First PANDORA Experiment for the Study of Photo-Nuclear Reactions of Light Nuclei

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1 Photo-Nuclear Reactions of Light Nuclei

Photonuclear reaction data are essential for understanding the response of nuclei to an external electric dipole ($E1$) field [1, 2]. The experimental data and theoretical predictions play a pivotal role in a wide range of applications such as nuclear physics, nuclear- and particle- astrophysics, radiation shielding, nuclear medicine and nondestructive investigation [2, 3]. One of the key aspects of the photonuclear reaction is excitation of the Isovector Giant Dipole Resonance (IVGDR), a collective dipole oscillation between neutrons and protons, that consists of the dominant part of the $E1$ response [4, 5]. Photonuclear reaction data are scarce in light nuclei below a mass of A=60 especially for the photoabsorption cross sections and for the partial cross sections of the charged particle decay channels. Prediction of the photonuclear reactions in this low mass region pose unique challenges to theoretical models such as greater impact of nuclear shell structure and nucleonic correlations including α-clustering as well as the importance of the direct and preequilibrium decays, and isospin-selection rule in the α-decay processes. Additionally, the IVGDR distribution in this region is often fragmented, making the study more complex, in contrast to case of heavier nuclei ($A \geq 90$)

The PANDORA (Photo-Absorption of Nuclei and Decay Observation for Reactions in Astrophysics) project [6] has been launched to attack this nuclear physics problem. The PANDORA project is a collaboration among the fields of experimental nuclear physics, theoretical nuclear physics, and particle astrophysics. The primary goal is to produce precise systematic data of the photo-nuclear absorption cross sections and decay branching ratios for key light nuclei in the mass region below iron. Two complementary methods will be applied to this purpose: virtual photon excitation by proton scattering and real photon excitation by a quasi-monoenergetic gamma-ray beam. Three facilities form the core of experimental part of project, RCNP (virtual photon), iThemba LABS (virtual photon), and ELI-NP (real photon), while several nuclear theory groups are developing theoretical models for systematic predictions of photo-nuclear reactions. The experimental and theoretical results will be implemented in TALYS, a general nuclear reaction code, and be available for applications. 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.

A white paper of the PANDORA project [6] and UHECR propagation simulation using predictions by a nuclear model [7] were published last year. As a related subject, photo-neutron emission on ^{13}C measured at NewSUBARU was published in the beginning of this year [8].

2 The first PANDORA experiment at RCNP

The first PANDORA experiment was held at RCNP under the program number E563 in October, 2023. The (p, p') cross sections together with the charged particle and gamma decays were measured at E_p=392 MeV covering a scattering angle from 0.0 to 7.8 degrees. The targets were ^{10,11}B for (p, p') cross sections and ^{12,13}C and ^{27}Al for (p, p') cross sections and charged particle decay coincidence. The photo-absorption cross sections will be determined from the (p, p') cross sections at 0.0-0.5 degrees by subtracting contributions from multipolarities other than $E1$, using multipole decomposition analysis (MDA) based on the angular distribution of the cross sections. The measured excitation energy is 7-32 MeV, that corresponds to the photon-energy for photo-absorption cross sections, covering most of the part of the IVGDR. The $(p, p'p)$ and $(p, p'\alpha)$ reactions were measured by decay charged-particle coincidence for extracting the branching ratios of the charged particle decay of the IVGDR for each of the daughter excited state. The emitted gamma-rays from the excited target nuclei were measured in coincidence for both of the (p, p') and charged-particle coincidence measurements for studying the gamma decay of IVGDR and for tagging the gamma-ray from the daughter excited states after particle decay.

The experimental setup is shown in Fig. 1. Two setups of the Grand Raiden (GR) spectrometer were used: zero-degree transmission mode [9] and the GRAF (Grand RAiden forward) [10] mode. In the former mode the GR spectrometer was placed at zero degrees to cover a scattering angle of 0.0-3.0 degrees. The primary

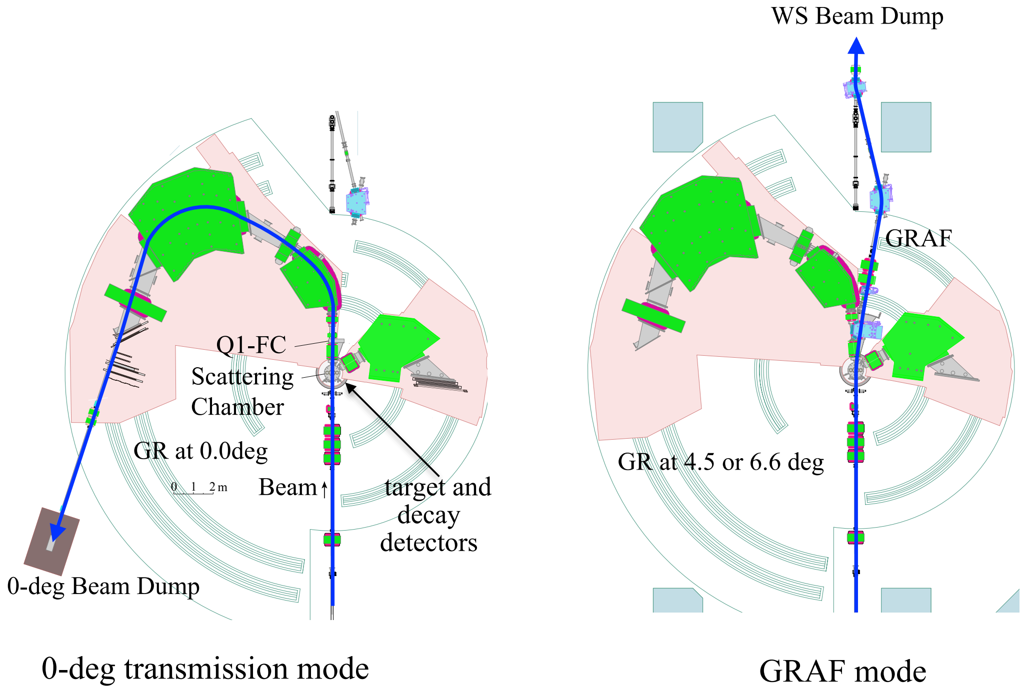

Figure 1: Experimental setup of the proton scattering measurement. Left panel: zero-degree transmission mode where the Grand Raiden (GR) spectrometer was placed at zero degrees and the primary beam was stopped at the zero-degree beam dump after transportation through the spectrometer. Right panel: GRAF (Grand RAiden Forward) mode where the spectrometer was placed at 4.5 or 6.6 degrees. The primary beam was deflected by the fist quadrupole magnet of the GR spectrometer and the bending magnet of the GRAF line and stopped at the WS beam dump located 20 m down stream of the target.

beam that passed that target was stopped at the zero-degree beam dump that was shielded by concrete after transporting in the GR spectrometer. Since the magnetic field of the spectrometer is fixed to transport the beam, the measured excitation energy is fixed to 7-32 MeV. In the latter mode, the spectrometer was placed at 4.5 or 6.6 degrees to cover a scattering angle ranging from 3.5 to 7.7 degrees. The primary beam was deflected by the first quadrupole magnet of the spectrometer (GR-Q1) and the two bending magnets of the GRAF beam line (WSF-BM1 and BM2). The beam was transported through the GRAF beam line, guided back to the straight section of the WS beam line, and to the WS beam dump embedded in the wall of the experimental hall located 20 m downstream of the target.

The silicon detector array, SAKRA (Silicon Array developed by Kyoto and osaka for Research into Alpha cluster states) [11], was placed in the target vacuum chamber dedicated to the PANDORA experiment as shown in Fig. 2. The SAKRA array consisted of five pairs of double sided silicon strip detectors (DSSSDs) with a thickness of 500 μm of the MMM design from the Micron Semiconductor Limited. The SAKRA array was placed at the backward angle side (upstream side) of the target covering $\sim \pi$ solid angle. The first layer of the DSSSDs can stop charged particles up to the energy of 8.3, 11.2 and 33.2 MeV for p, d and α particles, respectively. The SAKRA detectors could work up to a beam intensity of $\sim$4 nA for the used target with a thickness of $\sim$1 mg/cm^2.

The configuration of the SCγLLA (Supporting Construction for γ-ray-detecting Large LaBr3 Array) [10] was modified for accommodating the PANDORA scattering chamber and was placed at around the target position for detecting γ-rays from the IVGDR by using eight large-volume $LaBr_3$(Ce) detectors [12, 13] from Milano. The distance from the target to the front face of the $LaBr_3$(Ce) detectors is $\sim$200 mm.

The experimental setup was completed in three weeks on September 2023. Since it was the first PANDORA experiment and the setup comprises of three main detection systems, we needed relatively long time for the installation of the dedicated target chamber for PANDORA, modification of the LaBr3 detector array, installation of the SAKRA silicon detectors, setup of the DAQ system, and installation of the 0-degree beam line and the GRAF beamline. During the ssetup on September and the beamtime on October, in total 46 collaborators joined the work, out of which 31 were from abroad (South Africa, Romania, Italy, Germany, France, Norway and China).

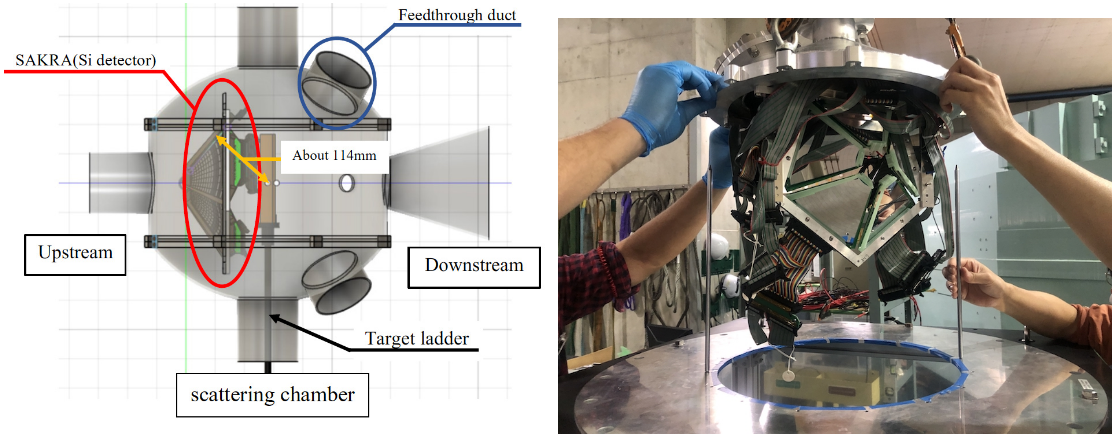

Figure 2: Experimental setup of the proton scattering measurement. Left panel: zero-degree transmission mode where the Grand Raiden (GR) spectrometer was placed at zero degrees and the primary beam was stopped at the zero-degree beam dump after transportation through the spectrometer. Right panel: GRAF (Grand RAiden Forward) mode where the spectrometer was placed at 4.5 or 6.6 degrees. The primary beam was deflected by the fist quadrupole magnet of the GR spectrometer and the bending magnet of the GRAF line and stopped at the WS beam dump located 20 m downstream of the target.

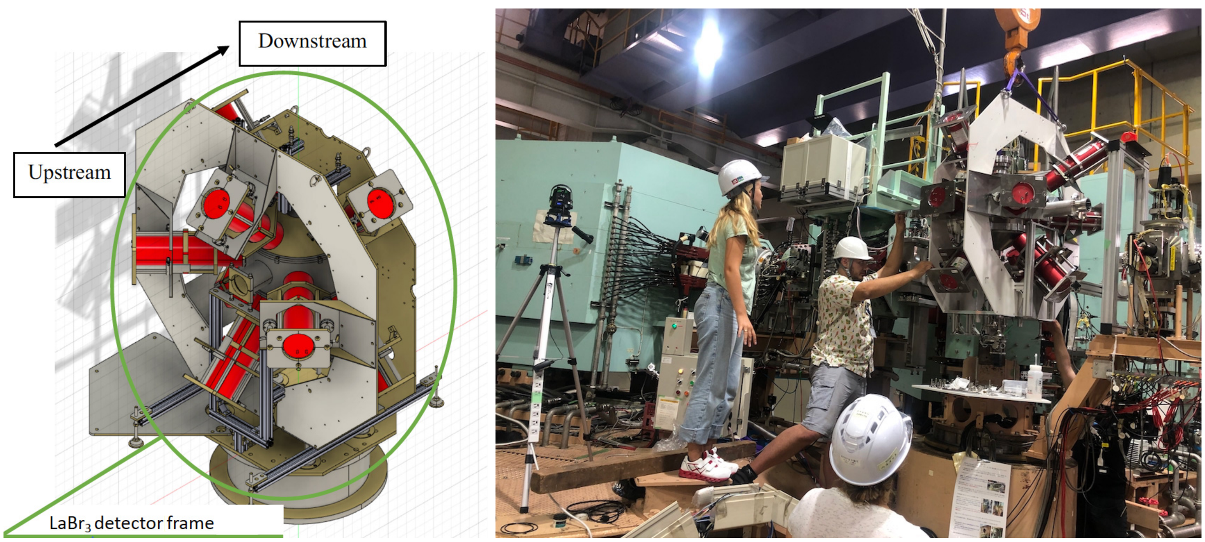

Figure 3: Left panel: a gamma-ray detector array SCγLLA [10] using eight large-volume $LaBr_3$(Ce) detectors [12, 13] was modified to accommodate the PANDORA scattering chamber at the center. Right panel: a picture during the placement of SCγLLA at the target position.

The measurement was successfully performed for a beamtime of the approved eight days. A day of beamtime was left due to troubles of the buncher between the two cyclotrons, interlock system of the radiation safety, and the trip of the main coil of the RING cyclotron. A scattering angle calibration of the GR spectrometer was separately performed on April, 2024, by using a half day of the remaining beamtime. The data analysis is in progress by the individual groups of Japan, South Africa and Romania, having a regular weekly meeting together. A preliminary results are plotted in Fig. 5 for (left panel) the excitation energy of ^{12}C at the spectrometer angle of zero-degrees after background subtraction and (right panel) the correlation between the energy deposited in the first layer of the SAKRA DSSSD's are the excitation energy measured by the GR spectrometer. In the right panel, proton decay events from the giant resonances in ^{12} are observed clearly as the most intense locus and the parallel lines above E_x=16 MeV corresponding to the daughter ground state and excited states, respectively. The decreasing curve observed above E_x 25 MeV is the proton decay events to the ground state for that the protons punched through the first layer of SAKRA DSSSDs. Vertical straight line at E_x=15 MeV is accidental coincidence events. In E_x=10-20 MeV, alpha-decay events are observed as vague tilted lines on top of accidental

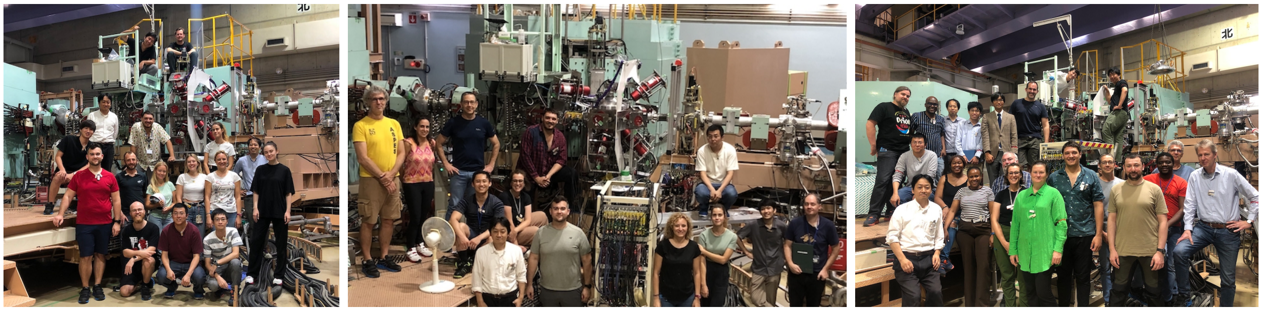

Figure 4: Left: Group photos during the PANDORA setup and beam time. Note that not all the participants are shown in the pictures.

coincidence events. Particle identification and coincidence analysis of the double layers of the SAKRA detectors are in progress and are not applied in the figure yet.

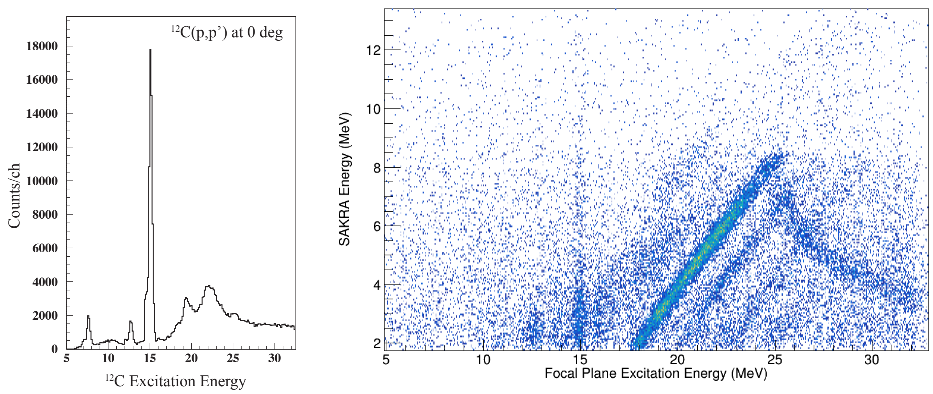

Figure 5: Left: Excitation energy spectrum of ^{12}C at 0-3° after background subtraction. Right: The coincidence matrix of energy detected in the first layer of SAKRA for decay charged particles versus the excitation energy of ^{12}C with the scattering angle coverage of 0-3°.

3 INTPART School and the 3rd PANDORA Workshop

Preceding the experiment at RCNP, an INTPART (International Partnerships for Excellent Education and Research) school 2023 for photo-nuclear reactions and the third PANDORA workshop were organized [14] (see Fig. 6) at Kafuu Resort Fuchaku in Okinawa for February 20 - March 3 and from March 5-7, respectively, in 2023. The school and the workshop were supported through the INTPART funding from Norway by the Department of Physics, Oslo university, bilateral funding between RCNP and Witwatersrand University, r-EMU and Nishina Center from RIKEN, and Center for Nuclear Study (CNS), University of Tokyo. We invited distinguished researchers, M.N. Harakeh (Univ. Groningen) for giant resonances, Y. Utsuno (JAEA and CNS, Univ. Tokyo) for the shell model , T. Otsuka (RIKEN and CNS, Univ. Tokyo) for the new aspects of nuclear structure, and D. Suzuki (RIKEN) for unstable nuclei in addition to topical lectures by A. Görgen (overview of the giant resonances), D. Allard (Ultra-High-Energy Cosmic Rays), P.-A. Söderström (Photonuclear Study at ELI-NP), L. Pellegri (Photonuclear Study at iThemba LABS), E. Sahin (Evolution of Magic Number), and K. Teruya (Culture and History of Okinawa). Hands-on sessions are organized for shell-model calculations (Y. Utsuno) and for data analysis of an unstable nuclear beam experiment (D. Suzuki). We also had sessions for student presentation and feedbacks as well as social events. In total 51 people participated, out of that 16 were from Norway, 9 from South Africa, and 23 from Japan.

The PANDORA workshop was held as hybrid of on-site and remote connection having 27 participation out of that 21 were on-site. Presentations and discussion were held for each of the nuclear experiment, nuclear theory, and particle astrophysics groups on such as the results of test measurement and experimental plan, progress of the theoretical predications, and results of UHECR simulations.

The school and workshop were quite beneficial for education of students and young researches, establishing the international communication among the participating groups, and for organizing the collaboration of the coming experiment.

Figure 6: A picture in the INTPART school 2023 during the lecture by M.N. Harakeh on giant resonances held at Kafuu Resort Fuchaku in Okinawa, Japan

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