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J dependence in the ^{50}Cr(^{7}Li,^{6}He)^{51}Mn reaction at 28 MeV

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The reaction ^{50}Cr(^{7}Li,^{6}He)^{51}Mn was investigated at extreme forward angles, $1.6° \le \theta \le 12°$, in order to study the j dependence for the (^{7}Li,^{6}He) reaction at 28 MeV. The ^{6}He ejectiles were detected with a position-sensitive (helix) counter in the focal plane of an Enge-split-pole spectrograph. A total energy resolution of about 30 keV was obtained. The angular distributions for seven low-lying states in ^{51}Mn show a pronounced j dependence for angles below 7° and the expected l dependence at angles $\theta \ge 9°$. Finite-range distorted-wave Born approximation calculations which include recoil effects reproduce the j-dependent angular distributions very well and permit a clear distinction between $p_{3/2}$, $p_{1/2}$, $f_{7/2}$, and $f_{5/2}$ final state angular momenta. The relative spectroscopic factors deduced were in reasonable agreement with those obtained in a recent ^{50}Cr(^{3}He,d)^{51}Mn reaction study.

[NUCLEAR REACTIONS ^{50}Cr(^{7}Li, ^{6}He)^{51}Mn, E_{Li} = 28 MeV; measured $E_{^6He}$ and $\sigma(\theta, E_{^6He})$ in split pole spectrograph with 30 keV resolution. Finite-range-DWBA analysis, deduced $j_{transfer}$, spectroscopic factors.]

I. INTRODUCTION

Several direct transfer reactions are known to have differential cross sections which exhibit a dependence on the transferred total angular momentum j, in addition to the familiar l dependence. However, the j-dependent effects for light ions frequently are small or are found in an angular range which is relatively time consuming or difficult to observe.[1-5] For this reason and because it has been difficult to account for these effects consistently in a distorted-wave Born approximation (DWBA) analysis only infrequent use has been made of this known light-ion j dependence in standard spectroscopic studies.

Recent studies of the (^{7}Li, ^{6}He) transfer reaction report a very pronounced j dependence at small angles[6-8] for a number of selected angular distributions. The examples available also include several transitions where the expected j effect is not, or not fully, seen. This seems to be caused by unknown nearby states of different j which remained unresolved. These early experiments typically were performed with experimental resolutions of $\geq$70 keV. It is important to perform (^{7}Li, ^{6}He) experiments with improved resolution and to extend them to different targets and beam energies in order to document the consistency of this j dependence.

Similarly, it is of interest to see if accurate theoretical predictions can be made for all transitions which can be resolved in a given reaction. We would expect some j dependence to be the rule for one-step transfers initiated by heavy ions: Whenever a transferred nucleon does not occupy S orbits in either projectile or target, more than one L transfer is possible. In a DWBA analysis the weight of one possible L transfer, relative to a second or a third one, is given by the square of a j-dependent Racah coefficient,[9] and the angular distributions are j-dependent mixtures of L transfers. For (^{7}Li, ^{6}He) transfer the selection rules which apply for the angular momenta L transferred in the reactions are

$$|1-l| \leq L \leq |1+l|$$

and

$$|\tfrac{3}{2}-j| \leq L \leq |\tfrac{3}{2}+j| \, ,$$

where l and j are the quantum numbers of the transferred proton in its final state in the residual nucleus, and where the Racah coefficient appropriate for a given L has the form $(W(lj1\tfrac{3}{2}, \tfrac{1}{2}L)$. Finite-range DWBA calculations predict that the expected j dependence is most pronounced at $\theta = 0°$ and becomes small at $\theta = 10°$. Hence the present experiment concentrated on the extreme forward angles, from 0° to the angle of the dominant stripping peak.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The ^{50}Cr(^{7}Li, ^{6}He)^{51}Mn reaction was studied with 28 MeV ^{7}Li ions from the Pittsburgh Van de Graaff accelerator. The target was prepared by evaporation of 96.8% enriched ^{50}Cr metal onto a thin carbon backing of 10 μg/cm^2. The thickness of the metallic ^{50}Cr film was about 25 μg/cm^2. The contaminants included 3% of ^{52}Cr and traces of ^{16}O, ^{28}Si, Cl, and Cu. The target thickness was measured by comparing small-angle ^{3}He and ^{7}Li scattering with optical model predictions. An uncertainty of 15% is ascribed to this method of thickness determination. The ^{7}Li beam and target integrity were monitored by charge collection and simultaneous measurement of the elastically scattered beam by Si-diode detectors positioned at ±25° with respect to the incident beam. The ratio of the counts of the +25° detector to those of the −25° detector also provided a useful check on the stability of the beam direction.

The reaction products were detected and identified by a helical cathode gas proportional counter ("helix counter") which is positioned at the focal plane of the Enge split-pole spectrograph.[10] The 40 cm long helix position detector is backed by a second gas proportional counter and a long plastic scintillator. The three counters constitute a three-section telescope, which was essential for background suppression at very small angles, particularly for the run where the spectrograph entrance aperture is placed at zero degrees (θ_{av} = 1.6°). Figure 1 shows a helix spectrum for ^{50}Cr(^{7}Li,^{6}He) taken at θ = 3°.

The energy resolution obtained in this experiment ranged from 25 to 35 keV. Because of the relatively low beam energy (4 MeV per nucleon), straggling and the differential energy loss in the target made a significant contribution to the resolution. Smaller, but comparable contributions came from the energy spread in the incident ^{7}Li beam and from kinematic broadening at larger scattering angles. The position detector resolution made a contribution of about 0.6 mm or 17 keV. At the smallest angles resolution was slightly diminished by the high background count rate.

Zero-degree measurements without a beam stop has been possible for the ^{50}Cr(^{3}He, d) experiment.[5] However, for ^{7}Li beams very large ^{7}Li^{++} count

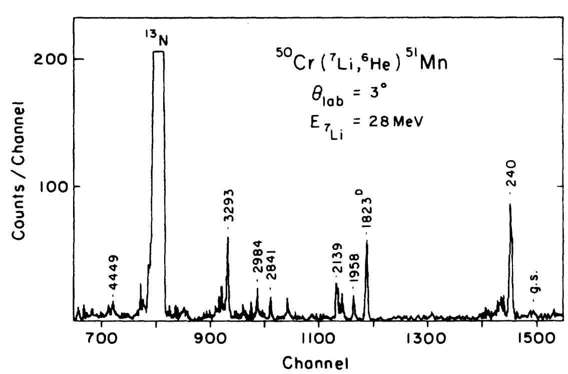

FIG. 1. Typical small-angle spectrum for the ^{50}Cr(^{7}Li,^{6}He)^{51}Mn reaction at E = 28 MeV. The excitation energies of levels for which angular distributions were extracted are given in units of keV.

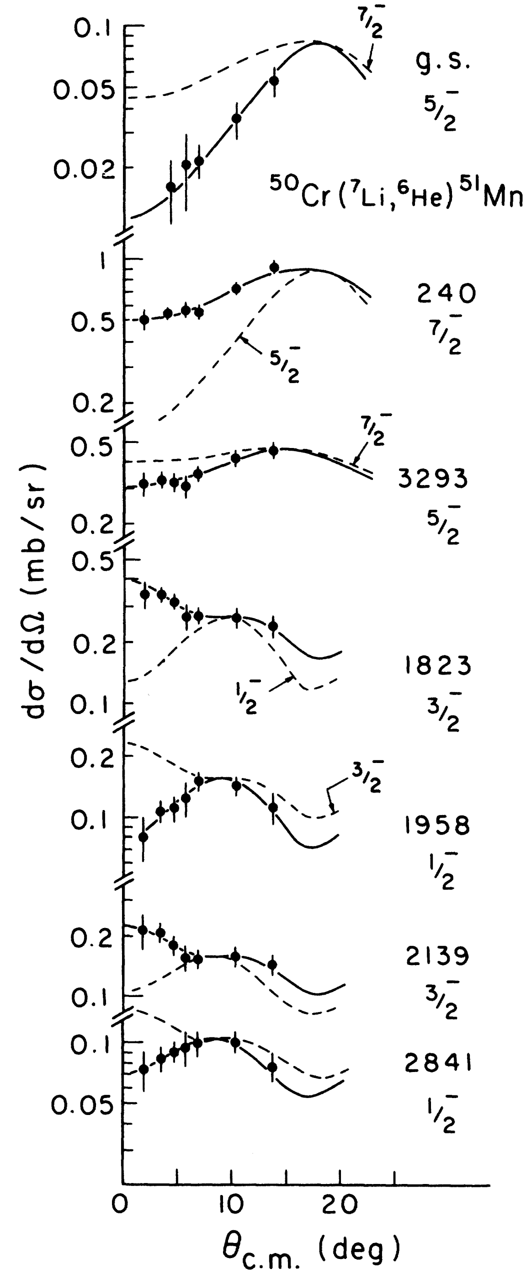

FIG. 2. Comparison of experimental angular distributions with finite range DWBA calculations for transitions to known levels of ^{51}Mn. The experimental error bars include all known and estimated (background) random errors. The calculations shown as solid lines result if the previously assigned j transfer values are used. Calculations for each alternate j value are shown as dashed curves. All calculations are normalized to the peak of the experimental stripping cross sections. Level energies are given in keV. Up to 3 MeV excitation the alternate curves are ruled out by the data. For the single available case above E^* = 3 MeV excitation the j dependent effect is reduced but still discernible. Use of the alternate optical model parameter set for ^{7}Li and ^{6}He scattering given in Table I yields nearly identical angular distributions at 28 MeV.

rates were seen for $\theta \leq 2^\circ$ runs in the focal plane detector in addition to the usual high background from multiple scattering and x rays. In order to eliminate the zero degree count-rate problem a 4 mm wide beam stop was placed about 17 cm behind the target. This beam stop adequately intercepted the incident unscattered ^{7}Li beam and those ejectiles leaving the target with $\theta \leq 0.68^\circ$. It was noticed that the zero-degree background would rise with the vacuum pressure P in the spectrograph. Successful runs were possible if $P \leq 10^{-6}$ Torr was maintained. The accuracy of the zero-degree position was ascertained by taking data at both sides of $\theta = 0^\circ$ for each experimental setup. The angular acceptance for the spectrograph was generally kept at $\Delta\theta = \pm 2^\circ$, but it was reduced to $\Delta\theta = \pm 1^\circ$ for angles smaller than 4°. The requirements of limited angular spread, high resolution (i.e., a thin target), combined with a relatively low three-stage ^{7}Li beam led to quite lengthy runs. Hence cross section measurements were restricted to extreme forward angles, i.e., $1.6^\circ \leq \theta_{c.m.} < 14^\circ$ where j-dependent effects were expected. Angular distributions for seven well resolved final states are shown in Fig. 2. It is noted that the $f_{7/2}$ and $f_{5/2}$ transitions are, indeed, quite dissimilar. The $p_{3/2}$ and $p_{1/2}$ angular distribution differ even in a qualitative way. Angular distributions for $p_{1/2}$ transfers fall steeply as $\theta \to 0$, whereas $p_{3/2}$ angular distributions rise. This is a consequence of the L selection rule which permits an $L = 0$ contribution for $p_{3/2}$ transfer but not for $p_{1/2}$ transfer.

III. FINITE RANGE DWBA ANALYSIS

The exact recoil finite range DWBA code LOLA[11] was used to calculate angular distributions for comparison with the experimental results. Code LOLA includes the Coulomb interaction potentials $\Delta V = V_{bx} + (V_{bA} - U_{bB})$ which are used in the "post" representation. (U_{bB} is the optical potential for the Coulomb term in the interaction between the ejectile b and the residual nucleus B. The transferred nucleon is denoted by x and the target by A.) The code DWUCK5 [12] which was also available to us contains only the first term in the above formula and yielded results which also fit the data; but they fit slightly less well. The "deep" optical model potentials (a) used for the calculations shown in Fig. 2 were taken from Strohbush *et al.*,[13] and are given in Table I. Calculations were also made with the very different, "shallow," parameter set (b) given in Ref. 7. Both sets of calculations were successful and yielded very similar angular distributions. However, the absolute cross sections predicted by the parameter set (a) are higher by a factor of 2 compared to calculations which use the parameters set (b).

Figure 3 displays the contributions to the full cross sections which arise from the individual L transfers for the four j transfers observed in this experiment. [All calculations used the parameter set (a) in Table I.] The forward peaking for $p_{3/2}$ transfers which arises from the $L = 0$ contribution is quite apparent; it is absent for $p_{1/2}$ transfer. For the $f_{7/2}$ transfer the strong $L = 2$ component prevents the drop at small angles which is seen for the $f_{5/2}$ transfer.

The experimental cross sections are related to the calculated ones by

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp} = (2j_f + 1)(C^2S)_{^7\rm Li}\,(C^2S)_{^{51}\rm Mn}\left(\frac{d\sigma}{d\Omega}\right)_{\rm LOLA}$$

We used the value $(C^2S)_{^7\rm Li} = 0.59$.[14] The values for

TABLE I. Optical-model parameters for the ^{50}Cr(^{7}Li, ^{6}He)^{51}Mn reaction at 28 MeV.

		V (MeV)	r_r (fm)	a_r (fm)	W_S (MeV)	W_D (MeV)	r_i (fm)	a_i (fm)	r_c (fm)	λ
^{7}Li + ^{50}Cr	a	290	(1.37)[c]	0.65	0	30	(1.37)[c]	0.65	2.0	
	b	49.72	1.78	0.58	8.52	0	1.78	1.01	1.78	
^{6}He + ^{51}Mn	a	250	(1.34)[d]	0.65	0	30	(1.34)[d]	0.65	2.0	
	b	47.37	1.78	0.58	11.56	0	1.675	0.90	1.78	
^{50}Cr + p	a	e	1.20	0.75					1.3	25
	b	e	1.25	0.65					1.25	25
^{6}He + p	a	e	1.20	0.75					1.3	25
	b	68.50	1.25	0.65					1.25	25

[a] Parameters from Ref. 13.
[b] Parameters from Ref. 7.
[c] $R_r = R_i = 0.9\,(A^{1/3} + 7^{1/3})$.
[d] $R_r = R_i = 0.9\,(A^{1/3} + 6^{1/3})$.
[e] Well depth adjusted by code to fit proton separation energy.

TABLE II. Spectroscopic results for ^{51}Mn and comparison with previous work. Spin values in brackets are tentative, or (in column 5) indicate the j value chosen for the calculation of C^2S.

$^{54}Fe(p,\alpha\gamma)$ (Ref. 17)		$^{50}Cr(^3He,d)^{51}Mn$, $E=18$ MeV (Ref. 5)				Present work $^{50}Cr(^7Li,^6He)$ $E=28$ MeV		
E_x (MeV)	(Refs. 15–17) J^π	E_x (MeV)	l	J^π	C^2S	$\frac{d\sigma}{d\Omega}$[a] (mb/sr)	J^π	C^2S
0	$\frac{5}{2}^-$	0	3	$(\frac{5}{2}^-)$	0.03	0.054	$\frac{5}{2}^-$	0.013
0.2374	$\frac{7}{2}^-$	0.240	3	$(\frac{7}{2}^-)$	0.28	0.93	$\frac{7}{2}^-$	0.12
1.1395	$\frac{9}{2}^-$	1.138[b]						
1.4881	$\frac{11}{2}^-$	1.488[b]						
1.8170	$(\frac{3}{2})$							
1.8246	$\frac{3}{2}^-$	1.823[c]	1	$(\frac{3}{2}^-)$	0.16	0.27	$\frac{3}{2}^-$	0.035
1.9589	$\frac{1}{2}^-$	1.958	1	$(\frac{1}{2}^-)$	0.12	0.14	$\frac{1}{2}^-$	0.029
2.1403	$\frac{3}{2}^-$	2.139	1	$(\frac{3}{2}^-)$	0.09	0.16	$\frac{3}{2}^-$	0.023
2.2559	$\frac{5}{2}^-$							
2.2759	$\frac{1}{2}^+$	2.275	0	$\frac{1}{2}^+$	0.03(2s)			
2.3102	$(\frac{5}{2}^-)$							
2.4159	$\frac{7}{2}^-$	2.416	3	$(\frac{7}{2}^-)$	0.01			
2.7105	$(\frac{5}{2}^-)$							
2.8414	$(\frac{1}{2}^-)$	2.841	1	$(\frac{1}{2}^-)$	0.11	0.10	$\frac{1}{2}^-$	0.028
2.8930	$(\frac{5}{2}^-,\frac{7}{2}^+)$							
2.9136	$(\frac{3}{2}^-)$	2.913	1	$(\frac{3}{2}^-)$	0.01			
2.9567	$(\frac{13}{2}^-)$							
2.9845	$\frac{5}{2}^+$	2.984	2	$(\frac{5}{2}^+)$	0.01(2d)			
3.0486		3.048[c]	(1) (3)					
3.052	$(\frac{3}{2}^-)$							
3.0915								
3.1305		3.132[b]						
3.2922	$\frac{5}{2}^-$	3.293	3	$(\frac{5}{2}^-)$	0.21	0.46	$\frac{5}{2}^-$	0.086
3.4233		3.426	(1)		0.03			

[a] Cross sections are given at $\theta_{c.m.}=10°$ for $l=1$ and at $\theta_{c.m.}=14°$ for $l=3$ transfers.
[b] Weak state.
[c] Doublet.

$(C^2S)_{^{51}Mn}$ were obtained by normalizing the LOLA results to the data. They are listed in Table II together with the deduced values for the transferred j and the spectroscopic factors from a previously published $^{50}Cr(^3He,d)$ study.[5] The absolute spectroscopic factors extracted for the $^{50}Cr(^7Li,^6He)$ reaction are *too small* by factors of about 2.3 for $f_{7/2,5/2}$ transfer and by about 4.2 for $p_{3/2,1/2}$ transfer for calculations with the optical model parameter set a. If the shallow parameter set b were used, all spectroscopic factors would be larger by a factor of about 2 so that the $f_{5/2}$ and $f_{7/2}$ spectroscopic factors would be comparable to the $(^3He,d)$ values whereas the $p_{1/2},p_{3/2}$ spectroscopic factors would be too small by a factor of 2. These divergent results reflect their large sensivity to the optical model parameters. We note that the sets of Table I were not derived from $^{50}Cr(^7Li,^7Li)$ scattering at 28 MeV. The usefulness of the ^6He parameters for ^{50}Cr which

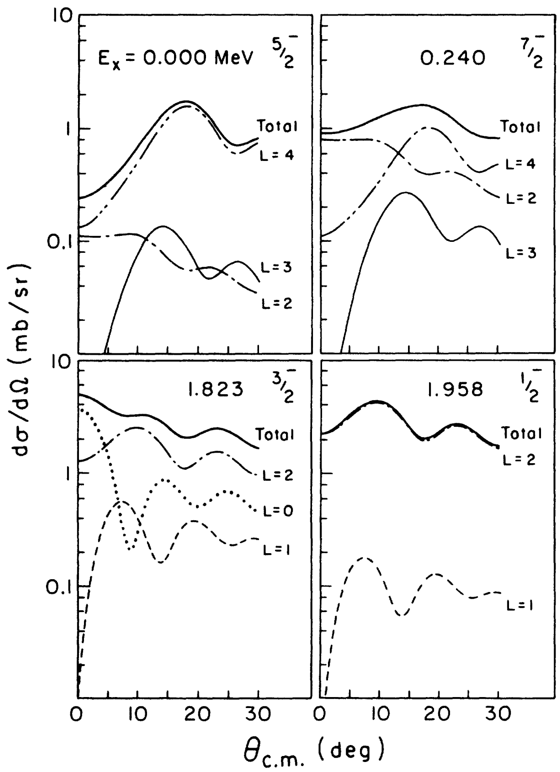

FIG. 3. Comparison of the magnitude of various L transfer contributions to the total calculated cross section. It is noted that the j_{lower} transitions are dominated by a single L component ($f_{5/2}$ by $L=4$, $p_{1/2}$ by $L=2$), whereas j_{upper} angular distributions are modified significantly by contributions from the smaller allowed L transfers.

were derived from ^{6}Li elastic scattering is even less well established. It is interesting to note that these parameter uncertainties affect the absolute cross sections much more strongly than the angular distributions.

IV. DISCUSSION AND CONCLUSIONS

The present experimental results are summarized in Fig. 2 and Table II. Seven (^{7}Li, ^{6}He) angular distributions were obtained, four for $p_{3/2}, p_{1/2}$ transfer and three for $f_{7/2,5/2}$ transfer. The transitions were well resolved from any known neighboring levels in ^{51}Mn. All angular distributions were well fitted by finite-range DWBA calculations, and the ^{51}Mn spins (J^π) deduced from this comparison agree with existing firm assignments in the literature.[15-17] The 2.841 level in ^{51}Mn had only a tentative $\frac{1}{2}^-$ assignment, but our result would confirm this value. Hence we concur with the conclusion of Refs. 6–9 that the j dependence in the (^{7}Li, ^{6}He) reaction is a systematic and well understood effect and can give important final state spin information. The absence of perturbations from unresolved levels of different J^π in our angular distributions and the inclusion of angles as small as 1.6° increases the confidence with which J^π assignments can be made and alternate fits can be ruled out. However, we note that for the ^{50}Cr(^{7}Li, ^{6}He)^{51}Mn reaction at 28 MeV the magnitude of the J-dependent effect decreases significantly with increasing Q value (see Fig. 2), in agreement with DWBA predictions. The j effect can still be seen at excitations of 3 MeV, but good statistics are needed. DWBA calculations suggest that the (^{7}Li, ^{6}He) j dependence, particularly for higher lying levels, would be stronger at 33 MeV bombarding energy. Hence such experiments are probably done very efficiently at energies above 30 MeV. The absolute cross sections and the spectroscopic factors yielded by our DWBA analysis are less satisfactory than the angular distributions. At a minimum more certain mass-6 and mass-7 optical potentials seem to be needed before accurate spectroscopic strengths can be extracted from these DWBA analyses. The (^{7}Li, ^{6}He) angular distributions are moderately l dependent, but their structure at larger angles is weak and the l transfer is difficult to extract with confidence. At this time it seems prudent to obtain and use high-resolution (^{3}He, d) data for the derivation of reliable energy levels, l transfers, and spectroscopic factors in single-proton-transfer studies. Our investigation adds further weight to the suggestion that, given this information, (^{7}Li, ^{6}He) angular distributions which include sufficiently small angles should provide a reliable indication of the J^π values of the states populated in proton transfer.

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