

ELITPC: the first experiments with the full-scale prototype of an active-target Time Projection Chamber

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ELITPC

C/O ratio importance



William Fowler, Nobel

Foundation archive

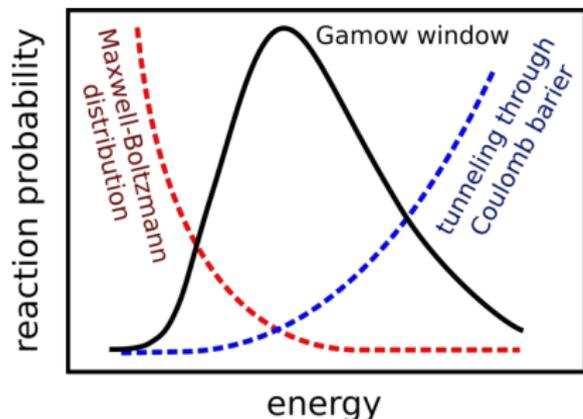
W. A. Fowler, Rev. Mod.

Phys. **56**, 149 (1984)

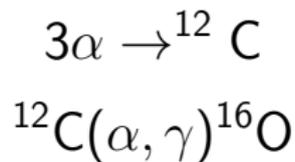
- stellar evolution modelling
- Ia supernova (standard candles)
light curves modelling
- influences the gap in black-hole
mass distribution

C/O ratio

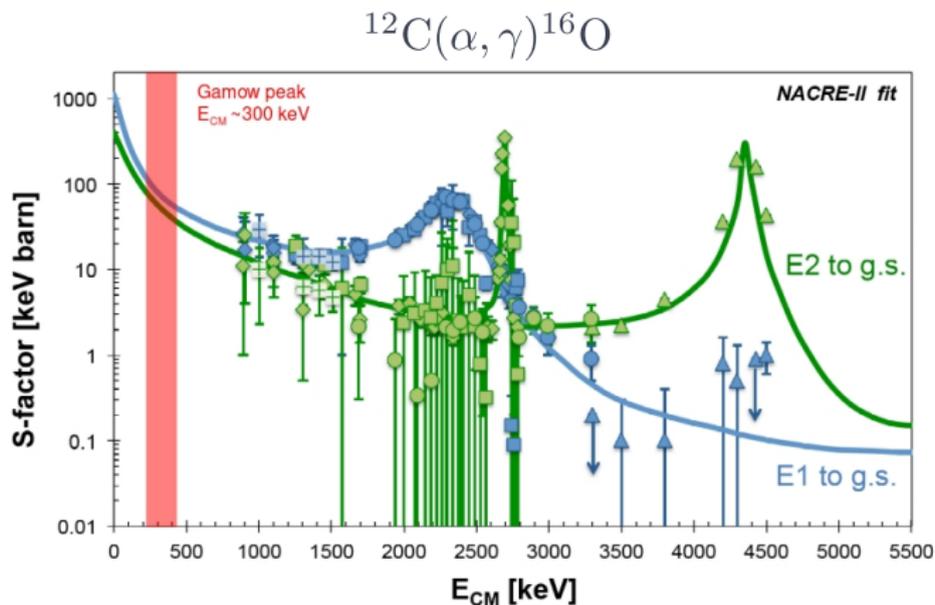
Stellar nuclear reactions
occur within narrow energy
windows



The $^{12}\text{C}/^{16}\text{O}$ ratio
depends on the relative
rates of the reactions:



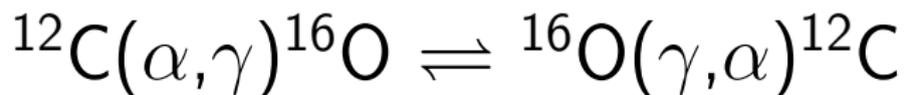
S-factor of $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction



Nacre II, Y. Xu et al., Nuclear Physics A 918 (2013)

$$\text{S-factor: } S(E) = \frac{E}{\exp(-2\pi\eta)} \sigma(E), \quad \eta = \frac{Z_1 Z_2 \alpha}{\beta}$$

The detailed balance principle



$$\sigma_{\alpha\gamma} = \sigma_{\gamma\alpha} \frac{2J_0 + 1}{(2J_\alpha + 1)(2J_C + 1)} \frac{E_\gamma^2}{E_{CM}} \frac{1}{\mu_{\alpha C} c^2}$$

$$\sigma_{\alpha, \gamma}(1 \text{ MeV}) \approx 50 \text{ pb}$$

$$\sigma_{\gamma, \alpha}(1 \text{ MeV}) \approx 2 \text{ nb}$$

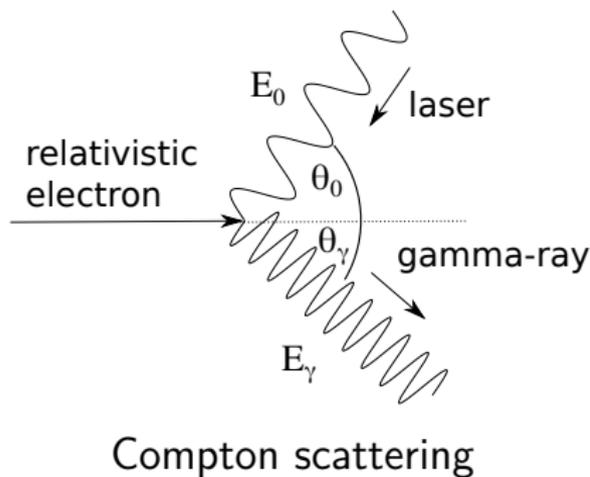
For comparison:

$$\sigma_{pp \rightarrow H^0}(13 \text{ TeV}) \approx 60 \text{ pb}$$

γ -beam facilities

- HI γ S (**H**igh **I**ntensity **G**amma-Ray **S**ource, USA)
 $10^8 \gamma/s$, 3% FWHM
- NewSUBARU (Japan)
 $10^5 \gamma/s$, 1.2% FWHM
- ELI-NP (**E**xtrême **L**ight **I**nfrastructure **N**uclear **P**hysics, Romania, under construction)
 $10^9 \gamma/s$, 0.5% RMS

High intensity γ -beams



VEGA (**V**ariable **E**nergy **G**amma) System at ELI-NP:

- laser:
500 / 1000 nm
- electron beam:
235 – 740 MeV
- γ -beam energy range:
1 – 20 MeV
- γ -beam bandwidth:
0.5%
- γ -beam intensity:
 $10^8 \gamma/s$

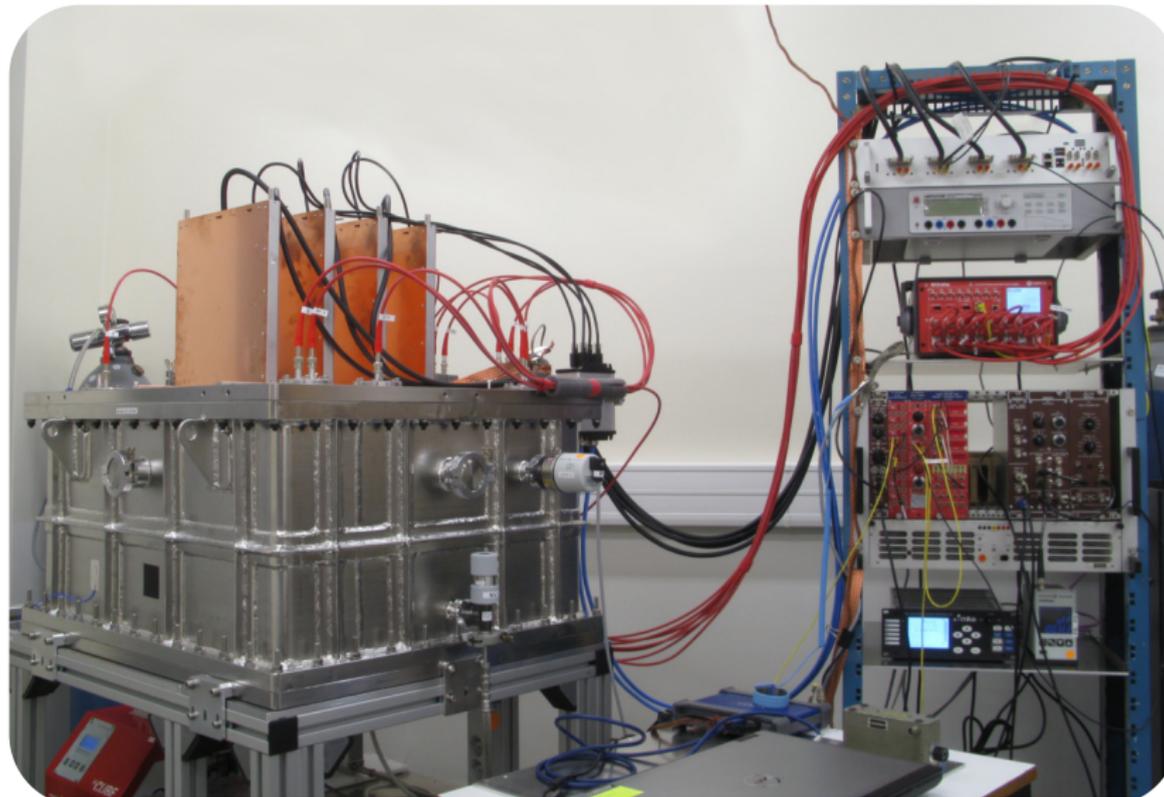
Requirements for $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ studies

- high intensity, monochromatic gamma beam,
- proper detector,
 - high efficiency
 - low background
 - low energy threshold
 - possibility to measurements of angular distribution

Solution

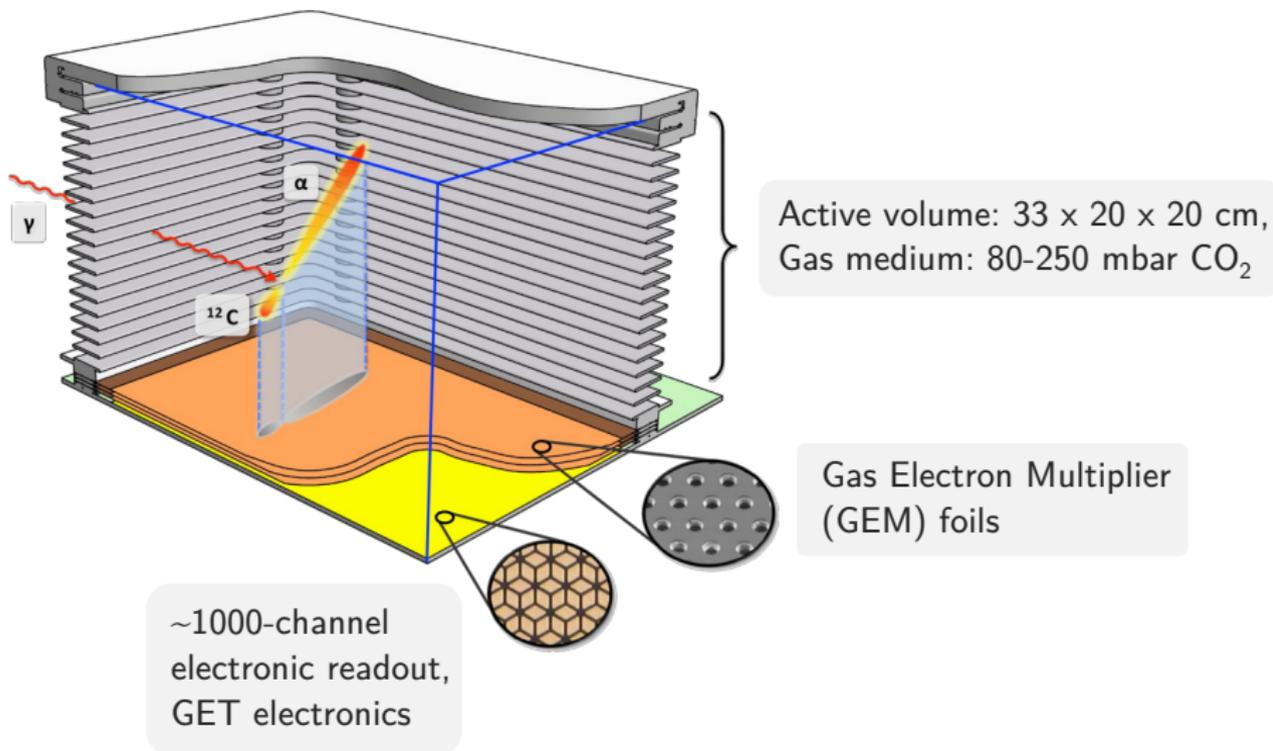
Active-Target Time Projection Chamber

Active-target TPC developed at FUW



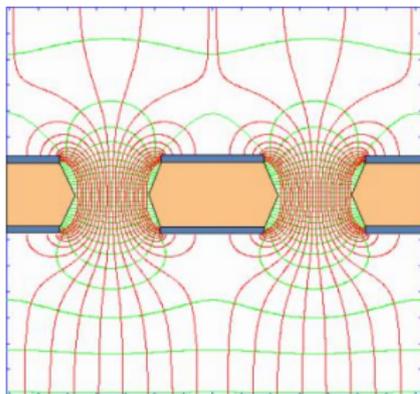
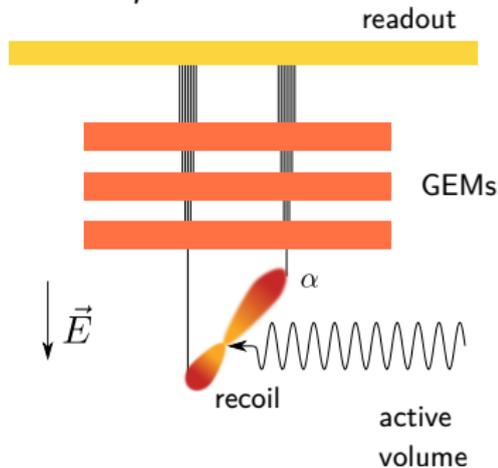
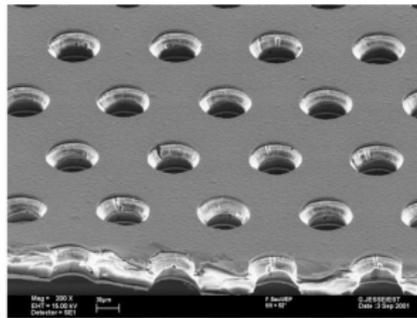
ELITPC full-scale prototype setup

Principles of operation



Charge amplification

Stack of 3 **G**as **E**lectron **M**ultiplier foils
standard CERN technology — 50 μm thick



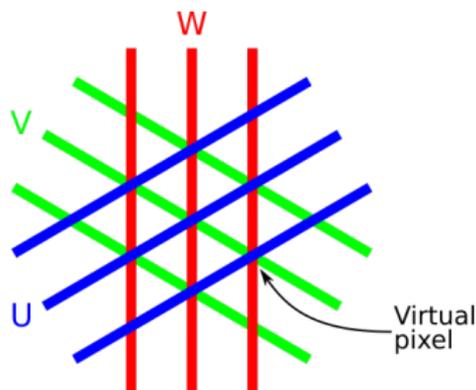
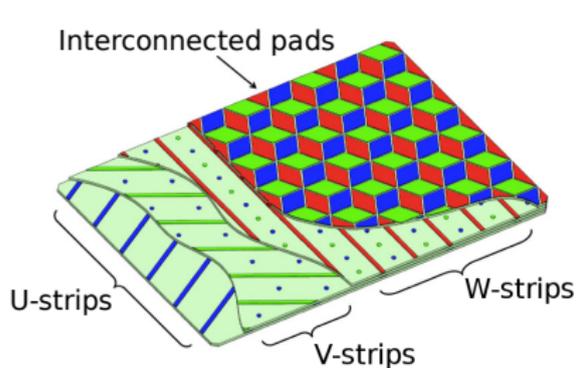
Electric fields $\sim 40 \text{ kV/cm}$
Total gain $\sim 10^4$

F. Sauli, Nucl. Instr. and Meth. A386 (1997)

Strip readout

XY plane: ~ 1000 channels (U,V,W)

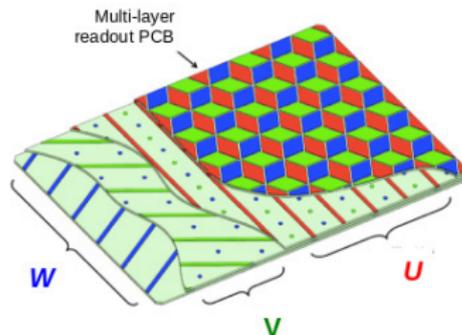
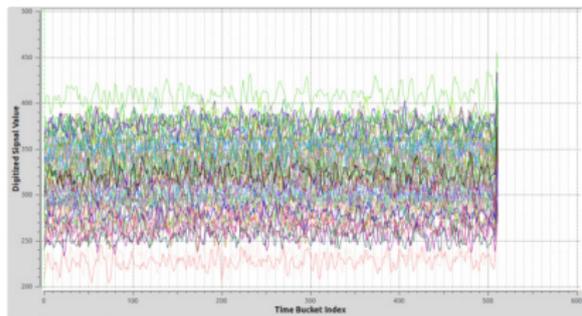
Z axis: drift time



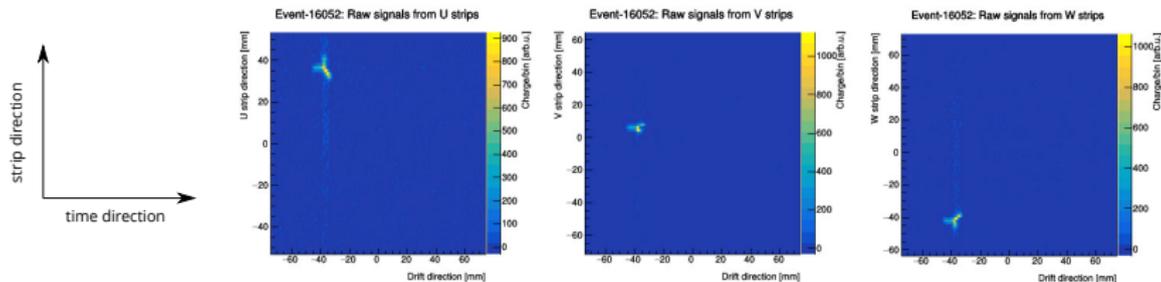
M. Ćwiok, Acta Phys.Pol. B 47 (2016)

$$\begin{pmatrix} u \\ v \\ w \\ t \end{pmatrix} = \begin{pmatrix} \cos(0) & \sin(0) & 0 \\ \cos\left(-\frac{2\pi}{3}\right) & \sin\left(-\frac{2\pi}{3}\right) & 0 \\ \cos\left(-\frac{\pi}{3}\right) & \sin\left(-\frac{\pi}{3}\right) & 0 \\ 0 & 0 & \frac{1}{v_d} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Strip readout



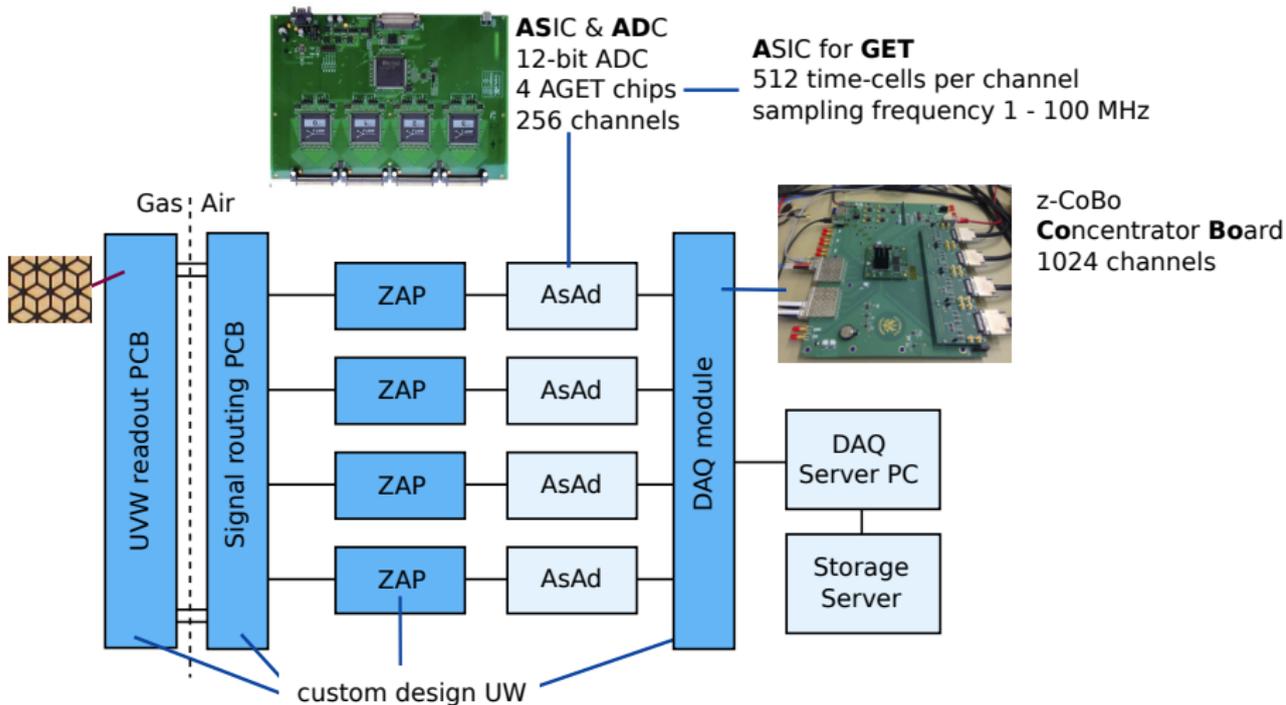
Rather than 3D picture our detector registers only 2D projections on strip directions sampled over time.



DAQ system

Generic Electronics for TPCs

(GET collab. CEA/IRFU, CENBG, GANIL, MSU/NSCL)



Detector Control System



Functions:
experimental equipment control & monitoring,
database logging

Experiment at HI γ S, USA

γ -beam energies: 11.5-13.9 MeV (300 keV steps)

Goals:

- measure $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ and $^{12}\text{C} + \gamma \rightarrow 3\alpha$ reactions cross-sections
- measure angular distribution of products

Planned **March 2022**

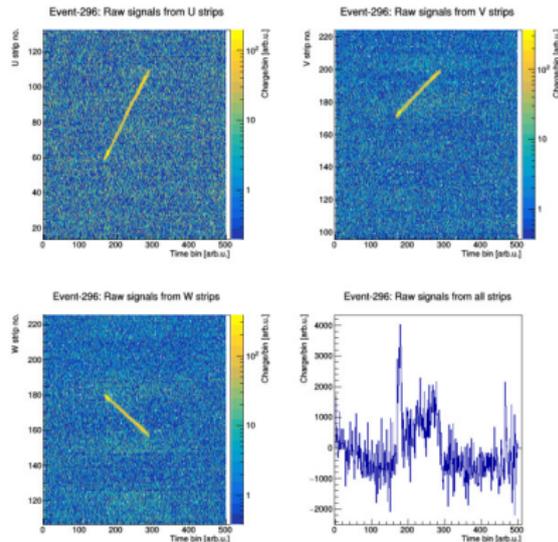
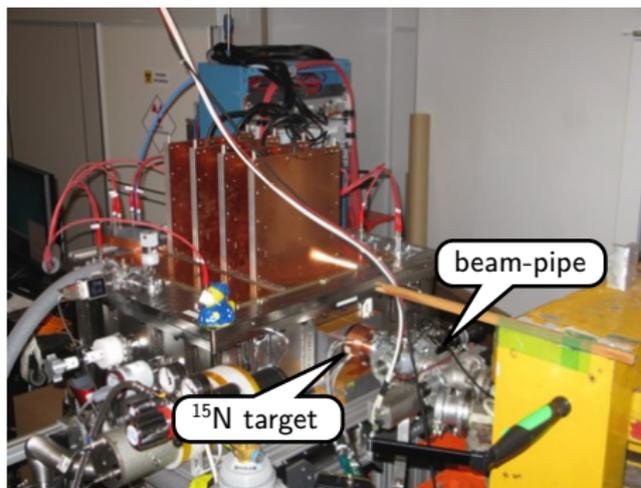
Experiment at the Van de Graaf accelerator (IFJ PAN, Cracow)

Goals:

- test TPC in-beam
- measure $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ reaction cross-section at $E_\gamma=13$ MeV
- measure angular distribution of α -particles
- test distinguishing $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$ and $^{18}\text{O}(\gamma, \alpha)^{14}\text{C}$ events
- test logistics

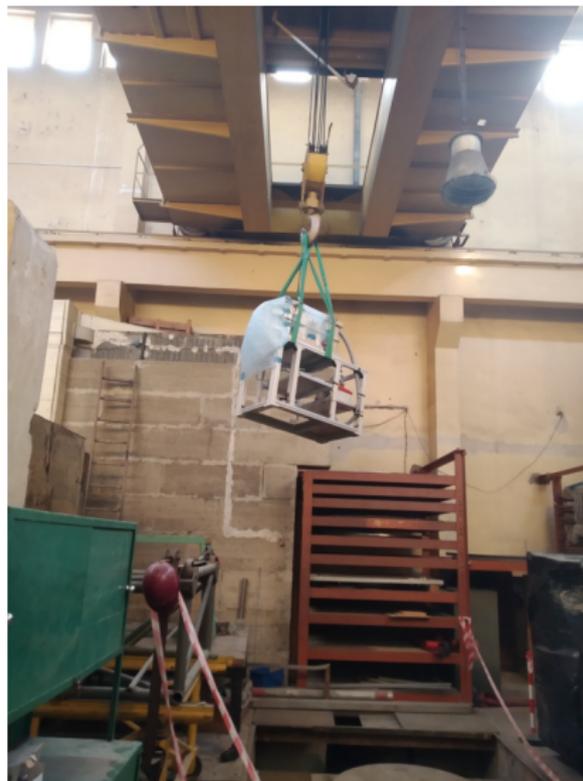
First experiments — June 2021

Van de Graaf accelerator (IFJ PAN, Cracow):
13 MeV gammas from $^{15}\text{N}(p, \gamma)^{16}\text{O}$ reaction



Data-taking successful: $\sim 2 \cdot 10^6$ events (2 TB)

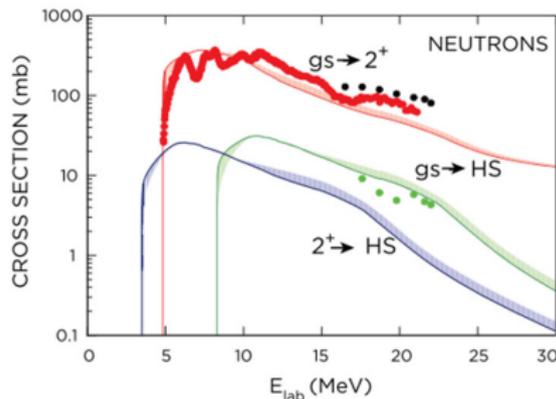
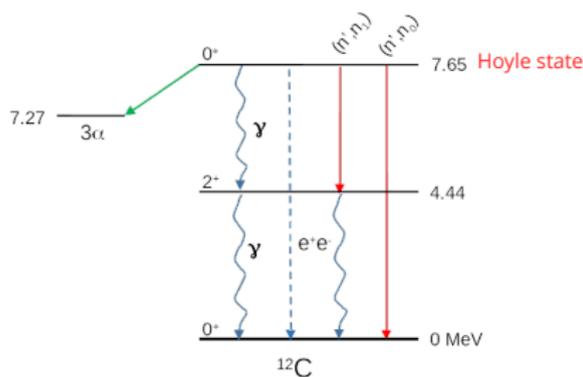
Moving for second experiment at the IFJ PAN



Experiment at the IGN-14 (IFJ PAN, Cracow)

Goals:

- populate ^{12}C Hoyle state in $^{12}\text{C}(n, n')^{12}\text{C}^{\text{Hoyle}}$ reaction at $E_n=14.1$ MeV
- measure $^{12}\text{C}^{\text{Hoyle}} \rightarrow 3\alpha$ reaction rate
- measure detector response over whole active area using scattering events

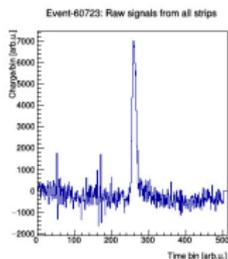
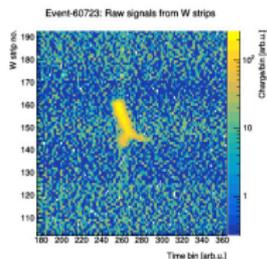
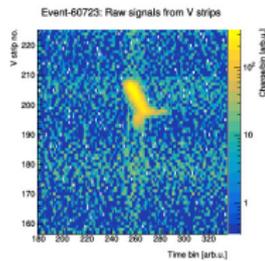
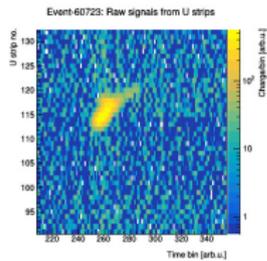


$\sigma_{gs \rightarrow \text{HS}}(14 \text{ MeV})$:

- H-F: 19 mb
- Kondo 8 mb
- Takahashi 8 (2) mb

First experiments — July, September 2021

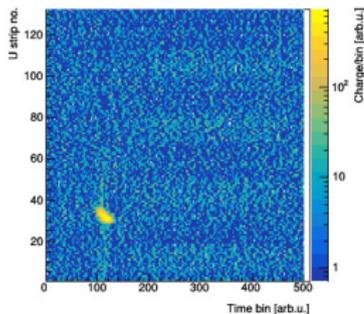
IGN-14 pulsed neutron generator (IFJ PAN, Cracow):
14.1 MeV neutrons from $T(d, n)\alpha$ reaction



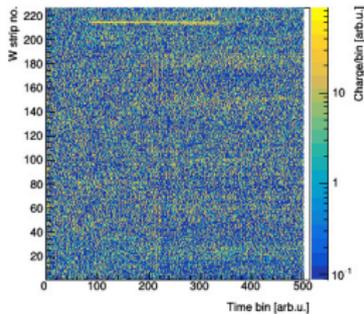
Data-taking successful: $\sim 12 \cdot 10^6$ events (12 TB)

Example event topologies

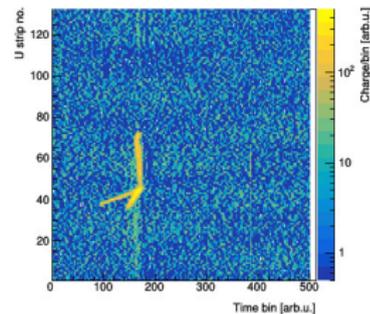
Event-5: Raw signals from U strips



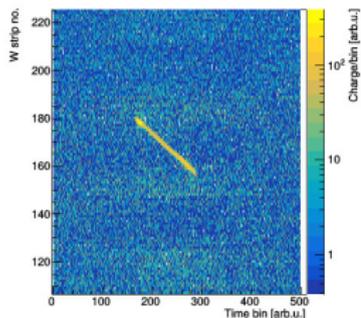
Event-320: Raw signals from W strips



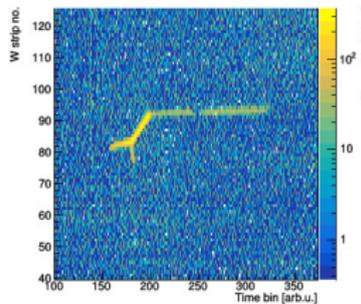
Event-50: Raw signals from U strips



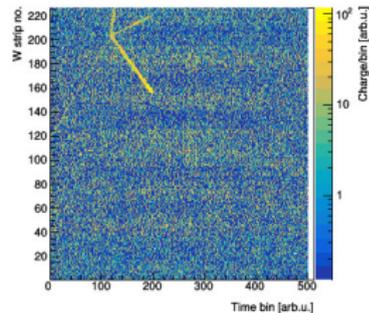
Event-296: Raw signals from W strips



Event-665: Raw signals from W strips

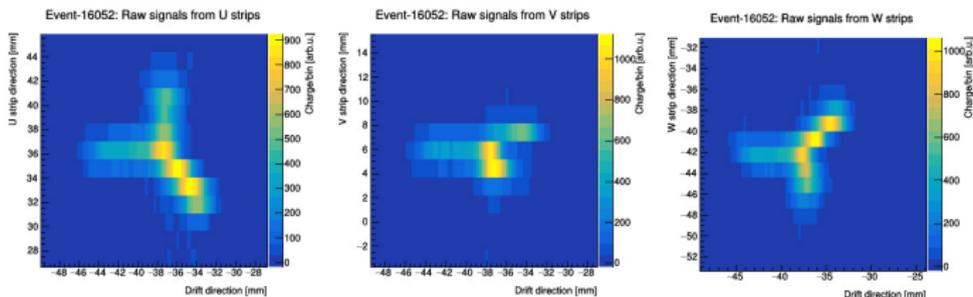


Event-319: Raw signals from W strips

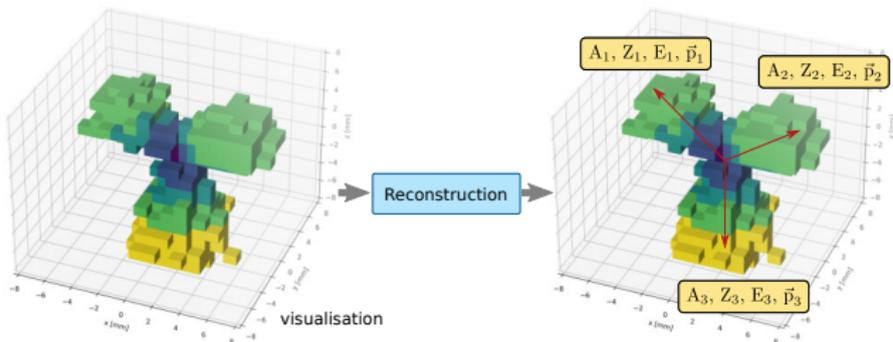


Example event topologies

Kinematic reconstruction (ongoing development)

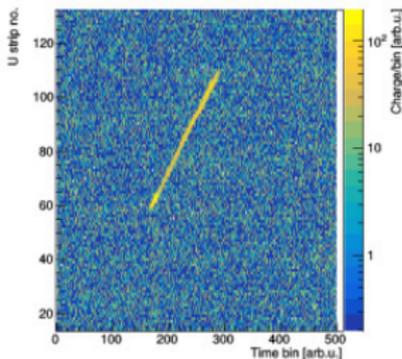


Reconstruction should be capable of identifying particles and obtaining their energies and momenta.

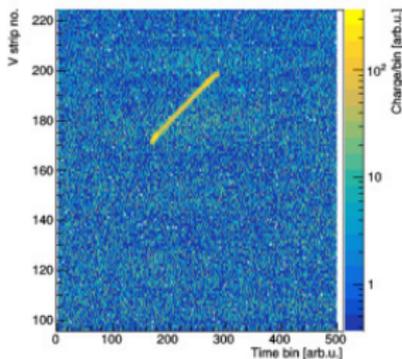


Kinematic reconstruction

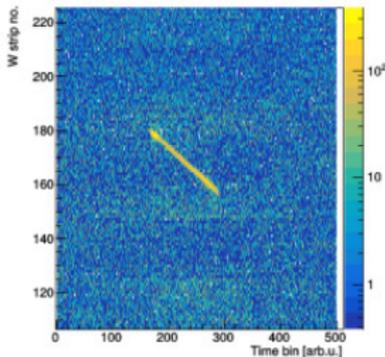
Event-296: Raw signals from U strips



Event-296: Raw signals from V strips

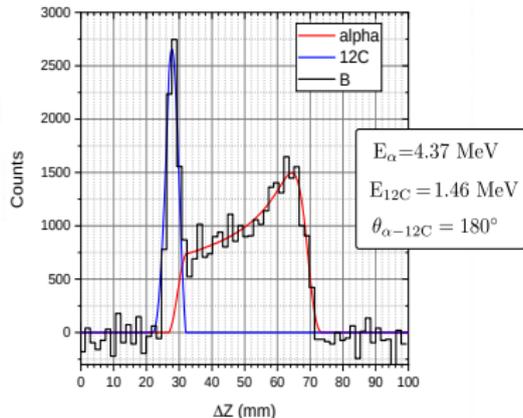


Event-296: Raw signals from W strips



Particle identification, energy and momentum can be obtained from:

- track length (range in medium)
- ionization along the track (Bragg curve)



Line detection – examples



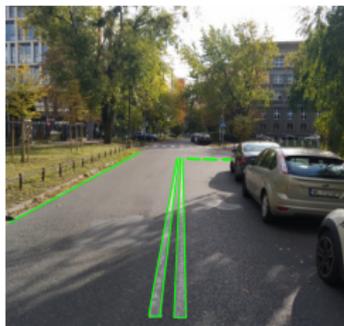
Hough, P. V. C., Conf. Proc. C 590914 (1959)



OpenCV tutorial



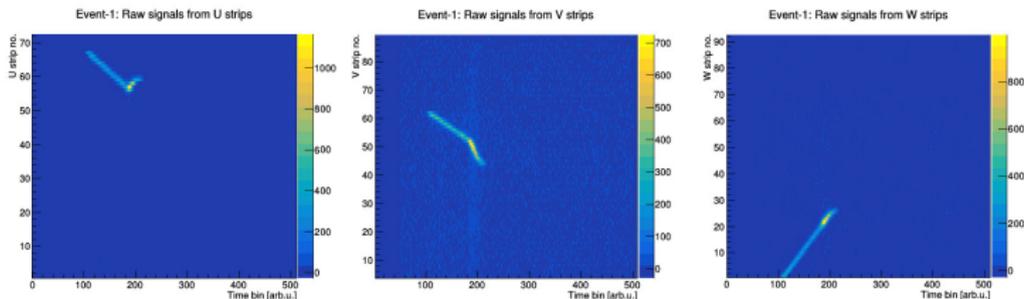
<https://github.com/gchlebus/tennis-court-detection>



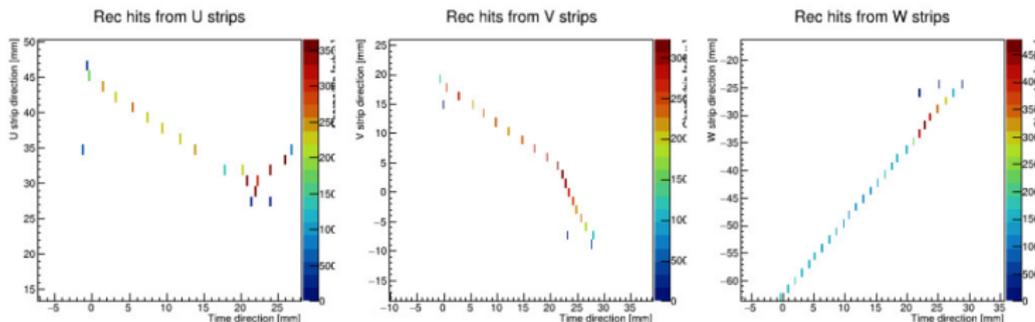
road line detection example

Reconstruction algorithm

Raw data



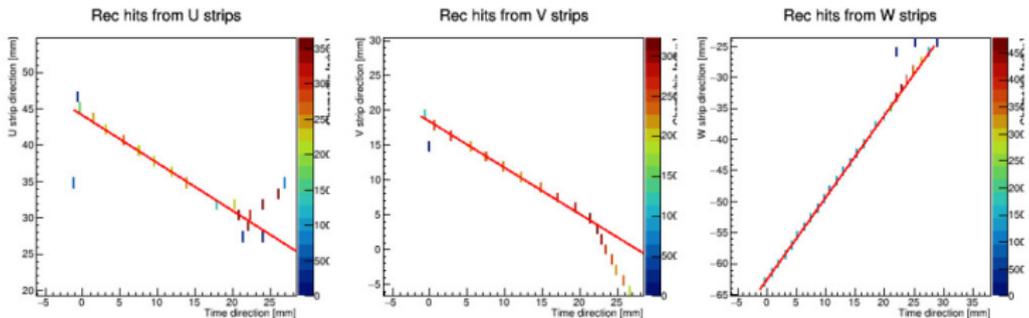
Hit seeds



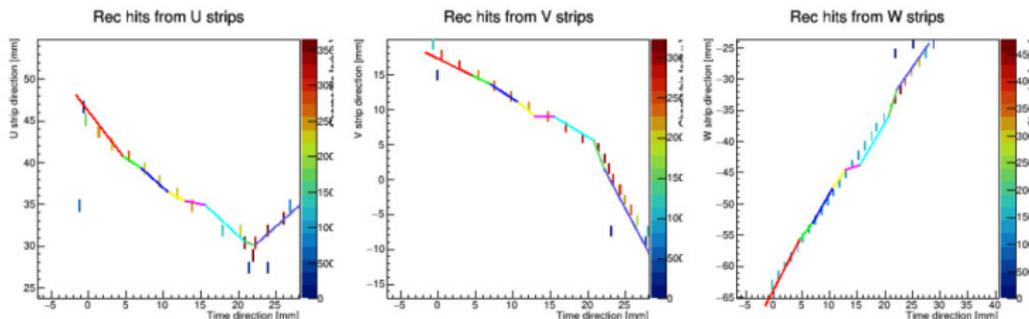
based on algorithm used in ICARUS detector

Reconstruction algorithm

Line detection

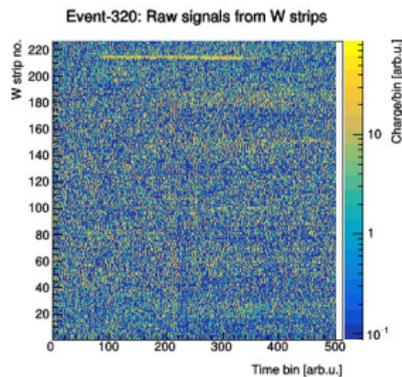
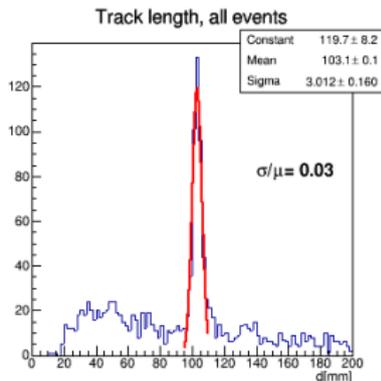
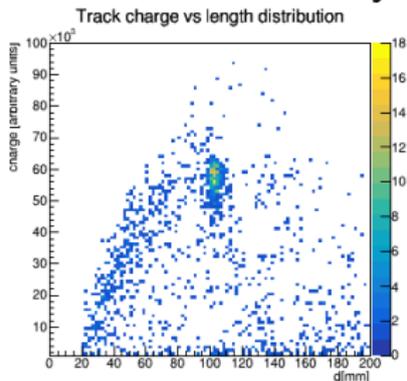


3D-segments fitting

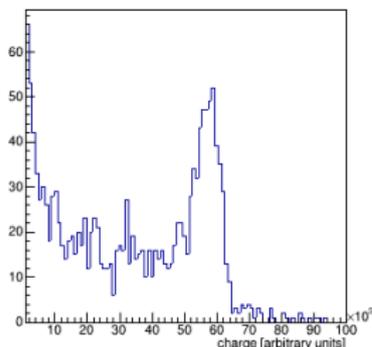


Reconstruction resolution

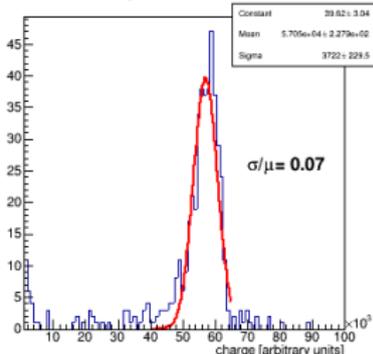
Preliminary at low statistics



Track charge, all events

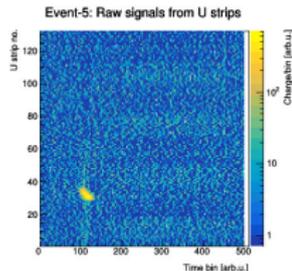
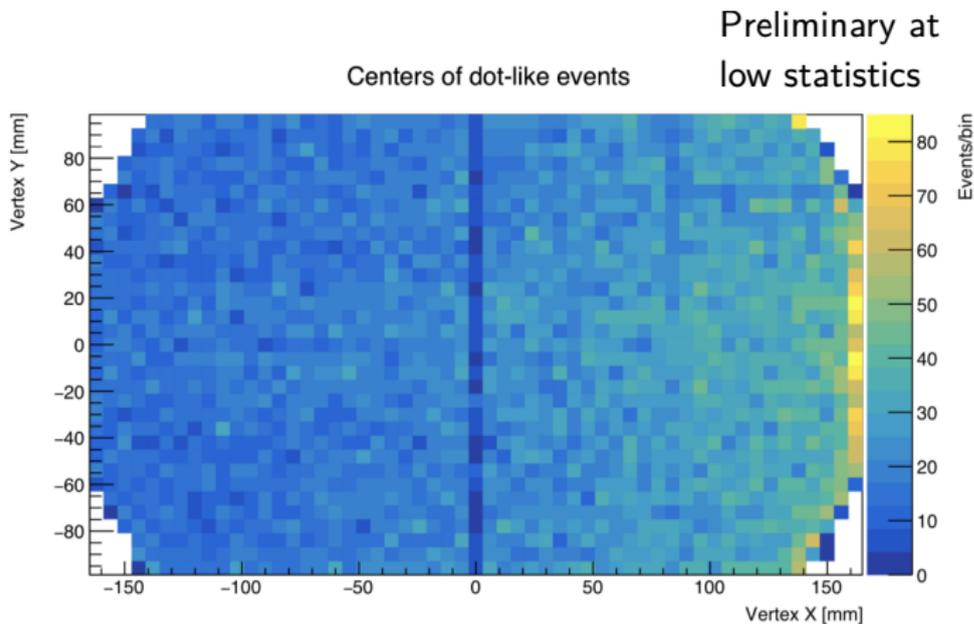


Track charge events with $95 < d < 110$ mm



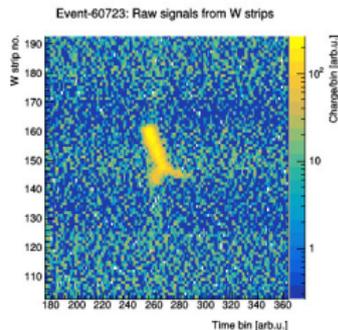
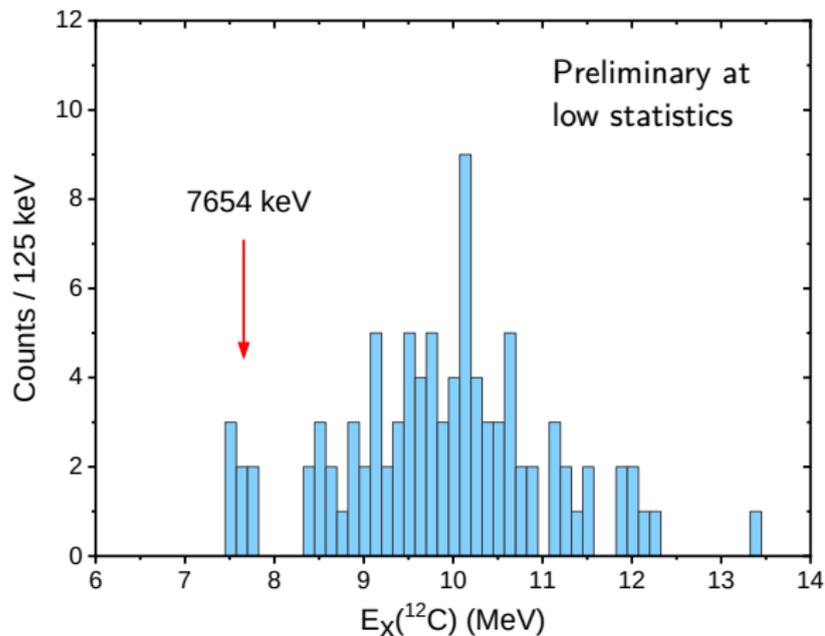
Track reconstruction in
example run at VdG
accelerator

Detector response uniformity



Distribution of dot-like events collected during example run with IGN-14 neutron beam

Reconstructed excitation energy of ^{12}C



Distribution of excitation energy in 3-track events in example run with IGN-14 neutron beam

Summary

- Active-target TPC with electronic readout has been developed at the University of Warsaw.
- The first experiments with the detector took place in June–September 2021 at IFJ PAN, Cracow. The detector proved to be operational.
- Ongoing data analysis and software development.
- Upcoming experiments with γ -ray beams of HI γ S (early 2022) and ELINP.

Scientific work supported by the Polish Ministry of Science and Higher Education from the funds for years 2019-2021 dedicated to implement the international co-funded project no. 4087/ELI-NP/2018/0, by University of Connecticut under the Collaborative Research Contract no. UConn-LNS_UW/7/2018 and by the National Science Centre, Poland, under Contract no. UMO-2019/33/B/ST2/02176.

Collaboration

FUW UW:

- ZCIOF:
M. Ćwiok, W. Dominik, M. Fila, A. Kalinowski,
M. Kuich, M. Zaremba
- ZFJ:
A. Fijałkowska, A. Giska, Z. Janas, C. Mazzocchi

IFJ PAN experiments:

- VdG group:
J. Lekki, Z. Szklarz, T. Pieprzyca
- IGN-14 group:
D. Grządziel, W. Janik, W. Królas,
A. Kulińska, A. Kurowski,
M. Scholz, M. Turzański,
U. Wiącek, U. Woźnicka

HI γ S experiment:

- Univ. of Connecticut, USA:
M.Gai, D.Schweitzer, S.Stern
- Sheffield Hallam Univ., UK:
R.Smith