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

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Nucleosynthesis in stars

- **H -** burning reactions

pp – chain
CNO cycle

$4p \rightarrow {}^4He + 2e^+ + 2\nu$

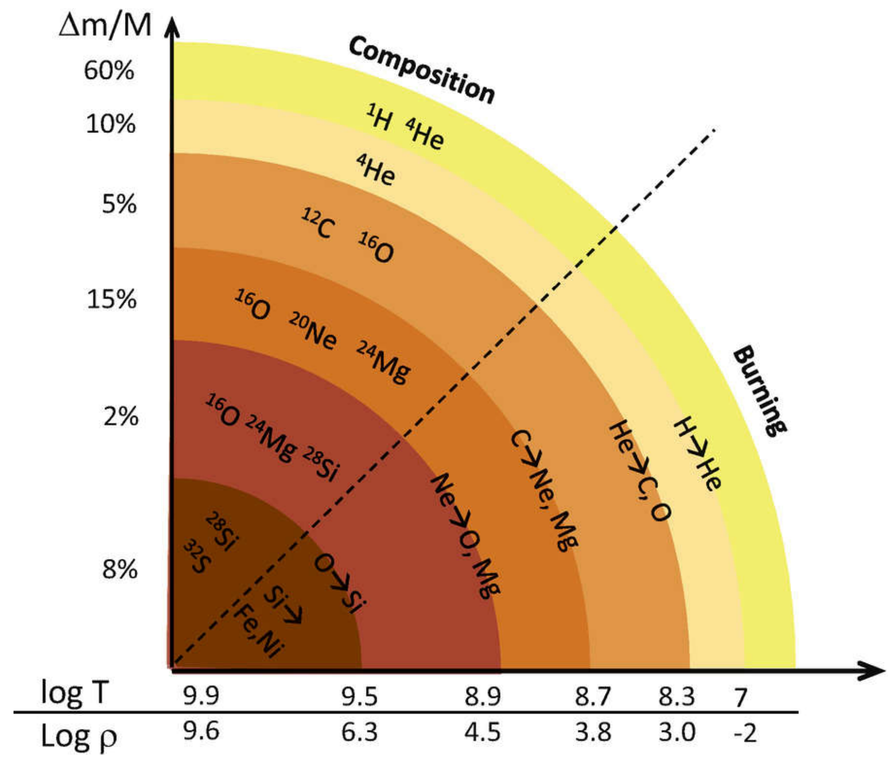
- **He -** burning reactions

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

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

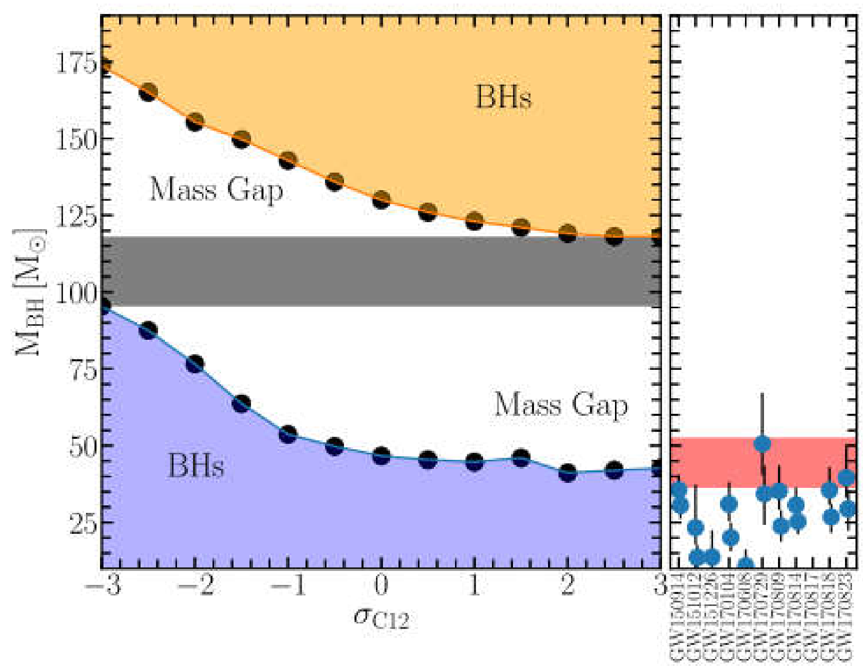
${}^{16}O(\alpha, \gamma){}^{20}Ne$

…



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

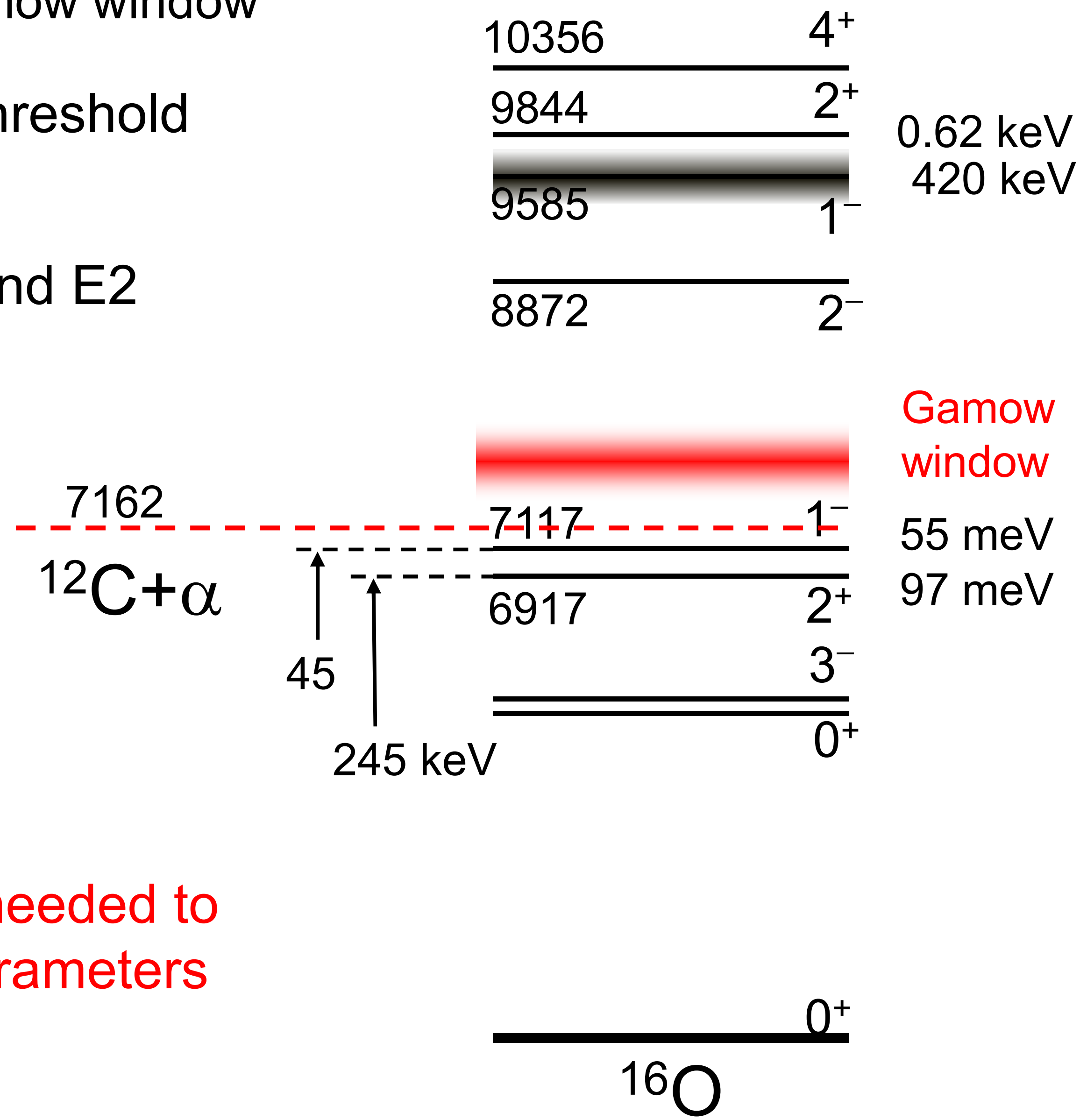
- determines C/O at the end of He burning
- important in evolution of low mass stars into SN Ia
- important in evolution of massive stars into SN II
- influences the gap in black-hole mass distribution



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

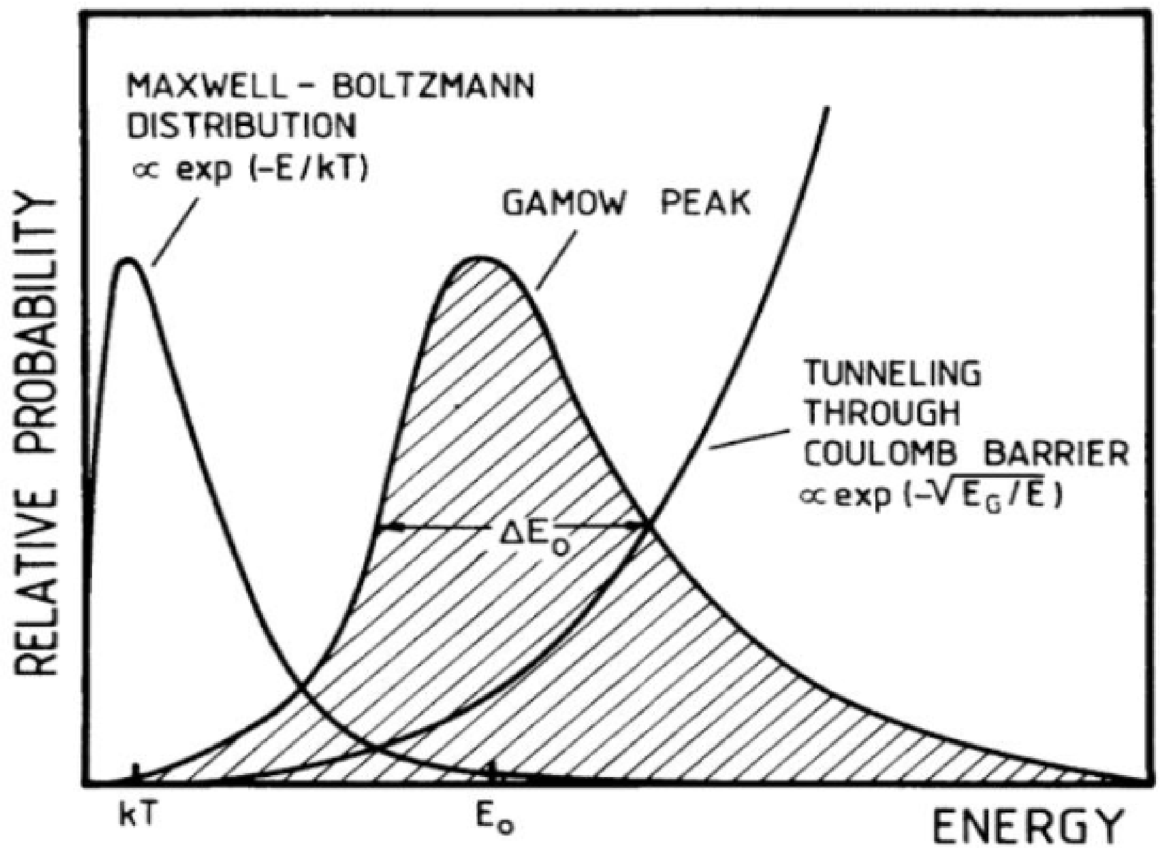
Mechanism of $^{12}C(\alpha, \gamma)$ reaction

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



- experimental data needed to constrain model parameters

Gamow window for astrophysical reactions

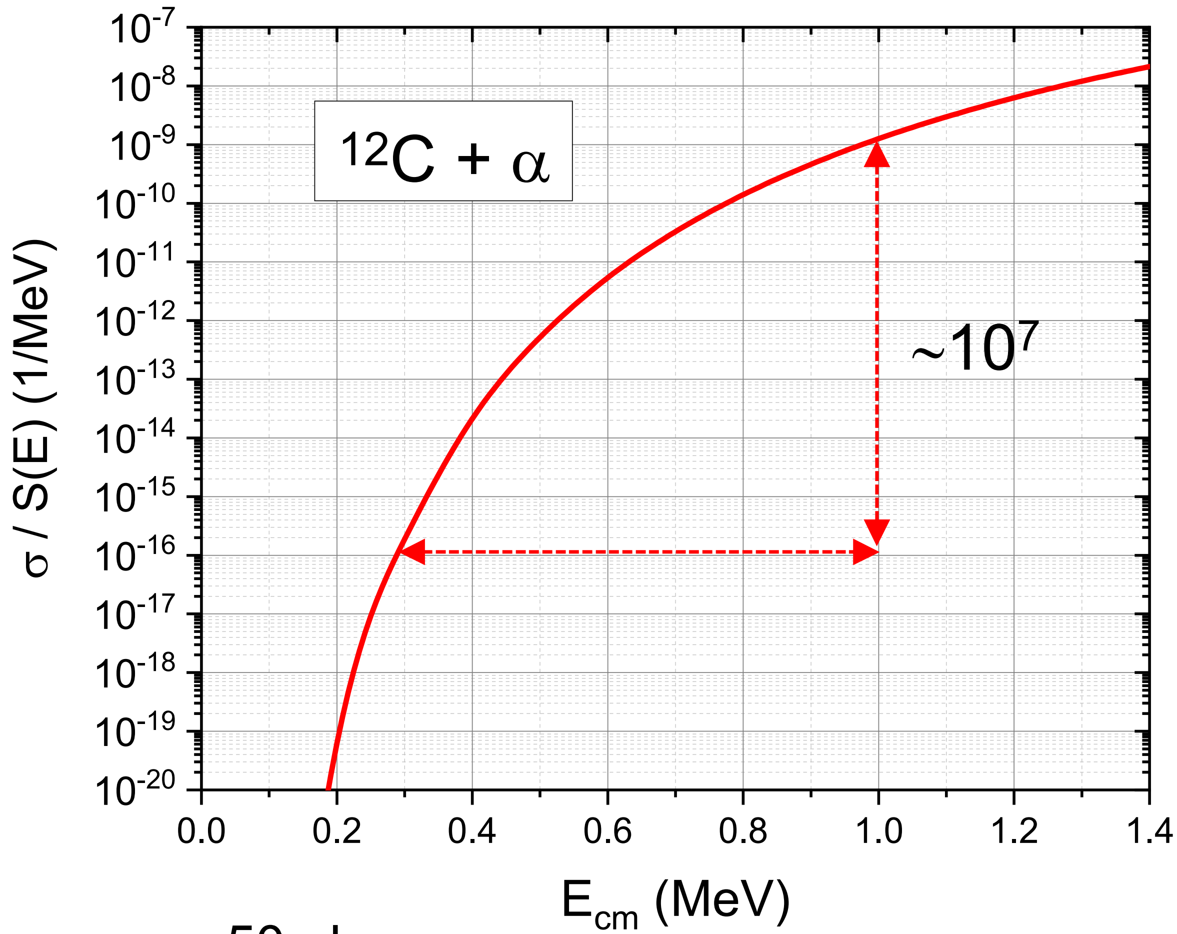


C.E. Rolfs, W.S. Rodney, Cauldrons in the Cosmos

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

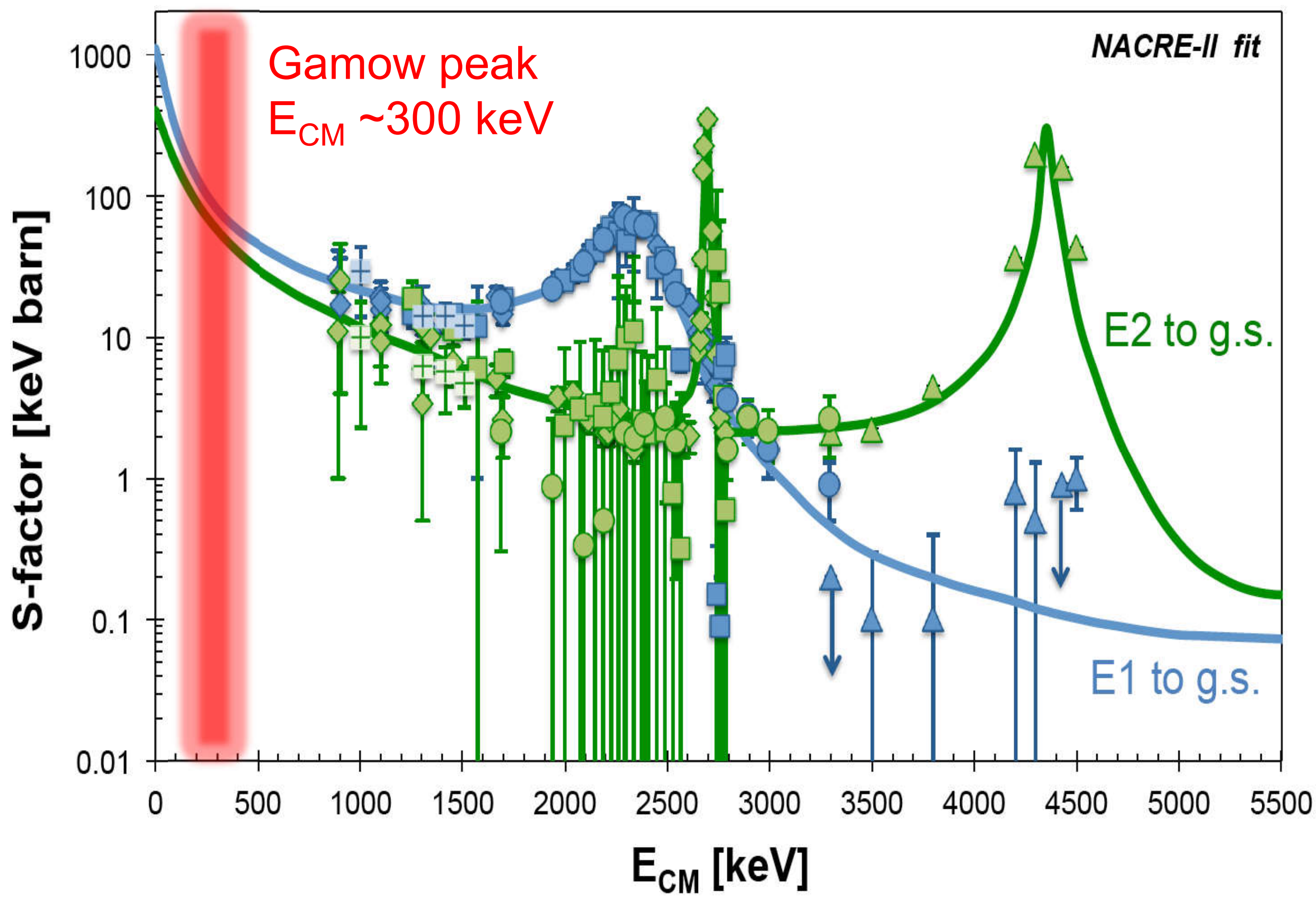
S(300keV) = (140 ± 20) keV·b   σ = 0.03 fb

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

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

$S(1\ \text{MeV}) = (40 \pm 10)\ \text{keV}\cdot\text{b}$ $\sigma = 50\ \text{pb}$

$S(300\ \text{keV}) = (140 \pm 20)\ \text{keV}\cdot\text{b}$ $\sigma = 0.03\ \text{fb}$



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

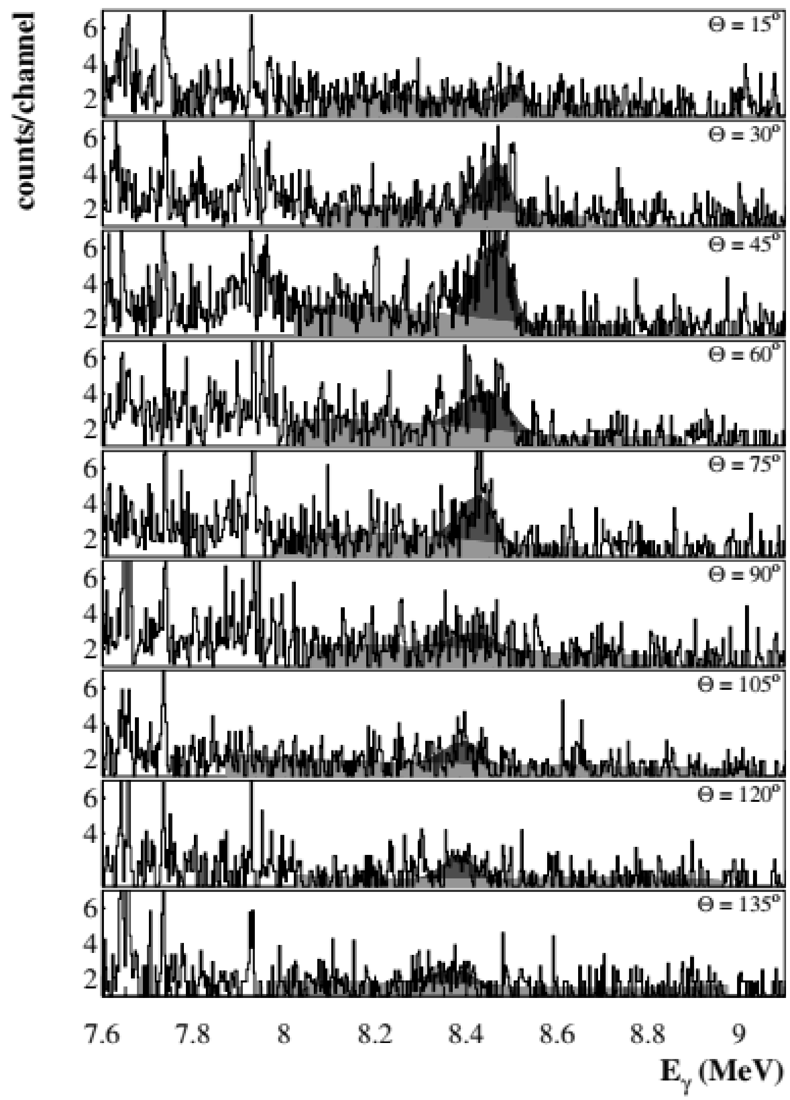
Time: 6 days

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
- proper detector / target
    - high efficiency
    - low background
    - low energy threshold
    - possibility to measure angular distribution

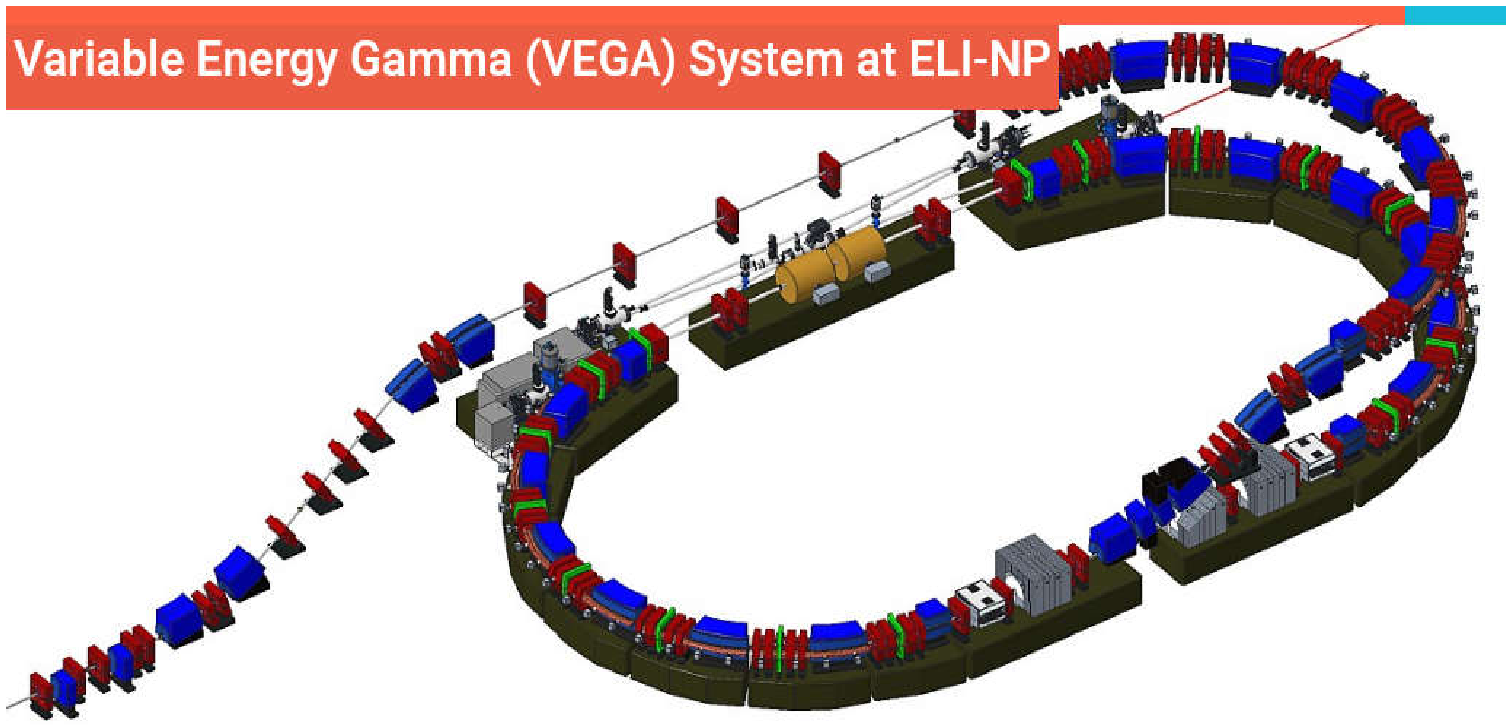
Solution

Active Target Time Projection Chamber

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

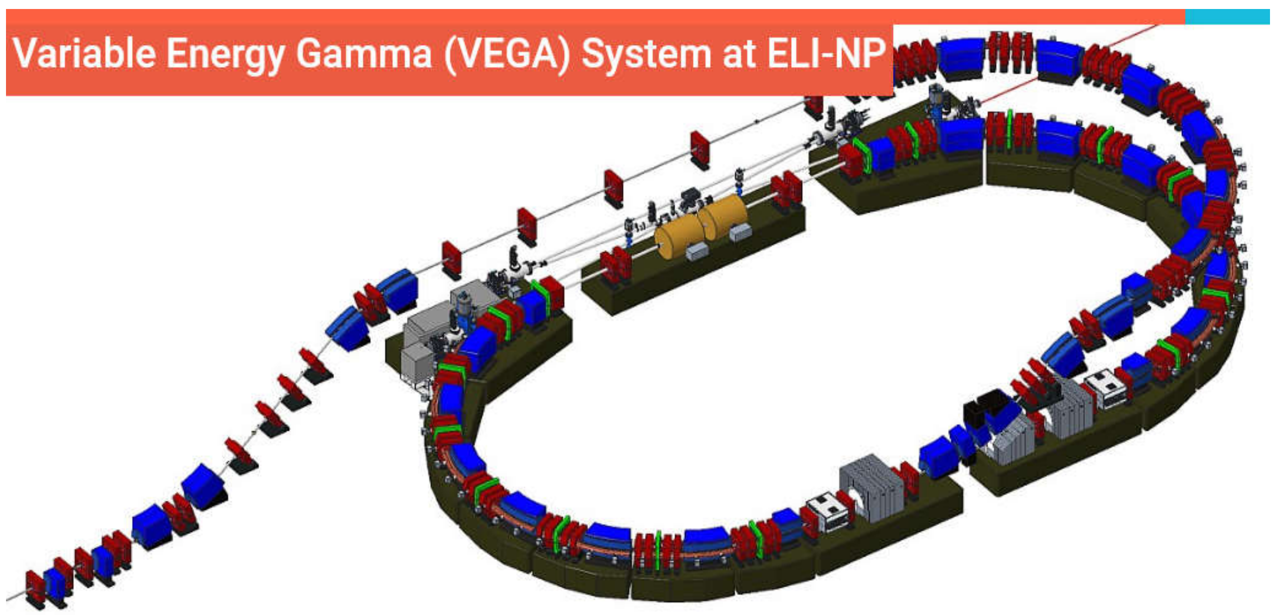
- high intensity, monochromatic gamma beam

Extreme Light Infrastructure - Nuclear Physics
Magurele-Romania

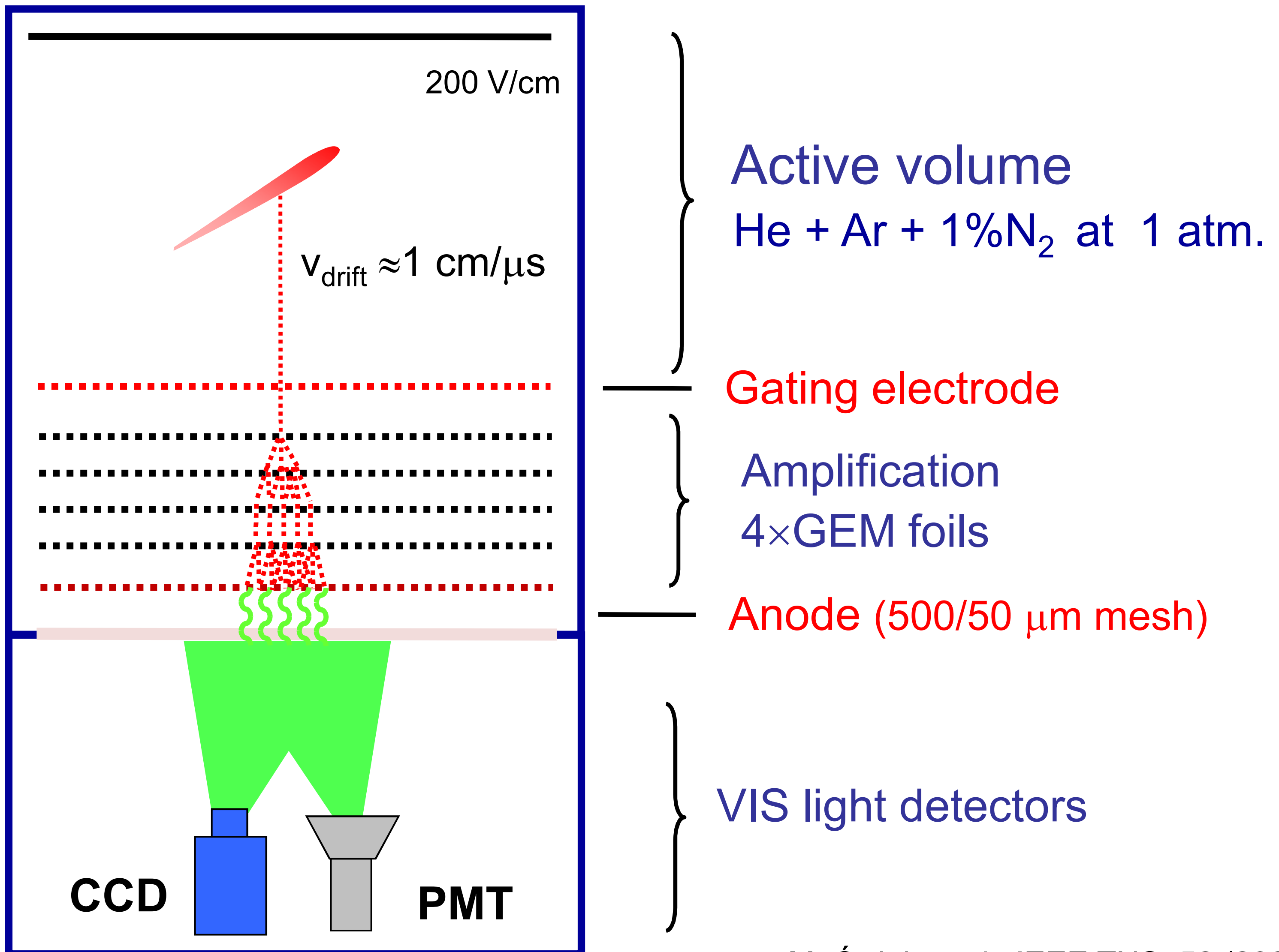


Extreme Light Infrastructure - Nuclear Physics Magurele-Romania

- Compton backscattering of light on electron beam
  - laser beam: 500 / 1000 nm
  - electron beam: 234 - 742 MeV
  - **E_γ= 1 - 20 MeV, ΔE/E = 0.5%**
  - **Intensity: 10^8 γ/s**



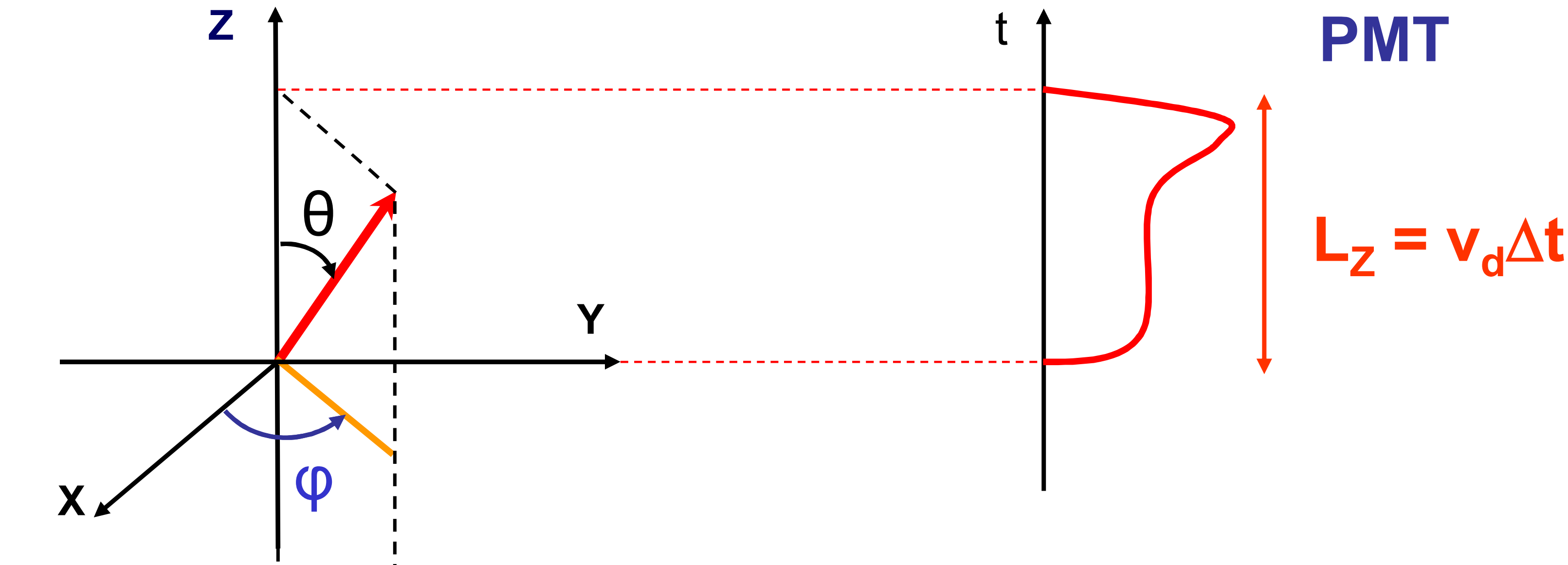
Optical Time Projection Chamber

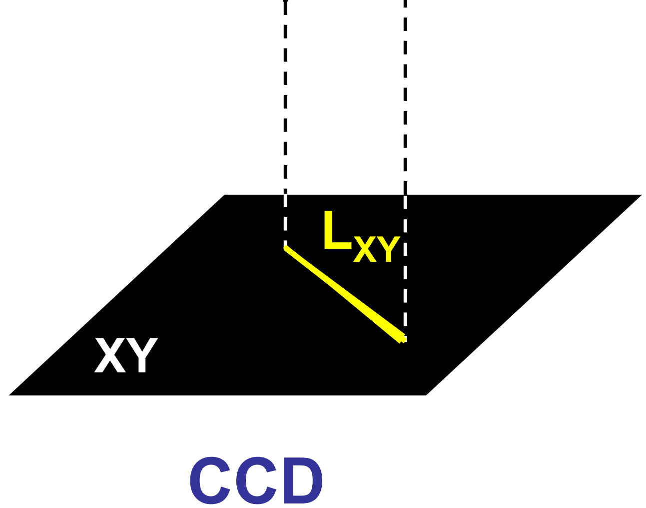


M. Ćwiok et al., IEEE TNS, 52 (2005) 2895

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

Idea of track reconstruction





Track coordinates (r, Θ, φ)

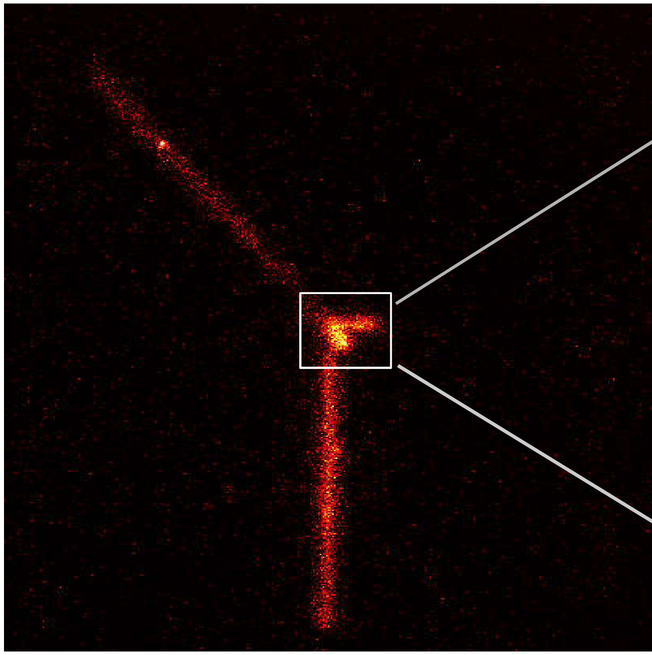
$L_{XY} = r \sin\Theta$

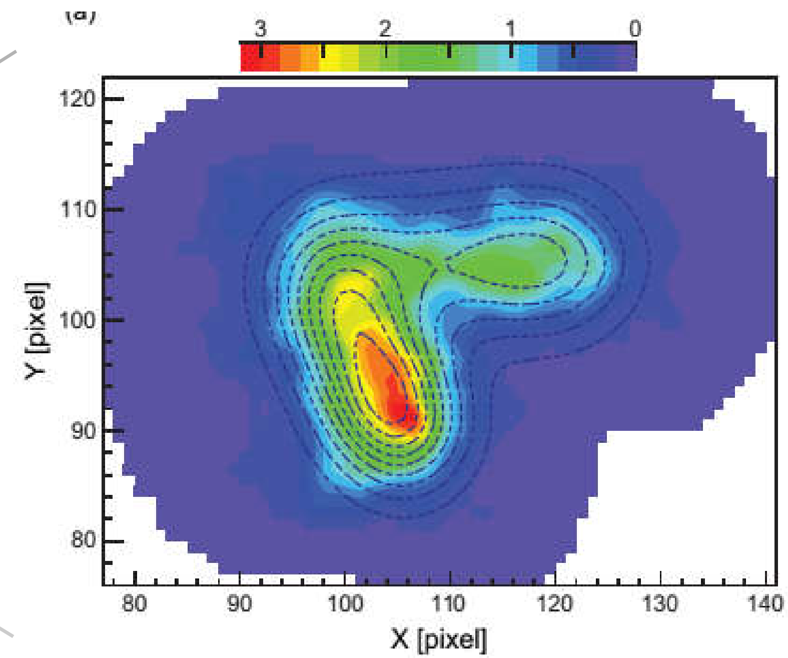
$L_Z = r \cos\Theta$

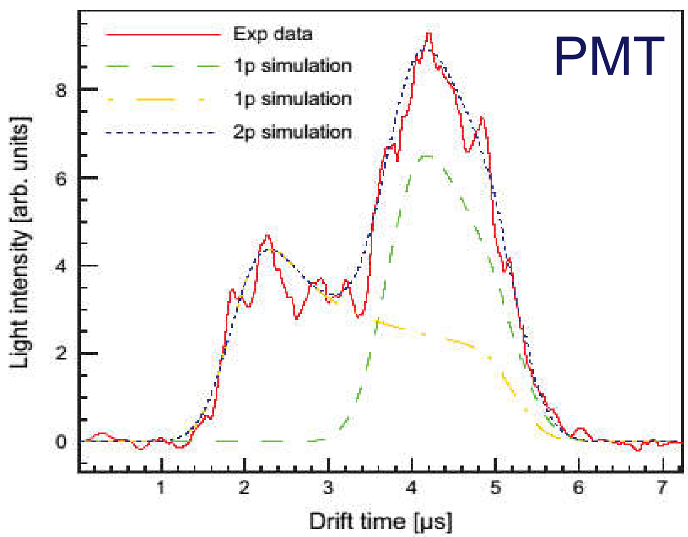
$r^2 = L_{XY}^2 + L_Z^2$

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

Reconstruction of 2p decay ^{48}Ni







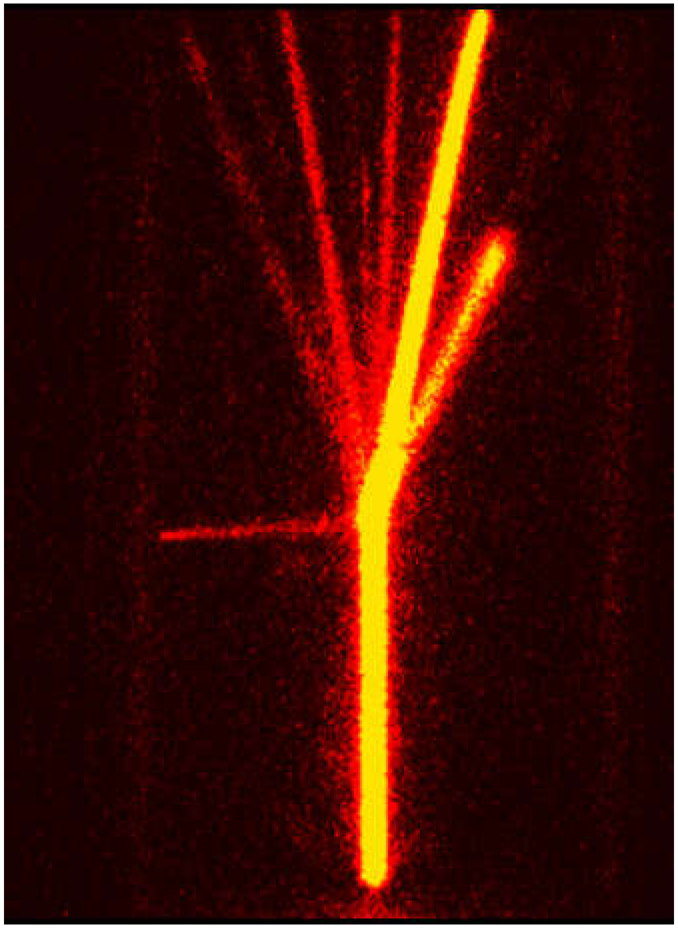
E_{p1}= 580 keV
θ_{p1}= 117°
φ_{p1} = 0

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

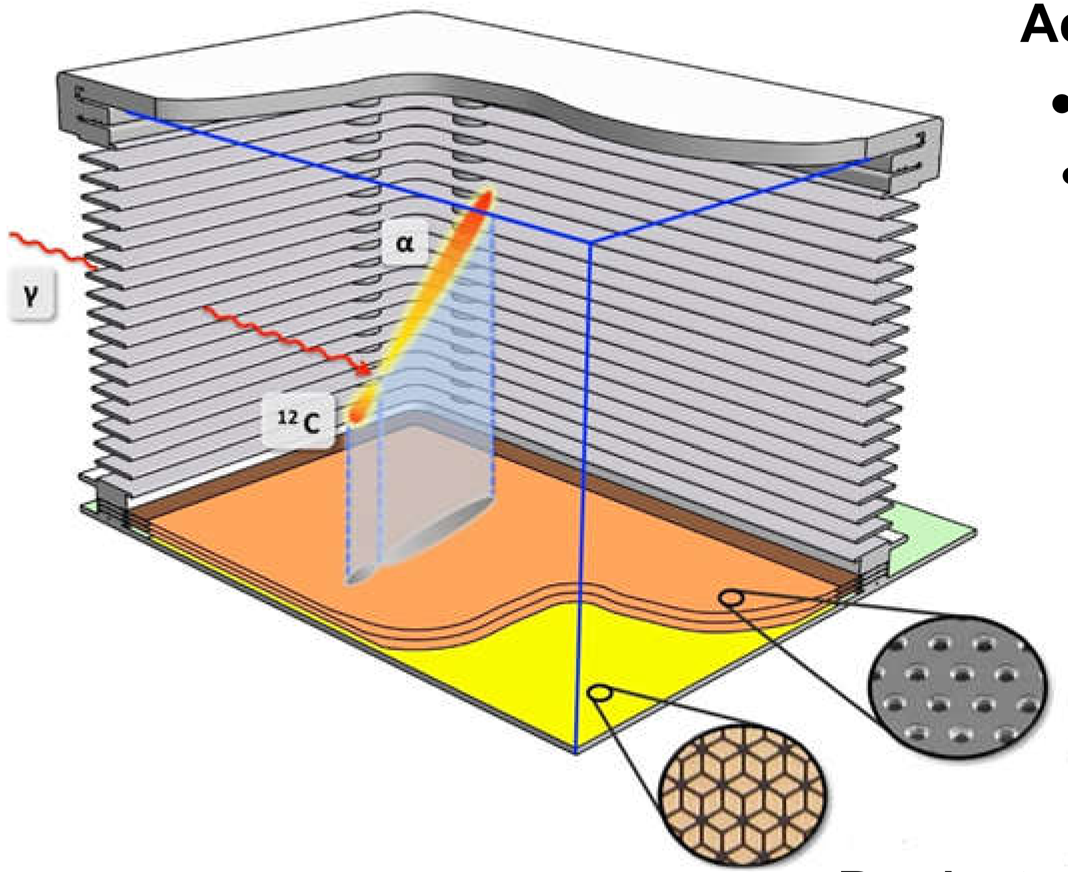
Q_{2p} = 1287(80) keV
θ_{pp} = 51(8)°

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:

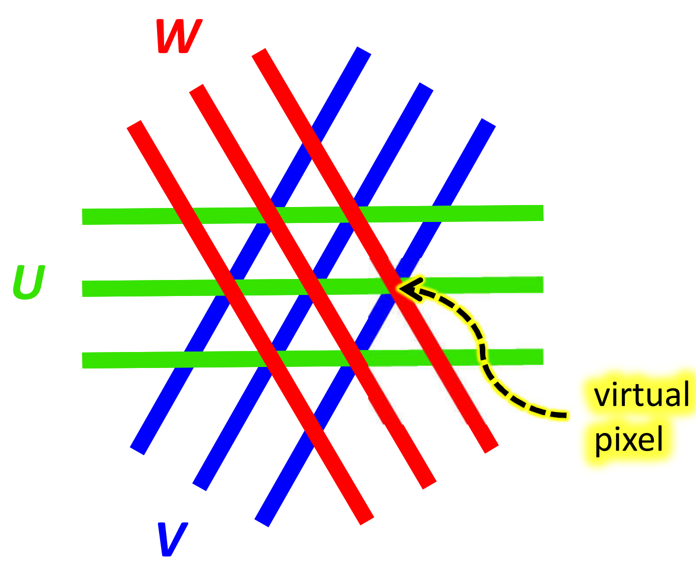
- 3 strip arrays
- 1000 channels
- GET electronics

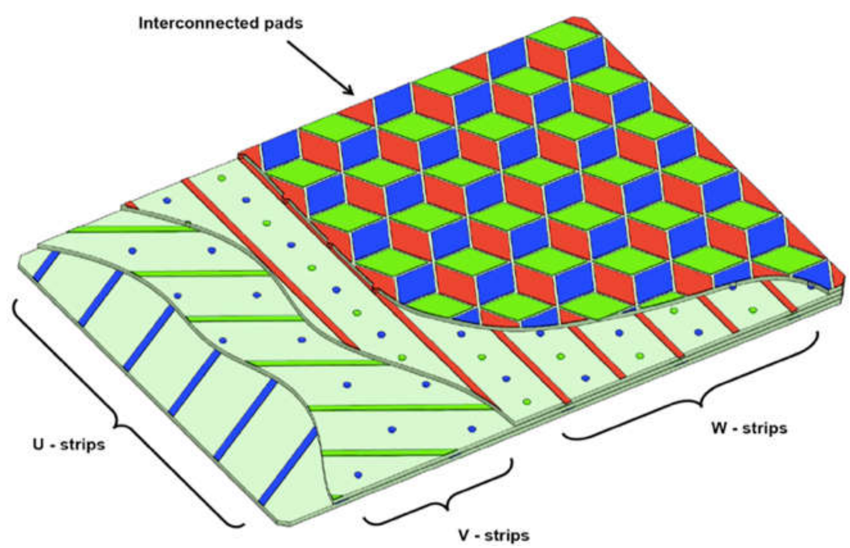
M. Ćwiok

Readout electrode of eTPC

3 grids of strips – crossed at 60° :

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

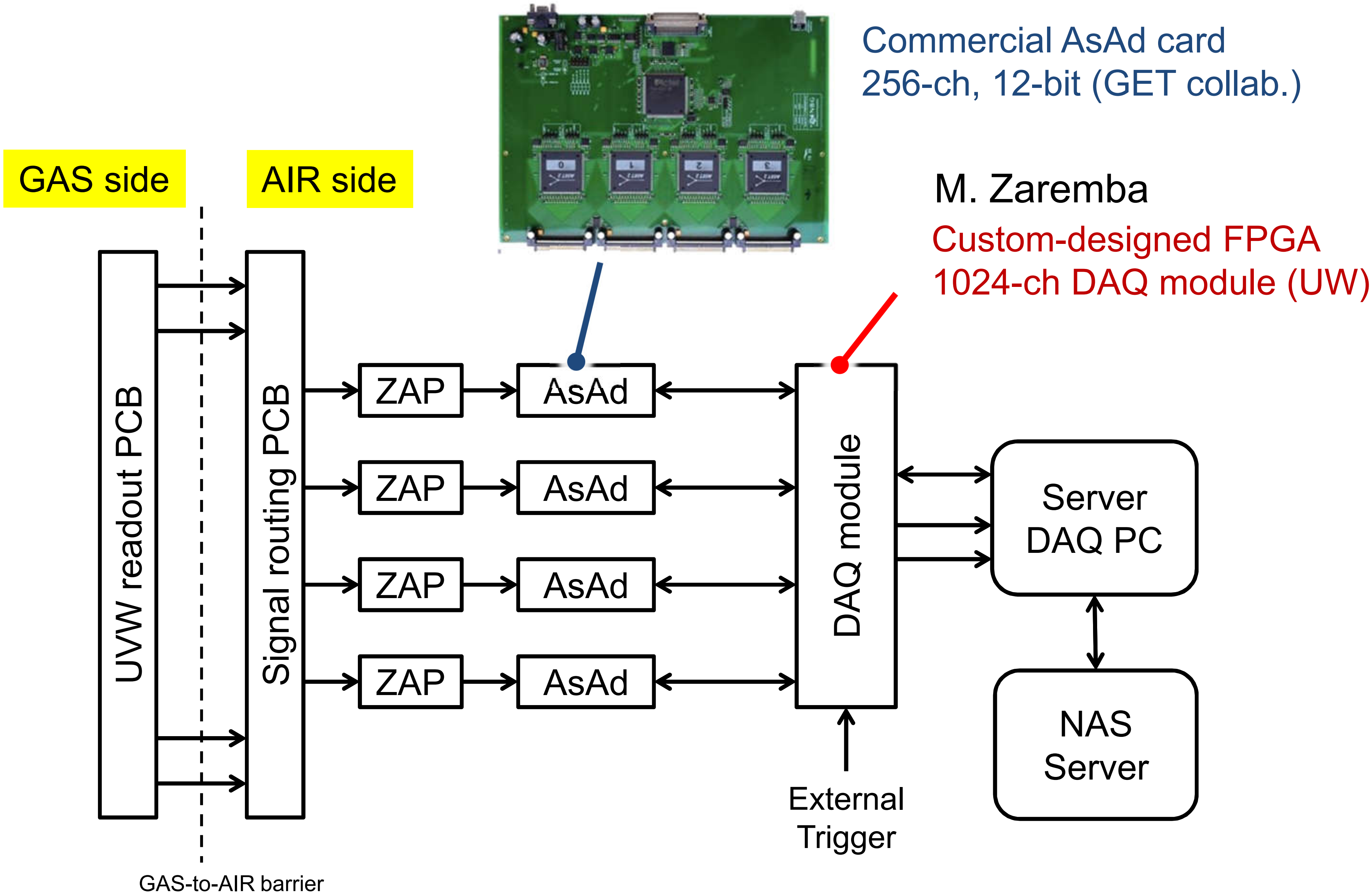




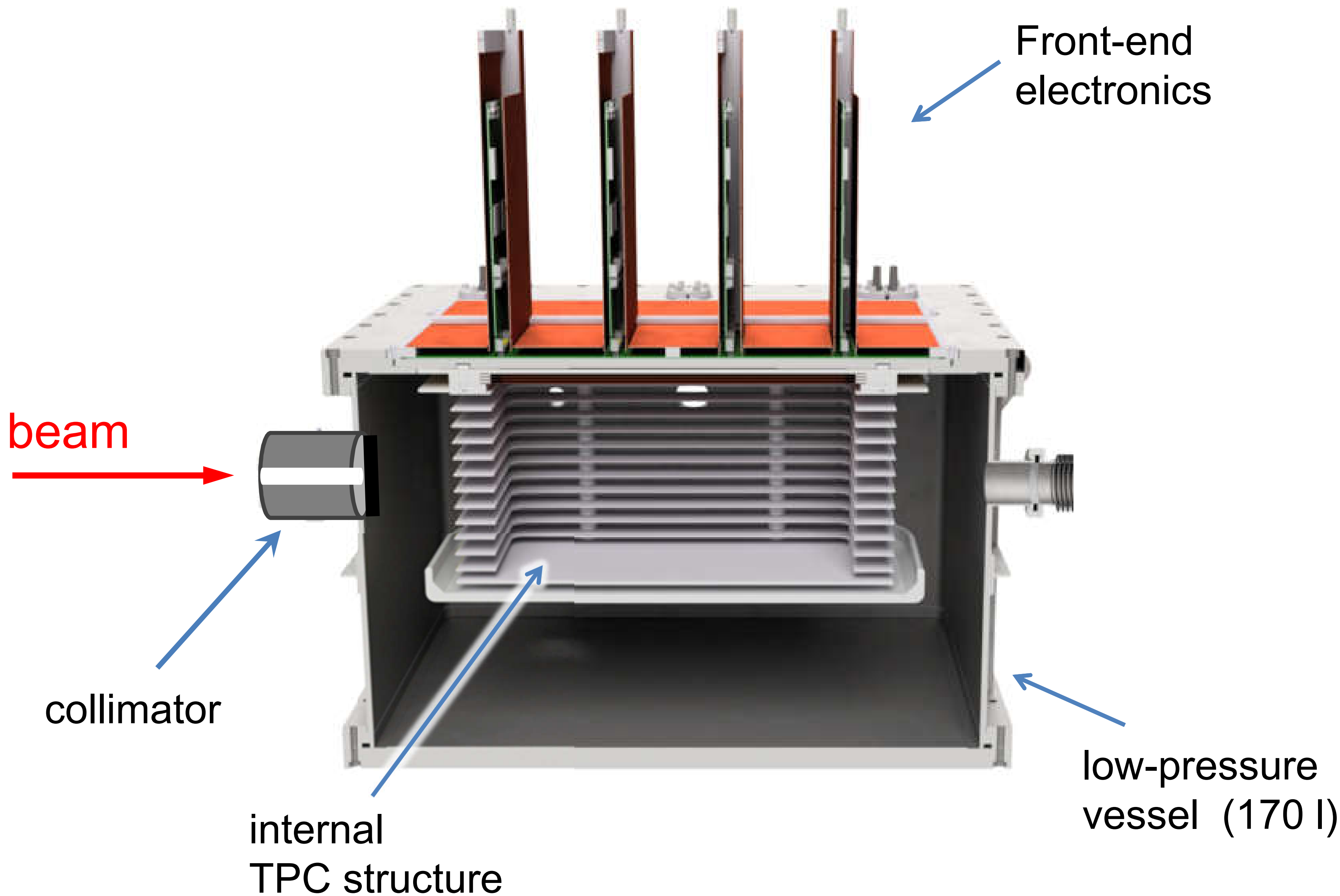
8-layer PCB, 4.2 mm-thick

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

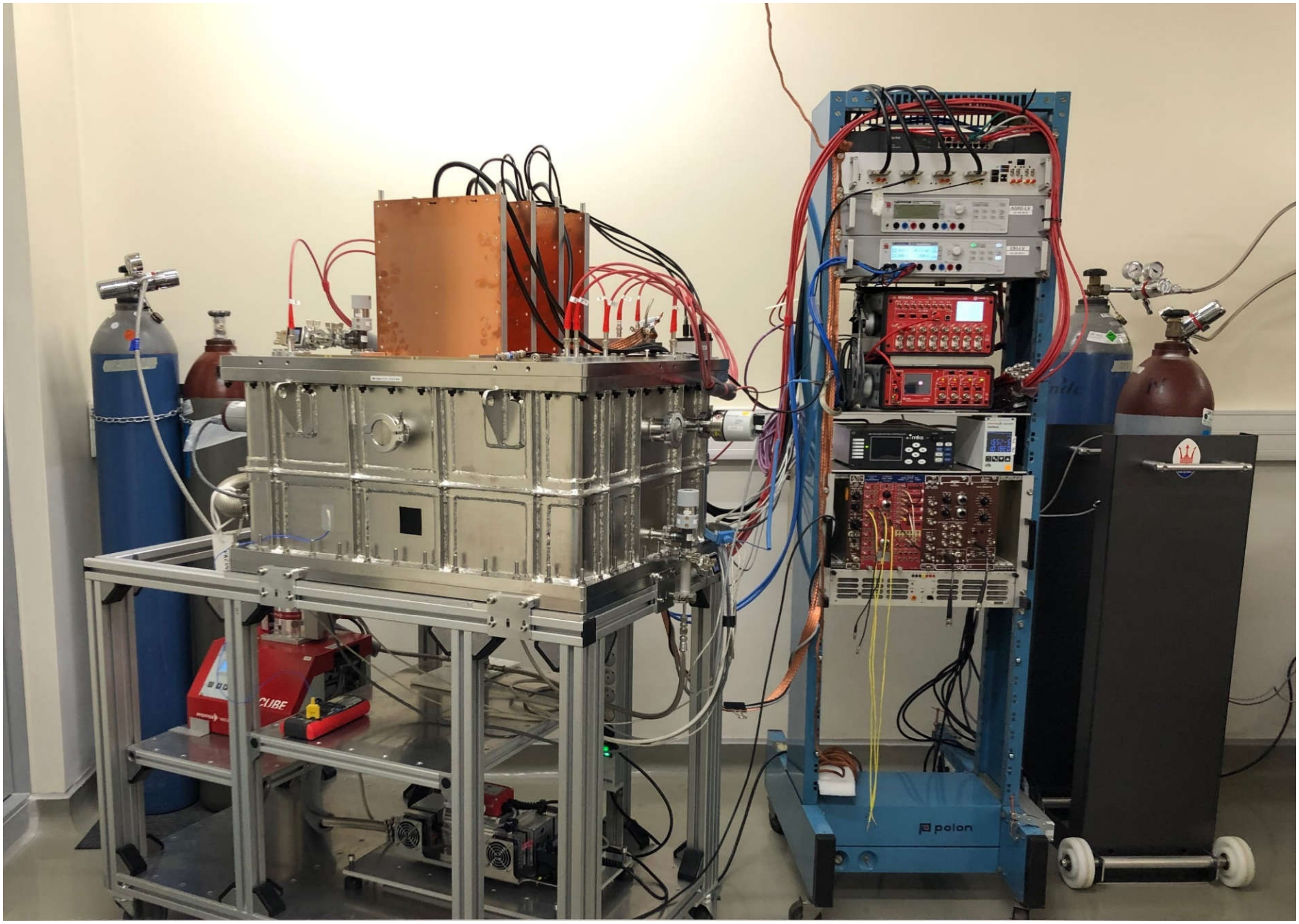
Readout electronics



Time Projection Chamber



Time Projection Chamber at FUW



Test of TPC at IFJ PAN Van de Graaff accelarator

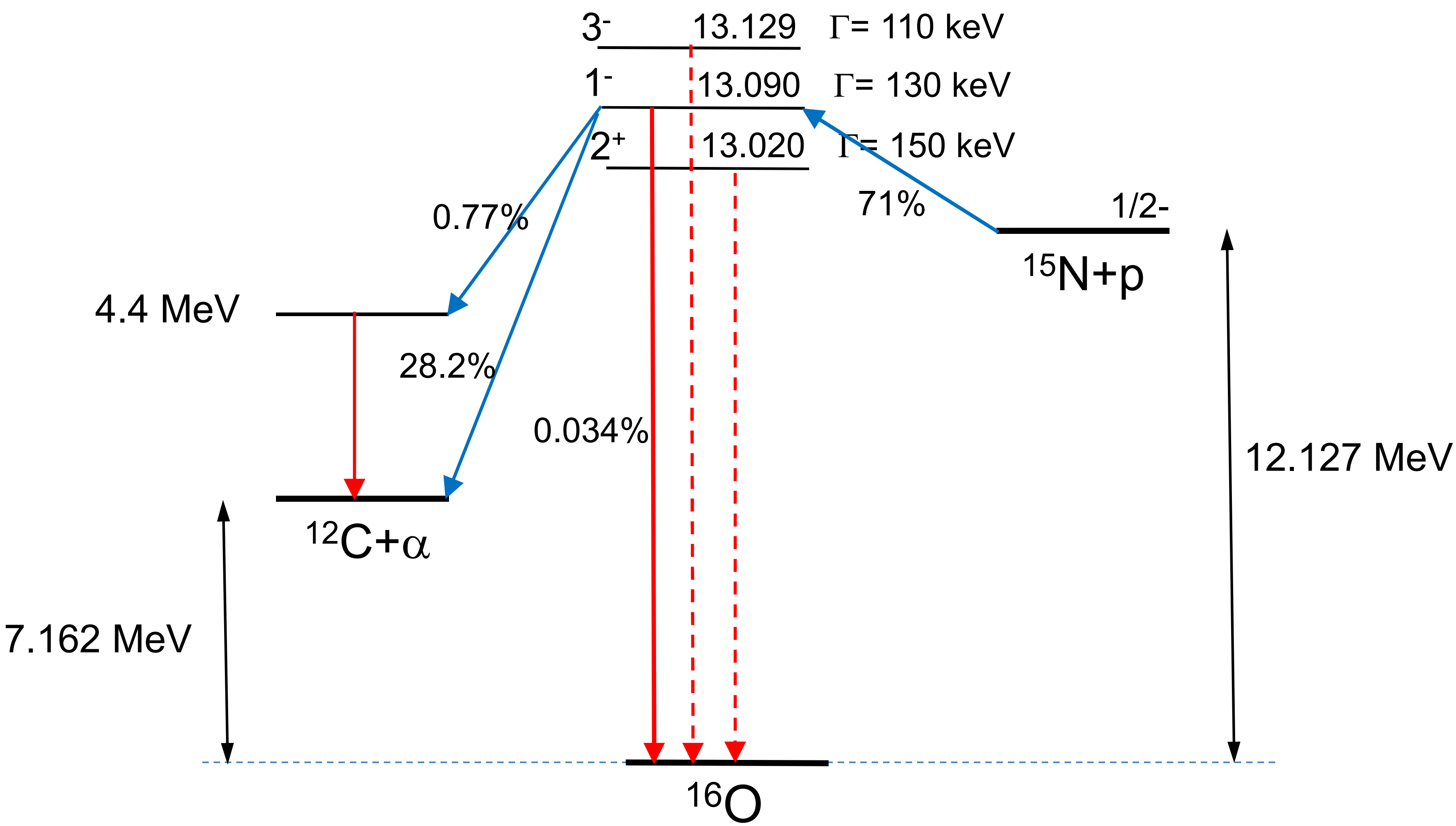
Idea

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

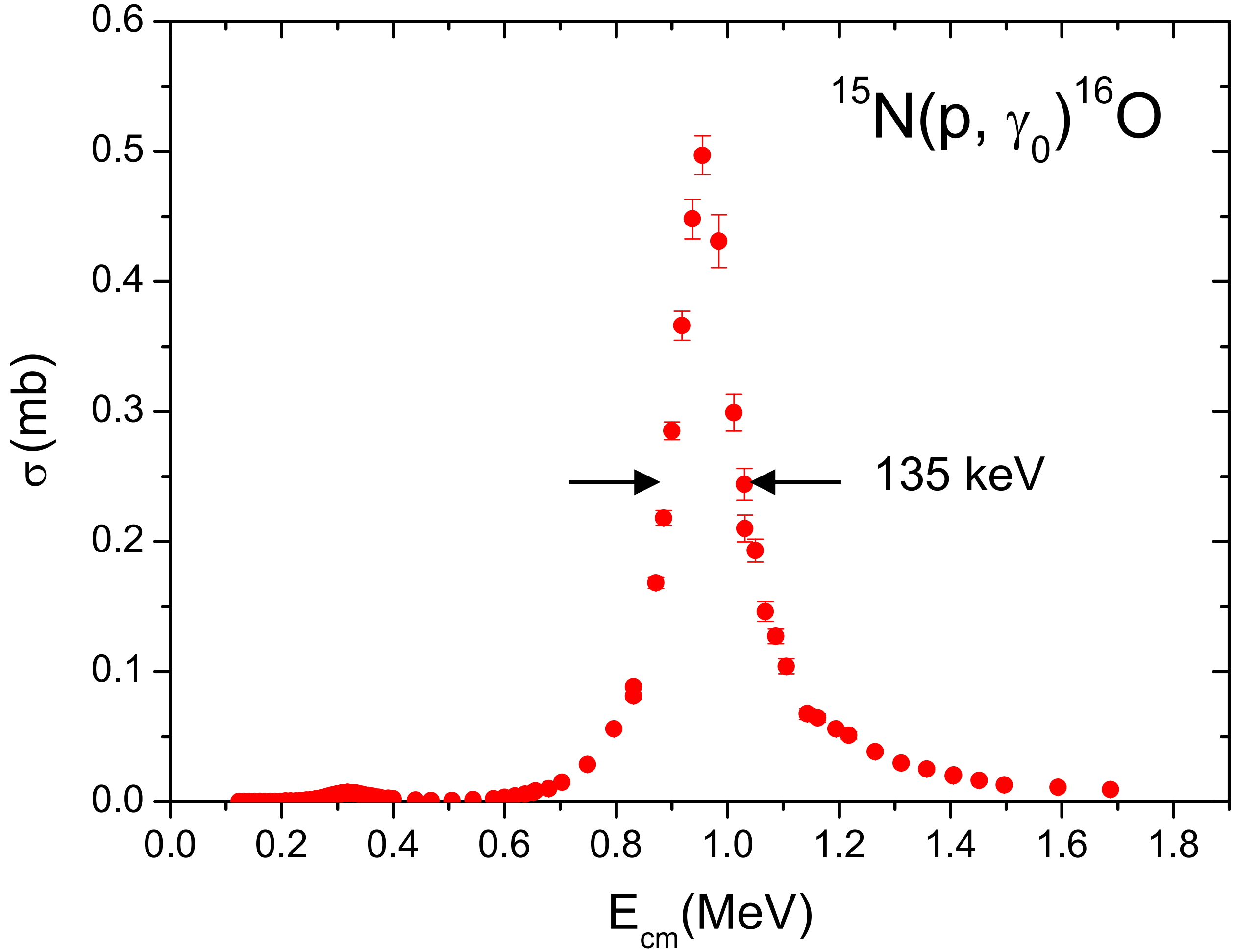
Goals

- 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

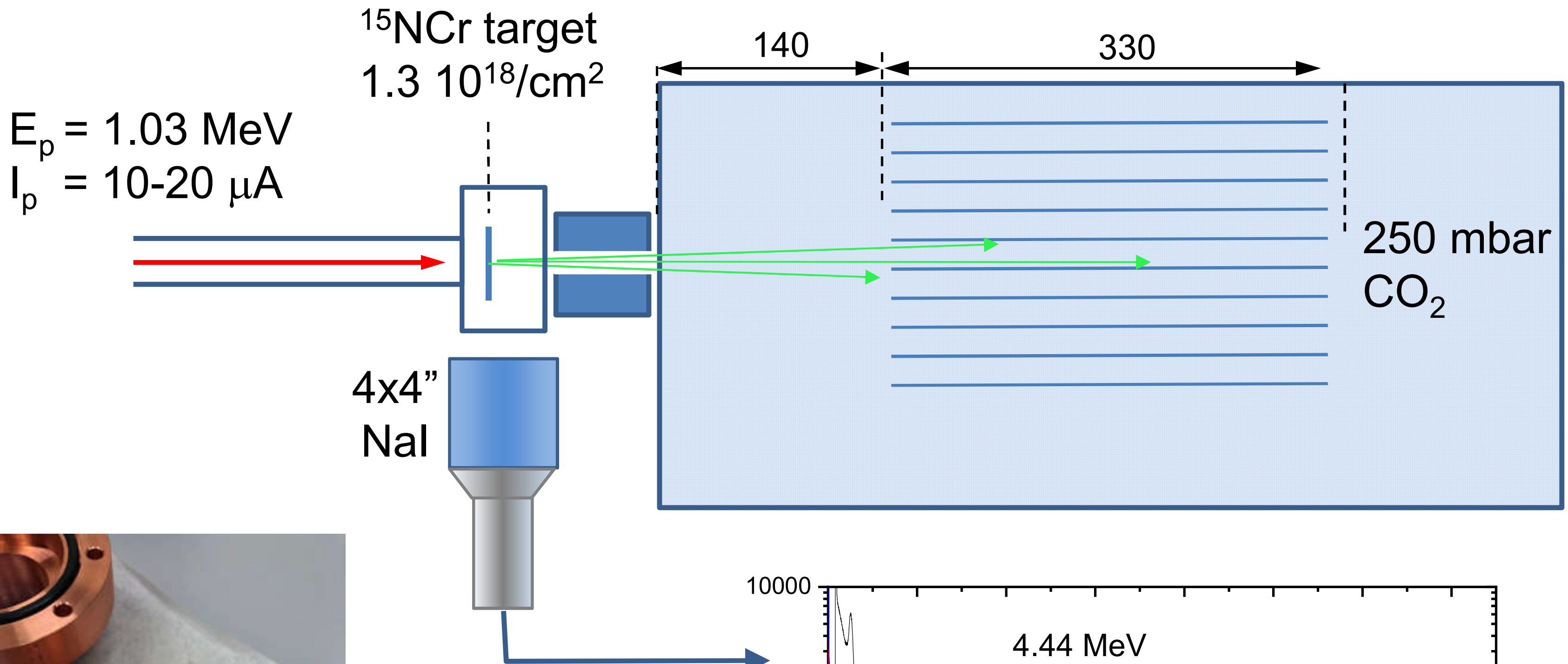
$^{15}N(p, \gamma)^{16}O$ reaction



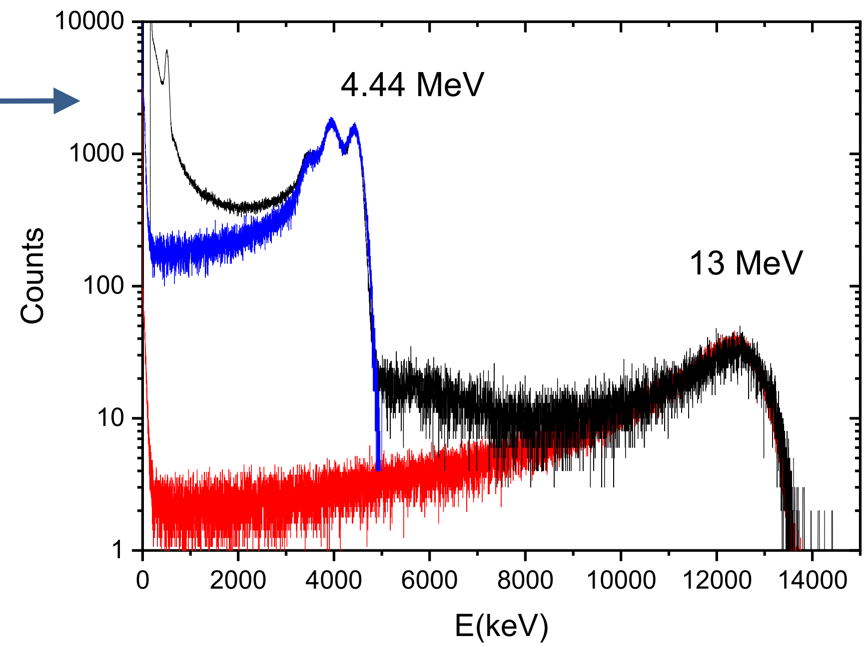
Cross section of $^{15}N(p, \gamma_0)\ ^{16}O$ reaction



TPC at VdG

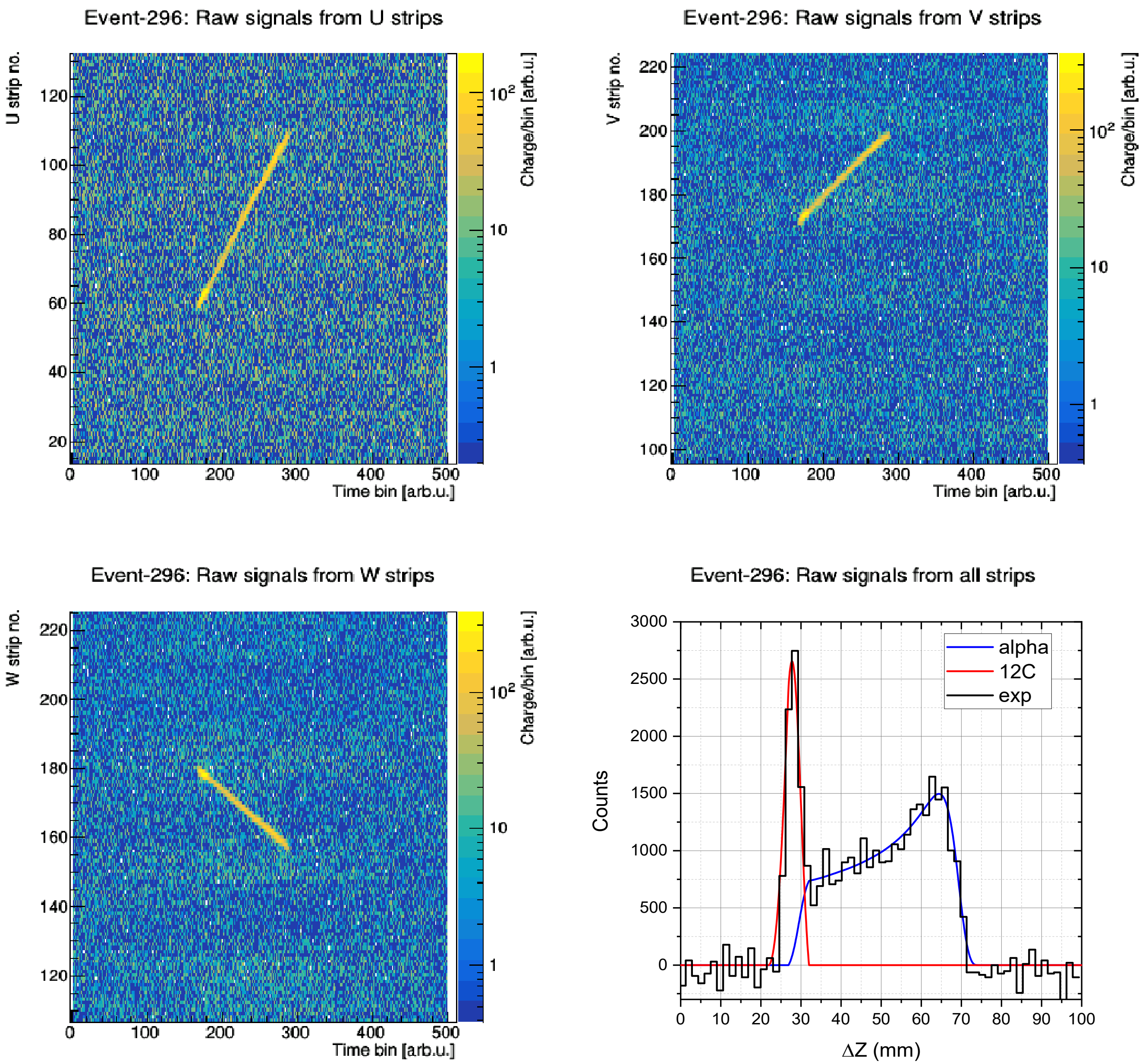


^{15}NCr target
1.3 10^{18}/cm^2
E_p = 1.03 MeV
I_p = 10-20 μA
140
330
250 mbar
CO_2
4x4”
NaI



4.44 MeV
13 MeV
Counts
E(keV)
10000
1000
100
10
1
0
2000
4000
6000
8000
10000
12000
14000

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

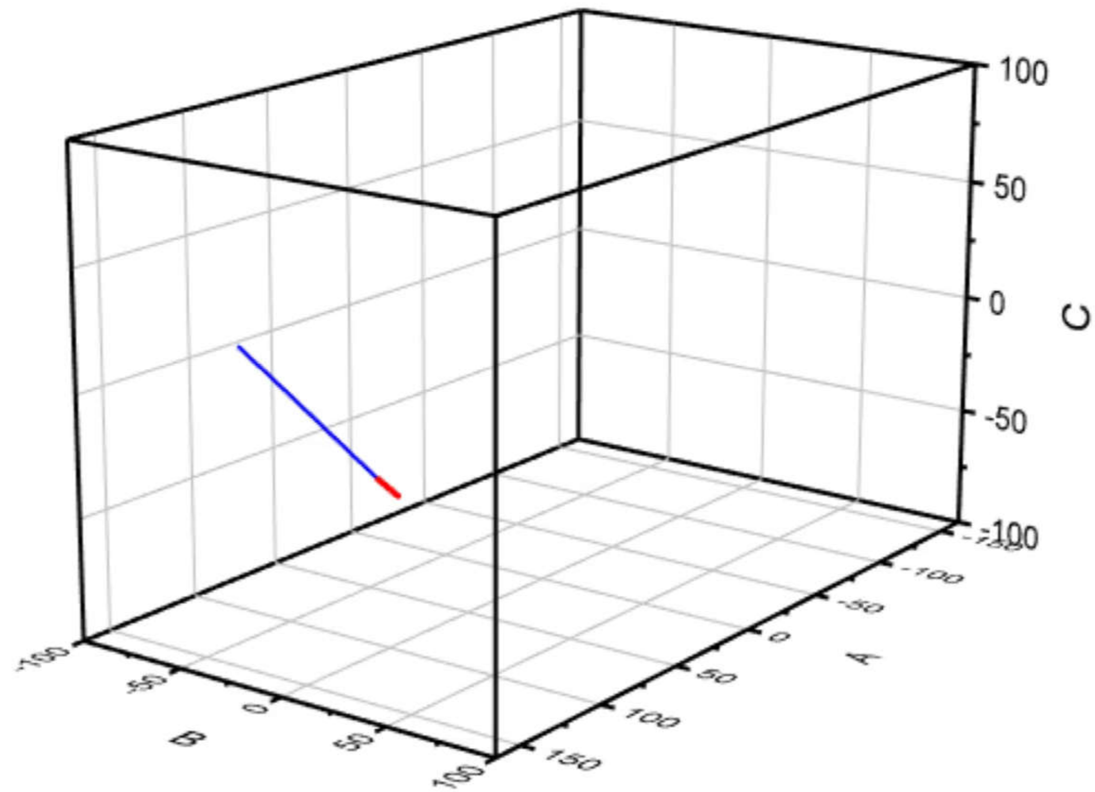


Reconstruction of $^{16}O(\gamma, \alpha)^{12}C$ event

E_{α} = 4.37 MeV

E_{12C} = 1.46 MeV

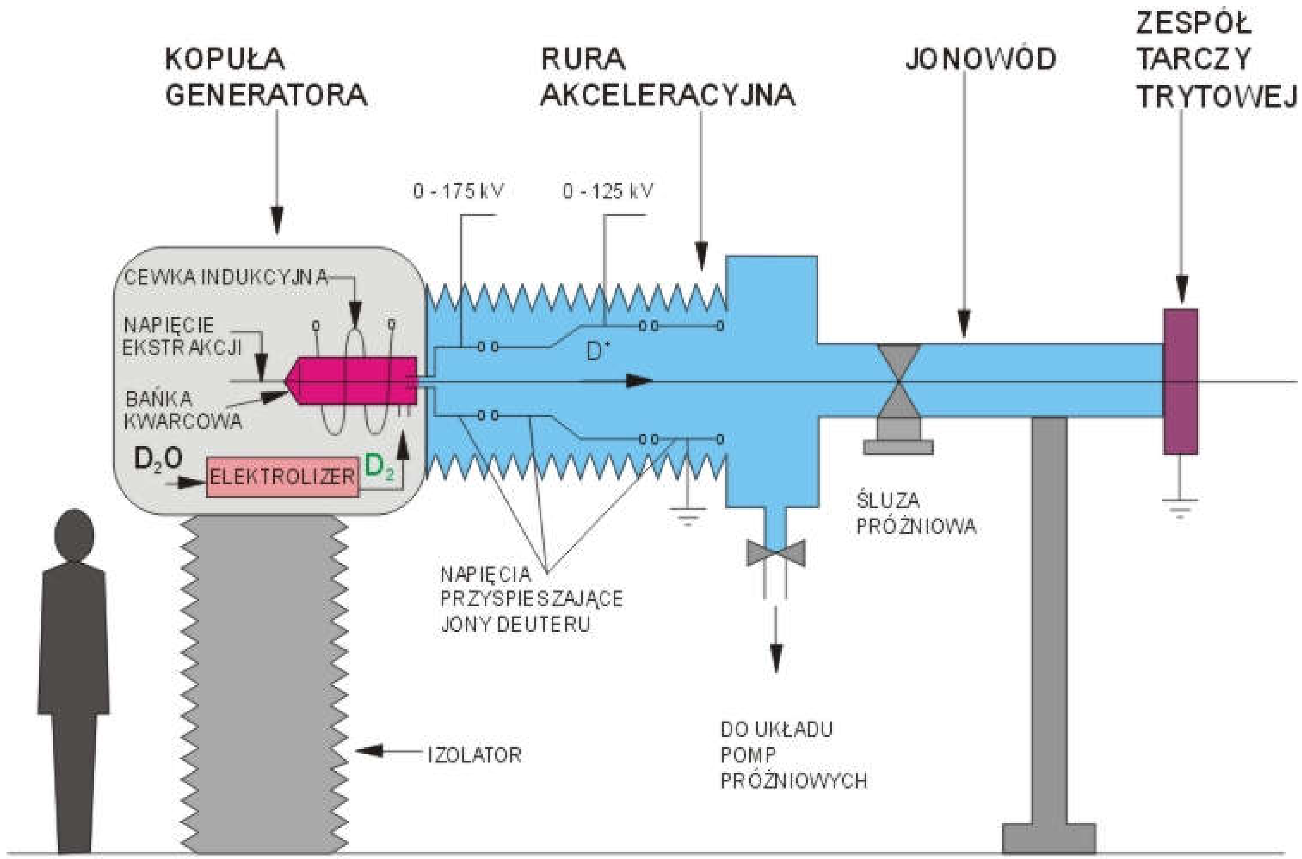
$\theta_{\alpha-12C}$ = 180°



Neutron generator at IGN-14

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

Yield: 5×10^8 n/s in 4π

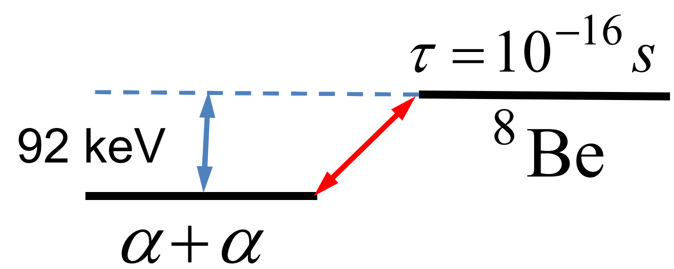


Synthesis of ^{12}C in 3-alpha reaction

- Step I

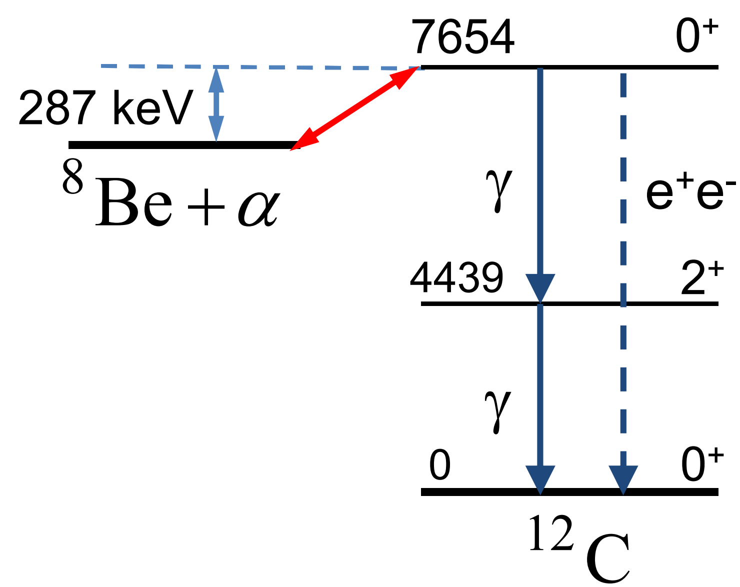
$$\alpha + \alpha \quad \leftrightarrow \quad {}^{8}\mathrm{Be}$$

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

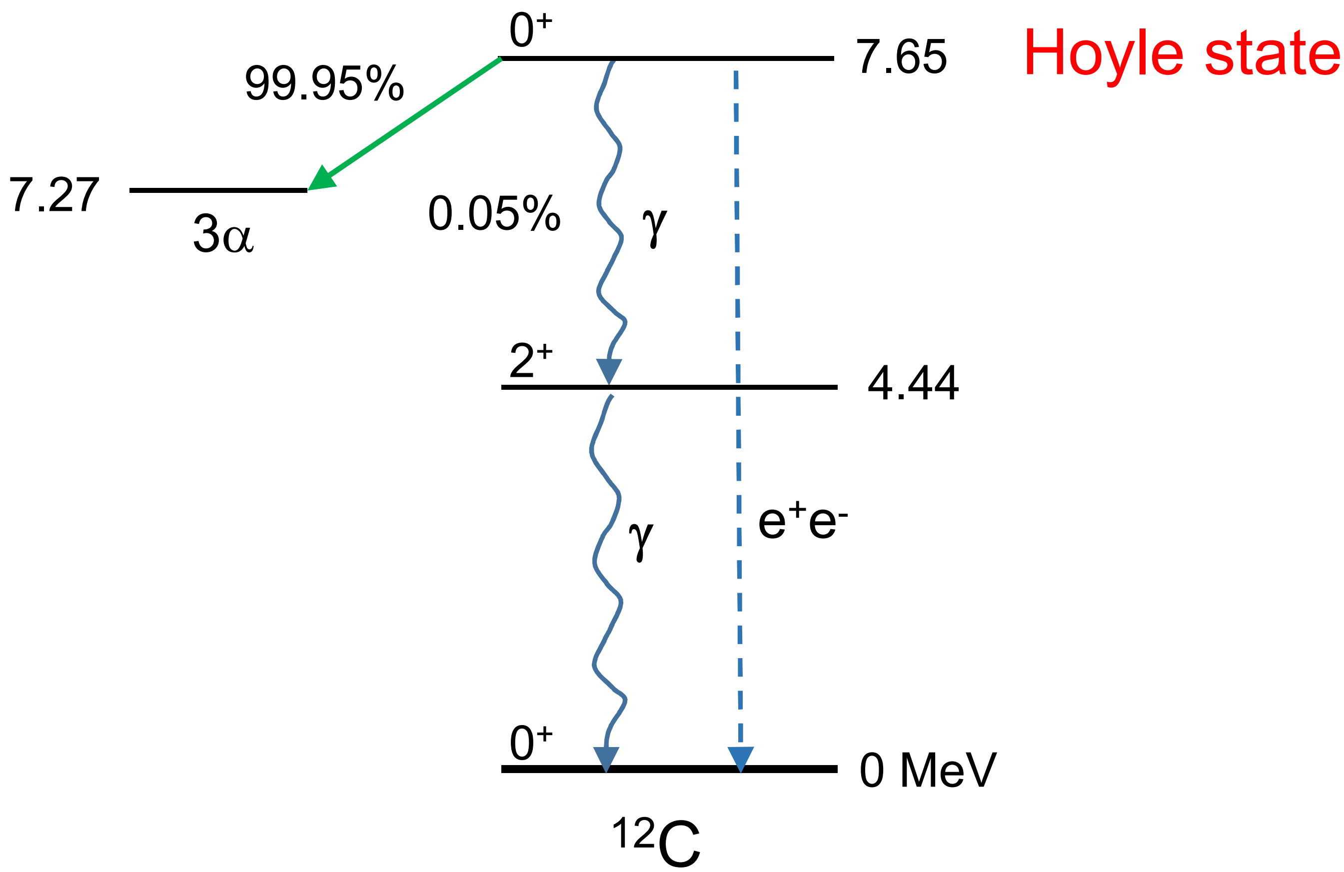


- Step II

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

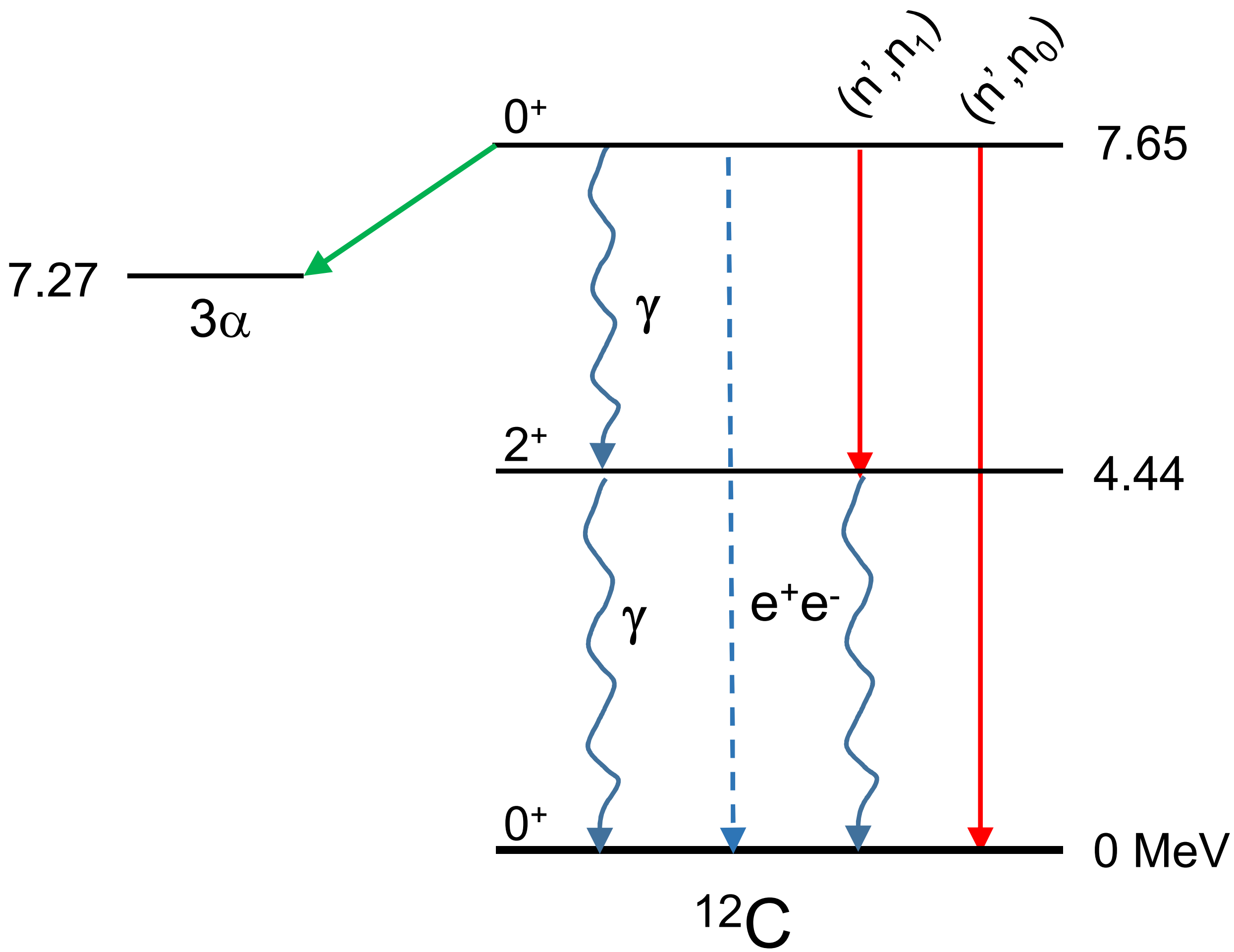


Decay of the Hoyle state – no influence of enviroment



Deexcitation of the Hoyle state in high density neutron environment

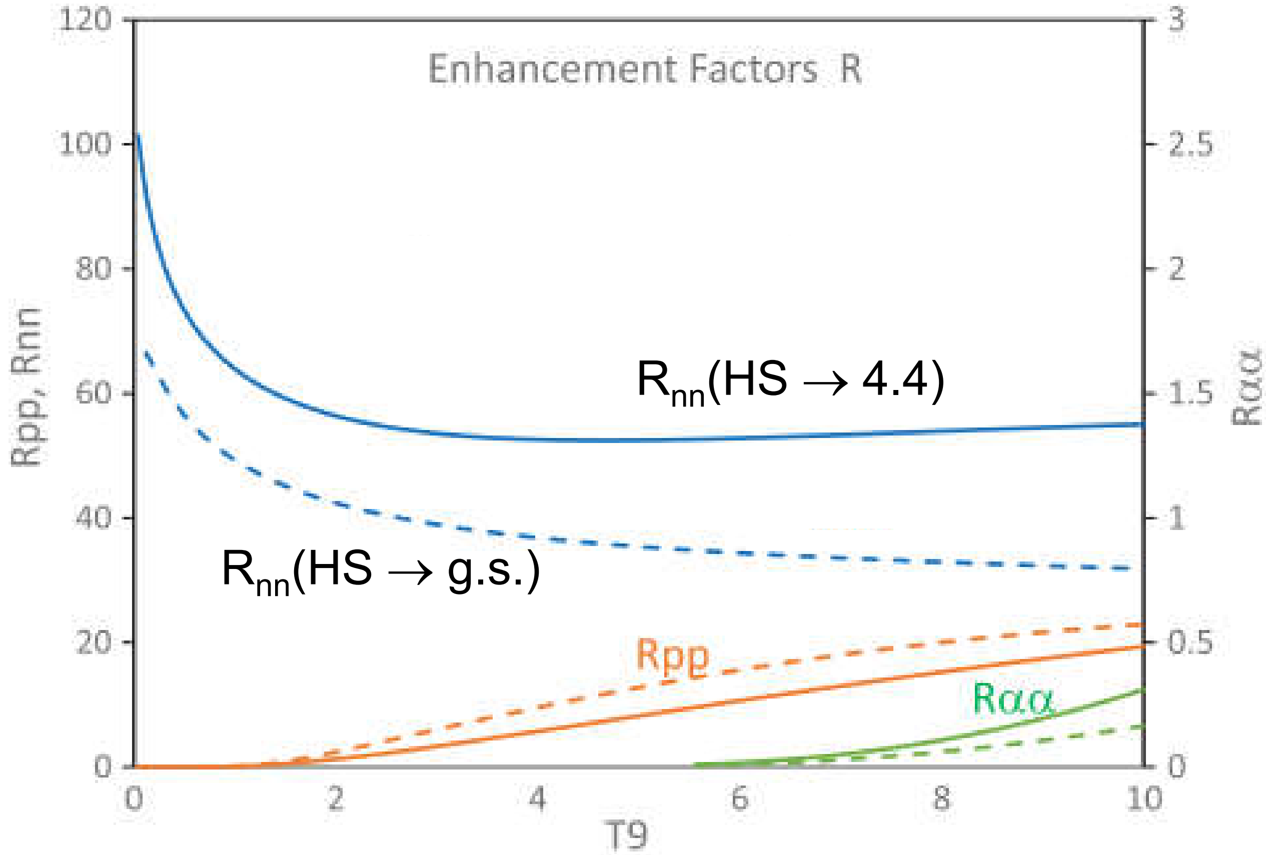
$$\Gamma_{n'n}(^{12}\mathrm{C}^{Hoyle}) = \hbar \cdot N_n \cdot \langle \sigma v \rangle_{n'n}$$



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

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

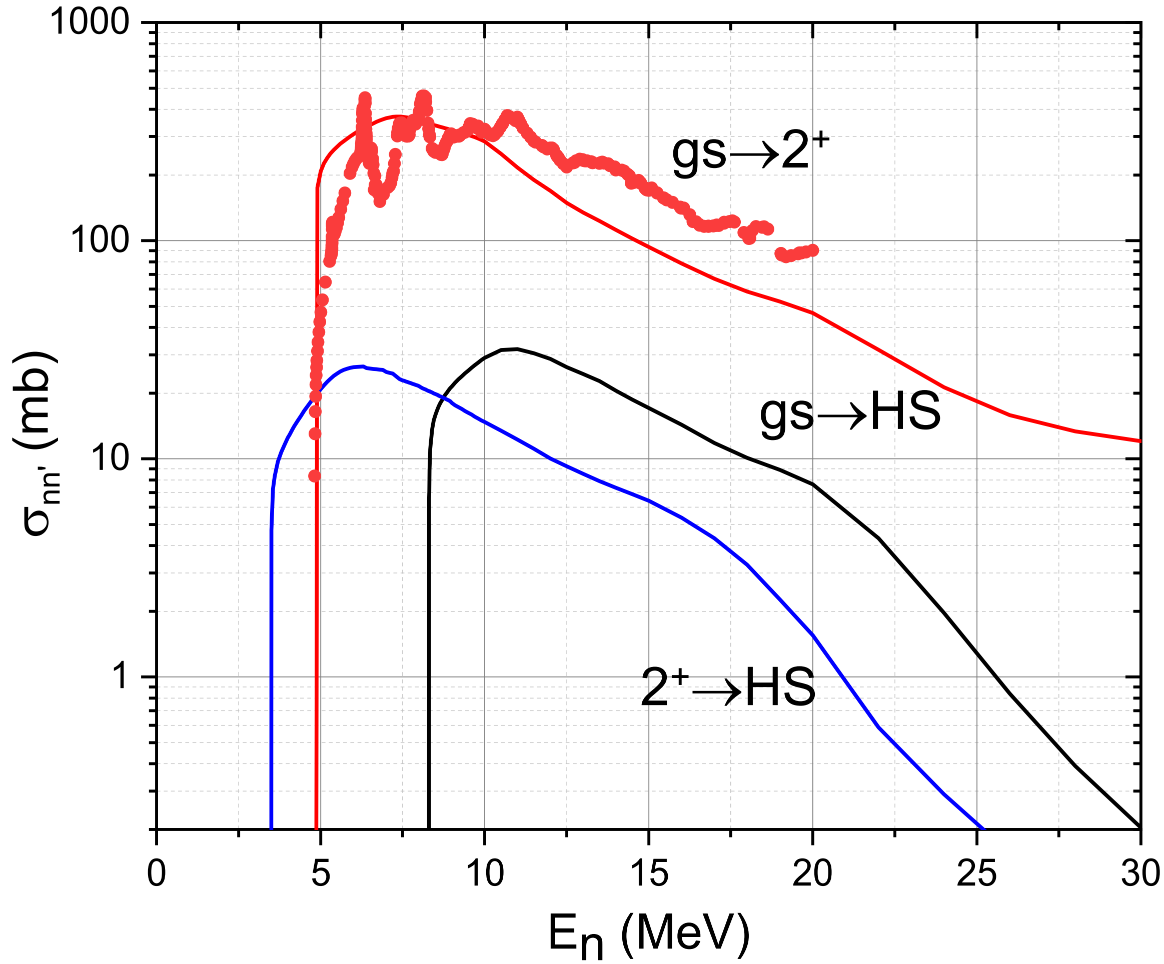
$N_n = 10^6$ g/cm^3



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

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

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

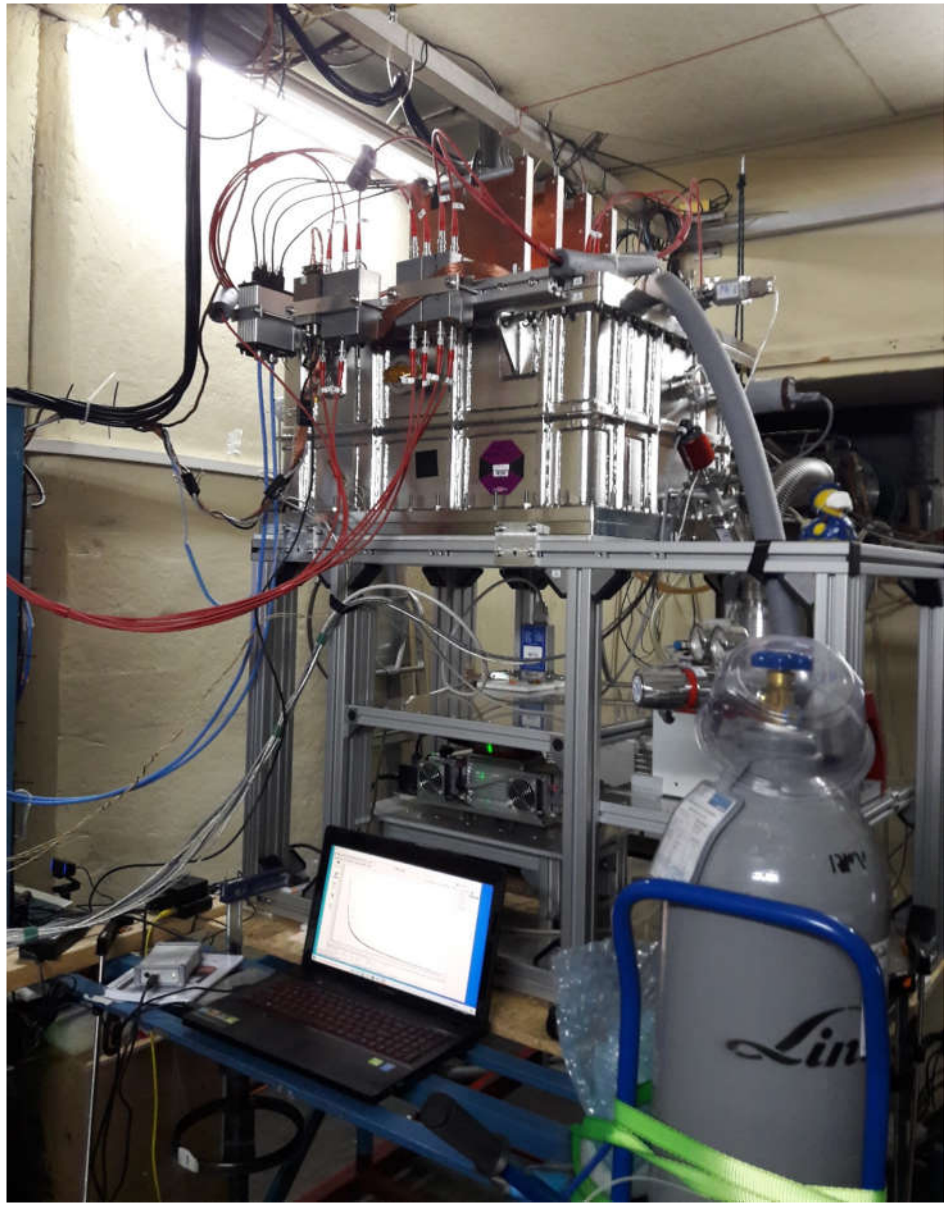


gs → HS at 14 MeV

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

Cross sections calculated within a factor 2-3

TPC at IGN-14



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

$n + {}^{12}\mathrm{C} \rightarrow n' + {}^{12}\mathrm{C}^*$

$\quad \hookrightarrow \alpha_1 + {}^{8}\mathrm{Be}^*$

$\qquad \hookrightarrow \alpha_2 + \alpha_3$ — 130 mb

$\qquad \hookrightarrow \alpha_2 + \alpha_3$ — 10 mb

$n + {}^{12}\mathrm{C} \rightarrow {}^{13}\mathrm{C}^* \rightarrow \alpha_1 + {}^{9}\mathrm{Be}^*$

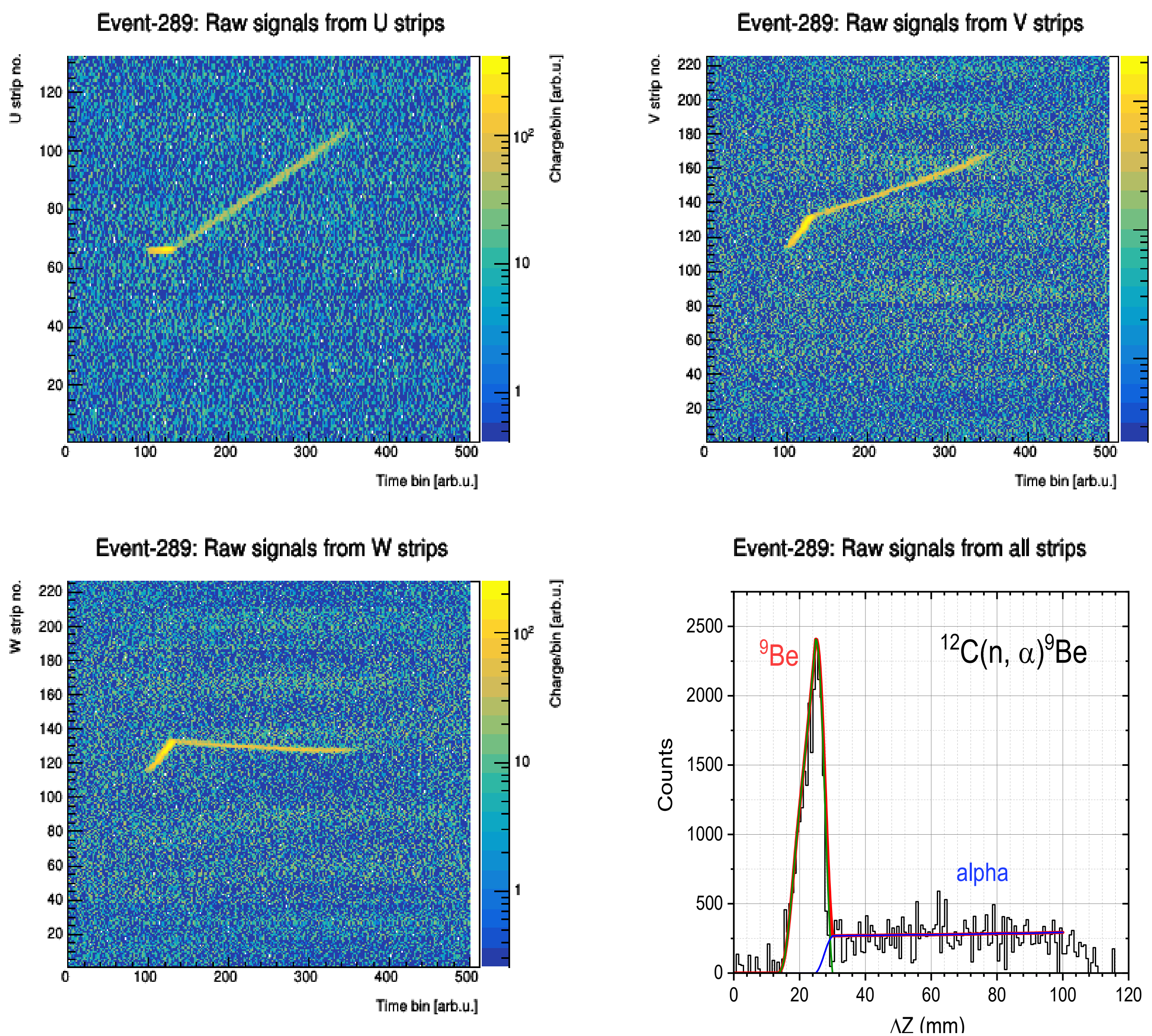
$\quad \hookrightarrow n' + {}^{8}\mathrm{Be}^*$

$\qquad \hookrightarrow \alpha_2 + \alpha_3$ — 85 mb

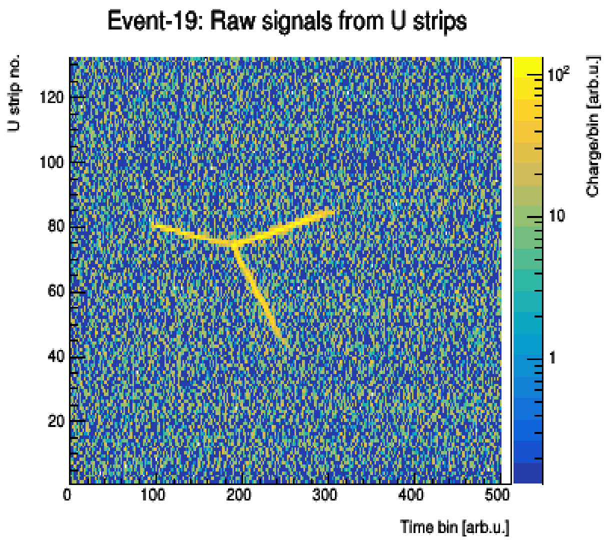
$n + {}^{12}\mathrm{C} \rightarrow {}^{13}\mathrm{C}^* \rightarrow \alpha + {}^{9}\mathrm{Be}$ — 70 mb

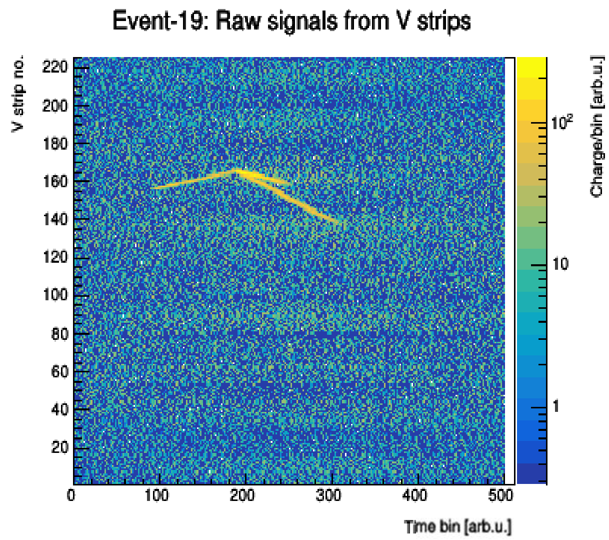
$n + {}^{16}\mathrm{O} \rightarrow {}^{17}\mathrm{O}^* \rightarrow \alpha + {}^{13}\mathrm{C}$ — 150 mb

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



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



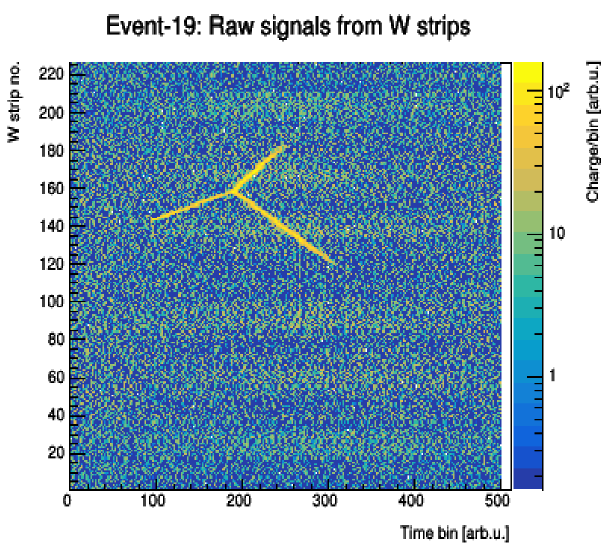


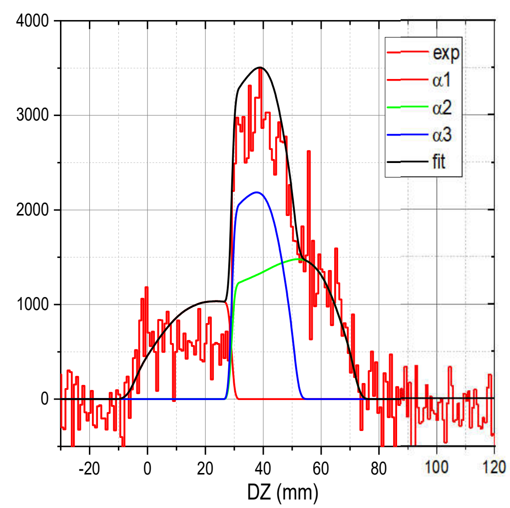
E_{a1} = 770 keV

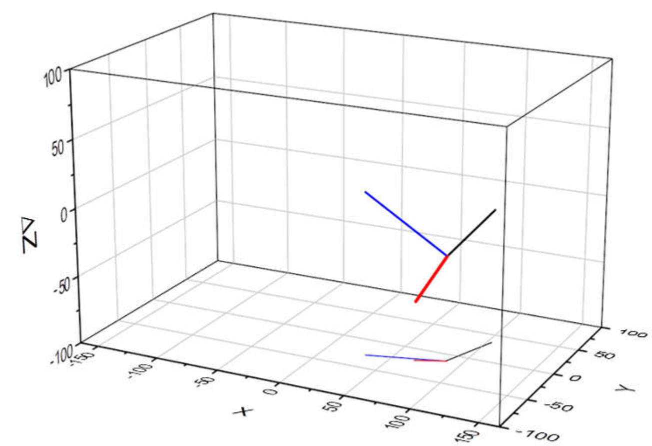
E_{a2} = 1580 keV

E_{a3} = 1175 keV

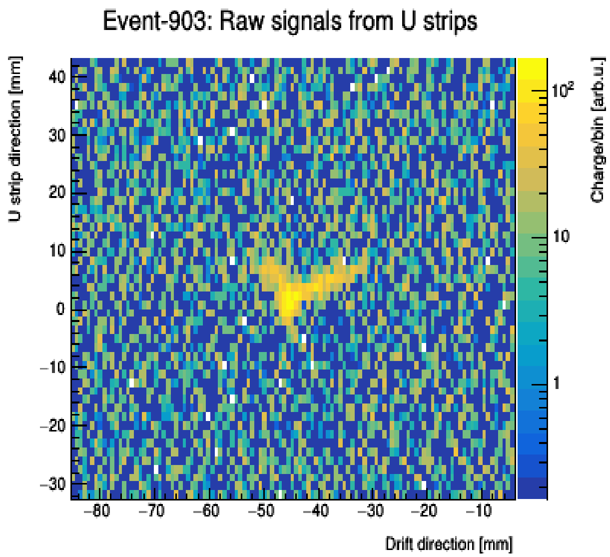
$E_x(^{12}C)$ =10.3 MeV

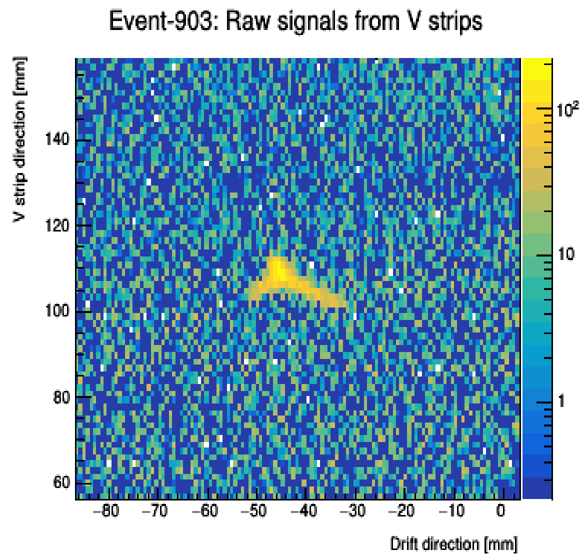






Example of $^{12}C(n, n')^{12}C^{HS}$ reaction



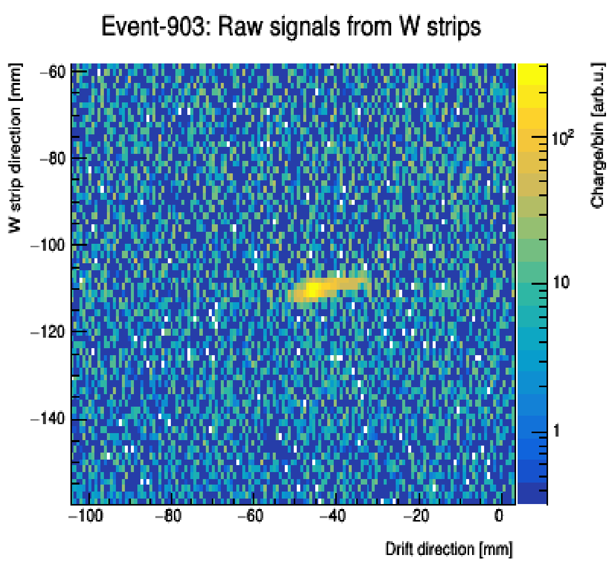


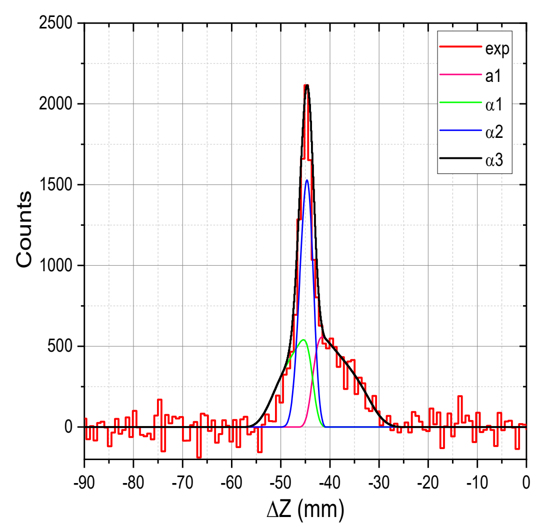
$E_{\alpha 1}$ = 145 keV

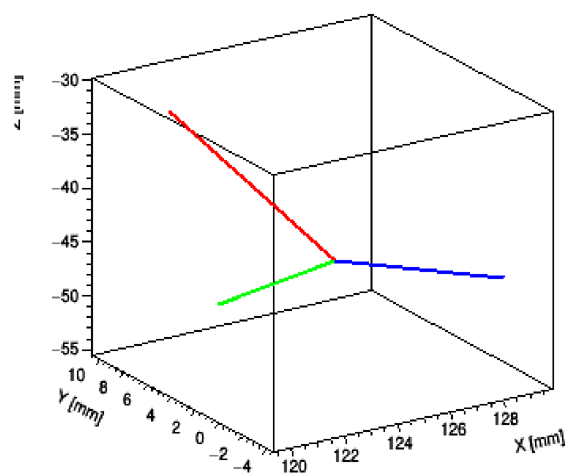
$E_{\alpha 2}$ = 108 keV

$E_{\alpha 3}$ = 60 keV

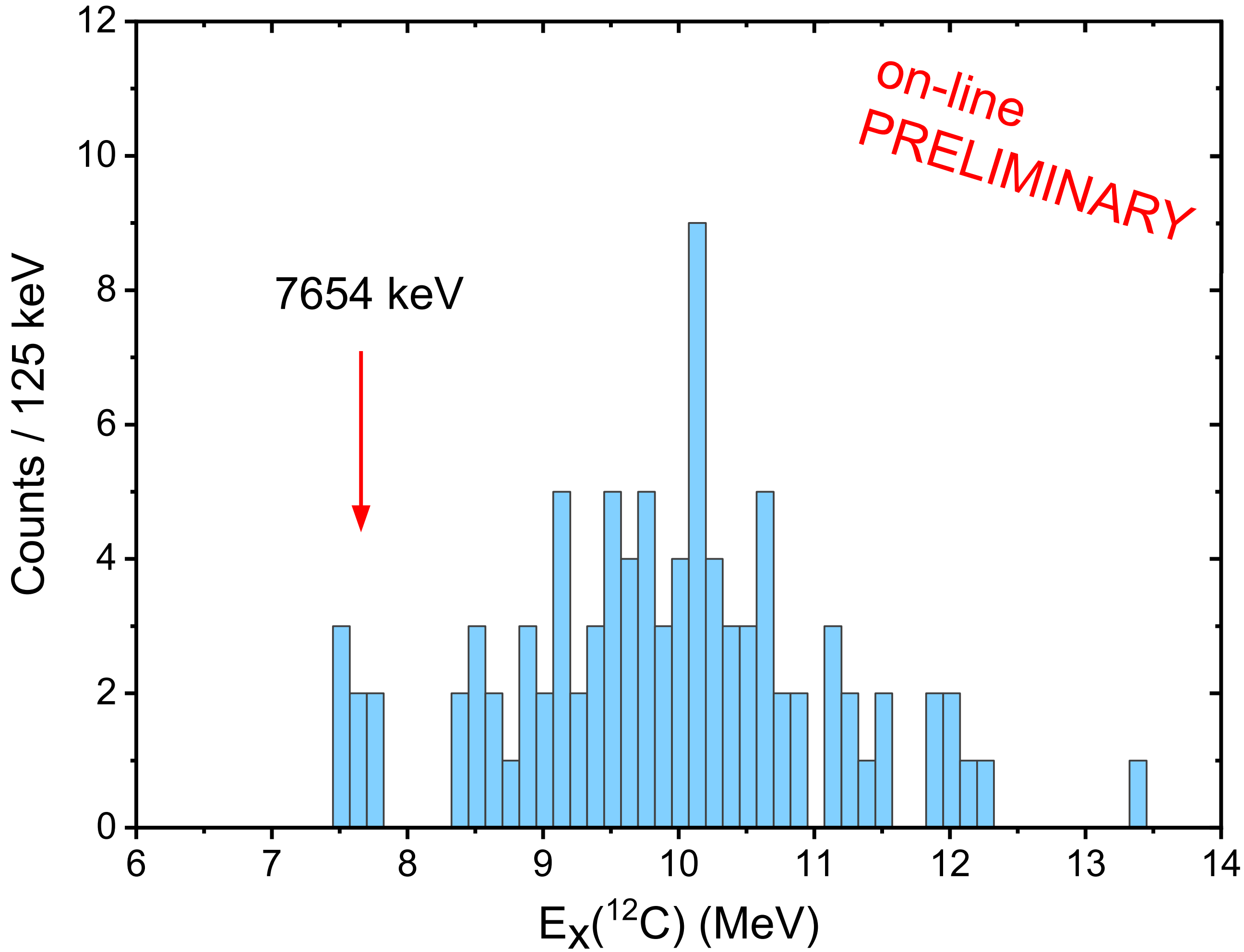
$E_x(^{12}C)$ =7.60 MeV







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)

Collaboration

FUW UW Warszawa

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A. Fijałkowska
A. Giska (PhD)
Z. Janas
C. Mazzocchi

IFJ PAN Kraków

- VdG group

J. Lekki
Z. Szklarz
T. Pieprzyca

- IGN-14 group

D. Grządziel
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