Near-Barrier Fusion of Sn+Ni and Te+Ni Systems: Examining the Correlation between Nucleon Transfer and Fusion Enhancement

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Near-barrier fusion of Sn+Ni and Te+Ni Systems: Examining the correlation between nucleon transfer and fusion enhancement

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The fusion excitation functions for radioactive ^{132}Sn+^{58}Ni and stable ^{130}Te+^{58,64}Ni were measured at energies near the Coulomb barrier. The coupling of transfer channels in heavy-ion fusion was examined through a comparison of Sn+Ni and Te+Ni systems, which have large variations in the number of positive Q-value nucleon transfer channels. In contrast with previous experimental comparisons, where increased sub-barrier fusion cross sections were observed in systems with positive Q-value neutron transfer channels, the reduced excitation functions were equivalent for the different Sn+Ni and Te+Ni systems. The present results suggest a dramatically different influence of positive Q-value transfer channels on the fusion process for the Sn+Ni and Te+Ni systems.

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Gaining insight into the dynamics of heavy-ion fusion at near- and sub-barrier energies has been the motivation for numerous research efforts [1, 2]. Nuclear fusion is the source of energy generation in stars and explosive stellar environments. Moreover, the synthesis and exploration of the heaviest elements is accomplished using heavy-ion fusion. In the collision between two nuclei, a barrier is formed from the sum of the attractive nuclear potential and a repulsive Coulomb potential. Fusion can occur if the system is able to overcome or tunnel through that barrier. Originally, the only degree of freedom thought to be important in the fusion process was the relative motion of the nuclei, as described by the one-dimensional barrier penetration model (BPM). However, the measured fusion probabilities at sub-barrier energies for heavy-ion reactions showed large enhancements beyond the BPM [1, 2]. In many cases, coupled-channels calculations have been able to describe the enhanced fusion probabilities through the coupling of inelastic excitations and nuclear deformations of the interacting nuclei [2, 3]. The ability to extract barrier distributions from precise fusion measurements has been instrumental in understanding the interplay among different degrees of freedom [2].

While nuclear structure couplings appear to be well described within the coupled-channels approach, the inclusion of nucleon transfer channels is difficult and, in most cases, can only be qualitatively included in the coupled-channels calculations [1–5]. Strong evidence of sub-barrier fusion enhancement due to coupling with nucleon transfer channels has been shown in numerous experiments and theoretical analyses [2, 5, 6]. For example, large enhanced sub-barrier fusion probabilities were observed in the ^{40}Ca+^{48}Ca [7], ^{28}Si+^{94}Zr [8], ^{32}S+^{96}Zr [9], ^{32}S+^{110}Pd [10], and ^{40}Ca+^{124}Sn [11] systems, which all have an increased number of positive Q-value neutron transfer channels, in comparison to their isotopic counterparts with no positive Q-value transfer channels. While these previous studies have shown correlations between the number of positive Q-value neutron transfer channels and enhanced sub-barrier fusion, it is important to note that the transfer couplings also depend on the states and Q-values populated by transfer and the transfer form factor.

Stefanini *et al.* studied the fusion of calcium and zirconium isotopes to examine the influence of transfer channels [12]. A significant increase in the sub-barrier fusion cross sections was observed in the ^{40}Ca+^{96}Zr system, which has 9 positive ground state to ground state (g.s.→g.s.) Q-value neutron transfer channels, in comparison to the ^{40}Ca+^{90}Zr system, which has no positive Q-value neutron transfer channels [13]. Additional comparisons with ^{48}Ca+^{90,96}Zr [14] and ^{40}Ca+^{94}Zr [12] systems provided a consistent interpretation that the enhancement in the systems with positive Q-value neutron transfer channels was due to the transfer couplings and could not be explained by differences in the nuclear structure. The systematic approach of Stefanini *et al.* provided relatively clear evidence of the presence of transfer coupling effects in a model-independent way.

In this letter, the role of transfer in relatively heavy systems, induced with stable and radioactive ion beams, is explored in order to determine if the enhancements observed in the lighter systems discussed above remain present. Similar to the Ca+Zr study by Stefanini *et al.* [12], the influence of transfer was explored with a model-independent approach through a systematic comparison of Sn+Ni and Te+Ni systems. New fusion measurements of ^{132}Sn+^{58}Ni and ^{130}Te+^{58,64}Ni were used in the study. The new ^{132}Sn+^{58}Ni and previous ^{132}Sn+^{64}Ni [15] measurements are of particular interest since both neutron transfer couplings and the use of

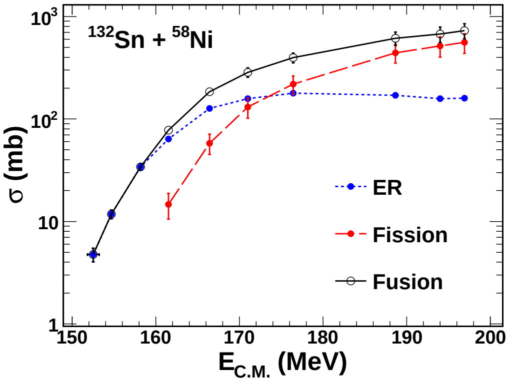

FIG. 1. (Color online) Evaporation residue (ER), fission, and fusion cross sections for the ^{132}Sn+^{58}Ni system as a function of the center-of-mass energy (E$_{C.M.}$).

neutron-rich radioactive ion beams have been predicted to provide enhanced fusion probabilities for the synthesis of super-heavy elements [16–18].

The 25 MV electrostatic tandem accelerator at the Holifield Radioactive Ion Beam Facility (HRIBF) was used to accelerate beams of radioactive ^{132}Sn and stable ^{130}Te to energies between 515 and 670 MeV. The ISOL (Isotope Separation Online) technique at the HRIBF was used to produce the ^{132}Sn radioactive ion beam (RIB) and is discussed in Ref. [19]. Beam rates for ^{132}Sn ranged from 20,000 to 175,000 particles per second. The ^{132}Sn and ^{130}Te beams bombarded 0.34 and 1.0 mg/cm^2 ^{58}Ni targets and a 1.0 mg/cm^2 ^{64}Ni target. The fitted spline method [15] was used to determine the effective reaction energies from the thick target measurements.

The fusion cross sections for ^{132}Sn+^{58}Ni and ^{130}Te+^{58,64}Ni reactions were determined from the sum of the evaporation residue (ER) and fission cross sections, as shown in Fig. 1. A detector system designed to provide high efficiency measurements of evaporation residues produced through inverse kinematics was used [20]. The apparatus consisted of two microchannel plate timing detectors (MCPs) placed before the target, which were used to monitor the beam. After the target, a $300\mu m$ annular silicon strip detector was mounted followed by a position sensitive MCP. Lastly, an ionization chamber was placed behind the final MCP at 0° relative to the beam. Additional details about the system can be found in Refs. [15] and [20].

The ERs were detected through the combination of a time-of-flight (ToF) measurement and energy-loss in the ionization chamber. The efficiency for ER detection was estimated using a Monte Carlo simulation where the angular distribution of the ERs was calculated from the PACE2 code [21]. The strong forward focus of the ERs, owing to the inverse kinematics, results in very high detection efficiencies ranging from 93.7% to 98.0%.

The annular silicon detector, placed after the target, was used to measure the energy and angle of the fission fragments. Separation of the fission events from elastic scattering and deep-inelastic collision (DIC) events was achieved by examining the kinematics, mass ratios, and folding angle distributions of the experimental data. Monte Carlo simulations were used to determine the efficiency of the silicon detector for fission fragments in coincidence. Depending on the beam energy, the efficiency for fission detection was ∼6-10%. A more complete description of the procedure and Monte Carlo simulations can be found in Ref. [15].

The reduced excitation function for the fusion of radioactive ^{132}Sn with ^{58}Ni is presented in Fig. 2. The fusion cross sections (σ) and center-of-mass energies (E$_{C.M.}$) were scaled by the geometrical cross section (πR^2) and Bass barrier height (V_{Bass}) [22], respectively. The radius was calculated as $R = r_0(A_{proj}^{1/3} + A_{tgt}^{1/3})$, where $r_0 = 1.2fm$ and A_{proj} (A_{tgt}) is the mass of the projectile (target). The cross section and E$_{C.M.}$ scalings remove the effects owing to differences in the nuclear radius and barrier position of the systems and and, thus, allow excitation functions of different systems to be compared.

A comparison of the ^{132}Sn+^{58}Ni and ^{132}Sn+^{64}Ni reduced excitation functions is shown in Fig. 2. The ^{132}Sn+^{64}Ni fusion data are from a previous measurement by Liang *et al.* [15, 23]. The results demonstrate, within the statistical uncertainty, no significant differences between the reduced excitation functions. The Q-values, calculated from the ground state masses, for different numbers of neutrons transfered from the Sn to the Ni nucleus are presented in Fig. 2(b). It should be noted that there are no positive Q-value channels for the transfer of nucleons from the Ni to Sn nucleus. The increased number of positive Q-value neutron transfer channels in the ^{132}Sn+^{58}Ni system (3-fold increase compared to ^{132}Sn+^{64}Ni) are not correlated with an enhancement in the sub-barrier fusion with respect to the ^{132}Sn+^{64}Ni system.

Additional insight can be gained through comparisons with stable Sn+Ni fusion measurements. In Fig. 2 the ^{58}Ni+^{124}Sn [24, 26], ^{64}Ni+^{124}Sn [26], and ^{64}Ni+^{118}Sn [26] fusion measurements are compared to the ^{132}Sn data. As shown in Fig 2(b), extreme differences in the number of the positive g.s.→g.s. Q-value transfer channels are present between the five systems. The ^{64}Ni+^{118}Sn system provides a “no transfer” reference since it has zero positive Q-value transfer channels. The reduced excitation functions for all five Sn+Ni systems are equivalent and showing no enhancements beyond the ^{64}Ni+^{118}Sn “no transfer” fusion excitation function.

The ^{64}Ni+^{118}Sn and ^{132}Sn+^{58}Ni measurements, which have the smallest (0) and largest (16) numbers of positive Q-value neutron transfer channels, are compared with the ^{40}Ca+^{90,96}Zr fusion excitation functions from Timmers *et al.* [13] in Fig. 3. The ^{40}Ca+^{96}Zr reaction has

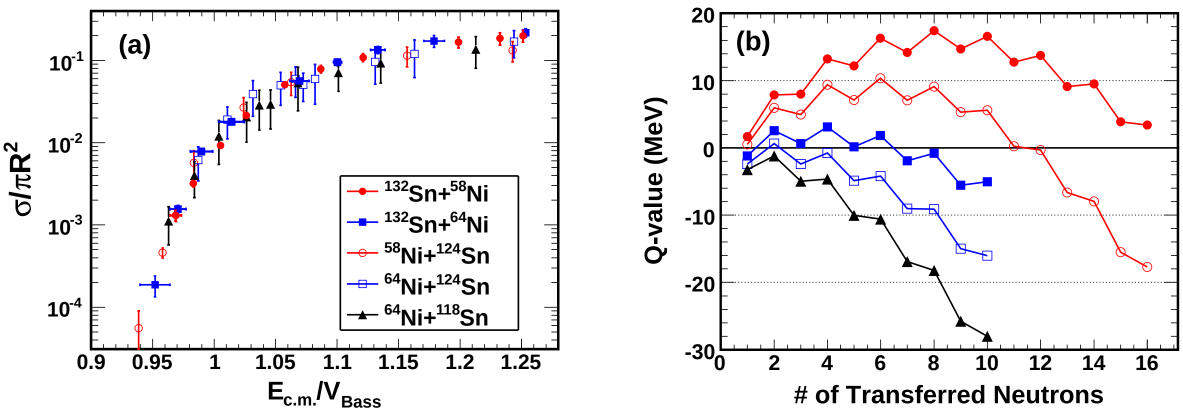

FIG. 2. (Color online) Reduced fusion excitation functions for ^{132}Sn+^{58}Ni (this work), ^{132}Sn+^{64}Ni [15, 23], ^{58}Ni+^{124}Sn [24, 25], ^{64}Ni+^{124}Sn [26], and ^{64}Ni+^{118}Sn [26] reaction systems. (b) g.s.→g.s. Q-values as a function of the number of neutrons transferred from the Sn to Ni nucleus for each of the reaction systems presented in (a). The legend shown in (a) also applies to (b).

nine positive g.s.→g.s. Q-value neutron transfer channels compared to zero for the ^{40}Ca+^{90}Zr reaction. The large positive Q-values for multi-neutron transfer corresponds to an enhanced sub-barrier fusion for the ^{40}Ca+^{96}Zr system relative to the ^{40}Ca+^{90}Zr system. At $E_{C.M.}/V_B$ = 0.96, the fusion probability for ^{40}Ca+^{96}Zr is an order of magnitude larger than the ^{40}Ca+^{90}Zr. In comparison, the Sn+Ni measurements are equivalent at $E_{C.M.}/V_B$ = 0.96 even though there are larger differences in the number of positive Q-value transfer channels. It is also interesting to note the strong similarity between the Sn+Ni and ^{40}Ca+^{90}Zr reduced excitation functions. These results clearly demonstrate that the strong correlation between sub-barrier fusion enhancement and the possession of large Q-values for multi-neutron transfer observed in previous experiments [7–14], such as Ca+Zr, is not present in the Sn+Ni systems.

The ^{130}Te+^{58,64}Ni fusion measurements, also shown in Fig. 3, provided additional confirmation that the presence of positive Q-value transfer channels have very little, if any, influence on the fusion process for the examined systems. The reduced excitation functions for the Te+Ni systems are equivalent even though the ^{130}Te+^{58}Ni system has 11 positive g.s.→g.s. Q-value transfer channels in comparison to 1 positive Q-value transfer channel for the ^{130}Te+^{64}Ni system. The Te+Ni fusion measurements demonstrate that the lack of transfer effects is not isolated to the Sn+Ni data. A consistent picture is presented from Figs. 2 and 3 showing no significant differences between the Te+Ni and Sn+Ni excitation functions, which is in stark contrast to the large enhancements observed in numerous experiments, with lighter systems, correlated with large positive Q-values for multi-neutron transfer.

The lack of strong transfer effects is additionally surprising because transfer reactions for the ^{58}Ni+^{124}Sn system, where the transfer of up to 6 neutrons was observed [27], were shown to represent a significant portion of the total reaction cross section [24] and a previous coupled-channels analysis by Esbensen *et al.* of the fusion excitation function indicated enhancement due to transfer couplings [28]. Despite these results, the experimental data (Figs. 2 and 3) provide no indication of enhancements due to increased numbers of positive Q-value transfer channels.

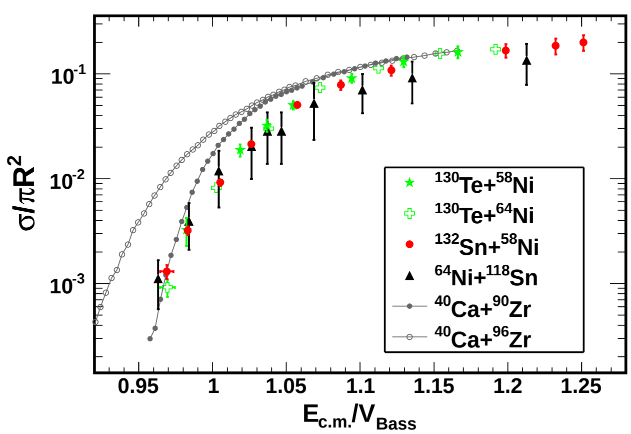

FIG. 3. (Color online) Reduced excitation functions for the ^{130}Te+^{58,64}Ni (this work), ^{132}Sn+^{58}Ni (this work), ^{64}Ni+^{118}Sn [26], and ^{40}Ca+^{90,96}Zr [13] systems.

Lastly, since the interpretation of the results depends on the ^{64}Ni+^{118}Sn system representing a “no transfer” reference coupled-channels calculations were performed, using the CCFULL code [29], to examine if the inelastic excitations alone, without transfer, could describe the

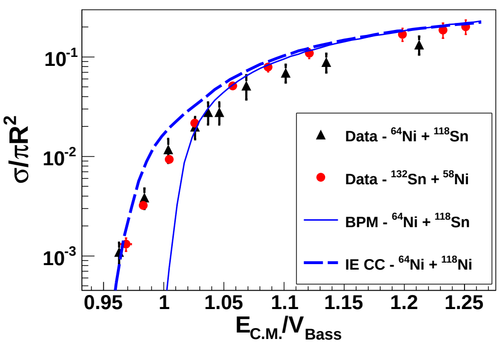

FIG. 4. (Color online) Reduced fusion excitation function for the ^{64}Ni+^{118}Sn reaction system (data taken from Ref. [26]) is compared with the 1-D barrier penetration model (BPM) and the coupled-channels calculations including inelastic excitations (IE CC) shown as the thin and thick dashed solid blue lines, respectively. Additionally, the experimental ^{132}Sn+^{58}Ni fusion excitation function is shown.

measured excitation function. CCFULL uses the incoming wave boundary condition, which requires a deep potential for calculating fusion cross sections at high energies [30]. Therefore, a minimization code was used to fit a potential with a depth of V_0=150 MeV to the Akyüz-Winther potential [31] by varying the radius (r_0) and diffuseness (a_0) to reproduce r_b, V_b, and $\hbar\omega$ of the A-W potential. Coupled-channels calculations including the 2^+ and 3^- states of ^{118}Sn and ^{64}Ni, all one-phonon excitations, the double phonon $(2^+)^2$ and $(3^-)^2$ states, and the 4 lowest-energy mutual excitations of double phonon states were completed using the modified deep potential. The B(E2) and B(E3) reduced transition probabilities were taken from Refs. [32] and [33], respectively, for the stable isotopes.

The coupled channel calculations are shown along with the experimental ^{64}Ni+^{118}Sn reduced excitation function in Fig 4. A strong enhancement in the fusion probability relative to the BPM (thin solid blue line), or uncoupled calculation, is observed. While the results of the calculation including inelastic excitations, IEs, (thick dashed blue line) slightly overestimate the cross sections above the barrier, the magnitude of the sub-barrier enhancement is reproduced. The overestimation of calculation above the barrier could be related to the observed fusion hindrance in the ^{64}Ni+^{118}Sn system [26]. The comparison demonstrates, within the coupled-channels approach, that transfer couplings are not needed to explain the ^{64}Ni+^{118}Sn sub-barrier fusion cross sections and helps validate the system as a “no transfer” reference. Again, the ^{132}Sn+^{58}Ni fusion excitation functions is shown indicating no enhancement beyond the ^{64}Ni+^{118}Sn data or CC calculation. Additional coupled channel calculations, examining the other Sn+Ni and Te+Ni fusion excitation functions, will be presented in a future publication.

In conclusion, the influence of transfer couplings in the fusion of Sn+Ni and Te+Ni systems has been investigated. The fusion excitation functions for the radioactive ^{132}Sn+^{58}Ni and stable ^{130}Te+^{58,64}Ni systems were measured and compared with previous Sn+Ni fusion measurements. A systematic comparison of the reduced excitation functions and coupled-channels calculations demonstrated that the influence of transfer channels on the fusion of Sn+Ni and Te+Ni is very weak with no significant differences observed in the reduced excitation functions. This is in contrast to a number of previous measurements, with lighter systems, that showed large fusion enhancements in correlation with increased positive g.s.→g.s. Q-value transfer channels.

While the current results further complicate the role of transfer in the fusion process, they should provide a useful benchmark for theoretical models. Development of a simultaneous description of the influence of transfer in lighter systems, where enhancements are observed, and in the Sn+Ni/Te+Ni systems would be challenging and enlightening. Additionally, continuing to examine the role of transfer in relatively heavy systems should help provide insight into the diminishing transfer effects in the fusion of Sn+Ni and Te+Ni. It would also be of interest to examine how the increasing presence of deep-inelastic collisions in these heavier systems could be related to the present results [24, 28]. While these results demonstrate how RIBs can allow for expanded systematic studies, future precision measurements to extract barrier distributions of the heavy stable systems would compliment the RIB measurements and allow for a more detailed examination of the transfer and nuclear structure couplings.

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