1-1-2005

Two-neutron transfer in the He6+Bi209 reaction near the Coulomb barrier

P. A. Deyoung

Patrick J. Mears

J. J. Kolata

E. F. Aguilera

F. D. Becchetti

See next page for additional authors

PHYSICAL REVIEW C **71**, 051601(R) (2005)

Two-neutron transfer in the ^{6}He + ^{209}Bi reaction near the Coulomb barrier

P. A. DeYoung,[1] Patrick J. Mears,[1] J. J. Kolata,[2] E. F. Aguilera,[3] F. D. Becchetti,[4] Y. Chen,[4] M. Cloughesy,[2] H. Griffin,[4] C. Guess,[1] J. D. Hinnefeld,[5] H. Jiang,[4] Scott R. Jones,[6] U. Khadka,[1] D. Lizcano,[3] E. Martinez-Quiroz,[3] M. Ojaniega,[4] G. F. Peaslee,[7] A. Pena,[1] J. Rieth,[1] S. VanDenDriessche,[5] and J. A. Zimmerman[6]

[1]*Department of Physics and Engineering, Hope College, Holland, Michigan 49423-9000*

[2]*Physics Department, University of Notre Dame, Notre Dame, Indiana, 46556-5670*

[3]*Departamento del Acelerador, Instituto Nacional de Investigaciones Nucleares, A.P. 18-1027, C.P. 11801, Mexico, D.F.*

[4]*Physics Department, University of Michigan, Ann Arbor, Michigan 48109-1120*

[5]*Physics Department, Indiana University South Bend, South Bend, Indiana 46634-7111*

[6]*Department of Chemistry, Southwest Missouri State University, Springfield, Missouri 65804-0094*

[7]*Department of Chemistry, Hope College, Holland, Michigan 49423-9000*

(Received 13 September 2004; published 13 May 2005)

The cross section for α-particle emission in the ^{6}He + ^{209}Bi reaction at energies near the Coulomb barrier is remarkably large. Possible reactions that may produce the observed α particles include two-neutron transfer, one-neutron transfer, and direct projectile breakup. Each of these mechanisms results in a distinctive angular correlation between the α particle and the outgoing neutron(s). A neutron-α-particle coincidence experiment was performed to study two-neutron transfer to unbound states of ^{211}Bi. It is shown that approximately 55% of the observed α-particle yield at and beyond the grazing angle is because of this process. This is more than 2.5 times the fraction attributable to single-neutron transfer. The corresponding $2n$-transfer cross section is 0.4 ± 0.1 b.

DOI: 10.1103/PhysRevC.71.051601 PACS number(s): 25.60.Je, 27.20.+n

Astonishingly large yields of α particles have been reported in studies [1,2] of ^{6}He + ^{209}Bi reactions at energies near the Coulomb barrier. More recently, similar large α-particle yields have been reported for ^{6}He incident on ^{64}Zn [3] and ^{63,65}Cu [4]. The angular distributions of the α-particle groups observed with all these targets were characteristic of a direct reaction. In the ^{209}Bi case, an integrated yield of nearly 800 mb at a center-of-mass (c.m.) ^{6}He energy of 21.8 MeV [1] was measured. In contrast, the fusion cross section at this energy was much smaller, only 310 mb [5]. This unusual and perhaps surprising result is attributed to the weak binding of ^{6}He. It has been suggested that one- and two-neutron transfer processes might play a decisive role here, because preliminary (and very schematic) coupled-channels Born approximation (CCBA) calculations [1] indicate that these direct transfer processes can be significantly enhanced by coupling to continuum states in the reactions of weakly bound nuclei. In addition, the contribution of direct projectile breakup in the Coulomb and/or nuclear field of the target must be evaluated.

In a recent experiment [6], Bychowski *et al.* studied the one-neutron transfer process ^{209}Bi(^{6}He,^{5}He)^{210}Bi at $E_{c.m.} =$ 22.3 MeV by detecting the neutron from the decay of ^{5}He in coincidence with an outgoing α particle. They found that this reaction accounts for $20 \pm 2\%$ of the yield of α particles in the interaction of ^{6}He with ^{209}Bi. Although the corresponding one-neutron-transfer cross section was quite large (155 ± 25 mb), this result still implies that 80% of the α-particle yield is unaccounted for. An array of eight 12.7-cm diameter × 5-cm-deep NE213 liquid scintillator detectors was used in Ref. [6] to detect the neutrons. These detectors were generally placed at angles that maximized the detection probability for neutrons coming from ^{5}He decay, which travel in approximately the same direction as the α particle. The detectors also had a relatively high neutron energy threshold (>1 MeV). As a result, the experiment was largely insensitive to neutrons coming from other processes. Nevertheless there was some evidence for a small isotropic component in the neutron angular distribution [6], which, together with the "missing" yield, suggested that other reaction mechanisms were involved.

Two-neutron transfer from ^{6}He clearly does not lead to projectile-associated neutron emission. However, the Q-value distribution shown in Ref. [1] implies that, although the one-neutron transfer process proceeds mainly to bound states of ^{210}Bi, essentially all of the yield from ^{209}Bi(^{6}He,^{4}He) must go to neutron-unbound final states in ^{211}Bi. Thus, the signature of this process would be the detection of an α particle in coincidence with low-energy neutrons "evaporated" from the ^{211}Bi residue. The statistical-model code PACE2 [7] was used to estimate the energies of these neutrons, which turned out to have a thermal distribution peaking at energies below 1 MeV. Because the angular distribution of the evaporation neutrons is isotropic in the c.m. system, their detection probability is much lower than that for neutrons from ^{5}He decay, which are "forward-focused" as mentioned above and also have a higher energy because they come from the decay of a rapidly moving projectile, as observed in Ref. [6]. (The neutron energy threshold in this experiment was >1 MeV, as mentioned above.) On the other hand, the predicted multiplicity of the evaporation neutrons is about 1.5, which improves the detection prospects by 50%.

The goal of the present work was to obtain a quantitative estimate of the importance of the two-neutron transfer process leading to neutron-unbound states of ^{211}Bi in the ^{209}Bi(^{6}He,^{4}He) reaction. To do this, it was necessary to use a highly efficient neutron detector. This detector, the "neutron

wall" was placed at an angle opposite to the outgoing α particle to avoid confusion with neutrons from ^{5}He decay and/or direct breakup, and it had a very low neutron energy threshold. The experiment was carried out at the Nuclear Structure Laboratory of the University of Notre Dame. A primary beam of ^{7}Li at a laboratory energy of 30.4 MeV was incident on a gas-cooled ^{9}Be production target. The TwinSol [8] radioactive nuclear beam facility was used to focus the resulting ^{6}He beam into a secondary target chamber located in a shielded room 7.5 m downstream of the primary target, while rejecting unwanted secondary beam species. To reduce the intense neutron and γ-ray background coming from the primary target, TwinSol was used in the "no-crossover" mode and 60 cm of high-density polyethylene followed by 30 cm of "heavimet" shielding was introduced on the beam axis between the primary and secondary targets. Furthermore, a wall of water containing dissolved borax (sodium tetraborate pentahydrate) was situated at the entrance to the room containing the secondary target chamber.

The ^{209}Bi target had an areal density of 3.25 mg/cm^2, and the laboratory energy of the ^{6}He beam at its center was 23.1 MeV. This is just above the Coulomb barrier, which is at approximately 20 MeV [1]. The α particles were detected in a Si ΔE-E telescope with a 2-cm-diameter circular aperture, mounted (in two separate runs) at angles of 90° and 120° relative to the beam axis. These angles are near to and beyond the "grazing angle," respectively [1]. Because the telescope was only 4 cm from the target and the beam was approximately 8 mm in diameter, a Monte Carlo simulation was carried out to determine an effective solid angle of 215 ± 2 msr, corresponding to an average angular resolution of $\pm 6°$. The signal from the α-particle detector also served as the event trigger for the neutron coincidence and time-of-flight measurement.

The "neutron wall" consists of an array of eight position-sensitive plastic scintillator bars, each of which is 160 cm high by 15 cm wide $\times$ 5 cm thick. This array was placed such that its center was at a distance of 299 cm from the target. The angle relative to the beam at the center of the wall was $-44°$, and the plane of the array was perpendicular to the radius vector to the target. The bars were placed at angles ranging from $-32°$ to $-57°$. Each bar subtended about 3.5° in the horizontal plane (somewhat more if one considers their vertical extent). However, the angular resolution was primarily determined by that of the Si detector telescope as mentioned above. Taking this into consideration, the angle between the α particle and the neutron could range from 116° to 153° when the Si telescope was at 90° and from 146° to 183° when the Si telescope was at 120°. The total solid angle covered by the neutron wall was 1.6% of 4π.

Because it was important to detect neutrons of energy less than 1 MeV with reasonable efficiency, the discriminator levels on the signals from the two photomultiplier tubes viewing each scintillator bar were set as low as possible and a fast coincidence was required between them to reduce the electronic noise. Further cuts were placed on the position spectrum (requiring the event to occur within the length of the scintillator bar) and on the light output from the scintillator. The latter cut required the light output to be consistent with the energy of the "neutron" as determined from its time of flight. At each energy, the neutron can produce a maximum light output corresponding to full transfer of its energy to a proton in the scintillator. Events having more than this empirically determined maximum energy-deposit generally corresponded to scattered γ rays that traveled a larger path from the target to the detector. The efficiency of the detectors was determined using a ^{252}Cf source, applying the same cuts to the data described above. The neutron spectrum from this source is well known [9]. The extracted efficiencies ranged from 33% at 0.3 MeV to a maximum value of 39% at 0.55 MeV to 28% at 6 MeV, which was the highest energy neutron accepted. Below 0.3 MeV, the neutron efficiency drops rapidly to zero so this was the lowest accepted energy.

The signal in this experiment is expected to be small. Considering the solid angle and efficiency of the detector and the neutron evaporation multiplicity, only about 1% of the two-neutron-transfer events will result in a detected neutron. Therefore, it was important to accurately determine the background. The major source of background was accidental coincidences between an α particle in the Si telescope and an event in the neutron wall. The probability of accidental coincidences, evaluated using the elastically scattered ^{6}He ions, was typically 0.2–0.4%. Background events can also come from neutrons and γ rays produced in a reaction in the target that scatter into the neutron wall from material in the environment. The probability for detection of these "scattered " events was determined by blocking the direct path to the neutron wall with a brass and "heavimet" blocker that attenuated the neutrons by a factor of at least 100 (and the γ rays by an even larger factor). The ratio of scattered to accidental events was 0.40 ± 0.37, and the additional background coming from scattered events was calculated to be 0.2%.

The energy spectra of the neutrons detected in this experiment are shown in Fig. 1, after subtraction of the background.

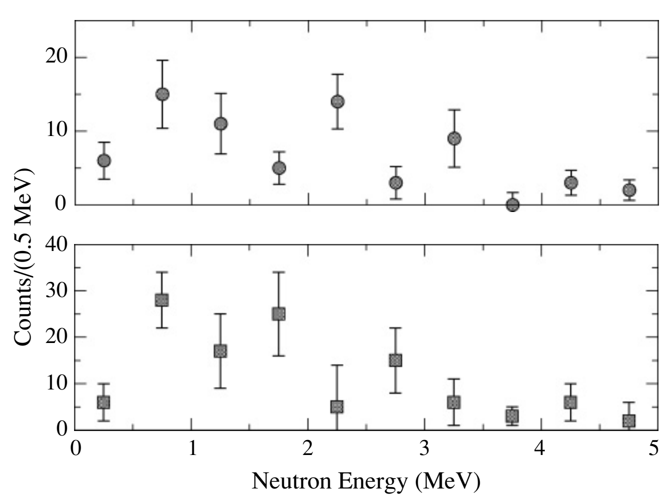

FIG. 1. The energy spectra of "evaporation" neutrons coincident with α particles, after subtraction of the background. The top plot shows neutrons in coincidence with the 120° detector, whereas the bottom plot shows neutrons in coincidence with the 90° detector. These data are not corrected for the neutron detection efficiency, which falls off rapidly below 0.3 MeV. See text for a further discussion.

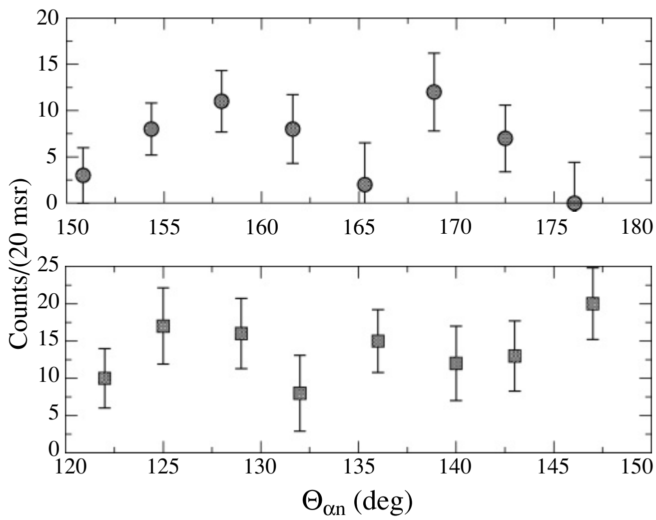

FIG. 2. The angular distributions of "evaporation" neutrons coincident with α particles, after subtraction of the background. The top plot shows neutrons in coincidence with the 120° detector, whereas the bottom plot shows neutrons in coincidence with the 90° detector. Both distributions are consistent with isotropy within experimental error ($\chi^2 = 0.96$).

As expected, they are consistent with a thermal distribution peaking at an energy below 1.0 MeV. Note that these spectra have not been corrected for the efficiency of the neutron detector, so the falloff in yield at energies below 0.5 MeV is mainly a detector effect. The calculated efficiency at energies below 0.3 MeV falls off so rapidly that a reliable value is not available for the data in the 0–0.5 MeV bin. The neutron angular distributions, shown in Fig. 2, are consistent with isotropy. It is important to note that kinematics ensures that only "evaporated" neutrons can be detected in the geometry of the present experiment, and the neutron energies and angular distributions reflect this restriction. The raw ratios of neutrons (between 0.3 and 6.0 MeV) to α particles were $9.4 \pm 1.1 \times 10^{-3}$ at a Si-telescope angle of 90° and $11.3 \pm 1.3 \times 10^{-3}$ at 120°. Corrected for background, these become $6.3 \pm 1.6 \times 10^{-3}$ and $5.6 \pm 2.1 \times 10^{-3}$, respectively.

These data can be used to deduce the fraction of the α particles coming from two-neutron transfer to neutron-unbound final states in ^{211}Bi. As mentioned above, the solid angle of the neutron wall is 1.6% of 4π, the average efficiency for neutron detection is 37%, and the neutron multiplicity was computed to be 1.47. In addition, there is a correction factor of 1.25 (calculated with PACE2 [7]) coming from the fact that the neutron angular distribution is isotropic in the c.m. of the recoiling ^{211}Bi, not in the laboratory frame. Taking all of these factors into account, the expected ratio of neutrons to α particles if ***all*** the α particles come from $2n$ transfer is 10.9×10^{-3}. The corresponding percentages of the reaction yield are $58 \pm 15\%$ at 90° and $51 \pm 19\%$ at 120°. Adding in the $1n$-transfer result [6], the total neutron transfer fraction from ^{6}He + ^{209}Bi is $75 \pm 12\%$ at angles equal to or greater than that of the "grazing peak." Presumably, the remaining 25% of the α-particle yield comes from direct breakup. However, this hypothesis must be verified in another experiment using a different detector geometry that is optimized for the detection of direct-breakup neutrons.

The differential cross sections were computed from the measured target thickness and the number of incident ^{6}He ions. Normalizing the observed elastic-scattering yield to the number of ions incident on the target and the target thickness, the ratios to the Rutherford cross section, averaged over the detector apertures, were 0.35 ± 0.05 at 90° and 0.094 ± 0.010 at 120°. (The uncertainties are dominated by systematic error.) These can be compared with the values of 0.37 at 90° and 0.101 at 120° computed at the energy of the present experiment from the optical-model parameters in Ref. [1], which were derived from a previous study of ^{6}He elastic scattering at nearby energies. This good agreement verifies the accuracy of the normalization procedure. Using the measured target thickness, the number of incident ions, and the number of α particles detected, the two-neutron-transfer cross sections were calculated to be 57 ± 17 mb/sr at 90° and 25 ± 10 mb/sr at 120°. The corresponding one-neutron-transfer cross sections [6] are 22 ± 3 mb/sr at 90° and 9 ± 2 mb/sr at 120°. Based on these data, and assuming Gaussian angular distributions as observed in Ref. [1], the total $2n$- and $1n$-transfer cross sections are 410 ± 122 mb and 155 ± 25 mb, respectively. Dominance of two-neutron transfer leading to fission was recently observed for ^{6}He incident on ^{238}U [10]. Surprisingly, there appears to be little or no evidence for fission following one-neutron transfer in these data [10]. It would be interesting to investigate if this is due to a target dependence of the reaction mechanism or to selectivity in the fission trigger.

There are several sources of systematic error that must be taken into account in this experiment, but most of them would not tend to decrease the large measured cross sections by very much or would even increase them. For example, it is unlikely that either the neutron efficiency or the angular distribution correction factor are more than 10% greater than their nominal values. In addition, a small number of events will result in neutrons having energies below the threshold of the detection system. The only significant factor that would tend to reduce the cross section is the neutron multiplicity, but it seems very unlikely that this could be as large as 2 rather than the nominal value of 1.47. Thus, even with a generous estimate of the systematic error, the minimum value of the $2n$-transfer fraction will not be less than 40%. On the other side, the data are bounded by the observation that 20% of the yield comes from $1n$ transfer [6]. As a result, a much smaller average neutron detection efficiency (say 25% rather than 37%) is not consistent with experiment, and the $2n$-transfer fraction must certainly lie between two and four times the previously measured $1n$-transfer fraction.

In conclusion, we have measured α particles coming from the ^{6}He + ^{209}Bi reaction at energies near the Coulomb barrier, in coincidence with neutrons in the backward hemisphere relative to the direction of the α particle. This geometry strongly discriminates against neutrons coming from either single-neutron-transfer or direct projectile breakup processes. The observed neutron energy spectra and angular distributions are consistent with those expected for neutrons "evaporated" from ^{211}Bi reaction products formed via two-neutron transfer. The fraction of α particles coming from $2n$ transfer is $55 \pm 12\%$

at angles greater than or equal to that of the "grazing peak," and the corresponding integrated cross section is 0.4 ± 0.1 b. These observations validate the hypothesis [1] that a major fraction of the very large α particle yield in this reaction comes from $2n$ transfer, because of the excellent overlap between the wave functions of the weakly bound neutrons in ^{6}He and those in neutron-unbound levels of ^{211}Bi. In fact, the $2n$-transfer yield is 2.5–3 times that of the previously measured [6] $1n$-transfer process. It would be very interesting to see if coupled-channel Born approximation calculations could shed light on the question of whether the $2n$-transfer process occurs mainly via successive or cluster transfer. Unfortunately, even the most sophisticated of such calculations are at present not able to treat this problem without severe truncation of the model space. This is basically a four-body problem involving unbound states of the projectile, the intermediate ^{5}He recoil, and the ^{211}Bi residual nucleus. Furthermore, the properties of the relevant ^{211}Bi states are poorly known.

It remains to measure the direct-breakup yield, which should result in projectile-related neutrons having a different energy and angular distribution than those from either $1n$ or $2n$ transfer. If one assumes that direct $2n$-breakup ($Q = -0.97$ MeV) occurs reasonably near to the distance of closest approach, then the outgoing neutrons would have very low energy. Kinematics prevents these neutrons from traveling in the direction opposite to that of the α particle in the laboratory system, which was one of the more important reasons for selecting the detector geometry used in the present work. Instead, they should be "forward focused" at an angle that is roughly 1/2 the laboratory angle of the detected α particle. Preliminary data, obtained in the present work with a charged-particle monitor detector at a more forward angle, suggest that direct breakup might possibly be measurable at α-particle angles corresponding to larger impact parameters, but additional experiments will be necessary to confirm this very tentative observation.

This work was funded through support from the U.S. National Science Foundation under Grants PHY02-44989 (University of Michigan), INT03-05347 (University of Notre Dame), PHY01-998061 (Hope College), PHY00-72314 (Indiana University South Bend), and by the CONACYT (Mexico). The construction of TwinSol was funded by the NSF under Academic Research Instrumentation Grant PHY95-12199.

[1] E. F. Aguilera *et al*., Phys. Rev. Lett. **84**, 5058 (2000).
[2] E. F. Aguilera *et al*., Phys. Rev. C **63**, 061603(R) (2001).
[3] A. Di Pietro *et al*., Phys. Rev. C **69**, 044613 (2004).
[4] A. Navin *et al*., Phys. Rev. C **70**, 044601 (2004).
[5] J. J. Kolata *et al*., Phys. Rev. Lett. **81**, 4580 (1998).
[6] J. P. Bychowski *et al*., Phys. Lett. **B596**, 26 (2004).
[7] A. Gavron, Phys. Rev. C **21**, 230 (1980).
[8] M. Y. Lee *et al*., Nucl. Instrum. Methods in Phys. Res. **A422**, 536 (1999).
[9] H. R. Bowman, S. G. Thompson, J. C. D. Milton, and W. J. Swiatecki, Phys. Rev. **126**, 2120 (1962); H. R. Bowman, J. C. D. Milton, S. G. Thompson, and W. J. Swiatecki, *ibid*. **129**, 2133 (1963).
[10] R. Raabe *et al*., Nature **431**, 823 (2004).