Fusion Hindrance and Pauli Blocking in ^{58}Ni + ^{64}Ni

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Abstract. ^{58}Ni +^{64}Ni is the first case where the influence of positive Q-value transfer channels on sub-barrier fusion was evidenced, in a very well known experiment by Beckerman et al., by comparing with the two systems ^{58}Ni +^{58}Ni and ^{64}Ni +^{64}Ni. Subsequent measurements on ^{64}Ni +^{64}Ni showed that fusion hindrance is clearly present in this case. On the other hand, no indication of hindrance can be observed for ^{58}Ni +^{64}Ni down to the measured level of 0.1 mb. In the present experiment the excitation function has been extended by two orders of magnitude downward. The cross sections for ^{58}Ni + ^{64}Ni continue decreasing very smoothly below the barrier, down to $\simeq$1 μb. The logarithmic slope of the excitation function increases slowly, showing a tendency to saturate at the lowest energies. No maximum of the astrophysical S-factor is observed. Coupled-channels (CC) calculations using a Woods-Saxon potential and including inelastic excitations only, underestimate the sub-barrier cross sections by a large amount. Good agreement is found by adding two-neutron transfer couplings to a schematical level. This behaviour is quite different from what already observed for ^{64}Ni+^{64}Ni (no positive Q-value transfer channels available), where a clear low-energy maximum of the S-factor appears, and whose excitation function is overestimated by a standard Woods-Saxon CC calculation. No hindrance effect is observed in ^{58}Ni+^{64}Ni in the measured energy range. This trend at deep sub-barrier energies reinforces the recent suggestion that the availability of several states following transfer with Q >0, effectively counterbalances the Pauli repulsion that, in general, is predicted to reduce tunneling probability inside the Coulomb barrier.

1 Introduction

The sequence of stable nickel isotopes from ^{58}Ni to ^{64}Ni offers several opportunities of studying fusion dynamics near and below the Coulomb barrier. The early experiments on fusion of Ni + Ni systems [1] are well-known and indicated for the first time the possible influence of transfer reactions on near- and sub-barrier cross sections. The excitation functions of the three systems ^{58}Ni + ^{58}Ni, ^{58}Ni + ^{64}Ni and ^{64}Ni + ^{64}Ni, besides the trivial differences due to the varying Coulomb barriers, show a remarkable feature, that is, the contrasting slope of the asymmetric system ^{58}Ni + ^{64}Ni, when compared to the other two symmetric cases. Indeed, the cross sections of ^{58}Ni + ^{64}Ni decrease much slower with decreasing energy. Shortly after, this was associated [2] with the availability, only in this system, of neutron transfer channels with positive Q-values. Later experiments for ^{58}Ni + ^{64}Ni [3] confirmed the flat shape of the excitation function, but the measured cross sections were anyway limited to $\sigma \geq$0.1 mb.

In more recent years it was found for many systems [4] that, at deep sub-barrier energies, the cross section decreases very rapidly [5], so that the excitation function is much steeper than the prediction of standard coupled-channels (CC) calculations. This phenomenon was named fusion hindrance. One of the first systems where this effect was clearly identified is ^{64}Ni + ^{64}Ni [6].

The original data of Beckerman et al. [1] were extended down to the level of $\approx$ 25 nb and the threshold of hindrance is around 0.1 mb. The effect was recognised also in the case of ^{58}Ni + ^{58}Ni at the level of 0.05 mb from the data of Ref. [1].

Low-energy hindrance is a matter of continuing experimental and theoretical interest. In the sudden approach proposed by Misicu and Esbensen [7, 8], a double folding potential is adopted (M3Y+repulsion), producing a shallow pocket as a consequence of the incompressibility of nuclear matter. This CC model has been quite successful in reproducing the hindrance behavior in a number of cases [9].

Alternatively, Ichikawa et al. [10], proposed an adiabatic neck formation between the colliding nuclei in

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the overlap region, leading to hindrance. More recently, Simenel et al. [11] introduced a new microscopic model and demonstrated, on the basis of density-constrained frozen Hartree-Fock calculations, that the main effect of Pauli repulsion is to reduce tunnelling probability inside the Coulomb barrier. It has been pointed out as well that when positive Q-value transfer channels are available to the system, this effect of Pauli blocking may be reduced or disappear altogether [12], because several final states can be populated, and valence nucleons can flow between the two nuclei, thus initiating fusion. This corresponds to what observed for the system ^{40}Ca+^{96}Zr that was investigated a few years ago [13, 14]. The flat shape of its sub-barrier fusion excitation function is very peculiar and was suggested to originate from the couplings to several Q >0 neutron pick up channels. ^{40}Ca+^{96}Zr was studied down to very small cross sections (2μb) and the phenomenon of fusion hindrance does not show up.

If that interpretation is correct, we expect a similar behaviour for ^{58}Ni +^{64}Ni which is a very attractive case in this sense because the Q-values for the neutron transfer channels are +3.9 MeV, for 2n and 4n pick up, and where a clear evidence of transfer couplings was already indicated below the barrier. The appearance of fusion hindrance in this case, would put serious doubts on the suggestion that Pauli blocking is not effective (or weakened) in systems with Q >0 transfer channels.

The experiment has been performed very recently, and the low-energy part of the excitation function for ^{58}Ni + ^{64}Ni has been extended down by about two orders of magnitude. The results of these measurements will be reported in this contribution.

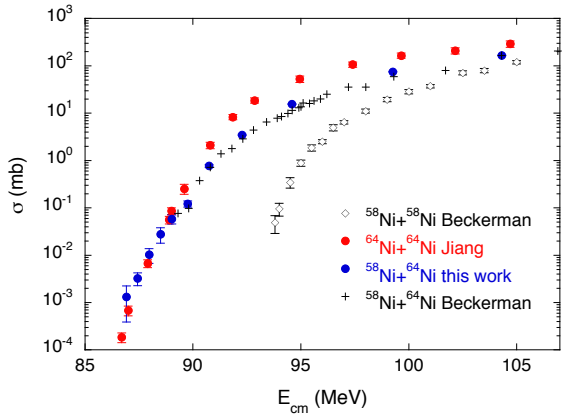

Figure 1. Fusion excitation functions for several Ni + Ni systems from the present and previous measurements (see text for setails).

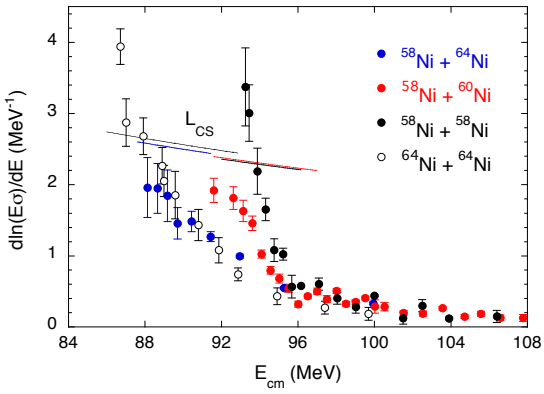

Figure 2. Logarithmic derivatives for several Ni + Ni systems.

2 Experimental set-up and Results

Fusion-evaporation cross sections have been measured for the system ^{58}Ni + ^{64}Ni at several energies near and below the Coulomb barrier, using the ^{58}Ni beam provided by the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro (LNL) of INFN in the energy range 167-201 MeV. The beam intensity was 3-4 pnA.

Fusion-fission is negligible for ^{58}Ni + ^{64}Ni in the measured energy range, hence fusion cross sections were obtained by detecting at forward angles the evaporation residues (ER) following compound nucleus formation. The ER were separated from the beam by using the electrostatic deflector (see [15] and Refs. therein) usually employed for fusion measurements at LNL

The set of fusion cross sections we have obtained for ^{58}Ni + ^{64}Ni are shown in Fig. 1 with blue dots, together with the previous results for the same system and for ^{58}Ni + ^{58}Ni [1] (black crosses and open dots, respectively), and with the more recent measurements of Jiang et al. [6] on ^{64}Ni + ^{64}Ni (red dots). It is evident that the cross sections for ^{58}Ni + ^{64}Ni continue decreasing very smoothly below the barrier, while the two symmetric systems have much steeper excitation functions. This trend is clearly observed down to the lowest-measured cross section of $\simeq$1.3 μb.

Fig. 2 shows the logarithmic slope of the excitation function, derived from the measured cross sections, as the incremental ratio of two near-by points, for the various Ni+Ni systems. In this case, the existing data on ^{58}Ni + ^{60}Ni [16] have been added to the systematics. It appears that the trend of this system is similar to that of ^{58}Ni + ^{64}Ni. For both these cases, in the measured energy range, the slope increases slowly below the barrier with decreasing energy without notable irregularities. It does not reach the value expected for a constant astrophysical S-factor (L_{CS} in Fig. 2), rather it seems to saturate around 2 MeV^{-1}. Indeed, the influence of 2n-transfer couplings at the lowest energies was qualitatively suggested for ^{58}Ni + ^{60}Ni. For the other two symmetric systems Fig. 2 shows (as already known) that the slope clearly overcomes the L_{CS} value, thus presenting hindrance.

The CC calculations we are going to present in the next Section, and the comparison with ^{64}Ni + ^{64}Ni, will tell us more about this point.

3 Coupled-Channels Analysis

The CCFULL code [17] has been used to perform CC calculations for ^{58}Ni + ^{64}Ni. The ion-ion potential was a Woods Saxon parametrisation with well depth V_0= 151.85 MeV, diffuseness a= 0.67 fm and radius parameter r_o= 1.10 fm. V_0 is much deeper than what one obtains from

the Akyüz-Winther potential [18]. It is used to remove unwanted oscillations of the low-energy excitation function that appear if the potential is too shallow, and consequently the incoming-wave boundary condition is not correctly applied. The parameters have been chosen to obtain a good data fit in the barrier region σ= 10-100 mb, when all channels, including the two neutron transfer (see later on) are taken into account in the calculations.

The nuclear structure information of the low-lying collective modes of ^{58}Ni and ^{64}Ni is reported in Table 1. The two nickel isotopes have quadrupole states at similar excitation energies and strengths. In the calculations we have considered up to two quadrupole phonons and only one octupole phonon (that has much higher excitation energy) in both nuclei.

Fig. 3 shows the results of the calculations when compared to the present experimental data (blue symbols). We notice that the CC results (blue line) strongly underestimate the data below the barrier. This indicates the possible effect of transfer couplings. Indeed in the recent work on ^{40}Ca + ^{96}Zr [19] it was pointed out that the effective Q-values for two-neutron as well as two-proton transfer are positive and both transfer channels can therefore influence the fusion. The situation is the same for ^{58}Ni + ^{64}Ni where the corresponding Q-values are +3.89 MeV and +2.6 MeV.

Therefore, further calculations have been performed, including a two nucleon transfer channel (+ 2N) besides the collective surface modes discussed above, using the approximate treatment of CCFULL where a pair transfer coupling between the ground states may be included. This uses the macroscopic coupling form factor given in Ref. [22]. The coupling strength F_t= 0.6 MeV has been used, adjusted for a best data fit. This rather large strength may be explained by the fact that it includes both proton and neutron transfer channels. The result is reported in Fig. 3 as a green solid line.

In the S-factor representation (Fig. 4) we can reach analogous conclusions. Indeed only including in the CC calculations the transfer coupling we have been able to reproduce the experimental S-factor trend where no maximum has been observed vs. energy.

The present results, and the comparison to CC calculations, indicate that hindrance does not show up in ^{58}Ni + ^{64}Ni in the measured energy range. At lower energies, we know that hindrance must appear, because the Q-value for fusion is negative Q_{fus}= -52.7 MeV [23].

4 Comparison with ^{64}Ni+^{64}Ni and ^{40}Ca+^{96}Zr

A comparison with the near-by system ^{64}Ni + ^{64}Ni is significant because in this case the hindrance phenomenon is present [6]. CCFULL calculations have been performed using the structure information of Table 1, and the Woods-Saxon ion-ion potential with parameters V_0= 75.98 MeV, diffuseness a= 0.676 fm and radius parameter r_o= 1.202 fm, as quoted in the original article [6]. In analogy with ^{58}Ni + ^{64}Ni, couplings to two quadrupole phonons and one octupole phonon have been considered. The result of the CC calculation is reported in Fig. 3 (see also Ref. [4]). We

Table 1. Excitation energies E_x, spin and parities λ^π, reduced transition probabilities and deformation parameters β_λ [20, 21] for the lowest quadrupole and octupole modes of ^{58}Ni and ^{64}Ni (see text). Nuclear and Coulomb deformation parameters have been taken to be the same in the present CC analysis.

Nucleus	E_x(MeV)	λ^π	B(Eλ)$_{W.u.}$	β_λ
^{58}Ni	1.454	2^+	10.0	0.183 (3)
	4.475	3^-	12.6	0.20 (1)
^{64}Ni	1.346	2^+	10.0	0.179 (9)
	3.560	3^-	15.0	0.203 (20)

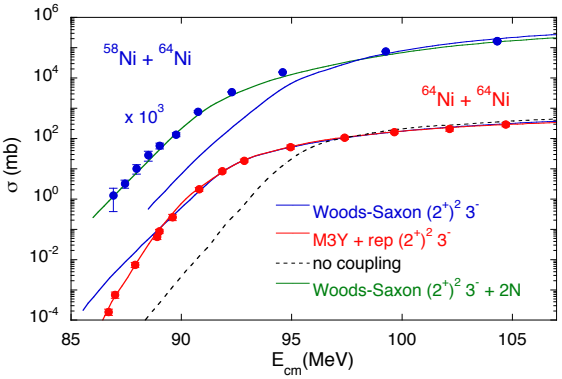

Figure 3. Fusion excitation function of ^{58}Ni + ^{64}Ni (blue dots) and ^{64}Ni + ^{64}Ni (red dots), compared with CC calculation (see text)

notice immediately that, at variance with ^{58}Ni + ^{64}Ni, the measured cross sections drop below the calculation (blue line) at low energies. Only using a shallow M3Y + repulsion potential [7, 8] (red line) one gets a good data fit, as already known.

The comparison of the excitation functions for the two systems with the corresponding CC calculations confirms that they behave quite differently in the low energy region. This is even more clear in the astrophysical S-factor representation, as reported in Fig. 4. The experimental S-factors of the two systems are found on opposite sides with respect to the corresponding calculations using standard WS potentials. In particular, the maximum of S observed for ^{64}Ni + ^{64}Ni but not for ^{58}Ni + ^{64}Ni, is not reproduced by the CC calculations.

The case of ^{58}Ni + ^{64}Ni, on the other hand, is very similar to ^{40}Ca + ^{96}Zr [13, 14] because of the flat shape of the two sub-barrier fusion excitation functions, probably originating in both cases from the couplings to several Q >0 neutron pick-up channels.

In ^{40}Ca + ^{96}Zr fusion hindrance does not show up and this rather unusual behaviour is also due to the Q >0 transfer couplings. Indeed, the barrier distribution of this system displays a very long tail towards low energies [14], and we know the hindrance phenomenon shows up below the energy where the barrier distribution vanishes. This led to the suggestion [12] that the reaction mechanism involves the Pauli exclusion principle that in general pro-

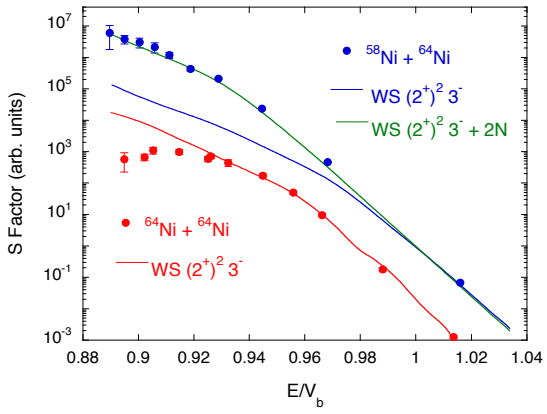

Figure 4. S-factor for ^{58,64}Ni + ^{64}Ni compared to CC calculations using a WS potential.

duces fusion hindrance [11], apart from the cases, as mentioned in the introduction, where several final states can be populated by nucleon transfer with Q >0.

The absence of hindrance in the present case of ^{58}Ni + ^{64}Ni reinforces that suggestion. The strong dissimilarity with respect to the near-by case of ^{64}Ni + ^{64}Ni contributes to clarify the sub-barrier fusion dynamics, and prompts us to contemplate the possibility that the repulsive part of the potential in the Misicu-Esbensen model [7, 8] is actually a consequence of the Pauli exclusion principle.

5 Summary and conclusions

The results of fusion excitation function measurements for ^{58}Ni + ^{64}Ni have been presented. The experiment was performed using the ^{58}Ni beam of the XTU Tandem accelerator of the LNL. The excitation function obtained previously [1, 3] has been extended downwards by two orders of magnitude to about 1μb. We observe that the logarithmic slope of the excitation function has a slow increase, and tends to saturate at the lowest energies. The astrophysical S-factor does not show any maximum vs. energy.

CC calculations using a Woods-Saxon potential have been performed. The results underestimate the sub-barrier cross sections by a large amount, when only inelastic excitations are included. Good agreement is however found by schematically adding the coupling to the two-neutron transfer. The behaviour of ^{58}Ni + ^{64}Ni is quite different from what already observed for ^{64}Ni+^{64}Ni, where no positive Q-value transfer channels are available. In this case a clear low-energy maximum of the S-factor shows up, and the logarithmic slope exceeds the L_{CS} value by a large amount. The measured excitation function is overestimated by a standard WS CC calculation. No hindrance effect is observed in ^{58}Ni+^{64}Ni in the measured energy range. This makes the sub-barrier trend of this system quite similar to ^{40}Ca + ^{96}Zr, and corroborates the recent suggestion that the availability of several states following transfer with Q >0, effectively counterbalances the Pauli repulsion that is predicted to reduce tunneling probability inside the Coulomb barrier.

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