Fusion calculations for the ^{6,7}Li+^{16}O systems

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Recently reported measurements of fusion for the ^{6,7}Li+^{16}O, ^{13}C, and ^{12}C systems using the characteristic γ-ray yield method were significantly larger than previous measurements for the same systems using the evaporation residue technique. The question of which set of measurements more accurately represents fusion and, indeed, the precise definition of what constitutes fusion is an important one, considering the recent interest in the question of whether fusion is inhibited or enhanced for weakly bound exotic nuclei such as ^{6}He and ^{11}Li. We present here fusion cross sections derived from continuum discretized coupled channels (CDCC) calculations using the barrier penetration model (BPM) that agree very well with the characteristic γ-ray method results.

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Recently, new measurements of fusion in the ^{6,7}Li $+^{16}$O, ^{13}C, and ^{12}C systems using the characteristic γ-ray yield method have been reported [1]. Significant discrepancies were found with previous measurements [2–5] using the evaporation residue technique. We report here calculated values of the fusion cross sections for the ^{6}Li+^{16}O and ^{7}Li $+^{16}$O systems at two lithium bombarding energies that agree very well with the γ-ray measurements [6–10]. However, the reason for the discrepancy between the two sets of measurements is still unexplained.

One might attempt to explain the difference as being due to different definitions of ''fusion.'' For light, weakly bound nuclei, like ^{6}Li and ^{7}Li, breakup is an important reaction process. Thus, the ^{6}Li or ^{7}Li may break up into its $\alpha+d$ or $\alpha+t$ constituents with just the α ''core'' going on to fuse. As the characteristic γ-ray yield method fusion cross sections are considerably larger than those obtained using the evaporation residue technique it is tempting to ascribe the difference as due to the inclusion of such ''partial fusion'' events in the γ-ray yield method results. However, a careful analysis of their data by Mukherjee and Dasmahapatra [1] appears to rule out this explanation.

An additional question concerns the similarity of the fusion cross sections for ^{6}Li and ^{7}Li. The measured fusion cross sections for ^{6,7}Li+^{12}C, ^{13}C, and ^{16}O are essentially identical, within the experimental error. This is a somewhat surprising result, given the known differences in nuclear structure between the two lithium isotopes. In this work, a simple explanation of this result is provided and implications for the study of fusion reactions of weakly bound radioactive nuclei such as ^{6}He and ^{11}Li are briefly commented on.

To obtain theoretical fusion cross sections, continuum discretized coupled channels (CDCC) calculations were carried out using the cluster-folding (CF) model for ^{6}Li and ^{7}Li. Dynamic polarization potentials (DPP's) were obtained from the CDCC calculations in the manner described by Thompson *et al.* [11]. The fusion cross sections were then obtained using the barrier penetration model (BPM), where the fusion is defined as the flux which penetrates a single barrier given by the combination of the real nuclear and Coulomb potentials and, in this case, the real nuclear potential is obtained from the ''bare'' CF optical potential plus the DPP derived from the channel couplings. This approach was utilized to obtain the fusion cross sections in order to enable the realistic inclusion of lithium breakup using the CDCC method, although it does have the disadvantage of being unable to distinguish between complete and partial fusion. However, we are unaware of any coupled-channels calculation that is able to do so unambiguously.

The CDCC calculations were performed using the code FRESCO [12]. The method used was similar to that described in Keeley and Rusek [13] and Bartosz *et al.* [14]. In ^{7}Li, couplings were included to the $1/2^{-}$ first excited state, the $7/2^{-}$ and $5/2^{-}$ resonances and the $L=0,1,3$ $\alpha-t$ continuum and in ^{6}Li to the 1^{+}, 2^{+}, and 3^{+} resonances and $L=0,1,2$ $\alpha-d$ continuum. The ^{7}Li model space was as described in Bartosz *et al.* [14], while the ^{6}Li model space was as described in Keeley and Rusek [13]. Calculations were carried out at lithium bombarding energies of 9 and 13 MeV and the results compared with the measured elastic scattering angular distributions of Poling *et al.* [15]. The coupled equations were integrated out to a radius of 30 fm for the calculations at 9 MeV and 25 fm for those at 13 MeV. In order to check the sensitivity of our results to the details of the continuum binning scheme, test calculations were carried out for both ^{6}Li and ^{7}Li where the $\alpha-d$ and $\alpha-t$ continuum bins were reduced in width from 0.25 to 0.2 fm^{-1}. The fusion cross sections were unaltered in both cases. A further test calculation for ^{7}Li where the $L=2$ $\alpha-t$ continuum was included found a negligible change in the fusion cross section, although the breakup cross section was slightly increased.

The CF model of ^{7}Li or ^{6}Li requires optical model potentials for $\alpha+$target and $t+$target or $\alpha+$target and $d+$target at 4/7 and 3/7 or 2/3 and 1/3 of the ^{7}Li or ^{6}Li bombarding energy, respectively. However, for an ^{16}O target there are few α, t, or d optical model potentials in the literature in the required energy range, thus we utilized those at the closest energies available and multiplied the real and

imaginary parts by renormalization factors that were adjusted to obtain the best fits to the ^{6,7}Li elastic scattering data. Such renormalization factors have been found to be necessary in order to fit ^{6}Li elastic scattering data for a wide range of targets and bombarding energies [16], and in a recent study of ^{7}Li+^{12}C elastic scattering [14]. However, the origin of these factors remains unclear.

For the ^{7}Li+^{16}O system, $\alpha+^{16}$O potentials are required at 5.14 and 7.43 MeV and $t+^{16}$O potentials at 3.86 and 5.57 MeV for ^{7}Li bombarding energies of 9 and 13 MeV respectively. The nearest available $\alpha+^{16}$O potential is that of Davis [17] for 10.05- MeV α particles, while the nearest available $t+^{16}$O potential is that of Pullen *et al.* [18] for 6.8-MeV tritons. These potentials were used for both calculations, with the real and imaginary renormalization factors being 0.45 and 0.7 for the 9-MeV calculation and 0.6 and 1.0 for the 13-MeV calculation.

For the ^{6}Li+^{16}O system, $\alpha+^{16}$O potentials are required at 6.0 and 8.67 MeV and $d+^{16}$O potentials at 3.0 and 4.33 MeV for ^{6}Li bombarding energies of 9 and 13 MeV, respectively. For the 9-MeV ^{6}Li+^{16}O calculation we again used the $\alpha+^{16}$O potential of Davis [17] and the $d+^{16}$O potential of Davison *et al.* [19] for 4.5-MeV deuterons. Real and imaginary renormalization factors of 0.18 and 0.4, respectively, gave the best fit to the ^{6}Li+^{16}O elastic scattering data. For the 13-MeV ^{6}Li+^{16}O calculation we used the global α potential of Avrigeanu *et al.* [20], as we were able to obtain a slightly better fit at this energy with this potential rather than that of Davis, and the $d+^{16}$O potential of Davison *et al.* The real and imaginary renormalization factors were 0.77 and 0.20 at this energy.

The calculated elastic scattering angular distributions are compared with the data in Fig. 1. The agreement with data is comparable to that of the global optical model potentials of Poling *et al.* [15]. In Table I we also give the calculated total reaction cross sections, total breakup cross sections and BPM fusion cross sections. It will be noted from Table I that while the calculated fusion cross sections at each energy are very similar for both ^{6}Li and ^{7}Li, the calculated total breakup cross sections are radically different, those for ^{7}Li being considerably smaller than those for ^{6}Li. This difference is at least partly due to ^{7}Li having a bound excited state, the 0.478-MeV$1/2^{-}$, which absorbs some of the strength that would otherwise contribute to breakup. The difference between the sum of the total breakup and BPM fusion cross sections compared to the total reaction cross section is due to absorption by channels not explicitly coupled (and simulated by the imaginary part of the CF model potential) and to the ground state reorientation of ^{6}Li or ^{7}Li (which is, however, negligible for ^{6}Li). The optical model potentials of Poling *et al.* [15] give total reaction cross sections for ^{6}Li+^{16}O and ^{7}Li+^{16}O that are essentially identical to each other at a given energy and which agree with our CF/CDCC values to within 20% or better. As may be seen from Table I, our calculations support the claim of Mukherjee and Dasmahapatra [1] that the fusion cross section is nearly equal to the total reaction cross section at the energies considered here.

In Fig. 2 we compare the BPM fusion cross sections derived from our CDCC calculations with the measured fusion

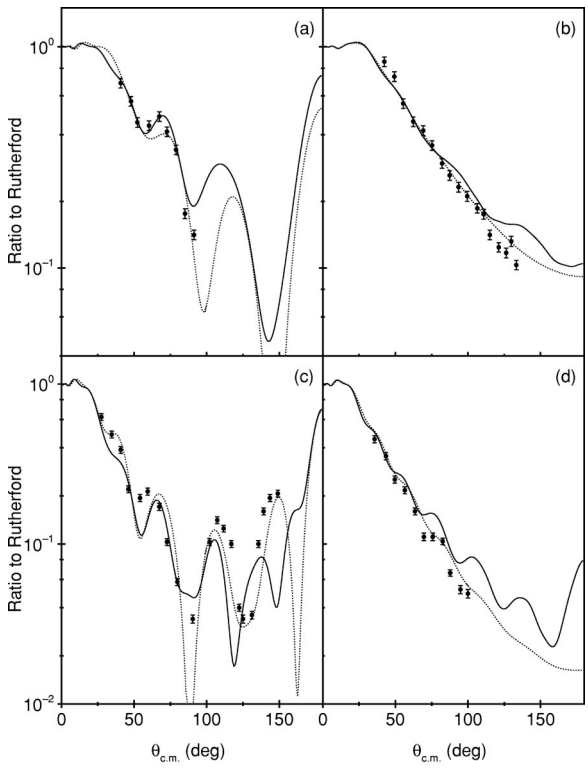

FIG. 1. Calculated elastic scattering angular distributions compared with the data for 9-MeV ^{6}Li+^{16}O (a) and ^{7}Li+^{16}O (b) and 13-MeV ^{6}Li+^{16}O (c) and ^{7}Li + ^{16}O (d). The data are taken from Poling *et al.* [15]. The full curves denote the results of our CDCC calculations, while the dotted curves denote the global optical model fits of Poling *et al.* [15].

cross sections from the γ-ray method [6–10] and the evaporation residue method [2–4]. The significant difference between the γ-ray and evaporation residue measurements noted by Mukherjee and Dasmahapatra [1] is immediately apparent (note the expanded cross section scale, which runs from 300 to 1400 mb). It will be noted from Fig. 2 that our calculated fusion cross sections agree very well with the measured values obtained from the γ-ray technique. As the calculated total breakup cross sections are small (see Table I) our results strongly suggest that the large difference between the fusion cross sections obtained from the γ-ray and evaporation residue techniques cannot be explained as being due to partial fusion—if the amount of breakup is small, partial fusion must also be small. Thus our calculations strongly support the γ-ray yield results, as we are unable to obtain a BPM

TABLE I. Calculated total reaction cross sections (σ_R), total breakup cross sections (σ_{bu}), and BPM fusion cross sections (σ_F).

Incident particle	E_{lab} (Li) (MeV)	σ_R (mb)	σ_{bu} (mb)	σ_F (mb)
^{6}Li	9	1009	39	744
^{7}Li	9	781	0.39	763
^{6}Li	13	1306	182	1050
^{7}Li	13	1186	3.6	1154

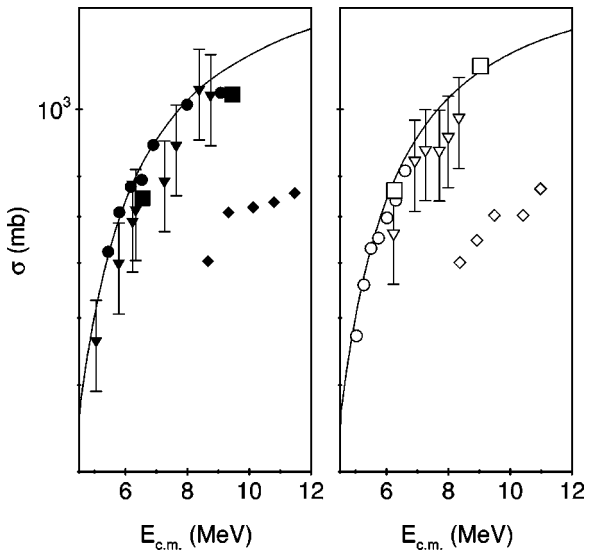

FIG. 2. Calculated and measured fusion cross sections for the ^{6}Li+^{16}O (left) and ^{7}Li+^{16}O (right) systems. The full curves denote total reaction cross sections obtained from the optical model potentials of Poling *et al.* [15]. The triangles denote the fusion cross sections obtained using the γ-ray technique from the work of Scholz *et al.* [9] for ^{6}Li+^{16}O and that of Glasner *et al.* [10] for ^{7}Li+^{16}O. The circles denote the fusion cross sections obtained using the γ-ray technique by Mukherjee *et al.* [6–8]. The diamonds denote the fusion cross sections obtained from the evaporation residue method [2–4]. Our calculated values of the fusion cross section are denoted by the squares.

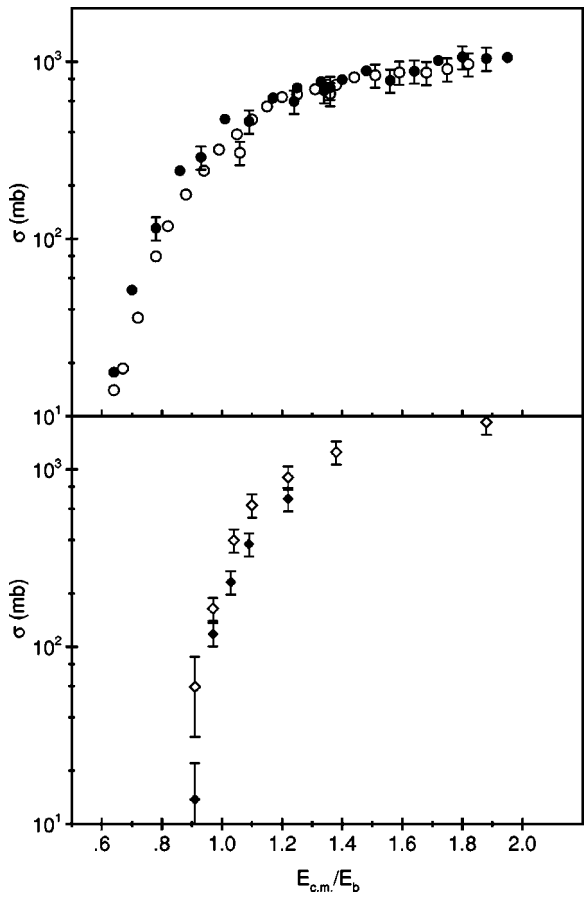

FIG. 3. Upper part: a comparison between the measured fusion cross sections for ^{6}Li+^{16}O (filled circles) and ^{7}Li+^{16}O (open circles), plotted as a function of the ratio of the center of mass energy ($E_{c.m.}$) to the Coulomb barrier energy (E_b). Lower part: a similar comparison between the BPM predictions of the fusion cross sections for ^{6}Li+^{208}Pb (filled diamonds) and ^{7}Li+^{208}Pb (open diamonds). The error bars represent either a nominal 15% error (as a typical value of an expected experimental error) or the uncertainty in the predicted fusion cross section due to the uncertainty in the real nuclear potential extracted from the optical model analysis of the elastic scattering data, whichever is the largest.

fusion cross section close to the evaporation residue measurements from a CDCC calculation that describes the corresponding elastic scattering.

However, a more interesting feature of the ^{6,7}Li+^{16}O fusion measurements is illustrated in Fig. 3. As can be seen, there is essentially no difference in the fusion cross section for the two lithium isotopes, even at the lowest energies measured. The same observation applies to the ^{6,7}Li+^{13}C and ^{6,7}Li+^{12}C fusion [1]. It is equally true of the fusion cross sections obtained from the evaporation residue measurements. This is a rather surprising result as, given that ^{6}Li is essentially spherical while ^{7}Li is considerably deformed (considered in the center of mass frame), one might have expected to observe a considerable difference in the fusion cross sections for the two isotopes, similar to that observed for the fusion of ^{16}O with ^{144,148,154}Sm where the presence or absence of deformation in the samarium target had a profound influence on the fusion cross section [21].

There is also the question of the influence of breakup on the fusion. As Table I shows, the calculated total breakup cross section for ^{6}Li is considerably larger than for ^{7}Li: the ratio $\sigma_{bu}(^6\mathrm{Li})/\sigma_{bu}(^7\mathrm{Li})$ is 100 for a lithium bombarding energy of 9 MeV and 50 for a lithium bombarding energy of 13 MeV. Test calculations have shown that the exact values of this ratio are somewhat sensitive to the details of the binning scheme used to describe the continuum, but the general result that the total breakup cross section for ^{6}Li is much larger than that for ^{7}Li remains valid [at 13 MeV, the inclusion of the $L=2$ component of the $\alpha-t$ continuum in the ^{7}Li calculation reduces the ratio $\sigma_{bu}(^6\mathrm{Li})/\sigma_{bu}(^7\mathrm{Li})$ to 20]. One might reasonably expect this very large difference in the breakup to be reflected in the fusion cross sections, but this is clearly not the case: they are virtually identical for both lithium isotopes at both energies. It could be argued that this is merely due to the fact that for these systems (^{6,7}Li+^{16}O) at the energies concerned breakup is not important (the predicted total breakup cross sections are small, much smaller than the fusion cross sections) due to the absence of significant Coulomb breakup for a light target.

However, Kelly *et al.* [22] and Signorini *et al.* [23] have measured the α yield for the ^{6,7}Li+^{208}Pb systems, where Coulomb breakup is expected to be important, and found a factor of 3–5 enhancement in yield for ^{6}Li compared to ^{7}Li for lithium bombarding energies close to the Coulomb barrier. Calculations, similar to those reported here, predicted a similar enhancement of the total breakup cross section for ^{6}Li compared to that for ^{7}Li, although the absolute magni-

tudes of the calculated total breakup cross sections were somewhat smaller than the corresponding α yields—a discrepancy that may be explained by α particles arising from processes other than breakup, in particular compound nucleus formation. Thus, although the difference in breakup is not as marked for the ^{208}Pb target as it is for ^{16}O it is still significant and one might expect to see this difference reflected in the fusion cross section if breakup has a significant influence on fusion.

Although there are at present no measurements of fusion for the ^{6,7}Li+^{208}Pb systems available we plot in Fig. 3 the BPM predictions using the optical potentials obtained from an extensive analysis of ^{6,7}Li+^{208}Pb elastic scattering [24]. Such predictions have proven remarkably accurate for the ^{16}O+^{58,62}Ni systems [25], thus we expect them to provide a reasonable estimate of the fusion for the ^{6,7}Li+^{208}Pb systems. As Fig. 3 shows, the predicted fusion for the ^{6,7}Li +^{208}Pb systems also shows very little difference for the two lithium isotopes, a remarkable result that, combined with the result for the ^{6,7}Li+^{16}O systems, suggests that differences in the importance of breakup are not reflected in the fusion cross section.

This apparent lack of influence of breakup on fusion may be explained quite simply using the barrier penetration picture. Using this model of fusion, the total fusion cross section will be the same for the two lithium isotopes if the combined barrier height (produced by adding the real parts of the bare potential and the DPP to the Coulomb potential) is the same. This is indeed found to be the case for both the ^{6,7}Li+^{16}O and ^{6,7}Li+^{208}Pb calculations (for the ^{6,7}Li +^{208}Pb calculations, the ''bare + DPP'' potential is approximated by an energy-dependent renormalization of the double-folded potential)—the barrier heights for the two lithium isotopes agree within about 5–10 %, although the ^{6}Li barriers are consistently somewhat wider than the corresponding ^{7}Li ones. While the BPM method is rather crude, it does provide a useful conceptual picture of the situation and a simple explanation of the data.

The fact that the measured fusion cross sections for ^{6,7}Li+^{16}O are very similar (essentially identical), whereas the predicted breakup cross sections are radically different has important implications for the study of the breakup of weakly bound radioactive beams such as ^{6}He and ^{11}Li. The apparent lack of difference in the fusion cross sections for ^{6,7}Li compared to the large differences in their breakup yields suggests that if one wishes to learn about the influence of the nuclear structure of weakly bound radioactive nuclei on their reaction processes one should measure the breakup yield directly rather than the fusion. Fusion is a complicated process affected by couplings to many channels (such as breakup, inelastic excitation, and transfer), making it difficult to disentangle the effect of any one process. Even for a given projectile, transfer Q values can differ radically for different targets, leading to a greater or lesser influence of a given transfer process on fusion. Our results for the stable lithium isotopes imply that nuclear structure differences that are manifest in the breakup yield for these nuclei are ''masked'' in the fusion yield by the complex interplay of these other processes.

To summarize, a recent publication [1] noted significant discrepancies between fusion cross section measurements obtained using γ-ray and evaporation residue techniques for the ^{6,7}Li+^{12}C, ^{13}C, and ^{16}O systems. We presented calculated fusion cross sections for ^{6,7}Li+^{16}O using a combination of the CDCC/CF and BPM techniques which support the γ-ray technique measurements [6–10] rather than the earlier evaporation residue measurements [2–5]. The rather surprising fact that the fusion cross sections for both lithium isotopes are very similar was investigated and possible implications of this result for the study of reactions with radioactive beams were explored.

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