Measurement of the $^{12}\mathrm{C}(^{12}\mathrm{C}, p_{0,1})^{23}\mathrm{Na}$ reaction cross section in the sub-barrier energy region using the thick-target scanning method

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Abstract

The 12C + 12C fusion reaction has attracted significant attention in the sub-barrier energy region due to its complex molecular resonance structures, holding great importance in both nuclear structure research and nuclear astrophysics. Due to the extremely low reaction yields at astrophysically relevant energies, direct measurement of the cross-section for this reaction is exceptionally difficult. To accurately characterize the complex resonance structures present in this reaction, this work applies an efficient thick-target scanning method. This method enables a continuous scan of the reaction cross-section over a width of up to several hundred keV in a single run using only a single initial beam energy. Utilizing this technique, this work successfully extracted the astrophysical S*-factors for the p0 and p1 exit channels of the 12C(12C, p)23Na reaction within the center-of-mass energy range of Ecm = 3.0 -5.3 MeV. The results demonstrate that the thick-target scanning method is an efficient and reliable tool for searching for potential molecular resonance structures in the extremely low-energy region, providing valuable experimental constraints for understanding the stellar carbon burning process.

Full Text

Preamble

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Measurement of the $^{12}\mathrm{C}(^{12}\mathrm{C}, p_{0,1})^{23}\mathrm{Na}$ Reaction Cross Section in the Sub-barrier Energy Region Using the Thick-Target Scanning Method

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Abstract

The $^{12}\mathrm{C}+^{12}\mathrm{C}$ fusion reaction has attracted significant attention in the sub-barrier energy region due to its complex molecular resonance structures, which hold profound importance for both nuclear structure research and nuclear astrophysics. Because the reaction yield is extremely low at astrophysically relevant energies, direct measurement of the cross-section is exceptionally challenging. To accurately characterize the complex resonance structures present in this reaction, this work employs an efficient thick-target scanning method. This approach enables a continuous scan of the reaction cross-section over a width of up to several hundred keV using only a single initial beam energy. Utilizing this technique, we successfully extracted the astrophysical S^* factors for the p_0 and p_1 exit channels of the $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$ reaction within the center-of-mass energy range of $E_{\mathrm{cm}} = 3.0 \sim 5.3$ MeV. The results demonstrate that the thick-target scanning method is an efficient and reliable tool for searching for potential molecular resonance structures in the extremely low-energy region, providing valuable experimental constraints for understanding the stellar carbon burning process.

Keywords: $^{12}\mathrm{C}+^{12}\mathrm{C}$; Thick-target scanning method; $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$; Astrophysical S^* factor

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1 Introduction

The $^{12}\mathrm{C}+^{12}\mathrm{C}$ fusion reaction is one of the most critical processes in stellar nucleosynthesis. It serves as the primary trigger for carbon burning in stars with masses greater than eight times that of the Sun. The rate of this reaction determines the subsequent evolutionary path of the star, influencing the production of heavier elements and the conditions leading to Type Ia supernovae. At the low energies relevant to stellar environments (the Gamow window), the cross-section of the $^{12}\mathrm{C}+^{12}\mathrm{C}$ reaction is extremely small due to the Coulomb barrier, making direct laboratory measurements exceptionally challenging.

In this work, we utilize the thick-target scanning method to investigate the $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$ reaction. This approach allows for a continuous measurement of the excitation function over a range of energies as the beam slows down within the target material. By measuring the proton yield from the decay of the compound nucleus, we can derive the cross-section and the corresponding S^* factor.

[Figure 1: see original paper]

The core proposition of evolutionary destiny in stellar physics lies in the nuclear reactions that govern stellar life cycles. Among the numerous nuclear reactions that dominate stellar evolution, carbon-carbon fusion ($^{12}\mathrm{C} + ^{12}\mathrm{C}$) holds an irreplaceable and critical position [?]. For stars with an initial mass between 8 and 10 solar masses ($M_\odot$), core carbon burning represents the final nuclear fusion stage of their life cycle. The remnants left behind after this stage will eventually evolve into oxygen/neon (O/Ne) white dwarfs. In contrast, for massive stars with masses exceeding 10 $M_\odot$, carbon burning serves as a critical precursor to the subsequent fusion stages of neon, oxygen, and silicon.

Furthermore, in binary systems containing accreting white dwarfs, the runaway ignition of carbon in deep, carbon-rich regions is widely recognized as the direct mechanism triggering Type Ia supernova explosions. As "standard candles" for measuring cosmological distances, Type Ia supernovae serve as a cornerstone for the discovery of dark energy and the theory of the accelerated expansion of the universe [?]. Similarly, within the extremely high-density accretion ash layers on the surfaces of neutron stars, carbon flashes drive X-ray superbursts [?]. In these typical high-temperature, high-density astrophysical plasma environments, the effective temperature range for carbon burning spans approximately 0.6 to 1.2 GK, which thermodynamically corresponds to a center-of-mass energy of approximately 1.0 to 3.0 MeV (the Gamow window) [?].

Within this sub-barrier energy region, positively charged carbon nuclei experience intense repulsion from a Coulomb barrier as high as approximately 6.6 MeV. According to the quantum tunneling effect, the probability of charged particles penetrating this barrier decays exponentially as energy decreases. Consequently, the theoretical reaction cross-section for $^{12}\mathrm{C} + 12\mathrm{C}$ within the Gamow window is extremely low, plummeting from 10^{-7} barns to an almost undetectable 10^{-21} barns.

The complexity is further compounded by the symmetry requirements of the entrance channel. Unlike non-identical nuclear systems, the $^{12}\mathrm{C} + 12\mathrm{C}$ system is strictly constrained by identical boson symmetry. Only states with even spin and positive parity ($J^\pi = 0^+, 2^+, 4^+, ...$) can participate. This prevents the statistical smoothing of broad molecular resonances, leading instead to regions where multiple closely spaced narrow resonances overlap and exhibit strong quantum interference [?]. These resonance peaks can cause the reaction cross-section to enhance by several orders of magnitude at specific energy points, thereby exerting a profound influence on global reaction rates in astrophysical network calculations [?].

For over half a century, nuclear physicists have made significant efforts to extend cross-section measurements into the extremely low-energy regions relevant to astrophysics [?]. However, direct measurements remain exceptionally challenging due to extremely low reaction yields and interference from backgrounds such as target impurities and cosmic rays [?]. Owing to these experimental limitations, direct measurements have mostly been conducted at $E_{\mathrm{cm}} > 2$ MeV. Furthermore, data in the lower energy regions carry large uncertainties, and results provided by different studies often show significant discrepancies.

Significant discrepancies exist among the cross-section values obtained from different measurements. At lower energy regions, current measurements rely primarily on indirect methods, most notably the Trojan Horse Method [?] and inverse kinematics [?]. However, results from various experimental groups still exhibit substantial divergence, underscoring the necessity of direct measurements. Future direct measurements are now transitioning to deep underground laboratories, such as LUNA in Italy [?] and JUNA in China [?].

Traditional thin-target techniques are limited by uncertainties in target thickness caused by carbon deposition and target surface damage under high-intensity beams. In contrast, the conventional thick-target differential method requires an extremely high expenditure of accelerator beam time. To address these issues, an efficient thick-target scanning method based on kinematic reconstruction has been developed [?]. This method allows for the continuous scanning of reaction cross-sections over a wide energy range while maintaining a single, constant incident beam energy. This paper focuses on presenting the continuous scanning results for the p_0 and p_1 channels of the $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$ reaction in the sub-barrier energy region.

2 Principles and Experimental Setup

2.1 Principles of the Thick-Target Scanning Method

At energies below the Coulomb barrier, the $^{12}\mathrm{C} +^{12} \mathrm{C}$ reaction forms a highly excited compound nucleus, $^{24}\mathrm{Mg}^{*}$, which subsequently decays into three primary reaction channels: 1. $^{12}\mathrm{C} +^{12} \mathrm{C} \rightarrow^{20} \mathrm{Ne} + \alpha + 4.62$ MeV 2. $^{12}\mathrm{C} +^{12} \mathrm{C} \rightarrow^{23} \mathrm{Na} + p + 2.24$ MeV 3. $^{12}\mathrm{C} +^{12} \mathrm{C} \rightarrow^{23} \mathrm{Mg} + n - 2.60$ MeV

The emitted protons are denoted as p_i, corresponding to the i-th excited state of the residual nucleus ^{23}Na. By precisely measuring the kinematic parameters of the reaction products, it is possible to continuously extract the reaction cross-sections over a wide energy range using a single-energy beam. When a ^{12}C beam with initial energy E_{beam} enters a thick carbon target, the beam particles undergo continuous energy loss. Protons produced in the reaction escape the target and strike a silicon detector, which records the proton energy E_p and the emission angle θ. According to the Q-value formula:

$$Q = E_p \left(1 + \frac{M_p}{M_{^{23}\mathrm{Na}}}\right) - E' \left(1 - \frac{M_{^{12}\mathrm{C}}}{M_{^{23}\mathrm{Na}}}\right) - 2\frac{\sqrt{M_{^{12}\mathrm{C}} M_p E' E_p}}{M_{^{23}\mathrm{Na}}} \cos\theta$$

By substituting the known Q-values ($Q_0 = 2.24$ MeV; $Q_1 = 1.80$ MeV), the beam energy E' at the moment the reaction occurs can be accurately determined.

[Figure 3: see original paper]

Figure 3 displays a typical proton Q-value energy spectrum. The p_0, p_1, and p_2 emission channels are clearly resolved. The highest point of each channel peak corresponds to the beam energy at the front of the target. As the beam penetrates deeper, the incident energy gradually decreases due to ionizing collisions. This local protrusion in the spectrum precisely corresponds to a strong nuclear molecular resonance structure.

2.2 Experimental Setup

The measurements were conducted at the University of Notre Dame using the 10 MV FN tandem accelerator, providing ^{12}C beams (0.5 to 1 μA) bombarding a 1 mm thick natural graphite target. Two 500 μm thick Micron-YY1 silicon strip detectors were positioned at backward angles (113.5° to 163.5°). To block α particles, a 12.7 μm thick aluminum foil was placed in front of each detector. The total solid angle subtended by the silicon detectors is 2.59% of 4π.

3 Data Analysis

Experimental measurements were performed across a beam energy range of $E_{\text{beam}} = 6.0$–10.6 MeV with a step size of 0.1 MeV. The cross-section is obtained using the formula:

$$\sigma(E) = \frac{dY}{dE}\frac{M_T}{\epsilon \cdot f \cdot N_A}\frac{dE}{d(\rho X)}$$

where ϵ is detection efficiency, M_T is the molecular weight of the target, f is the abundance fraction, N_A is Avogadro' s constant, and $dE/d(\rho X)$ is the mass stopping power from SRIM [**?**]. The reaction cross-section is converted into the S^* factor:

$$S^*(E_{\text{cm}}) = \sigma(E_{\text{cm}}) \cdot E_{\text{cm}} \cdot \exp(2\pi\eta + 0.46E_{\text{cm}})$$

The S^* factors for the p_0 and p_1 channels obtained via the thick-target scanning method are shown in [Figure 4: see original paper].

[Figure 4: see original paper]

The results demonstrate that for both channels, the S^* factor curves scanned across multiple independent beam energies exhibit excellent consistency in overlapping regions. For instance, the 8.6 MeV data connects smoothly with the 9.2 MeV data near $E_{\text{cm}} \approx 4.1 - 4.3$ MeV. In the energy region below 3.0 MeV, a significant enhancement in the S^* factor is observed, primarily due to impurities such as D_2O in the graphite targets.

4 Results and Discussion

4.1 Comparison of the S^* Factor

We compared the systematic scanning measurements with several key experimental datasets. Mazarakis et al. [?] and Becker et al. [?] employed thin-target methods. Later studies by Fruet et al. [?] and Tan et al. [?, ?] introduced particle-γ coincidence measurements to suppress backgrounds.

[Figure 5: see original paper]

The primary resonance shapes of p_0 and p_1 in this work are similar to those reported by Becker et al. [?]. In the region where $E_{\mathrm{cm}} < 4.18$ MeV, our results show a high degree of agreement with Tan et al. [?] regarding resonance positions, strengths, and widths. This indicates that even without complex particle-gamma coincidence techniques, the current method using high-resolution kinematic reconstruction with a silicon array can achieve significant results.

4.2 Systematic Differences

The p_0 and p_1 data exhibit some resonance peak shifting in the higher energy region compared to Becker et al. [?]. However, such energy scale discrepancies are prevalent; for example, Mazarakis' s data requires a 100 keV shift to align with Becker' s. The resonance positions in this work are in high agreement with the recent results of Tan et al. [?], suggesting that observed differences reflect intrinsic biases between different experimental calibrations rather than a flaw in the scanning technique.

4.3 Comparison of the p_1/p_0 Ratio

Figure 6 presents the ratio of the reaction cross-sections for the p_1 and p_0 channels. These are compared with experimental measurements from Mazarakis [?] and Becker [?], and theoretical calculations from TALYS [?].

[Figure 6: see original paper]

The p_1/p_0 ratios from the three datasets show good agreement. Except for small regions near $E_{\mathrm{cm}} = 4.0, 4.6$, and 5.2 MeV, p_1 is generally greater than p_0. In resonance regions, p_1 can reach 2 to 5 times the magnitude of p_0. TALYS theoretical calculations, based on the Hauser-Feshbach statistical model, serve as a reference baseline but cannot account for specific resonance structures.

4.4 Limitations of the Method

The primary objective of the thick-target scanning method is to search for unknown low-energy resonances in the $^{12}\mathrm{C} + ^{12}\mathrm{C}$ system. While efficient, there remains a discrepancy in energy accuracy compared to certain thin-target measurements due to the reliance on stopping power models and simplified angular distributions.

5 Conclusion

This work successfully measured the $^{12}\mathrm{C}(^{12}\mathrm{C}, p_{0,1})^{23}\mathrm{Na}$ reaction cross sections in the sub-barrier energy region using the thick-target scanning method. The extracted S^* factors clearly reveal complex molecular resonance structures. The consistency with previous high-precision data validates the efficiency and reliability of this method for nuclear astrophysics research. These results provide important experimental constraints for understanding stellar carbon burning and the evolution of massive stars.

Note: Figure translations are in progress. See original paper for figures.

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