PANDORA Project: Study of Photo-Nuclear Reactions Below A=60

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1 Introduction

Photonuclear reaction data are essential in understanding nuclear structure, collective excitations, and the response of nuclei to an external electric dipole ($E1$) field [1, 2]. The data and predictions play a pivotal role in a wide range of applications such as including nuclear physics, astrophysics, radiation shielding, nuclear medicine, nondestructive investigation. One of the key aspects of these reactions is excitation of the Isovector Giant Dipole Resonance (IVGDR), a collective excitation of nuclei, consisting the dominant part of the $E1$ response [3, 4]. Photoneutron cross sections data are scarce in light nuclei below a mass of A=60 especially for the total photoabsorption cross sections and for the partial cross sections of the charge particle decay channels. Even existing available photoneutron cross sections reveal that experimental data often lack mutual consistency and highlights the need for improved theoretical models. A typical example is shown in Fig. 1 for the ^{13}C(γ, xn) cross sections. Available data are plotted with theoretical predictions using the general reaction code TALYS with the Brink-Axel Lorentzian [5, 6] and Goriely's hybrid models [7]. Photonuclear reactions in this low mass region pose unique challenges, such as greater impact of nuclear shell structure and α-clustering as well as isospin-selection rules and isospin-mixing in the α-decay processes. Additionally, the IVGDR distribution in this region is often fragmented, making it more complex to study.

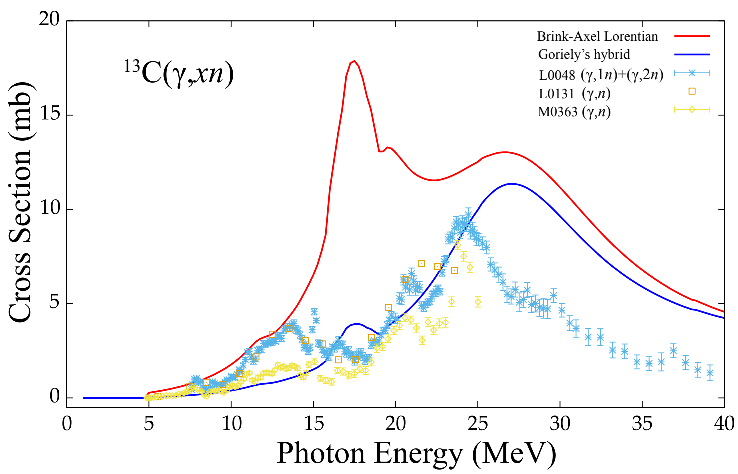

Figure 1: Photoneutron cross sections, ^{13}C(γ, xn), as a function of excitation energy (photon-energy). The theoretical cross sections are calculated using the reaction code TALYS with two models, the Brink-Axel Lorentzian [5, 6] (dashed line) and the Goriely's hybrid [7] (solid line). They are plotted in comparison with the available experimental data taken from the EXFOR database [8].

The PANDORA (Photo-Absorption of Nuclei and Decay Observation for Reactions in Astrophysics) project [9] aims to address these challenges by employing interdisciplinary research across experimental and theoretical nuclear physics and particle astrophysics. The project will generate a precise and systematic dataset of photoabsorption cross-sections and decay branching ratios for each of proton, neutron, α and γ decay channels. It will employ two complementary experimental methods: virtual photon excitation through relativistic proton scattering at very forward angles, and real photon excitation using a high-brilliance quasi-monoenergetic γ-ray beam. Theoretical models will be developed and evaluated against experimental data, with the aim to improve prediction of the photoabsorption cross-sections and decay branching ratios. The models include Antisymmetrized Molecular Dynamics (AMD) [10, 11], Relativistic Nuclear Field Theory (RNFT) [21, 22, 23], Random Phase Approximation (RPA) with density functional approach [24], Quasiparticle Phonon Model (QPM) plus Energy Density Functional (EDF) [25, 26], large-scale shell model calculations [27], and *ab initio* type calculations. The results will be implemented in the TALYS reaction code and made available for application in various fields. An anticipated outcome of the PANDORA project is a better understanding of the photo-interactions of Ultra High Energy Cosmic Rays (UHECR), which is critical for theoretical modeling of their extra-galactic propagation and acceleration in astrophysical sources.

2 Experimental Nuclear Physics

The PANDORA project aims to systematically study photoabsorption cross-sections and decay branching ratios in the mass region below $A = 60$. This pursuit requires a combination of cutting-edge methodologies, employed at facilities such as RCNP [4, 28], iThemba LABS [20], and ELI-NP [29, 30]. The former two facilities employ the method of virtual photon excitation via relativistic proton scattering and the last real photon excitation through high-brailliance quasi-monoenergetic γ beams. For ensuring the data consistency among the facilities, ^{27}Al was chosen as the reference nucleus for each campaign due to its ideal properties: easy fabrication, natural 100% isotopic abundance, relatively low separation energy, availability of the photo-absorption data [12]. To benchmark nuclear model predictions, a set of key nuclei were selected for study. These include ^{12}C and ^{16}O (importance of α-decay), ^{6}Li, ^{7}Li, ^{9}Be, ^{10,11}B (light nuclei), ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca (N=Z nuclei), and others. Targets used in the measurements will be either self-supporting pure targets or chemical compounds with high isotopic enrichment or natural isotopic abundance. This choice of the target nuclei aligns with the goal of understanding the photodisintegration path of UHECR nuclei in intergalactic propagation.

The PANDORA project will employ virtual-photon excitation at the Research Center for Nuclear Physics (RCNP), Osaka University. Protons accelerated to 392 MeV by two cyclotrons will be used to measure the $E1$ reduced transition strength, $dB(E1)/dE_x$. Two measurement modes will be used. The zero-degree inelastic scattering mode uses the Grand Raiden spectrometer to measure scattered protons at angles between 0 and 3 degrees. The Grand RAiden Forward Beamline (GRAF) mode measures protons scattered at 4.5, 6.5 degrees covering an angular range of 3.5-7.5 degrees. The proton beam at 392 MeV in the zero-degree mode covers an excitation-energy range of 7-32 MeV. The experimental technique involves a multipole decomposition analysis of the (p, p') reaction, where the angular distribution of the (p, p') cross-sections is fitted by the sum of theoretical angular distributions for multiple poles to extract the $E1$ component. This component is then converted to the $E1$ reduced transition strength $B(E1)$. The Silicon Array SAKRA (Si Array developed by Kyoto and osaka for Research into Alpha cluster states) [31], developed by Osaka and Kyoto groups, will be placed around the target for decay charged particle detection. The array consists of Double-Sided Silicon Strip Detectors (DSSSDs) with a thickness of 500 micrometers. SAKRA covers a solid angle of approximately 25% of 4π at backward angles with respect to the beam direction. Eight large-volume $LaBr_3$ detectors will be placed around the target chamber for decay gamma-ray detection. The first PANDORA experiment at the RCNP, scheduled for 2023, plans to use ^{12,13}C, ^{27}Al, and ^{24,26}Mg targets for decay measurement in coincidence with scattered protons, and ^{10,11}B solely for scattered protons.

The PANDORA project also includes experiments at iThemba LABS, which uses an $E1$ reduced transition strength measuring technique similar to that at the RCNP. The iThemba LABS is a unique facility for virtual photon excitation in Africa. The K600 magnetic spectrometer is used for scattering proton detection in the $0°$-$4°$ angular range. The spectrometer's high momentum and angular resolutions enable effective multipole decomposition, particularly for low-energy transitions. Additionally, iThemba LABS will use the ^{27}Al target for benchmarking and comparison with RCNP measurements. Coincidence measurements will be carried out for the p, d, and α decay channels using a silicon detector array CAKE (Coincidence Array for K600 Experiment) [32]. Complementary to this, gamma-ray detection will be performed using $LaBr_3$ detector array ALBA ()African Lanthanum Bromide Array.

The PANDORA project's final experimental phase will take place at ELI-NP. This facility will provide a high-intensity gamma beam for real photon excitation. This method significantly complements the virtual photon excitation performed at RCNP and iThemba LABS. ELI-NP experiments will provide precise absolute normalization of the photoabsorption cross-sections in additio to the proton, neutron, α, and γ decay branching ratios for several nuclei up to 20 MeV. These measurements will be used to validate and calibrate the photodisintegration models used for astrophysical applications.

To summarize, the PANDORA project aims to improve our understanding of photonuclear reactions essential in astrophysical processes. The project's combined experimental approach across multiple facilities will provide a comprehensive and reliable data set, significantly advancing our knowledge in this field.

3 Theoretical Nuclear Physics

UHECRs interact with cosmic microwave background (CMB) photons, resulting in boosted energies ranging from keV to MeV. This interaction is dominated by the IVGDR at lower photon energies, with additional contributions from quasideuteron emission and pion photoproduction at intermediate and high energies. Photodisintegration reactions cause nuclei to emit nucleons, and their accurate description is essential along the photodisintegration path from iron to protons. The TALYS nuclear reaction code provides estimates of photoreaction cross-sections up to 50 MeV, considering different reaction mechanisms. Using various nuclear structure models in these estimations allows for the assessment of associated theoretical errors.

The RPA coupled with an EDF is a standard tool for calculating $B(E1)$ distributions in nuclei. It offers a systematic reproduction of experimental data, including the properties of giant resonances, and predicts the existence of the PDR in a wide range of mass regions. The RPA-EDF approach is derived from the DFT as a linear response to external perturbations. It significantly reduces computational costs compared to other methods, making it applicable to heavy nuclei and infinite nuclear matter. However, its reliability diminishes for very light nuclei. The inability of RPA-EDF to reproduce experimental resonance widths is overcome by assuming a spreading width of 1-2 MeV. This method is particularly useful for describing the photonuclear cross-sections relevant to projects like PANDORA, and ongoing developments aim to improve its predictions for light nuclei by optimizing the Skyrme-EDF parameters.

RNFT combines various theories, including the Landau-Migdal Fermi liquid theory, Copenhagen-Milano Nuclear Field Theory (NFT), and Quantum Hadrodynamics (QHD). QHD, a covariant theory of nucleons and mesons, successfully describes nuclear ground states based on mean-field approximations. The time-dependent version of Relativistic Mean Field (RMF) and its response theory, such as Relativistic Random Phase Approximation (RRPA) or Relativistic Quasiparticle RPA (RQRPA) for superfluid systems, have provided good descriptions of collective vibrational states. RNFT extends the Covariant Density Functional Theory (CDFT) by considering many-body correlations associated with non-localities of nucleonic self-energy and effective interaction. It is applicable throughout the nuclear chart, including light and heavy nuclei, and provides a parameter-free extension of CDFT. The response theory within RNFT, known as Relativistic Quasiparticle Time Blocking Approximation (RQTBA), significantly improves the description of giant resonances and low-energy excitations, including the PDR.

The EDF-QPM approach combines an EDF with the QPM. It has been successfully used to study nuclear structure, including low-energy excited states, pygmy resonances, and giant resonances. The EDF-QPM method allows for a unified description of single-particle and multiphonon states, as well as the separation of PDR and IVGDR strengths. It employs large configuration spaces, including up to three-particle-three-hole (3p-3h) components, enabling accurate descriptions of nuclear spectral functions and precise nuclear data. The EDF-QPM approach has successfully predicted the properties and dynamics of new modes of nuclear excitation

The electric dipole states of light nuclei will be studied using the AMD model, combined with the shifted-basis method or the Realistic Eikonal Model (REM). The AMD framework describes the structure and response of atomic nuclei using Slater determinant wave functions of nucleon wave packets. To account for particle-hole states relevant to electric dipole states, the shifted-basis method or REM will be incorporated into AMD. The shifted-basis method has successfully described the PDR and IVGDR in ^{26}Ne. The advantages of AMD include its ability to describe collective and cluster states, restoration of rotational symmetry through angular momentum projection, and the incorporation of many-particle-many-hole states through REM. Additionally, the Laplace expansion method will be employed to study the decay branches (neutron, proton, photon, and alpha decays) within the AMD framework.

Shell-model calculations are successful in reproducing low-lying states and can be used to describe photonuclear reactions. For photonuclear reactions, larger valence shells are required due to the parity change in excitation from the ground state. Consideration of the $0\hbar\omega$ space for the ground state and the $1\hbar\omega$ space for the $E1$-excited states is necessary to satisfy the $E1$ sum. In the case where the Fermi surface is located in a major shell with harmonic-oscillator quantum number $\mathcal{N}_0\hbar\omega$, the valence shell consists of three major shells: $(\mathcal{N}_0 - 1)\hbar\omega$, $\mathcal{N}_0\hbar\omega$, and $(\mathcal{N}_0 + 1)\hbar\omega$. Large-scale shell-model codes like KSHELL can handle dimensions up to 10^{10}-10^{11}. The next leading order, $3\hbar\omega$, can be included by considering one-nucleon and three-nucleon excitations. However, for the sd-shell nuclei ($16 < A < 40$), only the $1\hbar\omega$ calculations can be performed. Comparisons between $1\hbar\omega$ and $(1 + 3)\hbar\omega$ calculations have shown that $(1 + 3)\hbar\omega$ calculations improve the description of $E1$ strengths above the IVGDR peak. The inclusion of empirical corrections allows for higher excitation energies in the $1\hbar\omega$ calculations. Different LSSM codes and interaction schemes can be utilized for theoretical predictions and compared with each other.

Ab initio studies of the IVGDR in light nuclei have been performed using no-core shell model calculations for nuclei such as ^{4}He, ^{10}B, and ^{16}O. The treatment of hard-core nuclear forces poses a challenge in these calculations, requiring large model spaces. Recent advancements have softened the nuclear force using techniques such as the similarity-renormalization-group (SRG) evolution. Successful descriptions of the GDR have been obtained using no-core shell model approaches with modern chiral N^{3}LO interactions. In this study, other softened interactions, such as the Daejeon 16 interaction, will be employed to perform no-core shell model calculations for obtaining the GDR of light nuclei. The KSHELL code will be used for these calculations, and further development may be necessary to handle large active shells. Additionally, effective operators for the E1 transition will be constructed to account for renormalization within the model space. In parallel, conventional phenomenological interactions like the WBT interaction will be employed for comparison with the *ab initio* approaches.

To estimate the photoreaction cross-sections of interest in this study, different reaction mechanisms will be simulated using the TALYS code. TALYS is a modern reaction code that incorporates state-of-the-art nuclear models to cover various reaction channels and observables. It considers a wide range of projectiles and ejectiles, as well as single- and multi-particle emissions and fission. The code incorporates experimental information on nuclear masses, deformation, and low-lying state spectra, or uses input models when experimental data is unavailable. The TALYS code provides a comprehensive description of reaction cross-sections, energy spectra, angular distributions, and other relevant quantities. The code includes different models for the dipole strength function, such as the Simple Modified Lorentzian model or the Gogny D1M+QRPA model, and allows for the use of experimental strength data. Recent improvements to TALYS include an updated description of the nuclear level density for light nuclei and the consideration of isospin forbidden transitions (IFT) in the single and multiple particle emission channels. The inclusion of IFT corrections can significantly affect photoemission cross-sections, especially for targets near the $N = Z$ line. While the statistical model of Hauser-Feshbach used in TALYS may not be well-suited for light nuclei, it still provides reasonable estimates for reaction rates, which can be adjusted in specific cases. Additionally, sensitivity analysis and empirical corrections can be applied to improve the accuracy of the calculations.

4 Ultra-High Energy Cosmic Rays

Despite over fifty years of research, the origins of UHECRs, cosmic rays above 10^{18} eV, remain elusive. The study of these cosmic rays, the most energetic particles in the universe, is a key area in high-energy astrophysics. High-quality and detailed measurements of the UHECR spectrum, composition, and arrival direction are now achievable through experiments such as AGASA citeAGSA, HiRes citeHiRes, the Pierre Auger Observatory citeAuger, and Telescope Array (TA) citeTA. These experiments use the detection of extended air showers caused by the interaction of UHECRs in the Earth's atmosphere. Evidence of the suppression of the UHECR flux above $3-5\times10^{19}$ eV is a significant observation at the highest energies. Additionally, composition analyses strongly suggest a mixed composition with a trend towards heavier elements above a few 10^{18} eV. This trend emphasizes the crucial role of complex nuclei in UHECR physics and suggests that UHECRs are accelerated in astrophysical sources, rather than directly produced by exotic high-energy particle physics phenomena. Anisotropies in the arrival directions of UHECRs provide critical insights into their origins. Recent data show clear evidence of large-scale anisotropy in the distribution of the highest energy events, supporting the general idea that UHECRs are of extragalactic origin. However, due to significant angular deflections caused by cosmic magnetic fields, tracing the astrophysical production sites of UHECRs is challenging.

The UHECR spectrum and composition observed on Earth are shaped by particle propagation in the extragalactic medium. During their journey from the sources to Earth, the injected cosmic-ray spectrum and mass composition are modified by interactions with background photons and cosmic magnetic fields, leading to energy and mass losses and deflections. One key feature of the UHECRs' extragalactic propagation is the predicted cut-off in the observed spectrum above a few 10^{19} eV. This cut-off is related to interactions of UHECR protons or nuclei with cosmic microwave background (CMB) photons as well as with infrared, optical, and ultraviolet extragalactic backgrounds. The interaction of cosmic-ray protons or nuclei with low-energy backgrounds (ranging from 10^{-3} eV (CMB) to a few eV (UV)) results in energy losses for the incoming ultra-relativistic cosmic rays either by deceleration or losing nucleons. Consequently, the composition of UHECRs is modified during their journey, emphasizing the importance of accurate models for these interactions in interpreting observational data. The propagation of UHECR nuclei has been less studied than that of protons. The most notable study of UHECR nuclei propagation was conducted by Puget, Stecker, and Bredekamp (PSB) [18], who provided detailed analysis and simple parametrizations for IVGDR and quasi-deuteron (QD) excitation cross sections. Recently, Khan et al [17]. proposed improved estimates of the IVGDR cross-section using the TALYS [19] nuclear reaction code, which showed better agreement with available data.

In recent years, interest in the propagation of UHECR nuclei has grown significantly, especially since recent analyses now indicate a significant contribution of nuclei at the highest energies. The availability of well-constrained and realistic IVGDR cross-section models is critical for extracting the most information from extragalactic UHECR propagation studies. However, the lack of experimental and theoretical constraints on nuclear reactions channels poses large uncertainty originated from the nuclear reactions. The propagation of UHECR nuclei (Ref. [33]) relies significantly on the nuclear interaction models employed. The latest research reveals substantial uncertainties related to photodisintegration cross-sections, particularly in light nuclei, which results from the absence of experimental data. As these cross-sections play a pivotal role in UHECR propagation, it's essential to evaluate the impact of these uncertainties on the predicted UHECR spectrum and mass composition at Earth.

5 Conclusion

The PANDORA project is a comprehensive initiative that aims to systematically explore photonuclear reactions, particularly those involving light nuclei with a mass below A=60. These reactions are important in several domains including nuclear structure and reaction studies, particle and nuclear astrophysics. The project combines experimental and theoretical nuclear physics with particle astrophysics, creating a collaborative approach to study these reactions. In order to measure photoabsorption cross-sections and the decay branching ratio of each decay channel, PANDORA will utilize two modern experimental methodologies: virtual photon excitation via proton scattering, and real photo absorption using a high-brilliance γ-ray beam produced by laser Compton scattering. To predict photonuclear reactions, several nuclear models will be utilized including anti-symmetrized molecular dynamics, mean-field type models, large-scale shell models, and ab initio no-core shell models. The project will also focus on the examination of uncertainties present in these model predictions. The findings will be implemented in the TALYSreaction calculation code, a widely used tool in various scientific fields.

In terms of timeframe, PANDORA's first nuclear physics experiments are set to begin in 2023 at the RCNP and iThemba LABS. The first commissioning of the LCS γ-ray facility at the ELI-NP is slated in 2025. Comprehensive data are expected to be obtained over the next 5-10 years. Concurrently, the development of nuclear models and their application to UHECR propagation simulations are ongoing.

The PANDORA project offers a comprehensive approach to understanding photonuclear reactions in light nuclei. By combining experimental data and theoretical predictions, it promises to advance our knowledge in the fields of nuclear physics, astrophysics, and beyond. The interactions between UHECR physics and nuclear physics have been growing stronger in recent years. The nuclear physics community, with its experimental facilities and theoretical capabilities, can contribute significantly to the UHECR physics field, particularly in reducing the uncertainties in the nuclear data relevant for UHECR propagation studies. This collaboration can undoubtedly lead to a better understanding of the nature and origins of UHECRs.

References

[1] A. Bracco, E. Lanza and A. Tamii, Prog. Part. Nucl. Phys. **106**, 360 (2019).

[2] A. Zilges, D. Balabanski, J. Isaak and N. Pietralla, Prog. Part. Nucl. Phys. **122**, 103903 (2022).

[3] Savran, D., Aumann, T. and Zilges, A. Prog. Parti. Nucl. Phys. **70**, 210-256 (2013).

[4] P. von Neumann-Cosel and A. Tamii, Eur. Phys. J. A **55**, 110 (2019).

[5] D. Brink, Ph.D. thesis, University of Oxford (1955).

[6] P. Axel, Physical Review **126**, 671 (1962).

[7] S. Goriely, Physics Letters B **436**, 10 (1998).

[8] EXFOR Library, https://www-nds.iaea.org/exfor/exfor.htm .

[9] A. Tamii *et al.*, (PANDORA collaboration), submitted to Euro. Phys. J. A.; arXiv:2211.03986 [nucl-ex];

[10] M. Kimura, T. Suhara and Y. Kanada-En'yo, Eur. Phys. J. A **52**, 373 (2016).

[11] Y. Taniguchi, M. Kimura and H. Horiuchi, Prog. Theor. Phys. **112**, 475 (2004).

[12] J. Ahrens *et al.*, Nucl. Phys. A **251**, 479 (1975).

[13] N. Nagano *et al.*, Nucl. Part. Phys. **18**, 423 (1992).

[14] R. U. Abbasi *et al.*, (HiRes Collaboration), Phys. Rev. Lett. **100**, 101101 (2008).

[15] J. Abraham *et al.*, (Pierre Auger Collaboration) Nucl. instrum. and Meth. in Phys. Res. A **523**, 50 (2004).

[16] H. Tokuno *et al.*, (Telescope Array Collaboration) J. Phys. Conf. Ser. **293**, 012035 (2011).

[17] Khan, E. *et al.*, Astroparticle Physics **23**, 191 (2005).

[18] Puget, J. L., Stecker, F. W. and Bredekamp, J. H., Astrophys. J. **205**, 638 (1976).

[19] A.J. Koning, S. Hilaire and M. Duijvestijn, TALYS: A nuclear reaction program, http//www.talys.eu (2004).

[20] R. Neveling *et al.*, Nucl. Instrum. Methods Phys. Res. A, **654**, 29 (2011).

[21] E. Litvinova, P. Ring and V. Tselyaev, Phys. Rev. C **78**, 014312 (2008).

[22] E. Litvinova, P. Ring and V. Tselyaev, Phys. Rev. Lett. **105**, 022502 (2010).

[23] C. Robin and E. Litvinova, Eur. Phys. J. A **52**, 205 (2016).

[24] T. Inakura, T. Nakatsukasa and K. Yabana, Phys. Rev. C **84**, 021302 (2011).

[25] N. Tsoneva, H. Lenske and C. Stoyanov, Phys. Lett. B **586**, 213 (2004).

[26] N. Tsoneva and H. Lenske, Phys. At. Nucl. **79**, 885 (2016).

[27] Y. Utsuno, N. Shimizu, T. Otsuka, S. Ebata, M. Honma and Prog. Nucl. Energy **82**, 102 (2015).

[28] A. Tamii *et al.*, Nucl. Instrum. Methods Phys. Res. A **605**, 326 (2009).

[29] S. Gales *et al.*, Rep. Prog. Phys. **81**, 094301 (2018).

[30] K.A. Tanaka *et al.*,Matter Radiat. Extremes **5**, 024402 (2020).

[31] Y. Fujikawa, K. Sakanashi, S. Adachi, T. Kawabata and T. Furuno *et al.*, private communication; S. Adachi *et al.*, RCNP Annual Report 2021 Highlights (2021), https://www.rcnp.osaka-u.ac.jp/ annurep/2021/.

[32] P. Adsley *et al.*, J. Instrum. **12**, T02004 (2017).

[33] D. Allard, Astropart. Phys. **39**, 33 (2012).