Studies of gamma-ray and neutron induced reactions with an active-target Time Projection Chamber

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IFJ PAN 28.10.2021

Nucleosynthesis in stars

- **H -** burning reactions

pp – chain
CNO cycle
} $4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu$

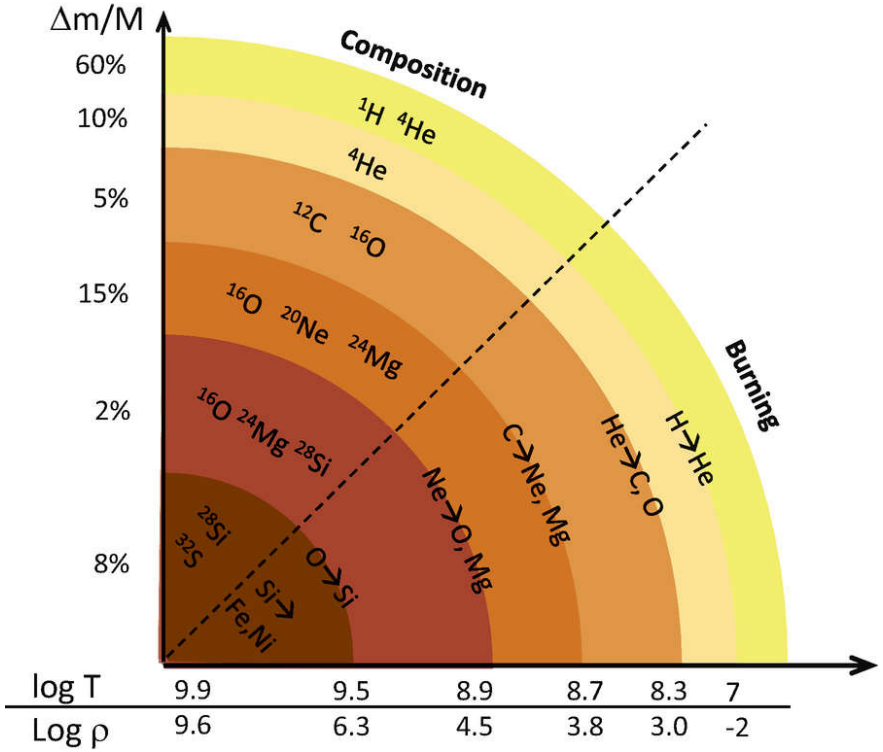
- **He -** burning reactions

$3\alpha \rightarrow {}^{12}\mathbf{C}$

$^{12}\mathbf{C}(\alpha, \gamma)^{16}\mathbf{O}$

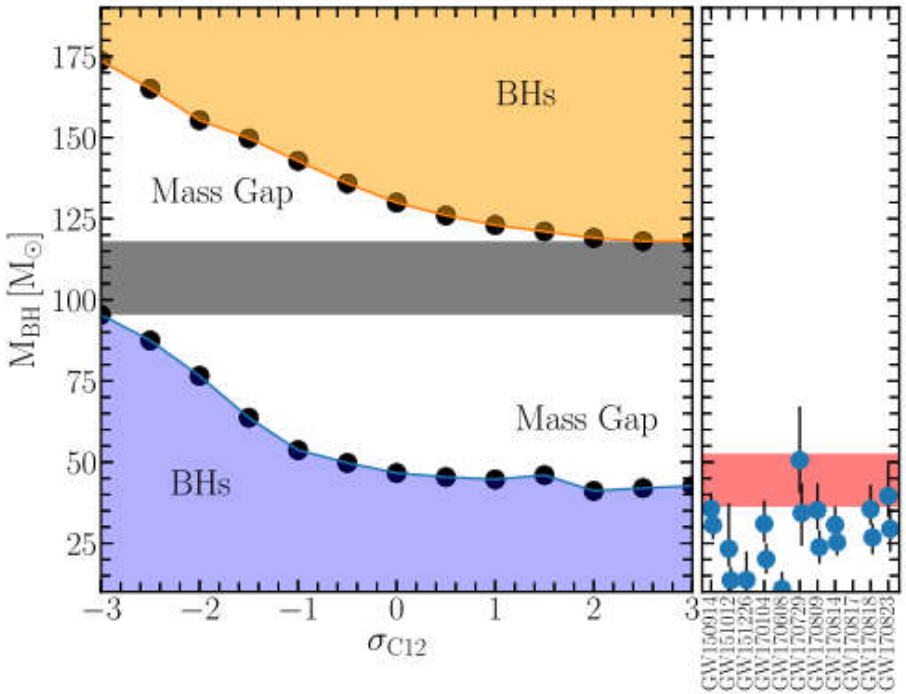
$^{16}\mathrm{O}(\alpha, \gamma)^{20}\mathrm{Ne}$

…



Significance of the $^{12}C(\alpha, \gamma)^{16}O$ reaction

- determines C/O at the end of He burning
- important in evolution of stars into type SN Ia and SN II type supernova
- influences the gap in black-hole mass distribution



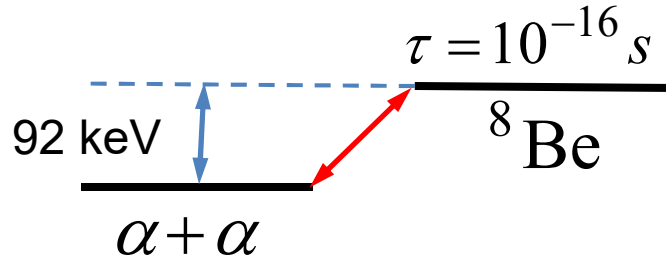
R. Farmer, Astr. J. Lett. 902 (2020) L36

Synthesis of ^{12}C in 3-alpha reaction

- Step I

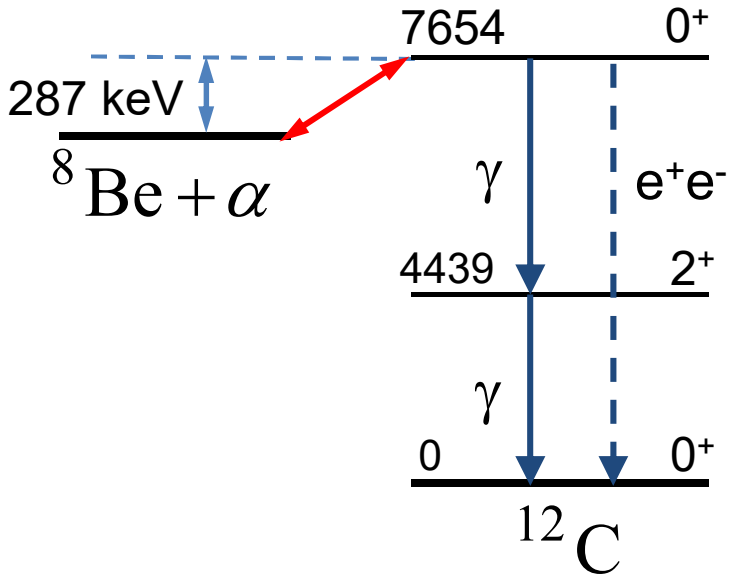
$$\alpha + \alpha \leftrightarrow {}^{8}\mathrm{Be}$$

$^{8}Be : {}^{4}He = 10^{-10}$

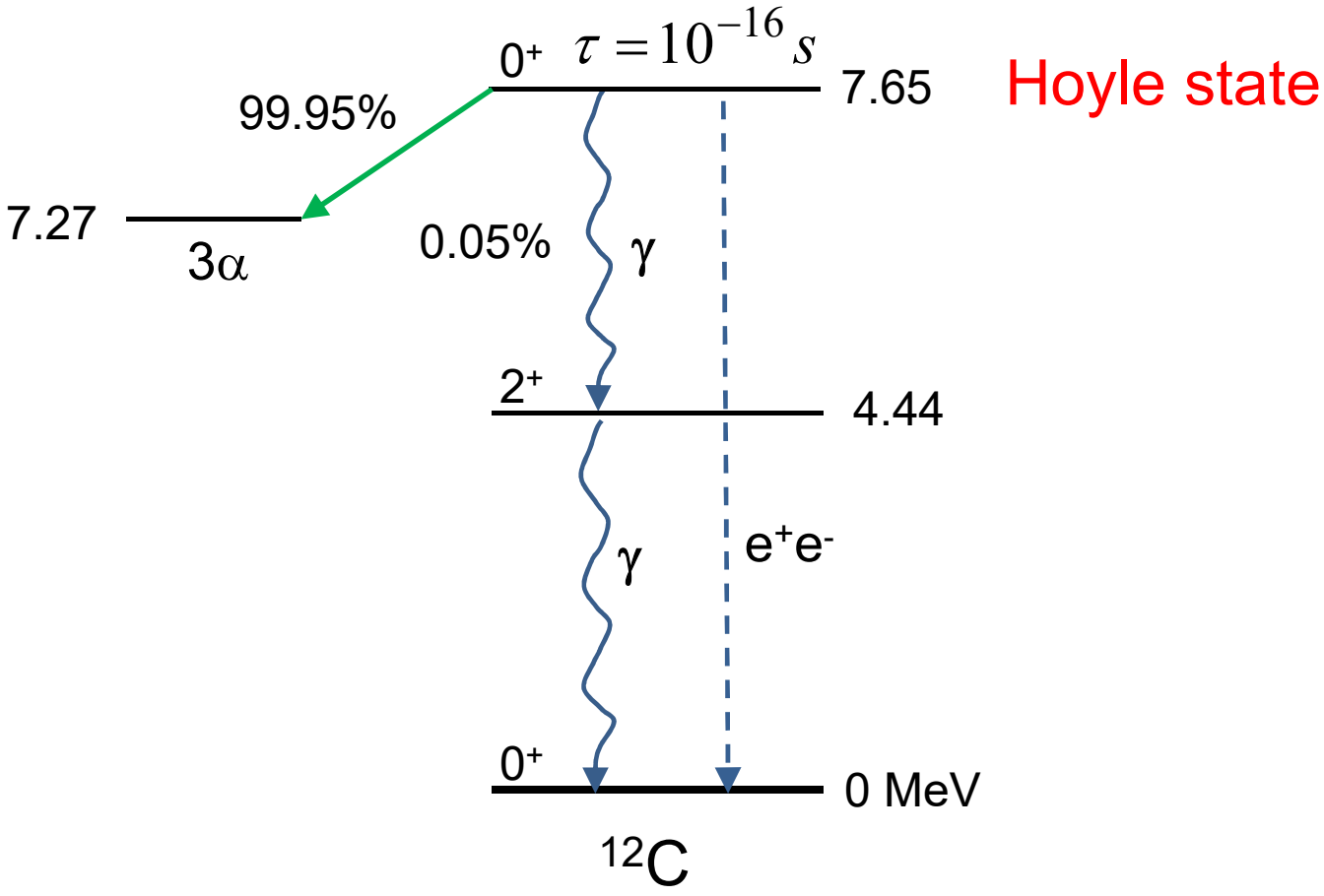


- Step II

$$\alpha + {}^{8}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + \gamma$$

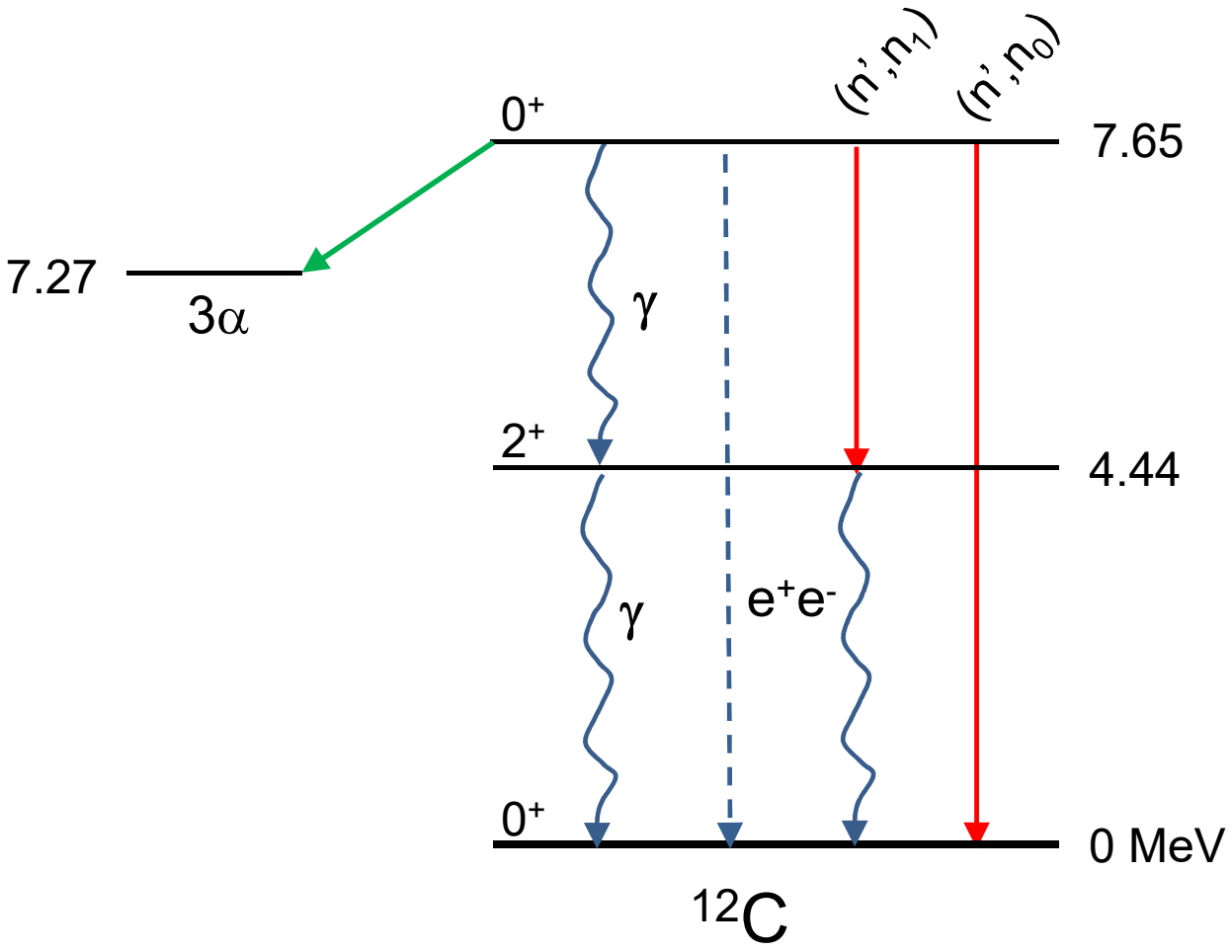


Decay of the Hoyle state – no influence of environment



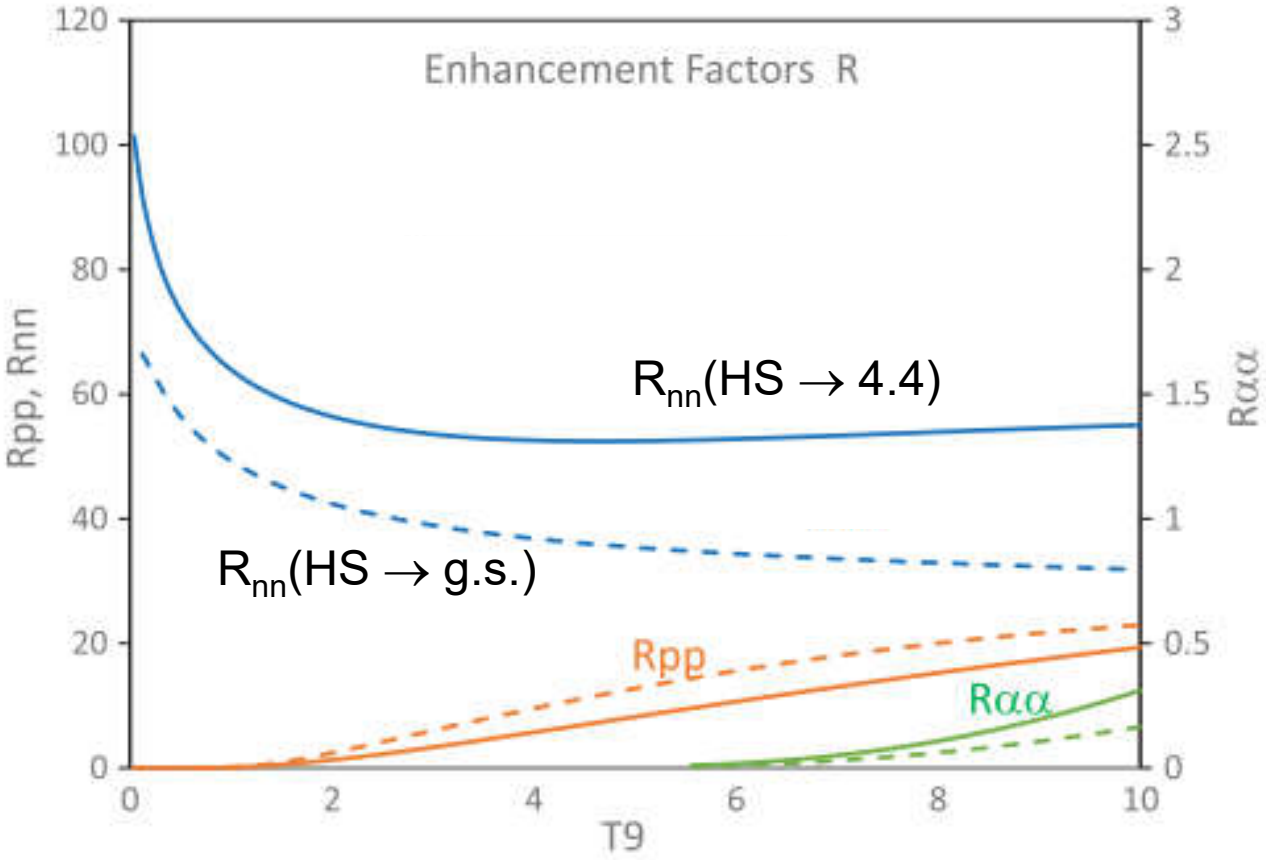
Deexcitation of the Hoyle state
in e.g. high density neutron environment

$$\Gamma_{n'n}(^{12}\mathrm{C}^{Hoyle}) = \hbar \cdot N_n \cdot \langle \sigma v \rangle_{n'n}$$



M. Beard, Phys. Rev. Lett. 119(2017)112701

Enhancement factor $R = \Gamma_{n'n} / \Gamma_{rad}$

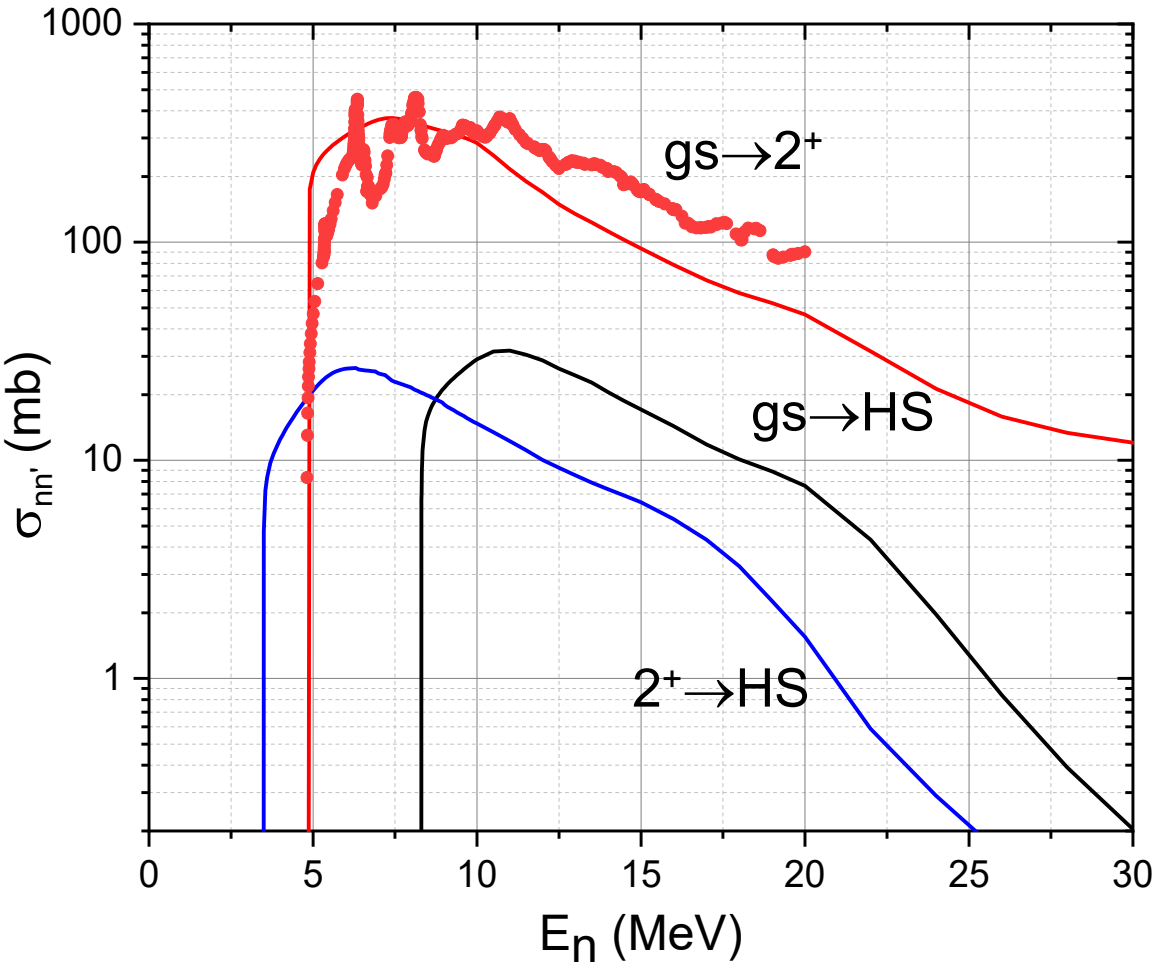


$N_n = 10^6$ g/cm^3

M. Beard, Phys. Rev. Lett. 119(2017)112701

^{12}C(n, n') cross section

$$\langle \sigma v \rangle_{nn'} = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{kT}\right)^{-3/2} \int_0^\infty E' \sigma_{n,n'}(E') \exp(-E'/kT) dE'.$$



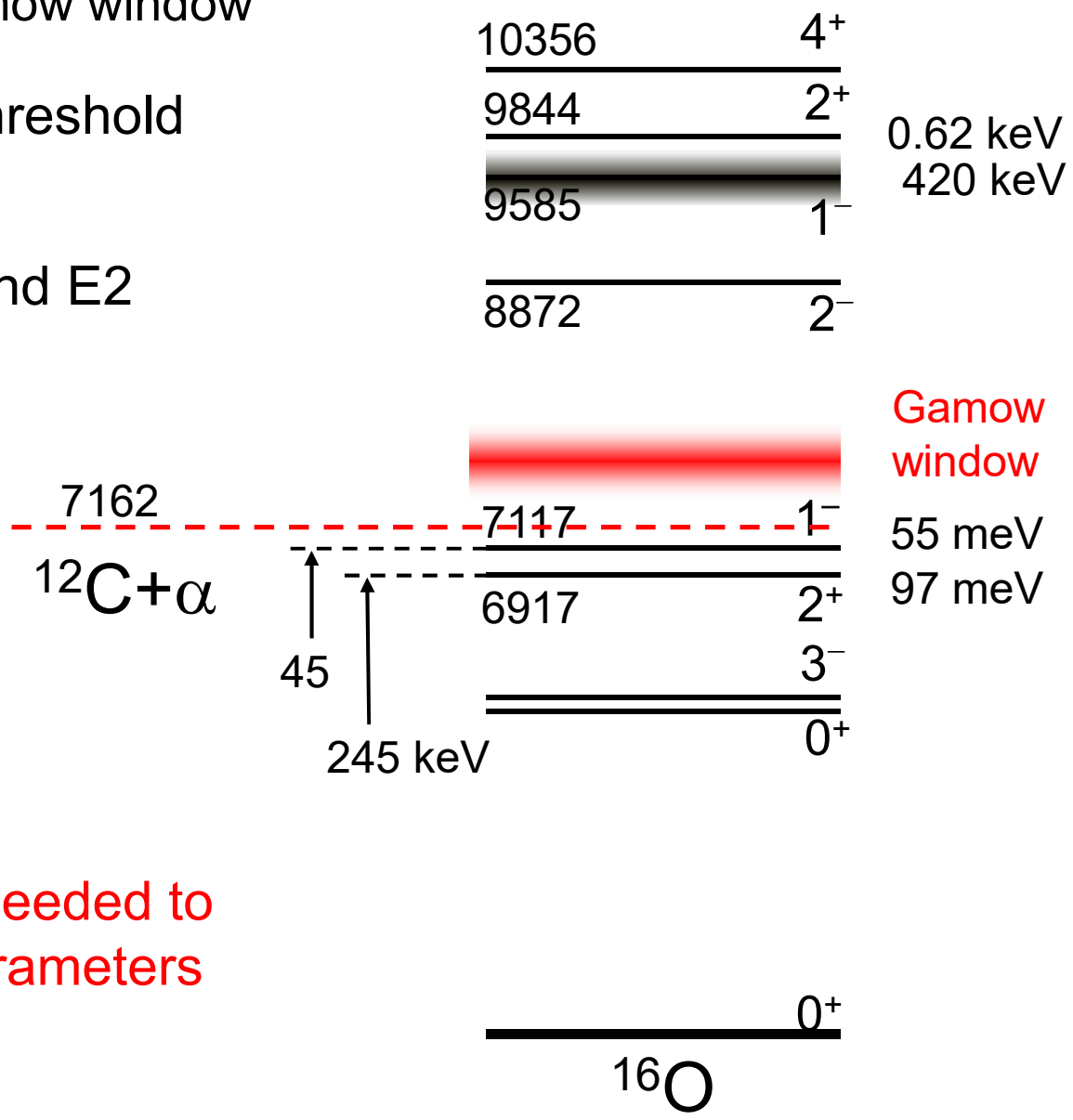
gs → HS at 14 MeV

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

Cross sections calculated within a factor 2-3

Mechanism of $^{12}C(\alpha, \gamma)$ reaction

- no resonances at Gamow window
- contribution of subthreshold resonances
- interference of E1 and E2 components

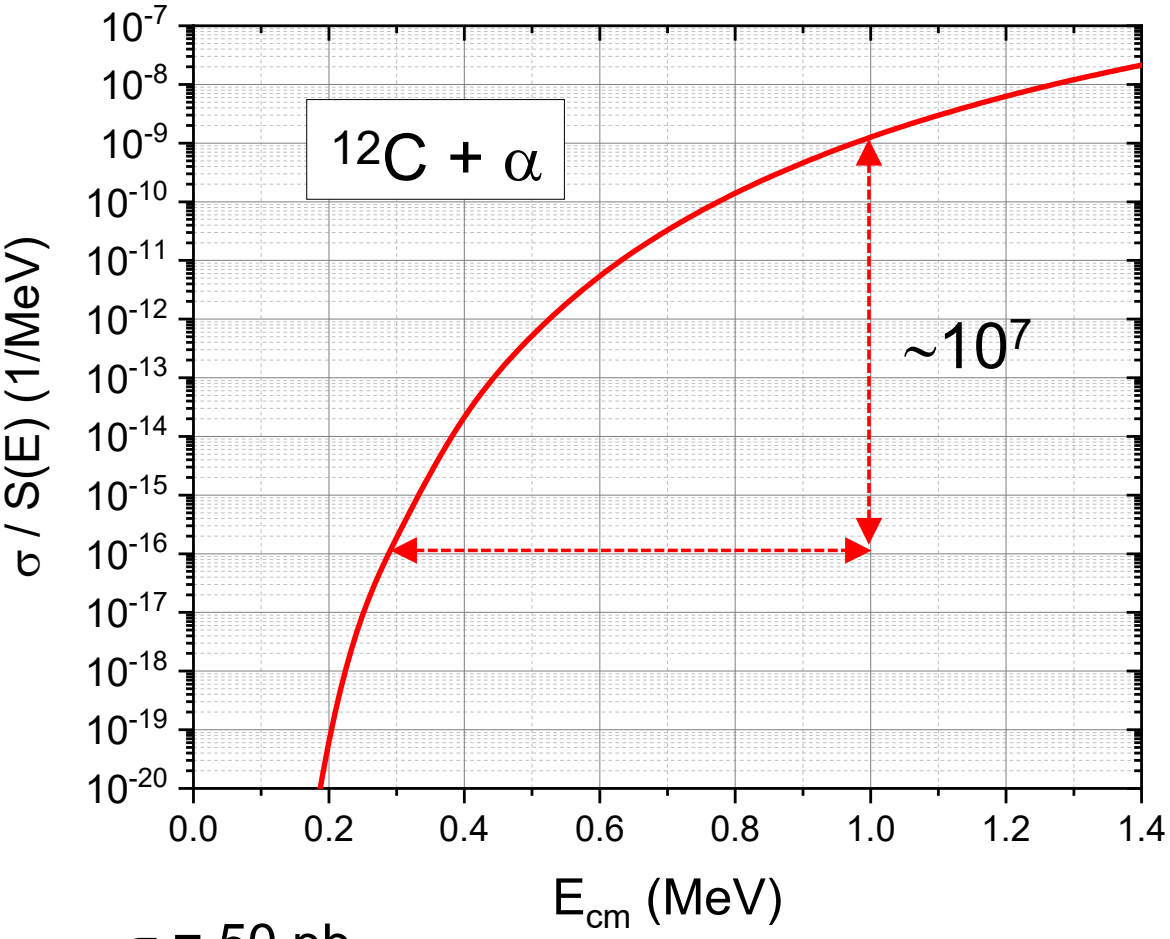


- experimental data needed to constrain model parameters

Astrophysical S-factor

$$\sigma(E) = S(E) \cdot \frac{1}{E} e^{-2\pi\eta}$$

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar c} \sqrt{\frac{\mu c^2}{E}}$$



S(1 MeV) = (40 ± 10) keV·b σ = 50 pb

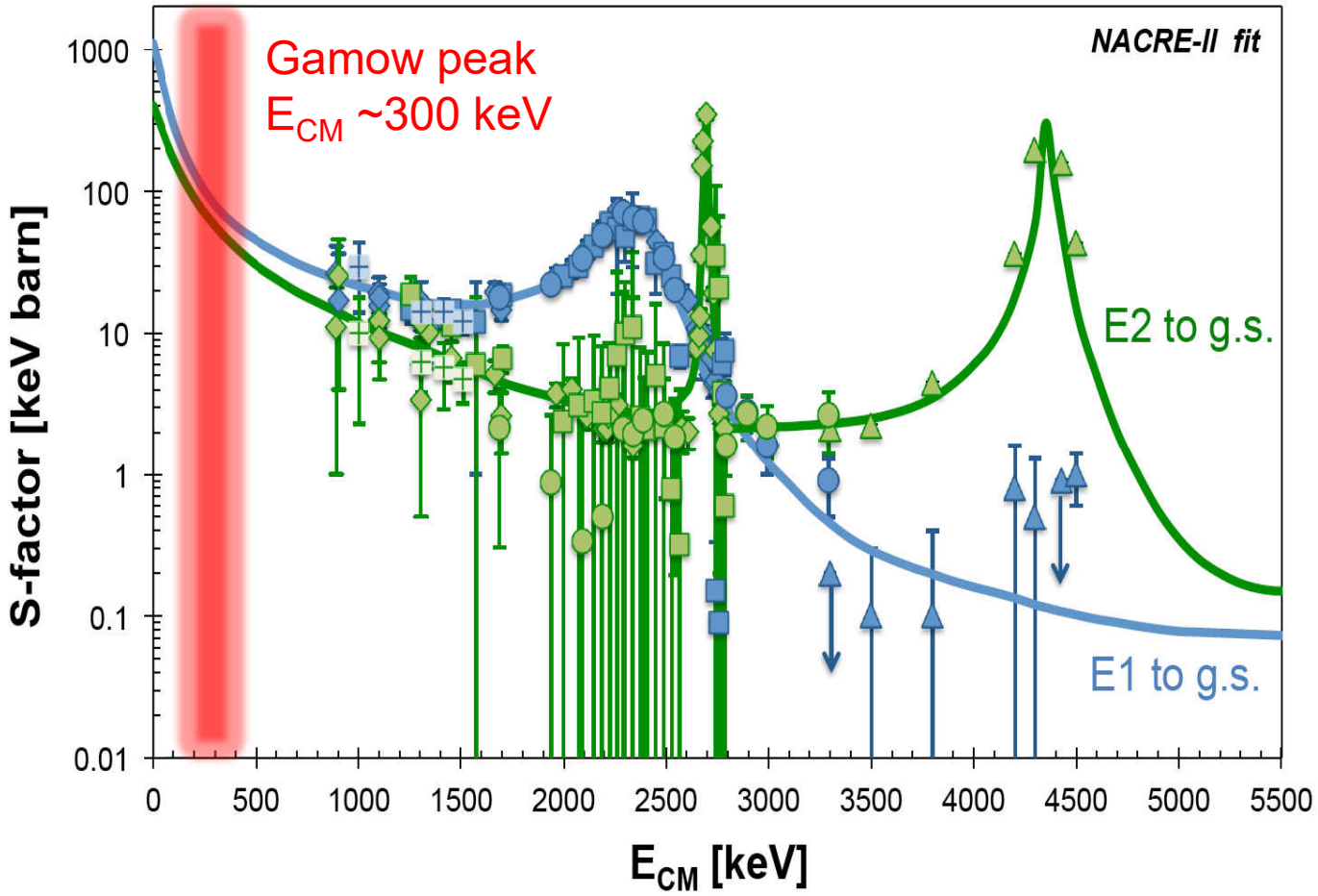
S(300keV) = (140 ± 20) keV·b σ = 0.03 fb

R.J. deBoer *et al*, Rev. Mod. Phys. 89 (2017)

S-factor for $^{12}C(\alpha, \gamma_0)^{16}O$ reaction

S(1 MeV) = (40 ± 10) keV·b σ = 50 pb

S(300 keV) = (140 ± 20) keV·b σ = 0.03 fb



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

Studies of $^{12}C(\alpha, \gamma)^{16}O$ reaction

Target: ^{12}C implanted in gold

Density: $2 \cdot 10^{18}$ atoms/cm^2

Beam: 400 μA

Detectors: Ge + BGO

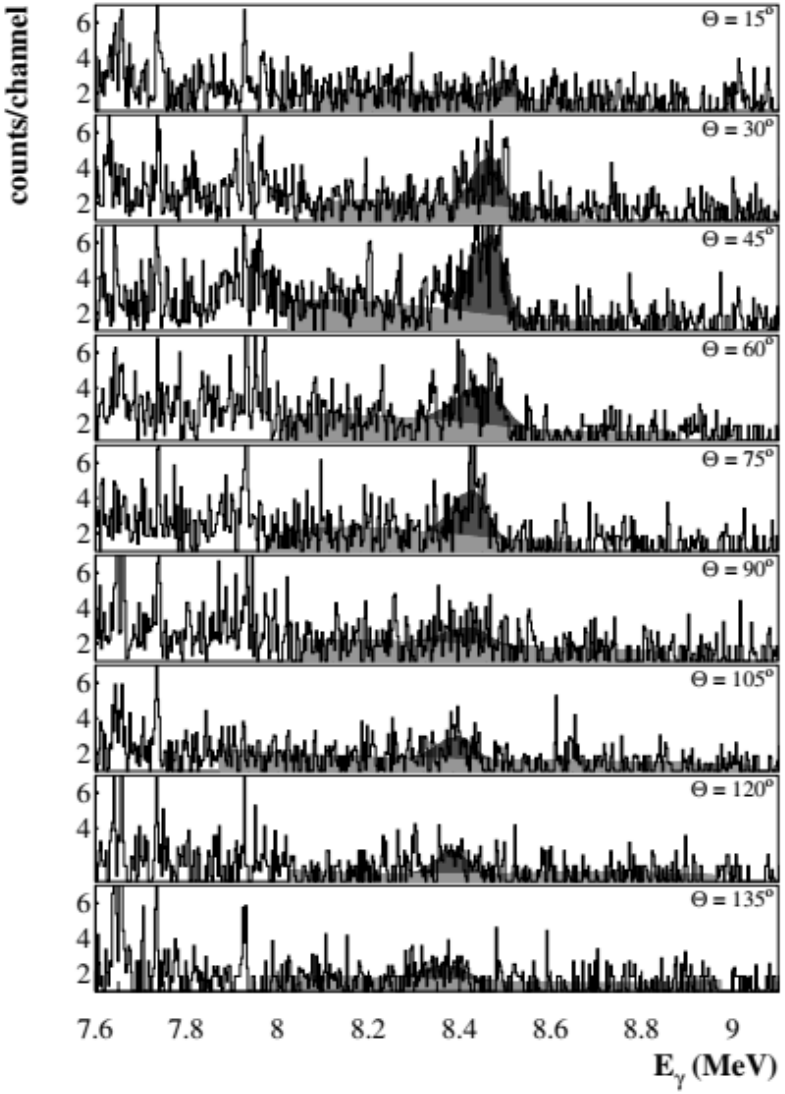
Time: 6 days

E_{cm}= 1.274 MeV

σ = 0.3 nb

Problems

- background $^{13}C(\alpha, n)$
- target deterioration
- uncertain beam energy



R. Kunz *et al.*, Phys. Rev. Lett. 86(2001)3244

Alternative approach to $^{12}C(\alpha, \gamma)^{16}O$

- study of time-reverse $^{16}O(\gamma, \alpha)^{12}C$ reaction
- use principle of detailed balance

$$\mathrm{A}(a, b)\mathrm{B} \quad \Leftrightarrow \quad \mathrm{B}(b, a)\mathrm{A}$$

$$\sigma_{ab} = \frac{(2J_B + 1)(2J_b + 1)}{(2J_A + 1)(2J_a + 1)} \cdot \frac{p_{Aa}^2}{p_{Bb}^2} \cdot \sigma_{ba}$$

for

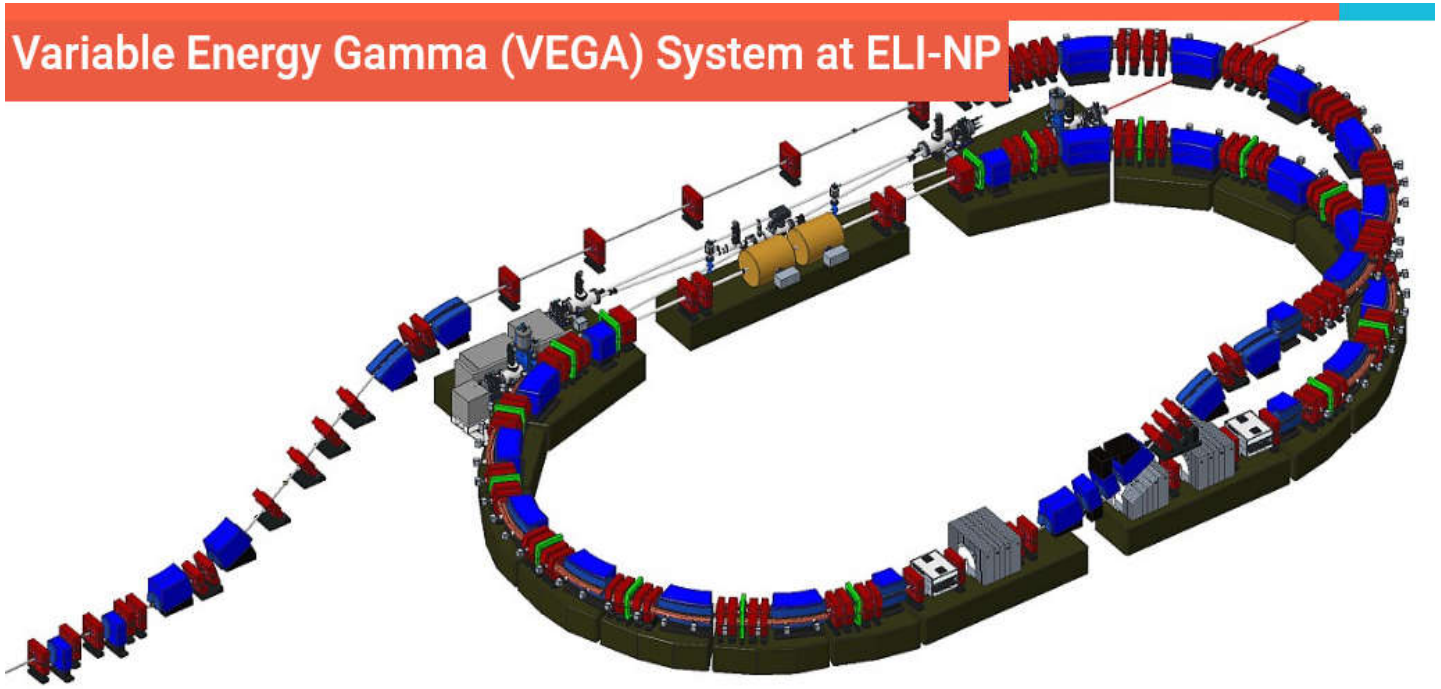
$$^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O} \quad \Leftrightarrow \quad ^{16}\mathrm{O}(\gamma, \alpha)^{12}\mathrm{C}$$

$$\sigma_{\alpha\gamma}(E_\alpha = 1\,\mathrm{MeV}) \;=\; \frac{1}{85} \cdot \sigma_{\gamma\alpha}(E_\gamma = 8.16\,\mathrm{MeV})$$

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

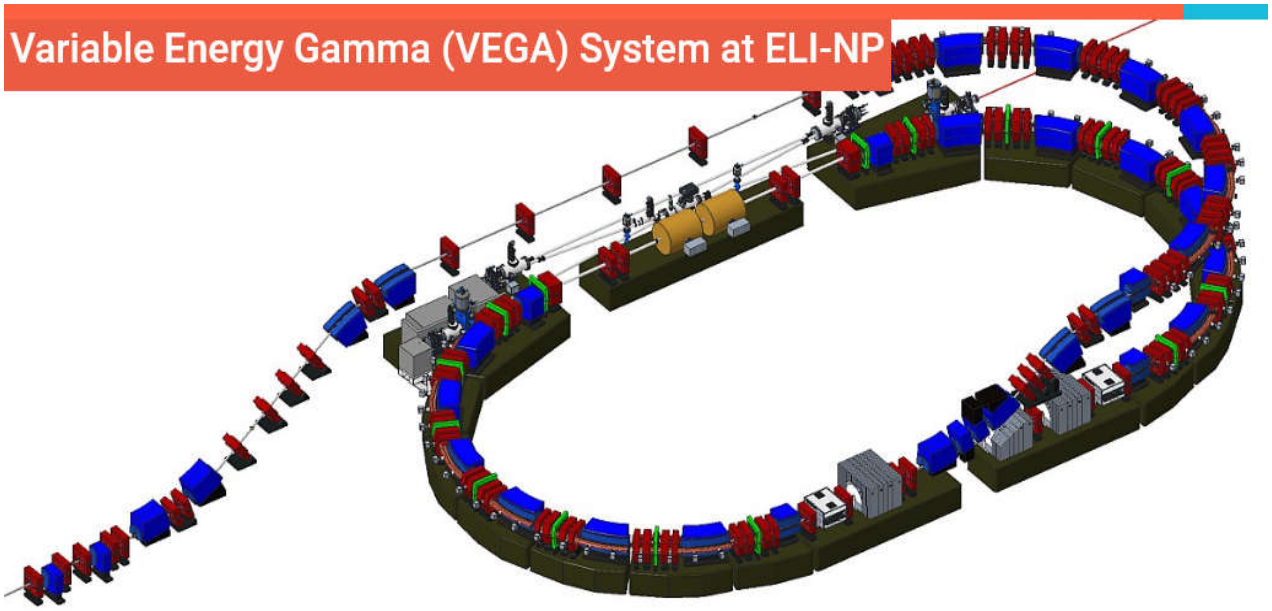
- high intensity, monochromatic gamma beam

Extreme Light Infrastructure - Nuclear Physics
Magurele-Romania



Extreme Light Infrastructure - Nuclear Physics Magurele-Romania

- Compton backscattering of light on electron beam
  - laser beam: 500 / 1000 nm
  - electron beam: 235 - 740 MeV
  - **E_γ= 1 - 20 MeV, $\Delta E/E$ = 0.5%**
  - **Intensity: 10^8 γ/s**



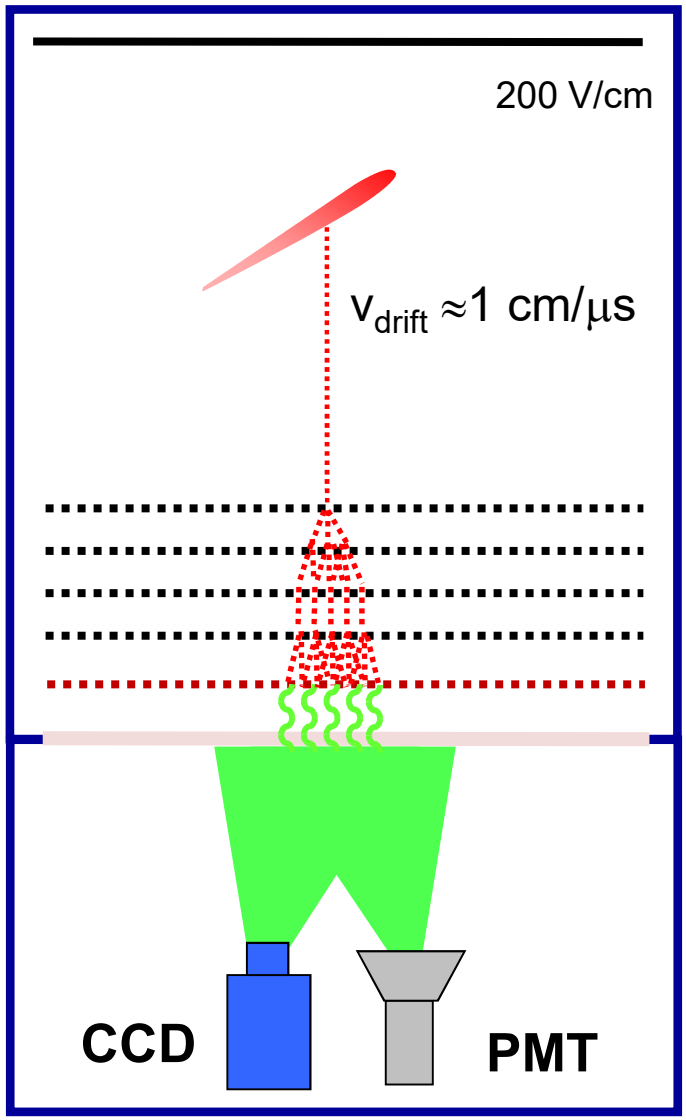
Requirements for $^{16}O(\gamma, \alpha)^{12}C$ studies

- high intensity, monochromatic gamma beam
- proper detector / target
  - high efficiency
  - low background
  - low energy threshold
  - possibility to measure angular distribution

Solution

Active Target Time Projection Chamber

Optical Time Projection Chamber



Active volume

He + Ar + 1%N_2 at 1 atm.

Amplification

4×GEM foils

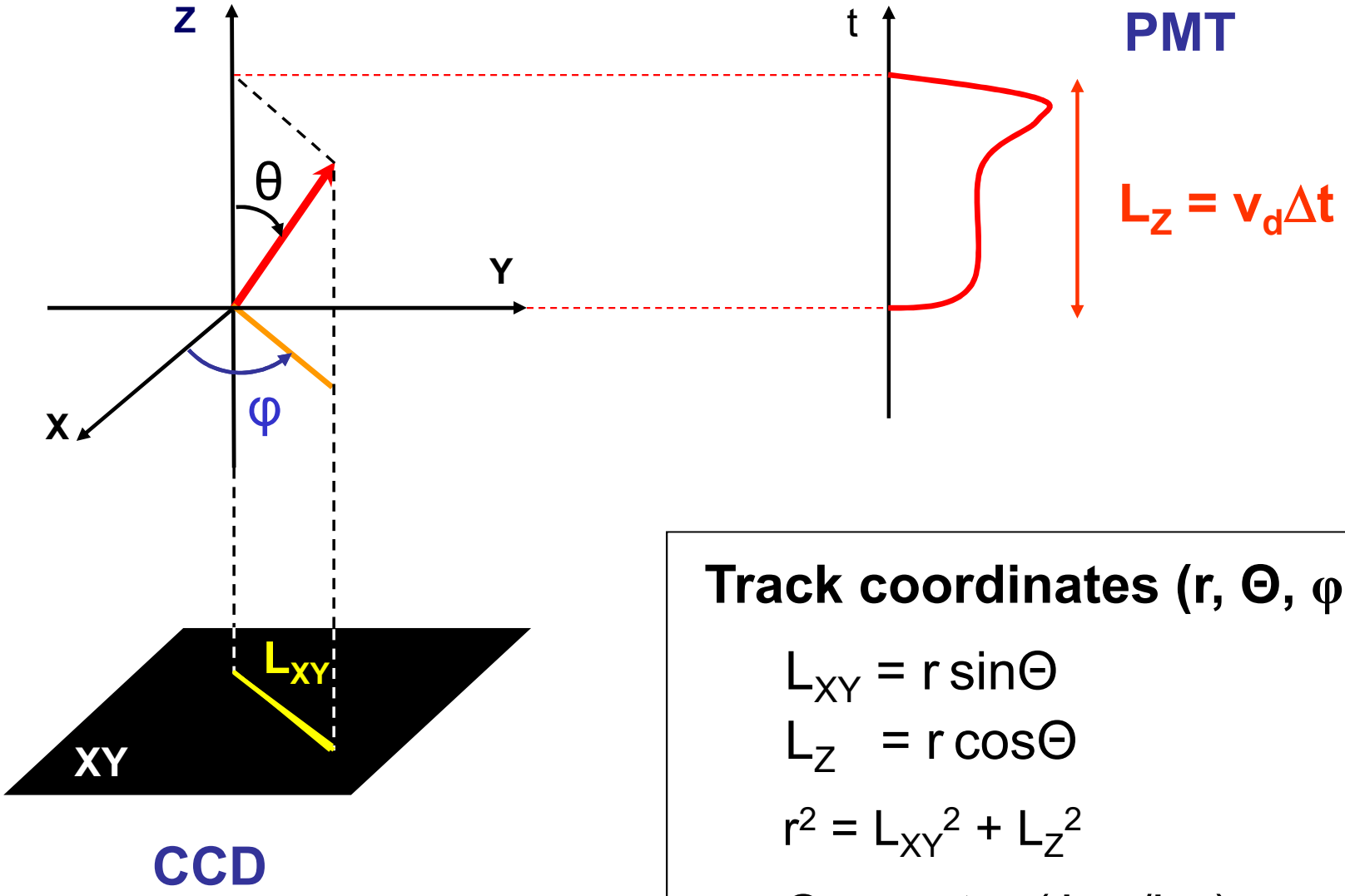
Anode (500/50 μm mesh)

VIS light detectors

M. Ćwiok et al., IEEE TNS, 52 (2005) 2895

K. Miernik et al., NIM A581 (2007) 194

Idea of track reconstruction



Track coordinates (r, Θ, φ)

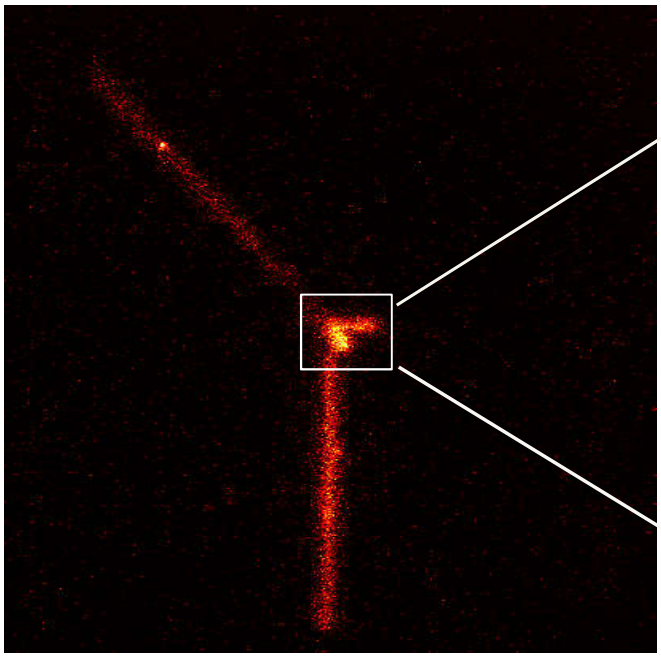
$L_{XY} = r \sin\Theta$

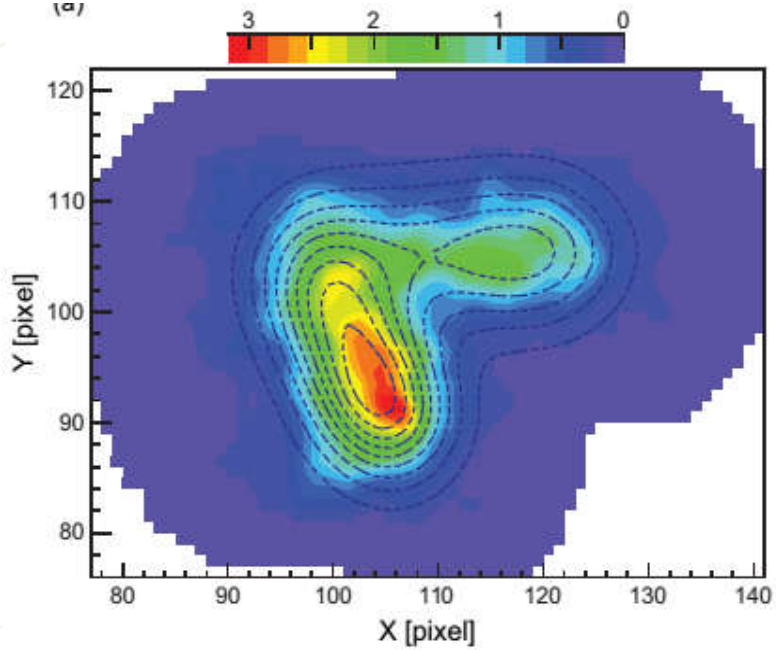
$L_Z = r \cos\Theta$

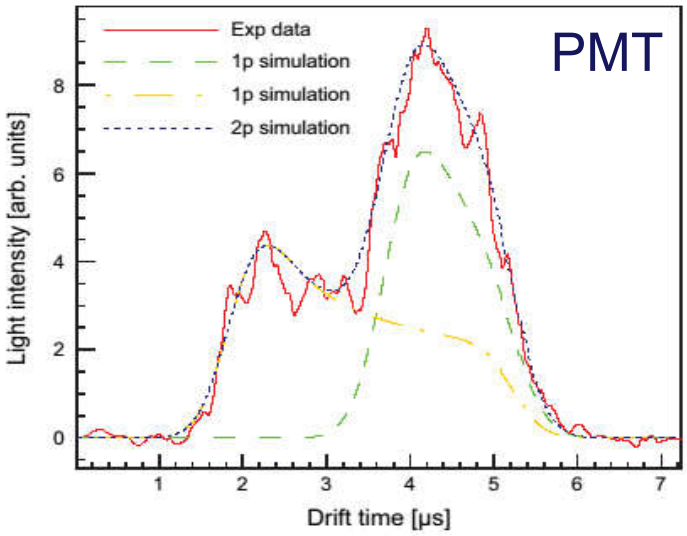
$r^2 = L_{XY}^2 + L_Z^2$

$\Theta = \arctan(L_{XY}/L_Z)$

Reconstruction of 2p decay ^{48}Ni







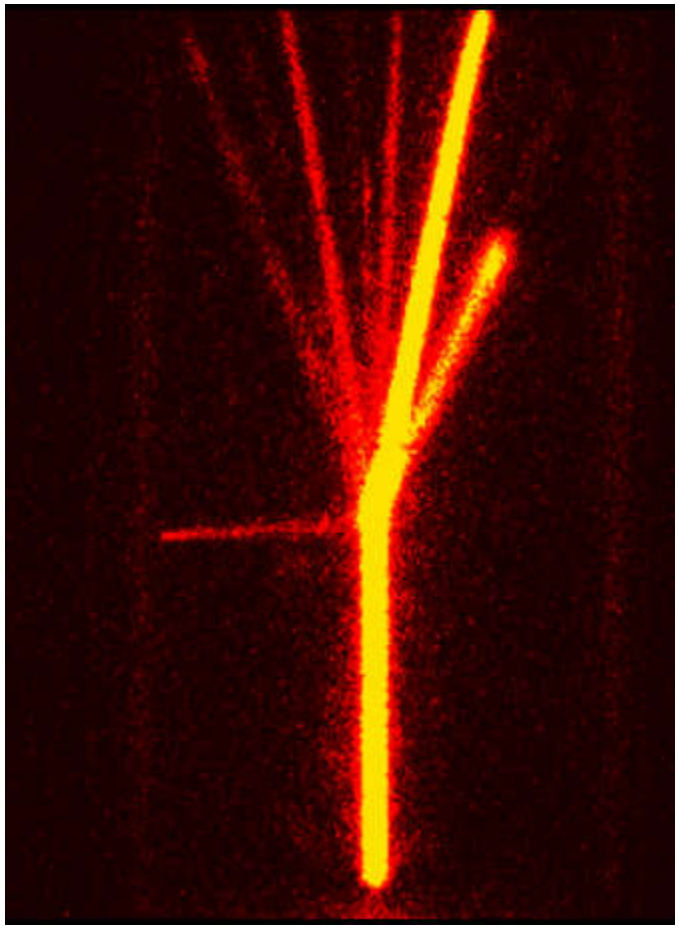
E_{p1}= 580 keV
θ_{p1}= 117°
φ_{p1} = 0

E_{p2}= 665 keV
θ_{p2}= 150°
φ_{p2} = -60°

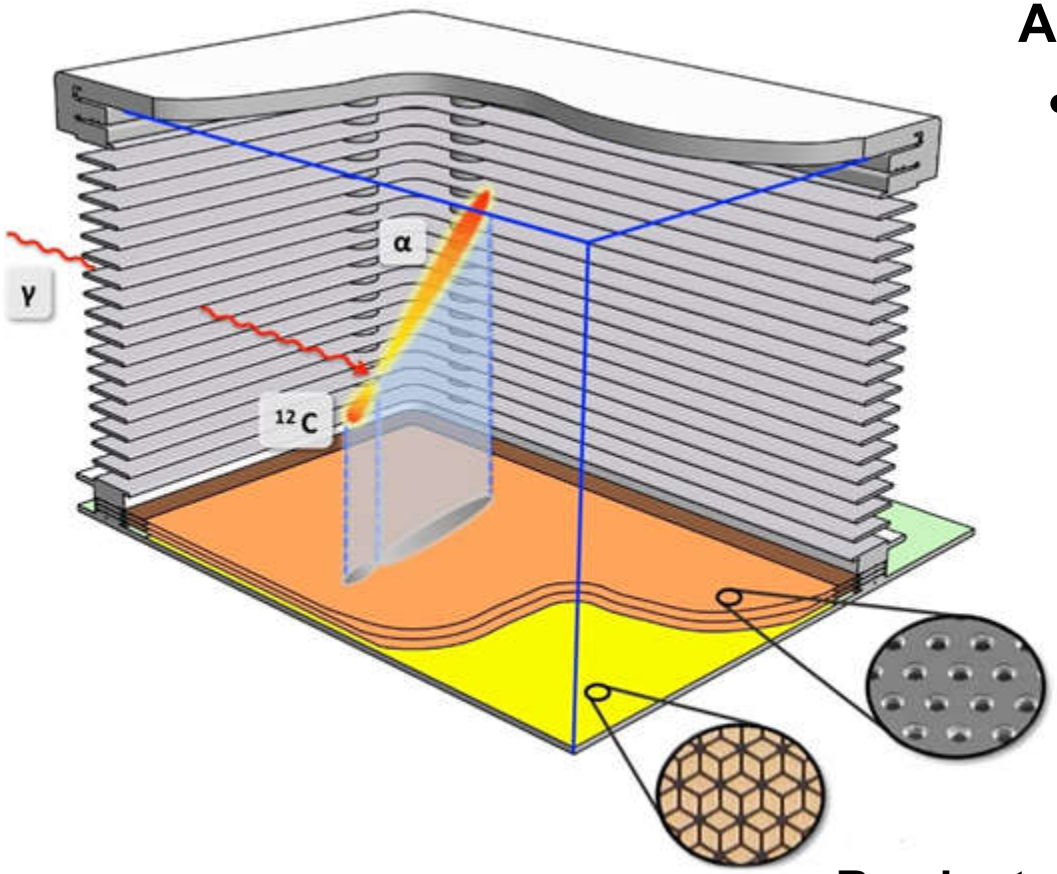
Q_{2p} = 1287(80) keV
θ_{pp} = 51(8)°

M. Pomorski et al., PRC 90 (14) 014311

Multi - fragmentation of ^{40}Ar seen in OTPC



Time Projection Chamber with electronic readout



Active volume:

- 33 x 20 cm^2 x 20 cm (drift)
- gas pressure 80-250 mbar

Charge amplification

- three GEM foils

Readout:

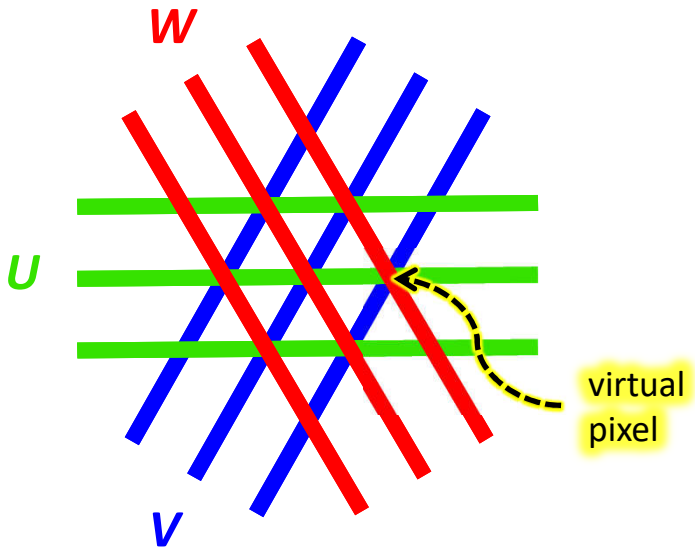
- 3 strip arrays
- 1000 channels
- GET electronics

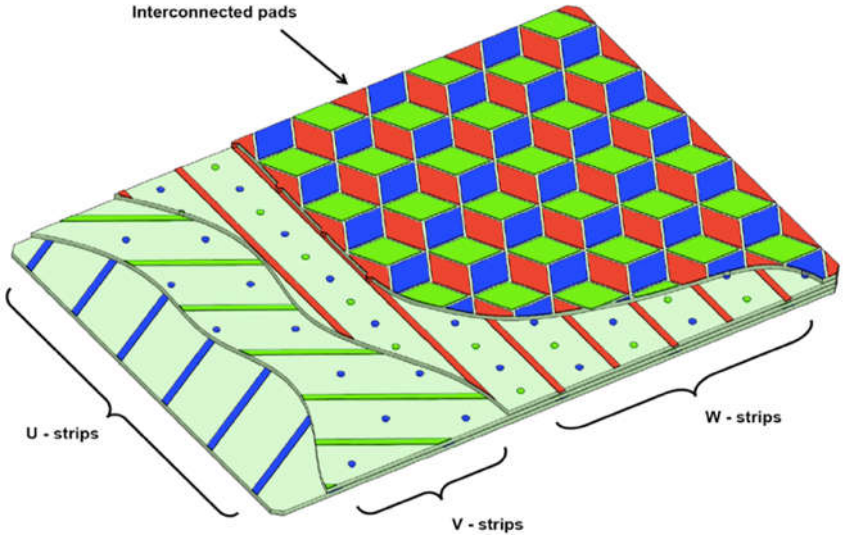
M. Ćwiok

Readout electrode of eTPC

3 grids of strips – crossed at 60° :

- 1.5 mm strip pitch
- ***U-V-W*** strip arrays on XY plane

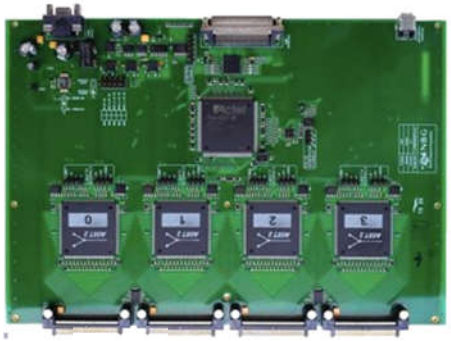




8-layer PCB, 4.2 mm-thick

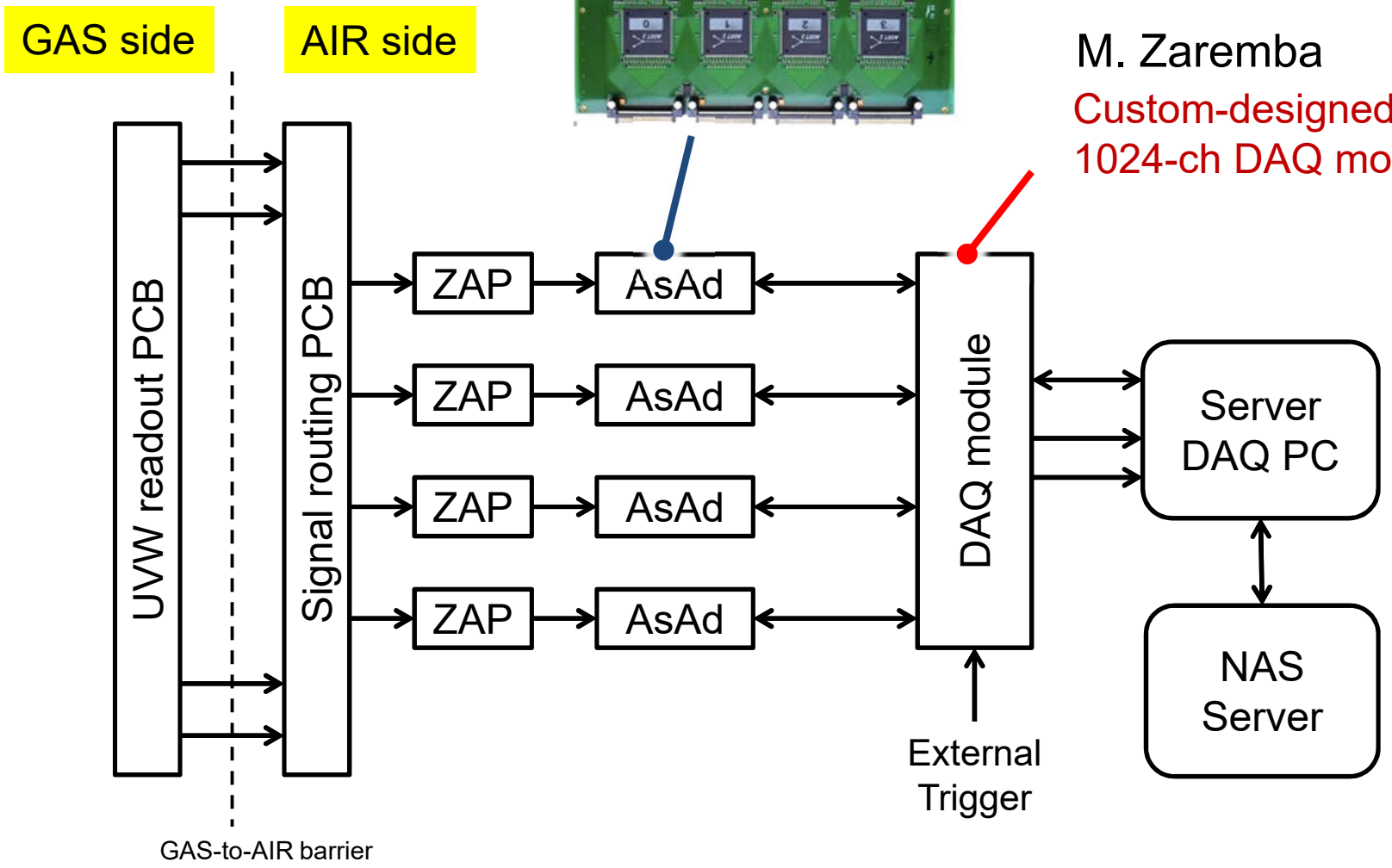
S. Bachmann et al., NIMA 478 (2002) 104
V. Ableev et al., NIMA 535 (2004) 294

Readout electronics

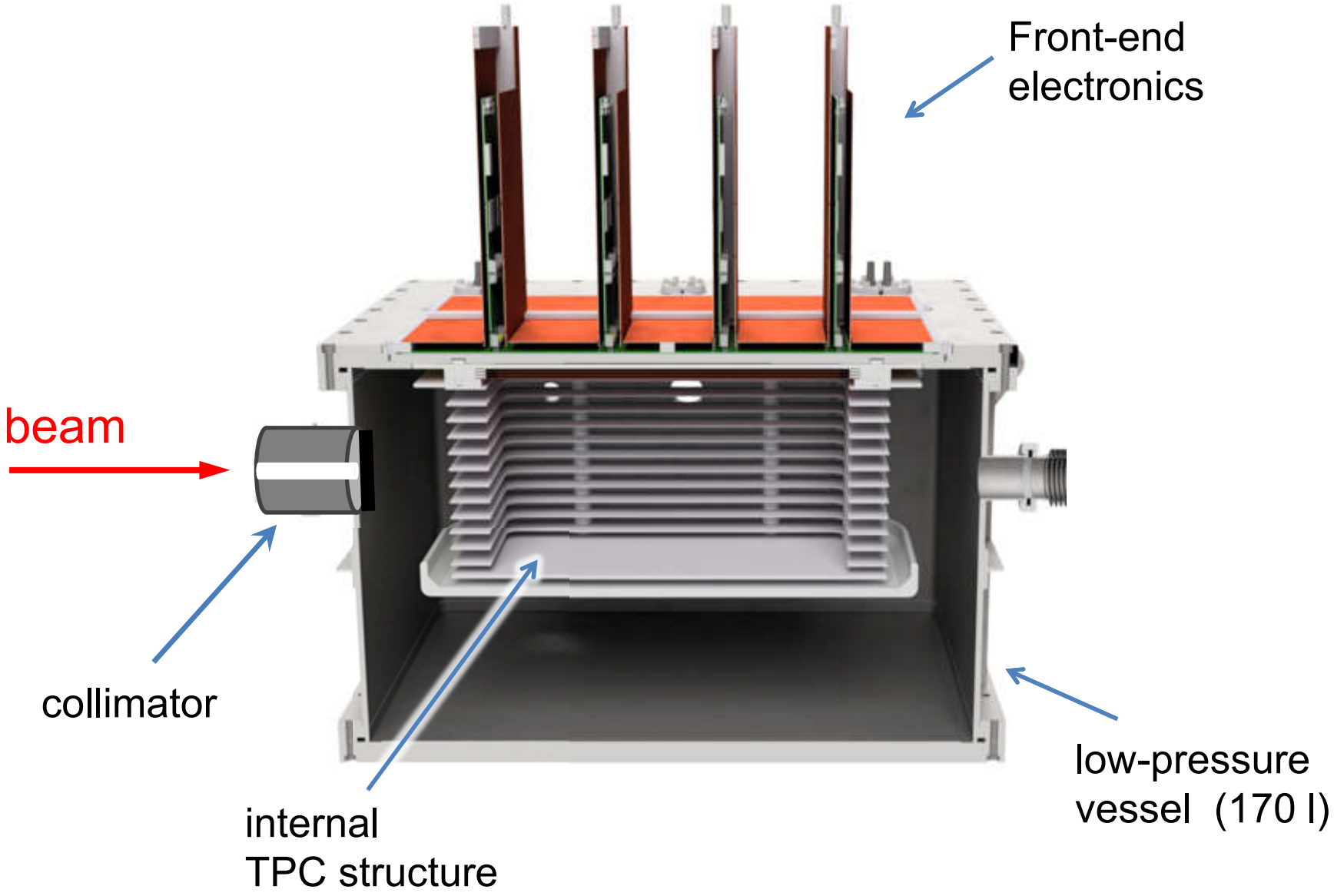


Commercial AsAd card
256-ch, 12-bit (GET collab.)

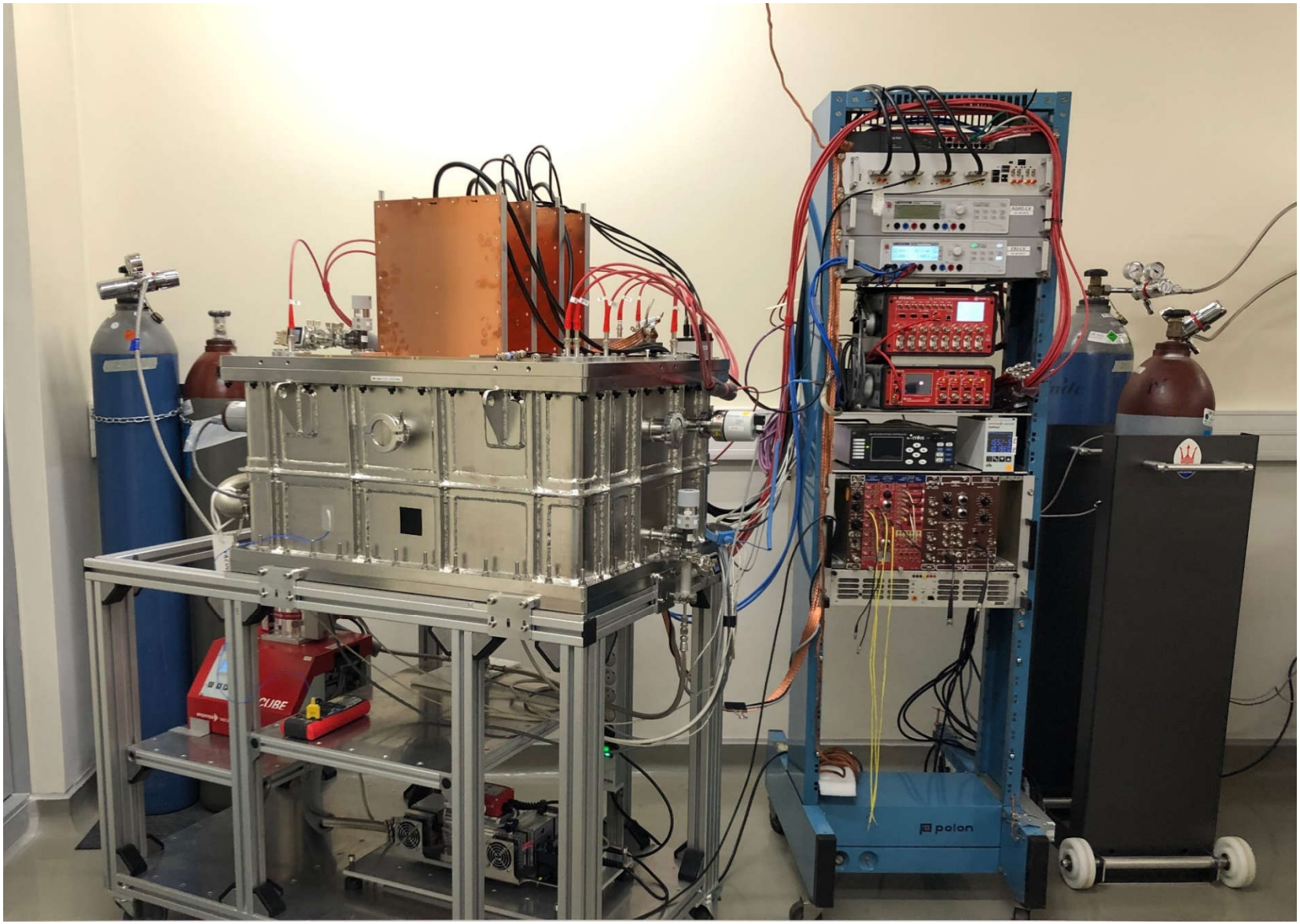
M. Zaremba
Custom-designed FPGA
1024-ch DAQ module (UW)



Time Projection Chamber



Time Projection Chamber at FUW



Test of TPC at IFJ PAN Van de Graaff accelarator

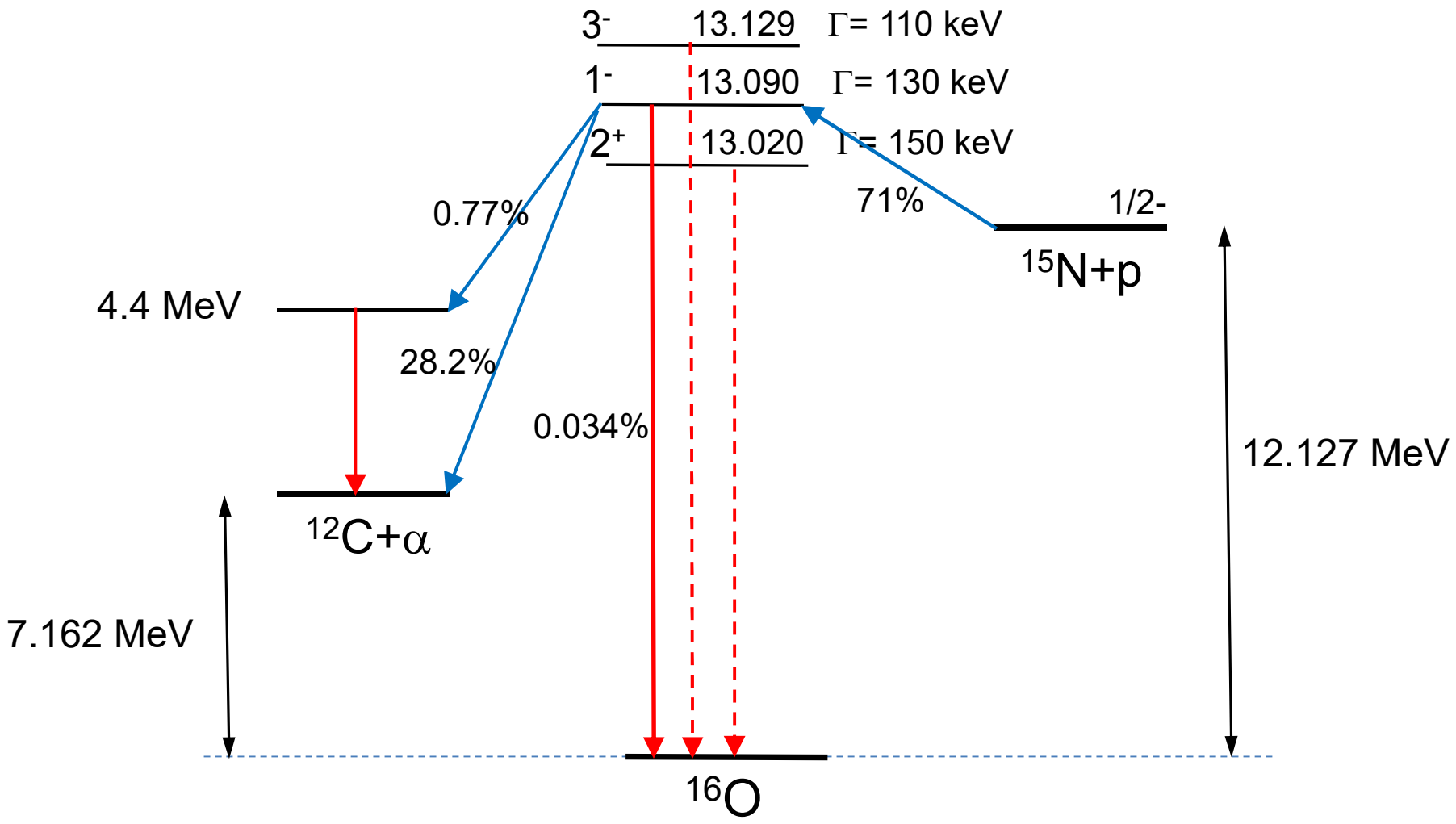
Idea

- produce 13 MeV gammas in $^{15}N(p, \gamma)^{16}O$ reaction
- observe $^{16}O(\gamma, \alpha)^{12}C$ in TPC

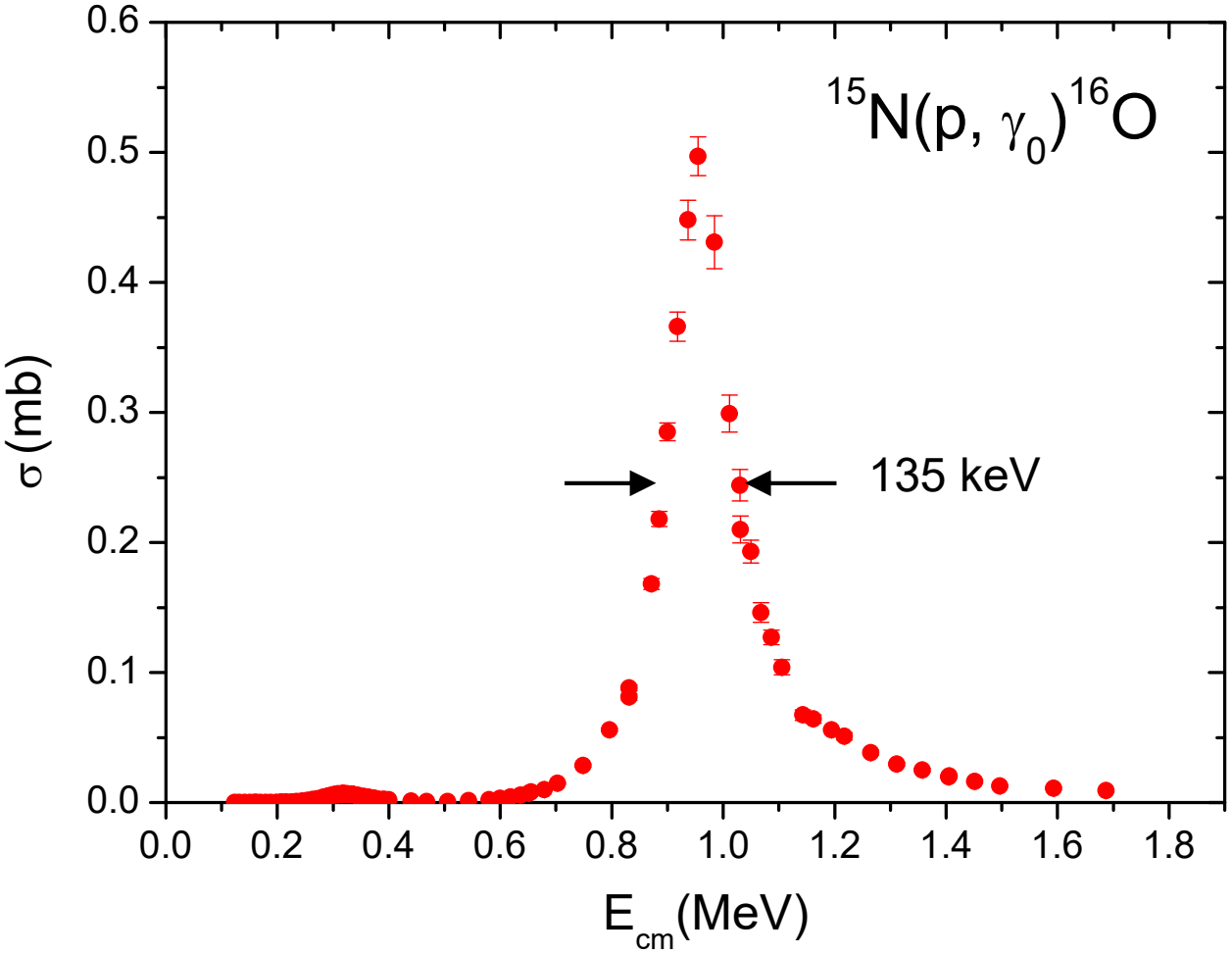
Goals

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

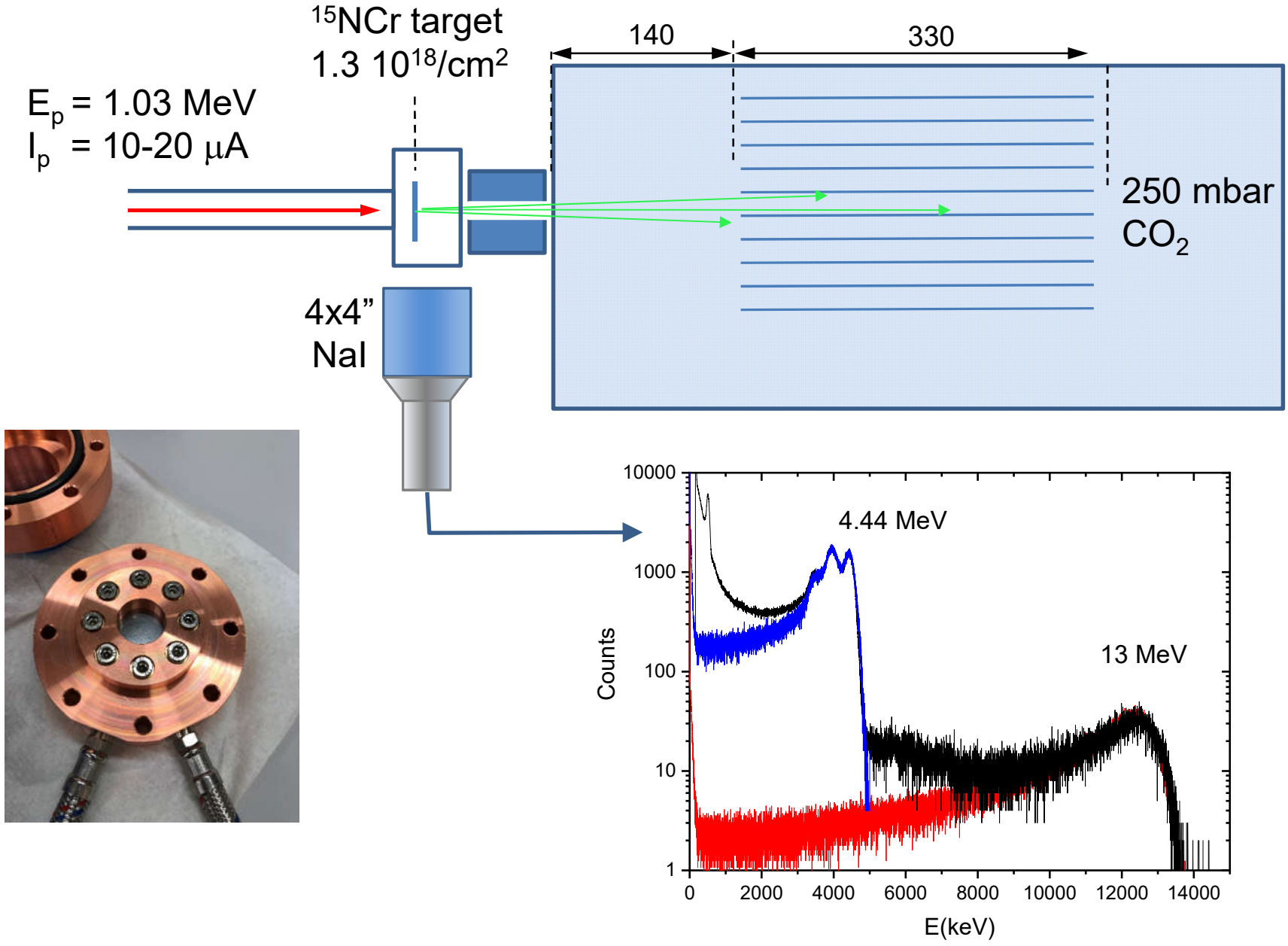
$^{15}N(p, \gamma)^{16}O$ reaction



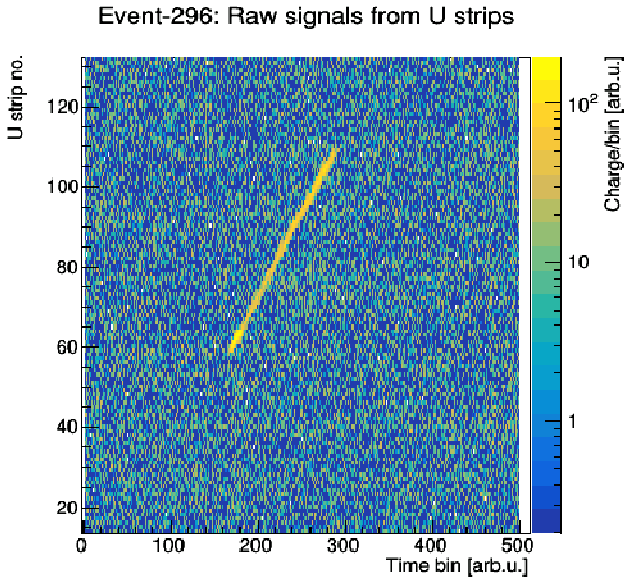
Cross section of $^{15}N(p, \gamma_0)\ ^{16}O$ reaction

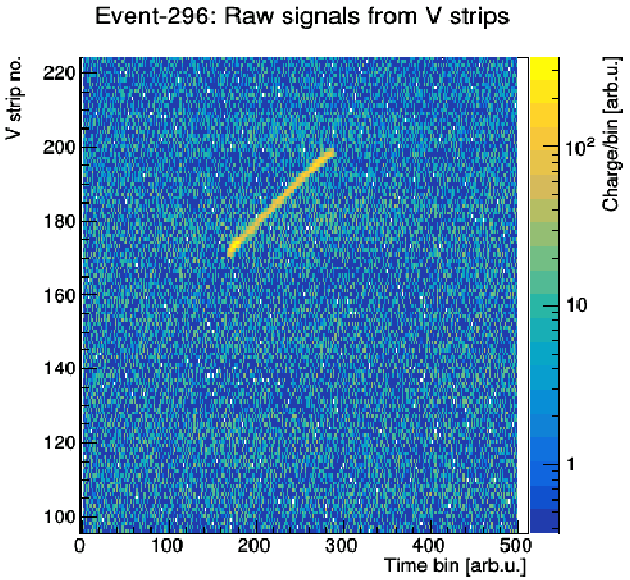


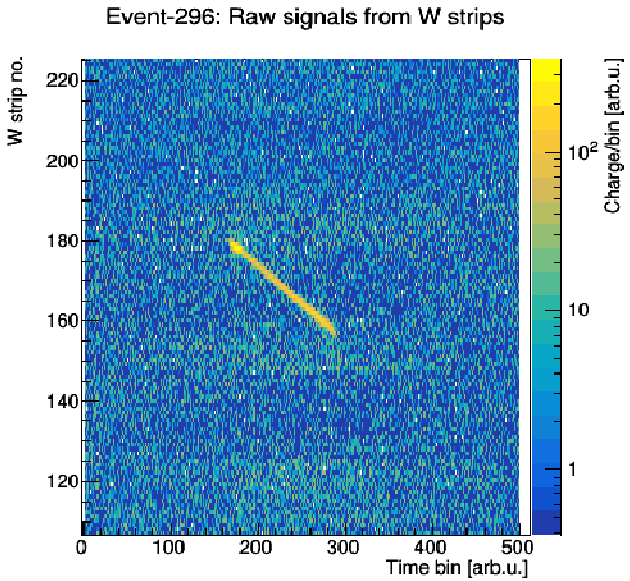
TPC at VdG

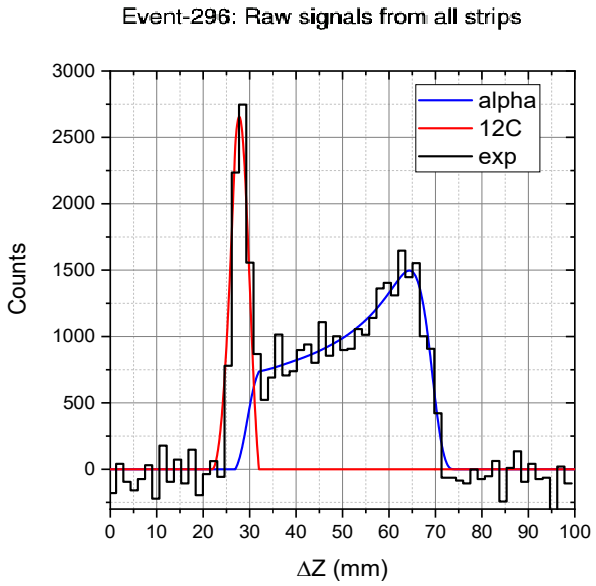

^{15}NCr target
1.3 10^{18}/cm^2
E_p = 1.03 MeV
I_p = 10-20 μA
140
330
250 mbar
CO_2
4x4”
NaI
10000
1000
100
10
1
Counts
4.44 MeV
13 MeV
0
2000
4000
6000
8000
10000
12000
14000
E(keV)

Example of $^{16}O(\gamma, \alpha)^{12}C$ reaction







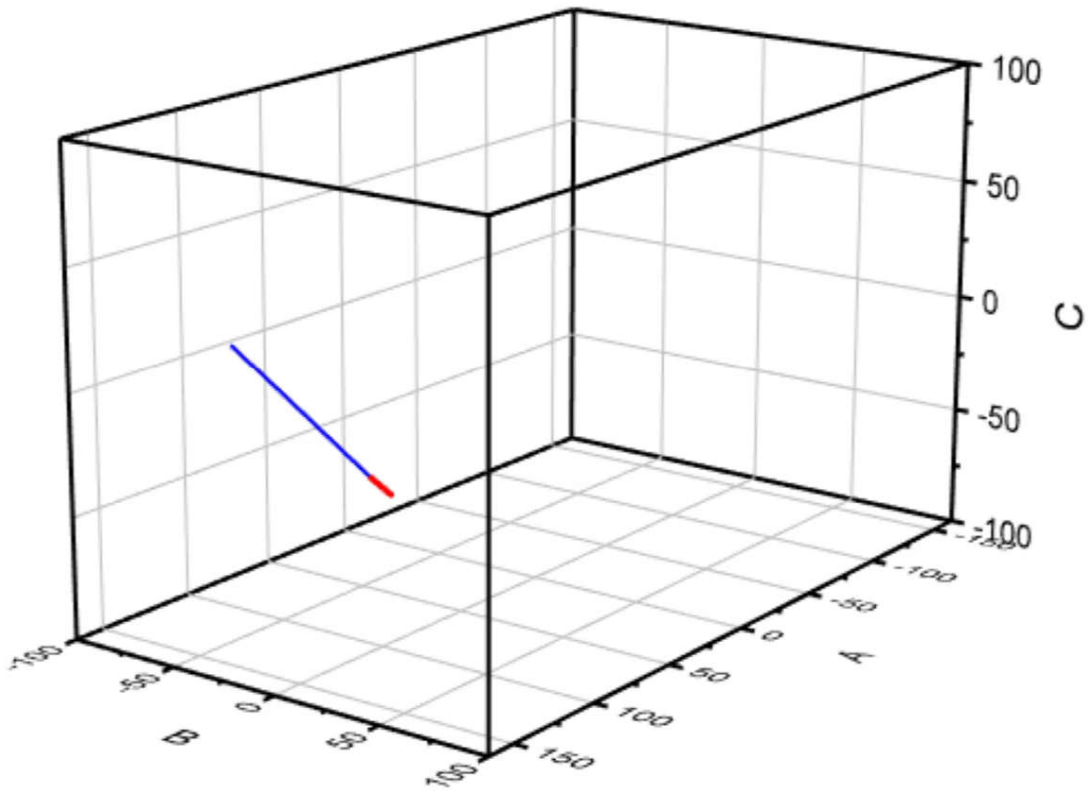


Reconstruction of $^{16}O(\gamma, \alpha)^{12}C$ event

$E_\alpha = 4.37$ MeV

$E_{12C} = 1.46$ MeV

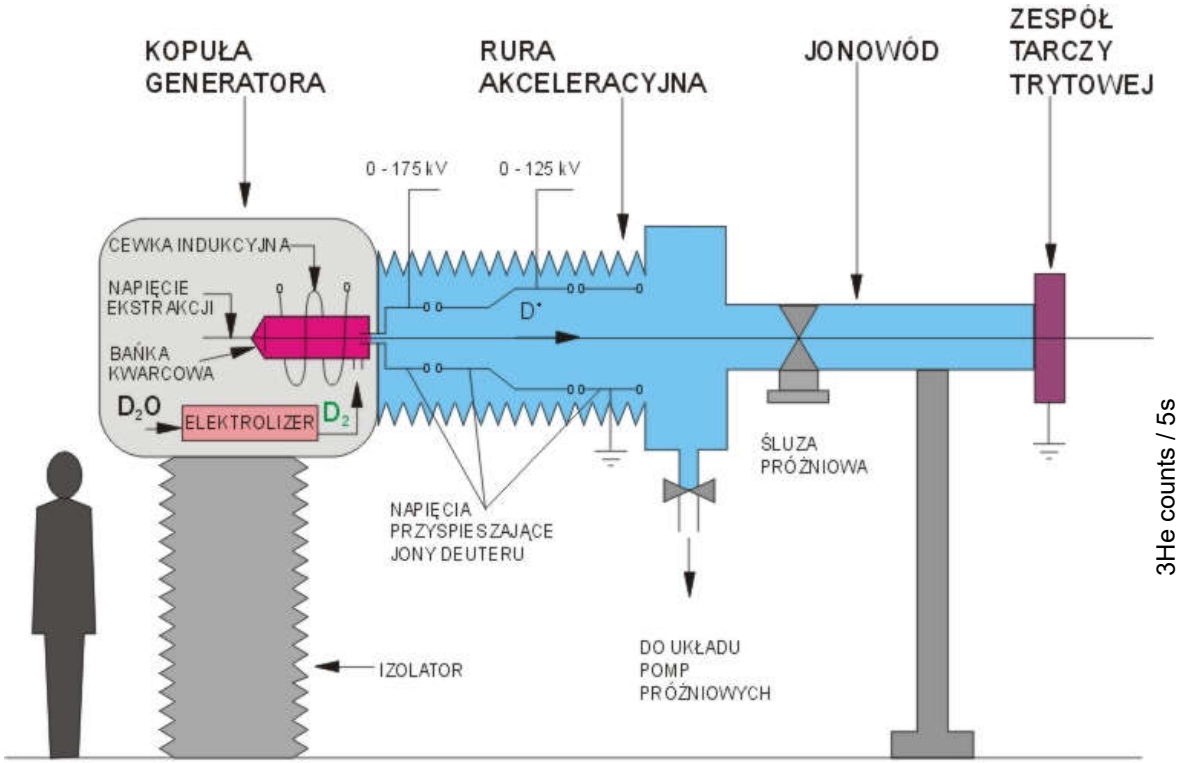
$\theta_{\alpha-12C} = 180°$

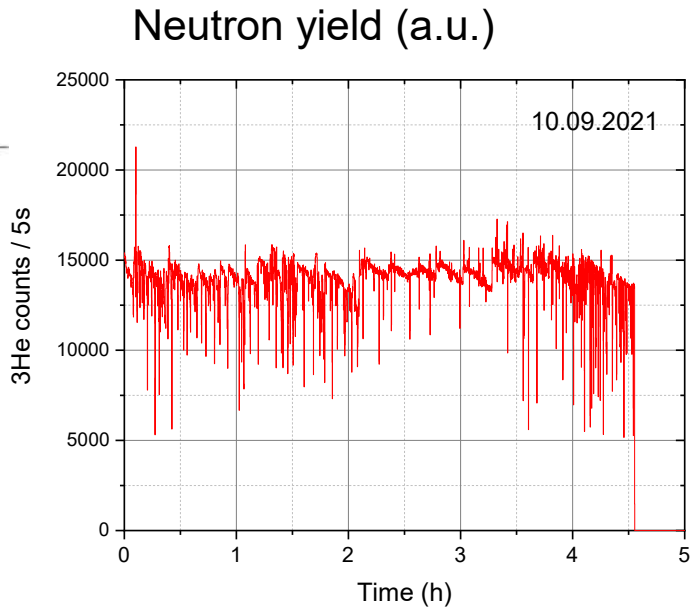


Neutron generator IGN-14

$$d + T \rightarrow \alpha(3.5\text{MeV}) + n(14.1\text{MeV})$$

Yield: ~ 5×10^8 n/s in 4π

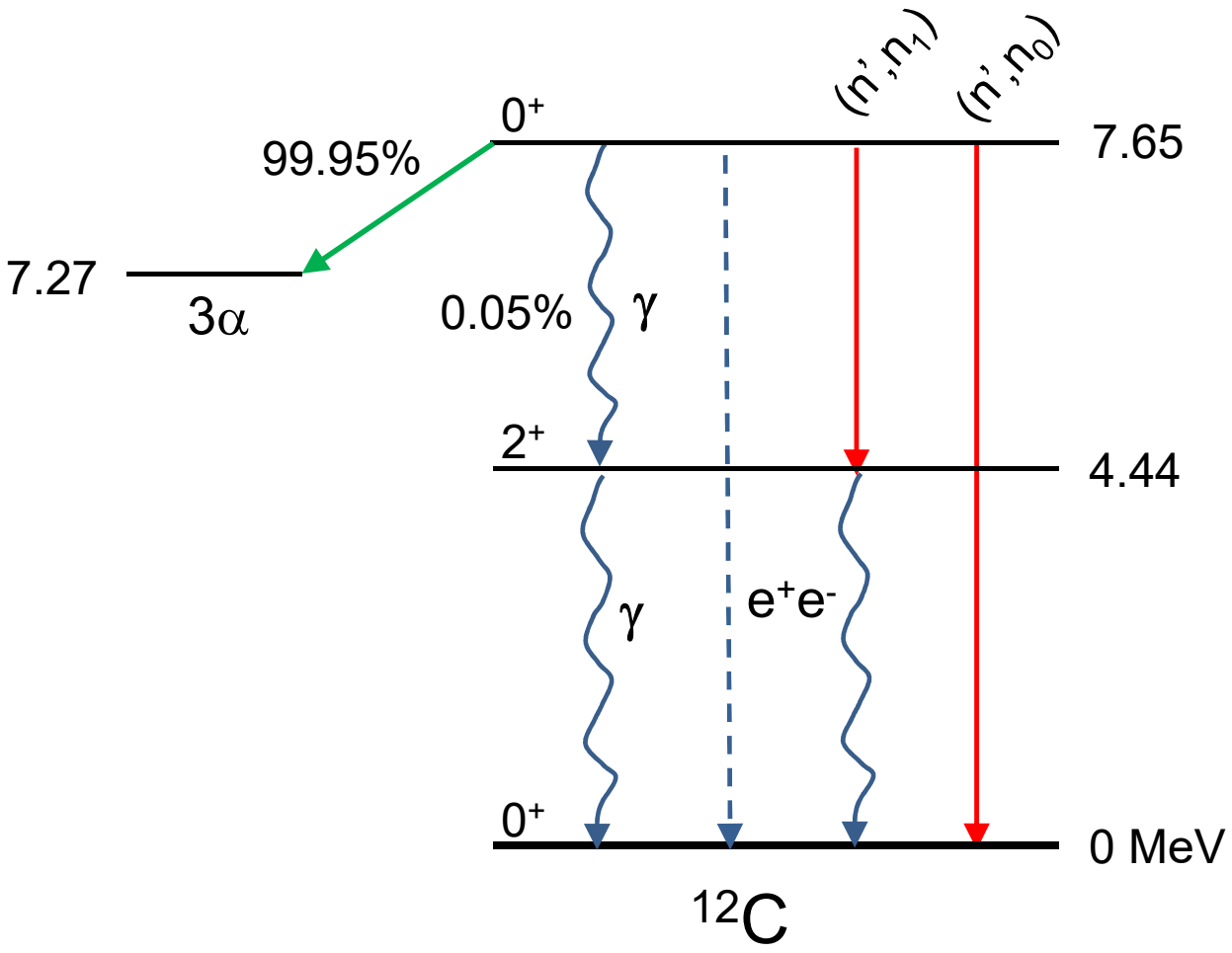




A. Kurowski

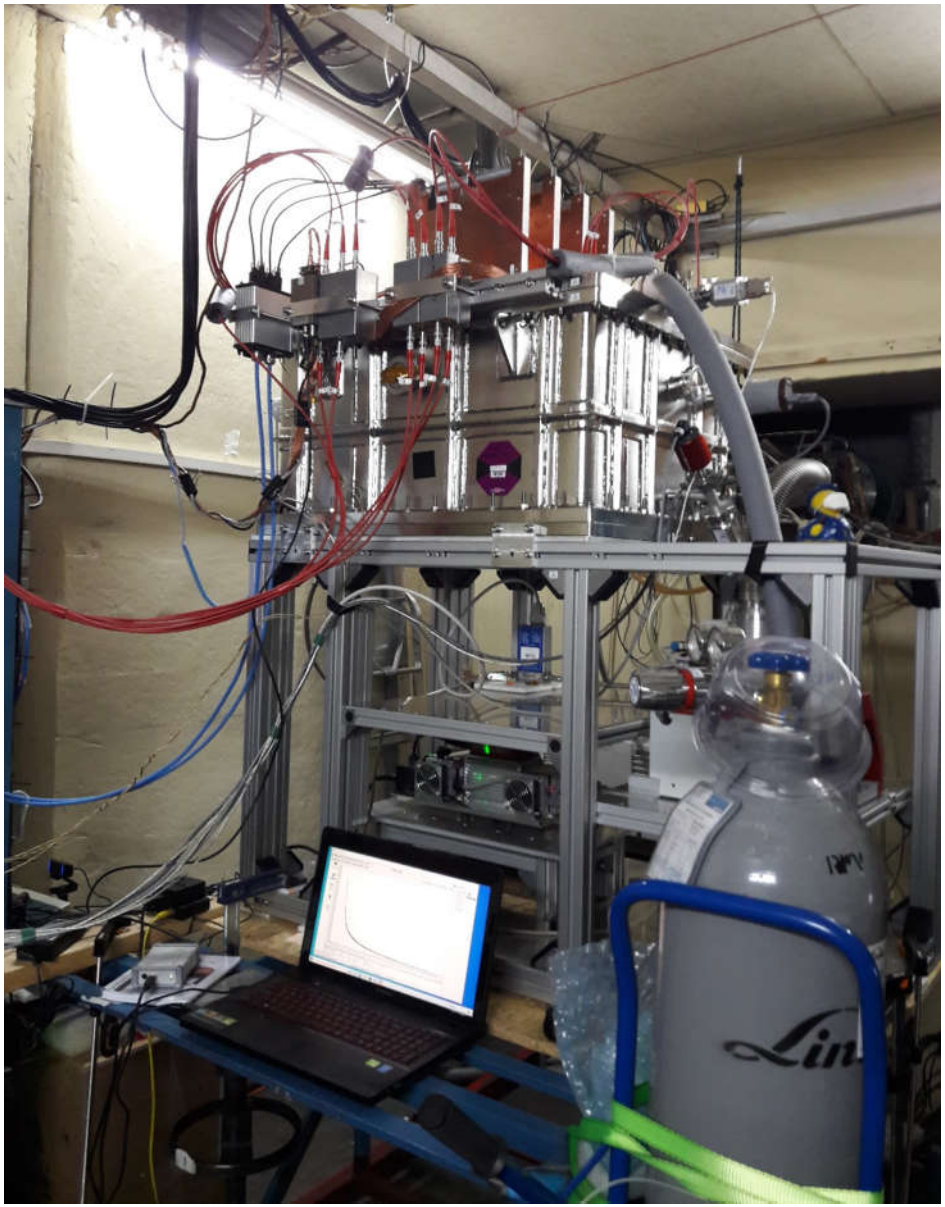
Deexcitation of the Hoyle state in high density neutron environment

$$\Gamma_{n'n}(^{12}\mathrm{C}^{Hoyle}) = \hbar \cdot N_n \cdot \langle \sigma v \rangle_{n'n}$$



M. Beard, Phys. Rev. Lett. 119(2017)112701

TPC at IGN-14



^{12}C+n and ^{16}O+n reaction channels at 14 MeV

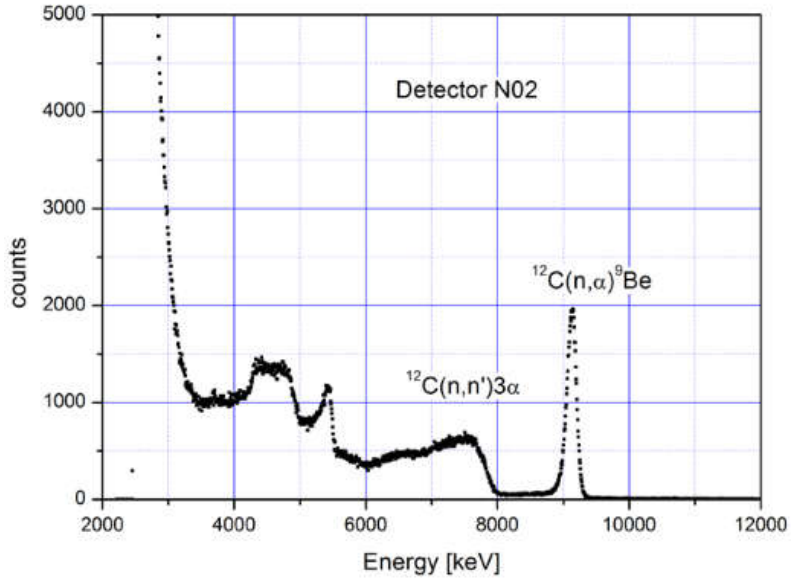
- single particle tracks

  - elastic scattering on ^{12}C and ^{16}O — 1500 mb

- two track events

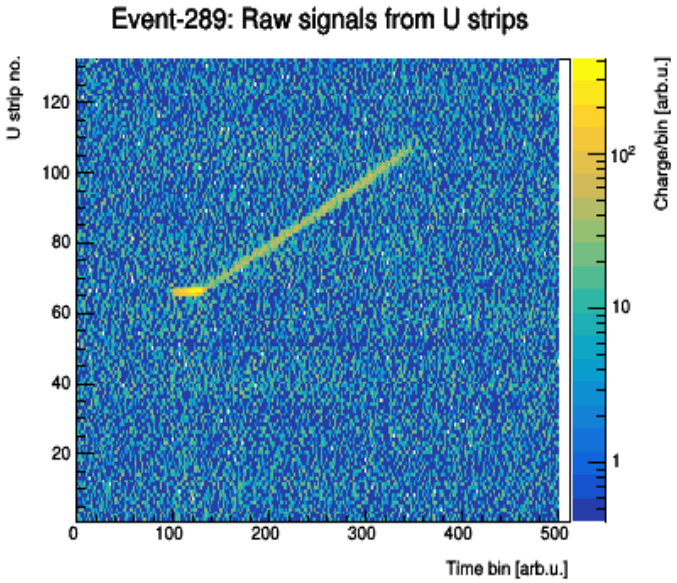
$$n + {}^{16}\mathrm{O} \rightarrow {}^{17}\mathrm{O}^{*} \rightarrow \alpha + {}^{13}\mathrm{C}$$ — 150 mb

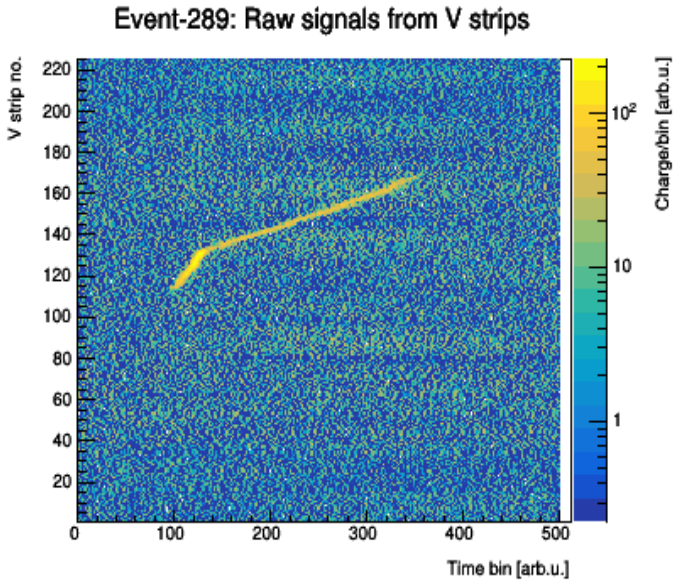
$$n + {}^{12}\mathrm{C} \rightarrow {}^{13}\mathrm{C}^{*} \rightarrow \alpha + {}^{9}\mathrm{Be}$$ — 70 mb

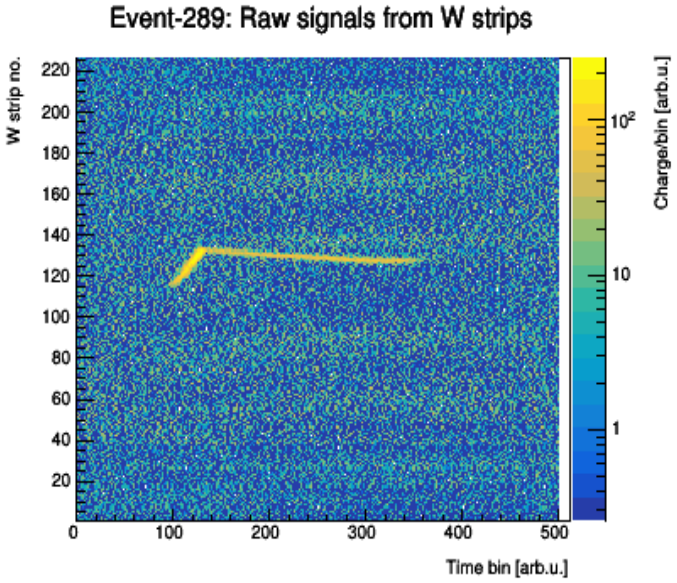


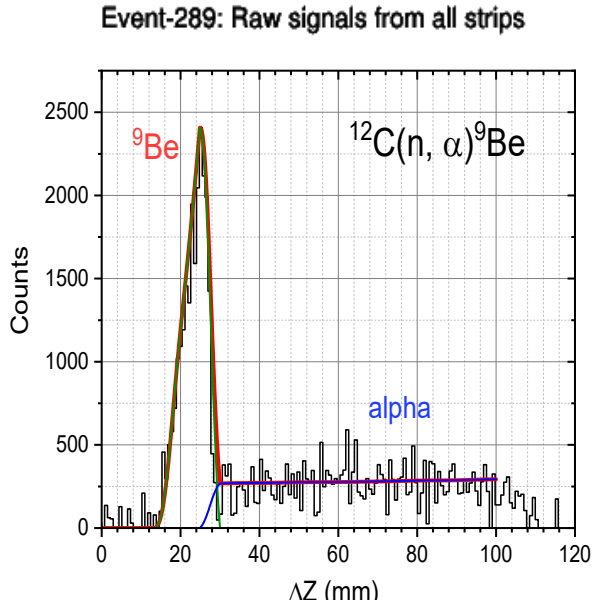
R. Kwiatkowski *et al*., Rad. Meas.138(2020) 106434

Example of $^{12}C(n, \alpha)^{9}Be$ reaction









^{12}C+n and ^{16}O+n reaction channels at 14 MeV

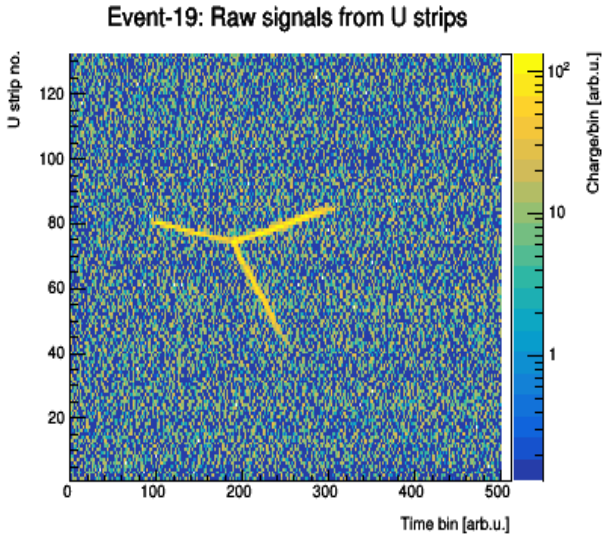
- triple track events

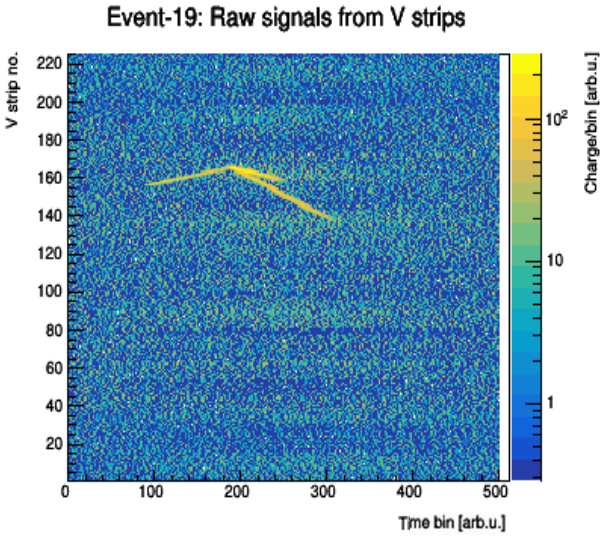
$$n + {}^{12}\mathrm{C} \rightarrow n' + {}^{12}\mathrm{C}^{*} \rightarrow \alpha_1 + {}^{8}\mathrm{Be}^{*} \rightarrow \alpha_2 + \alpha_3$$ 130 mb

$$n + {}^{12}\mathrm{C} \rightarrow n' + {}^{12}\mathrm{C}^{*} \rightarrow \alpha_1 + {}^{8}\mathrm{Be}^{*} \rightarrow \alpha_2 + \alpha_3$$ 10 mb

$$n + {}^{12}\mathrm{C} \rightarrow {}^{13}\mathrm{C}^{*} \rightarrow \alpha_1 + {}^{9}\mathrm{Be}^{*} \rightarrow n' + {}^{8}\mathrm{Be}^{*} \rightarrow \alpha_2 + \alpha_3$$ 85 mb

Example of $^{12}C(n, n')^{12}C$ reaction



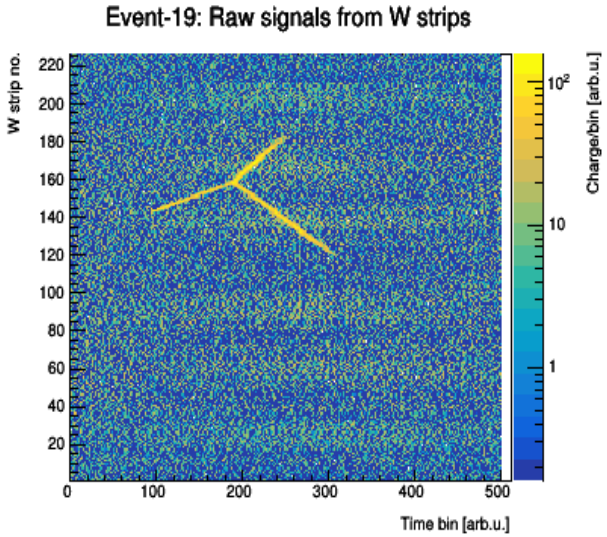


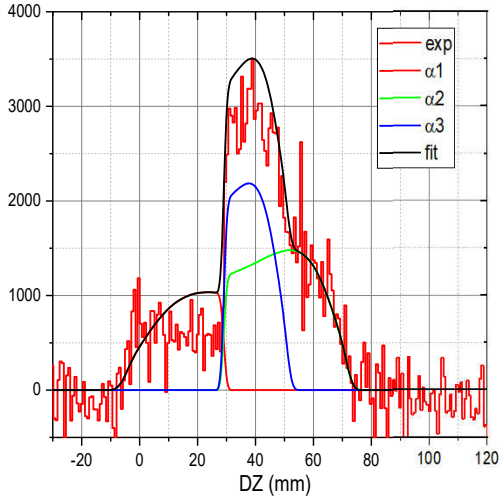
E_{a1} = 770 keV

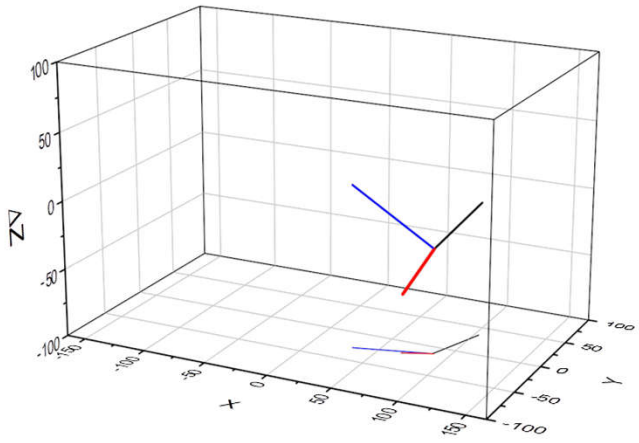
E_{a2} = 1580 keV

E_{a3} = 1175 keV

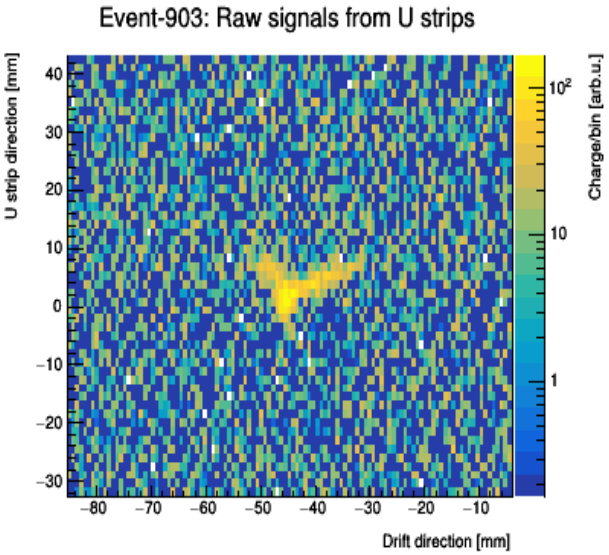
$E_x(^{12}C)$ =10.3 MeV

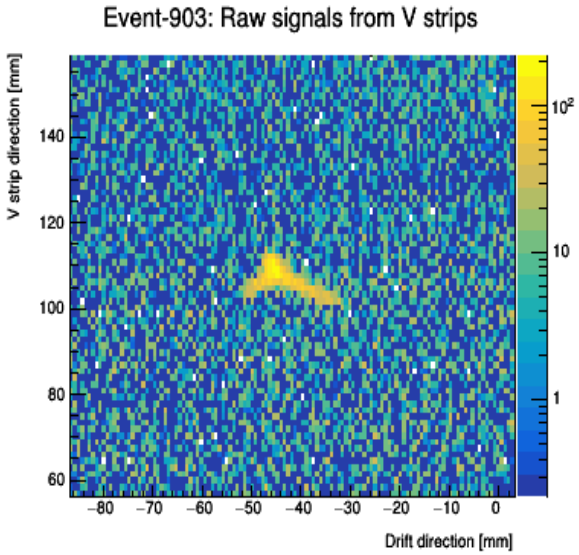






Example of $^{12}C(n, n')^{12}C^{HS}$ reaction



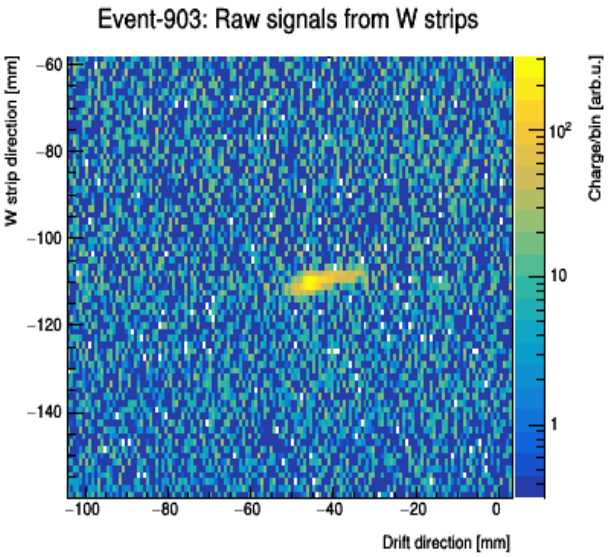


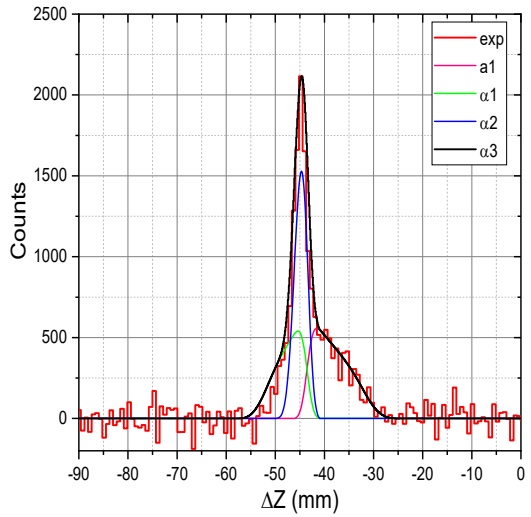
$E_{\alpha 1}$ = 145 keV

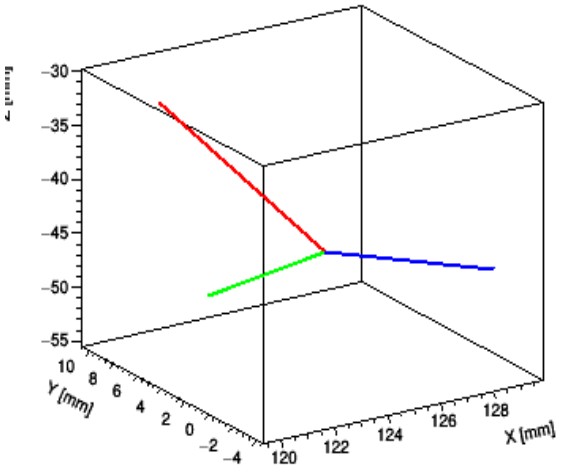
$E_{\alpha 2}$ = 108 keV

$E_{\alpha 3}$ = 60 keV

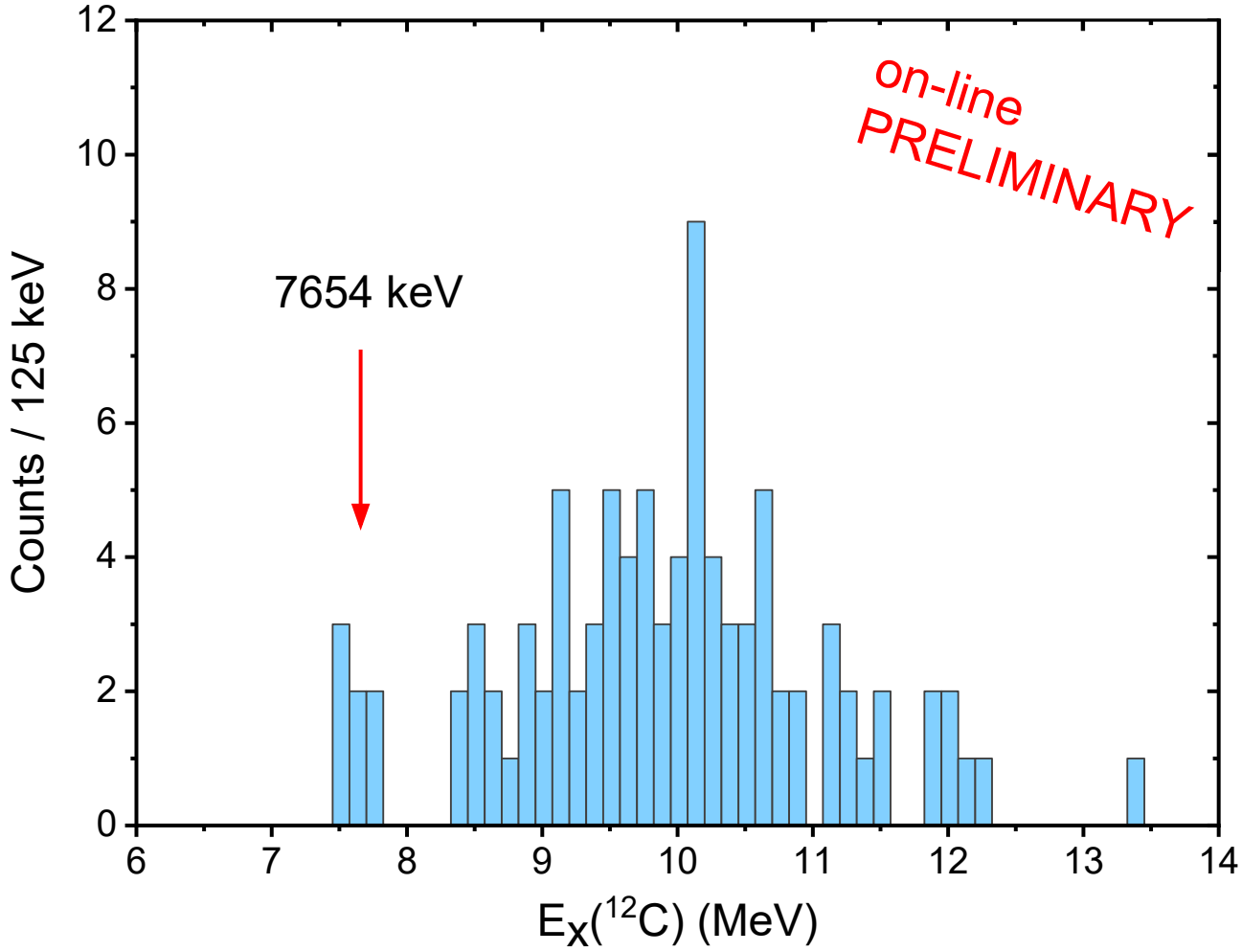
$E_x(^{12}C)$ =7.60 MeV







Reconstructed excitation energy of ^{12}C



Outlook

- studies of $^{16}O(\gamma, \alpha)^{12}C$ and $^{12}C(\gamma, 3\alpha)$ reactions at:
  - High Intensity Gamma Source (USA)
  - Exteme Light Infrastructure – Nuclear Physics (Romania)

- studies of $^{12}C(n, n')$ reaction at:
  - MONNET Geel (Belgium)
  - NFS GANILl (France)

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