The effect of transfer channels and of octupole vibrations in the sub-barrier fusion of $^{40}\text{Ca}+^{94}\text{Zr}$ system

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INTRODUCTION

The reaction mechanism for sub-barrier fusion reaction has been studied extensively over last decades. It has been established that the dynamics of the heavy-ion fusion at energies around the Coulomb barrier is strongly influenced by coupling to other reaction channels [1]. A large number of experimental results has brought out the role of collective excitations in enhancing the fusion cross section with respect to conventional barrier penetration models. Coupled channel calculations give a good representation of the experimental data in most cases. However, the role of positive ground state Q-value transfer channels in influencing the fusion process is not very clearly understood. Some experiments were performed to study the systems having positive ground state Q-value for neutron transfer channels. The systems $^{40,48}\text{Ca}+^{90,96}\text{Zr}$ studied at LNL [2-5] were a strong case to disentangle couplings of collective vibration and transfer contributions in the sub-barrier fusion process. In a comparison of fusion excitation functions for the systems $^{40,48}\text{Ca}+^{90,96}\text{Zr}$ in a reduced scale (Fig. 1), one notices that $^{40}\text{Ca}+^{96}\text{Zr}$ presents a large sub-barrier fusion enhancement compared to the other three systems. The $^{40}\text{Ca}+^{96}\text{Zr}$ system is the only one with positive Q-values for neutron-pickup channels, all other systems have unfavored Q-values for all transfer channels. The measured barrier distributions for the two systems $^{40}\text{Ca}+^{90,96}\text{Zr}$ were markedly different from each other. The barrier distribution for $^{40}\text{Ca}+^{96}\text{Zr}$ could be reproduced by full coupled channel calculation including only the coupling to the surface excitations of $^{96}\text{Zr}$. However, the barrier distribution for $^{40}\text{Ca}+^{96}\text{Zr}$ was observed to be broad and coupled channel calculations give a poor fit. Similarly, the extra cross section for $^{46}\text{Ca}+^{96}\text{Zr}$ could not be explained by such CC calculations. This extra enhancement was attributed to coupling to transfer channels, as for the system $^{40}\text{Ca}+^{90}\text{Zr}$ all the transfer channels had negative Q-values. These results were supported by measurements of multi nucleon transfer reactions [4] for $^{40}\text{Ca}+^{90,96}\text{Zr}$, where much larger transfer probabilities were observed for $^{40}\text{Ca}+^{96}\text{Zr}$.

In a recent semi-classical calculation [6], the barrier distributions for $^{40}\text{Ca}+^{90,96}\text{Zr}$ systems were explained by including the low lying 2$^-$ and 3$^-$ states of projectile, target and all transfer channels. They made a detailed analysis of the contribution from various inelastic channels, leading to the conclusion that the broad and peak-less shape observed for the barrier distribution for $^{40}\text{Ca}+^{90}\text{Zr}$ is essentially due to octupole vibration of $^{90}\text{Zr}$, which is much more collective and lies lower in energy than in $^{90}\text{Zr}$. These calculations can also reproduce the transfer data [4] for the above systems. From the comparative plots for fusion excitation function for the systems $^{40,48}\text{Ca}+^{90,96}\text{Zr}$ (Fig.1), we did not observe any strong enhancement in $^{40}\text{Ca}+^{96}\text{Zr}$ compared to $^{40}\text{Ca}+^{90}\text{Zr}$, where we still have strong octupole structure in $^{96}\text{Zr}$. It is still an ambiguity, whether neutron transfer or strong octupole strength plays a dominant role in sub-barrier fusion process in the $^{40}\text{Ca}+^{Zr}$ systems. From the experimental point of view, the best possible way to clear up the situation is to choose a case where one still has large neutron transfer Q-values but less strength of octupole vibration. The best system for this study is $^{40}\text{Ca}+^{94}\text{Zr}$. In this case, we still have large positive Q-values for neutron pickup channels, similar to the system $^{40}\text{Ca}+^{96}\text{Zr}$, but the strength of the octupole vibration in $^{94}\text{Zr}$ is much smaller and the excitation energy for octupole vibration is higher than in $^{96}\text{Zr}$. With this motivation we have performed an experiment to measure fusion excitation function and barrier distributions for the system $^{40}\text{Ca}+^{94}\text{Zr}$. The results of this experiment will hopefully disentangle the different ingredients (i.e strong octupole vibration and neutron transfer) in the fusion process.

EXPERIMENT

Fusion-evaporation cross sections have been measured for the reaction $^{40}\text{Ca}+^{94}\text{Zr}$ from well below to well above the Coulomb barrier ($E_{lab}= 126\text{MeV} \text{ to} 162\text{MeV}$), using the $^{40}\text{Ca}$ beams of the XTU Tandem accelerator of LNL. The $^{40}\text{Ca}$ beam was produced by a sputter ion source, where CaH samples were used. The beam energy from the Tandem accelerator was defined with an uncertainty less than ±1/800 and the beam current was in the range of 2 to 3 pA. The target used were of thickness 50 µg/cm$^2$ on carbon backings 15µg/cm$^2$. The targets were made by vacuum evaporation. The energy from the Tandem was varied, in 500 KeV steps, only downwards in order to...
minimize hysteresis effects in the analyzing magnet. Evaporation residues (ER) were detected at 0° by a energy-TOF detector telescope following beam rejection with an electrostatic deflector. Four silicon detectors were placed symmetrically around the beam direction to act as monitor detectors. These detectors detected Rutherford scattering from the target and established the beam direction for each run. Angular distributions for ER were measured in steps of 0.1° at (E_{lab} = 152 and 140 MeV). The transmission of the electrostatic deflector was assumed to be the same as the one measured for 40Ca^{+90,96}Zr, whose experimental value was 0.70±0.05. The measured angular distributions were fitted by a Gaussian and then integrated to obtain the yield at 0°. At each energy the number of ER events was normalized to the Rutherford scattering yield in the monitor detectors. By taking into account the solid angles, the transmission and the 0° to total ratio, the ER yields were transformed into total fusion cross section (fusion-fission is negligible for Ca+Zr systems near the barrier).

RESULTS

The measured cross sections for 40Ca^{+94}Zr along with previously measured 40,48Ca^{+90,96}Zr systems are displayed in Fig. 1. The experimental barrier distributions for 40Ca^{+94}Zr was obtained by the usual point difference formula and is plotted in Fig. 2.

From these two figures one sees immediately that the shape of the barrier distributions for 40Ca^{+94}Zr system is rather similar to the broad barrier distributions previously observed for 40Ca^{+96}Zr system. From the comparison of reduced cross sections (Fig. 1.), where trivial geometrical effects are corrected out, one notices that the cross sections for 40Ca^{+94}Zr are similar to the 40Ca^{+96}Zr system. Indeed, the two excitation functions are astonishingly similar. In both the systems 40Ca^{+94,96}Zr there is a sizable enhancement of cross sections compared to 40Ca^{+96}Zr system. Furthermore the cross sections for 40Ca^{+94,96}Zr is much more enhanced compared to 40Ca^{+90,96}Zr systems, where the Q-values for neutron transfer channels are all negative. This enhancement cannot be due to the strength of octupole vibration as this strength is much less in the case of 94Zr compared to 96Zr. The only common thing between 40Ca^{+96}Zr and 40Ca^{+94}Zr systems is the set of strong positive Q-values for neutron transfer channels.