A method for estimating and subtracting the hydrogen background in the natural carbon target used in the 12C + 12C experiment (postprint)

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Abstract

The experimental data of 100A MeV 12C + 12C elastic scattering are checked by using two-body kinematic calculation and 12C+p elastic scattering. It is shown that the measured data are true and reliable. In the paper, the transformation between the excited energy spectra of the 12C+12C system and the ground state energy spectra of the 12C+p system is introduced. The method of subtraction of the hydrogen background in the natural carbon target used in the experiment is elaborately described and the results are discussed. It is indicated that this method of subtraction of hydrogen background is reasonable and can be used in the data analysis. Based on the elastic scattering cross section of the previous experiment of 12C+p at 95.3A MeV, the hydrogen content entered into the reaction is analyzed. The final hydrogen content in the natural carbon target is $(2.73 \pm 0.12)\%$.

Full Text

Preamble

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A Method for Estimating and Subtracting the Hydrogen Background in Natural Carbon Targets Used in 12C + 12C Experiments∗

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Abstract. The experimental data for 100A MeV 12C + 12C elastic scattering have been validated using two-body kinematic calculations and 12C + p elastic scattering analysis, confirming the authenticity and reliability of the measurements. This paper introduces the transformation method between the excited energy spectra of the 12C + 12C system and the ground-state energy spectra of the 12C + p system. The procedure for subtracting the hydrogen background contribution from the natural carbon target is described in detail, and the results are discussed. The method is demonstrated to be reasonable and applicable to data analysis. Based on the elastic scattering cross section from a previous 12C + p experiment at 95.3A MeV, the hydrogen content participating in the reaction is analyzed. The final hydrogen content in the natural carbon target is determined to be $(2.73 \pm 0.12)\%$.

Keywords: Elastic scattering, Background subtraction, Hydrogen content
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Introduction

The role of the three-body force (TBF) in complex nuclear systems represents a key issue in both nuclear physics and nuclear astrophysics, particularly concerning high-density nuclear matter such as neutron stars and supernova explosions. In nuclear collisions, elastic scattering provides crucial information about nucleon-nucleon (NN) and nucleus-nucleus (AA) interactions. Recently, a double folding model (DFM) incorporating a new type of complex G-matrix interaction that includes TBF was developed in Refs. [1–7] and applied to calculate the optical potential for 12C + 12C elastic scattering in the 100A–400A MeV energy range. These calculations revealed that the real part of the optical potential transitions from attractive to repulsive character with increasing incident energy, and that the angular distribution of 12C + 12C elastic scattering exhibits different diffraction patterns depending on whether TBF effects are included. Through studying this evolution of the optical potential and elastic scattering angular distributions with incident energy, the contributions of TBF and tensor forces can be extracted [5]. However, theoretical and experimental studies for heavy ions at energies higher than deuteron energies remain limited [8]. Therefore, precise measurement of the angular distribution for 12C on 12C elastic scattering in the 100A–400A MeV incident energy range is needed to elucidate the repulsive nature of the optical potential and determine the transition energy at which the real part changes from attraction to repulsion, thereby providing important information about TBF effects, the medium effects of high-density nuclear matter, the energy dependence of TBF, and the role of tensor

forces.

Experimental Section

The 100A MeV 12C + 12C experiment was conducted at the Research Center for Nuclear Physics (RCNP) at Osaka University. The angular distribution was precisely measured using the magnetic spectrometer "Grand Raiden," which possesses excellent ion-optical properties [9]. To fully utilize the spectrometer's capabilities, the beam was transported under achromatic focusing along the WS beamline [10]. During the experiment, we employed a natural carbon target with a thickness of 1.181 mg/cm^2 and a (CH2)n target with a thickness of 11.40 mg/cm^2. Time-of-flight versus energy loss (TOF-ΔE) signals from focal plane detectors were used for particle identification; details of these detectors are described in Ref. [11].

Following particle identification, two-dimensional plots of outgoing 12C particle excitation energies versus laboratory angles were obtained when the central angle of the magnetic spectrometer was set to 2.0°, as shown in Fig. 1 [Figure 1: see original paper]. Three horizontal bands are clearly observed, corresponding to the ground state, the 4.44 MeV (2^+) state, and the 9.65 MeV (3^-) excited state of 12C + 12C scattering. However, an additional tilted band crossing the horizontal bands is also visible in Fig. 1. This band increases the apparent number of 12C + 12C scattering events, particularly at small angles, and its contribution cannot be neglected. Compared to the contributions from the excited states of 12C on 12C scattering, this tilted band is significantly larger at smaller angles. Consequently, failure to subtract this contribution would affect the measured differential cross section for 12C on 12C scattering. This paper introduces a method to subtract this disturbance and determine its origin from the experimental target.

Results and Discussion

A. Subtraction of Hydrogen Disturbance in Target

We first compared the results from the natural carbon target with those from the (CH2)n target, finding them to be similar. Moreover, no tilted band appeared in other plots from the natural carbon target at larger angles, leading us to conclude that the tilted band originates from 12C scattering on hydrogen. Second, we validated the experimental data using relativistic kinematic calculations. For a reaction A(a, b)B, where a, A, b, and B represent the projectile, target nucleus, scattered particle, and recoil nucleus, respectively, the Q-value (reaction energy) is defined as Q = K_B + K_b - K_a - K_A, where K_a, K_A, K_b, and K_B denote the kinetic energies of the projectile, target, scattered particle, and recoil nucleus, respectively (with K_A = 0). According to momentum conservation, p_B^2 = p_a^2 + p_b^2 - 2p_a p_b cos , where p_a, p_b, and p_B represent the momenta of the projectile, scattered nucleus, and recoil nucleus, respectively, and is the scattering angle in the laboratory

frame. Considering relativistic effects, the relationship between momentum and kinetic energy is given by p_i = √(K_i² + 2K_i m_i), where m_i denotes the rest mass of the respective nucleus (i = a, A, b, B). From these relations, the Q-value can be expressed as:

Q = K_b - K_a - K_B

with K_B determined through the momentum conservation equations.

Through these calculations for 100A MeV 12C + 12C scattering, we find that the first excited state at 4.4 MeV (2^+_1) of 12C + 12C crosses the ground state of 12C + p at 1.015°, while the 9.64 MeV (3^-_1) state crosses the 12C + p ground state at 1.5°. The influence of beam uncertainties (including angular and spatial shifts, estimated at about 2%) is negligible for calculating these crossing angles. As shown in Fig. 1, the observed crossing angles are approximately 1.0° and 1.5°, consistent with our calculations, thereby confirming the authenticity of the experimental data.

For convenient selection of 12C + p events, we transformed the energy spectrum of the 12C + 12C system shown in Fig. 1 into that of the 12C + p system, as displayed in Fig. 2 [Figure 2: see original paper]. During this conversion, we employed a polynomial function to rotate the spectrum while obeying the constraints that excitation energy cannot vary with angle and that the ground-state excitation energy must remain zero. This yields the transformation equation:

$$Q = 0.0275\,^{4} + 0.0333\,^{3} + 2.9658\,^{2} + 3.4918 - 2.2786 + Q$$

where Q and Q represent the outgoing 12C excitation energies in the 12C + p and 12C + 12C systems, respectively.

The uncrossed region of 1.7°–2.2° was selected for analysis, as it is dominated by 12C + p elastic scattering. Fig. 3 [Figure 3: see original paper] shows the outgoing 12C excitation energy spectrum at 1.8° and the corresponding fit. Applying this method to other angles yields the actual number of hydrogen-related reaction events and the width σ of the Gaussian distribution.

The differential cross sections for 96 MeV p + 12C elastic scattering from Ref. [12] were transformed to the laboratory frame for 12C + p elastic scattering at 95.3A MeV, as shown in Fig. 4 [Figure 4: see original paper]. To establish the relationship between angle and differential cross section, the experimental data were fitted from 0.8° to 2.2°. This fitting function was then used to calculate differential cross sections from 1.7° to 2.2°, and the ratios between these cross sections and the real counts at each angle were determined. The least-squares method was applied to optimize all ratios, yielding an optimized normalization factor. The reliability of this factor was verified by comparing normalized counts with real counts, as shown in Fig. 5 [Figure 5: see original paper]. All values fall within the error bars, confirming the reasonableness of the obtained normalization factor.

We also verified the background subtraction results in the uncrossed region of

1.7°–2.2° using this normalization factor. Fig. 6 [Figure 6: see original paper] shows the result at 1.8°, demonstrating that the peak can be subtracted within statistical fluctuations, leaving only the background. This confirms that our method for subtracting hydrogen disturbance is reasonable.

We subsequently applied this method to the crossed region of 0.9°–1.6°. The normalization factor was used to calculate the real counts in these crossed regions, along with data from 12C + p elastic scattering. These deduced counts were treated as Gaussian distributions in the excitation energy spectra of the 12C + 12C system. The center and width values of the fitted Gaussian distribution from Fig. 3 were transformed to the 12C + 12C system using Eq. (6), thereby determining the width and center parameters for the Gaussian distribution in the 12C + 12C system (typically using a 3σ width). Fig. 7 [Figure 7: see original paper] shows results at four example angles, clearly illustrating that the 12C + p elastic scattering contribution is substantial compared to 12C + 12C scattering, particularly in Fig. 7(c).

B. Extraction of Hydrogen Content in the Natural Carbon Target

The differential cross section is defined as:

$d\sigma/d\Omega = N/(\_d \ \_t \ N\_0 \ N\_T \ d\Omega)$

where N, _d, _t, N_0, N_T, and dΩ represent the reaction event counts, detector efficiencies, trigger efficiency, beam intensity, target nuclei per unit area, and solid angle, respectively. Having obtained the reaction counts from 12C + p elastic scattering in the uncrossed region (Fig. 3) and the differential cross sections from Fig. 4, the parameters _d, _t, N_0, and dΩ can be determined from the experimental setup and measurements. This allows us to calculate the hydrogen content at each angle, with results listed in Table 1 . Using the weighted mean method, the final hydrogen content in the natural carbon target is determined to be $(2.73 \pm 0.12)\%$.

Conclusion

In this work, we employed two-body kinematics to calculate the crossing angles between the ground state of 95.3A MeV 12C + p elastic scattering and the excited states of 100A MeV 12C + 12C scattering, including the 4.4 MeV (2^+_1) state and the 9.64 MeV (3^-_1) state. This method allowed us to calibrate the experimental angles and verify the experimental data. We then presented and discussed the method and results for subtracting hydrogen contamination. The elastic scattering of 12C on hydrogen from the experimental target contributes significantly at certain angles, necessitating its subtraction in data analysis. Finally, we extracted the hydrogen content in the natural carbon target, obtaining a result of $(2.73 \pm 0.12)\%$. The method developed in this paper will help improve future experiments, as measurements using the (CH2)n target can calibrate various parameters such as Faraday cup and detector efficiencies, providing a valuable technique for nuclear physics experiments.

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