“Other”indirect methods in Nuclear Physics for Astrophysics

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OMEG17

Chengdu, China, Sep. 8-12, 2024

Nuclear Physics for Astrophysics

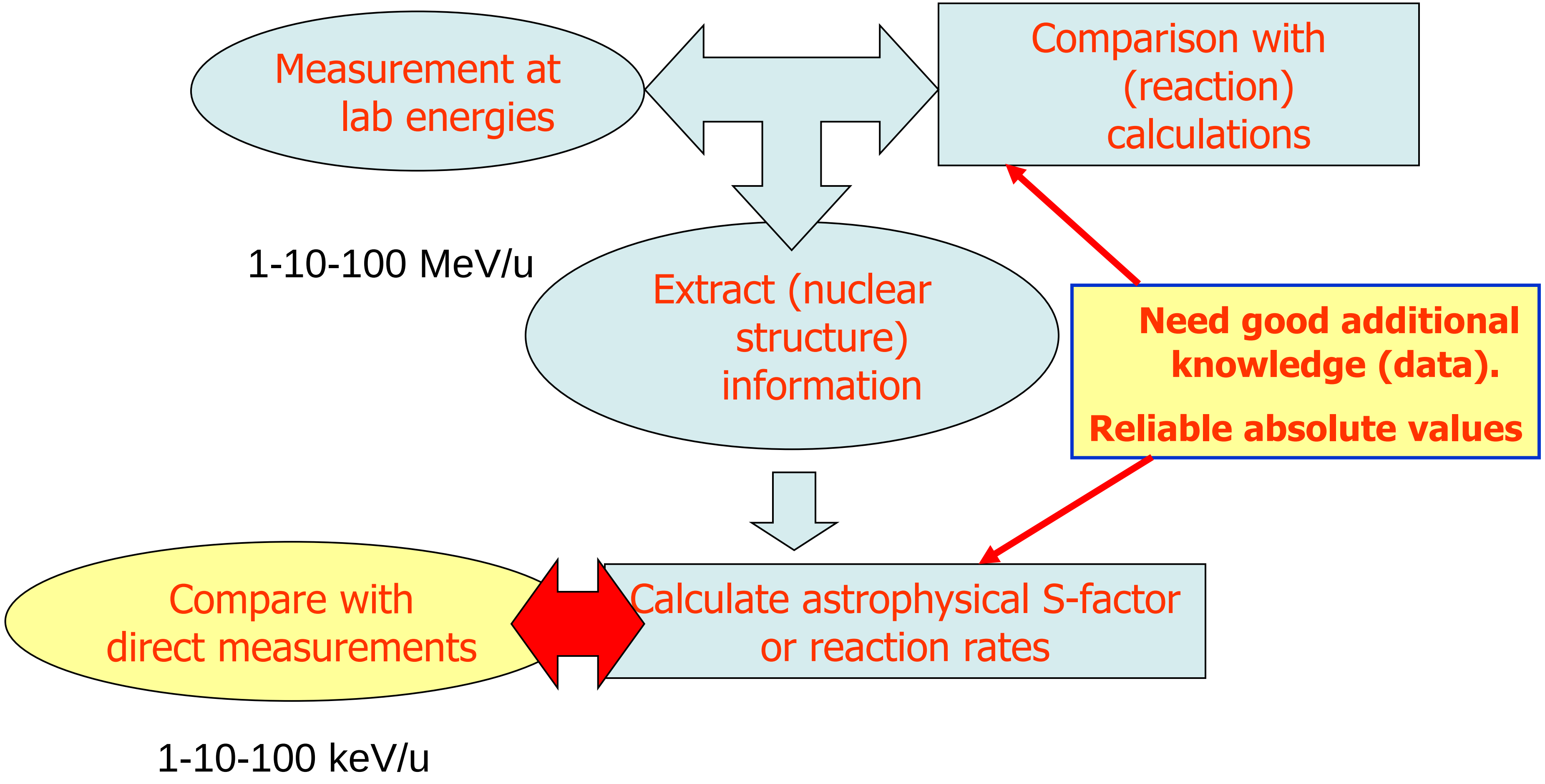
a) Direct measurements – reactions at the low energies the reactions occur in stars, or close to, followed by extrapolations

- Difficult because of extremely low cross sections
- Limited combinations of stable beams – targets

b) Indirect methods

- At higher (x10-1000), more convenient laboratory energies, extract relevant information
- Select quantities we measure $\rightarrow$ NA reaction rates
- Can use RIBs
- …

Indirect methods in nuclear astrophysics



The incomplete “list” of IMNA

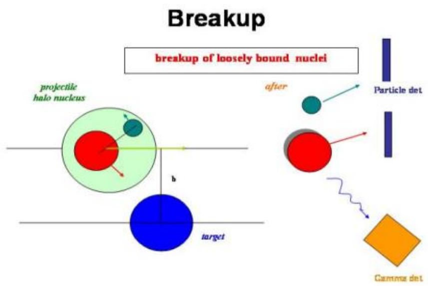
Dedicated methods:

A. Coulomb dissociation
B. Trojan Horse Method
C. Single-particle transfer reactions – ANC method
D. Nuclear breakup reactions – S_{17} and S_{18}
E. Spectroscopy of resonances:
   - Beta-delayed proton emission of ^{27}P
F. Ion-ion fusion studies: ^{13}C + …, ^{19}F + …
G. New?! Contribution of excited states
H. Reactions in laser induced plasmas

breakup of loosely bound nuclei vs rad p-capture

$$\sigma_{(p,\gamma)} \propto (C_{Bp}^{A})^2$$ P. Parker, 1962

Nuclear breakup



RIBF PAC15

$$\sigma_{-1p}^{\text{th}} = \sum \text{SF}(c;nlj)[\sigma_{\text{sp}}^{\text{stripp}}(nlj) + \sigma_{\text{sp}}^{\text{diff}}(nlj) + \sigma_{\text{sp}}^{C}(nlj)],$$

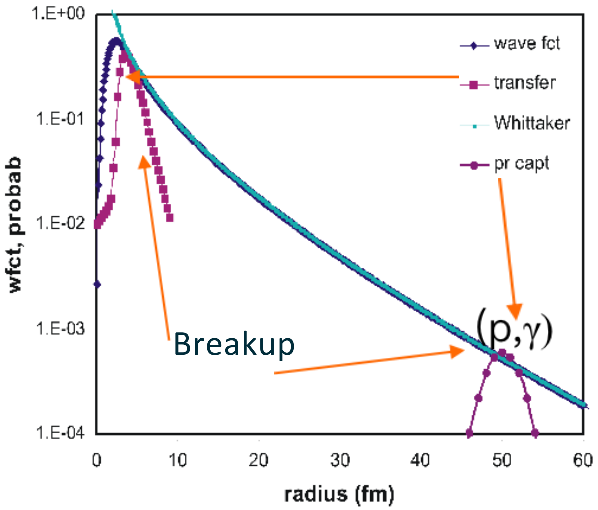
For ^{9}C case:

$$\sigma_{-1p} = [S(1p_{3/2}) + S(1p_{1/2})]\sigma_{sp}(1p_j)$$
$$= (C_{p_{3/2}}^2 + C_{p_{1/2}}^2)\sigma_{sp}(1p_j)/b_p^2$$

L. Trache et al., PRL 2001, PRC 66, 035801 (2002)

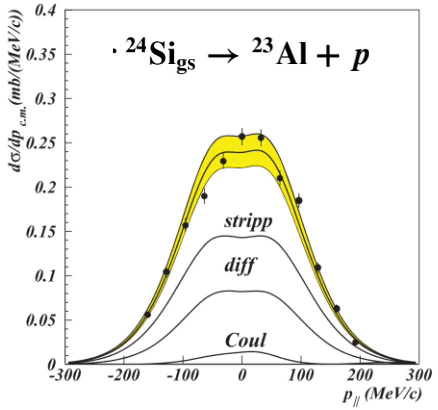
C(c,nlj) = the ANC of the system $^9C \rightarrow {}^8B+p$
b_p = the single-particle ANC

L. Trache, Exotic Beam Summer School 2012

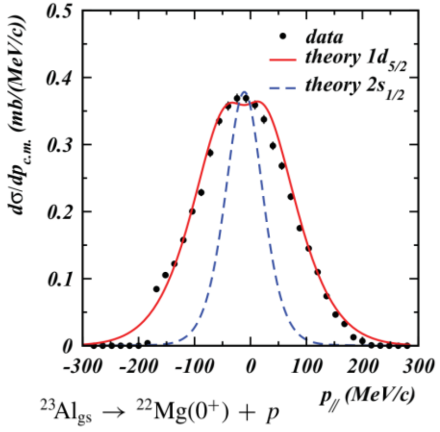


$$C_l^2 = \frac{\sigma_{\text{exp}}}{\sigma_{\text{sp}}^{\text{th}}} \left(\frac{r_L R_l(r_L)}{W_{-\eta,l+1/2}(2\kappa r_L)} \right)^2,$$

A. Banu et al., PRC 86, 015806 (2012)



A. Banu et al., PRC 86, 015806 (2012)



A. Banu et al., PRC 84, 015803 (2011)

S_{17} for solar neutrino: ANC extracted from ^{8}B breakup for $^{7}Be(p,\gamma)^{8}B$ with different interactions (2001, 2004)

Data from:

F. Negoita et al, Phys Rev C 54, 1787 (1996)

B. Blank et al, Nucl Phys A624, 242 (1997)

D. Cortina-Gil e a, EuroPhys J. 10A, 49 **(**2001).

R. E. Warner et al. – BAPS 47, 59 (2002).

J. Enders e.a., Phys Rev C 67, 064302 (2003)

All available breakup cross sections on targets from C to Pb and energies 27-1000 MeV/u give consistent ANC values!

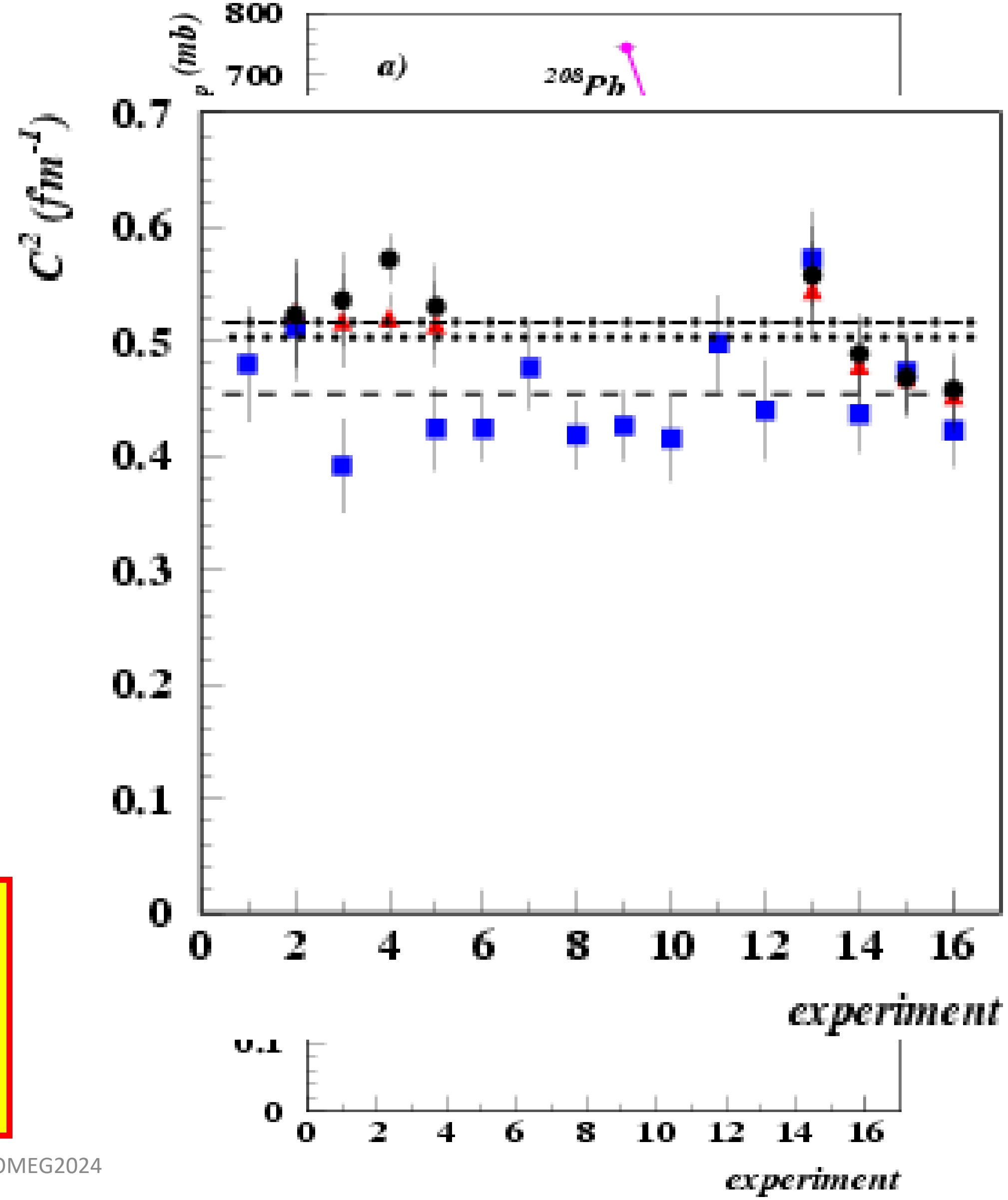
Summary of results:

LT ea, PRL 87, 2001

LT ea, PRC 67, 2004

3 different effective nucleon-nucleon interactions slightly different values & accuracy to about 10% :

$^{7}Be(p,\gamma)^{8}B$ (solar neutrinos probl.):
p-transfer: $S_{17}(0)=18.2\pm1.7$ eVb
Breakup: $S_{17}(0)=18.7\pm1.9$ eVb
Direct meas: $S_{17}(0)=20.8\pm1.4$ eVb



S_{18}: $^{9}C \rightarrow {}^{8}B+p$ breakup for $^{8}B(p,\gamma)^{9}C$

The reaction is important in the hot pp chains, in explosive H burning, at large temperatures, for creating alternative paths across the A=8 mass gap
(see e.g. M. Wiescher et al., Ap. J. 343 (1989)352.)

pp IV $^{8}B(p,\gamma)^{9}C(\beta^{+}\nu)^{9}B(p)^{8}Be(\alpha)^{4}He$ and
rap I $^{8}B(p,\gamma)^{9}C(\alpha,p)^{12}N(p,\gamma)^{13}O(\beta^{+}\nu)^{13}N(p,\gamma)^{14}O$.

Use breakup of $^{9}C \rightarrow {}^{8}B+p$ at intermediate energies to obtain $^{8}B(p,\gamma)^{9}C$ at astrophysical energies.

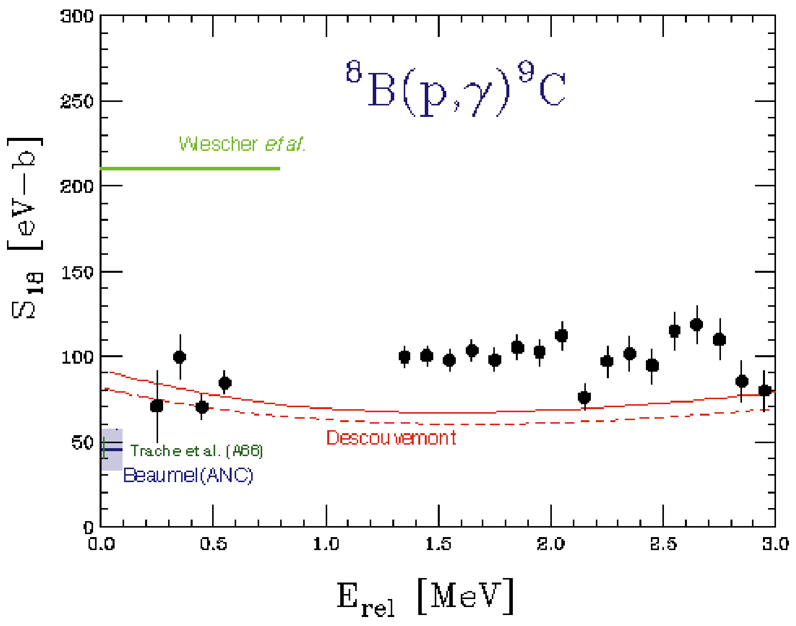
Eexisting data from:

B. Blank et al., Nucl Phys A624 (1997) 242
^{9}C @285 MeV/u on C, Al, Sn and Pb targets
Trache et al. ANC from breakup, 2002

Beaumel (ANC from (d,n) reaction)

Hisanaga, Motobayashi et al. (Coulomb dissociation)

Astrophysical S-factor

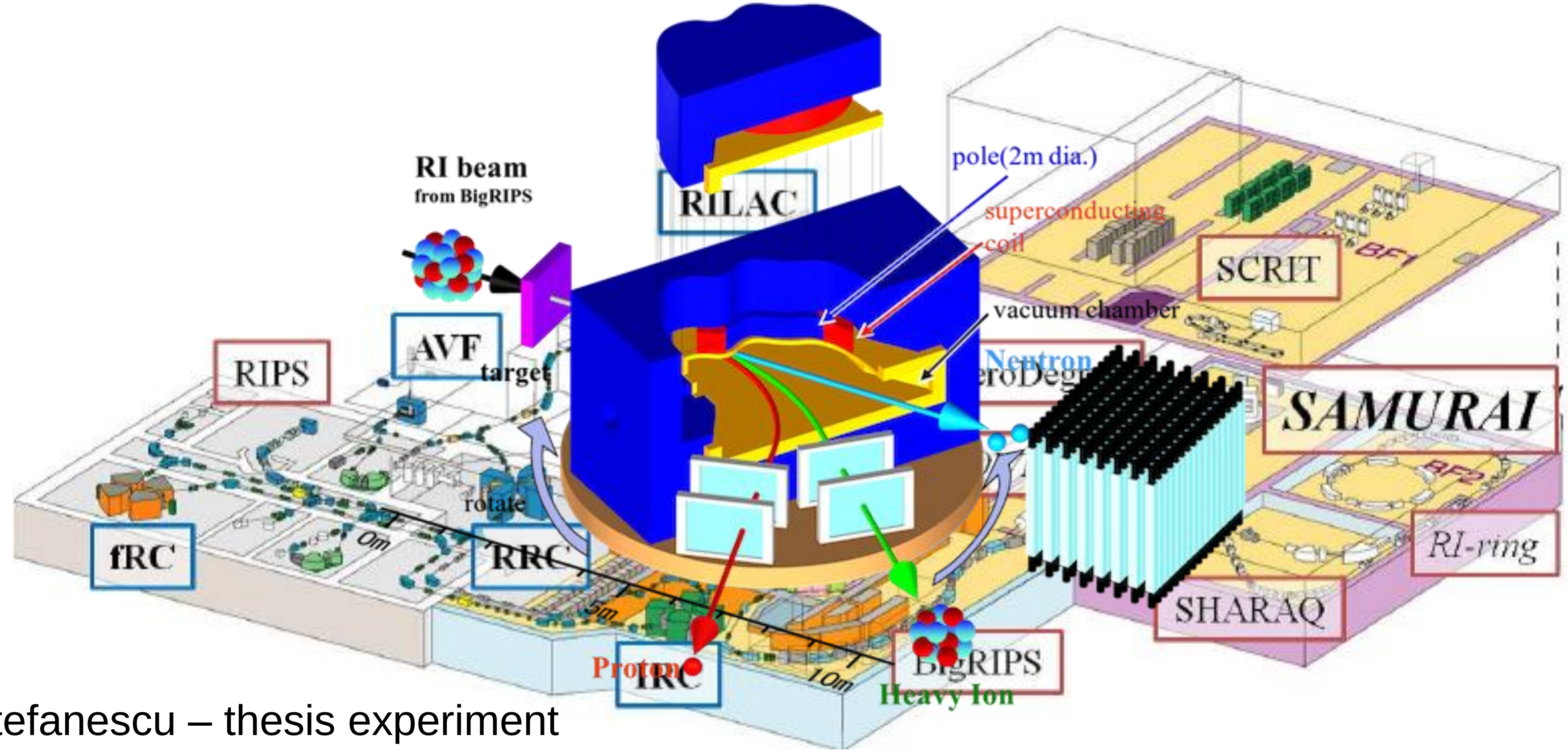


CD and ANC results disagree ?

July 2002 NIC-7

Exp. NP1412SAMURAI29

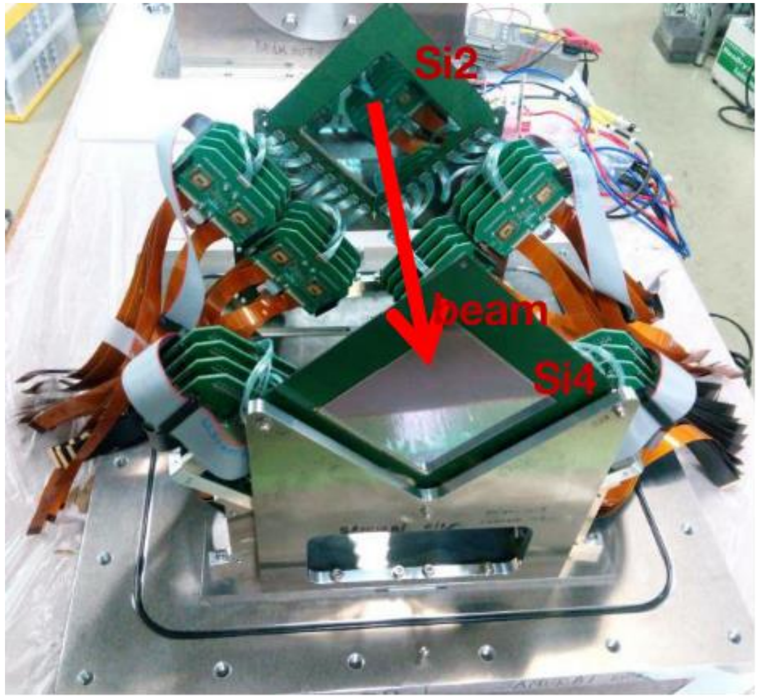
- Primary beam ^{18}O @ 260 MeV/u
- Secundary beam ^{9}C (160 MeV/u) ➔ target ➔ Si detector system ➔ SAMURAI ➔ detectors for p and HI



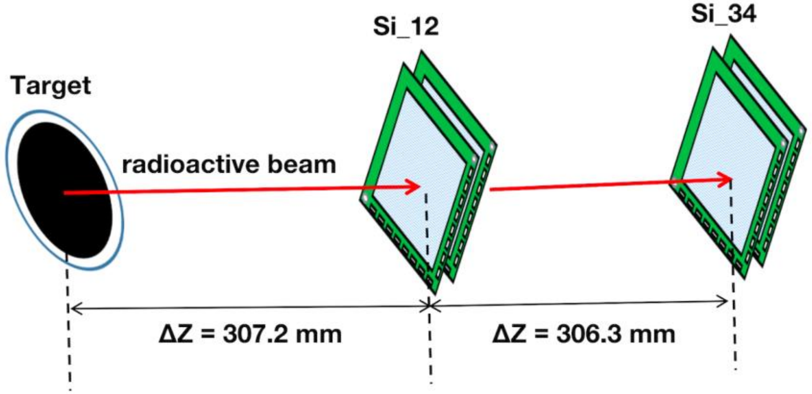
Alexandra Stefanescu – thesis experiment

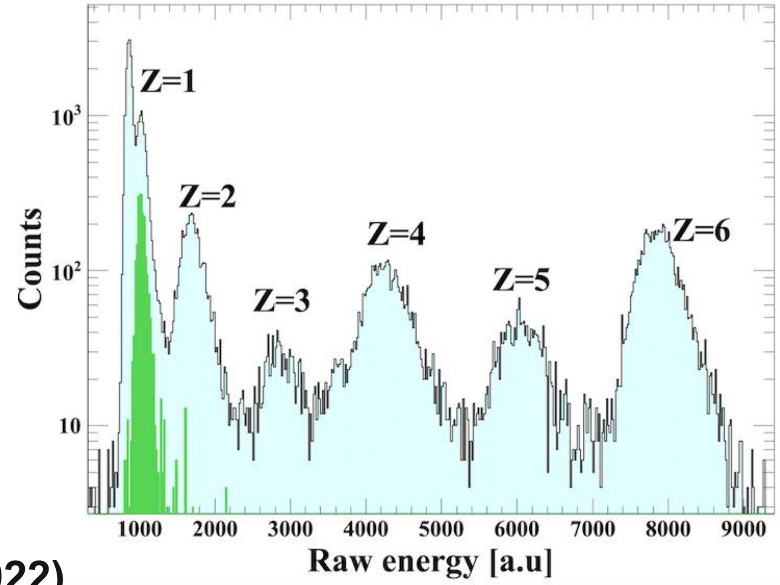
SAMURAI29 experiment

Detection systems at F13 focal plane: Silicon GLAST detectors



- System made up of 4 x position sensitive Si GLAST detectors
- placed between target and SAMURAI
- used for reaction products tracking (simultaneously)
- Active area: 87.552x87.552 mm^2
- Number of strips: 128 / detector (4x128=512 strips)
- Substrate thickness: 325 µm
- Strip pitch: 684 µm
- 2 x MotherBoard with 16 slots/MB: 2x32x16=1024 ch
- High dynamic range: 100 KeV (protons) and ~8-900 MeV (fragments), possible due to the dual gain preamplifiers



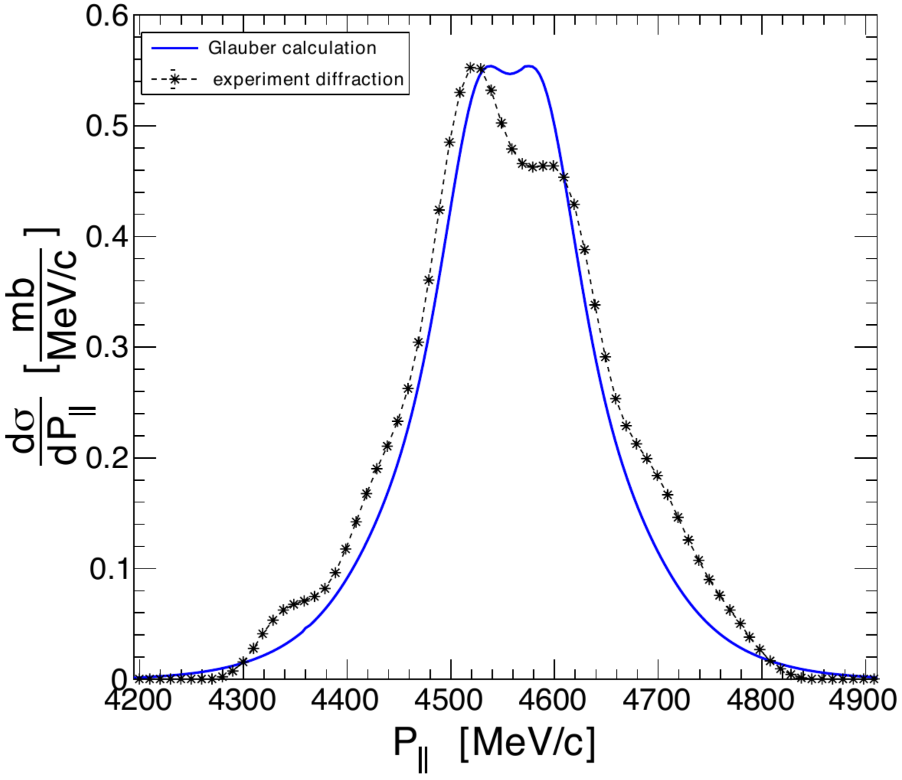


A.I. Stefanescu et al., Eur. Phys. J. A 58 (2022)

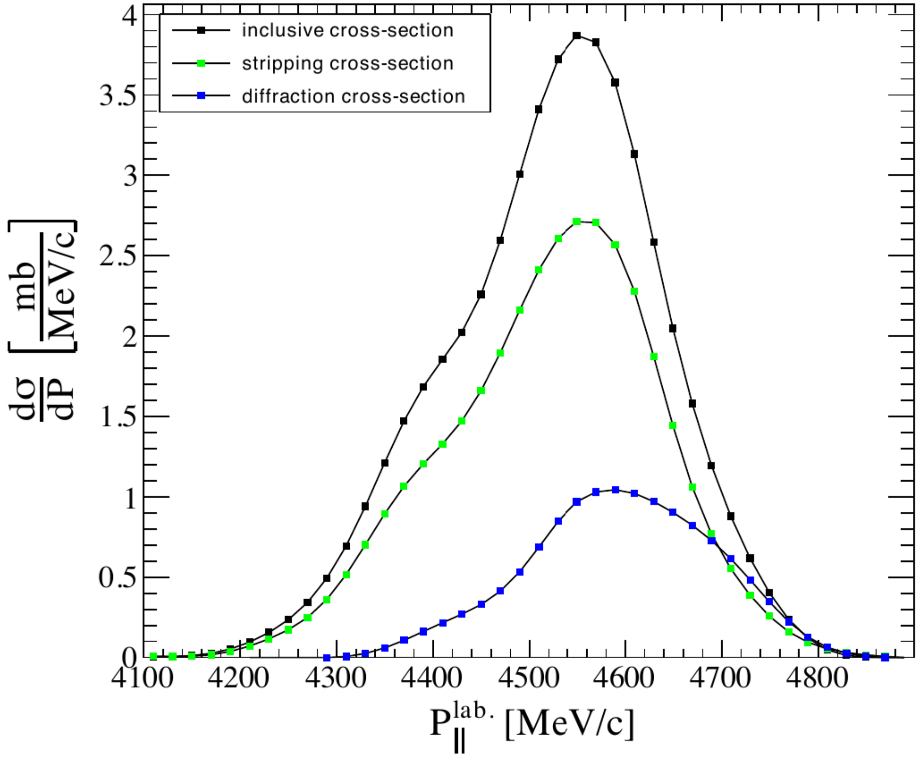
SAMURAI29 experimental results

Nuclear ^{9}C breakup on ^{12}C target

theoretical calculation with MOMDIS for proton in *1p* shell:



Experimental momentum distributions:



SAMURAI29 experimental results

Nuclear ^{9}C breakup on ^{12}C target

Process/ projectile	S29*,** exp. RIKEN	Blank(1997) exp. GSI [119]	Bazin(2009) exp. MSU [123]	Enders(2003) exp. MSU [124]	Schlemme(2019) exp. GSI [125]
$\sigma_{-1p}^{incl.}$ ^{9}C	50.3 ± 1.7 (mb) 160 AMeV on ^{12}C	48 ± 8 (mb) 285 AMeV on ^{12}C	56 ± 3 (mb) 97.9 AMeV on ^{9}Be	54 ± 4 (mb) 78.3 AMeV on ^{12}C	51.6 ± 1.3 (mb) 1670 MeV/u on ^{9}Be
$\sigma_{-1p}^{stripp.}$ ^{9}C	36.2 ± 1.4 (mb) 160 AMeV on ^{12}C	- 285 AMeV on ^{12}C	46 (mb) 97.9 AMeV on ^{9}Be	40 ± 5 (mb) 78.3 AMeV on ^{12}C	- 1670 MeV/u on ^{9}Be
$\sigma_{-1p}^{diff.}$ ^{9}C	13.1 ± 2.5 (mb) 160 AMeV on ^{12}C	- 285 AMeV on ^{12}C	13.8 ± 6 (mb) 97.9 AMeV on ^{9}Be	14 ± 4 (mb) 78.3 AMeV on ^{12}C	- 1670 MeV/u on ^{9}Be

Table 6.3: *Proton knockout reaction cross-sections from* ^{9}C

* need to be corrected with the experimental response function

** only the statistics errors are considered

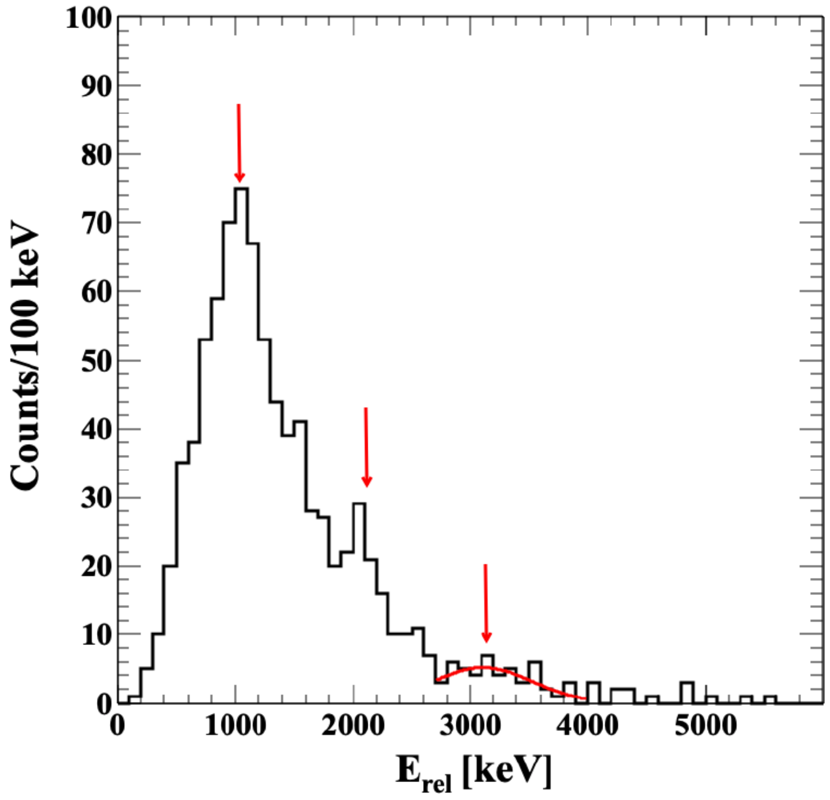
For now, same result: $S_{18}(0)$ =47 eVb (preliminary, unpublished)

SAMURAI29 experimental results

Coulomb breakup on Pb target

Invariant mass technique to obtain the exc. energy distribution

$$M_{inv}^2c^4 = (E_p + E_{^8B})^2 - (\overrightarrow{P_p} + \overrightarrow{P_{^8B}})^2 \cdot c^2$$
$$= M_p^2c^4 + M_{^8B}^2c^4 + 2\cdot\gamma_p\cdot M_pc^2\cdot\gamma_{^8B}\cdot M_{^8B}c^2\cdot(1-\beta_p\beta_{^8B}\cdot cos\Theta_{p^8B})$$
$$\rightarrow E^* = M_{inv}c^2 - M_{^8B}c^2 - M_pc^2 + S_p$$



$E_{rel.}$ [MeV]	E* [MeV]	Γ [keV]	J^π	Decay mode
0.918	2.218(11)	52 (11)	$-\frac{1}{2}$	$^9C \rightarrow p +^8 B^{2+}_{g.s}$
2.253	3.549(20)	673 (50)	$-\frac{5}{2}$	$^9C \rightarrow p +^8 B^{2+}_{g.s}$
3.104	4.40 (4)	2750 (110)	$(+\frac{1}{2}, +\frac{5}{2})$	$^9C \rightarrow p +^8 B_{1+}$
4.454	5.75(4)	601 (50)	-	$^9C \rightarrow p +^8 B_{3+}$

Collaborators:

- **IFIN-HH**: **A. Stefanescu,** D. Tudor, I.C.Stefanescu, A.E.Spiridon, F. Carstoiu, LT
- **RIKEN/CNS**: **V.Panin**, T. Motobayashi, K. Yoneda, T. Uesaka, H. Otsu, H. Baba, S. Ota, T. Kobayashi, Y. Togano, L. Stuhl, Y. Kubota, M. Sasano, J. Zenihiro, D. Ahn, Y. Shimizu, N. Iwasa, H. Sato …
- **TAMU**: **A. Saastamoinen**, C. Bertulani
- **ATOMKI**: Z. Halasz, Z. Elekes, G. Kiss
- **WU**: L. Sobotka, J. Elson
- **LPC Caen**: J. Gibelin

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DOE grants

Resonant Reaction Rates

* **Resonant** reaction is a two-step process.

$$\sigma_\gamma \propto \left|\langle E_f | H_\gamma | E_r \rangle\right|^2 \left|\langle E_r | H_f | A+p \rangle\right|^2$$

* The cross section (Breit-Wigner):

$$\sigma(E) = \frac{\lambda}{4\pi} \frac{2J+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_p \Gamma_\gamma}{(E-E_r)^2 + \left(\frac{\Gamma}{2}\right)^2}$$

* The contribution to the reaction rate:

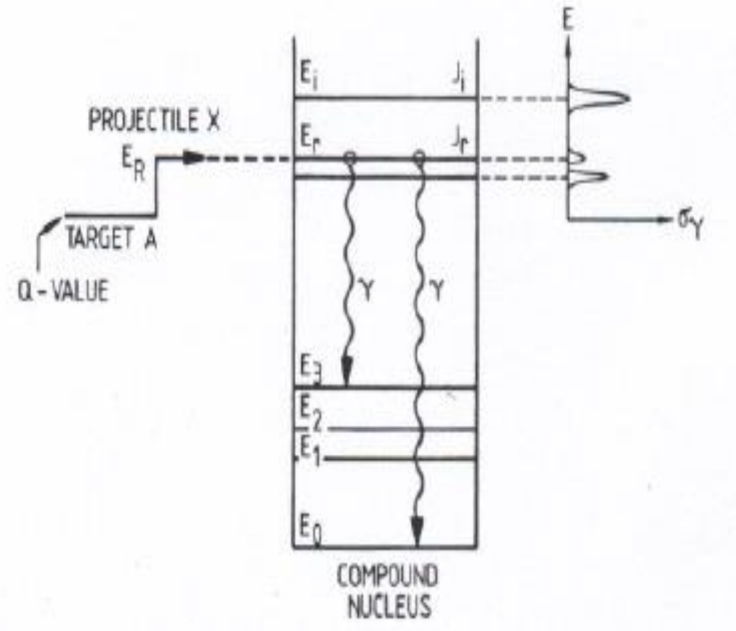
$$\langle \sigma \upsilon \rangle_{res} = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \omega\gamma \exp\left(-\frac{E_r}{kT}\right)$$

where

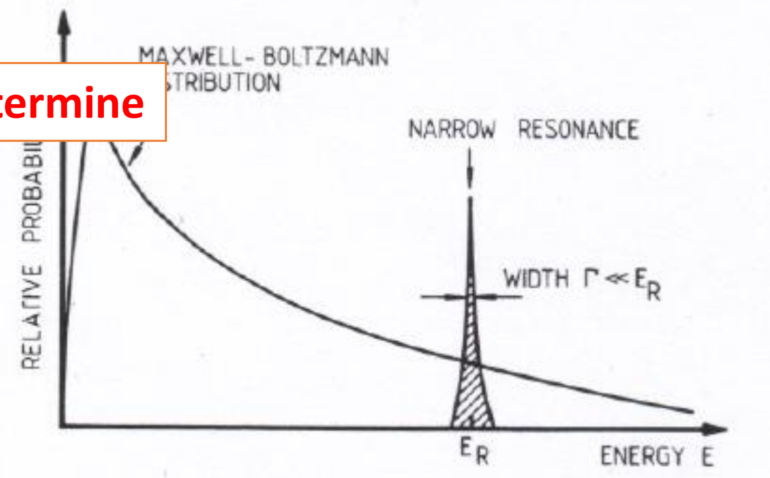
$$\omega\gamma = \frac{2J_r+1}{(2J_p+1)(2J_t+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_{tot}}$$

ωγ= resonance strength

to determine



* C. Rolfs and W. Rodney, "Cauldrons in the Cosmos".



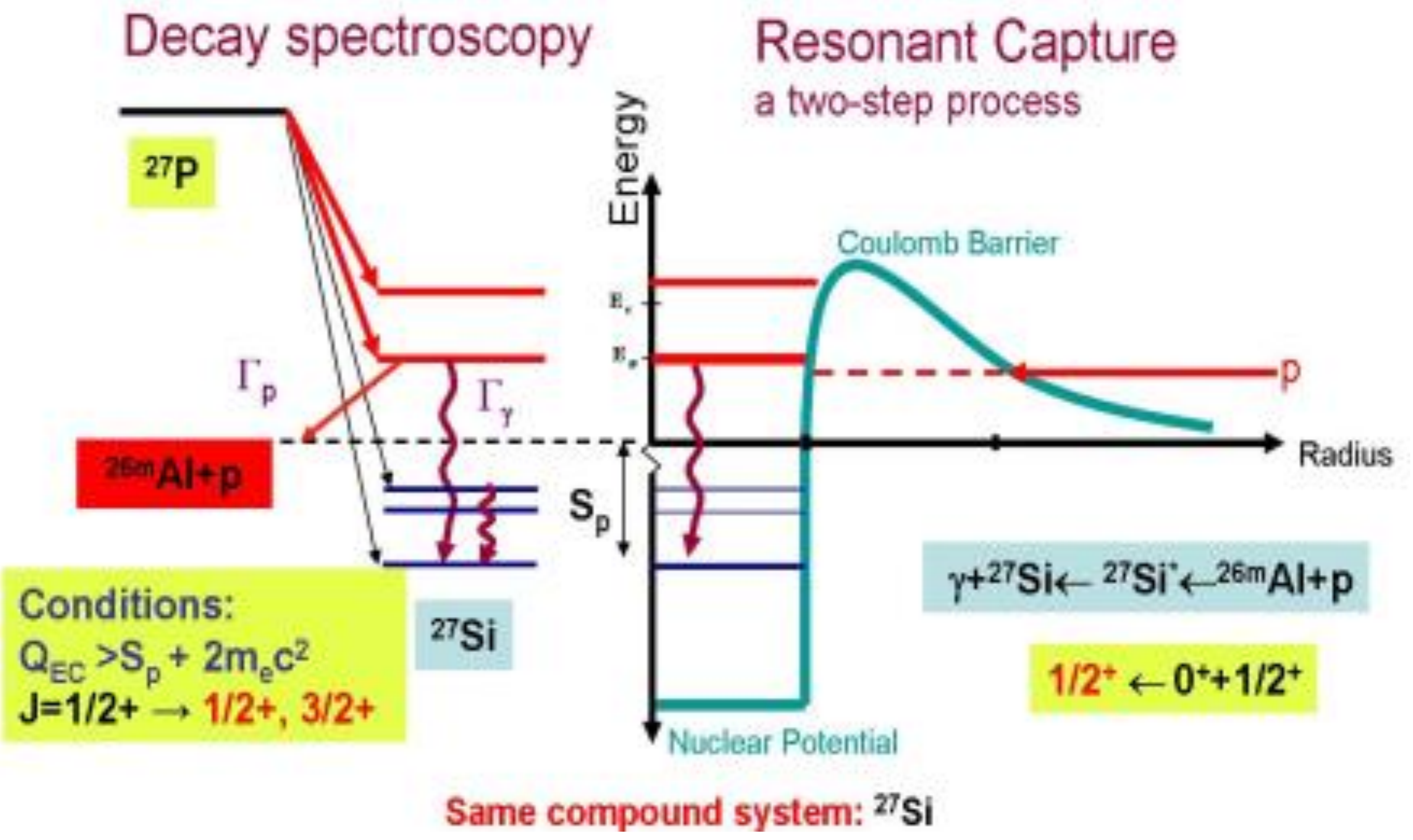
Spectroscopy of resonances

Locate and characterize resonances (by any means) => sufficient to evaluate the reaction rates

- Low energy resonances are the most important
- Energy of resonances are very important, and easier to determine
- "resonance strengths" … less so

Can do:

- Transfer reactions
- Trojan Horse Method measurements
- Gamma-ray spectroscopy
- Decay studies … like beta-delayed proton-decay βp

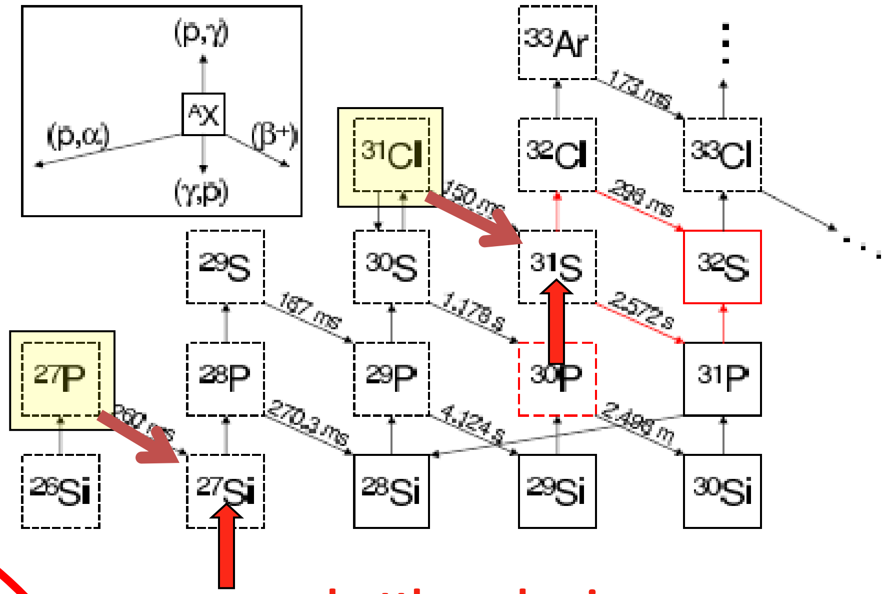


Lower proton energies <500 keV, most important, but very difficult:

- lower branching
- increased exp difficulties (det windows, background, etc…)

Decay spectroscopy

Beta- and beta-delayed proton-decay



Explosive H-burning in novae

&

IAS in T_z=-3/2 nuclei

Isospin mixing

GT strength distribution

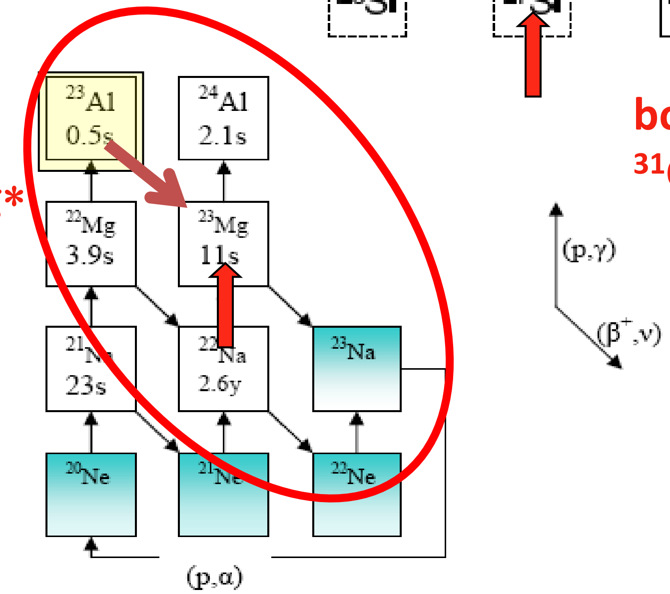
bottleneck r. in novae

^{31}Cl→^{31}S* ⇒ ^{30}P(p,γ)^{31}S*

^{22}Na depletion in novae

^{23}Al→^{23}Mg* ⇒ ^{22}Na(p,γ)^{23}Mg*

& ^{22}Mg(p,γ)^{23}Al



Comparison Si – gas detector

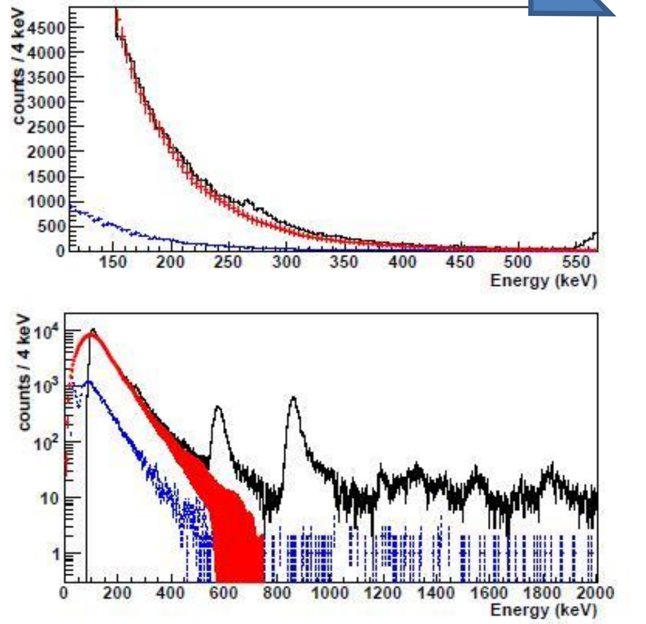
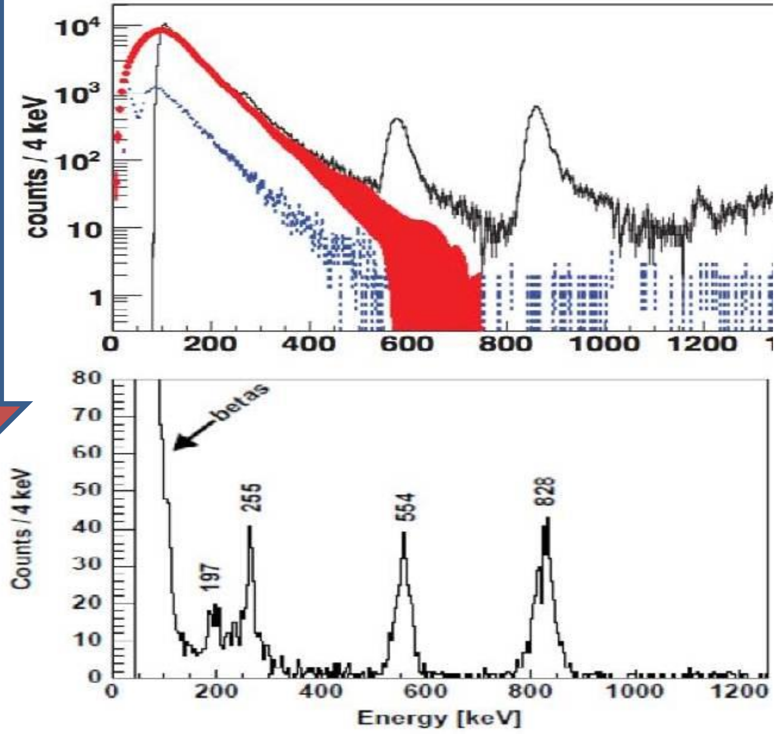


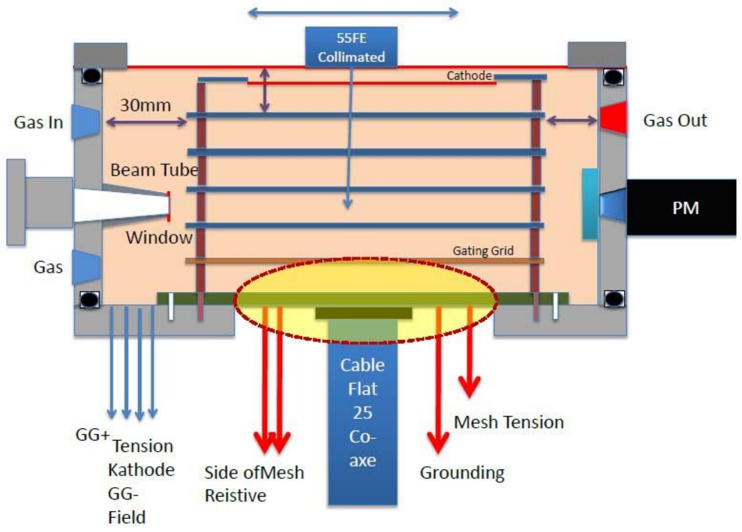
FIG. 7: (Color online) Full collected statistics for the ^{23}Al data (black, solid) and the ^{22}Mg data (blue, dashed). The energy is the total measured decay energy. Smoothed ^{22}Mg spectrum, scaled to match the ^{23}Al spectrum at 150 keV is shown with red dots and corresponding uncertainties. Upper panel shows only the low energy part where the proton group at $\sim$ 270 keV is clearly visible on top of the β background, whereas the lower panel shows the total spectra.

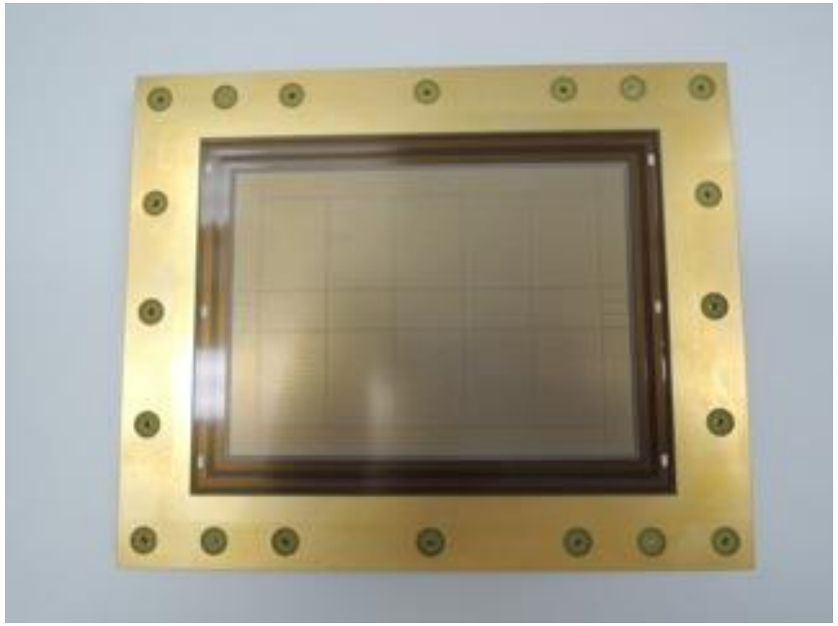


A. Saastamoinen, LT et al, PRC 83 (2011)

E. Pollacco, LT et al., NIM 2014

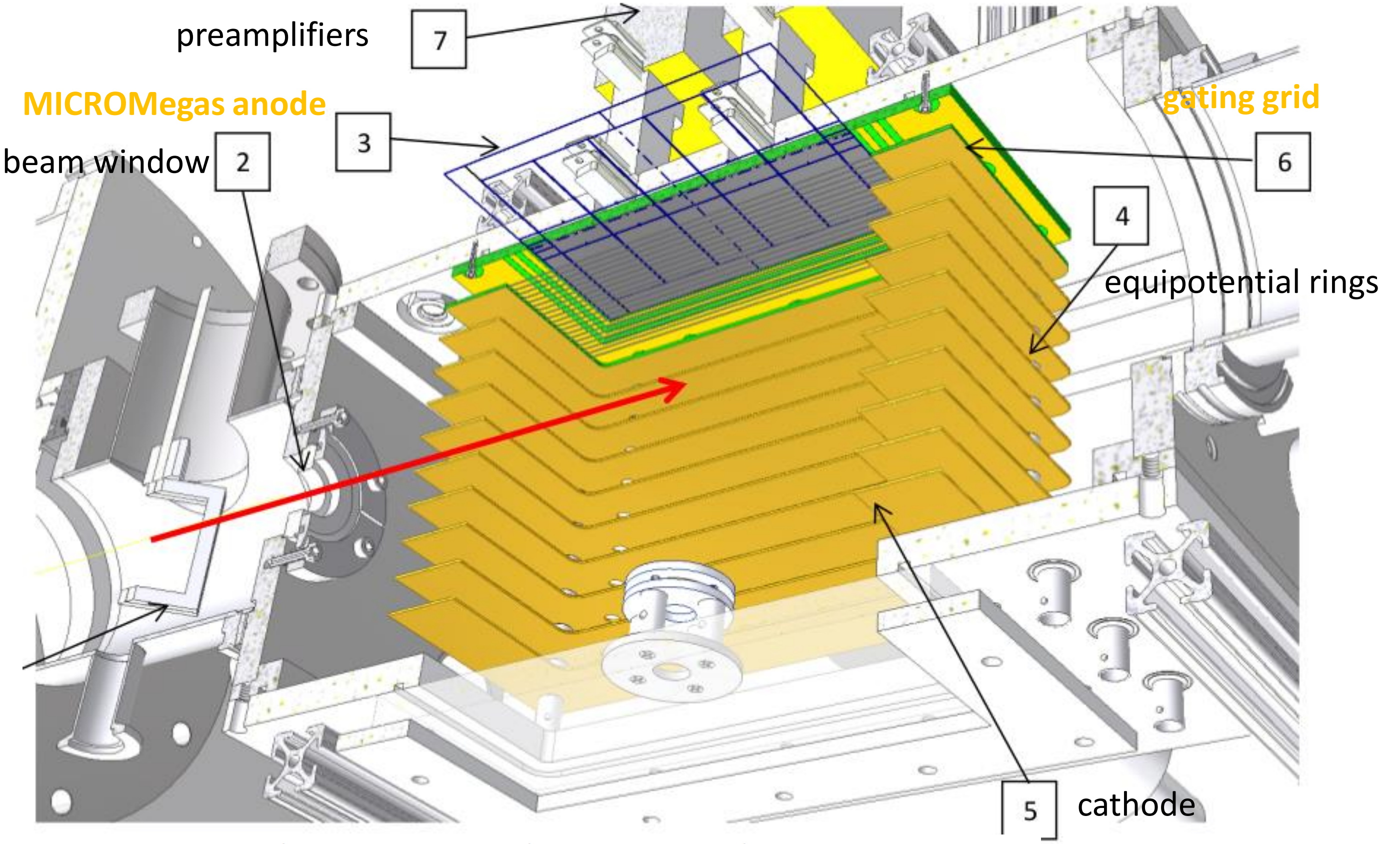
AstroBox2 - the micromegas detector

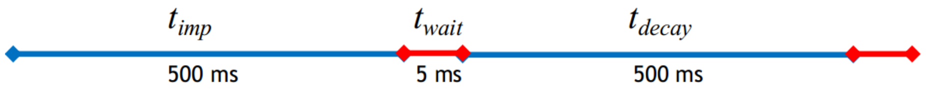




Chamber: design and prod: TAMU
Micromegas: Bucharest, Saclay, CERN
Electronics: Bucharest
Gas (P10) handling: existing at TAMU
Assembly and source tests: Saclay + TAMU

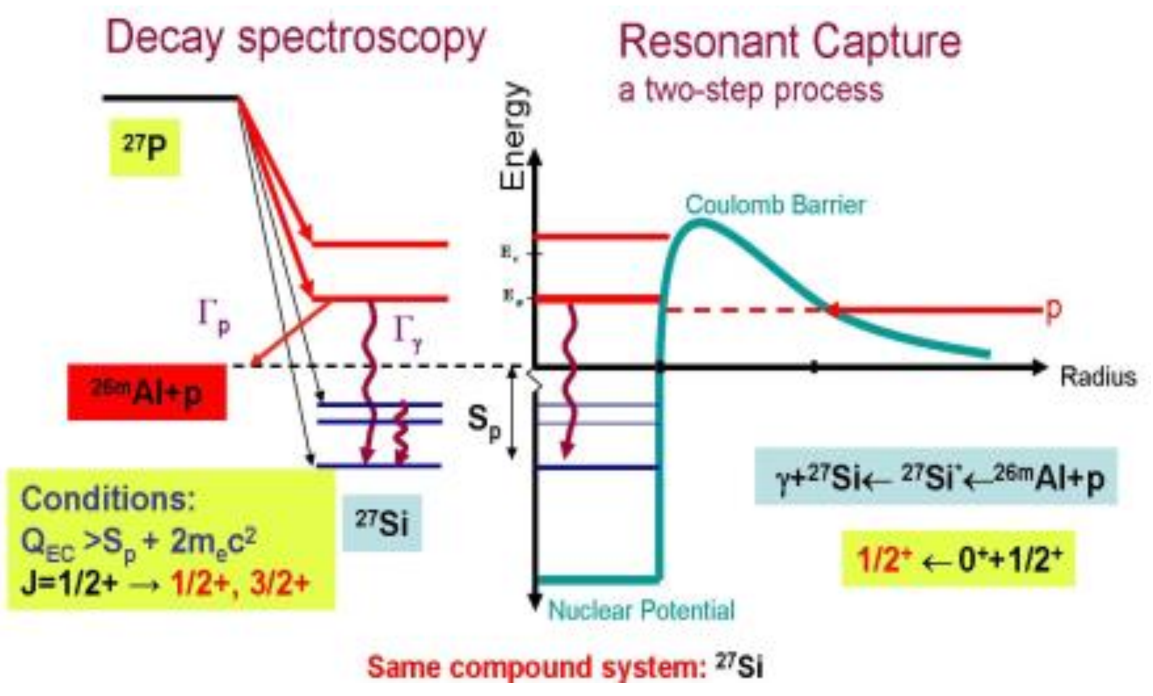
The Detector – AstroBox2

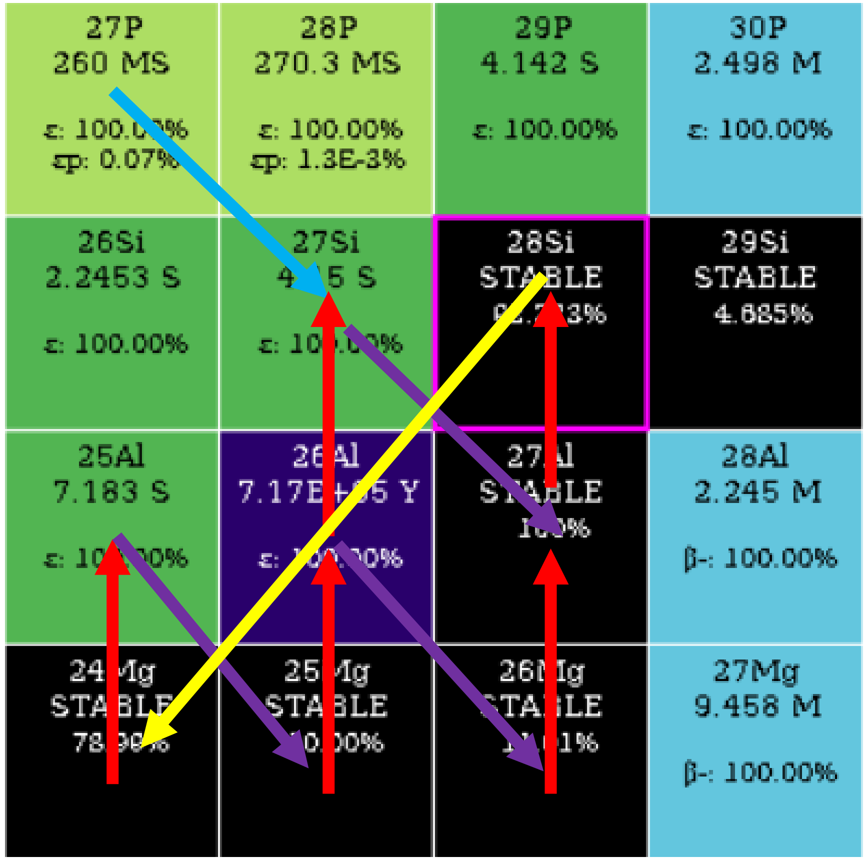




Motivation for studying ^{27}P decay

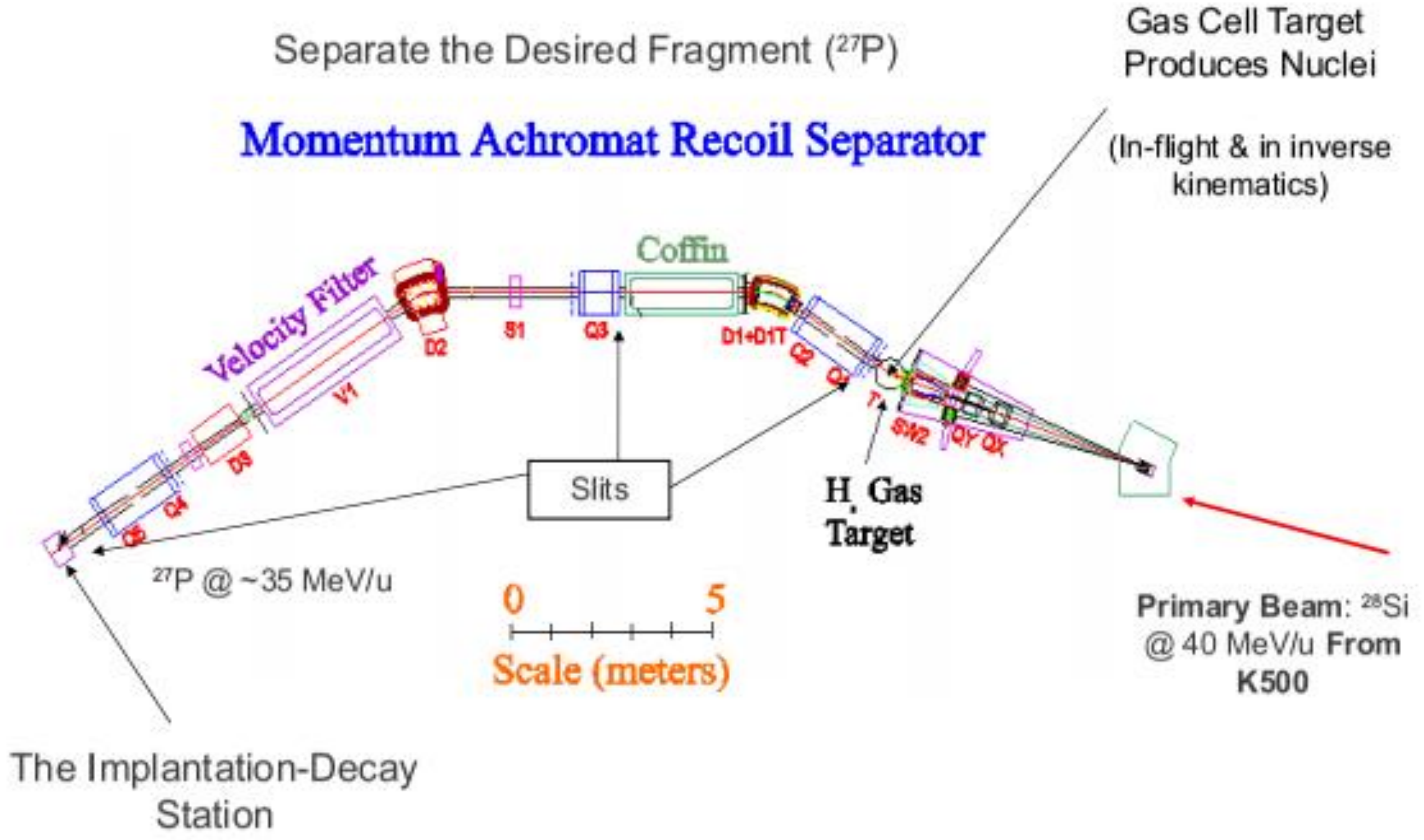
- Astrophysical motivation: prod of ^{26}**Al**



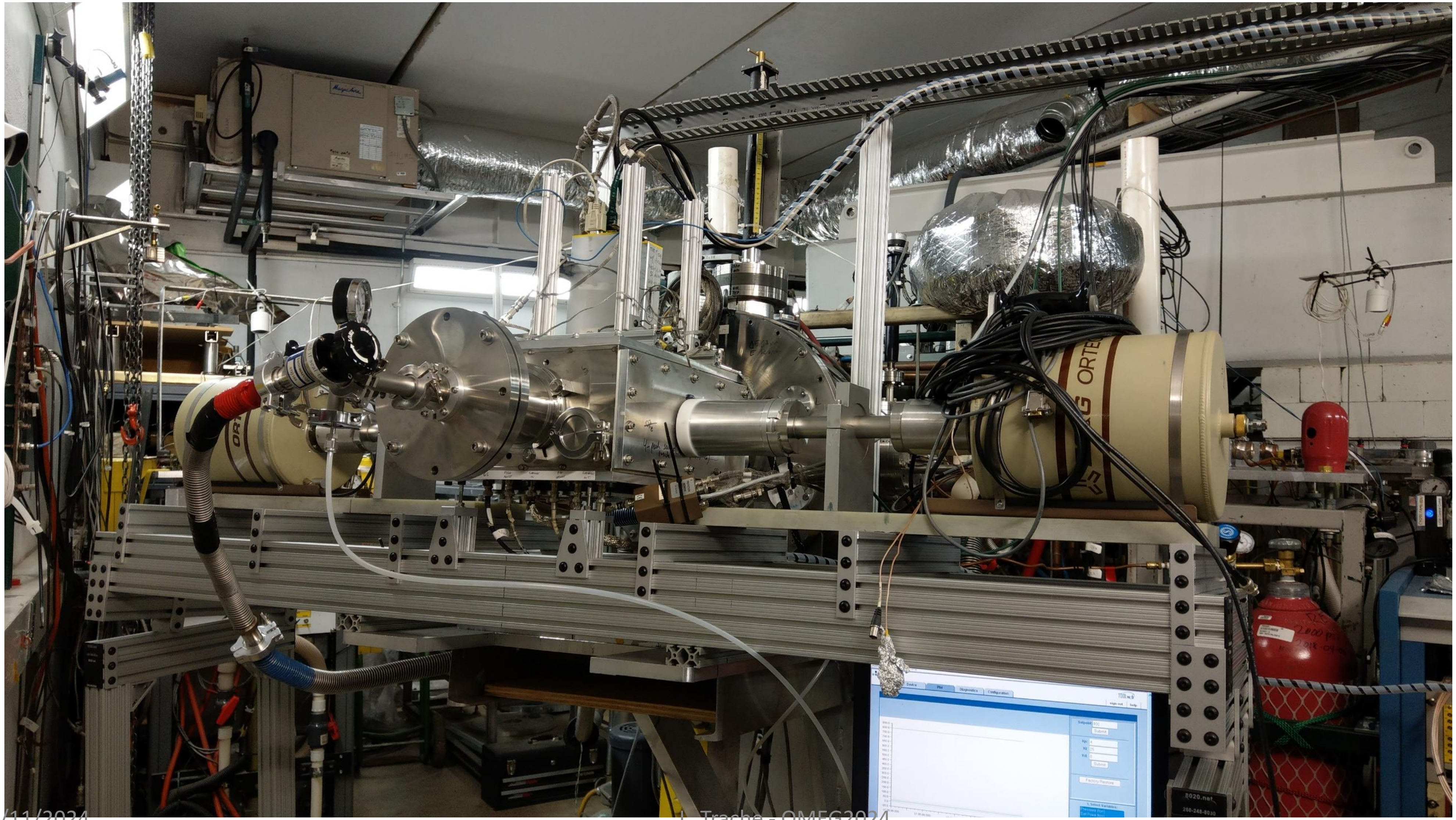


We need a beam of ^{27}P…

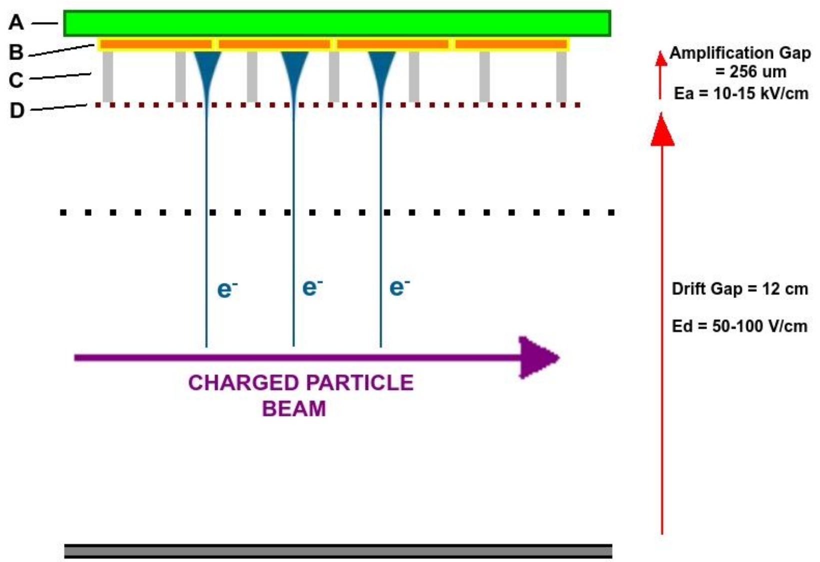
$^{28}Si^{10+}$ primary beam @40 MeV/u from K500 Cyclotron + LN2 H target
^{27}P in a (p,2n) reaction at Cyclotron Inst, Texas A&M Univerity

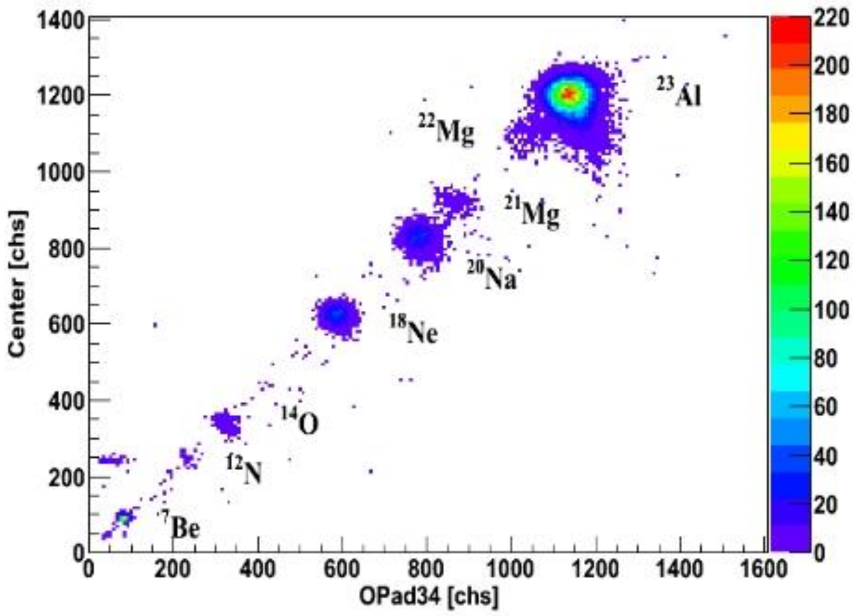


Experimental setup @TAMU

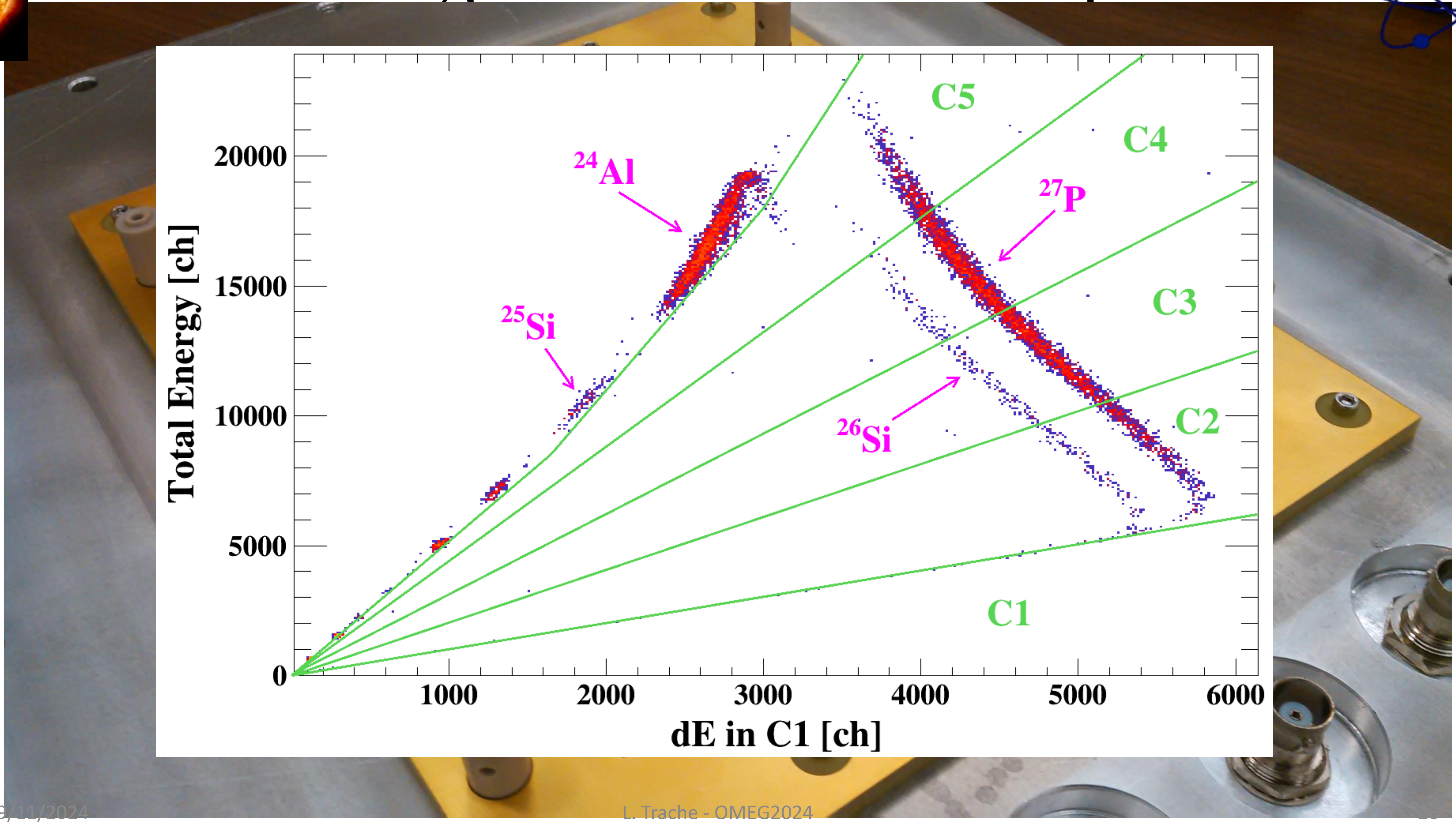


Detectors with micromegas



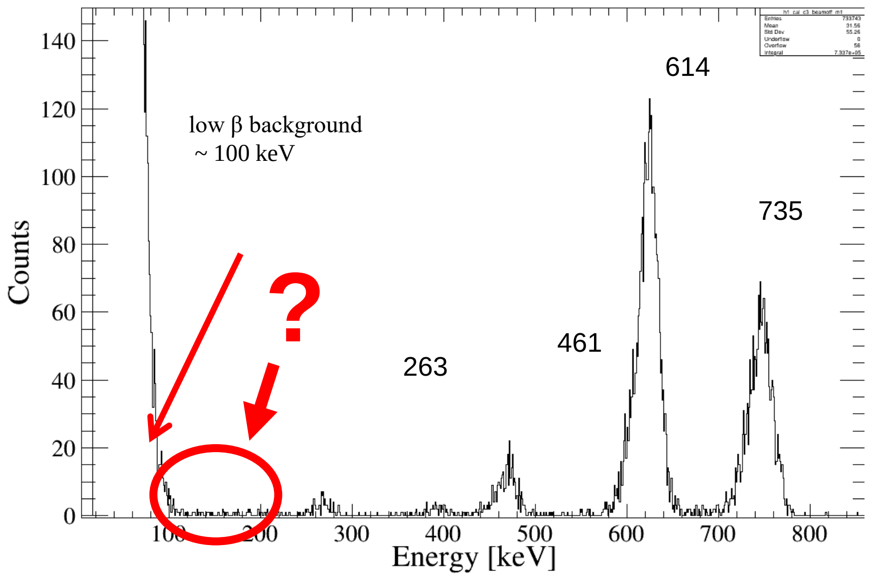


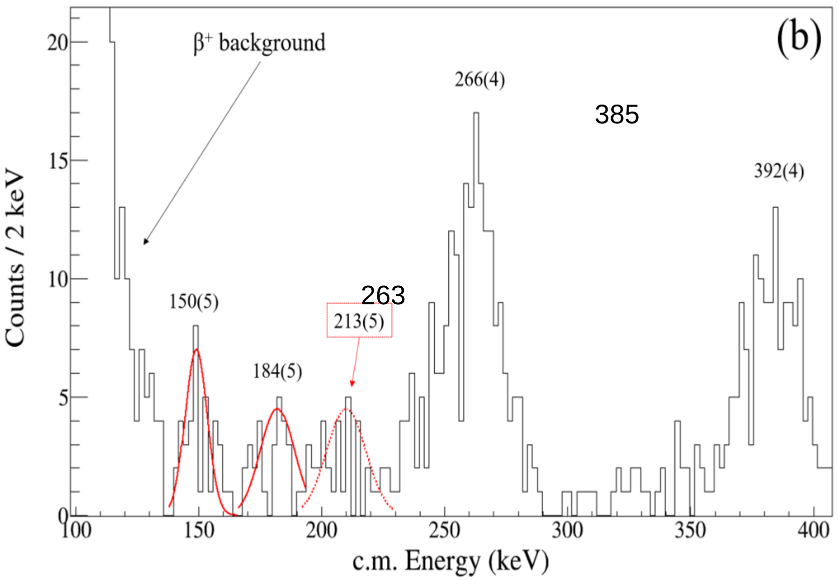
MICROMegas anode used in experiment



TAMU experiment

Ionut Stefanescu – thesis





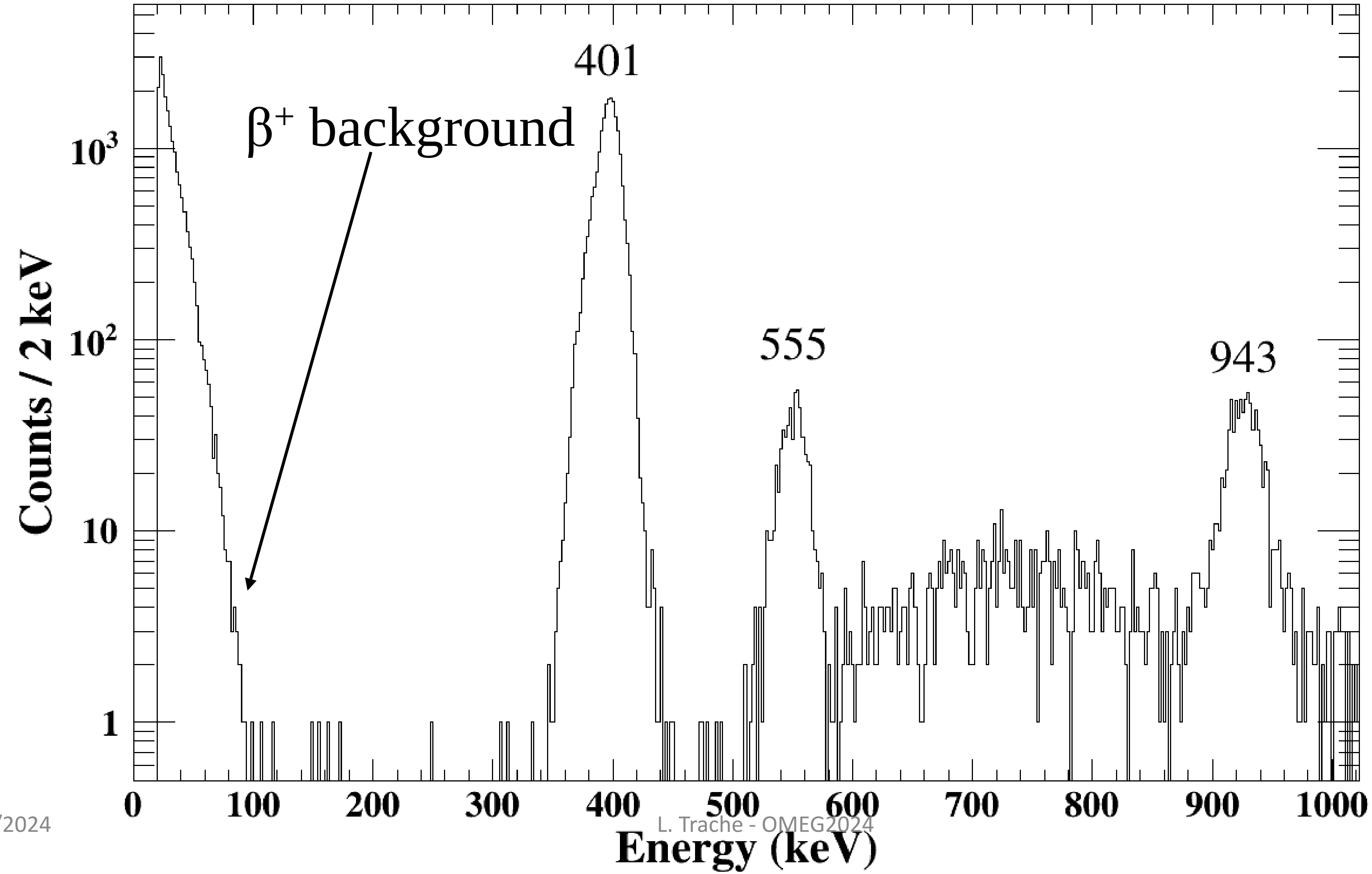
Resonant contributions to reaction rate:

$$\langle \sigma \upsilon \rangle_{res} = \left(\frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \omega\gamma \exp\left(-\frac{E_r}{kT} \right)$$

$$\omega\gamma \equiv \frac{2J_r + 1}{(2J_p + 1)(2J_t + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_{tot}}$$

Need energy, J_r and resonance strength

2019 experiment results
^{25}Si proton spectrum, m=1



$^{26m}Al(p,\gamma)$ resonances

E_p [keV]	E_level [keV]	Rel intens [%]	βp ratio [abs values]	ωγ [eV]
150(8)	7842(8)	0.09	$5.8(8) \times 10^{-7}$	2.64×10^{-7}
184(8)	7876(8)	0.29	$1.78(14) \times 10^{-6}$	6.34×10^{-6}
213(8)	7905(8)	0.18	$1.12(12) \times 10^{-6}$	5.09×10^{-5}
266(8)	7958(8)	1.23	$8.30(32) \times 10^{-6}$	9.12×10^{-4}
392(8)	8084(8)	1.14	$9.98(40) \times 10^{-6}$	6.26×10^{-2}
470(2)	8162(2)	7.94	$4.66(8) \times 10^{-5}$	0.25
619(2)	8311(2)	100	$5.88(3) \times 10^{-4}$	0.57
738(2)	8430(2)	96.8	$5.64(3) \times 10^{-4}$	0.63

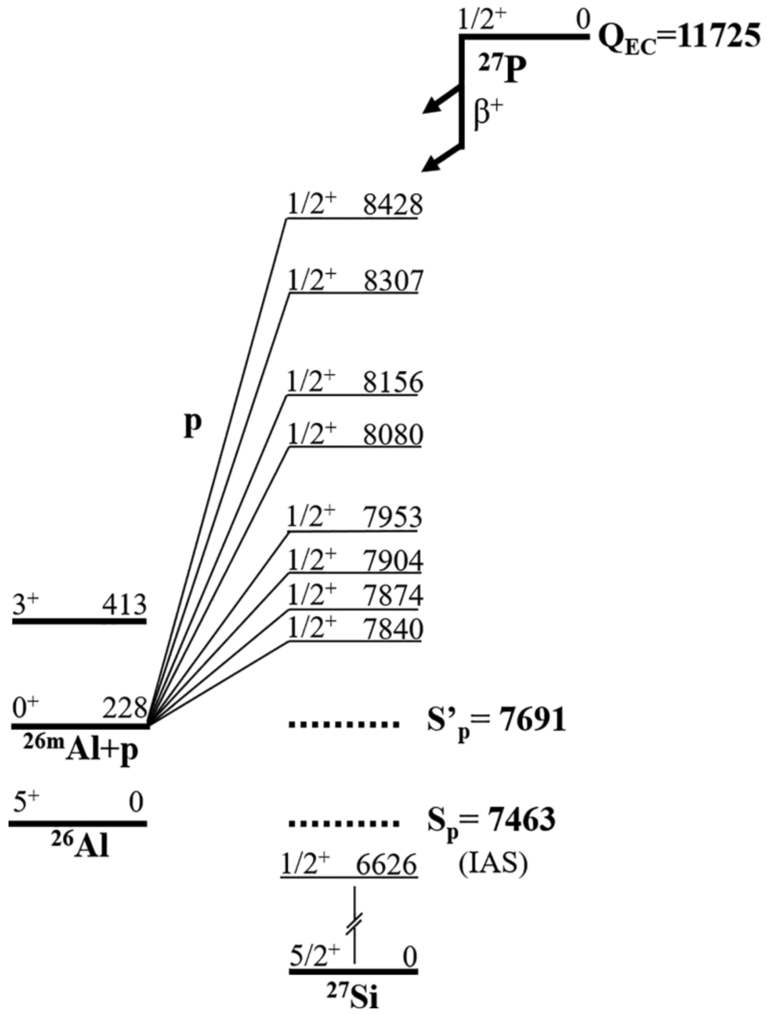
Resonance strengths evaluation

- $\omega\gamma$ evaluation: thru (guided) assumptions

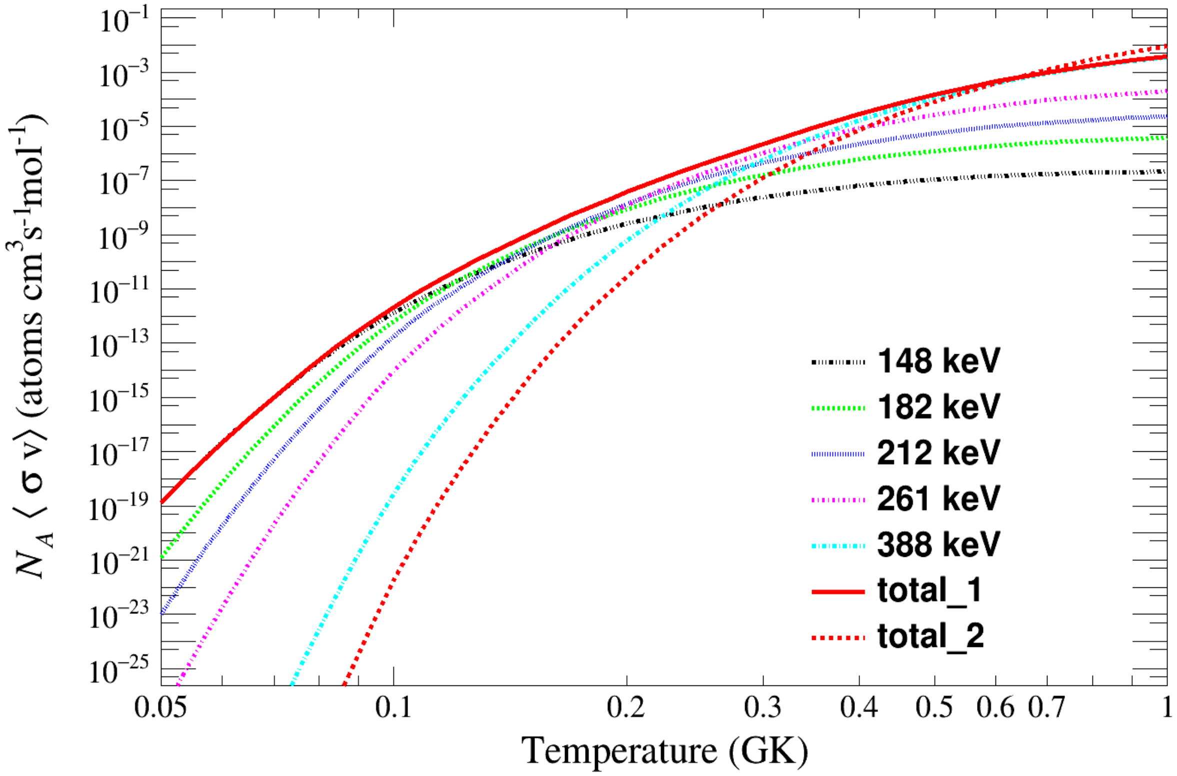
$$\omega\gamma = \frac{2J_r + 1}{(2J_{^{26}Al} + 1)(2J_p + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_{tot}},$$

$$\Gamma_p = 2\frac{\hbar^2}{mR^2} P C^2 S \theta_{pc}^2,$$

- With J^π=1/2$^+$; 1/Γ_γ=1 fs, and spectroscopic factor assumed C^2S=0.01 ; penetrability P calculated

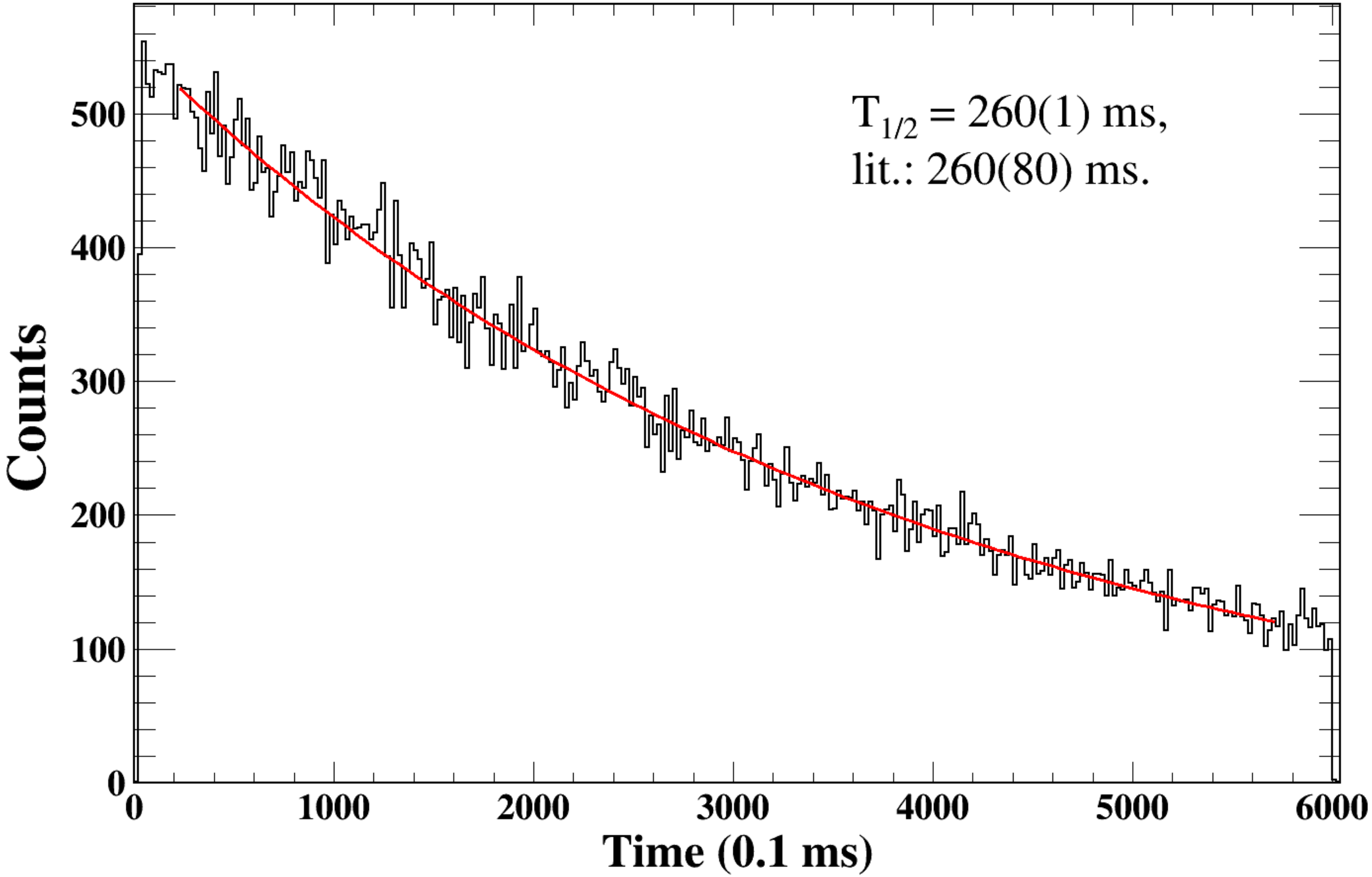


The reaction rate for $^{26m}Al(p,\gamma)\ ^{27}Si$ from ^{27}P βp-decay



IC Stefanescu, thesis March 2024 and
IC Stefanescu et al., **Phys. Rev. C 110, 015804 (2024)**

^{27}P half life – this experiment



“Other” method - ion-ion fusion mechanism at sub-Coulomb energies

Most sensitive method: activation + ultra-low background

Starting point

Current status

continuation

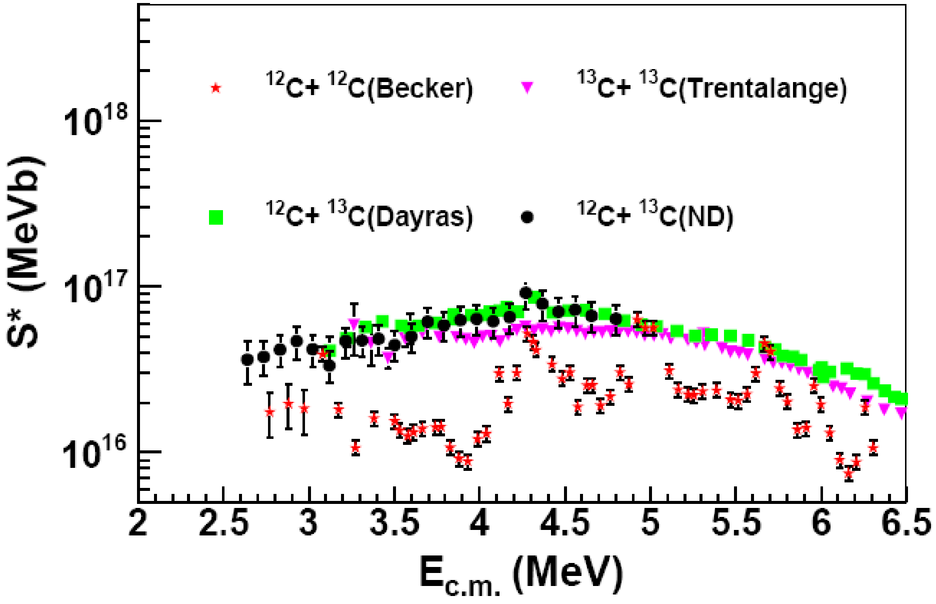
$^{13}C+^{12}C$ Exp Bucharest – Lanzhou

- Motivation: important reaction in nuclear astrophysics: $^{12}C+^{12}C$ (Supernovae, massive stars evolution …)
- very difficult to measure, fluctuating due to resonances!

- No resonances observed in $^{13}C+^{12}C$! Obs: for most energies, the $^{12}C+^{12}C$ cross sections are suppressed!

- proposed tests of nucleus-nucleus models using $^{13}C+^{12}C$, measured in the Gamow window
Test react mech below barrier

- Collaboration with group of prof. X. Tang – IMP Lanzhou, China

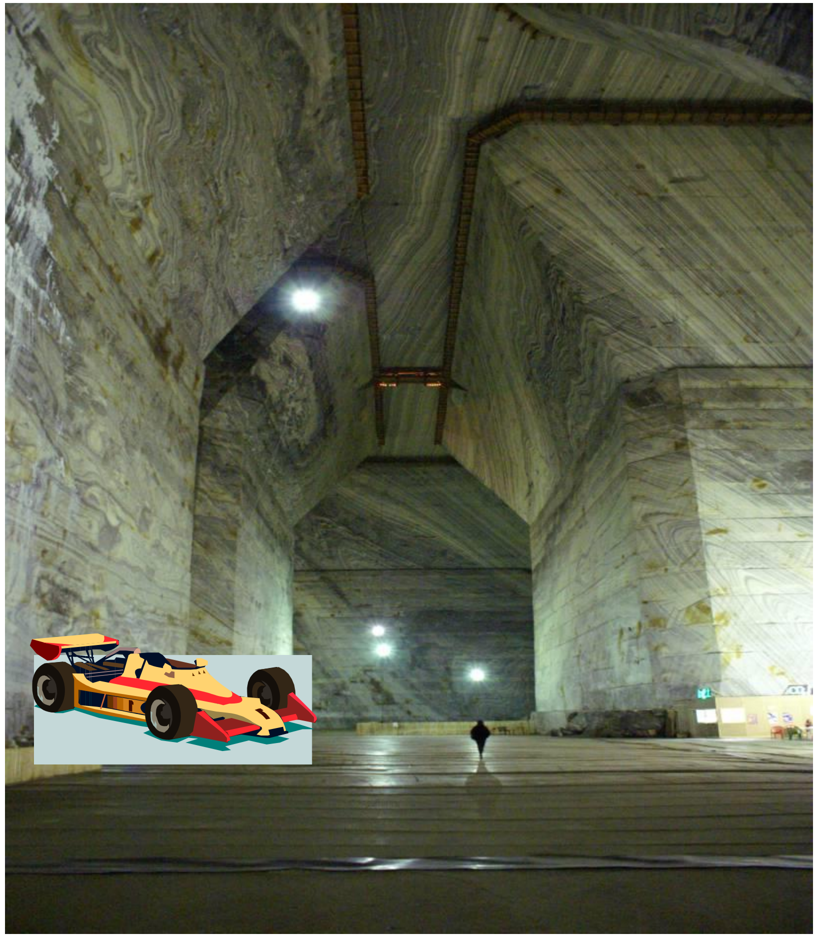


Activation and measurements in environments with ultralow background:

salt mine

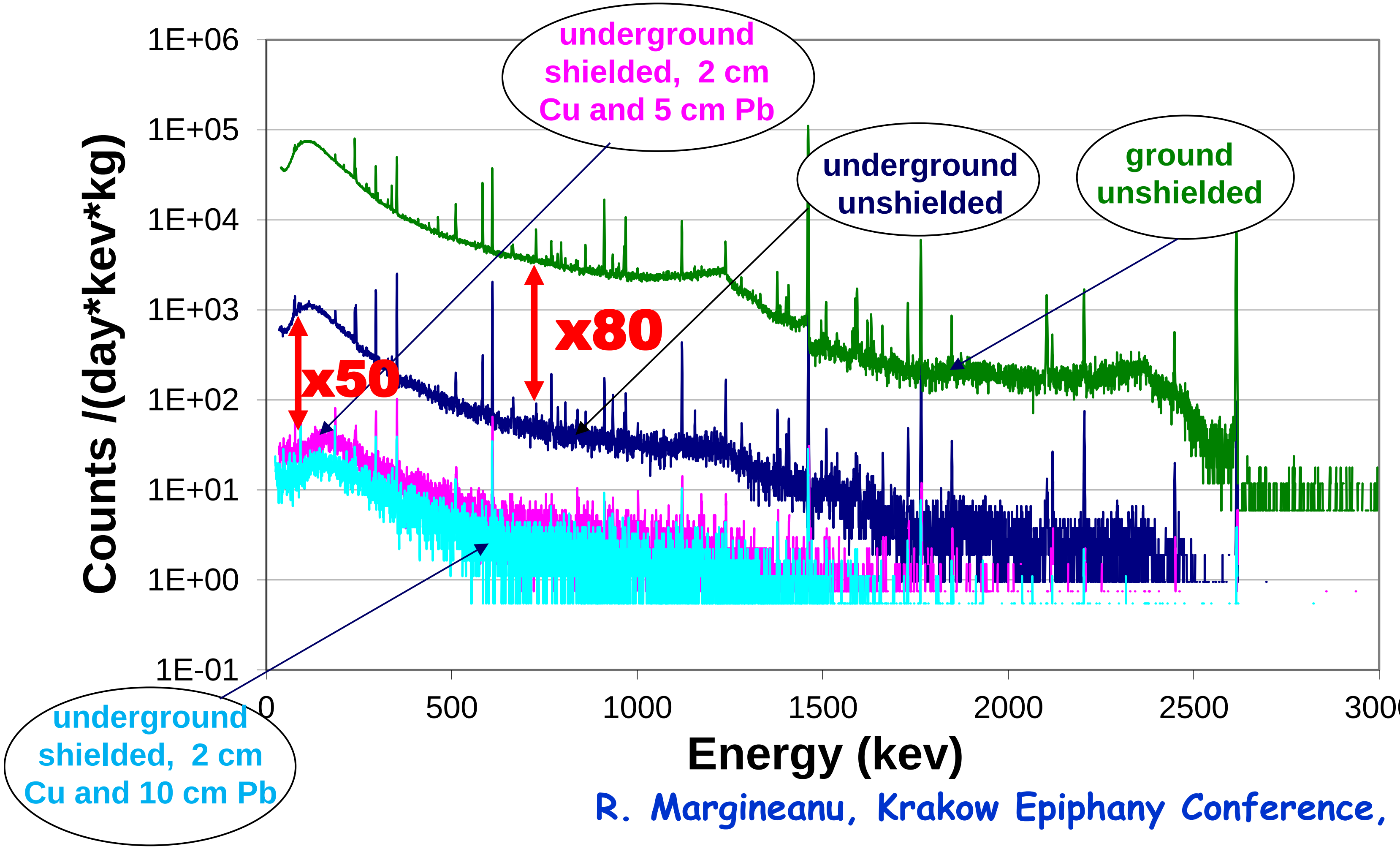
Activation in nuclear laboratory (this is the 3 MV tandetron)

Measurement in salt mine Slanic Prahova (2.5 hrs from Bucharest - very low gamma-ray background)



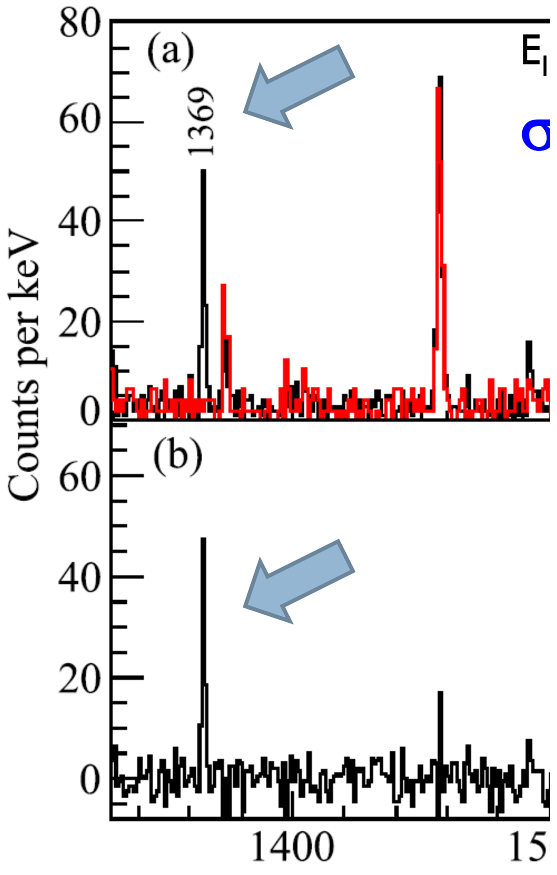
"microBq" Lab

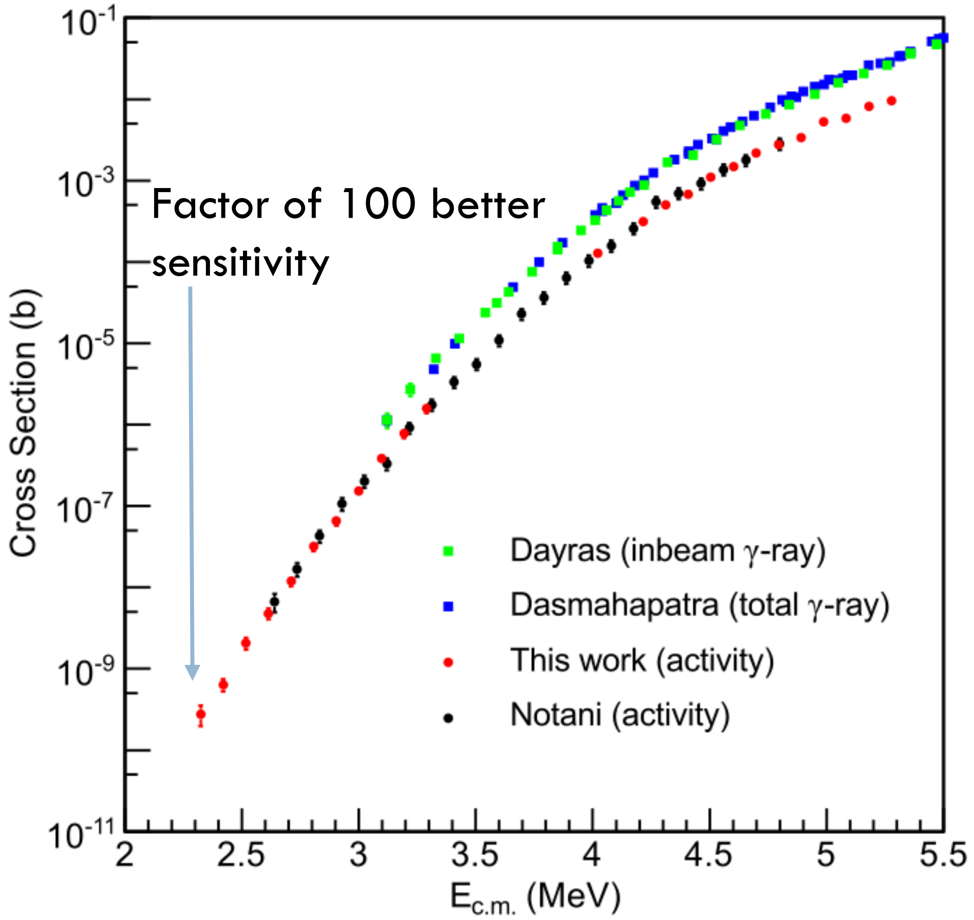
Background spectra collected with a CANBERRA HPGe detector with 100% relative efficiency



R. Margineanu, Krakow Epiphany Conference, 2010

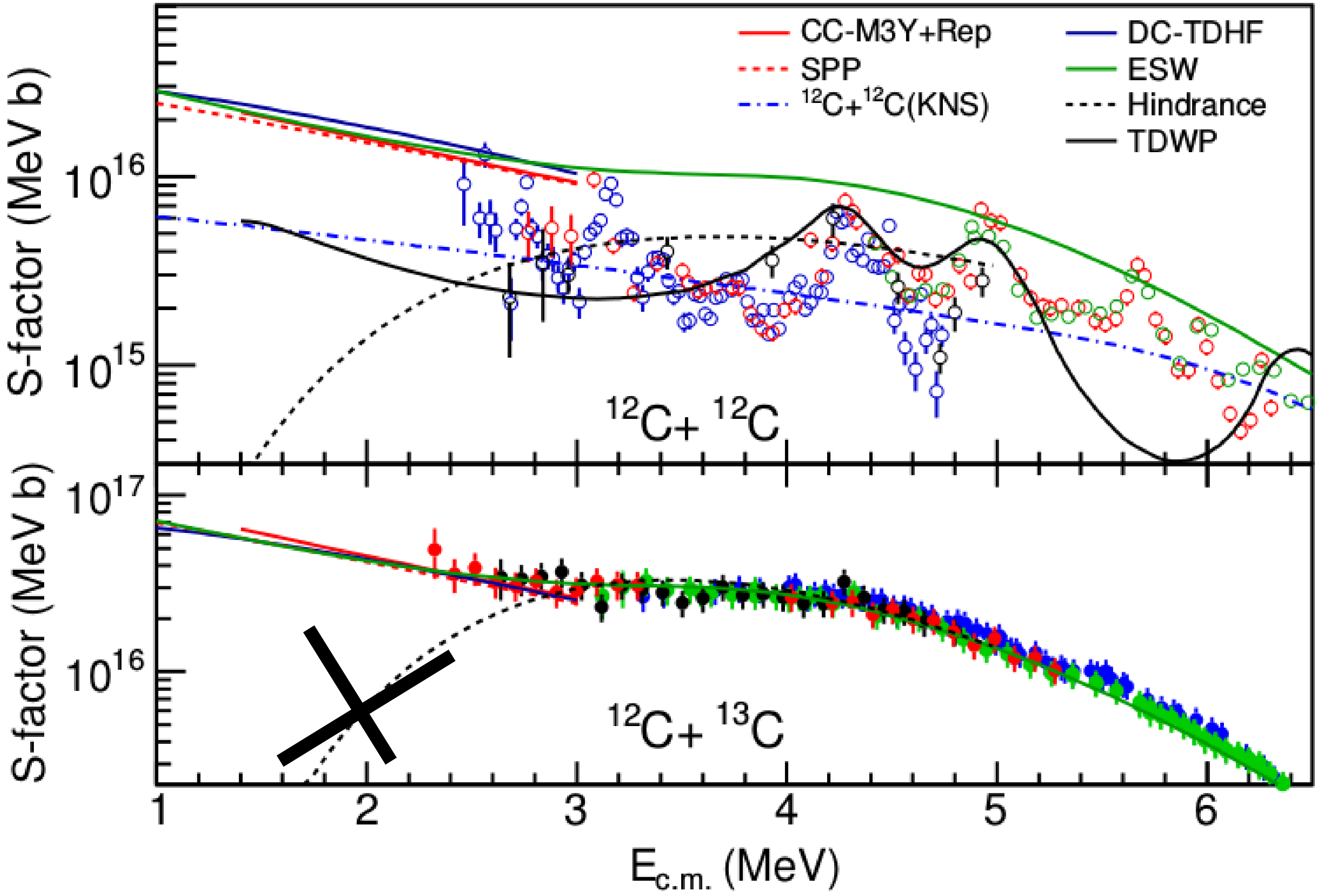
Low level background counting





Thick target method activation: 3 targets, 3.4 days; measurements: 3.9 days

$^{12}C + ^{12}C$



Zhang et al., *Phys. Letters B* **801** (2020)

“Other” method – other cases

- Program to study light ion-ion fusion mechanisms at sub-barrier energies - dr. Alexandra Spiridon in charge
- $^{12}C+^{12}C$, $^{12}C+^{16}O$, $^{16}O+^{16}O$ – none produces activation!
- Try to use neighboring isotopes: $^{13}C+^{16}O$, $^{19}F+^{12,13}C$ … most lead to short lived activities => no salt mine!
- Invent something else: clean spectra with coincidences in our lab
- Beta-gamma coincidences station BEGA: two HPGe detectors and a plastic scintillator
  - background reduction factor ~1000
  - down to $T_{1/2}$ ~2 min
- Future: fast changing target system

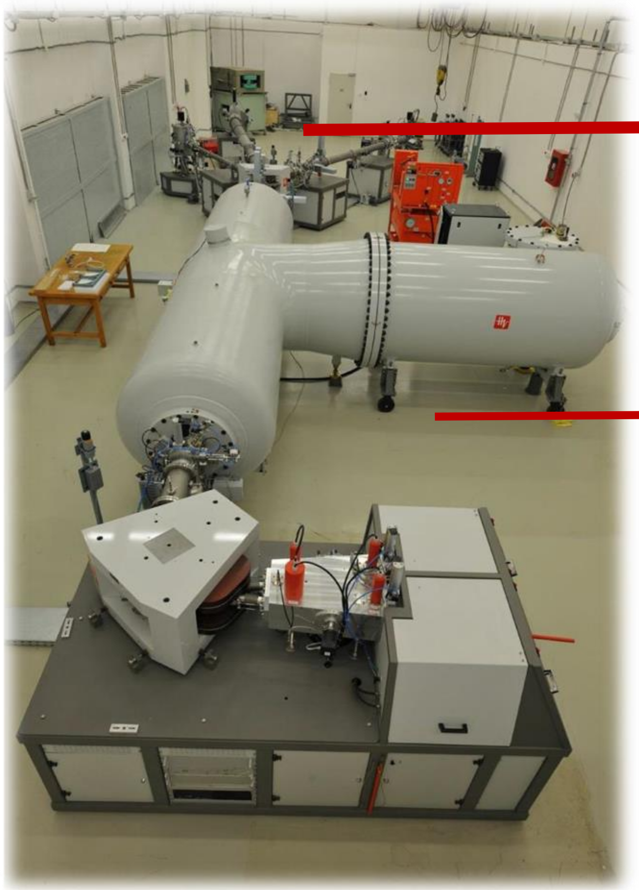
The $^{12}C+^{16}O$ Reaction

Problem: $^{12}C+^{16}O$ leads to stable residuals only

Solution: **try $^{13}C+^{16}O$**

Problem: ^{16}O target? Try oxide CeO_2

In beam irradiation, thick targets (CeO_2)



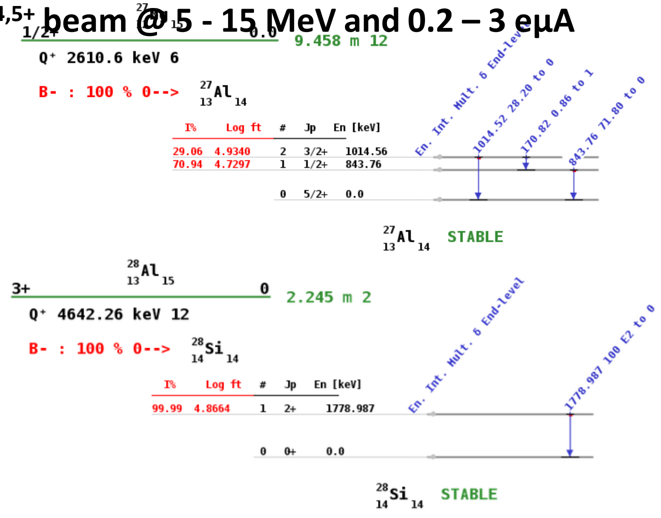
$^{16}O(^{13}C,p)\,^{28}Al$ - $T_{1/2}$ = 2.2 min

E_γ = 1779 keV

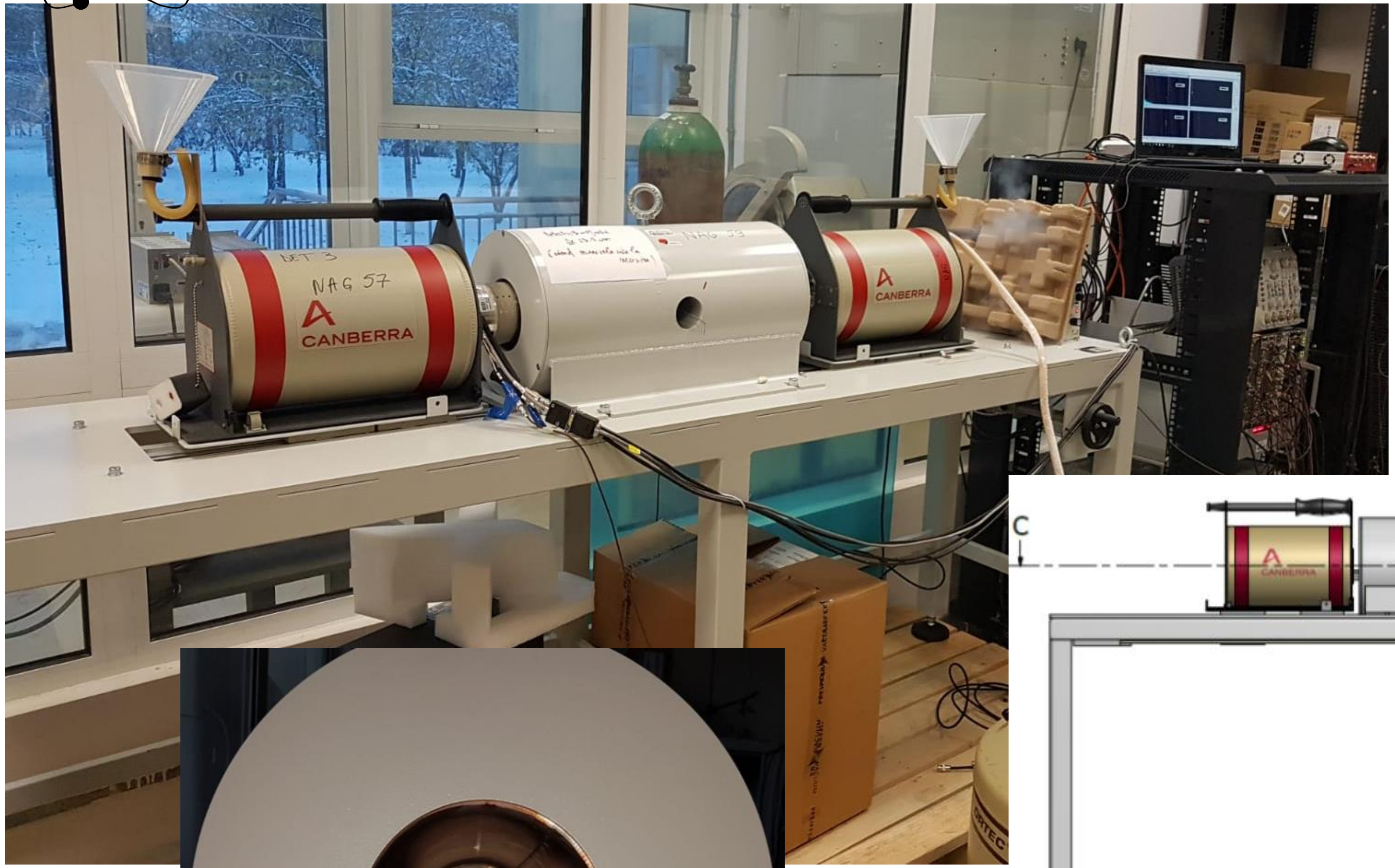
$^{16}O(^{13}C,2p)\,^{27}Mg$ - $T_{1/2}$ = 9.5 min

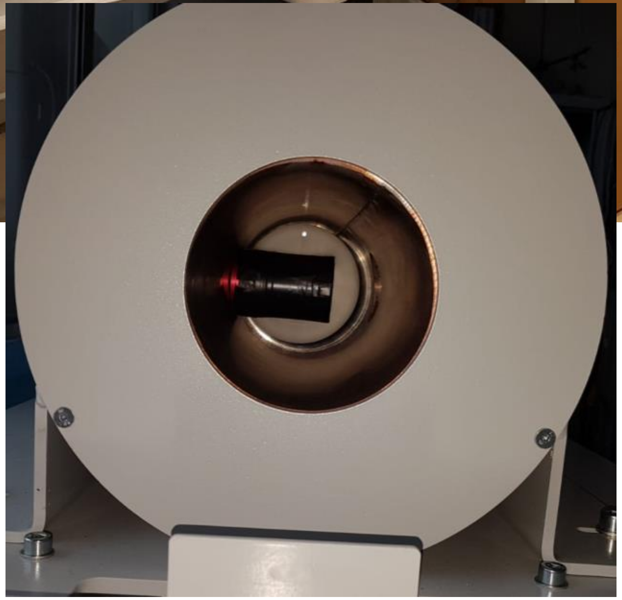
E_γ = 843.76 keV, 1014.52 keV

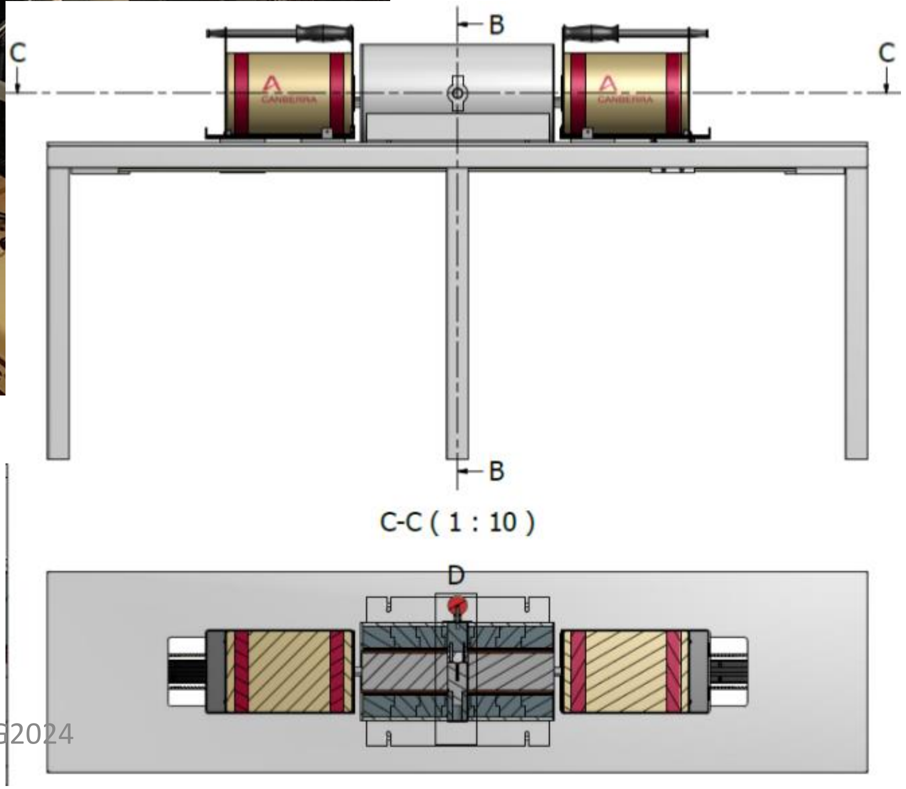
$^{13}C^{3,4,5+}$ beam @ 5 - 15 MeV and 0.2 – 3 eμA



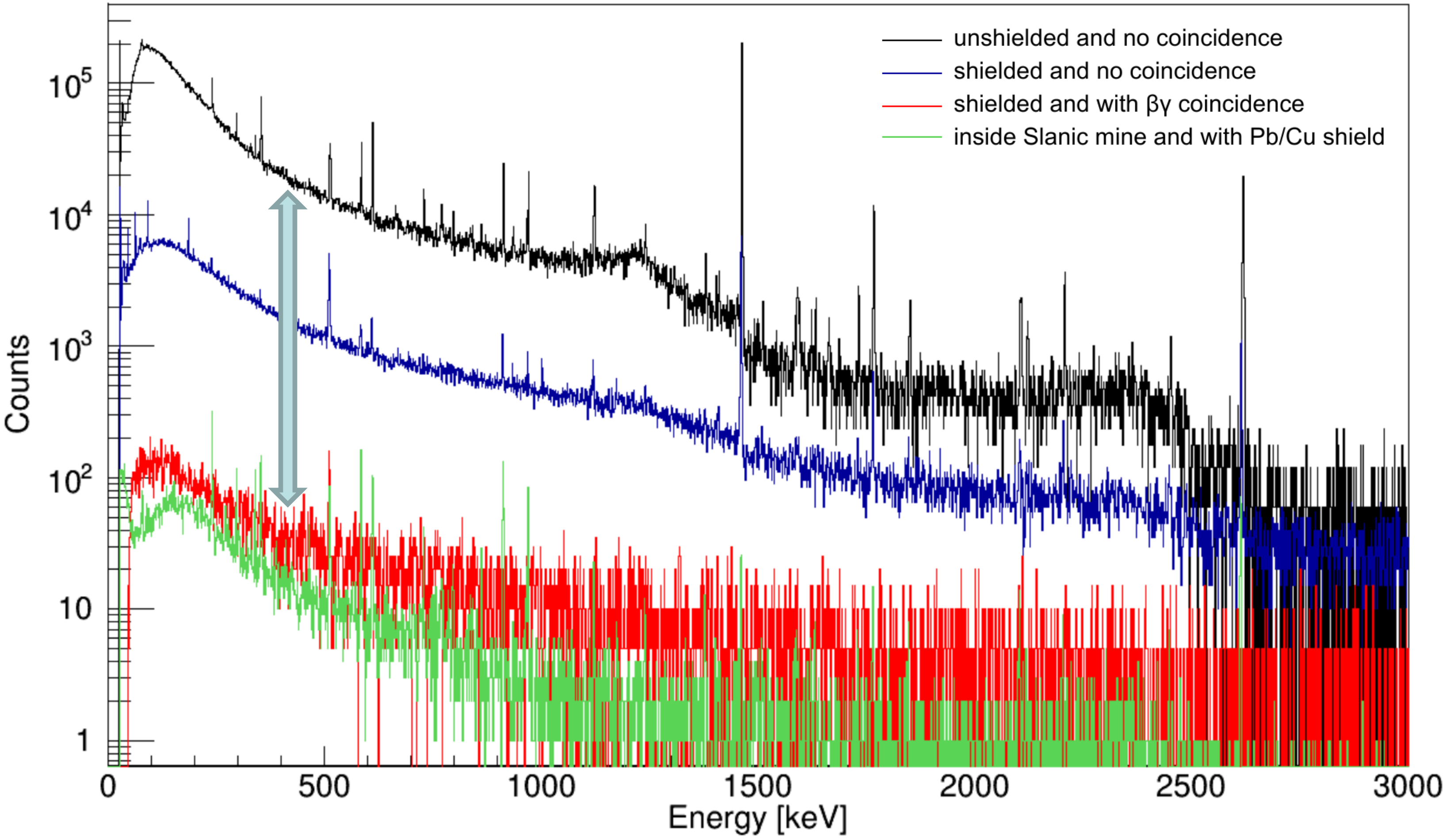
BeGa station (WIP)





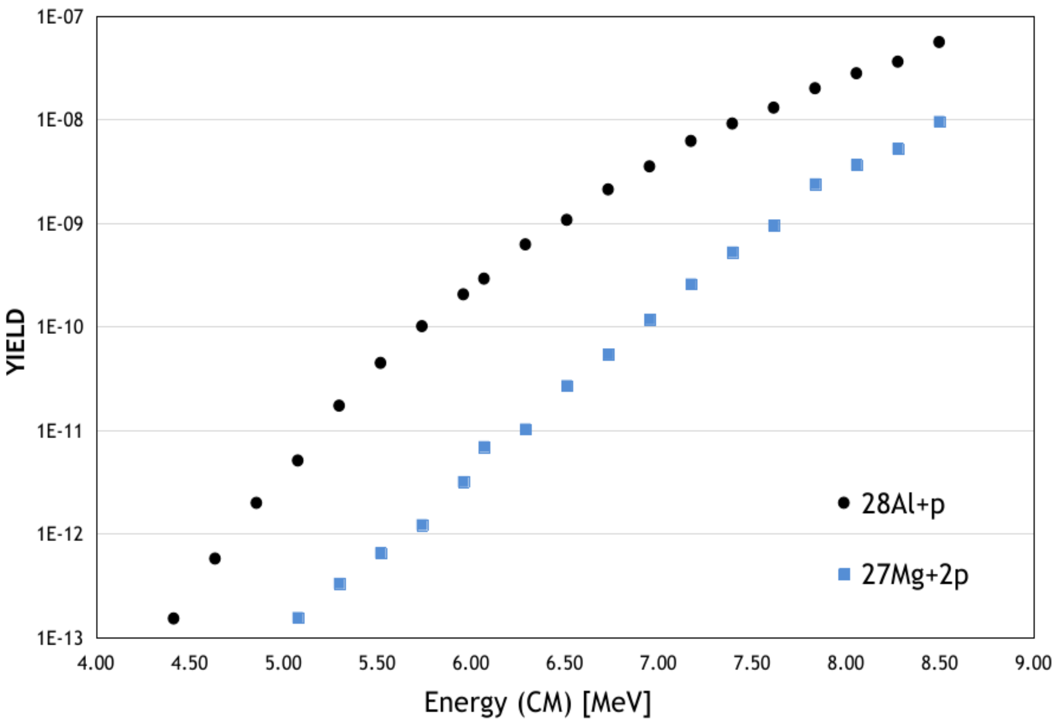


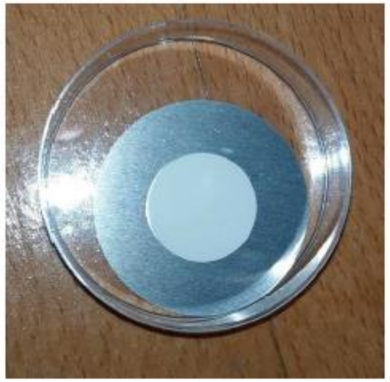
Background reduction ~ 1000 (red spectrum)



Further problems - targets
The $^{13}C+^{16}O$ Reaction – Preliminary results

CeO_2 targets





Alex Spiridon, PD grant (PN-III-P1-1.1-PD-2019-0234)

The $^{19}F+^{12,13}C$ Reaction

*Collaboration with L. Guardo et al @ INFN-LNS, through ChETEC-INFRA

In beam irradiation of thick targets followed by deactivation measurements

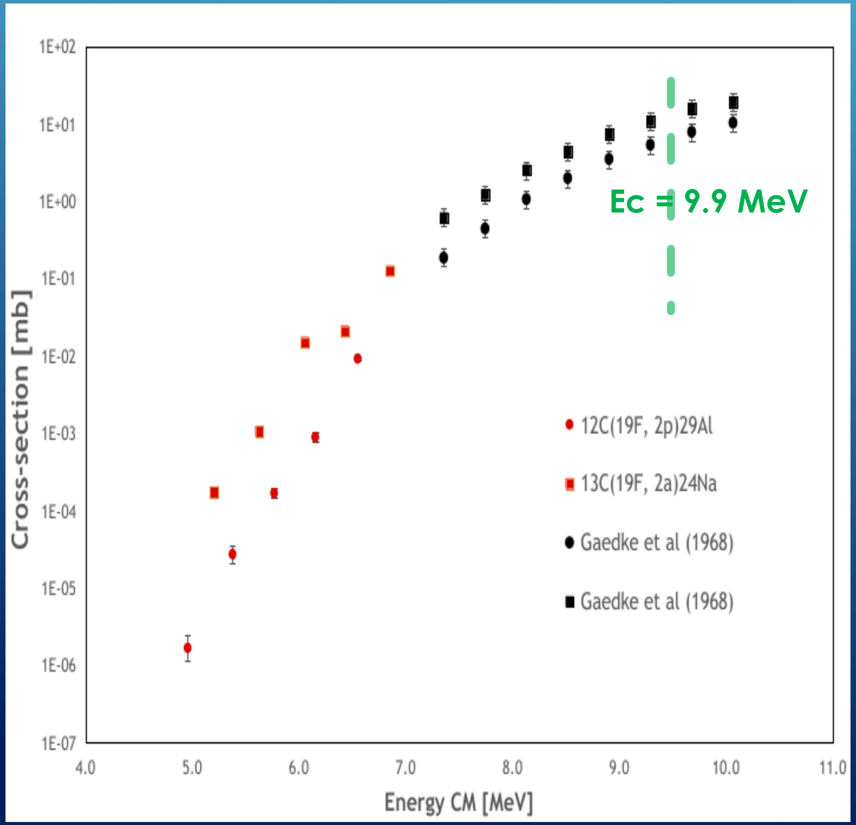
$^{19}F(^{12}C,2p)^{29}Al$ - $T_{1/2}$ = 6.5 min

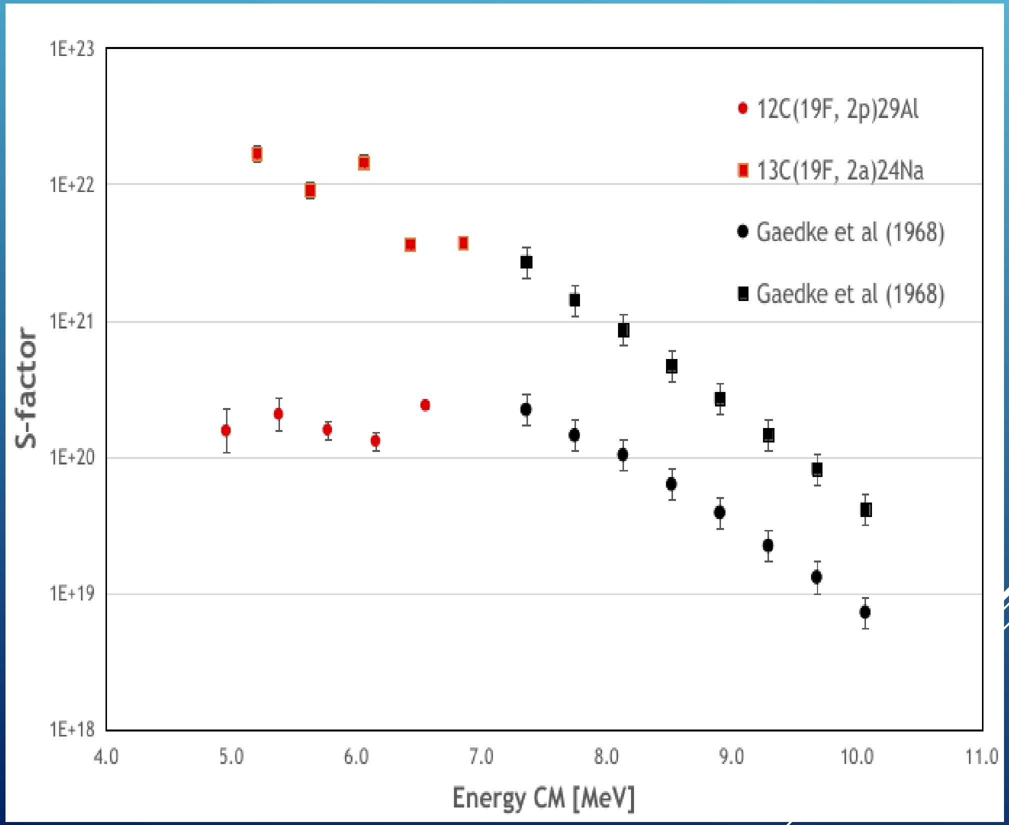
$^{19}F(^{13}C,2\alpha)^{24}Na$ - $T_{1/2}$ = 15 hrs

C or F beam @ 10 - 25 MeV and 0.2 – 20 μA

IFIN-HH

$^{19}F + ^{12,13}C$ – preliminary results





- No sign of hindrance, yet!
- Will proceed –
- next exp in Dec. 2024 – with IMP& Catania

Acknowledgements

- Collaborators:
  - NAG in E
    - Florin C
    - Alexan
    - Alexan
    - Dana T
    - Ionut S
    - Iuliana
    - Madali
  - MARS gr
  - RIKEN co
  - **AB2 coll** scovici (IFIN-HH)
- Acknowled
  - Grants fr PN1642(AIRIB, NAFRO,
  - DOE Gra

Carpathian Summer School of Physics 2020

Sinaia, Aug. 18-27, 2021

Carpathian Summer School of Physics 2023 in images

There will be **CSSP25**
after NIC June 22- July 3, 2025
Keep an eye on it, we will offer
fellowships for students!