Fusion of $^{32}$S+$^{48}$Ca near and below the Coulomb barrier

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Abstract.

The fusion excitation function of $^{32}$S + $^{48}$Ca has been experimentally studied in a wide energy range, from above the Coulomb barrier down to cross sections in the sub-$\mu$b region. The measurements were done at INFN-Laboratori Nazionali di Legnaro, using the $^{32}$S beam from the XTU Tandem accelerator. The excitation function has a smooth behavior below the barrier with a rather flat slope, and no maximum of astrophysical factor S vs. energy has been observed. However, other interesting features of the dynamics of this system can be noted. In particular, the fusion barrier distribution has an unusual shape with two peaks of similar height, lower and higher than the Akyüz-Winther barrier. Preliminary coupled-channels calculations and a comparison with nearby systems have been performed to get information on the possible influence of nucleon transfer channels with positive Q-value.

1. Introduction

In the interesting energy region below the Coulomb barrier, heavy-ion fusion cross sections result from a balance between the enhancement produced by couplings to internal degrees of freedom of the colliding nuclei and to nucleon transfers, and the limitation (“fusion hindrance”) generally observed at very low energies where the measured cross section decrease rather sharply below the predictions of standard coupled-channel (CC) calculations [1, 2, 3, 4]. This hindrance is suitably represented by using the logarithmic derivative $L(E) = d\ln(E\sigma)/dE$ (slope) which is very sensitive to the trend of the low-energy excitation function [5, 6]. This phenomenon is receiving much attention also from the theoretical side [7, 8, 9, 10]. It has frequently been observed that hindrance is so strong that a maximum of the astrophysical S-factor develops as a function of the energy. In our recent study of the sub-barrier fusion excitation function of $^{40}$Ca + $^{48}$Ca [11] an indication of an S-factor [6] maximum in this system with a positive Q value.
for compound nucleus formation has been observed for the first time. As a matter of fact, it is known [2] that for systems having $Q>0$ the presence of a maximum of the S-factor vs. energy is not algebraically requested. If clearly observed in other systems with $Q>0$, this feature will be turn out to be very important in nuclear astrophysics where fusion reactions of light heavy-ion systems occur at very low energies, which are presently unaccessible to laboratory studies and thus require extrapolations to estimate the reaction rates in stars.

This contribution reports on the measurement of the fusion excitation function of $^{32}$S+$^{48}$Ca ($Q=+7.66$ MeV) experimentally studied in a wide energy range, from above the Coulomb barrier down to cross sections in the sub-$\mu$b region. The measurements have been recently performed at Laboratori Nazionali di Legnaro (LNL) of INFN, using a set-up based on a beam electrostatic deflector to detect the evaporation residues at forward angles. From the fusion excitation function we have extracted the barrier distribution (BD) [12] that has an interesting double-peaked shape. The logarithmic slope $L(E)$ and the S factor $S(E)$ have been obtained. Since $^{32}$S+$^{48}$Ca has several neutron pickup transfer channels with positive Q-values, preliminary CC calculations have been carried out, including a transfer coupling simulating the $+2n$ pick up channel. A useful comparison with nearby systems has been performed.

2. The Experiment

The fusion excitation function of $^{32}$S+ $^{48}$Ca has been measured at LNL, using the high-quality and intense $^{32}$S beam ($\approx 30$ pnA) from the XTU Tandem accelerator, at laboratory energies from 60.0 MeV up to 89.4 MeV. The targets were 50$\mu$g/cm$^2$ evaporations of $^{48}$CaF$_2$ onto 15$\mu$g/cm$^2$ carbon backings.

The fusion cross section was obtained by detecting at forward angles the evaporation residues (ER) following compound nucleus formation. The ER were separated from the beam by using the set-up based on a beam electrostatic deflector (see [13] and Refs. therein) employed since long ago for these kind of measurements. The set-up is simple to operate, can rotate around the target position to measure angular distributions and one can also easily measure its transmission by comparing the ER yields with electric field on and off.

Recently we have implemented a second micro-channel plate detector (MCP) and a ionization chamber (IC) in the downstream telescope. The ER were detected by the two MCP, entered the IC giving an energy loss signal ($\Delta E$) and were finally stopped in a circular 600 mm$^2$ silicon detector placed in the same gas (CH$_4$) volume. The silicon detector provided the residual energy (E) and the start signal used for the two independent time-of-flights (TOF), triggering the data acquisition as well. The total length of the detector telescope is $\approx 105$ cm. Four silicon detectors were used for beam control and normalization between the different runs by measuring the Rutherford scattering from the target. They were placed at the same scattering angle $\theta_{lab}=16^\circ$, above and below, and to the left and right of the beam direction. The geometrical solid angle of the whole set-up (41.3$\pm 0.3\mu$sr) was measured by placing an $\alpha$-source at the target position, and was fixed by the silicon detector size.

ER angular distributions were measured at $E_{lab} = 70.4$, and 83.4 MeV in the range 0$^\circ$ to 8$^\circ$. An example of a two-dimensional spectrum obtained close to the barrier, and the two measured angular distributions are shown in Fig. 1.

Integrating the two angular distributions allowed us to convert the differential cross sections measured at 0$^\circ$ or 2$^\circ$ (depending on the beam background situation) to absolute cross sections. The systematic error on the absolute cross section scale is estimated $\approx 7\%$, due to the uncertainties in the geometrical solid angle, in the procedure of integrating the angular distribution, and in the measurement of the transmission of the electrostatic deflector. Relative errors are essentially determined by statistical uncertainties not exceeding 2–3% near and above the barrier, but becoming much larger at low energies where only few fusion events could be detected.
3. Results
We measured the fusion excitation function of \(^{32}\text{S}+^{48}\text{Ca}\), down to about 800 nb, and it is shown in Fig. 2. Plotted errors are purely statistical. It is evident that the cross sections decrease very smoothly below the barrier, with a rather flat slope. Fig. 3 shows actually the logarithmic slope, which we have derived from the measured cross sections, as the incremental ratio of two nearby points. In the measured energy range, the slope increases regularly below the barrier with decreasing energy, and it does not reach the value expected for a constant S factor (\(L_{CS}\) in Fig. 3), which implies that no maximum of S vs. energy shows up (see Fig. 4).

It should be noted that the hindrance threshold, according to the phenomenological systematics of Jiang [2, 14], is expected at \(\approx 40\) MeV. Our measurements extend almost 4 MeV below. It appears that hindrance of \(^{32}\text{S}+^{48}\text{Ca}\) fusion is ”weak”, or that it shows up at very low energies, possibly due to the influence of channel couplings. The comparison with the CC calculations, that we are going to present in the next section, will tell us more about this.

Other interesting features of the dynamics of this system can be recognized. This is the case, in particular, for the barrier distribution which we have extracted from the excitation function with the usual three-point formula and an energy step of \(\approx 1.8\) MeV. Fig. 5 shows that the barrier distribution is very wide (around 8 MeV) and that its shape is somehow unexpected, with two peaks of similar height on either side of the Akyüz-Winther (AW) [15] barrier calculated at \(E_{cm} = 43.4\) MeV. In the following, we try to provide a qualitative interpretation of these experimental evidences by means of a simplified CC approach and by a comparison with similar systems.

4. Analysis
Preliminary CC calculations have been performed using the code CCFULL [16] and employing the standard AW potential. The barrier height has been slightly adjusted, as it is usually necessary when using a potential coming from a large systematics. The adopted potential parameters, \(V_0=75.12\) MeV, \(r_0=1.12\) fm and \(a=0.65\) fm, have been obtained following the same criteria used for the similar analysis of \(^{36}\text{S} + ^{48}\text{Ca}\) [4] that we will consider later for comparison. We refer to that paper for details.

The lowest 2\(^+\) and 3\(^-\) states of both projectile and target have been included In the coupling
scheme, taking into account also all mutual excitations, and using the deformation parameters (coupling strengths) shown in the left panel of Fig. 6. The solid red line in Fig. 2 is the result of this calculation showing a very large enhancement compared with the no coupling limit (the dashed line in the same figure). Since the $2^+$ state of $^{32}\text{S}$ has a relatively low excitation energy and a large coupling strength, we have added a second quadrupole phonon in the calculation. The result is however only a very small increase of the fusion cross section as shown by the green curve. This suggests that the effect of low-lying collective excitations on fusion probability is fully taken into account. Nevertheless, the experimental data are still largely underpredicted.
$^{32}\text{S} + ^{48}\text{Ca}$ has several transfer channels with positive ground state Q-values for proton and alpha stripping, and for two- and four-neutron pick-up. The additional coupling of these transfer channels might provide the missing cross section.

The code CCFULL uses a macroscopic form factor [17] to take into account schematically the effect of pair transfer channels. The form factor F is related to the ion-ion potential $U_n$ by

$$F = F_{tr} \frac{dU_n}{dr}$$

The parameters $F_{tr} = 0.75$ fm for the strength and $Q_{tr} = +1.5$ MeV for the Q value have been varied, in order to obtain the best fit to our data. The result is shown by the blue curve in Fig. 2, and it is very nice.

The effect of transfer channels is also emphasized in the linear plot of the fusion cross sections vs. energy above the barrier (see right panel of Fig. 6) where one can notice that only by including the transfer coupling in the calculation, it is possible to reproduce the high-energy cross sections. Ignoring the transfer coupling, the calculation clearly overestimates the data above the barrier but underestimates the sub-barrier cross sections.

The CC calculations are also able to reproduce the slope of excitation function rather well (see Fig. 3). It is interesting to note that this is true for both calculations (without and with transfer). The slope is not sensitive to the presence of the transfer couplings in these schematic calculations. However, the S-factor is only fitted when transfer is included. This is evident from Fig. 4.

The BD of Fig. 5 is nicely reproduced only by the calculations including the transfer channels (blue line). On the contrary, inelastic couplings produce a BD very different from experiment (green line).

![Figure 6](image-url)  

**Figure 6.** Left panel: low-energy excitation spectra of $^{32}\text{S}$ and $^{48}\text{Ca}$. The deformation parameters $\beta_\lambda$ used in the CC calculations are also reported. Right panel: linear plot of the fusion excitation function.

We stress that the CCFULL calculations including transfer, have to be considered very approximate and qualitative. Further theoretical analyses are surely needed to really understand
the nature of couplings important for $^{32}\text{S} + ^{48}\text{Ca}$ near and below the barrier.

5. Comparison with nearby systems

Given the limitations of CC calculation, as far as the treatment of the transfer channels is concerned, a comparison with the nearby system $^{36}\text{S} + ^{48}\text{Ca}$ [4] can provide us with useful insights. The left panel of Fig. 7 is a plot of the two excitation functions with an energy scale normalized to the AW barrier. Two things are immediately evident: 1) above the barrier, $^{36}\text{S} + ^{48}\text{Ca}$ has larger cross sections, and 2) below the barrier its excitation function is much steeper. Moreover, the BD of the two systems show interesting differences (right panel of Fig. 7): only one main peak is visible in the case of $^{36}\text{S} + ^{48}\text{Ca}$, at variance with the double peak structure of $^{32}\text{S} + ^{48}\text{Ca}$.

For $^{36}\text{S} + ^{48}\text{Ca}$ all possible transfer channels have negative Q-values. Its excitation function was analyzed using CC calculations quite similar to those performed for $^{32}\text{S} + ^{48}\text{Ca}$ in the present work. We point out that in that case [4] only couplings to low-energy excitation modes were needed to reproduce the data, together with a WS potential with very large (unrealistic) diffuseness parameter.

The low-energy cross sections of $^{36}\text{S} + ^{48}\text{Ca}$ are suppressed compared to CC calculations based on a standard WS potential (see Fig. 8). This can be regarded as evidence of fusion hindrance, while the behaviour of $^{32}\text{S} + ^{48}\text{Ca}$ is quite different, as discussed above.

![Figure 7](image_url)

*Figure 7.* Left panel: fusion excitation functions of $^{32}\text{S} + ^{48}\text{Ca}$ and $^{36}\text{S} + ^{48}\text{Ca}$ are shown for comparison using a reduced energy scale $E/V_b$. $V_b$ is obtained from the AW potential. Right panel: BD of the two systems.

We consider now also $^{40}\text{Ca} + ^{48}\text{Ca}$ recently measured at LNL [11], so to extend the comparison to three systems where $^{48}\text{Ca}$ is involved. It should be emphasized that this system has positive Q values for various transfer channels and the influence of transfer on fusion was already suggested in Ref. [11]. Another common feature of the two systems $^{32}\text{S} + ^{48}\text{Ca}$ and $^{40}\text{Ca} + ^{48}\text{Ca}$ is the positive Q-value for compound nucleus formation. For $^{40}\text{Ca} + ^{48}\text{Ca}$ we have obtained a rather clear indication of an S-factor maximum. This is not the case for $^{32}\text{S} + ^{48}\text{Ca}$, at least in the measured energy range.

But let us concentrate our attention on the experimental data reported in Fig. 9. Above the barrier (right panel) we observe that the cross sections are very similar for $^{32}\text{S} + ^{48}\text{Ca}$ and
$^{40}\text{Ca} + ^{48}\text{Ca}$, and much smaller than for $^{36}\text{S} + ^{48}\text{Ca}$ (our "reference" system with negative Q value for all transfer channels). In the sub-barrier energy region (left side of Fig. 9), $^{36}\text{S} + ^{48}\text{Ca}$ has the smallest cross sections, and the other two systems behave similarly, at least down to the energy (the hindrance threshold) where the excitation function of $^{40}\text{Ca} + ^{48}\text{Ca}$ starts falling down steeply. At that point coupling effects (probably transfer couplings) still produce larger cross sections for $^{32}\text{S} + ^{48}\text{Ca}$, and the onset of hindrance should be looked for at smaller energies, for this system. The underlying reason has to be clarified by the help of more detailed model calculations.

**Figure 8.** Experimental excitation function of $^{36}\text{S} + ^{48}\text{Ca}$ and results of CC analysis [4]. The green and blue lines are the results of calculations using WS potentials with diffuseness parameters $a=0.65$ fm and $a=0.95$ fm, respectively.

**Figure 9.** Fusion excitation functions of the three systems $^{32,36}\text{S} + ^{48}\text{Ca}$ and $^{40}\text{Ca} + ^{48}\text{Ca}$ below and above the barrier (left and right panel, respectively). The energy scale is normalized to the barrier $V_b$. 


6. Summary
Fusion cross sections of $^{32}$S + $^{48}$Ca have been measured at LNL in a wide energy range. The excitation function has a smooth behavior below the barrier, with a rather flat slope. The logarithmic slope L(E) does not reach the value expected for a constant S factor, which implies that no maximum of S vs. energy develops. However, other interesting features of the dynamics of this system can be observed. In particular, the fusion barrier distribution has an unusual shape with two peaks of similar height, lower and higher than the AW barrier. Preliminary CC calculations have been performed using the code CCFULL including the lowest 2$^+$ and 3$^-$ states of both projectile and target, and the two-phonon quadrupole excitation of $^{32}$S. The results clearly underpredict the sub-barrier cross sections, although the slope of the excitation function is very well reproduced, while experimental data are lower than the calculations above the barrier. The predicted barrier distribution is very different from experiment, in particular the higher-energy peak is completely missing.

Since $^{32}$S + $^{48}$Ca has several neutron pickup transfer channels with positive Q-values, further schematic calculations have been carried out with CCFULL including also a transfer coupling simulating the +2n pick-up channel. It is interesting to observe that this further transfer coupling produces a fusion excitation function, a barrier distribution, a logarithmic derivative and a S-factor in close agreement with the data. It appears that transfer couplings push very much down in energy the threshold for hindrance, below the lowest measured energy. More detailed analyses and calculations are anyway necessary before drawing firm conclusions.

A comparison with $^{36}$S + $^{48}$Ca shows that this latter system has an excitation function much steeper than $^{32}$S + $^{48}$Ca below the barrier and larger cross section above it. Considering also the case of $^{40}$Ca + $^{48}$Ca, one observes that its behavior is very similar to $^{32}$S + $^{48}$Ca in the whole energy range. It is useful to remind that positive Q-value transfer channels are available for both these two systems.

7. References
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