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July 1965

Li^4 AND THE EXCITED LEVELS OF He^4[†]

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There is a continuing interest in a characterization of such nuclei as H^4 and Li^4; in addition, a determination of the mass of either should aid in locating the lowest T = 1 state of He^4, which is the subject of considerable current speculation. To accomplish this we have again[1] utilized the technique of simultaneous observation of (p,t) and (p,He^3) transitions to analog final states—here applied to the $Li^6(p,t)Li^4$ and $Li^6(p,He^3)He^{4*}$ (T = 1) reactions. The latter reaction and the $Li^7(p,\alpha)He^4$ reaction also allow the investigation of the T = 0 states of He^4.

Some of the recent data concerning the two lowest excited states of He^4 are summarized in Table I.[2-8] Since state I (≈20 MeV, probably 0+, T = 0) lies just above the p+t threshold at 19.81 MeV excitation and state II (≈22 MeV, probably 1- or 2-, T = 0), above the n+He^3 threshold at 20.58 MeV, their exact nature is uncertain. Besides these two states, Vlasov and Samoilov suggest[9] the possibility that the lowest T = 1 state lies at 24 or 25 MeV. This would require Li^4 to be unbound by 4.5 to 5.5 MeV.

We have used 43.7 MeV protons from the Berkeley 88-inch cyclotron to induce (p,t) and (p,He^3) reactions on Li^6 and (p,α) reactions on Li^7. Targets of separated isotopes were used; the general experimental setup was reported previously.[1]

Figure 1 presents a $Li^6(p,t)Li^4$ spectrum at 15 degrees. Such data, taken between 10 and 35 degrees in the laboratory, show a broad state which is unbound by 2.9 ± 0.3 MeV to He^3+p decay. (Though we shall denote this peak as the Li^4 ground state throughout this report, it is probably not a single state.[10]) The width of the unbound Li^4 state is 5.0 ± 0.5 MeV at all angles. Using this Li^4 mass, a Coulomb calculation predicts that the T = 1 excited state of He^4 is located at approximately 22.5 MeV (±0.3 MeV). Finally, one predicts that the analog H^4 nucleus is also unbound—by about 2.0 MeV.[11] These masses directly confirm the negative results of previous searches for the β-decay of H^4 or Li^4 (see Imhof et al.[12]).

Figure 2 presents spectra from the $Li^6(p,He^3)He^4$ and $Li^7(p,\alpha)He^4$ reactions. State I was observed in both of these reactions, appearing at 20.10 ± 0.15 MeV. If its 0+ assignment is correct, the (p,He^3) transition to this level should correspond to an angular momentum transfer of L = 0 (or 2), while the (p,α) transition would require L = 1 transfer. The angular distributions of Fig. 3a are in accord with these expectations and strongly support this 0+ assignment. First, the (p,He^3) transition is essentially identical to the $Li^6(p,He^3)He^4$ g.s. transition and both appear to be fairly pure L = 0, according to our two-nucleon transfer systematics in the light elements;[1] and, second, the limited (p,α) data are consistent with the $Li^7(p,\alpha)He^4$ g.s. transition which must have L = 1 transfer.

It is apparent from Table I that large discrepancies exist in both the location and width of state II as reported from different experiments. These fluctuations and the above Li^4 results lead us to postulate that there are in fact at least two states near 22 MeV. We expect one to be a T = 0 state with a width of about 1 MeV, clearly apparent in the work of Parker et al.[2] at 21.2 ± 0.2 MeV, and the other(s) to be the T = 1 state(s) predicted from our Li^4 mass to appear at 22.5 ± 0.3 MeV. An analysis of the data using the width[13] given by Parker et al. for the prominent peak which appears at 21.4 ± 0.25 MeV in the $Li^6(p,He^3)He^4$ spectra (Fig. 2a) indicates the presence of an additional, somewhat smaller peak at 22.5 ± 0.3 MeV. As expected, this new peak is broad; however, no width could be obtained due to the complexity of the spectra. This 22.5 MeV level can be postulated as the first T = 1 excited state of He^4—the analog of the Li^4 ground state.

Further confirmation of this assignment is presented in Fig. 3b, where both analog transitions, $Li^6(p,t)Li^4$ g.s. and $Li^6(p,He^3)He^{4*}$ (22.5 MeV, T = 1), are shown. The monotonically decreasing angular distributions to these T = 1 states over the observed angular range are similar to the $Li^6(p,He^3)He^{4*}$ (21.4 MeV, 1^- or 2^-, T = 0) angular distribution; all three transitions are consistent with the L = 1 angular momentum transfer that would be expected to 1^- or 2^- states. Finally—and most importantly—the relative cross sections to these two analog levels, after correcting for isospin coupling and phase space,[14] are quite similar (within the large uncertainties of peak separation and background subtraction) as would be required for transitions proceeding from identical initial to final states through ^1S, T = 1 pickup of two nucleons.

To summarize, we have observed the unbound ground "state" of Li^4 and predict that H^4 must be unbound by 2 MeV. We have obtained angular distributions to the 20.1 MeV state of He^4 which are consistent with its 0+ assignment and have identified the lowest T = 1 "state" of He^4 at an excitation of 22.5 ± 0.3 MeV.

It is a pleasure to acknowledge valuable discussions with Dr. H. G. Pugh and Dr. T. A. Tombrello and to thank Claude Ellsworth for preparation of the lithium targets.

FOOTNOTES AND REFERENCES

† Work performed under the auspices of the U. S. Atomic Energy Commission.

‡ CNRS and NATO Fellow, visitor from Laboratoire Joliot-Curie de Physique Nucleaire, Orsay, France.

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13. The apparent width of a short-lived state can vary with the nuclear reaction employed to study it. (See for example E. H. Berkowitz, Nucl. Phys. 60, 555 (1964).) However, the spectator particle velocity, which appears to be a relevant parameter influencing the width, is very similar in this experiment and that of Ref. 2.

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Table I. Evidence for the first two excited levels of He^4.

			State I		State II	
Ref.	Reaction	Bombarding energy (MeV)	Position (MeV)	Width (MeV)	Position (MeV)	Width (MeV)
2	$d(He^3,p)He^4$	31.8	19.94 ± 0.02	0.140 ± 0.025	21.24 ± 0.2	1.1 ± 0.2
3	$He^4(p,p')He^4$	40	20.46 ± 0.14	~ 0.3	22.0 ± 0.14	several MeV
4	$He^3(d,p)He^4$	6-10	20.08 ± 0.5	0.2 ± 0.05		
5	$He^4(p,p')He^4$	55			22.4 ± 0.7	1.7 ± 0.5
6	$T(d,n)He^4$	7.83	20.1	0.35 ± 0.05		
7	$T(d,n)He^4$	19			22	
8	$T(p,p)T$	resonance	20.3 ± 0.1			

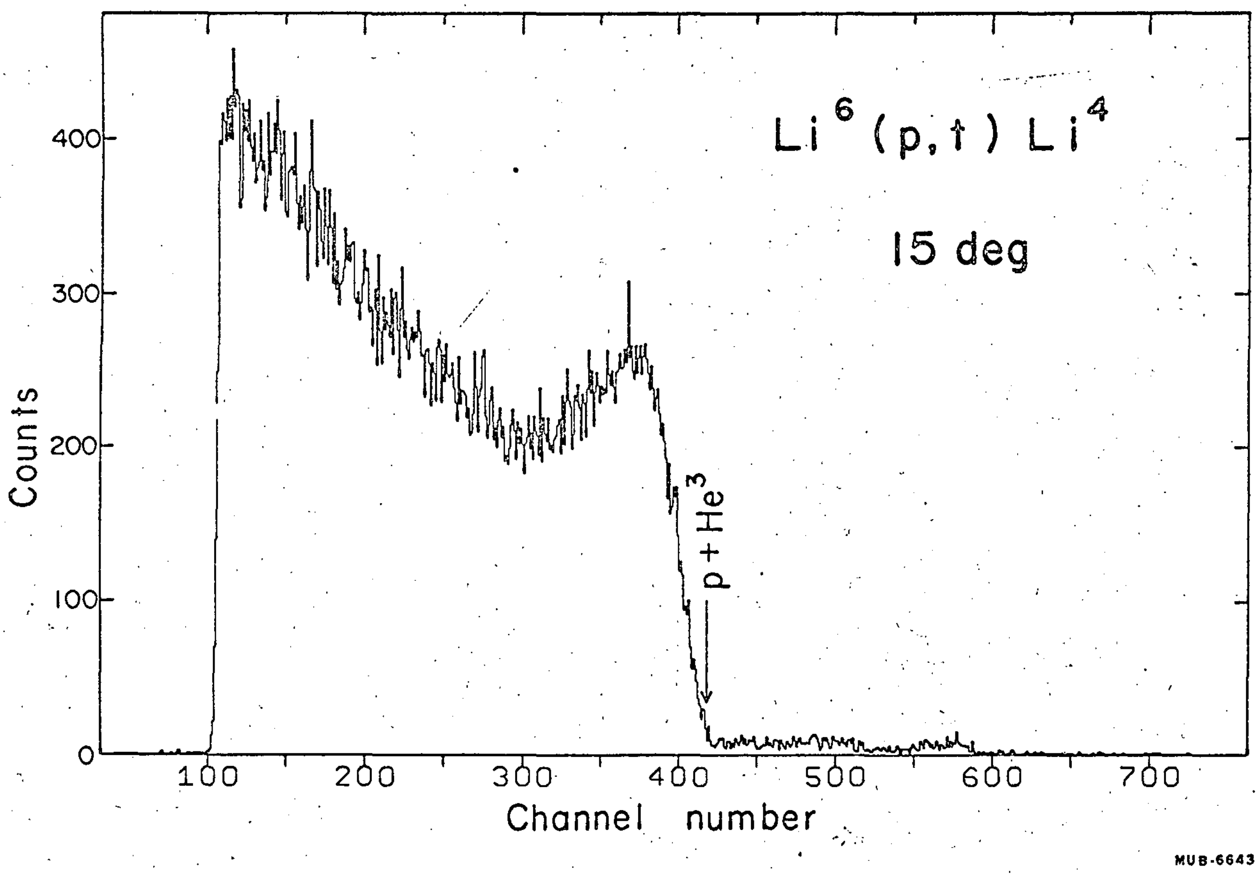
FIGURE CAPTIONS

Fig. 1. An energy spectrum of the $Li^6(p,t)Li^4$ reaction at 15° using 43.7 MeV protons. The counts above channel 420 arise from a slight deuteron breakthrough into the triton region of the identifier spectrum.

Fig. 2. Typical energy spectra from a) the $Li^6(p,He^3)He^4$ and b) the $Li^7(p,\alpha)He^4$ reactions at 43.7 MeV. Part a exhibits the analysis of the prominent peak at 21.4 MeV using the width reported by Parker et al.[2]

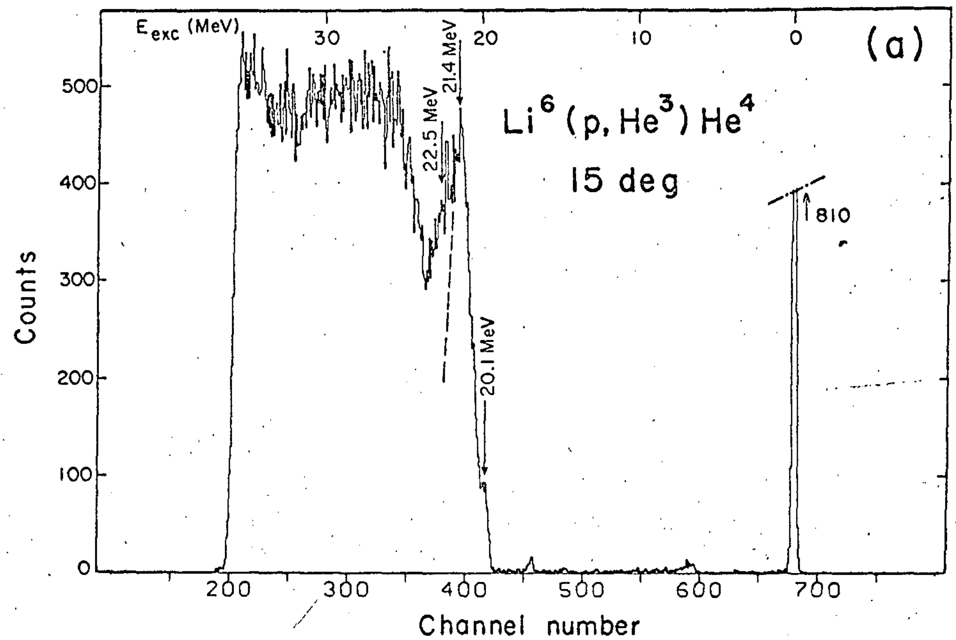
Fig. 3. a) Angular distributions to the 20.1 MeV excited state of He^4 for the two reactions $Li^6(p,He^3)He^{4*}$ and $Li^7(p,\alpha)He^{4*}$. The arbitrary unit, common to both distributions, corresponds roughly to 15-20 μb. ster^{-1}.

b) A comparison of the angular distributions of the analog reactions $Li^6(p,t)Li^4$ g.s. and $Li^6(p,He^3)He^{4*}$ (T = 1, 22.5 MeV). The (p,He^3) cross sections have been multiplied by 1.99 to adjust for isospin coupling and phase space factors. Due to the complexity of the spectra, the relative cross sections have been obtained from only the "corrected" peak heights, assuming comparable widths for these analog states. Probable uncertainties introduced by this procedure are indicated.

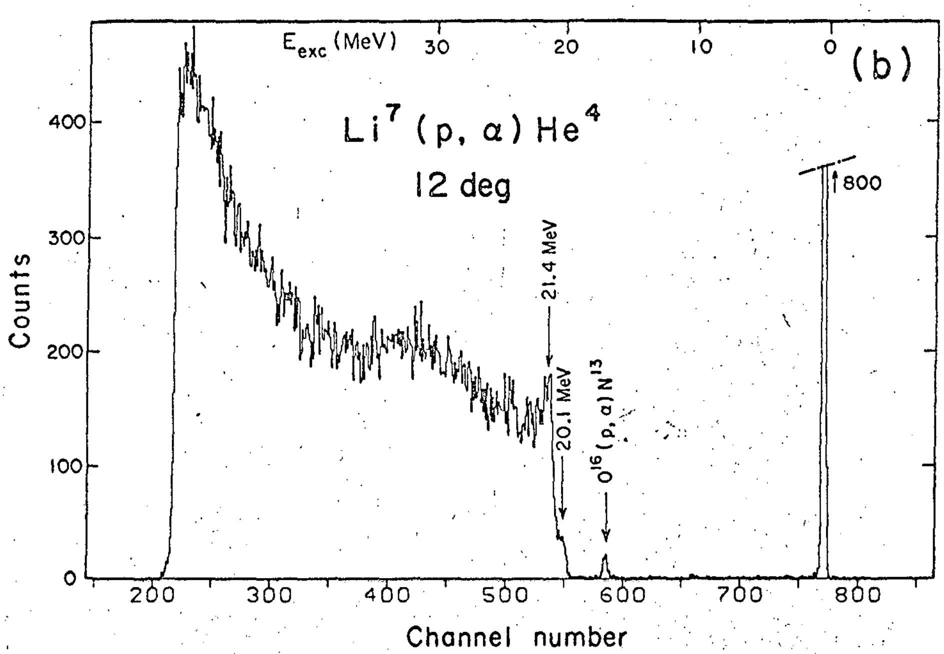


Li^6(p,t)Li^4
15 deg
p+He^3
Counts
Channel number
0
100
200
300
400
100
200
300
400
500
600
700
MUB-6643

Fig. 1



E_{exc} (MeV)
30
20
10
0
(a)
21.4 MeV
22.5 MeV
$Li^6(p, He^3)He^4$
15 deg
810
20.1 MeV
Counts
500
400
300
200
100
0
200
300
400
500
600
700
Channel number



E_{exc} (MeV)
30
20
10
0
(b)
$Li^7(p, \alpha)He^4$
12 deg
800
21.4 MeV
20.1 MeV
$O^{16}(p, \alpha)N^{13}$
Counts
400
300
200
100
0
200
300
400
500
600
700
800
Channel number
MUB-6644

Fig. 2

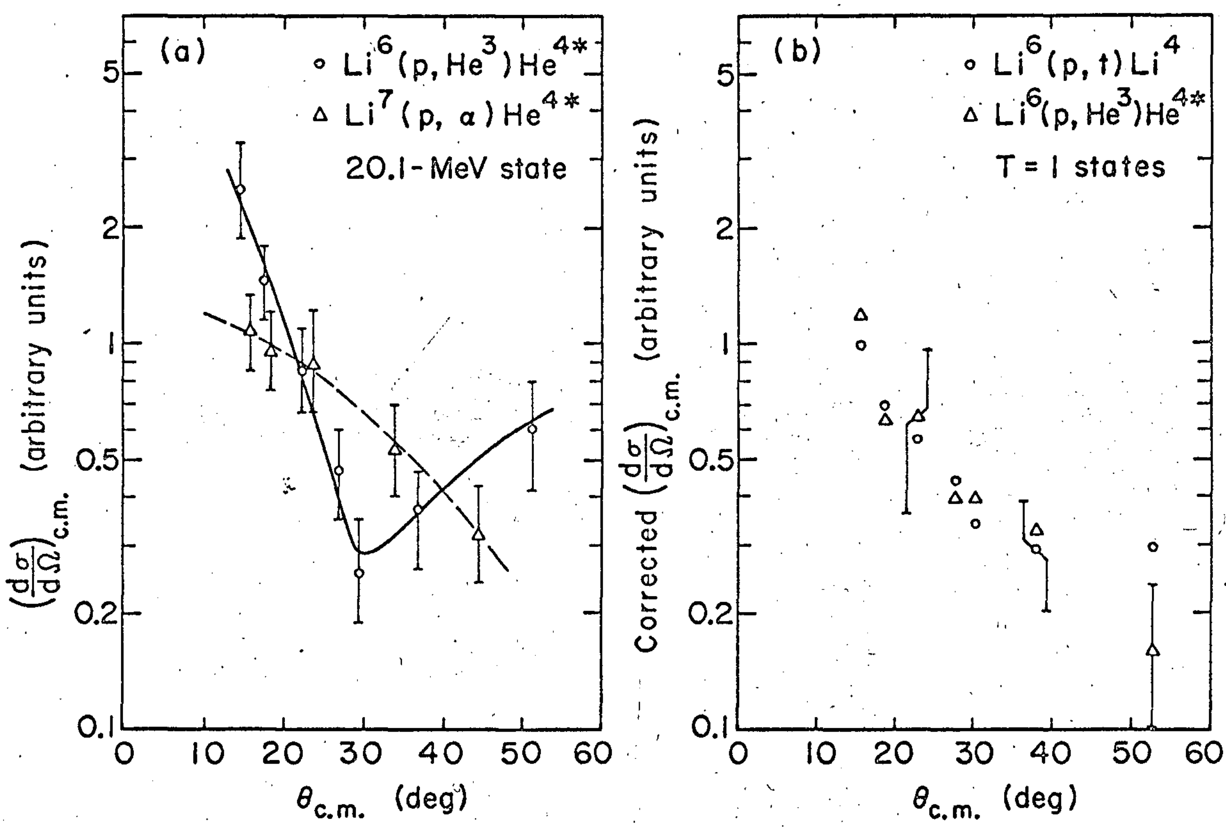

(a)
Li^{6}(p, He^{3})He^{4*}
Li^{7}(p, α)He^{4*}
20.1-MeV state
$\left(\frac{d\sigma}{d\Omega}\right)_{c.m.}$ (arbitrary units)
$\theta_{c.m.}$ (deg)
(b)
Li^{6}(p, t)Li^{4}
Li^{6}(p, He^{3})He^{4*}
T = 1 states
Corrected $\left(\frac{d\sigma}{d\Omega}\right)_{c.m.}$ (arbitrary units)
$\theta_{c.m.}$ (deg)
MUB-6645

Fig. 3