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Experimental investigation of the ^{12}C+^{12}C fusion at very low energies by direct and indirect methods

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Abstract. The ^{12}C+^{12}C fusion reaction plays a crucial role during stellar evolution. The astrophysically important energy range spans from 1 MeV to 3 MeV. However, its cross section has not been determined with enough precision, despite numerous studies, due to the extremely low reaction cross sections and the large experimental background. To allow measurements of the ^{12}C+^{12}C fusion at astrophysical energies, we developed an efficient thick-target method using large-area silicon strip detectors. Further measurements at even lower energies will be performed using coincidences between a silicon-detector and a Ge-detector array, at the high-current accelerator under construction at the University of Notre Dame. Since the coincidence method does not allow obtaining information about the channels without gamma-ray emission, a solenoid spectrometer has been constructed for complementary measurements. Meanwhile, we are also investigating the ^{24}Mg(α, α') reaction using the Grand Raiden Spectrometer at RCNP to search for potential resonances in the ^{12}C+^{12}C fusion reaction. Preliminary results from these measurements will be presented.

1. Introduction

The ^{12}C+^{12}C fusion reaction is a reaction critical for various astrophysical scenarios, e.g. in the interior of massive stars, type Ia supernovae, and X-ray superbursts [1, 2]. Carbon burning in the core of stars occurs at temperatures of T = 0.6-1.0 GK, depending on the mass of the star [3], corresponding to center of mass energies between 1.0 and 3.5 MeV [1]. The primary reaction channels are ^{12}C(^{12}C, p)^{23}Na (Q = 2.24 MeV), ^{12}C(^{12}C,α)^{20}Ne (Q = 4.62 MeV) and ^{12}C(^{12}C, n)^{23}Mg (Q = -2.60 MeV), as shown in Fig. 1. The stellar reaction rates of carbon burning governs the abundances of C, Ne, Na, Mg and other elements in the universe, The also determine the evolutionary paths of medium to massive stars. The production yields of ^{26}Al and ^{60}Fe in supernovae, two important radioactive tracers, are sensitive to the carbon fusion rate [4-6]. The carbon fusion reaction is also considered to be responsible for igniting the explosions in type Ia supernovae and superbursts [2].

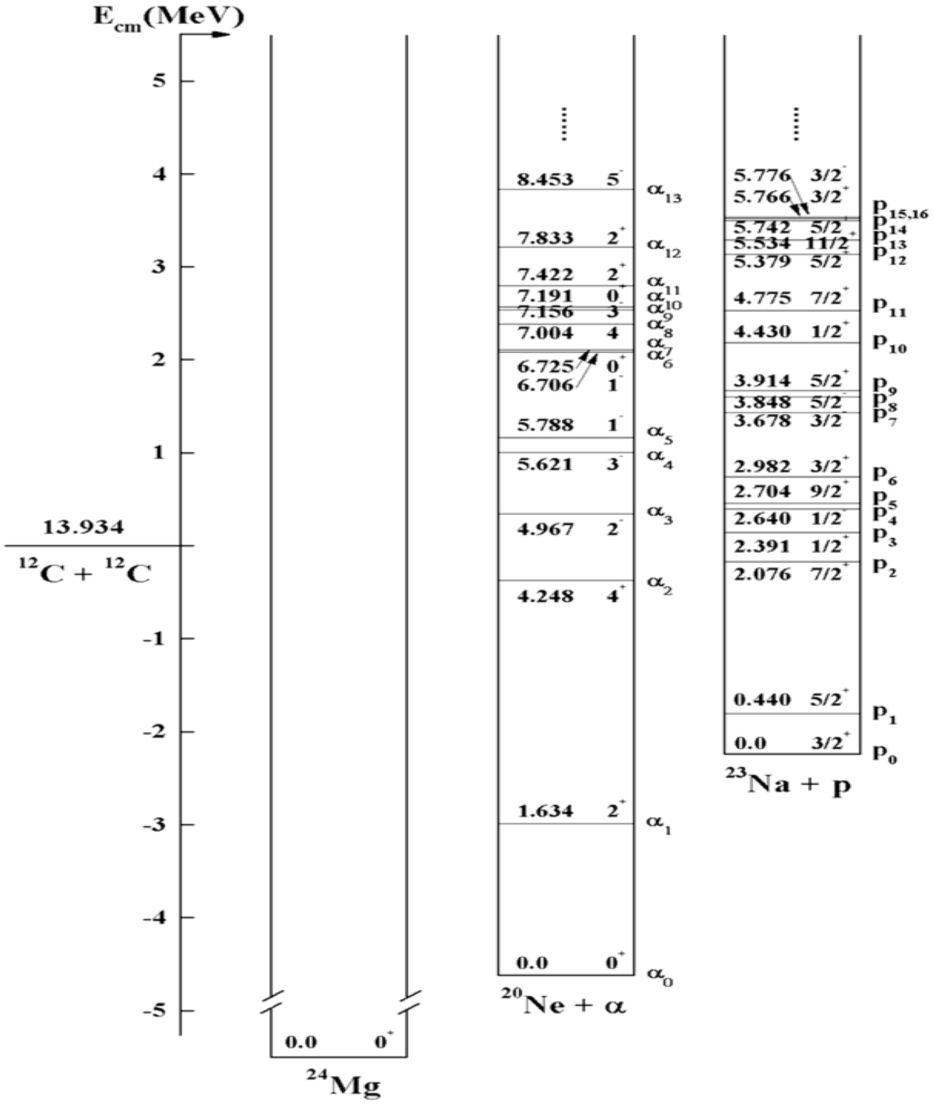


Fig 1. The primary reactions of carbon burning.

Besides its importance in astrophysical investigations, the resonances in the ^{12}C+^{12}C excitation function are also of interest in studies of reaction mechanisms and the nuclear structure. The cross section below the Coulomb barrier had been assumed to be dominated by the penetration through the Coulomb barrier, smoothly varying and exponentially decreasing with energy. However, in 1960 several sub-Coulomb resonances were discovered in elastic scattering and fusion of ^{12}C+^{12}C that provided the first evidence for the existence of nuclear molecules. For at least three energies, $E_{c.m.}$=5.68, 6.00 and 6.32 MeV, strong resonances were observed in the yield of collisional byproducts i.e. protons, gammas, alpha particles and neutrons. These resonances had widths of about 100 keV corresponding to a lifetime of 5×10^{-21} s, about a factor of 10 longer than the typical time duration of a simple collision [7].

Measurements of the $^{12}C+^{12}C$ fusion reaction at astrophysical energies are extremely challenging because of the small cross sections, varying from 10^{-20} to 10^{-7} barns. The pronounced resonance structure continues down to the lowest energies where measurements have been performed [8-13]. In order to express this strong energy dependence of the cross section in the sub-Coulomb barrier region, the currently adopted reaction rate is established based on the modified S factor $S^*(E)$ [8], defined as

$$S^*(E) = \sigma(E)E\exp\left[87.21\left(\frac{E}{MeV}\right)^{-1/2} + 0.46\left(\frac{E}{MeV}\right)\right] \qquad (1.1)$$

An averaged S^* factor of 3×10^{16} MeV b [9] was obtained by fitting the data measured by Patterson [8], Spinka [10] and Becker [11] (Fig. 2). This averaged value was extrapolated at low energies by assuming that the averaged S^* factor remains constant at sub-Coulomb energies [14, 15]. At present, nothing is known about energies and strengths of resonances in the energy region below $E_{c.m.} = 2$ MeV.

The most recently published measurement of the $^{12}C+^{12}C$ fusion reported an unusual resonance at $E_{c.m.}$=2.14 MeV [12] (Fig. 2), stronger than any resonance discovered at higher energies. The averaged S* factor is not appropriate for describing such a strong resonance. Motivated by this strong resonance, a hypothetical resonance was proposed at $E_{c.m.}$=1.5 MeV with a similar strength. This resonance increased artificially the carbon fusion reaction rate in the crust of neutron stars and, therefore, reduced the discrepancy between the theoretical prediction by their superburst model and the observationally inferred ignition condition [16]. However, the existence of such a strong resonance was challenged by an upper limit established by comparing the $^{12}C+^{12}C$, $^{12}C+^{13}C$, and $^{13}C+^{13}C$ fusion cross sections [17]. A measurement of $^{12}C(^{12}C, p_{0,1})$ at Naples has ruled out the existence of such a strong resonance in the proton channel [13]. Measurements of the alpha channel at low energies are urgently needed to verify the existence of such a strong resonance.

In addition to the uncertainty arising from the complicated resonant structure, a recent study of fusion hindrance has suggested a new extrapolation that is significantly smaller than the adopted one [14] (Fig. 2). Therefore, our understanding of the $^{12}C+^{12}C$ fusion rate is very uncertain.

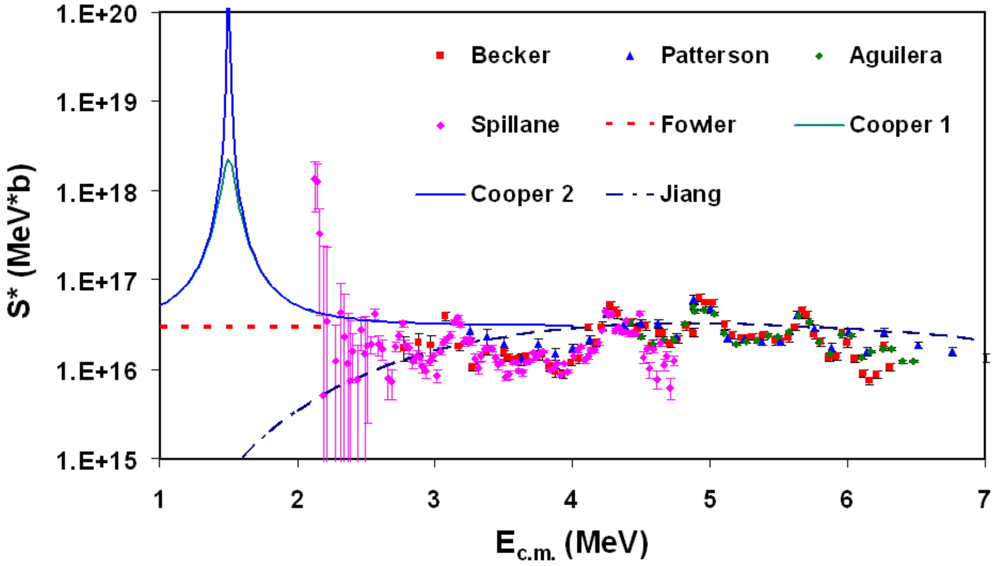


Fig 2. Comparison of the experimental data used to determine the total S* factor with various theoretical calculations. Resonance structures exist over the full energy range. The uncertainty of the experimental result increases progressively at energies below 2.7 MeV. The currently adopted S* factor (dotted red line) is based on the averaged value by fitting the data from Refs. [8, 10, 11]. The indication of a strong resonance at

2.14 MeV is questionable and needs to be verified [17]. The hypothetical resonance at $E_{c.m.}$=1.5 MeV is shown with two different strengths proposed in Ref. [16]. The extrapolation based on the hindrance model (Jiang) [18] is much smaller than the shown S* factors.

2. Previous experimental studies

In this section, we discuss the methods most commonly used to measure cross sections of the ^{12}C+^{12}C fusion reaction in the sub-Coulomb energy region. For most purposes, such as determination of the energy production rate in stars or the general path of nucleosynthesis, the total fusion cross section is needed. In previous measurements, several techniques have been used to determine the cross section (i) detection of γ rays emitted by fusion residues, (ii) detection of emitted light particles, (iii) detection of fusion residues, and (iv) detection of residual radioactivity [19]. Each of these methods has its advantages and disadvantages.

A typical γ-ray experiment usually involves a few small-volume Ge detectors or NaI detectors. The main advantage of a Ge detector is its excellent energy resolution. Since particle decays from the compound nucleus directly to the ground state of the final nucleus is not detected by the γ-ray method, the γ-ray yield from the low-lying states is not a direct measurement of the total fusion cross section. To obtain the total fusion cross section, information from statistical model calculations is required to provide the summing and branching corrections. When the measured energy approaches the Gamow window between 1 to 3 MeV, this approach suffers from cosmic ray or beam induced background and background from reactions with target contaminants. Using this approach, Spillane [12] performed measurements at energies as low as 2.1 MeV. However, as shown in Fig. 2, the measured S* factors have large error bars. The strong resonance reported at 2.14 MeV is highly questionable [17].

In light charged-particle detection experiments a series of Si detectors placed at various angles is employed. By measuring the energies of these particles, the reaction channels of different states (including the ground state) can be identified. The total fusion cross section is determined by fitting the differential cross section and then integrating over the solid angle. These particle reaction measurements at low energies suffer from similar problems as the γ-ray experiments. For example, a recent preliminary result from Naples indicated the possible existence of a resonance at $E_{c.m.}$=1.5 MeV that would have enhanced the reaction rate at T_9=0.5 by a factor of 5×10^4. However, a later experiment proved that the observed ‘resonance’ at 1.5 MeV was the result of deuterium contamination in their target [13]. Using a HOPG (highly-ordered pyrolytic graphite) target, their most recent preliminary data stop at energies around 2.1 MeV with a proton yield of 10^{-16} per incident ^{12}C. Measurements at lower energies can only be continued with a higher beam current and better detection systems with high efficiency and high selectivity.

The ^{12}C(^{12}C, n) reaction is a weak branching in the ^{12}C+^{12}C fusion reaction [3], but it is considered as a potential neutron source for the weak s-process in massive stars. There is an ongoing project in our group targeting this reaction at energies just above the neutron threshold at $E_{c.m.}$=2.6 MeV [20].

3. New techniques and preliminary results

Our work concentrates mainly on determining the total cross section of ^{12}C+^{12}C by developing two highly-efficient and selective charged-particle detection systems, one based on a Si detector array and the other on a solenoid spectrometer, to study the ^{12}C(^{12}C, p)^{23}Na and ^{12}C(^{12}C, α)^{20}Ne reactions. By coupling the silicon-detector array with the highly efficient Ge-detector array, GEORGINA (GE detector Online array for Gamma ray spectroscopy in Nuclear Astrophysics) [21], and a new high-current heavy-ion accelerator, we will be able to extend the heavy-ion fusion measurements to stellar burning energies. The expected new data will be extremely valuable for testing and developing advanced extrapolating models at deep sub-Coulomb energies.

3.1. Efficient thick target method

Thin carbon foils with thicknesses of the order of tens of μg/cm^2 have been previously used to measure the resonant structure in the ^{12}C+^{12}C fusion reaction. However, measurements suffer from carbon build up that leads to an increase of the target thickness. Besides, thin targets are easily damaged by the intense ^{12}C beam (> 10 pμA), which is required for measurements far below the Coulomb barrier. To solve these problems, a differential thick target method was proposed [17, 20]. In this technique, an approximately 1mm thick target is used to measure the thick-target yield Y. The cross section is then obtained by calculating the derivative (dY/dE) where E is the energy. Fine energy steps (e.g. ~50 keV in center-of-mass frame) are used. Since the thick-target yield only changes slightly with a small energy step, a large number of counts are required for each thick yield to determine reliable cross sections.

The Q-value of the reaction A(a, b)B is given by

$$Q=\left(\frac{M_a}{M_B}-1\right)E_a+\left(\frac{M_b}{M_B}+1\right)E_b-2\frac{\sqrt{M_aM_bE_aE_b}}{M_B}\cos(\theta) \quad (2.1)$$

where, M_a, M_b and M_B are the masses of the particles a, b and B, respectively. E_a is the energy of the beam particle a and E_b is the energy of the outgoing particle b. E_0 is the incoming beam energy and θ the scattering angle. In a thick target, the beam particles collide with the target nuclei and continuously lose energy until they either react with a target nucleus or stop within a few μm inside the target. Light particles produced by ^{12}C+^{12}C fusion, like protons and alpha particles, can easily penetrate the target, but suffer small energy losses at backward angles. If a reaction channel could be clearly identified in the E_b vs. θ spectrum, we can determine the Q-value for this channel and reconstruct the real reaction energy E_a by solving Eq. 2.1 with the measured E_b and θ for the outgoing proton or alpha particle. The thick-target method has been intensively used to study the resonance structures of exotic nuclei using elastic or inelastic reactions. In the present article, we report the first application of this method for the ^{12}C+^{12}C fusion.

We have performed several experiments with YY1-type silicon detectors to measure the proton channels of ^{12}C +^{12}C fusion in the center of mass energy range from 5.3 MeV down to 2.8 MeV using the FN Tandem accelerator at the University of Notre Dame. In the experiment, a 1 mm thick graphite target was used. With the information from the measured protons, we succeeded in mapping the resonance structure over a wide excitation energy range (~500 keV in the center-of-mass frame) as a function of the incident beam energy. Preliminary results are shown in Fig. 3.

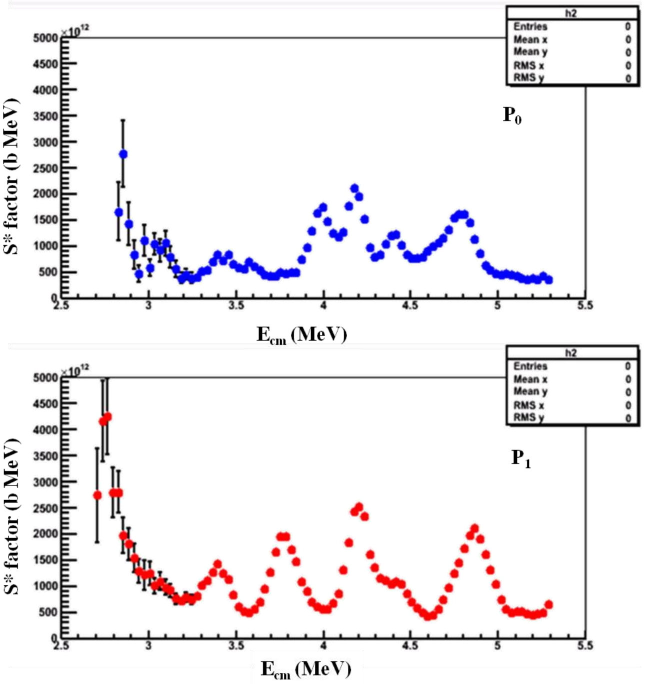


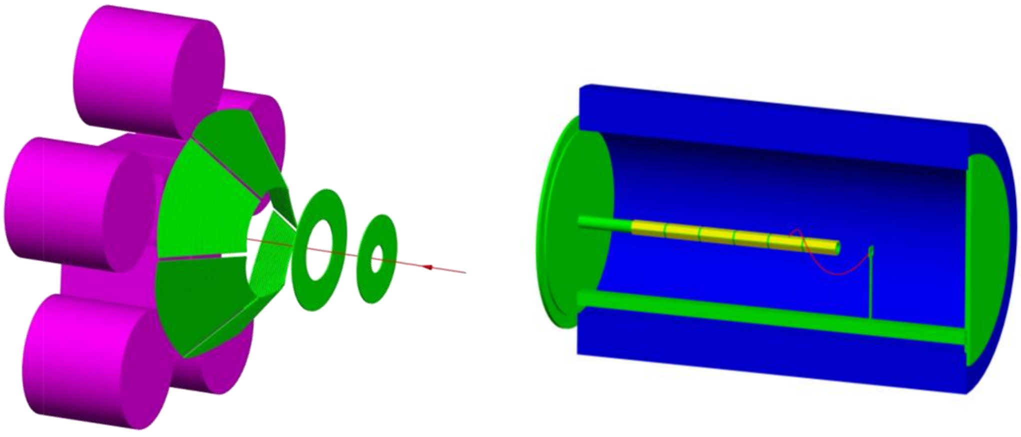
Fig 3. Preliminary S* factor for p_0 (top) and p_1 (bottom) channels obtained using the thick-target method measurement. The resonances are well mapped. Due to the beam-induced background, the S* factors rise quickly at $E_{c.m.}$< 3MeV.

3.2. Particle and gamma coincidence method

Obviously, background reduction is essential for measurements at lower energies. To improve the selectivity of the detection system, we propose to measure both charged particles and the cascading γ-rays in coincidence. This suppresses the background considerably. However, because of the low coincident rates this method can only be performed with highly efficient charged particle and γ-ray detector arrays.

The particle-gamma coincidence technique has been successfully tested at Argonne National Laboratory at E_{cm} = 4.0, 4.5 and 5.0 MeV using Gamma-sphere and a single large-area silicon detector [22]. To perform the experiment at lower energies with the high-current accelerator at Notre Dame, we are building a new silicon array, SAND (Silicon Array at Notre Dame), with an ASIC readout system [23]. The SAND detector system consists of six YY1-type silicon detectors and 2 CD-type silicon detectors. The setup is shown in Fig. 4(a). The silicon detectors will be placed at backward angles covering 100° – 170°. A compact highly-efficient germanium detector array (GEORGINA) will cover the forward 2π solid angle to detect the cascading γ-rays. With the position and energy information from these Si-detectors, the protons and alphas from various reaction channels will be identified. The cosmic, room and beam-induced backgrounds can be greatly suppressed by the coincidence between these two detector arrays. The Doppler broadening of γ-rays can be improved by using the angular information of the detected charged particles.

The major drawback of the particle-gamma coincidence measurement is that those channels are missing that do not emit γ-rays, such as p_0 and α_0. As the center of mass energy decreases, the number of open channels becomes smaller, while the p_0 and α_0 channels become more important. So a complimentary approach is necessary to obtain information for those missing channels.



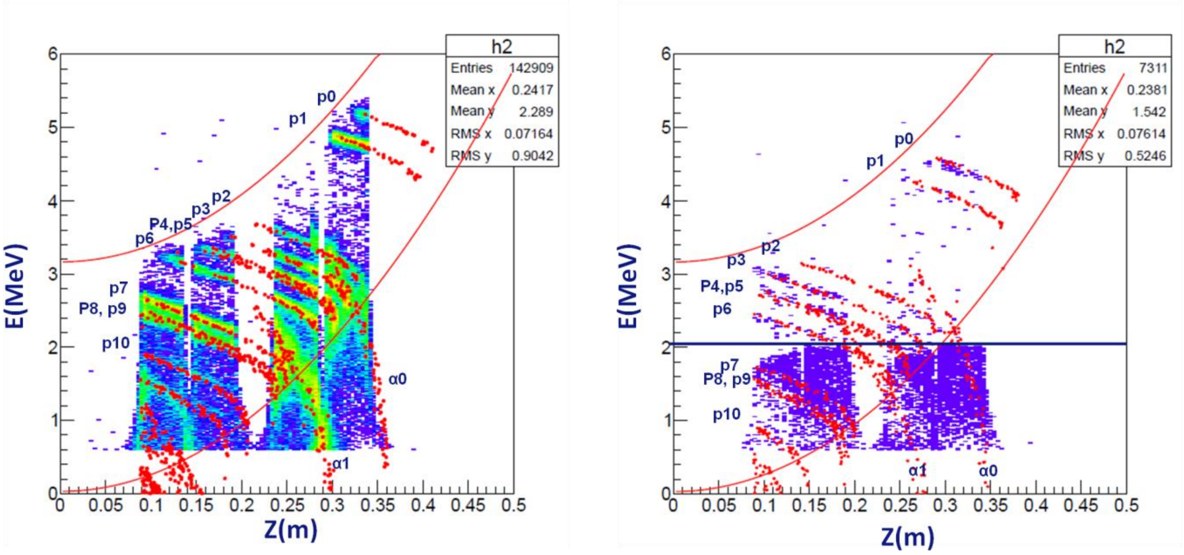
(a) (b)

Figure 4. (a) Schematic setup of the SAND charged particle array (green) in coincidence with the GEORGINA gamma array (magenta); (b) The proposed solenoid spectrometer at Notre Dame. The beam travels from left to right through the hollow tube along the axis of the solenoid and hits the target. A reaction product (red spiral) is emitted at a backward angle and bents back onto the axis after one cyclotron period. The position-sensitive Silicon detector array (yellow) with a length of 31 cm and a radius of 1.2 cm located around the axis, records energy, the distance between target and particle detection position and the TOF with respect to beam pulses. The distance from the target to the front edge of the detector array is 5 cm. The diameter of the vacuum chamber is 28 cm.

3.3. Solenoid Spectrometer for Nuclear Astrophysics (SSNAP)

The solenoid spectrometer project is a complementary approach for the study of the $^{12}C+^{12}C$ fusion reaction. It is based on the concept that charged particles undergo helical motion in a uniform magnetic field that is produced by a superconducting solenoid. Since the target and detectors are both placed along the solenoid axis in the field, the reaction products emitted from the target move along helical orbits and are bent back onto the axis where the silicon detectors are mounted. A schematic drawing of the proposed spectrometer is shown in Fig. 4(b). With the energy and target-to-detector distance information, it is possible to reconstruct the emitted angles and the excitation energies of the reaction products. Compared to the traditional silicon detectors, the solenoid spectrometer could provide much better energy resolution for the excited states (as good as 75 keV) and a large solid angle close to 4π, resulting in high-detection efficiency and excellent particle identification.

The first solenoid spectrometer HELIOS was built at ANL and demonstrated powerful abilities of investigating reactions in inverse kinematics [24]. We are building a similar spectrometer using the existing Twin-Solenoid at Notre Dame [25] to study the $^{12}C+^{12}C$ fusion reaction. A proof-of-principle measurement has been performed recently at energies $E_{c.m.} = 4.0$, 5.0 and 6.0 MeV, providing spectra of proton and alpha particles from the $^{12}C+^{12}C$ fusion reaction. Preliminary results are shown in Fig 5. In the test, only two 1×5 cm^2 position sensitive detectors were used. As the next step, we are working on the beam collimation system with the goal of getting a clean observation of particles in the α_0 channel, in the near future. Meanwhile, it is necessary to find funding to build a complete silicon array so that the measurement can be efficiently carried out at lower energies.



(a) (b)

Figure 5. (a) Comparison of the measurement at $E_{c.m.}$= 5 MeV with simulation (red dots) using GEANT4. The two red curves indicate the acceptance of the detectors for protons and alphas. The field was 3.96 Tesla. A 5.8 μm thick aluminium degrader was used in the front of the detectors to remove scattered ^{12}C particles. (b) Spectrum taken at $E_{c.m.}$= 4 MeV, where the cross section is a factor of 0.01 smaller. The setting of the spectrometer is identical to that of (a). Intense background events are observed below 2 MeV.

3.4. Determination of the total fusion cross section

Because of the complication of the decay schemes of the fusion residues and the various experimental backgrounds, it is difficult to determine the total fusion cross section from the observable decay channels. For example, in the past, gamma ray measurements were only focused on the cross sections of two characteristic lines: 440 keV for ^{23}Na and 1634 keV for ^{20}Ne. The charged particle measurements were limited to the channels above a huge background incurred by H/D contaminants in the targets. Furthermore, in most analyses of past experiments, the total $^{12}C+^{12}C$ fusion cross sections were obtained by a simple summation of the observed decay channels. Using a statistical model, we have estimated the contribution from those unobserved channels. The theoretical result was compared with the predicted cross section based on the partial cross sections measured by Becker et al. [11]. Our result shows that the total cross sections for the proton (σ_{ptot}) and alpha ($\sigma_{\alpha tot}$) channels in the range of 1 to 3 MeV can be determined by combining the information from both particle detection and gamma-ray detections using the following equations,

$$\sigma_{ptot} = \sigma_{p0} + \sigma_{p(440)} + \sigma_{p(2391)} + \sigma_{p(2640)} + \sigma_{p(2982)} \tag{3.1}$$

$$\sigma_{\alpha tot} = \sigma_{\alpha 0} + \sigma_{\alpha(1634)} \tag{3.2}$$

In these equations, σ_{p0} and $\sigma_{\alpha 0}$ are the cross sections for the decay channels to the ground states of ^{23}Na and ^{20}Ne respectively. $\sigma_{p(E\gamma)}$ and $\sigma_{\alpha(E\gamma)}$ are the cross sections for the gamma transitions in ^{23}Na and ^{20}Ne respectively, with the gamma ray energy Eγ (in keV) included in parentheses. The fraction of the missing decay channels is well below 4% at astrophysical energies [26].

3.5. The $^{24}Mg(\alpha, \alpha')$ study at RCNP

Using the molecular symmetry model, Erb and Bromley [27] predicted at least three $0^+/2^+$ resonances within the unmeasured energy range from 0 to 2.1 MeV. However, direct measurements of $^{12}C+^{12}C$ reaction at low energies with current experimental conditions are hardly suitable to verify their existence. We are studying the $^{24}Mg(\alpha, \alpha')$ reaction to establish indirectly reliable correlations between the ^{24}Mg states and the measured $^{12}C+^{12}C$ resonances. According to an AMD model calculation [28], the ground state of ^{24}Mg has two configurations: $^{16}O+ {}^{8}Be$ and $^{12}C+^{12}C$ [29]. If this is true, it should be possible to strongly populate the molecular resonant states in $^{12}C+^{12}C$ using the $^{24}Mg(\alpha, \alpha')^{24}Mg^*$ reaction via isoscalar excitations. We measured this reaction at the Research Center for Nuclear Physics, Osaka University, using a 206-MeV alpha beam. After a careful energy calibration, we observed correlations in energy between the populated ^{24}Mg states and the $^{12}C+^{12}C$ resonances, however, additional information, such as J^{π} and decay properties, are still needed to reach convincing conclusions.

4. Summary

The goal of our research is the development of a highly efficient detection system mainly for, but not limited to, the study of the carbon fusion reaction, to obtain better experimental measurements of carbon fusion at deep sub-Coulomb energies, and to estimate the potential resonances within the Gamow window.

According to the results presented in Ref. [22], the particle-gamma coincidence method would be able to provide reliable results below 3 MeV, with acceptable background levels. Meanwhile, measurements with the solenoid spectrometer, as a complementary project, have great potential to study $^{12}C+^{12}C$ fusion at very low energies. Besides the direct measurements, the relevant states in ^{24}Mg are also being studied using the $^{24}Mg(\alpha,\alpha')$ reaction. By combining all the information, we expect to be able to verify the existence of the strong resonance at 2.14 MeV and provide a more reliable reaction rate for carbon fusion.

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