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Do we understand heavy-ion fusion reactions of importance in stellar evolution?

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Abstract. Since the first observation of hindrance in heavy-ion fusion, many extrapolated cross sections for astrophysically interesting fusion reactions, such as ^{12}C + ^{12}C, ^{12}C + ^{16}O, ^{16}O + ^{16}O, ^{24}O + ^{24}O *etc.* need to be reexamined. In this contribution, the effects of fusion hindrance at extreme low energies are discussed.

Heavy-ion fusion reactions such as ^{12}C + ^{12}C, ^{12}C + ^{16}O and ^{16}O + ^{16}O are important during late stellar evolution, *e.g.*, in type Ia supernovae [1]. However, even in these explosive scenarios, the Gamow energies are still very low, and the corresponding cross sections are so small that they cannot be measured in the laboratory with existing technologies. Thus, the reaction rates used in simulations are obtained either from extrapolations of existing data or from model calculations. Other fusion reactions involving neutron-rich nuclei (^{24}O + ^{24}O, ^{28}Ne + ^{28}Ne, ^{24}Ne + ^{42}Mg *etc.*), occur in the inner crust of acreeting neutron stars. These reactions cannot be measured in the laboratory, and are only accessible through calculations [2].

The low-energy behavior of fusion cross sections is successfully discussed by introducing the so-called S factor: $S(E) = \sigma E exp(2\pi\eta)$. The experimental $S(E)$ factor for the system ^{16}O + ^{16}O is shown in Fig. 1a. The critical energy region (Gamow window) for a very high temperature of $T_9 = 2$ is given by the blue bar which is well outside the region covered by the experiments. At the lowest energies, the various measurements [3] differ by a factor of up to four. The previous calculations using different models [4] (Dias-Torres, dashed magenta line, Neff, black solid line), differ strongly among themselves and overestimate the cross sections at low energies. All these predictions increase with decreasing energy, while most of the experimental data saturate. This behavior is similar to the one, heavy-ion fusion hindrance, observed for reactions in medium-mass systems at extreme sub-barrier energies [5]. A typical example for the reaction ^{64}Ni + ^{64}Ni is found in Fig. 1b [5]. At near barrier energies, the excitation function can be reproduced well by standard coupled-channels (CC) calculations, while at lower energies, the S factor exhibits a maximum which cannot be reproduced by such calculations (red curve). It was soon realized that any system with negative Q value has to show an S factor maximum, since at the energy $E = -Q$ the cross section and $S(E)$ must be zero.

Later it was shown that fusion hindrance, the deviation between the experimental S factor and the CC prediction at low energies, is due to the saturation property of nuclear matter [6]. The question about whether the saturation property of nuclear matter can also play a role for light heavy-ion fusion systems was first discussed in Ref. [7].

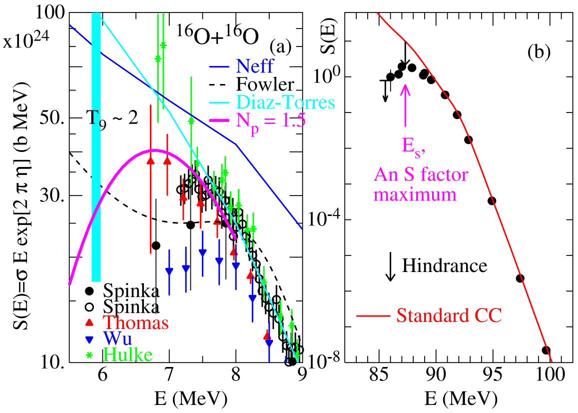

Figure 1. Plot of the $S(E)$ factor versus E for the systems ^{16}O + ^{16}O (a) and ^{64}Ni + ^{64}Ni (b).

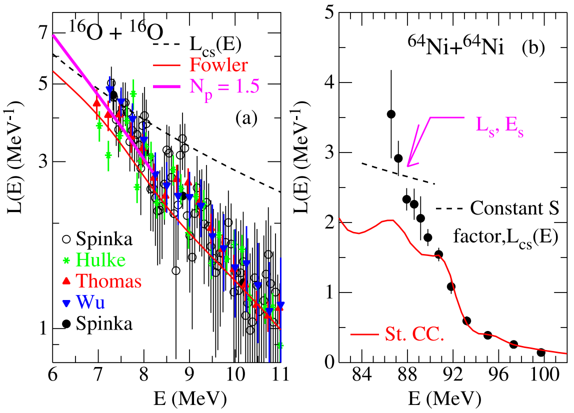

Figure 2. Plot of the logarithmic derivative $L(E)$ versus E for the systems ^{16}O + ^{16}O (a) and ^{64}Ni + ^{64}Ni (b).

Another sensitive way to analyze the experimental data at low energies uses the logarithmic derivative ($L(E) = d[ln(\sigma E)]/dE$) [8]. This approach has the advantage that it is independent of (multiplicative) scaling factors in the cross sections which can originate, *e.g.*, from the use of different detection efficiencies. It can be shown that the maximum in the S factor representation coincides with the crossing point between the experimental logarithmic derivative $L(E)$ and the function obtained for a constant S factor, $L_{cs}(E) = \pi\eta/E$.

The logarithmic derivatives for the systems ^{16}O + ^{16}O and ^{64}Ni + ^{64}Ni are presented in Fig. 2. As discussed above, the deviations between the different experiments for ^{16}O + ^{16}O are much less pronounced than in the $S(E)$ plot. While for ^{64}Ni + ^{64}Ni there is a clear crossing point between $L(E)$ and the constant S factor curve (black dashed line in Fig. 2), the situation for ^{16}O + ^{16}O is not as clear.

A phenomenological fit was made to the data points in the low energy region using the equation from Ref. [7]:

$$L(E) = A_0 + \frac{B_0}{E^{N_p}} \quad (\mathrm{MeV}^{-1}), \tag{1}$$

where N_p was taken as 1.5, which is the value obtained for a point charge model. This fit is shown in Fig. 2a by the magenta curve. The corresponding $S(E)$ factor for this new extrapolation recipe can be obtained from an equation (Ref. [7]):

$$\sigma(E) = \sigma_s \frac{E_s}{E} e^{[A_0(E-E_0) - \frac{B_0}{E_s^{N_p-1}(N_p-1)}[(\frac{E_s}{E})^{N_p-1}-1)]]} \quad (\mathrm{mb}), \tag{2}$$

and is seen in Fig. 1a as the magenta heavy curve. Here σ_s is the cross section at E_s. The new extrapolation is different from all the previous ones (*e.g.*, Fowler, black dash-dotted line [9]) and model calculations in predicting a decrease in $S(E)$ at energies which are of astrophysical interest.

The strong effects of these two kinds of "predictions" in nuclear synthesis calculations have been discussed by Gasques *et al.* [10]. It should be noted that the new recipe is not a theory, but rather a phenomenological analysis (though it was called the hindrance model in some papers). In the following we discuss its reliability.

The logarithmic derivatives for four fusion systems ranging from heavy (^{90}Zr + ^{92}Zr) to light nuclei (^{10}B + ^{10}B) are displayed in Fig. 3. The crossing angle between $L(E)$ and the constant S factor curve decreases drastically in going from the heavier to the lighter systems. Since a

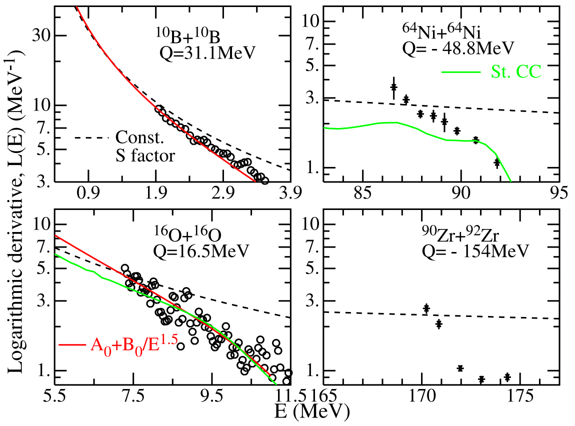

Figure 3. Plots of $L(E) - E$ for the systems ^{90}Zr + ^{92}Zr, ^{64}Ni + ^{64}Ni, ^{16}O + ^{16}O and ^{10}B + ^{10}B.

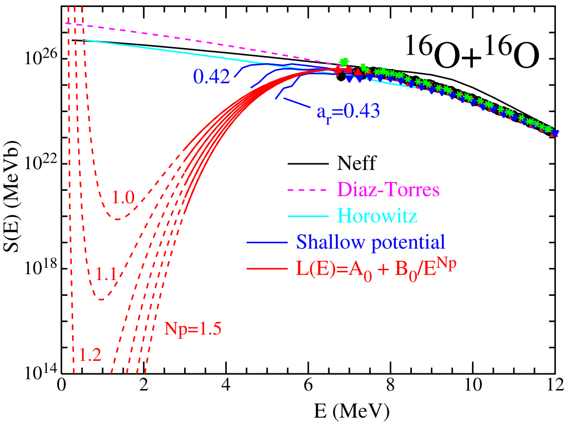

Figure 4. $S(E)$ factor for the system ^{16}O + ^{16}O. The red curves are obtained from the extrapolations discussed in the text with different exponents N_p = 1.5 - 1.0 in Eq. (1).

large crossing angle corresponds to a well defined S factor maximum [8], it becomes clear that for the lighter systems the S factor maximum will be less pronounced. Systems with positive Q value are not required to have an S factor maximum.

As mentioned above, the exponent N_p used in the extrapolation recipe (Eq. 1) originates from the (unrealistic) assumption of a point charge distribution. It was also known that, if $N_p <$ 1.5, the logarithmic derivative $L(E)$ may intersect with the constant S factor curve twice [7]. In order to test the sensitivity to the value of N_p, we have performed least squares fits with exponents $N_p < 1.5$. The results are given in Fig. 4 for the system ^{16}O + ^{16}O. In the energy region above ~ 3 MeV, the deviations between the different extrapolations (N_p = 1.5 - 1.0) are quite small. One should note that for a temperature $T_9 = 1$, the Gamow window is around 3.8 MeV. Thus, the new extrapolation recipe is not sensitive to the parameter N_p.

Misicu and Esbensen have suggested a shallow potential model to study fusion hindrance [6] by introducing a repulsive core which simulates the saturation property of nuclear matter. This shallow potential results in a thicker barrier as compared to the potentials used in standard CC calculations. This model can reproduce the hindrance phenomenon for many medium-mass systems. It is also able to reproduce the ^{16}O + ^{16}O fusion. In this model, there is a diffuseness parameter a_r in the repulsive core. Calculations for three values of a_r, 0.43, 0.425 and 0.42 are indicated in Fig. 4 by the blue curves. These calculations also predict small variations at energies E < 6 MeV, and they are in qualitative agreement with changing the parameter N_p discussed above.

In the energy region E < 3 MeV, extrapolations are shown with dashed curves, since they differ significantly. This is the region where possible effects due to hindrance are not yet understood well.

It should be noted that for studies of fusion of ^{24}O + ^{24}O, ^{28}Ne + ^{28}Ne or reactions between other neutron-rich nuclei, one can depend only on calculations, which should be based on a reliable description for ^{16}O + ^{16}O.

A similar plot of the S factor for the system ^{12}C + ^{12}C can be found in Fig. 5 [11], including the previous extrapolation by Fowler [9] (light blue dashed line), the calculation by Gasques [12] (black line) and the results from our least squares fit using Eq. (1) and N_p = 1.5 for experimental data published before 2007. The main problem for the ^{12}C + ^{12}C system is the

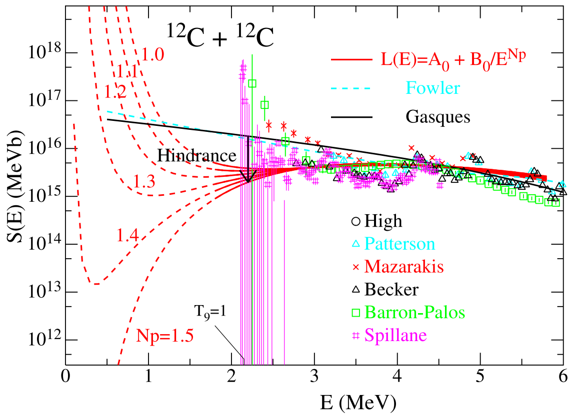

Figure 5. $S(E)$ for the system ^{12}C + ^{12}C.

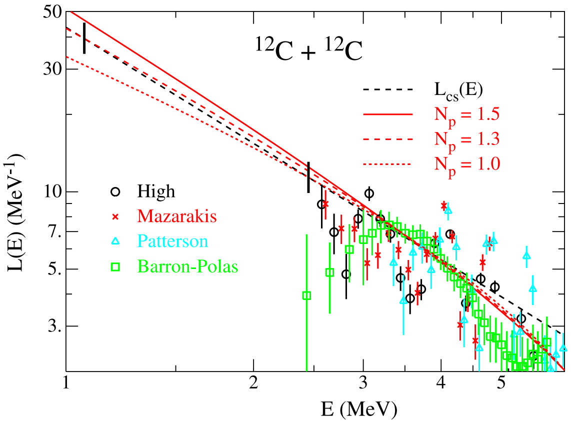

Figure 6. $L(E)$ for the system ^{12}C + ^{12}C.

presence of strong resonances which are not included in any of the theoretical calculations. In 2007, Spillane *et al.* published a new measurement (magenta points) [13]. Although the experimental uncertainties are large it seems that the new extrapolation recipe (with $N_p = 1.5$) can reproduce the experiment quite well down to energies as low as 2.5 MeV. In the energy region $E > 1.8$ MeV, the variations between different extrapolations ($N_p = 1.5$ - 1.0) are small with respect to the difference between the extrapolation with $N_p = 1.5$ and the previous calculations. Thus, the new extrapolation recipe is not very sensitive to the parameter N_p for this energy region. In the very low energy region, extrapolations are shown with dashed curves; here the situation remains rather uncertain. The variations for the extrapolation with different N_p can be well understood from the corresponding plots of $L(E)$ presented in Fig. 6, where two vertical bars are the energies of the second intersection between $L(E)$ and $L_{cs}(E)$ for $N_p = 1.3$ and 1.0.

The influence from resonances is much weaker in the neighboring system ^{12}C + ^{13}C. The latter has been studied by Dayras *et al.* [14] down to energies of 3.1 MeV (black circles in Fig. 7). The green solid line is the extrapolation for Dayras' data with the new recipe ($N_p = 1.5$), and shows considerable fusion hindrance when compared to the prediction of the Sao Paulo potential (black curve). Last year, these measurements were extended toward lower energies, down to 2.6 MeV, in a new experiment performed at Notre Dame [15] (red open circles). Combining the two data sets, a new extrapolation was obtained shown by the red curves. All extrapolations with different N_p values indicate some fusion hindrance. To establish the amount of the hindrance contribution quantitatively, however, requires a continuation of the experiments toward even lower energies.

As one can realize from the results for the three fusion reactions discussed above, the contributions of fusion hindrance are different for each system, since both the hindrance and nuclear structure effects can play a role. Extending the cross section measurements for these astrophysically important systems toward lower energies remains quite challenging. There are some light-ion reactions, such as those included in the compilation by Angulo *et al.* [16], that have been measured to rather low energies, *e.g.*, the reactions ^{6}Li(p,α) and ^{7}Li(p,α). The behavior of these light-ion reactions, however, is inconclusive, as an increase (^{6}Li(p,α)) and a decrease (^{7}Li(p,α)) in $S(E)$ with decreasing energy have been observed.

It is worthwhile to mention another approach to this issue. There are systems slightly heavier than ^{12}C + ^{12}C and ^{16}O + ^{16}O, with positive fusion Q values. Experiments with these reactions, while less important for nuclear astrophysics, can be used to explore the question of the occurence of a maximum in the S factor for systems with a positive Q value. Two of these reactions have

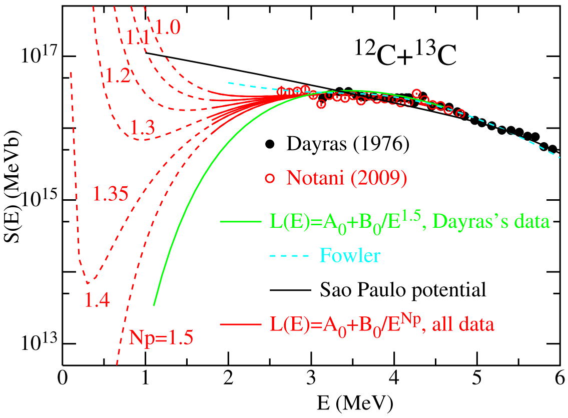

Figure 7. $S(E)$ for the system ^{12}C + ^{13}C.

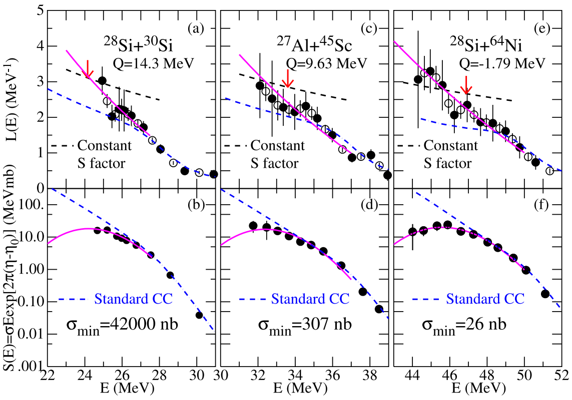

Figure 8. $S(E)$ and $L(E)$ for the systems ^{28}Si + ^{30}Si, ^{27}Al + ^{45}Sc and ^{28}Si + ^{64}Ni. σ_{min} are the smallest cross sections measured in the various experiments.

been measured at Argonne: ^{28}Si + ^{30}Si, Q = 14.3 MeV and ^{27}Al + ^{45}Sc, Q = 9.63 MeV [17]. The results are compared to the data from a system with a small negative Q value, ^{28}Si + ^{64}Ni (- 1.78 MeV) [5] in Fig. 8. Both the $L(E)$ and $S(E)$ curves for these three systems are very similar. Fusion hindrance is seen in all three cases, but so far an S factor maximum was only clearly delineated in the reaction with the negative Q value. Due to background reactions on target contaminants, the measurements could not be extended toward lower energies for the two systems with positive Q value.

Another measurement of a reaction with positive Q value, ^{36}S + ^{48}Ca (7.55 MeV), was measured at Legnaro [18], and the results can be found in Fig. 9. Again, no S factor maximum was found, although the measurement had already reached energies which are about 6 MeV below the expected energy of the S factor maximum obtained from systematics [7] :

$$E_s^{emp} = [0.495\zeta/(2.33 + 580/\zeta)]^{2/3} \quad \text{(MeV)}. \tag{3}$$

Here ζ is a parameter specific to the nuclei involved, $Z_1Z_2\sqrt{\mu}$, and μ is the reduced mass of the colliding nuclei [7]. Interestingly, for the neighboring case ^{48}Ca + ^{48}Ca, the patterns of the measured $L(E)$ and $S(E)$ are nearly the same as the results of ^{36}S + ^{48}Ca, and no S factor maximum has been found either, although this is a system with negative Q value (- 3.0 MeV), so an S factor maximum must exist. These studies suggest that the larger neutron excess, ($N - Z$ = 16, 12) for the systems ^{48}Ca + ^{48}Ca and ^{36}S + ^{48}Ca may push the hindrance behavior toward lower energies. Recently, fusion in the system with less neutron excess, ($N - Z = 8$), ^{40}Ca + ^{48}Ca (Q = 4.56 MeV) has been re-measured by an Argonne-Legnaro collaboration [19], and an indication of S factor maximum has been found. This is the first time an S factor maximum in a system with a positive Q value (see Fig. 9) has been observed. However, more data points at even lower energies are clearly desirable.

In summary, the question, “Do we understand heavy-ion fusion reactions that are important in stellar evolution?” The answer still has to be: ”No, not well enough!”

Experimental and theoretical studies have shown clearly that potential models often overpredict cross sections at low energies. Also, there are considerable differences in the various model predictions at low energy for fusion cross sections involving stable nuclei. This prevents us from extrapolating accurately fusion cross sections such as ^{12}C + ^{12}C and ^{16}O + ^{16}O to low energies, and predicting the excitation functions for more exotic nuclei (*e.g.* ^{24}O +

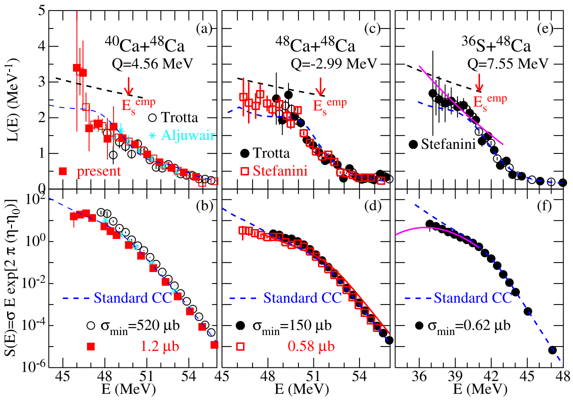

Figure 9. $S(E)$ and $L(E)$ for the systems ^{40}Ca + ^{48}Ca, ^{48}Ca + ^{48}Ca and ^{36}S + ^{48}Ca.

^{24}O), which cannot be measured in the laboratory. All measurements indicate the presence of fusion hindrance in light heavy-ion systems. However, the hindrance is not yet understood quantitatively well enough to allow for extrapolations beyond an energy range 1 - 3 MeV lower than the existing experimental data. More measurements at low energies are urgently needed to quantify this hindrance behavior in detail.

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