Recent data on fusion far below the barrier for ^{12}C +^{28}Si

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Abstract. Heavy-ion fusion reactions are essential to investigate the fundamental problem of quantum tunnelling of many-body systems in the presence of intrinsic degrees of freedom. Studying the fusion of light systems with Q > 0 and possibly identifying the hindrance phenomenon, requires challenging measurements. Investigating slightly heavier cases allows a reliable extrapolation towards the lighter astrophysical systems. We measured the fusion excitation function of ^{12}C + ^{28}Si down to hundreds of nanobarns, using ^{28}Si beams from the XTU Tandem accelerator of LNL. The charged particles evaporated after the fusion process were detected by two DSSDs around the target. The prompt γ-rays emitted by the evaporation residues (ER) were detected by the γ-spectrometer AGATA. The fusion cross-sections are obtained from the coincident events between γ-rays and charged particles. The light-charged particles have been identified through pulse shape analysis, using the rise time, vs their energy E_{part}. The main transitions from the ER have been identified, and the fusion cross section is obtained by the number of coincident γ-particle events for all observed evaporation channels. Neutron evaporation is calculated to be limited to a few per cent for this system in the measured energy range. Preliminary analyses provide promising results in studying fusion cross sections for light systems at deep sub-barrier energies.

1 Introduction

The fusion hindrance phenomenon far below the barrier was first observed about 20 years [1] ago for the system ^{60}Ni + ^{89}Y. Fusion hindrance is recognized in many cases by the trend of the logarithmic slope of the excitation function or by a maximum of the S-factor at low energies. Alternatively, a comparison with standard Coupled-Channels (CC) calculations can help to identify the phenomenon. Fig. 1 shows the two cases of ^{64}Ni + ^{64}Ni [2] and ^{16}O + ^{208}Pb [3] where the hindrance effect was clearly observed. The open symbols for ^{16}O + ^{208}Pb refer to the previous measurement of Ref. [4]. See Ref. [5] for additional details.

These two systems were studied down to deep sub-barrier energies. Standard CC calculations based on a Woods-Saxon potential overpredict the low-energy cross sections in both cases. Moreover, the astrophysical S-factor develops a maximum whose energy has been phenomenologically taken as the threshold for the hindrance effect. The physical origin of this phenomenon is still debated in the community where recently Simenel et al. [6] pointed out that the Pauli exclusion principle influences the ion-ion potential. As a consequence, low-energy fusion hindrance is produced, because the Coulomb barrier turns out to be thicker and higher.

In the case of light systems, the S-factor maximum becomes broader and the hindrance threshold is difficult to be recognized. Such light systems have positive fusion *Q*-

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value and, as a consequence, the existence of an S-factor maximum is not algebraically necessary. Indeed, the fusion hindrance in those cases is neither well-established nor understood. Relevant examples are shown in Fig. 2. In the case of ^{12}C + ^{12}C, it is not easy to recognise a general trend for the S-factor, because the data sets are not always in agreement with each other, and mainly due to the presence of many resonances. They completely disappear in ^{12}C + ^{13}C (centre) where, furthermore, the trend is not compatible with the hindrance expectation [7]. On the other hand, in the case of ^{16}O +^{16}O the experimental data might indicate the presence of a possible S-factor maximum.

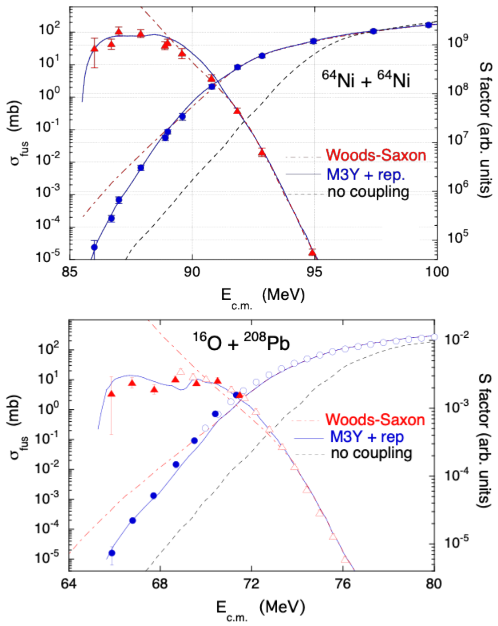

Figure 1. Coupled Channel calculations based on a Woods-Saxon potential overpredict the excitation function at low energies for both systems ^{64}Ni + ^{64}Ni (top) and ^{16}O + ^{208}Pb (bottom). The astrophysical S factor develops a maximum at the energy where the logarithmic slope reaches the value $L_{CS} = \pi\eta/E$.

2 The system ^{12}C +^{28}Si and the setup

Fig. 3 reports the state of the art for the case of ^{12}C +^{28}Si. The fusion Q-value of this system is positive (+ 13.4 MeV) and one sees the few points of the excitation function, available before the present experiment, which were measured by detecting the evaporation residues (ER) with the electrostatic deflector of LNL (these data are still unpublished). In the same figure, we show the results of CC calculations performed with the code CCFULL [10] including the lowest quadrupole and octupole excitations of ^{28}Si. The agreement with the few available points is reasonable, and no indication of hindrance is observed.

In order to obtain a clear trend, we decided to extend downwards the measurement of the excitation function using the combined setup of AGATA γ-ray spectrometer [11] and two double-sided Si-strip detectors (DSSD) in coincidence. The setup is schematically shown in Fig. 4

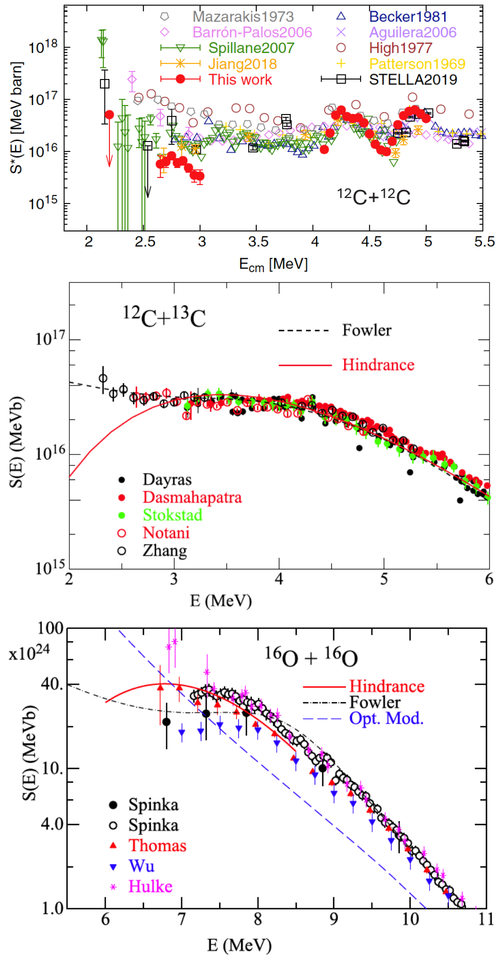

Figure 2. Astrophysical S-factors for the light systems ^{12}C + ^{12}C (top) [8], ^{12}C + ^{13}C (centre) [7] and ^{16}O +^{16}O (bottom) [9]. The ordinate of the top panel is the corrected S-factor as defined in Ref. [8]. This does not change the comments on the comparison with the other cases (see text). The energy axes report the centre of mass energies.

Ni foils of thicknesses of 15 and 2 μm (for forward and backward detectors respectively), covered the front of the DSSD to absorb the elastically scattered particles and electrons from the target. They were mounted with the ohmic side facing the target, to enable *psd* (pulse shape discrimination), see below. Enriched ^{12}C targets (99.8%) have been used with a thickness of about 50 $\mu g/cm^2$. The ^{28}Si beam intensity typically ranged from 10 to 20 pnA. Two monitor silicon detectors were installed at θ=12° to normalize the fusion yield to the Rutherford cross section.

3 The experimental results

Fig. 5 (top panel), shows the identification of evaporated particles using pulse shape analysis. The events are related to the reaction at 50 MeV and are detected in the intermediate ring (⊘ = 36.75 mm) of the forward silicon detector. α particles and protons events are well separated. The punch-through effect for the protons not stopped in the detector is evident.

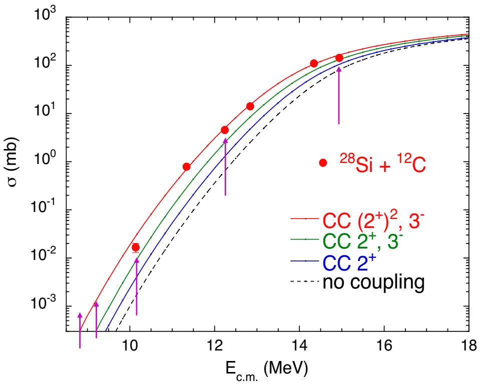

Figure 3. Experimental fusion excitation function of ^{28}Si + ^{12}C compared with CC calculations. The magenta arrows mark the energies where the present experiment with AGATA has been performed (E_{lab} = 29.5, 31, 34, 41, 50 MeV, corresponding to $E_{c.m.}$ = 8.8, 9.3,10.2, 12.3 and 15.0).

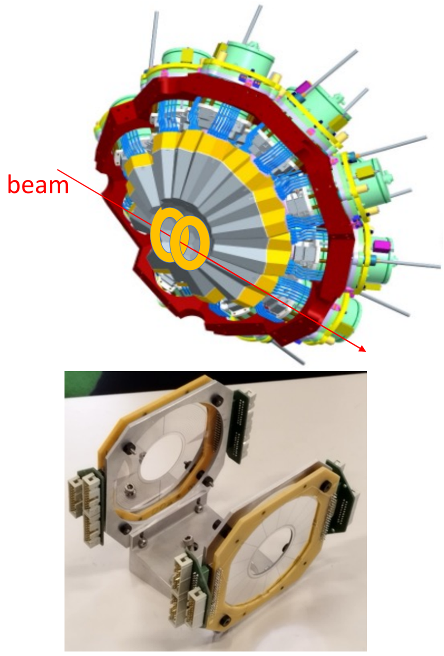

Figure 4. AGATA + DSSD set-up. S1 detectors (Micron), ⊘ = 4", at 5 cm from the target, upstream and downstream of the target with thicknesses of 1500 mm and 1000 mm, respectively, covering ~20 % of the total solid angle.

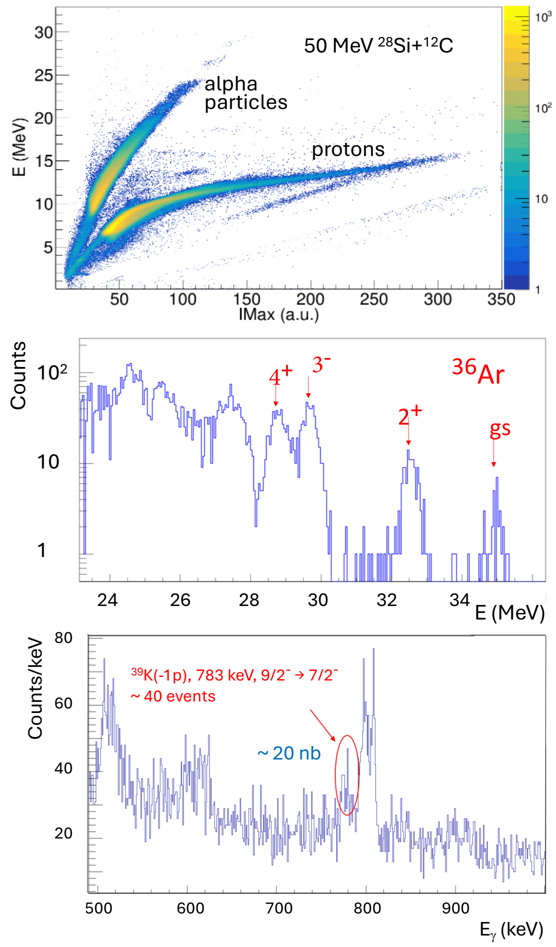

Figure 5. (top) Events detected in the ring at ⊘ = 36.75 mm, of the forward silicon detector. Light-charged particles detected by the DSSD are identified through pulse shape analysis, using their energy E_{part} vs the maximum of the signal derivative IMax. (center) Energy spectrum of α particles identified via *psd*, detected in the third ring ($\Delta\theta$=28.5°-29.9°) of the forward DSSD. (bottom) γ-spectrum in coincidence with the forward DSSD at 29.5 MeV, collected in 24h with a beam intensity of 20 pnA.

The energy spectrum of α-particles (see Fig. 5, centre) shows several structures corresponding to particle groups populating states in the ^{36}Ar residual nucleus. In particular, one can notice the α-particle groups populating the ground state and the lowest the $2^+, 3^-$ and 4^+ states, well separated from each other. This kind of particle identification has proven to be effective above ≈7 MeV in this experiment, partly due also to the electronic thresholds.

We show in Fig. 5, bottom, part of the Doppler-corrected γ spectrum in coincidence with evaporation protons, at the lowest ^{28}Si measured energy 29.5 MeV. The total fusion cross section for the 1p channel has been estimated ≈ 100 nb using the experimental data reported in Fig. 3 with consistent results from PACE4 calculations [12]. The marked peak is the $9/2^- \rightarrow 7/2^-$ transition of ^{39}K which amounts to around 20% of the total population of this nucleus. This preliminary result highlights the sensitivity of the adopted experimental procedure.

Fig. 6 shows a two-dimensional spectrum of γ-rays in coincidence with particle energy signals, where several representative γ-transitions are indicated. In Fig. 6 (bottom) further γ-transitions are marked. The final cross-sections will be obtained by integrating the proper γ transitions.

Finally, the comparison with ^{30}Si + ^{12}C [13] in Fig. 7, indicates that for the case of ^{28}Si + ^{12}C the additional experimental points at lower energies (31 and 29.5 MeV) will be important to establish if the fusion hindrance effect shows up for this system and if so, at which energy. These measurements will help to clarify the trend of excitation function at deep sub-barrier energies to allow a reliable extrapolation toward similar and lighter cases.

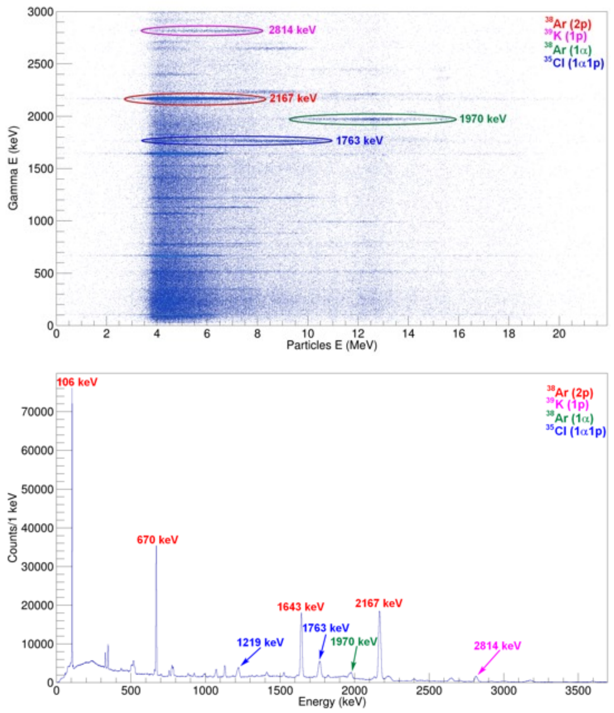

Figure 6. (top) γ-energy vs particle energy matrix at 50 MeV of ^{28}Si beam energy, in coincidence with the ring at 26.2° of the forward DSSD. (bottom) For the same reaction, γ-energy spectrum in coincidence with the whole forward DSSD.

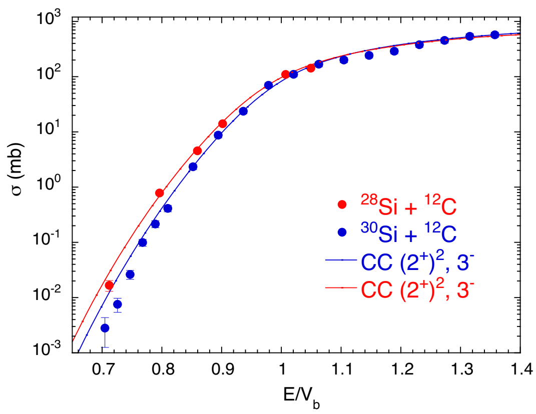

Figure 7. Fusion excitation functions of ^{28,30}Si + ^{12}C, previously measured. CC calculations, using Woods-Saxon potentials and including the 2$^+$ and 3$^-$ states of the Si isotopes, are also reported.

4 Summary

This contribution has presented the general features of the phenomenon of heavy-ion fusion hindrance at energies far below the barrier, and in particular, we have discussed the evidence of that effect for light systems, having fusion Q-value >0, whose trend is important for astrophysics.

We have considered the case of ^{12}C + ^{28}Si, compared with near-by medium-light systems, for which only a few experimental points are available from previous measurements at near- and sub-barrier energies. The set-up used in the most recent experiment on ^{12}C + ^{28}Si consisted of the γ-spectrometer AGATA and two DSSD near the ^{12}C target. Coincidences between the prompt γ-rays and the evaporated light-charged particles from the compound nucleus ^{40}Ca have been measured, taking into account that pure neutron evaporation is estimated to be only a few per cent of the total yield in the measured energy range.

Protons and α-particles have been identified through pulse shape analysis in the DSSD, using the energy and rise time of their signals. The measurements were performed at five beam energies, i.e. 50, 41, 34, 31 and 29.5 MeV of ^{28}Si, corresponding to fusion cross sections from 143 mb to $\approx$ 100 nb.

In a two-dimensional spectrum of γ-ray energies vs particle energies, the various evaporation channels are well-identified and the corresponding projection on the γ-energy axis allows us to clearly count the events for the individual channels.

The comparison of the two nearby systems ^{12}C + ^{28,30}Si shows a slight enhancement of the ^{28}Si case, to be confirmed by the additional experimental points at 31 and 29.5 MeV, whose analysis is in progress.

The positive results obtained for the present system ^{12}C + ^{28}Si suggest extending the investigation to lighter cases of astrophysical interest, using the same experimental setup.

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