PANDORA Project Status
and
Detection of Gamma-Rays from Laser Plasma

Atsushi Tamii

Research Center for Nuclear Physics (RCNP)
Osaka University, Japan

NEWS Colloquium, April 28th, 2023
RCNP and Online

Photo-Nuclear Reactions of Light Nuclei

What we wan to do

Prediction of photo-nuclear reactions from very light to A=60 nuclei

What are the problems?

Data are very scarce, especially for charged particle decays

Large mutual inconsistencies among the existing data.

There are no“good” predictions by theoretical models
(developments in AMD, Shell-Model, RPA, Ab-Initio,…)

Decay process is not described well by theoretical models.

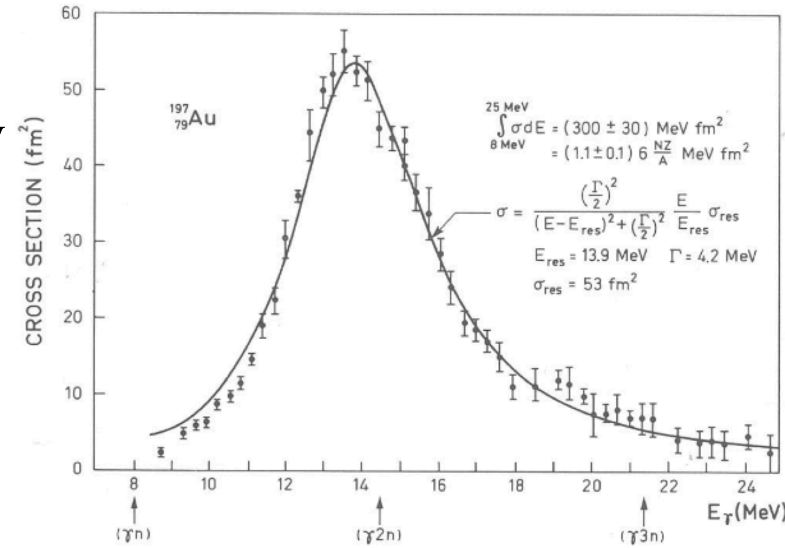
Direct and pre equilibrium decays are also important.

Statistical decay calculations are inapplicable to light nuclei

Is the photo-absorption cross section well understood?

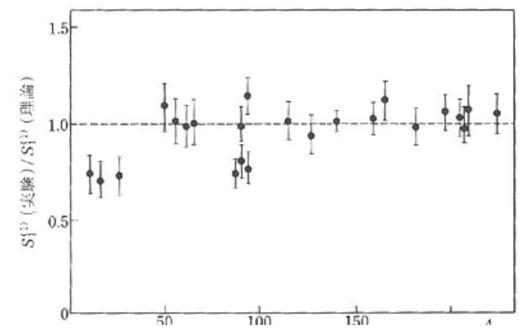
Being studied since the discovery of GDR

However, systematic studies are limited in heavy nuclei for (γ,xn) processes

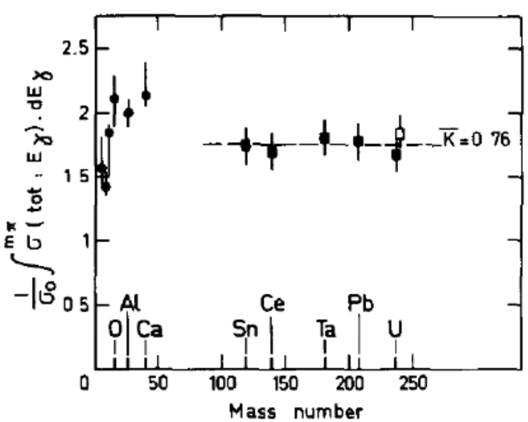


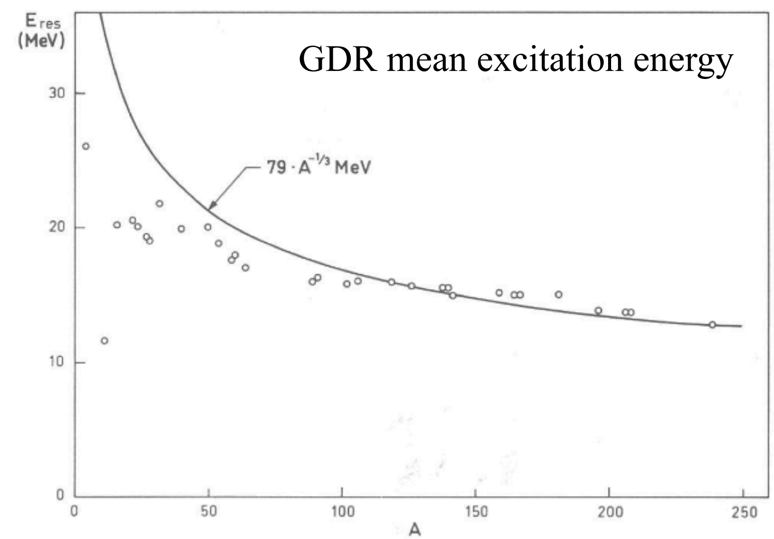
Comparison with the TRK sum rule

up to 30 MeV



up to 140 MeV





GDR mean excitation energy

Bohr and Mottelson

Is the photo-absorption cross section well understood?

For light and medium mass nuclei

- photo-abs. c.s. $\neq$ (γ,xn) c.s.

  significant contribution from *p* and α emission channels

- More complicated description is required for theoretical models

  Structure

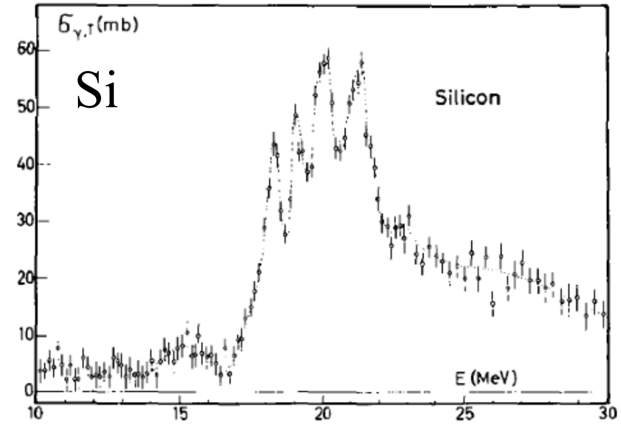
  - stronger shell effect
  - nuclear deformation
  - nucleon correlations:

    α clustering, *np* pairing, tensor correlation,…

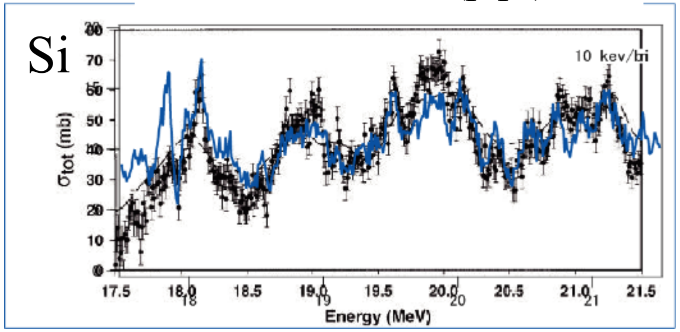
  Decay

  - pre-equilibrium decay process
  - isospin selection rule in the decay process

Ahrens et al. (γ,abs)



Harada et al. γ-transmission
Matsubara et al., (p,p')

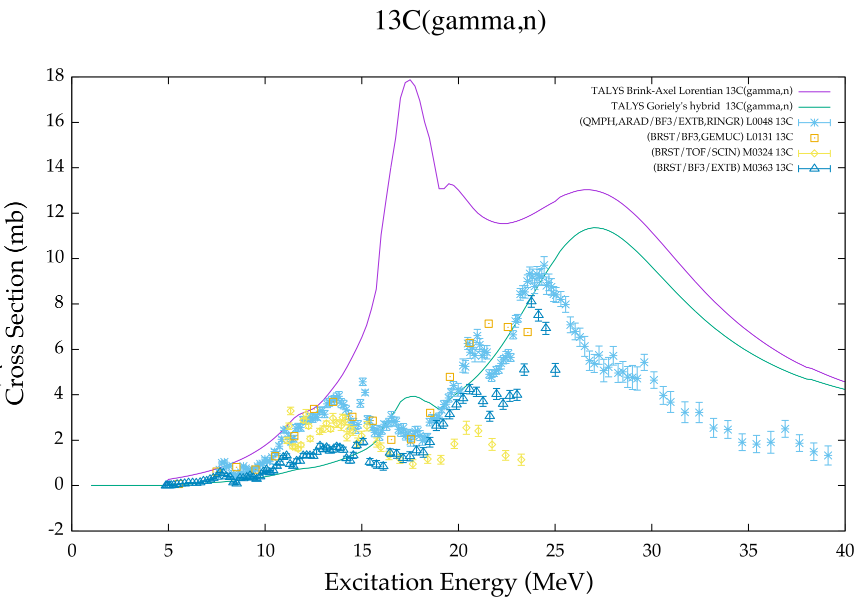


Is the photo-absorption cross section well understood?

For light and medium mass nuclei

- photo-abs. c.s. $\neq$ (γ,xn) c.s.

  significant contribution from *p* and α emission chann



Example: ^{13}C(γ,xn) reaction data and predictions

- More complicated description is required for theoretical models

  Structure

  - stronger shell effect
  - nuclear deformation
  - nucleon correlations:

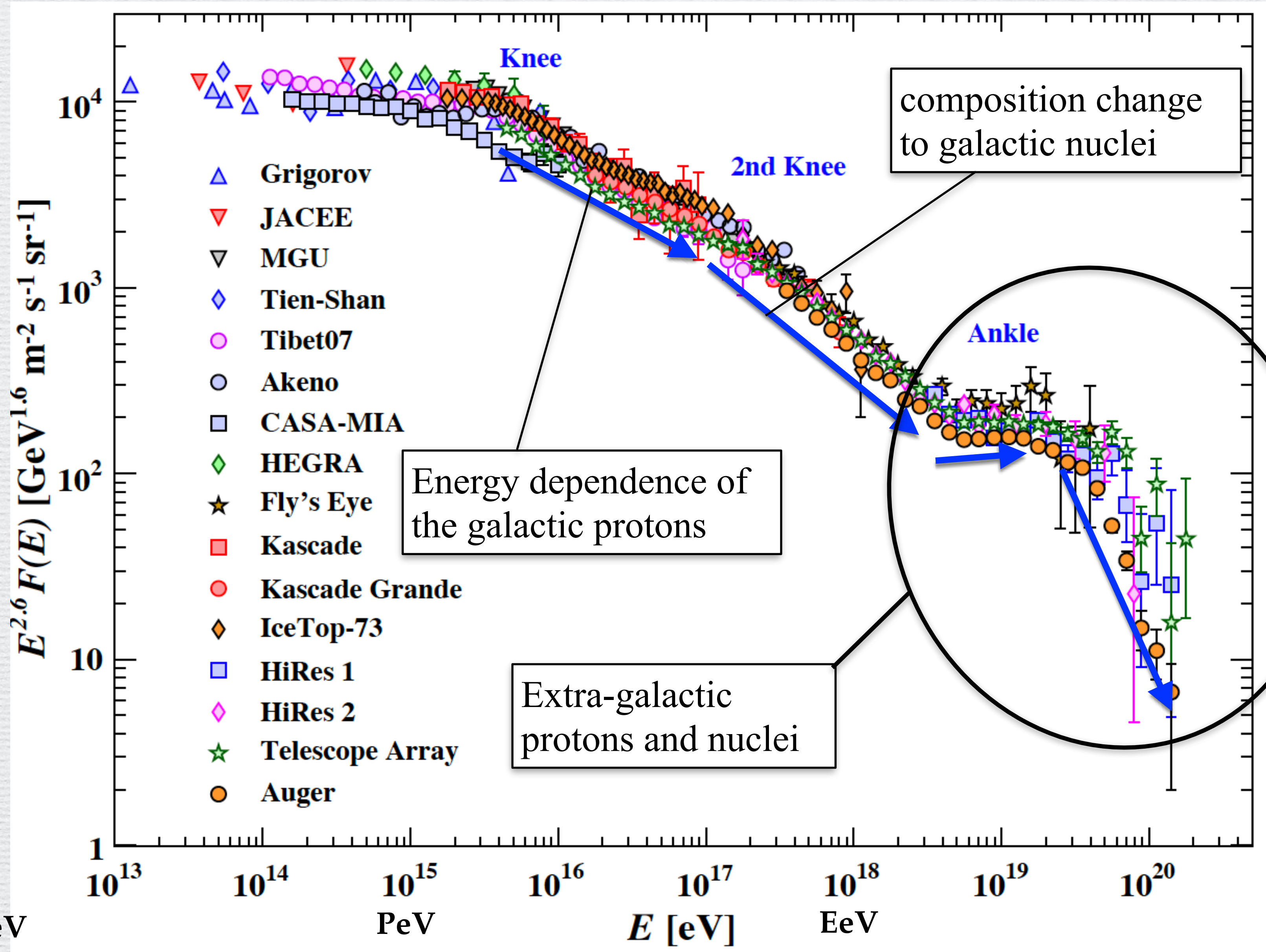
    α clustering, *np* pairing, tensor correlation,…

  Decay

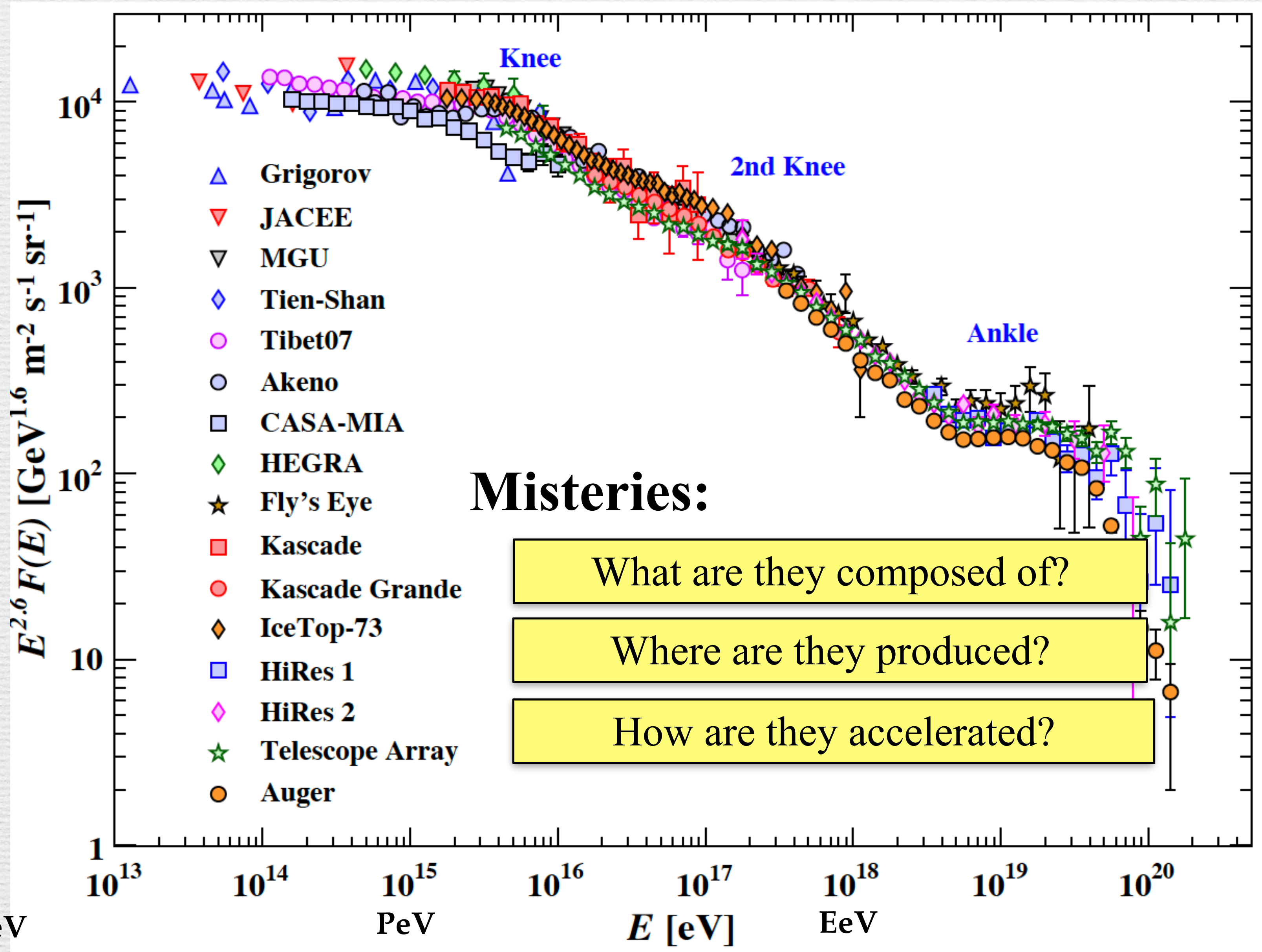
  - pre-equilibrium decay process
  - isospin selection rule in the decay process

- Lack of data especially for charged particle decays
- Large inconsistency among experimental data
- Unsatisfactory theoretical predications

Ultra-High-Energy Cosmic Rays (UHECRs) [PDG2018]



Ultra-High-Energy Cosmic Rays (UHECRs) [PDG2018]



Misteries:

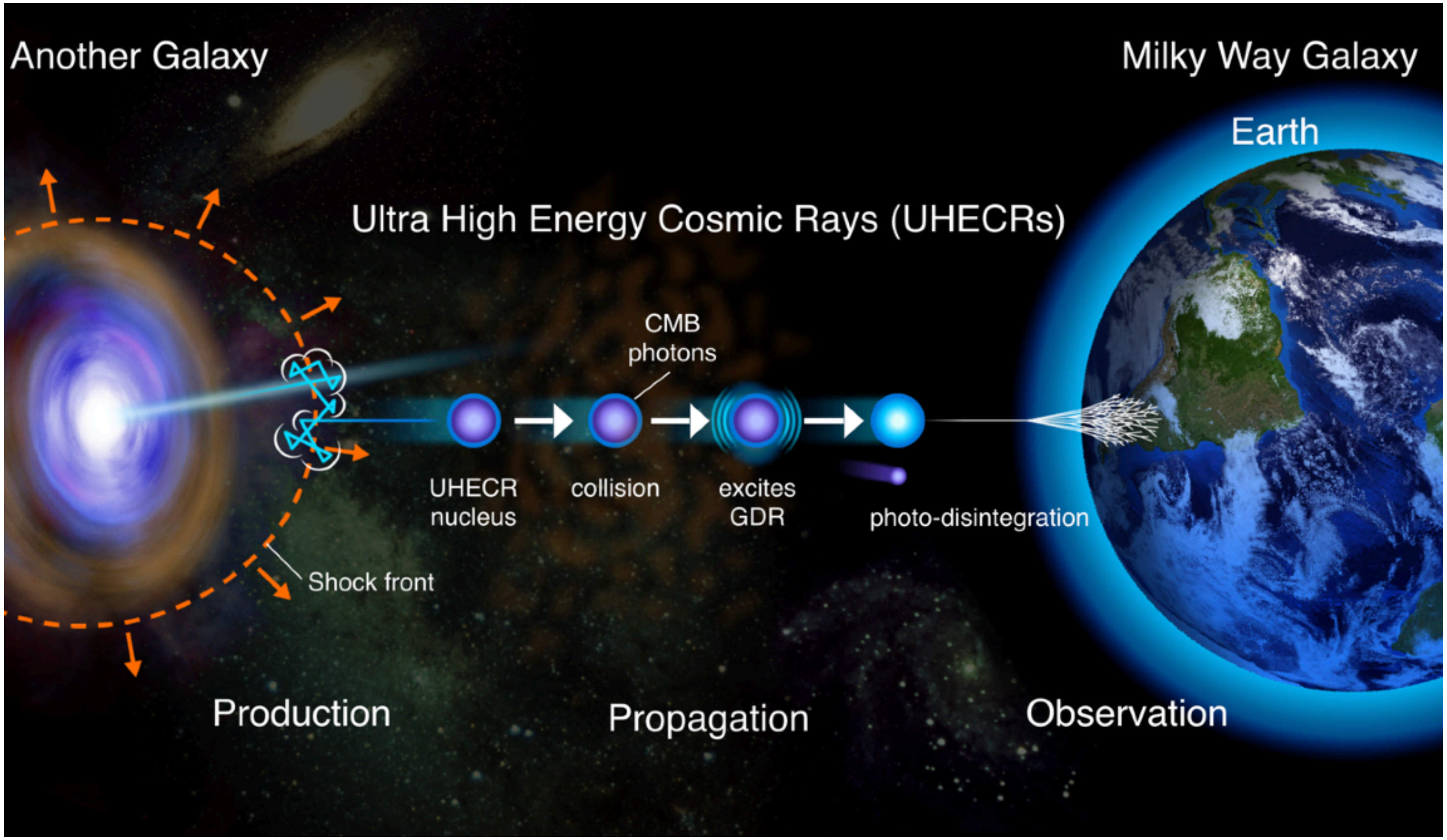
What are they composed of?

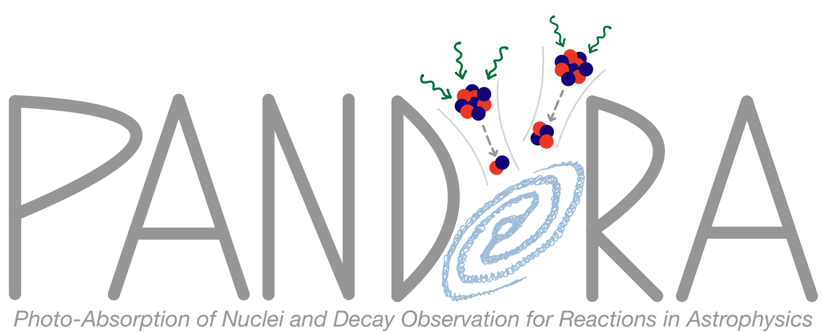
Where are they produced?

How are they accelerated?

PANDORA Project

Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics



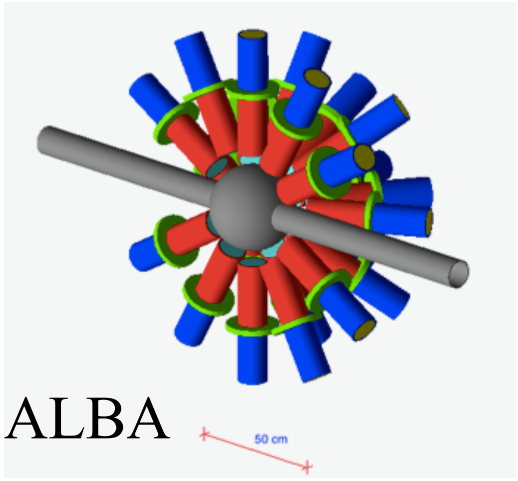


PANDORA Project

Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

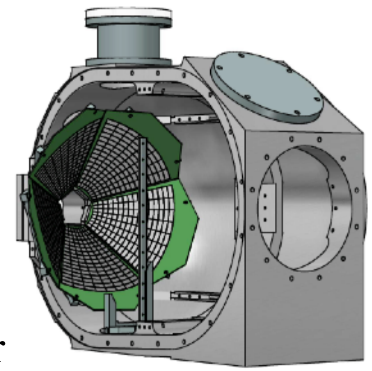
Joint project among three experimental facilities with nuclear theories and astrophysical simulations

iThemba LABS South Africa



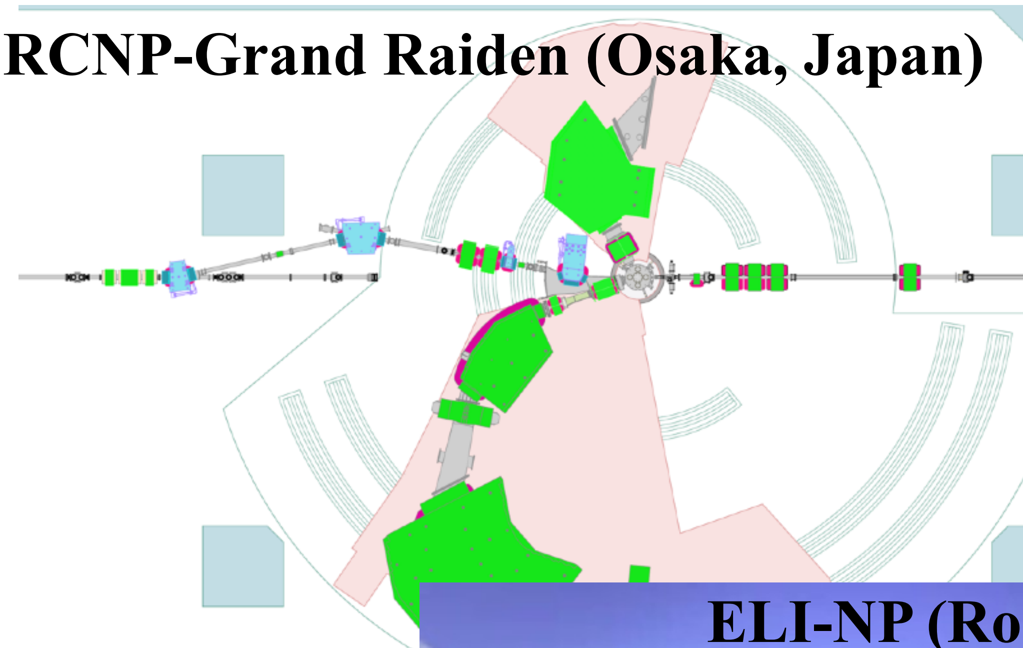
ALBA

CAKE



decay
charge
particle
detector
array

RCNP-Grand Raiden (Osaka, Japan)

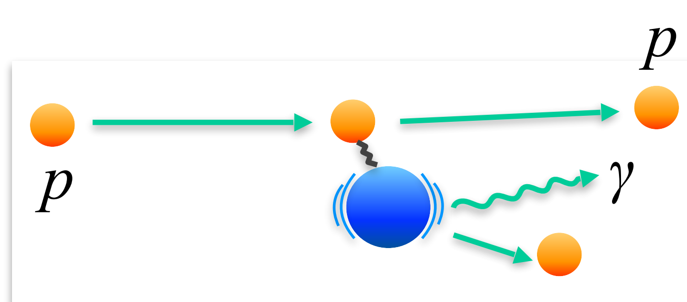


ELI-NP (Romania)

complementary experimental techniques

Probes for the Electric Dipole Response of Nuclei

1. Virtual photon excitation
   (Coulomb excitation)
   - proton inelastic scattering at 0 deg.



Proton beams at RCNP and iThemba LABS

E_x distribution in one shot measurement
total photo-absorption c.s.
up to 32 (24) MeV at RCNP (iThemba)

2. Real photon absorption
   - (γ,γ') Nuclear Resonance Fluorescence
   - (γ,n), (γ,2n), (γ,p), … photodisintegrations

Real γ-beam at ELI-NP

pure EM probe
precise absolute c.s.
partial strength including *n*
up to 20 MeV at ELI-NP

Targets

Measurements on 10-20 nuclei in 5-10 years 10% accuracy
with theoretical model developments

Candidate target nuclides

- ^{12}C, ^{16}O, and ^{27}Al first cases, alpha decay, reference target
- ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B light nuclei
- (^{20}Ne), ^{24}Mg, ^{28}Si, ^{32}S, (^{36}Ar), ^{40}Ca N=Z nuclei, α-cluster effect, deformation
- ^{26}Mg, ^{48}Ca, ^{56}Fe N>Z nuclei
- ^{13}C, ^{14}N, ^{51}V odd and odd-odd nuclei
- (γ,xn) on ^{18}O, ^{48}Ca, ^{64}Ni

extension to (e,e') and RI?

Experiment combining three complementary facilities

Virtual Photon Exp.

iThemba LABS 2023- ^{12}C and ^{27}Al

Total strength distribution up 24 MeV

p,α,γ-decays

iThemba LABS, Univ. Witwatersland, Stellenbosh Univ.

L. Pellegri, R. γ, F.D. Smit, J.A.C. Bekker, S. Binda, H, Jivan, T. Khumal, M. Wiedeking, K.C.W. Li, P. Adsley, L.M. Donaldson, E. Sideras-Haddado, K.L. Malatji, S. Jongile, A. Netshiya

RCNP **2023-** (^{10,11}B), ^{12,13}C, ^{24,26}Mg, ^{27}Al

Total strength distribution up 32 MeV

p,α,(γ)-decays

Osaka Univ.

A. Tamii, N. Kobayashi, T. Sudo, M. Murata, A. Inoue, **R. Niina**, T. Kawabata, T. Furuno, S. Adachi, K. Sakanashi, K. Inaba, Y. Fujikawa, S. Okamoto, Y. Fujita, H. Fujita

Real Photon Exp. LoI submitted

ELI-NP 2025?-

absolute c.s.

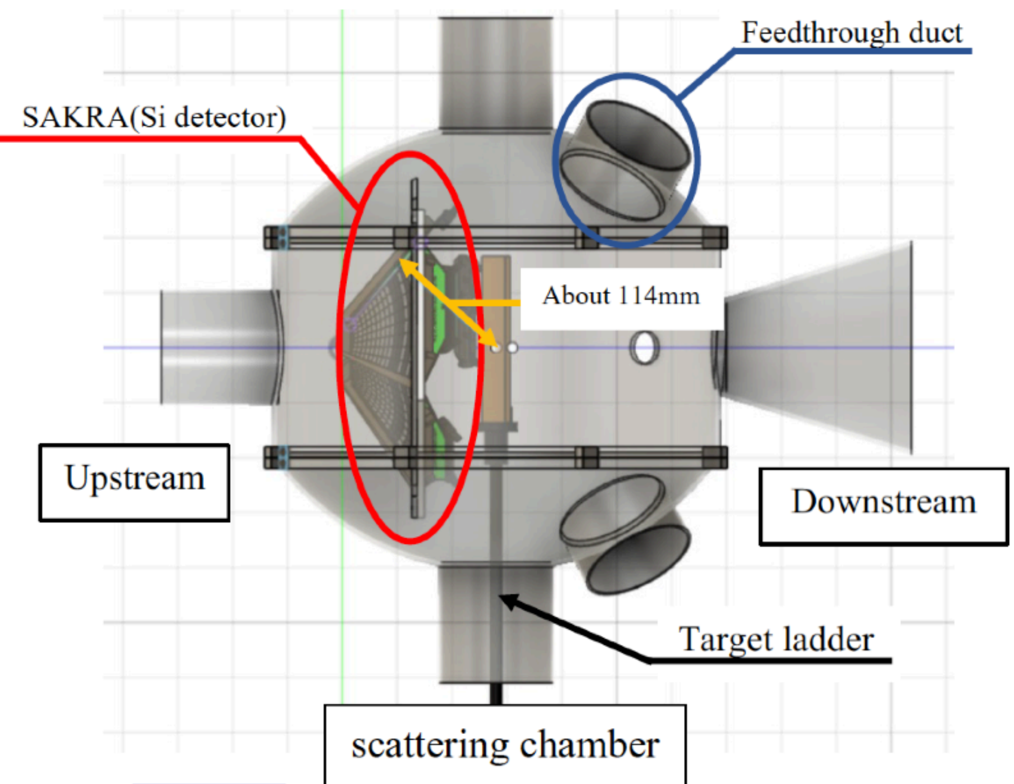
model independent separation of E1 and M1

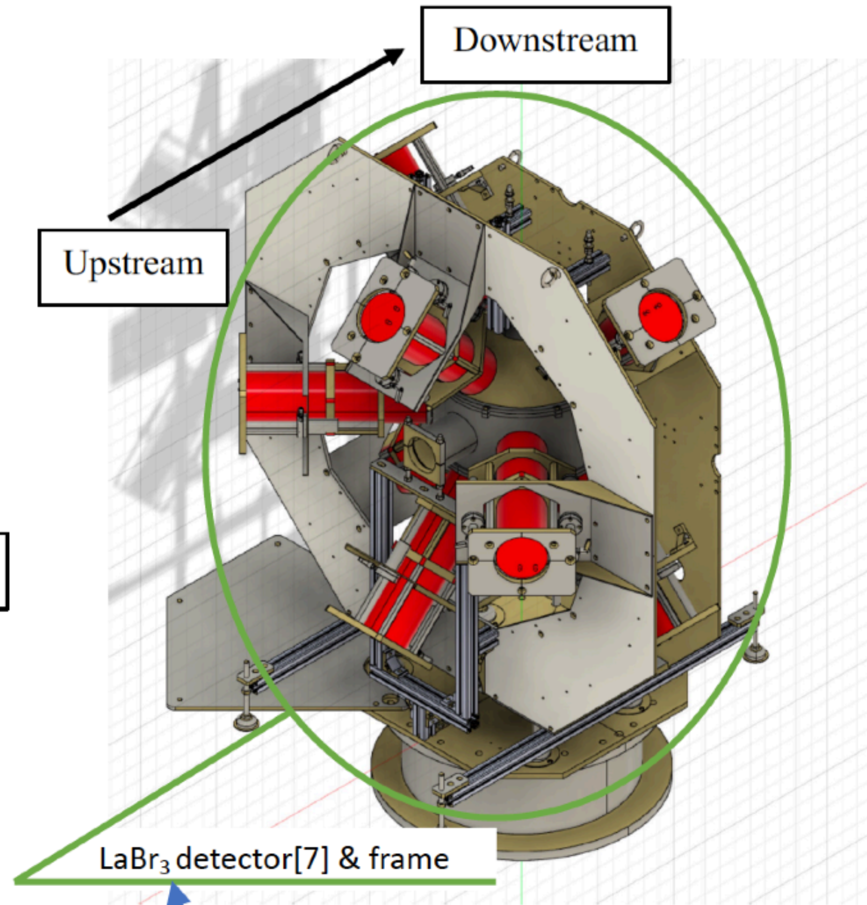
n,p,α,γ-decays up to 20 MeV

ELI-NP

P.-A. Söderström, D. Balabanski, L. Capponi, A. Dhal, T. Petruse, D. Nichita, Y. Xu

Features of this scattering chamber





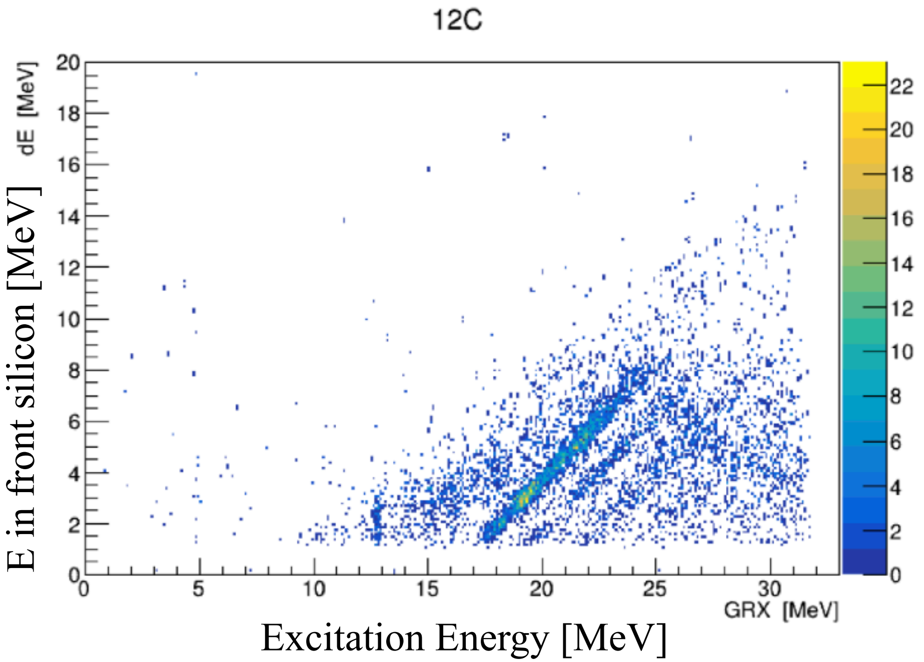
Features

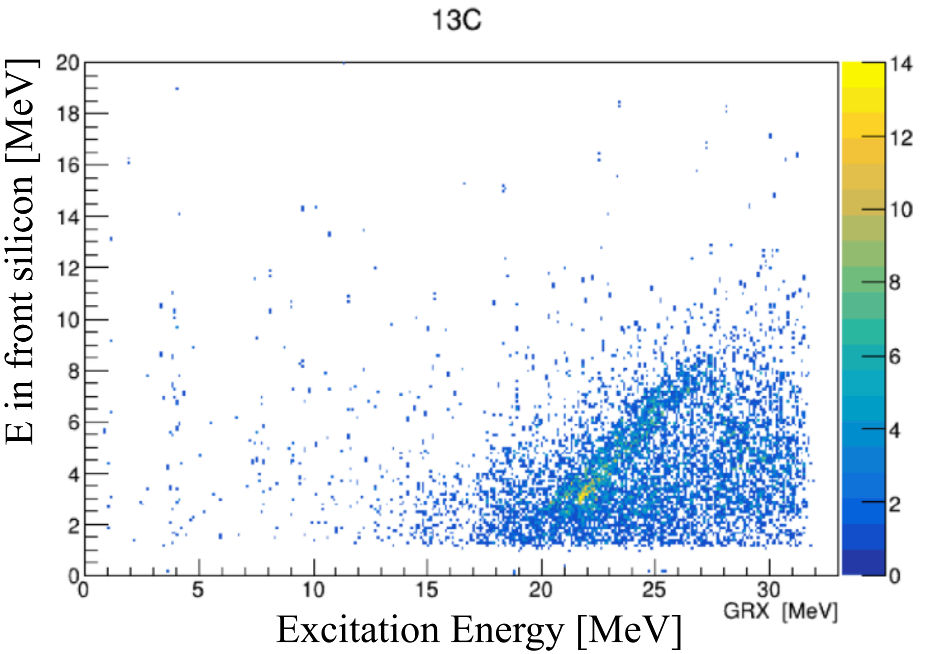
- Near Spherical shape
  - → To bring the detector closer
- SAKRA mounted on lid
  - →For easy SAKRA evacuation

This LaBr$_3$ detectors belongs to the Milan Group.

Design&Slide by R. Niina

PANDORA test experiment in Dec., 2023





Proton beam at 392 MeV with GRAF beam line, 1nA

GR at 4.5 deg

SAKRA: 3 pairs of silicon detectors

Standard scattering chamber

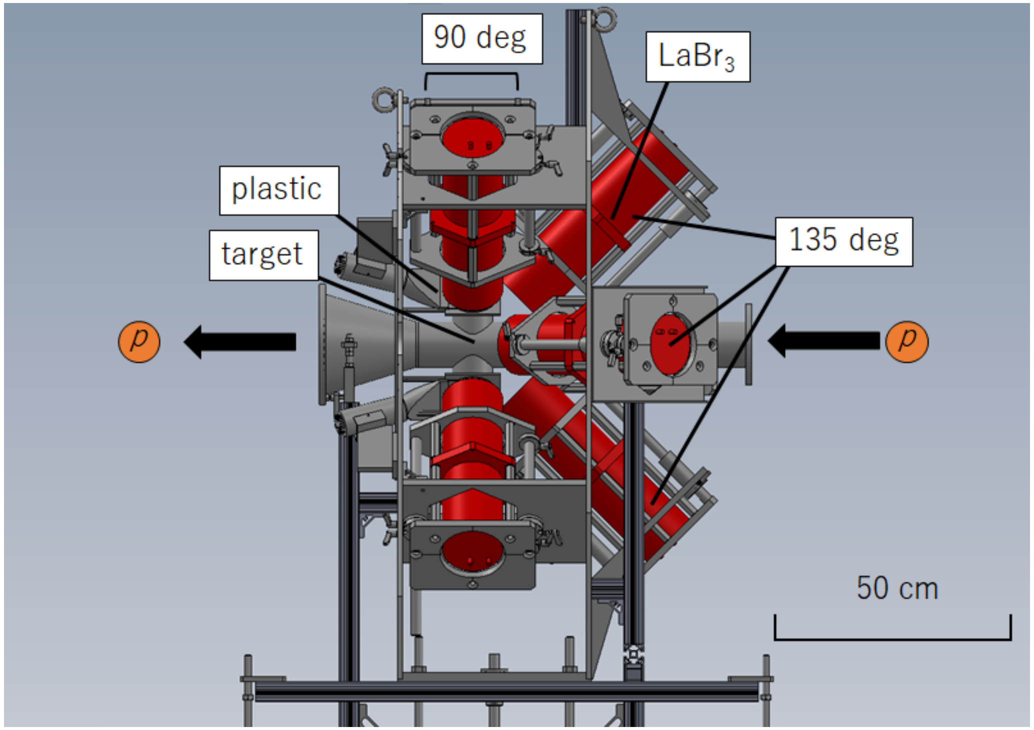
Test experiment planned in May, 2023

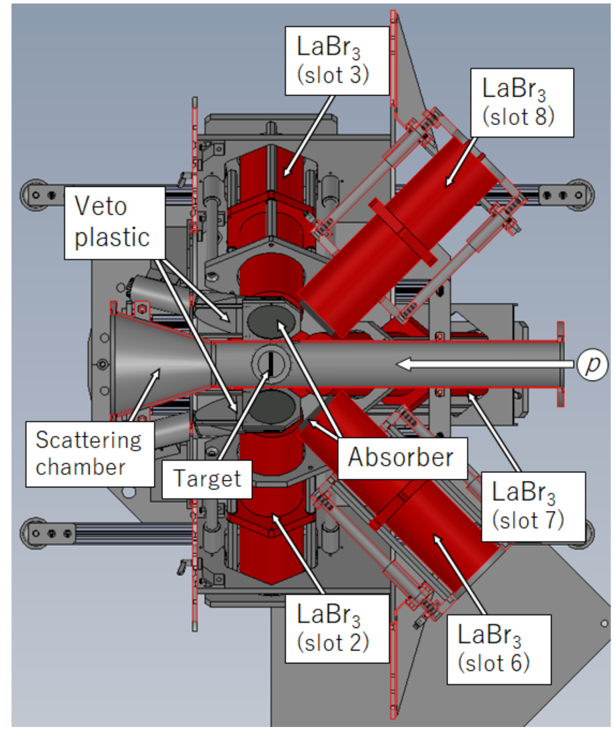
- better TOF resolution for particle ID
- higher beam current

R. Niina, master thesis, 2023

Gamma-Ray detectors: Large Volume $LaBr_3$:Ce

S. Nakamura, master thesis (RCNP)   E498





Large volume $LaBr_3$ detectors from Milano, 3.5”φ-8”L

A. Giaz et al. , NIMA**729**, 910 (2013)
G. Gosta et al. , NIMA**879**, 92 (2018)

Scattering chamber made of 3mm thick aluminum pipes

8 $LaBr_3$ detectors (4 at 90º and 4 at 135º)

distance of $LaBr_3$ face from the target: adjustable (137mm - ~200mm)

Pb(2mm)+Cu(4mm) absorbers, 2mm veto plastic for 90 deg detectors

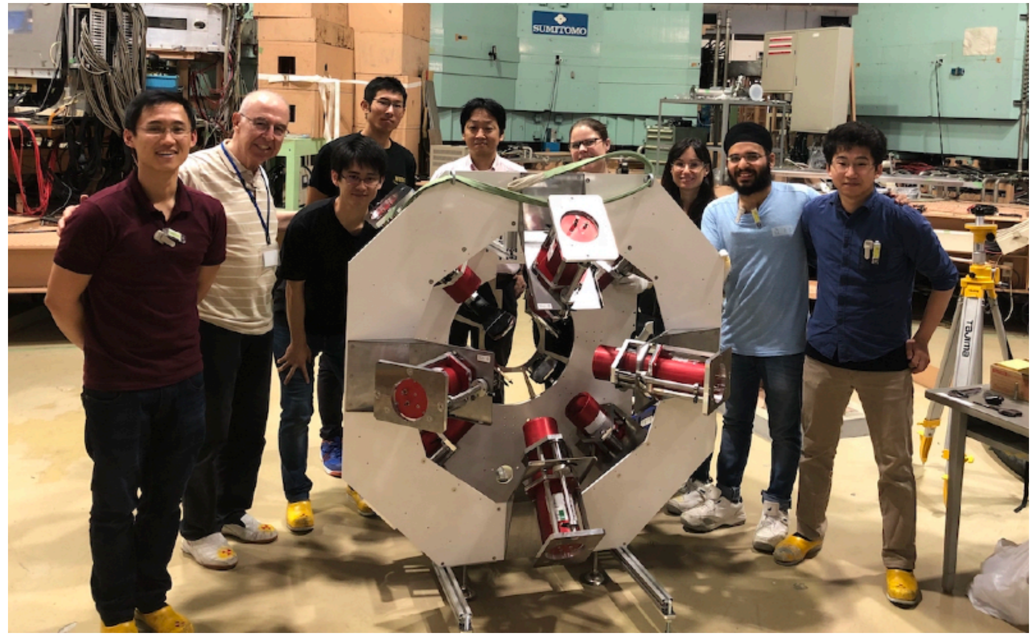
Requires min. 3 days of setup before exp.

The position arrangement will be optimized depending on the available detectors and physics requirements.

Target Ladder
(made of aluminum)

$LaBr_3$ Setup (Scγlla) E498

S. Nakamura, master thesis (RCNP)

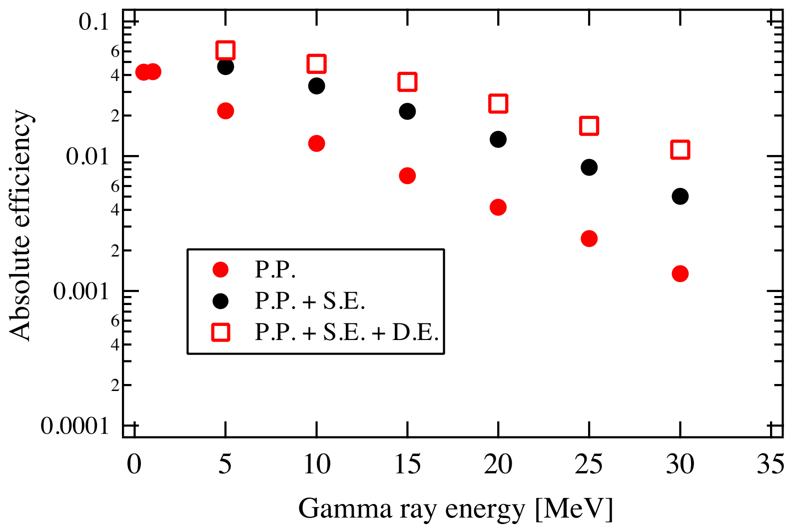


LaBr3 Setup (Scγlla) E498

Absolute gamma-detection efficiency in the E498 setup by a GEANT4 simulation

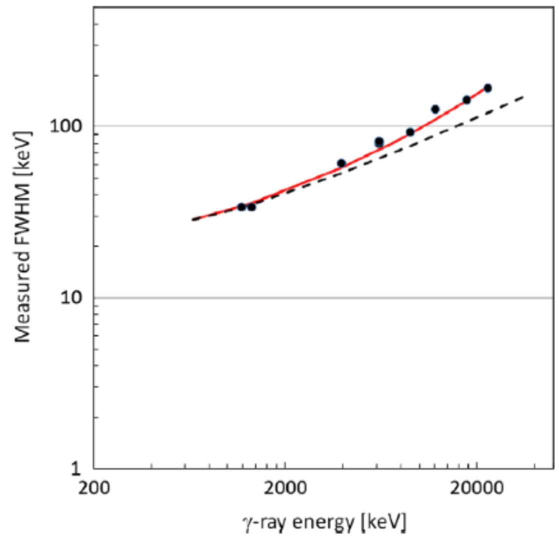
Photo Peak (P.P.), Single Escape (S.E.), Double Escape (D.E.)

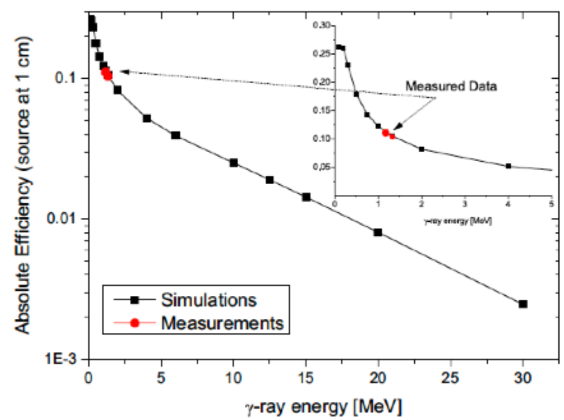
S. Nakamura, master thesis (RCNP)



LaBr3 (single detector) resolution and efficiency

A. Giaz et al. , NIMA**729**, 910 (2013)

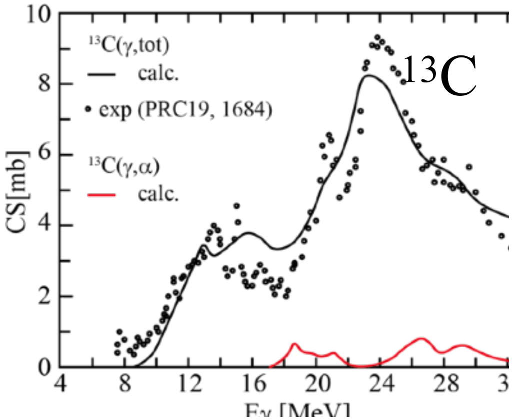


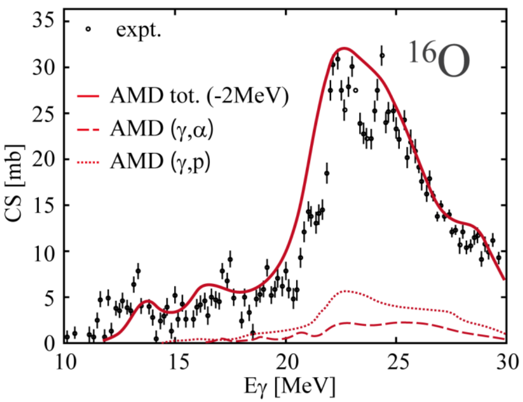


The LaBr3 resolution in E498 was significantly worse than expected in the beam measurement (FWHM~450 keV at 15.1 MeV). Due to noise, pile-up, or electronics? Needs to be improved.

Theoretical Model Developments

AMD + Laplace Expansion (M. Kimura et al.,)

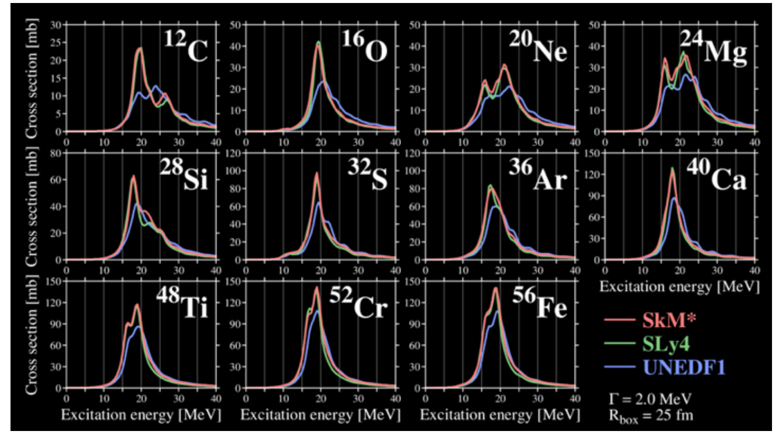




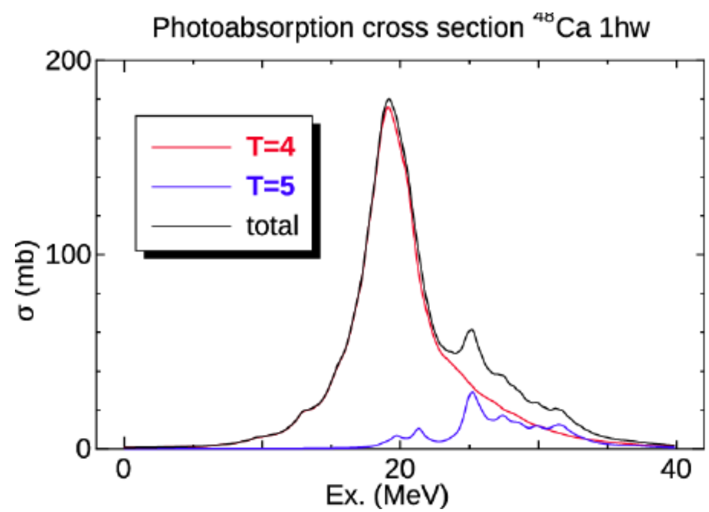
Isospin mixing and selection rule

M. Kimura et al., arXiv:2108.07592 (2021)

RPA by T. Inakura



N. Shimizu, Y. Utsuno, et al.,

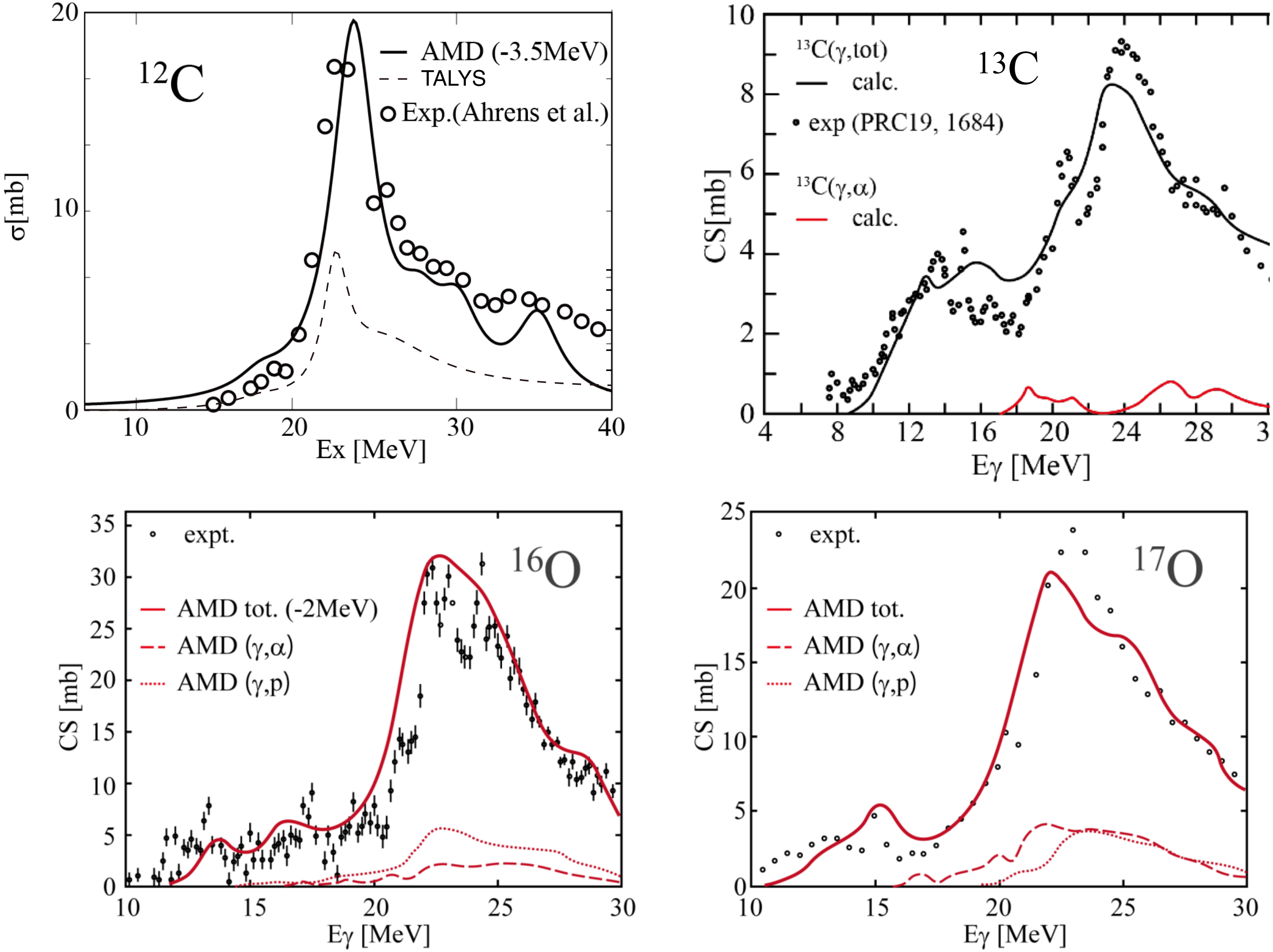


Development of theoretical models is inevitable to make predictions for all the relevant nuclei.

It is important to evaluate the uncertainty of the model predictions.

Predictions

AMD + Laplace Expansion (M. Kimura et al.,)



PANDORA Project: White Paper

Submitted to Euro. Pays. J. A

PANDORA project: photonuclear reactions below $A = 60$

A. Tamii[1,2,3,*], L. Pellegri[4,5], P.-A. Söderström[6], D. Allard[7], S. Goriely[8], T. Inakura[9], E. Khan[10], E. Kido[11], M. Kimura[12,13,11], E. Litvinova[14], S. Nagataki[11], P. von Neumann-Cosel[15], N. Pietralla[15], N. Shimizu[16], N. Tsoneva[6], Y. Utsuno[17], S. Adachi[18], P. Adsley[19,20], A. Bahini[5], D. Balabanski[6], B. Baret[10], J.A.C. Bekker[4,5], S.D. Binda[4,5], E. Boicu[6,21], A. Bracco[22,23], I. Brandherm[15], M. Brezeanu[6,21], J.W. Brummer[5], F. Camera[22,23], F.C.L. Crespi[22,23], R. Dalal[24], L.M. Donaldson[5], Y. Fujikawa[25], T. Furuno[3], H. Haoning[14], Y. Honda[3], A. Gavrilescu[6,26], A. Inoue[1], J. Isaak[15], H. Jivan[4,5], P.M. Jones[5], S. Jongile[5], O. Just[11,27], T. Kawabata[3], T. Khumalo[4,5], J. Kiener[10], J. Kleemann[15], N. Kobayashi[1], Y. Koshio[28], A. Kuşoğlu[6,29], K.C.W. Li[30], K.L. Malatji[5], R.E. Molaeng[4,5], H. Motoki[12], M. Murata[1], A.A. Netshiya[4,5,31], R. Neveling[5], R. Niina[1], S. Okamoto[25], S. Ota[1], O. Papst[15], E. Parizot[10], T. Petruse[6], M.S. Reen[32], P. Ring[33], K. Sakanashi[3], E. Sideras-Haddad[4], S. Siem[30], M. Spall[15], T. Suda[34], T. Sudo[1], Y. Taniguchi[35], V. Tatischeff[10], H. Utsunomiya[36,37], H. Wang[36,38,39], V. Werner[15], H. Wibowo[40], M. Wiedeking[4,5], O. Wieland[23], Y. Xu[6] and Z.H. Yang[41] (PANDORA Collaboration)

1 Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki 567-0047, Japan
2 Institute for Radiation Sciences (IRS), Osaka University, Toyonaka, Osaka 560-0043, Japan
3 Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
4 School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa
5 iThemba Laboratory for Accelerator Based Sciences, Somerset West 7129, South Africa
6 Extreme Light Infrastructure-Nuclear Physics (ELI-NP)/Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH), Str. Reactorului 30, Bucharest-Măgurele 077125, Romania
7 Laboratoire Astroparticule et Cosmologie, Université Paris Cité, CNRS, F-75013 Paris, France
8 Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus de la Plaine CP 226, 1050 Brussels, Belgium
9 Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8550, Japan
10 IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405 Orsay Cedex, France
11 RIKEN, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
12 Department of Physics, Hokkaido University, Sapporo 060-0810
13 Japan and Nuclear Reaction Data Centre, Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan
14 Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008, USA
15 Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany
16 Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8577, Japan
17 Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
18 Cyclotron and Radioisotope Center, Tohoku University, 6-3 Aoba Aramaki, Aoba, Sendai, Miyagi 980-8578, Japan
19 Department of Physics & Astronomy, Texas A&M University, College Station, 77843-4242, USA
20 Cyclotron Institute, Texas A&M University, College Station, 77843-3636, USA
21 University of Bucharest, Atomistilor 405, 077125 Bucharest-Măgurele, Romania
22 Dipartimento di Fisica dell'Università degli Studi di Milano, I-20133 Milano, Italy
23 INFN, Sezione di Milano, I-20133 Milano, Italy
24 Guru Jambheshwar University of Science and Technology, Hisar, India-125001
25 Department of Physics, Kyoto University, Kitashirakawa Oiwake-Cho, 606-8502 Kyoto, Japan
26 Politehnica University of Bucharest, Bucharest, Romania
27 GSI Helmholtzzentrum für Schwerionenforschung, Planckstrasse 1, D-64291 Darmstadt, Germany
28 Department of Physics, Okayama University, 700-8530 Okayama, Japan
29 Department of Physics, Faculty of Science, Istanbul University, Vezneciler/Fatih, 34134, Istanbul, Turkey
30 Department of Physics, University of Oslo, P.O. Box 1048, Blindern, N-0316 Oslo, Norway
31 Department of Chemical and Physical sciences, Walter Sisulu University, Mthatha 5100, South Africa
32 Department of Physics, Akal University, Talwandi Sabo, Bathinda, Punjab 151302, India
33 Physics Department, TU Munich, D-85748 Garching, Germany
34 Research Center for Electron-Photon Science, Tohoku University, 982-0826, Sendai, Japan
35 Department of Information Engineering, National Institute of Technology, Kagawa college, Takamatsu 761-8058, Japan
36 Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China
37 Department of Physics, Konan University, Kobe 658-8501,Japan
38 Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
39 University of Chinese Academy of Science, Beijing 100049,China
40 Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom
41 School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

arXiv:2211.03986v2 [nucl-ex]

Summary of the first part

- Electric dipole response of nuclei (photo-nuclear reactions) is fundamental information on the nuclear property important for nuclear structure, nuclear astrophysics, and other applications.

- The data are very scarce for light (A<60) nuclei especially for charged particle decays. The existing data have large mutually inconsistency.

- The PANDORA project plans to systematically measure the photo-absorption cross sections and decay branching ratios by using two modern techniques: virtual photo excitation by proton scattering and high-intensity quasi mono-energetic gamma-rays by LCS.

- The experiments are planned to start this year at RCNP and iThemba LABS and in ~2025 at ELI-NP. Test experiments are on going at RCNP.

- Theoretically works and UHECR propagation simulations are progressing.

Detection of Gamma-Rays from Laser plasma

Atsushi Tamii

RCNP, Osaka University

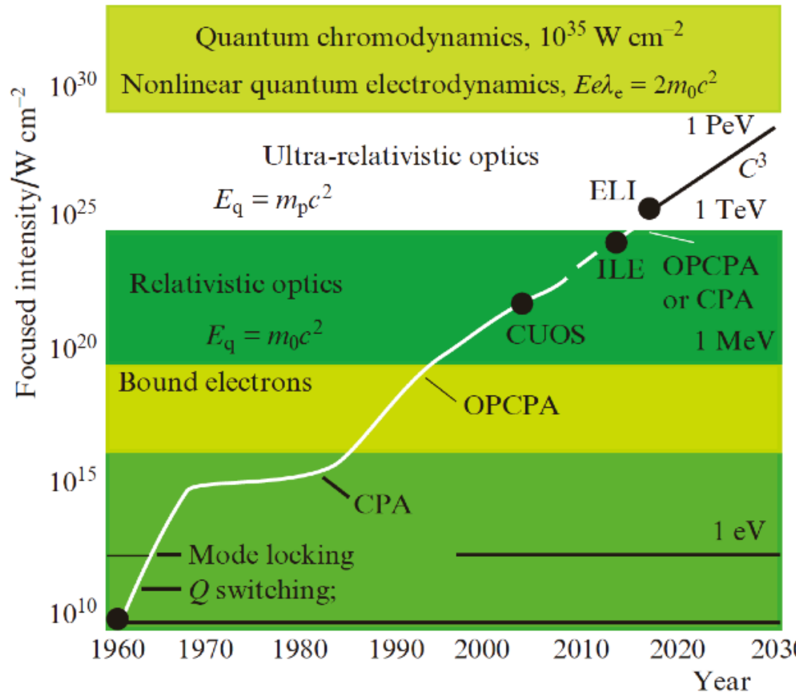
Advancement of High-Brilliance Lasers

High-power laser to solid material

→ generation of laser plasma

Rapid advancement of focused intensity

→ reaching to particle energies of several 10 MeV that can cause nuclear reactions



J-KAREN-P

@KPSI-QST in Japan

10^{21} - 10^{22} W/cm^2

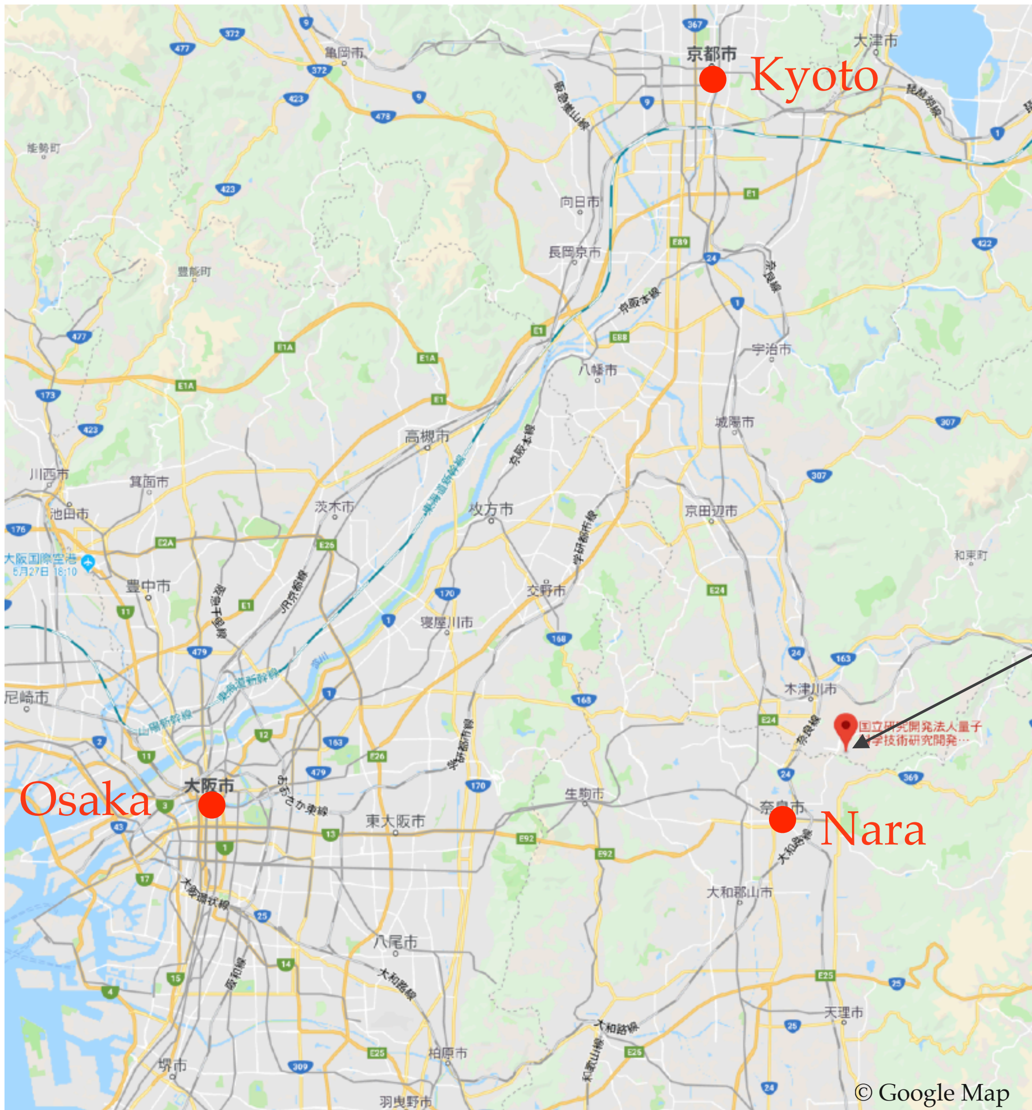
10J / 30 fs

0.1 Hz

2μmϕ

Kansai Photon Science Institute (KPSI)

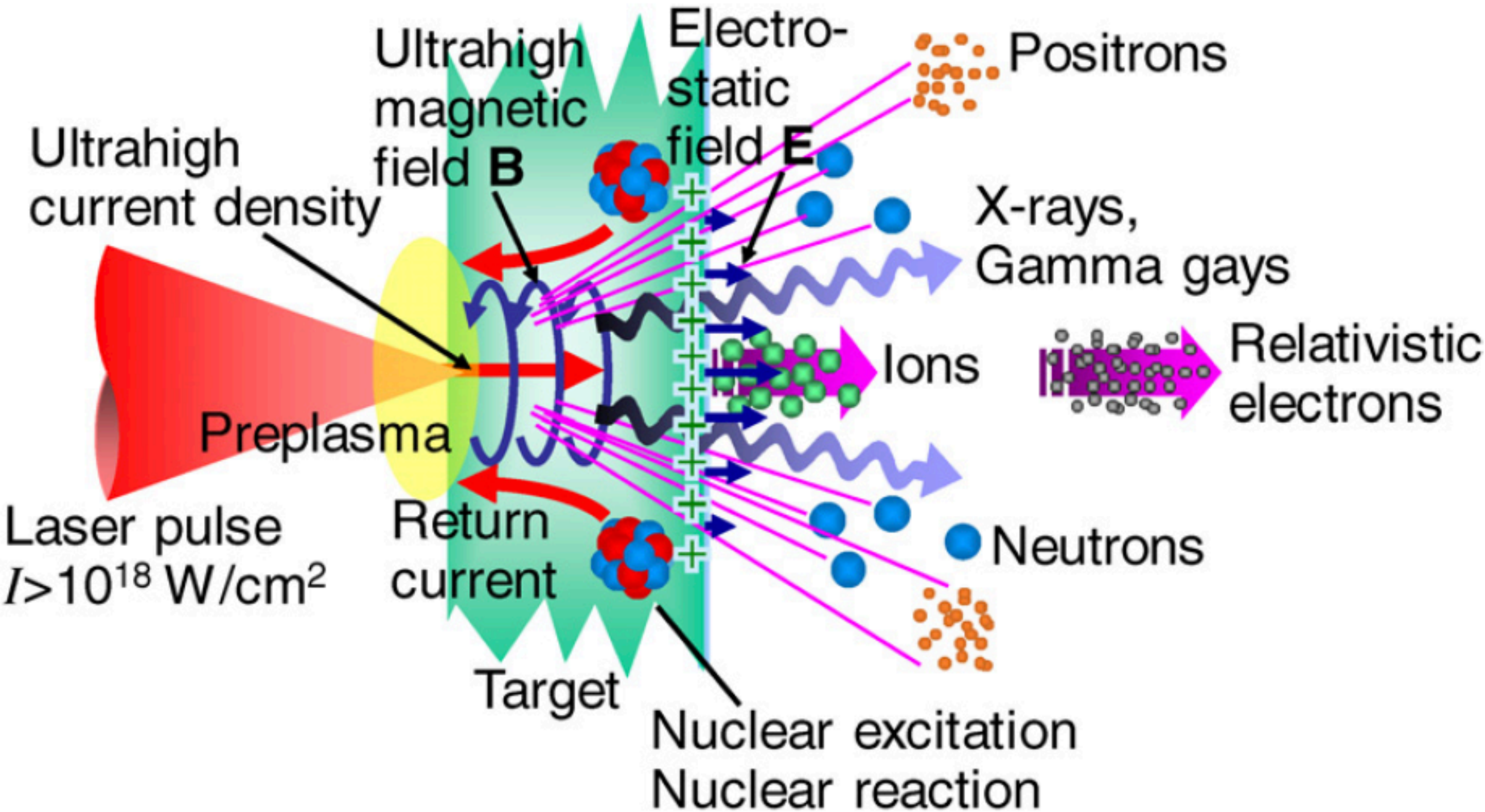
Quantum and Radiological Science and Technology (QST)



~1 hour by car
from RCNP

KPSI-QST

Laser Plasma Dynamics



at the plasma surface

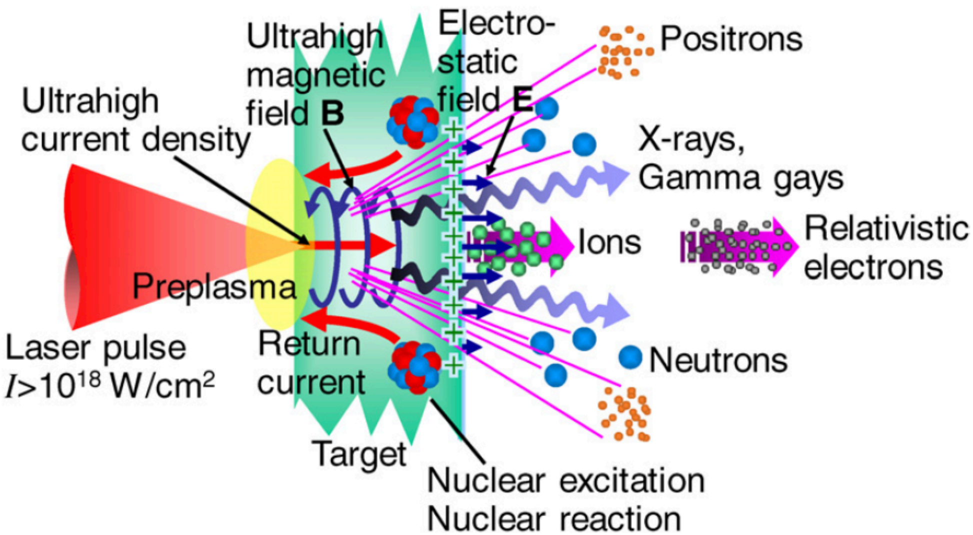
$B \sim 10^5$ T

$E \sim 10^{13}$ V/m

H. Daido et al., Rep. Prog. Phys. 75, 056401 (2012)

Laser Plasma Dynamics and Nuclear Reactions

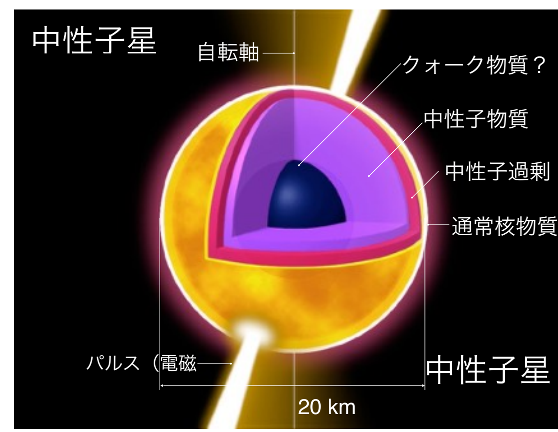
H. Daido et al., Rep. Prog. Phys. 75, 056401 (2012)



Laser Plasma

- High magnetic field ~ 10^5 T
- High electric field ~ 10^{13} V/m
- High ion-density close to solid material

a neutron star



Detection of gamma-rays from laser plasma

- Diagnostics for laser-plasma dynamics
- Characterization of the high energy photon field for applications
- Study of nuclear reaction in extreme conditions in future (e.g. in stars, neutron stars, magnetars)

Development of gamma-ray detection methods

for gamma-rays (photons above MeV)
flux and energy / angular distribution

Difficulties in the gamma-ray detection

- Massive gamma production in a shot — pile-up problem
- a few ten shots per day — low statistics problem
- laser properties are different for each shot — data sum-up problem

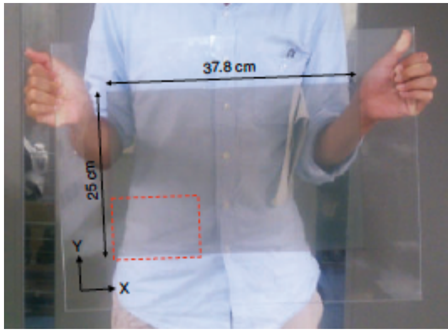
Methods under trial

- activation method
- scintillator stack signal deconvolution
- detection by nuclear emulsion

Development of the gamma-ray detection by nuclear emulsion

Pros

- Detection of individual gamma-rays of high-flux in a shot
- Particle identification of electrons, protons, ions, neutrons, and gamma-rays
- Measurement of energy distribution
- high-position resolution (1 μm) → good angular resolution

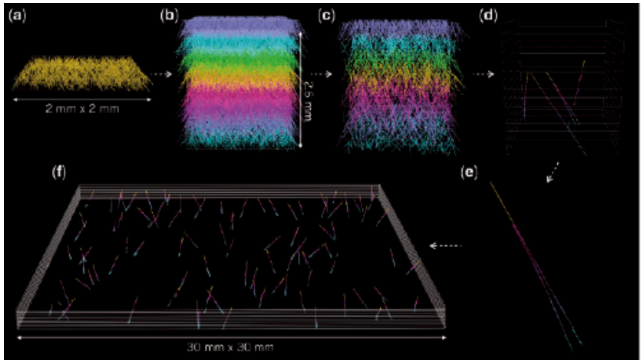


Cons

- Developing/scanning/analysis is required before getting data
- Special techniques for using emulsion are required

Useful for

- reliable data for calibration/confirmation of the other types of detectors, e.g. scintillator, and simulations.
- Gamma-ray angular distribution from one laser shot placing many emulsions.

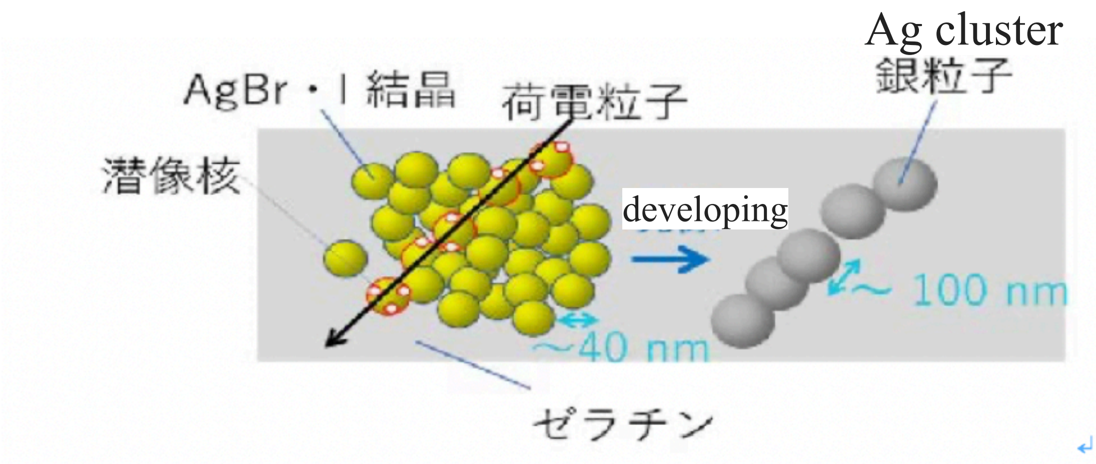


position resolution: 1 μm

up to 100 tracks / mm^2 for reconstruction

H. Rokujo et al., PTEP063H01(2018)

Nuclear emulsion developed at Nagoya university (F-Lab.)



microscope picture

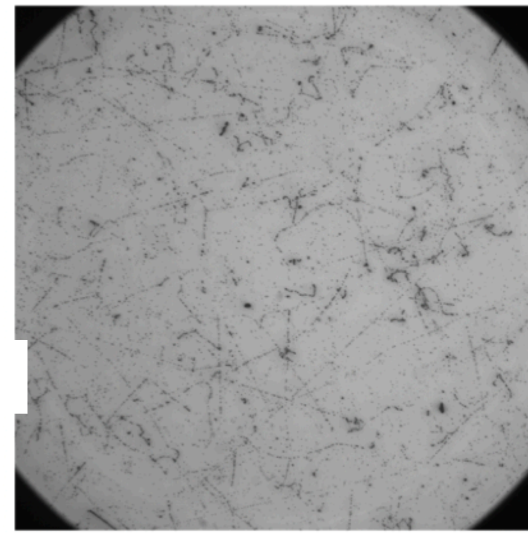
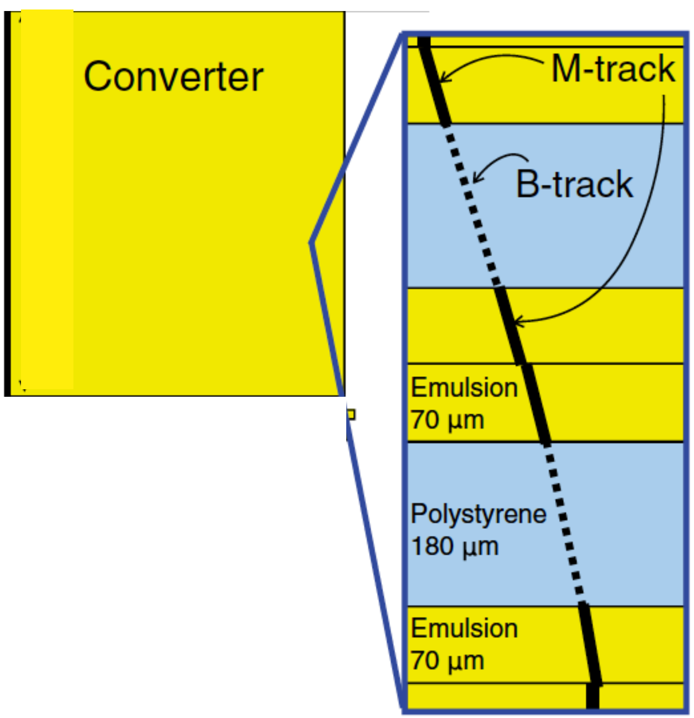
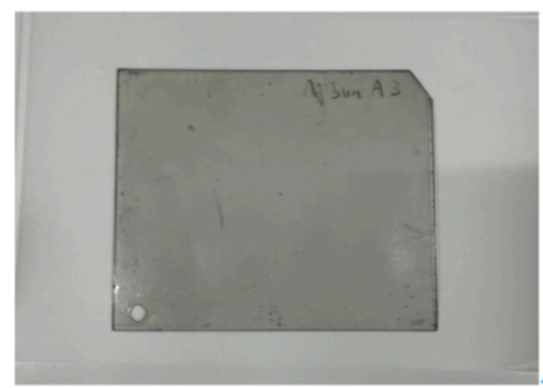


図 2.1.2 顕微鏡で見たエマルションの図

emulsion stack

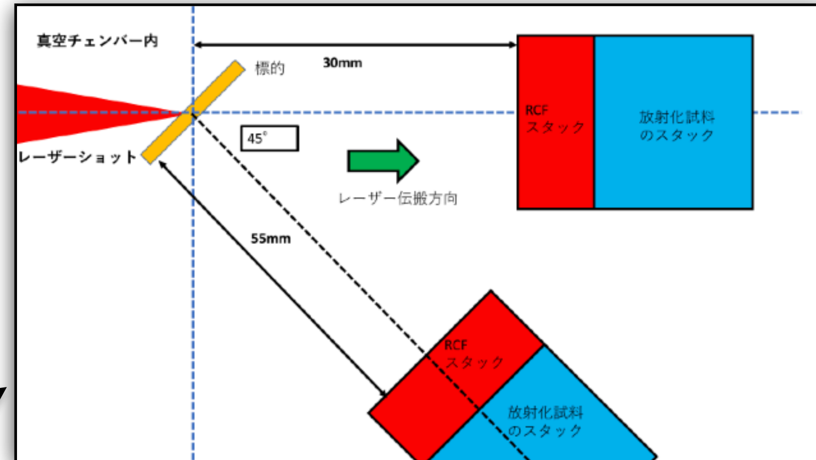


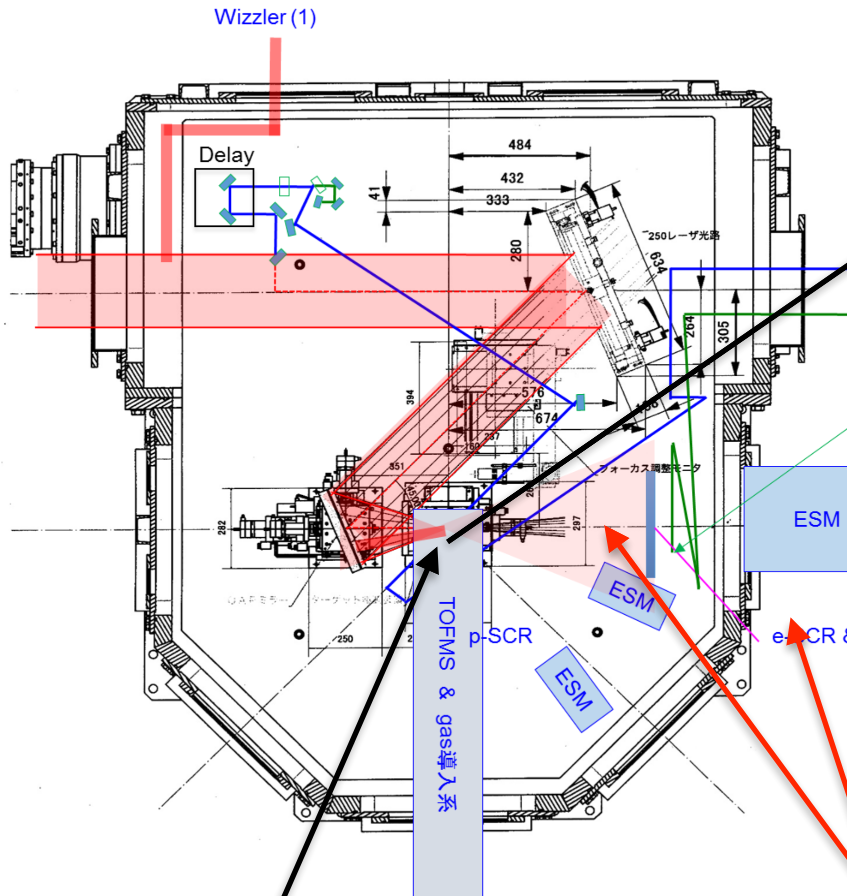
$25 \times 30\ \mathrm{mm}^2$
$\times(30+2)$ stacks



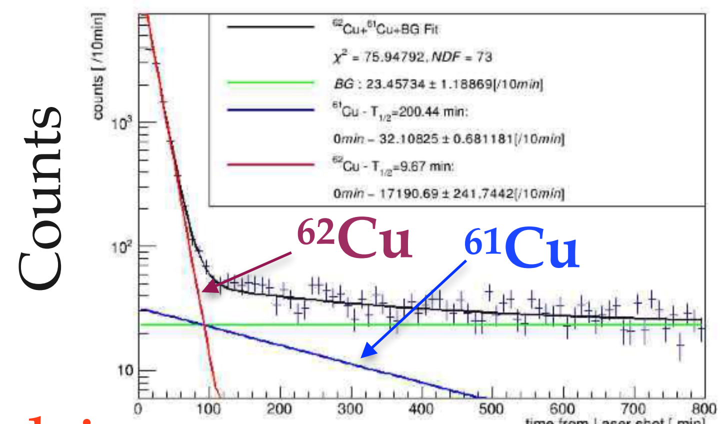
R. Iwasaki, Osaka Univ. 2022

Gamma-ray detection by activation method (copper plates)





Activation Analysis



Time (minutes)

laser target
Ag 5µm

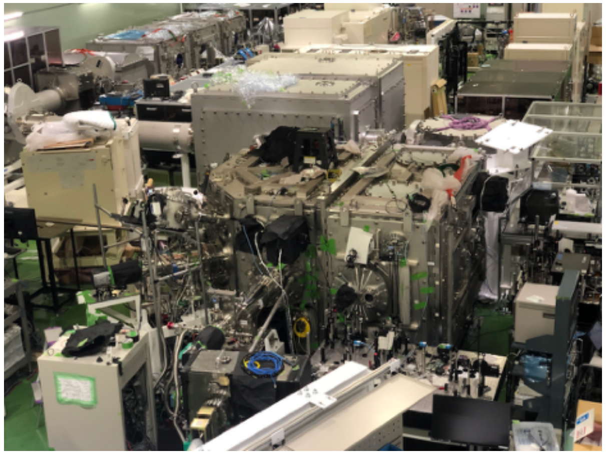
one shot
~10^{21} W/cm^2

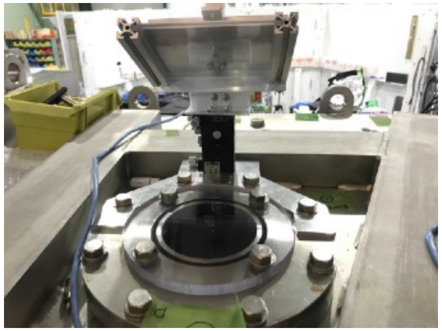
nuclear emulsion
in air

Emulsion measurement in collaboration with Nagoya/Gifu

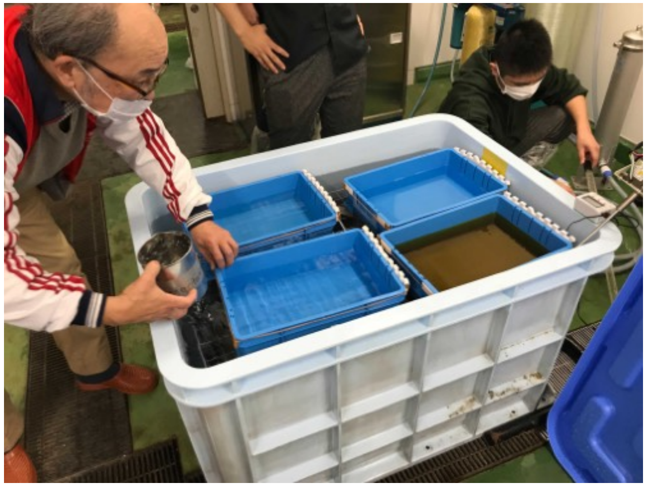
emulsion@Nagoya Univ.

measurement@KPSI-QST



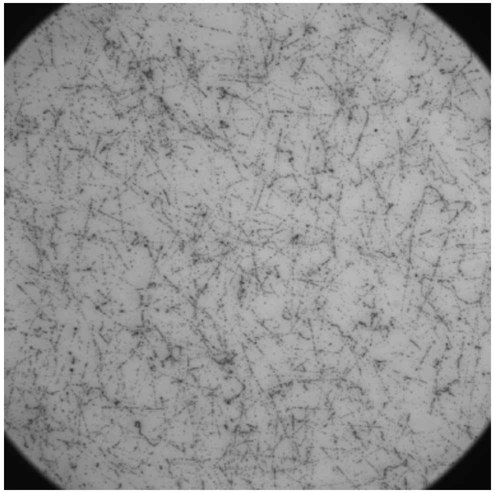


developing@Gifu Univ.



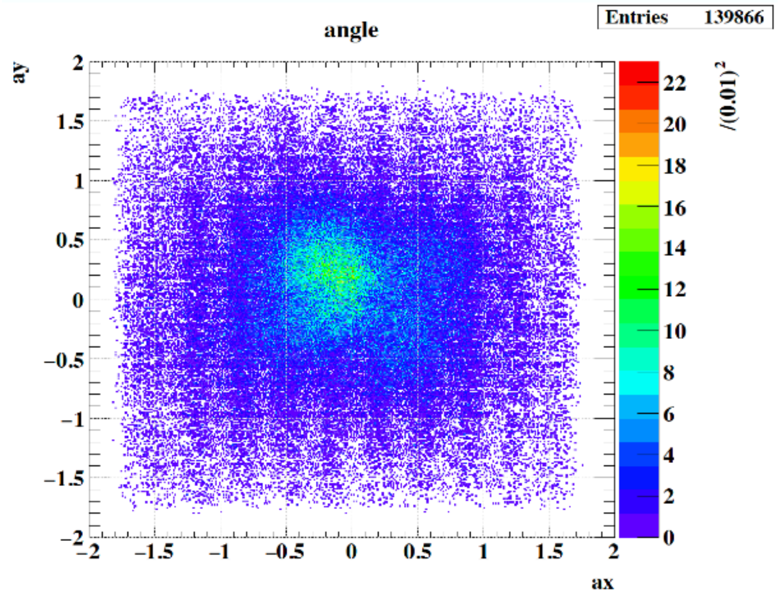
Emulsion measurement in collaboration with Nagoya/Gifu

Check by Microscope@Gifu Univ.

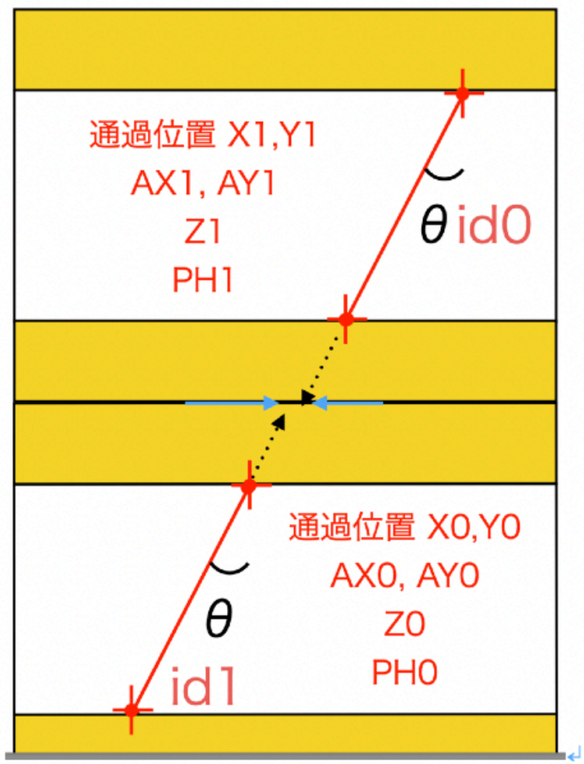


emulsion production/scan/analysis@Nagoya Univ

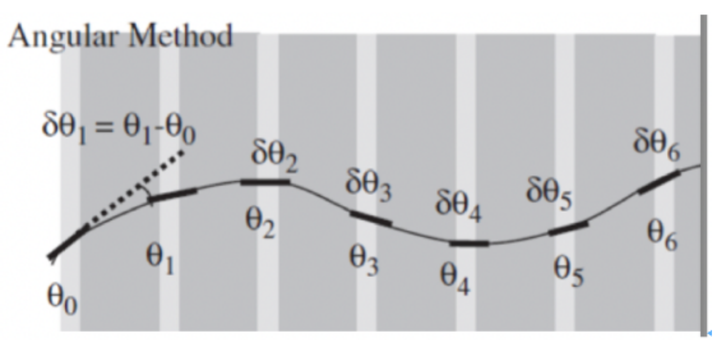
x-y track angles



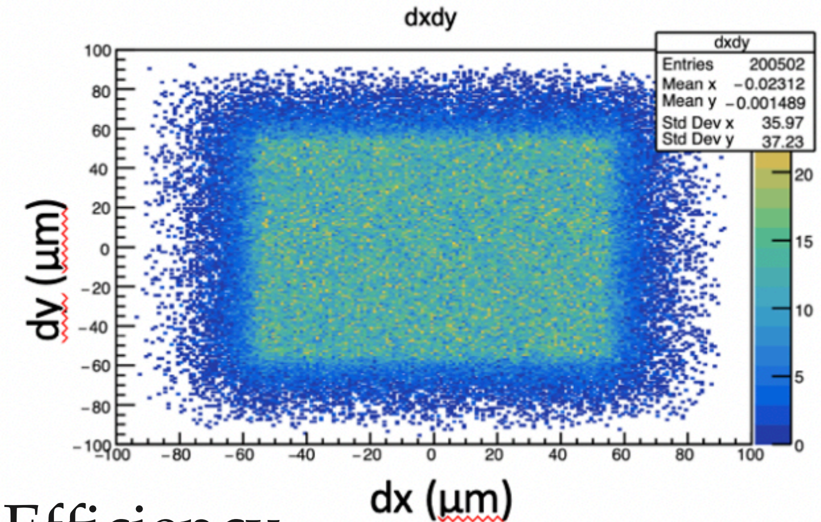
Emulsion track reconstruction



e- (e+) energy determination by multiple-scattering method



Positions



Efficiency

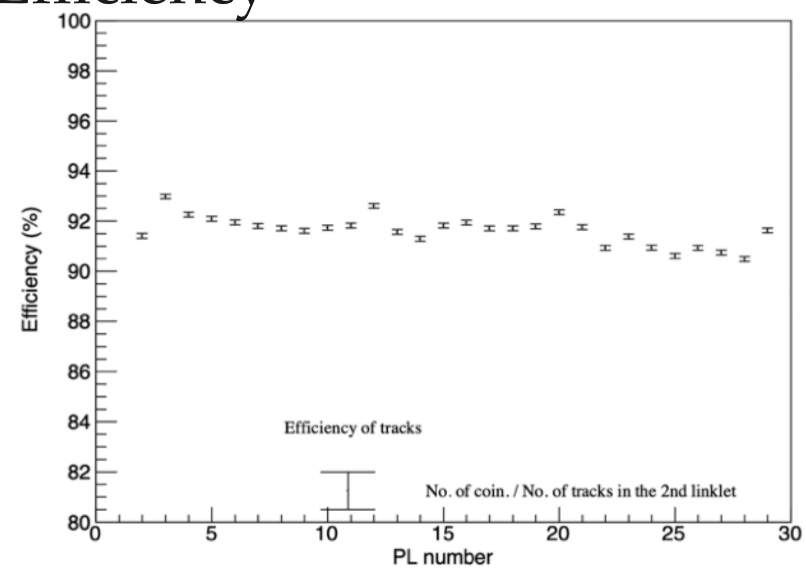


図 3.2.1 各エマルションの Efficiency

R. Iwasaki, Bachelor, Osaka Univ. 2022

Electron-positron pair creation events by gamma-rays

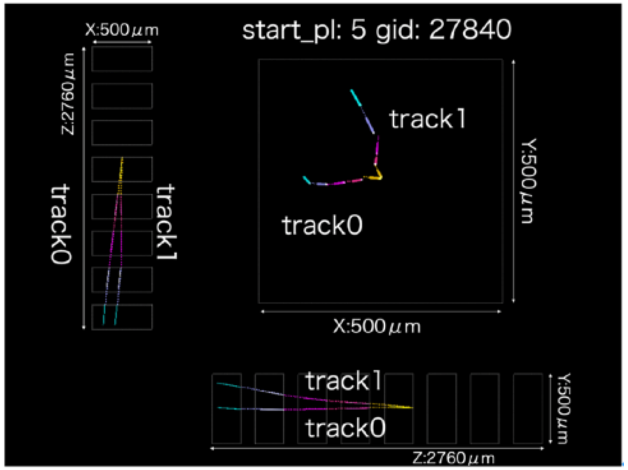


図 3.3.1 Event.27840 の電子対生成の軌跡図

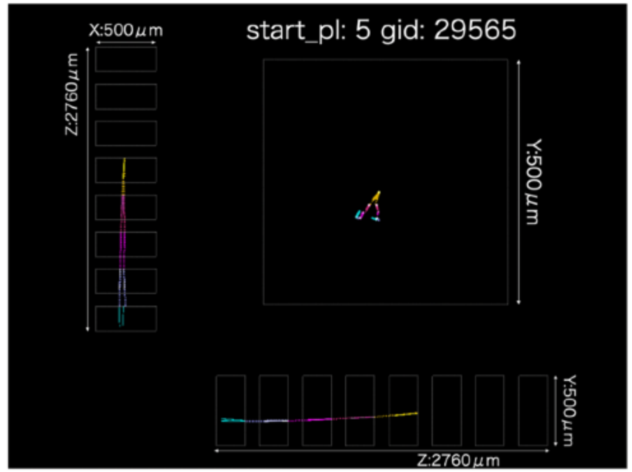


図 3.3.2 Event.29565 の電子対生成の軌跡図

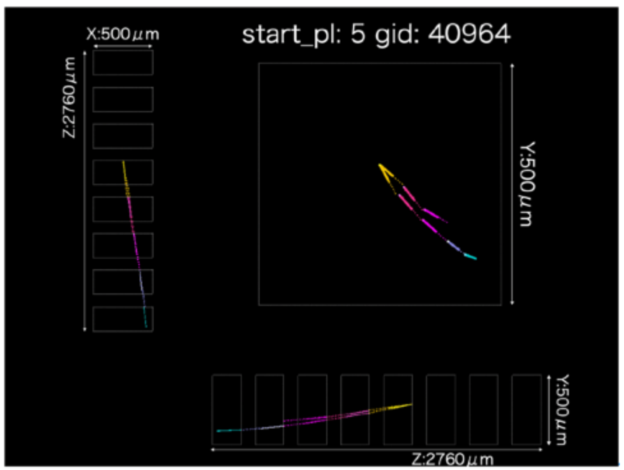


図 3.3.3 Event.40964 の電子対生成の軌跡図

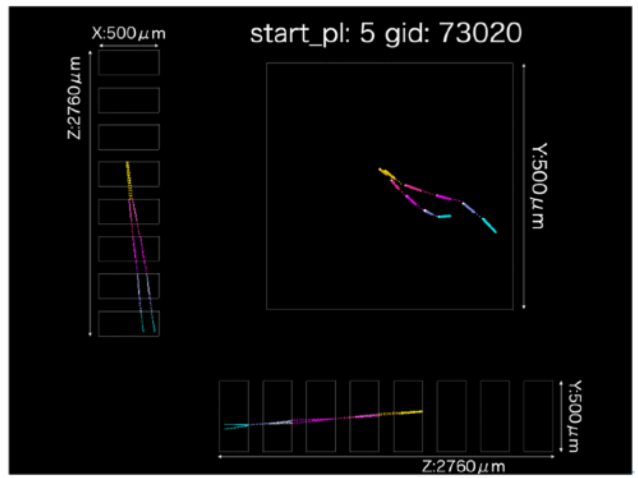


図 3.3.4 Event.73020 の電子対生成の軌跡図

Gamma-Ray energy

	MeV
Ev27840	44.5
Ev29565	75.8
Ev40964	46.4
Ev73020	39.1

Detection of four gamma-rays above ~40 MeV

R. Iwasaki, Bachelor, Osaka Univ. 2022

Gamma-ray observation (sensitivity)

Observed events: 4 events in 5 sheets of 1 cm^2 = 0.8 events/sheet/cm^2

pair-creation probability: 1.1×10^{-3}/sheet at 50 MeV

tracking efficiency for both e^+ and e^+ ~ 0.43

achieved sensitivity for gamma-rays

1.6×10^3 /cm^2 @ 100 cm = 1.6×10^7 /sr

= good sensitivity for observing gamma-rays from the target

The gamma-rays observed this time would have been generated
at the wall of the vacuum chamber by high-energy electrons from the target.

→ next experiment by placing the emulsion detector in vacuum (with thin window)

R. Iwasaki, Bachelor, Osaka Univ. 2022

Summary of the Second Part

- Direct gamma detection method from laser plasma above 10 MeV is under development.
- We tested nuclear emulsion as a gamma detector exploiting the high-granularity at KPSI-QST using the J-KAREN-P laser.
- For pair production events were detected in 5 sheets of $1\times1/\mathrm{cm}^2$.
- We have demonstrated the ability of observing a flux of v 1.6×10^3 $/\mathrm{cm}^2$ @ 100 cm for gamma-rays above 40 MeV.
- Next, we plan to place the emission in vacuum or with a window made of light-Z element for detecting gamma-ray from the target.