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Study of Mass 5 and 7 Nuclei by (p,t) and $(p,^3\mathrm{He})$ Reactions on ^{7}Li and ^{9}Be†

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Triton and ^{3}He energy spectra and angular distributions from 43.7-MeV-proton bombardment of ^{9}Be and ^{7}Li have been obtained. The restrictions on direct (p,t) reactions as compared to $(p,^3\mathrm{He})$ reactions may result in the absence of certain transitions for the former because these transitions are "S forbidden"; several examples of this selection rule were observed. Though the lowest $T=\frac{3}{2}$ states of the mass-7 product nuclei were readily observed, a search for $T=\frac{3}{2}$ states in mass 5 was unsuccessful.

I. INTRODUCTION

SIMULTANEOUS observation of direct (p,t) and $(p,^3\mathrm{He})$ reactions has been shown[1] to be a very useful tool for locating states with $T=|T_Z(\text{target})|+1$ in the lighter nuclei. Several further spectroscopic advantages of such comparisons remain to be explored. If one considers these two-nucleon pickup reactions, in first order, on targets with $T_Z\neq 0$ leading to final states with $T=|T_Z(\text{target})|$, then the (p,t) reaction requires $S=0$ for the transferred pair while the $(p,^3\mathrm{He})$ reaction may proceed by both $S=0$ and 1 transfer. This restriction on (p,t) transitions as compared to $(p,^3\mathrm{He})$ transitions may manifest itself in two ways:

(A) Some (p,t) transitions may not be observed because they are "J-forbidden." An example of this occurs in the search for the intermediate-coupling predicted[2] $\frac{7}{2}-$, $T=\frac{1}{2}$ state in ^{13}N-^{13}C via (p,t) and $(p,^3\mathrm{He})$ reactions on $^{15}\mathrm{N}(\frac{1}{2}-,\ T=\frac{1}{2})$, assuming ^{15}N to be a pure $1p^{11}$ nucleus. The conservation of total angular momentum and parity requires $L=4$ for the transferred pair in the (p,t) reaction and $L=2$ and/or 4 in the $(p,^3\mathrm{He})$ reaction; since a maximum L transfer of two is permitted in the pickup of two p nucleons, only the $(p,^3\mathrm{He})$ transition is allowed. Comparison of (p,t) and $(p,^3\mathrm{He})$ spectra and angular distributions can then permit identification of this $\frac{7}{2}-$ state, as will be reported in a future publication.[3]

(B) Some (p,t) transitions may not be observed because they are "S forbidden." Particularly in the lower part of the p shell where LS coupling of the target and final nuclei is appropriate, one can have transitions in which, though the relevant L transfer is allowed, the configuration of the final state requires a change of S incompatible with the restrictions on S of the transferred pair in the (p,t) reaction. This will be discussed further below; an example would be a $^2P_{3/2}\rightarrow {}^4P_{5/2}$ transition—forbidden in the (p,t) but allowed in the $(p,^3\mathrm{He})$.

We have investigated the (p,t) and $(p,^3\mathrm{He})$ reactions on ^{7}Li and ^{9}Be with the original intent of locating the lowest $T=\frac{3}{2}$ states in the product nuclei. Observation of the $T=\frac{3}{2}$ states in ^{7}Li-^{7}Be has been previously reported.[4] Transitions to several $T=\frac{1}{2}$ final states have been observed, some of which permit us to explore and then exploit spectroscopically the S-forbidden behavior of the (p,t) reaction in these light p-shell nuclei.

II. EXPERIMENTAL

The (p,t) and $(p,^3\mathrm{He})$ reactions were induced by a beam of 43.7-MeV protons from the Berkeley 88-in. spiral-ridge cyclotron. The general beam-transport system has been described previously[5]; measurements were made in a 36-in. scattering chamber.

A block diagram of the counting equipment is presented in Fig. 1. Particles were detected by a counter telescope that consisted of two semiconductor detectors: a 25.5-mg/cm^2 phosphorus-diffused silicon transmission counter backed by a 755-mg/cm^2 lithium-drifted silicon stopping counter. The 1.61×4.75-mm counter-telescope collimator was about 32 cm from the target. Identification of the reaction products was performed by a particle identifier[6] which employs the empirical relationship,

$$\text{Range}=aE^{1.73},$$

where a depends on the type of particle (and stopping material) and E is the incident energy. A typical particle-identifier spectrum is shown in Fig. 2. Total-energy pulses were fed into a 4096-channel pulse-height analyzer which was routed so that the triton, ^{3}He, and alpha-particle spectra were recorded simultaneously, each in a 1024-channel group. [Though the (p,α) data were taken, they will not be discussed; Ref. 7 presents some of the $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ results.] Pulses that corre-

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* CNRS and NATO fellow, visitor (1964–1965) from Institut de Physique Nucléaire, Orsay, France.

[1] J. Cerny, R. H. Pehl, and G. T. Garvey, Phys. Letters **12**, 234 (1964).

[2] D. Kurath, Phys. Rev. **101**, 216 (1956); S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965).

[3] D. G. Fleming, C. Maples, and J. Cerny (to be published).

[4] C. Détraz, J. Cerny, and R. H. Pehl, Phys. Rev. Letters **14**, 708 (1965).

[5] B. G. Harvey, E. Rivet, A. Springer, J. R. Meriwether, W. B. Jones, J. H. Elliott, and P. Darriulat, Nucl. Phys. **52**, 465 (1964).

[6] F. S. Goulding, D. A. Landis, J. Cerny, and R. H. Pehl, Nucl. Instr. Methods **31**, 1 (1964).

[7] J. Cerny, C. Détraz, and R. H. Pehl, Phys. Rev. Letters **15**, 300 (1965).

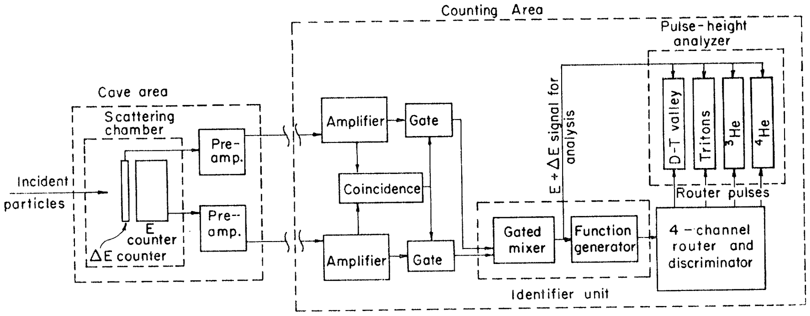

FIG. 1. Block diagram of counting equipment for recording energy spectra.

sponded to the deuteron-triton valley were routed into a fourth 1024-channel group to record any possible loss of tritons; such a loss proved to be negligible. The particle-identifier output was observed continuously on another pulse-height analyzer. Since no variation of peak or valley position occurred, the discriminator settings were not changed during the experiment. The average energy resolution was 170 keV for tritons and 200 keV for ^{3}He from the ^{9}Be target.

The beam intensity, which ranged from 20 to 300 nA as necessary depending upon the angle of observation, was measured by means of a Faraday cup and integrating electrometer. An additional 1110-mg/cm^2 lithium-drifted silicon detector rotated 50° with respect to the flight path of the scattered particles in order to increase its effective thickness and stop the elastic protons was placed at a fixed angle (≈ 20 deg); it served as a monitor during the experiment.

Self-supporting ^{7}Li and ^{9}Be targets 530 and 650 μg/cm^2 thick, respectively, were prepared by evaporation. Separated isotopes were used for the lithium targets. Neither of the targets contained an appreciable oxygen impurity.

III. MASS-7 NUCLEI

Typical $^9\mathrm{Be}(p,t)^7\mathrm{Be}$ and $^9\mathrm{Be}(p,{}^3\mathrm{He})^7\mathrm{Li}$ spectra are presented on Fig. 3 while Fig. 4 presents the well-

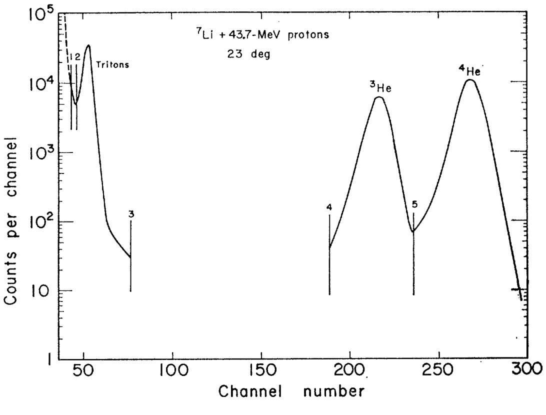

FIG. 2. Particle-identifier spectrum at a scattering angle of 23 deg from bombardment of ^{7}Li with 43.7-MeV protons. The discriminator settings are represented by lines 1–5.

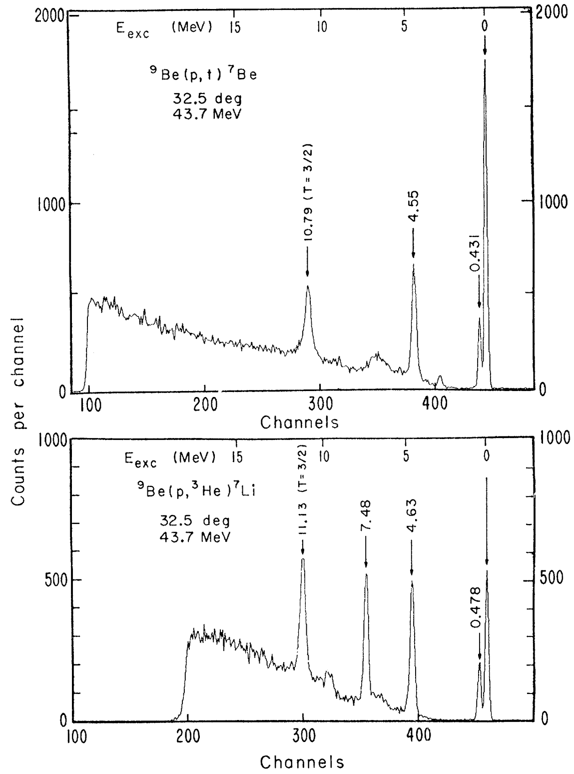

FIG. 3. Energy spectra for the reactions $^9\mathrm{Be}(p,t)^7\mathrm{Be}$ and $^9\mathrm{Be}(p,{}^3\mathrm{He})^7\mathrm{Li}$ at 32.5°.

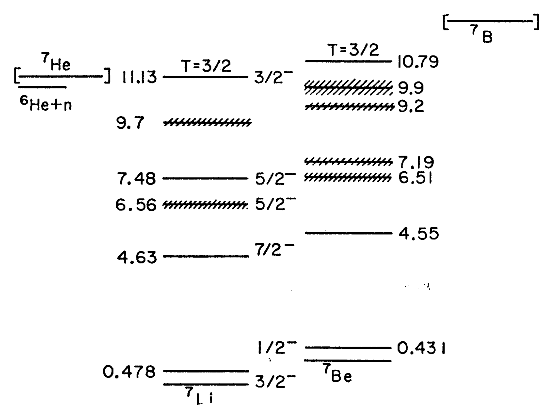

FIG. 4. Energy-level diagrams for the $A=7$ nuclei.

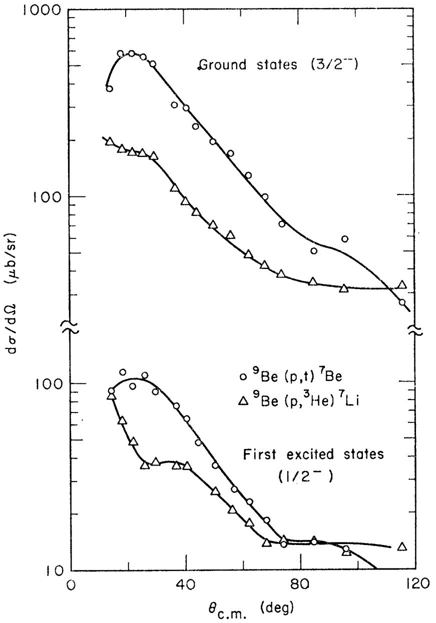

FIG. 5. Angular distributions of the transitions to the ground and first excited states of ^{7}Be and ^{7}Li.

established[8,9] energy levels of ^{7}Be and ^{7}Li through the first $T=\frac{3}{2}$ state.[4] On the basis of their dominant *LS* coupling, the ground and first four excited states are described as $^2P_{3/2}$, $^2P_{1/2}$, $^2F_{7/2}$, $^2F_{5/2}$, and $^4P_{5/2}$, respectively.[2,10]

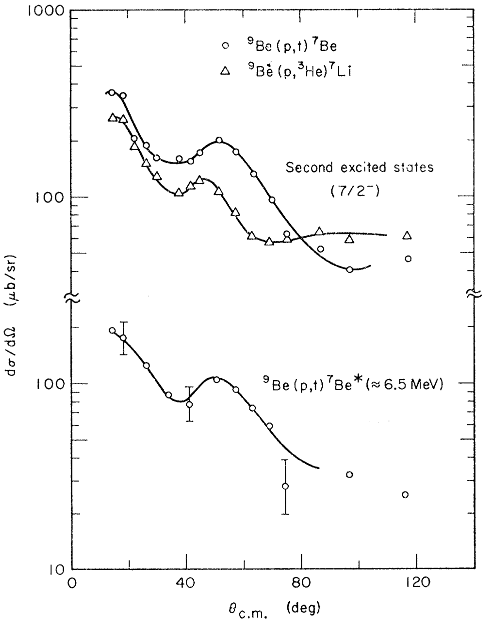

FIG. 6. Angular distributions of the transitions to the second excited states of ^{7}Be and ^{7}Li and to the ≈6.5 MeV level of ^{7}Be.

Figures 5 and 6 present the angular distributions to the ground and first three excited states of ^{7}Li and ^{7}Be with the exception of the broad 6.56-MeV state of ^{7}Li which was obscured by the transition to the 7.48-MeV state. Angular-momentum selection rules and the required pickup of two *p*-shell nucleons restrict the transitions to the 0.431-, 4.55-, and 6.51-MeV levels of ^{7}Be and to the 4.63-MeV level of ^{7}Li to $L=2$; the remaining transitions shown on Figs. 5 and 6 may proceed via $L=0$ and/or 2. If one considers the fairly fixed shape of $L=0$ and 2 angular distributions for these two-nucleon pickup reactions in the lighter elements,[1,11] as indicated for several other target nuclei on Figs. 7 and 8, one can see that the data on ^{9}Be agree with these trends. The transitions required to be $L=2$ show either the expected maximum near 20 deg c.m. or they possess a flattening shape at forward angles and a clear second maximum at the expected ≈50 deg c.m. (compare Fig. 8). The remaining transitions show a varying but mixed $L=0$ and 2 character. Barker[12] reproduced both the value of the *L* transfers and the

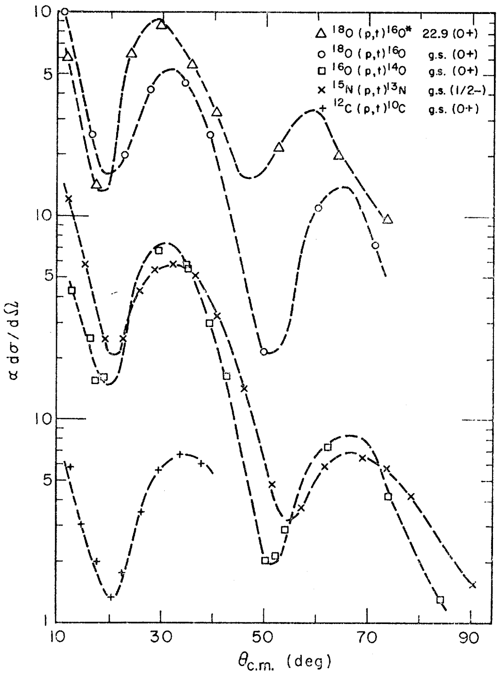

FIG. 7. Angular distributions—in arbitrary units—of several pure $L=0$ (p,t) transitions in the light elements.

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[8] T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. **78**, 1 (1966).

[9] R. J. Spiger and T. A. Tombrello, Bull. Am. Phys. Soc. **11**, 300 (1966).

[10] S. Meshkov and C. W. Ufford, Phys. Rev. **101**, 734 (1956); V. V. Balashov, At. Energ. (USSR) **9**, 48 (1960) [English transl.: Soviet J. At. Energy **9**, 544 (1961)].

[11] J. Cerny and R. H. Pehl, Phys. Rev. Letters **12**, 619 (1964); J. Cerny, R. H. Pehl, G. Butler, D. G. Fleming, C. Maples, and C. Détraz, Phys. Letters **20**, 35 (1966); D. G. Fleming and J. Cerny (unpublished data).

[12] F. C. Barker (private communication).

relative yields of the transitions using LS-coupled shell-model wave functions for the $A=7$ levels and intermediate coupling wave functions for the ^{9}Be ground state. New levels have been recently reported[13] at 5.9 and 6.2 MeV in ^{7}Be. There is no evidence for them in these data but we cannot rule out their presence if their cross section is smaller than about 50 μb sr^{-1}.

A striking difference between the (p,t) and $(p,^3\text{He})$ spectra of Fig. 3 is the strong excitation of the $\frac{5}{2}-$, 7.48-MeV ^{7}Li level while the mirror 7.19-MeV level of ^{7}Be is not appreciably populated. (This remains true even after compensating for the much greater width of the ^{7}Be level,[8] 720 keV as opposed to 89 keV in ^{7}Li.) Figure 9 shows the angular distribution to the 7.48-MeV level of ^{7}Li. This absence of the $^9\text{Be}[^2P_{3/2}](p,t)^7\text{Be}[7.19\text{ MeV}, ^4P_{5/2}]$ transition is an example of an S-forbidden reaction; the change of S required by the nuclear wave functions is forbidden by the $S=0$ requirement on the transferred two-neutron pair in the (p,t) reaction. However, the greater flexibility of the $(p,^3\text{He})$ reaction permits the analogous $^9\text{Be}[^2P_{3/2}](p,^3\text{He})^7\text{Li}[7.48\text{ MeV}, ^4P_{5/2}]$ transition through the additional allowed $S=1$ for the transferred neutron-proton pair. The allowed total orbital angular momentum transfers are $L=0, 2$; on comparison with the data of Figs. 7 and 8 one concludes that this transition is mixed with a somewhat dominant $L=0$ character. As further confirmation of this interpretation one may note that this $L=0$ contribution implies an $S=1$ requirement on a transferred pair between a $\frac{3}{2}-$ and a $\frac{5}{2}-$ state.

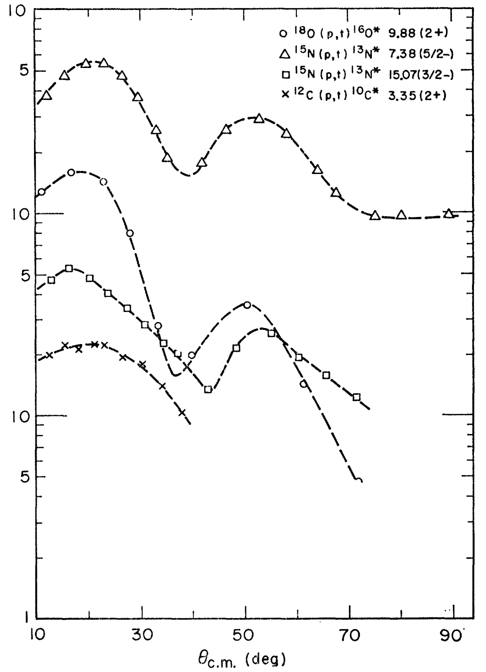

FIG. 8. Angular distributions—in arbitrary units—of several pure $L=2$ (p,t) transitions in the light elements.

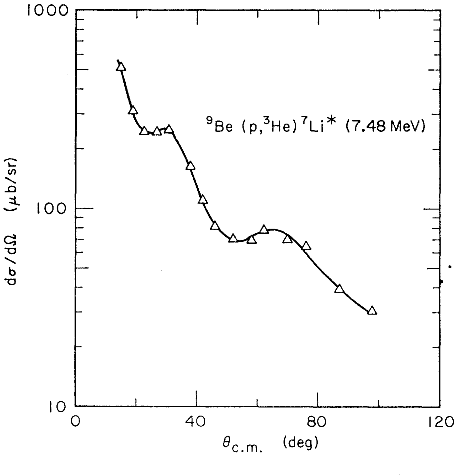

FIG. 9. The angular distribution of the $^9\text{Be}(p,^3\text{He})^7\text{Li}$ [7.48 MeV] transition.

An earlier report[4] has shown the strong peaks at 10.79 MeV in ^{7}Be and 11.13 MeV in ^{7}Li to be the lowest $T=\frac{3}{2}$ states in these nuclei.

IV. MASS-5 NUCLEI

Figures 10 and 11 show a typical energy spectrum for the $^7\text{Li}(p,t)^5\text{Li}$ and $^7\text{Li}(p,^3\text{He})^5\text{He}$ reactions, respectively, while Fig. 12 presents the present level scheme[8] for these nuclei. The widths of the ground states are 0.80±0.04 MeV for ^{5}He and 1.55±0.15 MeV for ^{5}Li in the n-^{4}He and p-^{4}He c.m. system, respectively.

The angular distributions of the two ground states are presented in Fig. 13 and indicate substantial mixing

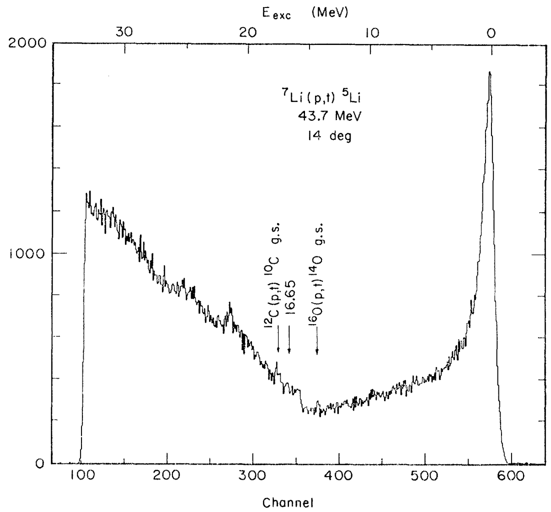

FIG. 10. The energy spectrum of the $^7\text{Li}(p,t)^5\text{Li}$ reaction at 14°.

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[13] H. Beaumevielle, J. P. Longequeue, N. Longequeue, and R. Bouchez, J. Phys. (Paris) 25, 60 (1964).

of $L=0$ and 2 transfer, as is consistent with the $^2P_{3/2}\rightarrow{}^2P_{3/2}$ nature of the transitions. A very broad level between 2 and 5 MeV of excitation was observed in both ^{5}He and ^{5}Li, but no attempt was made to extract either an excitation energy or a cross section.

At much higher excitation a striking difference again appears in comparing the (p,t) and $(p,^3\mathrm{He})$ spectra—namely, the absence in the ^{5}Li excitation spectrum of the two energy levels clearly apparent in the ^{5}He data. The first of these levels, known to be $\frac{3}{2}+$ and located at 16.70 MeV in ^{5}He and 16.65 MeV in ^{5}Li, is due to an S-wave interaction in d-t or d-^{3}He scattering. Transitions to this $^4S_{3/2}$ state[8] from the $^2P_{3/2}$ ground state of ^{7}Li require $L=1$ and $S=1$ for the transferred pair. As discussed above and already observed in the transitions to the mass-7 final nuclei, such a (p,t) transition is S forbidden. The allowed $(p,^3\mathrm{He})$ transition to the ^{5}He[16.70 MeV] level is shown on Fig. 14; its angular distribution is different from the characteristic $L=0$ and 2 transitions shown on Figs. 7 and 8 but quite similar to the only other well established $L=1$ transition known to us, that of ^{19}F$(p,t)^{17}$F[3.10 MeV, $\frac{1}{2}-$].[14]

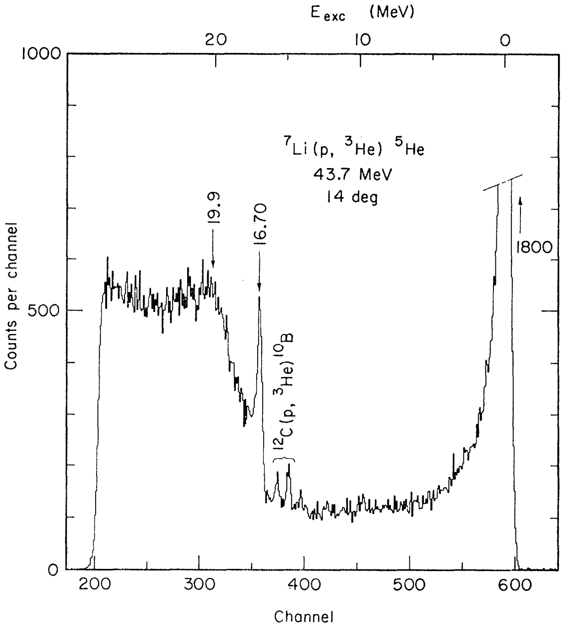

FIG. 11. The energy spectrum of the ^{7}Li$(p,^3\mathrm{He})^5$He reaction at 14°.

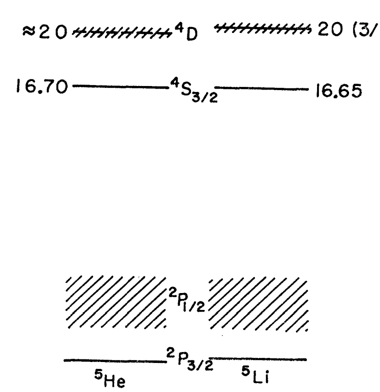

FIG. 12. Energy level diagrams for the $A=5$ nuclei.

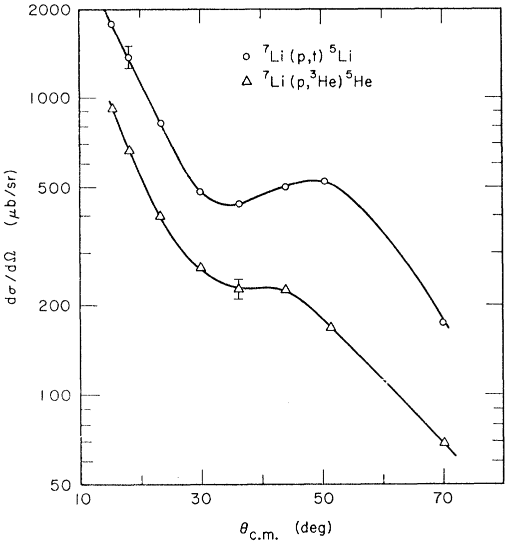

FIG. 13. Angular distributions of the transitions to the ground states of ^{5}Li and ^{5}He.

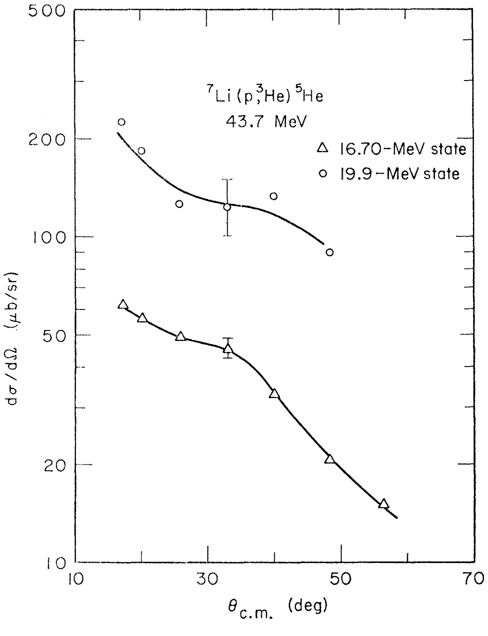

FIG. 14. Angular distributions of the $(p,^3\mathrm{He})$ transitions to the 16.70- and 19.9-MeV states of ^{5}He. The cross section of the latter transition is only representative.

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[14] G. M. Reynolds, J. R. Maxwell, and N. M. Hintz, University of Minnesota Linear Accelerator Laboratory Annual Progress Report No. 103, 1965 (unpublished).

The same argument holds again for the broad state near 20 MeV. A definite state at 20.0±0.5 MeV in ^{5}Li was recently observed[15] as a D-wave d-^{3}He interaction with a tentative spin assignment of $\frac{3}{2}+$ or $\frac{5}{2}+$; the mirror level in ^{5}He has only tentative support.[8,16] Comparative (p,t) and $(p,{}^3\text{He})$ data permit us to distinguish between the two possible total spin configurations for this state, ^{2}D and ^{4}D. The appearance of a state at 19.9±0.4 MeV in the $^7\text{Li}(p,{}^3\text{He})^5\text{He}$ data and the absence of transitions to the presumed mirror level at 20 MeV in the $^7\text{Li}(p,t)^5\text{Li}$ data imply that the latter transition is S forbidden and that the state is ${}^4D_{3/2\text{ or }5/2}$.[17]

A careful search was made for the first $T=\frac{3}{2}$ state in the mass-5 system. No states other than those discussed above were observed. Since the lowest $T=\frac{3}{2}$ state would be expected to be a doublet in total spin, the (p,t) reaction could populate it and would be expected to be fairly sensitive—except for the high triton continuum background—because of the above-mentioned absence of other transitions in the region about 20 MeV of excitation. In order to permit a more sensitive search for a possible $T=\frac{3}{2}$ state, a coincidence experiment capable of observing the decay properties of levels of ^{5}He and ^{5}Li from 16.6- to 28-MeV excitation is in progress.

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[15] T. A. Tombrello, A. D. Bacher, and R. J. Spiger, Bull. Am. Phys. Soc. **10**, 423 (1965).

[16] S. J. Bame and J. E. Perry, Phys. Rev. **107**, 1616 (1957).

[17] Preliminary results of a $^7\text{Li}(p,t)^5\text{Li}$ and $^6\text{Li}(p,d)^5\text{Li}$ experiment at 155 MeV appear to support these spin assignments. D. Bachelier, M. Bernas, I. Brissaud, F. Chavy, and P. Radvanyi (private communication).

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Theory of Coulomb Disintegration of Complex Nuclei*

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A general formulation of the Coulomb disintegration of complex nuclei is presented using the semiclassical approximation. This assumes that the center of gravity of the incident nucleus moves along a Rutherford orbit in the Coulomb field of the target nucleus. The main point of the formulation is the following: The configuration space of the product nuclei is divided into the external region and the internal region. In the external region, the wave function is assumed to be an outgoing free spherical wave. This wave function is then connected continuously to the internal wave function, which we take, following the Kapur-Peierls method, to be a superposition of compound-state eigenfunctions of the incident nucleus. This method is applied to the Coulomb disintegration of ^{6}Li and compared with the results which Gluckstern and Breit have already obtained. Some discussion about higher order corrections, which modify considerably the first-order perturbation calculation in the case of ^{6}Li, and about the stripping mechanism is added.

I. INTRODUCTION

THE study of the interaction of two complex nuclei is a newly developed field of research, in which theoretical results remain very few, in contrast with the experimental results which have been accumulating very rapidly in recent years.

Theoretically, the phenomena are expected to become simplest when the distance of the closest approach of two nuclei remains larger than the sum of their radii, preventing any nuclear force from acting effectively between the incident and the target nuclei. Even in this simplest case, we can expect many interesting types of reactions because of the intense Coulomb force. For example, Coulomb excitations of the target or the incident nucleus have been studied[1] extensively, both experimentally and theoretically, and have furnished much information about the spectroscopy of the nuclei.

However, Coulomb disintegration of the nuclei, which is expected to occur with a considerable probability in collisions of complex nuclei, has not yet been studied so fully, because of some difficulties with the detection techniques. For example, when α particles are observed in some heavy-ion reactions, it is not at all simple to distinguish α particles ejected from the direct Coulomb disintegration of the incident nucleus from those provided through the evaporation of the compound nucleus, or through the stripping or knockout processes.

In this respect, theoretical investigation of the Coulomb disintegration cross section, which is relatively easy to perform compared with other, more complicated nuclear processes, might serve to eliminate Coulomb contributions and separate out purely nuclear contributions from the observed cross sections. Furthermore, as will be discussed later, we might expect rather pure Coulomb disintegration of the incident nucleus in the

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* Work supported by the U. S. Atomic Energy Commission.

† On leave of absence from Tokyo University of Education, Tokyo, Japan.

[1] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956); K. Alder and A. Winther, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **32**, No. 8 (1960).