+00	1.8439E+00	1.3418E+00	3.8702E-01	1.4625E-01	5.2729E-02	1.5867E-03
22	3.1454E-01	1.4723E+00	1.8962E+00	1.2957E+00	3.6502E-01	1.3763E-01	4.9594E-02	1.4712E-03
23	4.2927E-01	1.6093E+00	1.9331E+00	1.2429E+00	3.4306E-01	1.2915E-01	4.6514E-02	1.3598E-03
24	5.8118E-01	1.7395E+00	1.9502E+00	1.1832E+00	3.2097E-01	1.2070E-01	4.3455E-02	1.2515E-03
25	7.6835E-01	1.8542E+00	1.9421E+00	1.1156E+00	2.9833E-01	1.1211E-01	4.0350E-02	1.1442E-03
26	9.8385E-01	1.9419E+00	1.9025E+00	1.0388E+00	2.7472E-01	1.0321E-01	3.7135E-02	1.0364E-03
27	1.2096E+00	1.9869E+00	1.8229E+00	9.5091E-01	2.4943E-01	9.3708E-02	3.3709E-02	9.2544E-04
28	1.4239E+00	1.9674E+00	1.6915E+00	8.4809E-01	2.2133E-01	8.3184E-02	2.9920E-02	8.0757E-04
29	1.6029E+00	1.8491E+00	1.4899E+00	7.2351E-01	1.8852E-01	7.0913E-02	2.5509E-02	6.7628E-04
30	1.7127E+00	1.6329E+00	1.2379E+00	5.8863E-01	1.5371E-01	5.7914E-02	2.0844E-02	5.4273E-04
31	1.8617E+00	7.8070E-01	5.6810E-01	2.7270E-01	7.2292E-02	2.7389E-02	9.8840E-03	2.5113E-04

Table 6

Multisphere spectrometer response matri for water

moderators (ρ=1.0 g cm^{-3}), 12.7 x 12.7 ^{6}Li detector.[8]

GRP.	BARE	2''	3''	5''	8''	10''	12''	18''
1	1.5104E-03	2.5296E-03	8.7698E-03	6.3491E-02	2.4975E-01	3.9218E-01	5.2049E-01	7.8702E-01
2	8.0742E-04	1.9519E-03	8.8890E-03	6.8267E-02	2.6149E-01	4.0135E-01	5.2029E-01	7.3250E-01
3	4.6054E-04	1.9269E-03	1.0684E-02	8.4035E-02	3.1406E-01	4.7339E-01	6.0275E-01	8.0450E-01
4	3.3241E-04	2.2526E-03	1.3293E-02	1.0049E-01	3.5086E-01	5.0673E-01	6.1869E-01	7.2782E-01
5	3.9104E-04	2.5843E-03	1.5057E-02	1.1126E-01	3.7406E-01	5.2558E-01	6.2322E-01	6.6466E-01
6	7.4214E-04	3.6308E-03	2.0266E-02	1.4789E-01	4.8521E-01	6.6785E-01	7.7389E-01	7.6150E-01
7	1.5989E-03	6.4220E-03	3.4901E-02	2.5497E-01	8.2649E-01	1.1215E+00	1.2771E+00	1.1772E+00
8	3.2678E-03	1.4492E-02	7.6378E-02	4.9293E-01	1.3582E+00	1.6671E+00	1.7194E+00	1.1662E+00
9	5.7206E-03	3.2494E-02	1.6607E-01	9.0431E-01	1.9715E+00	2.0890E+00	1.8603E+00	7.9403E-01
10	8.5852E-03	6.7546E-02	3.1881E-01	1.3841E+00	2.2451E+00	1.9703E+00	1.4471E+00	3.2286E-01
11	1.4210E-02	1.1685E-01	4.7817E-01	1.6280E+00	1.9940E+00	1.4712E+00	9.0866E-01	1.1358E-01
12	5.6420E-02	1.9009E-01	6.5312E-01	1.7680E+00	1.6836E+00	1.0722E+00	5.7828E-01	4.7507E-02
13	3.6809E-02	2.5747E-01	8.3769E-01	1.9214E+00	1.5311E+00	8.8931E-01	4.4576E-01	2.9933E-02
14	2.7451E-02	3.3788E-01	9.8542E-01	1.9308E+00	1.3278E+00	7.2260E-01	3.4677E-01	2.0641E-02
15	3.4721E-02	4.2613E-01	1.1138E+00	1.9024E+00	1.1887E+00	6.2223E-01	2.9224E-01	1.6228E-02
16	4.5538E-02	5.1715E-01	1.2319E+00	1.9180E+00	1.1001E+00	5.6207E-01	2.6095E-01	1.3826E-02
17	6.0466E-02	6.1534E-01	1.3494E+00	1.9237E+00	1.0377E+00	5.2105E-01	2.4009E-01	1.2247E-02
18	7.9981E-02	7.2418E-01	1.4695E+00	1.9315E+00	9.8776E-01	4.8915E-01	2.2416E-01	1.1046E-02
19	1.1246E-01	8.4622E-01	1.5922E+00	1.9358E+00	9.4281E-01	4.6151E-01	2.1059E-01	1.0036E-02
20	1.5998E-01	9.8212E-01	1.7156E+00	1.9323E+00	8.9925E-01	4.3584E-01	1.9820E-01	9.1338E-03
21	2.2750E-01	1.1315E+00	1.8367E+00	1.9183E+00	8.5543E-01	4.1111E-01	1.8646E-01	8.3014E-03
22	3.1454E-01	1.2925E+00	1.9509E+00	1.8907E+00	8.1012E-01	3.8656E-01	1.7496E-01	7.5162E-03
23	4.2927E-01	1.4620E+00	2.0531E+00	1.8483E+00	7.6345E-01	3.6216E-01	1.6367E-01	6.7752E-03
24	5.8118E-01	1.6343E+00	2.1369E+00	1.7899E+00	7.1526E-01	3.3774E-01	1.5248E-01	6.0733E-03
25	7.6835E-01	1.8001E+00	2.1936E+00	1.7129E+00	6.6482E-01	3.1284E-01	1.4114E-01	5.4004E-03
26	9.8385E-01	1.9466E+00	2.2126E+00	1.6151E+00	6.1144E-01	2.8702E-01	1.2946E-01	4.7498E-03
27	1.2096E+00	2.0556E+00	2.1798E+00	1.4926E+00	5.5373E-01	2.5954E-01	1.1706E-01	4.1108E-03
28	1.4239E+00	2.1010E+00	2.0756E+00	1.3393E+00	4.8937E-01	2.2925E-01	1.0343E-01	3.4678E-03
29	1.6029E+00	2.0418E+00	1.8709E+00	1.1443E+00	4.1429E-01	1.9417E-01	8.7670E-02	2.7957E-03
30	1.7127E+00	1.8646E+00	1.5825E+00	9.2772E-01	3.3506E-01	1.5730E-01	7.1124E-02	2.1523E-03
31	1.8617E+00	9.1860E-01	7.2293E-01	4.2098E-01	1.5451E-01	7.3026E-02	3.3172E-02	9.2931E-04

Table 7

Multisphere spectrometer response matrix for polyethylene moderators (ρ=0.95 g cm^{-3}), 12.7 mm diam x 0.051 mm thick, ^{197}Au detector.[8]

GRP.	BARE	2''	3''	5''	8''	10''	12''	18''
1	1.0958E-06	3.5764E-05	2.6695E-04	1.7654E-03	5.3156E-03	7.4577E-03	9.1699E-03	1.2250E-02
2	1.4338E-06	4.0742E-05	3.0074E-04	1.9544E-03	5.7352E-03	7.9092E-03	9.5577E-03	1.2108E-02
3	1.8589E-06	4.8941E-05	3.5196E-04	2.1991E-03	6.1595E-03	8.2618E-03	9.7218E-03	1.1396E-02
4	2.6307E-06	6.0172E-05	4.4350E-04	2.7306E-03	7.3727E-03	9.6154E-03	1.0978E-02	1.1642E-02
5	3.9027E-06	8.9492E-05	6.5595E-04	3.9478E-03	1.0220E-02	1.2911E-02	1.4238E-02	1.3402E-02
6	5.8073E-06	1.5223E-04	1.1056E-03	6.4672E-03	1.5920E-02	1.9387E-02	2.0565E-02	1.7034E-02
7	9.2158E-06	3.2013E-04	2.3067E-03	1.3470E-02	3.2257E-02	3.8200E-02	3.9204E-02	2.8860E-02
8	1.5544E-05	8.0242E-04	5.2567E-03	2.5876E-02	4.9749E-02	5.1308E-02	4.5898E-02	2.2246E-02
9	2.7383E-05	1.8176E-03	1.0502E-02	4.1700E-02	6.0706E-02	5.2276E-02	3.8919E-02	1.0562E-02
0	4.1547E-05	3.7879E-03	1.8916E-02	5.9257E-02	6.3591E-02	4.4743E-02	2.7044E-02	3.7297E-03
1	5.8559E-05	6.5192E-03	2.6965E-02	6.3683E-02	4.7807E-02	2.6576E-02	1.2633E-02	7.8133E-04
2	1.0299E-04	1.0203E-02	3.5155E-02	6.4491E-02	3.5881E-02	1.6704E-02	6.7614E-03	2.5998E-04
3	1.3888E-04	1.4141E-02	4.1231E-02	6.1057E-02	2.7229E-02	1.1430E-02	4.2997E-03	1.3727E-04
-4	1.4831E-04	1.7970E-02	4.5396E-02	5.6813E-02	2.1980E-02	8.7955E-03	3.2276E-03	9.5408E-05
15	2.3205E-04	2.1691E-02	4.8621E-02	5.3481E-02	1.8923E-02	7.4070E-03	2.6937E-03	7.6145E-05
16	4.3266E-04	2.5375E-02	5.1508E-02	5.1273E-02	1.7112E-02	6.6225E-03	2.3984E-03	6.5711E-05
17	7.4569E-04	2.9229E-02	5.4336E-02	4.9719E-02	1.5887E-02	6.1046E-03	2.2051E-03	5.8873E-05
18	1.2867E-03	3.3384E-02	5.7130E-02	4.8448E-02	1.4942E-02	5.7118E-03	2.0592E-03	5.3692E-05
19	2.3173E-03	3.7888E-02	5.9809E-02	4.7219E-02	1.4126E-02	5.3787E-03	1.9359E-03	4.9329E-05
20	5.1383E-03	4.2727E-02	6.2263E-02	4.5900E-02	1.3370E-02	5.0751E-03	1.8240E-03	4.5416E-05
21	6.5401E-03	4.7736E-02	6.4362E-02	4.4425E-02	1.2642E-02	4.7872E-03	1.7183E-03	4.1784E-05
22	6.5372E-03	5.3006E-02	6.5970E-02	4.2738E-02	1.1918E-02	4.5050E-03	1.6150E-03	3.8328E-05
23	4.0437E-03	5.8564E-02	6.6955E-02	4.0846E-02	1.1198E-02	4.2272E-03	1.5136E-03	3.5032E-05
24	1.4549E-02	6.4474E-02	6.7139E-02	3.8746E-02	1.0475E-02	3.9507E-03	1.4130E-03	3.1870E-05
25	3.2680E-04	6.9178E-02	6.6197E-02	3.6407E-02	9.7351E-03	3.6695E-03	1.3109E-03	2.8791E-05
26	6.1889E-03	7.4207E-02	6.4027E-02	3.3804E-02	8.9642E-03	3.3780E-03	1.2053E-03	2.5757E-05
27	2.7340E-01	7.7257E-02	5.9891E-02	3.0868E-02	8.1391E-03	3.0669E-03	1.0930E-03	2.2700E-05
28	1.4460E-02	5.3951E-02	5.2539E-02	2.7492E-02	7.2224E-03	2.7226E-03	9.6926E-04	1.9555E-05
29	1.0625E-02	5.2258E-02	4.6780E-02	2.3482E-02	6.1518E-03	2.3209E-03	8.2538E-04	1.6138E-05
30	1.1569E-02	4.7870E-02	3.9254E-02	1.9118E-02	5.0160E-03	1.8954E-03	6.7355E-04	1.2752E-05
31	2.9284E-02	2.3721E-02	1.8123E-02	8.8588E-03	2.3592E-03	8.9630E-04	3.1872E-04	5.7643E-06

DETECTOR[1] (Dimens. in mm)	MODERATORS[2]	ENERGY RANGE[3]	METHOD	REF
4x4	2,3,5,8 & 12	Therm.-15	Exper.	4
4x4	Bare, Cd.,cvd. 2,3,5,8, & 12	Therm.-160	Extrap. Grp. av.	80
4x4	2,3,5,8,10,18,16&18	Therm.-192	Theo.	7
4x4	2,3,5,8,10,12, 16 & 18	Therm.-192	Grp. av.	55
51 (diam.) BF_3	2,3,4,5,6,8,10&12	Therm.-14	Theo.	81
51 (diam.) BF_3	Bare, 3 & 6	Therm.-15	Theo.	82
4x4, 8x8, 12.7x12.7 & gold foil	Bare,2,3,5,8,10, 12 & 18	Therm.-100	Theo.	8
12.7 x 12.7	Bare,2,3,5,8,10, 12 & 18, H_2O	Therm.-100	Theo.	8
12.7 x 12.7	2,3,5,8,10,12&18	0.1-18 MeV	Exper.	27
4x4	2,3,5,8,10&12	Therm.-15	Theo.	39
51 (diam.) BF_3	3,5,8,10 & 12	Therm.-15	Theo.	39
203 (long) BF_3	Bare,1.18 & 2.36 thick cyl.	Therm.-15	Theo.	83
4x4	Bare & 2 to 20 1/2 inch increm'ts.	Therm.-17	Theo.	28

List of Tables & Titles

Table 1. Summary of Published Response Data for BSS Detectors.

Notes:

(1) All dimensions in mm. 4x4 means 4 mm diameter, 4 mm long right cylinder. ^{6}Li is assumed in place of ^{6}LiI(Eu) unless otherwise indicated.

(2) Diameter of moderators in inches. Material is polyethylene unless otherwise indicated.

(3) Energy in MeV.

Table 2. Energy Structure for 31 Group Response Functions.[8]

Table 3. Multisphere spectrometer response matrix for polyethylene moderators (ρ=0.95g cm^{-3}), 4 mm x 4mm ^{6}Li detector.[8]

Table 4. Multisphere spectrometer response matrix for polyethylene moderators (ρ=0.95 g cm^{-3}), 8 mm x 8 mm ^{6}Li detector.[8]

Table 5. Multisphere spectrometer response matrix for polyethylene moderators (ρ=0.95 g cm^{-3}), 12.7 mm x 12.7 mm ^{6}Li detector.[8]

Table 6. Multisphere spectrometer response matrix for water moderators (ρ=1.0 g cm^{-3}), 12.7 mm x 12.7 mm ^{6}Li detector.[8]

Table 7. Multisphere spectrometer response matrix for polyethylene moderators (ρ=0.95 g cm^{-3}), 12.7 mm diam x 0.051 mm thick, ^{197}Au detector.[8]

FIGURE CAPTIONS

1. The response of a multisphere spectrometer with a 4 mm x 4 mm ^{6}Li detector: I = bare, and at the center of polythene moderators, II = 2 inch, III = 3 inch, IV = 5 inch, V = 8 inch, VI = 10 inch, and VII = 12 inch diameters.[8]

2. Neutron energy spectra for: I = HPRR neutrons,[19] II = Cosmic-ray neutrons,[20] and III = ^{252}Cf neutron source.[21]

3. Multisphere response distributions for: I = HPRR neutrons,[19] II = Cosmic-ray neutrons,[20] and III = ^{252}Cf neutron source.[21]

4. Multisphere response distributions for three "monochromatic" neutrons. I = energy group 31, II = energy group 20, and III = Energy group 7.

5. Ratio of responses as a function of moderator density, material, and detector size. I = response ratio as a function of density (ρ = 0.90 to ρ = 0.95 g cm^{-3}) for polyethylene spheres 10 inch in diameter, II = ratio of the responses as a function of materials (H_2O to polyethylene) for 10 inch diameter spheres, with a 12.7 mm x 12.7 mm ^{6}Li detector,[8] III = ratio of the response of a 4 mm x 4 mm to that of a 12.7 mm x 12.7 mm ^{6}Li detector at the center of a 2 inch polyethylene sphere.

6. Phoswich assembly. $^{6}LiI(Eu)$ crystal is surrounded by a plastic scintillator cup cemented to a glass disc which is cemented to an aluminum can. The inside of the can is coated with Al_2O_3.

7. Events recorded by a 4 mm x 4 mm $^{6}LiI(Eu)$ crystal by a phoswich, for 48.3 hours, in a 10 inch polyethylene pseudosphere, due to environmental radiation. The solid squares represent all events. The open circles represent neutron signatures: slow pulses not accompanied by fast pulses.

8. Events recorded by a 8 mm x 8 mm $^{6}LiI(Eu)$ crystal in a phoswich, for 70.8 hours, in a 10 inch pseudosphere, due to environmental radiation. The solid squares represent all events. The open circles represent neutron signatures: slow pulses not accompanied by fast pulses.

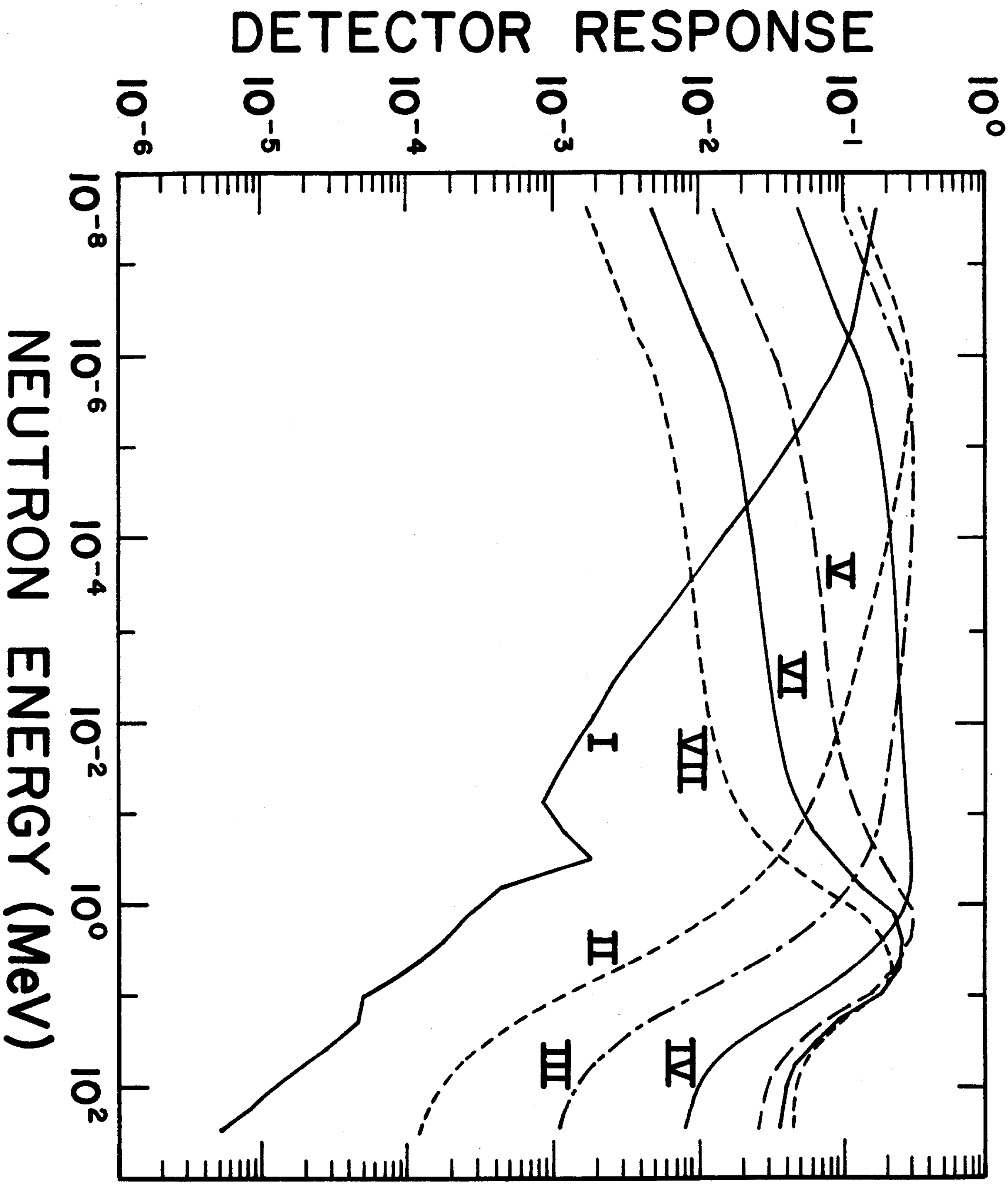
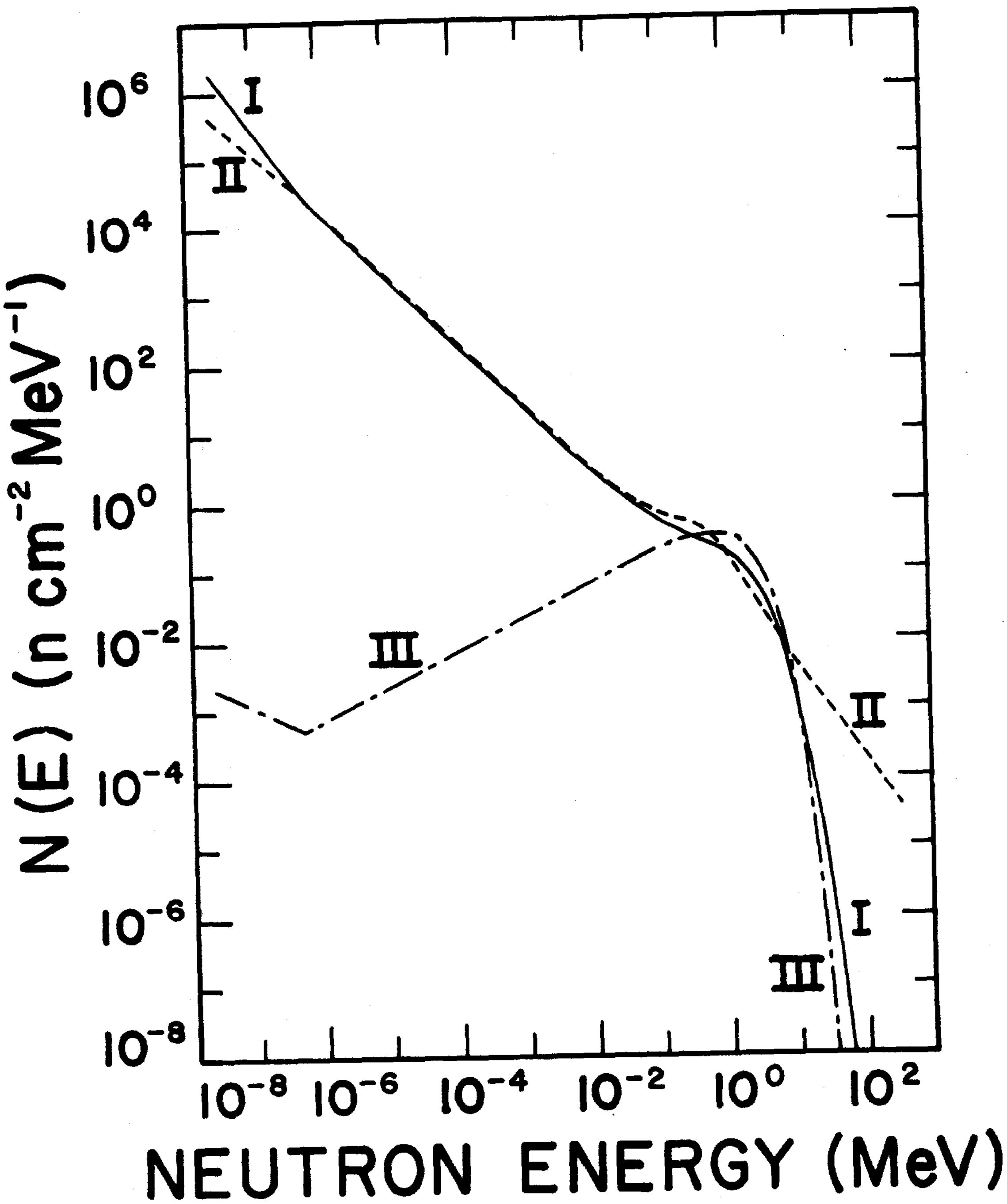

DETECTOR RESPONSE
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
NEUTRON ENERGY (MeV)
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
I
II
III
IV
V
VI
VII

Figure 1



N(E) (n cm^{-2} MeV^{-1})
NEUTRON ENERGY (MeV)
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
I
II
III
II
I
III

Figure 2

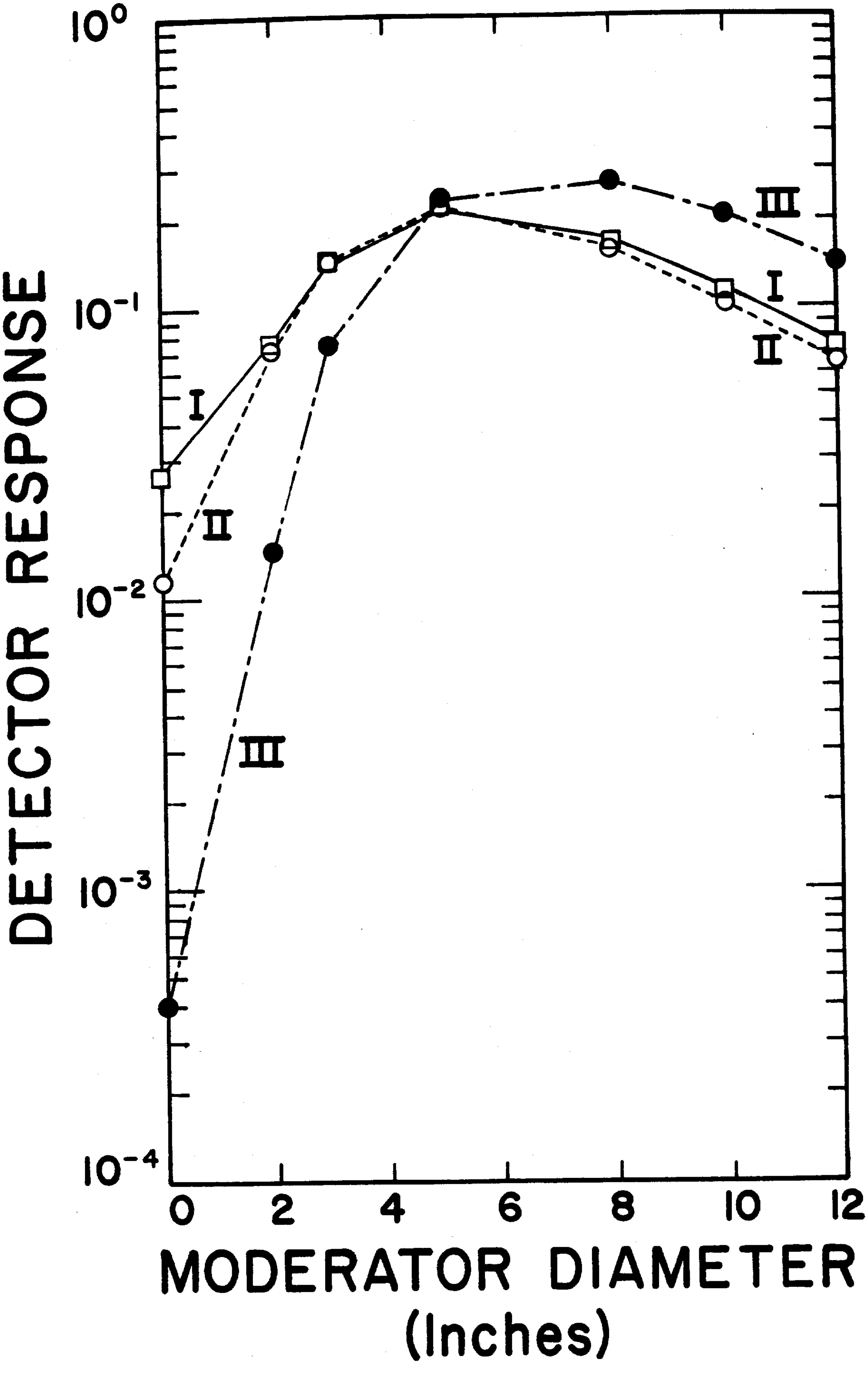

DETECTOR RESPONSE
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
I
II
III
0
2
4
6
8
10
12
MODERATOR DIAMETER
(Inches)

Figure 3

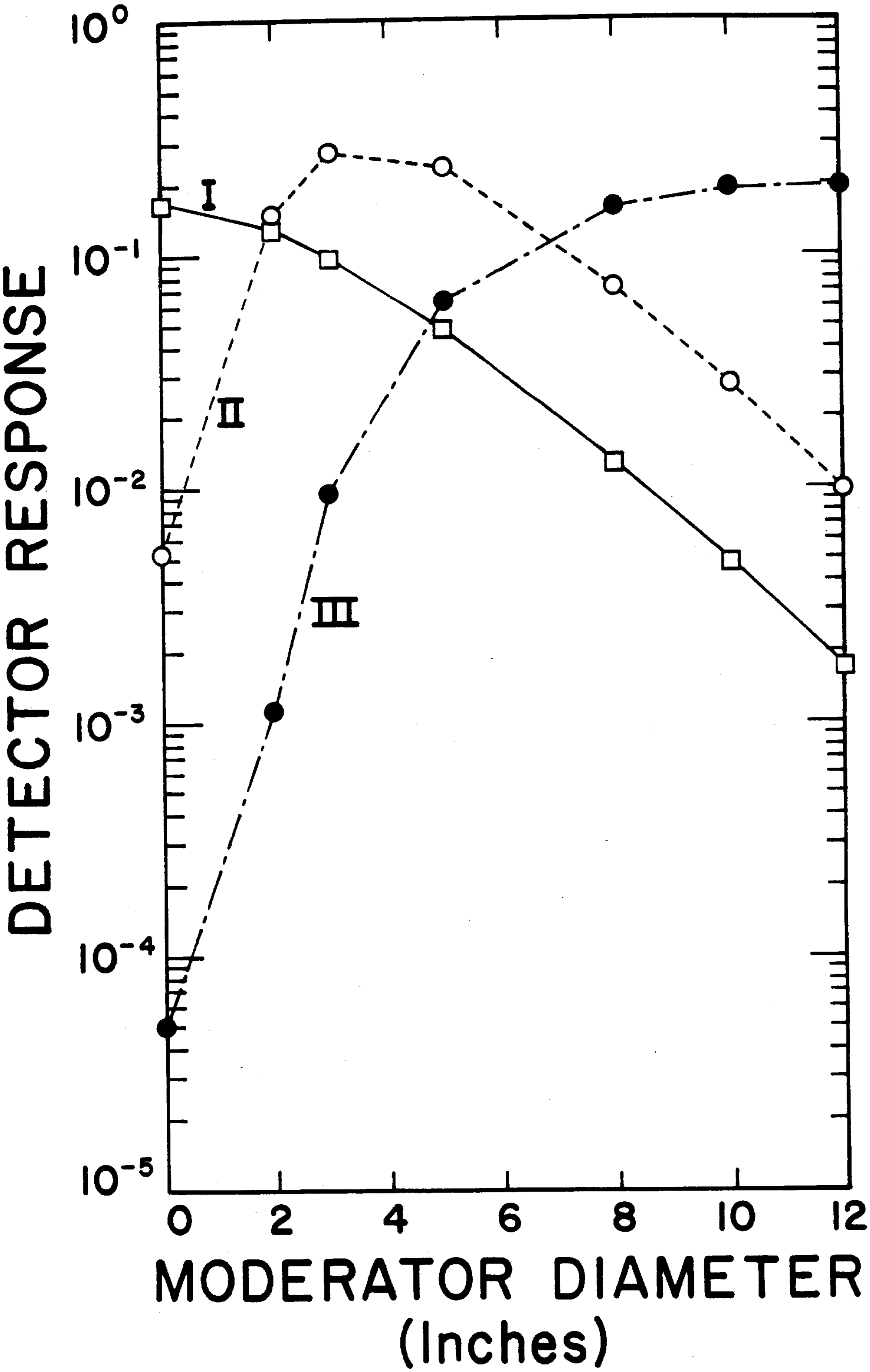

DETECTOR RESPONSE
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
I
II
III
0
2
4
6
8
10
12
MODERATOR DIAMETER
(Inches)

Figure 4

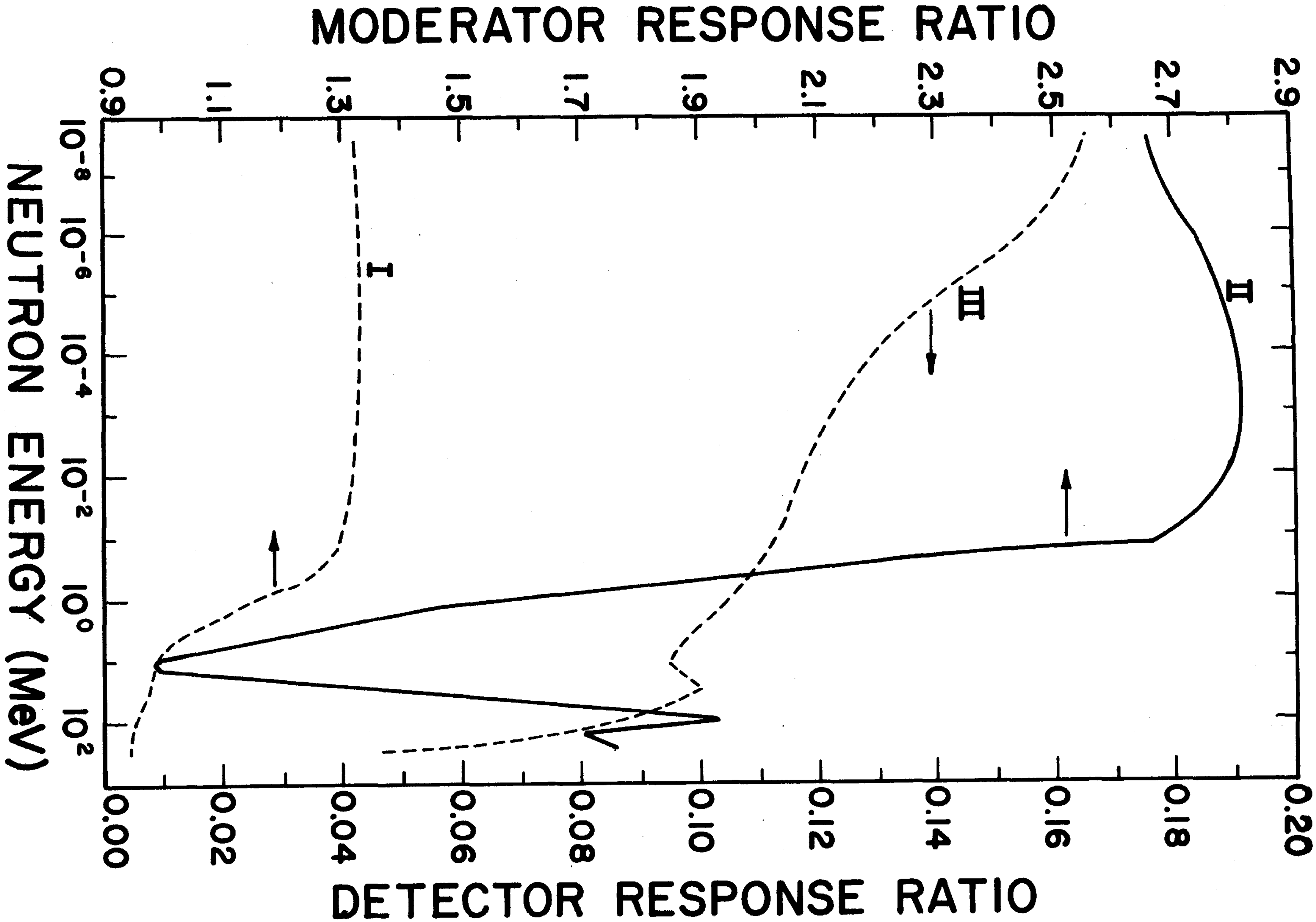

MODERATOR RESPONSE RATIO
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
NEUTRON ENERGY (MeV)
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
I
II
III
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
DETECTOR RESPONSE RATIO

Figure 5

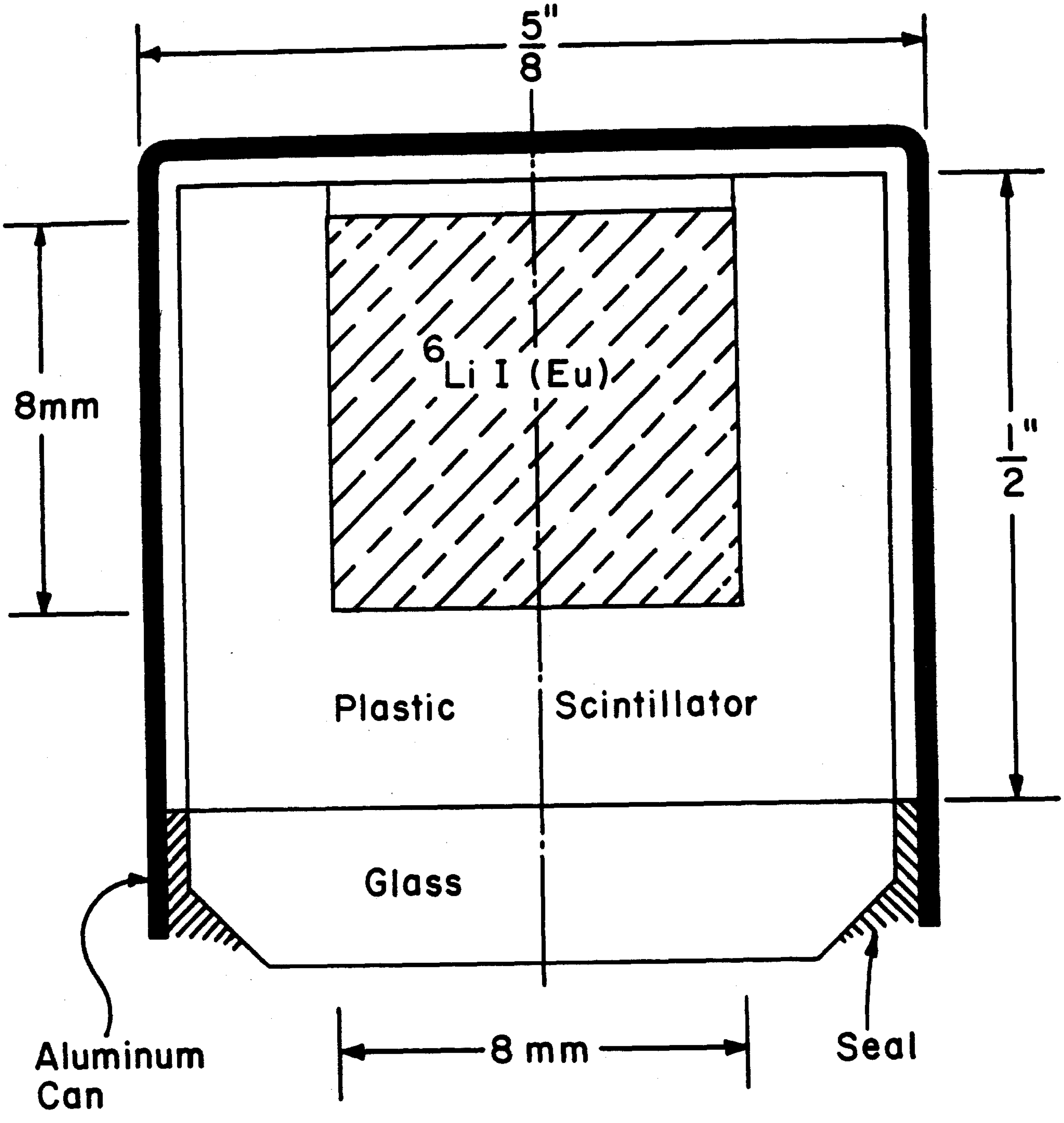

5"/8
8mm
6Li I (Eu)
1"/2
Plastic Scintillator
Glass
Aluminum Can
8 mm
Seal

Figure 6

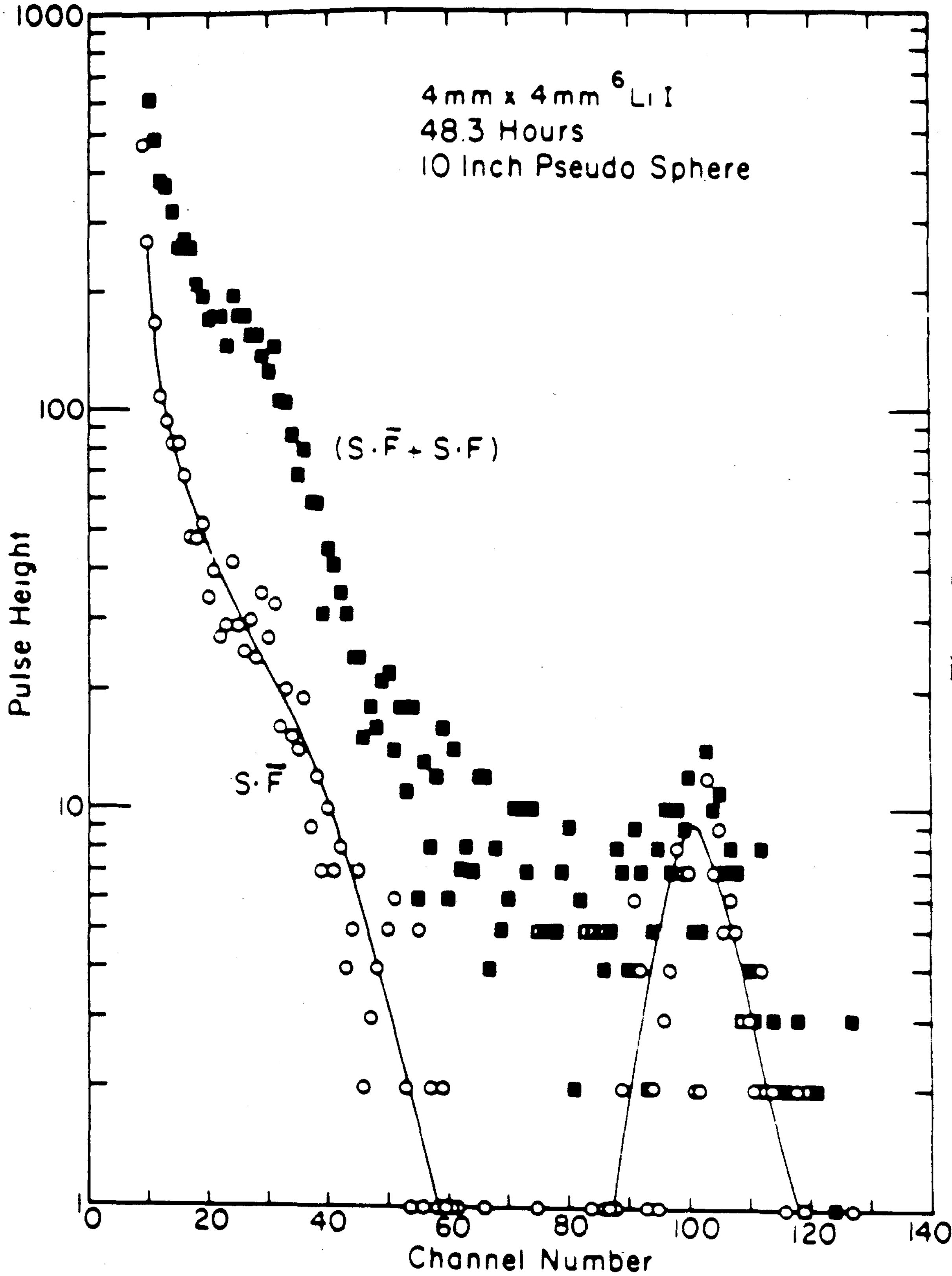
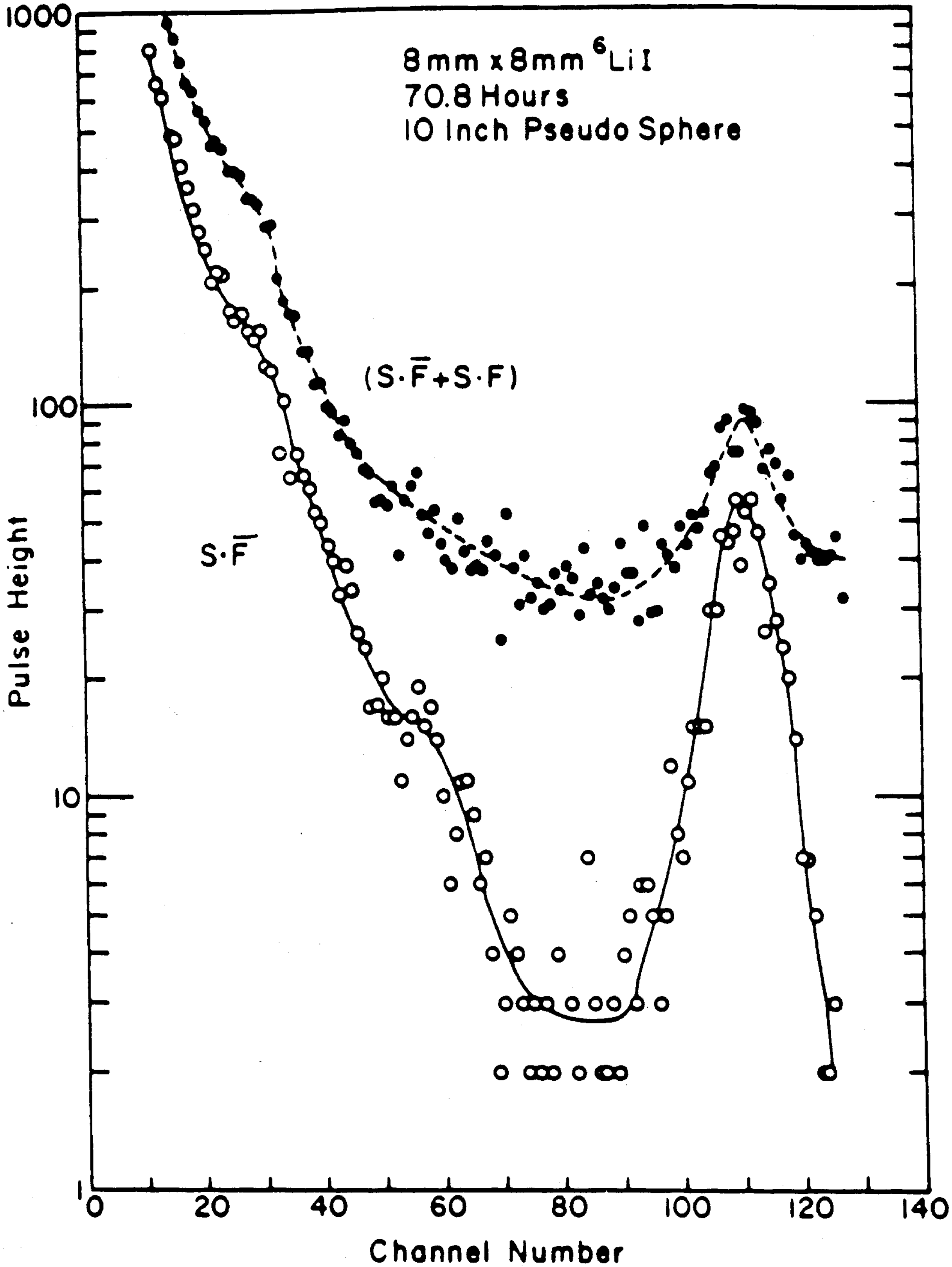

4 mm x 4 mm ^{6}Li I
48.3 Hours
10 Inch Pseudo Sphere
(S·F̄ + S·F)
S·F̄
Pulse Height
Channel Number
1000
100
10
1
0
20
40
60
80
100
120
140

Figure 7



8mm x 8mm ^{6}LiI
70.8 Hours
10 Inch Pseudo Sphere
$(S\cdot\bar{F}+S\cdot F)$
$S\cdot\bar{F}$
Pulse Height
Channel Number
1000
100
10
1
0
20
40
60
80
100
120
140

Figure 8