PHYSICAL REVIEW VOLUME 116, NUMBER 1 OCTOBER 1, 1959

Angular Distributions of Deuterons from $Li^7(p,d)Li^6$ Reactions*

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(Received May 15, 1959)

Angular distributions of deuterons from $Li^7(p,d)Li^6$ reactions induced by 17.5-Mev protons on a natural lithium target have been observed at angles less than 50 degrees in the laboratory system. Deuteron groups leaving Li^6 in its ground state and in states at 2.19 and 3.57 Mev were studied, and the branching ratios were compared with intermediate coupling shell theory. Pure or nearly pure L-S coupling was found to be adequate to explain the observed ratios.

I. INTRODUCTION

THE lithium isotopes have been extensively treated by using shell theory, and it has been found that an intermediate-coupling model quite near the L-S limit can produce wave functions which give generally good agreement with the data.[1] In fact, this seems to be one of the few areas where one can rely upon shell-model wave functions for over-all quantitative prediction of experimental results.

Deuteron stripping and pickup experiments have provided considerable information on nuclear spins and parities, and more recently these experiments have been used to test nuclear wave functions.[2] The procedure has been to fit an experimental angular distribution with a Butler-type curve, and to extract a quantity θ_l^2, which is essentially the overlap between the wave functions of the ground state of the target nucleus and the final state of the product nucleus (where we consider the pickup experiment). Since many simplifying assumptions have been introduced into the Butler theory, and since the magnitudes of observed cross sections are not at all in agreement with the simple theory, it has become standard practice to compare the θ_l^2 (hereafter referred to as reduced widths) for levels of the final nucleus which are not too far apart, and which are reached by pickup involving the same neutron orbital l. To calculate a single ratio, one needs to know the wave functions of three states: the target in its ground state, and the residual nucleus in both states of excitation. As to the reliability of this reduced width comparison, not much can be said at present, but it is clear that the usefulness of the procedure for testing wave functions can best be evaluated by investigating cases in which the wave functions are well known. The lithium region, then, is one in which data on stripping or pickup should be particularly significant. In addition, pickup ratios for (p,d) reactions on Li^7 to the low-lying levels of Li^6 place more emphasis on the wave functions of Li^6; in so far as these are believed to be more reliably known than the Li^7 wave functions, pickup reactions on Li^7 should provide a better test of the theory than stripping on Li^6.

Auerbach and French[3] have summarized pickup and stripping data in this region, and have found that Standing's[4] experimental value of 0.7 for the stripping ratio

$$Li^7(p,d)Li^6\ (2.19\ \text{Mev})/Li^7(p,d)Li^6\ (\text{ground state})$$

is in good agreement with the theoretical ratio calculated using intermediate-coupling wave functions with $a/K\simeq 1.5$, the value required to fit the Li^6 level spacings. In this note we report a pickup experiment leading to the ground and first two excited states of Li^6.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A foil of natural lithium metal was bombarded with protons of 17.5-Mev laboratory energy. The target, which was about 4 mg/cm² thick, was prepared by rolling the metal under dry mineral oil, as described by Standing.[4] Deuterons were detected in a counter telescope[5] consisting of a thin argon-filled dE/dx counter, backed by a sodium iodide scintillation counter. Coincident pulses from the two counters were recorded, using the two dimensional pulse-height

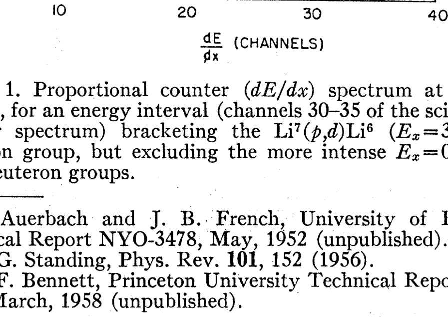

FIG. 1. Proportional counter (dE/dx) spectrum at $\theta_{\rm lab}=32$ degrees, for an energy interval (channels 30–35 of the scintillation counter spectrum) bracketing the $Li^7(p,d)Li^6$ ($E_x=3.6$ Mev) deuteron group, but excluding the more intense $E_x=0$ and 2.2 Mev deuteron groups.

* This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.
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[2] A. M. Lane, Proc. Phys. Soc. (London) **A66**, 977 (1953); **A68**, 189 (1955); **A68**, 197 (1955).
[3] T. Auerbach and J. B. French, University of Rochester Technical Report NYO-3478, May, 1952 (unpublished).
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[5] E. F. Bennett, Princeton University Technical Report NYO-8082, March, 1958 (unpublished).

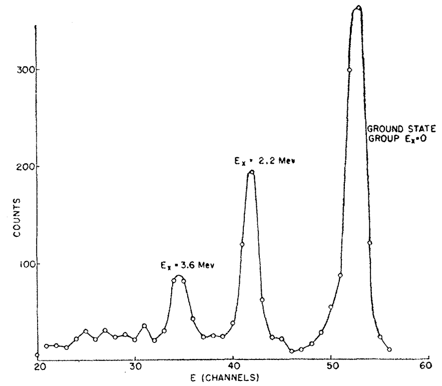

FIG. 2. Energy spectrum of deuterons from $Li^7(p,d)Li^6$ at $\theta_{lab}=20$ degrees. Most of the protons and tritons have been eliminated by reading out only the scintillation counter pulses coincident with pulses in the deuteron group of the proportional counter spectrum.

analyzer of Birk, Braid, and Detenbeck.[6] Data for all groups of singly charged particles were recorded on tape during each run with the cyclotron, and the tapes were subsequently read back through the analyzer to separate the results for protons, deuterons, and tritons. Energy spectra and angular distributions of protons inelastically scattered from the low-lying levels of Li^7, obtained in this experiment, have been reported in a paper by Levinson and Banerjee.[7] All of the measurements were made using the 60-inch scattering chamber described by Yntema and White.[8]

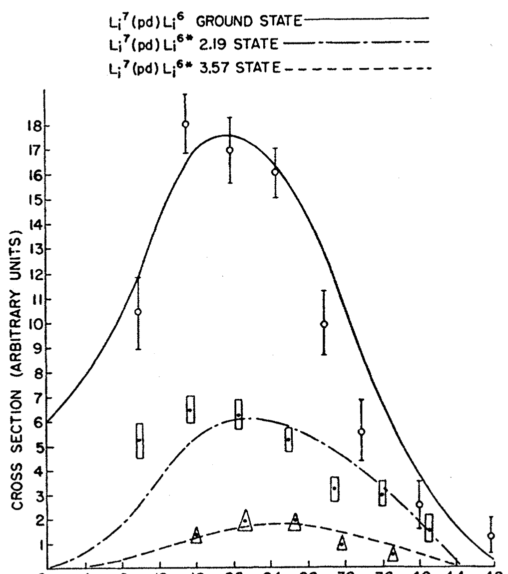

FIG. 3. Experimental and theoretical angular distributions of deuterons from $Li^7(p,d)Li^6$ reactions to the three lowest levels of Li^6. The same Butler parameters, $l_n=1$ and $r_0=5.8\times10^{-13}$ cm, were used for each of the theoretical curves.

[6] Birk, Braid, and Detenbeck, Rev. Sci. Instr. **29**, 203 (1958).
[7] C. A. Levinson and M. K. Banerjee, Ann. Phys. **2**, 471 (1957).
[8] J. L. Yntema and M. G. White, Phys. Rev. **95**, 1226 (1954).

Particles of different mass but equal charge and approximately equal energy were resolved by displaying the (dE/dx) spectrum of those proportional counter pulses which were coincident with the pulses in a narrow energy interval in the scintillation counter spectrum. Deuteron and triton groups then appeared as separate peaks of higher dE/dx than the scattered protons. Figure 1 shows the dE/dx spectrum for an energy interval bracketing the weakest ($E_x=3.57$ Mev) deuteron group observed. For the reactions to the ground and 2.19-Mev levels, the deuteron groups were much more intense and correspondingly more easily studied.

In Fig. 2 is shown the energy spectrum of deuterons from the $Li^7(p,d)Li^6$ reactions at a laboratory angle of 20 degrees. This spectrum was obtained by reading out

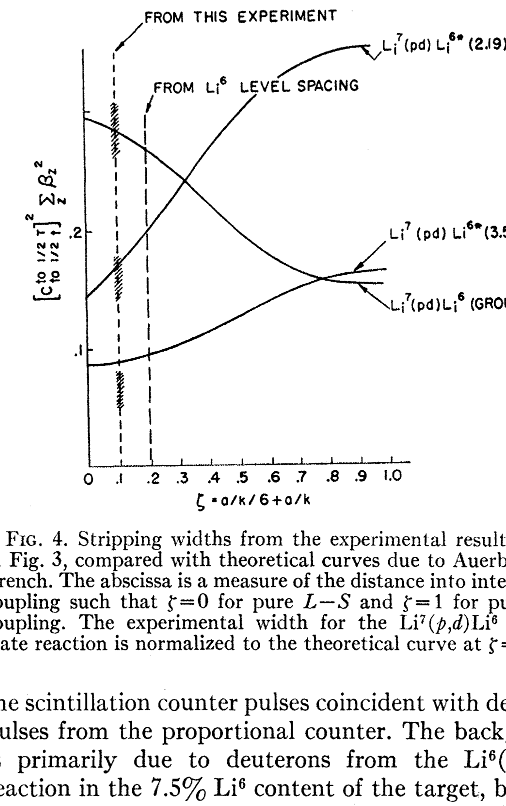

FIG. 4. Stripping widths from the experimental results shown in Fig. 3, compared with theoretical curves due to Auerbach and French. The abscissa is a measure of the distance into intermediate coupling such that $\zeta=0$ for pure $L-S$ and $\zeta=1$ for pure $j-j$ coupling. The experimental width for the $Li^7(p,d)Li^6$ ground-state reaction is normalized to the theoretical curve at $\zeta=0.1$.

the scintillation counter pulses coincident with deuteron pulses from the proportional counter. The background is primarily due to deuterons from the $Li^6(p,d)Li^5$ reaction in the 7.5% Li^6 content of the target, but also includes some tritons from the reaction $Li^7(p,t)Li^5$. Because of the extremely short lifetime of Li^5, these deuterons and tritons are widely spread in energy, so that the background in the energy spectrum is quite uniform and can be subtracted with little systematic error.

The experimental deuteron angular distributions are shown in Fig. 3, with Butler curves giving an "eye" fit to the data. The indicated limits of error are standard deviations, and include the uncertainties from counting statistics and background subtractions. The same parameters $l_n=1$ and $r_0=5.8\times10^{-13}$ cm were used for the three theoretical curves. From the relative cross sections shown in Fig. 3 we find the reduced width ratios

$$\theta^2(2.19\text{ Mev})/\theta^2(\text{ground}) = 0.56\pm0.07$$

and

$$\theta^2(3.59\text{ Mev})/\theta^2(\text{ground}) = 0.23\pm0.05.$$

Absolute differential cross sections for the reactions to the ground and 2.19-Mev levels were measured by Standing,[4] who obtained the somewhat larger value 0.7 ± 0.07 for the ratio $\theta^2(2.19\text{ Mev})/\theta^2(\text{ground})$. There is no obvious explanation for this discrepancy, which is barely within the combined limits of error of the two experiments. In the experiment reported here, however, all three deuteron groups were observed in the same run, whereas in the previous experiment, separate runs were required for the two groups observed.

III. DISCUSSION

Auerbach and French[3] have calculated the overlap integrals between the ground state of Li^7 and the three lowest levels of Li^6, for values of intermediate coupling ranging from $a/K=0$ $(L-S)$ to $a/K=\infty$ $(j-j)$. Their results are shown in Fig. 4, along with the reduced widths determined in this experiment. The ordinate is a quantity proportional to the reduced width, where the proportionality factor involves quantities which are assumed not to vary from level to level. The abscissa ζ is a measure of the distance into intermediate coupling such that $\zeta=0$ when $a/K=0$ and $\zeta=1$ when $a/K=\infty$. The experimental values are shown with cross-hatching to indicate the estimated errors. The experimental width for $Li^7(p,d)Li^6$ (ground) has been normalized to the shell-model value at $\zeta=0.1$. As can be seen from the figure, the experimental ratios are in reasonably good agreement with the theoretical prediction for pure or nearly pure $L-S$ coupling. The agreement argues well for the "stripping width" technique as a tool for the investigation of nuclear wave functions. With so many assumptions inherent in the derivation of a theory in closed form, one probably should not expect very great accuracy. On the other hand, the reduced width depends directly upon the nuclear wave functions, rather than upon matrix elements of electric or magnetic moment operators which in themselves may not be precisely understood.

IV. ACKNOWLEDGMENTS

We wish to express our appreciation to Mr. Robin Room for his work in reading data from the tapes, and to Mr. R. W. Detenbeck for his help with the operation and maintenance of the two-dimensional analyzer. The helpful comments of Professor R. Sherr and Professor C. A. Levinson are gratefully acknowledged.