of 4.5-Mev neutrons. The origin of this gamma ray was recognized only on the basis of energetics. It is entirely possible that other charged-particle reactions exist which lead to radiation of less than 4.5 Mev and these gamma rays would be confused with those due to inelastic scattering.

Neither the γ-γ coincidence technique nor gamma-ray threshold measurements can rule out the possibility of a given gamma ray being produced by a charged-particle reaction. The n-γ coincidence technique should determine if a given gamma ray is due to inelastic scattering but it will not give a unique assignment of the transition involved. Thus the necessity of observing the scattered neutron energy spectrum is clearly evident.

Preliminary work in this laboratory has indicated that the 920-kev gamma ray in Zr is not due to neutron inelastic scattering. Threshold measurements for the production of this gamma ray indicate that if it were due to inelastic scattering it could come only from the excitation of a level at about 920 kev in Zr. However the photographic plate method and the method of Eliot *et al.*[8] fail to reveal the presence of a neutron group corresponding to a level at 920 kev in Zr. Both methods however detect the 850-kev level in Fe. Since gamma-ray yield data taken here indicate that the cross sections for the production of the 920-kev gamma ray in Zr and the 850-kev gamma ray in Fe are approximately equal, the neutron spectrum measurements should have revealed the 920-kev level in Zr if this were a case of inelastic scattering. Therefore it seems likely that the 920-kev gamma ray in Zr is due to an unidentified charged-particle reaction. Further work is being done on this problem.

On this basis it seems evident that unless gamma-ray data such as reported here are correlated with direct neutron measurements there is no assurance that the observed gamma rays are from inelastic scattering only, nor can transitions be assigned uniquely.

The author gratefully acknowledges many helpful discussions with Dr. W. S. Emmerich and the authors of the following paper.

[8] Eliot, Hicks, Beghian, and Halban, Phys. Rev. **94**, 144 (1954).

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Scattering of 4.4-Mev Neutrons by Iron and Carbon*

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The results of photographic measurements of the neutron spectrum from the scattering at 90° of 4.4-Mev neutrons by iron have been combined with measurements of the energies of de-excitation gamma rays from the same process, as reported in the preceding paper, to give values for the energy levels excited in Fe^{56}. The $(d\sigma/d\Omega)_{90°}$ for the various processes have been estimated from the areas under the peaks in the histogram. The energy levels and corresponding $(d\sigma/d\Omega)_{90°}$ for Fe^{56} are: elastic 0.076±0.02 barn/sterad; inelastic 0.85±0.02 Mev, 0.036±0.010 barn/sterad; 2.05±0.036 Mev, 0.021±0.007 barn/sterad; 2.58±0.054 Mev, 0.012±0.006 barn/sterad, 2.90 Mev. 0.020±0.013 barn/sterad. Similar measurements on carbon resulted in a $(d\sigma/d\Omega)_{90°}$ for the elastic process of 0.061±0.016 barn/sterad.

INTRODUCTION

A MEASUREMENT of the neutron spectrum from the inelastic scattering of 4.4-Mev neutrons by Fe^{56} has been made by using the proton-recoil photographic plate technique. Such a measurement should, in principle, provide a direct means of determining the energy levels in the Fe^{56} nucleus excited by the (n,n') process and a measure of the cross sections for their production. However, because of the limitations of the photographic method, the results give only approximate locations of the energy levels in Fe^{56}. The energies of the de-excitation gamma rays accompanying inelastic scattering can be measured with greater accuracy by using a NaI scintillation spectrometer, but the results do not indicate unique energy levels because of the existence of gamma-ray cascade processes. However, with the approximate location of the energy levels in a given nucleus determined from the neutron spectrum, it is likely that the gamma-ray cascade structure may be established and the levels accurately located by proper combination of the measured gamma-ray energies. The energies of the gamma rays associated with the inelastic scattering of 4.4-Mev neutrons by Fe^{56} are reported, among others, in the accompanying paper by G. L. Griffith. The gamma-ray energies thus measured are combined to give more accurate energy level values than are possible from the neutron data alone.

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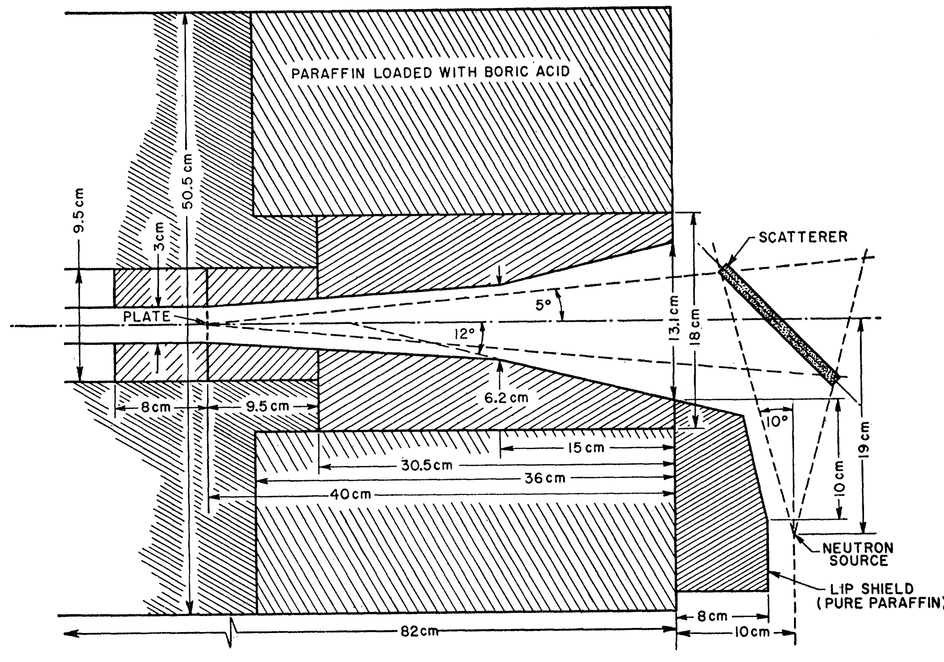

FIG. 1. Photographic plate exposure geometry.

Stelson and Preston[1] measured the inelastic scattering from Fe^{56} at 1.8-Mev neutron energy by the photographic method and found a level at 0.850 Mev also reported here. Other investigators have photographically studied inelastic neutron scattering at 14 Mev[2] and at 3.7 Mev.[3] Measurements of nonelastic cross sections[4] for these processes have been reported using various types of subtractive processes. As there is very little information available on the neutron spectra from the inelastic process, no detailed comparison with the gamma-ray measurements has hitherto been possible.

EXPERIMENTAL METHODS

Neutrons at 4.4 Mev with an energy spread of 100 kev were produced by bombarding a deuterium gas target with 1.3-Mev deuterons from the electrostatic generator, and the neutron yield from this source was determined by a "Hanson long counter" and calibrated Ra-Be source. To minimize room scattering of neutrons, all experiments were carried out in the center of a 17 ft×15 ft×15 ft sheet aluminum shed attached to the electrostatic generator building.

Standard proton-recoil photographic techniques[5] were used to measure the neutron spectrum from inelastic scattering. An exposure geometry similar to that of Stelson and Preston[2] was first used to study the spectrum from Fe^{56}. The results from the measurements of plates so exposed were not inconsistent with those reported here but the details of possible group structure in the low-energy region were obscured by a high background condition. By making use of a larger source-scatterer angle, as shown in Fig. 1, the number of scattered neutrons at the photographic plate was increased with no apparent increase in background. The scatterer, in this exposure geometry, takes the form of a thin elliptical plate set at 45° to the neutron forward direction and the thickness of the scatterer plates was chosen to give approximately an equal number of scatterer atoms. The iron scatterer was 6.4 mm thick and had an estimated multiple to single scattering ratio of about 12 percent. The carbon scatterer, where no inelastic scattering was expected, was 1.27 cm thick and had an estimated multiple to single elastic scattering ratio of 20 percent.

Ilford C-2, 200-micron plates were exposed in this geometry and the resulting proton tracks were measured by a plate reading group at Brown University, Providence, Rhode Island under the direction of Dr. Russell A. Peck, Jr. All tracks with n-p angles up to 15° and with equivalent neutron energies above 1 Mev were measured. The necessary angular corrections to the track length and calculation of the equivalent neutron energy were performed by an IBM computer. In order to be able to make a more realistic estimate of the errors in cross-section measurements derived from photographic data, a study was made of the variations in number of tracks accepted in similarly exposed plates by the various plate readers. At the energy of the elastic peak this variation was less than 20 percent

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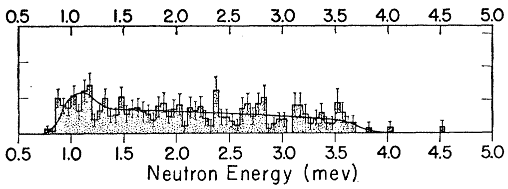

FIG. 2. Background. Results from exposure of plates in geometry of Fig. 1 without scatterer. 80 microampere-hours of integrated current on deuterium target. Histogram obtained by scanning 139 mm³ of emulsion. Background averaged as shown by line.

but the variation increased with decreasing neutron energy to about 50 percent at 1.5 Mev.

The results of these measurements are given in Figs. 2, 3, and 4 in the form of 50-kev interval histograms in which the unit of bar height has been corrected for the n-p cross section so that the histogram is proportional to the number of neutrons incident.

The background spectrum resulting from measurement of plates exposed in this geometry without the scatterer is given in the histogram of Fig. 2. This background has been averaged as shown by the solid line and is normalized to the same neutron exposure and volume of emulsion scanned as the exposure with the scatterer in place. The normalized background is then subtracted to give the results due to the scatterer alone.

RESULTS

The first excited state in C^{12} is known to be at 4.43 Mev,[6] so that no inelastic scattering is expected at the bombarding energy used. The neutron spectrum from carbon shown in Fig. 3 is of interest largely as a test of the experimental method. The elastic peak appears at

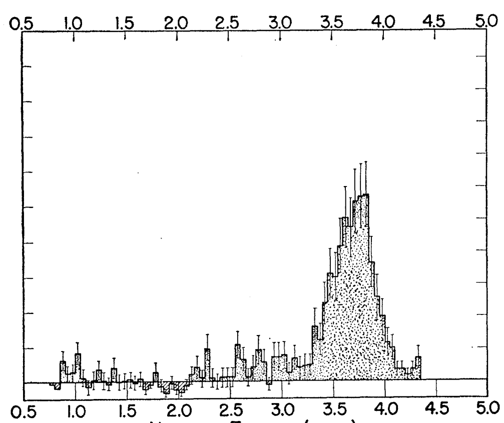

FIG. 3. Carbon. Neutron spectrum from plates exposed to carbon scatterer. 80 μa-hr integrated current on deuterium target. Histogram obtained by scanning 91.8 mm³ of emulsion. Averaged background of Fig. 2, normalized to same exposure and volume scanned, has been subtracted. Histogram corrected for (n-p) cross section. 730 tracks were measured from plates exposed to the scattering from carbon.

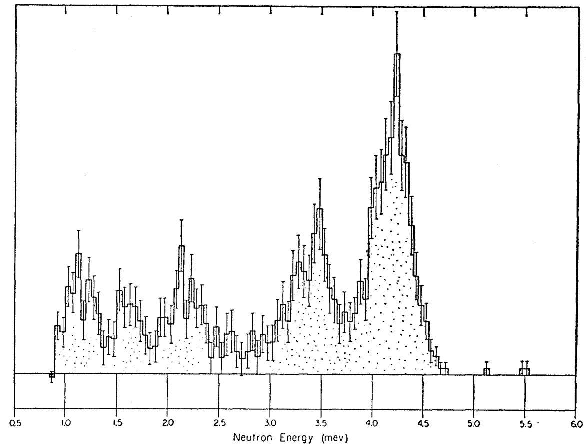

FIG. 4. Iron. Neutron spectrum from plates exposed to iron scatterer. 45.6 μa-hr integrated current on deuterium target. Histogram obtained by scanning 410 mm³ of emulsion. Averaged background of Fig. 2, normalized to same exposure and volume of emulsion, has been subtracted. Histogram corrected for (n-p) cross section. 1869 tracks were measured from plates exposed to scattering from iron.

3.7 Mev as expected from the 15 percent loss in neutron energy due to the momentum transfer in the neutron-carbon collision at 90°, and is broadened because of the geometrical conditions of the exposure. The slight asymmetry of the peak and the neutrons found just below 3.4 Mev are believed to be the result of multiple elastic scattering. The elastic differential cross section at 90° estimated from the area under the elastic peak is given in Table I. No gamma rays were found by G. L. Griffith from the inelastic scattering from carbon at 4.5 Mev.

The neutron spectrum from iron is shown in Fig. 4. Because of the high relative abundance of Fe^{56} in normal iron (91.52 percent), it is assumed that these neutron groups are due to this isotope alone. The

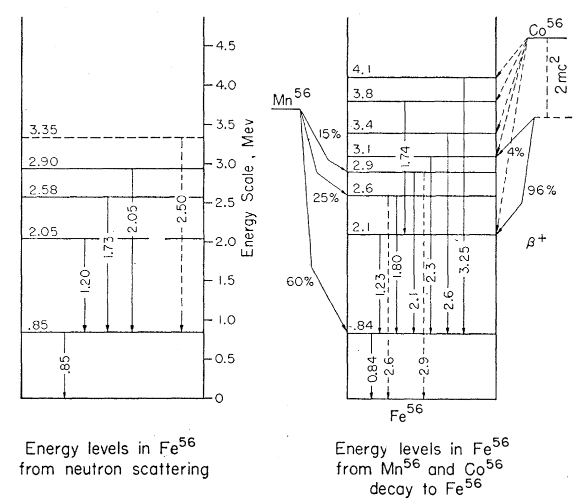

FIG. 5. Energy levels in Fe^{56}.

[6] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 24, 321 (1951).

neutron energies in the spectrum, the corresponding level energies, and the differential cross sections at 90° are given in Table I.

The errors in cross-section estimates are due mainly to uncertainties in the plate measurement process already discussed, and to an uncertainty of about 10 percent in the number of hydrogen atoms in the scanned volume of emulsion. Other errors in neutron source strength, geometry, etc., are probably small in comparison.

The total cross sections for the various processes may be approximated by assuming isotropic angular distribution for all inelastic processes and making use of measured[7] elastic angular distributions at nearby neutron energies. The sum of the total cross sections of the detailed processes may be compared with the transmission cross section measured at 4.4 Mev. The total elastic cross section for carbon is found to be 2.03±0.5 barns and may be compared with a measured transmission cross section of 1.8 barns.[8] The sum of the total elastic and inelastic cross sections for iron is 4.4±1.2 barns while the transmission cross section as measured by Nereson and Darden[9] is 3.7 barns.

DISCUSSION

With a knowledge of the approximate energies of the levels in Fe^{56} from the neutron spectrum measurement, it is possible to fit the gamma-ray energies reported by Griffith into a consistent energy level scheme as shown in Table II. The assumption made by Elliott and Deutsch,[10] Metzger and Todd,[11] and Sakai *et al.*[12] from the study of the decay of Mn^{56} and Co^{56} to Fe^{56}, that all strong gamma rays cascade through a level at 0.85 Mev, applies here and accounts for four of the gamma-ray energies observed. If the two remaining gamma rays at 2.50 and 3.52 Mev are also in cascade with the 0.85-Mev level, the energy levels involved are so high that the accompanying neutrons would not be observed in this experiment. The energy level scheme from Fe^{56} by inelastic neutron scattering studies and the levels observed by the decay of Mn^{56} and Co^{56} to Fe^{56} are shown in Fig. 5. Although it is observed that the levels in Fe^{56} from Mn^{56} are not the same as those from Co^{56}, the inelastic process appears to excite all possible levels. The agreement is quite good for the low-energy levels but is doubtful for levels above 3 Mev.

TABLE I. Neutron scattering from carbon and iron, photographic results.

Level	Neutron energy Mev	Level energy Mev	Cross section experimental $(d\sigma/d\Omega)_{90°}$ barns/sterad	Remarks
		Carbon		
Elastic	3.7	···	0.061±0.016	
		Iron		
Elastic	4.2	···	0.076±0.020	
Inelastic 1	3.4	0.8	0.036±0.010	
Inelastic 2	2.2	2.0	0.021±0.007	
Inelastic 3	1.6	2.6	0.012±0.006	
Inelastic 4	1.2	3.0	0.020±0.013	doubtful

TABLE II. Gamma rays from iron and the energy levels in Fe^{56}.

Gamma-ray energies, Mev	Level energies in Fe^{56}, Mev
0.85±0.02	0.85±0.02
1.20±0.03	2.05±0.036
1.73±0.04	2.58±0.054
2.05 } resolution	2.90
2.50 } doubtful	3.35 doubtful
3.52±0.09	4.37 doubtful

The present experimental cross section for elastic scattering may be compared to the theory of average cross sections developed by Feshbach, Porter, and Weisskopf.[13] The calculation carried out with a potential of

$$V_0(1+i\zeta)=-40(1+i0.05)\text{ Mev},$$

and a radius of 5.6×10^{-13} cm gave a $(d\sigma/d\Omega)_{90°}$ for the shape elastic scattering from Fe^{56} of 0.0904 barn as compared to the experimental elastic cross section of 0.076±0.02 barn. The inelastic cross sections may be calculated according to Hauser and Feshbach.[14] Preliminary attempts with transmission coefficients taken from Blatt and Weisskopf[15] yielded values incompatible with the experiments. Calculations making use of transmission coefficients of the Feshbach, Porter, and Weisskopf model are being deferred until more experience has been gained with the numerical constants V_0 and ζ from elastic scattering experiments.

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