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Partial residue cross sections for fusion and transfer have been measured from the intensities of characteristic γ-rays for the ^{4,6}He + ^{63,65}Cu systems at energies near the Coulomb barrier (V_b). Large reaction cross sections (compared to ^{4}He) were obtained from the measured elastic scattering angular distributions for ^{6,8}He. First direct measurements of transfer, isolated from breakup reactions, involving Radioactive Ion Beams (RIB) at energies near V_b are presented. The large measured transfer cross sections, compared to breakup, are shown to influence the understanding of fusion with weakly bound nuclei around the Coulomb barrier.

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Nuclei far from stability, characterized by small binding energies and large values of isospin, exhibit a variety of novel properties like extended wavefunctions of the valence nucleon(s), a Borromean structure (a three body bound system, where any of its two body subsystems are unbound) and large breakup probabilities. These features are expected to strongly affect the reaction dynamics with RIB especially at energies near the Coulomb barrier [1]. The recent advent of facilities using the Isotope Separation On-Line (ISOL) technique has opened up new challenges in measuring and understanding reactions with low intensity RIB at energies near V_b. Fusion reactions, which are relevant to the production of super heavy elements and reactions of astrophysical interest, are currently being investigated to understand the conflicting results/predictions of the influence of breakup with weakly bound nuclei [2–4]. The main difference with respect to well bound nuclei is the presence of additional contributions from the capture of fragments, arising from the breakup of the projectile, affecting both the experimental and theoretical interpretation of fusion. Due to the experimental limitations in disentangling breakup (all the projectile fragments survive after the interaction) and transfer (only one of the projectile fragments survives) contributions, studies of transfer reactions with RIB at energies near the Coulomb barrier are sparse. Only indirect estimates for the contributions of transfer have been attempted from the measurements of α particles in ^{6}He induced reactions [5, 6]. Transfer measurements in addition to being a spectroscopic tool [7], would address the relative importance of transfer and breakup in weakly bound nuclei and also their influence in a coupled channels framework on the fusion process (expected from studies with stable beams) [8, 9].

With this motivation, we report here measurements of in-beam γ-rays from residues and angular distributions of projectile like charged particles in the reactions of ^{6,8}He with ^{63,65}Cu at two energies above the Coulomb barrier to obtain fusion, transfer and total reaction cross sections. These were compared with measurements for ^{4}He+^{63,65}Cu systems at energies near V_b. Studies with ^{6,8}He (S_{2n}=0.97, 2.1 MeV) Borromean nuclei [10], provide a unique opportunity to measure and understand in a model independent way (relative to the stable ^{4}He), the role of the small binding energy and neutron correlations on the reaction mechanism.

The measurements with ^{4}He beams, were made at the 14UD BARC-TIFR Pelletron Accelerator Mumbai, in the energy range 16 to 34 MeV. The intensities of the low lying characteristic γ-rays from the evaporation residues (ER) were measured, using 4 efficiency calibrated Compton suppressed clover detectors, to obtain the total fusion cross sections [11, 12]. RIB of ^{6,8}He were obtained from the recently commissioned ISOL facility, SPIRAL at GANIL [13]. The fragmentation of 75 MeV/A ^{13}C beam on a graphite target was used to produce the ^{6,8}He ions which were accelerated by the CIME cyclotron to 19.5 ($\sim$1.8 V_b) and 30 MeV for ^{6}He and 27 MeV for ^{8}He (typical energy resolution, $\frac{\Delta E}{E} \sim 10^{-3}$). The ^{6}He and ^{8}He beams with 5 mm and 8 mm FWHM had average intensities of 1×10^7 particles/sec and 7×10^4 particles/sec which were measured using a Faraday cup with a current amplifier and a plastic scintillator ($2''\phi$) respectively. The targets were 2.8 mg/cm^2 and 3.2 mg/cm^2 rolled foils of enriched ^{63}Cu and ^{65}Cu. The characteristic γ-rays from the residues produced in the reactions were detected using 8 clover detectors of the EXOGAM array [14] placed at a distance of 10.5 cm from the target. The charged particles were detected in a 500 μm thick annular Si detector (active inner and outer diameter of 22 mm and 70 mm, with 16 rings and 16 sectors) having a typical energy resolution of ~300 keV for the elastic peak, placed 3.5 cm downstream from the target. Simulations were performed to obtain accurate angle and solid angles for the detector folding in the finite size of the beam.

Shown in Fig. 1 are the sum of the added-back γ-ray spectra of individual clover detectors. The intensities of the well studied low lying γ-transitions extracted from the inclusive γ-ray spectra were used to obtain the partial residue cross sections for the ^{4,6}He+^{65}Cu systems which are shown in Fig. 2. Thus absolute cross sections down to a few mb have been obtained from inclusive γ-ray measurements with RIB for the first time, despite the difficulties with such measurements [15]. The present work demonstrates the wide applicability of this technique for nuclear reaction studies with low intensity RIB and thin targets at energies around V_b.

The continuous lines in Fig. 2a are statistical model calculations for the evaporation residues formed in decay of the ^{4}He+^{65}Cu system with the code CASCADE [16]. The level density formalism of Ignatyuk [17], $a = A/9$ and a suitable choice of transmission coefficients for light particle emission were used to explain the measured excitation functions. The *same set* of parameters was used to predict the partial cross sections for the ^{6}He+^{65}Cu system (Fig. 2b). As can be seen from the figures the various partial cross sections are well explained by the statistical model except for the αn channel (^{66}Cu) for the ^{6}He induced reactions. These discrepancies between the measured (filled diamond) and calculated cross sections (thick curve) for ^{66}Cu in Fig. 2b are unexpected as in a compound nucleus picture ^{66}Cu should be sufficiently excited to emit more particles. Hence these large cross sections must arise from a non-fusion process.

The large production cross sections for ^{66}Cu in the ^{6}He+^{65}Cu reactions were investigated through particle-γ coincidence events. The γ-rays measured in coincidence with any charged particle in the Si detector were found to be dominated by transitions in ^{66}Cu (Fig. 1b). A representative α particle spectrum in coincidence with γ-rays from the first excited state in ^{66}Cu (full curve) is shown in Fig. 3a. This Q-value spectrum, which peaks near Q=0 is consistent with semi-classical matching conditions for neutron transfer (expected to peak near Q=Q_{opt}=0) [18]. Considering the large spectroscopic factor of α+2n for the ground state of ^{6}He [10] the above spectrum is interpreted as arising from a 2n transfer leading to α+^{67}Cu. As seen from Fig. 3a, the peak of the Q-value spectrum is well above S_{1n} (in the residual ^{67}Cu) and is consistent with the observed large cross section for ^{66}Cu and the

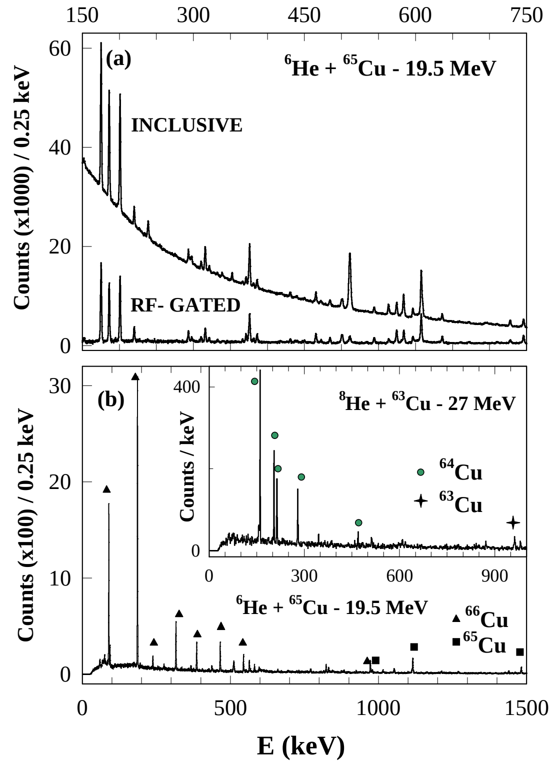

FIG. 1: γ-ray spectra for ^{6,8}He+^{63,65}Cu. (a)Inclusive spectrum for ^{6}He+^{65}Cu at 19.5 MeV and the spectrum gated with the pulsed beam showing the suppression of the background. All dominant peaks are identified. (b) Spectra in coincidence with charged particles detected in the annular Si detector for ^{6,8}He. The lines corresponding to target like products (arising from neutron transfer followed by evaporation) are labeled.

absence of ^{67}Cu (Fig. 1b). The occurrence of ^{65}Cu is expected for energies above S_{2n} and is confirmed by the observed Q-value spectrum gated by γ-rays from ^{65}Cu (dotted curve in Fig. 3a). These measured Q-value spectra are thus consistent with a two neutron transfer followed by evaporation [19]. The corresponding angular distributions for α particles in coincidence with ^{66}Cu are shown in Fig. 4a, peaking at grazing angles (measured from the elastic scattering angular distributions (Fig. 4b)), and are seen to be consistent with those for a transfer process. Similar conclusions were drawn at 30 MeV and also from the large excess for the production of ^{64}Cu (αn channel) observed in the ^{6}He+^{63}Cu system at 30 MeV. The measured neutron transfer cross section for the ^{6}He+^{65}Cu system at 19.5 and 30 MeV were 355±30 mb and 335±50 mb respectively.

The Q-value spectrum for the ^{8}He+^{63}Cu system at 27 MeV, in coincidence with the 159.1 keV transition to the ground state in ^{64}Cu is shown in Fig. 3b. The characteristics of this Q-value spectrum (and the dominance of the ^{64}Cu as seen in Fig. 1b) is similar to those discussed for the ^{6}He+Cu systems and is thus consistent with a direct

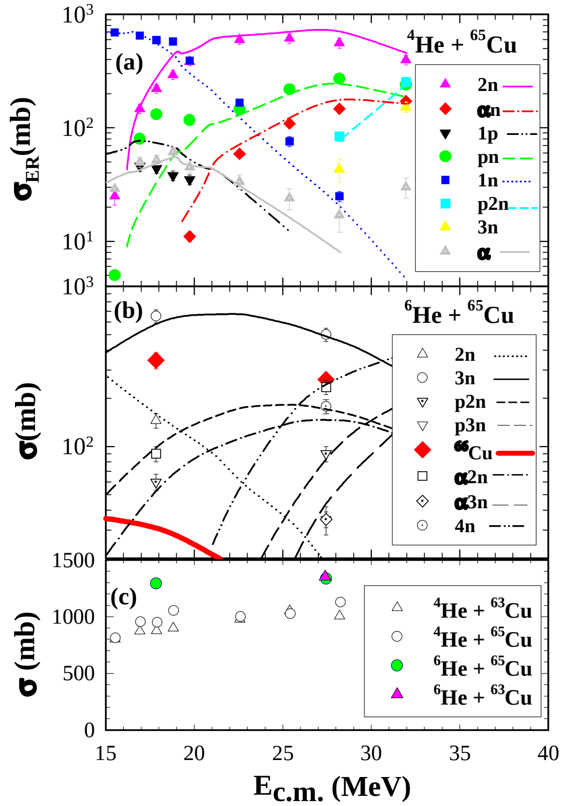

FIG. 2: (a) Measured partial residue cross sections, indicated by different symbols for ^{4}He+^{65}Cu system as a function of the centre of mass energy. The lines are obtained using the statistical model code CASCADE (see text). (b) Same as in (a) for the ^{6}He+^{65}Cu system. (c) Total residue cross section for ^{4}He+^{63,65}Cu (open symbols) and ^{6}He+^{63,65}Cu (filled symbols). Only statistical errors are shown.

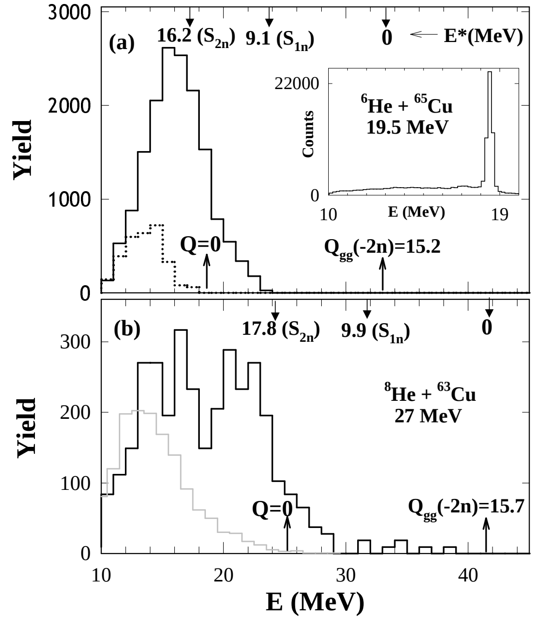

FIG. 3: Charged particles measured in the annular Si detector. (a) In coincidence with the 185.9 keV γ transition in ^{66}Cu (full line) and 1115.5 keV in ^{65}Cu (dotted line) for ^{6}He+^{65}Cu at 19.5 MeV at θ_{lab}=35°. The yields have been corrected for efficiency and branching of the gating transition. Inset shows the corresponding inclusive spectrum. (b) ^{8}He+^{63}Cu at 27 MeV gated by the 159.1 keV in ^{64}Cu at θ_{lab}= 37°. The gray curve is a calculated α evaporation spectrum using a statistical model. The ground state Q-values (Q_{gg}) and the neutron separation energies in the residual nucleus, in a two neutron stripping reaction are indicated.

evidence of $2n$ transfer followed by evaporation. The only difference from Fig. 3a is the presence of an additional peak at a lower energy which corresponds to expected α particles from compound nuclear evaporation (and *maybe* $4n$ transfer). Due to the large γ background from the β^- decay of the ^{8}He beam to excited states in Li, only an approximate estimate of the cross section could be made for this system. The present measurements of the heavy residues in coincidence with projectile like charged particles for ^{6,8}He are a direct evidence for the large transfer cross sections at energies near the Coulomb barrier.

An important contribution to the reaction cross section is the direct breakup of ^{6}He into α particles and neutrons. The breakup cross sections were inferred from the difference of the reaction and the measured sum of fusion and transfer cross sections (Fig. 2c). The reaction cross sections were obtained from measured elastic scattering angular distributions at 19.5 and 30 MeV and are shown in Fig. 4b. Large reaction cross sections were obtained for ^{6,8}He (compared to ^{4}He) by fitting the angular distribution (Fig. 4b,c) using ECIS97 [22] with a real and imaginary potential having a geometry similar to Ref [20, 21]. Breakup cross sections thus obtained are 210 mb and 280 mb for ^{6}He+^{65}Cu at 19.5 and 30 MeV respectively.

The present measurements clearly show that transfer cross sections are larger ($\sim$ 1.5) than the breakup cross sections contradictory to simple expectations. The measured large cross sections for this Q-matched transfer channel implies a strong coupling strength to the elastic channel [18]. Neutron transfer reactions involving nuclei near the drip line, with large positive Q values are expected to have a strong influence on the fusion process [9]. State of art coupled channels calculations [8] for fusion, incorporating the effect of breakup, have not yet taken into account coupling to the transfer channel and the evidence of large transfer cross section from the present work should stimulate efforts in this direction. The significant cross sections of transfer reactions with RIB at energies near the Coulomb barrier make it a feasible probe to investigate the structure of these weakly bound nuclei, *e.g.* the relative cross sections for $1n$ and $2n$ transfer could provide an insight to the spatial correlations of the valence neutrons in Borromean nuclei.

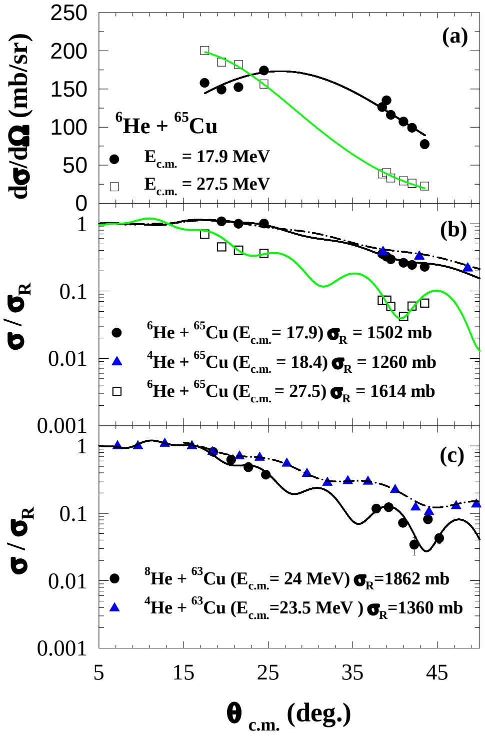

FIG. 4: (a) α particle angular distributions in coincidence with ^{66}Cu for ^{6}He+^{65}Cu. The lines are Gaussian fits to the data. (b) Elastic angular distributions for ^{6}He+^{65}Cu and for ^{4}He+^{65}Cu (Ref [20]). The lines are coupled channel calculations using ECIS. (c) Same as in (b) for ^{8}He+^{63}Cu and ^{4}He+^{63}Cu (Ref [21]). Only statistical errors are indicated

Complete fusion cross sections with RIB at energies above the barrier are expected to be "suppressed" compared to their stable counterparts as inferred from investigations with weakly bound stable nuclei [11, 23]. In the present measurement of the fusion cross sections with ^{6}He on medium mass targets, a suppression with respect to the stable isotope is not observed, as events (^{4}He+Cu) from the capture of the charged fragment arising from breakup could not be separated from the complete fusion (^{6}He+Cu) events. (The ratios of the various ER formed is similar in the two, given the energetics of breakup of ^{6}He and the Q-values involved.) In studies of fusion with weakly bound nuclei, capture of the neutral fragment by the target has not been considered and the present study shows that the cross section for the capture of the neutron(s) is large and arises from a direct process (transfer). These events lead to residues which can also be formed in complete fusion, emphasizing the need for identifying the mechanism of residue production (direct or compound) formed in reactions involving light neutron rich RIB. A sum of these residue cross sections which includes a direct contribution in addition to fusion would lead to erroneous conclusions of the effect of weak binding on the fusion process. Recent re-measurements for the ^{6}He + ^{238}U [24] system corroborate this fact, where α particles measured in coincidence with fission fragments show large cross sections for (neutron) transfer induced fission which contributed to the earlier quoted fusion-fission cross sections [25].

In summary, we have presented results for fusion, transfer, breakup and elastic scattering of ^{4,6,8}He on ^{63,65}Cu targets near the Coulomb barrier. The possibility of measuring small fusion and transfer cross sections with *inclusive* in beam γ-ray measurements using a highly efficient array in conjunction with low intensity ISOL beams has been demonstrated. A surprisingly large cross section for neutron transfer was measured and its implication for fusion is discussed, highlighting the important role of transfer in understanding reactions with RIB near the Coulomb barrier. Kinematically complete experiments with upcoming facilities should propel our understanding of the reaction dynamics of exotic nuclei to a deeper level.

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