Fusion of the positive Q-value system $^{36}S + ^{48}Ca$ well below the Coulomb barrier

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The fusion excitation function of $^{36}S + ^{48}Ca$ has been measured from well above the barrier down to very small cross sections at sub-barrier energies. A steady decrease of the fusion cross sections is observed below the barrier with no pronounced change of slope. The logarithmic derivative saturates and does not reach the value expected for a constant astrophysical S-factor. The S-factor does not show any maximum in the measured energy range. Coupled-channels calculations using a Woods-Saxon potential have been performed.

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I. INTRODUCTION

Heavy-ion fusion excitation functions near the Coulomb barrier are strongly influenced by couplings to nuclear surface vibrations, static deformations, and nucleon transfer channels between the colliding nuclei. Strong enhancements of the fusion cross sections, due to such couplings, were systematically observed in several experiments [1]. However, measurements of very small cross sections (down to 10–20 nb) have been performed in recent years for a number of systems [2–4], below the energy where the distribution of fusion barriers [5], produced by channel couplings, vanishes. These experiments have shown that the slope of the excitation function keeps increasing at lower energies, and this was named a "hindrance" effect.

The behavior of sub-barrier cross sections σ is appropriately displayed by means of the logarithmic slope $L(E) = d[ln(E\sigma)]/dE$ and by the S-factor [6], originally introduced in nuclear astrophysics [7] as a convenient representation of light-ion fusion reactions. It is defined as

$$S(E) = E\sigma(E)\exp(2\pi\eta), \quad (1)$$

where E is the center-of-mass energy and η is the Sommerfeld parameter. The slope expected for a constant S-factor is $L_{CS}(E) = \pi\eta/E$ [3]. The energy at which the experimental $L(E)$ equals $L_{CS}(E)$, if this happens, corresponds to a maximum of S [6] and is usually taken as the threshold energy for hindrance.

All this triggered a widespread discussion about the underlying physics [6,8–15], also because of the possible implications on the nuclear reaction rates in stars [3]. It was observed [11] that deep sub-barrier fusion cross sections may be sensitive to the shape of the nuclear potential in the inner side of the Coulomb barrier, and the hindrance was proposed [16,17] to arise from the saturation properties of nuclear matter, simulated by a repulsive core in the nuclear potential. A process with two steps (preceding and following the touching configuration) was recently suggested [18].

Unlike the reactions with heavier beams, the recent case of $^{16}O + ^{208}Pb$ [4] shows a steep but almost saturated logarithmic slope below the barrier. The evidences lead the authors to suggest a decoherence effect to be present. A shallow potential [19] based on a repulsive core at small ion-ion distances, fits those data, with an additional weak, short-ranged absorption above the barrier. Good fits have been achieved [20] also for $^{64}Ni + ^{64}Ni$ and $^{28}Si + ^{64}Ni$ having very different Q-values for compound nucleus formation (−48.8 MeV and −1.78 MeV, respectively).

Indeed, when the Q-value is negative (as in most heavy-ion systems) fusion can only occur down to $E = -Q$. Here $\sigma = 0$ and S is zero, since the Gamow factor is finite. Thus a maximum of S at some higher energy must occur. When $Q > 0$, however (as in many light-ion systems of astrophysical interest), fusion can take place, in principle, down to $E = 0$. Here S may still have a finite value, since $E\sigma(E) \rightarrow 0$ and $\exp(2\pi\eta) \rightarrow \infty$, so that no maximum of S at a higher energy is necessary [3]. This would imply no intersection between $L(E)$ and $L_{CS}(E)$, but not necessarily no fusion hindrance in general terms, if the saturation properties of nuclear matter, or other effects, determine fusion dynamics at far sub-barrier energies, with important modifications of the ion-ion potential in the inner side of the barrier. Actually, for the light systems with $Q > 0$ the situation is unclear since the maximum of S (if any) would be very broad [21], since $L(E)$ gets almost parallel to $L_{CS}(E)$. Apart from those light systems, recent sub-barrier fusion data for a $Q > 0$ system exist for $^{28}Si + ^{30}Si$ [22], where, however, the excitation function has only been measured down to 40 μb, so that a maximum of S does not show up clearly.

We decided to measure the fusion excitation function of $^{36}S + ^{48}Ca$ in a wide energy range. The closed-shell nature of the two nuclei makes a comparison with $^{16}O + ^{208}Pb$ very interesting, and leads to the expectation that fusion hindrance shows up at a relatively high energy. The threshold energy would be $E_s^{emp} = 42.4$ MeV, according to the systematics of Ref. [3]. $^{36}S + ^{48}Ca$, however, is relatively light and has a positive Q-value (+7.6 MeV), so that its behavior at sub-barrier energies, in particular the possible observation of a maximum of the S-factor, has to be clarified.

II. EXPERIMENTAL

Measuring very small fusion cross sections is very laborious and demanding from the experimental point of view. We used the ^{36}S beam from the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro of INFN. The beams of ^{36}S (10–20 pnA) had energies in the range 65–107 MeV with a maximum uncertainty in the energy of $\simeq$130 keV at 100 MeV [24]. The targets were ^{48}CaF$_2$ (50 μg/cm^2) evaporations on carbon 10 μg/cm^2 thick. The beam energy losses in the targets were taken into account, as well as the calcium isotopic enrichment (91.8% in mass 48), with a predominant 7.7% impurity of ^{40}Ca. The barrier for $^{36}\mathrm{S} + {}^{48}\mathrm{Ca}$ is $\simeq$9 MeV lower, in the laboratory system, with respect to ^{40}Ca. The impurity of ^{46}Ca is <0.01% with a barrier difference of $\simeq$2 MeV. All this produces small or even negligible corrections in the whole sub-barrier energy range.

An electrostatic deflector separated the recoiling evaporation residues (ER) from the transmitted beam and beam-like particles at 0° and at small angles [23,24]. The following detector setup (Fig. 1, top left) improves the original one, with larger-size MCP and Si detectors and two independent TOF signals (MCP1 vs. Si and MCP2 vs. Si). The efficiency of the MCP detectors for ER has been determined to be >98% in the present experiment.

Figure 1(a) is a E-TOF1 spectrum taken slightly below the Coulomb barrier, where the group of ER is clearly identified. Down to $E_{\mathrm{c.m.}} = 38.4$ MeV (i.e., at $\simeq$20 μb), the E-TOF1 spectrum alone was sufficient to identify the ER [panel (b)]. The complementary E-TOF2 spectrum [panel (e)] also discriminates clearly the ER, and was used as an independent condition to get rid of spurious events in E-TOF1 at lower energies. Spurious events are essentially random coincidences between the silicon and one of the MCP detectors; a signal from the Si detector (also triggering the acquisition system) may wrongly be associated with the TOF of a different ion, and the event may fall into the E-TOF window defined for the ER.

The data of (c) were taken at the second lowest measured energy: ten events fall inside the ER window defined at 38.4 MeV [panel (b)], but only seven of them (circled) meet also the condition defined in the corresponding window in E-TOF2 [panel (d)]. At the lowest energy 36.9 MeV three ER were identified using these criteria in a run of $\simeq$24 h; the corresponding cross section has a big error, consequently. The sensitivity of the overall setup is improved by a factor $\simeq$20 with respect to the original one [23,24] which allowed us to measure cross sections down to about 13 μb [25].

ER angular distributions were measured at $E_{\mathrm{lab}} =$ 101.0, 76.7, 72.2 MeV in the range $-7°$ to $+6°$ with steps of 1°. The absolute cross section scale is accurate within ±7%, with contributions arising from the geometrical solid angles (measured by placing an α-source at the target position), from the fits and integrations of the angular distributions, and from the transmission of the electrostatic deflector $T = 0.73 \pm 0.03$ (see Ref. [24]).

III. RESULTS AND ANALYSIS

The measured fusion cross sections σ are plotted in Fig. 2. They span more than 7 orders of magnitude, the highest energy being at 42% above the barrier. The cross sections decrease

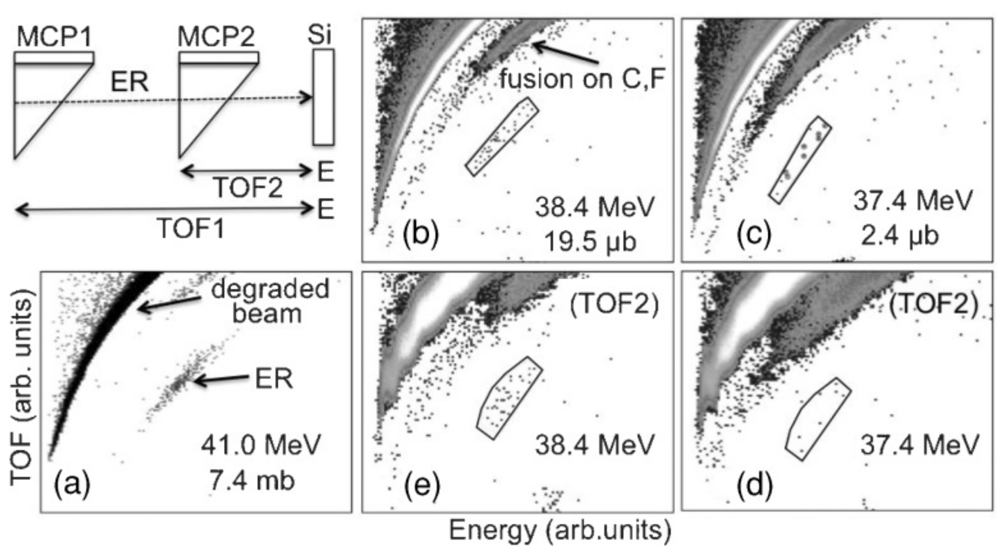

FIG. 1. The top left panel shows the detector setup. Evaporation residues (ER), after beam separation in the electrostatic deflector, were detected by two microchannel plate detectors (MCP1 and MCP2), and finally stopped in a 450 mm^2 silicon detector giving the energy (E) and the start signal used for the time-of-flights TOF1, TOF2, and triggering the data acquisition. The total length of the telescope was $\simeq$40 cm with a geometrical solid angle of 0.076 msr. The E-TOF spectra are discussed in the text. In panels (a), (b), and (c) TOF1 is the ordinate, while (d) and (e) show TOF2 vs. E spectra.

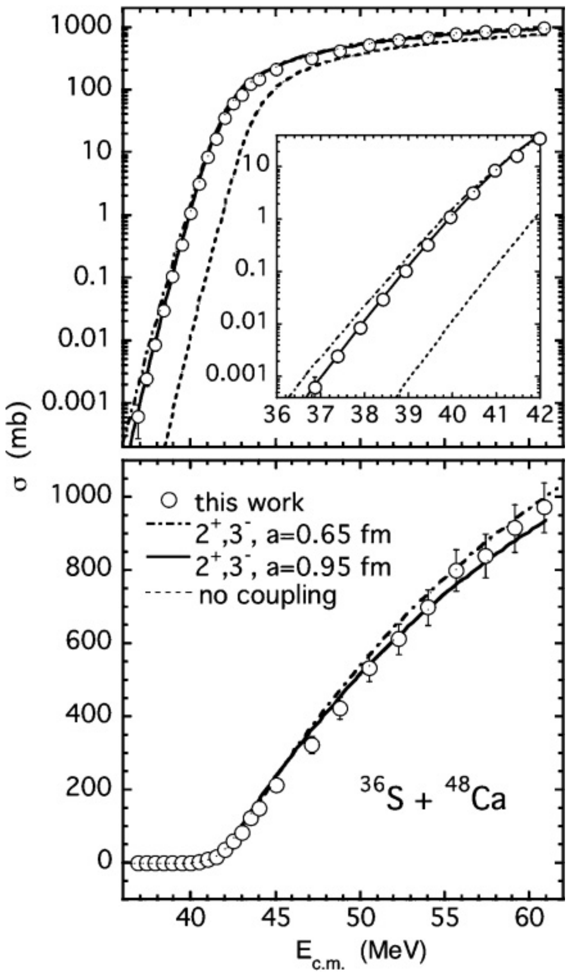

FIG. 2. (Top) Fusion excitation function of ^{36}S + ^{48}Ca. Only statistical uncertainties are reported. (Bottom) The same data in a linear scale; here the errors are total uncertainties (statistical plus systematic ones, see text).

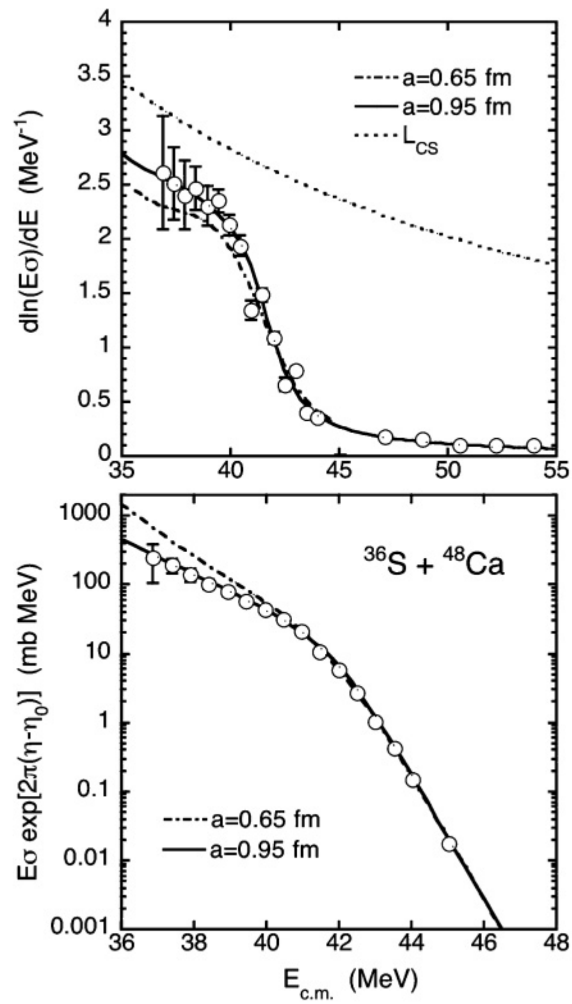

FIG. 3. (Top) Logarithmic derivative of $E\sigma$ with respect to the energy. The derivative is the incremental ratio for successive pairs of experimental points. (bottom) S-factor vs. energy derived from the present data and from coupled-channels calculations. For the S representation, a η_o value of 36.05 has been adopted. The quoted errors are purely statistical.

very regularly below the barrier, see the inset, down to the sub-μb level. The logarithmic derivative (see Fig. 3, upper panel) $d[ln(E\sigma)]/dE$ approaches $L_{\rm CS}$ below the barrier, but does not cross it as observed for various other systems [3]. In other words, there is no marked change of slope below the barrier for ^{36}S + ^{48}Ca. This is a purely experimental observation suggesting a peculiar behavior of the present system in the measured energy range. The slope appears to level off and to become parallel to $L_{\rm CS}$.

Figure 4 shows the representation of fusion barrier distribution derived from the second energy derivative of $E\sigma$ [5], using the three-point difference [26] formula with an energy step $\simeq$1.5 MeV (3.0 MeV above 46 MeV). The distribution has a single peak centered around 41 MeV. This is expected, given the very rigid structure of the two nuclei and was observed, e.g., for the systems ^{40}Ca + ^{40,48}Ca [1,27]. The S-factor for ^{36}S + ^{48}Ca is plotted in the lower panel of Fig. 3, showing no maximum vs. energy as a consequence of the behavior of the logarithmic slope. From this point of view ^{36}S + ^{48}Ca is similar to the much lighter systems where no clear maximum in the S-factor has been identified [28].

In order to check how far the present experimental evidences can be reproduced by the coupled-channels (CC) model, we have performed simple calculations with the code CCFULL [29], Two different bare Woods-Saxon (WS) potentials were used, with the condition that the barrier height (once couplings were included) matches the experimental value of Fig. 4, that is, $\simeq$41 MeV. The first WS potential has parameters $V_o = 65.0$ MeV, $r_o = 1.15$ fm, and $a = 0.65$ fm, giving a (bare) barrier height $V_b = 43.3$ MeV, that is, 0.65 MeV higher than the standard Akyüz-Winther potential [30]. The second potential gives the same barrier height, and mainly differs for the larger diffuseness $a = 0.95$ fm. A deeper well $V_o = 165$ MeV ensures a correct application of the IWBC for all partial waves; the radius is reduced accordingly. It has been pointed out [31] that large diffusenesses are necessary to fit the fusion cross sections, using a WS potential, above the barrier for several systems. The value $a = 0.95$ fm is well within that systematics. It has been suggested [31,32]

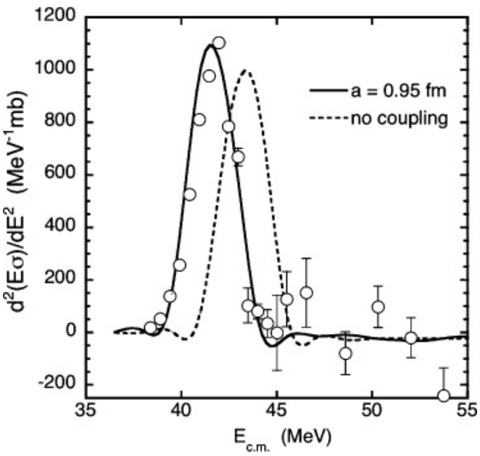

FIG. 4. The representation of fusion barrier distribution of ^{36}S + ^{48}Ca, together with the results of CC calculations.

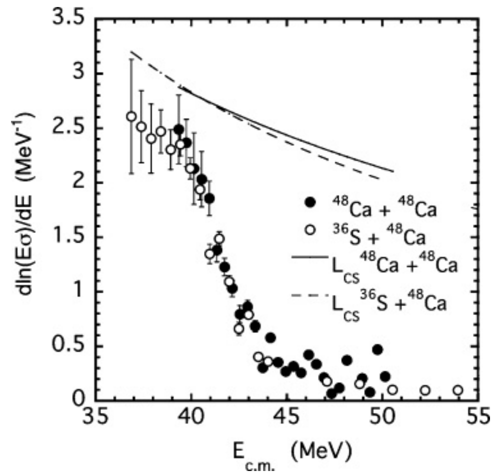

FIG. 5. Logarithmic derivatives of ^{36}S + ^{48}Ca (this work) and ^{48}Ca + ^{48}Ca [27]. The energy scale for ^{48}Ca + ^{48}Ca has been shifted down by 9.0 MeV, so to compensate for the different Coulomb barrier.

that such large a values may actually simulate the presence of competing reaction channels, such as deep inelastic reactions.

The low-lying 2^+ and 3^- vibrations of projectile and target were included in the calculations, as well as their mutual excitations. Both ^{36}S and ^{48}Ca are very stiff, those states are at 3.3 MeV or higher excitation energies with small β-values, except for the 3^- excitation of ^{36}S at 4.19 MeV with $\beta_3 = 0.38$ [33].

Figure 2 shows that both potentials allow a satisfactory fit of the excitation function above the barrier, given the experimental uncertainties of the cross sections. A more detailed theoretical analysis aimed at obtaining the "best potential" in that energy range, is outside the scope of the present work. Below the barrier, the calculation with a standard diffuseness close to $a = 0.65$ fm yields an energy dependence that is definitely too flat (see the inset in Fig. 2), while the calculation with $a = 0.95$ fm reproduces very closely the excitation function. This very good fit below the barrier reflects the experimental fact that no drastic increase of slope is observed, at least down to $\sigma_{\rm fus} \simeq 600$ nb.

IV. COMPARISONS

The behavior of ^{36}S + ^{48}Ca is very different from ^{28}Si + ^{64}Ni [20]: in the present system the "deviation" of the CC calculation with $a = 0.65$ fm from the data starts already at the level of 2–5 mb (very near to the barrier) and such deviation increases regularly going down in energy. In ^{28}Si + ^{64}Ni the deviation starts at the level of a few μb, where the experimental slope increases noticeably. The case of ^{36}S + ^{48}Ca seems to be different also from ^{16}O + ^{208}Pb [4], where the data cannot be reproduced in the CC model below *and* above the barrier, using a single WS potential. The logarithmic slope for ^{36}S + ^{48}Ca saturates below $E = 40$ MeV, does not reach $L_{\rm CS}$, and is more or less parallel to it, at variance with ^{16}O + ^{208}Pb where the slope flattens out, but reaches the $L_{\rm CS}$ value.

Figure 5 compares the present data for ^{36}S + ^{48}Ca with the previous ones for ^{48}Ca + ^{48}Ca [27]. This system is also very stiff and neutron-rich, but has a negative Q-value -2.99 MeV. The slopes of the two excitation functions are very similar, down to the lowest measured energy for ^{48}Ca + ^{48}Ca. Whether the slope for this system continues increasing, eventually crossing the $L_{\rm CS}$ line, or saturates, like ^{36}S + ^{48}Ca, is an interesting question awaiting further difficult and patient experimental work.

V. SUMMARY

The excitation function of ^{36}S + ^{48}Ca (with $Q > 0$) has been measured over a wide energy range from well above the barrier down to a cross section $\simeq$600 nb corresponding to the energy 36.9 MeV, that is, 13% below the threshold energy for hindrance obtained from the systematics of Ref. [3]. We have not observed any pronounced change of the slope below the barrier for the present system. The logarithmic derivative of the excitation function saturates below $E = 40$ MeV, and does not reach the $L_{\rm CS}$ value. As a consequence, no maximum of the S-factor shows up in the measured energy range. Obviously, this may occur at still lower energies. It is an appealing, but purely speculative, hypothesis that this behavior is related to the positive Q-value for compound nucleus formation of ^{36}S + ^{48}Ca. CC calculations with a standard diffuseness $a = 0.65$ fm of the WS potential, give a good fit above the barrier, but overestimate the sub-barrier cross sections with an energy slope which appears to be too flat. Using a larger diffuseness parameter $a = 0.95$ fm allows to reproduce the data above and below the barrier. Extending the present measurements to still lower energies would be of great interest, as well as performing detailed calculations with up-to-date models of deep sub-barrier fusion.

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