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Fusion reactions of ^{58,64}Ni+^{124}Sn

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Abstract

In order to better understand the influence of transfer in sub-barrier nuclear reactions, cross sections for the system ^{58,64}Ni+^{124}Sn have been measured down to 0.5-1 μb and compared to detailed coupled-channel calculations. In agreement with a phenomenological Q-value systematics, calculations show the importance of including the coupling to the transfer channel for these heavy systems. No clear evidence of fusion hindrance is observed, probably due to the fact that the cross sections measured in this experiment are not low enough for the appearance of that phenomenon.

In the last years many theoretical and experimental works on heavy-ion fusion reactions have been devoted to the study of the influence of nuclear structure on the fusion process and the main results have been summarized in several review articles [1–3].

It has been clear since the 80's that the structure of colliding nuclei strongly affects the fusion probability: the most evident effect is the large enhancement of the experimental fusion cross section with respect to the predictions of the one-dimensional barrier model. This effect can be explained by means of coupled-channels calculations, where couplings to the low-lying surface modes of the colliding nuclei are taken into account.

In more recent years, thanks to the capability of reaching cross sections at the nb level, the phenomenon of the fusion hindrance was discovered [4] and explained through the saturation properties of nuclear matter [5] or the damping of the coupling strength during the adiabatic fusion process [6].

A still open question for a more complete understanding of fusion reactions mechanisms is the influence of nucleon transfer between the colliding nuclei. Recent measurements on Ca+Ca [5–7] and Ca+Zr [8] systems have showed evidence for the effect of positive Q-value transfer coupling at sub-barrier energies but no unambiguous conclusion concerning heavier systems has yet been drawn. As a matter of fact in heavy systems involving soft vibrational nuclei multi-phonon excitations become dominant and, as a consequence, it is more difficult to disentangle a possibile influence of transfer in the trend of the excitation function.

Fusion in the Ni+Sn system, widely studied in the past down to cross sections of about 0.1-1 mb [9–12], can give important information in this sense. Two recent publications, concerning the influence of transfer in the fusion process, came to different conclusions. In the first one [13], where the excitation function of ^{58}Ni+^{132}Sn could only be measured down to the 0.1-1 mb region due to the low intensity of the secondary ^{132}Sn beam, it was claimed that the influence of transfer for Ni+Sn is negligible compared to lighter systems; in the other one [14] it was concluded that the fusion enhancement due to transfer couplings should be present in heavier systems as well.

In the latter an attempt of extracting a systematics from several cases is presented. The Wong formula [15] is used to explore the influence of transfer on fusion in a phenomenological way. This formula is a good approximation of the fusion cross section in the region from 1000 to around 1 mb by means of only three parameters, as we can see in Eq. 1:

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$$\sigma = \frac{R_C^2}{2E}\,\hbar\omega\, ln\left[1 + e^{\frac{2\pi}{\hbar\omega}(E-V_C)}\right], \tag{1}$$

where R_C, V_C and $\hbar\omega$ correspond to the radius, the height and the curvature of the fusion barrier, respectively.

The results clearly show that large values of $\hbar\omega$ (corresponding to thin barriers and then in favour to a fusion enhancement) are always associated with positive Q values for neutron transfer, in both medium (Ca+Ca, Si+Ni, Ni+Ni) and heavy systems (Ca+Zr, Ca+Sn, Ni+Sn). In particular, excitation functions have a shallower slope for systems where a neutron-poor projectile collides on a neutron-rich target [14].

In Figure 1 excitation functions for different Ni+Sn isotopes are reported and fitted with the Wong formula, which of course fails to reproduce the experimental trend in the deep sub-barrier energy region. For ^{58}Ni+^{124}Sn and ^{64}Ni+^{124}Sn the new experimental data are also reported but they are irrelevant for this part of the discussion.

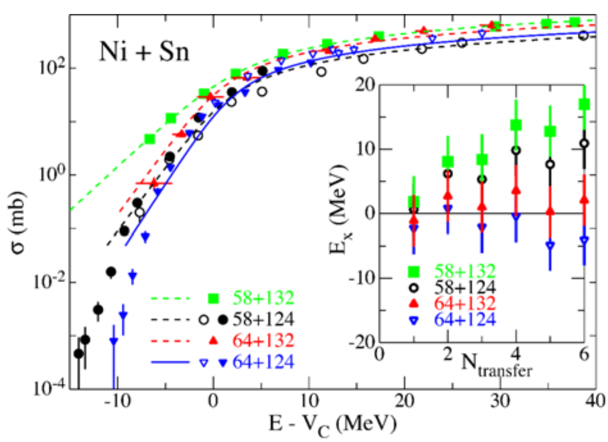

Figure 1: Fusion cross sections for different Ni+Sn systems plotted versus the difference between the centre-of-mass energy and the Coulomb barrier extracted from the fit with the Wong formula (see Equation 1). Insert: average excitation energies of neutron pickup reactions calculated from the Q-value systematics for the same systems. Colours in the online version.

The most remarkable feature is, as already pointed out, the close connection between transfer channels with positive Q value (see the insert in Figure 1 and Table 1) and the shallower slope of the associated excitation function.

This is not sufficient to draw the conclusion that the coupling to transfer

Table 1: Q-values for one- and two-neutron pickup by ^{58}Ni and ^{64}Ni from the two Sn isotopes of interest. For the combination neutron-poor projectile with neutron-rich target (or viceversa) the Q values are always positive and larger with respect to the more symmetric combinations.

	^{58}Ni+^{124}Sn	^{64}Ni+^{124}Sn	^{58}Ni+^{132}Sn	^{64}Ni+^{124}Sn
Q(+1n)	0.510 MeV	-2.391 MeV	1.656 MeV	-1.245 MeV
Q(+2n)	5.952 MeV	0.615 MeV	7.833 MeV	8.497 MeV

channels plays an important role also in the fusion process of heavier systems. A possible confirmation needs an extension of the experimental data to lower cross sections and a comparison with detailed coupled-channels calculations.

To this end an experiment was performed at the XTU Tandem accelerator of Laboratori Nazionali of Legnaro, Italy, using doubly-stripped beams of ^{58,64}Ni with a current of 1-3 pnA on a ^{124}Sn target with a thickness of 50 μg/cm^2, evaporated on a 20 μg/cm^2 carbon backing. The evaporation residues were detected with the LNL electrostatic separator in its upgraded configuration [16], consisting on two micro-channel plate detectors, one ionization chamber and a silicon detector. More details about the experiment can be found in Ref. [17].

In Figure 2 the experimental results are presented together with the theoretical calculations.

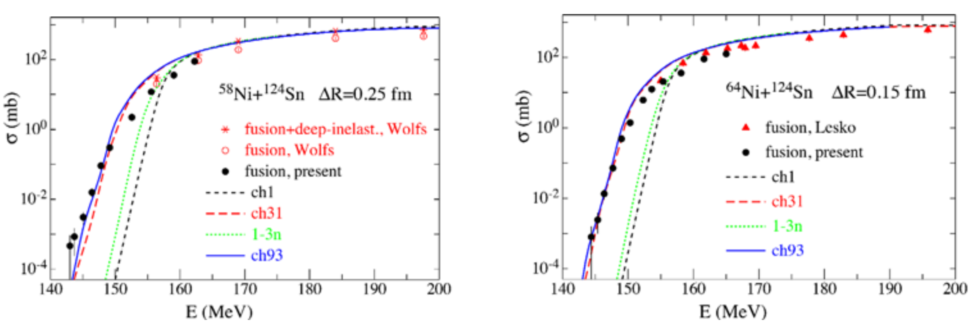

Figure 2: Experimental excitation functions from the present experiment and comparison with CC calculations for ^{58}Ni+^{124}Sn (on the left) and ^{64}Ni+^{124}Sn (on the right). The parameter ΔR represents the radius shift to be added to the fusion radius of the reactions in order to obtain a good reproduction of the experimental data at low energies. Colours in the online version.

The fusion excitation functions already include the fusion-fission contribution, measured by Lesko *et al.* [10] and Wolfs *et al.* [11]. In the vicinity of the Coulomb barrier the CC calculations still overestimate the fusion cross section, maybe because the deep-inelastic yield is not included, as it was measured only for ^{58}Ni and only at relatively high energies.

Figure 3 shows a zoom of Figure 2 in the low-energy region.

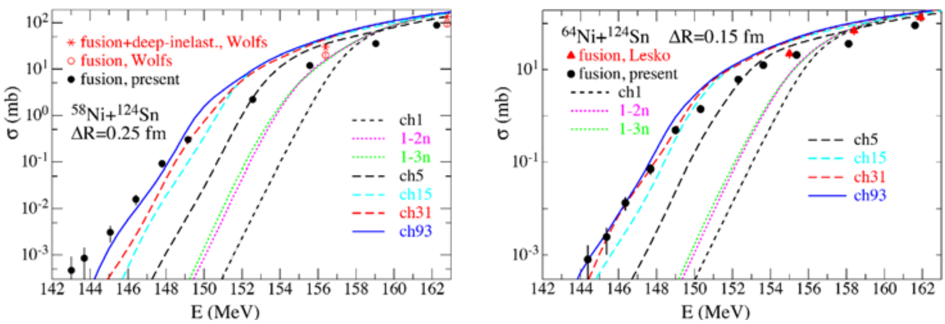

Figure 3: A zoom of Figure 2 in the low-energy region. For details on the CC calculations see text. Colours in the online version.

As no indication of fusion hindrance was observed, a standard Woods-Saxon potential has been used to describe the ion-ion interactions. In Figure 2 and 3 the black dot-dashed line (indicated with ch1) is the result of the calculation where no coupling is taken into account. The dotted magenta and green lines include the coupling to one- and two- (1-2n) and to one-, two- and three-neutron transfer (1-3n), respectively. The dashed curves represent the effect of including inelastic excitations. The black and light-blue lines show the effect of including one- (ch5) and two-phonon (ch15) excitations; in the latter all one- and two-phonon states and mutual excitations of the low-lying 2^+ and 3^- states in the projectile and/or the target are included. The red dashed curve shows the results of a three-phonon calculation where the three mutual one-phonon excitations and the mutual excitations of one- and two-phonon states are included whereas the three-phonon excitations of the same mode are excluded, resulting in 31 channels (ch31).

When we include in the calculations the couplings of both inelastic (one-, two- and three-phonon) and transfer (one- and two-neutron) reactions we obtain a total of 93 channels (ch93), represented by the solid blue line.

Parameters for inelastic excitations were taken from the literature: in the case of ^{58}Ni from previous coupled-channel calculations for multi-neutron transfer reactions in ^{58}Ni+^{124}Sn collisions around the Coulomb barrier [18]; in the case of ^{64}Ni from the analysis of the fusion of ^{64}Ni+^{64}Ni [19]. These parameters can be found, together with spectroscopic factors for the strongest one-neutron pickup channel by ^{58}Ni and ^{64}Ni and parameters of the Woods-

Saxon potentials used in the CC calculations, in Table II, III and IV of Ref. [17].

A comparison between the two excitation functions exhibits several interesting features.

- The largest enhancement of the fusion cross section is due to the coupling of inelastic excitations, as expected for these heavy systems.
- The system ^{58}Ni+^{124}Sn shows a larger influence from the coupling to transfer reactions, as expected from the Q-value systematics previously described. For the system ^{64}Ni+^{124}Sn the contribution from transfer is weaker, due to the smaller Q values, but not negligible.
- For both systems the influence of transfer shows up mainly in the cross section region below 1 mb. This may partially explain why in the work by Kohley *et al.* [13] no contribution from transfer was identified.
- Both systems show a reduction of the experimental cross section compared to the CC calculations around 151 MeV. The reason is not yet fully understood, although it could be ascribed, as pointed out before, to the contribution from the deep-inelastic scattering.
- There is no evidence for fusion hindrance. From systematics involving both soft (open-shell) and stiff (closed-shell) systems, the appearance of an S-factor maximum, which would be an evidence for hindrance, is expected at center-of-mass energies lower than 140 MeV and at cross sections at the nb level. Therefore to see the hindrance behaviour for these systems an improvement of the experimental sensitivity by a factor $\sim$100 is needed.

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