Gamma Rays from the Inelastic Scattering of 14-Mev Neutrons in C^{12} and O^{16}†

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A NaI scintillation spectrometer has been used to study the gamma rays produced by the inelastic scattering of 14-Mev neutrons in carbon and oxygen. The scattering material was placed around the neutron source with the gamma-ray detector outside the scatterer. A gamma ray from the 4.43-Mev level in C^{12} was obtained with a cross section of about 0.3 barn. Gamma rays from the known level at 6.13 Mev and levels close to 7 Mev were obtained from O^{16} with a total cross section of about 0.2 barn.

INTRODUCTION

ONE way to obtain information about the energy levels of a nucleus is to ascertain experimentally which of the lines of its gamma-ray spectrum are excited by inelastic scattering of fast neutrons and to determine the excitation cross sections.[1–4] In this experiment the scattering material was placed around the neutron source, and the gamma rays detected in a NaI scintillation spectrometer. Carbon and oxygen were investigated.

EXPERIMENTAL APPARATUS AND PROCEDURE

Monoenergetic 14.1-Mev neutrons were produced in the Rice Institute Cockroft-Walton accelerator using the $H^3(d,n)He^4$ reaction. The target was tritium absorbed in zirconium.

The geometry is shown in Fig. 1. The neutron source was essentially a point source 5 mm in diameter. The carbon scatterer consisted of graphite blocks. Water was used for oxygen. A liquid hydrocarbon (machine oil) was used in addition so that carbon and oxygen could be compared with approximately the same hydrogen content in the scattering material. For water, the end of the target tube was immersed in a beaker of water 5 inches in diameter and 4.5 inches deep. The target was 3 inches from the bottom of the beaker and 1.5 inches from the surface of the water. For machine oil, exactly the same geometry was used as with water. For graphite, a cylinder 4.5 inches in diameter and 4 inches high was used. The end of the target tube was placed at the bottom of a cylindrical hole 1.2 inches in diameter and 2 inches deep drilled in the center of one end of the graphite cylinder. For all three scatterers, the gamma-ray detector was mounted just below and in close proximity to the scatterer.

A NaI crystal 1.5 inches in diameter and 1 inch long mounted on a 6292 photomultiplier tube detected the gamma rays. The pulse sizes from the photomultiplier tube were determined by a single-channel pulse-height analyzer. Crystal and photomultiplier quality were such as to give 10 percent or less full width at half-maximum on the 0.66-Mev gamma ray from Cs^{137} and a peak-to-valley ratio much better than 10 to 1. For energy calibration the Cs and the Po-Be 4.43-Mev gamma rays were used. The window width of the single-channel analyzer was checked in the standard manner with a precision pulse generator.

The neutrons were monitored by a scintillation counter using an anthracene scintillator $\frac{3}{4}$ inch in diameter by 1 inch high, located 18 inches from the target as shown in Fig. 1. The bias was chosen to count proton recoils in the anthracene with more than 9-Mev energy. A calibration relating the number of neutrons counted by the monitor to the number of neutrons at the target was obtained using a special target chamber with a thin window opening into an alpha-particle proportional counter. From the number of alpha-particles counted and the solid angle of the alpha-counter window at the target, the number of neutrons from the source could be determined. In order to correct the monitor for the effect of scattering material placed between it and the target, careful measurements were made of the monitor rates with and without scattering material, using a stable beam.

Measurements consisted in surveying the pulse spectrum from the NaI crystal with scattering material

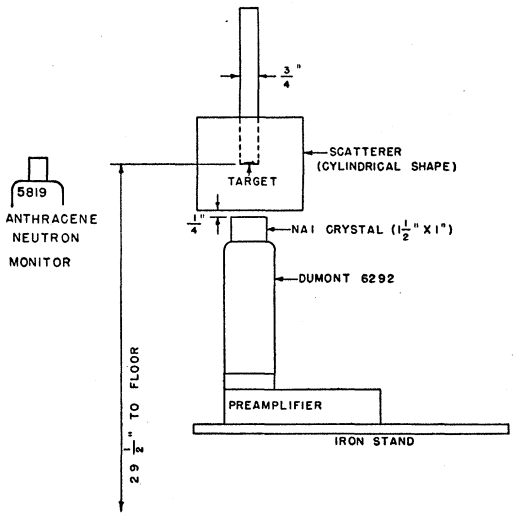

FIG. 1. Diagram of the relative position of the neutron source, scatterer, and NaI crystal.

† Supported by the U. S. Atomic Energy Commission.
[1] Lewis C. Thompson, Phys. Rev. **89**, 905 (1953).
[2] Robert B. Day, Phys. Rev. **89**, 908 (1953).
[3] Scherrer, Theus, and Faust, Phys. Rev. **89**, 1268 (1953).
[4] Scherrer, Theus, and Faust, Phys. Rev. **91**, 1476 (1953).

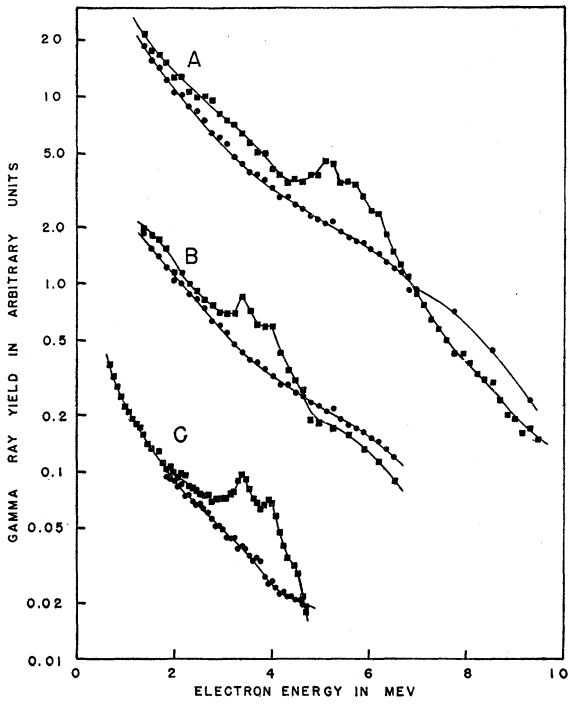

FIG. 2. The squares are the readings with the scatterer in place. The circles are the readings with the scatterer removed. *A* is water. *B* is machine oil. *C* is graphite. Different ordinate scales have been used for each set of curves. The curves of *B* have been plotted as 1/10 and the curves of *C* have been plotted as 1/200 of their intensity relative to *A*.

present and again with scattering material removed. A narrow window (1 volt) was used, and the points were spaced a window width apart in the regions of the peaks. The statistical accuracy was 3 percent up to 8 Mev and 6 percent at higher energies. The number of monitor counts was always at least a factor of 5 greater than the number of gamma-ray counts, so that the statistical uncertainty arose mainly from the number of gamma-ray counts.

RESULTS

The results of the measurements are plotted in Fig. 2. The squares represent points taken with scatterer in place; the circles represent background points taken with the NaI crystal exposed to the neutron source in the same position without scattering material. In Fig. 3 the background curves are subtracted to obtain the effect of the scatterer. In the subtraction no correction was attempted for the decrease in number of high-energy neutrons incident on the NaI due to the presence of the scatterer.

The pulse-height distribution from graphite (curve *C*) shows only a 4.4-Mev gamma ray, corresponding to the 4.43-Mev first excited[5] state in C^{12}. The distribution from water (curve *A*) shows 6.1-Mev and 7-Mev gamma radiation corresponding to the 6.13-Mev excited state and two states at about 7 Mev[6] in O^{16}.

Comparison of curve *A* from water with curve *B* from machine oil rules out the possibility that hydrogenous material increases the background effect in NaI in the 6-Mev region. Comparison of curve *B* with the graphite curve *C* indicates that the presence of two protons per carbon nucleus does not alter the carbon gamma-ray intensity by a detectable amount when intensities are referred to the same number of carbon scattering centers. Within the limits of accuracy of the present experiment, therefore, it is satisfactory to use water for its oxygen content.

The 6.13-Mev gamma ray in oxygen was estimated to have an intensity four times as great as the radiation at 7 Mev. The estimate was made graphically. It was assumed that the gamma radiation could be treated as two single lines, one at 6.1 and one at 7.0 Mev, and that each line would produce a pulse spectrum in the crystal-like curve *B* or curve *C* of Fig. 3 for the 4.4-Mev gamma ray from carbon. Using an intensity ratio of four for the 6.1 to one for the 7-Mev radiation resulted in a curve very similar to the experimental oxygen curve of Fig. 3.

The cross section for exciting the 4.43-Mev level in C^{12} was calculated by a numerical integration over the graphite scatterer, taking into consideration the solid angle subtended by each volume element of the scatterer at the target and at the crystal, the attenuation of neutrons in going from the target to the volume element, the attenuation of the gamma rays in going from the volume element to the crystal, and the probability that a 4.4-Mev gamma-ray incident on the crystal would

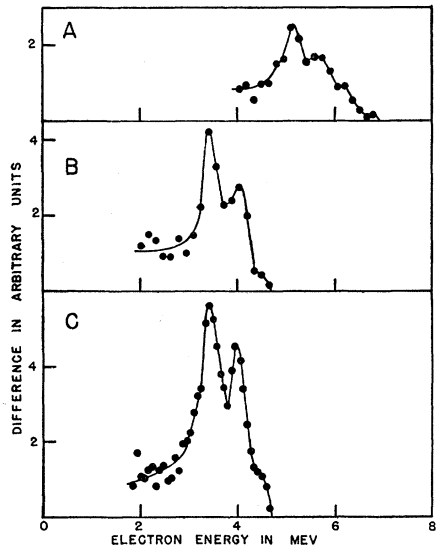

FIG. 3. Difference of the scatterer in place and scatterer removed in the vicinity of the pair peaks for the curves of Fig. 2. *A* is for water. *B* is for machine oil. *C* is for graphite.

[5] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952); see p. 355.

[6] See reference 5, p. 376.

result in a pulse in the peak of the pulse distribution. The value obtained by this method was 0.3 barn.

The ratios of the cross sections for exciting the 6.13-Mev level and the 7-Mev levels in O^{16} to the cross section for the 4.43-Mev level in C^{12} were obtained by comparing the areas under the curves A and B in Fig. 3 for water and oil, correcting for the difference in the densities of carbon and oxygen nuclei and for the variation of the probability of gamma-ray absorption by pair formation over the range 4.4 to 7.0 Mev. In this manner the cross section for the 6.13-Mev level in O^{16} was calculated to be 0.2 barn. The cross section for the 7-Mev oxygen gamma rays then becomes 0.05 barn.

The results from carbon are consistent with experiments on the energy distribution of inelastically scattered neutrons from carbon by the photographic plate method, both as regards cross section[7] and the larger probability of exciting the 4.43-Mev level than any other level.[8] The oxygen results are consistent with cloud chamber experiments on oxygen bombarded by 14-Mev neutrons,[9] where recoil O^{16*} nuclei were found with excitation energies principally in the range 6 to 7 Mev.

It can be seen from the character of the curves in Fig. 2, that a difficulty in this method of studying the excitation of gamma rays by inelastic neutron scattering arises from the effect of the neutrons on the NaI crystal itself and the impossibility of separating this effect from the effect of the gamma radiation from the scattering material unless there are clearly resolved peaks which are not observed with NaI alone. A number of geometrical arrangements were tried without finding one free from the objection that the presence of the scatterer changed the neutron background in the NaI crystal. The method, therefore, yields unambiguous results only in the case of scattering nuclei in which the low levels are widely spaced, so that gamma radiation is emitted in the form of a few relatively strong lines of high energy.

Acknowledgment is due Professor T. W. Bonner for many valuable suggestions.

[7] E. R. Graves and L. Rosen, Phys. Rev. **89**, 343 (1953).
[8] B. G. Whitmore, Phys. Rev. **92**, 654 (1953).
[9] J. P. Conner, Phys. Rev. **89**, 712 (1953).

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Polarization from Isolated Resonances

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Polarization from nuclear reactions may be obtained even from a single isolated level of the compound nucleus. Some aspects of this type of polarization are discussed and the implications of the one-level Wigner-Eisenbud formula are considered in this connection. A conjecture of Coester is discussed and compared with the Wigner-Eisenbud result.

I. INTRODUCTION

IN a recent paper,[1] the authors have derived a general formula for the state of polarization of the product beam from a nuclear reaction initiated by unpolarized particles. The polarization always results from interference between two different elements of the scattering matrix for the reaction. More explicitly, if the required angular momentum selection rules[2] are satisfied, polarization will arise under one of three conditions:

(a) The reaction goes with appreciable intensity by way of at least *two* compound states, differing in total angular momentum and/or parity. The initial and final orbital angular momenta and channel spins are unrestricted save by the selection rules governing complexity.

(b) The interference is between resonance elastic scattering and potential scattering. This possibility is limited to elastic scattering only, of course.

(c) The reaction goes with appreciable intensity through only *one* compound state. Under this restriction, the compound state must either be assembled or decay by means of at least *two* waves which differ in orbital angular momentum and/or channel spin.

It is further shown in A that the polarization (unlike the intensity) involves coefficients $i(R_1{}^*R_2-R_1R_2{}^*)$ [where R_1 and R_2 refer to the interfering matrix elements of $R\equiv S-1$] and therefore vanishes unless R_1 and R_2 differ in phase.

Relatively intense beams of high-energy polarized neutrons have been obtained from the $Li^7(p,n)$ reaction.[3] The polarization was detected by the use of elastic scattering from oxygen as an analyzer. The production reaction seems to be an example of type a and the detection is an example of type b. Reactions of type c seem, however, to offer considerable promise for several

[1] A. Simon and T. A. Welton, Phys. Rev. **90**, 1036 (1953), hereafter referred to as A.
[2] Reference 1, Sec. IV.
[3] H. B. Willard (private communication); Darden, Fields, and Adair, Phys. Rev. **93**, 931 (1954).