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Angular Distribution of $Li^7(p,\alpha)\alpha$

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The angular distribution of the alpha-particles from the reaction $Li^7(p,\alpha)\alpha$ has been investigated from 0.5 to 1.4 Mev with a photographic emulsion technique. Values of the coefficients of the $\cos^2\theta$ and $\cos^4\theta$ terms are given and compared with the results of other observers.

I. INTRODUCTION

THE angular distribution of the two alpha-particles produced when lithium is bombarded with protons has been investigated a number of times; but there are still a number of questions to be settled, especially with regard to the existence of a $\cos^4\theta$ term at lower energies and its dependence on energy. Early experiments[1–3] showed no deviation from spherical symmetry. This is not surprising, as the work was all done at rather low energies where the yield is small and the symmetry is still uncertain. Subsequent observers[4,6] showed the presence of a $\cos^2\theta$ term, so that the yield at any angle θ compared to the yield at 90° is given by

$$Y(\theta)/Y(90°)=1+A\cos^2\theta,$$

where A is a function of the bombarding energy. Heydenburg, *et al.*,[7] have recently found evidence of a $\cos^4\theta$ term in the region from 1 to 3.5 Mev, so that the equation becomes

$$Y(\theta)/Y(90°)=1+A\cos^2\theta+B\cos^4\theta,$$

where A and B are both functions of the bombarding energy. Critchfield and Teller[8] considered the possibility of a $\cos^4\theta$ term as early as 1941, and Inglis[9,10] has explained the distribution in terms of entrant p- and f-protons. In the present paper we have measured the angular distribution in the region from 0.5 to 1.4 Mev and calculated the coefficients A and B.

II. EXPERIMENTAL METHOD

The present work was done with the pressurized van de graaff generator of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, through the courtesy of Dr. Merle A. Tuve and his staff. Some preliminary work was carried out with the atmospheric pressure generator, and it is hoped that further work at the lower energies can be done with it. Both of these generators have been described in publications of the Department of Terrestrial Magnetism. The smaller machine has a range from 0 to about 1.1 Mev, while the pressurized generator operates from about 0.5 to 3.6 Mev.

The photographic emulsion method of recording has been used. The bombardment chamber is shown in Fig. 1. The proton enters from a slit at the top of the diagram striking the target at the center of the chamber. The target holder is mounted on a sylphon toggle so that it can be rotated from outside the chamber. A stove for evaporating lithium onto the target is shown at the lower right. A protecting sleeve on the stove can also be run in and out by a sylphon toggle. The lithium on the target is renewed before each run, as it is oxidized every time the vacuum is broken. This can be done rather quickly without contaminating the rest of the chamber with lithium by simply turning the target around to face the stove and bringing the sleeve up tight against the target while distilling lithium onto it. To the left is shown the removable box containing the

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[1] F. Kirchner, Physik. Z. 34, 785 (1933).
[2] J. Giarratanna and C. G. Brennecke, Phys. Rev. 49, 35 (1936).
[3] H. Neuert, Ann. Physik 36, 437 (1939).
[4] Young, Ellett, and Plain, Phys. Rev. 58, 408 (1940).
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[8] C. L. Critchfield and E. Teller, Phys. Rev. 60, 10 (1941).
[9] D. R. Inglis, Phys. Rev. 74, 21 (1948).
[10] Heydenburg, Hudson, Inglis, and Whitehead, Phys. Rev. 74, 405 (1948).

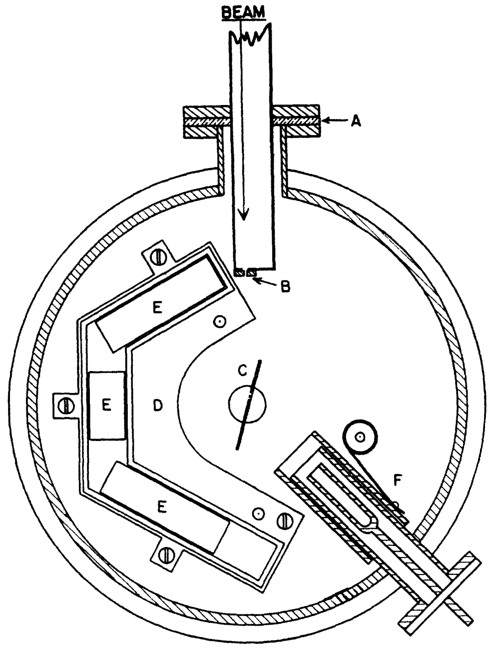

FIG. 1. Schematic diagram of bombardment chamber. The proton beam enters from above and is defined by the slit B, falling on the lithium target at C. The lithium targets are prepared by distilling metallic lithium from the stove F onto a beryllium plate C. C can be rotated from outside the chamber by a sylphon toggle. The alpha-particles are recorded in the photographic plates E (Eastman NTA 25-micron emulsions) which are mounted in the removable "camera" D at 45 degrees to the plane of the diagram. The insulator A permits the measurement of the beam current passing through B. A current integrator connected between the chamber and ground can then be used to indicate relative exposures. A Lucite cover, fitted with a neoprene gasket, is placed on the chamber to permit evacuation of the chamber during target preparation and bombardment.

photographic plates which we shall call the "camera." The three plates are mounted on 45° blocks. The alpha-particles enter the camera through aluminum foil windows. These windows not only keep the camera light-tight but can be so varied as to discriminate between alpha-particles and the scattered protons. The camera lid has breather-cap to allow the inside of the camera to be evacuated. The lid of the chamber is made of Lucite with a neoprene gasket.

Eastman NTA plates have proved very satisfactory for this work. The only difficulty is that they show a tendency to peel, apparently because of the placing of thick emulsions in high vacuum. A thin line of shellac around the edge of the plate seems to have ended this difficulty. A set of three plates are processed together, using stain racks and dishes such as are used for biological slides. Exposures ranging from a few minutes to an hour, depending on the voltage, with from about 0.1 to 0.8 μamp proton current have been made. The yield varies considerably, but we try for the best compromise between too few tracks for good statistics and too many overlapping tracks for accurate counting. We like to have about 1000 tracks per square mm at 90°, which makes the maximum density several thousand per square mm. At first, the tracks were counted directly with a binocular microscope under low power, using the area defined by a Whipple disk as an increment of angle. This was about one square mm of the emulsion. Fatigue and the possibility of large counting errors made us substitute a system of making enlargements. The one square mm of emulsion area is enlarged to about 10 in.$\times$10 in. Counting from these enlargements has proved to be much easier, and, we believe, has reduced errors considerably. It is possible to mark each track with a pencil, or stylus, to prevent missing or double counting. And it is also possible for several observers to check their counting techniques against each other. Using this method, we always checked each other within one or two counts per thousand.

Usually the tracks at 10 to 14 different angles are counted for each run, so that the calculation for any one run is based on the counting of 20,000 to 30,000 tracks. Several runs were made at each energy. A table has been prepared changing various positions on the plates into angles subtended at the target. Corrections must, of course, be made for oblique incidence and for the inverse square law to get the angular distribution in the laboratory coordinates. The angles and counts are then corrected to center-of-mass coordinates, according to the method described by Heydenburg and Inglis.[11]

III. NUMERICAL CALCULATIONS

The pairs of numbers (x, y), where $y=Y_\theta/Y_{90°}$ and $x=\cos^2\theta$, can be used in several ways to evaluate A and B. They can, firstly, be plotted on a graph and a curve drawn "by eye" giving A and B directly. Secondly, a least squares analysis can be employed.[12] Then, with either of the above methods there is the choice either of evaluating each run separately or of combining all points from runs taken at any given bombardment energy into a single graph or analysis. If each run is calculated separately, there arises the further problem of assigning weights to the A and B values of all runs at any one energy to obtain the "grand mean."

Since small changes in curvature can yield quite different values of A and B, the graphical method was rejected as entirely too subjective. Because there was no satisfactory criterion for the assignment of weights, the separate evaluation of each run was also rejected. The only method remaining, that of using all points from runs at a single bombardment energy in a least-squares analysis, was the one used in this paper. The coefficients a, b, and c in the equation

$$y_c = a + bx + cx^2, \qquad (1)$$

which gave the best fit to the observed points were found in this way. When Eq. (1) is divided by a, the

[11] N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948).

[12] E. T. Whittaker and G. Robinson, *The Calculus of Observations* (Blackie and Son, Ltd., London, 1944), fourth edition.

equation is reduced to

$$y' = 1 + (b/a)x + (c/a)x^2,$$

and A and B are given directly as b/a and c/a, respectively.

The residuals, d, having been defined as

$$d = y_c - y,$$

the probable errors in A and B were computed by using the formula[13]

$$p_A = 0.6745[(A_{22}/D)\Sigma d^2/(n-3)]^{\frac{1}{2}},$$
$$p_B = 0.6745[(A_{33}/D)\Sigma d^2/(n-3)]^{\frac{1}{2}},$$

where n is the number of points, D is the determinant of the three "normal" equations used in the least-squares analysis, and A_{ii} is the cofactor of the element D_{ii} in D.

It should be noted that the probable errors are defined above in terms of the internal consistency of the observed data. Following the suggestion of Birge[14] a separate least-squares calculation was made for each run. The values of A and B so obtained were used to evaluate probable errors based on external consistency by means of the formulas,

$$p_{A\ \mathrm{ext}} = 0.6745[\Sigma(A-\bar{A})^2/N]^{\frac{1}{2}},$$
$$p_{B\ \mathrm{ext}} = 0.6745[\Sigma(B-\bar{B})^2/N]^{\frac{1}{2}},$$

where $\bar{A}$ is the average of A's at any one energy, $\bar{B}$ is the average of B's at any one energy, and N is the number of runs at the energy under consideration. Birge states[15] that if the ratio $p_{\mathrm{ext}}/p_{\mathrm{int}}$ exceeds unity by several times, the results so compared are inconsistent; i.e., some experimental error has altered the conditions under which the different observations were made. The results obtained here indicate that there have been changes in the experimental conditions from run to run. One of the most serious sources of these changes is undoubtedly the variation in target thickness from one run to the next, a factor which is very difficult to evaluate.

IV. DISCUSSION OF RESULTS

Figure 2 shows a typical set of data for one energy showing the experimental points for several runs and also the curve obtained from them by the least-squares method. Table I and Fig. 3 show our values of A and B together with their probable errors for the energies 0.5 Mev through 1.4 Mev. Figure 4 compares our results with those of Heydenburg *et al.*, and with those recently reported by a group in Melbourne.[16,17]

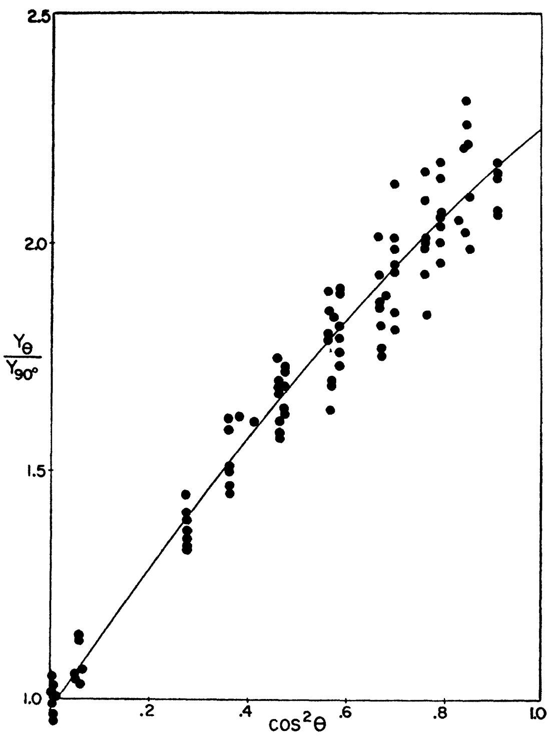

FIG. 2. Curve shows typical least-squares fit to the observed data. The points were obtained from several runs made at a bombardment energy of 0.7 Mev. θ is the angle in center-of-mass coordinates of the observed points to the incident beam. $Y_\theta/Y_{90°}$ is the relative yield.

Comparison of the probable errors using external and internal consistency (see above) gave ratios ranging from about three to six. Hence, the probable errors indicated in Table I and Fig. 3 may be somewhat optimistic. Nevertheless, since these estimates are derived from a single computation which includes all of the observations at any one energy, all discrepancies between individual runs have been incorporated into the probable errors as listed herein. For this reason it is felt that the results of this paper effectively define the limits within which the true values of A and B must lie. It is generally accepted that the region defined by twice

TABLE I. Angular distribution coefficients A and B, as defined by $Y_\theta/Y_{90°} = 1 + A\cos^2\theta + B\cos^4\theta$, for the reaction $Li^7(p,\alpha)\alpha$. E is the energy in Mev, and p and σ are the probable error and standard deviation, respectively.

E	A	p_A	σ_A	B	p_B	σ_B
0.5	0.95	0.11	0.16	0.15	0.12	0.17
0.6	1.22	0.08	0.12	0.34	0.09	0.14
0.7	1.58	0.09	0.14	0.31	0.10	0.15
0.8	1.85	0.08	0.12	0.31	0.09	0.13
0.9	2.38	0.12	0.17	0.54	0.12	0.18
1.0	2.43	0.09	0.14	0.53	0.10	0.15
1.1	2.71	0.12	0.18	0.76	0.13	0.19
1.2	2.78	0.14	0.20	0.75	0.15	0.22
1.3	2.32	0.11	0.16	0.63	0.12	0.17
1.4	2.46	0.10	0.14	0.92	0.11	0.16

[13] Reference 12. p_A and p_B as defined here are actually the errors in "b" and "c" of Eq. (1). However, the factor $1/a$ is used only to correct for having used an observed $Y_{90°}$ instead of a true $Y_{90°}$, and it can easily be demonstrated that the error in "a" does not appear in A or B

[14] R. T. Birge, Phys. Rev. **40**, 215 (1932).

[15] Reference 14, p. 219.

[16] Martin, Bower, Dunbar, and Hirst, Nature **164**, 310 (1949).

[17] Martin *et al.*, Australian J. Sci. Res. **A2**, 25 (1949).

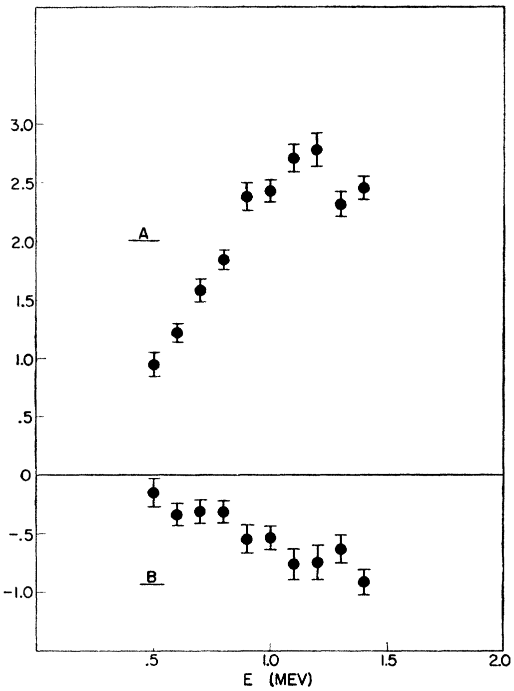

FIG. 3. Variation with the bombardment energy of the coefficients A and B in the equation $Y_\theta/Y_{90°}=1+A\cos^2\theta+B\cos^4\theta$. The probable errors are indicated.

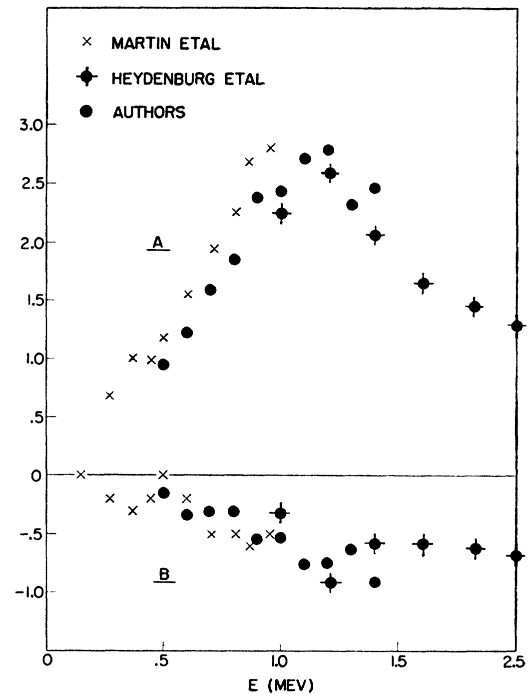

FIG. 4. Comparison with previous results.

the standard deviation[18] must encompass the true values.

It will be noted that our values are slightly displaced from those of the Melbourne group, probably indicating some systematic difference between measurements of the two laboratories. The displacement is in the direction which could be caused by our targets being thicker than theirs. All the targets used here were about 25 kev thick or less as indicated by the breadth of the 440 gamma-ray resonance. However, since they were placed at an angle of 15° to the incident proton beam, the effective thickness was of the order of 100 kev. This places all of our A and B values at an energy of approximately 50 kev higher than the correct energy. If this correction is applied, the values of A so obtained agree remarkably well with those obtained by Martin *et al.*, at Melbourne.

The position of our target has an additional deleterious effect in that the area defined by the beam on the target is also increased by a factor of about four over the actual cross section of the beam. If we pursue the problem further, we will probably put our lithium targets on thin beryllium[19] foils so mounted as to permit observation of α-particles that have passed through the beryllium as well as those coming off the front of the target. In this way the plane of the target can be kept nearly perpendicular to the proton beam, decreasing both the effective target thickness and bombarded area, while permitting observations at $\theta=0°$, instead of being limited to angles greater than 20° as at present.

We wish to express our appreciation of the hospitality and assistance of the staff of the Department of Terrestrial Magnetism, and particularly to Dr. Norman P. Heydenburg, without whose help we could not have pursued this investigation. We also wish to thank Dr. David Inglis for suggesting the problem and advising us along the way.

[18] 2σ defines a probability of 0.95. The results obtained here establish the existence of B beyond any reasonable doubt, since the possibility that a $\cos^4\theta$ term has been observed only because of a fortuitous combination of statistical fluctuations and experimental errors is considerably less than one in a thousand. This is consistent with Inglis's statement that f-protons enter into this reaction.

[19] Martin *et al.*, used aluminum leaf, which is satisfactory at lower energies; but at higher energies considerable difficulty is experienced with the emission of x-rays from the aluminum target backing. Beryllium is completely satisfactory in this respect, and also has the advantage of being very transparent to the product alphas.