PHYSICAL REVIEW VOLUME 104, NUMBER 4 NOVEMBER 15, 1956

Scattering of 4.4-Mev Neutrons by Aluminum, Calcium, Chromium, and Bismuth*

J. B. WEDDELL
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania
(Received June 4, 1956)

The spectra of neutrons scattered by aluminum, chromium, calcium, and bismuth for an incident neutron energy of 4.4 Mev have been measured by the proton-recoil nuclear plate technique. The energies of the levels excited by the $(n,n'\gamma)$ process, given here, are obtained from previous measurements of the de-excitation gamma-ray energies while the cross sections are based on the nuclear plate results alone.

The results are: aluminum, scattering angle 82°: elastic, 46±10 mb/sterad; unresolved inelastic levels at 0.84 and 1.01 Mev, 19±7 mb/sterad; 2.23-Mev level, 15±5 mb/sterad; 3.0-Mev level, 10±5 mb/sterad; calcium at 82°: elastic, 49±12 mb/sterad; inelastic—none; chromium at 90°: elastic, 37±7 mb/sterad; 1.45-Mev level, 14±5 mb/sterad; 2.43-Mev level (partially resolved), 5.0±2.5 mb/sterad; 3.13-Mev level (partially resolved), 14±7 mb/sterad; bismuth at 82°: elastic, 185±40 mb/sterad; unresolved spectrum in energy range 0.9 Mev to 2.5 Mev, 135±45 mb/sterad.

INTRODUCTION

MEASUREMENTS of the neutron spectrum from the interaction of Mev-neutrons with nuclei provide information on the cross section for elastic scattering at the angle of measurement and on the energies and excitation cross sections for levels excited in the $(n,n'\gamma)$ process. In order to relate this information to the general problem of nuclear structure, these results may be compared to values calculated from some theoretical description of the fast neutron scattering process. At the present time, the energies of the levels excited cannot be satisfactorily calculated, and these results can only be compared with energy levels obtained by other methods of excitation. Cross sections may, on the other hand, be calculated from the theory of Feshbach, Porter, and Weisskopf and the extension of this theory to inelastic scattering by Hauser and Feshbach. The results of such a comparison, although at present necessarily incomplete, give some indication of the validity of the theory in predicting the inelastic processes.

The selection of elements which may be studied is limited by the experimental technique. For practical results, the scatterers must be essentially monoisotopic and in the elemental form, and the energy levels to be investigated must have wide level spacing. Aluminum and chromium were selected for a study of the detailed line structure, and Bi^{209}, to investigate the type of neutron spectrum from a heavy element. Calcium, although known to have no inelastic levels which may be observed by this technique at 4.4-Mev bombarding energy, was of interest because of its elastic cross section.

EXPERIMENTAL

The neutron spectra from the scattering of 4.4±0.05 Mev neutrons by aluminum, calcium, and bismuth were measured at a scattering angle of 82°±5°, and by chromium at 90°±5°, by the proton-recoil nuclear plate technique. The exposure geometry and other details of the experiment are similar to those described in a previous report.[1] The scatterers were in the form of flat elliptical disks 13.8 cm × 8.8 cm by such thickness as to give approximately the same number of scatterer atoms. The thickness of the various scatterers and the estimated double to single scattering ratios were: Al, 0.44 cm, 4%; Ca, 2.54 cm, 8%; Cr, 0.64 cm, 5%; and Bi, 1.59 cm, 22%.

The standard method of calculating cross sections[2] from nuclear plate exposures was employed in the earlier work. This method involves calculation of the absolute nuclear plate sensitivity and a measurement of the integrated absolute neutron flux incident upon the scatterer. The experimental quantities entering into these determinations are subject to possible systematic errors of unknown magnitude. Some of these uncertainties may be eliminated by adapting the well-known ratio method of cross-section measurement to the nuclear plate technique.[3]

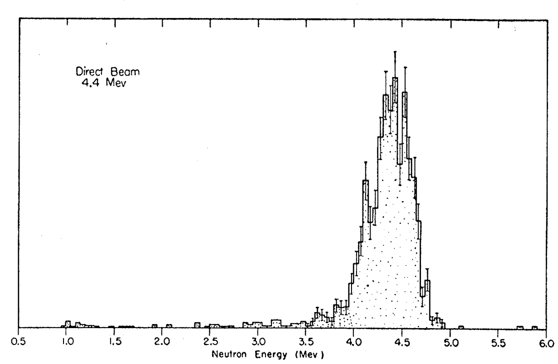

FIG. 1. Spectrum of direct beam neutrons. 1051 tracks measured in 51.1 mm³ of emulsion.

[1] Jennings, Weddell, Alexeff, and Hellens, Phys. Rev. 98, 582 (1955).
[2] L. Rosen, Nucleonics 11, Nos. 7 and 8 (1953).
[3] M. Walt and J. R. Beyster, Phys. Rev. 98, 677 (1955); M. Walt and H. H. Barschall, Phys. Rev. 93, 1062 (1954).

* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

TABLE I. Level energies and excitation cross sections.

Element, level, and scattering angle	Mean energy of scattered neutron group Mev	Level energy from reported measurements of de-excitations Mev	Level energy from other measurements Mev	Cross section from neutron spectrum mb/sterad	Cross section calculated from theory mb/sterad	Remarks
Al^{27}, elastic, 82°	4.0	...	...	46 ±10	49	
Al^{27}, inelastic, 82°, levels 1 and 2	3.1	0.84 1.01	0.844[a] 1.016[a]	19 ±7	13.2	
Al^{27}, inelastic, 82°, level 3	1.9	2.23	2.259[a]	15 ±5	9.2	
Al^{27}, level 4	Not observed	Not observed	2.782[a]	<3	...	
Al^{27}, inelastic, 82°, level 5	1.2	3.0	3.046[a]	10 ±5	...	
Cr, elastic, 90°	4.2	...	...	37 ±7	40	
Cr^{52}, inelastic, 90°, level 1	2.8	1.45	1.46[b] 1.46[c]	14 ±5	...	
Cr^{52}, inelastic, 90°, level 2	1.9	2.43	...	5.0±2.5	...	Not resolved
Cr^{52}, inelastic, 90°, level 3	1.3	3.13	...	14 ±7	...	Not resolved
Ca, elastic, 82°	4.2	...	...	49 ±12	See discussion	
Bi^{209}, elastic, 82°	4.3	...	...	185 ±40	165	
Bi^{209}, inelastic, 82°, level 1	3.4	0.895	...	20 ±10	...	
Bi^{209}, inelastic, 82°, energy interval 0.9 to 2.5 Mev	...	...	...	135 ±45	...	

[a] Inelastic proton scattering—reference 5.
[b] β decay of V^{52}—reference 11.
[c] β decay of Mn^{52}—reference 12.

This method, used in the present report, requires the exposure of an additional nuclear plate to the primary neutron beam in such a manner as to measure the integrated neutron flux at the scatterer. The nuclear cross section may be calculated simply from the results of the scattering experiment and this exposure, assuming only that the nuclear plates have the same sensitivity.[4] It is impractical to make the primary beam exposure concurrently with the scatterer experiment, but by making them separately and monitoring both with a Hanson long counter the result may be calculated. The histogram, Fig. 1, shows the spectrum of neutrons from the source as measured in the direct beam exposure.

RESULTS AND DISCUSSION

Aluminum

The neutron spectrum from the scattering of 4.4-Mev neutrons by Al^{27} (Fig. 2) shows a line spectrum in which the levels, except for the first two, are well resolved. The energies of the accompanying de-excitation gamma rays from the 4.4-Mev bombardment of Al^{27} have been measured by Griffith,[5] and by comparison with the neutron spectra it is evident that all gamma-ray transitions are directly to the ground state. Thus the measured gamma-ray energies may be interpreted as energy levels in Al^{27}. The elastic cross section at 82°, the energies and cross sections of the inelastic processes are shown in Table I.

The energy levels in Al^{27} have been measured by

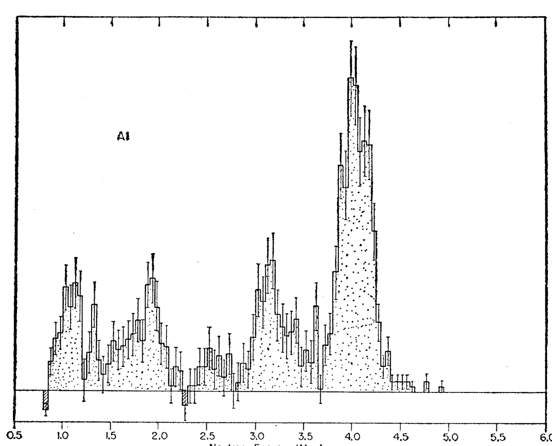

FIG. 2. Spectrum of neutrons scattered at 82° by Al. 2287 tracks measured in 523 mm³ of emulsion. Background subtracted.

[4] The differential cross section for scattering into a given energy interval is $(d\sigma/d\omega)=(AD^2/BN)$. A is the number of measured tracks, less background, per emulsion volume per long-counter event, in the given energy interval, for the scattering exposure; B is the corresponding number in the "peak" of the direct beam spectrum; the ratio A/B is corrected for the dependence on energy of the neutron-proton cross section; D is the rms average distance from the scatterer to the plates, and N is the number of atoms in the scatterer.

[5] G. L. Griffith, Phys. Rev. 98, 579 (1953).

inelastic proton scattering and the values as given by Reilly *et al.*[6] up to 3.1 Mev are included in Table I for comparison. All levels within the energy range measured here are excited by the neutron process except one at 2.73 Mev, for which there is at present no evidence in either the neutron or gamma-ray spectrum from inelastic neutron scattering.†

Emmerich[7] has carried out a series of calculations of the cross sections and angular distribution of elastic neutron scattering based on the cloudy crystal ball model of Feshbach, Porter, and Weisskopf, and has evaluated the necessary theoretical constants by a "best fit" comparison with experiment over a wide range of energies and elements. From this description, transmission coefficients were calculated for the Hauser and Feshbach theory of inelastic scattering and calculations were made of the cross sections for inelastic scattering through the various levels in Al^{27}. The energy level scheme assumed for aluminum is shown in Fig. 3 where the ground state spin was taken from Endt and Kluyver[8] and the ground state parity and the spins

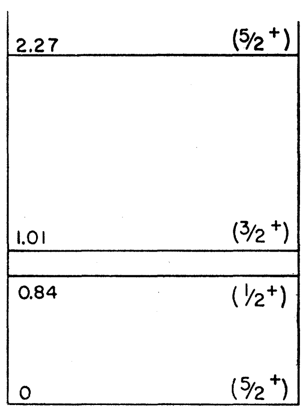

FIG. 3. Energy levels in Al^{27}.

and parities of the first and second levels are from Bothe.[9] A configuration of (5/2+) was assumed for the 2.23-Mev level to give the largest possible cross section as required by experiment. The sum of calculated values for the first two levels in Al^{27}, 13.2 mb/sterad, may be compared with the unresolved experimental result of 19±7 mb/sterad and the calculated value of the third level, 9.2 mb/sterad, with the experimental result, 15±5 mb/sterad. While the observed values are about 40% greater than the predicted values, the theoretical and experimental ratios of the cross sections for the first two levels to the cross section for the third level are in close agreement. This suggests that the above spin and parity assignments are correct.

[6] Reilly, Allen, Arthur, Bender, Ely, and Hausman, Phys. Rev. **86**, 857 (1952).

† *Note added in proof.*—A 2.72-Mev gamma ray has since been observed to accompany neutron scattering. I. L. Morgan, Phys. Rev. **103**, 1031 (1956).

[7] W. S. Emmerich (private communication).

[8] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 115 (1954).

[9] W. Bothe, Z. Naturforsch. **9a**, 402 (1954).

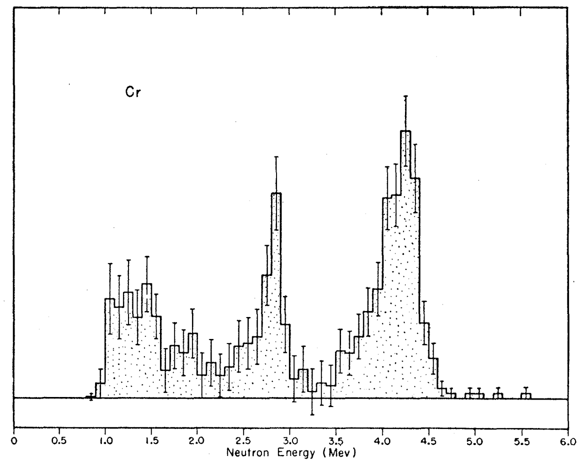

FIG. 4. Spectrum of neutrons scattered at 90° by Cr. 1582 tracks measured in 258 mm³ of emulsion. Background subtracted.

Chromium

The neutron spectrum from Cr, Fig. 4, shows the elastic group and one well-defined inelastic group at a neutron energy of 2.8 Mev. There are indications of two additional, poorly defined neutron groups at 1.9 and 1.3 Mev. Measurements of the de-excitation gamma-ray energies have been made by Sinclair[10] at 4.4 Mev and Scherrer, Allison, and Faust[11] at 3.2 Mev. A strong gamma ray at 1.43 Mev was found by both observers; it is associated with the 2.8-Mev neutron group reported here and is due to a transition from the first excited state in Cr^{52} to the ground state. Measurements of the β decay of V^{52} [12] and Mn^{52} [13] indicate that the weaker 0.75-Mev and 0.97-Mev gamma rays produced in inelastic scattering are in cascade with each other and

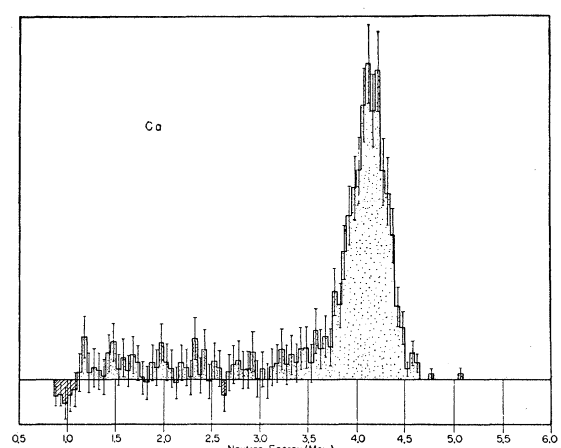

FIG. 5. Spectrum of neutrons scattered at 82° by Ca. 1657 tracks measured in 419 mm³ of emulsion. Background subtracted.

[10] R. M. Sinclair (private communication).

[11] Scherrer, Allison, and Faust, Phys. Rev. **96**, 386 (1954).

[12] G. A. Renard, Ann. phys. **5**, 385 (1950).

[13] W. G. Peacock and M. Deutsch, Phys. Rev. **69**, 306 (1946).

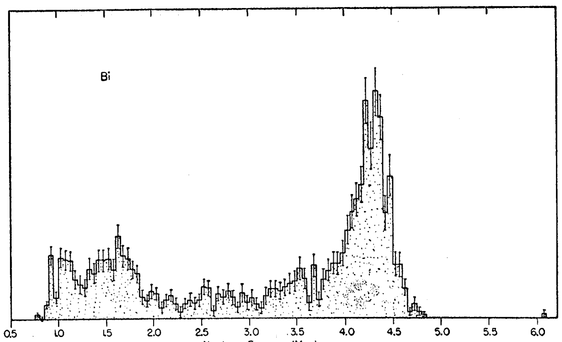

FIG. 6. Spectrum of neutrons scattered at 82° by Bi. 2434 tracks measured in 238 mm^3 of emulsion. Background subtracted.

with the 1.43-Mev gamma ray, and correspond to levels in Cr^{52} at approximately 2.43 and 3.13 Mev. Evidence from the neutron spectrum is not adequate to substantiate uniquely the presence of these two higher levels but is not in contradiction to it. Theoretical calculations of the cross sections for inelastic scattering from chromium have not been made as yet.

Calcium

The neutron spectrum from calcium is shown in Fig. 5. The elastic cross section at the energy and angle of this experiment is shown in Table I, and the absence of energy levels in Ca^{40} below the known first excited state at 3.35 Mev[14] is confirmed.

Theoretical calculations, based on the cloudy crystal ball model of the nucleus, predict values of the shape elastic cross section of 9 to 16 mb/sterad at this energy and angle, depending on the value of the absorption constant assumed in the theory. As the elastic cross sections calculated from this theory for other elements are in good general agreement with experiment, the discrepancy between the theoretical value for Ca and the experimental result of 49 ± 12 mb/sterad is outstanding. However, based on the present understanding of fast-neutron scattering, the cross section for formation of a compound nucleus is essentially independent of its mode of decay. The fact that Ca^{40} has no energy levels below 3.35 Mev through which inelastic scattering may occur suggests that the above discrepancy may be due to compound elastic scattering where the compound nucleus decays directly to the ground state.

Bismuth

The neutron spectrum from Bi^{209}, Fig. 6, shows the elastic group and a poorly defined inelastic group at 3.4 Mev, probably due to a known level in Bi^{209} at 0.895 Mev.[15] Below 2.5 Mev, a continuous spectrum of neutrons is observed increasing in numbers toward the low-energy end. This continuum shows some evidence of group structure particularly around 1.6 Mev which may be due to a level in Bi^{209} at 2.60 Mev as predicted from gamma-ray evidence.[16]

The distortion of this continuous spectrum from Bi^{209}, probably by partially resolved neutron groups, makes it impossible to apply the statistical evaporation description to this part of the spectrum.

ACKNOWLEDGMENTS

The author is particularly indebted to Dr. Werner S. Emmerich for the theoretical results which are compared to those of the experimental measurements reported here and for aid in understanding of their significance. He is also indebted to Dr. Russell A. Peck, Jr., of Brown University, to the plate readers there and at the University of Pittsburgh, and to Mr. Bruno Romeo and Mr. Richard Kronk for aid in the operation of the electrostatic generator.

[14] Braams, Bockelman, Browne, and Buechner, Phys. Rev. **91**, 474 (A) (1953).

[15] R. M. Kiehn and C. Goodman, Phys. Rev. **95**, 989 (1954); Eliot, Hicks, Beghian, and Halban, Phys. Rev. **94**, 144 (1954).

[16] M. A. Rothman and C. E. Mandeville, Phys. Rev. **93**, 796 (1954).