Fusion of ^{48}Ti + ^{58}Fe and ^{58}Ni + ^{54}Fe below the Coulomb barrier

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Background: No data on the fusion excitation function of ^{48}Ti + ^{58}Fe in the energy region near the Coulomb barrier existed prior to the present work, while fusion of ^{58}Ni + ^{54}Fe was investigated in detail some years ago, down to very low energies, and clear evidence of fusion hindrance was noticed at relatively high cross sections. ^{48}Ti and ^{58}Fe are soft and have a low-lying quadrupole excitation lying at ≈800–900 keV only. Instead, ^{58}Ni and ^{54}Fe have a closed shell (protons and neutrons, respectively) and are rather rigid.
Purpose: We aim to investigate (1) the possible influence of the different structures of the involved nuclei on the fusion excitation functions far below the barrier and, in particular, (2) whether hindrance is observed in ^{48}Ti + ^{58}Fe, and to compare the results with current coupled-channels models.
Methods: ^{48}Ti beams from the XTU Tandem accelerator of INFN-Laboratori Nazionali di Legnaro were used. The experimental setup was based on an electrostatic beam separator, and fusion-evaporation residues (ERs) were detected at very forward angles. Angular distributions of ERs were measured.
Results: Fusion cross sections of ^{48}Ti + ^{58}Fe have been obtained in a range of nearly six orders of magnitude around the Coulomb barrier, down to $\sigma \simeq 2\ \mu$b. The sub-barrier cross sections of ^{48}Ti + ^{58}Fe are much larger than those of ^{58}Ni + ^{54}Fe. Significant differences are also observed in the logarithmic derivatives and astrophysical S factors. No evidence of hindrance is observed, because coupled-channels calculations using a standard Woods-Saxon potential are able to reproduce the data in the whole measured energy range. Analogous calculations for ^{58}Ni + ^{54}Fe predict clearly too large cross sections at low energies. The two fusion barrier distributions are wide and display a complex structure that is only qualitatively fit by calculations.
Conclusions: It is pointed out that all these different trends originate from the dissimilar low-energy nuclear structures of the involved nuclei. In particular, the strong quadrupole excitations in ^{48}Ti and ^{58}Fe produce the relative cross section enhancement and make the barrier distribution ≈2 MeV wider, thus probably pushing the threshold for hindrance below the measured limit.

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I. INTRODUCTION

A variety of phenomena have been observed and widely studied in the process of fusion between two heavy ions. They originate from the close link existing between nuclear structure and reaction dynamics, in the energy range near the Coulomb barrier [1,2]. The coupled-channels model associates fusion cross sections and enhancements, and barrier distributions (BDs) [3], to the low-lying collective excitation modes of the colliding nuclei and, in some cases, to the exchange of nucleons between them. Additionally, we have to take into account that the ion-ion potential is not known *a priori*, and can be substantially modified by nuclear structure and by the interaction.

Therefore, the experiments on sub- and near-barrier heavy-ion fusion give us a multiplicity of information. Only when (if) this information is complete enough in several cases can we hope to disentangle and understand more subtle effects, like the fusion limitation (hindrance) that has been observed in recent years at energies far below the Coulomb barrier [4,5]. Having all this in mind, we decided to perform an experimental study of the system ^{48}Ti + ^{58}Fe, where no data existed previously, and to compare in detail the results to the analogous evidences for the near-by case ^{58}Ni + ^{54}Fe whose excitation function was studied down to ≃1 μb some years ago [6].

The difference in nuclear structure between those two system is notable. Indeed, ^{48}Ti and ^{58}Fe are soft and have a low-lying quadrupole excitation lying at ≈800–900 keV only. Instead, ^{58}Ni and ^{54}Fe have a closed shell (protons and neutrons, respectively) and are rather rigid. The octupole vibrational states are high in energy and weak, in all cases. It was observed that the cross sections of ^{58}Ni + ^{54}Fe decrease very steeply at the lowest energies, so that the hindrance effects show up already at the level of the relatively large cross section of ∼200 μb [6].

The nature of the hindrance phenomenon is not yet clearly understood, and two main theoretical approaches have been developed in recent years. On one side Mişicu and Esbensen [7] proposed an ion-ion potential having a shallow pocket arising from nuclear incompressibility, and they were able to reproduce the lowenergy behavior of many systems. On the other side, Hagino and Ichikawa [8] used an adiabatic approach where the standard coupled-channels (CC) model is extended by introducing a damping factor into the coupling matrix elements at very low energies. This has been successfully applied, among others, to the case of ^{58}Ni + ^{54}Fe. In order to discriminate between the two approaches, measurements of still lower cross sections would be required, and this is very challenging.

A partial and preliminary version of the present data on ^{48}Ti + ^{58}Fe was reported at the Fusion14 Conference [9]. This paper presents the final results from the measurements on ^{48}Ti + ^{58}Fe, comparing and contrasting them with the behavior of ^{58}Ni + ^{54}Fe. Section II describes the experimental setup and methods, and Section III presents the results obtained for ^{48}Ti + ^{58}Fe and a purely experimental comparison with ^{58}Ni + ^{54}Fe. A more detailed discussion is performed in Sec. IV with the help of coupled-channels calculations, and the conclusions of the present work are given in Sec. V.

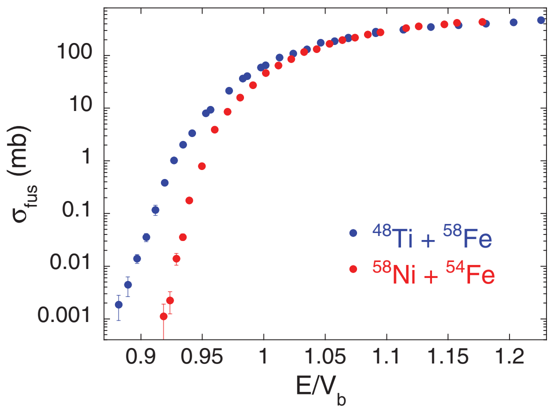

FIG. 1. (Color online) Fusion excitation functions of ^{48}Ti + ^{58}Fe measured in this work, and of ^{58}Ni + ^{54}Fe as reported in Ref. [6]. The abscissa is the energy relative to the AW Coulomb barrier.

II. THE EXPERIMENT ON ^{48}Ti + ^{58}Fe

The ^{48}Ti beam from the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro of INFN was used, at energies ranging from 119 to 165 MeV, with average intensities ∼10 p nA. The targets were 50 μg/cm^2 iron evaporations, on 15 μg/cm^2 carbon layers, isotopically enriched to 99.915% in mass 58. Four collimated silicon detectors were placed symmetrically around the beam direction at $\theta_{lab} = 16^\circ$, to check the beam position and focusing and to allow normalization between the different runs. The fusion evaporation residues (ERs) were detected by a double time-of-flight ΔE-energy telescope following an electrostatic beam deflector at 0° and at small angles. The experimental setup and the procedures are described in some detail in recent papers [6,10].

ER angular distributions were measured at two energies near the Coulomb barrier, $E_{lab} = 127$ and 141 MeV in the range -8° to $+8^\circ$. This allowed us to determine the ratio between the differential ER cross sections and the total, angle-integrated one (for ^{48}Ti + ^{58}Fe in the measured energy range fusion-fission is surely negligible). We did not measure any significant variation with energy of the width of the angular distribution.

The accuracy of the absolute cross section scale (∼±7% overall) relies on such angular distribution measurements, on the beam quality and focusing precision, and, additionally, on the knowledge of the relevant solid angles and of the transmission efficiency of the electrostatic deflector. Statistical uncertainties are generally very small, apart from the very-low-energy points. These statistical (relative) errors determine the accuracy of the slope and barrier distribution extracted from the excitation function; see below.

III. RESULTS AND QUALITATIVE COMPARISONS

The measured excitation function is plotted in Fig. 1 vs the energy with respect to the Akyüz-Winther (AW) [11] Coulomb barrier. In the same figure, the cross sections for ^{58}Ni + ^{54}Fe [6] are also shown in the corresponding energy scale. This allows us to notice immediately the large enhancement, and less steep slope, of ^{48}Ti + ^{58}Fe fusion with respect to the other, more stiff, system, in the sub-barrier region.

As a matter of fact, it was already observed that the cross sections of ^{58}Ni + ^{54}Fe decrease very steeply at the lowest energies, and the logarithmic slope of the excitation function keeps increasing, reaches and overcomes the value L_{CS} expected for a constant astrophysical S factor [12]. Consequently, a nice maximum develops with decreasing energy. This is reported in Fig. 2, where we also notice that the behavior of ^{48}Ti + ^{58}Fe is remarkably different; indeed, its slope saturates below the barrier and remains much lower than L_{CS}. No maximum of the S factor develops, so that, in other words, no fusion hindrance seems to show up in this case.

All this is hardly recognizable from a comparison of the two barrier distributions. The BD of ^{58}Ni + ^{54}Fe was already reported in Ref. [14]. Figure 3 indicates that the BD of ^{48}Ti + ^{58}Fe extends more toward low energies, and this is sufficient to explain the larger cross sections (Fig. 1). The two BDs have a complex structure with several partially resolved peaks that resemble the case of ^{58}Ni + ^{60}Ni [15].

IV. COUPLED-CHANNELS ANALYSIS

We have compared the measured cross sections with standard CC calculations performed with the CCFULL [16] code using the Woods-Saxon geometry for the nuclear potential with parameters reported in Table I. The diffuseness a is the same as in the AW potential [11], but the radius parameter r_o and the well depth V_o have been modified to fit the excitation function in the barrier region.

We chose to perform CC calculations for ^{58}Ni + ^{54}Fe with the same geometry of the potential (radius parameter and diffuseness, see table). The requirement to reproduce the cross sections near the barrier implies a well depth $V_o = 101.16$ MeV that is ≈20% larger than the value used in the original analysis of Ref. [6]. Anyway, this difference has a negligible influence on the results, and the following conclusions are unchanged.

The nuclear structure information of the low-lying collective excitations included in the CC calculations is reported in

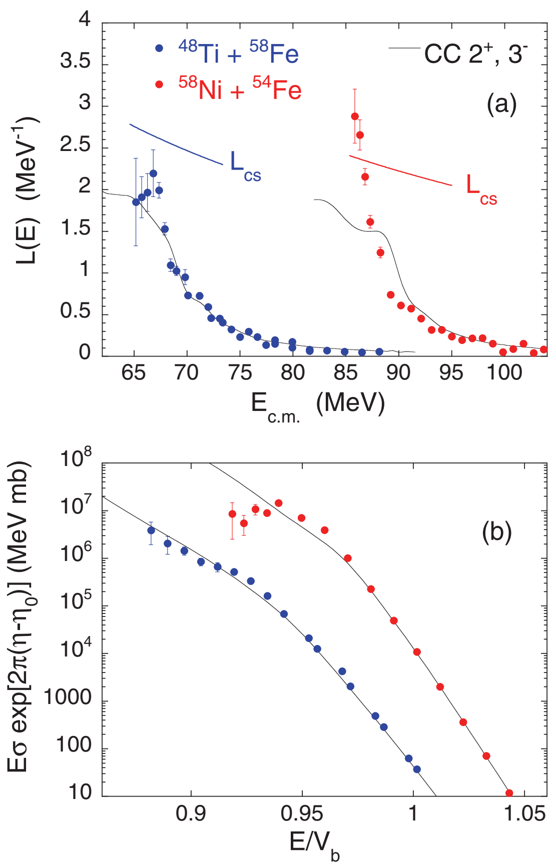

FIG. 2. (Color online) (a) Logarithmic derivatives of the excitation functions for ^{48}Ti + ^{58}Fe and ^{58}Ni + ^{54}Fe, obtained as incremental ratios between nearby points. (b) Astrophysical S factors for the two systems. They are normalized using the Sommerfeld parameter η_0 calculated in the vicinity of the Coulomb barrier.

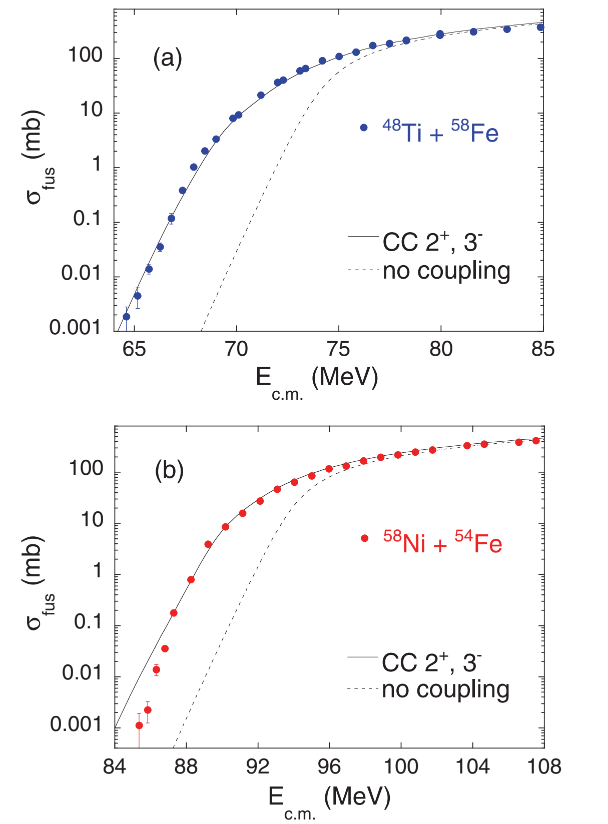

FIG. 4. (Color online) Excitation functions of ^{48}Ti + ^{58}Fe (a) and of ^{58}Ni + ^{54}Fe (b), compared to the CC calculations discussed in the text.

Table II. The quadrupole states of ^{48}Ti and ^{58}Fe are low in energy and rather strong, so that two-phonon excitations of this kind were included too. The 2^+ states of ^{58}Ni and ^{54}Fe are higher in energy and much less collective; anyway the corresponding two-phonon excitations were also considered for consistency. The octupole vibrations are weak and above 3.3 MeV in all cases. Two-phonon excitations of this kind were not taken into account, because the effect of such high-energy octupole states (if existing) is included to a large extent in the adjustment of the ion-ion potential. No mutual excitations of states in the same nucleus were considered.

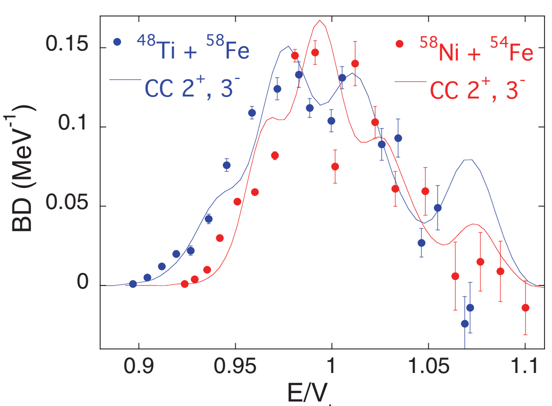

FIG. 3. (Color online) Barrier distributions BD obtained, for both systems, as the second derivative of the energy-weighted cross sections, using the three-points formula [13] with a step $\Delta E \simeq 1.0$ MeV. The lines are the results of the CC calculations discussed in the text.

The calculated excitation functions are shown in Fig. 4. They reproduce quite well the ^{48}Ti + ^{58}Fe data in the whole energy range. This reinforces the qualitative evidence from Fig. 2 that no hindrance is observed down to $\simeq 1$ μb. A very different situation is seen for the stiff system ^{58}Ni + ^{54}Fe, for which the analogous calculation strongly overpredicts the cross sections below $\simeq 200$ μb, as observed in the original paper [6]. Apart from this, it is also clear that a larger fusion enhancement takes place for ^{48}Ti + ^{58}Fe, with respect to the no-coupling calculation.

TABLE I. Parameters of the Woods-Saxon potential used for the CC calculations for fusion of ^{48}Ti + ^{58}Fe and ^{58}Ni + ^{54}Fe (see text).

System	V_o (MeV)	r_o (fm)	a (fm)
^{48}Ti + ^{58}Fe	100.12	1.13	0.67
^{58}Ni + ^{54}Fe	101.16	1.13	0.67

TABLE II. Excitation energies E_x, spins and parities λ^π, reduced transition probabilities, and deformation parameters β_λ [17,18] for the lowest quadrupole and octupole modes of ^{48}Ti, ^{58}Fe, ^{58}Ni, and ^{54}Fe. We have used equal nuclear and Coulomb deformation parameters in the present CC analysis (see text).

Nucleus	E_x (MeV)	λ^π	$B(E\lambda)$ (W.u.)	β_λ
^{48}Ti	0.984	2^+	14.0	0.269 (7)
	3.359	3^-	7.7	0.197 (20)
^{58}Fe	0.811	2^+	18.0	0.259 (4)
	3.861	3^-	9.9	0.189 (8.6)
^{58}Ni	1.454	2^+	10.4	0.183 (2.6)
	4.475	3^-	12.6	0.198 (9)
^{54}Fe	1.408	2^+	10.2	0.195 (8)
	4.782	3^-	3.6	0.114 (5)

Now we consider again Fig. 2. The flat logarithmic slope of the excitation function observed for ^{48}Ti + ^{58}Fe at low energies is correctly predicted by the calculation, and the different behavior observed for the second system is missed. Analogous considerations can be done for the S factors [panel (b) of that figure]. The CC calculation with a standard Woods-Saxon potential does not produce any maximum vs energy in either case, in contrast to the observation for ^{58}Ni + ^{54}Fe.

The strong quadrupole modes of both ^{48}Ti and ^{58}Fe are likely to be responsible for the cross section trends well below the barrier, and the two-neutron transfer channel which has a positive Q value (+ 1.4 MeV) might also play a role. It appears that the hindrance threshold is pushed to very low energies in the fusion of this system (below the measured limit), when compared to ^{58}Ni + ^{54}Fe.

The calculated barrier distributions are shown in Fig. 3. Their width and overall shape closely resembles those extracted from the experimental data, even if the positions of the several peaks are not correctly reproduced for ^{58}Ni + ^{54}Fe.

V. CONCLUSIONS

This paper shows that the relevant differences in nuclear structure between the two pairs ^{48}Ti–^{58}Fe and ^{58}Ni–^{54}Fe lead to large differences in the sub-barrier fusion excitation functions. A complete measurement was already performed for ^{58}Ni + ^{54}Fe, showing that fusion cross sections decrease very fast in this system, and fusion hindrance shows up already at around 200 μb.

In this work, fusion cross sections have been measured for ^{48}Ti + ^{58}Fe from hundreds of mb down to $\sigma_{fus} \simeq 1$ μb, with high statistical accuracy. Below the barrier, the excitation function of ^{48}Ti + ^{58}Fe is much larger than what was measured for ^{58}Ni + ^{54}Fe, where the logarithmic slope increases steadily from the barrier down, well above the value L_{CS}. Rather, the slope of ^{48}Ti + ^{58}Fe develops a plateau and stays much lower than L_{CS}, so that no maximum of the S factor shows up, and we have no evidence for hindrance in the measured energy range.

The present data for ^{48}Ti + ^{58}Fe can be reproduced by CC calculations using a Woods-Saxon potential, including the logarithmic slope of the excitation function. The analogous calculations for ^{58}Ni + ^{54}Fe largely overpredict the cross sections below $\simeq$200 μb, as observed in the original paper [6], and do not reproduce the fast increase of the slope.

The experimental studies presented here, together with, possibly, further and more detailed theoretical analyses, greatly help the comprehension of sub-barrier fusion dynamics, and of its relation to the low-energy structure of the colliding nuclei.

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