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

Zenon Janas
on behalf of
Warsaw ELITPC group

NTNPD-2021 Workshop

Nucleosynthesis in stars

- **H -** burning reactions

pp – chain
CNO cycle

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

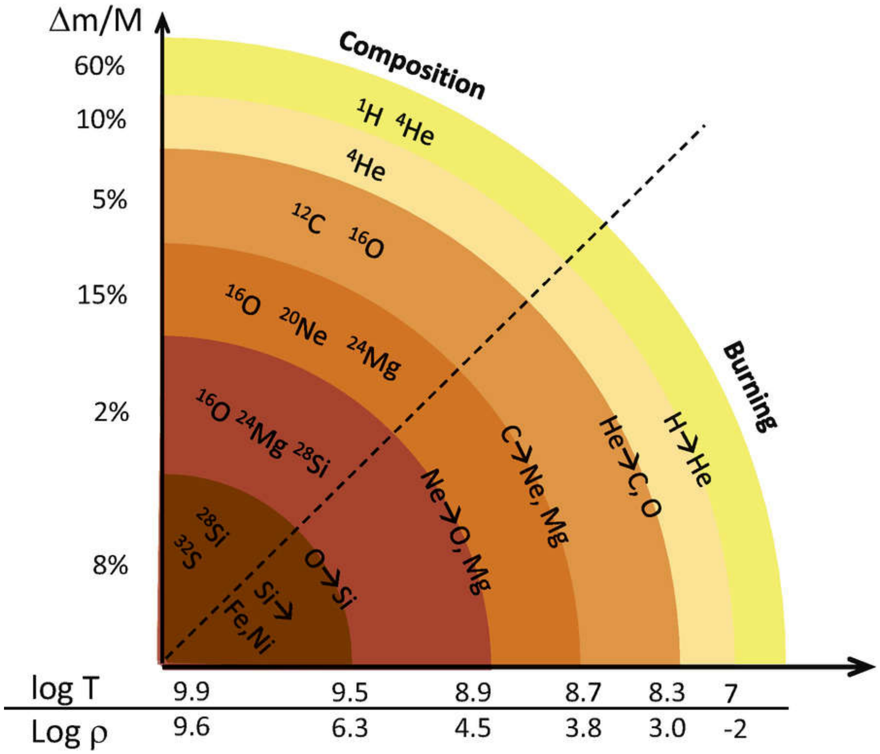
- **He -** burning reactions

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

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

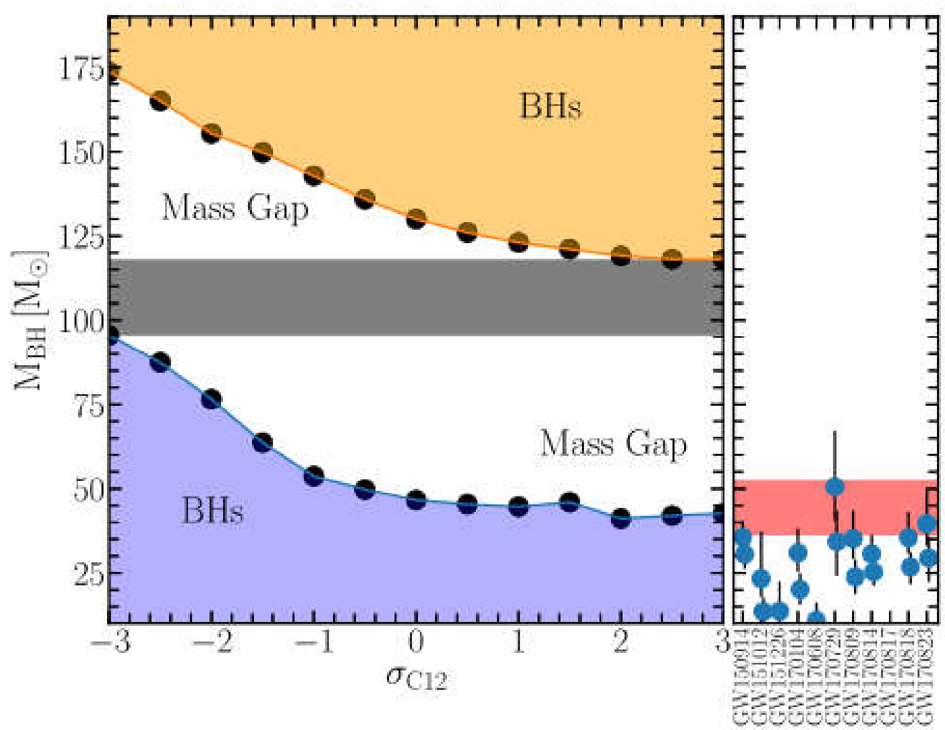
$${}^{16}\text{O}(\alpha, \gamma){}^{20}\text{Ne}$$

…



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

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



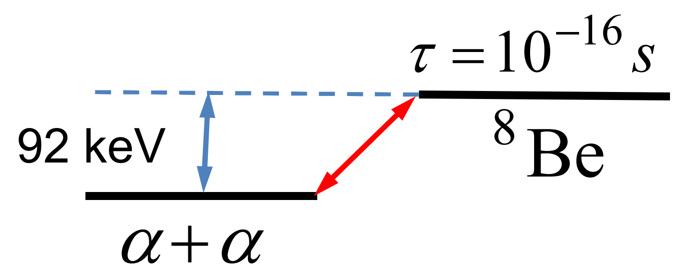
R. Farmer, Astr. J. Lett. 902(2020)L36

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

- Step I

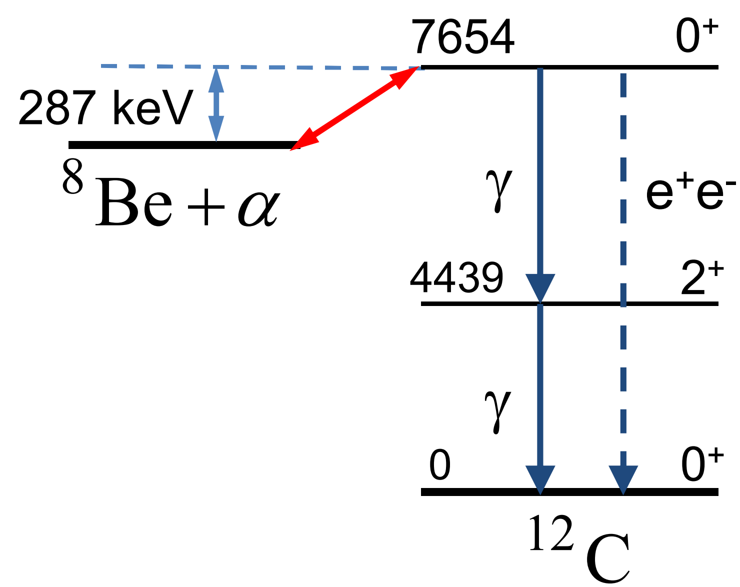
$$\alpha + \alpha \quad \leftrightarrow \quad {}^{8}\mathrm{Be}$$

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

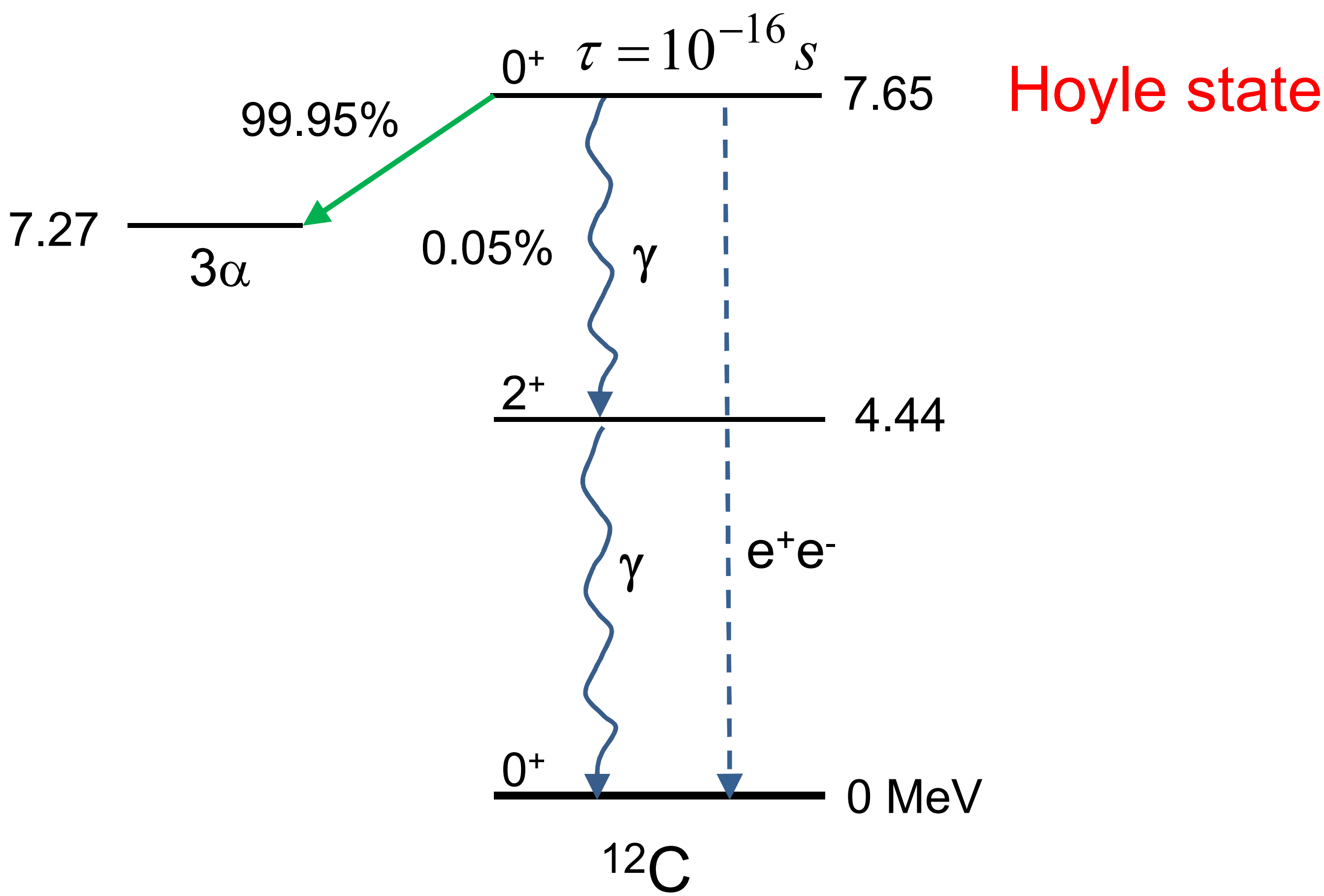


- Step II

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

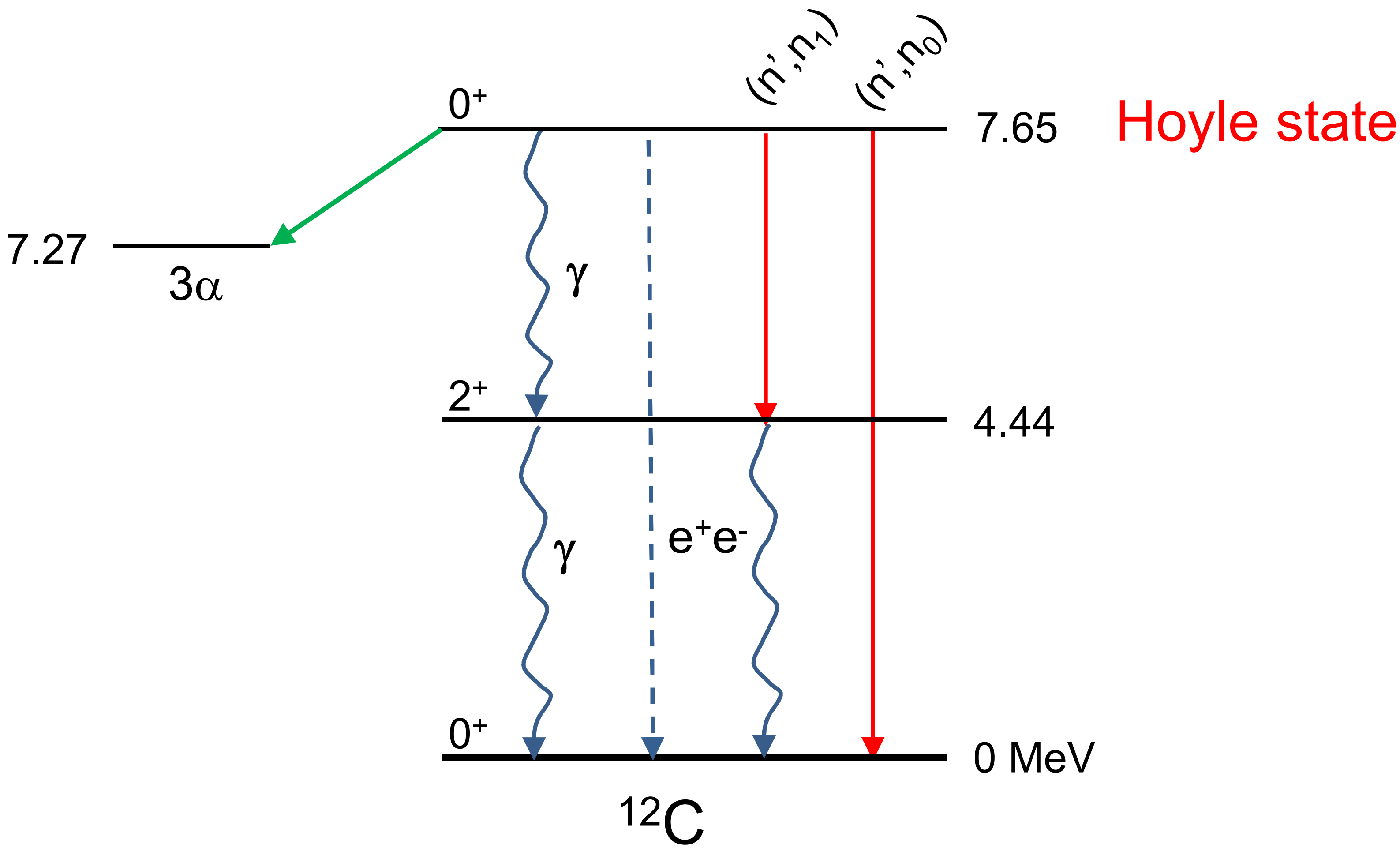


Decay of the Hoyle state – no influence of enviroment



Deexcitation of the Hoyle state in high density neutron environment

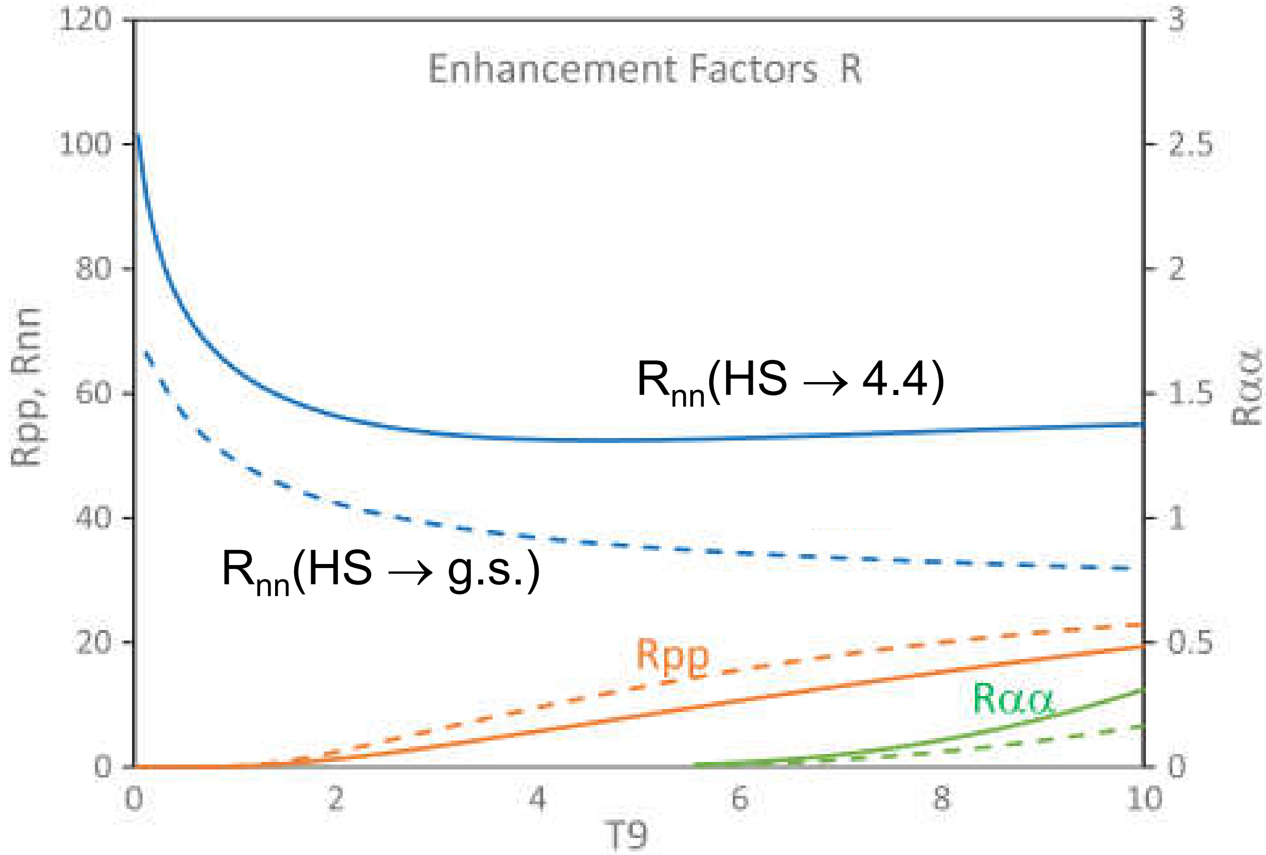
$$\Gamma_{n'n}({}^{12}\mathrm{C}^{Hoyle}) = \hbar \cdot N_n \cdot \langle \sigma v \rangle_{n'n}$$



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

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

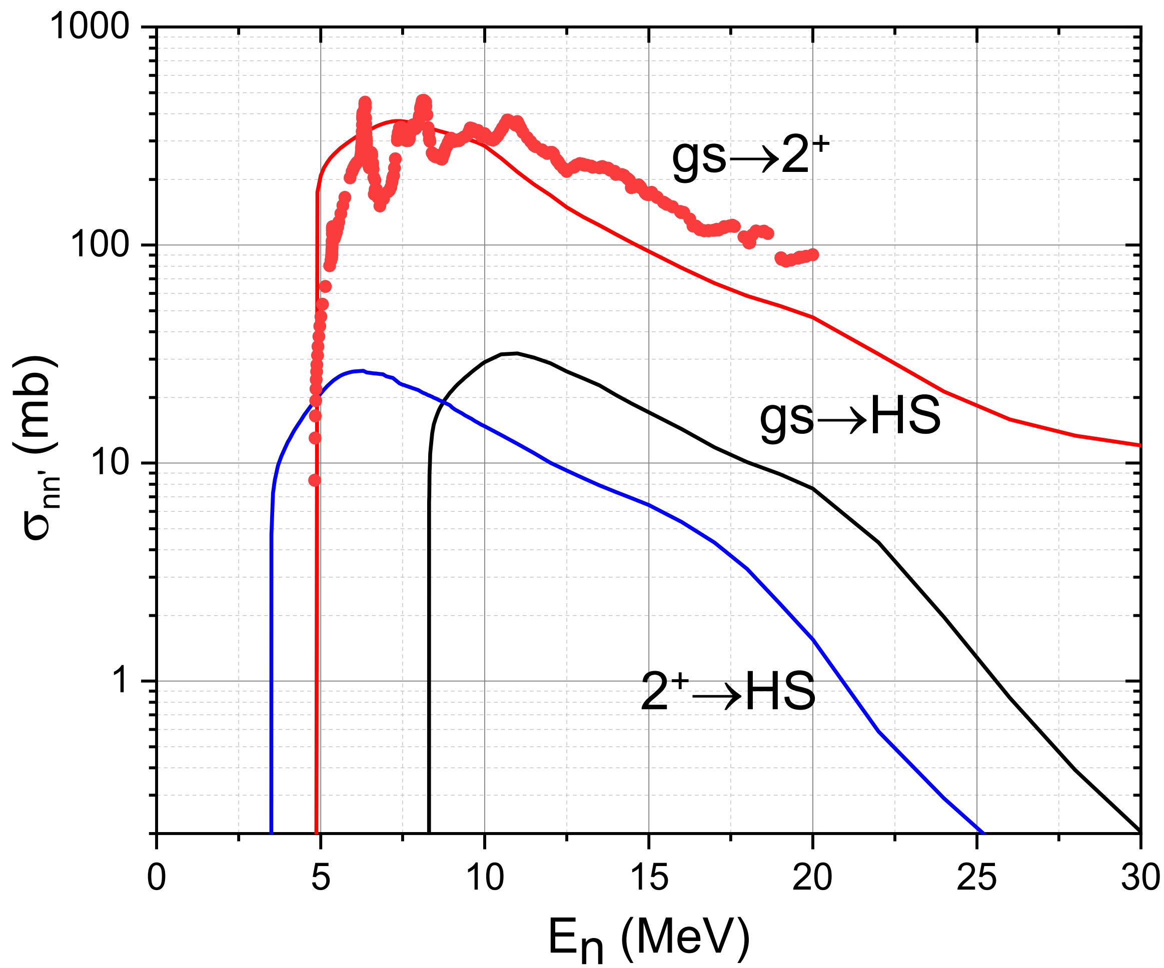
$N_n = 10^6 \text{ g/cm}^3$



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

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

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



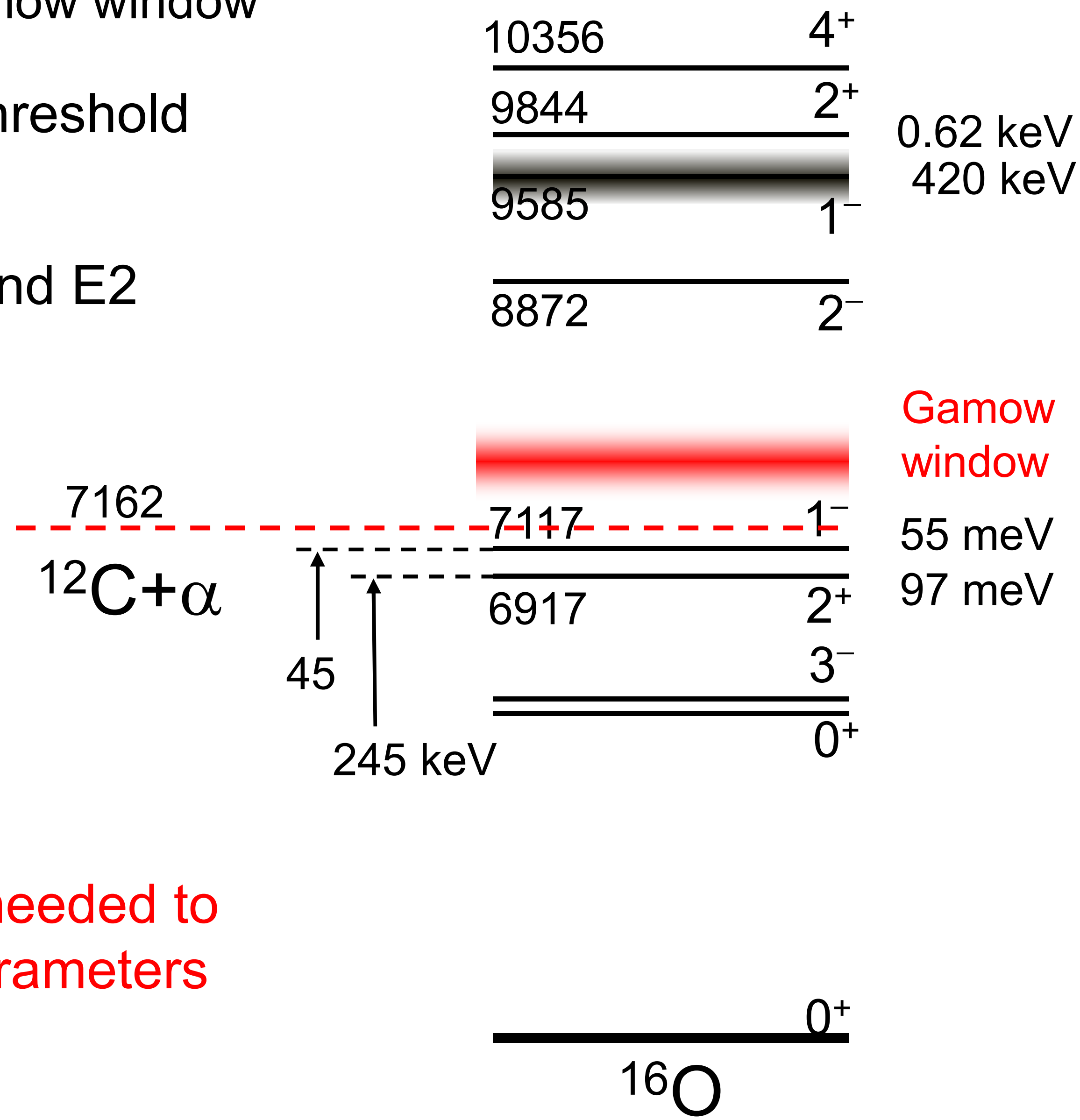
gs → HS at 14 MeV

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

Cross sections calculated within a factor 2-3

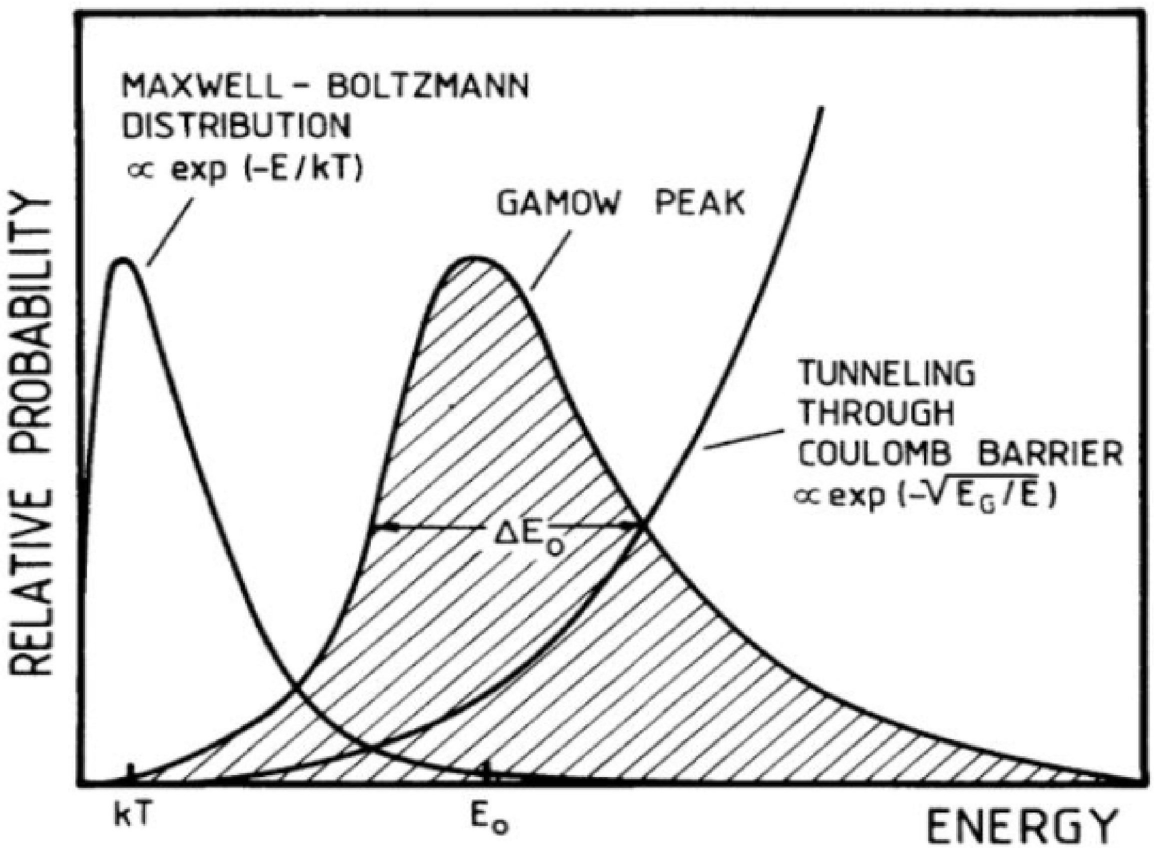
Mechanism of $^{12}C(\alpha, \gamma)$ reaction

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



- experimental data needed to constrain model parameters

Gamow window for astrophysical reactions

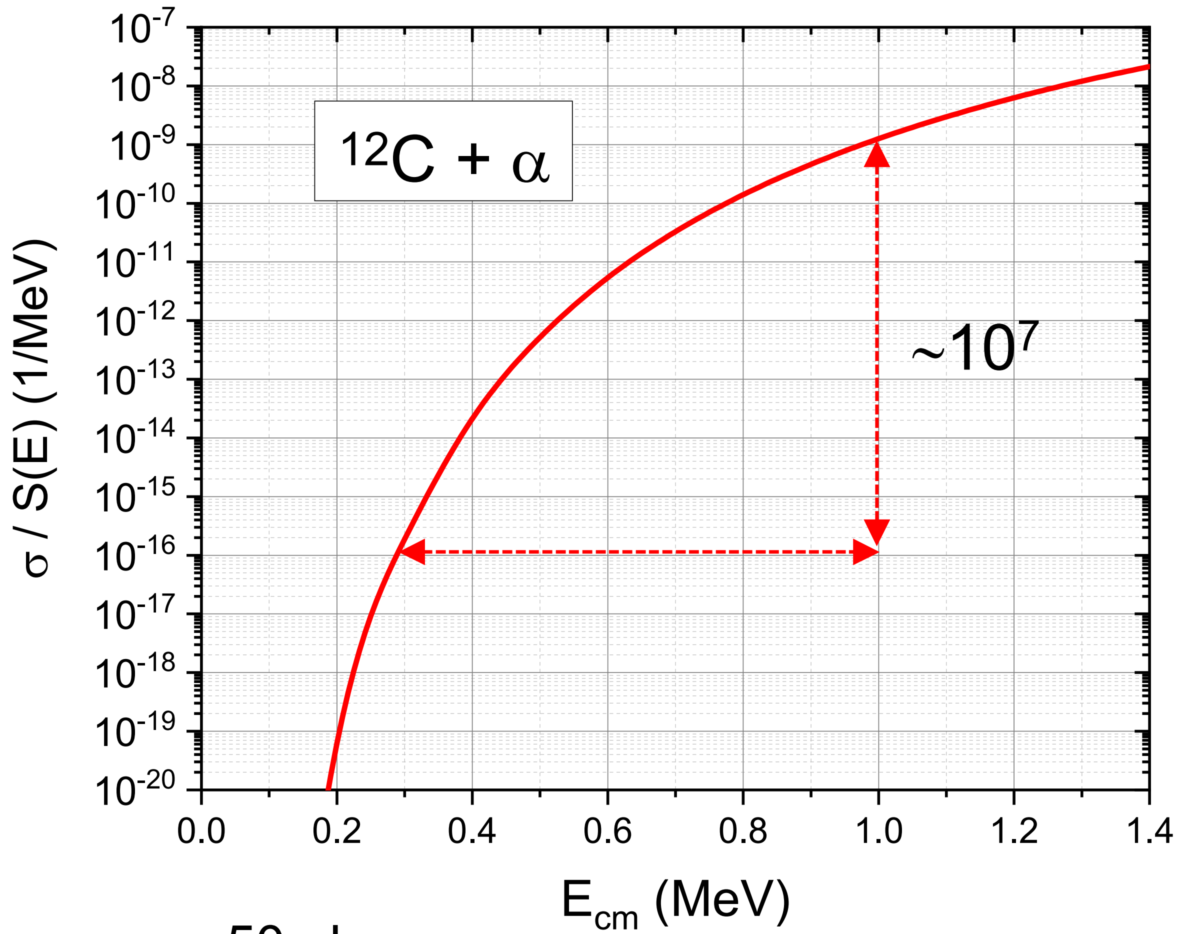


C.E. Rolfs, W.S. Rodney, Cauldrons in the Cosmos

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

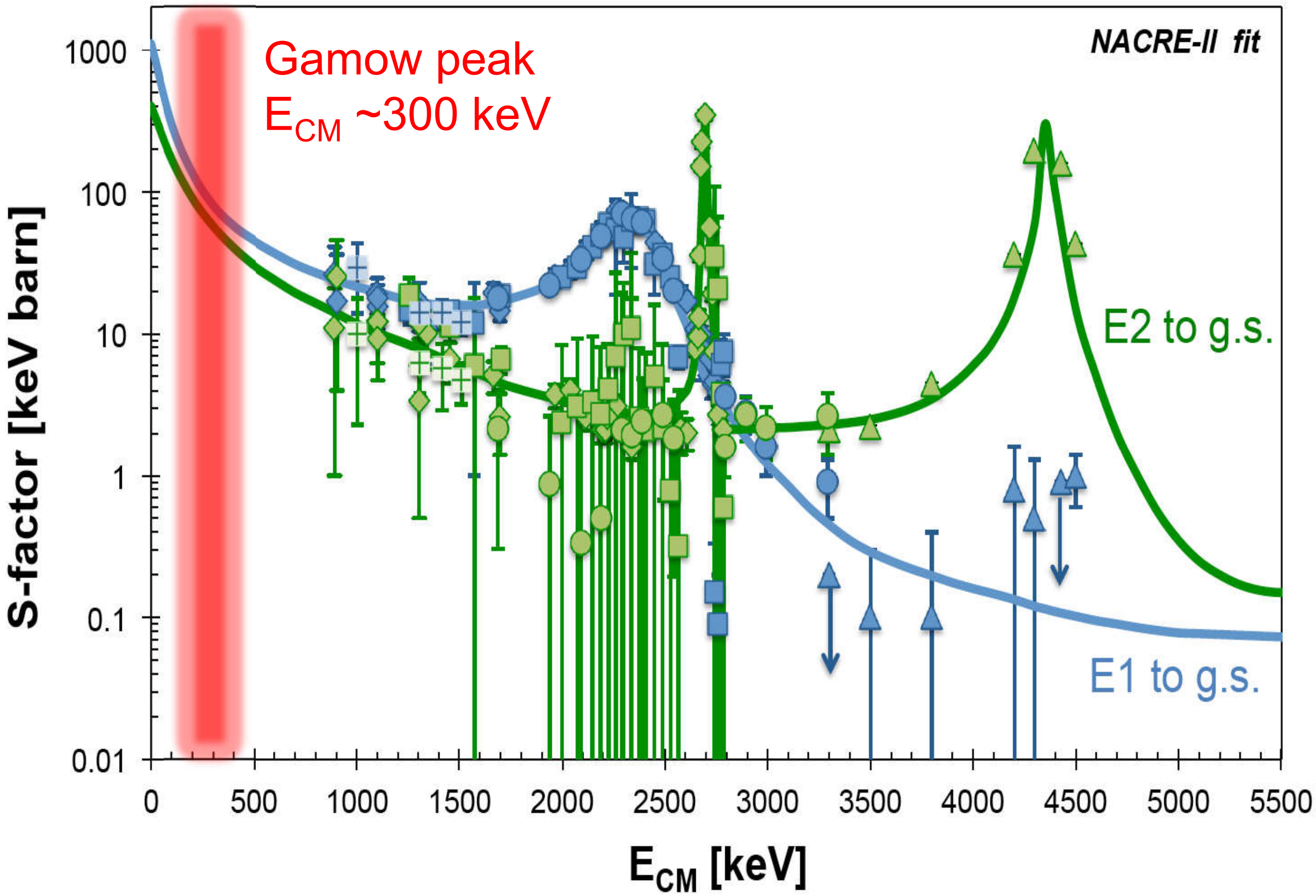
S(300keV) = (140 ± 20) keV·b   σ = 0.03 fb

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

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

S(1 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

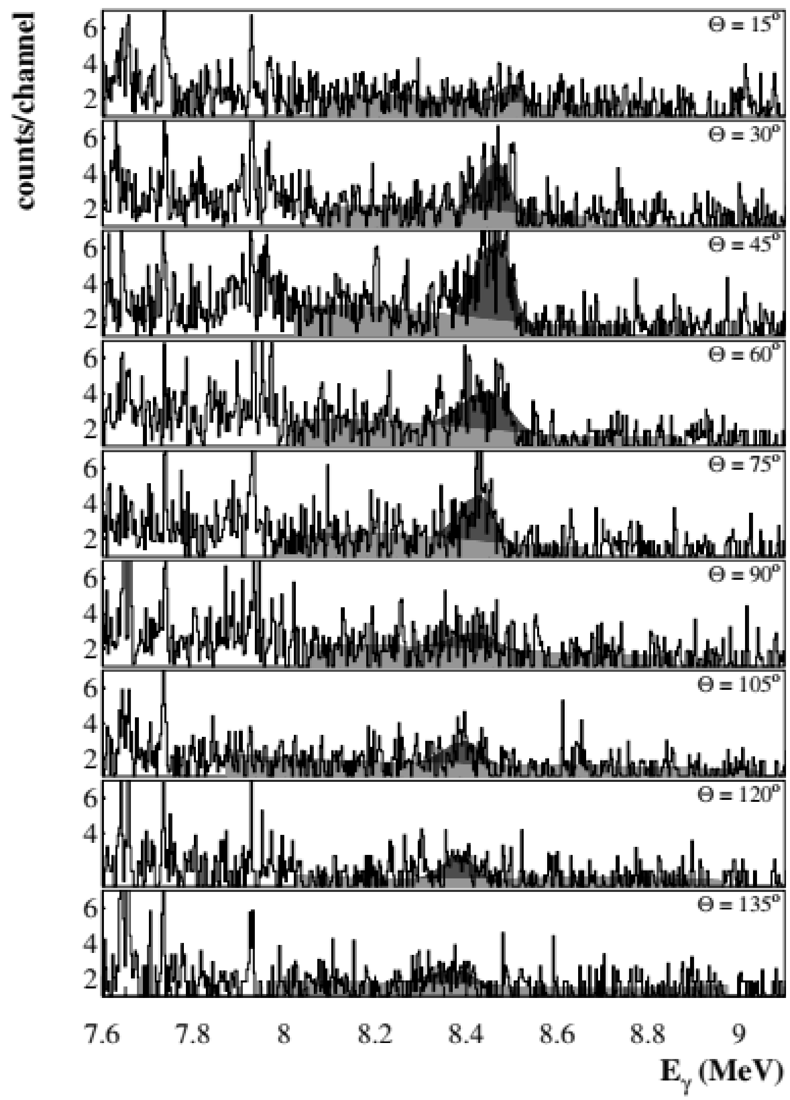
Time: 6 days

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

$$A(a, b)B \quad \Leftrightarrow \quad B(b, a)A$$

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

for

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

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

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

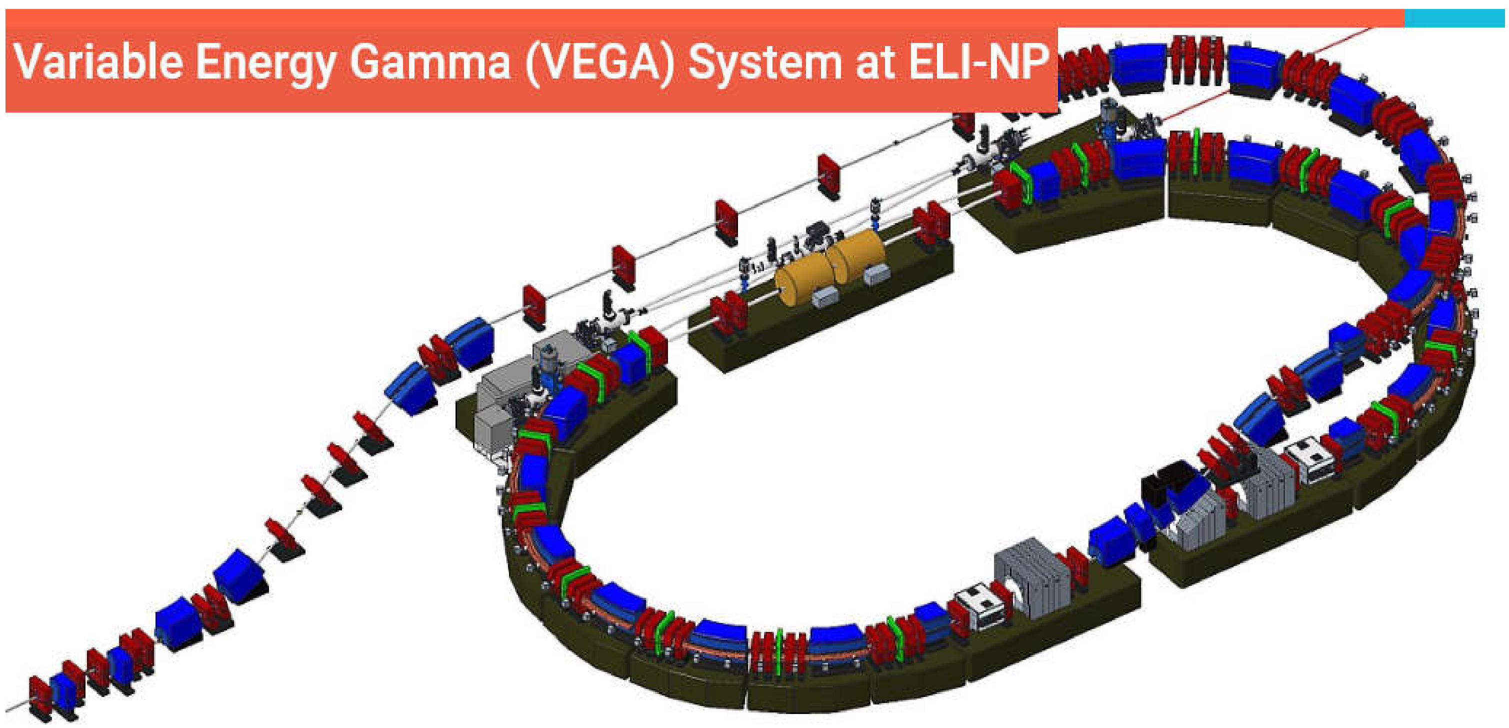
Solution

Active Target Time Projection Chamber

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

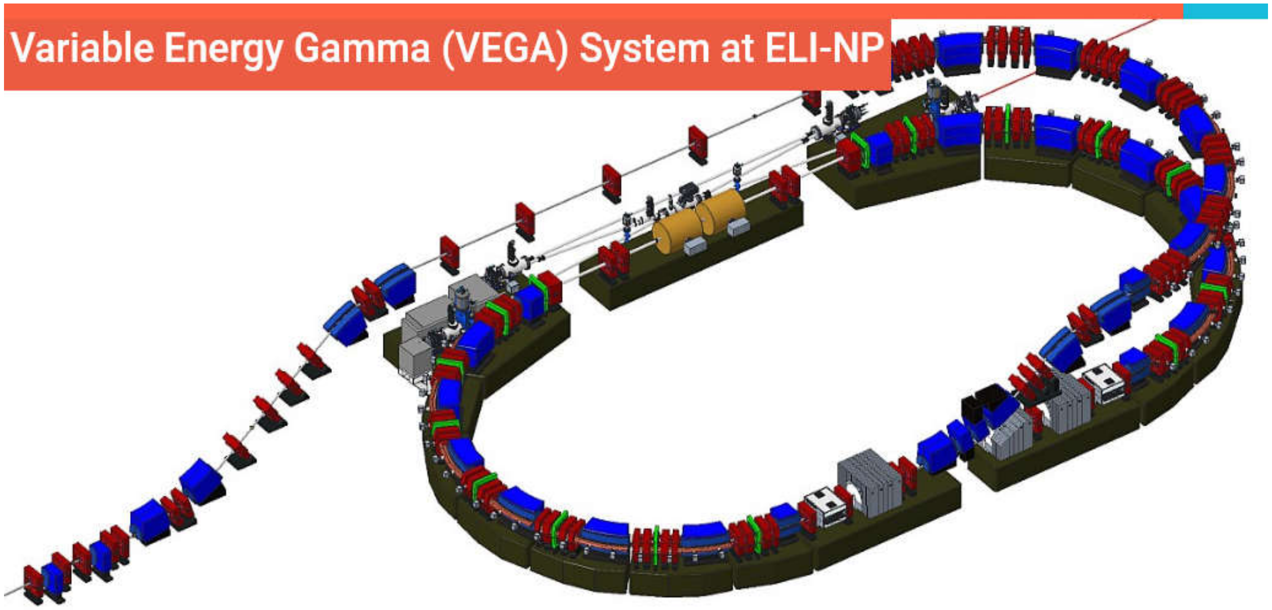
- high intensity, monochromatic gamma beam

Extreme Light Infrastructure - Nuclear Physics
Magurele-Romania

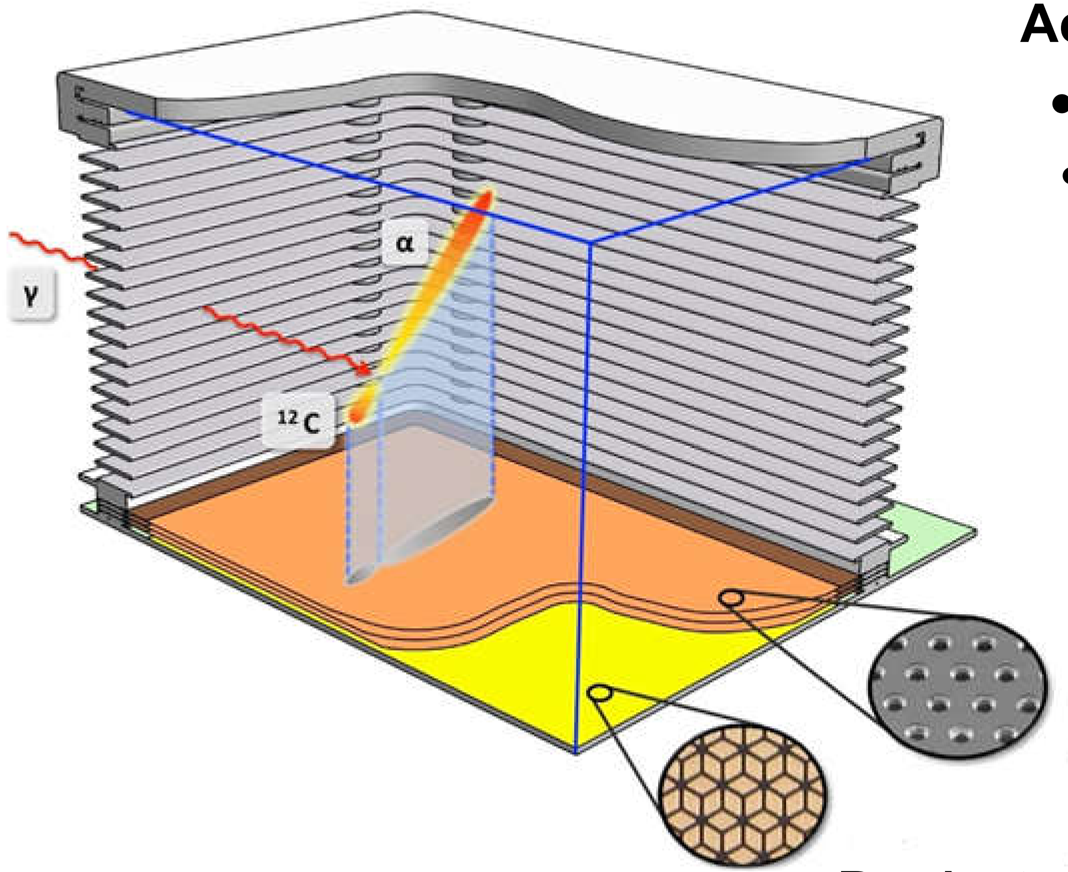


Extreme Light Infrastructure - Nuclear Physics Magurele-Romania

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



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

Test of TPC at IFJ PAN Van de Graaff accelarator

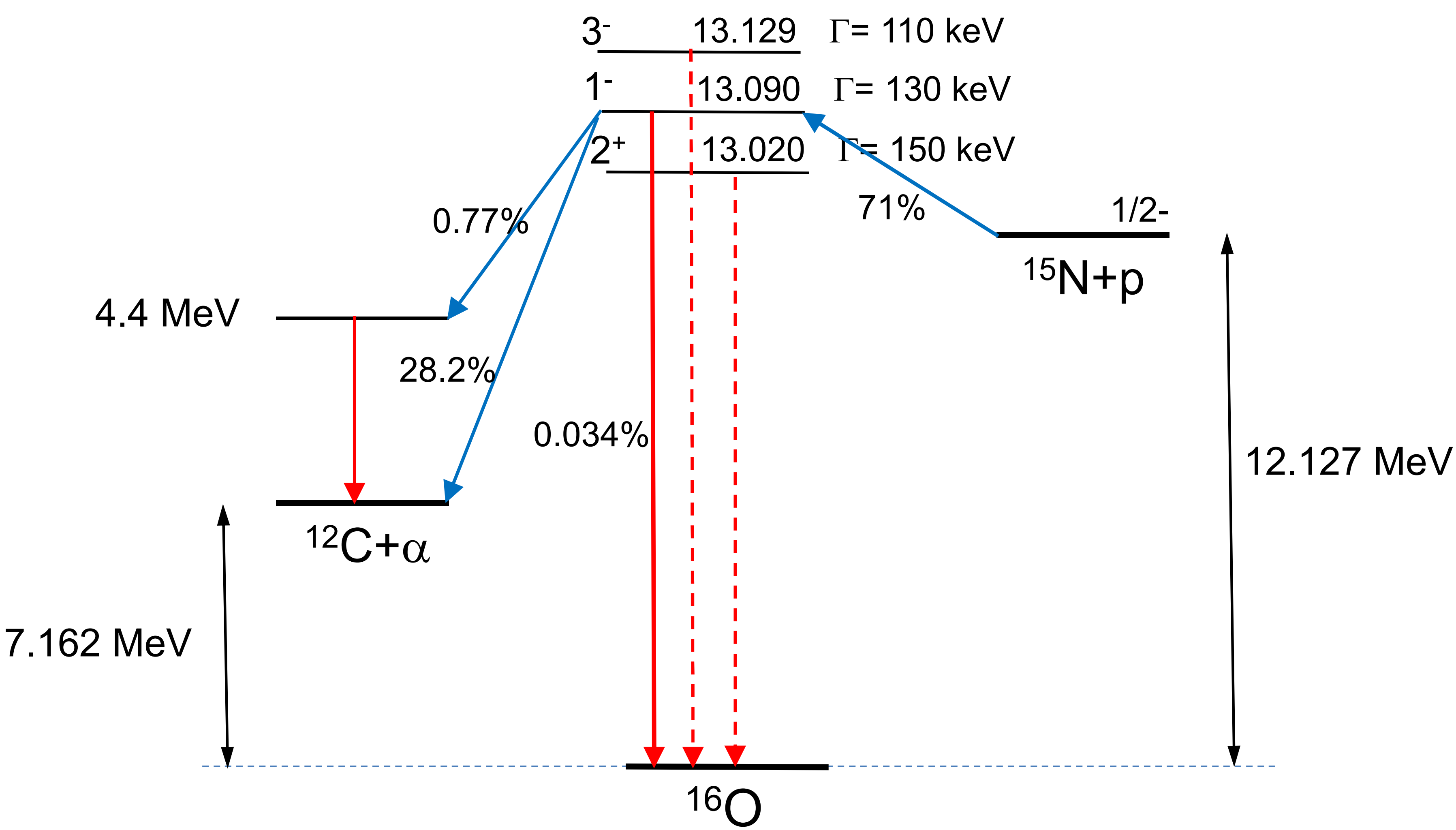
Idea

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

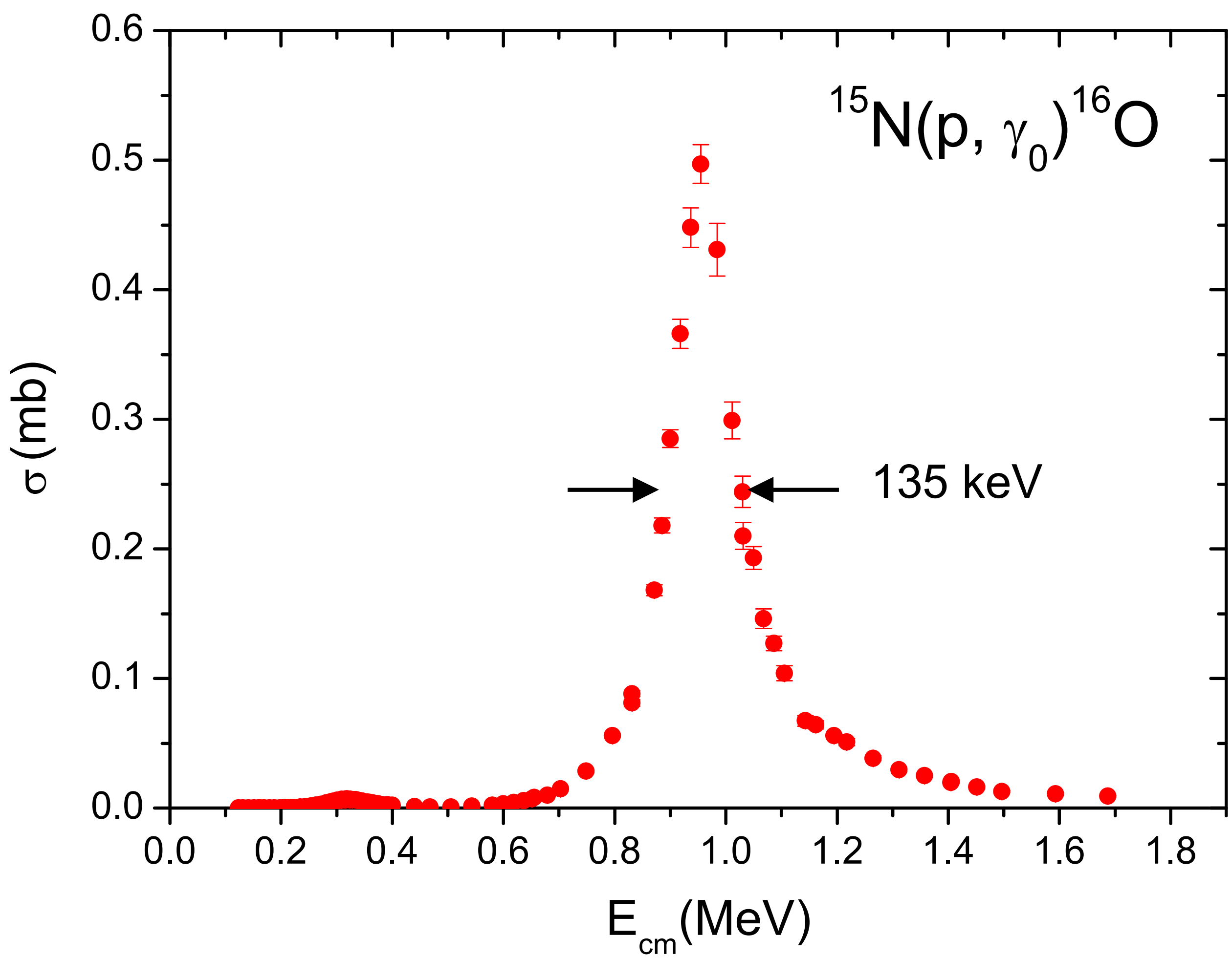
Goals

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

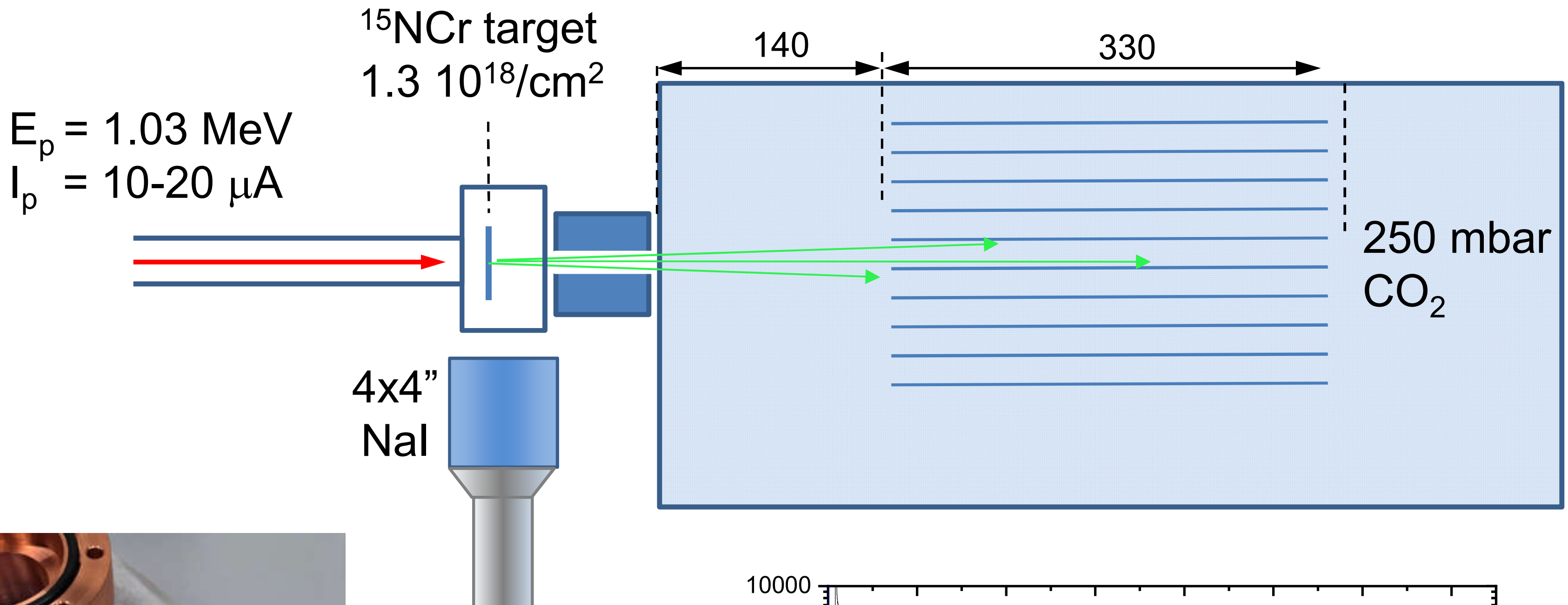
$^{15}N(p, \gamma)^{16}O$ reaction



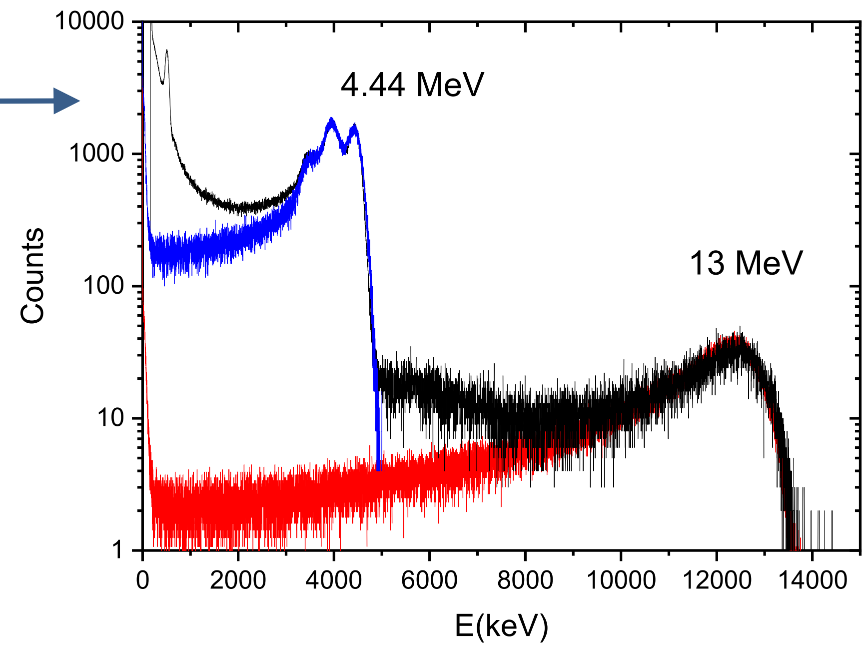
Cross section of $^{15}N(p, \gamma_0)\ ^{16}O$ reaction



TPC at VdG

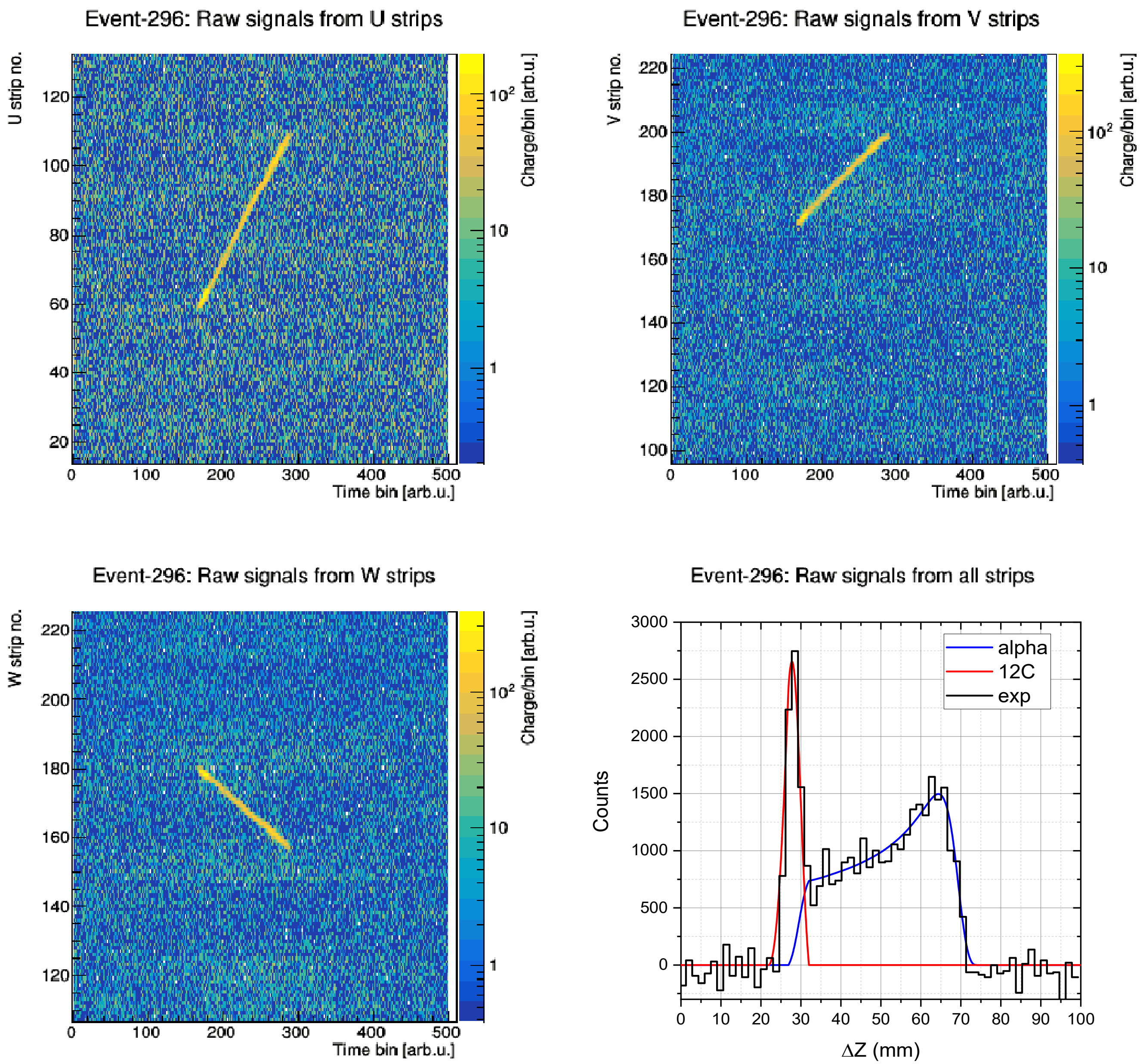


^{15}NCr target
1.3 10^{18}/cm^2
E_p = 1.03 MeV
I_p = 10-20 μA
140
330
250 mbar
CO_2
4x4”
NaI



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

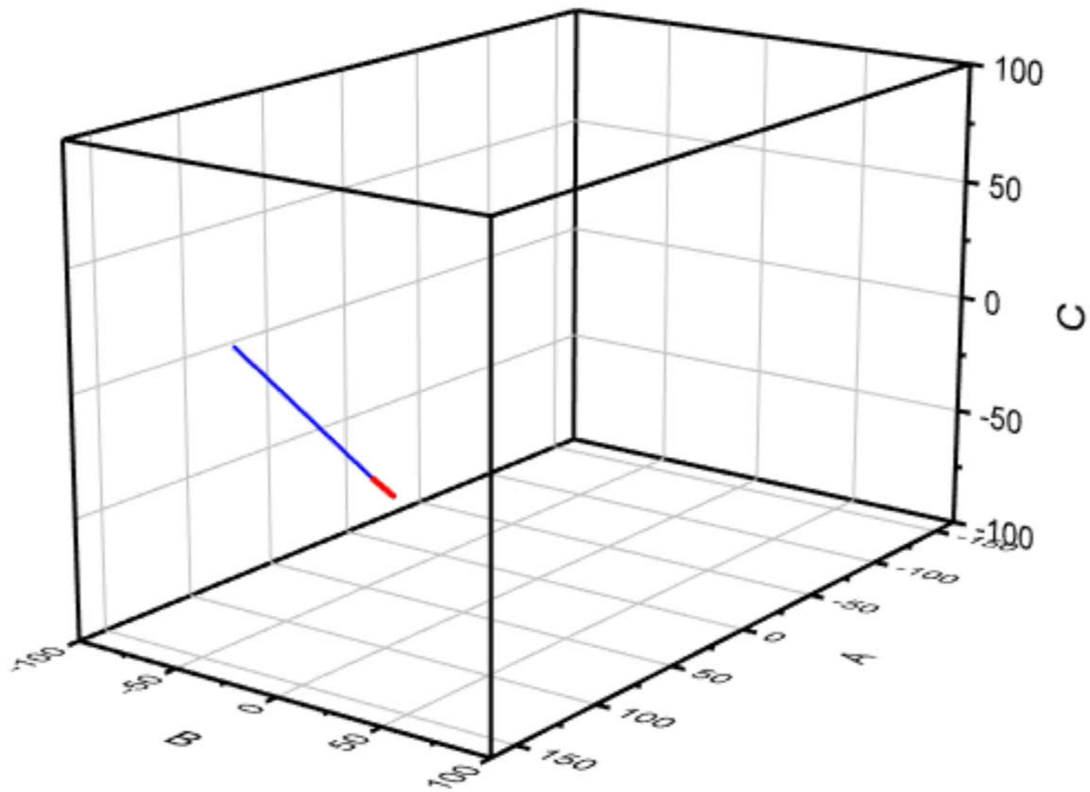


Reconstruction of $^{16}O(\gamma, \alpha)^{12}C$ event

E_{α} = 4.37 MeV

E_{12C} = 1.46 MeV

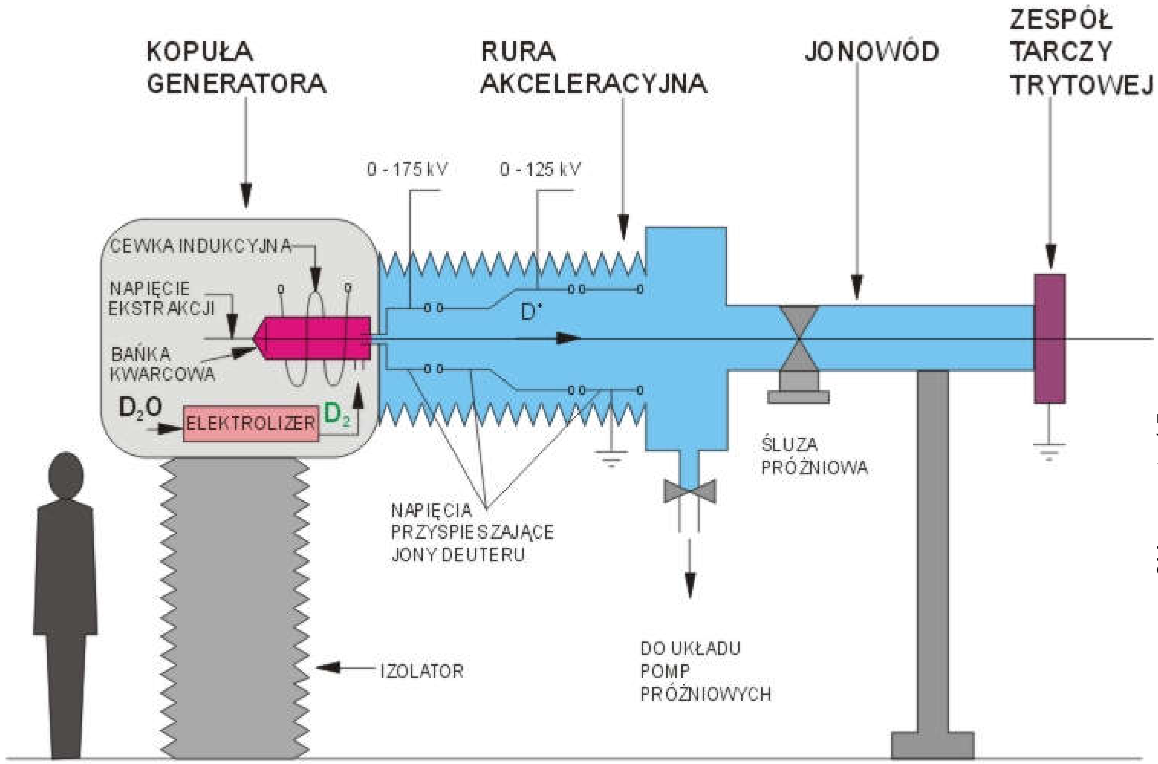
$\theta_{\alpha-12C}$ = 180°



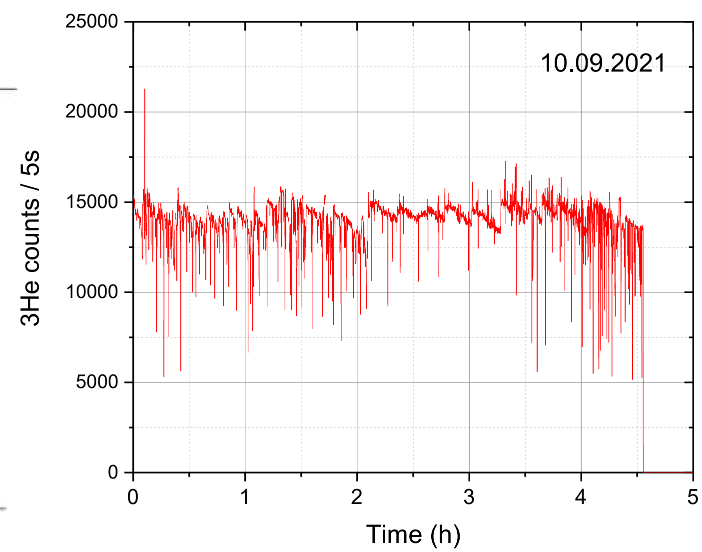
Neutron generator IGN-14

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

Yield: $\sim 5\times10^{8}$ n/s in 4π



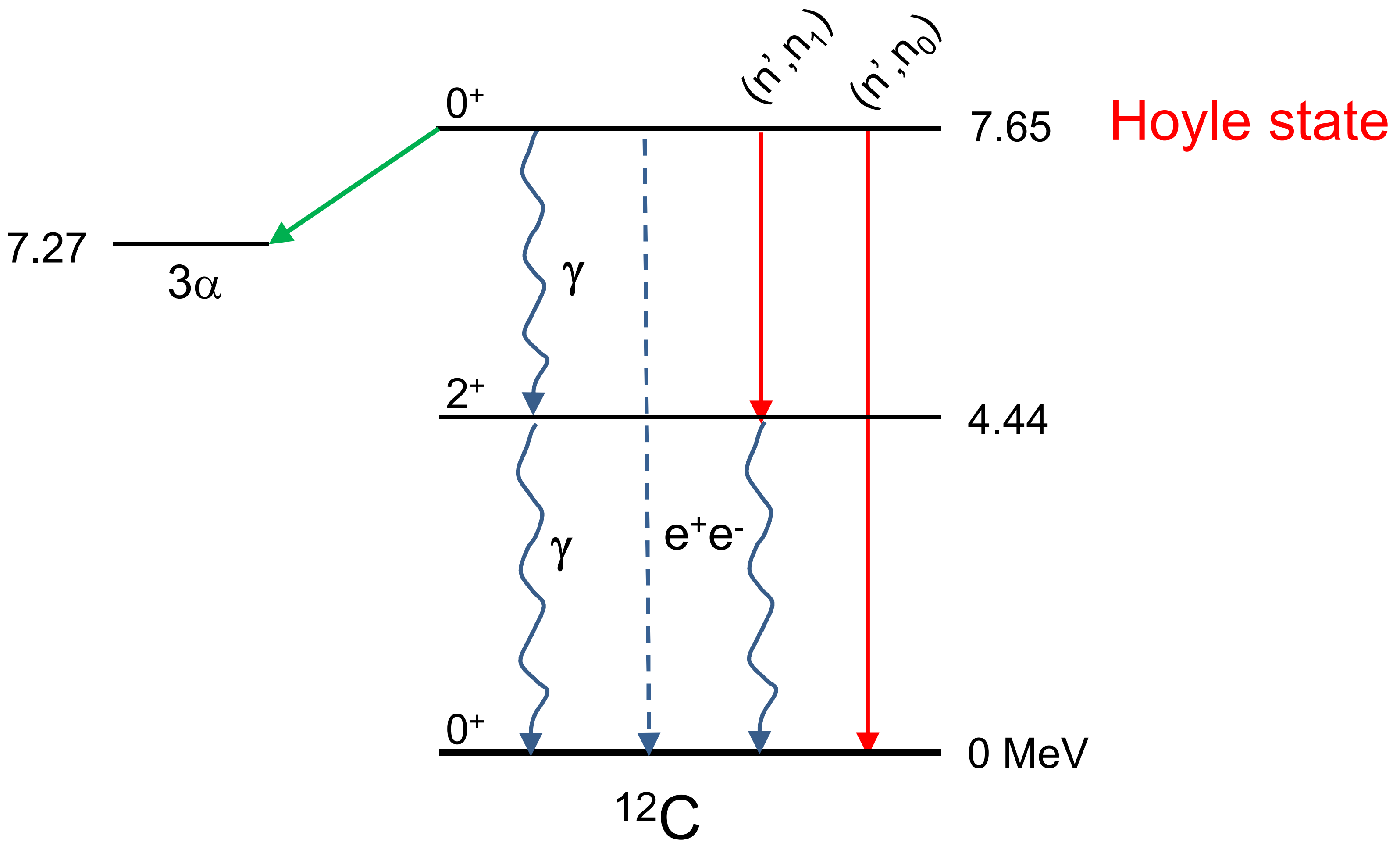
Neutron yield (a.u.)



A. Kurowski

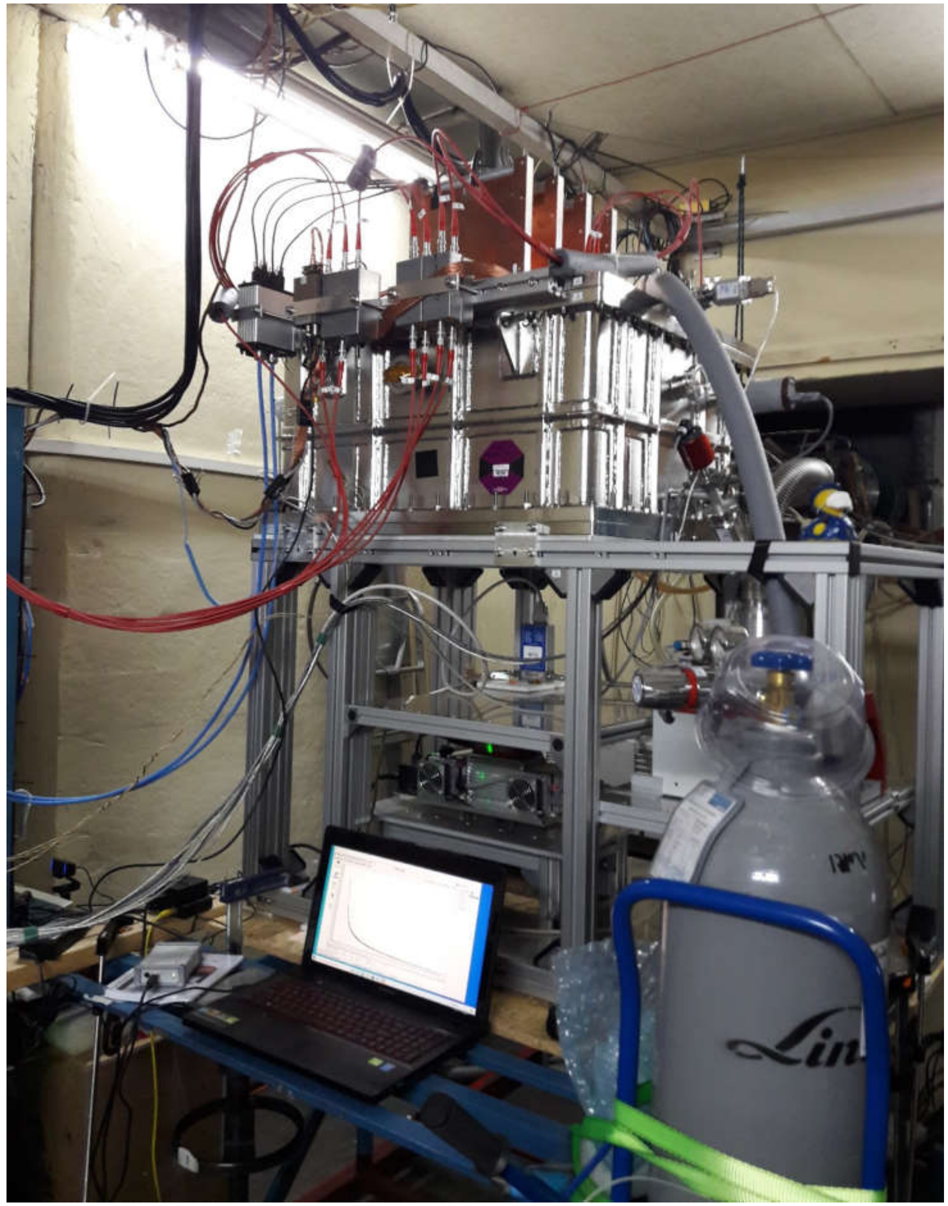
Deexcitation of the Hoyle state in high density neutron environment

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



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

TPC at IGN-14



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

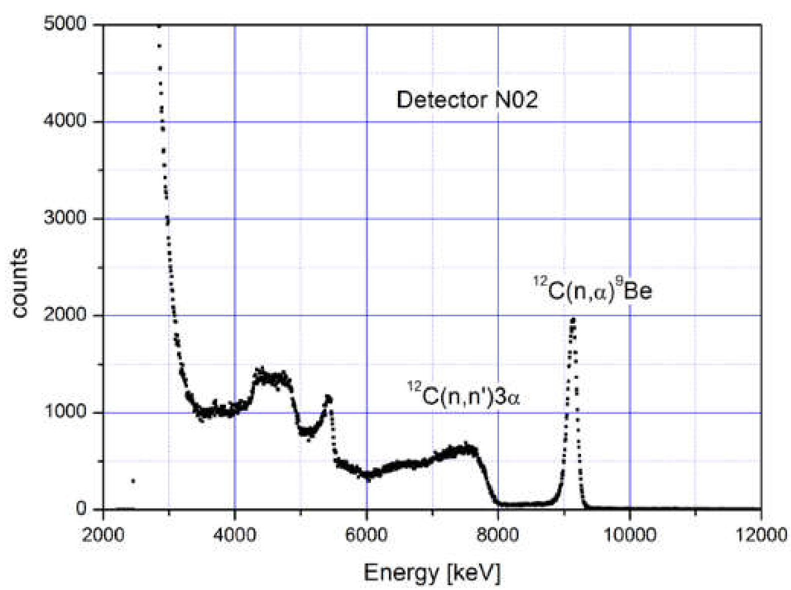
- single particle tracks

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

- two track events

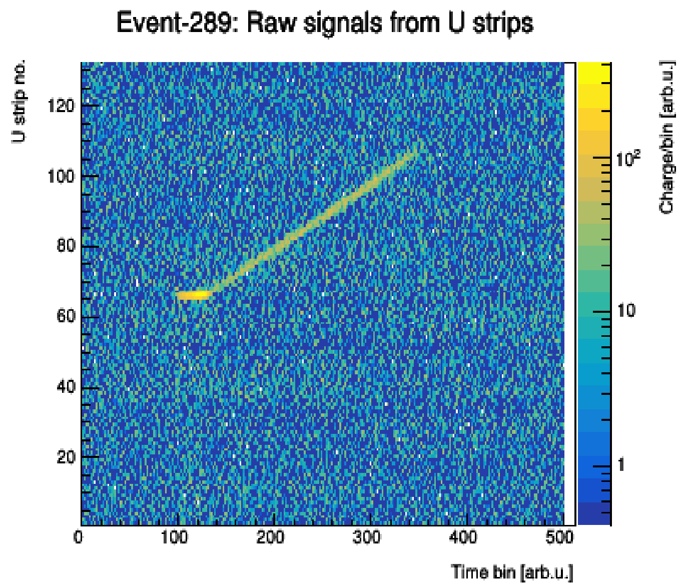
$$n + {}^{16}\mathrm{O} \rightarrow {}^{17}\mathrm{O}^* \rightarrow \alpha + {}^{13}\mathrm{C}$$ 150 mb

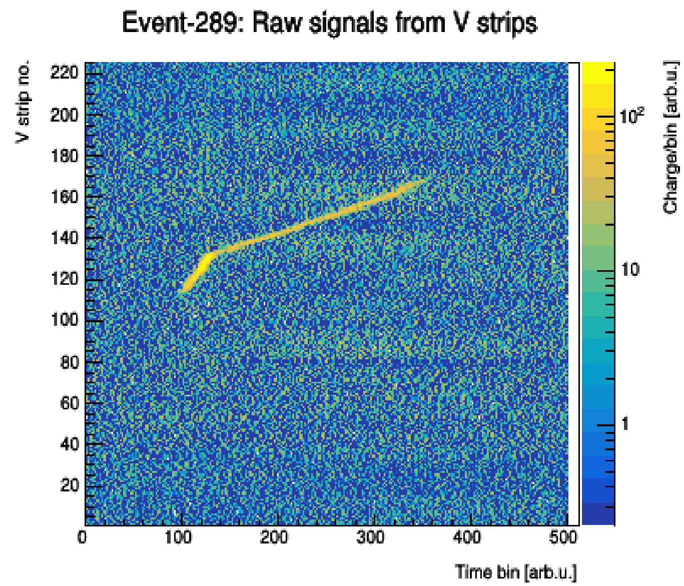
$$n + {}^{12}\mathrm{C} \rightarrow {}^{13}\mathrm{C}^* \rightarrow \alpha + {}^{9}\mathrm{Be}$$ 70 mb

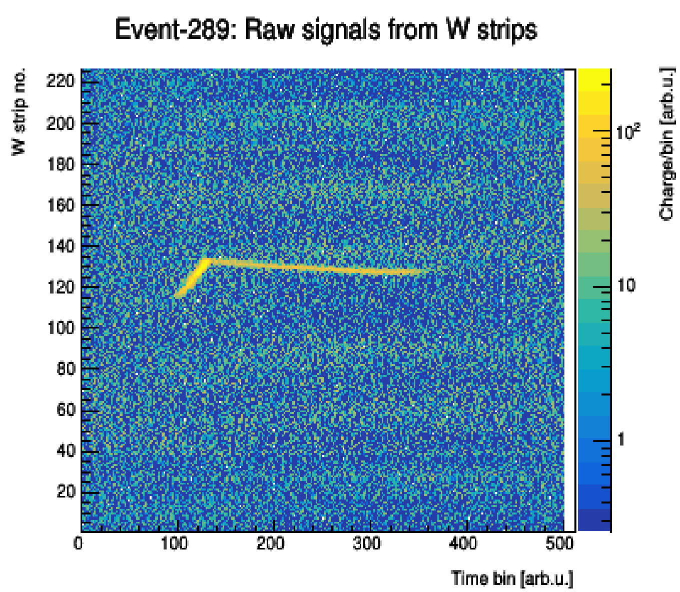


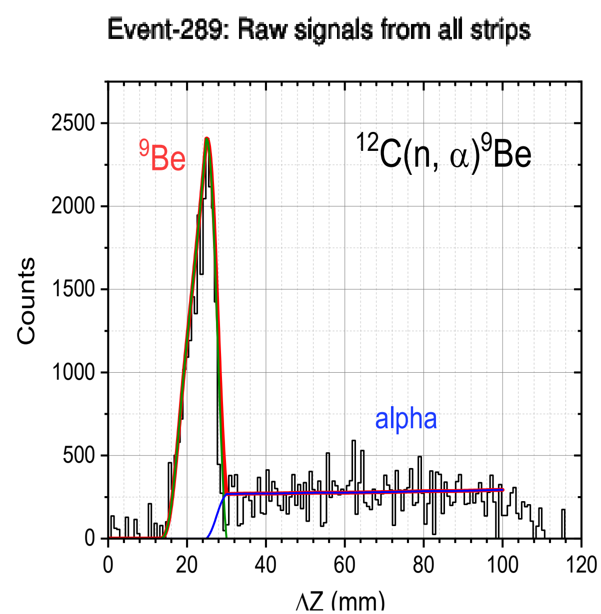
R. Kwiatkowski *et al.*, Rad. Meas.138(2020) 106434

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









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

- triple track events

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

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

$$\hookrightarrow \alpha_2 + \alpha_3 \qquad \text{130 mb}$$

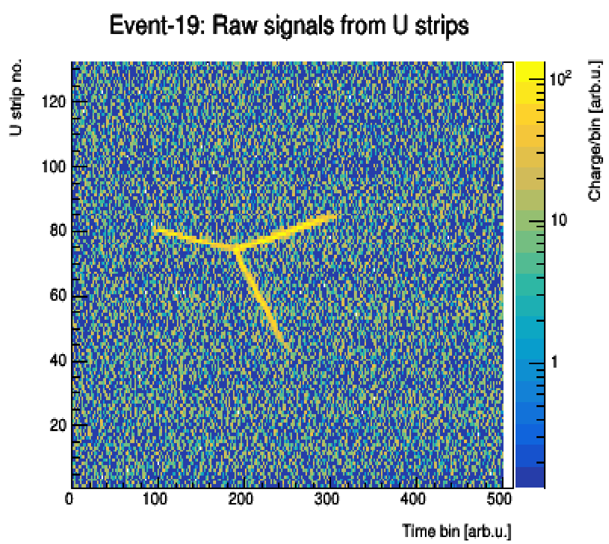
$$\hookrightarrow \alpha_2 + \alpha_3 \qquad \text{10 mb}$$

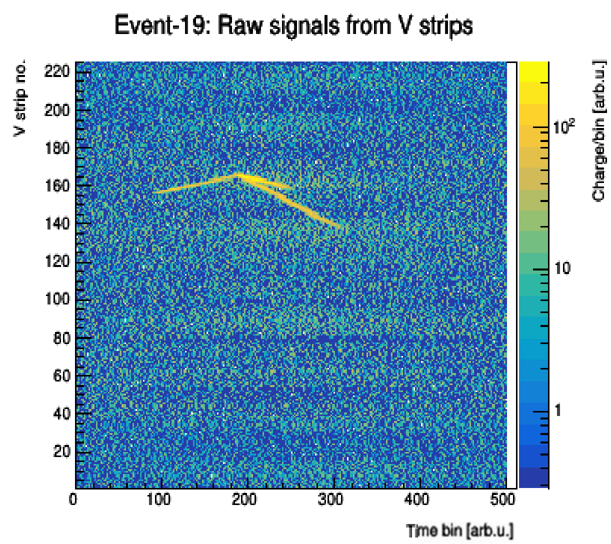
$$n + {}^{12}\mathrm{C} \rightarrow {}^{13}\mathrm{C}^{*} \rightarrow \alpha_1 + {}^{9}\mathrm{Be}^{*}$$

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

$$\hookrightarrow \alpha_2 + \alpha_3 \qquad \text{85 mb}$$

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



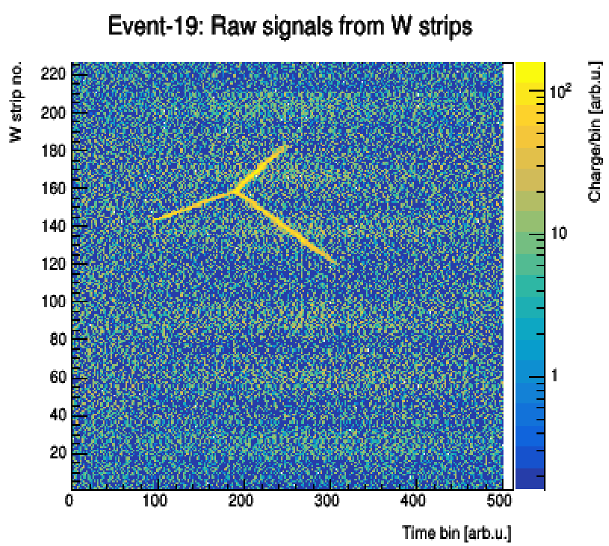


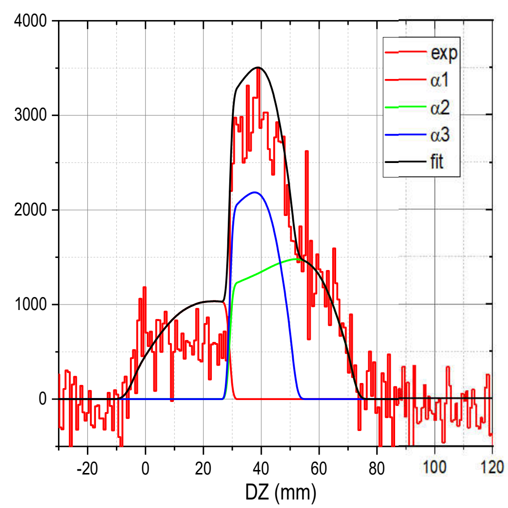
E_{a1} = 770 keV

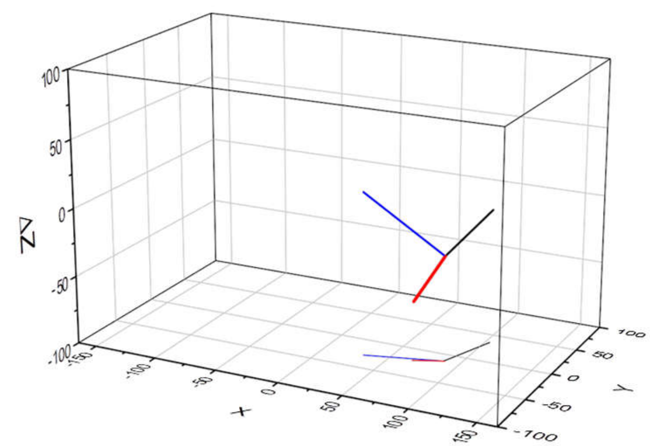
E_{a2} = 1580 keV

E_{a3} = 1175 keV

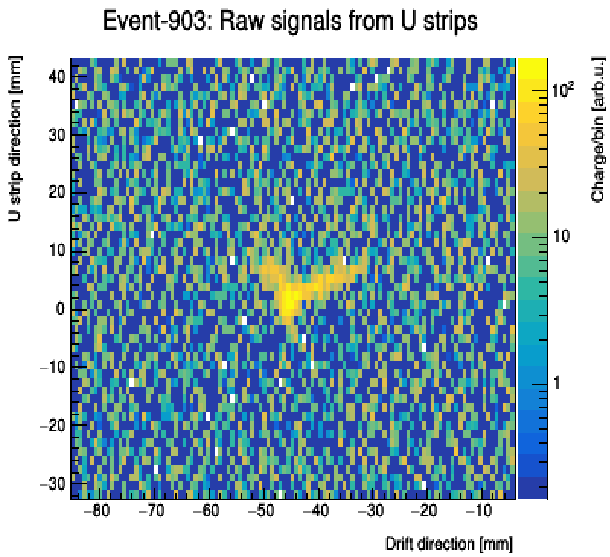
$E_x(^{12}C)$ =10.3 MeV

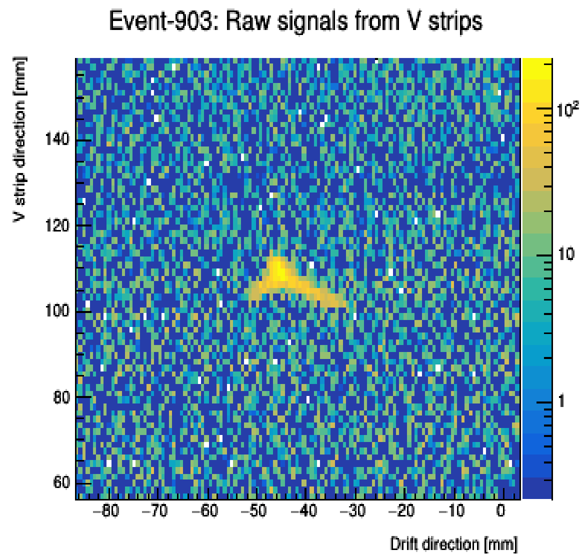






Example of $^{12}C(n, n')^{12}C^{HS}$ reaction



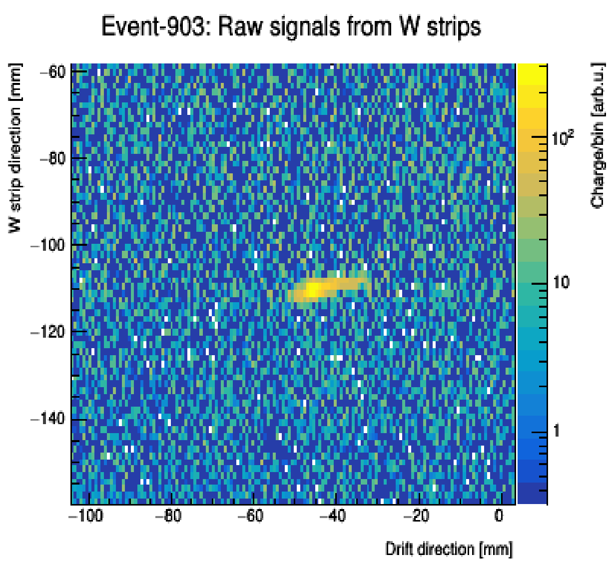


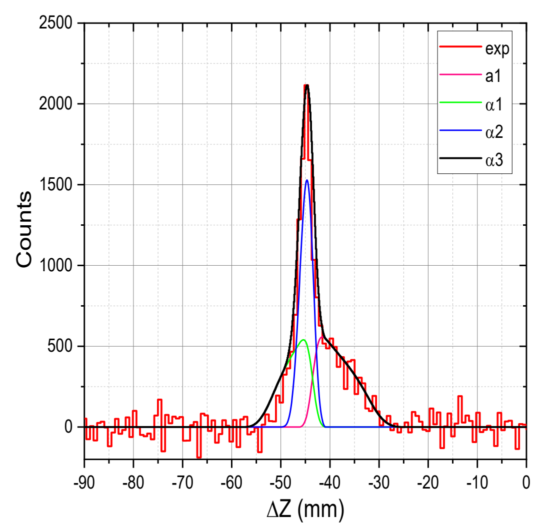
$E_{\alpha 1}$ = 145 keV

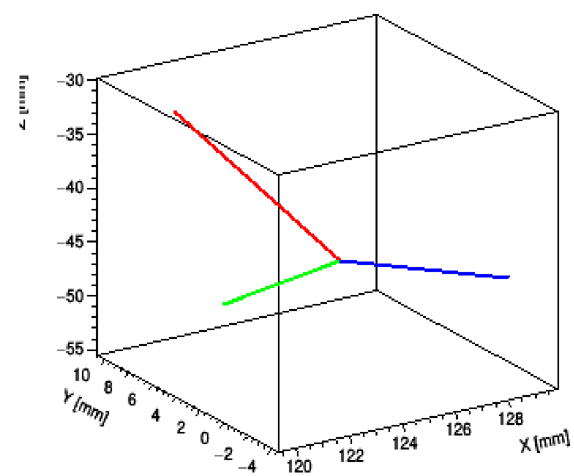
$E_{\alpha 2}$ = 108 keV

$E_{\alpha 3}$ = 60 keV

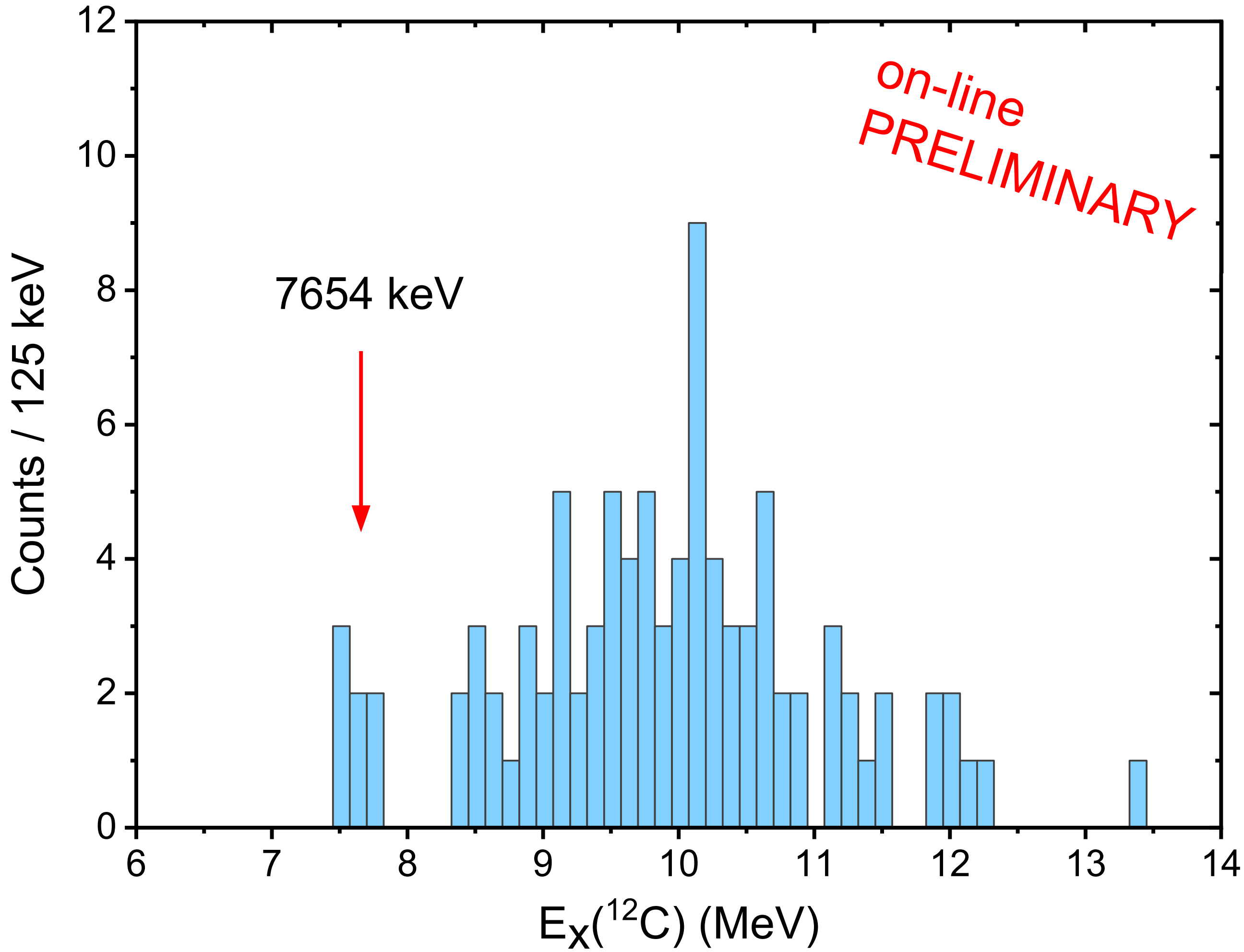
$E_x(^{12}C)$ =7.60 MeV







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)

Collaboration

FUW UW Warszawa

M. Ćwiok
W. Dominik
M. Fila (PhD)
A. Kalinowski
M. Kuich
M. Zaremba

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
W. Janik
W. Królas
A. Kulińska
A. Kurowski

M. Scholz
M. Turzański
U. Wiącek
U. Woźnicka

Acknowledgements

This work was 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,

- the University of Connecticut under the Collaborative Research Contract no. UConn-LNS UW/7/2018 and

- the National Science Centre, Poland, under Contract no. UMO-2019/33/B/ST2/02176.