PANDORA WORKSHOP 2020

30th June - 1st July 2020

Report

Summary of the UHECRs session:

Chair - Vincent Tatischeff

In this session we discussed the physics of ultra-high energy cosmic rays (UHECRs) and the nuclear ingredients that are currently missing to interpret the data accumulated mainly by the Pierre Auger Observatory and the Telescope Array. The spectrum of cosmic rays (one of the "wonders of the physical universe"; *Etienne Parizot*) extends over more than 13 orders of magnitude in energy. Above the so-called "ankle" at ~4×10^{18} eV, the UHECRs are most probably of extragalactic origin, but their astrophysical sources are still unknown. Measurements by the Pierre Auger collaboration of the depth of the maximum of the air showers produced by UHECR interactions in the Earth atmosphere (X_{max}) indicate that their composition becomes increasingly heavier with energy, with intermediate mass elements such as CNO being probably dominant above ~10^{19} eV. The astrophysical interpretation of these data requires a detailed model for the propagation of UHECRs from their sources to the Earth (*Denis Allard*), in the course of which the cosmic-ray spectrum and composition are modified by interactions with extragalactic photon fields, mainly the cosmic microwave background (CMB), but also the infrared, optical and ultra-violet backgrounds. A major interaction process for complex nuclei (A = 2 and heavier) is photodisintegration through excitation of the giant dipole resonance (GDR), which, for interactions with CMB photons (~10^{-3} eV), can occur in nuclei of Lorentz factor above ~$10^{9.5}$.

The UHECR propagation models thus require a good knowledge of the total photoabsorption cross section for at least the most abundant complex nuclei in the universe (^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si… ^{56}Fe) and ideally for around 380 isotopes up to ^{56}Fe. Comparison of various nuclear models (from Inakura et al. 2009, 2011 and TALYS-1.95) shows that the predicted GDR peak energies and cross sections can vary by large factors, which can induce significant changes in the UHECR propagated spectra (*Eiji Kido*). We also need a better knowledge of the decay branching ratios in these nuclei. Thus, changing some input parameters of TALYS-1.95, in particular to take into account isospin forbidden transition effects, can modify predictions for alpha emission channels by up to an order of magnitude, which can have a significant effect on the speed of CNO photodisintegration (*Denis Allard*). Good measurements of (γ,α) cross sections for CNO nuclei are required to constraint the nuclear models, but most previous measurements using nuclear emulsion techniques have not resulted in consistent results. More reliable measurements are those of the radiative capture cross sections (α,γ), which are related to the photodisintegration cross sections (γ,α) via the detailed balance theorem (*Jürgen Kiener*).

Future work should include in the calculations photoabsorption data and corresponding GDR parameters from available data compilations (see Plujko et al. 2018, At. Data Nucl. Data Tables 123-124, 1). It should also account for some known discrete levels in light nuclei (lighter than A ~ 24), which could have a significant effect on the photodisintegration probabilities. Then, the effect on the propagation model of the most important remaining nuclear uncertainties should be quantified through statistical comparison of the model results with the relevant astrophysical data: the measured UHECR spectrum and the energy evolution of the mean mass <ln(A)>.

Summary of the Nuclear Reaction session:

Chair - Elias Khan

The nuclear reaction session first provided a status of the TALYS code, showing how it can be useful to predict photodisintegration cross-sections through the statistical model and also with considering discrete levels. The application to light nuclei involved in the UHECR physics was also discussed, including those which could be measured at ELI-NP.

<u>The main conclusions of this session are</u>:

- Data on photostrength on light nuclei is needed in order to constrain QRPA-like calculations.
- This data is not only useful for UHECR (other applications).
- Theoretical uncertainties on the calculations should be provided in order to compare with the astrophysical one.
- One possibility is to perform Monte Carlo sampling on the input of the TALYS calculation, in order to provide error bands.

- There are three main dependencies of the TALYS results on the inputs: i) the E1 strength, ii) the isospin reduction and iii) the level density.
- The optical potential has a little impact on the results, at least in the neutron emission case.
- There is also a dependency related to the statistical Hauser-Feshbach approach, compared to the contribution of discrete levels, which needs to be taken into account in these light nuclei involved.
- ^{17}O could be a relevant benchmark nuclei to test the TALYS predictions

Summary of the Experiments session:

Chair - Luna Pellegri

In this session a survey on currently available data and a description of the experimental methods was given by *Atsushi Tamii*. From this analysis it is clear that the available data on the relevant nuclei for UHECRs are poor and inconsistent. The use of monoenergetic or quasi-monoenergietic photon beams was indicated as essential to reduce the uncertainties in the GDR measurements since an almost direct measurement of the photabsorption cross section is possible. An alternative technique to real photon beams relies on the use of virtual photons exchanged via Coulomb excitation induced by high-energy proton scattering (Ep > 200 MeV). In this kind of experiment in addition to the excitation response, the gamma and particle decays can also be measured and used to extract the relevant decay branching ratios. Two additional important requirements were outlined for these measurements: good energy resolution (below 200 keV) to reduce fluctuations by fine structure and good absolute cross section normalization (5-10%) are required.

The three facilities involved in the PANDORA project were presented. RCNP and iThemba LABS will use the Virtual Photon technique to extract the total E1 strength distribution up to 32 MeV and 24 MeV, respectively. The high-resolution magnetic spectrometers, Gran Raiden and K600, will be used. The gamma-, proton- and alpha-decay branching ratio will be extracted with the use of ancillary detectors. The first experiment on 12C and 27Al will run in 2021 at iThemba LABS. RCNP will restart performing experiments from 2022 onwards; a proposal will be submitted to the RCNP-PAC in 2021. ELI-NP will make use of high-flux monoenergetic real photon beam with very high-energy resolution (< 0.5% FWHM) to measure the absolute photoabsorption cross section up to 20 MeV. Neutron, proton, alpha, gamma-decays will be measured using ELIGANT and ELISSA.

Possibility to measure neutron-alpha decay. The facility will be in operation from 2023 onwards. The consistency between experiments will be cross-checked by using a target of 27Al. Details on the three facilities can be found in the individual talks.

Relevant points of the discussion:

- Improvement made at the Tagged-photon facility in Darmstadt will allow measurements of the photoabsorption cross section in light nuclei (A < Ca) where the atomic background can be precisely calculated by theoretical models. *Peter von Neuman-Cosel* proposed to use the 27Al as the feasibility test target for this facility.
- For UHECRs physics, the most important information that needs to be extracted from the experiment is the total branching ratio for particle decays in particular alpha-decay. Information on the isospin mixing and direct decay of GDR should also be investigated to improve the models used in the TALYS calculations.
- To obtain the total branching ratio for the nuclei of interest, the lowest experimental alpha-energy threshold can be set at about 2 MeV since lower-energy alpha emission will be inhibited by the Coulomb barrier and therefore would have minimal contribution to the total alpha branching ratio.
- Type of reactions and reaction parameters that are relevant in UHECRs: from calculation performed by *Denis Allard*, it seems that multi-particle emission channels are particularly relevant for the photodisintegration paths when considering specific settings of TALYS. Important to investigate the multi-particle emission experimentally to test TALYS models → possibility to investigate it at RCNP at the highest excitation energy accessible.
- 10-11B nuclei could be important to be measured because of their relevance in the photodisintegration chain of UHECRs since they preferentially decay to 8Be and subsequently by 2-alphas).

Summary of the Structure Theory session:

Chair - Peter von Neumann-Cosel

In this session microscopic approaches for the calculation of the electric dipole response in the nuclei of interest and of branching ratios for particle emission were presented. *Tsunenori Inakura* discussed the RPA approach and the influence of different interactions, *Elena Litvinova* presented Relativistic Nuclear Field Theory (RNFT) and *Maasaki Kimura* the

Antisymmetric Molecular Dynamics (AMD) model. It became clear in the presentations and discussions that these models are complementary in their advantages and limitations. RPA is a versatile approach, where interactions can be tuned to globally improve the predictive power for certain observables (like the GDR properties in the present case). RNFT is comparable on the RPA level but allows to include coupling to complex configurations providing a more realistic picture of the resonance spreading. Both models can be extended to include nucleon emission but (at present) not α emission. AMD on the other hand includes particle-hole and cluster degrees of freedom on equal footing and is therefore well suited to predict widths and branching ratios including α decay but uses a simple phenomenological interaction which needs to be tuned to the specific case.

For the goals of the PANDORA experiments the following theoretical studies and developments would be important. Since work with RPA and RNFT in light nuclei is limited so far, their predictive power needs to be studied for the range of nuclei to be investigated experimentally. In particular, it would be important to see how the microscopic models compare with the semi-phenomenological approaches presently used (discussed by *Stephane Goriely*). AMD can provide theoretical results directly comparable to the expected experimental results for partial photoabsorption cross sections into different decay channels. However, it needs to be investigated how well the interactions work over a larger range of nuclei and if full network calculations of the mass distribution can be based on that.