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Description Of Multi-nucleon Transfer And Fusion Reactions With The coupled-channels Method

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We discuss nucleon transfer and fusion reactions of the ^{40}Ca+^{58}Ni and ^{40}Ca+^{64}Ni systems with the coupled-channels approach. It is first shown that a simple treatment for the transfer in the coupled-channels method cannot reproduce simultaneously the transfer probabilities and the sub-barrier enhancement of the fusion cross sections. An alternative scheme for the transfer, that takes into account other collective states in the pair transfer channel is proposed.

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1. Introduction

An extra enhancement of fusion cross sections at low energies is often attributed to different transfer processes. Several approaches have been employed in order to reproduce this enhancement. In our previous analysis [1], we attempted to reproduce simultaneously the experimental transfer probabilities and the fusion cross sections for the reaction ^{96}Zr+^{40}Ca [2]. The strategy was to adjust the transfer coupling to the experimental transfer data and to compare the fusion cross sections obtained with this approach to the experimental data. A slight underestimation of the fusion cross sections was found at low energies. On the other hand, Esbensen *et al.* [3] showed that it was possible to reproduce perfectly the fusion cross sections for this system if one takes into account in addition the proton transfer channels.

In this contribution, we test this approach on the ^{40}Ca+^{58}Ni and ^{40}Ca+^{64}Ni systems, for which the fusion cross sections have been measured in ref. [4]. The TDHF theory [6] has shown that the major difference between these two systems is due to the neutron transfer. It is expected that the transfer probability for the ^{40}Ca+^{64}Ni system is by about one order of magnitude higher than that for the ^{40}Ca+^{58}Ni system. In the present contribution, we shall try to reproduce the neutron and proton transfer probabilities simultaneously with the enhancement of the fusion cross sections at low energies.

2. Experiment

The experiment has been recently performed at INFN-Laboratori Nazionali di Legnaro (LNL) in inverse kinematics at energies around and below the Coulomb barrier. ^{64}Ni and ^{58}Ni beams were delivered by the Legnaro XTU Tandem accelerator ($E_{\rm lab}$=174, 190 and 210 MeV for ^{64}Ni, and $E_{\rm lab}$=170 and 201 MeV for ^{58}Ni) onto a 100 micro g/cm^2 strip ^{40}Ca target deposited on a 15 micro g/cm^2 ^{12}C backing. The ^{40}Ca target-like ions were detected and identified by the large acceptance ($\pm$ 5°) PRISMA magnetic spectrometer around $\theta_{\rm lab}$ = 45°. Four transfer channels were identified: +1n, +2n, -1p and -2p, where the + sign means a transfer from the Ni fragment to the ^{40}Ca one. For more details, see ref. [5].

3. Coupled-channels method

The coupled-channels calculations have been carried out with the program CCFULL [7], that has been modified in order to compute the neutron and proton transfer probabilities.

Table 1: Parameters of Woods-Saxon real and imaginary potentials employed in the coupled-channels calculations.

System	V_0 [MeV]	r_0 [fm]	a [fm]	W_0 [MeV]	r_W [fm]	a_W [fm]
^{40}Ca+^{58}Ni	60.41	1.17	0.66	35	1.1	0.2
^{40}Ca+^{64}Ni	68.70	1.16	0.66	35	1.1	0.2

The same method as in ref. [1] has been used, with parameters for the nucleus-nucleus potential given in Tab. 1 and with the coupling parameters to the transfer channel in Tab. 2. This model assumes that the pair transfer is a sum of two processes, a direct pair transfer and a sequential transfer. The sequential transfer coupling is assumed to be equal to the single transfer, i.e. a_{12}=a_{01}. As in ref. [4], we take into account the excitation to the first 3^- state in ^{40}Ca at energy 3.736 MeV with a coupling strength of $\beta = 0.4$, the 2^+ state in ^{58}Ni at 1.454 MeV with $\beta = 0.18$, and the 2^+ state in ^{64}Ni at 1.346 MeV with $\beta = 0.16$. Following ref. [8], we treat the collective excitations and the transfer process as independent degrees of freedom.

Table 2: Coupling constants for the transfer channels employed in the coupled-channels calculations. The parameters a are given in fm, β in MeV.fm and Q in MeV.

System	n,p	a_{01}	β_{01}	Q_{01}	a_{02}	β_{02}	Q_{02}
^{40}Ca+^{58}Ni	n	1.06	-52.4	-3.85	1.06	-2	-2.62
^{40}Ca+^{58}Ni	p	1.06	-59.4	-4.94	1.06	-18.5	-6.19
^{40}Ca+^{64}Ni	n	1.2	-40	-1.29	1.06	-19	0
^{40}Ca+^{64}Ni	p	1.16	-27	-0.874	1.06	-21	0

The transfer probabilities are computed as the ratio of the transfer cross sections to the elastic plus inelastic cross sections. The coupling parameters have been adjusted in order to reproduce the experimental transfer results as shown on the left part of figs. 1 and 2. In these figures, the transfer probabilities are shown as a function of the distance of closest approach D based on the Rutherford trajectory. As expected from the Q-value, the transfer probabilities are by one order of magnitude less for the ^{40}Ca+^{58}Ni system than for the ^{40}Ca+^{64}Ni system. In the former system, the coupled-channels reproduces well the fusion cross sections because the transfer effect is too small to enhance the fusion cross sections.

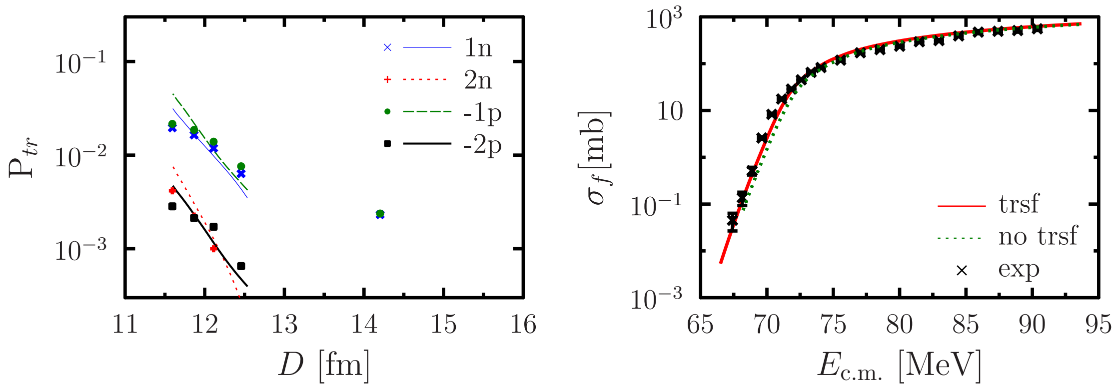

Figure 1: Left: The transfer probabilities obtained experimentally (marker) and with the coupled-channels method (lines) for the ^{40}Ca+^{58}Ni reaction. Right: Corresponding fusion cross sections obtained experimentally and with the coupled-channels method with and without taking into account the couplings to the transfer channels (lines).

For the ^{40}Ca+^{64}Ni fusion reaction shown in Fig. 2, the coupled-channels method predicts a small effect of the transfer. In contrast, experimentally the fusion cross sections are enhanced at energies below the barrier. Note that we can also invert the procedure, that is, by fitting the transfer coupling in order to reproduce the fusion cross sections and then comparing the transfer probabil-

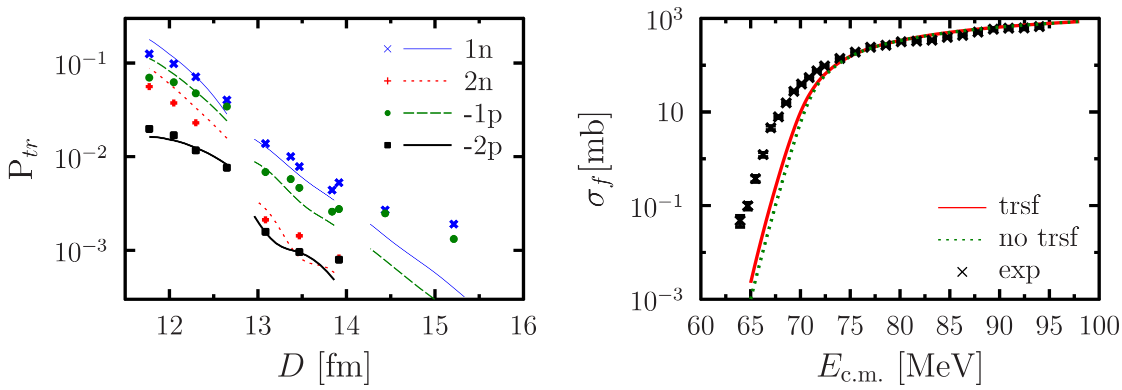

Figure 2: Same as Fig. 1, but for the ^{40}Ca+^{64}Ni reaction.

ities to the experimental data. In that case, the fusion cross sections will be well reproduced but the predicted transfer probabilities would be overestimated by about a factor of 10. In either way, it does not seem possible with this approach to reproduce simultaneously the transfer probabilities and the sub-barrier enhancement of the fusion cross sections.

4. Alternative scheme

We then propose a new scheme for the treatment of the transfer and collective states in the coupled-channels framework. Based on the observation that the the first 2^+ of the ^{42}Ca is at an energy of 1.524 MeV with a coupling strength β=0.247 while the first 2^+ state in ^{40}Ca is at an energy 3.904 MeV with β=0.123, we take into account some additional collective states that should arise after the pair transfer. This scheme is somewhat inspired by the quantum diffusion approach [9].

In addition of the 3^- state in the ^{40}Ca like fragment and the 2^+ state in the ^{64}Ni like fragment we take into account two additional effective states at the energies of 1 and 2 MeV with respectively β=0.35 and 0.49. All the mutual excitations are also taken into account leading to a total of 36 states. A direct transfer coupling from the ground state to those states is also taken into account with the same coupling as that for the ground to ground state transfer coupling. Similarly to the coupling scheme employed by Esbensen and Landowne [8], the zero neutron transfer collective states are coupled to the corresponding transfer channel as shown in Fig. 3.

Table 3: Same as Tab. 2, but for the alternative coupling scheme.

System	n,p	a_{01}	β_{01}	Q_{01}	a_{02}	β_{02}	Q_{02}
^{40}Ca+^{64}Ni	n	1.16	-50	-1.29	1.16	-7	0
^{40}Ca+^{64}Ni	p	1.16	-27	-0.874	0.9	-20	0
^{40}Ca+^{96}Zr	n	1.23	-55	0	0.79	100	0

The parameters readjusted with this scheme are given in Tab. 3. The corresponding results are shown in Fig. 4. We can see that, with this new coupling scheme, there is an important enhancement of the fusion cross sections at low energies, while the transfer probabilities remain similar to the

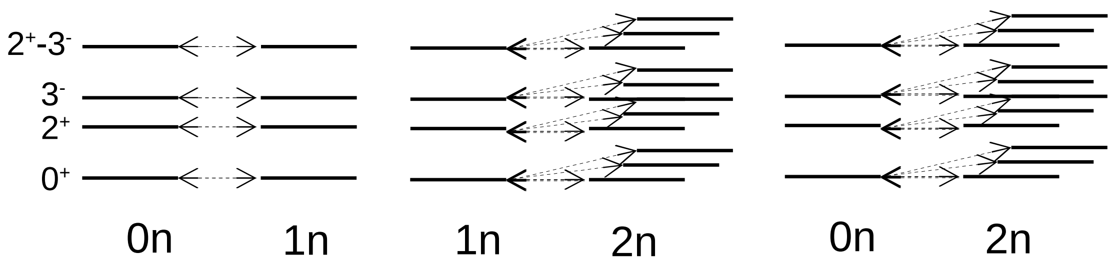

Figure 3: Transfer coupling scheme for neutrons. The same coupling scheme is used for the transfer of protons.

previous calculations shown in Fig. 2. Nevertheless, the result is not perfect around the $E_{c.m.}$=68 MeV region. This is probably due to limitations of the present new scheme, which makes several assumptions about the transfer coupling.

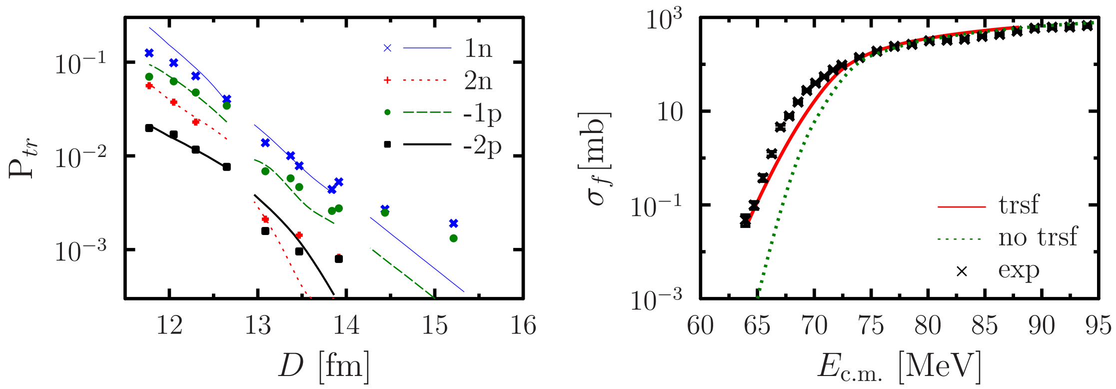

Figure 4: Same as Fig. 2, but with the alternative scheme, that take into account additional collective states after the pair transfer.

We test also a similar scheme for the extensively studied ^{40}Ca+^{96}Zr system [2, 10, 11]. In our previous description [1], it was not possible to reproduce simultaneously the fusion cross section and the transfer probabilities. Like in the ^{40}Ca+^{64}Ni case, two additional collective states are added after the pair transfer at the energies 1 and 2 MeV with β of 0.346 and 0.489. The transfer couplings are given in Tab. 3. The parameters of the nucleus-nucleus interaction as well as the coupling to excited states are the same as in ref [1]. With this scheme, the fusion cross section is well reproduced as shown in Fig. 5.

5. Conclusion

In conclusion, this analysis has shown that a scheme that considers the same collective states after the transfer process cannot reproduce simultaneously the fusion and the transfer cross sections.

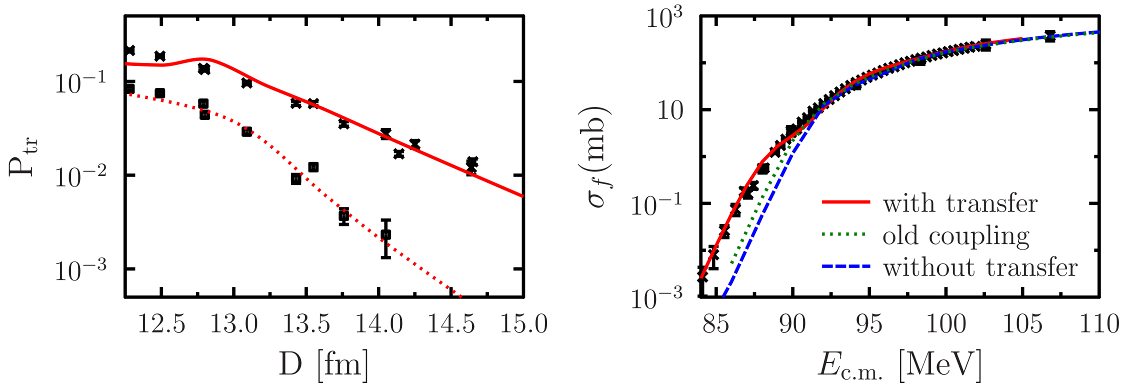

Figure 5: Left : Transfer probabilities for the reaction ^{40}Ca+^{96}Zr, the experimental data from ref. [2] for one-neutron (crosses) and two-neutron (square) are compared to coupled-channels calculations (solid line for 1n and dotted line for 2n). Right : fusion cross section from the experimental data [10, 11] (dashed blue line) compared to the coupled-channels calculation of ref. [1] (dotted green line) and the present calculation (solid red line)

Nevertheless, if we take into account additional collective states after the pair transfer then it is possible to partially account for the low energy enhancement of the fusion cross sections for the ^{40}Ca+^{64}Ni and ^{40}Ca+^{96}Zr systems. This study indicates that it is not only the transfer by itself that enhances fusion cross sections but also a change in the coupling scheme after the pair transfer.

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