Eur. Phys. J. A **13**, 117–121 (2002)

THE EUROPEAN PHYSICAL JOURNAL A

Transfer, breakup, and fusion reactions of ^{6}He with ^{209}Bi near the Coulomb barrier

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Received: 1 May 2001 / Revised version: 31 August 2001

Abstract. The fusion of ^{6}He with a ^{209}Bi target displays a large enhancement at energies near to and below the Coulomb barrier. Recently, a ^{4}He group of remarkable intensity, which dominates the total reaction cross-section, has also been observed in the near-barrier interaction of the same system. It is argued that this transfer/breakup channel acts as a doorway state to fusion.

PACS. 25.60.-t Reactions induced by unstable nuclei – 25.60.Bx Elastic scattering – 25.60.Dz Interaction and reaction cross sections – 25.60.Gc Breakup and momentum distributions

1 Introduction

Theoretical studies of near-barrier and sub-barrier fusion of the exotic "neutron halo" nucleus ^{11}Li [1–5] have generated a considerable amount of interest and controversy. This system contains two valence neutrons that are only very weakly coupled to a relatively tightly bound ^{9}Li core, and neither the n-^{9}Li nor the n-n subsystems are bound. As a result, the particle stability of ^{11}Li is achieved only via three-body interactions. Systems of this kind, referred to as "Borromean" nuclei [6], provide an unusual opportunity to study three-body forces in the nucleus.

It has been known for some time that sub-barrier fusion of stable nuclei can be enhanced by several orders of magnitude beyond expectations from simple one-dimensional barrier penetration calculations due to couplings to internal degrees of freedom of the target and projectile [7]. This dynamical effect is a very sensitive probe of the nuclear structure of the colliding partners, which was the rationale for the studies mentioned above. Strong sub-barrier fusion enhancement, resulting in a lowering of the effective barrier by 20% or more, is a general feature of all these calculations. The role played by projectile breakup channels, which are important due to the weak binding of the valence neutrons, has generated the controversy. Several groups [2–4] have reported that coupling to breakup channels reduces the fusion cross-section near the barrier, leading to an intriguing structure in the excitation function in this region. These calculations have been criticized by Dasso and Vitturi [5], who report only the enhancement of the fusion yield, even in the presence of strong breakup channels.

Unfortunately, experimental studies of ^{11}Li fusion near the Coulomb barrier are not possible at present, due to the low flux and poor energy resolution of the available beams at these low energies. However, the ^{6}He nucleus, with two weakly bound neutrons around a ^{4}He core, is the simplest of the Borromean nuclei and its fusion with ^{209}Bi near the barrier has been studied [8]. Despite the weak binding of the valence neutrons, little evidence was found for suppression of fusion due to projectile breakup, but a large enhancement of sub-barrier fusion was observed. (This result has recently been confirmed in a study of ^{6}He $+^{238}$ U fusion [9].) The fusion data [8] are shown in fig. 1 in comparison with a number of different models that are appropriate for the fusion of normal nuclear systems. First (dot-dashed curve), the highest-energy points were fit to a straight line on a $1/E_{\rm cm}$ plot to determine the fusion barrier height and radius (see, *e.g.*, Gupta and Kailas [10]). A PACE prediction [11] for the total fusion cross-section is the dashed curve in fig. 1, and the dotted curve is an (uncoupled) calculation using the code CCFUS [12]. None of these models provides an adequate representation of the behavior of the experimental data below the barrier, which are strongly enhanced relative to these simple estimates that do not incorporate mechanisms for sub-barrier fusion enhancement. However, the solid curve in fig. 1, which fits the data very well, was generated in the Stelson model [13]. In this model, a distribution of barriers with uniform weight extending from some threshold energy T to $2B$-T (where B is the nominal barrier) is introduced. The "threshold barrier" deduced from the fit (fig. 1) implies a 5 MeV lowering of the barrier, which is the largest such shift that has been observed as a percentage of the nominal barrier energy (25%). Stelson *et al.* have shown that the threshold barrier T correlates with neutron binding energies (not collective properties of the participating nuclei), as would be expected if the fusion cross-section in the near sub-barrier region reflects a neck formation

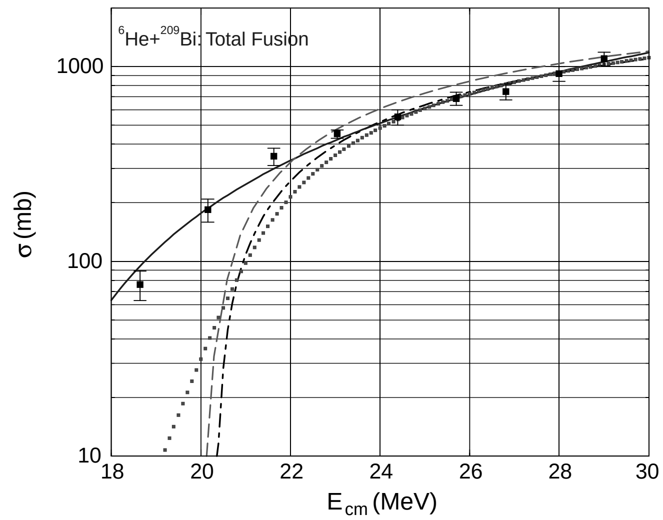

Fig. 1. Total cross-section for $^{6}\mathrm{He} + {}^{209}\mathrm{Bi}$ fusion. The dashed curve is a PACE prediction for the total fusion cross-section, the dot-dashed curve is the result of a least-squares fit to the high-energy data on a $1/E_{\mathrm{cm}}$ plot, and the dotted curve is an uncoupled CCFUS calculation. The solid curve was generated in the Stelson model (see text).

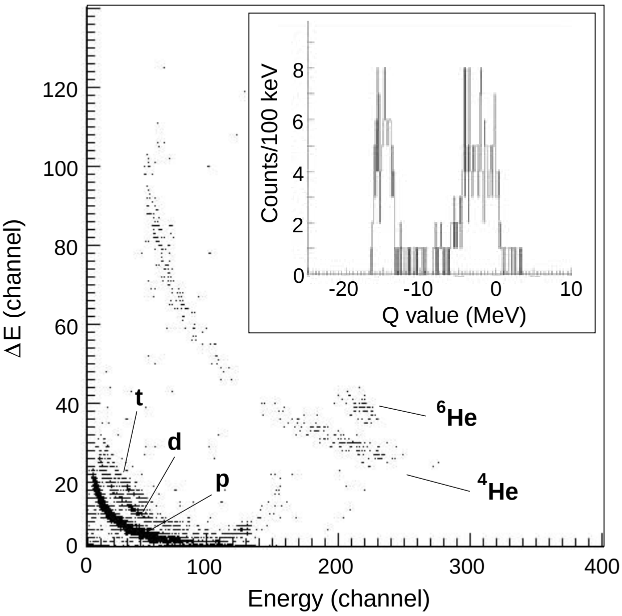

Fig. 2. A ΔE *vs.* E_{total} spectrum taken at $\Theta_{\mathrm{lab}} = 135°$, at a cm ^{6}He energy of 21.4 MeV. A Q-value spectrum for the ^{4}He group is shown in the inset.

promoted by the "neutron flow" [13]. We, therefore, speculated [8] that the explanation for the observed very large enhancement in the sub-barrier fusion cross-section might lie in the neutron transfer channels of the $^{6}\mathrm{He} + {}^{209}\mathrm{Bi}$ system. In this paper, I will discuss the results of an experiment that was undertaken to test this speculation.

2 Experimental setup and results

The ^{6}He beam used in the experiment was produced by the *TwinSol* radioactive nuclear beam facility at the University of Notre Dame [14], developed in collaboration with the University of Michigan. Two large superconducting solenoids act as thick lenses to collect and focus the secondary beam of interest onto a spot that is typically 5 mm full width at half maximum (FWHM). In this experiment, a maximum ^{6}He rate of 10^{5} s^{-1} was produced. The secondary beam was contaminated by ions having the same magnetic rigidity as the desired ^{6}He beam, which was reduced by placing an absorber foil at a crossover point between the two solenoids to eliminate unwanted ions from the beam via differential energy loss. 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 secondary target was a 3.2 mg/cm^{2} Bi layer evaporated onto a 100 μg/cm^{2} polyethylene backing. The reaction events were detected with five Si ΔE-E telescopes placed at various angles on either side of the beam. Each telescope had an effective angular resolution of between 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 21.4 MeV and an angle of 135°, is shown in fig. 2. 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. 2 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, but this possibility was eliminated in a separate experiment with a ^{3}H beam of the appropriate energy, which showed no events in this region. Angular distributions obtained for the isolated ^{4}He group are broad and approximately Gaussian in the form, with a centroid that moves backward at a lower energy as expected for a predominantly nuclear process. A striking feature of these data is the very large magnitude of the total cross-section, equal to 773 mb at 21.4 MeV. For comparison purposes, the fusion cross-section [8] measured at this energy is only 280(50) mb. This very surprising result was confirmed by the elastic-scattering angular distribution which implied a total reaction cross-section of about 1065 mb, consistent with the sum of the fusion and ^{4}He yields within experimental error. See ref. [15] for a more extensive discussion of this experiment.

Very recently, an excitation function for the ^{4}He group was measured over the cm energy range from 14.3–21.4 MeV. Figure 3 illustrates the total reaction cross-section for $^{6}\mathrm{He} + {}^{209}\mathrm{Bi}$, taken as the sum of the

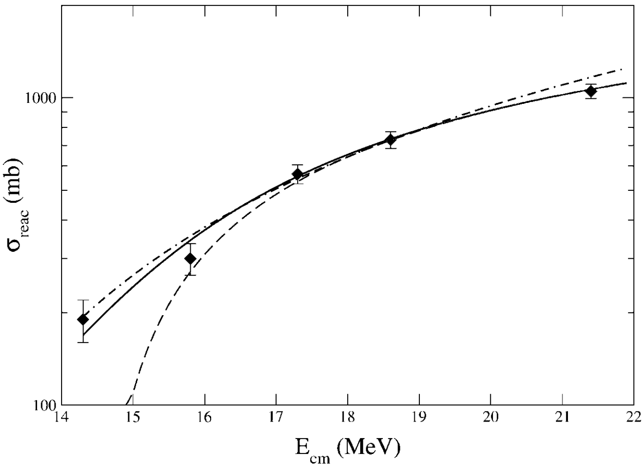

Fig. 3. Total reaction cross-section for ^{6}He + ^{209}Bi.

fusion cross-section plus the cross-section for producing the ^{4}He group. The fusion cross-section is negligible at the lowest three energies. As discussed in ref. [8], the nominal barrier for the ^{6}He + ^{209}Bi system is approximately 20 MeV, so the lowest-energy data in fig. 3 were taken at nearly 6 MeV below the barrier. Nevertheless, the total reaction cross-section at this energy is a remarkable 200 mb! The dashed curve in fig. 3 was generated by fitting the highest-energy points to a straight line on a $1/E_{\mathrm{cm}}$ plot to determine the "barrier height", as discussed above. Since it is the reaction cross-section, not the fusion cross-section, that is being fit, this procedure does not yield a fusion barrier. However, the "effective barrier" of 14.5 MeV extracted in this way is reasonably consistent with the "threshold barrier" of 15.4 MeV deduced from the Stelson-model fit to the fusion data [8]. This suggests a tight correlation between the reaction mechanism producing the ^{4}He group and the very strong sub-barrier fusion enhancement observed for this system [8]. The dot-dashed curve in fig. 3 is a Stelson-model fit to the reaction data which was computed in an attempt to place bounds on the extrapolation of the data to lower energies. It appears that the extrapolated reaction cross-section at 10 MeV (half the barrier height!) is between 1 and 10 mb. It will certainly be very interesting to extend the measurements to these very low energies to study transfer/breakup processes in the far sub-barrier regime.

As in ref. [15], we also measured the elastic scattering of ^{6}He during this experiment. The results are shown in fig. 4. Note that the 18.6 MeV point from ref. [15] was repeated and both data sets are shown as an illustration of the consistency of the results. The curves in this figure are the result of an optical-model fit to the data. The parameters of the fit are discussed in more detail below. However, the total reaction cross-section predicted by the optical model is shown as the solid curve in fig. 3. Thus, the same parameters that fit the elastic data also generate a reaction cross-section in agreement with the experiment. This is an important verification of the very large reaction cross-sections that have been measured since it suggests,

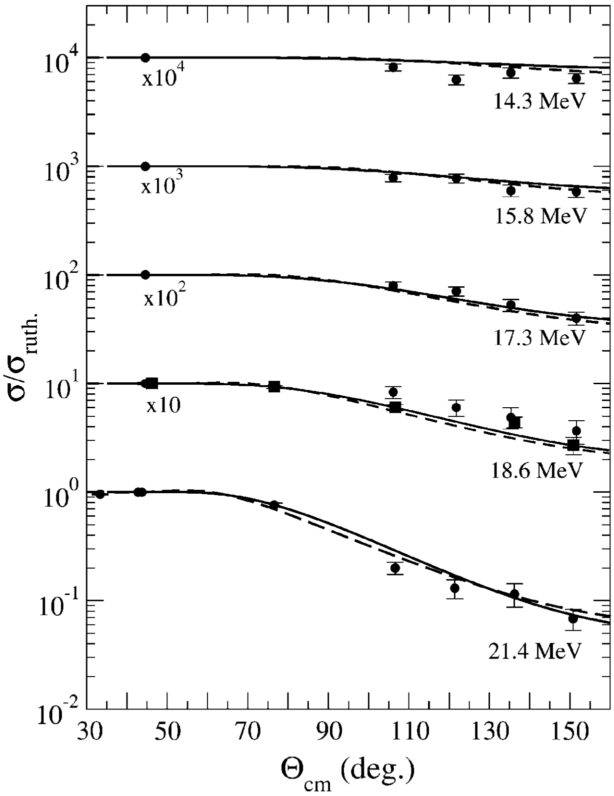

Fig. 4. Elastic scattering of ^{6}He + ^{209}Bi at the cm energies shown.

for example, that the absolute normalization of the reaction data has been properly computed.

The optical-model parameters that we have used are purely phenomenological. It was found to be necessary and sufficient to vary only one parameter: the imaginary diffuseness. Equivalent fits can be generated by varying the imaginary radius parameter instead, but not the imaginary well depth unless an exceptionally strong variation in this parameter, far stronger than the variation found by Signorini *et al.* in their study of ^{9}Be + ^{209}Bi elastic scattering [16], is deemed to be acceptable. The predicted angular distributions are not very sensitive to the parameters of the real potential, consistent with the observation that the ^{6}He + ^{209}Bi system is dominated by absorption from the elastic channel. The well-depth, radius, and diffuseness parameters of the empirical real Woods-Saxon potential were 150 MeV, 7.95 fm, and 0.68 fm, respectively. The depth and radius of the empirical volume Woods-Saxon imaginary potential were 25 MeV and 9.38 fm, respectively. Finally, the imaginary diffuseness was given by: $(1.964 - 0.045 * E_{\mathrm{cm}})$ fm.

3 Discussion

The ^{4}He group seen in this experiment dominates the total reaction cross-section near to and below the barrier, so it is important to determine the reaction mechanism that accounts for its very large yield. Unfortunately,

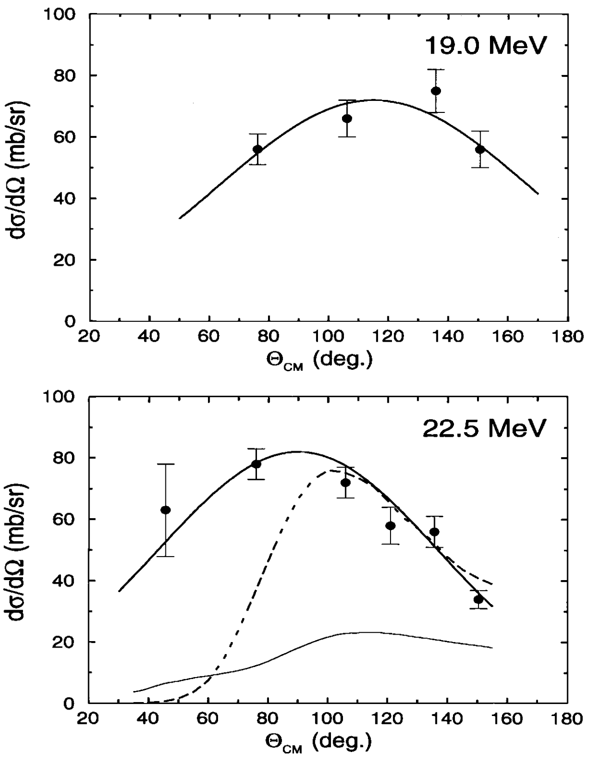

Fig. 5. Angular distributions for the ^{4}He group taken from ref. [15]. See text for a discussion of the curves.

neutron transfer cannot be separated from breakup modes using only the present data, since the fate of the neutron(s) is unknown. Based on the absence of events in the appropriate energy region (fig. 2), two-nucleon transfer to the ground state of ^{209}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 (see ref. [15]). 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 perhaps be accelerated by the Coulomb field of the target to approximately the energy of the observed group, so neither process can be eliminated based solely on energy considerations.

As discussed in ref. [15], the angular distribution of the ^{4}He group reveals some information about the reaction mechanism. The sideward peaking at the barrier, and the fact that the maximum of the distribution shifts to a larger angle at lower energy, suggests a nuclear process. The result of a coupled-channels calculation of direct nuclear breakup at 22.5 MeV is shown as the thin solid line in fig. 5. The predicted cross-section is too small, and the angular distribution peaks at too large an angle. However, part of this discrepancy may be due to the neglect of Coulomb breakup, which is certainly strong in this system. Unfortunately, breakup calculations including the Coulomb term are much more difficult to carry out because of the long range of the couplings and a fully converged solution has yet to be obtained. Another possibility is the neutron transfer to states of ^{211}Bi. The result of a preliminary transfer calculation (including continuum states; see ref. [15]) is encouraging. In this calculation, based on the Q-value spectrum shown in fig. 2, the valence neutron pair in ^{6}He was transferred into a range of unbound states in ^{211}Bi up to 8 MeV above the threshold. Under these conditions, the wave function of the valence di-neutron is very extended, as there are no Coulomb or angular momentum barriers to overcome. Since the favored "Q-window" for neutron transfer is at $Q \simeq 0$, the reaction is also kinematically enhanced. As a result, the predicted cross-section is comparable to the experimental yield, and the angular distribution is characteristic of a nuclear process and appears similar in both magnitude and shape to the dashed curve in fig. 5. Furthermore, coupling to the fusion channel was included in the calculation, and it predicts an enhancement in the sub-barrier fusion comparable to that observed. However, this is still a schematic calculation since the properties of unbound ^{211}Bi states are unknown and have only been inferred from the standard shell model.

As to speculations regarding the "neutron flow", the observed Q-value spectrum implies that the ground-state transfer, with its high positive Q-value, is unimportant. The positive Q-value does play a role, however, in making the continuum states in ^{211}Bi accessible within the preferred Q window.

In conclusion, we have measured for the first time near-barrier and sub-barrier transfer/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 greatly exceeds the fusion yield both at 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 a direct breakup together with the 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, and 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 transfer mechanism bears some resemblance to the "neutron flow" as discussed by Stelson *et al.* [13]. Finally, the calculations also predict an enhancement in the sub-barrier fusion yield due to the coupling to the transfer/breakup channel, which strongly suggests that this is the "doorway state" that accounts for the remarkable reduction in the fusion barrier observed [8] in this system.

This work was supported in part by the U.S. National Science Foundation under Grant No. PHY99-01133. The experiments were carried out in collaboration with groups from the University of Michigan (led by F.D. Becchetti), Hope College in Holland, MI (led by P.A. DeYoung) and ININ-Mexico (led by

E.F. Aguilera). The coupled-channels calculations were carried out by F. Nunes of the Universidade Fernando Pessoa in Porto, Portugal. Participants at Notre Dame include V. Guimarães, G. Rogachev, D. Peterson, and P. Santi.

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