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Optical model parameters for the $^{12}C(^7Li,^7Li)^{12}C$ reaction at 63 and 78.7 MeV

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Elastic and inelastic scattering of ^{7}Li from ^{12}C have been measured at incident energies of 63 and 78.7 MeV. The experimental data were obtained over an angular range from $\theta_{lab}=8°$ to 40°. Optical model parameters have been extracted by fitting the elastic scattering data, and deformation lengths have been obtained for the ^{7}Li* (0.48 MeV) state and the ^{12}C* (4.44 MeV) state. No single parameter set was found that fitted the elastic scattering over a wide range of energies via simple changes in the depths of the potentials.

[NUCLEAR REACTIONS $^{12}C(^7Li,^7Li)$ and $^{12}C(^7Li,^7Li')$ $E(^7Li)=63$ and 78.7 MeV; measured $\sigma(\theta)$; deduced optical model parameters; deduced deformation lengths for ^{7}Li* and ^{12}C*. Natural targets, DWBA analysis, $\theta_{lab}=8-40°$, $\Delta\theta=1°$.]

I. INTRODUCTION

In a recent study of ^{7}Li scattering from ^{54}Fe, Kemper *et al.*[1] found that one optical model (OM) parameter set could describe the experimental data obtained over an energy range of 36–48 MeV. This was in contrast to the work by Cutler *et al.*,[2] who found an apparent energy dependence for ^{7}Li scattering from ^{40}Ca between 28 and 34 MeV. Poling *et al.*[3] obtained an energy-independent parameter set by fitting the elastic scattering data of ^{7}Li on ^{12}C from 4.5 to 36 MeV. The parameter set, however, did not provide a satisfactory fit to the elastic scattering data obtained on ^{12}C by Zeller *et al.*[4] at 48 MeV. Two Igo related parameter sets (i.e., a deep and shallow real potential with the same value for the imaginary potential) were found to provide equally good fits to the 48 MeV data.

Little data have been obtained for ^{7}Li scattering at energies above 50 MeV. In this paper, we present results for elastic and inelastic scattering of ^{7}Li on ^{12}C at 63 and 78.7 MeV. The data place additional constraints on OM parameter sets and, in particular, provide the first opportunity to investigate whether a unique OM parameter set exists that can fit experimental data over a rather large range of energies. In addition to the elastic scattering fits, distorted-wave Born approximation (DWBA) calculations have been carried out for the inelastic excitations in order to narrow further the choice of OM parameter sets.

II. EXPERIMENTAL PROCEDURES

^{7}Li particles accelerated to 63 and 78.7 MeV by the Texas A&M University 224 cm cyclotron impinged on natural carbon targets of ~170 $\mu g/cm^2$. On target beam currents varied from several nA at small scattering angles to 1 μA at large angles. Beam energies were determined to an accuracy of 100 keV by calibrating the analyzing magnet relative to alpha beams of the same rigidity; the alpha beam energies were measured in a separate experiment. ^{7}Li particles were detected in the focal plane of an Enge split-pole magnetic spectrograph by a detector consisting of two 20 cm single-wire proportional counters that were backed by a thin plastic scintillator. The two dE/dx signals from the gas proportional counters were usually sufficient to identify the ^{7}Li events; the plastic scintillator signal and the particle time of flight were available as additional constraints.

The length of the focal plane detector limited the excitation energy range to 6 MeV at a particular magnetic field setting. Thus data were taken only for the ground state, the ^{7}Li* (0.48 MeV) state, and the ^{12}C* (4.44 MeV) state. The mutually excited state of ^{7}Li* (0.48 MeV) and ^{12}C* (4.44 MeV) was observed; however, the yield was quite small (the reaction mechanism responsible for this mutual excitation has been discussed previously[4,5]). Data were taken in 1° steps for laboratory angles from 8°–30° and 2° steps to 40°. The polar acceptance angles were 0.52° and 0.67° for 63 and 78.7 MeV, respectively. The integrated beam current was used to normalize the data at different angular settings. In order to ensure that the normalization was accurate, the integrator was compared to a monitor counter and was found to be reproducible to within the uncertainty in the number of monitor events (< 3%). As an additional check, an angular distribution was measured at 48 MeV and compared with the results of Ref. 4. The agreement between the relative cross sections was better than ±4%.

Absolute cross sections were obtained by fitting the most forward angle elastic scattering cross sections with several OM parameter sets; the normalization factor was treated as a free parameter. The magnitude extracted for the cross section was found to be relatively independent of the choice of OM sets. It is estimated that this technique results in an uncertainty of about ±12% in the absolute cross sections. Including the uncertainties in angle settings and the beam energy, we estimate the overall uncertainty to be about ±15%.

III. ANALYSIS

A. Optical model analysis

The elastic scattering data were analyzed with the standard optical potential, which is defined in Table I. Using the 48 MeV potential sets[4] as starting parameters, analyses were made by two parameter searches with either (V_0, W), (R_{0i}, a_r), or (R_{0r}, a_i) as search parameters. Additionally, four parameter searches were performed with (V_0, W) held constant. The resulting parameter sets are given in Table I. The parameter sets are listed as deep (D) or shallow (S), depending upon whether the sets were obtained from the deep or shallow sets at 48 MeV (listed at the end of Table I). It should be noted that the 48 MeV sets are, in fact, Igo related. The same Igo constants are found for sets I and II, for the 63 MeV data. The OM parameter sets I and III were obtained by using the 48S values as starting parameters, while sets II and IV were generated from the 48D parameters. Parameter set V was obtained by searching on the set I parameters instead of the 48S parameter.

The fits from the various parameter sets are compared to the elastic scattering data in Fig. 1. In this figure, as in subsequent ones, the shallow set is shown as the solid line and the deep set the dashed line. The dash-dotted line shown for the 63 MeV data is the result of an OM fit using the 48S parameter set. For the 78.7 MeV data, the dash-dotted line is the prediction resulting from the set V. As the figure shows, the 48S set does not provide a good fit to the data. Simply changing (V_0, W) did not significantly improve the fit. Neither the data at 63 nor that at 78.7 MeV could be adequately fit by simple changes in the depths of the potentials for parameter sets that provided good fits at other energies. This apparent lack of a simple energy dependence is in contrast to the analysis of lower energy data carried out by Poling *et al.*[3] Since we have searched for an energy-dependent parameter set, no attempt was made to find a set having derivative absorption. At 48 MeV, derivative sets were tried but they did not provide as good a fit to the data as the volume absorption sets. Since the fits to the single nucleon transfer data were good at 48 MeV,[4] there was no reason to further pursue parameter sets with surface absorption.

B. DWBA calculations

The optical potentials obtained from the elastic scattering were used to calculate cross sections for the inelastic excitations via the DWBA code DWUCK4 (Ref. 6) using a complex form factor with both real and imaginary deformed potentials. Deformation parameters β_L were extracted by normalizing to the experimental data through the relationship

$$\sigma_{\text{exp}} = (I_i LK0 \mid I_F K)^2 \beta_L{}^2 \sigma_{\text{DWUCK}}$$

where $(I_i LK0 \mid I_F K)$ is a Clebsch-Gordan coefficient between the initial and final states. The deformation length $\beta_L R_w$ is derived from the imaginary radius, since the imaginary potential is the determining factor in the magnitude of the inelastic scattering. Our motivation for extending the calculations to inelastic excitations was to restrict further the choice of OM parameter sets. In particular, it is interesting to discern whether the

TABLE I. Optical model parameters. We use the potential $V(r) = U_c(r) - V_0 f(x_r) - iWf(x_i)$, where $U_c(r) = (zZe^2/2R_c)[3-(r/R_c)^2]$, $r \le R_c$, $U_c(r) = zZe^2/r$, $r > R_c$, and $f(x) = (1+e^x)^{-1}$, $x = (r-R)/a$, $R_k = R_{0k}A_{\text{tgt}}^{1/3}$, $r_c = 1.3$ fm.

Set	E_{lab} (MeV)	V_0 (MeV)	R_{0r} (fm)	a_r (fm)	W (MeV)	R_{0i} (fm)	a_i (fm)	Type
I	63	58.36	1.488	0.785	10.12	2.306	0.696	S
II	63	118.70	1.283	0.734	8.33	2.382	0.724	D
III	78.7	40.37	1.764	0.673	16.32	1.961	0.926	S
IV	78.7	140.20	1.022	0.968	21.34	1.879	0.809	D
V	78.7	48.28	1.666	0.674	12.02	2.216	0.843	S
48S	48[a]	65.22	1.518	0.828	11.91	2.230	0.688	S
48D	48[a]	145.60	1.217	0.830	12.09	2.219	0.693	D

[a] Reference 4.

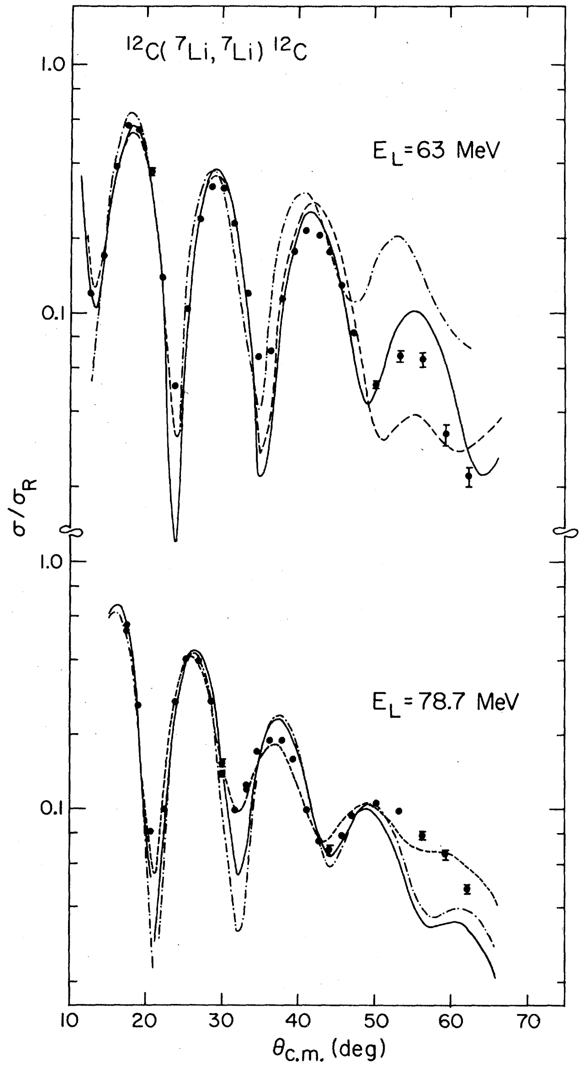

FIG. 1. Elastic scattering and the OM calculations. The solid lines are calculations using the shallow sets (I for 63 MeV and III for 78.7 MeV) and the dashed lines are the deep set (II and IV, respectively) calculations. The dash-dotted lines are, respectively, a calculation to the 63 MeV data with the 48*S* potential and the fit to the 78.7 MeV data with set V.

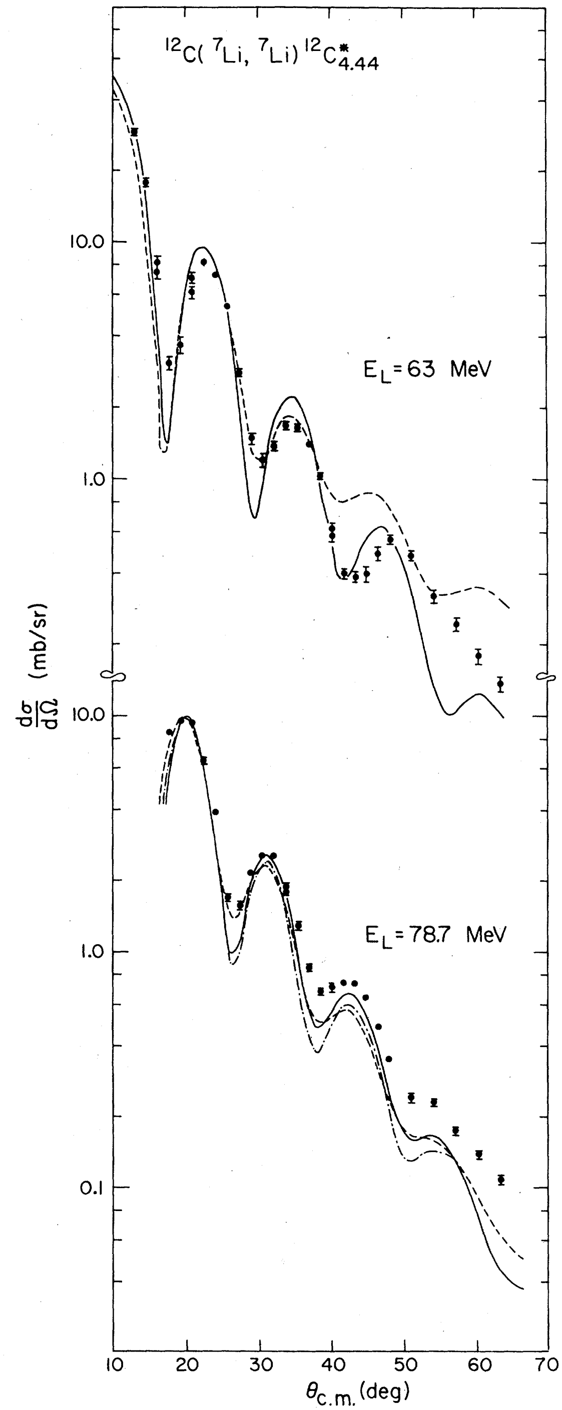

FIG. 2. Inelastic angular distributions for the $^{12}C^*$ (4.44 MeV, 2^+) state with the DWBA calculations. The curves are defined in the same way as in Fig. 1.

results of the DWBA are sensitive to the very different parameter sets labeled as deep and shallow. Of course, the results of these analyses are only reliable if we can assume a dominant single step reaction mechanism. For the two excitations discussed below, we would expect the single step mechanism to dominate.

Results of the DWBA calculations for the $^{12}C^*$ (4.44 MeV, 2^+) and the $^{7}Li^*$ (0.48 MeV, $\frac{1}{2}^-$) states are compared to the experimental data in Figs. 2 and 3. The fits to the $^{12}C^*$ data are quite good at the more forward angles, while $^{7}Li^*$ results are not good, tending to be seriously out of phase with the data. This effect has been seen previously in the ^{7}Li inelastic scattering[1,4,7] as well as for other projectile excitation[8]; at present there

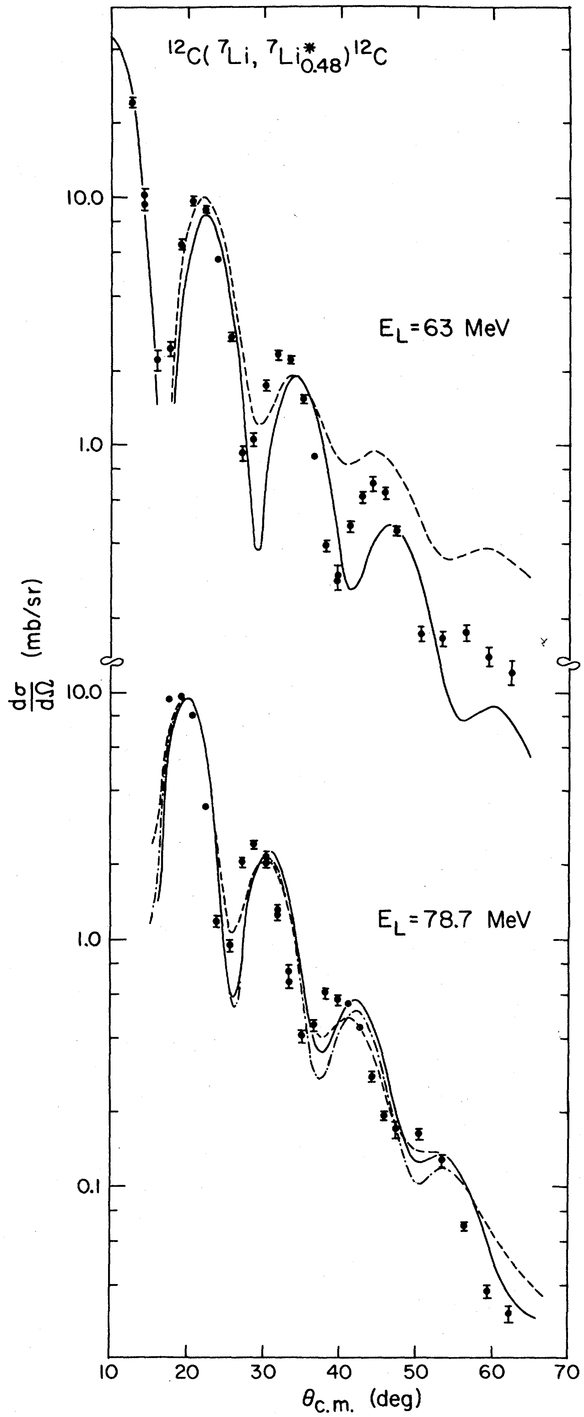

FIG. 3. Inelastic angular distributions for the $^7Li^*$ (0.48 MeV, $\frac{1}{2}^-$) state with the DWBA calculations. The curves are defined in the same way as in Fig. 1.

is no clear resolution of this problem.[9] Calculations for the $^7Li^*$ angular distribution that include Coulomb excitation have been carried out for the data obtained at 48 MeV (Ref. 4) as well as

TABLE II. Deformations and deformation lengths.

Energy (MeV)	Set	Type	$^{12}C^*$(4.44 MeV) β_2	$\beta_2 R_w$ (fm)	$^7Li^*$ (0.48 MeV) β_2	$\beta_2 R_w$ (fm)
36[a]			0.307	1.52	0.71	3.50
48[b]	48*S*	*S*	0.278	1.40	0.82	4.17
	48*D*	*D*	0.298	1.52	0.89	4.50
63	I	*S*	0.278	1.47	0.71	3.77
	II	*D*	0.264	1.44	0.77	4.18
78.7	III	*S*	0.285	1.28	0.81	3.61
	IV	*D*	0.355	1.44	0.98	4.22
	V	*S*	0.277	1.41	0.78	3.96
			($^6Li, ^6Li'$)			
34[a]			0.28	1.42		
36[a]			0.32	1.58		
36.4[c]			0.29	1.49		
40[c]			0.28	1.46		

[a] Reference 6.
[b] Reference 4.
[c] Reference 10.

for the $^{54}Fe(^7Li, ^7Li^*)\,^{54}Fe$ reaction[1]; in both cases the fits were not significantly improved. Since the grazing angle is $<4°$, any contribution from Coulomb excitation should be small over the angular range covered here.

The extracted deformations and deformation lengths are listed in Table II, along with results from other ^7Li and ($^6Li, ^6Li'$) measurements. We have included deformation parameters for $^7Li^*$ in Table II. Since the DWBA predictions do not reliably reproduce the experimental angular distributions, however, we must assign a large uncertainty to these results. We estimate the uncertainty for the $^{12}C^*$ deformation parameters to be ±15%. The values for $\beta_2 R$ found for the $^{12}C^*$ level are consistent with those found from light-ion work.[11] Because of the recurring problem found in fitting the projectile excitation data,[8,9] the values of $\beta_2 R$ for the $^7Li^*$ state listed in Table II are given only as an indication of the consistency of the calculations and not as reliable parameters. While one may question the validity of a simple DWBA analysis for large angles where inelastic channels are of comparable magnitude to the elastic channel, the small angle analysis should still be valid. Thus the poor fit obtained at backward angles is not serious.

It should also be noted that, in general, the values of β and βR_w found from the shallow potentials are more consistent than those obtained from the deep potentials, although they are all in reasonable agreement with results extracted from ^6Li inelastic scattering.

IV. CONCLUSION

The present analysis of the ^{7}Li scattering on ^{12}C shows that a single potential set does not appear to describe the data in the energy range from 48 to 78.7 MeV. Although there are some trends that favor the shallow potential set at 78.7 MeV, the ambiguity between the shallow and deep potentials cannot be completely resolved with the present elastic scattering data. The existing optical potentials do give a satisfactory fit to the experimental data in a limited angular range but by no means cover the whole angular range. In order to attack further the problem of searching for a unique potential for ^{7}Li scattering, it appears that more experimental data, including more complete angular distributions as well as higher energies, are needed.

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