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^{6}He+^{209}Bi fusion-fission reaction

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Fission following the fusion of ^{6}He with a ^{209}Bi target has been studied near the Coulomb barrier, at excitation energies of 32 and 34 MeV in the compound system. These new experimental data are in disagreement with previous work which reported an anomalously large fusion-fission yield, when compared with ^{4}He-induced fission of ^{209}Bi at similar excitation energies. In fact, the ^{6}He-induced fusion-fission yield appears to be smaller than that for ^{4}He, in qualitative agreement with conventional statistical model calculations. [S0556-2813(98)50201-4]

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The production and use of radioactive nuclear beams (RNB) at several different laboratories throughout the world has generated a considerable amount of interest and excitement in the nuclear physics community. In particular, the investigation of reactions induced by exotic ''halo'' and ''skin'' nuclei is now becoming practical. These systems contain one or more weakly bound neutrons around a relatively tightly bound core, and this unusual composition can manifest itself in both the structure of the nucleus itself, as in the existence of low-lying E1 modes [1], and in reactions with other nuclei. For example, a considerable number of theoretical studies have been carried out on the fusion of ^{11}Li with ^{208}Pb near the Coulomb barrier (see, e.g., Refs. [2–6]). A general feature of these calculations is a lowering of the barrier due to the larger radius of the ^{11}Li ''halo'' wave function and the coupling to the soft $E1$ mode [2]. The role played by projectile breakup is considerably more controversial. Several groups [3–5] have reported that coupling to the breakup channels can reduce the fusion cross section near the barrier, leading to intriguing structure in the excitation function in this region. However, this point of view has been criticized by Dasso and Vitturi [6] who suggest only enhancement of the yield.

Unfortunately, the ^{11}Li+^{208}Pb system is at present inaccessible near the Coulomb barrier due to the low flux and poor energy resolution of ^{11}Li beams at these low energies. However, the fusion of ^{6}He with ^{209}Bi has recently been studied [7,8] at the Flerov Laboratory for Nuclear Reactions in Dubna, Russia. The ^{6}He nucleus, with two weakly bound neutrons around a ^{4}He core, has a ''neutron-skin'' structure [9], and is expected to display effects similar to those discussed above. The $4n$ fusion-evaporation channel from the Dubna work appears to be consistent with expectations from statistical-model calculations [10], although the data have rather large error bars and do not extend below the barrier (at about 22 MeV) where the largest effects are expected to occur. However, the fusion-fission channel is reported to be strongly anomalous [8]. In particular, the fission cross section at equal excitation energy in the compound system is a factor of 3 to 4 greater than that for ^{4}He+^{209}Bi [11–13]. On the other hand, experiments [8,12] in which ^{213,215}At compound nuclei are formed using stable beams and targets have shown that the dependence of the fission barrier on the neutron number of the compound nucleus is weak or nonexistent in this mass region, and statistical-model calculations that reproduce ^{4}He-induced fusion-fission [10] predict a smaller cross section (by up to a factor of two) in the ^{6}He case. This very large discrepancy between the experimental fusion-fission yield and expectations from previous work led Signorini [10] to speculate that the fissioning system is actually ^{211}Bi, produced at high excitation energy by the transfer of two neutrons in the (^{4}He, ^{6}He) reaction which has a +9 MeV Q value. Since Fomichev *et al.* [8] used plastic track detectors in their experiment, this transfer-fission process could not be distinguished from compound-nucleus fission. The present experiment was motivated by the reported anomaly in the fusion-fission yield, and was specifically designed to identify the transfer-fission process, if it occurs.

The ^{6}He beam used in this work was produced by *TwinSol* (Fig. 1), a modified and upgraded version of an RNB facility that has been in operation at the University of Notre Dame since 1987 [14,15]. Specifically, two large superconducting solenoids act as thick lenses to collect and focus the secondary beam of interest [16]. For the purposes of this

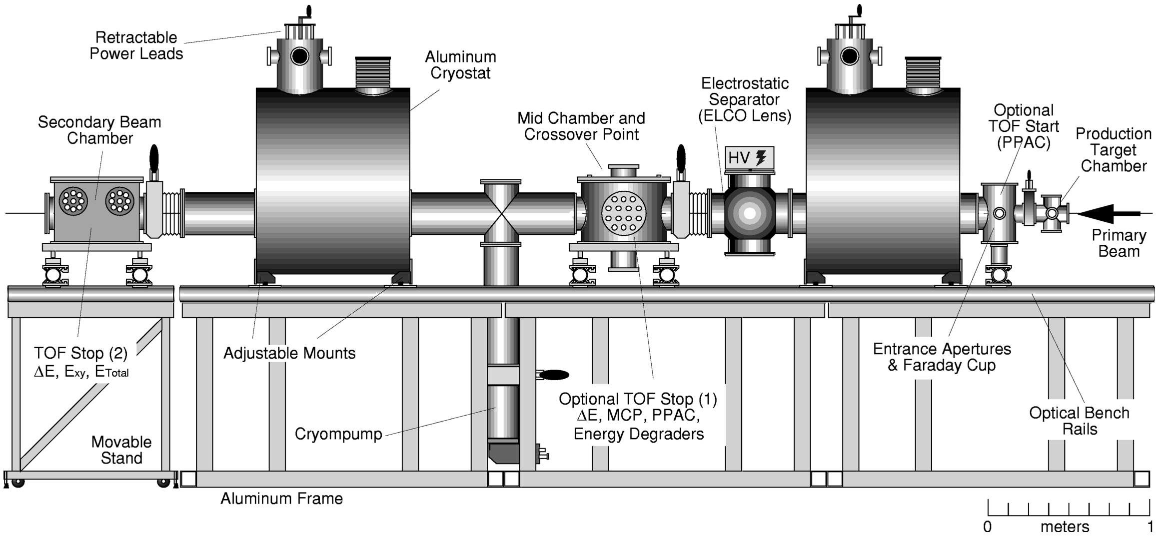

FIG. 1. The *Twinsol* Radioactive Nuclear Beam facility.

experiment, the most important feature of the upgrade was an increase in the maximum axial field integral from 1.5 T m with the previous version to 3.9 T m with the current system. This means that the energy of all secondary beams is now limited by the maximum primary beam energy from our accelerator rather than by the bending power of the solenoids. For example, we have been able to produce a 34.5 MeV ^{6}He beam, which is sufficient to study the fusion-fission cross section of interest at 34 MeV in the ^{215}At compound nucleus. In this case, the primary beam was ^{7}Li at an energy of 40 MeV, incident on a target consisting of a 12 μ foil of ^{9}Be. Primary beam currents of up to 200 particle nA (pnA) are available. The secondary beam flux was initially calibrated by inserting a Si ΔE-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. In this way, we determined that the ^{6}He production rate was 310 particles per second per pnA, and the maximum secondary beam intensity was over 200 times that available in the Dubna experiment [8], allowing us to use Si detectors to register the fission fragments.

This experiment was performed in an early-implementation phase of the *Twinsol* project, and only one of the two solenoids was cooled to liquid He temperature while the secondary target was actually located at the ‘‘crossover’’ point in the midplane chamber (Fig. 1). Since the function of the second solenoid is to enable purification of the secondary beam by inserting an energy-loss foil (or electrostatic elements) at the crossover point, the purity of the ^{6}He beam (determined using the telescope at the secondary target position) is potentially a concern. The observed rate of ^{7}Li at the secondary target was 30 particles per second per pnA, which translates to a beam reduction factor of 5×10^{-9} and a rate that is only 10% that of ^{6}He. Furthermore, all of these particles were in the 2^{+} charge state, so their energy was 29.6 MeV which is well below the Coulomb barrier for ^{7}Li on ^{209}Bi. As in the earlier work [8], the major contaminant was ^{3}H with a rate of 325 particles per second per pnA at an energy of 17.3 MeV. This is considerably worse than in the Dubna experiment, where a beam purity of 95% was obtained. However, the compound nucleus ^{212}Po is formed at an excitation energy of 24 MeV. Previous work [11] has shown that ^{210}Po formed at this excitation energy in ^{4}He $+^{209}$Bi fusion-fission has a yield of only 1 μb, which is negligibly small, and we expect a similar cross section in the present case due to the weak dependence of the fission yield on neutron number noted above. Furthermore, the Q value for two neutron transfer from ^{3}H is only 1.26 MeV so transfer fission is also not expected to contribute. Finally, there was no evidence for ^{3}H-induced fission in the previous experiment [8] at the level of 1 mb.

The experimental setup is illustrated in Fig. 2. Fission events were identified using two Si strip detectors having an outer diameter of 10 cm and a 5 cm diameter hole through which the ^{6}He beam passed; one was placed 3.0 cm upstream of the Bi target, and the other was 3.5 cm downstream of the target. Both are double-sided strip detectors, with 16 nested ring-shaped strips on one side, and 16 pie-shaped sectors on the other side. Each ring and sector was connected to a separate electronic channel which provided both time and energy information. The geometrical efficiency for detection of a fission event in this setup is 24±3 % when we require a coincidence between fission fragments from a stationary source in the two detectors. The range was determined by assuming three different angular distributions: uniform, $1/\sin(\theta)$, and $1+1.2\cos^{2}(\theta)$. The latter distribution is appropriate for ^{4}He$+^{209}$Bi fusion-fission near the barrier [11]. A more accurate Monte Carlo calculation, including such effects as the lab. velocity of the fused system, the angular distribution and spot size of the incoming beam, the energy distribution of the fission fragments, and multiple scattering and energy loss in the target, gave an efficiency of 18±3 % for the same three distributions; this was the value used in the calculation of the fission cross sections measured in this experiment. The efficiency calculation was corroborated using a ^{252}Cf fission source, and found to be accurate within the stated range. The target consisted of 1.0 mg/cm^{2} of natural Bi evaporated onto a 0.2 mg/cm^{2} Al backing; its thickness was determined by measurement of the energy loss of ^{4}He particles passing through it, and also via a Rutherford

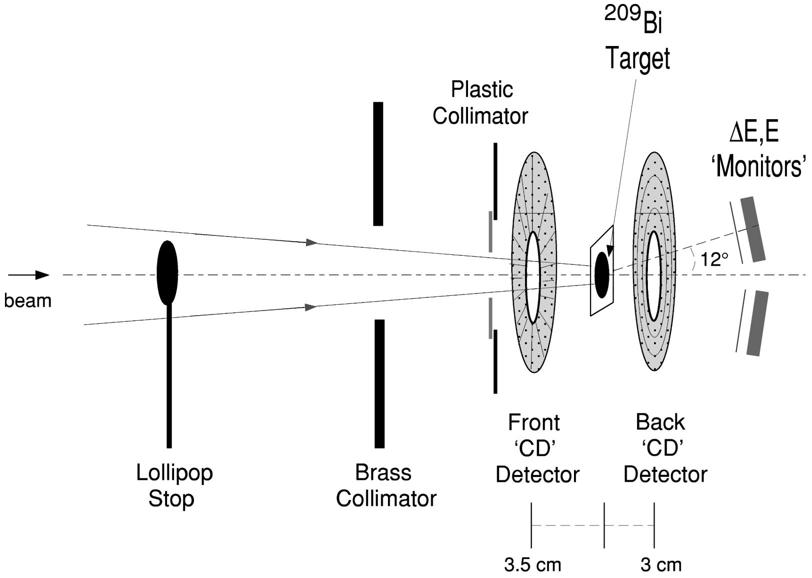

FIG. 2. Diagram of the experimental setup, showing the double-sided Si strip detectors (''CD''). The function of the ''Lollipop Stop'' is to improve the purity of the ^{6}He beam by eliminating particles that have too low magnetic rigidity and therefore come to a focus prior to the collimator at the entrance to the scattering chamber.

back-scattering (RBS) measurement. During the course of the experiment, the secondary beam intensity and composition was monitored using two Si ΔE-E counter telescopes at $\pm 12°$ to the average beam direction. Because of the angular divergence of the beam, the Rutherford scattering formula did not give an accurate measurement of its absolute intensity. However, the results from this monitoring technique were consistent with that from the more reliable method described above. See Ref. [17] for a further discussion of the effect of the angular divergence of the incident beam on the measured elastic-scattering yield.

The great advantage of Si strip detectors is their multi-hit capability, which allows for the identification of transfer fission with nearly 100% probability. The signature of these events is a threefold coincidence between the fission fragments and a forward-going ^{4}He transfer product. The ''strong-absorption'' angle for ^{6}He+^{209}Bi at 35 MeV is 56° and the ''grazing'' angle is 48° [7], in the center-of-momentum (c.m.) frame. Transfer products are expected to appear in this range, possibly somewhat forward of the ''grazing'' angle if the reaction is very peripheral. The downstream detector subtends the cm region between 37° and 56.5°; this region is extended still further, though at lower efficiency, by the $\pm 3°$ angular divergence of the incident beam. Thus, we expect to detect nearly every transfer product that is in coincidence with a fission event, and the overall efficiency for transfer-fission detection is expected to be the same as that for compound-nucleus fission.

The energy distribution of the incident beam in the present experiment required careful consideration. On the one hand, the resolution of 300 keV full width at half maximum (FWHM) is very much better than the corresponding value of 8.5 MeV in the Dubna experiment [8] (at comparable excitation energies in the compound system). On the other hand, the (^{7}Li, ^{6}He) RNB production reaction on the ^{9}Be primary target populates states in the residual ^{10}B nucleus at 0.0, 0.72, 1.74, 2.15, and 3.59 MeV, and the corresponding ^{6}He groups appear at the secondary target with an intensity ratio of 1.0:1.0:0.4:0.4:0.08. Thus, it was necessary to weight the experimental data according to this energy distribution. We used the statistical-model excitation function of Ref. [10] for this purpose; it agrees fairly well in shape (though of course not in magnitude) with the data of Ref. [8] and with the ^{4}He+^{209}Bi fusion-fission yield curve [11]. In this way, we computed excitation energies in the compound nucleus of 34.0 ± 0.3 MeV and 32.1 ± 0.4 MeV for the two different primary beam energies used in this experiment, where the error bars include an estimate of the systematic error introduced by this averaging technique. For comparison purposes, use of a very unrealistic constant cross section model for the fission yield results in an excitation energy of 33.8 MeV rather than 34.0 MeV, and simultaneously lowers the reported cross section by 15%. All of these energies were computed at the center of the ^{209}Bi target.

As mentioned above, the experiment was carried out using two different primary beam energies, beginning at 38 MeV. It soon became clear that the event rate at this energy was at least an order of magnitude lower than expected, bringing into question the ability of the Si strip detectors to detect fission products. We over-biased the detectors, and also tried using positive bias on the sector side rather than negative bias on the ring side (in each case grounding the non-biased side), to eliminate possible surface dead layers. No effect on the count rate was observed. In addition, the detectors produced good signals for 3.5 MeV ^{4}He particles, which have the same range as the fission fragments and, as noted, we were able to detect the fission fragments from a ^{252}Cf source with the expected efficiency. We therefore concluded that the fission yield must in fact be much less than expected from previous work. The cross section obtained from the present experiment is 2.4 ± 0.8 mb at an excitation energy of 32.1 ± 0.4 MeV, compared with an expected yield of 40 ± 30 mb from the Dubna experiment. Since the fission yield near threshold can vary dramatically with excitation energy, we made a second measurement with a 40-MeV pri-

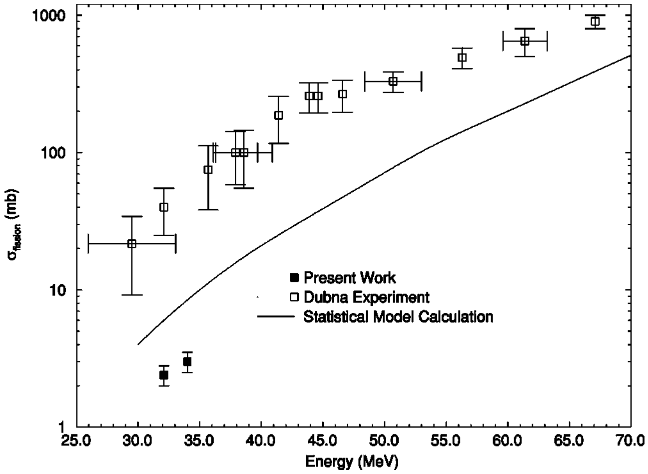

FIG. 3. Comparison of data from Ref. [8], the statistical-model calculation from Ref. [10], and the results of the present experiment. Representative horizontal error bars are shown for the Dubna experiment; those for the present data are the same size as the points.

mary beam and found a cross section of 3.0±1.0 mb at an excitation energy of 34.0±0.3 MeV, compared with 56±30 mb from the earlier work [8]. The results from the two experiments are compared in Fig. 3.

In conclusion, our measurements of ^{6}He+^{209}Bi fusion-fission suggest that the cross section for this process in the region of 30 to 35 MeV of excitation in the compound system is more than an order of magnitude smaller than reported in a previous work [8]. The new result is qualitatively consistent with the statistical-model calculation of Ref. [10] in that the ^{6}He-induced fission yield is smaller than that for ^{4}He. The need to hypothesize a large contribution from ''transfer fission'' is therefore removed. The present experiment was designed to have high sensitivity to the latter process, but within the limited statistics afforded by the low observed yield we found no events of this kind, leading to an upper limit of 0.5 mb for transfer fission in the energy region probed. In quantitative terms, the observed fission yield may actually be as much as a factor of two smaller than expected from the particular calculation of Ref. [10], which could suggest a suppression of fusion in the vicinity of the barrier as predicted in Refs. [3–5]. However, this calculation also overpredicts the fission yield for ^{4}He+^{209}Bi at low excitation energy. In view of this fact, and the problems imposed by the low fission yield, it is much more efficient to search for fusion suppression (or enhancement) near and below the barrier by measuring the fusion-evaporation channels. Specific experiments aimed at this goal are currently in progress using the *Twinsol* facility.

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