Breakup and transfer processes in the $^{9}Be+^{208}Pb$ reaction

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α-Particle singles and doubles yields for the reaction of $^{9}Be+^{208}Pb$ have been measured from below to well above the fusion barrier energy. These yields have been reproduced by calculations including both neutron transfer and inelastic excitation. The calculations predict breakup cross sections to persist to very low energies, where the latter process dominates.

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I. INTRODUCTION

With the increasing use of radioactive nuclei as beams, the role of projectile breakup in nuclear reactions has become of interest. For weakly bound projectile nuclei, breakup can become a dominant reaction mode and can greatly influence the flux going into the other reaction processes. These effects have to be understood before we can reliably extract spectroscopic or structure information on nuclei produced in these exotic beam studies.

There have been a number of studies of the effect of breakup on the elastic scattering channel, in particular using ^{6}Li, ^{7}Li, and ^{9}Be projectiles [1–7]. These are the most weakly bound of the stable nuclei and have breakup thresholds similar to radioactive nuclei. These investigations showed that the real part of the optical potential required to fit the elastic scattering appears to be weaker than expected from systems where breakup does not occur.

More recently, there have been a number of studies which explore how breakup modifies the fusion yield [6–11]. The situation here is much less clear, with competing theoretical approaches predicting that fusion is hindered or enhanced [12,13]. Precision measurements for the $^{9}Be+^{208}Pb$ system showed that at energies above the fusion barrier region, there is a substantial suppression of complete fusion and large yields of incomplete fusion [8], which was attributed to breakup of the ^{9}Be projectile. For the ^{9}Be projectile, breakup can proceed through the $^{8}Be+n$ channel ($E_{\mathrm{thresh}}=1.665$ MeV) or the $^{5}He+\alpha$ channel ($E_{\mathrm{thresh}}=2.467$ MeV), but in both cases it results in the emission of two α particles and a neutron since both ^{8}Be and ^{5}He are unbound. The process of incomplete (partial) fusion involves the subsequent capture of one of the α particles, leading to the products of the element Po, as observed [8].

One experimental difficulty encountered in such studies is that transfer reactions which lead to unbound states can feed the same exit channels that result from breakup reactions. In a study of the $^{9}Be+^{209}Bi$ system, Signorini *et al.* [14] compare the experimental summed transfer and breakup yields to coupled channels predictions and find them to be a factor of 2–3 larger.

In the context of this paper, where we investigate breakup and transfer processes in the $^{9}Be+^{208}Pb$ reaction, ''breakup'' is defined as the excitation of the ^{9}Be projectile to energies above the threshold for one or more decay channels, as a result of which the projectile disassociates, ultimately leading to the production of α particles. This excitation may be mediated by Coulomb and/or nuclear forces populating either resonant states which then undergo sequential breakup, or continuum states which undergo nonresonant (direct) breakup. Since breakup can be initiated by the Coulomb force, then it can be expected to extend to energies far below the classical reaction barrier. In this work we show calculations that predict that it probably extends down to extreme sub-barrier energies and can have a major impact on the other reaction processes.

II. EXPERIMENT AND RESULTS

Breakup yields for the $^{9}Be+^{208}Pb$ system, which largely result from the ^{8}Be (g.s.)$+n$ channel, have been extracted from data taken in a previous measurement [15]. The experimental setup is described in Ref. [15] and will only be briefly outlined here. Beams of ^{9}Be from the 14UD Tandem Van de Graaff at the Australian National University were used to bombard targets of 180 $\mu g\,cm^{-2}$ $^{208}PbCl_2$ on 15 $\mu g\,cm^{-2}$ natural carbon foils. An array of telescopes using position sensitive silicon detectors enabled reaction products to be identified, and their energy and scattering angle to be recorded (to improve the angular resolution, masks with ten slots were placed in front of the telescopes). Each detector subtended $\pm 6.3°$ by $\pm 1.4°$ with respect to the center of the detector. Normalization of the yields was achieved relative to monitor detectors placed at $\pm 15°$, which recorded Rutherford scattering. Data were obtained over a sufficiently wide angular range ($25°–172°$) to allow angle integrated yields to be determined. Two contributions from breakup processes can be identified in the data, in events where a single α

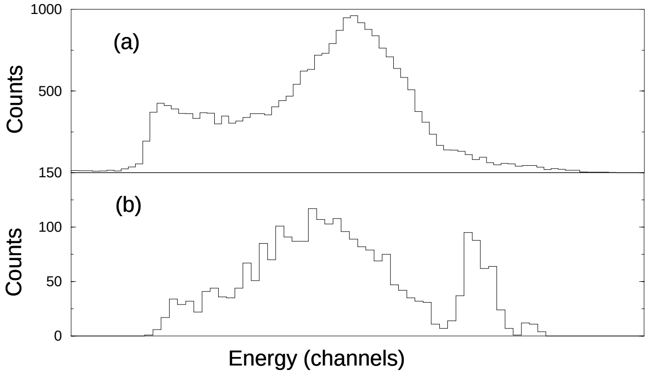

FIG. 1. Example energy distributions for (a) single-α events and (b) double-α events. The large peak in the singles data is centered at the beam velocity.

particle is detected and in events where two α particles are detected in coincidence in a single detector.

The α-singles spectrum, shown in Fig. 1(a), shows an exponential falloff consistent with an evaporation yield, probably resulting from reactions with light elements in the target, in addition to a broad peak at an energy which corresponds to the beam velocity. The αs in the peak can comprise two components, breakup of ^{9}Be and neutron transfer leading to the ^{8}Be g.s. which breaks up into two α particles. Kinematic considerations lead us to expect that the α particles produced from these processes would have energies near the beam velocity, and this includes the situation where breakup is followed by incomplete (partial) fusion, leaving a single α particle. The breakup may proceed sequentially via the excited (resonant) states of ^{9}Be or may be a direct three-body process. In addition, some αs are removed from this spectrum by breakup followed by partial fusion of one of the α particles.

The number of α-singles events was determined by subtracting off an exponentially falling background, resulting from reactions on light components of the target. It was important that this yield should be less than that obtained from ^{208}Pb to allow a reliable extraction, and this was the case for angles backward of 70°–90°. The yield of α-singles events was determined for each slit formed by the masks.

Double-α events arising from the decay of ^{8}Be can be identified in the $\Delta E-E$ spectrum from the detector telescopes where they appear as ^{7}Li events (two α particles hitting the detector simultaneously produce a combined energy loss signal similar to that which a ^{7}Li nucleus would produce). For the double-α hits, due to the low statistics, the data across the whole of the detector were taken, and the solid angle ratio adjusted accordingly. For these data the scattering angle was taken as the center of the detector. The energy spectrum for these events is shown in Fig. 1(b) and reveals three features; two peaks at high energy and a broad continuum at lower energies. Following Stahel *et al.* [16], the two peaks are attributed to neutron transfer to the ^{208}Pb target, leaving ^{9}Be in the g.s. but populating two multiplets of single-particle states in ^{209}Pb, while the broad continuum at a lower energy is attributed to breakup arising from inelastic scattering and decay to the ^{8}Be ground state.

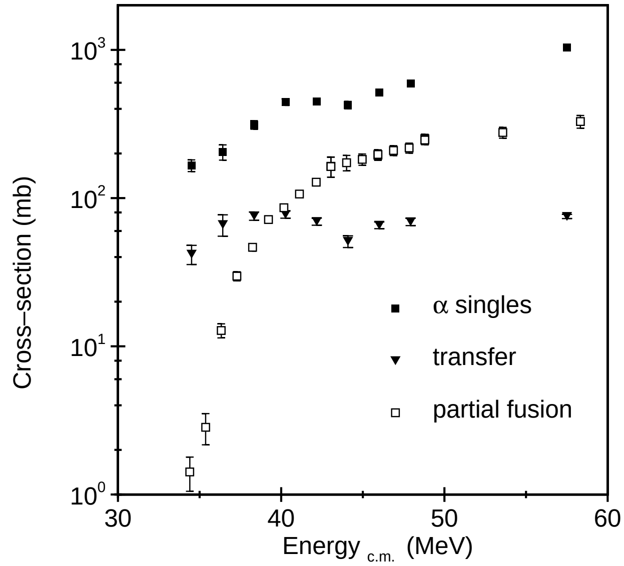

FIG. 2. Excitation functions for the α-singles cross sections (filled squares), transfer cross section (triangles), and previously measured partial fusion cross sections from Ref. [8] (open squares).

No background subtraction was necessary for the double-α hits, but these had to be adjusted for the efficiency of observing both the α particles at the same time. This was determined using a Monte Carlo simulation of the detection parameters, assuming an isotropic breakup for ^{8}Be. Separate simulations were made for each beam energy. While it is possible to extract transfer cross sections from these data by correcting for the double hit efficiency of the detectors, breakup cross sections could not be directly extracted as the breakupvia inelastic scattering (Coulomb and/or nuclear) can proceed via two possible channels, $^{9}\mathrm{Be}^{*}\rightarrow\alpha+{}^{5}\mathrm{He}$ ($\rightarrow \alpha + n$) or $^{9}\mathrm{Be}^{*} \rightarrow \mathrm{n}+{}^{8}\mathrm{Be}$ ($\rightarrow \alpha + \alpha$). Each route results in a different relative energy between the two α particles after breakup, resulting in a different geometrical efficiency for detection in a telescope. While in principle all these can occur, the spectrum will probably be dominated by the α decays from the ^{8}Be ground state, as the efficiency of detecting the products from the $\alpha+{}^{5}$He channel, or from decay of excited states of ^{8}Be, is very small. However, since the relative amounts of breakup into the various channels is unknown, these events cannot be used to calculate the breakup cross section directly [17].

As explained above, those quantities that can be determined unambiguously are the cross section for the beam velocity α-singles particles and the transfer cross section leading to the ^{8}Be ground state. For both of these yields, the differential cross sections were angle integrated to extract the total cross sections. Figure 2 shows the excitation function for the α-singles cross section (solid squares) and the transfer cross section (triangles), compared to the previously measured incomplete fusion data (open squares) [8]. The α-singles yields substantially exceed the incomplete fusion cross sections both above the barrier (measured to be at 38.3 ± 0.6 MeV [8]) and, increasingly, below the barrier. These observations are strong evidence that breakup of the

TABLE I. Parameters used in the DWBA calculations.

V_R (MeV)	R_R (fm)	a_R (fm)	W_I (MeV)	R_I (fm)	a_I (fm)	R_C (fm)	
180.25	9.114	0.6454	8.42	11.571	0.3646	9.046	
E_x (^{9}Be) (MeV)	J^π	β	ΔL ($\hbar$)	E_x (^{209}Pb) (MeV)	J^π	C^2S	ΔL ($\hbar$)
1.685	$\frac{1}{2}+$	0.114	1	1.567	$\frac{5}{2}+$	0.98	1,3
2.429	$\frac{5}{2}+$	0.217	2	2.032	$\frac{1}{2}+$	0.98	1
2.800	$\frac{1}{2}-$	0.114	2	2.491	$\frac{7}{2}+$	1.05	3,5
				2.537	$\frac{3}{2}+$	1.07	1,3

projectile, by one mechanism or another, is playing a major role in all reaction processes.

III. DISCUSSION

We can use the measured cross sections in Fig. 2 to deduce the breakup cross section σ_{breakup} in this reaction. The premise is that if we interpret the observed beam velocity α-singles cross section $\sigma_{\alpha\ \text{singles}}$ to comprise α particles from (1) breakup of the ^{9}Be into two α particles and a neutron—this could either be sequentially through excited states in ^{9}Be or directly by three-body decay, (2) neutron transfer onto ^{208}Pb followed by breakup of the ^{8}Be ejectile into two α particles, and (3) breakup of ^{9}Be followed by incomplete fusion of one of the α particles, then we can expect the following relationship:

$$\sigma_{\alpha\ \text{singles}} \approx \sigma_{\text{incomplete fusion}} + 2(\sigma_{\text{transfer}} + \sigma_{\text{breakup}}), \qquad (1)$$

where the factor of 2 reflects the fact that these processes result in two α particles in the exit channel. Since all quantities except σ_{breakup} are known at each beam energy, the excitation function for σ_{breakup} can be determined. To test this relationship, we have used distorted wave Born approximation (DWBA) calculations to model the reaction process. The calculations were carried out using the CHUCK code and included neutron transfer to the strong single-particle states in ^{209}Pb as well as inelastic excitation of ^{9}Be to the first three excited states. This projectile excitation was assumed to model the sequential breakup yield proceeding through these unbound states in ^{9}Be (but would not reflect any direct three-body breakup if this occurs). Woods-Saxon potentials extracted from fits to the elastic data measured in this experiment were used [13]. Spectroscopic factors (C^2S) for the ^{209}Pb states were obtained from a similar study by Stahel *et al.* [16]. As no experimental spectroscopic factors for the ^{9}Be states were available, these were taken as 1.0. The neutron transfer was calculated within the zero angle finite range approximation (ZAFRA) framework [18]. The deformation parameters β used for the inelastic excitations were from (α,α) scattering data [19] for the (1/2+) and (5/2+) states, and from (p,p) scattering data for the (5/2−) state [20]. There is no experimental evidence to determine the (1/2−) state deformation, so an average of the others was used for this calculation. Both Coulomb and nuclear excitations were included. Table I contains a summary of the parameters used in the calculations.

Figure 3 shows the measured transfer cross section (triangles) and the deduced breakup cross section σ_{breakup}, (squares) compared to the DWBA predictions. Given that there are no free parameters in these calculations, the agreement is excellent, giving confidence both in our interpretation of the different yields and in the accuracy of the DWBA model. The calculations do not include the direct three-body breakup of ^{9}Be. Their agreement with the deduced breakup cross sections is in agreement with the findings of Ref. [21], where the beam velocity α-particle yield at sub-barrier energies was found to be largely due to ^{9}Be ground state decay.

By extending the DWBA calculations to lower energies, we can explore how far below the barrier the breakup process extends. The dashed and dot-dashed line in Fig. 4 shows the predicted breakup and transfer yields, and the solid line

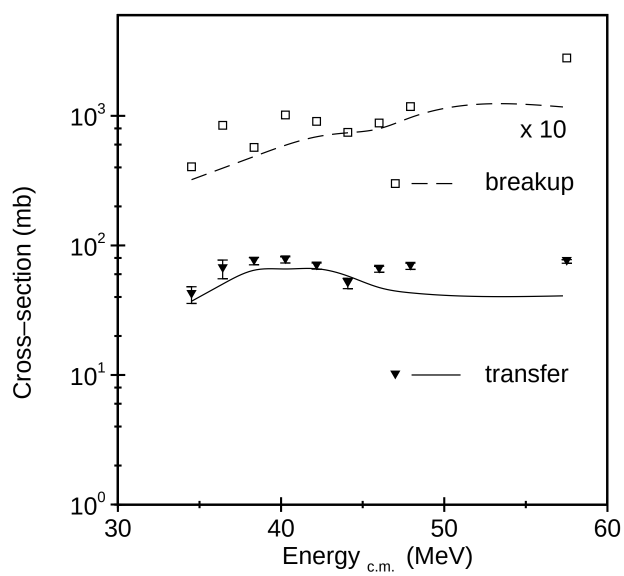

FIG. 3. The breakup (squares) and neutron transfer excitation functions (triangles). The breakup cross sections are derived using Eq. (1), details in the text. The lines are the corresponding cross sections calculated by the DWBA approach described in the text. For clarity, the breakup cross section has been multiplied by a factor of 10.

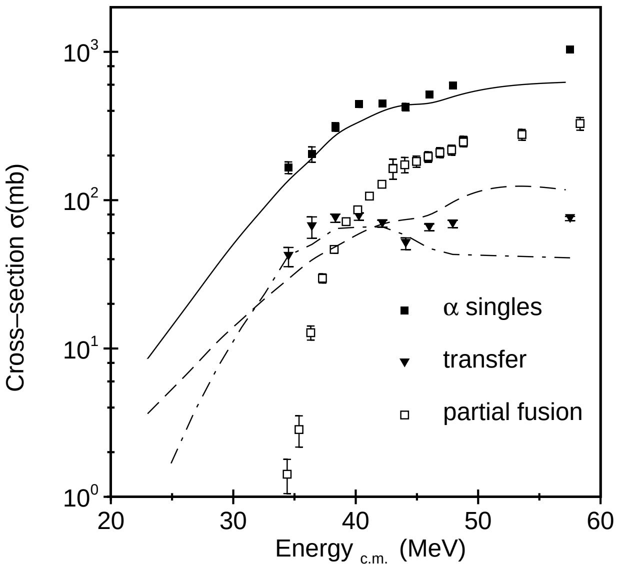

FIG. 4. Excitation functions from the DWBA calculations described in the text, (neutron transfer (dot-dashed line), and sequential breakup (dashed line), as well as the α-singles yield predicted by summing these cross sections and the incomplete fusion cross section of Ref. [8] according to Eq. (1) (solid line). Also shown are the transfer (triangles) and α-singles (filled squares) data from this measurement and the incomplete fusion data from Ref. [8] (open squares).

the result of summing these cross sections with the measured incomplete fusion cross sections as in Eq. (1). These model calculations suggest that not only does breakup occur at extreme sub-barrier energies, but there is also a large neutron transfer yield. This presumably arises because of the large spatial extension of the neutron wave function resulting from the low binding energy.

IV. SUMMARY

In summary, we have shown that with a weakly bound projectile (^{9}Be), not only is breakup a dominant feature in the reaction, but it extends down to extreme sub-barrier energies. We have also seen that the neutron transfer yield remains large below the barrier, attributed to the weakly bound neutron. Hence, to obtain reliable spectroscopic information from studies with weakly bound projectiles, all these reaction processes will need to be modeled in a full coupled reaction channel (CRC) formalism. However, our success at achieving good agreement between the total integrated yields feeding the different reaction processes using a simple DWBA calculation gives hope that more rigorous CRC calculations can successfully reproduce differential cross sections to specific states—a necessary precursor to spectroscopic work. What is now needed for such tests is a full set of exclusive data for all reaction channels, in a system where microscopic wave functions are available from which the necessary transition potentials can be calculated. A recent cluster model calculation [22] may provide this for the ^{9}Be projectile. Detailed comparison of these predictions (that breakup and transfer processes extend to extreme sub-barrier energies) with experimental measurements will further extend our understanding of breakup processes involving ^{9}Be.

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