The PANDORA Project: Investigating Photonuclear Reactions in Light Nuclei.

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Abstract. The PANDORA (Photo-Absorption of Nuclei and Decay Observation for Reactions in Astrophysics) project focuses on both experimental and theoretical studies of photo-nuclear reactions involving light nuclei with mass numbers below $A = 60$. This research plays a crucial role in understanding ultra-high-energy cosmic rays (UHECRs), where energy loss mechanisms are primarily driven by electromagnetic interactions between nuclei and the cosmic microwave background, particularly through the isovector giant dipole resonance (IVGDR). However, current propagation models and reaction calculations are hindered by the limited availability of reliable experimental data for several key nuclei. In this context, the project presents new results on ^{12}C and ^{13}C, obtained through inelastic (p,p') scattering at 392 MeV using the virtual photon method, conducted at the Research Center for Nuclear Physics (RCNP) in Japan.

1 Introduction

The field of nuclear astrophysics relies heavily on accurate experimental data to model and interpret physical phenomena [1]. A prime example is the simulation of ultra-high-energy cosmic ray (UHECR) propagation, where nuclei undergo photodisintegration via absorption of Lorentz-boosted cosmic microwave background photons. These simulations require input from a wide range of nuclei with mass numbers below 56 [2]. While it is impractical to obtain detailed data for every relevant nucleus, a subset of nuclei plays a significant role in driving these interactions and validating propagation models.

This experimental campaign focuses on extracting the total photoabsorption cross section within the excitation energy range of the isovector giant dipole resonance (IVGDR) for light nuclei, approximately 16–30 MeV. In addition to the total photoabsorption, the partial branching ratios for charged-particle decay channels were also determined. This was achieved using relativistic Coulomb excitation in combination with the virtual photon absorption method [3]. The IVGDR region is dominated by a dense spectrum of E1 gamma transitions, making it a vital channel for understanding the photodisintegration processes that shape the energy and mass evolution of UHECRs during their journey through space.

The PANDORA project was established to address this specific need for total photoabsorption cross sections and decay branching ratios required for UHECR propagation models, as well as for a broad range of applications in nuclear structure and astrophysics [4]. In this paper, we discuss preliminary results from measurements performed on ^{12}C.

2 Experimental Method

The experiment utilized a 392 MeV proton beam produced by the Ring cyclotron at RCNP, Japan, and analyzed using the Grand Raiden (GR) spectrometer. The GR's ability to operate at 0°, combined with the semi-relativistic proton energies provided by the cyclotron, are critical for suppressing contributions from reaction channels other than E1 Coulomb excitation [5]. The GR was also operated in the GRAF mode which allows data to be taken at 4.5° and 6.6° central angle settings, which will be used to isolate the E1 component of the cross sections. [6].

The focal-plane detection system consisted of two multi-wire drift chambers (MWDCs) for position tracking and two plastic scintillators for timing purposes and particle identification. Secondary decay particles from the target were detected using SAKRA, a backward-angle double-sided silicon strip detector (DSSSD) array. The experimental setup also included a $LaBr_3$:Ce array, named SCYLLA, for potential detection of secondary gamma rays resulting from IVGDR decay. Photographs of the focal plane and SAKRA detector systems are shown in Fig. 1.

Figure 1: *(Left)*: The focal plane detection system, with plastic scintillators positioned behind the vertical drift chambers. The zero-degree beam line is visible, passing within centimeters of the detectors. *(Right)*: The cherry blossom-shaped SAKRA DSSSD array prior to installation in the scattering chamber. It covers approximately 25% of the downstream solid angle.

3 Focal Plane Results

In studies of photo-induced nuclear reactions, the double-differential cross section (DDCS) is a fundamental observable that provides the probability of nuclear excitation as a function of both emission angle and energy of the scattered particle [7]. It is experimentally determined using:

$$\frac{d^2\sigma}{d\Omega\, dE} = \frac{10^{27} \cdot N_c}{N_0 \cdot \rho \cdot D \cdot \Delta\Omega \cdot \Delta E \cdot \epsilon_{tot}} \tag{1}$$

with the parameters defined as:

- N_c: Number of counts in an energy bin,
- N_0: Number of incident protons on the target,
- ρ: Areal density of the target in mg/cm^{2}in this case 1 mg/cm^2,
- $\Delta\Omega$: Detector solid angle (3.36 msr),
- ΔE: Energy bin width (e.g., 0.05 MeV),
- ϵ_{tot}: Total detection efficiency of the GR spectrometer, usually around 0.85-0.90,
- D: Fraction of recorded events, corrected for live-time usually 0.98,
- 10^{27}: Unit conversion factor to yield $\mathrm{mb}/(\mathrm{sr} \cdot \mathrm{MeV})$.

The total number of incident protons, N_0, is determined from the current integrator using:

$$N_0 = \frac{CI \cdot R \cdot 10^{-12}}{e} \tag{2}$$

where CI is the integrator readout, R the range setting (nA), and e the elementary charge.
To assess MWDC performance, the efficiency of each wire plane (e.g., X_1 or X_2) is calculated as:

$$\epsilon(X_{1,2}) = \frac{N_{\text{events}}(X_1 X_2, U_1, U_2)}{N_{\text{events}}(X_{2,1}, U_1, U_2)} \tag{3}$$

where the numerator represents full 4-plane coincidences and the denominator omits the plane under test. This efficiency quantifies each plane's contribution to reliable track reconstruction and each plane's efficiency is usually between 0.88-0.95. The results of the calculation and its comparison to a previous experiment is shown in Fig 2.

The DDCS can be converted to the total photoabsorption cross section using the virtual photon method[3], which recasts Coulomb excitation as the absorption of a spectrum of virtual photons. For the present kinematics, the Eikonal approximation was necessary to ensure the method remains valid at 0° scattering angles.

4 Coincidence Results

Additional information on the decay modes of excited ^{12}C was obtained by analyzing coincidence events between the GR focal plane and the SAKRA array (Fig. 3). Monte Carlo simulations of the IVGDR decay kinematics were used to guide identification of physical loci.

True coincidences were isolated using timing information from plastic scintillators and the RF clock signal. Clear decay branches to the ground and excited states of ^{11}B were identified in both simulation and experiment. The proton punch-through threshold at 8 MeV is visible in the data, indicating the energy beyond which protons exit the first layer of silicon detectors without full energy deposition.

Graphical cuts, combined with SAKRA time-of-flight information, are being applied to distinguish between protons and α-particles. This separation will allow for construction of particle-specific histograms, enabling calculation of branching ratios for each decay channel — a crucial input for constraining IVGDR decay models in light nuclei.

5 Outlook

The next phase of analysis involves isolating the pure E1 contribution from other multipolarities present in the excitation spectrum. This will be achieved using either Multipole Decomposition Analysis (MDA) or the Difference of Spectra (DoS) method. This is necessary, since even though the experimental setup was chosen to minimize the contributions from other multipolarities, they cannot be completely done away with and still contribute towards the measured results.Both require Distorted Wave Born Approximation (DWBA) calculations to generate theoretical angular distributions.

In MDA, angular distributions for various multipolarities, along with a quasifree background component, are simultaneously fitted to the data. The resulting E1 component is extracted bin-by-bin [8]. Alternatively, the DoS

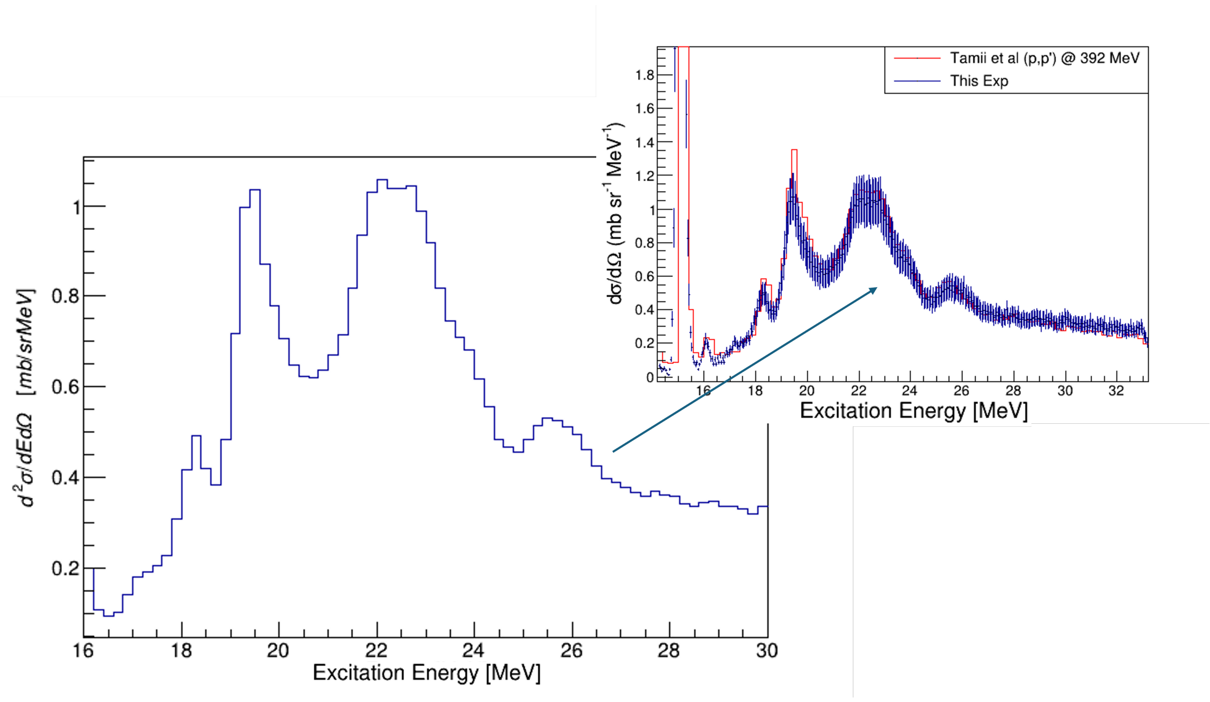

Figure 2: Comparison of the DDCS for 392 MeV protons on ^{12}C from this work with a previous experiment using dispersion matching. The current setup did not employ dispersion matching due to the less stringent resolution requirements for GDR studies.

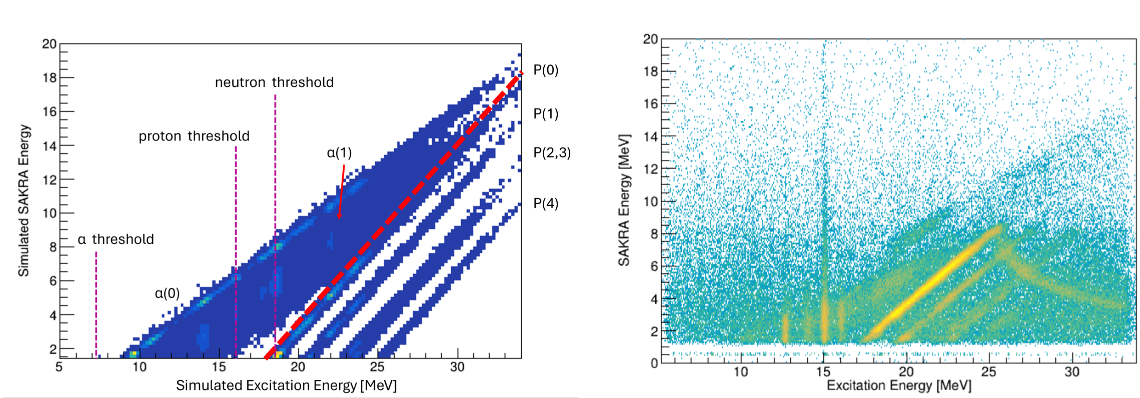

Figure 3: *(Left)*: Kinematic simulation of ^{12}C decay showing the loci of decay products. The red separation line differentiates α-particles and protons based on threshold energies. *(Right)*: Experimental coincidence data between the focal plane and SAKRA for ^{12}C. Proton punch-through is clearly visible.

method identifies the first minimum in the E1 angular distribution and subtracts the spectrum at that finite angle from the 0° data, isolating the E1 response after correcting for geometric and instrumental effects [9].

Once the pure E1 contributions are extracted, the corresponding branching ratios and total photoabsorption cross sections can be finalized.

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