Transfer reactions at sub-barrier energies: the $^{60}$Ni$^{+}$\textsuperscript{116}Sn case

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INTRODUCTION

The pairing interaction induces particle-particle correlations, that are essential in defining the properties of finite quantum many body systems in their ground and neighboring states. For nuclei far from the closed shells the pairing interaction modifies the ground state population pattern by spreading the paired nucleons over several single particle states at around the nominal Fermi surface.

We studied transfer probabilities for one- and two-neutron transfer channels in the $^{60}$Ni$^{+}$\textsuperscript{116}Sn system [1] up to very large distances of closest approach. The experimental yields of reaction products have been measured with the PRISMA large acceptance magnetic spectrometer via an excitation function. The employed microscopic theory, for the first time in a heavy ion collision, provided a consistent description of one and two neutron transfer reactions, by incorporating in the reaction mechanism all known structure information of entrance and exit channels nuclei. These microscopic calculations very well match the experimental data in all energy range, in particular the two neutron transfer channel has been very well reproduced, both in magnitude and slope, by considering solely the ground-ground state transition.

THE EXPERIMENT

The measurement was performed in inverse kinematics by using a $^{116}$Sn beam with average currents of $\sim$ 2 pnA onto a 100 $\mu$g/cm$^2$ strip $^{60}$Ni target, employing the superconducting PIAVE-ALPI accelerator complex of LNL. Target isotopic purity was 99.81%. We measured, by detecting Ni-like recoils in PRISMA at $\theta_{\text{lab}}=20^\circ$, an excitation function from above to well below the Coulomb barrier varying the beam energy from 500 to 395 MeV in steps of $\sim$ 10 MeV and further intermediate steps using a C-foil as degrader. For normalization, two monitor silicon detectors have been used at $\theta_{\text{lab}}=55^\circ$ and $60^\circ$ to get pure Rutherford scattered $^{60}$Ni ions.

The identification of Ni-like fragments in PRISMA has been done on an event-by-event basis through the reconstruction of the trajectories of the ions [2] inside the magnetic elements, making use of the time of flight and position information at the entrance and at focal plane of the spectrometer. The atomic number Z has been assigned by reconstructing the range of the ions as function of the total energy released in the ionization chamber. The very good mass resolution $\Delta A/A \sim 1/240$, shown in the two-dimensional (mass vs. TKEL) plot of Fig. 1, is ensured by the high kinetic energy of the recoils ($\sim$ 6 MeV/A).

RESULTS

We decided to represent the outcome of a transfer reaction in terms of transfer probabilities $P_{\text{tr}}$, defined as the ratio of the transfer cross section to the corresponding Rutherford cross section, plotted as a function of the distance $D$. This is quite appealing since the angular distributions at different

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Matrix of mass vs total kinetic energy loss (TKEL) for Ni isotopes at $E_{\text{lab}}=410$ MeV. One sees the clear separation between quasi-elastic and (1$n$) and (2$n$) transfer channels and the concentration of the TKEL distributions in a narrow range close to $\sim$ 0 MeV.}
\end{figure}
bombarding energies all converge in a single line at large distances. In this way, measurements of excitation function at fixed angle and angular distribution at fixed energy can be directly compared.

For the \((1n)\) and \((2n)\) channels the measured transfer probabilities are plotted in the lower panel of Fig. 2. The transfer probability is directly related to the square of the matrix element governing the transfer process and this, due to the very large internuclear distance, is proportional to the tail of the single particle wave functions of the connected states \([3, 4]\). In the same figure (top panel) it is reported the ratio of the \(^{60}\text{Ni}\) experimental yield over the Rutherford cross section. The ratio has been normalized to unity for large \(D\) (i.e. below the barrier) where the quasi-elastic scattering coincides with the Rutherford one. This quasi-elastic distribution was used to construct from the theoretical cross section the transfer probability in a way consistent with the experimental definition. The calculations are performed in a Distorted Wave Born Approximation (DWBA) by using for the wave functions of relative motion their CWKB form. For the one-neutron transfer channel the inclusive cross section is simply obtained by summing up all the contributions coming from the single particle transitions. For the two-neutron transfer channel we included only the ground to ground state transition in the successive approximation (we remind that the simultaneous component is canceled out by the non orthogonality correction).

**CONCLUSIONS**

We measured transfer probabilities for one- and two-neutron transfer channels from the Coulomb barrier energy to energies corresponding to very large distances of closest approach where the nuclear absorption is negligible. The employed microscopic theory, that incorporates nucleon-nucleon correlations very well reproduces the experimental data in all energy range. In particular, the transfer probability for two neutrons is very well reproduced, in magnitude and slope, by considering solely the ground-ground state transition. For the first time in a heavy ion collision, it has been possible to provide a consistent description of one and two neutron transfer reactions by incorporating, in the reaction mechanism, all known structure information of entrance and exit channels nuclei. In particular, there is no need to introduce any enhancement factor for the description of two neutron transfer. This has to be considered a significant step forward in the understanding of two-neutron transfer processes.

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