

Fusion of $^{24}\text{Mg} + ^{30}\text{Si}$ - hindrance for a positive- Q -value system

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INTRODUCTION

The phenomenon of heavy-ion fusion hindrance at extreme low energies was discovered about ten years ago [1–3]. The experimental evidence was first observed for medium-heavy systems, for which fusion Q values are negative. A characteristic behavior is that there is an S -factor maximum appearing at deep sub-barrier energies, which is not expected by the standard Coupled-channels (CC) predictions but is required from the principle of energy conservation [4]. Later, the suppression of the fusion probability at low energies was explained successfully with the saturation properties of nuclear matter [5] or the decreasing of coupling strength after the touching of two colliding nuclei [6].

For system with a positive fusion Q -value, it is not necessary to have an S -factor maximum, since a finite cross section can be expected at zero incident energy from the energy conservation law. However, assuming that the hindrance is due to the saturation properties of nuclear matter or the decrease in the coupling strength after the touching of nuclei, it is expected that fusion hindrance must appear also for light heavy-ion fusion [7].

In recent years, fusion excitation functions of many slightly heavier systems with positive Q -value [8–12], and negative Q value [13–16] have been measured or remeasured to lower energies. Indications of fusion hindrance have been observed in all cases since these excitation functions always drop faster than predicted by the CC calculations with a standard Woods-Saxon potential. An indication of an S -factor maximum has been observed so far only in the $^{40}\text{Ca} + ^{48}\text{Ca}$ system but it is not very pronounced [10].

EXPERIMENT AND RESULTS

In order to investigate this question further, we have remeasured the fusion excitation function for the system $^{24}\text{Mg} + ^{30}\text{Si}$ ($Q = 17.89$ MeV), which has previously been studied down to cross sections of about $73 \mu\text{b}$ by Morsad *et al.* [17], which is already in the region where fusion hindrance plays an important role. The experiment was

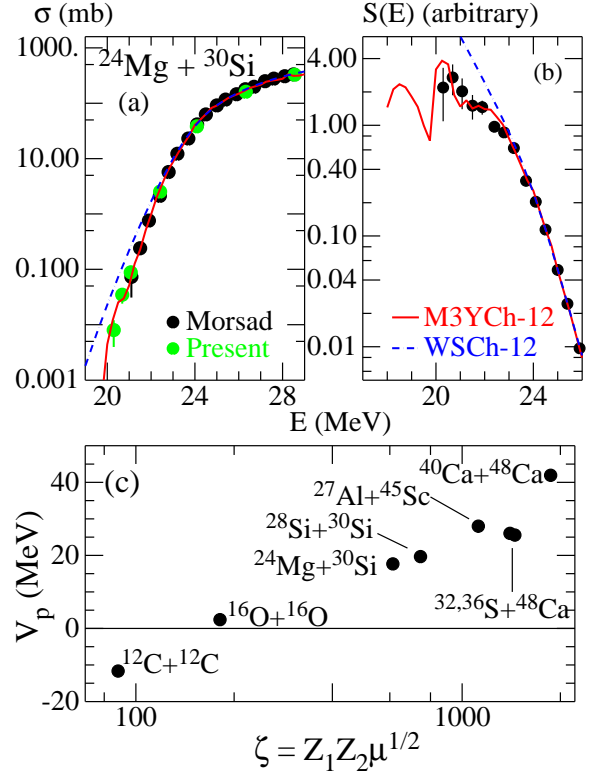


FIG. 1: Excitation function (a) and S factor (b) of $^{24}\text{Mg} + ^{30}\text{Si}$. Black and green points are measured by Morsad *et al.*, [17] and present experiments, respectively. Curves are for CC calculations (see text for detail). Panel (c) is a collection of V_p (minimum of potential) for positive- Q -value systems.

performed at the XTU Tandem accelerator of Laboratori Nazionali di Legnaro, INFN, Italy. A ^{24}Mg beam of 5 - 10 pA bombarded a SiO_2 target with thickness $\sim 30 \mu\text{g}/\text{cm}^2$ (evaporated on a $20 \mu\text{g}/\text{cm}^2$ carbon backing). The isotopic abundance of ^{30}Si was 96.78%. The evaporation residues were detected with an electrostatic separator in its upgraded configuration [11]. The detector system consists of two micro-channel plate detectors, one ionization chamber and a silicon surface-barrier detector. Details of the experimental setup, and the data analysis have been described elsewhere (see Ref. [3, 12, 14, 18]).

The main focus was the study of the low-energy hindrance behavior. Measurements were performed at seven energies, with five of them coinciding with the earlier experiment. Events of evaporation residues are well separated from background in the measurements even at the lowest measured energy. Our measurements are normalized to Morsad's cross sections at four energies. Thus we obtain two new data points at low energies. At the lowest energy of Morsad's experiment, 21.1 MeV, three fusion events were collected, with an uncertainty of cross section of 58%. The fusion events collected at center of mass energies, $E = 21.1, 20.68, \text{ and } 20.29$ MeV in the present experiment are 11, 11 and 4 counts, respectively.

The excitation function and the S -factor data are shown in Figs. 1a and 1b, respectively. The green circles are the present results, and the black circles are from Morsad *et al.*, [17]. The uncertainties of the present data represent the statistical and normalization errors. The data reach the S -factor maximum but fall short of a precise definition of its location. Nevertheless, it is more convincing than the result in the past, *i.e.*, as compared with the first evidence of a maximum in the positive Q -value system, $^{40}\text{Ca} + ^{48}\text{Ca}$ [10].

Coupled-channels calculations are shown in Figs. 1a and 1b. The CC calculation with a standard Woods-Saxon potential provides an excellent description of the data above the Coulomb barrier and is presented by the blue-dashed curves, denoted WSCh-12. At lower energies, it overpredicts the experimental data which implies that there is strong fusion hindrance. With the combination of a M3Y potential and a repulsive core (M3Y+Rep potential), the CC calculations (red) describe well the experimental result over the whole energy range. These CC calculations include 12 channels, namely both the 2^+ and 3^- states of ^{24}Mg and ^{30}Si , and up to two-phonon excitations, except the two-phonon excitations of 3^- states.

There is a minimum at an energy of V_p , 17.7 MeV in the M3Y+Rep potential. When the incident energy is equal or less than V_p , the fusion cross sections must be zero, as indicated in the M3YCh-12 calculations. There is a minimum in the S factor slightly below 20 MeV, which appears because all excited channels are closed below that energy.

The systematics of the pocket value V_p of the M3Y+Rep potential for many systems with positive fusion Q value is given in Fig. 1c. We find that, except for the system $^{12}\text{C} + ^{12}\text{C}$, all V_p are positive. This indicates that for systems as light as $^{16}\text{O} + ^{16}\text{O}$, there should be an S -factor maximum located at an energy higher than the V_p . By using the extrapolation recipe [7], there is also an S -factor maximum for $^{12}\text{C} + ^{12}\text{C}$. If these observations

are true, a large influence for the reaction rates would exist at low energies in the carbon and oxygen burning. Gasques *et al.*, studied the implications of low-energy fusion hindrance on stellar burning and nucleosynthesis [19]. They concluded that, when the hindrance behavior is included, much higher ignition densities for *e.g.*, Ia supernovae, are required and changes in the abundance of many isotopes in massive late-type stars are needed.

ACKNOWLEDGEMENTS

We are grateful to the XTU Tandem staff for their professional work. We also acknowledge Mr. Loriggiola for preparing the excellent targets. This work was supported by the US Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357 and the European Union Seventh Framework Programme FP7/2007-2013 under Grant Agreement No. 262010-ENSAR. A.G. was partially supported by the P210 Excellence Laboratory.

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