Searching the reason for sub-barrier fusion enhancement through multineutron transfer channels

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Background: The influence of inelastic excitations on sub-barrier fusion enhancement is well established; however, the transfer channel effect can be surprising. Recently, it has been shown that the $2n$ transfer channel is mainly responsible for sub-barrier fusion enhancement despite having a positive-Q value for many-neutron transfer channels. Moreover, some systems do not show enhancement even if they possess positive-Q-value transfer channels. It has also been reported that enhancement can be found in those systems for which deformation of nuclei increases after neutron transfer.
Purpose: The aim of this work is to examine the role of multineutron transfer channels on sub-barrier fusion enhancement.
Method: Fusion cross sections were measured with a recoil mass separator for the $^{40}Ca + ^{70}Zn$ system and analyzed theoretically within the framework of coupled-channels calculations.
Results: Positive Q-value neutron transfer channels seem to be essential for the sub-barrier region, since inelastic excitation coupling was unable to reproduce the trend of experimental fusion cross sections. However, up to $2n$ pick-up channel was found to be sufficient for describing the sub-barrier cross sections.
Conclusions: Sub-barrier fusion in the $^{40}Ca + ^{70}Zn$ system is hardly affected by transfer of more than two neutrons. The fusion enhancement due to the transfer channel can be observed in systems for which the deformation of colliding nuclei increases after transfer, though the amount of enhancement does not seem to be proportional to the deformation change.

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I. INTRODUCTION

Though the fusion reaction around the Coulomb barrier is an extensively studied phenomenon, it has still prompted questions about the observed enhancement of fusion cross sections in the lower-energy region. It is known that fusion dynamics is affected by the nuclear structure of the colliding nuclei and neutron transfer channels [1]. Past experimental investigations have already established the role of nuclear deformation [2,3] and vibrations [4–7] via coupling of inelastic excitations in theoretical models. However, a complete understanding of the role of neutron transfer channels is still missing. A possible reason for this may be the scarcity of experimental data on transfer and the difficulty in incorporating these channels in theoretical models.

The fusion enhancement due to the transfer of neutrons at sub-barrier energies was attributed to the positive-Q-value transfer channels [8,9]. This Q-value effect was confirmed with various systems, e.g., $^{32}S + ^{48}Ca$ [10], $^{40}Ca + ^{48}Ca$ [11,12], $^{32}S + ^{96}Zr$ [13], $^{28}Si + ^{94}Zr$ [14], and $^{40}Ca + ^{96}Zr$ [15,16]; however, this effect was not found in all the systems [17]. A research work on fusion showed that there are systems in which no significant enhancement is observed due to neutron transfer [18–20]. A comparison between positive and negative-Q-value transfer channels in different systems exhibited the same trend of fusion excitation on a reduced scale; i.e., no enhancement due to positive-Q-value transfer was reported in the articles [18,19]. This observation was supported by Stefanini *et al.* [20], where inelastic excitations were able to fit the experimental excitation function, though the chosen system had a positive-Q value for a two-neutron pick-up channel. It was reported that positive-Q-value transfer channels affect fusion only if the deformation strength of nuclei increases and mass asymmetry decreases after transfer [21]. Enhancement of fusion cross sections was observed for the systems $^{32}S + ^{96}Zr$, ^{110}Pd, $^{40}Ca + ^{96}Zr$, $^{124,132}Sn$, and $^{58}Ni + ^{64}Ni$, which were in accordance with the presence of positive-Q-value transfer channels. For all these systems, deformation increases and mass asymmetry decreases after transfer of neutrons. In this article, no enhancement was observed for the $^{17}O + ^{144}Sm$, $^{18}O + ^{74}Ge$, and $^{58,64}Ni + ^{124,132}Sn$ systems due to weak deformation of nuclei after transfer. This effect of deformation on transfer coupling was also reported in other literature [22–24]. The effect of nuclear structure on sub-barrier fusion enhancement was also highlighted in an article by Stefanini *et al.* [25] where fusion cross sections at sub-barrier energies were found to be relatively larger for the $^{48}Ti + ^{58}Fe$ system compared to the $^{58}Ni + ^{54}Fe$

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system. ^{48}Ti and ^{58}Fe are soft nuclei, whereas ^{58}Ni and ^{54}Fe are rigid, which might be responsible for the different behavior of the fusion excitation function in the two systems. In one of our recent works, it was observed that transfer channels for fusion are more effective in those systems where participating nuclei are less deformed or spherical [26].

Realizing the fact that other factors could be important along with the presence of positive-Q-value transfer channels in affecting the sub-barrier fusion mechanism, Rachkov *et al.* [27] analyzed experimental data for various projectile-target combinations using the semiclassical model [28]. It was found that the effect of a one-neutron transfer channel and a two-neutron transfer channel is more prominent and this happens because the coupling of neutron transfer channels cannot influence fusion once the Coulomb barrier is overcome [27]. A similar kind of behavior within the same coupling scheme was observed for several fusion reactions [29]. Along with neutron transfer, the positive-Q-value proton transfer channel may also affect the sub-barrier fusion enhancement [30]. In an article, fusion cross sections were measured for the ^{40}Ca + ^{58,64}Ni systems [31]. Again, experimental data were well reproduced by incorporating the Q value corresponding to the $2n$ transfer; i.e., the contribution of only two neutrons is sufficient for the explanation of fusion cross sections. Further, the Q value corresponds to the first excited 0^+ state of ^{42}Ca.

The influence of positive-Q-value neutron transfer channels on fusion was further described in an article by Jia *et al.* [32]. A comparison was made between ^{32}S + ^{94,96}Zr systems. Multineutron transfer cross sections were calculated using the code GRAZING [33] and were found to be relatively larger for ^{96}Zr than ^{94}Zr. Additionally, the magnitudes of positive-Q values in ^{32}S + ^{96}Zr were higher than those in ^{32}S + ^{94}Zr. Experimental fusion cross sections were not correlated with this observation, i.e., cross sections of ^{94}Zr show a larger sub-barrier enhancement as compared to ^{96}Zr. This was found to be consistent with measurements by Kolata *et al.* with heavy-mass systems [34]. Although enhancement was related to positive-Q values, it did not appear to be proportional to the magnitude of the Q value. The importance of positive-Q-value transfer channels was further highlighted for heavy ^{58,64}Ni + ^{124}Sn systems [35] as well as for medium-mass ^{40}Ca + ^{92,94}Zr systems [36].

A systematic analysis was performed by Jiang *et al.* [37] to estimate the influence of transfer on fusion. The systems were distinguished as neutron-rich and neutron-deficient. It was concluded that the neutron-deficient projectile and the neutron-rich target have a shallower slope (more enhancement) for fusion excitation function than pure neutron-rich and neutron-deficient projectile-target systems and this was in correlation with transfer cross sections that followed Q-value systematics.

As the relevance of transfer channels to fusion is not yet clarified and positive-Q-value arguments are still confusing, further investigation of multineutron transfer and fusion may be helpful in better understanding of this problem. In past years, the ^{40}Ca nucleus was preferred as a projectile with a wide range of target nuclei in the medium-heavy region (from isotopes of calcium to uranium) for the study of fusion as well as multineutron transfer reactions. The reason for this lies in its doubly magic nature that ruled out the effect of deformation in playing a role in sub-barrier fusion enhancement. Hence, the effect of transfer channels can be visible clearly. As the aim is to examine the effect of multineutron transfer on near- and sub-barrier fusion cross sections, it is important to examine a system having a reservoir of neutrons with a large probability of transfer. For the present investigation, the ^{40}Ca + ^{70}Zn system is selected where the multineutron transfer channels are important and may play a key role in understanding the fusion enhancement mechanism. This system favors neutron transfer with positive-Q values for seven neutron pick-up channels ($Q > 0$: $2n$–$8n$). To the best of our knowledge, no measurements on fusion were reported earlier with ^{70}Zn as a target.

In this article we are reporting the study of the fusion reaction for the ^{40}Ca + ^{70}Zn system. A brief outline of the experiment is mentioned in Sec. II. Results obtained from the experimental data are given in Sec. III, followed by theoretical interpretation, making use of available coupled-channels codes. Under the same section, a comparison is also presented between positive- and negative-Q-value systems taking ^{40}Ca as a projectile for all the target nuclei. The work is summarized in the Sec. IV.

II. EXPERIMENT

The experiment was performed with a ^{40}Ca pulsed beam (250-ns pulse separation) from the Pelletron accelerator of the Inter-University Accelerator Centre (IUAC), New Delhi, India. Fusion cross sections were measured with a self-supporting ^{70}Zn target (isotopic enrichment =95%) of thickness ≈670 μg/cm^2. These measurements were carried out from beam energy 142 to 106 MeV covering the energy range from ∼17% above and 12% below the Coulomb barrier (V_b) in 2 MeV step size. Fusion cross sections were obtained from the yield of evaporation residues (ERs), which were separated from the scattered beam particles using the Heavy-Ion Reaction Analyzer (HIRA) [38]. For the present experiment, HIRA was kept at zero degree with respect to beam direction with 5 mSr solid angle of acceptance.

To detect ERs, a multiwire proportional counter (MWPC) of dimensions 15 × 5 cm^2, followed by a segmented ionization chamber (IC) with a 7.0 × 3.5 cm^2 entrance window and active lengths of 3, 5.8, and 13 cm, was placed at the focal plane of HIRA. MWPC isobutane gas pressure was maintained at ∼2 mbar, whereas pressure for the IC was ∼30 mbar throughout the experiment. Two silicon-surface barrier detectors were placed inside the target chamber to monitor the beam tuning during the experiment and for normalization of cross sections. A carbon foil 40 μg/cm^2 in thickness was placed 10 cm downstream from the target for equilibration of the charge states of ERs. To estimate the transmission efficiency of ERs through HIRA, a high-purity germanium detector was mounted on top of the target chamber at an angle of 90° to the beam direction.

The ERs were separated from the beamlike particles through a two-dimensional spectrum of energy deposited in

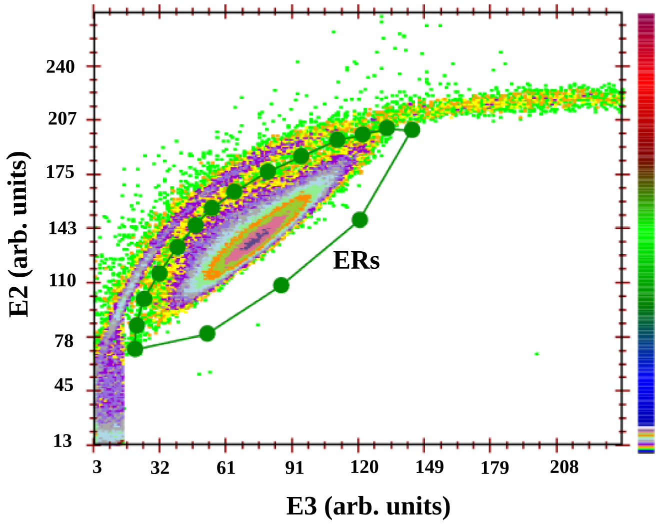

FIG. 1. Two-dimensional spectrum of energy deposited in the second segment versus energy deposited in the third segment of an IC at $E_{\rm lab} = 142$ MeV for the ^{40}Ca + ^{70}Zn system.

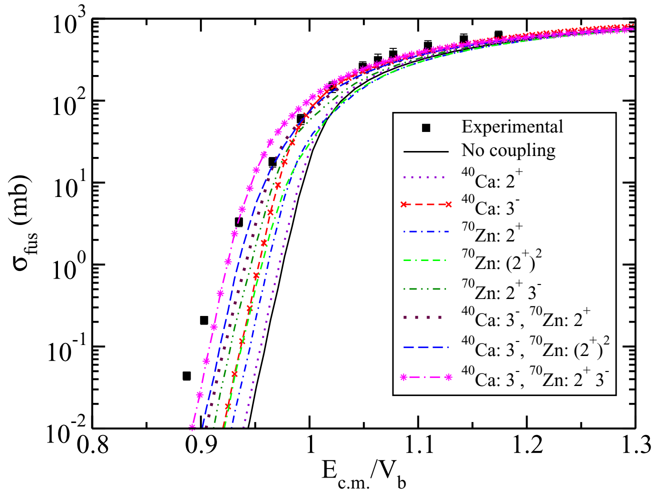

FIG. 2. Experimental fusion excitation function for the ^{40}Ca + ^{70}Zn system compared with cross sections obtained after the coupling of inelastic excitations using the CCFULL code.

different segments of the IC (segment 2 vs segment 3) as shown in Fig. 1.

III. RESULTS AND DISCUSSION

The fusion cross sections were calculated using the ERs and monitor detector yields following the same procedure as given in the literature [26]. The transmission efficiency of HIRA was also included in the calculation of fusion cross sections. The semimicroscopic Monte-Carlo code TERS [39] was used to estimate the theoretical efficiency of HIRA. The efficiency for the ^{40}Ca + ^{70}Zn system was found to be 7.6% at $E_{\rm lab} = 130$ MeV using the TERS code. The HIRA transmission efficiency was also measured experimentally by the γ-ray coincidence technique at 130 MeV laboratory energy. The details of the technique are described in the literature [14]. The efficiency value estimated experimentally was found to be 7.8% [40]. The experimentally measured fusion cross sections ($\sigma_{\rm fus}$) as a function of projectile energy in the center-of-mass frame ($E_{\rm c.m.}$) are shown in Fig. 2. The fusion cross sections obtained experimentally were analyzed within the framework of coupled-channels (CC) calculations using the CCFULL code [41]. These fusion cross sections were first compared with theoretically obtained one-dimensional barrier penetration model (1D BPM), i.e., no coupling cross sections. Further, to investigate the channel coupling effects around the Coulomb barrier energies, the contributions of inelastic states of colliding nuclei were incorporated in the calculations. The low-lying inelastic states of the projectile and the target along with the corresponding deformation strength and excitation energies are given in Table I [42,43]. The Akyuz-Winther (AW) parametrization [44] was used to obtain the Woods-Saxon potential parameters for CC calculations. These potential parameters along with the barrier energy V_b, the barrier radius R_b, and the barrier curvature $\hbar\omega$ are listed in Table II.

As shown in Fig. 2, inclusion of the 3^- state of ^{40}Ca enhanced the fusion cross sections by a significant amount, whereas the effect of the 2^+ state was found to be negligible. The lower excitation energy and the large deformation strength of the 3^- state with respect to the 2^+ state of ^{40}Ca may be the cause of the observed enhancement. An analogous effect was also observed by Stefanini *et al.* for the ^{40}Ca + ^{94}Zr system [45]. The states 2^+ and 3^- of ^{70}Zn enhanced the cross sections by similar amounts. This might be due to the comparable quadrupole and octupole deformation strengths. A slight difference in the inelastic coupling effect of target and projectile nuclei on fusion cross sections was observed. However, inclusion of these channels in the calculations enhanced the fusion cross sections, but failed to reproduce the experimental fusion cross sections. Therefore, multiphonon and mutual excitations of these states (2^+, 3^-) were included in the calculations. The effect of state 2^+ (two phonons) of the target on enhancement of fusion cross-section was observed to be negligible (Fig. 2). However, the contribution of mutual excitation, i.e., $2^+ \otimes 3^-$, was found to be significant. The coupled-channels calculations with either projectile or target excitations underestimated the fusion cross sections in the sub-barrier energy region. Hence, the combined effect of the projectile (P) and the target (T) was included in the calculations. P(^{40}Ca): 3^- and T(^{70}Zn): 2^+ (two phonons) reproduced the experimental data for the

TABLE I. Excitation energies and deformation parameters for the excited states of the projectile and the target.

Nucleus	J^π	E_J (MeV)	β_J
^{40}Ca	2^+	3.90	0.123
	3^-	3.74	0.330
^{70}Zn	2^+	0.88	0.228
	3^-	2.86	0.216

TABLE II. The AW potential parameters (V_0, r_0, a_0) and the resulting barrier parameters (V_b, R_b, $\hbar\omega$) used in coupled-channels calculations for the ^{40}Ca + ^{70}Zn system.

V_0 (MeV)	r_0 (MeV)	a_0 (fm)	V_b (MeV)	R_b (fm)	$\hbar\omega$ (fm)
69.87	1.176	0.666	76.76	10.48	3.70

above-barrier energies, whereas the combination of P: 3^- and T: $2^+ \otimes 3^-$ slightly overestimated the cross sections in this energy region. But, it failed to explain the fusion data in the below-barrier energy region. Calculations with three phonons vibrational states of projectile and target, i.e., $(2^+)^3$ and $(3^-)^3$ as well as mutual excitations of the type T: $(2^+)^2 \otimes (3^-)^2$; P: 3^-, T: $(2^+)^3$; P: $(3^-)^2$, T: $(2^+)^3$; P: $(3^-)^2$, T: $(2^+)^2 \otimes 3^-$ were also performed. The importance of these excitations on the enhancement of fusion cross sections was found to be insignificant. Because the ^{40}Ca + ^{70}Zn system has positive-Q values for neutron pick-up channels, multineutron transfer channels may be expected to affect the fusion dynamics.

An empirical coupled-channels (ECC) model was proposed by Zagrebaev *et al.* [46] that includes inelastic as well as multineutron transfer channels for calculation of fusion cross sections. The model is based on a semiclassical approximation in which the quantum penetration probability of the Coulomb barrier is calculated using the barrier distribution arising from the multidimensional nucleus-nucleus interaction. In the case of transfer, a multidimensional Coulomb barrier is considered due to different neutron transfer channels. Further, the quantum penetration probability is also modified for the sequential neutron transfer channels. For the present calculations, the ECC approach was followed to incorporate the transfer channels.

Initially, no transfer channel was taken into account in the calculations for the ^{40}Ca + ^{70}Zn system using the ECC model. Later, neutron transfer channels were also included in the calculations. The calculated fusion cross sections against center-of-mass energies are plotted in Fig. 3. It is evident from Fig. 3 that up to two-neutron transfer channels with positive-Q values are sufficient to reproduce the sub-barrier fusion cross sections. The effect of multineutron transfer channels (more than two neutrons) with positive-Q values was observed to be insignificant. Similar results were observed in earlier studies with various systems [27,29].

A systematic analysis is always advantageous to investigate the behavior of a mechanism. However, a suitable parametrization is required to analyze different sets of data in a systematic manner. For the present case, a procedure was followed to analyze the various sets of experimental data so that the behavior of 1D BPM (no coupling) became system independent [47]. The system-independent fusion cross sections and center-of-mass energies were defined as

$$\widetilde{\sigma}_{\rm fus} = \frac{2\sigma_{\rm fus}E_{\rm c.m.}}{R_b^2\hbar\omega}, \qquad \widetilde{E}_{\rm c.m.} = \frac{E_{\rm c.m.} - V_b}{\hbar\omega},$$

where $\widetilde{\sigma}_{\rm fus}$ and $\widetilde{E}_{\rm c.m.}$ are termed as the reduced fusion cross section and the reduced center-of-mass energy, respectively.

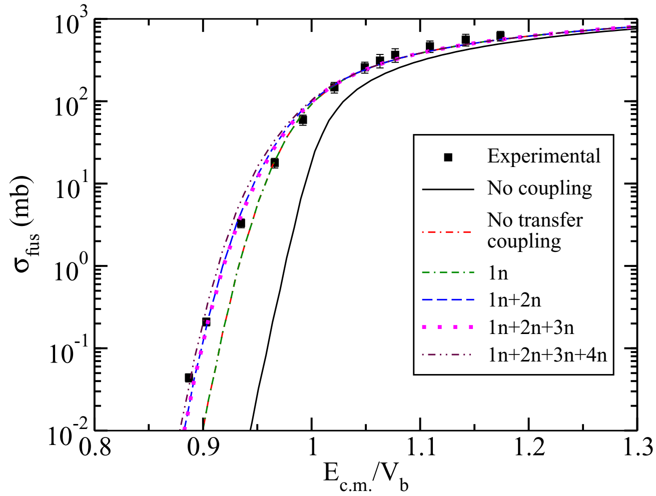

FIG. 3. Experimental fusion excitation function for the ^{40}Ca + ^{70}Zn system compared with cross sections obtained after the coupling of neutron transfer channels using the ECC code.

It is difficult to isolate the role of transfer from collective excitations, but the effect of transfer can be examined by comparing positive-Q-value systems with negative-Q-value systems. The Q values of neutron pick-up channels for the selected systems are shown in Fig. 4 [18], where ^{40}Ca is considered as the projectile. The reduced fusion cross sections as a function of reduced center-of-mass energies are shown in Fig. 5.

The comparison was made between nuclei with similar quadrupole and octupole deformation strengths to omit the effect of inelastic excitations if present. The deformation parameters along with excitation energies of the low-lying states for the systems investigated are given in Table III.

It was observed from Fig. 4 that ^{90}Zr [48], ^{40}Ca [49], and ^{58}Ni [50] have negative-Q values for the $2n$ pick-up channel

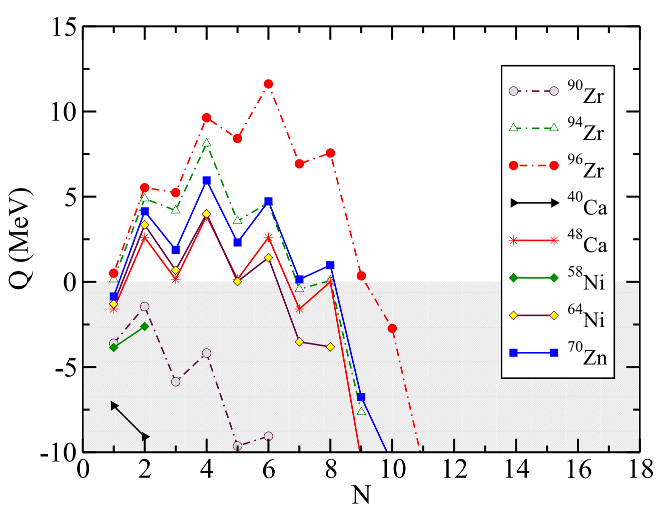

FIG. 4. Q value (ground state to ground state) versus the number of neutron transfer for all the selected systems. ^{40}Ca is the projectile for all the given target nuclei.

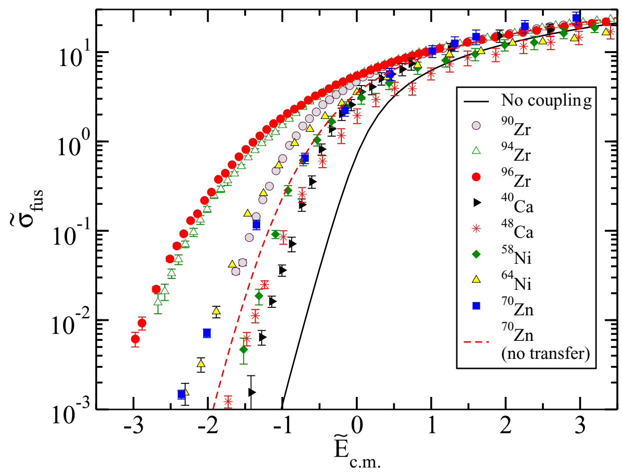

FIG. 5. Comparison of the fusion excitation functions of $+Q_{2n}$ systems with those of $-Q_{2n}$ systems on reduced scales. The experimental fusion cross sections for the systems ^{40}Ca + ^{90,94,96}Zr, ^{40}Ca + ^{40,48}Ca, ^{40}Ca + ^{58,64}Ni are taken from Refs. [45,48], Refs. [49,51], and Refs. [31,50], respectively. The fusion cross sections for the ^{40}Ca + ^{70}Zn system are the present data.

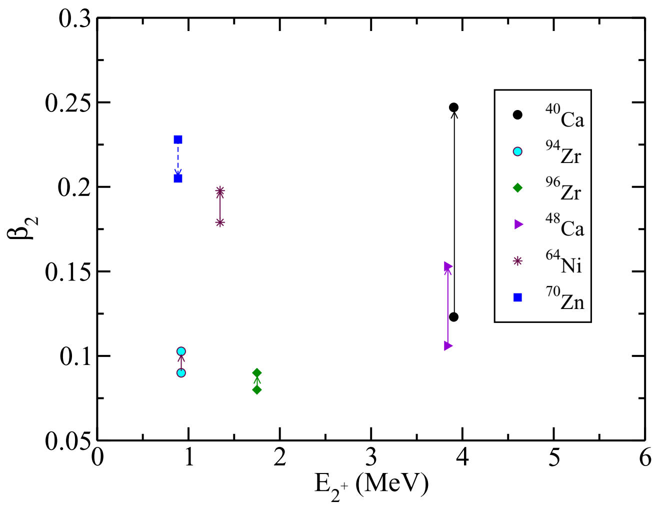

FIG. 6. Quadrupole deformation parameters and excitation energies for selected systems. Solid lines and dashed lines represent increases and decreases in deformation after the transfer of two neutrons, respectively.

($-Q_{2n}$); therefore, the effect of transfer channels on enhancement of fusion cross-section around the barrier is expected to be negligible. However, ^{94,96}Zr [45,48], ^{48}Ca [51], and ^{64}Ni [31] have positive-Q values for the $2n$ pick-up channel ($+Q_{2n}$) and show enhancement in the sub-barrier region as compared to their negative-Q-value systems, i.e., ^{90}Zr, ^{40}Ca, and ^{58}Ni. Here, the following pairs of systems were compared: (^{94,96}Zr :^{90}Zr), (^{48}Ca :^{40}Ca), and (^{64}Ni :^{58}Ni).

All these $+Q_{2n}$ systems for which deformation increases after $2n$ transfer agree with the previously reported work by Sargsyan *et al.* [24]. As per Sargsyan *et al.* [24], sub-barrier cross sections show enhancement for positive-Q-value systems only if deformation of colliding nuclei increases substantially after neutron transfer. If there is negligible change or decrease in deformation then transfer channels weakly influence the fusion process. Further, mass asymmetry decreases after transfer of two neutrons for all the systems under consideration, except for ^{40}Ca + ^{40}Ca, which is a negative-Q-value system. Therefore, the present analysis is also in agreement with the work of Zhang *et al.* [21]. To understand the effect of change in deformation due to flow of neutrons between colliding nuclei, a plot was generated between quadrupole deformation strengths and excitation energies of the 2^+ state (Fig. 6). In Fig. 6, a solid line represents the increase in deformation after $2n$ transfer, whereas a dashed line shows the decrease in deformation after the transfer of two neutrons. It can be observed that the deformation change after $2n$ transfer for ^{94,96}Zr is negligibly small, but the enhancement of fusion cross sections is significantly large with respect to ^{90}Zr as observed in Fig. 5. On the other hand, there is a small enhancement in fusion cross sections of ^{48}Ca with respect to ^{40}Ca, although the deformation change is large after $2n$ transfer.

The present ^{40}Ca + ^{70}Zn system was also compared on the same reduced scale with its no transfer coupling data. The system showed an enhancement due to its positive-Q value for the two-neutron pick-up channel, although there is a decrease in deformation for ^{70}Zn after the transfer of neutrons. Because ^{40}Ca shows an increase in deformation after $2n$ transfer, fusion enhancement for the ^{40}Ca + ^{70}Zn system may be attributed to the projectile (^{40}Ca).

TABLE III. Excitation energies (E_J) and deformation parameters (β_J) for the excited states (J^π) of the selected nuclei.

Nucleus	J^π	E_J (MeV)	β_J
^{90}Zr	2^+	2.19	0.089
	3^-	2.75	0.211
^{94}Zr	2^+	0.92	0.090
	3^-	2.06	0.193
^{96}Zr	2^+	1.75	0.080
	3^-	1.90	0.283
^{40}Ca	2^+	3.90	0.123
	3^-	3.74	0.330
^{48}Ca	2^+	3.83	0.110
	3^-	4.51	0.250
^{58}Ni	2^+	1.45	0.183
	3^-	–	0.190
^{64}Ni	2^+	1.34	0.179
	3^-	3.56	0.203
^{70}Zn	2^+	0.88	0.228
	3^-	2.86	0.216

IV. SUMMARY

The article reports on the measurement of fusion cross sections for the system ^{40}Ca + ^{70}Zn that were analyzed using the coupled-channels framework CCFULL and ECC codes. Because the system has a positive-Q value for neutron pick-up channels, transfer channels are expected to play a major role along with inelastic excitation coupling. Among inelastic excitations, the 3^- (octupole) state of ^{40}Ca was observed to be essential for enhancement of fusion cross sections. The contribution of the transfer channel towards fusion enhancement was found to be significant in the case of the $2n$ pick-up channel and negligible for the $4n$ pick-up channel, although the Q value was positive for both the transfer channels.

A comparison was made between $-Q_{2n}$ and $+Q_{2n}$ systems involving a ^{40}Ca projectile that allowed us to explore the transfer process. Sub-barrier fusion enhancement was observed in $+Q_{2n}$ systems as compared to $-Q_{2n}$ systems for which deformation increases after $2n$ transfer, though this enhancement was not found to be proportional to the deformation change as expected. According to the discussion on deformation change, enhancement should be larger for Ca, but it was observed to be larger for Zr. In the case of ^{70}Zn, deformation decreases for targetlike particles but increases for projectilelike particles after $2n$ transfer and hence the observed enhancement can be associated with projectile ^{40}Ca.

In conclusion, it was observed that $2n$ transfer has a strong effect on sub-barrier fusion enhancement. It will be interesting to compare the fusion data of ^{62}Zn (negative-Q-value system) with ^{70}Zn to understand the influence of $2n$ pair transfer on fusion. Additionally, an individual transfer study on ^{70}Zn can be done for better interpretation of the transfer process.

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