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Stripping with 28-Mev Deuterons*

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A study of a (d,t) and several (d,p) reactions was performed using 28-Mev deuterons. The outgoing particles were analyzed with a scintillation spectrometer. The absolute differential cross section of the following processes was measured: $Li^7(d,t)Li^6$, $Be^9(d,p)Be^{10}$, $Be^9(d,p)Be^{10*}-3.37$ Mev, $B^{10}(d,p)B^{11}$, $C^{12}(d,p)C^{13}$, and $C^{12}(d,p)C^{13*}-3.68$ Mev.

The angular distributions were fitted by means of direct-interaction plane-wave theoretical curves. All the reactions reported here take place between states of known spin and parity. The $Li^7(d,t)Li^6$ reaction can be fitted with a "pickup" curve corresponding to $l=1$ and $a=5$ f, where l is the angular momentum change and a is the interaction radius. With the exception of the reaction $C^{12}(d,p)C^{13*}-3.68$ Mev, the stripping angular distributions exhibit a secondary oscillation that was interpreted as due to a second value of l contributing to the cross section. Therefore the angular distributions of the following processes were fitted by superimposing the theoretical curves of $l=1$ and $l=3$: $Be^9(d,p)Be^{10}$ with an interaction radius $a=3.5$ f, $Be^9(d,p)Be^{10*}-3.37$ Mev with $a=3.8$ f, $B^{10}(d,p)B^{11}$ with $a=3.6$ f, and $C^{12}(d,p)C^{13}$ with $a=3.5$ f. Finally the $C^{12}(d,p)C^{13*}-3.68$ Mev angular distribution was fitted with a theoretical curve of $l=1$ and $a=3.4$ f. The stripping reduced widths were calculated for the different l contributions to the experimental cross section. The appearance of the f component in addition to the p component predicted by the shell model in the differential cross sections, tentatively assumed here, could be due to configuration mixing, and the levels connected by the transitions should not be pure shell-model states.

I. INTRODUCTION

RECENTLY Macfarlane and French[1] pointed out the absence of experimental information concerning the stripping reactions above 15-Mev laboratory bombarding energy, and they suggested the need of performing experiments at 20 Mev, or at higher energies, to test the validity of the theory, and then to obtain the single-particle reduced widths in order to ascertain their energy dependence.

The 28-Mev deuteron external beam of the Buenos Aires synchrocyclotron[2] has been used to obtain information about (d,p) reactions on several light nuclei. Although the center-of-mass energy is different for each of the studied nuclei, the results exhibit a systematic behavior. The captured neutron, either in the ground state of the residual nucleus or in a low lying level, should belong to the $1p$ shell. Therefore, the direct reactions should yield angular distributions belonging to an orbital angular momentum value $l=1$. The experimental data reported in the following sections show a secondary oscillation, that was interpreted as due to the additional contribution to the cross section of an $l=3$ component. The main difference with respect to the current experimental results is the energy of the incoming deuterons, that is higher by a sizable amount. This circumstance also validates the stripping Born approximation with undistorted waves somewhat better than at lower energies.

No significant compound nucleus contribution to the cross section should be expected on account of the higher deuteron energy, because multiple reactions are favored through that reaction mechanism.

II. EXPERIMENTAL PROCEDURE

A. Machine and Facilities

The 28-Mev external deuteron beam facilities of the Buenos Aires 180-cm synchrocyclotron have been described elsewhere up to the scattering chamber.[2,3] The latter and the auxiliary equipment were described in detail in an earlier paper on elastic and inelastic deuteron scattering.[4] The particle detection and spectrometry was achieved with NaI(Tl) and CsI(Tl) crystals, a phototube (EMI 6097), and a single-channel pulse-height analyzer. The particle separation and identification procedure can also be found in the above-mentioned paper.[4] The proton spectra from beryllium and boron were obtained filtering the reaction products with enough aluminum absorber, in order to transmit protons only. Some minor changes in the electronics were adopted during the work with the boron target, in order to obtain the differential particle spectrum together with the integral above the lower window limit; the latter was registered simultaneously on a second scaler, thus permitting a constant cross check of the collected data.

B. Targets

The lithium target was prepared by rolling the chemically pure element and the carbon target was a foil of commercially available polyethylene. Both were described in an earlier paper together with the technique followed to avoid the hydration of lithium.[4] The beryllium target was a chemically pure foil 20-mg/cm² thick at 45° with respect to the beam direction.

The boron target was prepared with the chemically pure element in powder form using the following procedure: A boron emulsion in water was poured on a very thin cellulose acetate backing, and the liquid was allowed to evaporate naturally in the open air, without

* Based on communications to the Asociación Física Argentina during the following meetings: XXXIV (September, 1959), XXXV (May, 1960), XXXVI (September, 1960), XXXVII (May, 1961), and XXXVIII (September, 1961).

[1] M. H. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).

[2] J. Rosenblatt and R. J. Slobodrian, Rev. Sci. Instr. **31**, 863 (1960).

[3] P. A. Lenk and R. J. Slobodrian, Phys. Rev. **116**, 1229 (1959).

[4] R. J. Slobodrian, Phys. Rev. (to be published).

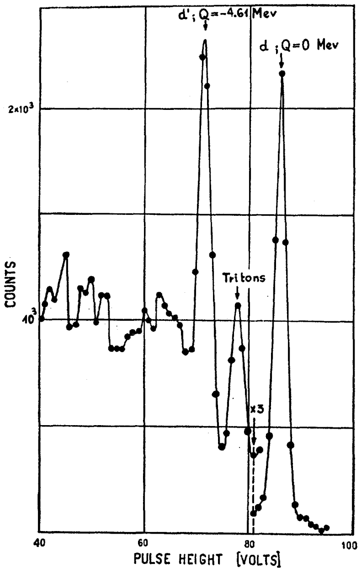

FIG. 1. Charged particle spectrum from lithium at $\theta_{lab}=35°$.

turbulence. Some targets of very good uniformity were obtained after several trial operations. The thickness measurement of the beryllium and boron targets was performed as described by Conzett.[5] The error of such measurements was determined using aluminum targets of known thickness, and it is not larger than 5%. The boron targets backing thickness was negligible with respect to their 20-mg/cm² average thickness.

C. Errors and Experimental Uncertainties

A full discussion can be found in the paper on deuteron scattering repeatedly quoted.[4] It may be worth while to mention that the beam energy determinations performed during the measurements of the angular distributions for Be and B indicate a beam energy of 27.7 Mev±1%. This value is somewhat lower than the one determined previously and it may be a consequence of some iron configuration changes, performed to raise the beam intensity. Nevertheless the beam energy can be maintained very stable as stated elsewhere,[4] with little precaution on the parameters of the deflector and the magnetic field of the machine.

The absolute differential cross sections reported here are known within an error of 5% for carbon and 8% for lithium, boron, and beryllium, besides the relative errors indicated on the experimental curves. The values quoted here are due to the error in current integration, in solid angle, and in target thickness.

The scintillator particle detection efficiency was taken to be one, because it was reasonable to expect that all particles accepted by the defining apertures were counted. Particular care was taken to avoid multiple-scattering effects, placing the aluminum filter immediately in front of the crystal. The loss of particles due to reactions was certainly negligible.

[5] Homer E. Conzett, Phys. Rev. **105**, 1324 (1957).

III. RESULTS AND CONCLUSIONS

A. General

Figures 2, 4, 5, 7, 9, and 10 contain the experimentally determined absolute differential cross sections referred to the center-of-mass system; the conversion was effected with the help of tables due to Marion *et al.*[6] They also contain the plane-wave direct-interaction theoretical curves, obtained from tables prepared by Lubitz.[7] The formulas and parameters were used in the form presented by Macfarlane and French.[1] The stripping reduced width $\theta^2=S\theta_0^2$, where θ_0^2 is the single-particle reduced width, and S is a spectroscopic factor, was obtained by peak fitting of the theoretical curves and is given in units of the Wigner limit $(3/2)\hbar^2/2\mu a^2$. More precisely the calculated value is $C^2\theta^2$, where C is an isotopic spin Clebsch-Gordan vector coupling coefficient, although it is equal to one for the (d,p) reactions starting from an $(n-p)_T$ configuration.[1] The usual angular momentum and parity selection rules follow from the so called "stripping approximation," and are well known. Such an approximation neglects the interaction V_{np} between neutron and proton in the deuteron, and $V_{\xi p}$ between the proton and the target nucleus, in the Schrödinger equation describing the reaction. Instead, when the nuclear interaction of the proton cannot be neglected it is necessary to use the general selection rule derived from the principle of conservation of angular momentum for the complete system:

$$|\mathbf{J}_A+\mathbf{J}_B+\mathbf{s}_a+\mathbf{s}_b|_{\min}\leqslant l\leqslant J_A+J_B+s_a+s_b, \qquad (1)$$

together with the usual parity conservation rule $\Pi_A\Pi_B=(-1)^l$; $\mathbf{J}_A$ and $\mathbf{J}_B$ are the spins of the initial and final states, $\mathbf{s}_a$ and $\mathbf{s}_b$ are the spins of the projectile and of the reaction product respectively. Due to the higher energy of the incoming deuterons one might expect that the "stripping approximation" is less valid here than at the lower energies previously used, because the nucleons should come closer to the target nucleus.

B. Angular Distributions

1. $Li^7(d,t)Li^6$

Figure 1 contains a typical particle spectrum from lithium obtained during the experiment. The identification of the triton group was a consequence of the combined use of kinematics and the specific energy loss dE/dx of tritons in aluminum, and it is judged to be unambiguous. The direct reaction may proceed at least in two different ways: inverse stripping or "pickup" and "knockout." Butler derived the theoretical angular

[6] J. B. Marion, T. I. Arnette, and H. C. Owens, Oak Ridge National Laboratory Report ORNL-2574 (unpublished).
[7] C. R. Lubitz, Numerical Table of Butler-Born Approximation Cross Section, University of Michigan, 1957. (unpublished).

distribution[8] that is formally analogous for both processes:

$$d\sigma/d\Omega \propto |1/(Q^2+\kappa^2)W\{j_l(Qr),h_l(i\kappa r)\}_{r=a}|^2. \quad (2)$$

The "pickup" or inverse stripping reaction in the case of a (d,t) process simply involves the attachment of a neutron to the deuteron. The average momentum transfer for a "pickup" reaction $A(a,b)B$ is

$$\mathbf{Q}=|(M_B/M_A)\mathbf{k}_a-\mathbf{k}_b|,$$
$$\kappa=(1/\hbar)(2M_a\epsilon_{ai})^{\frac{1}{2}},$$

$\mathbf{k}_a$ and $\mathbf{k}_b$ are the wave vectors of the incoming and outgoing particles, ϵ_{ai} is the binding energy of particle a in the initial nucleus A and M stands for the masses of the nuclei and particles involved.

The picture of the "knockout" reaction is obvious from its name. The outcoming particle is knocked out by the projectile. It can be shown that the average momentum transfer is[9]

$$Q=|[(M_A-M_b)/M_A]\mathbf{k}_a-[(M_B-M_a)/M_B]\mathbf{k}_b|,$$
$$\kappa=(1/\hbar)[(2M_b\epsilon_{bi})^{\frac{1}{2}}+(2M_a\epsilon_{af})^{\frac{1}{2}}],$$

where ϵ_{bi} and ϵ_{af} are the binding energies of the reaction product in the initial nucleus and of the projectile in the final nucleus respectively. The experimental angular distribution together with the theoretical curves of the above-mentioned processes are shown in Fig. 2. The measured points start beyond the first maximum of the theoretical curves fitted to them. Both belong to an $l=1$ value with interaction radii of $a=5$ f for "pickup" and $a=7.2$ f for 'knockout." The latter interaction radius seems to be unreasonably high, when compared with the deuteron-lithium interaction radius of 4.1 f found through the analysis of the elastic scattering angular distribution,[4] particularly taking into account the picture of the "knockout" process. The experimental points disagree strongly from the theoretical curves around 70° in the center-of-mass system. Some attempts to include an $l=3$ contribution to give account of the disagreement were made. It should be necessary to attribute the oscillation around 70° to the second maximum of the $l=3$ curve for the "pickup" process with an interaction radius $a=7.5$ f.

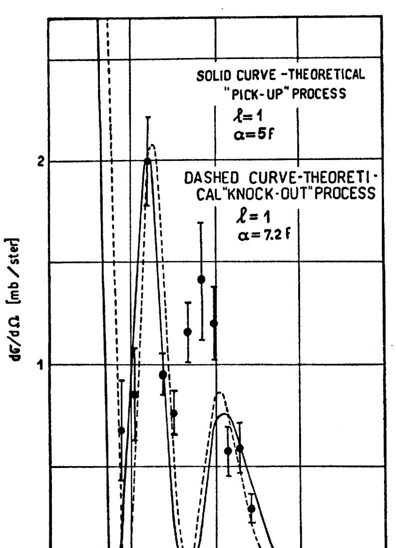

FIG. 2. Angular distribution of tritons from the reaction $Li^7(d,t)Li^6$.

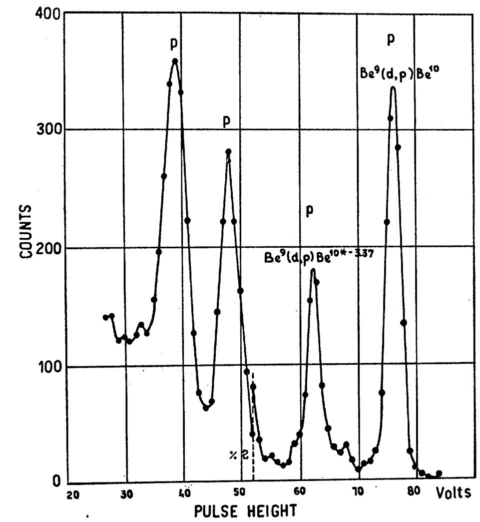

FIG. 3. Proton spectrum from beryllium at $\theta_{lab}=15°$.

Instead of a stripping reduced width θ^2 one obtains from the experimental data the value $\Lambda\theta^2$, where Λ is a normalization constant. The value obtained for the $Li^7(d,t)Li^6$ reaction is $\Lambda\theta^2=18$. The normalization constant, as determined at lower energies, is $\Lambda=230$, and if it is valid to employ it here, the stripping reduced width $\theta^2=0.078$. Macfarlane and French[1] quote a value of $\Lambda=190\pm40$ consistent with the table on stripping reduced widths from deuteron-triton reactions, wherefrom the value for Li^7 was extracted. The value obtained in this experiment is some three times larger than the value given by Levine, Bender and McGruer[10] using 15-Mev deuterons.

2. $Be^9(d,p)Be^{10}$ and $Be^9(d,p)Be^{10*}-3.37$ Mev

Figure 3 contains a proton spectrum obtained filtering the reaction products with an adequate thickness of aluminum. The two higher energy groups correspond to the ground and first-excited states of Be^{10}. The remaining two are the result of the reunion of several levels of the final nucleus.

[8] S. T. Butler, Phys. Rev. **106**, 272 (1957).
[9] J. G. Likely and F. P. Brady, Phys. Rev. **104**, 118 (1956).
[10] S. H. Levine, R. S. Bender, and J. N. McGruer, Phys. Rev. **97**, 1249 (1955).

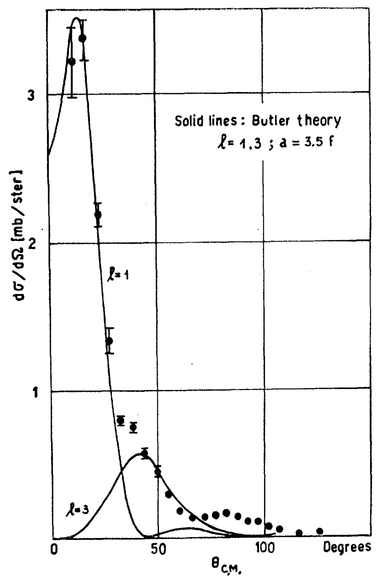

FIG. 4. Angular distribution of protons due to the reaction $Be^9(d,p)Be^{10}$.

The reader is referred to reference (1) and to a paper by Zeidman and Fowler[11] for information concerning earlier work on the just mentioned stripping reactions.

Figure 4 shows the experimental angular distribution of the $Be^9(d,p)Be^{10}$ reaction, together with the direct interaction theoretical curves. The experimental points could not be fitted with a single theoretical curve. Instead they follow closely the superposition of the curves of $l=1$ and $l=3$ with $a=3.5$ f. The initial and final spin and parities are respectively $\frac{3}{2}$ odd and 0 even. The "stripping approximation" angular momentum and parity rules yield as the only possible value $l=1$. The

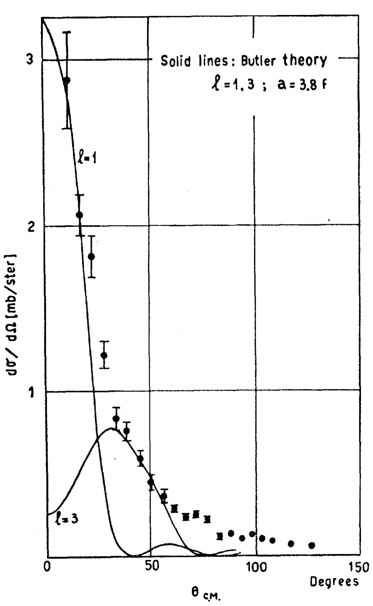

FIG. 5. Angular distribution of protons due to the reaction $Be^9(d,p)Be^{10*}$ -3.37 Mev.

[11] B. Zeidman and J. M. Fowler, Phys. Rev. **112**, 2020 (1958).

additional $l=3$ contribution assumed here tentatively is permitted by the general angular momentum selection rule (1). The $l=3$ value of the orbital momentum of the captured neutron corresponds to the spin-flip of the proton during the interaction. Consequently the "stripping approximation" should not be valid any more. The "spin-flip" hypothesis was formulated by Wilkinson[12] in order to explain the stripping results of the reaction $B^{10}(d,p)B^{11*}-2.14$ Mev. In this case an alternative explanation was given by Evans and French[13] assuming exchange effects in the interaction. The polarization experiment of Hensel and Parkinson[14] supports the "spin-flip" hypothesis of Wilkinson. Nevertheless Evans and French point out that both descriptions involve a close interaction of the whole deuteron with the target nucleus, and the polarization is implicit in their treatment of the problem, making the difference between them perhaps more apparent than real. The angular distributions reported here were followed down to 150° in the laboratory system, and the cross section

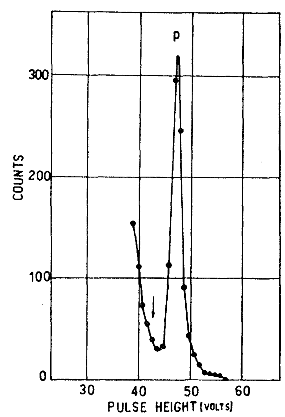

FIG. 6. Proton spectrum from boron at $\theta_{lab}=20°$.

remains certain at the same order of magnitude than that of the last point drawn. No significant backward rise of the cross section was observed. Qualitatively, the nucleon exchange curves of Evans and French[13] seem to be applicable to the results reported here, extrapolating to the much higher energy used to obtain them. Nevertheless the theoretical rise of the cross section for backward angles was not observed in this experiment. In addition the "spin-flip" does not mean necessarily nucleon exchange and vice versa. The $l=3$ contribution to the cross section is obviously forbidden by the usual pure shell model of the nucleus, because the captured neutron should be a $1p$ and not a $1f$ nucleon as it results via "spin-flip" without nucleon exchange. A possible explanation of the observed effect could be a configuration mixing. Table I contains the reduced widths calculated as explained previously.

[12] D. H. Wilkinson, Phys. Rev. **105**, 666 (1957).

[13] A. P. French, Phys. Rev. **107**, 1655 (1957); N. T. S. Evans and A. P. French, *ibid.* **109**, 1272 (1958).

[14] J. C. Hensel and H. C. Parkinson, Phys. Rev. **110**, 128 (1958); J. C. Bowcock, *ibid.* **112**, 923 (1958).

TABLE I. Stripping reduced widths θ^2 of the captured nucleon in the (d,p) reactions.

Reaction	Value	θ^2
$Be^9(d,p)Be^{10}$ (ground state)	1	0.28
	3	0.52
$Be^9(d,p)Be^{10*}-3.37$ Mev	1	0.0047
	3	0.02
$B^{10}(d,p)B^{11}$ (ground state)	1	0.073
	3	0.17
$C^{12}(d,p)C^{13}$ (ground state)	1	0.032
	3	0.072
$C^{12}(d,p)C^{13*}-3.68$ Mev	1	0.066

Figure 5 shows the angular distribution of the $Be^9(d,p)Be^{10*}-3.37$ Mev reaction together with the theoretical curves. The $l=3$ contribution is allowed by both the restricted "stripping approximation" and the general angular momentum selection rule. The experimental points show that its contribution to the cross section is somewhat stronger than in the previous case.

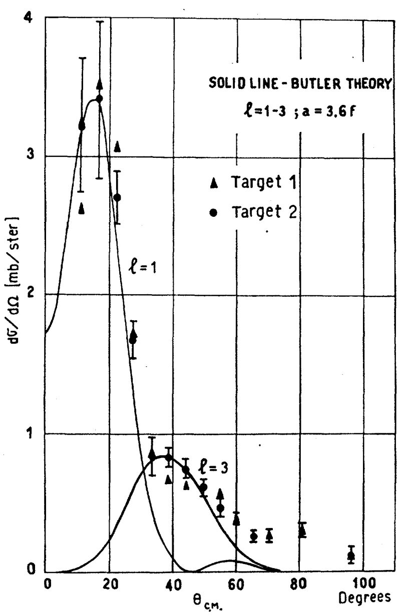

FIG. 7. Angular distribution of protons due to the reaction $B^{10}(d,p)B^{11}$.

3. $B^{10}(d,p)B^{11}$

Figure 6 contains a typical proton spectrum. As is well known, natural boron consists of 18.8% of B^{10} and 81.2% of B^{11}. The high value of $Q=9.24$ Mev was the reason that enabled the measurement of the absolute differential cross section shown in Fig. 7. The arrow points the position where the proton group of the reaction $B^{10}(d,p)B^{11*}-2.14$ Mev should be found. The angular distribution of the last mentioned process could not be measured due to the high proton background from the processes $B^{11}(d,p)B^{12}$, B^{12*}, although at several angles it was clearly visible. The same reason imposed severe restrictions on the beam intensity. A recent paper by Bilaniuk and Hensel[15] contains information on the configurations of B^{11} using 7.8-Mev deuterons, but the angular distributions are not given in terms of absolute cross sections. Macfarlane and French[1] point out that the lack of absolute cross sections obscure the arguments in favor of the single particle nature of the levels. The

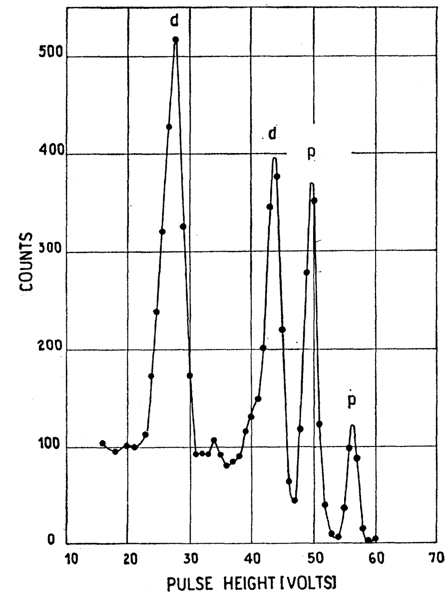

FIG. 8. Charged particle spectrum from C^{12} at 45° laboratory angle with 200 mg/cm² of aluminum in front of the crystal.

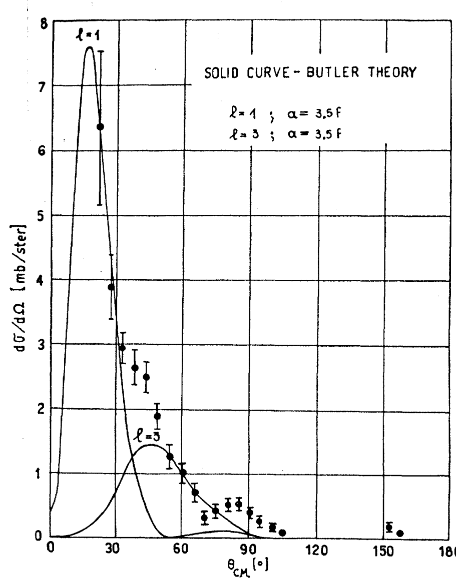

FIG. 9. Angular distribution of protons from the reaction $C^{12}(d,p)C^{13}$.

[15] O. M. Bilaniuk and J. C. Hensel, Phys. Rev. **120**, 211 (1960).

angular distributions can be fitted again by superimposing the $l=1$ and $l=3$ theoretical curves with $a=3.6$ f. The "stripping approximation" rules applied to the transition (3 even to $\frac{3}{2}$ odd) allow the following values for the orbital momentum of the captured nucleon: 1, 3, and 5. Indeed, with a slightly larger interaction radius the first maximum of the $l=5$ theoretical curve would fit the points around 80°, although this seems rather implausible. The reduced widths for the $l=1$ and $l=3$ contributions are given in Table I.

4. $C^{12}(d,p)C^{13}$ and $C^{12}(d,p)C^{13*}-3.68$ *Mev*

Figure 8 shows a typical particle spectrum used to obtain both angular distributions. In this case it was not necessary to use an aluminum filter thick enough to stop all the reaction products with the exception of protons.

Figure 9 contains the absolute differential cross section of the reaction $C^{12}(d,p)C^{13}$. It can be fitted with the theoretical curves of $l=1$ and $l=3$ with $a=3.5$ f. The transition occurs between a 0 even and a $\frac{1}{2}$ odd state, and the $l=3$ value is not permitted either by the restricted or the general selection rule (1). Nevertheless it is worth while to point out that the reaction might also take place via the excitation of the target nucleus prior to the stripping process. No attempt was made to estimate the cross section for such a reaction mechanism.

The angular distribution of the reaction $C^{12}(d,p)C^{13*}$ -3.68 Mev is shown in Fig. 10. It was fitted with a single theoretical curve of $l=1$ and $a=3.4$ f. This is consistent with the $\frac{3}{2}$ odd spin and parity assignment of the level. A small additional contribution of the $l=3$ curve would improve the agreement with the experimental results, giving account of the absence of a distinct minimum in the differential cross section. In this case the second l value is permitted by the general selection rule (1).

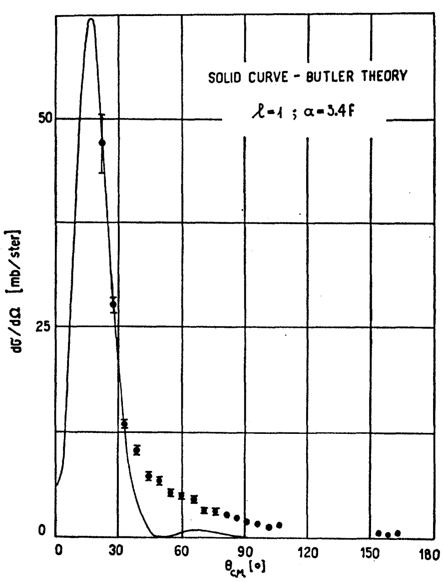

FIG. 10. Angular distribution of protons from the reaction $C^{12}(d,p)C^{13*}-3.68$ Mev.

C. Conclusions

All the angular distributions reported here exhibit a direct reaction behavior. As there is no large-angle significant rise in the cross section one may conclude that there is a small contribution, if any, due to compound nucleus, exchange, and heavy-particle stripping processes.

The systematic use of the incoherent superposition scheme of theoretical curves belonging to different l values reproduces adequately the observed angular distributions, implying, in case it is correct, the configuration mixing of the levels involved in the reactions. The observed effects can be probably ascribed to the higher deuteron energy.

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