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Fusion of ^{28}Si + ^{28}Si: oscillations above the barrier and the behavior down to 1μb

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Abstract. Fusion excitation functions of light heavy-ion systems show oscillatory structures above the Coulomb barrier, caused by resonances or due to the penetration of successive centrifugal barriers well separated in energy. In heavier systems, the amplitude of oscillations decreases and the peaks get nearer to each other. This makes the measurements very challenging.
We have performed a first experiment for ^{28}Si + ^{28}Si, by measuring fusion cross sections (σ) in an energy range of ≃15 MeV above the barrier, with a small ΔE_{lab} = 0.5 MeV step. Three regular oscillations are clearly observed, which are best revealed by plotting the energy-weighted derivative of the excitation function. The excitation function has been recently measured down to cross sections ≤1μb with larger energy steps.
Coupled-channel (CC) calculations based on a shallow potential in the entrance channel are able to reproduce the oscillations. A further analysis will provide a stringent test for the calculations, in particular for the choice of the ion-ion potential, because the sub-barrier excitation function has to be reproduced as well.

1 Introduction

Oscillatory structures were observed above the Coulomb barrier in the fusion excitation function of light heavy-ion systems like ^{12}C + ^{12}C, ^{12}C + ^{16}O and ^{16}O + ^{16}O, long time ago [1–4]. Sometimes the oscillations have been associated with resonances, but there are suggestions, supported by coupled-channels (CC) calculations [5], that they may be due to the penetration of successive angular momentum (L) barriers. Indeed, in such light systems, the separation between nearby barriers is large with respect to the intrinsic energy width associated with their quantal penetration, so that the oscillations become observable. In Ref. [5] it has been pointed out that those structures can be best revealed by plotting the first (energy-weighted) derivative of the excitation function. It seems that a shallow potential [6] is required for fitting sub-barrier as well as above-barrier cross sections, because the oscillations are not reproduced by using a conventional Woods-Saxon potential. Hence, analogies in the description of the oscillations and of the low-energy fusion hindrance appear, because both phenomena are sensitive to the ion-ion potential.

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2 Sub- and near-barrier excitation function

Hindrance effects are stronger and more clearly observed in heavier systems, hence a careful search for oscillations in selected cases is very attractive. this despite the difficulties one can anticipate, due to the successive L-barriers getting closer to each other, and to the decreasing amplitude of the oscillating structures, as a consequence of couplings to several reaction channels. Nevertheless, structures can be probably observed in a system as heavy as ^{28}Si +^{28}Si, where previous data [7] already exist, but the errors are rather large and the energy steps are too large to allow clear-cut conclusions. This system is symmetric, therefore only even values of L contribute to fusion. This is an advantage, because the peaks are more distant from each other. The distance between two successive peaks, as estimated in Ref. [5] and on the basis of the old data is ≃3 MeV in the lab system, while the FWHM of the peaks is ≈2.2 MeV at E_{cm} ≃35 MeV for L=20.

This case of ^{28}Si +^{28}Si is particularly interesting because we have recently measured its fusion excitation function down to very low energies [8]. The lowest measured cross section is ≃500 nb, and the full excitation function is shown in Fig. 1 with red symbols.

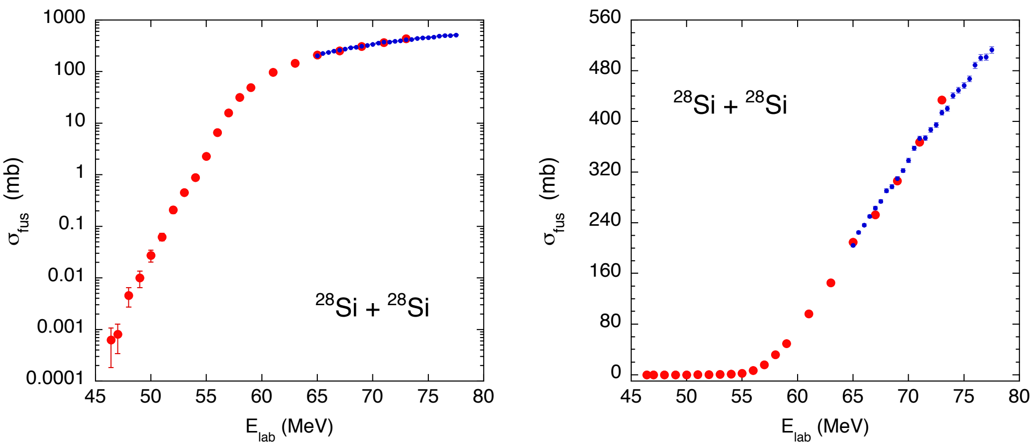

Figure 1. Fusion excitation function of ^{28}Si +^{28}Si, in a logarithmic (left) and linear (right) scale. The blue symbols are the small-step measurements performed above the barrier, see below in this paper.

A preliminary CC analysis of the sub-barrier excitation function has been performed, using a Woods-Saxon (WS) potential with parameters a=0.63 fm, r_0=1.04 fm, V_0=73.6 MeV. The radius and depth have been adjusted to fit the data in the barrier region, while the diffuseness is taken from the Akyüz-Winther [9] systematics. The collective 2^+ state of ^{28}Si at E_x= 1.779 MeV has been coupled in. It has simply been treated as a vibrational state, and the result is satisfactory (see Fig. 2, left). The overall trend of the logarithmic derivative of the excitation function (right panel), is also reproduced by the calculation, even if the irregularities that appear just below the barrier need further investigation, both experimentally and theoretically.

3 Oscillations above the barrier

A first series of careful measurement above the barrier has ben performed, with an energy step small enough (ΔE_{lab} = 0.5 MeV) to resolve the structures associated with the individual centrifugal barriers,

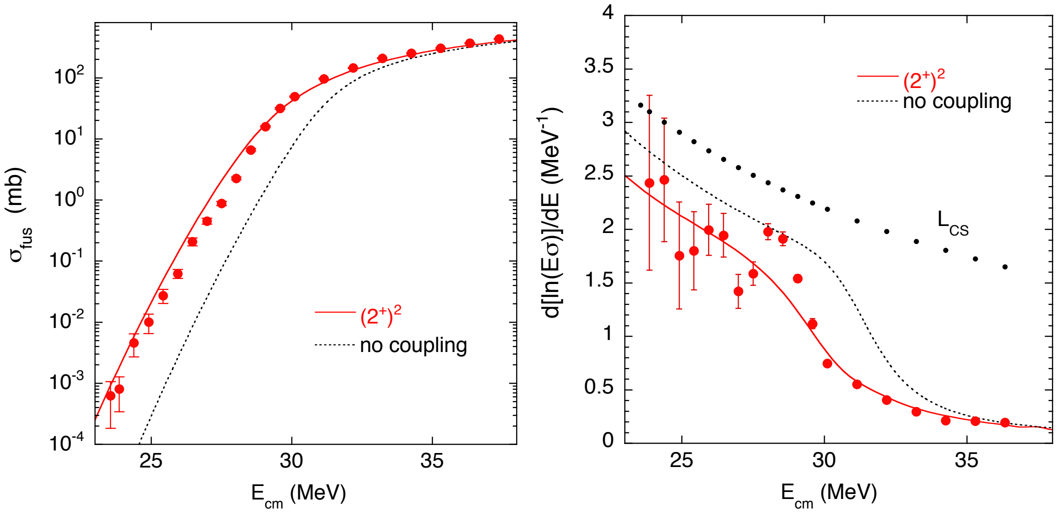

Figure 2. Fusion excitation function of ^{28}Si +^{28}Si (left), and its logarithmic derivative (right), compared to the CC calculations described in the text. The red line marked $(2^+)^2$ is the calculation including two phonons of the 2^+ state. L_{CS} (black dots) is the slope expected for a constant astrophysical S factor.

if any. The ^{28}Si beam has been provided with high quality and precision by the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro (LNL) of INFN, in the energy range ≃65-78 MeV. The targets were 50μg/cm^2 evaporations of ^{28}Si onto 15μg/cm^2 carbon backings. The fusion-evaporation residues (ER) were separated from the beam by using the set-up based on an electrostatic deflector (see [10] and Refs. therein), which was systematically employed for sub- and near-barrier fusion measurements at LNL. The set-up is very simple to operate, allowing fast and reliable measurements of relative and absolute cross sections.

For each energy, at least 10000 ER were detected, thus reducing the statistical error to 1% or less. The preliminary results are the blue points in Fig. 1, and they are reported in an enlarged energy scale in Fig. 3. The small irregularities that can be seen in the excitation function (left panel), become rather regular oscillations when the derivative is observed (right panel). Three peaks show up in this representation. The blue line in Fig. 3 is the CC prediction of Ref. [5]. The agreement with our data is good, at least for the two lower energy peaks which are calculated to correspond to L=18 and L=20.

4 Summary

Fusion cross sections of ^{28}Si +^{28}Si have been measured in a wide energy range down to ≤1μb. A preliminary CC analysis using a WS potential, has been performed for the near- and sub-barrier excitation function, giving a good agreement with data; no indication of fusion hindrance shows up in the measured energy range. Above the barrier, we have clear indication of oscillations of the excitation function, probably due to the penetration of successive centrifugal barriers. The observed oscillations are in rather good agreement with recent CC calculations [5] based on a shallow M3Y+ repulsion potential. The full comparison of the results of this experiment from the deep sub-barrier region up to where the oscillations develop, will allow us to check the consistency of such a shallow ion-ion potential in a very wide energy range, so that a severe test of CC calculations will be provided.

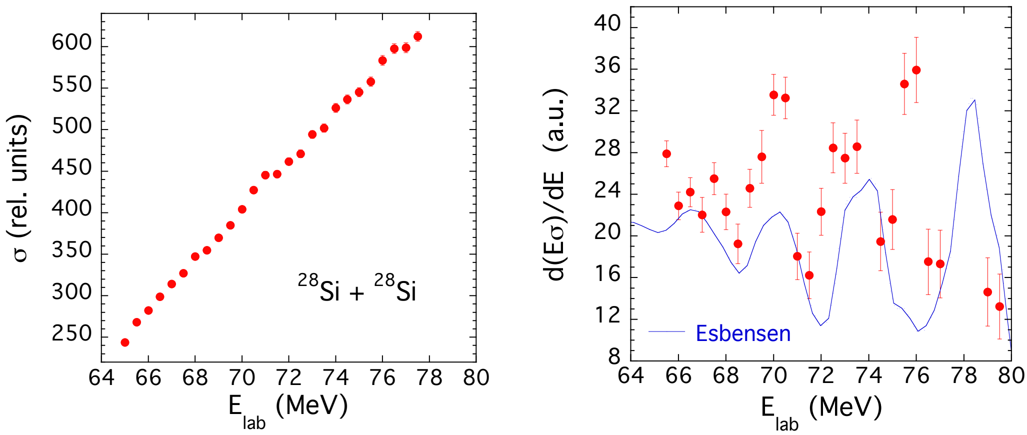

Figure 3. Fusion excitation function of $^{28}Si + ^{28}Si$ above the Coulomb barrier (left), together with its energy weighted derivative (right). Only statistical errors are plotted.

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