V. CONCLUSIONS

There appears to be little doubt that internal conversion electrons are accompanied by a weak continuous γ-radiation. The probability of this effect is of the same order of magnitude as given by the semiclassical theory. The angular distribution of the radiation seems to be quite different from that predicted. However, there is some reason to expect that the quantum-mechanical calculation might give results in poorer agreement with the semiclassical calculation in the case of internal conversion than in the case of β-decay, where the agreement is very good. This arises from the consideration of the nature of the calculation. In the case of β-decay the second-order calculation involves a single intermediate state, i.e., the first step of the transition is the emission of an electron from the nucleus, and the second step is then the emission of a photon of the continuous radiation. On the other hand, there are two possible intermediate states involved in the calculation for internal conversion: the first step may be the emission of either an electron or of a photon; the second step then supplies, respectively, a photon or an electron.

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The Photodisintegration Cross Section of Beryllium at 2.185 Mev

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The cross section for the photodisintegration of Be^9 at 2.185 Mev has been measured using gamma-rays which follow the beta-decay of Pr^{144}. A value of 3.9×10^{-28} cm^2 was found, in reasonably good agreement with the valence neutron model. This value is lower than the values at 1.81 Mev and 2.50 Mev, in agreement with the theoretical prediction that a minimum value of the cross section should be found near 2.2 Mev.

THE cross section for the photodisintegration of Be^9 has been measured at several energies.[1,2] The cross section increases from zero at the threshold (1.66 Mev) to a value of 10×10^{-28} cm^2 at 1.70 Mev (Sb^{124}). At 1.81 Mev (Mn^{56}) it has decreased to 6×10^{-28} cm^2. At 2.50 Mev (La^{140}) its value is 5×10^{-28} cm^2, while at 2.76 Mev (Na^{24}) it has increased one again to 7×10^{-28} cm^2. These results are shown in Fig. 1. It is clear that there is a minimum value of the cross section in the region between 1.81 and 2.50 Mev. The first maximum in the cross section can be ascribed to S neutrons whereas the second increase in the cross section is caused by the emission of higher angular momentum (D) neutrons. Measurements of the angular distribution of the neutrons[3] indicate that the distribution is spherically symmetric near the first peak and is of the form $a+b\sin^2\theta$ near the region of the second increase in cross section.

Guth and Mullin[4] have calculated the cross section and angular distribution as a function of gamma-ray energy using a valence neutron model. The Be^9 nucleus is pictured as consisting of a neutron moving in the field of a Be^8 core. Although Be^8 is unstable against decay into two alpha-particles by about 120 kev, the lifetime is very long compared to the time required to emit a neutron from Be^9. The cross section is calculated for $P\rightarrow S$ and $P\rightarrow D$ transitions. The former is the major contributor to the cross section near threshold whereas the latter interaction is more important at higher energies, i.e., near the second maximum. Guth's curve is shown in Fig. 1.

The cross-section data and angular distributions agree with the theoretical predictions made with the valence neutron model. However, no data have been available to check the theory in the region of the minimum. There is a scarcity of gamma-ray emitters with useful half-lives having energies near 2.2 Mev. When the presence of a line near this energy[5] was reported in the fission product chain $Ce^{144}-Pr^{144}$, a study of the $Be(\gamma,n)$ cross section was undertaken using these isotopes.

METHOD

Approximately one curie of 282-day[6] Ce^{144} was obatined from Oak Ridge as a sulfate in solution; it was treated with 6M NH_4OH and precipitated as $Ce(OH)_4$. The precipitate was ignited to CeO_2, which was canned in a 0.030-inch-wall stainless steel cylinder, one centimeter in diameter and one centimeter in height. The capsule was placed in a cavity in a beryllium sphere. The sphere had an outer diameter of 1.5 inches and was made in two sections and was assembled by screwing

[1] Russell, Sachs, Wattenberg, and Fields, Phys. Rev. **73**, 545 (1948).
[2] A. Wattenberg, *Photoneutron Sources, Preliminary Report No. 6*, Nuclear Science Series, Division of Mathematics and Physical Sciences, National Research Council (unpublished).
[3] Hamermesh, Hamermesh, and Wattenberg, Phys. Rev. **76**, 611 (1949).
[4] E. Guth and C. J. Mullin, Phys. Rev. **76**, 234 (1949).
[5] M. Goldhaber and E. der Mateosian, Brookhaven National Laboratory Report No. 51, (S-5), 1950 (unpublished).
[6] R. P. Schuman and A. Camilli, Phys. Rev. **84**, 158 (1951).

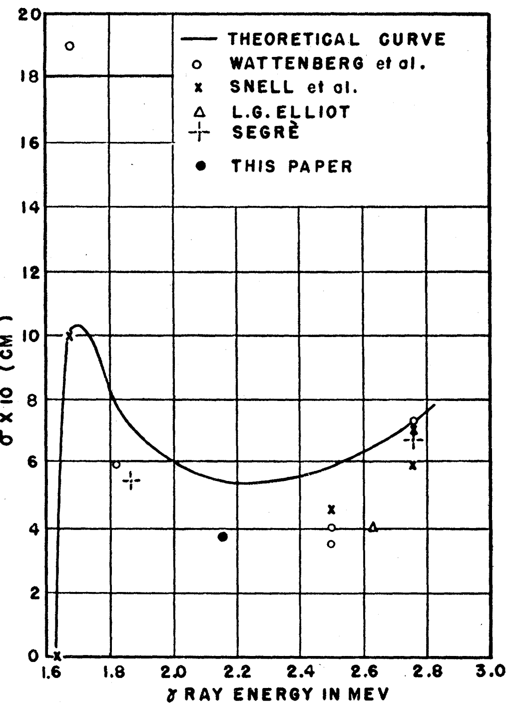

FIG. 1. The photodisintegration cross section of Be^9 [from E. Guth and C. J. Mullin, Phys. Rev. **76**, 234 (1949), and including result found in present experiment].

the two threaded pieces together. The neutron measurements were made one year after the preparation of the sample.

The detector was an enriched BF_3 pulse-ion chamber imbedded in a paraffin cylinder 20 centimeters in diameter. The response of the detector to neutrons was relatively independent of energy. The Ce−Be neutron yield was determined by comparison with a Ra−Be source of identical geometry whose strength was found by comparison with Argonne source No. 38 in the Argonne uranium-graphite pile by the method described by Hughes.[7]

The decay schemes of Ce^{144} and Pr^{144} have recently been studied.[8,9] Figure 2 shows Alburger's decay scheme. The major difference between this and Porter and Cook's result is in the intensity of the beta-branch leading to the 2.185-Mev level. Porter and Cook indicate that the branching ratio is the order of one percent.[10] The strength of the 2.185-Mev line could be determined by comparison with a source of known strength having a gamma-ray of nearly the same energy. Because of the difficulty mentioned previously in finding useful gamma-rays in this energy region, the comparison was made between the 1.48-Mev line from Nd^{144} and the 1.38-Mev line from Na^{24}. A NaI(Tl) crystal and a 5819 phototube were used in conjunction with a very stable twenty-channel pulse-height analyzer in order to make the comparison. Assuming that the efficiencies of detection by the crystal were identical for the 1.38 and 1.48-Mev lines and using the relative intensities of the 1.48 to 2.185-Mev lines as given in reference 8, the strength of the 2.185 lines was determined. The standard sodium source used for the comparison was prepared by irradiating a small sample of NaF in a known flux in the Argonne heavy water—moderated reactor; the size of sample and the duration of irradiation were chosen so that the activity of the 1.38-Mev line of the Na^{24} was approximately the same as that of the 1.48-Mev line in Nd^{144}. The value of the sodium cross section used was 0.505 barn.[11] The energy region around 1.5 Mev was scanned with the twenty-channel pulse-height discriminator. The data were plotted and a planimeter was used to compare the areas under the respective curves, which areas gave the relative intensities of the 1.38 to 1.48-Mev lines.

RESULTS AND CONCLUSIONS

The strength of the Ra−Be source was 1.38×10^6 neutrons/second. Relative to this the Ce−Be source gave a neutron yield of 4.3×10^3 neutrons/second. Using 2.185-Mev γ-rays (see Fig. 2 and reference 8), the strength of the 2.185-Mev line was 6.0×10^7 disintegrations/second.

The following formula (1) for the neutron yield was obtained by assuming that the cylinder in which the cerium was contained could be replaced by a sphere of the same volume located at the center of the beryllium and also assuming radial symmetry in the γ-ray emission:

$$\text{neutrons/second} = \sigma\rho q(0.6/\text{M.W.})(R-R'), \quad (1)$$

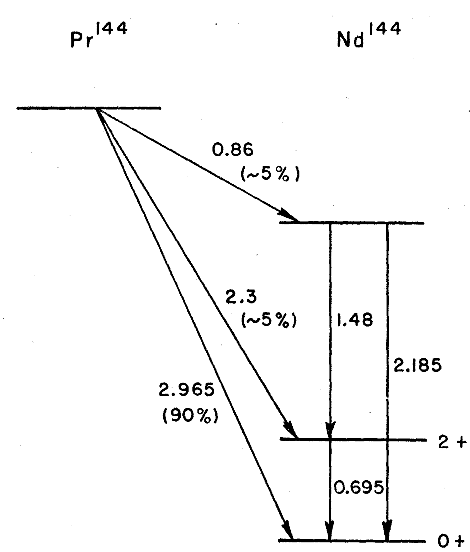

FIG. 2. The decay scheme of Pr^{144} according to D. Alburger and J. Kraushaar, Phys. Rev. **87**, 448 (1952).

[7] D. J. Hughes, Nucleonics **6**, No. 6, 50 (1950).
[8] D. E. Alburger and J. J. Kraushaar, Phys. Rev. **87**, 448 (1952).
[9] F. T. Porter and C. S. Cook, Phys. Rev. **87**, 464 (1952).
[10] Private communication with C. S. Cook indicates that their result is not less than 0.6 percent for this ratio.
[11] D. Rose (unpublished).

where σ is the photoneutron cross section in barns; ρ is the density of beryllium; q is the strength of the 2.185-Mev line; R is the outer diameter of the beryllium sphere; R' is the diameter of the equivalent spherical cavity in the beryllium; and M.W. is the molecular weight of beryllium.

Substituting the experimental data into the above formula, we found $\sigma=4.1\times10^{-28}$ cm^2.

This result requires one important correction, since some photoneutrons arise from the bremsstrahlung from the 2.96-Mev β-rays. A calculation was made to determine the relative importance of this yield of neutrons compared to the yield of neutrons from the 2.185-Mev γ-ray. This depends on the relative intensities of the 0.86-Mev β-rays to the 2.96-Mev β-rays. Assuming that the branching ratios of the 0.86 and the 2.3-Mev β-branches are equal and neglecting the bremsstrahlung photoneutron yield from the 2.3-Mev β-rays compared to the 2.96-Mev β-rays, Eq. (1) is corrected to

$$\frac{\text{neutrons}}{\text{second}}=\rho q\frac{0.6}{\text{M.W.}}(R-R')\times\left[\sigma+22\times10^{-8}\times\frac{1.5}{1.1}\times\frac{1-2B}{B}\right], \quad (2)$$

where σ is in barns and B is the above-mentioned branching ratio. The correction decreases the value of σ. Table I gives the calculated change in cross section as a function of B.

TABLE I. Change in σ caused by correction for bremsstrahlung yield of photoneutrons.

B (percent)	0.6	1	2	3	4	5
$\Delta\sigma(10^{-28}$ cm$^2)$	−0.5	−0.29	−0.14	−0.09	−0.07	−0.05

Table I shows that if we use Alburger's decay scheme, there is a negligible correction to the cross section. On the other hand, if we use Porter and Cook's value for B of about one percent, then the cross section would be 3.8×10^{-28} cm^2.

Comparing these values with Fig. 1, it can be seen that there is a minimum value of the cross section in the region of 2.185 Mev. Furthermore, the experimental value of about 3.9×10^{-28} cm$^2\pm15$ percent is in reasonably good agreement with the predictions of the valence neutron model.

It gives us great pleasure to thank Dr. M. Hamermesh for the calculation of the bremsstrahlung yield of photoneutrons.

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Fourth-Order Corrections to the Scattering of Pions by Nonrelativistic Nucleons*

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Fourth-order corrections to the field theoretical phase shifts for pion nucleon scattering have been calculated for a linear and extended coupling and no nucleon recoil. The results support the use of the "Dancoff approximation," since those processes passing through intermediate states which contain three pions turn out to be much less important than processes involving only one and two pions.

I. INTRODUCTION

A BROAD program of theoretical calculations is being carried out at the University of Illinois to see to what extent the experimental information on the pion-nucleon interaction at energies less than 1 Bev can be correlated on the basis of a Yukawa theory in which nucleon recoil is relatively unimportant. The qualitative arguments for the supposition that at these low energies the nucleon may be approximately regarded as a fixed "source" have been summarized by Blair and Chew.[1] These same arguments also lead to the conclusion that the pion-nucleon interaction is linear in the pion field and not very strong and that, therefore, an essentially weak-coupling calculational technique is in order. The purpose of this paper then is to present the results of a calculation, up to the fourth order in the coupling constant, of the pion-nucleon scattering phase shifts, when the nucleon is regarded as infinitely heavy. Our conclusions here form the basis for the more satisfactory method of calculation reported by Chew.[2] The notation of reference 2 will be used throughout.

II. PROCEDURE

With the neglect of nucleon recoil, pions interact with nucleons only in P states.[1] With charge inde-

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[1] J. S. Blair and G. F. Chew, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1952), Vol. II, p. 163 (1952).
[2] G. F. Chew, Phys. Rev. **89**, 591 (1953).