Knockout, Charge Exchange and Two-Step Transfer Components in ^{13}C$(p,n)^{13}$N Reaction

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Introduction

The ^{13}C$(p,n)^{13}$N reaction is a key neutron source in i-process nucleosynthesis, situated between the slow s-process and the rapid r-process. Elements in the mass range around 90, including those near niobium, are believed to be synthesized through the i-process along with the r-process nucleosynthesis. Consequently, precise characterization of the production pathways for these nuclei is important. Accurate modeling of the neutron source requires a detailed understanding of the reaction dynamics, as ^{13}C exhibits a ^{12}C+n cluster structure under the Wood-Saxon potential.

The ^{13}C$(p,n)^{13}$N reaction, being a direct reaction, encompasses various neutron production mechanisms, such as charge exchange, proton-induced neutron knockout, and double-step transfers. Each of these mechanisms is sensitive to the incident proton energy. To delineate the neutron production systematics, it is necessary to measure the angular distribution of the ejected neutrons. These measurements facilitate the identification of production mechanisms, the quantification of their relative strengths, and the evaluation of their contributions.

Experimental details

Firouzbakht et al.[1] reported angular distributions for the ^{13}C$(p,n)^{13}$N reaction at proton energies between 3.30 MeV and 3.75 MeV, but measurements were limited to angles beyond the extreme forward direction, necessitating additional data at zero degrees for a complete analysis. There is also a lack of angular distribution data near the

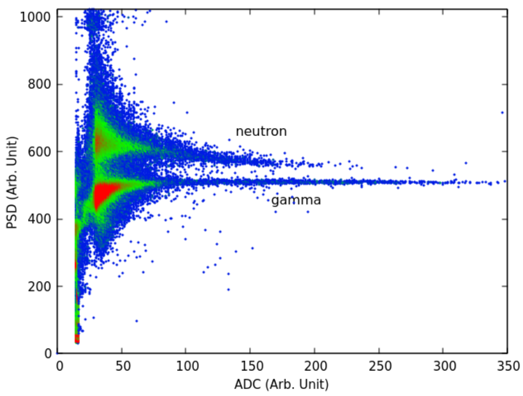

FIG. 1: Obtained n/γ discrimination in ADC-PSD correlations

^{13}C$(p,n)^{13}$N^{g} cross-section, particularly for the ^{13}N$^{1/2^-}$ state, where coupling effects become significant[2]. Accurate reproduction of the neutron-induced reaction on ^{13}N requires detailed knowledge of the radial wave function for the ^{13}N$^{1/2^-}$ state due to the importance of coupling ratios in the knockout, charge exchange, and double-step transfer processes.

The cross sections for the ^{13}C$(p,n)^{13}$N reaction were measured in inverse kinematics using the TIFR PLF 15° north beam line, with a pulsed ^{13}C beam of 75 MeV directed at a TiH$_2$ target, backed by 33 mg/cm^2 of Tantalum. Neutron detectors (EJ301) were positioned at 0°, 18°, 30°, 40°, and 60° in the lab frame, and neutron/gamma discrimination (Figure 1) was performed using the Messytech-MPD4 module in zero crossover mode. The time-of-flight data were used to generate and fit the neutron spectrum, focusing on the n_0 colony for the

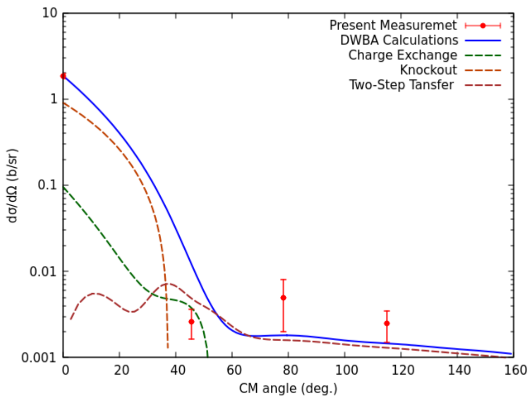

FIG. 2: Differential Cross sections along with fitted direct, charge exchange and Two step transfer couplings

ground state of ^{13}N, by removing the contribution from satellite neutrons and continuum from Ti. The neutron detector efficiency was simulated with Geant4, resulting in absolute differential cross sections for these angles.

Theoretical DWBA calculations were carried out to explore the physics of the $^{13}C(p,n)^{13}N$ reaction using an in-house developed Multi-Step DWBA code optimized with GPU-based computation to enhance numerical efficiency. The Schrödinger equations for the proton-^{13}C and neutron-^{13}N channels were solved using GPU-accelerated versions of NumPy, SciPy, and SymPy, with optical potentials describing these channels. The neutron-proton (n-p) interaction potential from RIPL-3 was incorporated into the distorted-wave Born approximation (DWBA), and the matrix element was computed by integrating the product of the entrance and exit wave functions with the n-p potential. This matrix element, which determines the scattering amplitude, was used to calculate the angular distribution by squaring its modulus, resulting in the differential cross-section $\frac{d\sigma}{d\Omega}$ as a function of the center-of-mass scattering angle. Additionally, charge exchange and two-step transfer couplings were included along with knockout couplings, and the calculated angular distribution was compared with experimental cross sections to validate the model.

Results and Discussion

Differential cross sections for the $^{13}C(p,n)^{13}N$ reaction, corresponding to the ground state of ^{13}N, were measured over an angular range of $0° - 120°$ in the center-of-mass (CM) frame using inverse kinematics. The measured data, shown in Figure 2, were compared with a theoretical model based on distorted-wave Born approximation (DWBA), incorporating neutron knockout, charge exchange, and two-step transfer processes. Individual contributions from these mechanisms, along with their sum, are also presented in Figure 2.

The theoretical calculations show strong agreement with the experimental data, especially at forward angles. Proton-induced neutron knockout dominates at small angles, while charge exchange and two-step transfer couplings become significant at larger angles. The results underscore the importance of multiple coupling processes in theoretical models and confirm the accuracy of DWBA in predicting the angular distribution of the emitted neutrons.

References

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[2] Wong et al.,Phys. Rev. 123, 598 (1961)