Test of extrapolating models for heavy ion fusion reactions at deep sub-barrier energies

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Goals of the experiments proposed; motivation

The heavy-ion fusion reactions between ^{12}C and ^{16}O isotopes, namely, ^{12}C+^{12}C, ^{12}C+^{16}O and ^{16}O+^{16}O, are crucially important in a wide variety of stellar burning scenarios. These reactions represent key processes in nuclear astrophysics since they influence not only the nucleosynthesis, such as the production of ^{26}Al and ^{60}Fe, but also the subsequent stellar evolution. At present, these reactions have only been measured down to energies which are higher than the energies of astrophysical interest. An extrapolation towards the relevant astrophysical energies is inevitable with the existing experimental data. The situation is even more complicated by the strong, relatively narrow resonances in some reactions, such as ^{12}C+^{12}C and ^{12}C+^{16}O [1,2].

Traditionally, optical model or equivalent square-well optical model (ESW) is used to fit the average cross section and predict the reaction cross sections at the energies of astrophysical interest. It has been found that the traditional optical model, eg. Akyuz-Winther, always over-predicts the fusion cross section at deep sub-barrier energies. This phenomenon is quoted as hindrance effect [1,3,4]. It is explained as the result of incompressibility of the nuclear matter due to the fusion process. Recently, several new models have been developed to provide more reliable prediction at deep sub-barrier energies. Esbensen and his collaborators developed a microscopic model based on a microscopic potential, M3Y, and a repulsive core [3]. Jiang suggested a formula with four tunable parameters to fit the fusion cross sections at sub-barrier energies[4]. The TDHF method developed by Umar and Oberacker also can predict the fusion cross section with none tunable parameter. Among them, the most striking one is the Jiang model, which provides reasonable fit to existing data while it predicts much smaller cross sections than other model at astrophysical energies. The goal of this project is to test these models by pushing the lowest measured energies down towards the astrophysically relevant region.

The entrance channel of the ^{12}C+^{13}C reaction is similar to that of the ^{12}C+^{12}C system while the total fusion cross section does not show strong resonant structure. Therefore, it provides an excellent opportunity to test the predictive powers of various theoretical models. A comparison between experimental data and theoretical calculations are shown in Fig. 1. While all the models except the traditional optical model (Akyuz-Winther) provide reasonable description to the existing data, there is a large deviation at Ecm<2.6 MeV at which measurement stops. For example, at Ecm=2 MeV, the M3Y+Rep model and the TDHF predicts S*=4.43E16 MeV*b and the Jiang_new model predicts S*=1.4E16 MeV*b. [S*(E)=E*sigma*exp(87.21/sqrt(E)+0.46*E)]

The ^{12}C+^{13}C fusion reaction was studied before with gamma spectroscopy. In our recent study [1,2], we measured the ^{12}C(^{13}C,^{24}Na)p reaction in an energy range from $E_{c.m.}$=2.6 MeV to 4.77 MeV by detecting the residual activity of the ^{24}Na ($T_{1/2}$=15 hr) with beta-gamma coincidence technique. After correcting for the decay branching ratio obtained from statistical model, the total fusion cross sections are obtained. In this measurement, we have pushed the lowest measured cross section from the published 10 μb down to 20 nb. The measurements at lowest energies, Ecm=2.6 MeV, was limited by the production yield and the background. Our data agree reasonable well with the existing models except the conventional optical model (Akyuz-Winther). Besides of testing the predictive power of various models, we also found an interesting correlation between ^{12}C+^{12}C, ^{12}C+^{13}C and ^{13}C+^{13}C. The ^{12}C+^{13}C and ^{13}C+^{13}C fusion cross sections constrain the upper limit for the ^{12}C+^{12}C fusion cross sections [2].

To further test/calibrate the predictive power of the extrapolating model, it is important to extend measurement down to lower energies. In our recent experiment [2], the beam intensity was limited to be below 1 puA. The recently installed high current tandem at Bucharest is expected to deliver more intense ^{13}C beam up to 10 puA. The existing underground laboratory provides an excellent counting environment for the detection of the decay of ^{24}Na nuclei. Since I am lacking of detailed information from this lab, it is not feasible for me to give an exact number. Given a factor of 80 improvement, we would be able to push the measurement down to Ecm=2.2 MeV and, meanwhile, achieve better error bar in the measured energy range. I am interested to perform a short term experiment to explore the possibility.

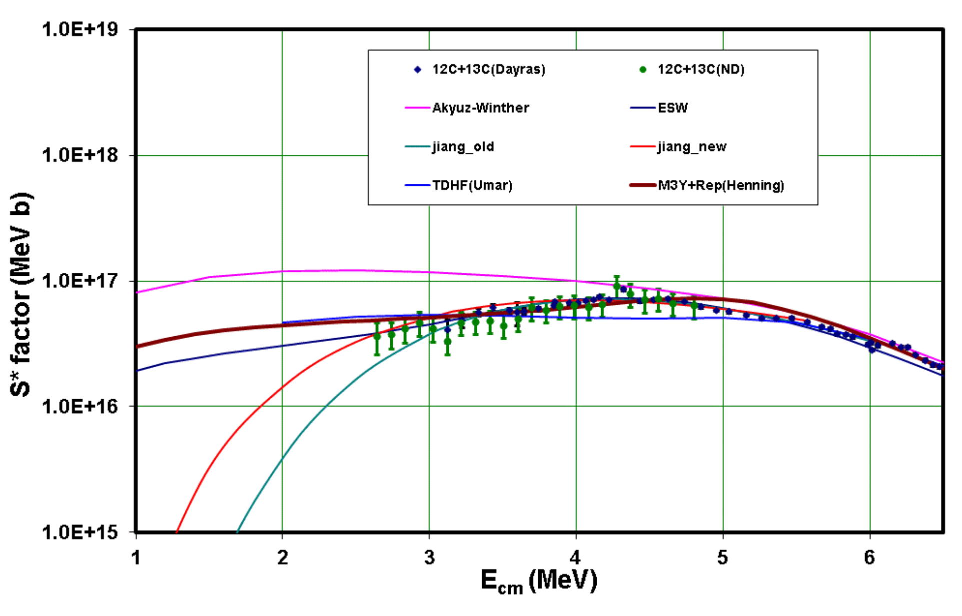

Fig. 1 Comparison between experimental data (shown as points) and theoretical calculations. The ESW model is the one used in the current reaction rate library to predict fusion cross sections at astrophysical energies. The TDHF model is lower than experimental data at energies around Ecm=4.3 MeV because the coupling to transfer channel is not included. Otherwise, this model agrees well with the M3Y+Rep model. The Jiang model provides two different predictions, Jiang_old and Jiang_new, based on

two fits to different data sets. The Jiang_old model is based on a fit to the Dayras data stopping at Ecm=3.1 MeV while the Jiang_new model is a new fit to both the Dayras data and our recent measure which stops at Ecm=2.6 MeV.

Collaborators

At this point we are looking forward to obtain the characteristics of 13C beams accelerated by this machine (intensity and energy stability at U=2.2 MV), work which is intended under a separate proposal (L. Trache et al.).
We are counting on the collaboration with the groups in that proposal: the gamma-ray spectroscopy group (N. Marginean) and the group running the Ultra-Low Background Laboratory in Slanic (R. Margineanu et al.), as well as on the thery support from prestigious theoreticians in the field: H. Esbensen (ANL), F. Carstoiu (IFIN-HH), etc.

Beamtime request

We estimate we will need two days of accelerator time (6 BTU) in the fall of 2013 and two weeks of beam time in the first 3 quarters of 2014 (42 BTU).

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