Gamma Rays from Neutron Inelastic Scattering in B^{10}, F^{19}, and Fe^{56}†

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(Received September 21, 1959)

The cross section for excitation of the 0.72-Mev gamma ray in the $B^{10}(n,n'\gamma)B^{10}$ reaction has been measured for neutron bombarding energies from threshold to 5.2 Mev. Resonances were observed at 1.93 Mev, 3.31 Mev, 4.1 Mev, and 4.73 Mev, with evidence of a broad resonance at 2.6 Mev. The angular distributions of the 0.110-Mev and 0.197-Mev gamma rays in the $F^{19}(n,n'\gamma)F^{19}$ reaction and the 0.847-Mev gamma ray in the $Fe^{56}(n,n'\gamma)Fe^{56}$ reaction were also measured at a neutron energy of 2.56 Mev. The first of these was isotropic, as would be expected for the decay of a spin-$\frac{1}{2}$ level; the last two showed anisotropies but were symmetrical about 90°. The angular distribution of the Fe^{56} gamma ray agrees very well in both shape and absolute magnitude with calculations based on the statistical model. Since this model predicts angular distributions for Fe^{56} that have a strong dependence on the spin assumed for the excited state, it appears that such angular distribution measurements may be a useful technique in nuclear spectroscopy.

INTRODUCTION

MEASUREMENTS of the gamma rays produced by inelastic scattering of fast neutrons have already proved to be a useful tool in nuclear spectroscopy. It has been found, for example, that, except for the case of light nuclei, the lowest neutron energy at which inelastic scattering is observed is very close to that which one would calculate from the conservation of energy.[1] Thus, the threshold for observation of a gamma ray provides information on the excited state from which it originates. Furthermore, from the relative intensities of the gamma rays appearing at the threshold one obtains the branching ratios for the decay of that state. In addition, in light nuclei resonances in the gamma-ray yield indicate the position of levels in the compound nucleus.

Experiments of the type mentioned above give information principally on the positions and decay schemes of excited states. There is some theoretical evidence from the work of Hauser and Feshbach[2] on the statistical model of the compound nucleus that the cross sections for inelastic scattering depend on the spin and parity of the excited state; however, the experimental evidence on this point has been rather contradictory.[3] A measurement that might be expected to yield more information on spin and parity is that of the gamma-ray angular distribution. This technique has already proved to be a very powerful one in (p,γ) reactions and it was hoped that it might prove useful in neutron inelastic scattering also.

In the work reported here the angular distribution of the gamma rays from the first excited state of Fe^{56} was measured in order to test the statistical model and to see how much information on spin and parity could be obtained from such measurements. This nucleus was chosen because the first excited state is abundantly produced by neutrons and the gamma-ray intensity is therefore favorable. Furthermore, the elastic and nonelastic neutron cross sections for Fe^{56} have been studied extensively; hence the optical model parameters for neutron interactions with this nucleus are fairly well known.

The gamma-ray angular distributions for the first two excited states of F^{19} were also measured. Although the statistical model would not be expected to apply here, these measurements were made partly as a test of the experimental method since the spin of $\frac{1}{2}$ for the first excited state of F^{19} requires that its gamma-ray angular distribution be isotropic.

In another experiment the cross section for the excitation of the 0.717-Mev gamma rays from the first excited state of B^{10} was measured for neutron energies from the threshold to 5.2 Mev.

EXPERIMENTAL PROCEDURE

The experimental procedure was similar to that described previously.[4] Monoenergetic neutrons were produced by bombarding a gaseous tritium target with protons from an electrostatic accelerator. The tritium was contained at a pressure of 35 cm Hg in a thin-walled stainless steel cell 3 cm long with a nickel entrance foil 1.2×10^{-4} cm thick. The neutron energy resolution was approximately 30 kev over most of the energies reported on here; however, below 2.5 Mev the energy spread increased slowly, becoming 35 kev at a neutron energy of 1.9 Mev and 40 kev at 1.5 Mev. A NaI(Tl) crystal 2.57 cm long by 2.54 cm in diameter mounted on a DuMont 6292 photomultiplier was used to detect the gamma rays. The photomultiplier output, after amplification by a Los Alamos Model 250 preamplifier and amplifier, was fed into a 10-channel pulse-height analyzer, which allowed a separation of the photopeak signal from the background caused by

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[1] Joan M. Freeman, in *Fast Neutron Physics*, edited by J. L. Fowler and J. B. Marion (Interscience Publishers, New York, to be published).
[2] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[3] R. M. Kiehn and C. Goodman, Phys. Rev. **95**, 989 (1954); J. B. Guernsey and A. Wattenberg, Phys. Rev. **101**, 1516 (1956).
[4] R. B. Day, Phys. Rev. **102**, 767 (1956).

Compton scattering of gamma rays and by the inelastic scattering and absorption of neutrons in the crystal and nearby material.

Ring geometry was used. The detector was located in front of the neutron source, and a ring of material containing either B^{10}, Fe^{56}, or F^{19} was placed around the detector. The axis of the ring passed through the source and detector so that gamma rays entering the detector from all points in the ring made approximately the same angle with the incident neutrons. The NaI crystal was shielded from the neutron source by a cone of tungsten alloy 30 cm long.

For the measurement of the $B^{10}(n,n'\gamma)$ excitation function, a ring 2.11 cm thick with 5.08-cm inside diameter and 10.4-cm outside diameter was placed with its center 43.1 cm from the center of the neutron source. The ring consisted of compressed amorphous boron powder enriched to 95% B^{10}; a binder of $(B^{10})_2O_3$ amounting to 8% by weight of the entire material was added for mechanical strength. The density of the resulting material was 1.10 g cm^{-3}. With the NaI crystal inside the boron ring, the average angle between the directions of the observed gamma rays and the incident neutrons was 95°. The rings used for the measurements on F^{19} and Fe^{56} were 1.0 cm thick with inside and outside diameters of 7.6 cm and 9.6 cm, respectively. The materials used were Teflon and cold-rolled steel. In the angular distribution experiments the samples were placed with their centers 46.8 cm from the center of the neutron source, and the distance between detector and source was varied to measure the gamma rays produced at different angles to the incident neutrons.

The data were analyzed as described in a previous report.[4] For the $B^{10}(n,n'\gamma)$ reaction, cross-section values were obtained from a knowledge of the neutron flux striking the sample, the number of B^{10} nuclei in the sample, and the gamma-ray flux observed with the scintillator. The neutron flux was obtained from the counting rate of a "long counter" whose efficiency had been calibrated with the use of known sources and with a counter telescope. The gamma-ray flux was computed from the number of counts in the photopeak of the pulse-height distribution, the crystal efficiency having been determined by observing the counting rate produced by calibrated sources placed in the position normally occupied by the B^{10} ring. Corrections were made for the absorption of gamma rays in the boron. No correction was made for multiple scattering or for attenuation of the neutron beam in the ring since for the ring size used these two effects nearly cancel, with a resulting error of only a few percent.

In the angular distribution measurements the distance between the scattering ring and detector was changed for each angle; thus the detection efficiency was a function of angle. In order to obtain the correct angular distribution the detector efficiency at each angle was calculated using Eq. (1) of reference 4. In this way the self-absorption of the scattering rings was also taken into account. At large angles the photomultiplier partially shielded the NaI crystal from the gamma rays emitted by the scattering ring. The effect of this absorption was determined by measuring the photopeak counting rate as a gamma-ray source of appropriate energy was rotated about the detector. For this purpose sources of Mn^{54} and Lu^{177} were used, since they emit gamma rays whose energies are nearly the same as those observed in Fe^{56} and F^{19}, respectively. The cross sections for excitation of the gamma rays in F^{19} and Fe^{56} were obtained by normalizing the angular distributions to agree with the values previously measured at 95°.[4] The latter values have been reduced by 4% to take into account the more accurate values recently obtained for the long counter efficiency.[5]

RESULTS

The cross section for the production of 0.72-Mev gamma rays by inelastic scattering of neutrons from B^{10} is given as a function of energy in Fig. 1. The measurements were made only at 95° and the values given in the figure are 4π times the differential cross section for gamma emission at 95°. These values will equal the total cross section for gamma emission if the gamma rays are produced isotropically. The circles denote data obtained in one run from 1.1 Mev to 5.2 Mev and the triangles indicate the cross sections at intermediate energies found by a later run progressing from 5.2 Mev to threshold. The close agreement between the two sets of values is indicative of the consistency of the measurements. The absolute error in the cross-section scale, taking into account uncertainties in the neutron flux, gamma-ray yield, etc., is 10%. This figure shows resonances in the cross section at 1.93 Mev, 3.31 Mev, ~4.1 Mev, and 4.73 Mev. In addition, the peaks at 1.93 Mev and 3.31 Mev appear

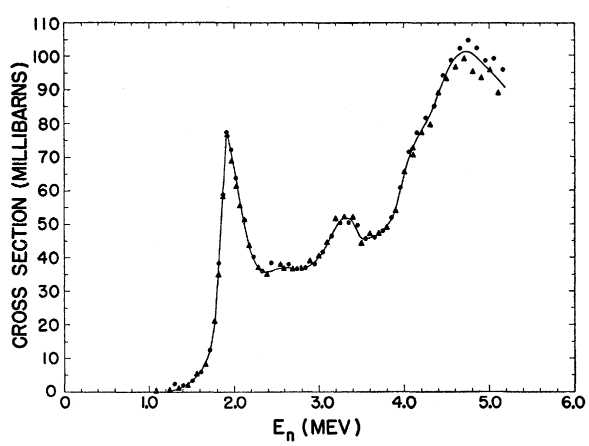

FIG. 1. Cross section for production of 0.72-Mev gamma rays in the reaction $B^{10}(n,n'\gamma)B^{10}$. The circles and triangles refer to data obtained in two separate runs. The cross sections shown here are 4π times the differential cross section at 95°.

[5] J. E. Perry, Jr. (private communication).

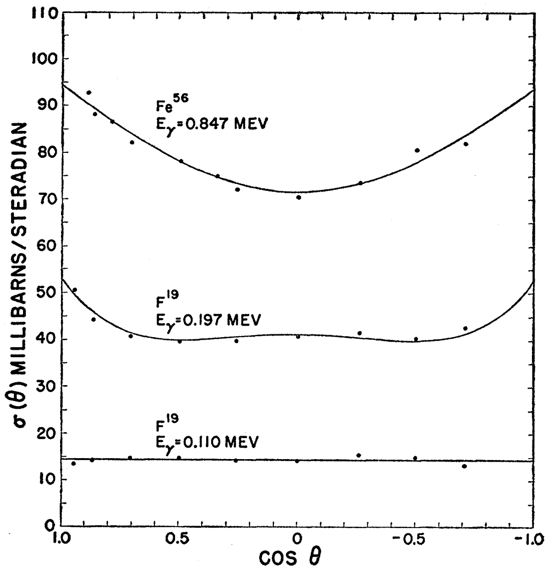

FIG. 2. Gamma-ray angular distributions for F^{19} and Fe^{56} at $E_n=2.56$ Mev. The solid lines are the least-squares fits to the data.

to be superimposed on a broad resonance centered at 2.6 Mev. The width at half maximum of the peak at 1.9 Mev is 0.43 Mev; however, if one subtracts the background on which it is superimposed, the width at half maximum is reduced to 0.26 Mev. The latter figure is probably a better value for the width of the 1.9-Mev resonance in this reaction. The resonance at 3.31 Mev is the only other one sufficiently pronounced for its width to be measured here. If one subtracts a reasonable background from the other resonances, the resulting curve for the 3.31-Mev resonance has a width of 0.37 Mev.

Resonances for B^{10} plus neutrons in the energy range covered here have previously been observed in neutron total cross-section measurements at 1.8 Mev, 2.73 Mev, and 4.1 Mev,[6] and in the $B^{10}(n,\alpha)Li^7$ reaction at 1.86 Mev, 2.8 Mev, and 4.1 Mev.[7] These energies are in fair agreement with the energies of the resonances observed here at 1.93 Mev, 2.6 Mev, and 4.1 Mev. The 3.31-Mev and 4.73-Mev resonances have not been seen before.

Figure 2 gives the differential cross section for production of the 0.847-Mev gamma rays from Fe^{56} and for the 0.110- and 0.197-Mev gamma rays from F^{19}. In each case the incident neutron energy was 2.56 Mev. The angular distributions are symmetric about 90°, a condition which is required for isolated levels. Within the experimental uncertainties, the angular distribution of the 0.110-Mev radiation from F^{19} is isotropic, in agreement with the theoretical predictions for transitions from an excited state with spin $\frac{1}{2}$. This result shows that the method of measuring angular distributions used here does not distort the distribution. The shape of the angular distribution curve for Fe^{56} is in good agreement with those obtained by Cranberg and Levin[8] at neutron energies of 2.25 Mev and 2.45 Mev.

The data shown in Fig. 2 have been fitted to a Legendre polynomial expansion of the form

$$\sigma(\theta)=\alpha_0+\alpha_2P_2(\cos\theta)+\alpha_4P_4(\cos\theta),$$

by means of a least-squares procedure. The coefficients thus obtained, together with their errors, are summarized in Table I.

We have compared the results of the gamma-ray

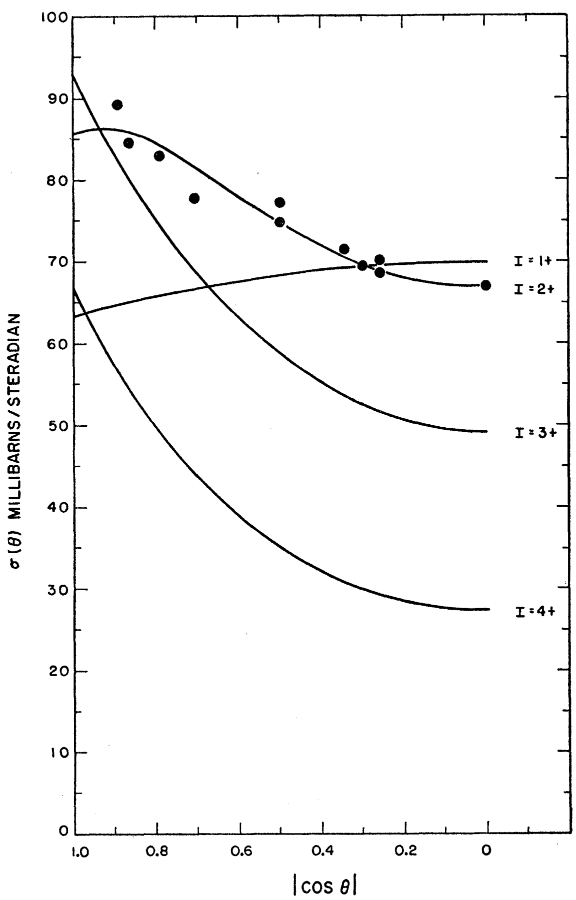

FIG. 3. Comparison of the statistical model predictions with the experimental angular distribution of the 0.847-Mev gamma rays from Fe^{56}. The solid curves are the theoretical predictions for various assumed spins of the first excited state, while the circles are the experimental points. The curves for $I=1+$ and $2+$ have been corrected for the angular resolution of the detector. This correction was always less than 4%.

[6] Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951). N. G. Nereson, Los Alamos Scientific Laboratory Report LA-1655 (unpublished). This work has also been included in *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958), 2nd ed.

[7] Petree, Johnson, and Miller, Phys. Rev. **83**, 1148 (1951); H. Bichsel and T. W. Bonner, Phys. Rev. **108**, 1025 (1957).

[8] L. Cranberg and J. S. Levin, Phys. Rev. **103**, 343 (1956).

angular distribution for Fe^{56} with the predictions of the statistical theory by using the formulas given by Satchler.[9] In these calculations we have used the neutron transmission coefficients given by Beyster *et al.*,[10] which were obtained by fitting neutron scattering data with a diffuse surface complex potential well. The results of the calculations for different assumptions as to the spin of the first excited state of Fe^{56} are compared with the experimental data in Fig. 3. The experimental data given here are the measured data decreased by 3.5 millibarns/steradian to take into account the cascading to the 0.847-Mev state from the second excited state at 2.08 Mev. The value 3.5 was obtained from the cross section for exciting the 2.08-Mev level at a neutron energy of 2.56 Mev[4] by assuming that the contribution of the cascade transition is isotropic. This state, which has spin and parity of 4+, was also taken into account in the theoretical calculations.

The agreement between the experimental data and the calculated angular distribution for $I=2$ (the known spin of the first excited state) is remarkably good in view of the fact that no normalization or adjustable parameter has been used in the calculations other than the selection of complex potential well parameters to fit the elastic scattering data. Thus it is seen that the statistical model gives a very good account of the inelastic scattering in this case. In order to establish the range of validity of the model it will be necessary to compare it with experimental data for a number of other elements and neutron energies. In this connection it appears that the best procedure is to select the parameters of the complex potential well to fit the experimental values of the total cross section, the differential elastic cross section, and the inelastic collision cross section and then to use these parameters to calculate the transmission coefficients required by the statistical model.

TABLE I. Coefficients obtained in a least-squares fit of the gamma-ray angular distribution data to a Legendre polynomial. The coefficients are in millibarns/steradian.

Element	E_γ(Mev)	α_0	α_2	α_4	$4\pi\alpha_0$(mb)
F^{19}	0.110	14.5±0.8	−0.9±1.8	−0.4±0.7	182
F^{19}	0.197	42.2±1.4	5.7±3.2	5.1±1.2	530
Fe^{56}	0.847	79.8±2.4	15.5±5.8	−1.0±2.2	1003

It is interesting to note that the theoretical angular distributions shown in Fig. 3 have a strong dependence on the spin assumed for the excited state. In the particular cases illustrated here only even parity was considered for the excited states; however, other calculations have shown that the cross sections can also be sensitive to the parity assumed. Thus, for cases where the statistical model may be valid, it is seen that the model may be very useful in obtaining the spin and parity of excited states. An attempt was made to apply the statistical model to the case of the F^{19} angular distributions also. However, the calculated cross sections did not agree with those observed, indicating that the assumptions of the model are probably not fulfilled for so light a nucleus.

ACKNOWLEDGMENT

We should like to thank John G. Wills for coding the statistical model calculations for computation on an IBM 704 computer.

[9] G. R. Satchler, Phys. Rev. **104**, 1198 (1956); **111**, 1747 (1958). In the expression given here for the gamma ray angular distribution following neutron inelastic scattering the quantity $(2J_1+1)$ following the summation sign should be replaced by $(2J_1+1)^{\frac{1}{2}}(2J_2+1)^{\frac{1}{2}}$.

[10] Beyster, Schrandt, Walt, and Salmi, Los Alamos Scientific Laboratory Report LA-2099 (unpublished).