Angular Distribution of 2.6-Mev Gamma Rays from the Reaction $Pb^{208}(n,n'\gamma)Pb^{208}$†

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(Received May 2, 1961)

Gamma rays produced through inelastic scattering by lead of a collimated beam of fast neutrons from a reactor have been detected with a NaI(Tl) crystal. The relative yield of 2.6-Mev γ rays from Pb^{208} was measured as a function of the angle between the incident neutrons and outgoing γ rays. Good agreement is obtained between the experimental angular distribution and a calculated distribution based on a statistical model, and using quantum numbers 3^- for the 2.6-Mev state in Pb^{208}.

I. INTRODUCTION

STUDIES of the energy spectrum of γ rays from $(n,n'\gamma)$ reactions have yielded considerable information concerning the location of bound, excited states in nuclei. Measurements of the cross sections for such reactions help to determine an appropriate model to be used in considering the neutron-nucleus interaction. An example of such measurements and of their interpretation is the work of Lind and Day.[1]

Satchler[2] has proposed that by studying the angular distribution of γ rays following neutron inelastic scattering, information can be obtained about the angular momentum and parity of the nuclear states involved in the γ-ray transition. Satchler uses a statistical model of the system formed by the incident neutron and the target nucleus to obtain an expression for the yield of γ rays from an $(n,n'\gamma)$ reaction as a function of the angle between the incident neutron and the outgoing γ ray. His expression depends among other things, on the angular momentum and parity of the nuclear states involved in the γ-ray transition. This expression has been checked by Day and Walt,[3] who obtained good agreement between experimental and calculated values for the differential cross section for production of 0.85-Mev γ rays from the reaction $Fe^{56}(n,n'\gamma)Fe^{56}$. Day and Walt used incident neutrons with energies of 2.56 Mev.

In the work described here, the angular distribution of 2.6-Mev γ rays emitted from the 3^- state in Pb^{208}, in the reaction $Pb^{208}(n,n'\gamma)Pb^{208}$, has been measured, and compared with the calculated distribution. Fast neutrons from fission were used to excite the lead nuclei. Although neutrons from fission can have, for practical purposes, any energy from a few kev up to about 10 Mev, two facts allow a reasonable comparison to be made between the measured and calculated angular distributions. The product of the shapes of the fission-neutron energy spectrum and of the total cross section for the $Pb^{208}\{n,n'\gamma(2.6\text{ Mev})\}Pb^{208}$ reaction, calculated from the theory of Hauser and Feshbach,[4] has a maximum at about 4 Mev, with a half-width of about 1.5 Mev. Also, as shown in Sec. III, the calculated angular distribution of this reaction is not very dependent on incident neutron energies, for neutron energies in the vicinity of 4 Mev.

II. EXPERIMENTAL PROCEDURE

The arrangement used is shown in Fig. 1. Neutrons from a pool reactor pass through: (a) a 4-in. bismuth plug, which reduces the γ-ray background in the experimental area, (b) an aluminum flange, which keeps the water in the pool, and (c) a 3-in. LiF plug, which removes thermal neutrons from the beam. A lead collimator one foot long and a paraffin collimator 2 ft long limit the diameter of the beam at the target to about 2 in. The target is located about 5 ft from the end of the collimator. The total distance from the bismuth plug to the target is about 14 ft.

Gamma rays produced in the target were detected with a 3-in. diameter×3-in. length NaI(Tl) crystal, and pulses from the photomultiplier tube were recorded in a 128-channel pulse-height analyzer. The distance from the target to the detector was from 30 to 40 in., so that the angular spread was less than $\pm 3°$. The angle between incident neutrons and emitted γ rays was varied from 110° to 150°. At angles less than 90° and greater than 150°, high background at the detector made the collection of data difficult.

Figure 2 shows the γ-ray spectrum obtained at one angle using a lead target $\frac{1}{4}$ in. thick. The data plotted as dots were obtained with a natural lead target. Those plotted as crosses result from a radio-lead target (Pb^{206} abundance$\simeq$88%). Gamma rays from well-known energy levels at 0.80 Mev in Pb^{206} and 2.6 Mev in Pb^{208} are seen clearly. The peak at 2.1 Mev results from the es-

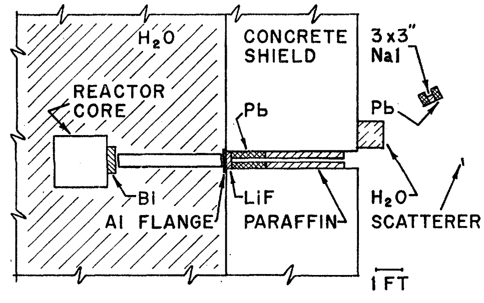

FIG. 1. Experimental arrangement.

† Supported in part by the U. S. Atomic Energy Commission.
[1] D. A. Lind and R. B. Day, Ann. Phys. 12, 485 (1961).
[2] G. R. Satchler, Phys. Rev. 104, 1198 (1956); 111, 1747 (1958).
[3] R. B. Day and M. Walt, Phys. Rev. 117, 1330 (1960).
[4] W. Hauser and L. H. Feshbach, Phys. Rev. 87, 366 (1952).

cape of a single annihilation-radiation photon following pair production in the crystal by a 2.6-Mev γ ray.

From a study of the data illustrated in Fig. 2, we have concluded that, within the precision of the experiment, (a) all of the 2.6-Mev γ rays originate in Pb^{208}, and (b) no other γ rays are present which come from Pb^{208}. Weak γ rays, with intensities a few percent of the 2.6-Mev γ rays, or γ rays from Pb^{208} with energies less than about 550 kev could not have been seen in this experiment.

The energy level scheme of Pb^{208} indicates that it is unlikely that the 2.6-Mev γ ray is in cascade only with γ rays with energies less than 550 kev. We have assumed, in analyzing the angular distribution data, that there are no γ rays in cascade with the 2.6-Mev γ ray from Pb^{208}.

To investigate the effect on the measured angular distributions of multiple scattering of neutrons, distributions were measured using targets with thicknesses of $\frac{1}{8}$ in. and $\frac{1}{16}$ in. No difference in the angular distributions was detected. That no difference was observed is not surprising, since only about 6% of the incident neutrons suffer an elastic collision in a $\frac{1}{8}$-in. target, and the precision of the individual measurements with different target thicknesses is only about 5%.

Finally, the possibility that the observed γ rays resulted from capture by lead nuclei of thermal neutrons was eliminated by looking for the presence of 7.4-Mev γ rays. These are the predominant γ rays emitted in the (n,γ) reaction in lead, and none were observed in this experiment.

Data were collected as follows: with the power level of the reactor fixed, and with the detector at a given angle, γ rays from the target were counted for a fixed time, between six and thirteen minutes. The target was then removed and the room background counted for the same length of time. Data obtained from a $\frac{1}{8}$-in. thick target, including the room background, and with background subtracted, are shown in Figs. 3 and 4, respectively. As indicated in Fig. 3, the room background is large. The signal at 2.6 Mev is about 15% of the total counting rate. The triangle shown in Fig. 4 is the shape of the total-energy peak expected at 2.6 Mev. This expected shape was measured using 2.8-Mev γ rays from radioactive Na^{24}. Figure 4 shows that after subtracting room background, some background still remains. A measure of this background at 2.6 Mev was obtained from the counting rates at energies between 2.6 and 3.5 Mev (between channels 90 and 120 in Fig. 4).

The area within the triangle shown in Fig. 4 was used as a measure of the intensity of 2.6-Mev γ rays. Approximately ten measurements of this area were made at each of seven angles between 110° and 150°, five measurements using a $\frac{1}{8}$-in.-thick scatterer, and five using a $\frac{1}{16}$-in.-thick scatterer. From a statistical analysis of these data, we concluded that the ratio of intensities of the 2.6-Mev γ rays at two different angles could be obtained from a single pair of measurements with a standard deviation of about 10%. Since no systematic

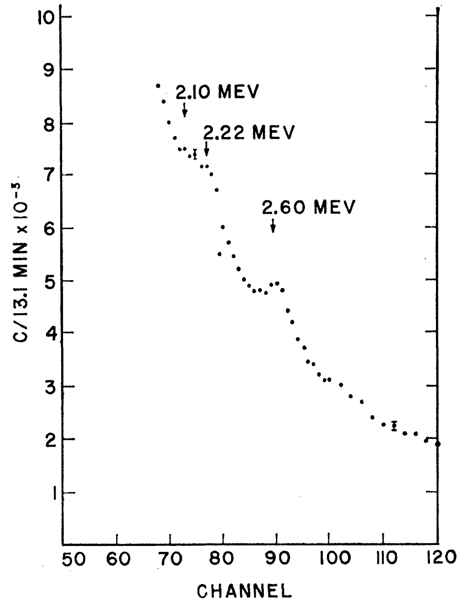

FIG. 3. Signal and background from a $\frac{1}{8}$-in.-thick scatterer. The 2.22-Mev γ rays are from the $H^1(n,\gamma)H^2$ reaction.

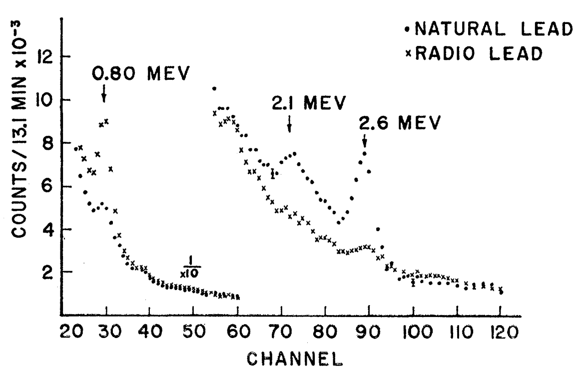

FIG. 2. Gamma rays from $Pb(n,n'\gamma)Pb$ reaction. The dots result from a natural lead target, and the crosses from a radio-lead target. Target thickness was $\frac{1}{4}$-in.

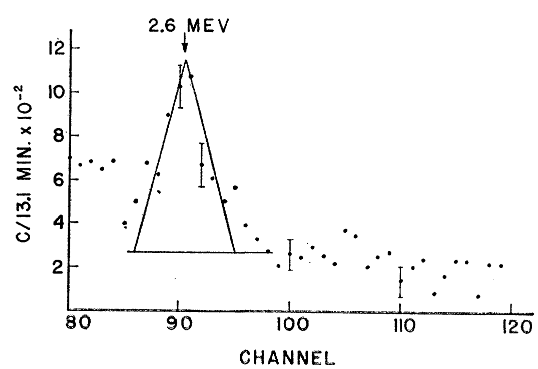

FIG. 4. Signal from $\frac{1}{8}$-in. scatterer, with room background subtracted.

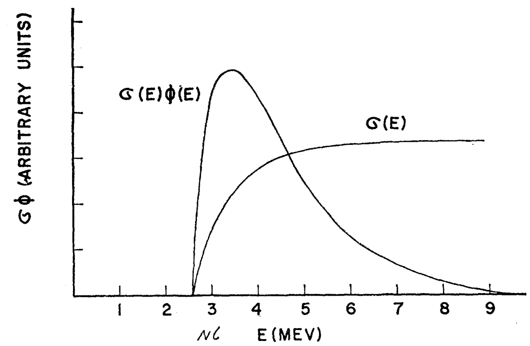

FIG. 5. Calculated shape of the cross section $\sigma(E)$ of the $Pb^{208}\{n,n'\gamma(2.6\text{ Mev})\}Pb^{208}$ reaction, and product $\sigma(E)\Phi(E)$ of this cross section with the shape of the fission-neutron energy spectrum.

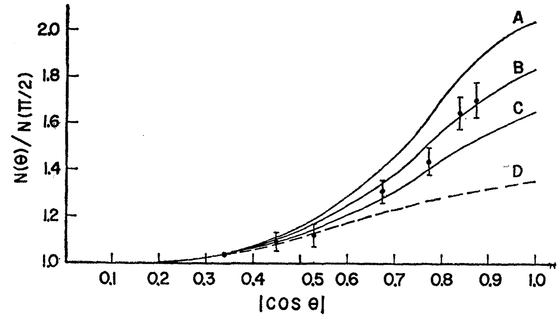

FIG. 6. Relative yield of 2.6-Mev γ rays as a function of $|\cos\theta|$, where θ is the angle between the incident neutron direction and outgoing γ-ray direction. Curves A, B, and C were calculated assuming that the 2.6-Mev state in Pb^{208} is a 3^- state, and using incident neutron energies of 3.5, 4.1, and 6.0 Mev, respectively. Curve D was calculated assuming the 2.6-Mev state is a 2^+ state, and using an incident neutron energy of 4.1 Mev.

difference could be seen between the $\frac{1}{8}$- and $\frac{1}{16}$-inch data, all the data were averaged, so that the final standard deviation of the ratio of intensities at two different angles is between 3 and 4%.

III. RESULTS

In order to compare the experimental and theoretical angular distributions, it is necessary to have some notion of the energy of the incident neutrons which cause the reaction. Figure 5 shows a plot of the shape of the cross section for the reaction $Pb^{208}\{n,n'\gamma(2.6\text{ Mev})\}Pb^{208}$, calculated from the theory of Hauser and Feshbach.[4] Also shown in Fig. 5 is the shape of the curve which results when this cross section is multiplied by the shape of the fission-neutron energy spectrum. Only qualitative conclusions can be drawn from the shape of this reaction rate curve, because the theoretical cross-section curve is not well established, and because the energy spectrum of fast neutrons from the beam port of a pool reactor is distorted somewhat from the fission spectrum. Within these limitations, we find that (a) the reaction rate curve has a maximum at about 3.5 Mev, (b) about 70% of the reactions are induced by neutrons with energies between 3.2 and 6 Mev and (c) the median neutron energy at which the reaction occurs (half the reactions occur at greater energies) is about 4.2 Mev.

Figure 6 shows the measured angular distribution, together with several theoretical distributions, calculated from Satchler's equation for several different conditions. Curves A, B, and C were calculated assuming that the 2.6-Mev state in Pb^{208} is a 3^- state, as it is known to be, and using incident-neutron energies of 3.5, 4.1, and 6 Mev, respectively. Curve D results from assuming that the state in Pb^{208} has quantum numbers 2^+, and using 4.1 Mev as the incident-neutron energy. The transmission coefficients used were those tabulated by Beyster *et al.*[5] for bismuth. For calculations using the 3^- quantum numbers, incident waves with $l\leq 4$ and outgoing waves with $l\leq 3$ were considered. For curve D only neutrons with $l\leq 3$ were considered. The experimental data in Fig. 6 are plotted so that the point at 110° falls on the calculated curve.

From the curves and data shown in Fig. 6 we have concluded that, for the particular reaction studied here, (a) the energy dependence of the angular distribution given by Satchler's equation is sufficiently small that the validity of the equation can be checked using neutrons with the energy distribution resulting from fission; (b) the experimental angular distribution is well described by Satchler's distribution for a $3^-\rightarrow 0^+$ transition; and (c) the angular distribution is sufficiently sensitive to the quantum numbers of the states involved in the transition that a $3^-\rightarrow 0^+$ transition can easily be distinguished from $2^+\rightarrow 0^+$ transition.

ACKNOWLEDGMENT

Discussions with C. H. Blanchard concerning this work have proved helpful.

[5] J. R. Beyster, R. G. Schrandt, M. Walt, and E. W. Salmi, Los Alamos Scientific Laboratory, Rept. No. 2099 (unpublished).