Transfer and/or Breakup Modes in the ^{6}He + ^{209}Bi Reaction near the Coulomb Barrier

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Reaction products from the interaction of ^{6}He with ^{209}Bi have been measured at energies near the Coulomb barrier. A ^{4}He group of remarkable intensity, which dominates the total reaction cross section, has been observed. The angular distribution of the group suggests that it results primarily from a direct nuclear process. It is likely that this transfer and/or breakup channel is the doorway state that accounts for the previously observed large sub-barrier fusion enhancement in this system.

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A recent investigation of near-barrier and sub-barrier fusion of the exotic "Borromean" [1] nucleus ^{6}He on a ^{209}Bi target revealed a striking enhancement of the fusion cross section, corresponding to a 25% reduction in the nominal fusion barrier [2]. Lowering of the barrier by such an extreme amount is a general feature of theoretical predictions for fusion of the "neutron halo" nucleus ^{11}Li [3–6], due to the very extended radius of the valence neutron wave function in ^{11}Li which allows the attractive nuclear force to act at longer distances. The two-neutron separation energy for ^{6}He is considerably larger than that of ^{11}Li (0.98 MeV vs 0.30 MeV), and the valence neutrons are primarily in a $1p$ state and so experience an angular momentum barrier. As a result, the ^{6}He valence neutron wave function does not extend to as large a radius as in ^{11}Li and the remarkable suppression of the fusion barrier reported in Ref. [2] was unexpected. Its origin is investigated in more detail in this work.

A modest dynamical enhancement of the ^{11}Li fusion cross section was also obtained in some of the calculations [3,4] by coupling to the soft $E1$ mode. A similar effect undoubtedly occurs for ^{6}He but is unlikely to be the complete explanation for the observations. The role played by the projectile breakup channels, which are possibly important due to the weak binding of the valence neutrons, is considerably more controversial. Some groups [4,5] have reported that coupling to these channels reduces the fusion cross section near the barrier, while Dasso and Vitturi [6] predict only enhancement. None of these calculations include the nucleon-transfer degree of freedom. It was suggested in Ref. [2] that the observed enhancement may result from coupling to positive Q-value neutron transfer channels, leading to "neutron flow" between the projectile and target as discussed by Stelson *et al.* [7]. In this Letter, we report the results of an experiment to measure transfer and/or breakup products from the ^{6}He + ^{209}Bi reaction near to and below the barrier to shed light on the mechanism causing the strong suppression of the fusion barrier in this system.

The ^{6}He beam used in the experiment was produced by the *TwinSol* radioactive nuclear beam facility at the University of Notre Dame [8]. Two large superconducting solenoids act as thick lenses to collect and focus the secondary beam of interest onto a spot that was typically 5 mm full width at half maximum (FWHM). The primary beam was ^{7}Li at an energy of 30.5 MeV, incident on a gas target with a 2μ Havar entrance window. The cell was 2.5 cm long and contained He gas at a pressure of 1 atm to cool the exit window, a 12μ foil of ^{9}Be in which ^{6}He is produced via the ^{9}Be(^{7}Li, ^{6}He) reaction. Primary beam currents of up to 300 particle nA (pnA) resulted in a maximum ^{6}He rate of 10^5 s^{-1}. The secondary beam flux was calibrated by inserting a Si ΔE-E telescope at the secondary target position and reducing the intensity of the primary beam by 3 orders of magnitude, so that the ^{6}He particles could be directly counted while at the same time the primary beam current was measured in a Faraday cup. The secondary beam was contaminated by ions having the same magnetic rigidity as the desired ^{6}He beam. This contamination was reduced by placing an 8μ Havar foil at the crossover point between the two solenoids. Differential energy loss then helps to eliminate unwanted ions from the beam prior to the secondary target, which was a 3.2 mg/cm^2 Bi layer evaporated onto a 100 μg/cm^2 polyethylene backing. The remaining contaminant ions were identified by time-of-flight (TOF) techniques, using the time difference between the occurrence of the secondary reaction and the rf timing pulse from a beam buncher. The time resolution of better than 3 ns (FWHM) was adequate to separate ^{6}He from all contaminants, except for ^{3}H

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which has the same mass-to-charge ratio and therefore the same velocity as ^{6}He. The laboratory energy of the ^{6}He beam was 22.5 MeV for the above-barrier measurement, reduced to 19 MeV for the below-barrier measurement via energy loss in a polyethylene foil. In both cases, the energy resolution of the beam was 1.2 MeV FWHM.

The reaction events were detected with five Si ΔE-E telescopes placed at various angles on either side of the beam. Each telescope had a circular collimator that subtended a solid angle between 26–48 msr, corresponding to an effective angular resolution of 9°–11° (FWHM), computed by folding in the acceptance of the collimator with the spot size and angular divergence of the beam. A typical spectrum, taken at 22.5 MeV and an angle of 135°, is shown in Fig. 1. The elastic ^{6}He group is visible, along with ^{4}He and H isotopes. A strong, isolated group of ^{4}He ions having a mean energy about 2.5 MeV less than that of the ^{6}He elastic group is clearly visible. This spectrum is gated by TOF so scattered ^{4}He ions in the secondary beam (which have an energy 1.5 times that of ^{6}He) have been identified and removed. The ^{4}He ions at lower energy, below the isolated peak, come from reactions in the backing of the target, as determined from a separate spectrum taken with a backing foil without Bi. Also visible in Fig. 1 is a ^{3}H group, which cannot be identified on the basis of TOF. The ^{209}Bi(^{3}H, ^{4}He) reaction has a large positive Q-value and the ^{4}He ions in the isolated group might be coming from this reaction. This possibility was eliminated in a separate experiment with a ^{3}H beam of the appropriate energy (half that of ^{6}He) which showed no events in this region.

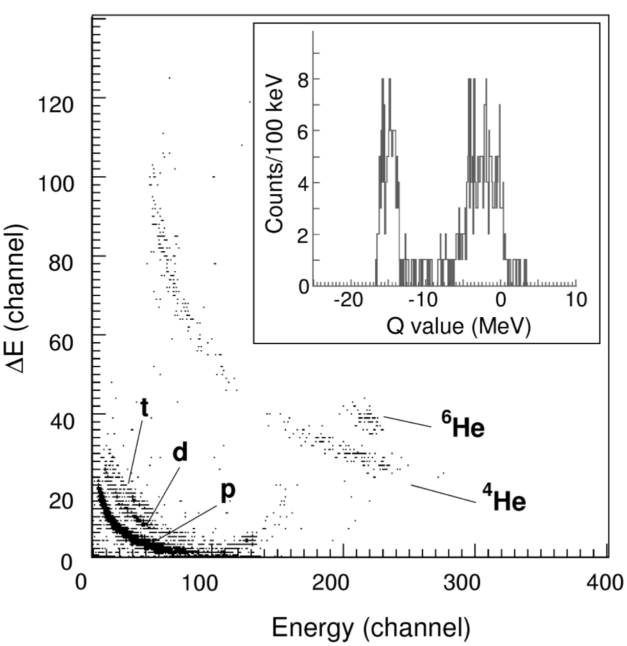

FIG. 1. A ΔE vs E_{total} spectrum taken at $\Theta_{\mathrm{lab}} = 135°$, at a laboratory ^{6}He energy of 22.5 MeV. A Q-value spectrum for the ^{4}He group is shown in the inset.

Angular distributions obtained for the isolated ^{4}He group (Fig. 2) are broad and approximately Gaussian in form, with a centroid that moves backward at lower energy (Table I). Their most striking feature, however, is the very large magnitude of the total cross section, equal to 773 mb at 22.5 MeV and 643 mb at 19 MeV. For comparison purposes, the fusion cross sections [2] measured at these energies are 310(45) and 75(17) mb, respectively. This very surprising result was confirmed by the elastic-scattering angular distributions (Fig. 3) which imply total reaction cross sections of about 1170 and 670 mb at the two energies, consistent with the sum of the fusion and ^{4}He yields within experimental error. The curves shown in Fig. 3 are obtained from optical-model fits to the data, resulting in the parameters given in Table II. The imaginary well depth was found to be about 75% greater at the lower energy. This rapid energy dependence implies that the effective imaginary potential is not well described by a Woods-Saxon form. Also shown in Fig. 3 are optical-model predictions using parameters obtained from ^{4}He scattering, but with radius parameters increased to correspond to the larger size of ^{6}He. This illustrates the expectations for elastic scattering of a "normal" nuclear system near and below the barrier. The

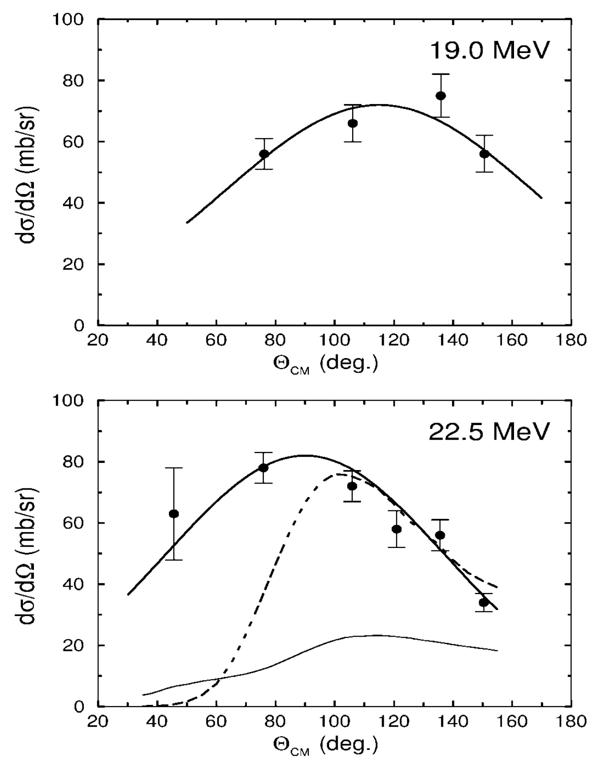

FIG. 2. Experimental angular distributions for the ^{4}He group measured in this work. The solid curves are Gaussian fits to the data, with the parameters given in Table I. The thin solid curve is the result of a direct nuclear breakup calculation. The dashed curve is a calculation of transfer to a barely bound state; the magnitude of the predicted yield has been multiplied by a factor of 10 in this case.

TABLE I. Parameters of the Gaussian fits to the data shown in Fig. 2.

E_{lab} (MeV)	Centroid (deg)	FWHM (deg)	σ_{total} (mb)
22.5	86.2 (2.5)	119.6 (5.6)	773 (31)
19.0	116.6 (5.3)	131.8 (19.7)	643 (42)

predicted total reaction cross sections are 238 and 5.2 mb, respectively.

The ^{4}He group seen in this experiment dominates the total reaction cross section near the barrier, so it is important to determine the reaction mechanism that accounts for its very large yield. Unfortunately, neutron transfer cannot be separated from breakup modes using only the present data. Based on the absence of events in the appropriate energy region, two-nucleon transfer to the ground state of ^{211}Bi ($Q = +8.8$ MeV) is unimportant. This agrees with a finite-range DWBA calculation for dineutron transfer; the predicted maximum yield was less than 0.1 mb/sr. Here and in the other calculations reported below (i) the two neutrons were coupled to a relative s state and their motion relative to both ^{4}He and ^{209}Bi has $\ell = 0$, (ii) the incoming and outgoing distorted waves were defined by the optical-model parameters given in Table II, and (iii) the code FRESCO [9] was used and the transfer operator included the remnant term.

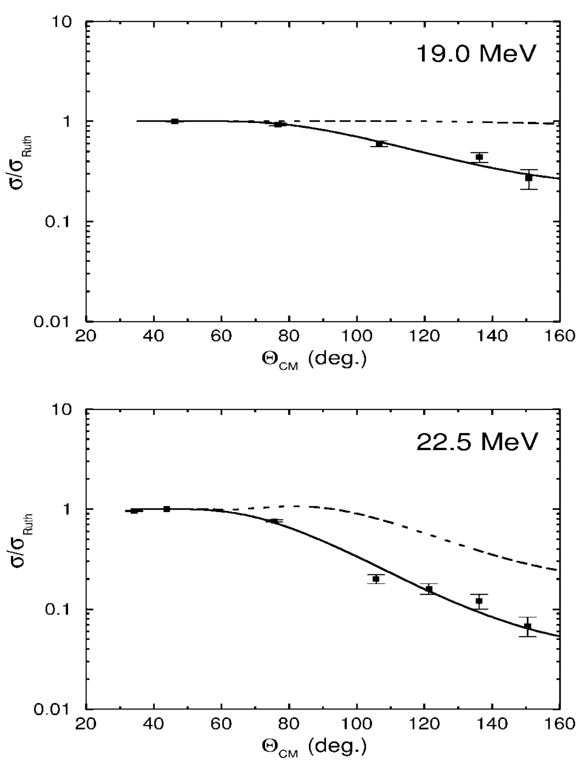

FIG. 3. The experimental elastic-scattering angular distributions. The ratio to the Rutherford cross section is compared with optical-model fits (solid curves), which yield the parameters given in Table II. The dashed curves are calculations made with potentials appropriate for ^{4}He + ^{209}Bi [14], but with a radius appropriate for ^{6}He. The total reaction cross section computed with this potential at 19.0 MeV is 5.2 mb. Reaction cross sections corresponding to the other curves are given in Table II.

TABLE II. Optical-model parameters used in the calculations shown in Fig. 3. The third row gives a potential determined for ^{4}He + ^{209}Bi at an incident energy of 22.0 MeV [14]. In each case, the Coulomb radius was taken to be 7.12 fm.

E_{lab} (MeV)	V (MeV)	R (fm)	a (fm)	W (MeV)	R_I (fm)	a_I (fm)	σ_{reac} (mb)
22.5	150.0	7.96	0.68	27.8[a]	9.38	0.99	1167
19.0	150.0	7.96	0.68	47.8[a]	9.38	0.99	668
22.5	100.4	8.57	0.54	44.3[b]	7.12	0.40	238

[a]Volume imaginary potential.
[b]Surface imaginary potential.

Single neutron transfer followed by breakup of the remaining unstable ^{5}He has a very different Q-value, as does direct breakup into ^{4}He plus two neutrons. However, outgoing ^{4}He ions resulting from either of these mechanisms could be accelerated by the Coulomb field of the target to approximately the energy of the observed group, so neither process can be eliminated based on energy considerations. We will return to this point.

The experimental angular distributions do reveal some information about the reaction mechanism. The sideward peaking, and the fact that the maximum of the distribution shifts to a larger angle at lower energy, argues for a nuclear process. The result of a coupled-channels calculation of direct nuclear breakup at 22.5 MeV is illustrated by the thin solid line in Fig. 2. In this calculation, the NN-α interaction was adjusted to reproduce the features of the known ^{6}He resonance [10]; the continuum was included up to 4 MeV above threshold using the coupled discretized continuum channels (CDCC) method [11]. The predicted maximum yield is too small by a factor of 4, and the angular distribution is somewhat broader than observed. Part of the discrepancy at forward angles might be due to the contribution from Coulomb breakup. Breakup calculations including the Coulomb term are much more difficult to perform because of the very long range of the couplings, and full convergence has not yet been attained.

Another possibility is transfer to excited states in ^{211}Bi. We first assumed $\ell = 0$ transfer of a dineutron to a state having a binding energy of 0.1 MeV. The calculated angular distribution is shown as the dashed line in Fig. 2. The absolute yield is much too small; the theoretical prediction in Fig. 2 has been multiplied by a factor of 10. The result of a preliminary nucleon-transfer calculation including continuum states is more encouraging. In this CDCC calculation, the valence neutron pair in ^{6}He was transferred into a range of unbound states in ^{211}Bi, up to 8 MeV above threshold. All couplings between these states and the ^{209}Bi ground state were included, and the interaction in the ^{211}Bi continuum was assumed to be the same as that which binds the dineutron in the ground state. This is the best that can be done given the lack of knowledge of the structure of ^{211}Bi at high excitation. Under these conditions, the wave function of the valence dineutron is very extended, as there are no Coulomb or angular momentum barriers to be overcome. Since the favored "Q-window" for neutron transfer is at $Q \simeq 0$, close to the observed maximum in the experimental yield, the reaction also gains a kinematic enhancement. As a result, the predicted cross section is very large, comparable to the experimental yield, and the angular distribution is characteristic of a nuclear process and appears very similar to the dashed curve in Fig. 2. In addition, coupling to the fusion channel is included consistently, and the calculation predicts an enhancement in sub-barrier fusion which is comparable to our previous measurement [2].

It is also possible that single neutron transfer followed by breakup of ^{5}He could occur. The ^{4}He residue would then be Coulomb accelerated as discussed above. The states near the Fermi surface all have high angular momentum, though, so the transfer might be suppressed by an angular momentum barrier. In any event, this calculation has not yet been attempted. Clearly, more theoretical work remains to be done before the origin of the very strong ^{4}He group is understood in any detail.

As to the speculation [2] regarding neutron flow, the observed Q-value spectrum conclusively shows that ground-state transfer is unimportant. However, the positive Q-value does play a role in making the continuum states in ^{211}Bi accessible within the preferred Q-window. The transfer to these unbound states could be described as neutron flow, though transfer and/or breakup seems more appropriate under the circumstances. Nevertheless, the preliminary CDCC calculations do show that coupling to the transfer and/or breakup channels has the potential to explain the large sub-barrier fusion enhancement seen in the ^{6}He + ^{209}Bi system. Apparently it is the strength of the transfer channel and not the positive Q-value *per se* that determines the enhancement, in agreement with the conclusions of Henning *et al.* [12] for normal nuclei.

In conclusion, we have for the first time measured near-barrier and sub-barrier transfer and/or breakup yields for an exotic Borromean nucleus, ^{6}He, on a ^{209}Bi target. An isolated ^{4}He group was observed at an effective Q-value of approximately -2.5 MeV. The integrated cross section for this group is exceptionally large, greatly exceeding the fusion yield both above and below the barrier. Simultaneously measured elastic-scattering angular distributions require total reaction cross sections that confirm this large yield. Preliminary coupled-channels calculations suggest that the reaction mechanisms can best be described by direct breakup and neutron transfer to unbound states in ^{211}Bi. The latter process is enhanced by the large radial extent of the wave function of the unbound states, leading to excellent overlap with the weakly bound valence neutron orbitals of ^{6}He. It also experiences a kinematic enhancement due to the fact that the large positive ground-state Q value for transfer makes the neutron unbound states accessible within the optimum Q-window. The resulting mechanism bears some resemblance to neutron flow [7], and to the "neutron avalanche" discussed by Fukunishi *et al.* [13]. Finally, the calculations also predict an enhancement in the sub-barrier fusion yield due to coupling to the transfer and/or breakup channel, which strongly suggests that this is the "doorway state" that accounts for the remarkable suppression of the fusion barrier [2] in this system.

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