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$^{13}C(^{6}Li,p)^{18}O$ reaction at $E(^{6}Li)=28$ MeV

M. J. Smithson* and D. L. Watson†
Postgraduate School of Physics, University of Bradford, Bradford BD7 1DP United Kingdom

H. T. Fortune
Physics Department, University of Pennsylvania, Philadelphia, Pennnsylvania 19104
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The reaction $^{13}C(^{6}Li,p)$, at a bombarding energy of 28 MeV, has been used to populate states of ^{18}O up to an excitation energy of 16 MeV. Complete angular distributions were measured and compared with results of standard Hauser-Feshbach calculations. The overall magnitudes of the cross sections are reasonably well reproduced. A preponderance of slight forward peaking in the data suggests the presence of an additional nonstatistical mechanism.

The search continues for evidence of a reaction that proceeds by direct transfer of five nucleons. Existing data for the (^{7}Li,d) reaction[1] are consistent with a compound-nucleus reaction mechanism. Data[2] for $^{12}C(^{6}Li,p)$ are tantalizing but inconclusive. In the latter work (Ref. 2), cross sections for several states exceeded those expected from Hauser-Feshbach calculations, and several states had angular distributions that were slightly forward peaked. However, direct transfer, if present, was small.

We report here on an investigation of the $^{13}C(^{6}Li,p)^{18}O$ reaction. Experimental details were as in Ref. 2. The target was 50 $\mu g/cm^2$ of enriched (99%) ^{13}C and was self-supporting. A spectrum is displayed in Fig. 1. Peaks are numbered consecutively with the ground state being zero. Extracted peak positions were used to compute excitation energies at all angles. These were averaged to obtain the values listed in Tables I and II. The present excitation energies are within 5–10 keV of those in the literature.[3]

All known[3] levels up to 9 MeV in ^{18}O have been observed. The broad peak between levels 27 and 28 in Fig. 1 suggests that the 9.362-, 9.41-, 9.48-, and 9.673-MeV levels are weakly populated although none can be positively identified. Several levels are strongly excited—in particular levels 14 (7.12 MeV, 4^+), 38 (11.70 MeV, 6^+), 39 (11.85 MeV, 3^-), 44 (12.54 MeV, 6^+), and 51 (15.80 MeV, 1^-).

Levels 31 (10.63 MeV), 36 (11.26 MeV), 43 (12.44 MeV), 46 (13.23 MeV), 47 (13.48 MeV), 48 (13.60 MeV), and 50 (14.14 MeV) do not correspond with any previously observed levels in ^{18}O. They do not correspond with any states from possible impurities in the target. Furthermore, they are all seen at several angles and do not

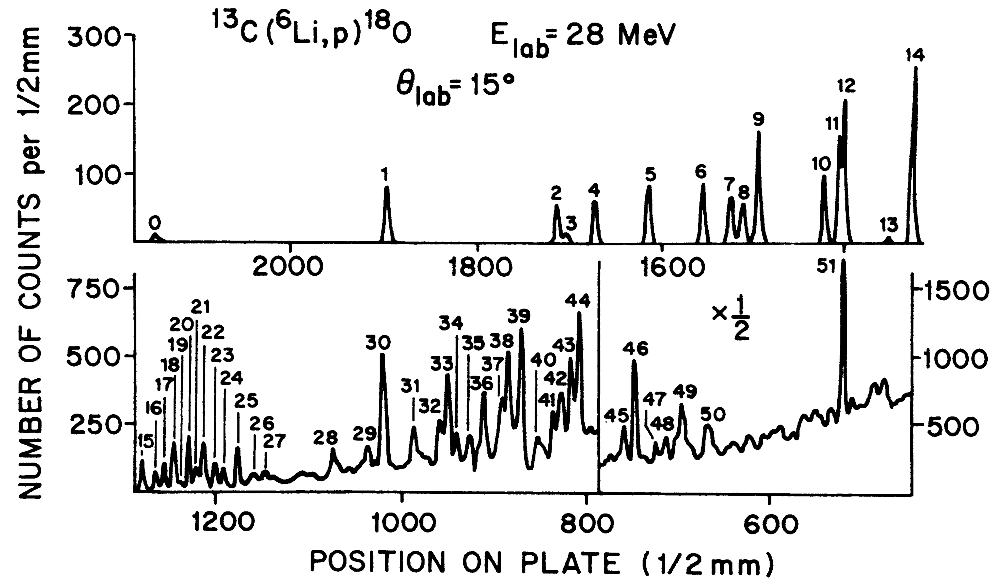

FIG. 1. Spectrum of protons from the reaction $^{13}C(^{6}Li,p)^{18}O$.

TABLE I. Results of the reaction ^{13}C(^{6}Li,p)^{18}O, at E(^{6}Li)=28.0 MeV.

	Excitation energy (MeV±keV)							
Level	Present	Previous[a]	J^{π} [a]	σ_{tot} (μb)	$\frac{\sigma_{\text{tot}}}{2J+1}$ (μb)	σ_{0-90} (μb)	σ_{90-180} (μb)	$\frac{\sigma_{0-90}}{\sigma_{90-180}}$
0	0	0	0^+	6.1±0.3	6.1	4.0±0.3	2.2±0.2	1.82
1	1.987±8	1.982 07±0.09	2^+	39±1	7.7	26±1	13±1	2.02
2	3.555±10	3.554 84±0.40	4^+	56±1	6.2	36±1	20±1	1.77
3	3.632±15	3.633 76±0.11	0^+	13±1	12.9	9.4±0.4	3.6±0.3	2.61
4	3.926±6	3.920 44±0.14	2^+	36±1	7.1	23±1	13±1	1.80
5	4.455±8	4.455 54±0.10	1^-	46±1	15.2	34±1	12±1	2.80
6	5.095±11	5.097 78±0.54	3^-	74±1	10.5	41±1	33±1	1.26
7	5.256±9	5.2604±1.2	2^+	44±1	8.9	26±1	19±1	1.38
8	5.374±8	5.3364±0.6 5.3778±1.2	0^+ 3^+	35±1	4.4	23±1	12±1	1.89
9	5.532±8	5.530 24±0.29	2^-	45±1	9.0	36±1	9.5±0.4	3.75
10	6.199±8	6.198 22±0.40	1^-	37±1	12.2	28±1	8.4±0.4	3.36
11 12	6.383±11	6.3513±0.6 6.4044±1.2	(2^-) 3^-	131±2	(10.9)	96±2	34±1	2.80
13	6.882±19	6.880 45±0.27	0^-	5.3±0.4	5.3	2.8±0.2	2.5±0.3	1.12
14	7.117±5	7.1169±1.2	4^+	208±2	23.1	108±2	100±2	1.09
15	7.618±10	7.618±4	1^-	33±1	10.9	24±1	8.6±0.4	2.79
16	7.764±14	7.771 07±0.50	2^-	37±1	7.4	25±1	12±1	1.98
17	7.850±13	7.860±4	$(4^+,5^-)$[b]	101±1	(11.2,9.2)	65±1	35±1	1.84
18	7.962±12	7.977±4	$(3^+,4^-)$	84±1	12.0 or 9.3	62±1	22±1	2.85
19	8.026±14	8.038±3	1^-	19±1	6.4	14±1	5.4±0.5	2.54
20	8.120±12	8.126±3	5^-	140±2	12.8	83±1	57±1	1.46
21	8.200±17	8.216±3	2^+	48±1	9.6	35±1	13±1	2.62
22	8.274±15	8.287±3	3^-	103±2	14.7	74±1	29±1	2.59
23	8.401±12	8.411±8		45±1		33±1	12±1	2.62
24	8.496±15	8.521±6		75±1		51±1	24±1	2.18

[a] Reference 3.

[b] Reference 3 gives $J^{\pi}=(4^+)$, but 5^- is assigned by W. D. M. Rae and R. K. Bhowmik, Nucl. Phys. **A420**, 320 (1984).

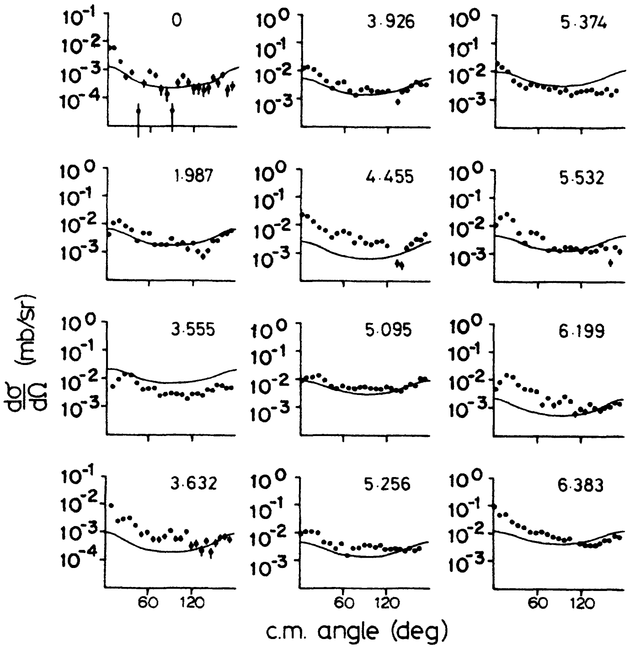

FIG. 2. Angular distributions for ^{13}C(^{6}Li,p)^{18}O leading to the states indicated. Curves are results of Hauser-Feshbach calculations discussed in the text.

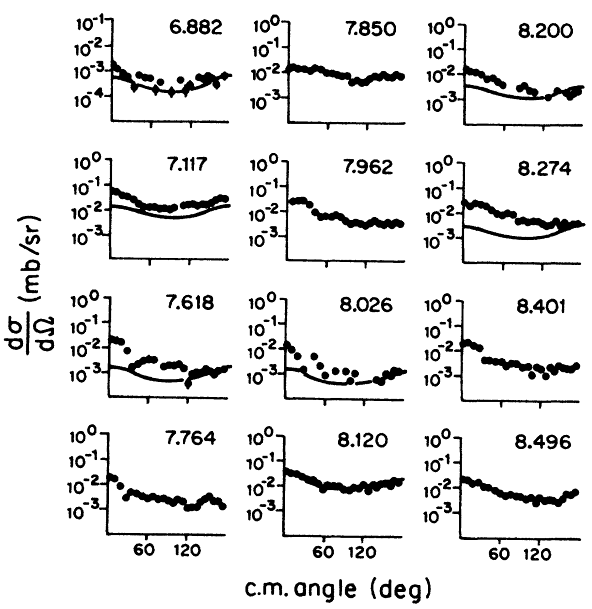

FIG. 3. As Fig. 2, but for states between 6.5 and 8.5 MeV.

TABLE II. Results of the reaction $^{13}C(^{6}Li,p)^{18}O$ for levels above 8.5 MeV excitation.

	Excitation energy (MeV±keV)			
Level	Present	Previous[a]	J^{π}[a]	σ_{max} ($\mu b/sr$)
25	8.667±13	8.660±6		20.8±1.0
26	8.82±20	8.817±12		13.0±0.9
27	8.96±20	8.956±4		16.3±1.0
		(9.03)		
		(9.10)		
		9.362±6		
		9.414±18		
		9.48±24		
		9.673±7		
28	9.72±30	9.713±7		26.3±1.3
		9.890±11		
29	10.09±30	10.119±10	3^-	30.6±1.5
30	10.28±30	10.295±14	4^+	100±5
		10.396±9	3^-	
		10.595±15		
31	10.63±30			31.3±1.6
		10.82±20		
32	10.90±30	10.91±20		42.7±2.1
33	10.99±20	10.99±20		84.8±4.2
34	11.12±20	11.13±20		17.7±0.9
35	11.26±20			33.9±1.7
		11.39±20	2^+	
36	11.42±30	11.41±20	4^+	46.6±2.3
37	11.61±30	11.62±20	5^-	34.1±1.7
38	11.70±30	11.69±20	6^+	75.4±3.8
39	11.85±30	11.82±20	(3^-)	81.9±4.1
40	12.07±30	12.04±20	(2^+)	34.2±1.7
41	12.23±30	12.25±20	(1^-)	32.1±1.6
42	12.33±30	12.33±20	5^-	50.4±2.5
43	12.44±30			96.0±4.8
		12.50±20	4^+	
44	12.54±30	12.53±20	6^+	90.2±4.5
45	13.08±30	13.1	1^-	48.4±2.4
46	13.23±30			99.3±5.0
47	13.48±30			24.6±1.2
48	13.60±30			29.0±1.5
49	13.81±30	13.8	1^-	159±8
50	14.14±30			92.7±4.6
		14.7	1^-	
51	15.80±30	15.8	1^-	136±7
		16.38±10	$T=2$	

[a] Reference 3.

move relative to other peaks in the spectrum. Hence, we assign them to new states in ^{18}O.

Angular distributions are displayed in Figs. 2–6. Curves are results of Hauser-Feshbach calculations for states of known J^{π} and are discussed later. Differential cross sections have been integrated to obtain total cross sections listed in Table I. That table also lists separately the forward and backward angle cross sections, and their ratios. For states with known J^{π}, the ratio $\sigma_{tot}/(2J+1)$ is tabulated and σ_{tot} is plotted vs $2J+1$ in Fig. 7. Above 8.5 MeV excitation, angular distributions are not complete. Those states are listed in Table II.

The average of 19 values of $\sigma_{tot}/(2J+1)$ is 10.2 μb, with only two states differing by more than a factor of 2 from the average. These are the 3^+-0^+ doublet at 5.3 MeV (which is weak) and the 4^+ state at 7.11 MeV, which is quite strong. In fact the 7.11-MeV level is 1.52 times as strong as the next strongest state and 2.44 times as strong as the average of all other states of known J^{π}. The extreme selectivity of this state in the present and other heavy-ion reactions[4] is still a puzzle.

Nearly all of the angular distributions are forward peaked, as evidenced by the ratio $\sigma(0-90)/\sigma(90-180)$—whose average value in the present data is 2.21 for the first 24 angular distributions. This result is evidence against a pure statistical compound-nucleus pro-

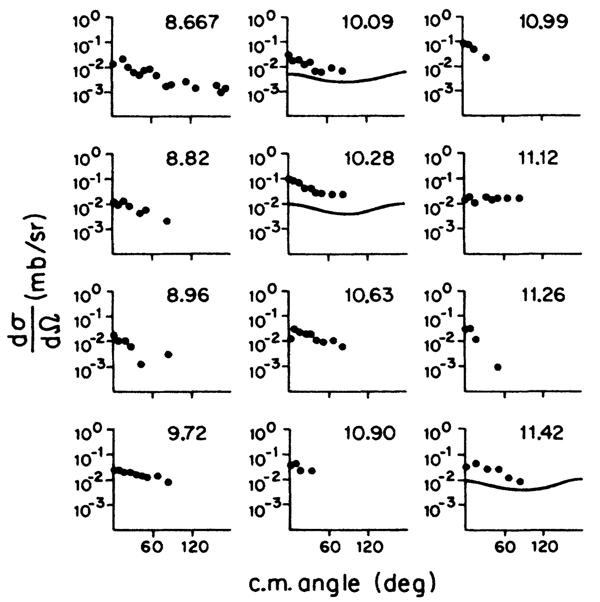

FIG. 4. Angular distributions for states with 8.5 MeV $< E_x <$ 11.5 MeV.

cess, for which we expect roughly symmetric angular distributions. Hence, two independent sets of quantities—forward-backward ratios and values of $\sigma_{tot}/(2J+1)$—suggest the presence of some mechanism in addition to the statistical decay of an equilibrated compound system.

The correlation of selectivity in the present reaction with that of $^{12}C(^7Li,p)^{18}O$ has been noted,[5] though the reason for the correlation is not known. We turn now to

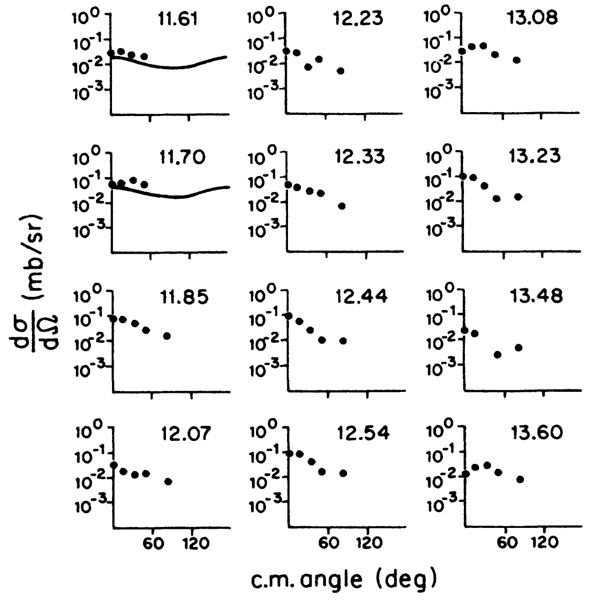

FIG. 5. As Fig. 4, but for $E_x = 11.6–13.6$ MeV.

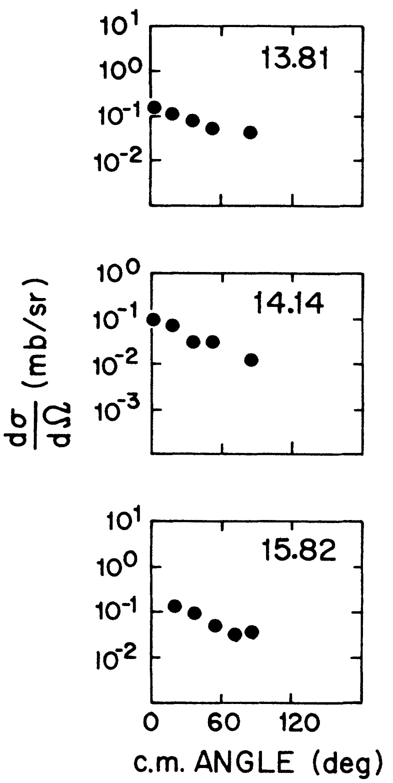

FIG. 6. Three additional partial angular distributions.

a quantitative comparison of the current data with compound-nucleus calculations.

Compound-nucleus (CN) calculations were performed with the code STATIS,[6] as described in Ref. 2. Transmission coefficients were computed with a modified version of the optical-model code PENNY,[7] using the parameters[8,9] given in Table III. The entrance and decay channels considered are depicted in Fig. 8, in which the hatched areas represent the excitation energy regions in which the level-density formula was used.

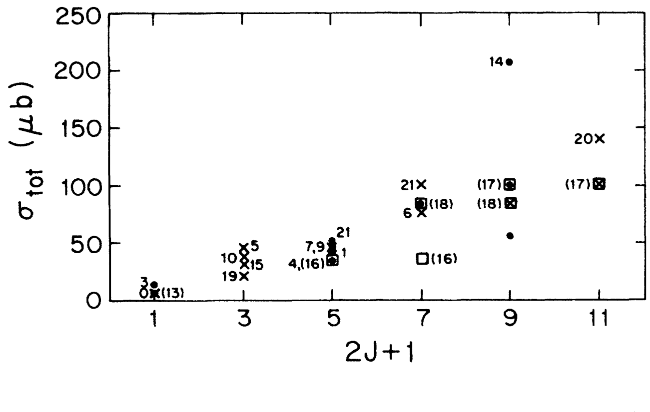

FIG. 7. Angle-integrated cross sections vs $(2J+1)$ for $^{13}C(^6Li,p)^{18}O$.

TABLE III. Optical-model parameters used in the calculation of transmission coefficients for the $^{13}C(^{6}Li,p)^{18}O$ reaction. (Strengths in MeV, lengths in fm.)

Channel	Real potential			Imaginary potential				Coulomb
Ref.	V	R	a	W_S	W_D	R	a	R_C
$^{13}C + {}^{6}Li$	444.0	2.47	0.71	13.2	0.0	4.53	0.87	5.87
$^{18}O + p$	44.4	2.94	0.69	2.0	19.56	3.67	0.43	3.01
$^{18}F + n$	50.6	2.80	0.74	0.0	28.4	3.35	0.7	
$^{17}O + d$	92.84	2.66	0.787	0.0	22.9	3.48	0.727	3.34
$^{15}N + \alpha$	195.0	3.16	0.654	21.0	0.0	3.16	0.654	3.20

Results of the STATIS calculations—for states whose J^{π} values are known—are compared with the data in Figs. 2–5. We note that the general trends of the data are reproduced. However, the curves are seen to overestimate the measured cross sections in many places. This could not be the case if the experimental cross section is an incoherent sum of two processes, one of which is CN. Thus, either the STATIS calculations need to be renormalized downward or the CN-like process is coherent with the other reaction amplitude.

In Fig. 9 we plot the measured angle-integrated cross sections versus those predicted by STATIS. In general, the data lie above the curve—indicating that CN processes alone do not describe the data. Figure 10 contains separate plots for 0°–90° and 90°–180° of the measured vs STATIS cross sections, both divided by $2J+1$. We first note some scatter in the calculations—hence σ_{HF} is not proportional to $2J+1$. Some of the scatter arises from Q-value dependence, but also high J states are predicted to be much stronger than a $2J+1$ behavior would suggest. Even so, the 7.11-MeV 4^+ state is significantly stronger than predicted. This is offset, somewhat, by the fact that the 3.55-MeV 4^+ and 8.28-MeV 5^- states are weaker than predicted.

Perhaps the most significant feature of Fig. 10, however, is the difference for 0°–90° (top) and 90°–180° (bottom). For forward angles, the spread in the measured cross sections is 4–5 times the spread in back-angle data. The forward-angle enhancements are hence not related to the predicted Hauser-Feshbach (HF) cross sections, nor to the final J value. This latter point is obvious from Fig. 11, where we plot the difference in forward and back angle cross sections—divided by $2J+1$—versus excitation energy. The data seem to be divided into two distinct groups—one in which the data are only slightly forward peaked contains primarily low-lying positive-parity states, whereas the other exhibits substantial forward peaking and primarily contains negative-parity states. In this latter group is one positive-parity state (0^+ at 3.63 MeV) that is known[10] to be predominantly a core-excited state and a 2^+ level at 8.2 MeV that may really be a doublet—in which case dividing by $\Sigma(2J+1)$ would reduce the value of the point plotted.

In summary, even though much of the current data resemble somewhat the expectations from a statistical

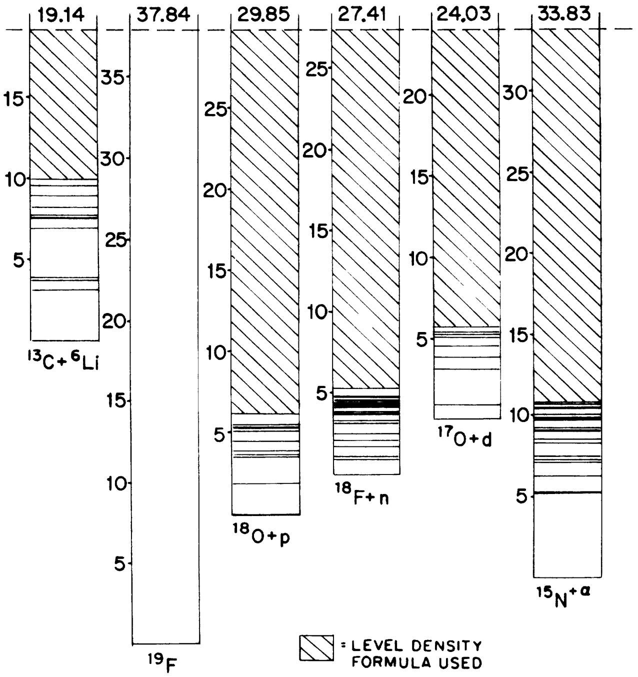

FIG. 8. Decay channels used in calculating the Hauser-Feshbach denominator for the $^{13}C(^{6}Li,p)^{18}O$ reaction.

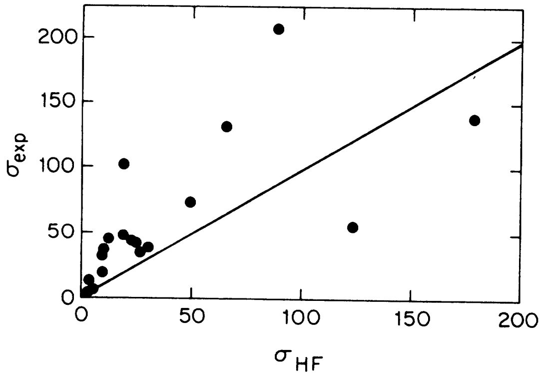

FIG. 9. Comparison of experimental and Hauser-Feshbach angle-integrated cross sections, in μb.

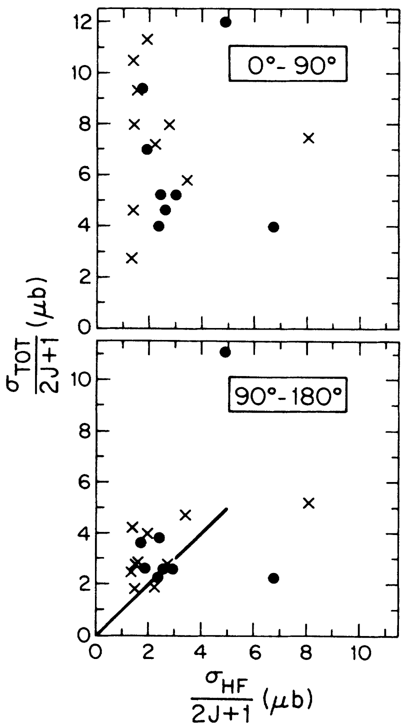

FIG. 10. Plot of measured vs HF cross sections, both divided by $2J+1$, for 0°–90° (top) and 90°–180° (bottom).

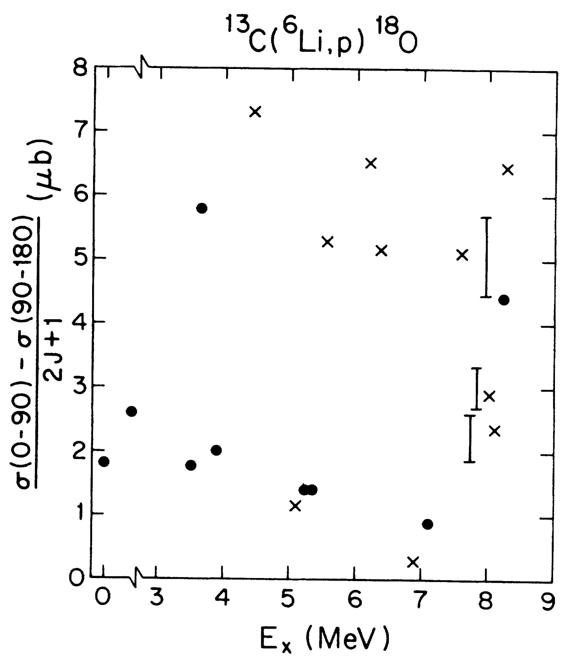

FIG. 11. Forward angle excess cross sections, divided by $2J+1$, vs excitation energy.

compound-nucleus process, the deviations are pronounced and of a sort that would suggest the presence of an appreciably "direct-like" five-nucleon transfer amplitude. If such an amplitude indeed exists, it should predominate over CN processes at higher bombarding energies. It is hoped the current data and analysis presents a challenge to both the theorists and experimenters.

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*Present address: Science and Engineering Research Council, Daresbury Laboratory, Daresbury Warrington, United Kingdom.

†Present address: Department of Physics, University of York, York YO1 5DD, United Kingdom.

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