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Fusion hindrance and Pauli blocking in $^{58}\mathrm{Ni} + {}^{64}\mathrm{Ni}$

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Summary. — The early experiments on fusion of Ni + Ni systems are well-known and indicated for the first time the possible influence of transfer reactions on sub-barrier cross sections. The influence of the positive Q-value transfer channels on sub-barrier fusion cross sections of the system $^{58}\mathrm{Ni} + {}^{64}\mathrm{Ni}$ was evidenced in an experiment by Beckerman *et al.* Subsequent experiments for the two systems $^{58}\mathrm{Ni} + {}^{58}\mathrm{Ni}$ and $^{64}\mathrm{Ni} + {}^{64}\mathrm{Ni}$ showed that fusion hindrance is clearly present in both cases. The lowest measured cross section for $^{58}\mathrm{Ni} + {}^{64}\mathrm{Ni}$ was relatively large (0.1 mb), so that no hindrance was observed. In the present measurement the excitation function has been extended by two orders of magnitude downward. The present experiment indicates that the flat trend of the sub-barrier cross sections for $^{58}\mathrm{Ni} + {}^{64}\mathrm{Ni}$ continues down to the level of μb and 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, so fusion hindrance is not observed. This trend at far sub-barrier energies suggests that the presence of the transfer channel with $Q > 0$, effectively counterbalances the effect of Pauli repulsion that is predicted to reduce tunneling probability.

1. – Introduction

The early experiments on fusion of Ni + Ni systems [1] 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, show 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 decreases much slower with decreasing energy. This was associated with the availability, only in this system, of neutron transfer channels with positive Q-values.

2. – Experimental set-up and results

Fusion cross sections were experimentally determined by the direct detection of evaporation residues (ER) using a ^{58}Ni beam provided by the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro (LNL) of INFN in the energy range of 167–201 MeV. The beam intensity was 3–4 pnA.

The apparatus consists of an electrostatic deflector, that allows the separation at forward angles of the ER from the residual beam exploiting their different electrical rigidity [2]. The deflector is followed by an energy (E), energy loss (ΔE) and time of flight (TOF) telescope.

Four silicon detectors are placed at a detection angle of $\theta_{lab} = 16.05°$ with respect to the beam line. These detectors are used to normalize the fusion yields to the Rutherford cross section and to monitor the beam position on the target.

The telescope provides the TOF, the total energy loss ΔE and the residual energy E. By correlating these variables, it is possible to identify the ER and obtain the total fusion cross sections.

The absolute cross section scale was fixed by equalizing the ER yield we obtained at the highest measured energy ($E_{lab} = 198.8$ MeV) to the corresponding cross section quoted in ref. [1].

The set of fusion cross sections we have obtained for ^{58}Ni + ^{64}Ni is shown in fig. 1 left 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 measurements of Jiang *et al.* [3] on ^{64}Ni + ^{64}Ni (red triangles). It's evident that the cross sections for ^{58}Ni + ^{64}Ni continue decreasing very smoothly below the barrier, while the ^{58}Ni + ^{58}Ni and ^{64}Ni + ^{64}Ni systems have much steeper excitation functions. This trend is clearly observed down to the lowest-measured cross section of $\simeq$1.3 μb.

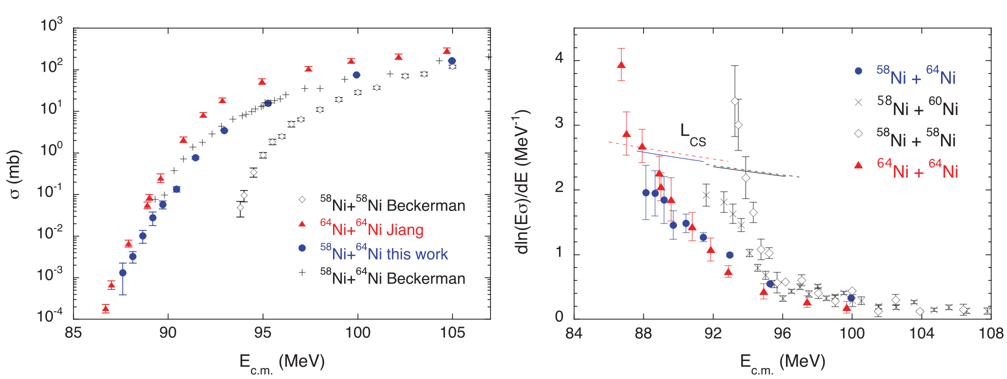

Fig. 1. – Left: fusion excitation functions for Ni + Ni systems from the present and previous measurements, see text for details. Right: logarithmic derivatives for several Ni + Ni systems.

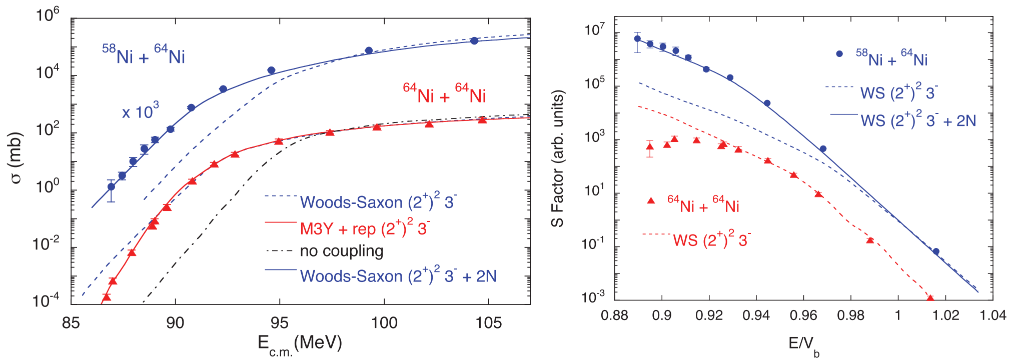

Fig. 2. – Left: fusion excitation function of ^{58}Ni + ^{64}Ni (blue dots) and ^{64}Ni + ^{64}Ni (red triangles), compared with CC calculation. Right: S-factor for ^{58,64}Ni + ^{64}Ni compared to CC calculations.

Also the logarithmic derivative (fig. 1, right) and the astrophysical S-factor (fig. 2, right) have been extracted. As expected,the logarithmic derivative remains always lower than the value expected for a constant astrophysical S-factor (L_{CS} line) and consequently there is no maximum for the astrophysical S-factor. For the other two systems, the slope clearly overcomes the L_{CS} value, thus presenting hindrance.

3. – Coupled-channels analysis

The CC calculations were performed by means of the CCFULL code [4] employing a Woods-Saxon potential based on the empirical Akyüz-Winther parametrization [5] with well depth $V_0 = 151.85$ MeV, diffuseness $a = 0.67$ fm and radius parameter $r_0 = 1.10$ fm.

The lowest quadrupole and octupole modes of ^{58}Ni and ^{64}Ni have been used in the calculations where up to two phonons of the quadrupole mode and only one phonon of the octupole mode (that has much higher excitation energy) in both nuclei were considered.

The resulting calculation is shown in fig. 2, left, the CC calculation underestimates the cross sections at low energies, so that there is no evidence of hindrance for this system. This effect may be attributed to the presence of neutron transfer channels with positive Q-value ($Q = 3.89$ MeV) for the ^{58}Ni + ^{64}Ni system. The CCFULL code allows including the pair-transfer between the ground states of the interacting nuclei through the schematic form factor [4]. The coupling strength F_t best fitting the data is $F_t = 0.6$ MeV. The result is reported in fig. 2, left as a blue solid line.

From the S-factor calculations (fig. 2, right) a similar conclusion can be reached, since the experimental value of the logarithmic derivative always remains lower than the L_{CS} limit, so that there is no maximum of the astrophysical S-factor indicating that hindrance does not show up in ^{58}Ni + ^{64}Ni.

4. – Comparison with ^{64}Ni + ^{64}Ni

The behavior of the ^{64}Ni + ^{64}Ni system has been considered [3], performing the CC calculation using the Akyüz-Winther potential with $V_0 = 127.92$ MeV, $r_0 = 1.12$ fm and $a_0 = 0.68$ fm. The results obtained are shown in fig. 2, left. Also for this system the CC calculation has been performed with two quadrupole phonons and one octupole phonon. The comparison of the excitation functions for the two systems with the corresponding

CC calculations confirms the different behavior in the low energy region. This is even clearer in the astrophysical S-factor representation, as reported in fig. 2 (right). In particular, the maximum of S observed for ^{64}Ni + ^{64}Ni but not for ^{58}Ni + ^{64}Ni, confirms the presence of hindrance for the first system and its absence for the second one. This different behavior suggests that the existence of $Q > 0$ transfer channels in ^{58}Ni + ^{64}Ni, given the very similar low-energy vibrational nature of the two nuclei, allows the valence nucleons to flow more freely from one nucleus to the other without being hindered by Pauli blocking.

5. – Summary and conclusions

We have presented the results of fusion excitation function measurements for the reaction ^{58}Ni + ^{64}Ni investigated by performing an experiment at the XTU Tandem of Laboratori Nazionali di Legnaro. An electrostatic deflector and a detector telescope have been used for the separation of the fusion evaporation products from the beam particles. In this way, fusion cross sections have been measured in a wide energy range from above down to far below the barrier ($V_b = 98.63\,\mathrm{MeV}$) reaching a minimum cross section of about 1 μb. The data have been compared with the CC calculations, showing that the theoretical predictions including two quadrupole phonons and one octupole phonon strongly underestimate the experimental cross section below the Coulomb barrier and there is a clear need for additional couplings. Including also the two neutron transfer channels, the theoretical prediction is in good agreement with the experimental data. The logarithmic derivative and the astrophysical S factor have been extracted from the data. The logarithmic slope increases slowly and doesn't reach the constant S factor value, so that there is no evidence for the hindrance phenomenon. This shows how the presence of neutron transfer channels with positive Q-value enhances the fusion cross section at low energies. The obtained results have been compared with the ^{64}Ni + ^{64}Ni system that presents a similar nuclear structure but doesn't have transfer channels with positive Q-value, and in this system the hindrance effect is observed. The behaviour of ^{58}Ni + ^{64}Ni at deep sub-barrier energies is a strong experimental evidence of the validity of the recent suggestion that the availability of several states following transfer with $Q > 0$, effectively counterbalances the repulsion caused by the Pauli exclusion principle.

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