Fusion Hindrance for Ca + Ca Systems
Influence of Neutron Excess

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INTRODUCTION

Fusion hindrance at extreme low energies - a falloff of the fusion cross sections, which is steeper than predicted by standard coupled-channels (CC) calculations - is a well established effect in reactions between medium-mass nuclei [1]. This falloff has been studied either by analyzing the logarithmic derivative of the fusion cross section ($L(E) = d[\ln(\sigma E)/dE]$) or by introducing the so-called S factor ($S(E) = \sigma E \exp(2\pi\eta)$), which partially eliminates the strong energy dependence of the fusion cross section at low energies. In the S factor representation a maximum in $S(E)$ appears for all systems with negative Q values. This behavior can be understood from the definition of $S(E)$: since $\sigma(E)$ has to be 0 for energies $E \leq -Q$, the S factor will also be 0. While many subsequent studies have shown that fusion hindrance seems to be a common behavior for all heavy-ion fusion systems, even with positive Q values ([2–6]), the question whether a maximum in $S(E)$ also appears in fusion reactions with positive Q values has not been answered yet.

In three earlier experiments, fusion excitation functions for the systems ^{28}Si + ^{30}Si (Q = 14.3 MeV) [7], ^{36}S + ^{48}Ca (Q = 7.55 MeV) [8] and ^{27}Al + ^{45}Sc (Q = 9.63 MeV) [9] were measured down to $\sim$ 40 μb, 600 nb and 300 nb, respectively. Indications of fusion hindrance have been observed in all of these systems since the excitation functions drop faster than predicted by CC calculations. However, no evidence of S factor maximum has been observed in the energy ranges covered by these experiments.

In order to investigate fusion hindrance for systems with positive Q value in more detail, we have remeasured the fusion cross sections in the system ^{40}Ca + ^{48}Ca (Q = 4.56 MeV), which was previously been measured down to about 500 μb [10, 11], well above the energy region where fusion hindrance plays a role.

EXPERIMENTAL PROCEDURE AND RESULTS

The experiment was performed at the XTU tandem of Laboratori Nazionali di Legnaro, Italy. A ^{40}Ca beam of 5-10 pnA was bombarded on a CaF_2 target (thickness of about 50 μg/cm^2 and evaporated on a 20 μg/cm^2 carbon backing). The isotopic abundance of ^{48}Ca was 96.78%. The evaporation residues were detected with the electrostatic separator in its upgraded configuration, together with a detector system consisting with two microchannel plate detectors, one ionization chamber and a silicon surface-barrier detector. Details of the experimental setup, procedure and the analysis have been described in Ref. [5, 8, 12]. The data analysis is still in progress and, thus, the cross section values presented are preliminary.

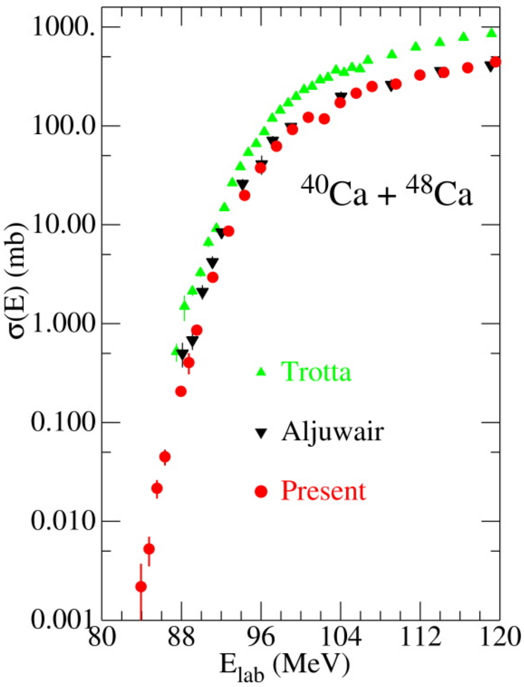

Fig. 1. Excitation functions of ^{40}Ca + ^{48}Ca measured in three different experiments. The red circles are from the present measurements.

Experimental excitation functions for ^{40}Ca + ^{48}Ca from this experiment are shown in Fig. 1 by red circles, together with two previous measurements for the same system by Trotta et al. (green upward-triangles), and Aljuwair et al. (black downward-triangles), [10, 11]. The uncertainties shown for the present data are statistical only. Data of the lowest two energies are obtained from two and nine counts, respectively. The uncertainty of the absolute cross sections is estimated to be about ±7%.

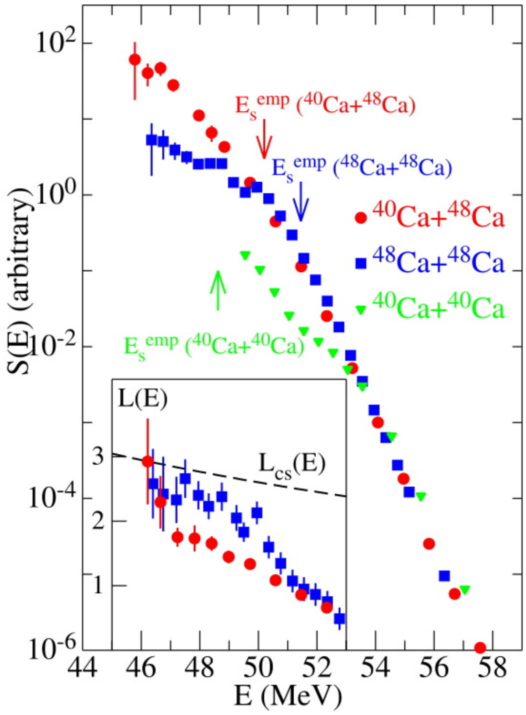

Fig. 2. The comparison of the S factors for three systems, ^{40}Ca + ^{48}Ca, ^{40}Ca + ^{40}Ca and ^{48}Ca + ^{48}Ca. Three arrows are the energy locations of S factor maxima, predicted from the systematics. The corresponding $L(E)$ are shown in the insert.

Overall, our results agree well with Aljuwair's data. The angular distributions and transmissions of the separator have been measured in the present experiment. Then the reason that why there is a big discrepancy between Trotta's data and the present data is unknown yet. That may be checked again in a forthcoming experiment submitted by Stefanini [13]. As seen from Fig. 1 the present experiment has extended the cross section measurement downwards by two orders of magnitude to ~ 2 μb, where fusion hindrance is expected to appear.

DISCUSSION

A plot of the S factor vs. center of mass energy E for ^{40}Ca + ^{48}Ca is shown in Fig. 2. Although the experimental fusion cross sections show a change in slope at the lowest energies, and the corresponding logarithmic derivative, $L(E)$ reaches the constant S factor function $L_{cs}(E)$ (see insert) the question about the existence of a maximum in S(E) can not be answered yet. For this the measurements need to be extended towards even lower energies. This is planned in a future experiment [13].

Also included in Fig. 2 are the S factors for the systems ^{48}Ca + ^{48}Ca [12] and ^{40}Ca + ^{40}Ca [11]. The S factors for the three systems have been normalized to coincide in the energy range of 53 - 58 MeV. Predicted locations for the S factor maxima, E_s^{emp}, which are obtained from the systematics [2] and represent upper limits for the locations of the maxima, are also shown in Fig. 2.

As can be seen from Fig. 2 patterns of S factor for these three systems at low energies are rather different; and none of the three systems shows evidence for a S factor maximum yet, although for ^{48}Ca + ^{48}Ca a maximum in $S(E)$ must exist. It was suggested in Ref. [9], that the large neutron excess $N-Z$ for ^{48}Ca + ^{48}Ca might push the fusion hindrance to lower energies. The large variation in $N-Z$ accessible in the Ca + Ca reactions makes this an ideal system to study this interesting nuclear structure effect (a $N-Z$ dependence of the fusion hindrance behavior, $E_s - E_s^{emp}$). More experiments covering the low energy region are planned for the future.

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[1] C.L. Jiang et al., Phys. Rev. Lett., 89 (2002) 052701; Phys. Rev. Lett., 93 (2004) 012701; Phys. Rev., C71 (2005) 044613; Phys. Lett., B640 (2006) 18.
[2] C.L. Jiang et al., Phys. Rev., C69 (2004) 014604; Phys. Rev., C73 (2006) 014613; Phys. Rev., C75 (2007) 057604.
[3] M. Dasgupta et al., Phys. Rev. Lett., 99 (2007) 192701.
[4] M. Trotta et al., Nucl. Phys., A787 (2007) 134C.
[5] A.M. Stefanini et al., Phys. Rev., C in press.
[6] C.L. Jiang et al., Phys. Rev., C75 (2007) 015803; Phys. Rev., C79 (2009) 044601.
[7] C.L. Jiang et al., Phys. Rev., C78 (2008) 017601.
[8] A.M. Stefanini et al., Phys. Rev., C78 (2008) 044607.
[9] C.L. Jiang et al., Phys. Rev., C81 (2010) 024611.
[10] M. Trotta et al., Phys. Rev., C65 (2001) 011601(R).
[11] H.A. Aljuwair et al., Phys. Rev., C30 (1984) 1223(R) .
[12] A.M. Stefanini et al., Phys. Lett., B 679 (2009) 95.
[13] A.M. Stefanini et al., accepted proposal, No. 18, Feb. 2010, LNL.