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DISCLAIMER

VERY LIGHT NEUTRON-RICH NUCLEI STUDIED VIA THE (^{6}Li, ^{8}B) REACTION*

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Abstract

Results from investigations of the $T_z = 3/2$ nuclei ^{5}H, ^{7}He and ^{9}Li and of the $T_z = 1$ nuclide ^{4}H employing the (^{6}Li, ^{8}B) reaction at 80 and 93 MeV are presented. In ^{9}Li the locations of several low-lying 1p-shell levels are indicated; in ^{7}He and ^{4}H the ground states are clearly observed. No evidence is found for the formation of a narrow ^{5}H ground state.

NUCLEAR REACTIONS ^{6}Li(^{6}Li, ^{8}B), ^{7}Li(^{6}Li, ^{8}B), ^{9}Be(^{6}Li, ^{8}B), ^{11}B(^{6}Li, ^{8}B), E = 80.0,93.3 MeV; measured $\sigma(\theta)$.

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1. Introduction

There has been much interest in the level structure of light $T_z = \frac{N - Z}{2} = 3/2$ nuclei near the edge of nucleon stability$^{1,2)}$ as an important test of nuclear models. Up to the present time, these relatively inaccessible nuclides have been studied most commonly by charge-exchange and stripping reactions. We wish to report here on results, obtained with the (^{6}Li,^{8}B) reaction, which arise from the first investigation by two-proton pickup of the nuclides ^{5}H(and ^{4}H), ^{7}He and ^{9}Li. Previous studies with this reaction have led to the mass measurement$^{3)}$ of the $T_z = 5$ nucleus ^{46}Ar and to improved spectroscopic knowledge of the heavier 1p-shell nuclides$^{4)}$; both results indicate that the (^{6}Li,^{8}B) reaction might be a useful spectroscopic probe of very light neutron-rich nuclei. This particular reaction offers several experimental advantages for such an investigation. It is the lightest of the broadly feasible two-proton pickup reactions and so has the smallest kinematic contribution to the energy resolution; furthermore, ^{8}B has no bound excited states so that its energy spectra have no shadow peak ambiguities.

In this paper we will report on results from our investigation of the reactions ^{11}B(^{6}Li,^{8}B)^{9}Li, ^{9}Be(^{6}Li,^{8}B)^{7}He, ^{6}Li(^{6}Li,^{8}B)^{4}H and ^{7}Li(^{6}Li,^{8}B)^{5}H. This order of discussion reflects a hierarchy of decreasing knowledge about the final nuclei and also of increasing particle instability arising from the increasing neutron to proton ratio.

Apart from ^{4}H, and to a lesser extent ^{9}Li, these light nuclei have been studied with only a very few reactions. Investigations of ^{7}He via the ^{7}Li(t,^{3}He)^{7}He and ^{7}Li(n,p)^{7}He reactions$^{5,6)}$ have led to knowledge of the mass and width of its ground state$^{2)}$ with its spin and parity still undetermined. Studies of ^{5}H, which have involved$^{2)}$ ^{7}Li(π^-,d) and ^{7}Li(π^-,pn) reactions as well as those[7,8]) of ^{9}Be(α, ^{8}B)^{5}H and ^{3}H(t,p)^{5}H, have shown no evidence for ^{5}H ground state formation nor for any sharp ^{5}H states[2]). States of ^{9}Li have been investigated with the ^{7}Li(t,p)^{9}Li reaction[9]). While the locations of several excited states have been found, neither the spin nor parity of most of the levels in ^{9}Li have been firmly determined[2]). Finally in ^{4}H, which has been studied with many reactions[1]), the only state reasonably well established is the 2^{-} ground state at 3.4 MeV above the t + n threshold, though there is evidence for two higher lying 1^{-} states and also for a 0^{-} level.

From the previous survey of the (^{6}Li, ^{8}B) reaction in the lp-shell[4]), one would expect the (^{6}Li, ^{8}B) reaction to populate strongly only low-lying negative parity states in ^{9}Li and ^{7}He and, as in the earlier study, the transitions to final states in these nuclei can be compared with the available two-nucleon transition strengths[10]). No theoretical calculations applicable to pickup across shells as occurs in the study of ^{4}H and ^{5}H via the (^{6}Li, ^{8}B) reaction are available; however, since many ambiguities remain in the current description of these latter nuclides[1,2]), any new experimental approach toward elucidating more of their character is of interest.

2. Experimental Procedure

The general techniques for the production of lithium beams at the Lawrence Berkeley Laboratory 88-inch cyclotron and the identification of ^{8}B reaction products have been described previously[3,11]), so only the main details of the experiments under discussion will be presented here.

For the studies conducted with the ^{11}B and ^{9}Be targets, an 80.0 MeV $^{6}Li^{2+}$ beam was used, while for reactions on the ^{6}Li and ^{7}Li targets, as well as for an additional study with the ^{9}Be target, a 93.3 MeV $^{6}Li^{2+}$ beam was employed; these beam energies were measured by magnetic analysis in a high resolution beam transport system[12]). A split Faraday cup was used to determine the direction of the beam and typically 0.5 μA of fully-stripped beam was available after analysis by a bending magnet to $\Delta E/E \sim 0.14\%$.

Self-supporting targets were used (see Table I). Target thicknesses were measured by comparing with tabulated values[13]) the energy loss of alpha-particles from ^{212}Po and ^{212}Bi sources for the ^{9}Be and ^{11}B targets and by weighing portions of the lithium targets after they were fully oxidized. The accuracy of these determinations is estimated to be about 15% and is mainly due to inhomogeneities in the targets and to the presence of contaminants. The extent of contamination was monitored during the experiments and determined either from elastic scattering or from the yield of related reaction products. A typical scattering chamber vacuum was 4×10^{-5} Torr and, by employing a series of liquid nitrogen cooled traps near the target, carbon buildup was reduced.

Two independent detector telescopes were employed on either side of the beam. The detectors were cooled to -30°C by thermo-electric cooling and collimated by tantalum slits, with apertures similar to the size of the beam spot ($\sim$ 1.5 by 2.5 mm^2), placed at a distance of ∿ 15 cm from the target.

The resulting acceptance angles (see Table I) were a main contributor to the energy resolution of ∿ 500 keV in the ^{7}He and ^{9}Li spectra. Each telescope consisted of four silicon detectors: two Ortec surface barrier transmission (ΔE) detectors 34-μm and 24-μm thick, a 200-μm phosphorus-diffused E-detector and a 1-mm lithium-drifted detector, the last being employed to reject those events which did not stop in the E-detector. Two independent particle identifications (P.I.) were performed with each telescope; a comparison of these permits better overall particle identification and results in lower background. Figure 1 presents a P.I. spectrum; the absence of the particle-unbound nuclides ^{7}B and ^{9}B from these spectra also aids in background reduction.

For each event the ratio of the two P.I. signals, the total energy signal, and a P.I. signal generated using the summed energy losses in the transmission detectors as a ΔE signal were written on magnetic tape. The analysis program LORNA$^{14)}$ was used to construct energy calibration curves for the determination of excitation energies. Calibration points were provided by the centroids of known peaks produced by the (^{6}Li, ^{8}B) reaction on the ^{9}Be and ^{11}B targets plus additional data from ^{12}C and ^{16}O targets at several angles. Since carbon and oxygen were sizable contaminants in the ^{6,7}Li targets, data were collected sequentially from a series of ^{6}Li, ^{7}Li, ^{12}C and ^{16}O targets at each set of observed angles. Finally, in the analysis of the data, kinematic shifts were utilized to discern the levels of interest from those arising from target contaminants.

3. Experimental Results

For the $^{11}B(^{6}Li,^{8}B)^{9}Li$ and $^{9}Be(^{6}Li,^{8}B)^{7}He$ reactions discussed below, a comparison can be made between the measured cross sections and the calculated two-proton transition strengths (such a comparison though is only qualitative since it neglects any kinematic effects). Recent predictions for ^{9}Li and ^{7}He are shown in Table II. The transition strengths SMAG (L=0) and DMAG (L=2), which are defined in ref. 10), are analogous to the L=0 and L=2 spectroscopic factors of single-nucleon transfer. Both SMAG and DMAG refer to spatially symmetric two-proton transfer. Anti-symmetric transfer strengths 11) are not shown in Table II since a survey 4) of the $(^{6}Li,^{8}B)$ reaction in the 1p-shell indicates that this transfer mode does not contribute significantly to the $(^{6}Li,^{8}B)$ reaction on light targets. As can be seen from Table II, there is some disagreement among the theoretical predictions for the location of levels in ^{9}Li and ^{7}He; this difference illustrates the sensitivity of calculations to the two-body interaction used.

3.1 $^{11}B(^{6}Li,^{8}B)^{9}Li$

An energy spectrum of the $^{11}B(^{6}Li,^{8}B)^{9}Li$ reaction with an incident ^{6}Li energy of 80.0 MeV is shown in fig. 2. The ^{9}Li ground state is a probable $3/2^-$ level 2) and its strong population is consistent with its large calculated transition strength (see Table II). Spectra were taken at angles between $\Theta_{lab} = 10^{\circ}$ and 16°; the ground state cross-sections are shown in fig. 3a.

The angular distributions of all the transitions observed in this present investigation are similar to those found in the previous study of the $(^{6}Li,^{8}B)$ reaction in the 1p-shell 4) (see fig. 3 for representative distributions). The differential cross sections generally decreased monotonically with angle;

this is consistent with what one might expect for a high-energy heavy-ion reaction on light targets when one is beyond the grazing angle. Because these distributions are rather featureless, the discussion of the present results will concentrate on other spectroscopic aspects of the two-proton pickup (^{6}Li, ^{8}B) reaction.

In the ^{11}B(^{6}Li, ^{8}B)^{9}Li reaction, three higher-lying states in ^{9}Li are also populated (see fig. 2). These were seen weakly at several angles and are the first excited state at 2.69 MeV (probable[2]) $J^\pi = 1/2^-$) and states at 4.31 and 6.41 MeV. Good relative agreement between the observed yields of these transitions and the calculated transition strengths[10]) is unlikely due to their weak yield. This is indicated by the fact that the predicted transition strength to the first excited state in ^{9}Li is very sensitive to small admixtures in the ^{11}B ground state wave function[15]). However, as in the similar reaction[4]) ^{13}C(^{6}Li, ^{8}B)^{11}Be, the fact that these states are consistently seen in this reaction indicates that they probably are 1p-shell states and thus have negative parity. Conclusions drawn from the results of the ^{7}Li(t,p)^{9}Li reaction[9]) support this view. In the latter it was suggested, mainly on the basis of the similarity of the experimental and calculated level locations and widths, but also by comparisons to predicted relative populations of states, that the levels seen at 4.31, 5.38 and 6.41 MeV correspond to predicted $J^\pi = 5/2^-$, $3/2^-$, and $7/2^-$ states, respectively[9]).

3.2 ^{9}Be(^{6}Li, ^{8}B)^{7}He

Shown in fig. 4 is an energy spectrum of the ^{9}Be(^{6}Li, ^{8}B)^{7}He reaction at 9.7° lab with an incident ^{6}Li energy of 80.0 MeV. The smooth curve drawn in this figure is the shape of three-body phase-space corresponding to the breakup $^6\text{Li} + {}^9\text{Be} \rightarrow {}^8\text{B} + {}^6\text{He} + n$. Also indicated are the thresholds for the breakup into ^{5}He + 2n and α + 3n; therefore four and five body phase-space distributions could also be contributing to the spectrum seen at higher excitation energies. The ground state of ^{7}He, which is unbound to ^{6}He + n by 440 keV^{2}), was clearly populated, in agreement with the relatively large strength calculated for transitions to the predicted $3/2^{-}$ ground state (see Table II); that this level is populated in this two-proton pickup reaction indicates that the ground state of ^{7}He has negative parity, which is as expected. The cross section at forward angles for production of the ground state falls monotonically with increasing angle (see fig. 3b).

These data at 80.0 MeV, and additional studies at 15° and 18° at 93.3 MeV, show no indication of any sharp excited states in ^{7}He below $\sim$ 10 MeV excitation. However, weak transitions to a possible broad excited state in ^{7}He could have been obscured by counts from multi-body breakup: if a level near 3.6 MeV excitation in ^{7}He (chosen for its large predicted strength, see Table II) had the same fraction of ground state strength as was seen in the similar ^{11}B(^{6}Li,^{8}B)^{9}Li reaction ($\sim$ 10%, see Table II) it would have been difficult to discern if it were broader than $\sim$ 1.5 MeV. In summary, then, these data and the two previous investigations of ^{7}He, via the ^{7}Li(t,^{3}He) and ^{7}Li(n,p) reactions^{5,6}), fail to show any sharp excited states in ^{7}He.

3.3 ^{6}Li(^{6}Li,^{8}B)^{4}H and ^{7}Li(^{6}Li,^{8}B)^{5}H

An energy spectrum of the ^{6}Li(^{6}Li,^{8}B)^{4}H reaction with an incident ^{6}Li energy of 93.3 MeV is shown in fig. 5a. As in the previous study^{4}), this (^{6}Li,^{8}B) reaction on the $T_z = 0$ ^{6}Li target can be compared to results from the analogous ^{6}Li(p,t)^{4}Li reaction^{16}); both show very similar structure. In the ^{6}Li(^{6}Li,^{8}B)^{4}H spectrum a smooth curve corresponding to the phase-space distribution for the three-body breakup $^{6}\text{Li} + {}^{6}\text{Li} \rightarrow {}^{8}\text{B} + \text{t} + \text{n}$

has been drawn. The observed enhancement above this phase-space distribution can be attributed to the known$^{2)}$ t + n final-state interaction corresponding to transitions to the 2^- ground state of ^{4}H with possible contributions from transitions to probable 1^- and 0^- levels in ^{4}H. This enhancement was seen with appropriate kinematics at all of the four angles studied (between $\Theta_{lab} = 11°$ and $16°$). Assuming that all of the counts above phase space correspond to transitions to the ground state of ^{4}H, then the observed yield at $\Theta_{lab} = 14.7°$ in fig. 5a is equivalent to a (c.m.) cross section of $\sim$ 4 μb/sr.

Unlike this two-proton pickup study of ^{4}H, the spectrum of the ^{7}Li(^{6}Li,^{8}B)^{5}H reaction at 93.3 MeV displayed in fig. 5b shows no evidence for a strong final-state interaction in the ^{5}H system below 10 MeV. This spectrum was taken for a total of 6200 μC ($^6\text{Li}^{3+}$), a factor of 6.5 more than for the ^{4}H spectrum. The counts seen above the smooth curve drawn in fig. 5b, which corresponds to the phase-space distribution for the four-body breakup $^6\text{Li} + {}^7\text{Li} \rightarrow {}^8\text{B} + t + n + n$, can arise from contributions from other multi-body breakup channels, such as the three-body breakup ^{8}B + t + (2n) or ^{8}B + ^{4}H + n, and events from the (^{6}Li,^{8}B) reaction on carbon and oxygen contaminants in the ^{7}Li target. As a measure of the experimental sensitivity to possible ^{5}H levels, the yield at low excitation above the phase-space curve corresponds to $\sim$ 100 nb/sr-MeV, which may be compared with the cross-section of the final-state interaction in ^{4}H of $\sim$ 1 μb/sr-MeV. Data taken at three other angles (between $\Theta_{lab} = 11°$ and $15°$) showed very similar results. In summary this investigation, as was the case in the earlier studies$^{2,7,8)}$, has produced no evidence for any sharp ^{5}H states.

4. Summary

Results of an investigation of the $T_z = 3/2$ nuclei ^{5}H, ^{7}He, and ^{9}Li by the (^{6}Li,^{8}B) two-proton pickup reaction have been presented, completing a study of the series of very light $T_z = 3/2$ nuclei: 3n^{17}), ^{5}H, ^{7}He, ^{9}Li and ^{11}Be^{4}). The previous survey^{4}) of the (^{6}Li,^{8}B) reaction in the 1p-shell established the selectivity of this reaction, and from the present work an assignment of negative parity for several excited states in ^{9}Li and for the ground state of ^{7}He is indicated. While the ground states of ^{9}Li and ^{7}He were populated in the (^{6}Li,^{8}B) reaction, no evidence for formation of a narrow ^{5}H state via the ^{7}Li(^{6}Li,^{8}B)^{5}H reaction was found even though a strong final-state interaction in the $T_z = 1$ ^{4}H system was clearly seen in the ^{6}Li(^{6}Li,^{8}B)^{4}H reaction. It would appear that in ^{5}H, as in the lowest possible $T_z = 3/2$ nuclide 3n^{17}), there is as yet no firm indication of a narrow state below at least 10 MeV of excitation.

Acknowledgments

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Table I. Target data and detector geometries.

	Targets		Detector Collimation	
	Isotopic Purity (%)	Thickness (mg/cm^2)	Angular Acceptance (deg.)	Solid Angle (msr.)
^{6}Li	99.3	.40	Sys. 1, .6	.27
			Sys. 2, .6	.27
^{7}Li	99.99	.33	same as for ^{6}Li	
^{9}Be	100	.13	Sys. 1, .6	.31
			Sys. 2, .6	.19
^{11}B	98.0	.21	same as for ^{6}Li	

Table II. Summary of experimental and theoretical results for ^{9}Li and ^{7}He.

Product Nucleus	Known Levels[a] J^{π}	Known Levels[a] MeV	Levels Observed in this work MeV	Levels Observed in this work ±keV	Predicted Levels J^{π}	Predicted Levels Barker[b]	Predicted Levels Kumar[c]	Predicted Levels Norton and Goldhammer[d]	Predicted Levels Cohen and Kurath[e]	Predicted Levels Kurath[f]	Transition Strengths[g] Cohen and Kurath SMAG	Transition Strengths[g] Cohen and Kurath DMAG	Cross Section[h] (c.m.) $\Theta_{c.m.} \sim 25°$ μb/sr
^{9}Li	$(3/2)^-$	0	0		$3/2^-$	0	0	0	0		.67	1.4	5.8
	$(1/2^-)$	2.69	2.59	100	$1/2^-$	2.89	2.22	3.23	3.88		.00	.03	.6
		4.31	4.36	100	$5/2^-$	2.89	3.08	5.16	3.79		.00	.51	.7
		5.38			$3/2^-$	4.31	4.65	5.97	4.88		.14	.06	<.3
		6.41	6.38	120	$7/2^-$		5.20	6.81	6.18		.00	.00	.8
^{7}He		0	0		$3/2^-$	0	0	0		0	1.2	.35	2.1
					$1/2^-$	1.46	3.18	4.34		2.55	.00	.01	
					$5/2^-$	3.08	4.04	4.34		3.64	.00	.36	<.2
					$3/2^-$		5.63	7.8		3.87	.00	.05	
					$3/2^-$					8.43	.00	.00	

[a] Ref. 2.

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[e] Ref. 10.

[f] D. Kurath, private communication.

[g] SMAG and DMAG are from refs. e and f (see text).

[h] A comparison of relative cross sections and transition strengths is only expected in general to be qualitative since such a comparison neglects kinematic effects.

Figure Captions

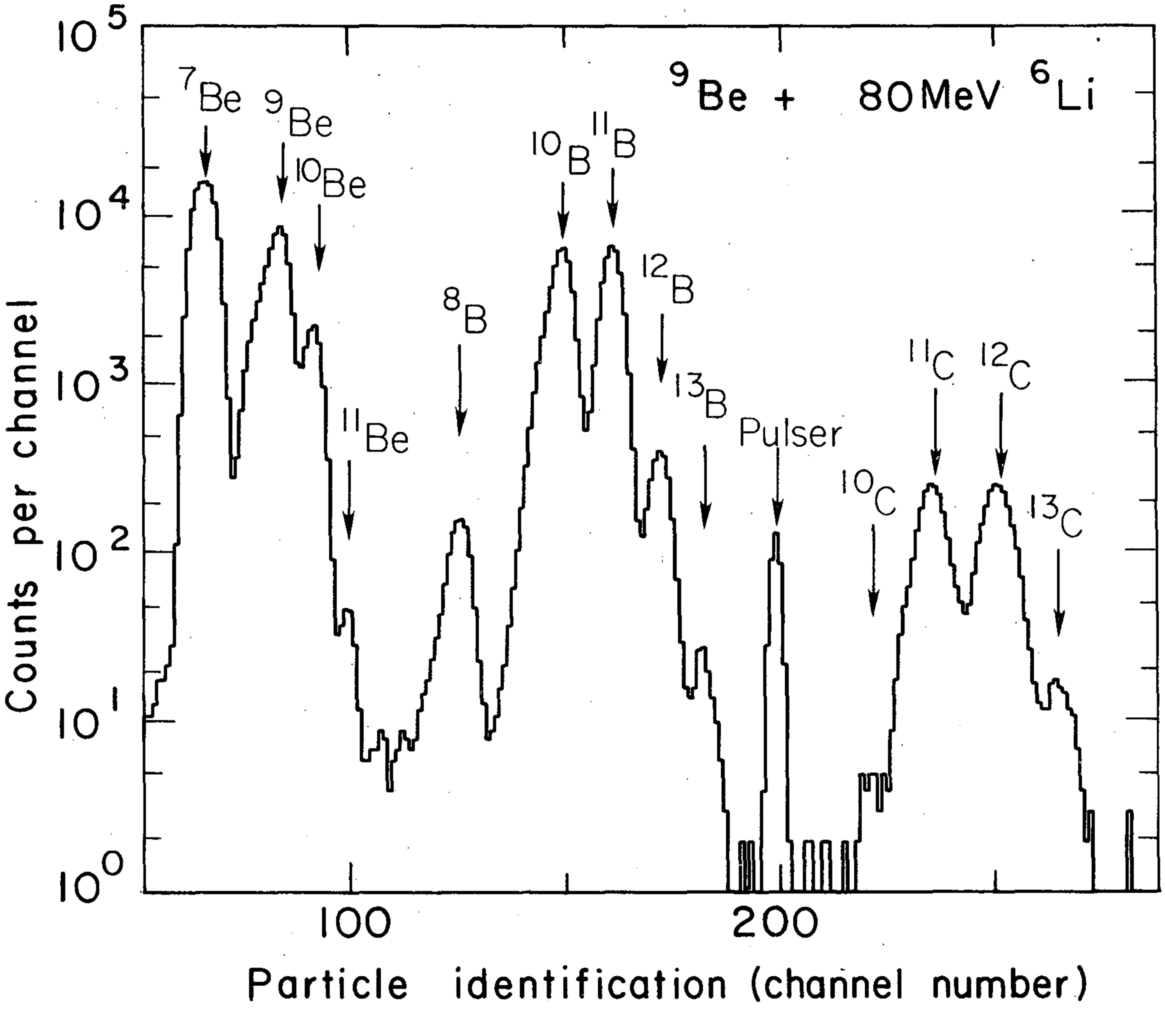
Fig. 1. Particle identification spectrum resulting from the bombardment of ^{9}Be by 80.0 MeV ^{6}Li.

Fig. 2. A composite spectrum of the ^{11}B(^{6}Li,^{8}B)^{9}Li reaction (E (^{6}Li) = 80 MeV) collected at Θ_{lab} = 12.4° and 16.4° (for 5000 μC total) in which the latter data were kinematically shifted to Θ_{lab} = 12.4°. Oxygen contamination produced the ^{14}C peak.

Fig. 3. Angular distributions for reactions induced by an 80.0 MeV ^{6}Li beam: (a) ^{11}B(^{6}Li,^{8}B)^{9}Li g.s.; (b) ^{9}Be(^{6}Li,^{8}B)^{7}He g.s.; (c) ^{12}C(^{6}Li,^{8}B)^{10}Be g.s.; and (d) ^{13}C(^{6}Li,^{8}B)^{11}Be* (0.32 MeV, $1/2^{-}$). Statistical error bars are indicated; the absolute cross section could be in error by as much as 30%.

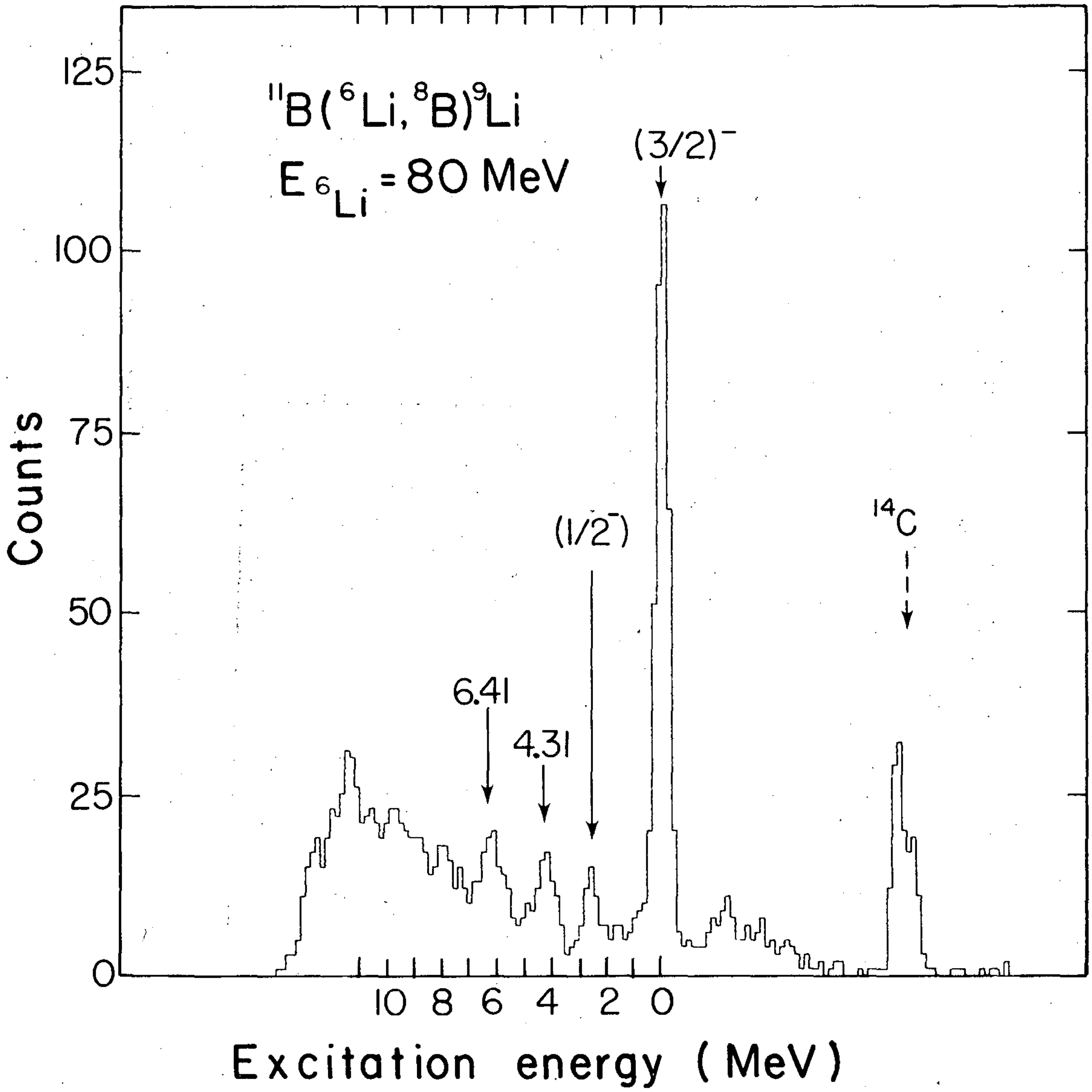
Fig. 4. An energy spectrum of the ^{9}Be(^{6}Li,^{8}B)^{7}He reaction (E (^{6}Li) = 80 MeV) collected at Θ_{lab} = 9.7° for 9200 μC. The curve corresponds to three-body phase-space (see text).

Fig. 5. (a) An energy spectrum of the ^{6}Li(^{6}Li,^{8}B)^{4}H reaction (E (^{6}Li) = 93.3 MeV) collected at Θ_{lab} = 14.7° for 950 μC. The curve corresponds to three-body phase-space (see text). (b) An energy spectrum of the ^{7}Li(^{6}Li,^{8}B)^{5}H reaction (E (^{6}Li) = 93.3 MeV) collected at Θ_{lab} = 14.7° for 6200 μC. The curve corresponds to four-body phase-space. The ^{10}Be and ^{14}C levels arise from ^{12}C and ^{16}O contaminants in the target (see text). In (a) and (b) excitation energies are given relative to zero binding energy for ^{4}H and ^{5}H, respectively.



XBL768-3902

Fig. 1



XBL768-3904

Fig. 2

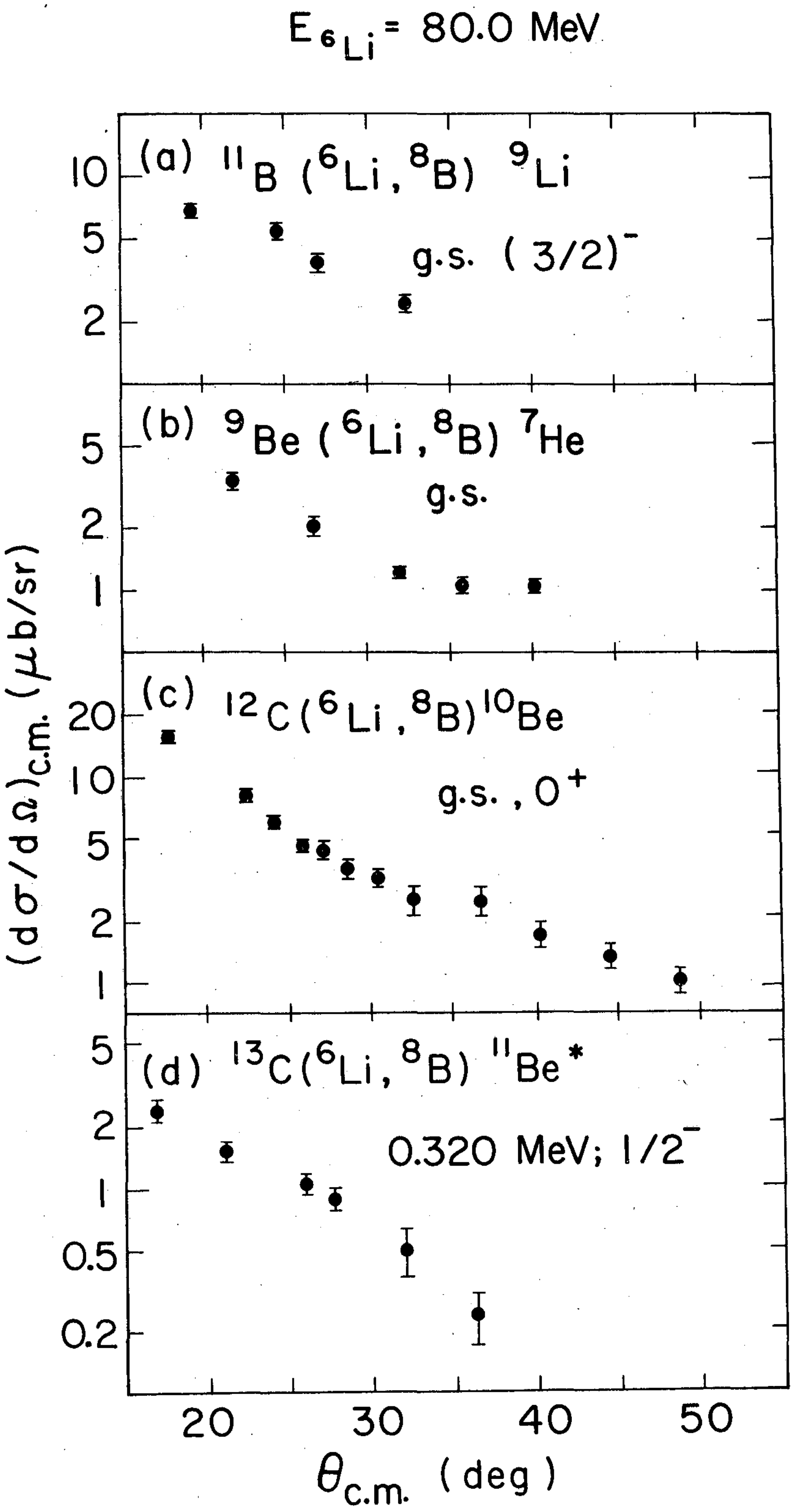


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Fig. 3

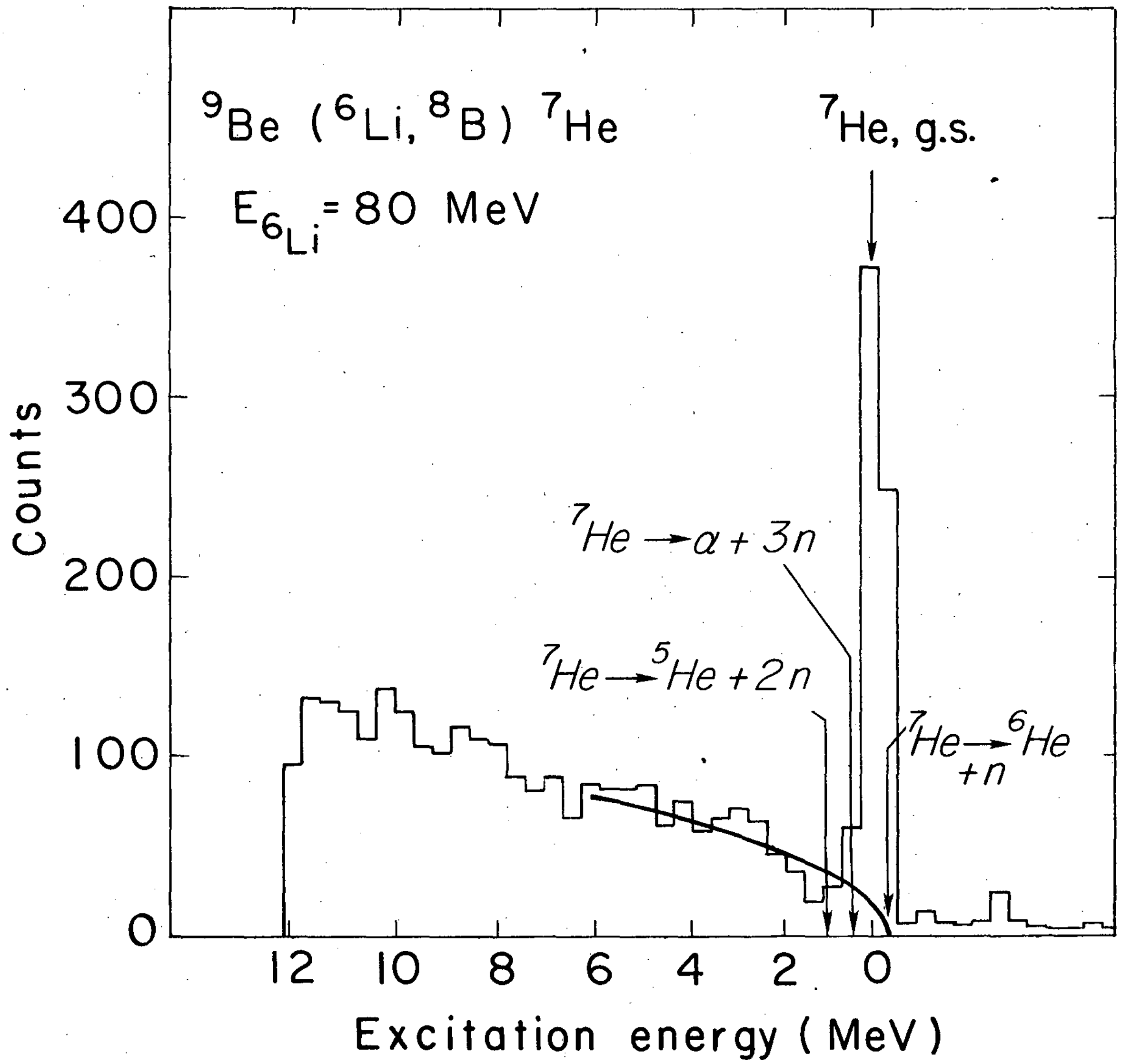

Fig. 4

XBL768-3903

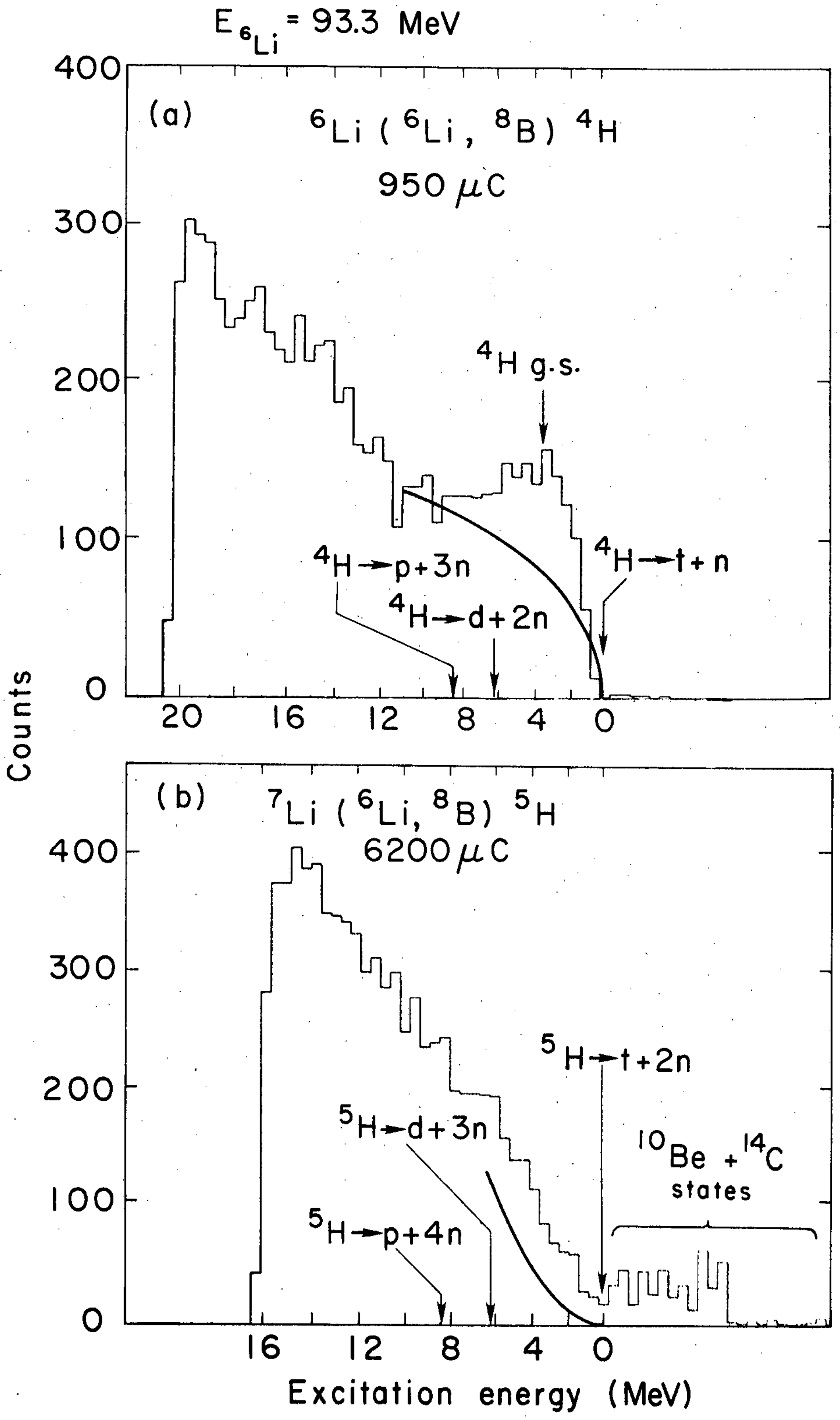

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Fig. 5

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