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Fusion measurements of $^{12}C+^{12}C$ at energies of astrophysical interest

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Abstract

The cross section of the $^{12}C+^{12}C$ fusion reaction at low energies is of paramount importance for models of stellar nucleosynthesis in different astrophysical scenarios, such as Type Ia supernovae and X-ray superbursts, where this reaction is a primary route for the production of heavier elements. In a series of experiments performed at Argonne National Laboratory, using Gammasphere and an array of Silicon detectors, measurements of the fusion cross section of $^{12}C+^{12}C$ were successfully carried out with the γ and charged-particle coincidence technique in the center-of-mass energy range of 3-5 MeV. These were the first background-free fusion cross section measurements for $^{12}C+^{12}C$ at energies of astrophysical interest. Our results are consistent with previous measurements in the high-energy region; however, our lowest energy measurement indicates a fusion cross section slightly lower than those obtained with other techniques.

In the interior of highly developed stars the fusion of $^{12}C+^{12}C$, known as carbon burning, drives the nucleosynthesis of heavier elements [1]. Because of its importance in nuclear astrophysics, many measurements of the $^{12}C+^{12}C$ reaction have been performed in the past [2–9]. However, the uncertainty in the cross section measured at and near the Gamow window is too large to put constraints on computations of nuclear abundances and reaction rates. At the moment, one has to rely on phenomenological extrapolations and/or model calculations in order to obtain the appropriate astrophysical reaction rates for use in stellar models. Even in explosive scenarios, such as Type Ia supernovae and X-ray superbursts, where the temperature is high compared to many stellar environments, the corresponding Gamow energies for the $^{12}C+^{12}C$ reaction are still very low (roughly between 1 and 3 MeV in the center of mass). This results in extremely small cross sections and, at this moment, direct measurements at low center-of-mass energies ($E_{\mathrm{c.m.}} < 3$ MeV) are extremely challenging.

The $^{12}C+^{12}C$ fusion cross section can be measured in the laboratory by impinging a beam of ^{12}C ions onto a carbon target. The two ^{12}C nuclei fuse to form a highly excited nucleus of ^{24}Mg, which then decays primarily by emitting protons or α particles. The resulting evaporation residue is often left in an excited state, which then decays to the ground state via γ emission. This is schematically depicted in Fig. 1. There are numerous $^{12}C+^{12}C$ fusion cross section measurements and in general they agree for $E_{\mathrm{c.m.}} > 3$ MeV, with few exceptions. However, there are very large discrepancies between the different experimental results of Refs. [2–9] in the low-energy region that can be attributed to the difficulties of measuring low cross sections in combination with various known and yet-unknown backgrounds. In the

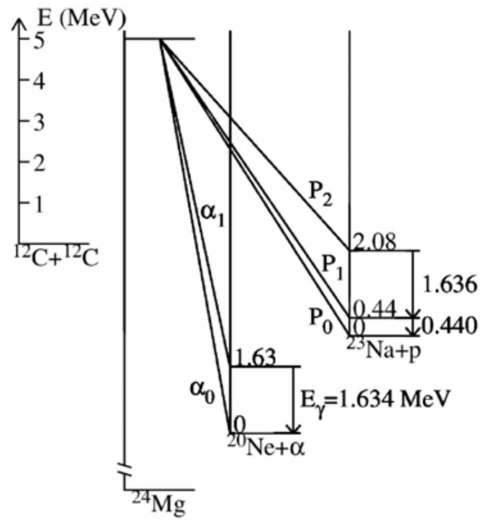

Figure 1: Most favorable decay channels of ^{24}Mg following the fusion of ^{12}C+^{12}C at low center-of-mass energies.

experiments mentioned above, only a single signal from the decay cascade is measured. Although serious attempts were made to reduce the backgrounds, such as those arising from hydrogen and deuterium contaminants in the target, the background is not completely eliminated, especially at the lowest energies.

In order to circumvent these experimental difficulties we have developed a coincidence technique that effectively suppresses the background in ^{12}C+^{12}C fusion measurements [10]. For this, we utilize thin carbon targets (thickness $\sim$ 50 μg/cm^2) and a compact array of silicon detectors placed at the center of Gammasphere, which is an array of over 100 high-purity germanium detectors. Figure 2 shows a hemisphere of Gammasphere with the charged-particle detector chamber located at the center. A schematic picture of the array of silicon detectors inside the detector chamber is presented in Fig. 3. By detecting γ rays and charged particles from the decays of excited ^{24}Mg states in coincidence, the background has been substantially reduced. Furthermore, any measured event from ^{12}C+^{12}C fusion identified by energy signals from a charged particle and from a γ ray can be clearly separated from the background events. Thus, a cross section measurement of the ^{12}C+^{12}C fusion reaction of interest is possible, even with low statistics, as a result of such well-characterized events.

A series of experiments have been performed since 2010 [11] at Ar-

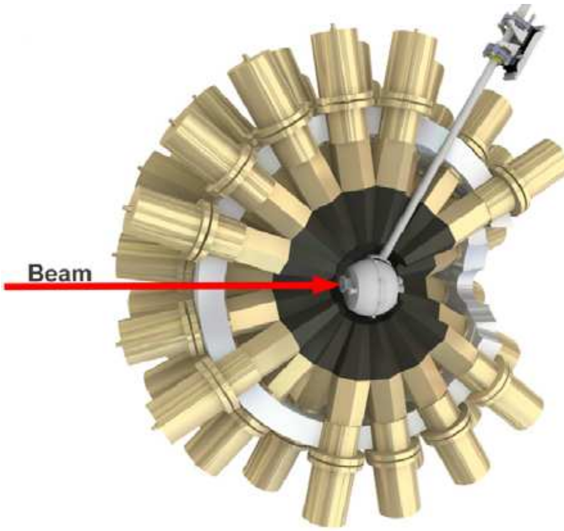

Figure 2: Hemisphere of Gammasphere with the chamber for Si detectors and (thin) targets located at the center.

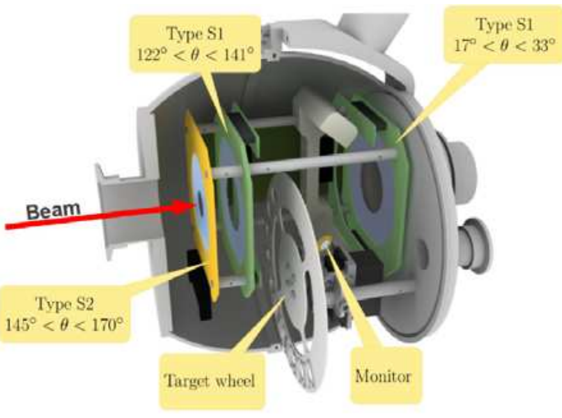

Figure 3: Target and Si detector chamber cut away showing the experimental setup. For the Si detectors, the labels show the angles covered in the laboratory reference frame. The detector labeled "Monitor" and a Faraday cup (not shown) located downstream of the chamber were used for normalization.

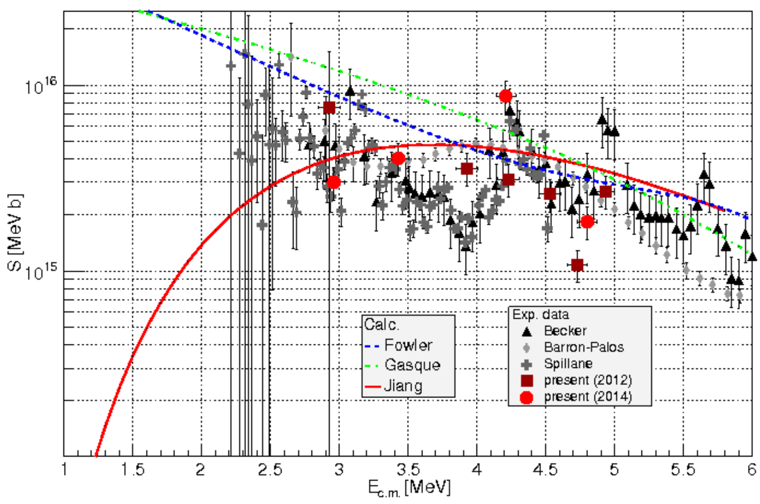

Figure 4: S-factor for the $^{12}C+^{12}C$ fusion reaction as a function of center-of-mass energy.

gonne National Laboratory (ANL) using the coincidence technique described above. Background-free measurements of the fusion cross section of $^{12}C+^{12}C$ were successfully carried out with the γ and charged-particle coincidence technique in the center-of-mass energy range of 3-5 MeV. In order to compensate for the strong Coulomb effect we present the extracted S factor ($S(E) = \sigma E e^{2\pi\eta}$) in Fig. 4 instead of the cross section. Two of our data sets are presented, one from the most recent experiment in 2014 and another one from an experiment performed in 2012 [12]. The lowest energy point in the 2012 data set was obtained from one count only and is therefore only an upper limit. Data points from Refs. [5, 6, 8] are presented as well. In general, our results are consistent with previous measurements in the high-energy region, especially our latest results from 2014 (evidence that the coincidence technique has matured from its earlier implementations). However, our lowest energy measurement from 2014 indicates a fusion cross section slightly lower than those obtained with other techniques. The calculations with the barrier penetration model [13, 14] and empirical extrapolations with fusion hindrance [15] result in opposite trends with decreasing energy. New measurements at lower energies will be carried out at ANL in the near future. The new data may help to discern between the extrapolations shown in Fig. 4. The ramifications of using the fusion hindrance extrapolation method on simulations of the late stages of giant star evolution are substantial [16] and, in the astrophysical community, there is a keen interest to settle this question on the basis of solid experimental data.

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