Barrier Distributions and Signatures of Transfer Channels in the $^{40}$Ca+$^{58,64}$Ni Fusion Reactions at Energies around and below the Coulomb Barrier

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INTRODUCTION

$^{40}$Ca+$^{58}$Ni and $^{40}$Ca+$^{64}$Ni were measured from energies well below the Coulomb barrier to energies above the Coulomb barrier. The measurements were done at INFN-Laboratori Nazionali di Legnaro (LNL) in October 2012. For the $^{40}$Ca+$^{58}$Ni system, results for the fusion cross section, essentially above the barrier, were already published by Sikora et al. [1]. However, the fusion excitation function for $^{40}$Ca+$^{64}$Ni was completely unknown before the present work. Our purpose was to study the influence of the projectile and target structure as well as of the transfer channels in these two systems, particularly in the system $^{40}$Ca+$^{64}$Ni, which has positive Q-values for the transfer of two neutrons from $^{64}$Ni to $^{40}$Ca and one proton from $^{40}$Ca to $^{64}$Ni.

EXPERIMENT

The experiment was successfully performed, using high-quality and intense $^{40}$Ca$^{+9,10}$ beam (9 pnA) from the XTU Tandem accelerator, at laboratory energies ranging from 104.75 MeV to 153.5 MeV in steps of 1.25 MeV below the Coulomb barrier, and 2.5 MeV above the Coulomb barrier. The Coulomb barriers for the $^{40}$Ca+$^{58}$Ni and $^{40}$Ca+$^{64}$Ni systems are located at 127.96 MeV and 121.33 MeV respectively. $^{58}$Ni and $^{64}$Ni targets of 50 $\mu$g.cm$^{-2}$ were deposited on a 20 $\mu$g.cm$^{-2}$ 12C backing. The fusion-evaporation residues emitted at forward angles were separated from the beam by using the LNL electrostatic deflector in its upgraded setup mode [2]. They were subsequently detected by two micro-channel plates detectors (position and time signals), entered in an ionization chamber (energy loss signal) and were finally stopped in a silicon detector (residual energy signal) placed in the ionization chamber. Four silicon detectors, located above, below and to the left and right of the beam at the same scattering angle $\theta_{lab}=16.05^\circ$, were used for beam control and normalization between the different runs by measuring the $^{40}$Ca Rutherford scattering from the nickel targets. Two angular distributions were measured at 121 MeV and 138.5 MeV in the range $-4^\circ$ to $+6^\circ$ in steps of $1^\circ$.

PRELIMINARY RESULTS AND CC CALCULATIONS

The experimental fusion excitation functions and distributions of barriers for the systems $^{40}$Ca+$^{58,64}$Ni are plotted in Figs. 1, 2, 3 and 4. We performed preliminary coupled-channels calculations with the CCFULL code [3], using the Akyüz and Winther potential [4] and taking into account one octupole phonon for $^{40}$Ca and one quadrupole phonon for $^{58,64}$Ni, noted [0110].

For the system $^{40}$Ca+$^{58}$Ni, the Akyüz and Winther potential has parameters $V_0=67.41$ MeV, $r_0=1.18$ fm and $a=0.66$ fm. The corresponding fusion barrier position and height are respectively $R_{bAW}=10.15$ fm and $V_{bAW}=73.81$ MeV. By considering the couplings [0110], the experimental and theoretical fusion excitation functions are in agreement at energies at and below the fusion barrier (Fig. 1). As expected with a bare Akyüz and Winther potential, the theoretical fusion excitation function matches the experimental fusion excitation function at energies above the fusion barrier. Indeed, these couplings between relative motion and internal degrees of freedom have time to affect the nuclear potential at low energy, whereas the system does not have enough time to rearrange its nuclear density at high energy. As seen on Fig. 2, the couplings shift the distribution of barriers downward in energy (dotted black line vs. blue curve). This results in a decrease of the fusion barrier height and an increase of the fusion cross section.

![Fig. 1: Experimental (blue points) and theoretical (blue curve) fusion excitation functions for the system $^{40}$Ca+$^{58}$Ni.](image-url)
For the system \(^{40}\text{Ca}+^{64}\text{Ni}\), the Akyüz and Winther potential has parameters \(V_0=68.70\) MeV, \(r_0=1.18\) fm and \(a=0.66\) fm. The corresponding fusion barrier position and height are respectively \(R_{\text{b}AW}=10.36\) fm and \(V_{\text{b}AW}=72.47\) MeV. The diffuseness parameter was adjusted at 0.69 fm in order that the theoretical fusion cross sections, once couplings [0110] were included, match the experimental fusion cross sections at energies around the fusion barrier.

At very low energies, the fusion cross sections of \(^{40}\text{Ca}+^{64}\text{Ni}\) are larger than those of \(^{40}\text{Ca}+^{58}\text{Ni}\). The same couplings were used for these two systems because \(^{58}\text{Ni}\) and \(^{64}\text{Ni}\) nuclei have almost an identical structure. Nevertheless, contrary to the system \(^{40}\text{Ca}+^{58}\text{Ni}\), the system \(^{40}\text{Ca}+^{64}\text{Ni}\) has positive Q-values for several proton and neutron transfer channels. The increase of the fusion cross section may come from this additional reaction channel.

Concerning the distribution of barriers above 80 MeV, its extraction is more difficult at these energies because the slope of the fusion excitation function is smaller than below the Coulomb barrier. Thus the apparent structure in \(^{40}\text{Ca}+^{64}\text{Ni}\) will have to be confirmed in eventual future measurements in that region in smaller steps like the data obtained below the Coulomb barrier.

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