VI. THE CASE OF HYDROGEN ATOMS AS THIRD BODY

To the present approximation,[2] the difference between protons and hydrogen atoms is that the orbital electron produces an (attractive) screening field; electronic transitions are of course not considered here. The effect of the screening field is to make the total interaction with a hydrogen molecule weakly attractive for separations greater than $1.3a_0$, with a maximum depth of $-0.02e^2/a_0$ at $r=1.8a_0$; at smaller distances ($r\lesssim a_0$) the effect of the screening field is negligible, and the field is again repulsive.

In the case considered previously[2] the attractive potential is of no importance at the lower energies ($\sim$5 ev), although it does give a contribution at large energies. In the present case the closest distance of approach for protons is greater than $1.3a_0$, so that the screening field affects the one-dimensional matrix element very strongly. If the correction method is applied in the usual way, one finds a correction factor $\zeta\sim(+)10^{-3}$ to 10^{-2} for the $(0\rightarrow1)$ transition, i.e., for energies $\gtrsim$1 ev, and $\zeta\sim(-)10^{-2}$ for thermal energies (dissociation and elastic scattering). The change of sign of ζ arises from the change of sign of the potential with increasing distance. The calculation is relatively difficult, because it is impossible to use the Bessel function method and the much more tedious WKB method must be used instead. The result is that for thermal energies, elastic scattering cross sections and three-body coefficients are increased by a factor of ten over those for protons, while the $(0\rightarrow1)$ cross sections are not changed in their order of magnitude, although the change of sign of ζ with the corresponding zero in the cross section falls not far above the threshold of the $(0\rightarrow1)$ transition.

The conclusion is that we may perhaps accept the thermal energy cross sections very tentatively: the three-body coefficient for two hydrogen atoms recombining in the presence of a third is of order 3×10^{-36} cm^6 sec^{-1}, while the cross section for the elastic scattering of a hydrogen atom of energy $\frac{3}{2}kT$ by a hydrogen molecule is of order 5×10^{-15} cm^2. Thus we see that it is still not possible to understand the experimental value of the three-body coefficient; electronic resonance processes are hardly likely as most other gases (nitrogen, halogens) give similar values for C_3 as does hydrogen.[3]

I should like to thank Dr. T. Y. Wu for suggesting this problem and for many helpful suggestions.

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An Investigation of Alpha-Particle Groups from $Al^{27}(d,\alpha)Mg^{25}$*

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The alpha-particle groups produced by the bombardment of aluminum by 10.8-Mev deuterons have been measured using nuclear emulsion plates for detection. Seven new levels in Mg^{25} were found at 6.98, 7.85, 8.62, 9.06, 975, 10.78, and 11.89 Mev. The previously known level at 4.01 Mev has been resolved into two levels at 3.96 and 4.12 Mev.

INTRODUCTION

Several investigations have been made of the lower-lying levels in Mg^{25} from the $Al^{27}(d,\alpha)Mg^{25}$ reaction.[1] Recently Schelberg, Sampson, and Cochran[2] extended this work to show ten levels in Mg^{25} with a maximum excitation of 6 Mev.

The present investigation was initiated with the aim of extending this work to higher excitations since the previous results showed an approximately constant level spacing of about 0.6 Mev. The energy levels above 7 Mev in Mg^{25} have been obtained in neutron scattering experiments,[3] and it seemed of interest to extend the $Al^{27}(d,\alpha)Mg^{25}$ work to overlap this region.

The present investigation was carried out with the use of nuclear emulsions as detectors to facilitate the measurement of lower energy alpha-particles leading to higher excitation in the residual nucleus. The results for lower energy alpha-particles were limited however, by the presence of background tracks.

EXPERIMENTAL PROCEDURE

The deuteron bombardments of the target were made in the same way as previously described.[2] The deuterons from the Indiana University cyclotron were passed through the analyzing magnet before striking the target foil. The beam energy was thus determined to be 10.82 ± 0.08 Mev and was held at this value for the duration of the bombardment.

The targets were of aluminum foil, 0.17 mg/cm^2 surface density, and were supported by a brass ring in such a manner that the beam was prevented from striking the brass. Fresh targets were prepared for each bombardment to reduce the accumulation of contami-

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* This work was assisted by the joint program of the ONR and AEC.

[1] E. McMillan and E. O. Lawrence, Phys. Rev. **47**, 343 (1935); Pollard, Sailor, and Wyly, Phys. Rev. **75**, 725 (1949); A. P. French and P. B. Treacy, Proc. Phys. Soc. (London) **63**, 665 (1950).

[2] Schelberg, Sampson, and Cochran, Phys. Rev. **80**, 574 (1950).

[3] D. E. Alburger and E. M. Hafner, Revs. Modern Phys. **22**, 373 (1950).

nants such as pump oil. The target holder was arranged to rotate about its central axis. It was set so the plane of the foil made equal angles with the beam and the camera.

The reaction particles resulting from the bombardment were detected by the use of 1×3 inch, 50-micron nuclear emulsion plates (Kodak NTA No. 443,959–24). The plates were exposed in a conventional type of camera. A removable brass plate holder was designed to press down on the edges of the emulsion, which prevented peeling of the plates during exposure in vacuo. Two adjustable slits separated by 2.5 cm provided collimation of the particles entering the camera. The slit opening used in the present work was such as to give an angular resolution of plus or minus one-half degree. The plate holder was held in the camera so that the surface of the emulsion made an angle of 7° with the axis of the collimating slits.

The camera was designed to be used in the bombardment chamber previously used,[2] and could be set at any angle with an accuracy of 15 minutes between 15° and 140° in the laboratory coordinates. The incident beam from the analyzer was defined by a system of slits to limit the energy spread to about ±40 kev for the beam energy of 10.8 Mev.

A number of plates were exposed at various angles for the different lengths of time. The total exposure was determined by monitoring the beam current to the target with a current integrating circuit. The exposures ranged from 3 to 14 microcoulombs of charge.

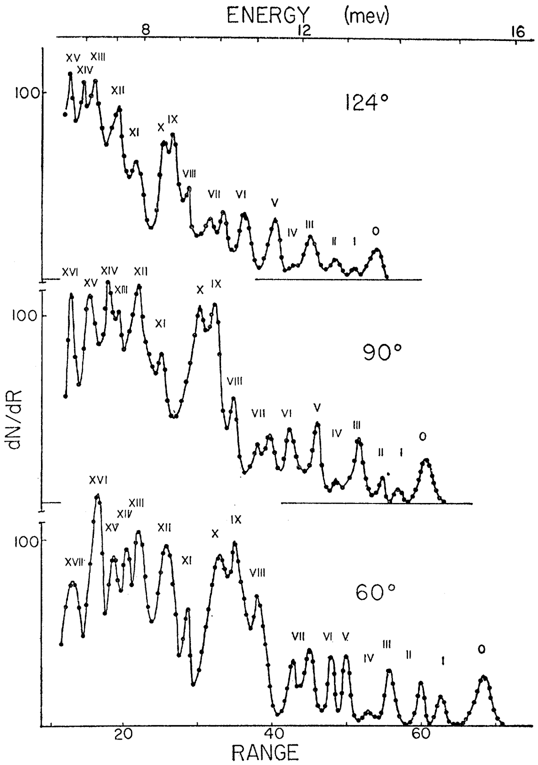

FIG. 1. Plots of the range of alpha-particle tracks in the emulsion *vs* the number per range interval for three plates taken at 60°, 90°, and 120° (1 unit = 1.674 microns).

PROCESSING AND MEASUREMENT OF PLATES

Standard processing procedures were followed, developing the plates for six minutes in full strength D-19b developer at 18°C, and fixing for one hour. It was found that the use of a hardening bath following development (10 min in Kodak SB-3) prevented the tendency of the emulsion to form blisters.

The alpha-particle track lengths were measured with a Spencer 5LP binocular research microscope. The left eyepiece contained an eyepiece scale which was calibrated against a stage micrometer. The right body tube was fitted with a simple angular scale, which enabled tracks with excessive angular divergence to be rejected.

The presence of large numbers of protons, from competing reactions, and scattered deuterons made the measurement of alpha-particle tracks in the emulsion difficult. An attempt was made to utilize underdevelopment of the plates to give better discrimination between the different types of tracks. This method proved unsatisfactory as the visibility of the alpha-particle tracks became so low as to make the observations very tedious and slow.

The phenomenon of fading of the latent image of tracks in nuclear emulsions on delayed development[4] provides one with a method of eliminating the unwanted proton and deuteron tracks, since the fading is much more marked for these tracks than for alpha-particle tracks.

The procedure used on most of the plates was to delay development for one day. This was sufficient to nearly eradicate the proton tracks and still allow the alpha-particle tracks to remain. The preponderance of scattered deuterons in the forward direction makes the use of nuclear emulsion detection particularly difficult at these angles. One plate exposed at 60° was allowed to fade for six days. Upon development the deuteron tracks were found to be almost completely obliterated while the alpha-particle tracks were still visible.

The track lengths in the emulsion were converted to energy by means of the range-energy relation previously reported.[5]

Observations on two unexposed control plates disclosed the presence of a large number of short tracks which were quite evidently alpha-particle tracks. They were isotropically distributed and varied in range from 5 to 20 microns (1.5 to 5.1 Mev). These same tracks were again observed on portions of the reaction plates not exposed to the target and of comparable intensity. The density of tracks in a single group from the target reaction is of the same order of magnitude. The back-

[4] H. Yagoda, *Radioactive Measurements with Nuclear Emulsions* (John Wiley and Sons, Inc., New York, 1949).

[5] Steigert, Toops, and Sampson, Phys. Rev. **83**, 474 (1951).

TABLE I. Energy levels in Mg^{25}. The errors assigned to the energy levels were determined from shifts in the relative values of group energies from plate to plate and are therefore less than the absolute errors in the Q values.

Energy of alpha group (Mev)	Q value (Mev)	Energy levels (Mev) Present work	Previously reported (b)	Previously reported (c, d, e)
14.37±0.05	6.694±0.01[a]			
13.82±0.05	6.11 ±0.07	0.58±0.02	0.57	
13.56±0.10	5.76 ±0.12	0.93±0.04	0.96	
12.96±0.10	5.07 ±0.12	1.62±0.03	1.63	
12.53±0.20	4.60 ±0.22	2.09±0.05	1.97	
11.98±0.10	3.95 ±0.12	2.74±0.03	2.74	
11.43±0.10	3.33 ±0.12	3.36±0.03	3.36	
10.92±0.10	2.73 ±0.12	3.96±0.04	4.01	
10.81±0.10	2.57 ±0.12	4.12±0.04		
10.14±0.10	1.82 ±0.12	4.87±0.03	4.81	
9.54±0.10	1.13 ±0.12	5.56±0.03	5.48	
9.23±0.10	0.76 ±0.12	5.93±0.03	5.95	
8.33±0.10	−0.29 ±0.12	6.98±0.03		
7.57±0.15	−1.16 ±0.16	7.85±0.04		7.40 7.58 7.73 7.90 8.01 8.16
6.91±0.20	−1.94 ±0.22	8.62±0.05		8.41 8.59
6.53±0.15	−2.37 ±0.16	9.06±0.04		8.92 8.96
5.94±0.15	−3.06 ±0.16	9.75±0.04		9.76
5.06±0.15	−4.09 ±0.16	10.78±0.04		
4.09±0.15	−5.20 ±0.16	11.89±0.05		

[a] See reference 7. [b] See reference 8. [c] See reference 8. [d] See reference 9. [e] See reference 10.

ground thus becomes objectionable in measuring track lengths less than 20 microns in length. All track lengths less than 20 microns were therefore rejected from the measurements.

RESULTS AND DISCUSSION

Alpha-particle tracks were measured on ten nuclear emulsion plates which had been exposed to the reaction particles from the aluminum target bombarded by deuterons from the cyclotron. A total of nine thousand tracks were measured. Only those tracks were measured that satisfied conditions of geometry which insured their origin in the center of the target.

The tracks were plotted graphically by means of a triangle method similar to that given by Slätis, Hjalmar, and Carlsson.[6] The peaks were then obtained by numerical integration of the triangles. The half-widths of the triangles used are equal to one unit on the abscissa in Fig. 1. This value was taken as corresponding to the maximum uncertainty in the track length measurement as estimated from the possible distortions, dip, errors due to scale, etc. The half-width used corresponds almost precisely to the half-width of the Po and Th alpha-particle groups used to calibrate the plates.

[6] Slätis, Hjalmar, and Carlsson, Phys. Rev. 81, 641 (1951).

The data obtained from three plates taken at 90°, 124°, and 60° to the beam are presented in Fig. 1. The total number of tracks measured on each of the plates was 1400, 1200, and 1600, respectively. The peak labeled 0 corresponds to the alpha-particle group leaving Mg^{25} in the ground state.

The energy of each alpha-particle group was obtained from the average value of measurements made on several plates so that even the lowest intensity group corresponds to a total of 300 tracks. The ground-state Q value was taken as 6.694±0.010 Mev from the work of Enge *et al.*,[7] and the energy levels obtained by subtraction from this value. Since the relative differences of the track lengths may be measured much more accurately than the absolute value, the energy levels are correspondingly more accurate. The chief error in the particle energies was from a variation of the deuteron energy from plate to plate which however does not affect the differences in the Q values.

It may be noted that the group labeled VII is a doublet of 180-kev spacing. This appeared in the previous work[2] as a single broad group. Best resolution of this group is obtained on the 124° data.

The energy levels and Q-values obtained by averaging the data for all of the plates are presented in Table I with the previous results shown for comparison. It is seen that the agreement is satisfactory for the two methods of detection.

Nuclear levels calculated from the neutron resonance data of several investigators[8–10] are also given in Table I. These values were obtained by adding the neutron binding energy 7.32±0.02 Mev to the neutron resonance energy (center-of-mass energy). This value was

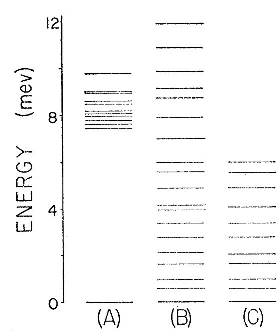

FIG. 2. Comparison of energy levels in Mg^{25}. (A) Neutron levels (see references 8–10), (B) present work, (C) Schelberg, Sampson, and Cochran (see reference 2).

[7] Enge, Buechner, Sperduto, and Van Patter, Phys. Rev. 83, 31 (1951).
[8] M. R. MacPhail, Phys. Rev. 57, 669 (1940).
[9] Freier, Fulk, Lampi, and Williams, Phys. Rev. 78, 508 (1950).
[10] R. E. Fields and M. Walt, Phys. Rev. 83, 479 (1951).

obtained by using the Q-value 5.094±0.010 Mev for the $Mg^{24}(d,p)Mg^{25}$ reaction,[11] and 2.230±0.007 Mev for the binding energy of the deuteron.[12] If one takes level XII as corresponding to the average of the first six neutron levels, XIII and XIV to the next two doublets, respectively, then the agreement would seem satisfactory. It would appear that at least for the higher excitation of Mg^{25} that the levels obtained in this work may be composed of closely spaced unresolved groups rather than distinct levels.

An energy level diagram comparing the present work with the groups reported by Schelberg[2] and the neutron resonances[8–10] is given in Fig. 2.

[11] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. 81, 747 (1951).
[12] R. E. Bell and L. G. Elliot, Phys. Rev. 79, 282 (1950).

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Angular Distribution in the High Energy Deuteron Photoeffect*

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Consideration is given to the possible use of the electric dipole isotropic part of the deuteron photodisintegration cross section as an indicator of weak odd state noncentral forces. This cross section is not very sensitive to weak tensor forces of the usual type, but is strikingly affected by a singular spin-orbit coupling. While for the usual tensor forces the ratio, a/b, of the isotropic to the $\sin^2\theta$ term in the cross section varies slowly over a broad energy range, it rises rapidly with energy if the noncentral force is strongly singular. Calculation is done in first Born approximation. A detailed estimate of the magnetic isotropic cross section is included, for this is an unexpectedly large "background" to the electric term which is of interest.

I. INTRODUCTION

The ground state is the only even parity state of the NP system which is important in deuteron photodisintegration, and its wave function is fairly well known through studies[1] of the many low energy phenomena into which it enters. Considerably less is known about the important states of odd parity. For these, high energy scattering studies[2] have led to a belief in the "even theory," that is, that the exchange dependence of the nuclear forces is such that two nucleons in an odd parity state of relative motion do not interact. The data do not, however, justify the complete exclusion of odd state noncentral interactions, as these are found not to have strong influence on the NP scattering cross section.[2,3] More definite information about them can in principle be obtained from photodisintegration measurements; therefore careful photodisintegration calculations with odd state noncentral forces are desirable. These would supplement the high energy photodisintegration calculations which were recently done for pure central forces.[4,5]

Odd state noncentral interactions do not much affect the total cross section for photodisintegration, but it has long been known from numerical calculation in special cases[6,7] that they do cause one striking qualitative change in the angular distribution. This change consists of the introduction of an isotropic term in the *photoelectric* cross section, which appears if noncentral interactions are effective in the ^3P continuum states. It is produced by interferences between the three ^3P_J states, and is basically a high energy effect, since nucleons in a relative P state cannot interact when the energy is low.

The present work is intended to determine with what sensitivity the isotropic term might actually measure the strength of a weak ^3P state noncentral force. It was begun after accurate low energy measurements of the photodisintegration angular distribution had become available,[8] and when some attempts were being made to perform such experiments at higher energies.[9–13] Energies up to $\hbar\omega = 100$ Mev are considered. This is a range in which it is possible to disregard relativistic and free meson effects[4] and to use the usual phenomenological formalism.[14]

* This work is a portion of the author's doctoral thesis.
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[1] For a recent study of this type see Feshbach and Schwinger, Phys. Rev. 84, 194 (1951). A copy of their work was supplied to the author by Dr. J. Eisenstein.
[2] R. S. Christian and E. W. Hart, Phys. Rev. 77, 441 (1950).
[3] K. M. Case and A. Pais, Phys. Rev. 80, 203 (1950).
[4] L. I. Schiff, Phys. Rev. 78, 733 (1950).
[5] J. F. Marshall and E. Guth, Phys. Rev. 78, 738 (1950).
[6] W. Rarita and J. Schwinger, Phys. Rev. 59, 436 and 556 (1941).
[7] T. M. Hu and H. S. W. Massey, Proc. Roy. Soc. (London) A196, 135 (1949).
[8] For a summary of recent work see Bishop, Collie, Halban, Hedgran, Siegbahn, du Toit, and Wilson, Phys. Rev. 80, 211 (1950); Bishop, Halban, Shaw, and Wilson, Phys. Rev. 81, 219 (1951); Bishop, Beghian, and Halban, Phys. Rev. 83, 1052(L) (1951).
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[10] P. V. C. Hough, Phys. Rev. 80, 1069 (1950).
[11] Phillips, Lawson, and Kruger, Phys. Rev. 80, 326 (1950).
[12] G. Goldhaber, Phys. Rev. 81, 930 (1951).
[13] Gibson, Green, and Livesey, Nature 160, 534 (1949).
[14] See, for example, R. G. Sachs and N. Austern, Phys. Rev. 81, 705 (1951).