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(α,Li^6) Reaction on C^{12}, N^{14}, Al^{27}, and Ni at 42 MeV*†

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Angular distributions for the $N^{14}(\alpha,Li^6)C^{12}$ and $C^{12}(\alpha,Li^6)B^{10}$ reactions have been measured at a bombarding energy of 42 MeV. Assuming that these reactions proceed through the pickup of a deuteron cluster and that the plane-wave Born approximation is applicable, it is found that the reduced width for a deuteron cluster in the ground state of N^{14} is five times larger than that for the C^{12} ground state. Distorted-wave Born approximation calculations did not agree with experiment. The (α,Li^6) reaction was also observed with aluminum and nickel targets. Though the (α,Li^7) reaction contaminated the spectra and the experimental resolution was insufficient to separate discrete final states, it is clear that the (α,Li^6)-reaction cross sections for aluminum and nickel were smaller than that for nitrogen by at least a factor of 50 and 1000, respectively.

I. INTRODUCTION

ONE of the nuclei most likely to show cluster structure is Li^6, the cluster description being ($\alpha+d$) with the alpha particle and the deuteron in a relative S state.[1,2] If this is the case, the reaction (α,Li^6) may be considered a "deuteron pickup" reaction on any target nucleus with a ground state that contains the configuration (core+deuteron). It is quite possible that N^{14} meets this requirement as previously discussed by Inglis.[3] Of obvious interest would be the comparison of (α,Li^6) reaction cross sections for N^{14} and for C^{12} which forms the "core" of the assumed $C^{12}+d$ configuration of the N^{14} ground state. A strong enhancement of this reaction on N^{14} compared to C^{12} would be compatible with the simple cluster model interpretation of the reaction

$$N^{14}(C^{12}+d)+\alpha\rightarrow C^{12}+Li^6(\alpha+d).$$

Several factors could reduce this enhancement. First, the (α,Li^6) reaction should occur on all nuclei simply by successive nucleon pickup. Second, the (α,Li^6) reaction should have some small probability of occurrence through the formation of a compound nucleus and the subsequent re-emission of a Li^6 ion. In fact, the (α,Be^7) reaction has been studied[4,5] previously by radiochemical techniques and the results interpreted in terms of compound nucleus formation. Third, the "core," in this case C^{12}, may itself have a large "core+deuteron" configuration. In the case of C^{12}, recent high-energy (α,2α) measurements[6] suggest that the ground state clusters into three alpha particles. This does not, however, exclude the possibility of a large fraction of the configuration ($B^{10}+d$) in the ground state. Fourth, the particular cluster model invoked, i.e., core +deuteron, may not give a good spatial description of Li^6 and N^{14}. The recently discovered "p-shell dip"[7] for Li^6 in high energy (p,$2p$) studies indicates that there are fewer low-momentum components for the "p" proton than a cluster model would predict. Further, cluster model wave functions appear incapable of yielding the observed Coulomb energy difference[8] for the mirror nuclei, C^{10} and Be^{10}.

The present experiment was undertaken to compare the (α,Li^6) reaction on C^{12} and N^{14} and then to extend its observation to heavier nuclei.

II. EXPERIMENTAL

The bombardments with 42-MeV alpha particles were carried out in the 60-in. scattering chamber of the University of Washington 60-in. cyclotron. The external-beam system has been described previously.[9] With

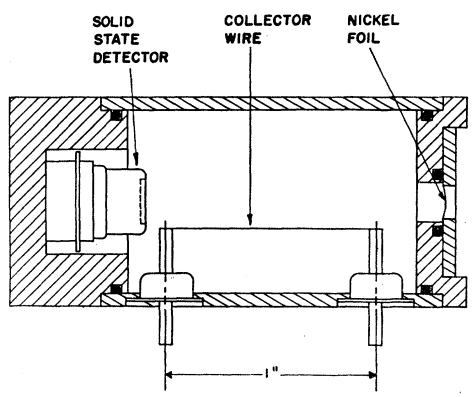

FIG. 1. The dE/dx–E counter. Particles enter through a collimator placed just outside the nickel window.

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† This work was done in partial fulfillment of the requirements for the Ph.D. degree at the University of Washington. A preliminary account of this work appeared in Bull. Am. Phys. Soc. 9, 56 (1963).

[1] G. C. Phillips and T. A. Tombrello, Nucl. Phys. **19**, 555 (1960).
[2] K. Wildermuth and T. Kanellopoulos, Nucl. Phys. **7**, 150 (1958).
[3] D. R. Inglis, Phys. Rev. **126**, 1789 (1962).
[4] G. Bouchard and A. W. Fairhall, Phys. Rev. **116**, 160 (1959).
[5] C. Hower, thesis, University of Washington, 1962 (unpublished).
[6] G. Igo, L. F. Hanson, and T. J. Gooding, Phys. Rev. **131** 337 (1963).
[7] G. Tibell, O. Sundberg, and U. Miklavzic, Phys. Letters **1**, 172 (1962).
[8] Francis J. Bartis, Phys. Rev. **132**, 1763 (1963).
[9] See, for example, A. J. Lieber, F. H. Schmidt, and J. B. Gerhart, Phys. Rev. **126**, 1496 (1962).

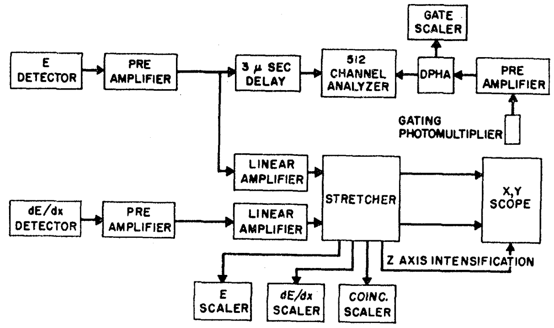

FIG. 2. Block diagram of electronic circuitry.

the slit positions that were used, the alpha-particle energy was determined to be 42±0.2 MeV with an energy spread of approximately 100 keV. The reaction products were detected and identified with a dE/dx–E system. The dE/dx detector was a proportional counter filled with $\frac{1}{10}$ atmosphere P-10 counting gas[10] and was operated with 600 V on its 0.002-i.n-diam collector wire. The E counter was contained within the proportional counter assembly as shown in Fig. 1. This E counter was a silicon diffused-junction solid-state detector[11] with a depletion region of sufficient thickness to stop 42-MeV alpha particles. Identical low-noise, charge-sensitive preamplifiers[12] were used for both detectors.

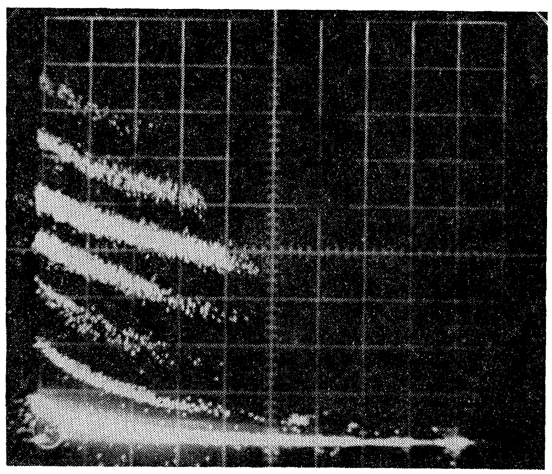

FIG. 3. Photograph of x,y oscilloscope displaying dE/dx versus E during alpha-particle bombardment of a Cymel target. The lowest bright curve is due to alpha particles. Those above are due to Li, Be, B, C, N, and O.

Particle identification was accomplished with the aid of a plotting-oscilloscope system. A dual-channel pulse stretcher[13] held the amplified dE/dx and E signals flat-topped for 1 μsec, then promptly returned to zero output and was ready for a second event within 1 μsec. For coincident dE/dx and E signals, the pulse stretcher unit also provided a 0.2 μsec intensifying pulse which was applied to the Z axis of a Tektronix 536 x,y oscilloscope, as shown in Fig. 2. An example of the display obtained during the 42-MeV alpha-particle bombardment of a Cymel (carbon+nitrogen) target is shown in Fig. 3, which is a time exposure of the x, y oscilloscope face. The various curves are due to He, Li, Be, B, C, N, and O ions. These ions are reaction products and recoil nuclei from (α,x) reactions on C and N. Singly charged particles are not seen in this display since the bias of the system excludes them. The dE/dx resolution is insufficient to separate masses within a given charge group.

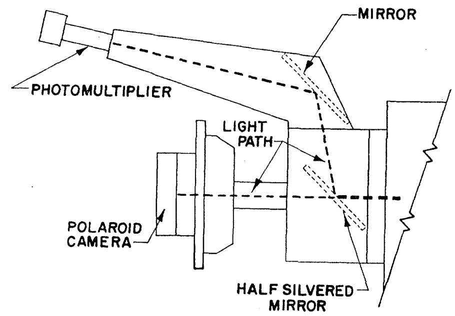

FIG. 4. Diagram of the gate generating photomultiplier mounting. The half-silvered mirror allowed time exposures of the oscilloscope to be made during the entirety of a data run.

When this system was used for Li ion identification, the vertical scale was expanded and a black paper mask placed over the oscilloscope face so that only events due to Li ions were visible. A photomultiplier tube viewed

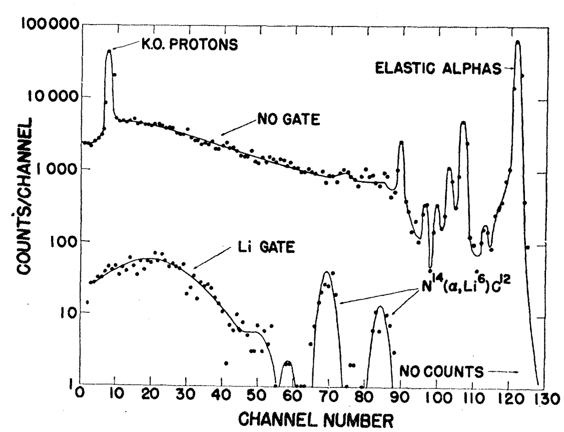

FIG. 5. Gated and ungated spectra from a Cymel target. These spectra were obtained for the same net charge on target and show the capability of the particle identification system.

[10] This mixture was obtained from the Matheson Company, Newark, California.

[11] RCA type C-4-400-2.0 obtained from the RCA Victor Company, Ltd., Montreal, Canada.

[12] ORTEC Model 101 preamplifier obtained from Oak Ridge Technical Enterprises Corporation, Oak Ridge, Tennessee.

[13] Annual Progress Report (1961) Cyclotron Research, University of Washington, p. 51 (unpublished).

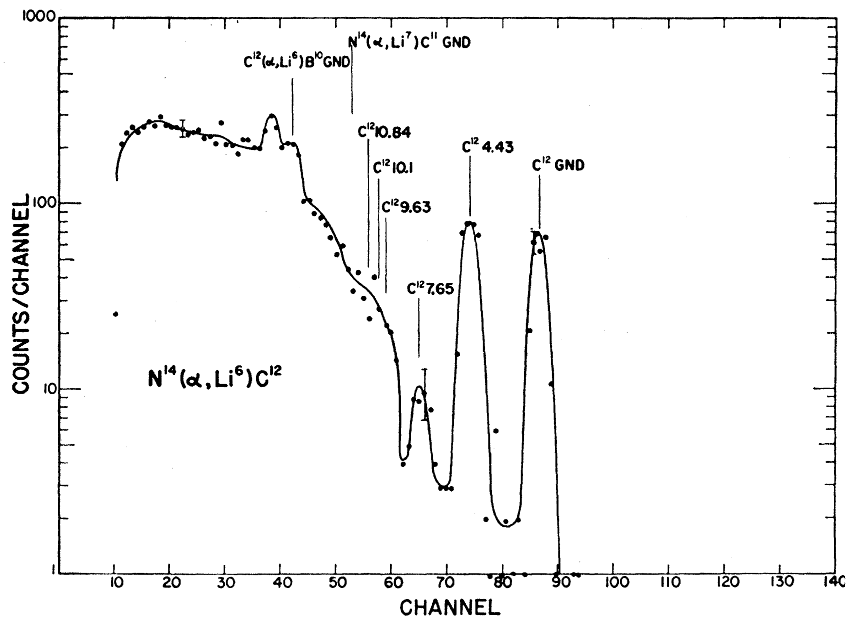

FIG. 6. Li spectrum from $N^{14}(\alpha,Li^6)C^{12}$ at a laboratory angle of 20°.

the masked oscilloscope face, as shown in Fig. 4, and produced a pulse only for a proper Li event. This pulse was used to gate a 512 channel analyzer as shown in Fig. 2. Figure 5 demonstrates the ability of the system to reject particles other than Li ions. Since the gating photomultiplier was mounted on the viewing port of an oscilloscope camera, a time exposure of the masked oscilloscope face could be made during a data run. This was always done to ensure against any unnoticed drifts, or the occurrence of electronic pileup during a run.

The beam was collected in a Faraday cup, and the charge measured with an integrating electrometer. The accuracy of the system was ±5% as determined from Coulomb scattering measurements on gold. Elastically scattered alpha particles were detected by a fixed CsI(Tl) counter which served as a monitor of target thickness.

Target thicknesses were measured by weighing known areas. The carbon targets were typically 1 mg/cm^2 carbon foils made by evaporating a "dag" suspension on a glass plate and floating the resulting foil off in water. The nitrogen targets were typically 2.5 mg/cm^2 foils of Cymel. Cymel is a butylated melamine resins containing 60.5% C, 29.5% N, 7.4% H, and 4.9% O, by weight.[14] These foils were made by spraying the resin on glass plates which had previously been coated with gold by vacuum evaporation. After curing, the resin was separated from the gold by amalgamating the gold in a dish of mercury.

Energy calibrations of the detector were carried out as follows: Thin natural lithium targets evaporated on various backings were bombarded with the 42-MeV alpha-particle beam. The elastically scattered Li^6 and Li^7 ions were observed at various angles. Since the energy of the elastically scattered ions as a function of angle can be computed exactly, an energy calibration of the E pulse height for Li^6 and Li^7 could be obtained simultaneously. Energy resolution throughout the experiment was typically 1-MeV full width at half-maximum.

III. RESULTS

A. $N^{14}(\alpha,Li^6)C^{12}$

Figure 6 shows a spectrum of Li ions for $N^{14}(\alpha,Li^6)C^{12}$ at a laboratory angle of 20°. As shown on the figure, lithium ions from the $N^{14}(\alpha,Li^7)C^{11}$ and $C^{12}(\alpha,Li^6)B^{10}$

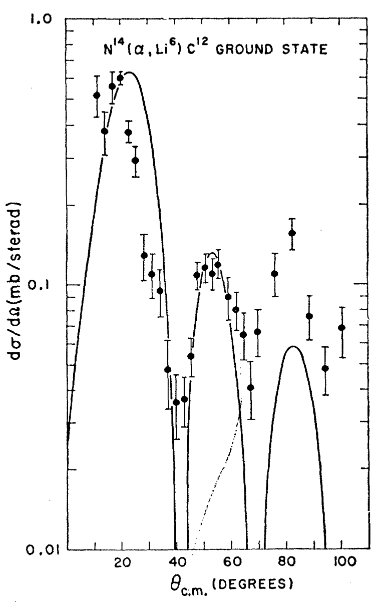

FIG. 7. Angular distribution of Li^6 ions from $N^{14}(\alpha,Li^6)C^{12}$ exciting the C^{12} ground state. The solid curve is expression (1) with $L=2$, $R_0=4$ F.

[14] This information was obtained from the American Cyanimid Company, Seattle, Washington.

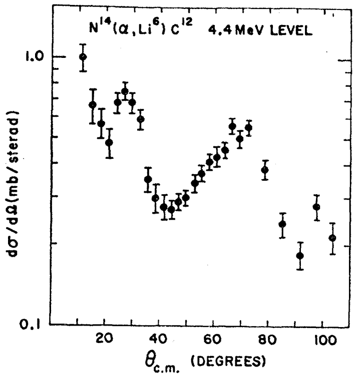

FIG. 8. Angular distribution of Li^6 ions from $N^{14}(\alpha,Li^6)C^{12}$ exciting the C^{12} 4.43-MeV level.

reactions interfered with the region corresponding to high excitations in C^{12}. The ground state and first two excited states are resolved with the 7.65 level only weakly excited. Angular distributions for the ground state and 4.43-MeV level of C^{12} are given in Figs. 7 and 8. The strong oscillations and foward peaking are characteristic of a direct reaction mechanism.

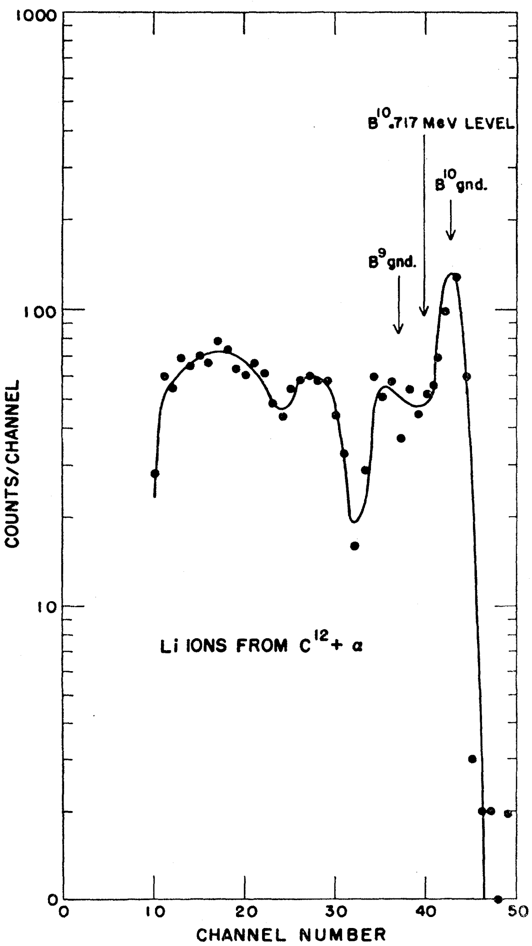

FIG. 9. Li spectrum from $C^{12}(\alpha,Li^6)B^{10}$ at a laboratory angle of 20°.

B. $C^{12}(\alpha,Li^6)B^{10}$

Figure 9 shows a spectrum of Li ions from the alpha-particle bombardment of a carbon target. Only the ground-state transition could be resolved since the $C^{12}(\alpha,Li^7)B^9$ reaction obscured most of the spectrum, as indicated in Fig. 9. The 0.717-MeV level in B^{10} could not be fully resolved from the ground state. From the observed line shapes the 0.717-MeV transition was less than one-half the intensity of the ground-state transition. This is in agreement with the ratio of spin multiplicities of these two states. In order to obtain angular distributions for the ground-state group, the peak was fitted with the measured resolution function of the detector. Figure 10 shows the angular distribution so obtained.

C. $Al^{27}(\alpha,Li^6)Mg^{25}$ and $Al^{27}(\alpha,Li^7)Mg^{24}$

Since $Al^{27}(\alpha,Li^6)Mg^{25}$ and $Al^{27}(\alpha,Li^7)Mg^{24}$ have similar Q values of -15.68 and -15.76, respectively, and since the energy resolution was insufficient to separate the levels of Mg^{25}, a clear interpretation cannot be made of the spectrum of Li ions observed from alpha-particle bombardment of aluminum. Figure 11 shows such a spectrum with the expected positions of the ground and first excited states of Mg^{24} and Mg^{25}. It is clear that the observed cross section has dropped sharply in comparison to that for a carbon or nitrogen target. The ground-state transition for either $Al^{27}(\alpha,Li^6)Mg^{25}$ or $Al^{27}(\alpha,Li^7)Mg^{24}$ cannot exceed 20 μb/sr. at this angle ($\theta_{lab}=25°$). All energy intervals in this spectrum show forward peaking in their angular distributions.

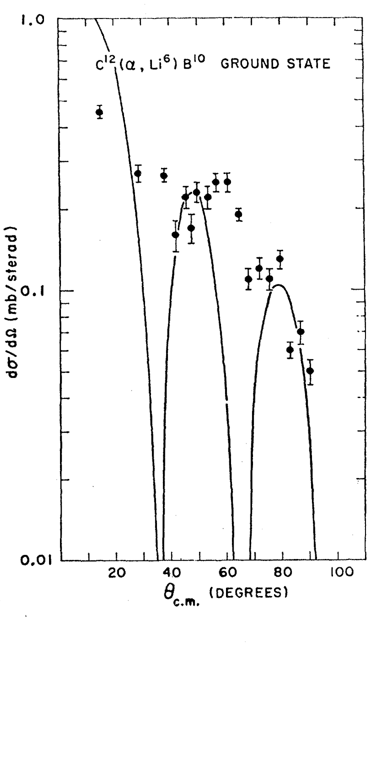

FIG. 10. Angular distribution of Li ions from $C^{12}(\alpha,Li^6)B^{10}$ (ground state). The solid curve is expression (1) with $L=2$ and $R_0=5.4$ F.

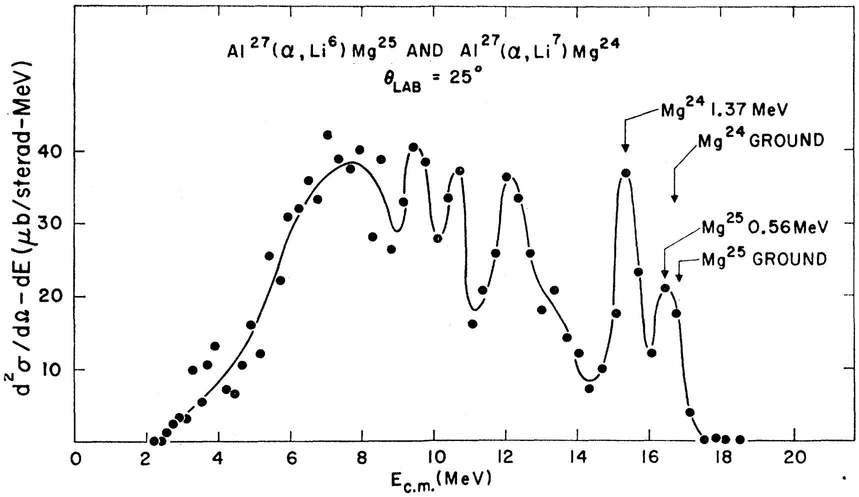

FIG. 11. Lithium ion spectrum from $Al^{27}+\alpha$.

D. Ni(α,Li)

Figure 12 shows a spectrum of lithium ions observed at a laboratory angle of 30° resulting from alpha-particle bombardment of a natural nickel target. (α,Li^6) and (α,Li^7) reactions on both Ni^{58} and Ni^{60} have similar Q values, as shown in the figure. The location of the Coulomb-barrier height for lithium ions is shown in the figure. Since the yield to the ground state of the residual nucleus is so small, no more than $\frac{1}{2}$ μb/sr for either $Ni^{58}(\alpha,Li^6)Co^{56}$ or $Ni^{60}(\alpha,Li^6)Co^{58}$, it seemed possible that the reactions could now be proceeding through the evaporation of a Li ion from a compound nucleus. If this were the case, symmetry about 90° should be observed since the statistical assumption would be valid for the assumed compound nucleus. An angular distribution of the total differential cross section for Li^6 and Li^7 production is shown in Fig. 13. The strong forward peaking indicates the predominance of a direct reaction mechanism.

IV. DISCUSSION

A. $N^{14}(\alpha,Li^6)C^{12}$

If the ground-state reaction proceeds by pickup of a deuteron from N^{14} the deuteron should be in an $L=2$ state, corresponding to the $p_{1/2}$ proton and $p_{1/2}$ neutron circulating together about the C^{12} core, as discussed by Inglis.[3] The angular distribution for the ground-state transition should then be of the form expected for $L=2$ pickup. The plane-wave Born approximation expression for the stripping (or pickup) of two nucleons from (or by) a projectile has been shown by El-Nadi and Sherif[15] to reduce to

$$\frac{d\sigma}{d\Omega}\propto\frac{K_f}{K_i}\frac{2J_f+1}{2J_i+1}F(\theta)[j_L(qR_0)]^2 \qquad (1)$$

for a single value of L, the angular momentum of the stripped (or picked up) pair. j_L is the spherical Bessel function of order L, $\bar{q}=(m_f/m_i)\bar{k}_i-\bar{k}_f$ is the momentum transfer for a pickup reaction, R_0 is the interaction radius, $F(\theta)$ is a slowly varying damping factor which reduces the cross section at large angles, and J_i and J_f are the spin of the initial and final nuclei. Figure 7 shows the ground-state angular distribution fitted by $[j_2(qR_0)]^2$ with $R_0=4$ F. This is an unreasonably small interaction radius when compared with those found by similar methods from (α,d)-,[16,17] (α,p)-,[9] and (d,α)-[18] reaction data in this mass region. Essentially, the oscillations in the observed angular distribution of Fig. 7 are too widely spaced for a simple surface interaction model.

A distorted-wave Born approximation (DWBA) calculation might be expected to yield a more reasonable fit to the data. Accordingly, DWBA calculations for a

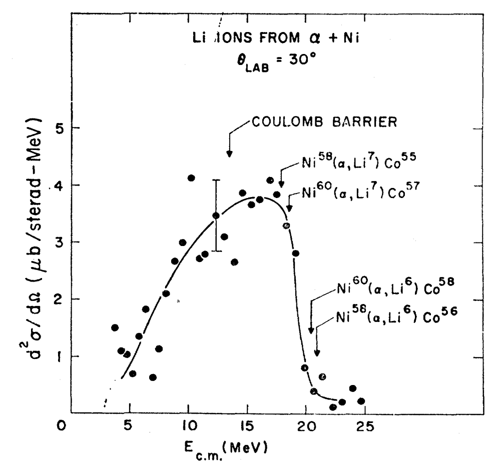

FIG. 12. Lithium ion spectrum from $Ni+\alpha$.

[15] M. El-Nadi and H. Sherif, Nucl. Phys. **28**, 331 (1961).

[16] C. Zafiratos, thesis, University of Washington, 1962 (unpublished).

[17] J. Cerny, B. G. Harvey, and R. H. Pehl, Nucl. Phys. **29**, 120 (1962).

[18] G. E. Fischer and V. K. Fischer, Phys. Rev. **114**, 533 (1959).

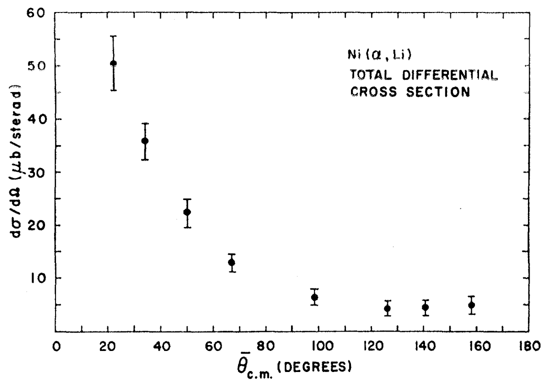

FIG. 13. Angular distribution of all lithium ions from Ni+α. Each segment of the observed spectrum showed similar forward peaking.

deuteron pickup were carried out with the Gibbs-Tobocman code[19] on an IBM-7094 computer. In this calculation only the alpha-deuteron interaction is taken into account and that interaction is taken in zero range. Both these assumptions and the assumption that an optical potential gives meaningful wave functions for the entrance and exit channel are questionable in a nucleus as light as N^{14}. The optical potential for alpha particles was chosen to be similar to that which gave a good fit to the elastic scattering of 42-MeV alpha particles on carbon.[20] The optical potential for Li ions was chosen to be similar to those found from the scattering[21] of $N^{14}+Be^9$ and Li^7+C^{12} scattering[22] at lower energies. Figure 14 shows the result of a typical DBWA calculation. The real and imaginary parts of the optical potentials were of the Woods-Saxon form with radius R and diffuseness a. The picked-up particle was assumed to be in a harmonic oscillator well with radius parameter R_N. The parameters used were $R_{\mathrm{Li}}=5.34$ F, $a_{\mathrm{Li}}=0.55$ F, $R_\alpha=4.8$ F, $a_\alpha=0.42$ F, $V_{\mathrm{Li}}=-40$ MeV, $W_{\mathrm{Li}}=-5$ MeV, $V_\alpha=-24$ MeV, $W_\alpha=-13$ MeV, and $R_N=4.8$ F. No fit to the data could be obtained for any reasonable variation of parameters. As in the comparison with the plane-waves expression (1), the DWBA calculation shows a shorter period of oscillation in the angular distribution than that observed. The absolute magnitude of the calculation is reasonable, the calculated value of the forward peak being just a factor of 2 larger than the observed forward peak. DBWA calculations assuming $L=0$ gave similar disagreement in the location of the first peak and in the period of oscillation of the angular distribution. No other L values are allowed by the spin and parity of the initial and final states. Calculations carried out with the DWBA code SALLY[23] gave similar results.[24]

B. $C^{12}(\alpha,Li^6)B^{10}$

Figure 10 shows a comparison of the observed angular distribution and expression (1) for $L=2$, $R_0=5.4$ F. DWBA calculations were carried out and again the shape was poorly fitted as it was for $N^{14}(\alpha,Li^6)C^{12}$. The absolute magnitude showed a large discrepancy, the calculated value of the forward peak being a factor of 20 larger than observed.

C. Comparison of $C^{12}(\alpha,Li^6)B^{10}$ and $N^{14}(\alpha,Li^6)C^{12}$

Expression (1) may be used to extract relative reduced widths for the pickup of a deuteron cluster in these two reactions if $F(\theta)$ is written out

$$F(\theta)=1/(Q^2+K^2) \tag{2}$$

with $\bar{Q}=[(A-2)/A]\bar{K}_\alpha-\bar{K}_{\mathrm{Li}^6}$ and $K=(1/\hbar)2M_d(\epsilon_d)^{1/2}$, where ϵ_d is the binding energy of the picked-up deuteron in the target nucleus. Fitting these expressions to the observed angular distributions at 50° center-of-mass angle, we find

$$\frac{(d\sigma/d\Omega_{\mathrm{exp}})(N^{14})}{(d\sigma/d\Omega_{\mathrm{exp}})(C^{12})}\times\frac{(d\sigma/d\Omega_{\mathrm{theory}})(C^{12})}{(d\sigma/d\Omega_{\mathrm{theory}})(N^{14})}=5.$$

That is, the reduced width for a deuteron cluster in

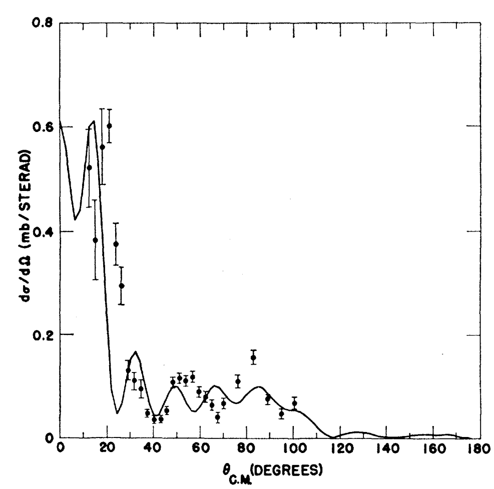

FIG. 14. Angular distribution for $N^{14}(\alpha,Li^6)C^{12}$ (ground state). The solid line results from a DWBA calculation for $N^{14}(\alpha,Li^6)C^{12}$ as described in the text.

[19] W. Tobocman, Phys. Rev. **115**, 98 (1959).
[20] D. K. McDaniels, D. L. Hendrie, R. H. Bassel, and G. R. Satchler, Phys. Letters **1**, 295 (1962).
[21] J. A. Kuehner and E. Almqvist, in *Proceedings of the Third Conference on Reactions Between Complex Nuclei*, edited by Albert Ghiorso, R. M. Diamond, and H. E. Conzett (University of California Press, Berkeley, 1963), p. 11.
[22] J. R. J. Bennett and I. S. Grant, in *Proceedings of the Third Conference on Reactions Between Complex Nuclei*, edited by Albert Ghiorso, R. M. Diamond, and H. E. Conzett (University of California Press, Berkeley, 1963), p. 50.
[23] R. H. Bassel, R. M. Brisko, and G. R. Satchler, Oak Ridge National Laboratory Report, ORNL-3240 (unpublished).
[24] G. R. Satchler (private communication).

N^{14} is 5 times larger than in C^{12}. If the results of the DWBA calculations are substituted for $d\sigma/d\Omega_{\text{theory}}$ in the above expression this ratio increases to 10. Though no real fit to the angular distribution has yet been obtained with these DWBA calculations the absolute magnitudes consistently give this ratio over a wide range of parameters.

D. The (α,Li) Reactions on Al^{27} and Ni

As shown by the observed strong forward peaking a direct reaction mechanism still seems to dominate the (α,Li) reactions on aluminum and nickel, though the cross section for the ground-state transition drops by a factor of 50 for aluminum and by three orders of magnitude for nickel as compared to the (α,Li^6) cross section for light elements. This decrease in cross section with increasing A could be due to the fact that shell-model levels are filling out of phase in this mass region and reducing the correlation needed to form deuteron clusters.

V. CONCLUSIONS

The larger deuteron reduced width obtained for N^{14} compared to that for C^{12} and the rapid drop in cross section with increasing A are consistent with an interpretation of the (α,Li^6) reaction at medium energies as a deuteron-pickup reaction. DWBA calculations based on this model are unable to reproduce the experimental angular distributons. However, in view of the simplicity of the interaction chosen in such calculations, and the questionable validity of the optical model in this region, this lack of agreement is not necessarily meaningful.

ACKNOWLEDGMENTS

The author wishes to thank Professor F. H. Schmidt for his guidance in this work. He also thanks Dr. William R. Gibbs of the Los Alamos Scientific Laboratory for assistance with the DWBA calculations. He is grateful to the entire operating staff of the University of Washington cyclotron for assistance with the experimental aspects of the work.

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Spin Dependence of the Thermal Neutron Cross Section of Ho^{165}†

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Transmission experiments have been carried out with polarized, monochromatic neutrons and polarized Ho^{165} nuclei using a single crystal sample of holmium metal. (61.0±2.8)% of the thermal capture is into $I-\frac{1}{2}=3$ states, which establishes the contribution of one or more bound levels to the thermal cross section. Additional measurements on a polycrystalline sample show that the scattering cross section has no appreciable spin dependence.

I. INTRODUCTION

THE interaction of slow neutrons with Ho^{165} can proceed via compound states of total angular momentum $J=I+\frac{1}{2}=4$ or $J=I-\frac{1}{2}=3$. The fraction of neutrons captured in each spin state is of interest in the analysis of capture gamma-ray measurements.[1] By studying the transmission of polarized neutrons through a target of Ho^{165} nuclei polarized in a holmium metal single crystal, we have determined that (61.0±2.8)% of the thermal absorption cross section is into $I-\frac{1}{2}$ states. An additional study on a polycrystalline sample shows that the scattering has essentially no spin dependence—i.e., is almost entirely coherent. The experiment and its analysis are quite similar to that already performed on Co^{59},[2] so that this report is a brief one.

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] H. T. Motz and E. T. Jurney, Bull. Am. Phys. Soc. **9**, 31 (1964).
[2] R. I. Schermer, Phys. Rev. **130**, 1907 (1963).

II. GENERAL CONSIDERATIONS

Monochromatic, polarized slow neutrons from a crystal spectrometer are passed through a nuclear sample which is contained in a demagnetization cryostat mounted on the spectrometer arm. We measure the transmission of the sample for neutrons polarized parallel (τ_p) and antiparallel (τ_a) to the externally applied magnetic field which orients the nuclei. The transmission effect is defined by

$$\mathcal{E}=(\tau_p-\tau_a)/(\tau_p+\tau_a). \tag{1}$$

The theoretical expression for this quantity including the effects of magnetic scattering has been derived for a simple ferromagnet, e.g., cobalt.[2] Although holmium has a spiral structure in low fields, our field of 17.5 kOe applied along an easy direction of the single-crystal sample is sufficient to produce magnetic saturation.[3] We thus produce the equivalent of a simple ferromagnet

[3] D. L. Strandburg, S. Legvold, and F. H. Spedding, Phys. Rev. **127**, 2046 (1962).

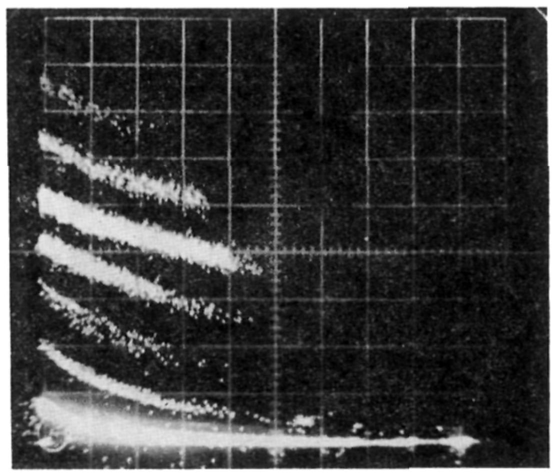

FIG. 3. Photograph of x,y oscilloscope displaying dE/dx versus E during alpha-particle bombardment of a Cymel target. The lowest bright curve is due to alpha particles. Those above are due to Li, Be, B, C, N, and O.