

Photonuclear reactions for ultra-high
energy cosmic-ray propagation and
disintegration

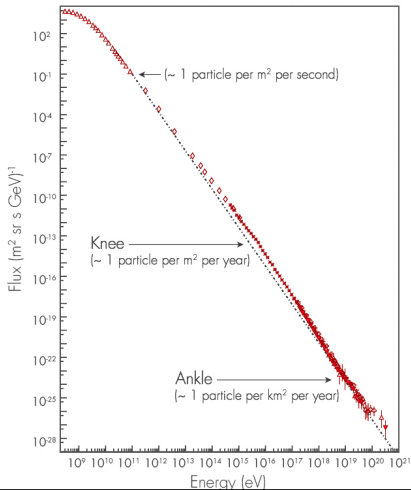
Pär-Anders Söderström
par.anders@eli-np.ro

Nuclear Physics in Astrophysics XII (NPA-XII)

What are cosmic rays?

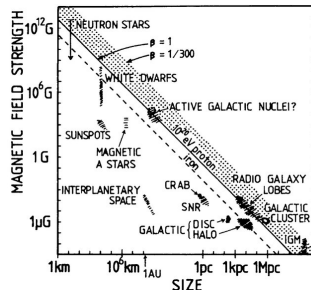
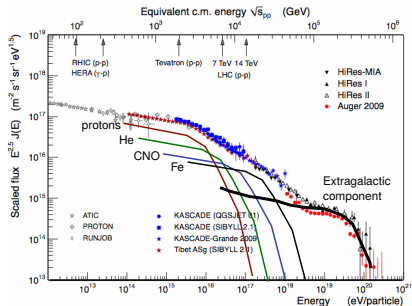


FLUXES OF COSMIC RAYS



- ▶ In nuclear physics, cosmic rays often appear as detector background
- ▶ But, very broad spectrum: 12 orders of magnitude in energy and 32 in flux
- ▶ Low energy, high flux: satellite and atmospheric balloons
- ▶ High energies, low fluxes: air shower detectors
- ▶ Highest energies (10^{20} eV), lowest fluxes ($< 1/\text{km}^2/1000$ years): Giant air shower detectors
- ▶ The most energetic particles known to exist in the universe

What is the UHECR spectrum?

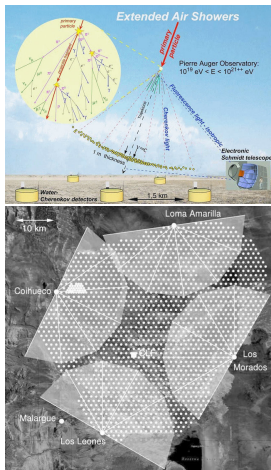


A. M. Hillas.: *Ann. Rev. Astron.*

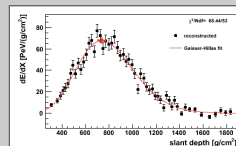
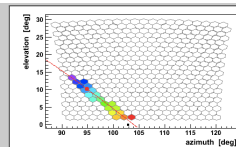
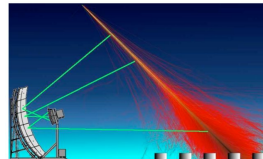
Astrophys. 22, 425 (1984)

- ▶ Need a cosmic accelerator that can do up to EeV, keep the particles in the accelerator!
- ▶ Limit: $E_{\max} = ZuBL$, Z charge, u flow velocity of accelerating matter, B magnetic field, L size of accelerator
- ▶ Strong magnetic fields or large size. Active galactic nuclei? Gamma-ray bursts? Galaxy clusters? Young neutron stars?

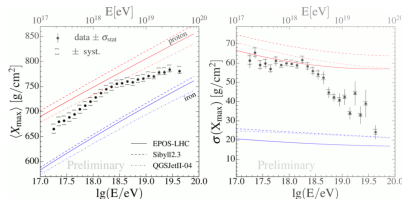
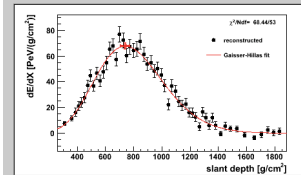
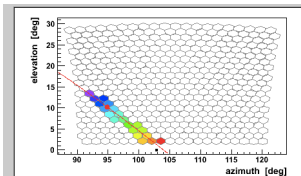
Example: Pierre Auger - Hybrid detector system



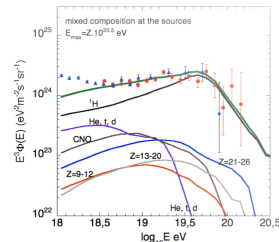
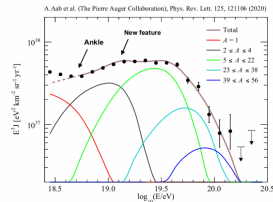
- ▶ Scintillator detectors for energy
- ▶ Fluorescence (UV) detectors from N_2 molecules
- ▶ $\sim 10\%$ of events in both
- ▶ The UV picture of the shower development is captured by the PMTs
- ▶ The position of the maximum of longitudinal development ($X_{\max}$) constrains the composition
- ▶ $X_{\max}$ is the atmospheric depth of the maximum of air shower development - can be calculated for a given primary mass and energy



Some results from Pierre Auger

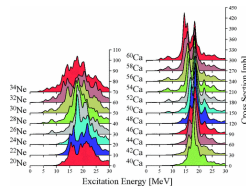
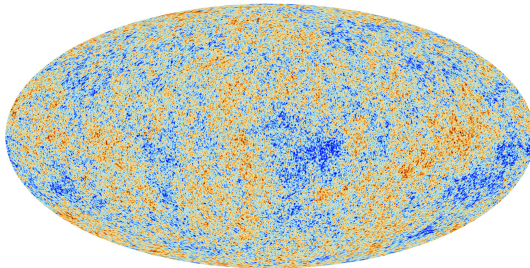
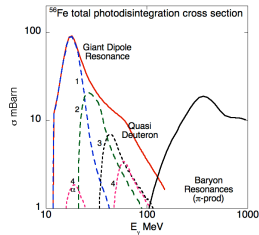
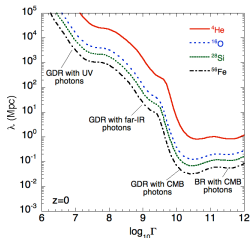


- ▶ Example: Mixed composition similar to that of low energy galactic cosmic-rays
- ▶ Incompatible with data from Auger!
- ▶ Dominant sources of UHECR do not accelerate protons to the highest energies

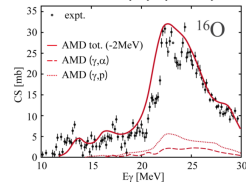


D. Allard: private communication

Extragalactic UHECRs fly through empty space... almost



T. Inakura, et al.: *Phys. Rev. C* 84, 021302(R) (2011)

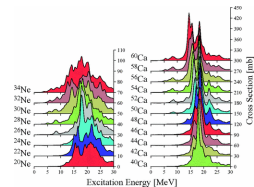
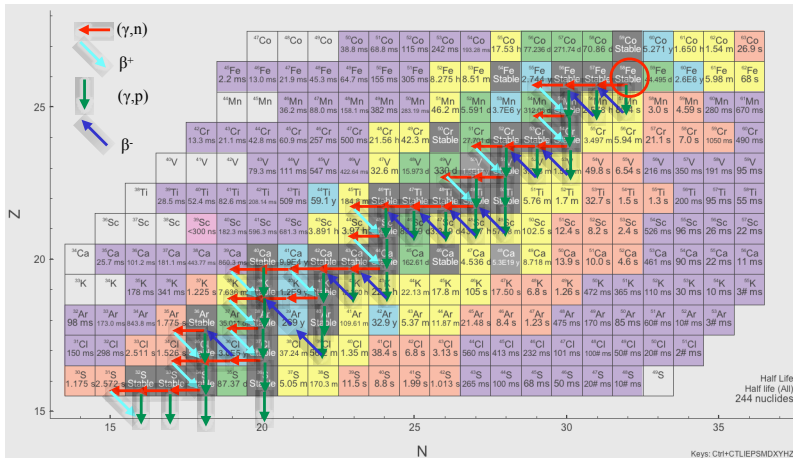


M. Kimura, Y. Taniguchi:
Private communication

D. Allard: *Astropart. Phys.* 39-40, 33 (2013)

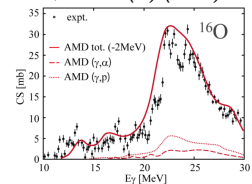
- ▶ Very low density in extragalactic space
- ▶ Except for Cosmic Microwave Background!
- ▶ Extremely high energy, extreme Doppler shifts
- ▶ Enough for nuclear excitations to reduce the mean-free path!

Nuclear data for Ultra High-Energy Cosmic Rays



T. Inakura, et al.: Phys. Rev.

C 84, 021302(R) (2011)



M. Kimura, Y. Taniguchi:

Private communication

Astroparticle physics



Japan



Romania



South Africa

Nuclear physics

Theory

- ▶ Propagation Calculations
- ▶ Galactic magnetic field
- ▶ Acceleration mechanisms

Experiment

- ▶ Pierre Auger
- ▶ Telescope Array
- ▶ Source direction
- ▶ Composition

Theory

- ▶ Reaction theory
- ▶ Structure theory
- ▶ Shell model, mean-field models, ab-initio models...

Experiment

- ▶ $(p, p'x)$
 - ▶ RCNP, Japan
 - ▶ iThemba LABS, South Africa
- ▶ $(\gamma, \gamma'x)$, ELI-NP

- ▶ Oct 2023, RCNP: ^{10}B , ^{11}B , ^{12}C , ^{13}C , ^{27}Al
- ▶ Oct 2025, RCNP: ^{12}C , ^{27}Al , ^{24}Mg , ^{56}Fe
- ▶ High-priority to-do: ^6Li , ^7Li , ^9Be (Lightest IVGDR), ^{24}Mg , ^{28}Si , ^{32}S , ^{40}Ca (α -clustering), ^{26}Mg , ^{48}Ca ($N > Z$), ^{14}N , ^{51}V (odd-even and odd-odd effects)

A. Tamii, et al.: *Eur. Phys. J. A*, 59 (2023) 208

Probes for the Electric Dipole Response of Nuclei

1. Real photon absorption

- (γ, γ') Nuclear Resonance Fluorescence
- (γ, n) , $(\gamma, 2n)$, (γ, p) , ... photodisintegrations



a γ -beam at ELI-NP

pure EM probe by quasi-monoenergetic γ
precise absolute strength
partial strength for each decay channel including n
clear selection of E1 and M1 (polarized-gamma)
up to 20 MeV at ELI-NP

2. Virtual photon excitation (Coulomb excitation)

- proton inelastic scattering at 0 deg.



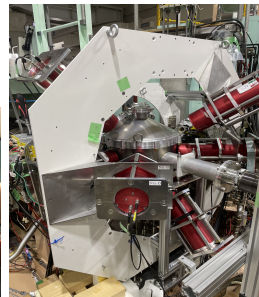
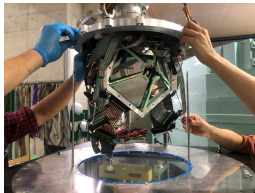
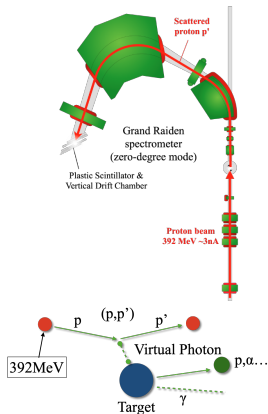
a proton beam at RCNP
and iThemba LABS

dominantly electric excitation: req. decomposition
 E_x distribution is obtained in one shot
sensitive to the total strength
up to 32 MeV at RCNP

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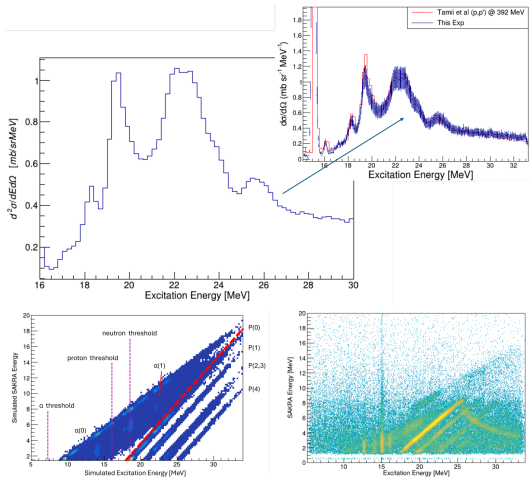


A. Tamii: private communication



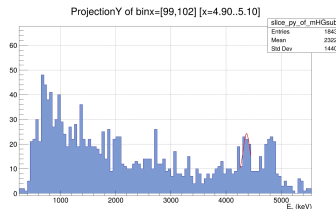
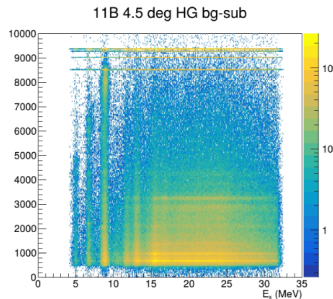
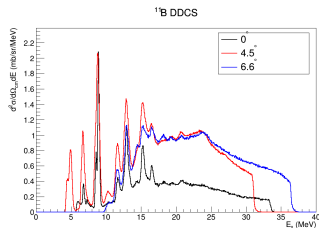
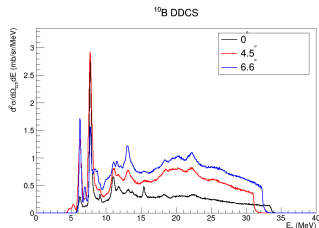
- ▶ Virtual photon excitation
- ▶ Grand Raiden for excitation energy
- ▶ SAKRA for charged particles
- ▶ SC γ LLA for γ rays

Y. Suzuki, et al.: private communication



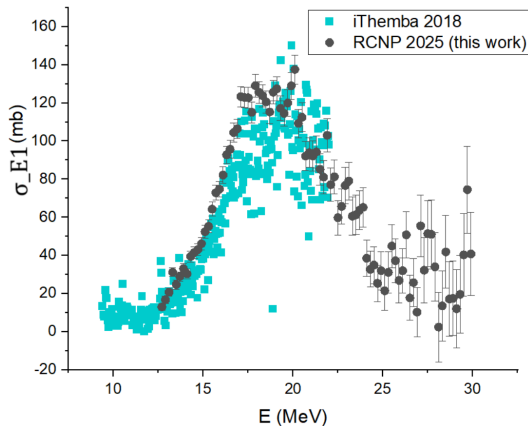
J.A.C. Bekker, et al.: *Proceedings of SAIP 2025 (2025)*

- ▶ PhD Thesis of Jacob Bekker, University of the Witwatersrand, South Africa. Defended 2025.
- ▶ Total cross-section in agreement with previously published results
- ▶ In addition: Decay branching of charged particles (SAKRA Si detector)
- ▶ Clear proton bands, in agreement with simulations
- ▶ What about the α structures? should be isospin forbidden?
- ▶ Detailed angular distribution analysis in progress



- PhD Thesis of Andreea Gavrilesu. In progress.
- Double-differential cross sections show a complex angular dependence.
- In addition: Decay branching of γ rays (SC γ LLA scintillator detector)
- Detailed angular distribution analysis in progress

A. Gavrilesu, et al.: Poster presentation



D. Chelaru, et al.: Poster presentation

- ▶ Second experiment in October 2025
- ▶ Masters Thesis of Daniel Chelaru. Presented 2026. PhD work in progress
- ▶ Corrected double-differential cross sections; equivalent photo-absorption and E1 strength inferred using the virtual photon method
- ▶ Detailed angular distribution analysis in progress
- ▶ Additional future work: Decay branching of γ rays (SC γ LLA scintillator detector) and charged particles (SAKRA silicon detector)

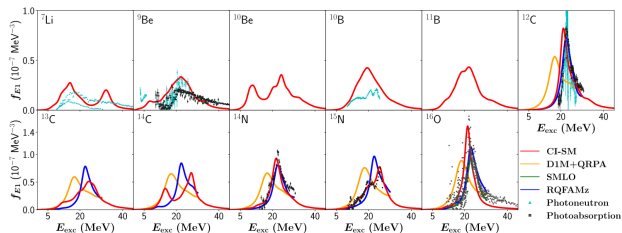
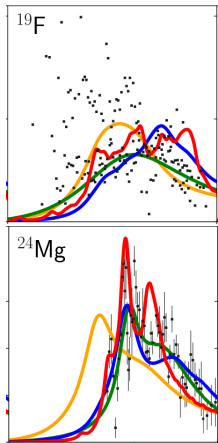


FIG. 1. Photoabsorption strength functions in p -shell nuclei. Results obtained in this work (red lines) are compared with available experimental data [31] (symbols), RQFAMz results from Ref. [49] (blue lines), SMLO PSFs [15,16] (yellow lines), and D1M + QRPA calculations [18].

O. Le Noan, et al.: Phys. Rev. C 113, 044319 (2026)

- ▶ Reliable theory critical, little data available
- ▶ Even when data exist, is it even useful?
- ▶ Can not measure everything, but hopefully enough for calculations to fill in the gaps



PANDORA Project for the study of photonuclear reactions below $A = 60$

PANDORA Collaboration

A. Tamii^{1,2,3,a} , L. Pellegrini^{4,5}, P.-A. Söderström⁶, D. Allard⁷, S. Goriely⁸, T. Inakura⁹, E. Khan¹⁰, E. Kido¹¹, M. Kimura^{11,12,13}, E. Litvinova¹⁴, S. Nagataki¹¹, P. von Neumann-Cosel¹⁵, N. Pietralla¹⁵, N. Shimizu¹⁶, N. Tsoneva⁶, Y. Utsuno¹⁷, S. Adachi¹⁸, P. Adsley^{19,20}, A. Bahini⁵, D. Balabanski⁶, B. Baret⁷, J. A. C. Bekker^{4,5}, S. D. Binda^{4,5}, E. Boicu^{6,21}, A. Bracco^{22,23}, I. Brandherm¹⁵, M. Breznanu^{6,21}, J. W. Brummer⁵, F. Camera^{22,23}, F. C. L. Crespi^{22,23}, R. Dalal²⁴, L. M. Donaldson⁵, Y. Fujikawa²⁵, T. Furuno³, H. Haoning¹⁴, R. Higuchi¹¹, Y. Honda³, A. Gavrilescu^{6,26}, A. Inoue¹, J. Isaak¹⁵, H. Jivan^{4,5}, P. Jones⁵ , S. Jongile⁵, O. Just^{11,27}, T. Kawabata³, T. Khumalo^{4,5}, J. Kiener¹⁰, J. Kleemann¹⁵, N. Kobayashi¹, Y. Koshio²⁸, A. Kuşoğlu^{6,29}, K. C. W. Li³⁰, K. L. Malatji⁵, R. E. Molaeng^{4,5}, H. Motoki¹², M. Murata¹, A. A. Netshiy^{4,5,31}, R. Neveling⁵ , R. Niina¹, S. Okamoto²⁵, S. Ota¹, O. Papst¹⁵, E. Parizot¹⁰, T. Petruse⁶, M. S. Reen³², P. Ring³³, K. Sakanashi³, E. Sideras-Haddad⁴, S. Siem³⁰, M. Spall¹⁵, T. Suda³⁴, T. Sudo¹, Y. Taniguchi³⁵, V. Tatischeff¹⁰, H. Utsunomiya^{36,37}, H. Wang^{36,38,39}, V. Werner¹⁵, H. Wibowo⁴⁰, M. Wiedeking^{4,5}, O. Wieland²³, Y. Xu⁶, Z. H. Yang⁴¹

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