Compound-nucleus contributions to ^{6}Li+ ^{12}C scattering

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Statistical compound-nucleus contributions to enhanced back-angle cross sections for ^{6}Li + ^{12}C elastic scattering and for inelastic scattering to the channels, ^{6}Li(3^+, 2.18 MeV) + ^{12}C(g.s.) and ^{6}Li(g.s.) + ^{12}C(2^+, 4.44 MeV), are studied. Differential cross sections and vector analyzing powers in the range $\Theta_{\text{c.m.}} \approx 130°-165°$ have been measured at $E_{\text{c.m.}}$ = 20 MeV by detecting recoil ^{12}C nuclei from $^6\overrightarrow{\text{Li}}$ elastic scattering and inelastic scattering to the ^{6}Li(3^+, 2.18 MeV) state. Adding a statistical compound-nucleus contribution is shown in general to reduce the magnitude, and to leave unaffected the sign, of theoretical calculations of vector analyzing powers. Analysis, including Hauser-Feshbach calculations, of the above data along with previous data indicates that compound-nucleus contributions are unimportant in the elastic and inelastic ^{6}Li(2.18 MeV) scattering channels, and are insufficient to resolve discrepancies between current coupled-channels calculations and large-angle data for inelastic ^{12}C(4.44 MeV) scattering.
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Numerous measurements [1–6] of elastic scattering between light heavy-ion systems have shown a large-angle enhancement in cross section over that expected for strongly absorbing systems. This enhancement has been attributed to either single nucleon, or cluster transfer, in cases where the difference between the projectile and target mass equals the mass of the required transferred particle. For example, ^{9}Be + ^{12}C elastic scattering [3] has a significant contribution from ^{3}He transfer at large angles. For the case of ^{6}Li + ^{12}C, not only does the elastic scattering have a larger than expected cross section at large angles, but so does the scattering to either ^{6}Li(2.18 MeV) + ^{12}C(g.s.) or ^{6}Li(g.s.) + ^{12}C(4.44 MeV). Two recent works [1,7] have suggested that the enhanced back-angle cross sections in elastic, or inelastic, scattering can be attributed to compound-nucleus contributions when the difference between the projectile and target in the system is neither a single nucleon nor a small cluster nucleus such as ^{3}He or ^{4}He.

The present work explores statistical compound-nucleus contributions to ^{6}Li + ^{12}C scattering cross sections and vector analyzing powers at 30 MeV ($E_{\text{c.m.}}$ = 20 MeV), where Kerr *et al.* [8] have recently completed a coupled-channel (CC) analysis of extensive data sets measured with both polarized and unpolarized ^{6}Li beams for the elastic channel and for two inelastic channels, ^{6}Li(3^+, 2.18 MeV) + ^{12}C(0^+, g.s.) and ^{6}Li(1^+, g.s.) + ^{12}C(2^+, 4.44 MeV). New data is presented that extends measurements of vector analyzing powers (VAP) for elastic scattering of 30 MeV $^6\overrightarrow{\text{Li}}$ on ^{12}C from the previously reported [9] largest center-of-mass angle of about 130° to 165°. Measurements of differential cross sections and VAP in this angular range are also extended to the inelastic ^{6}Li(2.18 MeV) + ^{12}C(g.s.) channel. These data were measured using an experimental system and laser-pumped ion source beam whose characteristics were the same, excepting the following details, as those reported previously in the work of Kerr *et al.* [10]. Scattered ^{6}Li particles are quite low in energy at these large angles, making particle separation of the scattered ^{6}Li from the much more prolific α particles difficult with our previously used $\Delta E-E$ detection system. Consequently, the large-angle measurements reported here were obtained by detecting the recoil ^{12}C particles at lab angles from 6.8°–24° and then applying kinematics to convert these results to the ^{6}Li + ^{12}C system. The t_{10} beam polarization was 1.06 ± 0.08. These data include energy averaging over ≈ 55 keV in the center-of-mass frame resulting from the energy spread of the ^{6}Li beam and energy losses in the self-supporting natural carbon targets of thickness 100 μg/cm^2. A typical spectrum is shown in the top half of Fig. 1. The bottom half of Fig. 1 shows the results of subtracting the scattering data with its spin down orientation from spin up. This difference is a measure of the VAP at this angle. The VAP were determined at each angle from the measured yields. Errors in the measured VAP reflect the counting statistics and, for the ^{6}Li(2.18 MeV) data, the need to subtract a continuum background that is present.

Angular distributions that include the differential cross sections and VAP measured in this work along with data from previous works [9,11–13] are shown in Fig. 2 for ^{6}Li + ^{12}C elastic scattering and for inelastic scattering leading to the ^{6}Li(3^+, 2.18 MeV) + ^{12}C(0^+, g.s.) and ^{6}Li(1^+, g.s.) + ^{12}C(2^+, 4.44 MeV) exit channels. Figure 2 also displays the results of coupled-channels (CC) calculations by Kerr *et al.* [8] for these scattering channels. The CC predictions generally agree with the differential cross sections measured for these three scattering channels except for a significant divergence in the ^{12}C(4.44 MeV) channel at center-of-mass angles greater than 60°, where the data at many angles ex-

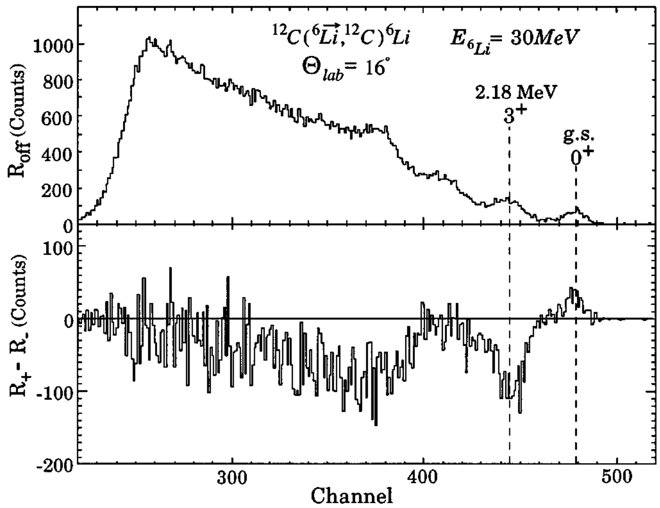

FIG. 1. Energy spectra of ^{12}C recoil nuclei detected in a single $\Delta E-E$ detector from ^{6}Li + ^{12}C scattering at $E_{\mathrm{c.m.}}$ = 20 MeV. The top spectrum was measured with an unpolarized ^{6}Li beam. The lower spectrum is the result of subtracting a spectrum measured with a spin-down orientation of the polarized ^{6}Li beam from a spin-up spectrum.

ceeds the calculated cross sections by at least an order of magnitude. Published large-angle excitation functions [14] show only small variations with energy of the inelastic ^{12}C(4.44 MeV) cross sections near $E_{\mathrm{c.m.}}$ = 20 MeV, so that the order-of-magnitude discrepancy between the data and the CC calculations cannot be attributed to a nearby resonance or fluctuation.

A Hauser-Feshbach (HF) [15] calculation has been performed in order to examine the statistical compound-nucleus contributions to the cross sections for ^{6}Li + ^{12}C scattering at $E_{\mathrm{c.m.}}$ = 20 MeV. The calculations have been performed using the computer code HELGA [16]. Decay channels leading to excitations in 10 residual pairs are included in the calculations. Excitation energies, spins, and parities of low-lying discrete levels in the heavier nucleus of each residual pair were taken from standard compilations [17]. In the continuum region, the level density has been computed from the composite level-density formula of Ref. [18] with parameters that were determined using the methods described in Ref. [19]. Transmission coefficients were determined from optical-model parameter sets [11,20–27] which have been extracted from elastic scattering data. The calculations include critical upper limits, ℓ_c = 9 for the orbital angular momentum in the entrance channel and J_c = 10 for the total angular momentum, with which the sums over transmission coefficients yield a formation cross section that equals the measured ^{6}Li + ^{12}C fusion cross section at $E_{\mathrm{c.m.}}$ = 20 MeV [28]. Cutoffs on the orbital angular momenta, in addition to those imposed by J_c, for cluster evaporation channels (ejectile mass A $\geqslant$ 3) can also be used to ensure that the sums of transmission coefficients in these channels reproduce the fusion cross sections for the time-reversed reactions [29]. We have not applied additional angular momentum cutoffs to the evaporation channels from the fusion of ^{6}Li + ^{12}C since we have determined that the changes generated by such cutoffs are comparable to the uncertainties in our HF cross sections which include the uncertainties in the level-density parameters [19] and the error introduced by using an optical-model parameter set derived from n + ^{16}O scattering [20] for the n + ^{17}F evaporation channels. The results of the HF calculations, shown in the left side panels of Fig. 2, are estimated to predict the energy-averaged compound-nucleus cross sections within a factor of 2 for the three ^{6}Li + ^{12}C exit channels. In the elastic channel, where the cross sections are well described by the CC calculations, the compound-nucleus component is predicted to be negligible at all angles except for those in the range from $\Theta_{\mathrm{c.m.}}\approx 100°$ to 110°. There its magnitude is only 10 to 20% of the measured cross sections. The compound-nucleus contribution is unimportant also to the inelastic ^{6}Li(2.18 MeV) + ^{12}C(g.s.) cross sections. The HF cross sections calculated for the ^{12}C(4.44 MeV) channel are not significant at center-of-mass angles forward of 60°. At larger angles, the HF cross sections are comparable in magnitude to those from the CC calculations, yet the incoherent sum of the two greatly underestimates the observed cross sections.

The effect of adding a Hauser-Feshbach compound-nucleus contribution to the usual direct term does not appear to be well known in the case of analyzing powers. Following the notation of Stephenson and Haeberli [30], we define analyzing powers $T_{kq}(\Theta,E)$, energy-averaged over fluctuations, by the ratio:

$$T_{kq}(\Theta,E)=\langle\sigma_{kq}(\Theta,E)\rangle/\langle\sigma_{00}(\Theta,E)\rangle \quad (1)$$

wherein

$$\langle\sigma_{kq}(\Theta,E)\rangle=\sigma_{kq}^{\mathrm{D}}+\sigma_{kq}^{\mathrm{HF}} \quad (2)$$

is an incoherent superposition of the direct (D) and compound-nucleus (HF) terms. The polarized ''cross sections'' for odd k-values have zero compound-nucleus terms. Consequently, for odd k-values and in particular, therefore, for vector analyzing powers:

$$T_{kq}=T_{kq}^{\mathrm{D}}\left(1+\frac{\sigma_{00}^{\mathrm{HF}}}{\sigma_{00}^{\mathrm{D}}}\right)^{-1} \quad (3)$$

in which T_{kq}^{D} is the analyzing power from the direct term alone (i.e., $\sigma_{kq}^{\mathrm{D}}/\sigma_{00}^{\mathrm{D}}$). For odd k values, the analyzing powers are damped by the multiplicative factor in brackets so that $|T_{kq}|\leqslant|T_{kq}^{\mathrm{D}}|$ with the equality arising only when $\sigma_{00}^{\mathrm{HF}}=0$. The observed values of T_{kq} will be vanishingly small whenever $\sigma_{00}^{\mathrm{HF}}\gg\sigma_{00}^{\mathrm{D}}$, or of course when T_{kq}^{D} vanishes. There are no correspondingly simple rules for even values of k since $\sigma_{kq}^{\mathrm{HF}}$ is not in general equal to zero for k = 2, 4, etc.

The result expressed by Eq. (3) provides an independent and complementary method for determining if the enhanced cross sections observed at large angles for ^{6}Li + ^{12}C scattering can be explained by including a statistical compound-nucleus contribution in the theory. Large and oscillatory VAP are observed in all three exit channels; see Figs. 2(b), 2(d), and 2(f). The CC calculation of Kerr *et al.* [8] predicts the sign and maximum magnitudes of the data for both the elastic and the inelastic ^{6}Li(2.18 MeV) scattering channels. In contrast, the CC prediction for the ^{12}C(4.44 MeV) channel, see Fig. 2(f), oscillates out of phase with the data in

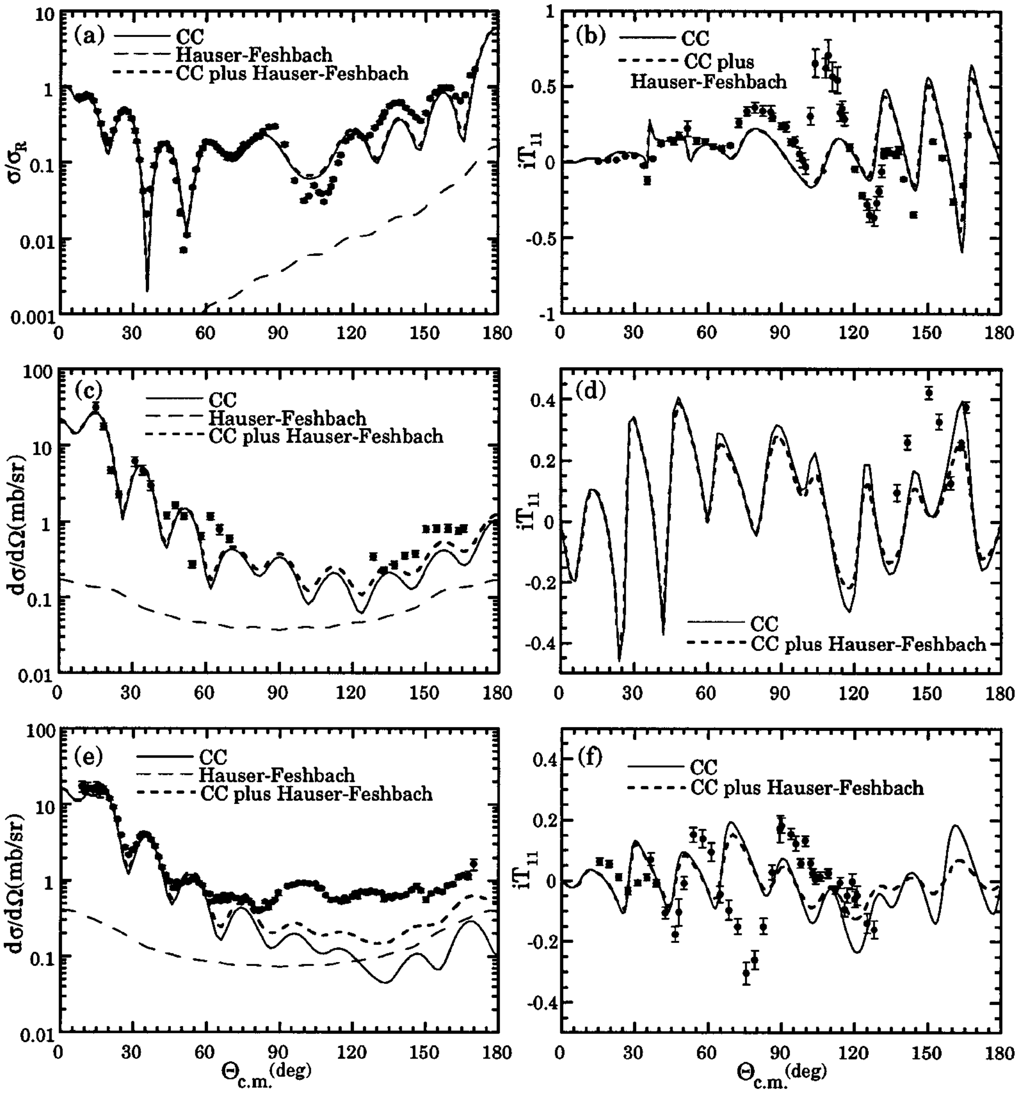

FIG. 2. Comparison of results from Hauser-Feshbach (HF) and coupled-channels (CC) calculations to differential cross sections and VAP measured for ^{6}Li + ^{12}C scattering at $E_{c.m.}$ = 20 MeV. The CC calculation results are from Ref. [8]. The incoherent sums of the CC and HF calculations are also shown. (a) Measured differential cross sections are from Ref. [11]. (b) Vector analyzing powers (VAP) for elastic scattering. The data are from Ref. [9]. (c) Differential cross sections for scattering to the ^{6}Li(3^+, 2.18 MeV) + ^{12}C(0^+, g.s.) channel. The forward-angle data are from Ref. [12]. (d) VAP for scattering to the ^{6}Li(2.18 MeV) channel. (e) Differential cross sections and (f) VAP for scattering to the ^{6}Li(1^+, g.s.) + ^{12}C(2^+, 4.44 MeV) channel. The data are from Ref. [12].

several angular regions beginning most notably at $\Theta_{c.m.} \approx 60°$, which is also where the summed CC and HF cross sections initially diverge from the enhanced differential cross sections. Adding a HF component produces a more significant reduction at large angles in the magnitudes of the oscillations of the VAP calculated for ^{12}C(4.44 MeV) scattering than for the scattering in either of the two other channels. However, the calculations for ^{12}C(4.44 MeV) scattering still predict large and positive VAP in the region from $\Theta_{c.m.} \approx 60°$ to 80°, whereas the VAP measured for this region are large and negative. Adding an even larger HF component to the calculation could improve its description of the measured cross sections, but it would not change the sign of the calculated VAP and, thus, resolve the discrepancy with the data. Consequently, a mechanism other than statistical compound-nucleus must be considered as the source of the enhanced ^{12}C(4.44 MeV) cross sections at back angles.

The large vector analyzing powers observed at back angles for $^{6}\vec{\mathrm{Li}}$ + ^{12}C elastic scattering and inelastic scattering to the ^{6}Li(2.18 MeV) + ^{12}C(g.s.) and ^{6}Li(g.s.) + ^{12}C(4.44 MeV) channels limit the magnitudes of possible statistical compound-nucleus contributions to these scattering channels. Together, this result and the Hauser-Feshbach analysis provide strong evidence that compound-nucleus contributions cannot explain the enhanced cross sections observed at large angles in these ^{6}Li + ^{12}C scattering channels.

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