

Reaction cross sections for ${}^6\text{He}+{}^{209}\text{Bi}$ below the Coulomb barrier

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In a recent experiment, we have for the first time measured near-barrier and sub-barrier transfer and/or breakup yields for an exotic Borromean nucleus ${}^6\text{He}$, on a ${}^{209}\text{Bi}$ target. An isolated ${}^4\text{He}$ group was observed at an effective Q -value of approximately -2.5 MeV whose integrated cross section was exceptionally large, greatly exceeding the fusion yield both above and below the barrier. Simultaneously measured elastic-scattering angular distributions required total reaction cross sections that confirmed this large yield. Preliminary coupled-channels calculations suggested that the reaction mechanism can best be described by direct breakup and neutron transfer to unbound states in ${}^{211}\text{Bi}$. The calculations also predicted an enhancement in the sub-barrier fusion yield due to coupling to the transfer and/or breakup channel, which strongly suggested that this is the doorway state that accounts for the remarkable suppression of the fusion barrier that was observed in a previous experiment. In this work we extend these measurements to even lower energies, down to 14.7 MeV, which is nearly 6 MeV below the barrier. It is found that the ${}^4\text{He}$ group completely dominates the total reaction yield at these energies and some evidence is given that a new process might become important at low energies.

Keywords: Exotic beam; near-barrier fusion; neutron transfer

En un experimento reciente, hemos medido por primera vez la transferencia de neutrones y/o rompimiento del proyectil cerca y abajo de la barrera, para el núcleo "Borromeano" exótico ${}^6\text{He}$, sobre un blanco de ${}^{209}\text{Bi}$. Se observó un grupo aislado de ${}^4\text{He}$ a una Q efectiva de aproximadamente -2.5 MeV, cuya sección eficaz integrada fue excepcionalmente grande, excediendo la sección de fusión tanto arriba como abajo de la barrera. Las distribuciones angulares elásticas, medidas simultáneamente, requirieron de una sección eficaz total que confirmó estos resultados. Cálculos preliminares de canales acoplados sugirieron que los mecanismos de reacción pueden ser mejor descritos como rompimiento directo y transferencia de neutrones a estados no ligados en ${}^{211}\text{Bi}$. Los cálculos también predijeron un acrecentamiento en la sección de fusión abajo de la barrera debido al acoplamiento del canal de transferencia y/o rompimiento, lo cual fuertemente sugiere que éste es el "estado puerta" que explica la gran disminución de la barrera de fusión observada en un experimento previo. En este trabajo, extendemos estas medidas a energías aún más bajas, hasta 14.7 MeV, la cual está alrededor de 6 MeV abajo de la barrera. Se encontró que el grupo de ${}^4\text{He}$ domina completamente la sección de reacción total a estas energías y se presenta evidencia de que un nuevo proceso puede estar tomando importancia a bajas energías.

Descriptores: Haz exótico; fusión cerca de la 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 ${}^6\text{He}+{}^{209}\text{Bi}$ reaction at energies below the Coulomb barrier. Similar measurements at two energies, one above and one below the barrier, have been previously reported [1]. Interest in ${}^6\text{He}$ -induced reactions originated, among other things, from some recent theoretical studies about fusion near the barrier of the ${}^{11}\text{Li}+{}^{208}\text{Pb}$ system, which generated some controversies. The Borromean radioactive nucleus ${}^{11}\text{Li}$ (half life of 8.7 ms), which can be seen as a structure consisting of two neutrons weakly bound (300 keV) around a ${}^9\text{Li}$ core, has been considered as a neutron skin" [2] or a "neutron halo" [3] nucleus. Some groups [4–6] have reported that in the fusion of this system, the coupling of the breakup channel to the fusion channel reduces the fusion cross section leading to some structure in the excitation function in the barrier region. However, other authors [7] reported only an enhancement in the fusion yield, even in the presence of strong breakup channels. Since the competition between the projectile breakup and the sub-barrier fusion is very important in the formation of superheavy elements via fusion with exotic projectiles, it is important to solve this controversy. At the present time, the ${}^{11}\text{Li}+{}^{208}\text{Pb}$ system is not available because of the low intensity of ${}^{11}\text{Li}$ beams and bad energy resolution. However, the ${}^6\text{He}$ nucleus, with two neutrons weakly bound (0.97 MeV) around a ${}^4\text{He}$ core, is radioactive (half life of 806 ms) and has also a "neutron skin" structure, so that it could be expected that it should show some effects similar to those mentioned above for ${}^{11}\text{Li}$. In addition, ${}^6\text{He}$ is the simplest Borromean nucleus, and this provides an unusual opportunity to study three-body interactions in the nucleus.

In particular, if a neutron skin nucleus, such as ${}^6\text{He}$, approaches a stable nucleus, neutrons in the skin can touch the target before protons in the core can do so, because 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 soft-dipole mode excitations in which the weakly bound neutron halo performs collective oscillations against the residual nuclear core. This could contribute to enhance the fusion probability at sub-barrier energies because the polarization of the projectile induced by the Coulomb field of the target brings the neutron halo closer to the target. The corresponding "neutron flow" has been viewed as "neutron avalanche" by some authors [8]. This same polarization mechanism has the potential to induce separations of the halo from the ${}^4\text{He}$ 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 ${}^{11}\text{Li}$, as mentioned above. The possible effects of the

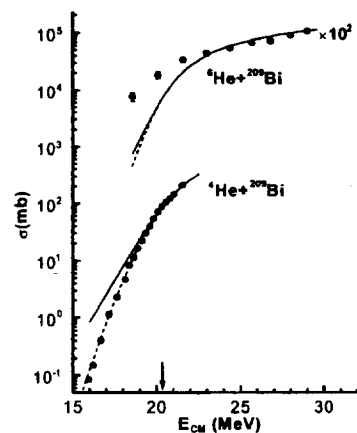


FIGURE 1. Fusion excitation functions of ${}^{6,4}\text{He}+{}^{209}\text{Bi}$ (Kolata, *et al.* [9], Barnet, *et al.* [10]). Curves are BPM calculations using the parabolic (—) or the WKB (---) approximation. From these fits, for the ${}^6\text{He}+{}^{209}\text{Bi}$ system $V_{\text{bf}} = 20.3$ MeV.

exotic structure of ${}^6\text{He}$ over reactions with ${}^{209}\text{Bi}$ are experimentally investigated in this work.

2. Antecedents

In a recent work [9], we reported our measurements of near and sub-barrier fusion of ${}^6\text{He}+{}^{209}\text{Bi}$. The corresponding excitation function is reproduced in the upper part of Fig. 1, along with the result of one-dimensional barrier penetration model (BPM) calculations, which lend a fusion barrier $V_{\text{bf}} = 20.3$ MeV. For comparison purposes, corresponding data for the ${}^4\text{He}+{}^{209}\text{Bi}$ system are also shown [10], in the lower part of the figure. The curves correspond to the parabolic approximation (—) and to the WKB approximation (---). 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 ${}^6\text{He}$. We also notice that there is no evidence of fusion suppression or structure in the fusion excitation function at the barrier energy for ${}^6\text{He}+{}^{209}\text{Bi}$ so that, in case that projectile breakup is present, it is not having the effects that were mentioned above. Similar conclusions were obtained in Ref. [11] for the ${}^6\text{He}+{}^{238}\text{U}$ system. It is therefore important to measure the breakup channel in the ${}^6\text{He}+{}^{209}\text{Bi}$ reaction.

A particularly enlightening way to present the fusion data has been introduced by Stelson *et al.* [12] who noted that many fusion excitation functions near the barrier have the property that $(\sigma E_{\text{cm}})^{1/2}$ is linear, even in the presence of large enhancements relative to potential-model estimates, leading to the formula $\sigma(E) = \pi R^2 (E_{\text{cm}} - T)^2 / [4(V_0 - T)]^{1/2}$,

where V_0 is the nominal barrier and R is the barrier radius. They further show that this behavior results from the introduction of a distribution of barriers with uniform weight extending from some threshold energy T to $2V_0 - T$. By making a fit of this formula to the ${}^6\text{He}+{}^{209}\text{Bi}$ fusion data, a threshold barrier $T_f = 15.4$ MeV was deduced in Ref. 9, meaning that there is a 25% dynamic reduction in the barrier height caused by some reaction mechanism that becomes important at an energy near T_f . According to Stelson *et al.*, this could probably be interpreted as due to neck formation promoted by "neutron flow", a view that is further supported by the positive Q -value 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, it is also important to measure the neutron transfer channels in this system.

In the one-neutron transfer channel, the residual ${}^5\text{He}$ 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 ${}^6\text{He}$ beam used in the experiment was produced by the *TwinSol* radioactive nuclear beam facility at the University of Notre Dame [13, 14]. The primary beam was ${}^7\text{Li}$ which reacts with a primary target of ${}^9\text{Be}$ losing a proton to produce the secondary beam of ${}^6\text{He}$. 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 (FWHM). The high ${}^6\text{He}$ -beam purity and good resolution from contaminants obtained by *TwinSol* has been reported in Ref. 14. The secondary target was a 3.2 mg/cm² Bi layer evaporated onto a 100 $\mu\text{g}/\text{cm}^2$ polyethylene backing. The reaction events and also elastically scattered particles were detected with a set of $\Delta E - E$ silicon telescopes placed at various angles on either side of the beam. Figure 2 presents a typical spectrum taken at $E_{\text{lab}} = 22.5$ MeV and $\Theta_{\text{lab}} = 135^\circ$, where the elastic and the α -particle groups are clearly distinguished.

The low energy tail of the ${}^4\text{He}$ group 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 with ions having the same magnetic rigidity as the desired ${}^6\text{He}$ 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 ${}^6\text{He}$ 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.

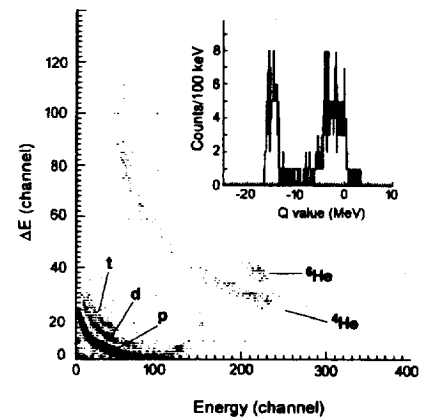


FIGURE 2. ΔE vs. E_{total} spectrum taken at $\Theta_{\text{lab}} = 135^\circ$, at a laboratory ${}^6\text{He}$ energy of 22.5 MeV. The energy calibration is 80 keV/channel. A Q -value spectrum for the ${}^4\text{He}$ group is shown in the inset [1].

In order to eliminate this possibility we did a separate experiment with a ${}^3\text{H}$ beam of the appropriate energy (one-half the ${}^6\text{He}$ energy), which showed no events in this region. The α particles 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 ${}^6\text{He}$ with ${}^{209}\text{Bi}$.

It is worthwhile to notice that the measurements, from 22.5 MeV to 14.7 MeV, were developed in two experiments. The first one, previously reported [1], started at an energy of 22.5 MeV for ${}^6\text{He}$ (which is above the barrier) and then a 6.54 mg/cm² mylar foil was used to reduce it to 19.0 MeV, which is below the barrier. In the second experiment, the bombardment was started at 19.2 MeV and, by inserting a 2.47 mg/cm² polypropylene foil, an energy of 17.9 MeV was reached; 16.2 MeV and 14.7 MeV were then reached by inserting the mylar and mylar plus polypropylene absorbers, respectively. The thickness of the Bi target, polyethylene backing and mylar and polypropylene absorbers was determined in separate experiments by energy loss measurements using alpha-particle sources.

4. Results and discussion

The alpha angular distributions obtained at the four energies in the second part of the experiment are shown in Fig. 3, along with gaussian fits to the data. The centroids and widths of the gaussians are presented in Table I. The last column in the Table gives the total alpha 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, which exceed by far the fusion cross sections at the same energies. Even at the lowest measured energy, which is nearly 6 MeV below the barrier, the cross section is still large.

The elastic angular distributions are shown in Fig. 4. The solid curves are the result of an optical model fit where all parameters were kept fixed except for the imaginary diffuseness, which had the simple linear variation shown in the cap-

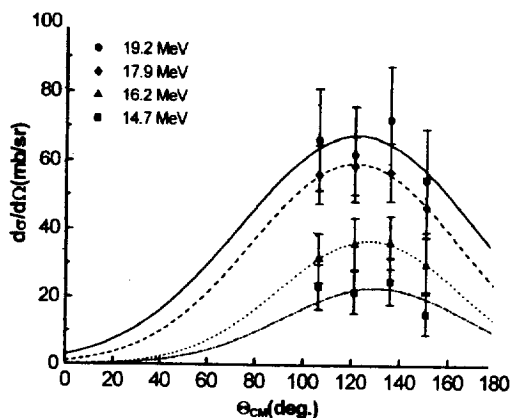


FIGURE 3. Angular distributions of α -particles from the ${}^6\text{He}+{}^{209}\text{Bi}$ reaction and gaussian fits to the data. Energies are given in the laboratory system.

TABLE I. Parameters of the gaussian fits to the data shown in Fig. 3 and to those reported in Ref. 1. The values labeled with (*) are taken also from this Reference. The last column gives the total cross section for the measured alphas.

E_{lab} (MeV)	Centroid (deg)	FWHM (deg)	σ_{α} (mb)
22.5*	86.2 (2.5)	119.6 (5.6)	773 (31)
19.2	122.0 (16.9)	114.4 (80.9)	637 (70)
19.0*	116.6 (5.3)	131.8 (19.7)	643 (42)
17.9	121.0 (8.8)	100.8 (36.5)	528 (38)
16.2	127.0 (9.2)	86.9 (41.7)	296 (31)
14.7	130.0 (13.0)	89.9(58.8)	189(27)

tion. Even though we emphasized here fits to the total reaction cross sections (discussed below), the comparison with experiment is very nice, except perhaps at 14.7 MeV. The dotted line at 22.5 MeV is the optical model prediction using parameters obtained from ${}^4\text{He}$ scattering, but with radius parameter increased to correspond to the larger size of ${}^6\text{He}$, according to an $A^{1/3}$ scaling. This illustrates the expectation for elastic scattering if ${}^6\text{He}$ were a "normal" nucleus (with no halo).

Figure 5 shows the total reaction cross sections, which were taken as the sum of fusion plus alphas, for the five measured energies. The dashed curve represents the optical model predictions mentioned above, and we can see that it gives a really nice fit to the data. In order to have some additional insight we applied some simple models to these data. Since the reaction cross section below the barrier should vary mainly because of barrier-penetration effects, one can expect that a barrier penetration model should be appropriate. A fit to the data of the classical BPM gave the dotted line, with a barrier height V_{br} of 14.5 MeV and a radius R_{br} of 10.3 fm. Note that V_{br} is remarkably close to the value for the threshold barrier, $T_f = 15.4$ MeV, deduced from the Stelson-model fit to the fusion data. A possible interpretation for this is that the measured alpha channels, which give the main contribution to the reaction cross section (and that can be seen as a "new process" with respect to the simple assumptions of the BPM),

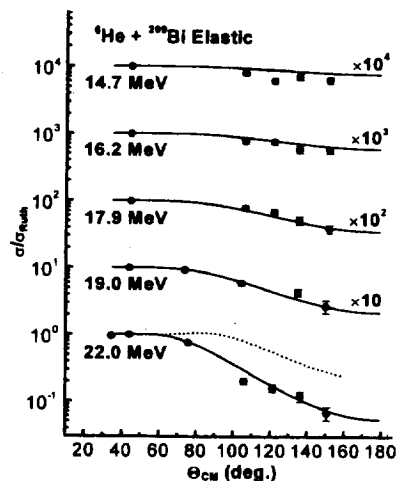


FIGURE 4. Experimental elastic scattering angular distributions and optical model fits to the data (—). The optical potential parameters are $V=150$ MeV, $R=7.95$ fm, $a=0.68$ fm, $W_I=25.0$ MeV, $R_I=9.38$ fm, $a_I=1+0.0438(22.0-E_{\text{lab}})$ fm. The dotted curve is a calculation made with a potential appropriate for ${}^4\text{He}+{}^{209}\text{Bi}$ [10], but with a radius appropriate for ${}^6\text{He}$ (see text).

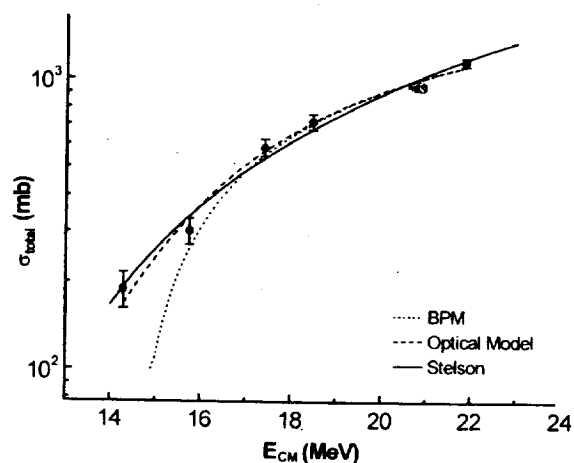


FIGURE 5. Total reaction cross sections for the ${}^6\text{He}+{}^{209}\text{Bi}$ system and some model predictions.

become important at around 15 MeV and this produces the threshold energy T_f for the barrier distribution of the Stelson model. Finally, the solid curve is a Stelson model fit to the total reaction data, with the above values of V_{br} and R_{br} . This leads to a new threshold barrier $T_r = 10.7$ MeV which, following the previous line of reasoning, could mean that a new process is taking over at this lower energy. The validity of this speculation, of course, remains to be seen. And this takes us to the conclusions of this work.

5. Summary and conclusions

Transfer and/or breakup yields were measured, through the respective alpha particles, for the borromean nucleus ${}^6\text{He}$ on a ${}^{209}\text{Bi}$ target in an energy interval going from nearly 2 MeV

above the barrier, down to about 6 MeV below it. By adding these to the previously measured fusion yields, total reaction cross sections were deduced. Simultaneously measured elastic scattering angular distributions could be described by using an optical potential with a simple energy variation, which did also nicely reproduce the total reaction cross sections. A simple barrier penetration model, applied to the total reaction cross sections, gave a barrier height remarkably close to the previously deduced threshold barrier for fusion (from the Stelson model), indicating that the measured alpha channels are most probably responsible for the large fusion enhancement previously observed. When the Stelson model was in time applied to the total reaction data, a new threshold barrier $T_r = 10.7$ MeV was obtained, which could be an indi-

cation that a new process is taking over at this low energy. In order to investigate this possibility, it would be worthwhile to extend the measurements down to this energy, which is about one half the nominal fusion barrier. Given the high cross sections obtained even at the lowest measured energy, this endeavour seems to be reachable.

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