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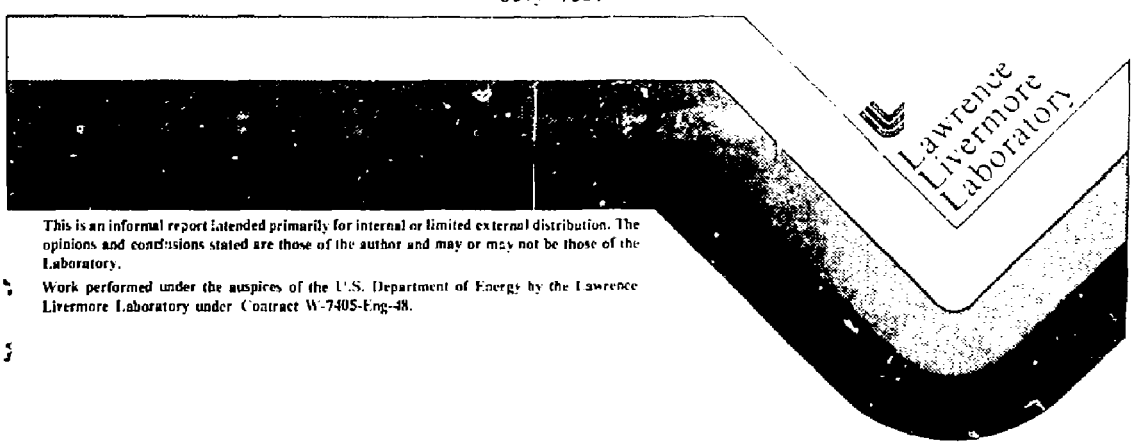
July 1981



GAMMA-RAY SPECTRA FROM NEUTRON CAPTURE ON ^{87}Sr

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ABSTRACT

The gamma-ray spectrum following neutron capture on ^{87}Sr was measured at 3 neutron energies: E_n = thermal, 2 keV, and 24 keV. Gamma rays were detected in a three-crystal Ge(Li)-NaI-NaI pair spectrometer. Gamma-ray intensities deduced from these spectra by spectral unfolding are presented.

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I. INTRODUCTION

Neutron-capture reactions are of both basic and applied interest in testing nuclear reaction models. In the mass-90 region many of the reactions of applied interest involve unstable nuclei and we must depend on calculations to provide the required cross sections. These calculations in turn require many input parameters including optical model parameters and gamma-ray strength functions. For nuclei near closed shells such as in the mass-90 region, these parameters are more uncertain than they are away from closed shells. To validate these calculations we can compare predictions with measurements on neighboring nuclei that are stable.

This experiment determined the shape of the gamma-ray spectrum from neutron capture by ^{87}Sr at three neutron energies: E_n = thermal, 2 keV, and 24 keV. These data therefore provide tests of the calculations. We expect the measured spectra to set limits on alternative descriptions of the gamma-ray strength function in particular and perhaps on other parameters. This document describes the experiment and presents the measured spectra. The measured gamma-ray yields were corrected for detector efficiency and normalized for an intensity of 0.95 per capture for the transition from the 2^+ first excited state to the ground state. Averaged over 100-keV intervals, the gamma ray intensities are presented in tabular form.

II. EXPERIMENT

The experiment was performed at the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory. Thermal, 2-keV, and 24-keV beams from the

filtered beam facility[1] were used to irradiate a sample of ^{87}Sr. The 24-keV beam at this facility has a width of 1.9 keV (FWHM) and is centered at 24.3 keV. The 2-keV beam is 0.9 keV wide (FWHM), and is centered at 1.95 keV. Both of these beams had intensities of approximately 4×10^7 neutrons sec^{-1} and at the sample they were uniformly distributed over a 4-cm x 4-cm area. The thermal beam was collimated to a circle 1.5 cm in diameter at the sample, and its intensity was approximately 10^8 neutrons sec^{-1}.

Sample parameters are given in Table 1. The Sr sample was in the form of $^{87}Sr\ (NO_3)_2$, packed into a container fabricated of 0.25 mm thick aluminum. Several other samples were irradiated for calibration and background subtraction purposes. A graphite sample whose thickness was chosen to simulate neutron scattering from the Sr target at E_n = 24 keV provided a measure of the contribution of scattered neutrons to the backgrounds. A NaCl sample provided well-known gamma rays resulting from neutron capture on Cl for efficiency and energy calibrations. Other calibration lines from neutron capture on Pb (E_γ = 7.4 MeV) and H (polyethylene) (E_γ = 2.2 MeV) were used to help determine the response function of the gamma-ray detector. All samples were of uniform 5-cm x 5-cm in cross section with the exception of the NaCl.

Gamma rays from neutron capture were detected in a Ge(Li) detector positioned at 90 degrees to the beam at a distance of 37 cm (see Fig. 1). The Ge(Li) crystal was at the center of a NaI(Tl) scintillator (25 cm diameter by 23 cm long) into which a cylindrical cavity had been cut. The NaI was divided optically into halves and coupled to photomultipliers, and the system was used as a pair spectrometer as described below. The Ge(Li) detector was a 40 cm^3 closed-end coaxial detector which was mounted sideways to optimize

escape of annihilation photons.[2] The detectors were shielded from stray gamma-rays and neutrons with bismuth, Li epoxy, polyethylene, borated polyethylene, ^{6}Li, and lead; $^{6}LiCO_3$ was placed between the sample and the detector to prevent neutrons which are thermalized in the shielding from reaching the sample.

The energy resolution of the NaI detectors at the 511-keV full energy peak for annihilation photons was approximately 10% (FWHM). The signals from the NaI detectors were processed by timing single channel analyzers (TSCA), with windows set at 511 keV $\pm$ 15%. The signals from the Ge(Li) were processed in a conventional manner and then applied to a linear gate, which passed these signals only when signals from the Ge(Li) and the two TSCAs were time coincident within 40 ns. This process selected those events in which the photon interacted in the Ge(Li) via pair production and in which each annihilation photon escaped the Ge(Li) crystal to deposit its full energy in one of the NaI detectors. The gated Ge(Li) spectra thus consisted primarily of peaks at the energy of the gamma ray minus two electron masses, with the other peaks and the Compton events strongly suppressed. This method yields the clean and easily parameterized spectra characteristic of pair spectrometers, although at a cost in peak efficiency.

The analog pulse from the linear gate was stored in an on-line computer after processing by an analog-to-digital converter (ADC). The gain of the system was stabilized by injecting stable pulser signals into the detector preamplifier at both the high energy and low energy regions of the spectrum. These signals were processed by a stabilizer which controlled the conversion gain of the ADC. The resulting spectra were written out on tape; these were transferred to Lawrence Livermore National Laboratory for analysis.

III. ANALYSIS

The spectra were corrected initially for background contributions. Two types of background were considered. The background due to scattered neutrons was obtained from the spectra taken at each energy with a carbon (graphite) sample, corrected for the appropriate scattering cross sections of C, Sr, N, and O. The background normalization was verified by comparing the intensities of the 7631-keV and the 7645-keV gamma rays from neutron capture on ^{56}Fe in the background spectra to those intensities in the Sr spectra. (The ^{56}Fe is a component of various structures in the experimental area.) A sample-out background correction was also made, although this generally turned out to be negligible.

The advantage of using a pair spectrometer is that spectra of individual gamma-ray transitions can be unfolded from the measured spectra in a reasonably straightforward manner. This is possible because the response function of the system for a gamma ray of given energy is fairly easily parameterized.[2]

The spectra taken with lead and polyethylene targets, as well as with ^{228}Th (E_γ = 2.6 MeV), $^{238}Pu(Be)$ (E_γ = 4.4 MeV), and $^{238}Pu(^{13}C)$ (E_γ = 6.1 MeV) sources, were used to parameterize the response function. This response function can be described in four parts (see Fig. 2). First there is a single channel peak at the double escape peak energy. This accounts for between 20% and 80% of the total counts, depending on the photon energy ($F = 0.885 - 1.22 \times 10^{-4} E_\gamma + 5.21 \times 10^{-9} E_\gamma^2$, where F is the ratio of peak counts to total counts in the spectrum). The actual response for a gamma-ray line is (of course) more than one channel wide in the peak,

but, for purposes of unfolding, each peak is considered to be a superposition of adjacent single-channel peaks. The second component of the response function is a "shoulder" on the high energy side of the double-escape peak extending in energy out to about $E_\gamma - 2m_e c^2$ + 120 keV. The amplitude of this shoulder is proportional to the total number of counts, and the amplitude and shape of this shoulder have been found to be independent of photon energy. We defined this shape by thirteen points. The number of counts in a given channel in this region is thus interpolated between the appropriate pair of points. The third component of the response function is a shoulder on the low energy side of the peak. This shoulder extends out to about $E_\gamma - 2m_e c^2$ - 900 keV and it is lower in amplitude than the high energy shoulder. The shape and amplitude of the low energy shoulder are also energy independent, and it is treated in stripping exactly like the high energy shoulder, except that we define it by nineteen points spaced at 50 keV intervals rather than thirteen points spaced at 10 keV intervals. The integral number of counts in the two shoulders account for about 10% of the total counts due to a single gamma ray. The final component of the response function is a flat portion extending from threshold to the double escape peak. The ratio of the amplitude of this flat portion to the total number of counts was parameterized as a linear function of photon energy.

Therefore two arrays describing the shoulders and two parameters describing the flat portion are needed to define a response function, and these were extracted from the five "monoenergetic" spectra mentioned above. Unfolding of the spectra then proceeded as follows: First the spectrum being stripped was divided into convenient groups 120 keV in width. Starting with the highest energy group, the data were examined for "peak" channels, defined

as those channels with more than the average number of counts in that group. Next, a given fraction f of the counts in each peak channel was subtracted and recorded in a separate spectrum. Values of f were varied from 0.75 in the first rough attempts to 0.5 in the final stripping, although the particular value of this parameter did not strongly affect the results. Then for each channel from which peak counts were subtracted, the associated continuum (shoulders and flat portion) was subtracted from the entire spectrum and transferred to a third spectrum. Each region was processed in this manner in order of decreasing energy. When the entire spectrum had been stripped once, the entire process was repeated. As each region was reconsidered, we determined whether the remaining counts in the region met two conditions: the average number of counts per channel had to be less than 0.1, and the maximum number of counts in any channel had to be less than two standard deviations above zero. If both conditions were satisfied, the region was flagged and processing for that egion was halted. When all regions had been flagged in this manner, the stripping was complete. The counts remaining in the original spectrum served as a measure of the quality of our parameterization.

The gamma-ray yields were corrected for the relative efficiency of the detector as a function of energy (see Fig. 3). The relative efficiency curve was deduced from the results obtained from a NaCl target, for which the relative intensities of the lines from thermal neutron capture on Cl are well known.[3] The spectra were then normalized for an intensity of 0.95 per capture for the transition from the 2^+ first excited state to the ground state. Finally, the spectra were averaged over 100-keV intervals for comparison with calculations.

IV. RESULTS

The results are shown in both Figure 4 and Table 2. Errors shown are only statistical. Uncertainties in the response function, primarily in the two parameters used to describe the flat portion, may introduce systematic errors. Varying these parameters suggests that this error is less than or on the order of 10% at the low energy end of the spectra, and that it is negligible at the high energy end. Theoretical calculations of these gamma-ray spectra are in progress and will be presented later.

V. *ACKNOWLEDGEMENTS*

We would like to thank Dr. Robert C. Haight, Dr. John C. Browne, and Dr. R. E. Chrien for their valuable advice and encouragement.

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1) R. C. Greenwood and R. E. Chrien, Nucl. Instr. and Meth. 138, 125(1976).

2) M. L. Stelts and J. C. Browne, Nucl. Instr. and Meth. 133, 35(1976).

3) M. L. Stelts and R. E. Chrien, Nucl. Instr. and Meth. 155, 253(1978).

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4. Gamma-ray spectra from neutron capture on ^{87}Sr at E_n = 24 keV, 2 keV, and thermal.

TABLE 1

Sample Properties and Irradiation Times

Sample	Thickness (g/cm^2)	Irradiation Time (s)
Pb	5.40	1.23×10^4
NaCl	(a)	1.39×10^4
$(CH_2)_n$	0.117	9.34×10^3
graphite (thermal)	1.19	9.64×10^4
graphite (2 keV)	1.19	5.06×10^5
graphite (24 keV)	1.19	4.19×10^5
$^{87}Sr(NO_3)_2$ (thermal)	2.43 (b)	8.52×10^4
$^{87}Sr(NO_3)_2$ (2 keV)	2.43 (b)	4.07×10^5
$^{87}Sr(NO_3)_2$ (24 keV)	2.43 (b)	6.34×10^5

(a) 0.9 g sample, entirely within the beam

(b) plus two layers of 0.25-mm aluminum

TABLE 2

Photons/(keV-1000 Captures)

E_γ(MeV)[a]	E_n		
	24 keV	2 keV	Thermal
1.75	2.28(33)	1.81(14)	2.67 (3)
1.85	12.0(3)	11.4(2)	12.80(4)
1.95	1.63(21)	1.20(9)	1.36(2)
2.05	1.02(18)	0.443(64)	0.370(14)
2.15	1.18(15)	0.996(64)	1.11(1)
2.25	2.40(19)	1.35(9)	1.22(1)
2.35	0.97(12)	0.804(49)	1.40(1)
2.45	0.854(96)	0.646(41)	0.378(11)
2.55	1.09(9)	0.670(39)	1.01(1)
2.65	0.729(78)	0.490(35)	0.626(9)
2.75	0.740(72)	0.517(31)	0.620(8)
2.85	0.631(65)	0.396(28)	0.517(7)
2.95	0.604(60)	0.468(27)	0.764(8)
3.05	0.744(59)	0.632(26)	1.937(9)
3.15	0.516(53)	0.362(22)	0.524(6)
3.25	0.601(54)	0.435(23)	0.669(6)
3.35	0.474(48)	0.385(21)	0.651(6)
3.45	0.645(45)	0.478(21)	0.748(6)
3.55	0.469(43)	0.368(19)	0.698(6)
3.65	0.405(41)	0.323(18)	0.516(5)
3.75	0.457(38)	0.329(17)	0.554(5)
3.85	0.382(38)	0.308(16)	0.679(5)
3.95	0.367(37)	0.272(16)	0.504(5)
4.05	0.388(33)	0.368(16)	0.721(5)
4.15	0.368(32)	0.274(15)	0.554(5)
4.25	0.349(31)	0.186(13)	0.281(4)
4.35	0.299(30)	0.273(14)	0.409(4)
4.45	0.335(30)	0.278(13)	0.436(4)
4.55	0.296(29)	0.217(12)	0.535(4)
4.65	0.268(27)	0.248(12)	0.600(4)
4.75	0.300(28)	0.224(12)	0.247(3)
4.85	0.242(26)	0.221(12)	0.211(3)
4.95	0.226(26)	0.243(12)	0.249(3)
5.05	0.234(25)	0.234(11)	0.193(3)
5.15	0.284(26)	0.171(11)	0.444(4)
5.25	0.225(23)	0.189(10)	0.420(4)
5.35	0.310(24)	0.290(11)	0.349(3)
5.45	0.367(26)	0.250(11)	0.410(4)

TABLE 2 (Continued)

Photons/(keV-1000 Captures)

E_γ (MeV)[a]	E_n		
	24 keV	2 keV	Thermal
5.55	0.174(22)	0.110(10)	0.248(3)
5.65	1.089(22)	0.356(11)	0.350(3)
5.75	0.226(20)	0.157(10)	0.416(3)
5.85	0.343(23)	0.197(10)	0.181(3)
5.95	0.151(20)	0.0548(84)	0.147(3)
6.05	0.266(21)	0.121(9)	0.306(3)
6.15	0.206(21)	0.211(10)	0.834(4)
6.25	0.067(22)	0.306(11)	1.421(5)
6.35	0.215(26)	0.097(10)	0.283(3)
6.45	0.230(22)	0.138(10)	0.116(2)
6.55	0.136(21)	0.105(10)	0.0559(24)
6.65	0.682(35)	0.560(16)	1.449(5)
6.75	0.515(34)	0.346(14)	0.221(3)
6.85	0.494(31)	0.800(16)	1.019(5)
6.95	0.330(22)	0.208(10)	1.061(5)
7.05	0.160(12)	0.214(8)	0.131(2)
7.15	0.244(13)	0.215(8)	0.0851(20)
7.25	0.033(10)	0.0296(62)	0.0547(20)
7.35	0.043(10)	0.0276(52)	0.0386(20)
7.45	0.124(17)	0.140(8)	0.156(3)
7.55	0.175(13)	0.583(11)	1.262(5)
7.65	0.070(16)	0.0475(75)	0.0732(22)
7.75	0.076(15)	0.0475(68)	0.0636(19)
7.85	0.0193(66)	0.0345(46)	0.0236(15)
7.95	0.073(11)	0.0184(44)	0.0171(16)
8.05	0.0103(54)	0.0055(31)	0.0182(16)
8.15	0.0141(57)	0.0053(31)	0.0128(15)
8.25	0.0108(58)	0.0053(32)	0.0119(16)
8.35	0.0227(10)	0.0624(46)	0.384(3)
8.45	0.0574(77)	0.0074(35)	0.0322(19)
8.55	0.0148(78)	0.0115(42)	0.0084(15)
8.65	0.0094(51)	0.0029(26)	0.0065(15)
8.75	0.0125(59)	0.0094(34)	0.0055(15)
8.85	0.0110(69)	0.0046(32)	0.0054(15)
8.95	0.0196(82)	0.0069(47)	0.0043(14)
9.05	0.0171(70)	0.0044(32)	0.0043(15)
9.15	0.0131(59)	0.0031(26)	0.0071(15)
9.25	0.254(12)	0.0150(38)	0.0074(15)
9.35	0.0329(81)	0.0065(34)	0.0038(15)
9.45	0.0034(26)	0.	0.00098(74)
9.55	0.	0.	0.

[a]Center of 100 keV wide bin.

Three-Crystal [NaI-Ge (Li)] Pair Spectrometer

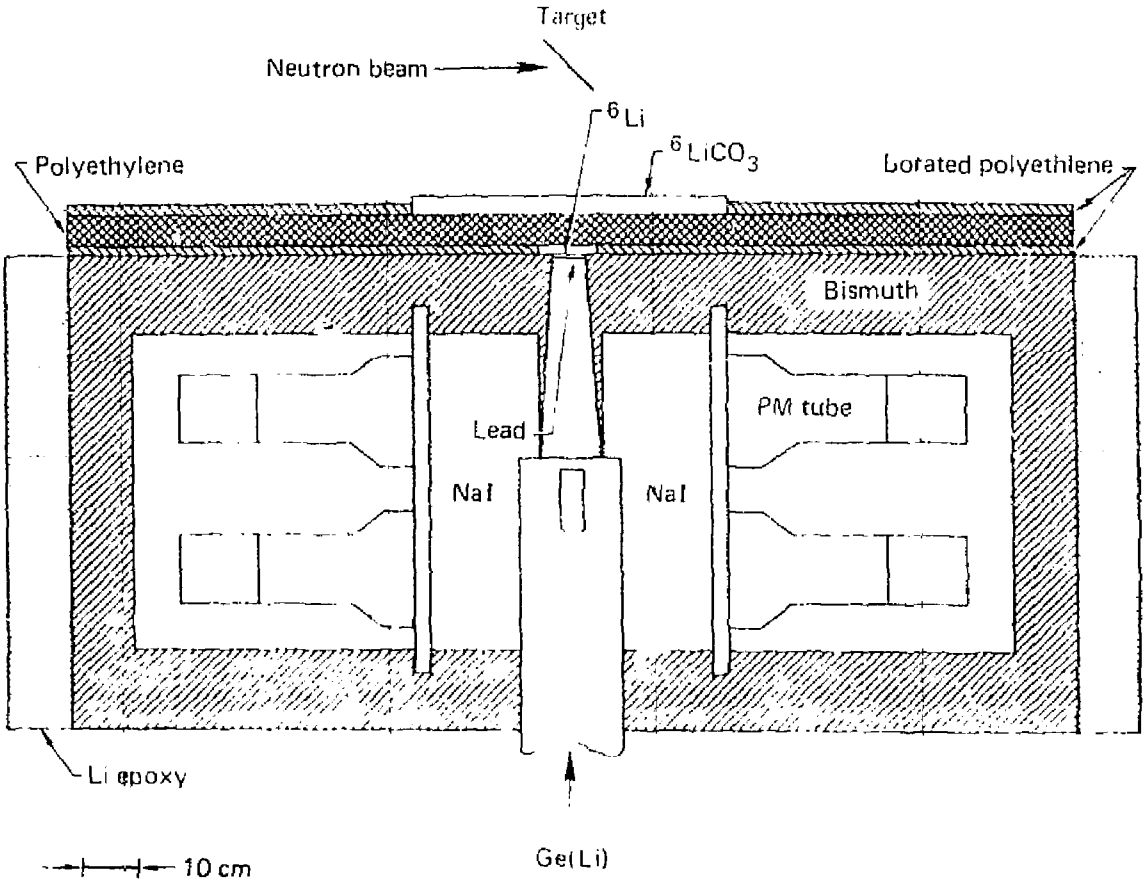

Figure 1

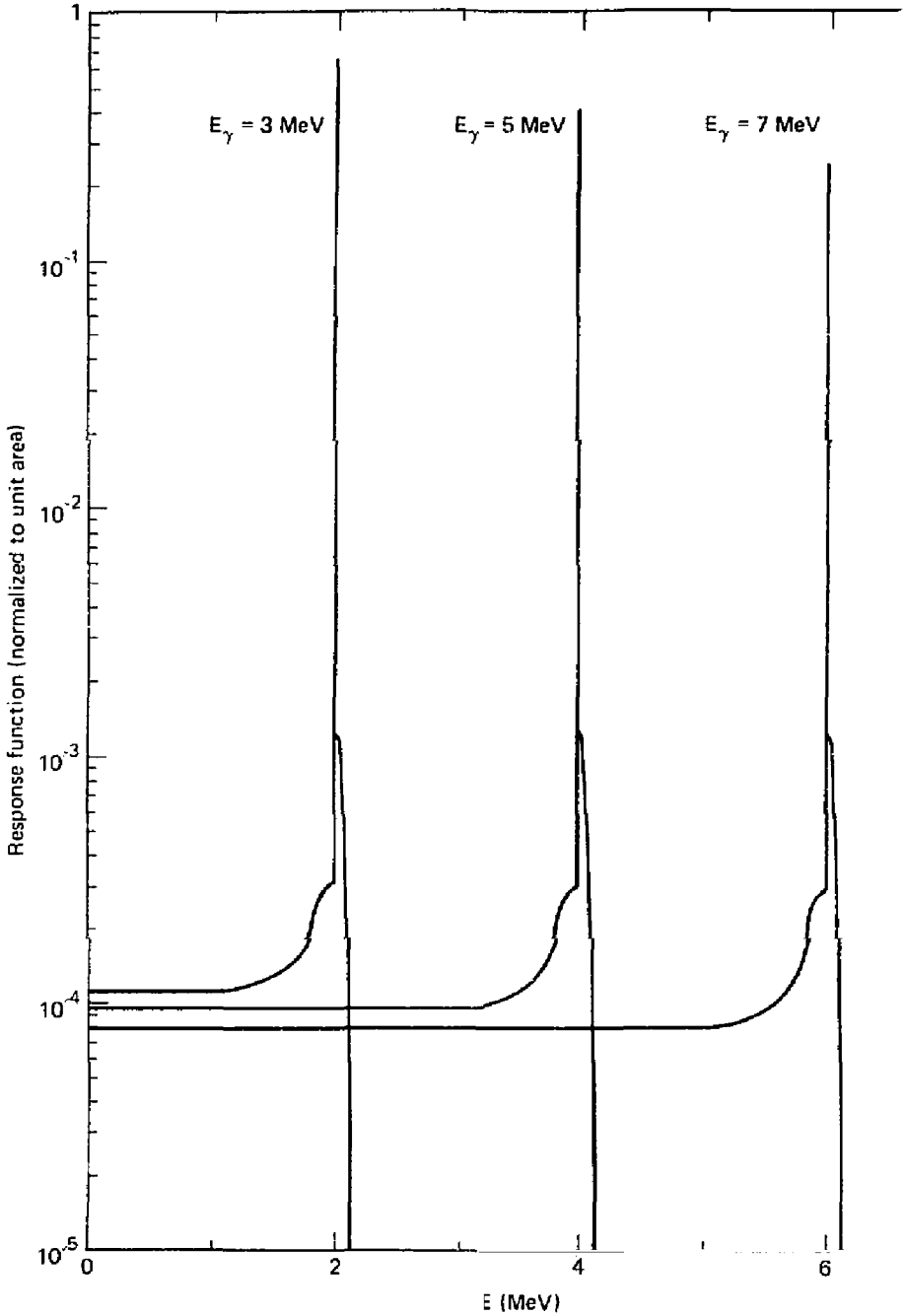
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
E_γ = 3 MeV
E_γ = 5 MeV
E_γ = 7 MeV
Response function (normalized to unit area)
0
2
4
6
E (MeV)

figure 2

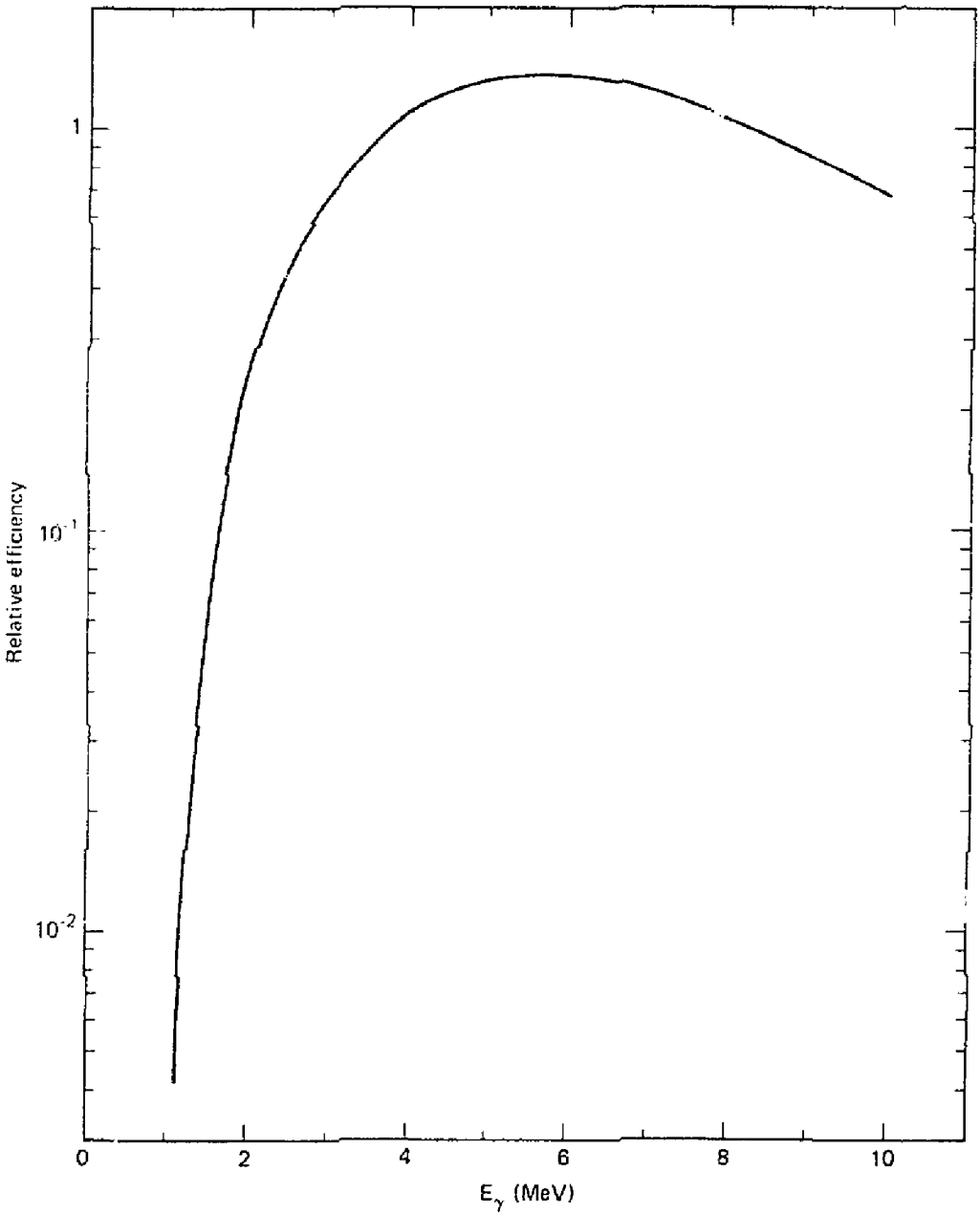

figure 3

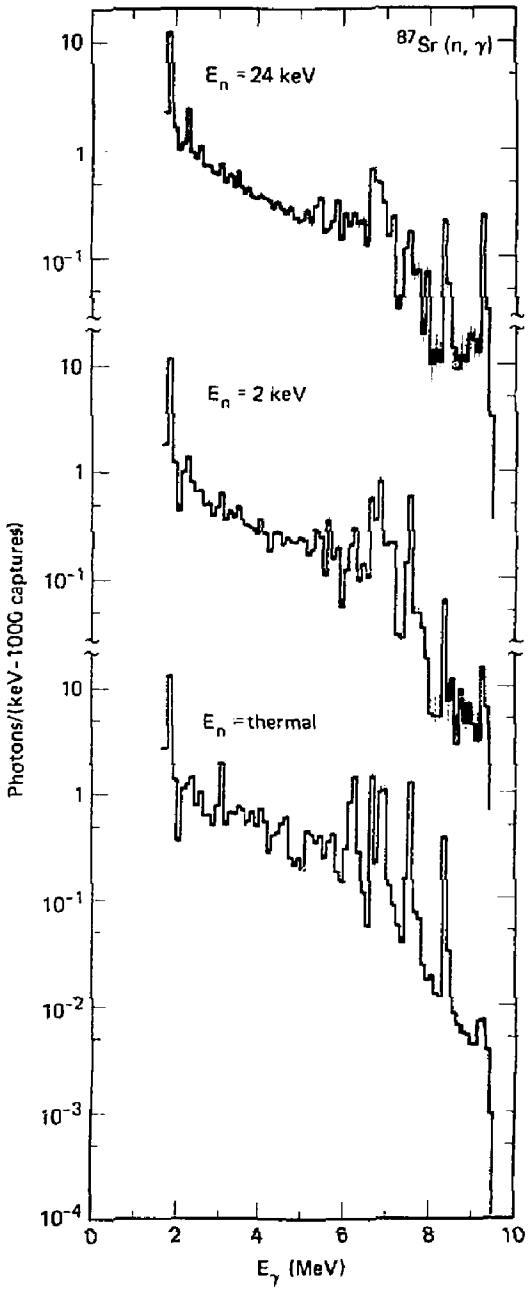
^{87}Sr (n, γ)
E_n = 24 keV
E_n = 2 keV
E_n = thermal
Photons/(keV-1000 captures)
E_γ (MeV)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10

figure 4