Letters to the Editor

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Theory of the Angular Distribution of Photo-Neutrons from Be^9

C. J. MULLIN AND E. GUTH
University of Notre Dame, Notre Dame, Indiana
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THE simple theory[1] of the photo-disintegration of Be^9 which was adequate for the interpretation of the empirical total cross section *versus* γ-ray energy data,[2] may be used to interpret the data recently obtained on the angular distribution of the photo-neutrons from Be^9. The prospective (loosely bound) photo-neutron is assumed to move in the "effective field" (non-tensor) of the remainder of the nucleus (Be^8). The disintegration process at low energies results from electric dipole transitions from the ground ${}^2P_{3/2}$ state to S and D states of positive energy. These transitions lead to an angular distribution

$$d\sigma/d\Omega = a + b\sin^2\theta, \tag{1}$$

for the ejected neutrons. a and b are functions of the γ-ray energy and may be expressed in terms of the cross sections for the $P\rightarrow S$ and $P\rightarrow D$ transitions. Values of a/b have been obtained for the following three cases:

(1) The ground state is a ${}^2P_{3/2}$ state. The ${}^2D_{5/2}-{}^2D_{3/2}$ splitting of the unbound D doublets may be neglected. Then

$$a/b = (17/12) + (25/12)(\sigma_{PS}/\sigma_{PD}), \tag{2}$$

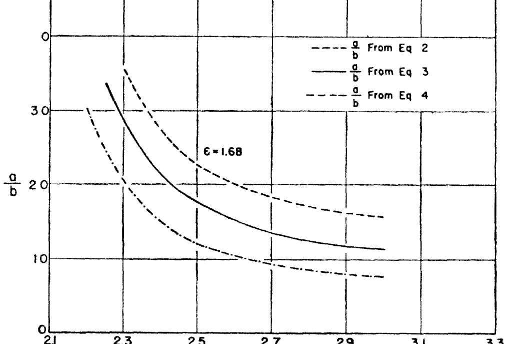

FIG. 1. Values of a/b obtained from Eqs. (2)–(4).

where σ_{PS} is the cross section for the $P_{3/2}\rightarrow S_{1/2}$ transition, and σ_{PD} is the cross section for the $P_{3/2}\rightarrow D_{5/2,3/2}$ transition.

(2) The $D_{5/2}-D_{3/2}$ splitting may not be neglected. For energies less than about 3 Mev, only one D component (the one of lower energy) participates in the transitions. Since the ${}^2P$ splitting seems to be inverted, it is reasonable to assume that the ${}^2D$ splitting also is inverted; thus the $D_{5/2}$ level should occur at a lower energy than the $D_{3/2}$ level. Using $P_{3/2}\rightarrow S_{1/2}$ and $P_{3/2}\rightarrow D_{5/2}$ transitions only,

$$a/b = 1 + (5/3)(\sigma_{PS}/\sigma PD_{5/2}, \tag{3}$$

where $\sigma PD_{5/2}$ is the cross section for the $P_{3/2}\rightarrow D_{5/2}$ transition.

(3) The $P_{3/2}-P_{1/2}$ splitting of the bound P levels and the $D_{5/2}-D_{3/2}$ splitting of the unbound D levels may be neglected. Then

$$a/b = \tfrac{2}{3}[1 + (2\sigma_{PS}/\sigma_{PD})]. \tag{4}$$

Some general conclusions may be drawn from Eqs. (2)–(4). Empirical data[2] indicate that the total cross section has a maximum at about $h\nu = 1.7$ Mev, a minimum at about 2.5 Mev, and a subsequent rise beyond 2.5 Mev. Thus for energies somewhat less than 2.5 Mev, $\sigma_{PS} \gg \sigma_{PD}$, and the angular distribution should be spherically symmetrical. For γ-ray energies $\geqslant 2.5$ Mev, the angular distribution should deviate markedly from spherical symmetry.

Quite recently the angular distribution of the photo-neutrons was measured[3,4] for γ-ray energies of 1.70, 1.81, and 2.76 Mev. The distribution was found to be spherically symmetrical for the 1.70 and 1.81 Mev γ-rays. At 2.76 Mev, Hamermesh, Hamermesh, and Wattenberg obtained $a/b = 1.22$, and Meiners obtained $a/b = 1.15 \pm 0.07$. The experimental values of a/b at 2.76 Mev are consistent with Eq. (3) but do not agree with the results predicted by Eqs. (2) or (4). Equation (2) gives a lower limit of $17/12 \cong 1.4$ for a/b. Since $\sigma_{PS} \ll \sigma_{PD}$ at 2.76 Mev, Eq. (4) predicts a value of a/b which is considerably smaller than the observed value.

In order to obtain numerical values for a/b from Eqs. (2)–(4), σ_{PS}, σ_{PD}, and $\sigma PD_{5/2}$ have been calculated for a nuclear model in which the interaction between the loosely bound neutron and the remainder of the nucleus is represented by a potential well of radius 5×10^{-13} cm. The well depth for S and D states was taken as 3.0 Mev. These parameters were chosen so that the theoretical total cross section *versus* γ-ray energy curve agrees with the experimental one.[5] The well depth for the ground P state was chosen so that the photo-disintegration threshold energy has the correct value. Since there is considerable uncertainty about the value of the threshold energy, two limiting values for this energy, namely, $\epsilon = 1.63$ Mev and $\epsilon = 1.68$ Mev, were used in the calculations. The calculated values for the cross sections have been used to evaluate a/b from Eqs. (1)–(4). The results are shown in Fig. 1. It may be seen that Eq. (3), which is based upon the assumption that the disintegration results from $P_{3/2}\rightarrow S_{1/2}$ and $P_{3/2}\rightarrow D_{5/2}$ transitions, leads to a value for a/b which is in excellent agreement with the empirical results at 2.76 Mev.

An experiment in which γ-rays obtained from the Van de Graaff generator are to be used to determine the angular distribution of the photo-neutrons from Be^9 over an energy interval extending from the threshold energy up to about 3 Mev is underway at Notre Dame.

[1] E. Guth and C. J. Mullin, Phys. Rev. **74**, 833 (1948); Phys. Rev. **76**, 234 (1949).
[2] Russell, Sachs, Wattenberg, and Fields, Phys. Rev. **73**, 545 (1948).
[3] Hamermesh, Hamermesh, and Wattenberg, Phys. Rev. **76**, 611 (1949).
[4] E. Meiners, Private communication; see also Meiners, Smith, and Slack, Phys. Rev. **75**, 1632 (1949).
[5] Actually, the results obtained for the cross section depend chiefly upon the location of the energy levels of the S, P, and D interactions. If these levels are held fixed, the cross sections are rather insensitive to reasonable changes in the well radius or depth. Furthermore, it may be shown for the two body model that the cross section for photo-disintegration at low energies does not depend upon the shape of the effective potential but only upon two parameters: the effective range and the scattering length. The Be^9 problem obviously is very similar to the problems of $N-P$ scattering and photo-disintegration of the deuteron in this respect (J. Blatt and J. D. Jackson, Phys. Rev. **76**, 18 (1949); H. A. Bethe, Phys. Rev. **76**, 38 (1949)).