Transfer/Breakup Modes in the $^6$He + $^{209}$Bi Reaction Near and Below the Coulomb Barrier

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(March 30, 2022)

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/breakup channel is the doorway state that accounts for the previously observed large sub-barrier fusion enhancement in this system.

PACS Numbers: 25.60.-t, 25.60.Gc, 25.60.Je, 27.20.+n

A recent investigation of near-barrier and sub-barrier fusion of the exotic “Borromean” $^6$He nucleus 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, in fact, a general feature of theoretical predictions for the fusion of the “neutron halo” nucleus $^{11}$Li [3,4]. However, the leading effect in these calculations is purely static and results from 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 rather than a $2s$ state and so experience an angular momentum barrier. For these reasons, the $^6$He valence neutron wave function does not extend to as large a radius as in $^{11}$Li. The remarkable suppression of the fusion barrier reported in Ref. [2] was therefore somewhat unexpected. Its origin is investigated in more detail in this work.

In addition to the static effect, a modest dynamical enhancement of the $^{11}$Li fusion cross section was 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. Several groups [4,5] have reported that coupling to these channels reduces the fusion cross section near the barrier, while Dasso and Vitturi [7] predict only enhancement even in the presence of very strong projectile breakup. Finally, as pointed out in Ref. [2], none of the existing calculations include the nucleon-transfer degree of freedom. It was suggested there 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. [8]. In this work, we report the results of an experiment to measure transfer and/or breakup products from the $^6$He + $^{209}$Bi reaction near 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 (RNB) facility at the University of Notre Dame [1]. 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). In this work, the primary beam was $^7$Li at an energy of 30.5 MeV, incident on a gas target with a 2µm Havar entrance window. The cell was 2.5 cm long and contained He gas at a pressure of 1 atm. The purpose of the gas was 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) proton transfer reaction. Primary beam currents of up to 300 particle nA (pnA) were available, resulting in a maximum $^6$He rate of $10^5$ s$^{-1}$. The secondary beam flux was calibrated by inserting a Si ∆E-E telescope at the secondary target position and reducing the intensity of the primary beam by three 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 on an event-by-event basis using time-of-flight...
(TOF) techniques. The TOF of the particles was obtained from 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 which has the same mass-to-charge ratio and therefore the same velocity as $^6$He. As discussed below, this required us to carry out a separate experiment with a $^3$H beam of the appropriate energy, also produced using TwinSol. The laboratory energy of the $^6$He beam was 22.5 MeV for the above-barrier measurement. This was 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 determined to be 1.2 MeV FWHM.

The reaction events, and also elastically-scattered particles, 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 overall 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 150°, 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 MeV less than that of the $^6$He elastic group is clearly visible. Note that this spectrum is gated by TOF, so that 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 as noted above cannot be identified on the basis of TOF. This could be a problem since 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.

Angular distributions obtained for the isolated $^4$He group are illustrated in Fig. 2. They are broad and approximately Gaussian in form, with a centroid that moves backward at the 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 measured at these energies (Ref. [2]) are 310 mb and 75 mb, respectively. This initially very surprising result was confirmed by the elastic-scattering angular distributions (Fig. 3) which imply total reaction cross sections of about 1170 mb and 670 mb at the two energies, consistent with the sum 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.

The predicted maximum yield is too small by a factor of four, and the angular distribution is somewhat broader than expected. Part of the discrepancy at forward angles between theory and experiment in Fig. 2 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...
“barely-bound” state with 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 ten. The result of a preliminary nucleon-transfer calculation including continuum states is more encouraging. In this 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 based on the present 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. Furthermore, since the favored “Q-window” for neutron transfer is at $Q \simeq 0$, i.e. close to the observed maximum in the experimental yield, the reaction 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 the remaining $^5$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, much more theoretical work remains to be done before the origin of the observed very strong $^4$He yield is understood in any detail.

As to the speculation in Ref. [2] regarding “neutron flow”, the observed Q-value spectrum conclusively shows that ground-state transfer, with its corresponding high positive Q value, is unimportant. However, as discussed above, 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/breakup seems more appropriate under the circumstances. Nevertheless, the preliminary coupled-channels calculation does show that coupling to the transfer/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. [4] for “normal” nuclei.

In conclusion, we have for the first time measured 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 MeV. The integrated cross section for this group is exceptionally large, greatly exceeding the fusion yield both above and below the barrier. Moreover, simultaneously-measured elastic scattering angular distributions require total reaction cross sections that confirm this large yield. Preliminary coupled-channels calculations suggest that the corresponding reaction mechanism can best be described as direct breakup plus 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” at $Q \simeq 0$. The resulting mechanism bears some resemblance to “neutron flow” [2], and to the “neutron avalanche” discussed by Fukunishi, et al. [3] in the context of “neutron skin” nuclei. Finally, the calculations also predict an enhancement in the sub-barrier fusion yield due to coupling to the transfer/breakup channel, which strongly suggests that this is the “doorway state” that accounts for the remarkable suppression of the fusion barrier observed in a previous experiment [2].

This work was supported by the National Science Foundation under Grants No. PHY99-01133, PHY98-70262, PHY98-04869, and PHY97-22604, and by the CONACYT (Mexico). One of us (V.G.) was financially supported by FAPESP (Fundação de Amparo a Pesquisa do Estado de São Paulo - Brazil) while on leave from the UNIP (Universidade Paulista).

[1] M.V. Zhukov, B.V. Danilin, D.V. Federov, J.M. Bang, I.J. Thompson, and J.S. Vaagen, Phys. Rep. 231, 151 (1993).
[2] J.J. Kolata, et al., Phys. Rev. Lett. 81, 4580 (1998).
[3] C. Dasso, J.L. Guisardo, S.M. Lenzi, and A. Vitturi, Nucl. Phys. A597, 473 (1996).
[4] N. Takigawa, M. Kuratani, and H. Sagawa, Phys. Rev. C47, R2470 (1993).
[5] M.S. Hussein, M.P. Pato, L.F. Canto, and R. Donangelo, Phys. Rev. C46, 377 (1992); ibid., Phys. Rev. C47, 2398 (1993).
[6] M.S. Hussein, Nucl. Phys. A588, 85c (1995).
[7] C. Dasso and A. Vitturi, Phys. Rev. C50, R12 (1994).
TABLE I. Parameters of the Gaussian fits to the data shown in Fig. 2.

| $E_{lab}$ (MeV) | Centroid (deg) | FWHM (deg) | $\sigma_{total}$ (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)              |

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) | $\sigma_{reac}$ (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.

FIG. 1. A $\Delta E$ vs. $E_{TOTAL}$ spectrum taken at $\Theta_{LAB} = 150^\circ$, at a laboratory $^6$He energy of 22.5 MeV. The energy calibration is 80 keV/channel.

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.

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.
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