Fusion and transfer reactions around the Coulomb barrier for $^{28}\text{Si}+^{90,94}\text{Zr}$ systems

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Abstract. Fusion excitation functions and transfer probabilities were measured for $^{28}\text{Si}+^{90,94}\text{Zr}$ systems around the Coulomb barrier, using the recoil mass separator, Heavy Ion Reaction Analyzer (HIRA) at Inter University Accelerator Centre (IUAC), New Delhi. The aim of these experiments was the study of coupling effects of inelastic and transfer channels on the sub-barrier fusion cross section enhancement. The experimental fusion cross sections were found to be strongly enhanced as compared to one dimensional barrier penetration model (1-d BPM) predictions in both the cases. The trend of data could be easily reproduced theoretically using coupled channels code CCFULL in the case of $^{28}\text{Si}+^{90}\text{Zr}$ but the observed enhancement could not be explained in the case of $^{28}\text{Si}+^{94}\text{Zr}$, which may be attributed to the coupling of multinucleon transfer channels as both isotopes have similar collective strengths. The transfer probabilities in the case of $^{94}\text{Zr}$ were found to be substantially higher than for $^{90}\text{Zr}$ in the sub-barrier region.

1. Introduction

Heavy ion collisions around the Coulomb barrier offer a very rich variety of phenomena [1-3]. The coupling of various channels with each other results in the splitting of the barrier and hence, the fusion cross sections are substantially enhanced in the sub-barrier region as compared to the predictions of one dimensional barrier penetration model. It is in this energy regime where transfer reactions constitute a significant part of reaction cross section. Inspite of a large number of investigations in the last few decades, the role of the static deformations and the collective vibrations in enhancing fusion cross sections is well established, whereas the role of multinucleon transfer channels in influencing the sub-barrier fusion cross sections is not so clear [4,5].
The medium mass nuclei are the most suitable for the study of the coupling effects as they avoid the complications arising from the presence of the enormous number of open channels during reaction. In the mid mass region, the $^{40,48}$Ca+$^{90,96}$Zr [4,6], $^{36}$Si+$^{90,96}$Zr [7], $^{40}$Ca+$^{94}$Zr [8], $^{33}$Si+$^{90,91,92}$Zr [9] and $^{58}$Ni+$^{90,94}$Zr [10] systems have been extensively studied to explore the isotopic effects and the role of transfer channels on the fusion cross sections in the sub-barrier region. In the systems where the transfer channels have positive Q-values, the sub-barrier fusion cross section could not be explained simply by including the inelastic excitations in the coupled channels calculations. Various studies have been carried out for exploring the importance of one or two nucleon transfer channels on the sub-barrier fusion enhancement. But very few data exist to explain the coupling effects of the multinucleon transfer channels on the sub-barrier fusion cross section enhancement. The study of the multinucleon transfer channels around the Coulomb barrier in itself serves a wide range of objectives.

Here, we report the results of two experiments performed to measure the fusion cross sections [11] and the transfer probabilities around the Coulomb barrier for $^{28}$Si+$^{90,94}$Zr systems. The aim of these experiments was to observe the role of multinucleon transfer channels in the enhancement of fusion cross sections (both the isotopes have similar quadrupole and octupole strengths). In the case of zirconium isotopes, $Z=40$ leads to the sub shell closure which results in the suppression of the proton transfer channels. The $^{90}$Zr nucleus, being neutron magic, leads to suppression of neutron transfer channels as well. Whereas, in the case of $^{94}$Zr, there are four neutrons outside the closed shell which lead to positive Q-values for up to four neutron pickup channels. Another motivation for performing these experiments was to study the dominant mechanism (simultaneous or sequential) of multinucleon transfer around the Coulomb barrier.

2. Experimental Details

The experiments were carried out using pulsed $^{28}$Si beams from the 15UD Pelletron accelerator at IUAC, New Delhi using HIRA [12]. The enriched $^{90,94}$Zr targets (97.65% and 96.07% respectively), each with thickness of 280 $\mu$g/cm$^2$ on 45 $\mu$g/cm$^2$ carbon backings, were used [13]. The fusion excitation function measurements were performed at beam energies of 82, 84, 86, 88, 90, 92, 94, 96, 98, 100, 103, 107, 110, 115 and 120 MeV (in laboratory frame) for both the systems. In the sliding target chamber of HIRA, two silicon surface barrier detectors were placed at angles of $\pm 25^\circ$ with respect to the beam direction for normalization and beam monitoring. A carbon charge reset foil of 35 $\mu$g/cm$^2$ thickness was used for charge re-equilibration which was placed 10 cm downstream the target. The particles entering the HIRA were dispersed at the focal plane according to their m/q values. A position sensitive Multi Wire Proportional Counter (MWPC) with an active area of 150 x 50 mm$^2$ was placed at the focal plane of HIRA. During the fusion excitation function measurements, HIRA was kept at $0^\circ$. HIRA was placed at $6^\circ$ with respect to beam direction for measuring the transfer reactions with a solid angle acceptance of 5 msr ($\pm 2.28^\circ$). For measuring the angular distributions of evaporation residues (ERs), HIRA solid angle was changed to 1 msr and measurements were performed in steps of $2^\circ$ from $0^\circ$ to $10^\circ$, at 103 MeV ($E_{lab}$) for $^{28}$Si+$^{90,94}$Zr systems by rotating HIRA. A time of flight (TOF) was setup with the arrival of particles at the focal plane (in MWPC) as the start signal and delayed RF as the stop signal. This TOF was used to separate multiply scattered beam-like particles reaching the focal plane from the ERs as shown in figure 1. A gated two dimensional spectrum taken during transfer experiment, between the time of flight of recoiling particles and MWPC position, is shown in figure 2. During the transfer run, a silicon surface barrier detector of active area 20 x 20 mm$^2$ was used in the target chamber at back angle for setting up the kinematic coincidence between the forward moving recoils and the back scattered projectile-like particles. HIRA was scanned for charge states, mass and energy of ERs as well as the transfer products for both the systems (120 MeV for fusion run and 95.5 MeV for the transfer run). For other incident energies, HIRA fields were scaled appropriately.

In the fusion excitation functions, the fusion cross sections were estimated from the ER cross sections as fission was negligible for these systems. The ER cross sections were calculated using the expression
\[ \sigma_{\text{fus}} = \frac{1}{\eta} \left( \frac{Y_{ER}}{Y_M} \right) \left( \frac{d\sigma}{d\Omega} \right) \Omega_M \]

where \( \eta \) is the average HIRA efficiency for ER detection, \( Y_{ER} \) the yield of ERs, \( Y_M \) the geometric mean of the monitor yields, \( (d\sigma/d\Omega)_R \) the Rutherford cross section in laboratory and \( \Omega_M \) the solid angle subtended by the monitor at the target.

HIRA transmission efficiency was measured by the coincident \( \gamma \)-ray method for \( ^{28}\text{Si} + ^{94}\text{Zr} \) system at 103 MeV (\( E_{\text{lab}} \)). Singles gamma ray spectrum was recorded. During off-line analysis, gamma spectrum was analyzed in coincidence with the particles reaching the focal plane. The transmission efficiency of HIRA for the above system was estimated from the ratio of counts for a specific gamma in coincidence spectrum (\( N_{\text{coin}} \)) to those in singles (\( N_{\text{singles}} \)) spectrum. For the identified gamma line (675.2 keV), HIRA efficiency so obtained was 3.2%.

3. Results and Discussions

Figure 3 shows the measured fusion excitation function along with the corresponding coupled channels calculations using CCFULL code [14] for the \( ^{28}\text{Si} + ^{90}\text{Zr} \) system. The ion-ion potentials used in these calculations were Woods-Saxon parameterization of Akyuz-Winther (AW) [15] potential. These potential parameters were used without any attempt to vary them to fit the above barrier data. In the case of \( ^{28}\text{Si} + ^{90}\text{Zr} \) system, the experimentally measured cross sections were larger by an order of magnitude as compared to 1-d BPM calculations in the sub-barrier region. The calculations show that coupling to \( 2^+ \) and two phonons of \( 3^\text{rd} \) state of the \( ^{90}\text{Zr} \) and \( 0^+, 2^+ \) states of \( ^{28}\text{Si} \) explains the experimental cross sections reasonably well. Target and projectile mutual excitations were also taken into account. Since the transfer channels have negative Q-values, their effect on the sub-barrier fusion cross section enhancement will be negligible.

Coupled channels calculations considering the same inelastic channels were performed for \( ^{28}\text{Si} + ^{92}\text{Zr} \) system for which the fusion excitation function data were taken from reference [16]. The calculations along with the experimental results are shown in figure 4. For this system, two neutron pickup channel has positive Q-value. It turned out that apart from the coupling to inelastic channels, the transfer channel was needed to reproduce experimental fusion cross sections. The strength of form
factor for two particle transfer in CCFULL was varied to reproduce the experimental fusion cross sections (with equivalent $\beta = 0.30$).

![Figure 3: $^{28}$Si+$^{90}$Zr fusion excitation function along with the theoretical calculations using CCFULL.](image1)

Figure 3: $^{28}$Si+$^{90}$Zr fusion excitation function along with the theoretical calculations using CCFULL.

Fusion excitation function for the $^{28}$Si+$^{94}$Zr system was also analyzed using similar couplings to inelastic states. For this system, it was found that the coupling to inelastic states under predicted the fusion cross sections in the sub-barrier region as shown in figure 5. Inclusion of the two neutron pickup channel was not sufficient to reproduce the experimental cross sections. As already mentioned, for this system up to four neutron pickup channels have positive Q-values. It seems that one needs to include more transfer channels to reproduce the cross sections. As CCFULL provides for an option of including just one pair transfer channel and treats it in too simple a way, therefore, it is inadequate to infer the role of transfer channels in the observed enhancement unambiguously. Hence, full coupled channels calculations including all the transfer channels appropriately may help in pointing out the role of multinucleon transfer.

![Figure 4: $^{28}$Si+$^{92}$Zr fusion excitation function along with the theoretical calculations using CCFULL.](image2)

Figure 4: $^{28}$Si+$^{92}$Zr fusion excitation function along with the theoretical calculations using CCFULL.

![Figure 5: $^{28}$Si+$^{94}$Zr fusion excitation function along with the calculations using CCFULL.](image3)

Figure 5: $^{28}$Si+$^{94}$Zr fusion excitation function along with the calculations using CCFULL.

![Figure 6: The reduced fusion excitation functions for $^{28}$Si+$^{90,92,94}$Zr on a reduced scale.](image4)

Figure 6: The reduced fusion excitation functions for $^{28}$Si+$^{90,92,94}$Zr on a reduced scale.
A comparison of the reduced cross sections for $^{28}\text{Si}^{90,92,94}\text{Zr}$ systems is shown in the figure 6. The symbol $V_b$ is used for Coulomb barrier and $R_b$ is for barrier radius in above figures. The cross sections for $^{28}\text{Si}^{92,94}\text{Zr}$ systems are much more enhanced than those for the $^{28}\text{Si}^{90}\text{Zr}$ system. The cross sections for $^{28}\text{Si}^{92}\text{Zr}$ system were found to be an order of magnitude larger than the ones for $^{28}\text{Si}^{90}\text{Zr}$ system, which may be due to the effect of one and two neutron pickup channels. The sub-barrier cross sections were still higher, by an order of magnitude for the $^{28}\text{Si}^{94}\text{Zr}$ system which may be due to the contribution of multinucleon transfer channels. Hence, the experimental fusion cross sections clearly indicate the importance of multinucleon transfer channels in the sub-barrier fusion cross section enhancement.

In the transfer experiment, the forward moving recoils were dispersed at the focal plane according to their $m/q$ values as shown in figure 2. The transfer probability was taken as the ratio of the yield of the particular transfer channel to the total yield of elastic, inelastic and transfer channels (quasielastic yield). The transfer probability of one neutron pickup for $^{94}\text{Zr}$ was found to be almost an order of magnitude higher than that for $^{90}\text{Zr}$ at each energy. The transfer channels observed with $^{94}\text{Zr}$ target were up to four neutron pickup and one proton stripping, whereas in the case of $^{90}\text{Zr}$ only up to three neutron pickup channels were observed.

4. Summary

Fusion excitation functions and the transfer probabilities were measured for the $^{28}\text{Si}^{90,94}\text{Zr}$ systems around the Coulomb barrier to study the channel-coupling effects. Both the isotopes have similar quadrupole and octupole strengths. It was observed that AW potential parameters are able to reproduce the experimentally observed fusion cross sections reasonably well for these systems. It is observed that the couplings to inelastic states were sufficient to explain the observed fusion excitation function for $^{28}\text{Si}^{90}\text{Zr}$ system. In the case of $^{28}\text{Si}^{92}\text{Zr}$ system, the inclusion of two neutron pickup reproduced the data fairly well using coupled channels code CCFULL. Whereas, in the $^{28}\text{Si}^{94}\text{Zr}$ system, even the coupling to two neutron pickup was not sufficient to explain the data and a large part of the enhancement observed in the sub-barrier fusion cross sections remains unexplained which may be due to coupling to the multinucleon transfer channels. Independent of CCFULL calculations, the trend of the data supports the fact that multinucleon transfer channels with positive Q-values play an important role in the sub-barrier fusion cross section enhancement.

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References

[1] Rehm K E 1991 Annu. Rev. Nucl. Part. Sci. 41 429
[2] Reisdorf W 1994 J. Phys. G 20 1297
[3] Dasgupta M, Hinde D J, Rowley N and Stefanini A M 1998 Annu. Rev. Nucl. Part. Sci. 48 401
[4] Timmers H, Corradi L, Stefanini A M, Ackermann D, He J H, Beghini S, Montagnoli G, Scarlissara F, Segato G F and Rowley N 1997 Phys. Lett. B399 35
[5] Sonzogni A A, Bierman J D, Kelly M P, Lestone J P, Liang J F and Vandenbosch R 1998 Phys. Rev. C 57 722
[6] Stefanini A M, Scarlissara F, Beghini S, Montagnoli G, Silvestri R, Trotta M, Behera B R, Corradi L, Fioretto E, Gadea A, Wu Y W, Szilner S, Zhang H Q, Liu Z H, Ruan M, Yang F and Rowley N 2006 Phys. Rev. C 73 034606
[7] Stefanini A M, Corradi L, Vinodkumar A M, Feng Yang, Scarlissara F, Montagnoli G, Beghini S and Bisogno M 2000 Phys. Rev. C 62, 014601
[8] Stefanini A M, Behera B R, Beghini S, Corradi L, Fioretto E, Gadea A, Montagnoli G, Rowley N, Scarlassara F, Szilner S and Trotta M 2007 Phys. Rev. C 76 014610
[9] Corradi L, Skorka S J, Lenz U, Lobner K E G, Pascholati P R, Quade U, Rudolph K, Schomburg W, Steinmayer M, Thies H G, Montagnoli G, Napoli D R, Stefanini A M, Tivelli A, Beghini S, Scarlassara F, Signorini C and Soramel F 1990 Z. Phys. A 335 55
[10] Scarlassara F, Beghini S, Soramel F, Signorini C, Corradi L, Montagnoli G, Napoli D R, Stefanini A M and Zhi-Chang Li 1991 Z. Phys. A 338 171
[11] Kalkal Sunil, Mandal S, Madhavan N, Prasad E, Verma S, Jhingan A, Sandal Rohit, Nath S, Gehlot J, Behera B R, Saxena Mansi, Goyal Savi, Siwal Davinder, Garg Ritika, Pramanik U D, Kumar Suresh, Varughese T, Golda K S, Muralithar S, Sinha A K, Singh R 2010 Phys. Rev. C 81 044610
[12] Sinha A K, Madhavan N, Das J J, Sugathan P, Kataria D O, Patro A P, Mehta G K 1994 Nucl. Instrum. Methods Phys. Res. A 339 543
[13] Kalkal Sunil, Abhilash S R, Kabiraj D, Mandal S, Madhavan N and Singh R 2010 Nucl. Instrum. Methods Phys. Res. A 613 190
[14] Hagino K, Rowley N and Kruppa A T 1999 Comput. Phys. Commun. 123 143
[15] Broglia R A and Winther A Heavy Ion Reaction Lecture Notes, Volume 1: Elastic and Inelastic Reactions (Benjamin/Cummings, Reading, 1981).
[16] Newton J O, Morton C R, Dasgupta M, Leigh J R, Mein J C, Hinde D J, Timmers H and Hagino K 2001 Phys. Rev. C 64 064608