seems to be inverted.[10] Inglis[11] has explained the magnitude and inverted nature of the splitting in Li^7 as being due to relativistic spin-orbit coupling. Dancoff[12] has given numerical estimates for the splitting in He^5 by using a central field model. He points out that tensor forces lead to the observed normal doublet, giving the right order of magnitude for the splitting.

From the above-mentioned results for Li^7 and He^5 it seems likely that the $^2P_{\frac{1}{2}}$ state in Be^9 is a bound state. If this is the case, the $^2P_{3/2}\rightarrow{}^2P_{\frac{1}{2}}$ magnetic dipole transition should be observed in inelastic scattering experiments or by detection of the γ-ray resulting from the transition, either directly or through internal conversion. Since no empirical results on the $^2P_{\frac{1}{2}}$ level are available, it does not seem profitable, at present, to speculate about the nature of the forces which may be responsible for the ^2P splitting.

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[5] Kusch, Millman, and Rabi, Phys. Rev. **55**, 666 (1939).

[6] Julian Schwinger, personal communication.

[7] Schmidt (Zeits. f. Physik **106**, 358 (1937)) has used this model to explain the magnetic moments of nuclei. As expected, the representation is better for medium and heavy nuclei than it is for light nuclei.

[8] This instability was first shown by Glueckauf and Paneth, Proc. Roy. Soc. **A165**, 229 (1938). The value 162 kev is due to Arthur Hemmendinger, Phys. Rev. **73**, 806 (1948).

[9] H. Staub and H. Tatel, Phys. Rev. **58**, 820 (1940). H. Staub and E. Stevens, Phys. Rev. **55**, 731 (1939).

[10] L. H. Rumbaugh and L. R. Hafstad, Phys. Rev. **50**, 681 (1936).

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Theory of the Photo-Disintegration of Be^9

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RECENTLY the cross section for the photo-disintegration of Be^9 has been determined as a function of energy by Wattenberg and his associates.[1] Their results, as well as results of other workers, have been kindly communicated to us by Dr. Wattenberg; these results are shown in Fig. 1. It should be noted that the experimental results indicate that the photo-disintegration cross section has a maximum and a minimum in the energy range of the experimental data. Undoubtedly, there is also a second maximum beyond the range of these data.

It is possible to give a fairly accurate explanation of the observed results by applying the two-body model discussed in the preceding letter. It is assumed that the ground state is a $^2P_{3/2}$ state. Then the incident photons should produce electric dipole transitions from the ground P state to S and D states. It is also possible that a magnetic dipole transition $^2P_{3/2}\rightarrow{}^2P_{\frac{1}{2}}$ occurs. As in the case of the deuteron, the photoelectric and photo-magnetic disintegration cross sections exhibit maxima when plotted as a function of energy. For the interpretation of the experimental data, the photo-magnetic cross section does not seem necessary. Consequently, it has been assumed that the two maxima are due to the electric dipole $P\rightarrow S$ and $P\rightarrow D$ transitions, the first maximum resulting from the $P\rightarrow S$ transition. The locations and widths of the maxima are determined, at least in part, by the characteristics of the resonance levels of the states of positive energy corresponding to the final states of the disintegrated Be^9.

For simplicity, the interaction between the Be^8 and the neutron has been represented by a rectangular potential well. From general considerations, the radius of the well should probably be about $3-5\times10^{-13}$ cm. The value $r=5\times10^{-13}$ cm has been employed in the calculations; this radius determines the well depth to be 12.16 Mev for the P state. The dependence of the Be^8 neutron force upon the angular momentum has been taken into account in a schematic way by assuming that the well depth is a function of parity. For the S and D states (both with even parity) a well depth of 3 Mev has been used. (The same radius, $r=5\times10^{-13}$ cm, has been used for all states.) With this well, the first S state is bound by about 100 kev. This loosely bound state yields a resonance effect in the disintegration cross section similar to that which would be obtained with a virtual state.[2] The theoretical photo-disintegration cross section is given by the solid curve in Fig. 1. A continuation of the theoretical curve to higher energies yields a second maximum.

The theory predicts that the angular distribution of the ejected photo-neutrons should be spherically symmetric for energies near the threshold (that is, in the region of the first maximum), and should be given by $[P_2(\cos\theta)]^2$ for energies somewhat beyond the minimum of the cross-section curve. If the second peak were due to a magnetic dipole transition, the angular distribution for energies somewhat beyond the minimum would be given by $\sin^2\theta$. The angular distribution of the photo-neutrons has been found to be spherically symmetric for energies near the threshold by Goloborodko and Rosenkewitch.[3] According to Dr. Wattenberg, an investigation of the angular

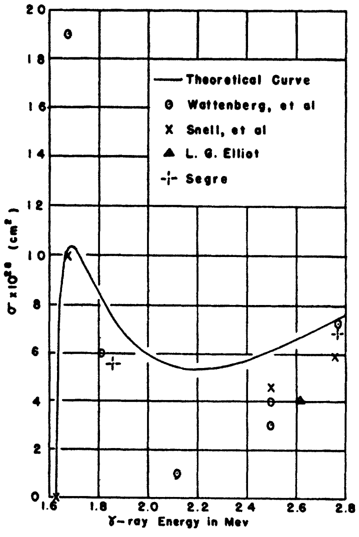

FIG. 1. Photo-disintegration cross sections for Be^9.

distribution of the photo-neutrons from Be^9 is planned by him and his group at the Argonne National Laboratories. Such an investigation would show whether or not the neglect of the $^2P_{3/2}\rightarrow{}^2P_{\frac{1}{2}}$ magnetic dipole transition is justified, or whether it must be included with the other transitions.

Very recently, in experiments on the inelastic scattering of protons on Be^9, a sharp resonance level has been found by Davis and Hafner[4] at 2.41 Mev (0.78 Mev above the photo-threshold). This resonance has been attributed by Longmire[5] to a $^2D_{5/2}$ resonance level. Such a $^2D_{5/2}$ level should be detected in the photo-disintegration measurements; however, the photo cross section has not yet been measured at the energies where this level is important. If this resonance were due to an F state, its effect on the photo cross section would probably be much less. The results of Davis and Hafner also seem to indicate the existence of an S resonance level of the type assumed to explain the first maximum in the photo-disintegration curve. However, the experimental data on this point are not conclusive.[6]

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[1] Russell, Sachs, Wattenberg, and Fields, Phys. Rev. **73**, 545 (1948).

[2] By using a larger radius for the potential well, it seems possible to interpret the experimental data with an "S well depth" which places the resonance state in the continuum.

[3] Goloborodko and Rosenkewitch, Physik. Zeits. Sowjetunion **11**, 78 (1937). Cf. also Chadwick and Goldhaber, Proc. Roy. Soc. **A151**, 479 (1935).

[4] K. E. Davis and E. M. Hafner, Phys. Rev. **73**, 1473 (1948).

[5] Longmire, Thesis, University of Rochester, 1948, to be published soon. The authors wish to thank Dr. Longmire and Professor Marshak for communicating their data to us.

[6] In these experiments the inelastically scattered protons were observed. It is also possible, of course, to observe the ejected neutrons.

Theory of Electrodisintegration of Be^9

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THE disintegration of Be^9 by electrons was first observed by Collins, Waldman, and Guth[1] in 1939. At that time, one of us[2] made an approximate calculation of the cross section right above the threshold, using the central field model discussed in a preceding letter. The value obtained was in good agreement with that observed by Collins, Waldman, and Guth. Subsequently, Wiedenbeck[3] determined the cross section as a function of energy, using a thin Be target. His results are given in Fig. 1. (The dotted part of the experimental curve is an extrapolation from Wiedenbeck's lowest point to the threshold.)

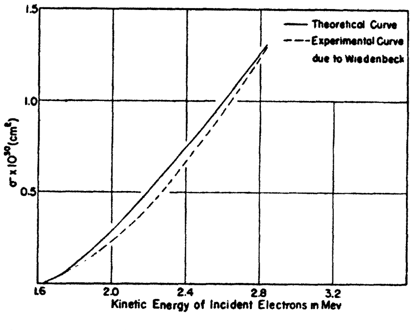

FIG. 1. Electrodisintegration cross sections for Be^9.

Using the theoretical cross section for photo-disintegration obtained in the preceding letter, we have calculated the cross section for electrodisintegration as a function of energy. The result, shown in the figure, agrees well with the experimental curve. If it is assumed (see the preceding letter) that the photo-disintegration cross section, $\sigma(h\nu)$, results from photoelectric transitions, then the cross section for electrodisintegration, $\sigma(E_i)$, may be written

$$\sigma(E_i)=\int_{1.63}^{E_i}\sigma(h\nu)N(E_i,\, h\nu)d(h\nu), \tag{1}$$

where E_i is the kinetic energy of the incident electron, $\sigma(h\nu)$ is the cross section for photo-disintegration determined in the preceding letter, and $N(E_i, h\nu)$ is the number of virtual quanta by which the action of the field of the electron may be represented in the production of photoelectric disintegration. $N(E_i, h\nu)$ was computed by using the Born approximation. (Actually, the equivalent method due to Møller was used.) Since $\sigma(h\nu)$ is in fairly good agreement with the experimentally determined photo-disintegration cross section, it may be regarded as an empirical result. Consequently, the only assumption involved which is dependent upon the nuclear model comes in through the use of $N(E_i, h\nu)$ corresponding to a *photoelectric* transition. If $\sigma(h\nu)$ is due in part to a magnetic dipole transition, a different value of $N(E_i, h\nu)$ must be used for this transition. Assuming that $\sigma(h\nu)$ results from photoelectric transitions only, the determination of the electrodisintegration cross section is reduced to an electromagnetic, rather than a nuclear, problem. The theoretical cross section obtained from Eq. (1) is plotted in the accompanying figure. The agreement with experiment is very good and is an argument for the photoelectric nature of the photo cross section. Near the threshold, the cross section increases as the square of the energy of the ejected neutron. It should be noted that, because of the integration indicated in Eq. (1), the electrodisintegration cross section is relatively insensitive to the assumed nuclear model.

Inelastic scattering of electrons on Be^9 may reveal the S resonance level postulated in the theory of the photo-disintegration of Be^9 and may also detect the resonance level at 0.78 Mev (above threshold) found by Davis and Hafner.[4] The theory for the inelastic scattering process is included in the theory of electrodisintegration.

Mamasachlisov[5] has given a theory of the electro-disintegration of Be^9, assuming only a $P\rightarrow S$ transition. His results, which were based in part on the results of Bethe and Peierls for the electrodisintegration of the deuteron, appeared to give good agreement with the experimental measurement of Collins, Waldman, and Guth at 1.73 Mev. However, the result of Bethe and Peierls used by Mamasachlisov was marred by two algebraic errors which were subsequently corrected by Wick.[6] The correction of these errors reduced Mamasachlisov's theoretical cross section by a factor of about one-half and led to a less favorable comparison with the experimental result. Caldirola[7] tried to improve the theory of Mamasachlisov by introducing, *ad hoc*, a magnetic dipole transi-