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Alpha Particle Emission from6He + 209Bi

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In a recent experiment, we have for the first time studied near-barrier and sub-barrier fusion of the exotic "Borromean" nucleus ^{6}He with ^{209}Bi and found that the sub-barrier fusion of this system is exceptionally enhanced, implying a 20% reduction in the nominal fusion barrier. It was suggested that this striking effect might be due to coupling to positive Q-value neutron transfer channels, leading to "neutron flow" and consequent neck formation between the projectile and target. The results of a new experiment using the radioactive nuclear beam facility at the University of Notre Dame to measure fast α-particle emission from ^{6}He + ^{209}Bi are discussed. A exceptionally strong transfer/breakup group was observed at near-barrier and sub-barrier energies; this is very likely to be the "doorway state" that explains the enhanced sub-barrier fusion.

Keywords: Near-barrier fusion; sub-barrier fusion; neutron transfer

En un experimento reciente hemos estudiado por primera vez la fusión del núcleo "Borromeano" exótico ^{6}He con ^{209}Bi a energías cercanas y por abajo de la barrera, y encontramos que la fusión sub-barrera de este sistema está muy fuertemente acrecentada, implicando una reducción del 20% en la barrera nominal de fusión. Se sugirió que este sorprendente efecto puede deberse al acoplamiento a canales de transferencia de neutrones de valor Q positivo, que llevarían a un flujo de neutrones y una consecuente formación de cuello entre el proyectil y el blanco. Se discuten los resultados de un nuevo experimento usando la instalación *Twinsol* de haces radioactivos en la Universidad de Notre Dame, para medir emisión de partículas α rápidas de ^{6}He + ^{209}Bi. Un grupo excepcionalmente fuerte de transferencia/rompimiento fue observado a energías cercanas y por abajo de la barrera; éste es muy probable que sea el "estado puerta" que explica el acrecentamiento de la fusión sub-barrera.

Descriptores: Fusión; barrera; sub-barrera; transferencia de neutrones

PACS: 25.60.-t; 25.60.Gc; 25.60.Je; 27.20.+n

1. Introduction

In this work we report on our measurements of α particles produced in the ^{6}He + ^{209}Bi reaction at energies near and below the Coulomb barrier. Interest in ^{6}He-induced reactions comes mainly from the exotic nature of this radioactive nucleus. ^{6}He is the simplest of the Borromean neclei and this can provide an unusual opportunity to study three-body interactions in the nucleus. With two weakly bound neutrons around a ^{4}He core, it has a "neutron-skin" [1] or "neutron-halo" [2] structure, which is expected to have prominent effects on nuclear reactions. For instance, if a neutron-skin nucleus approaches a stable nucleus, neutrons in the skin can touch the other nucleus before protons can do so, since those neutrons are distributed outside protons. Since the Fermi energy is so different between the two nuclei, neutrons in the skin may flow into the stable nucleus thus enhancing the reaction cross section.

Another possibility that has been considered is the existence of a soft-dipole mode in which the weakly bound neutron halo performs collective oscillations against the residual nuclear core. This could contribute to enhance the fusion probability at subbarrier energies because the polarization of the projectile induced by the Coulomb field of the target brings

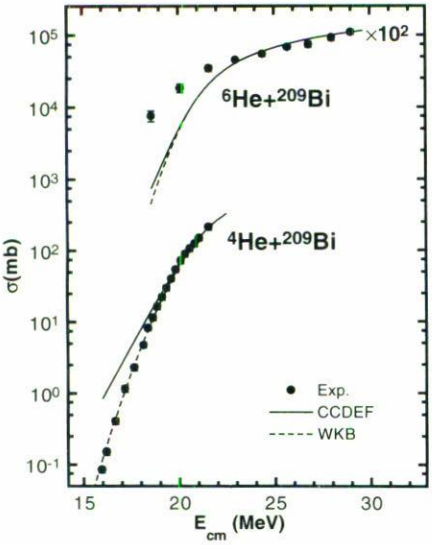

FIGURE 1. Fusion excitation functions for ^{6}He,^{4}He + ^{209}Bi. Curves are BPM calculations using the parabolic (continuous) or the WKB (dashed) approximation.

the neutron halo closer to the target; the larger overlap of the nuclear densities and the resulting attractive forces can then drive the systems into fusion confronting a substantially lower resistance. The corresponding "neutron flow" has been viewed as "neutron avalanche" by some authors [3]. This same polarization mechanism has the potential to induce separations of the halo from the ^{4}He core that stretch beyond the point that can be sustained by the weak residual forces that hold them together. The relevance of this break-up process at the bombarding conditions that may lead to fusion has generated considerable controversy recently for the case of the neutron-halo nucleus ^{11}Li. Several groups [4–6] have reported that coupling to these channels reduces the fusion cross section near the barrier producing in addition some structure in the excitation function in this region. However, other authors [7] report only enhancement of the fusion yield, even in the presence of strong breakup channels.

The possible effects of the neutron-skin structure of ^{6}He on reactions with ^{209}Bi are experimentally investigated in this work. The antecedents that motivated the present investigation are given in Sec. 2. Section 3 describes some details of the experimental procedure and in Sec. 4 the corresponding data along with the results of some preliminary calculations are presented. Finally, the conclusions of this work are given in Sec. 5.

2. Antecedents

In a recent work [8] we reported our measurements of near- and sub-barrier fusion of ^{6}He + ^{209}Bi. The corresponding excitation function is reproduced in the upper part of Fig. 1, along with the results of one-dimensional barrier penetration model (BPM) calculations. For comparison purposes, corresponding data for the ^{4}He + ^{209}Bi system are also shown [9], in the lower part of the figure. The curves correspond to the parabolic approximation (solid lines) and to the WKB approximation (dashed lines). The latter should give better results for these light systems at the lowest energies since the one-dimensional potential barrier can hardly be approximated by a simple parabola here. While the data for the lighter system show no enhancement at all, those for the heavier system show a striking enhancement of the fusion cross section with respect to the BPM predictions. Clearly, this large enhancement must be related to some reaction mechanism that appears because of the exotic structure that the additional two neutrons confer to the projectile, *i.e.*, the "neutron-skin" or "neutron-halo" structure of ^{6}He. We also notice that there is no sign of fusion suppression or structure in the fusion excitation function of ^{6}He + ^{209}Bi so that, in case that projectile breakup is present, it is not having the effects that were mentioned above. It is therefore important to measure the breakup channels in this reaction.

By making a linear fit to the ^{6}He + ^{209}Bi data in a Stelson plot [10], it was deduced in Ref. 8 that there is a 25% dynamical reduction in the barrier height, which according to Stelson *et al.* could probably be interpreted as due to neck formation promoted by "neutron flow". This view is further supported by the positive Q values for one- and two-neutron transfer in this system. It would appear, therefore, that neck formation via neutron flow is a good candidate to explain the observed large sub-barrier fusion enhancement. Clearly, the measurement of the neutron transfer channels in this system is also an important endeavour.

In the one-neutron transfer channel the residual ^{5}He rapidly decays (2×10^{-21} s) into an α particle plus a neutron. The two-neutron transfer channel directly gives a residual α particle and so does the breakup channel. The common signature of all three channels is then the emission of an α particle per event. We thus designed an experiment to measure the α particles produced in this system.

3. Experimental procedure

The ^{6}He beam used in the experiment was produced by the *TwinSol* radioactive nuclear beam facility at the University of Notre Dame [11]. The primary beam was ^{7}Li which reacts with a primary target of ^{9}Be losing a proton to produce the secondary beam of ^{6}He. Two large superconducting solenoids act as thick lenses to collect and focus the secondary beam onto a spot in the secondary target which was typically 5 mm full width at half maximum. The secondary target was a 3.2 mg/cm^2 Bi layer evaporated onto a 100 μg/cm^2 polyethylene backing.

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. Figure 2 presents a typical α-particle spectrum taken at 22.5 MeV and 105°, obtained by projection of the corresponding ΔE-E spectrum

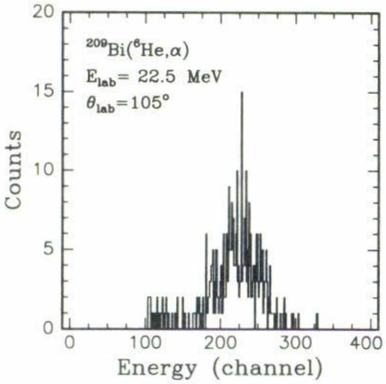

FIGURE 2. α spectrum taken at $\Theta_{\mathrm{LAB}} = 105°$, at a laboratory ^{6}He energy of 22.5 MeV. The energy calibration is 80 keV/channel.

onto the energy axis. The low energy tail is produced by reactions in the backing of the target, as determined from a separate spectrum taken with a backing foil without Bi. Since the secondary beam is contaminated by ions having the same magnetic rigidity as the desired ^{6}He beam, we used time-of-flight techniques to identify and eliminate α's produced by any contaminant beam, except by tritons. Tritons of the same magnetic rigidity as ^{6}He have also the same velocity so that they can not be discriminated by time-of-flight measurements. It turns out that the contaminant triton beam has just the right energy to produce, in reactions with the Bi target, α's which would fall in the region of the peak in Fig. 2. In order to eliminate this possibility we did a separate experiment with a ^{3}H beam of the appropriate energy, which showed no events in this region. The α's in the peak of Fig. 2, which have a mean energy about 2 MeV below that of the elastic group, are then produced by actual reactions of ^{6}He with ^{209}Bi. When compared to the elastic group (not shown), this peak is strikingly strong. We obtained an angular distribution at 22.5 MeV, which is above the barrier, and then used a polyethylene foil to reduce it to 19 MeV, which is below the barrier, and took another angular distribution at this new energy.

4. Results and discussion

The angular distributions obtained at the two energies are shown in Fig. 3 along with Gaussian fits to the data (thick solid curves). The centroids and widths of the Gaussians are presented in Table I and we can see that the centroid moves backward at the lower energy. The last column in the table gives the total cross sections, obtained by integration of the Gaussians over the whole solid angle. The most striking feature of these measurements is the very large magnitude obtained for these cross sections, equal to 643 mb at 19 MeV and 773 mb at 22.5 MeV. For comparison purposes, the fusion cross sections measured [8] at these energies are 75(17) mb and 310(45) mb, respectively, and we can see that they are much lower than the respective α cross sections.

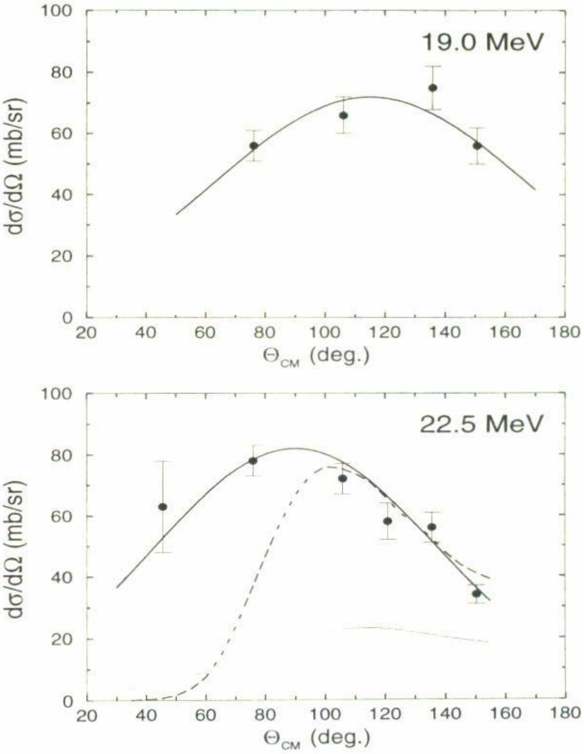

FIGURE 3. Experimental angular distributions for the ^{4}He group measured in this work. The solid curves are Gaussian fits to the data, with the parameters given in Table I. The thin solid curve is the result of a direct nuclear breakup calculation. The dashed curve is a calculation of transfer to a 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. 3.

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)

This very surprising result was confirmed by the elastic-scattering angular distributions, shown in Fig. 4. The solid curves there are optical model fits which yield the parameters of Table II. The total raction cross sections implied by these fits are 668 mb at 19 MeV and 1167 mb at 22.5 MeV. The dashed curves are optical model predictions using parameters that are appropriate for ^{4}He scattering, but with radius parameter increased to correspond to the larger size of ^{6}He. This illustrates what could be expected if the ^{6}He were a "normal" nuclear system and we can see the striking contrast with the actual results obtained for the real exotic nucleus. The calculated reaction cross sections can be compared to the sum of the fusion and the α cross sections for each energy, 718(45) mb at 19 MeV and 1083(55) mb at 22.5 MeV, and we see that there is a nice consistency between the two results.

TABLE II. Optical-model parameters used in the calculations shown in Fig. 4. The third row gives a potential determined for ^{4}He + ^{209}Bi at an incident energy of 22.0 MeV [9]. In each case, the Coulomb radius was taken to be 7.12 fm.

$E_{\rm lab}$ (MeV)	V (MeV)	R (fm)	a (fm)	W (MeV)	R_I (fm)	a_I (fm)	$\sigma_{\rm reac}$ (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.

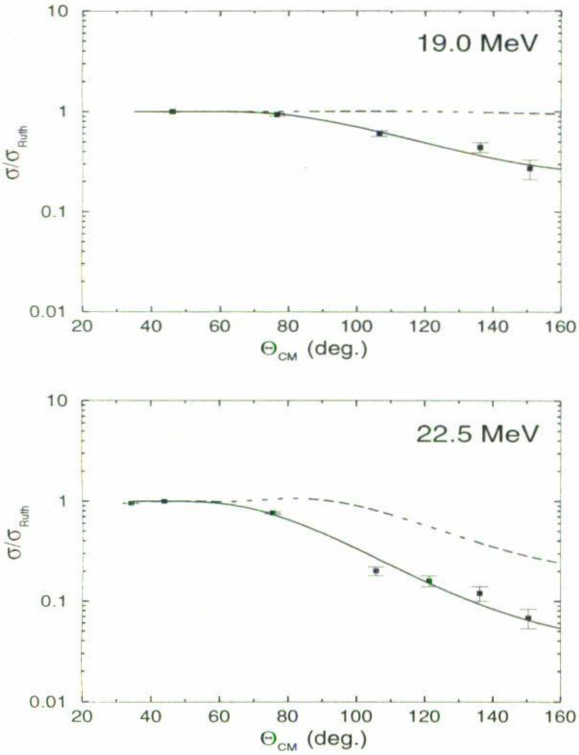

FIGURE 4. The experimental elastic-scattering angular distributions. The ratio to the Rutherford cross section is compared with optical-model fits (solid curves), which yield the parameters given in Table II. The dashed curves are predictions made with potentials appropriate for ^{4}He + ^{209}Bi [9], 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.

It is then clear that the α group seen in this ex- periment dominates the total reaction cross section at near- and sub-barrier energies. It is therefore important to determine the reaction mechanism that accounts for this very large yield. Unfortunately, it is not possible to reparate neutron transfer from breakup modes using only the present data. As mentioned before, there are three possible channels that may be contributing to the observed α yield. For the case of single neutron transfer followed by breakup of the remaining ^{5}He, kinematic calculations using the known Q value indicate that the ^{4}He residue could certainly fall in the energy region of the observed alphas. However, the states near the Fermi surface in ^{210}Bi have high angular momentum, so the transfer might be suppressed by an angular momentum barrier. A complete theoretical calculation to test this expectation is still missing, though.

Two-neutron transfer to the ground state of ^{211}Bi can be discarded because the large positive Q value would situate the ^{4}He residues in a region of much higher energy than observed. The preferred "Q-Window" for this process is at $Q \simeq 0$, which suggests that transfer to a barely bound state or to unbound states might be important. A calculation, using the code FRESCO [12], of $l = 0$ transfer of a dineutron to a "barely bound" state with binding energy of 100 KeV gave an absolute yield much too small. The dashed line in Fig. 3 shows the result multiplied by a factor of ten. A preliminary calculation of two-neutron transfer including continuum states gave results 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. The predicted cross section is very large, comparable to the experimental yield, and the angular distribution appears very similar to the dashed curve in the figure. 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 [8]. As to the speculation regarding "neutron flow", the transfer to these unbound states could be described as neutron flow, though transfer/breakup seems more appropriate under the circumstances.

Finally, the thin solid line in Fig. 3 is the result of a direct nuclear breakup calculation in which the continuum was included up to 4 MeV above threshold. 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. Since Coulomb dissociation has a forward-peaked angular distribution, we would expect the corresponding contribution to reduce the discrepancy between theory and experiment at forward angles. 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, but from these preliminary calculations we may say that there are two reaction mechanisms that are important. One is direct breakup which apparently gives only about 20% or so of the observed yield. The other is transfer to unbound states in ^{211}Bi, which subsequently decays via neutron emission. This latter appears to be the dominant mechanism and most probably is also the doorway channel that accounts for the remarkable suppression of the fusion barrier that we observed in a previous experiment.

5. Conclusions

We have for the first time measured transfer/breakup modes for the exotic Borromean nucleus ^{6}He on a ^{209}Bi target at energies near and below the Coulomb barrier. A strong ^{4}He group was observed at an effective Q value of $Q \simeq -2$ MeV. The obtained cross sections for this group were very large, greater than the corresponding fusion cross sections. Simultaneously measured elastic scattering angular distributions yield total reaction cross sections that confirm this large yield. Preliminary coupled channel calculations indicate that there are two reaction mechanisms that are important. One is direct breakup of the projectile and the other is $2n$-transfer to unbound states in ^{211}Bi. This latter mechanism bears some resemblance to the "neutron flow" discussed by Stelson *et al.* [10] or the "neutron avalanche" discussed by Fukunishi *et al.* [3] and most probably provides the doorway state to fusion that explains the remarkable enhancement observed in the sub-barrier fusion cross section for this system.

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