Nuclear Astrophysics
Lecture 3

Overview of lectures

1. A little stellar astronomy
2. A bit more on scattering theory
3. $^{12}C(\alpha,\gamma)^{16}O$, some discussion, new results
4. $^{40}Ca(\alpha,\gamma)^{44}Ti$
5. $\mathbf{^{7}Be(p,\gamma)^{8}B}$ experiment
6. $^{7}Be(p,p)^{7}Be$
7. TACTIC
8. Radioactive beam experiments at TRIUMF

3rd lecture

$^{8}Li(\alpha,n)^{11}B$

r-process in entropy rich bubble of SNIIs starts out with nuclei disintegrated into nucleons, i.e. protons and neutrons. These recombine to form heavy elements with an excess of neutrons present. The mass 5 and 8 stability gaps have to be bypassed in the process.

Three possibilities: (i) 3α process;

(ii) $\alpha(\alpha,n\gamma)^{9}Be$

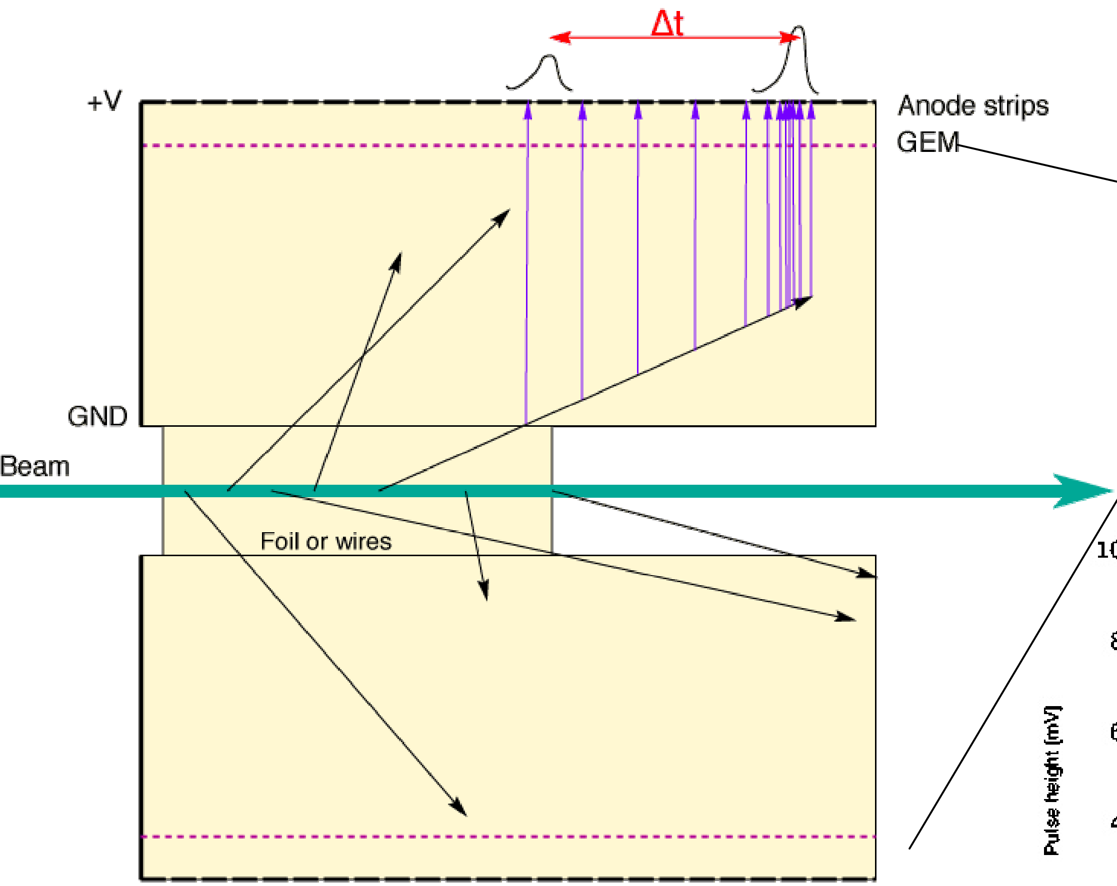
(iii) $\alpha(t,\gamma)^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B$

$T_9 = 0.62$ Gamow peak: $E_{c.m.}$ =240 to 580 keV

or E_{lab} = 90 to 220 keV/u

Lowest energy ISAC/TRIUMF: 120 keV/u

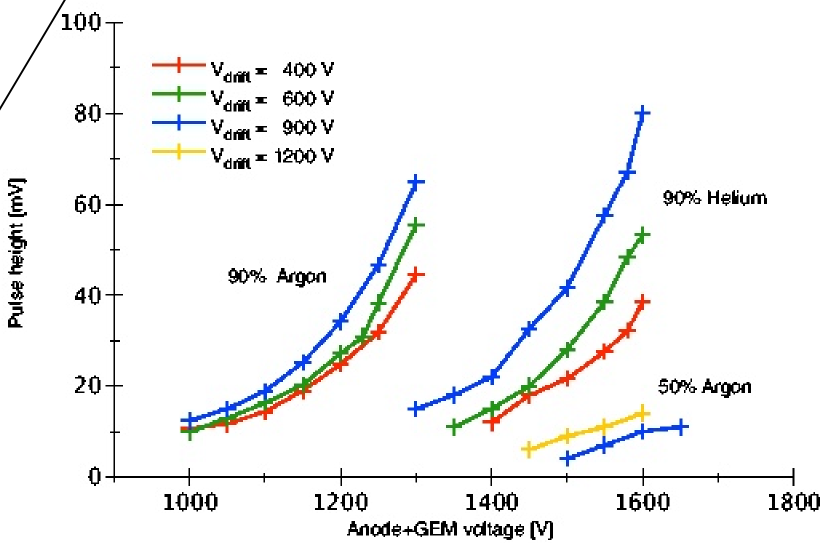
Tactic: Principle and Signals



TRIUMF Annular Cylindrical Tracing Ionization Chamber

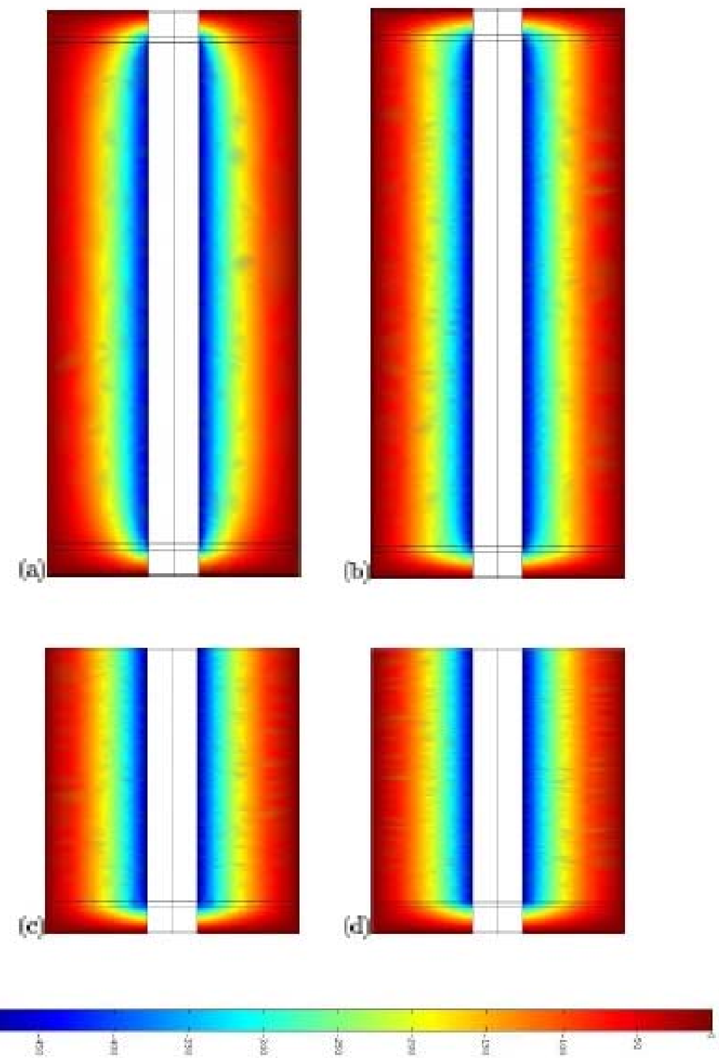
GEM (Gas Electron Multiplier) acts as preamplifier

Signals from Test Chamber

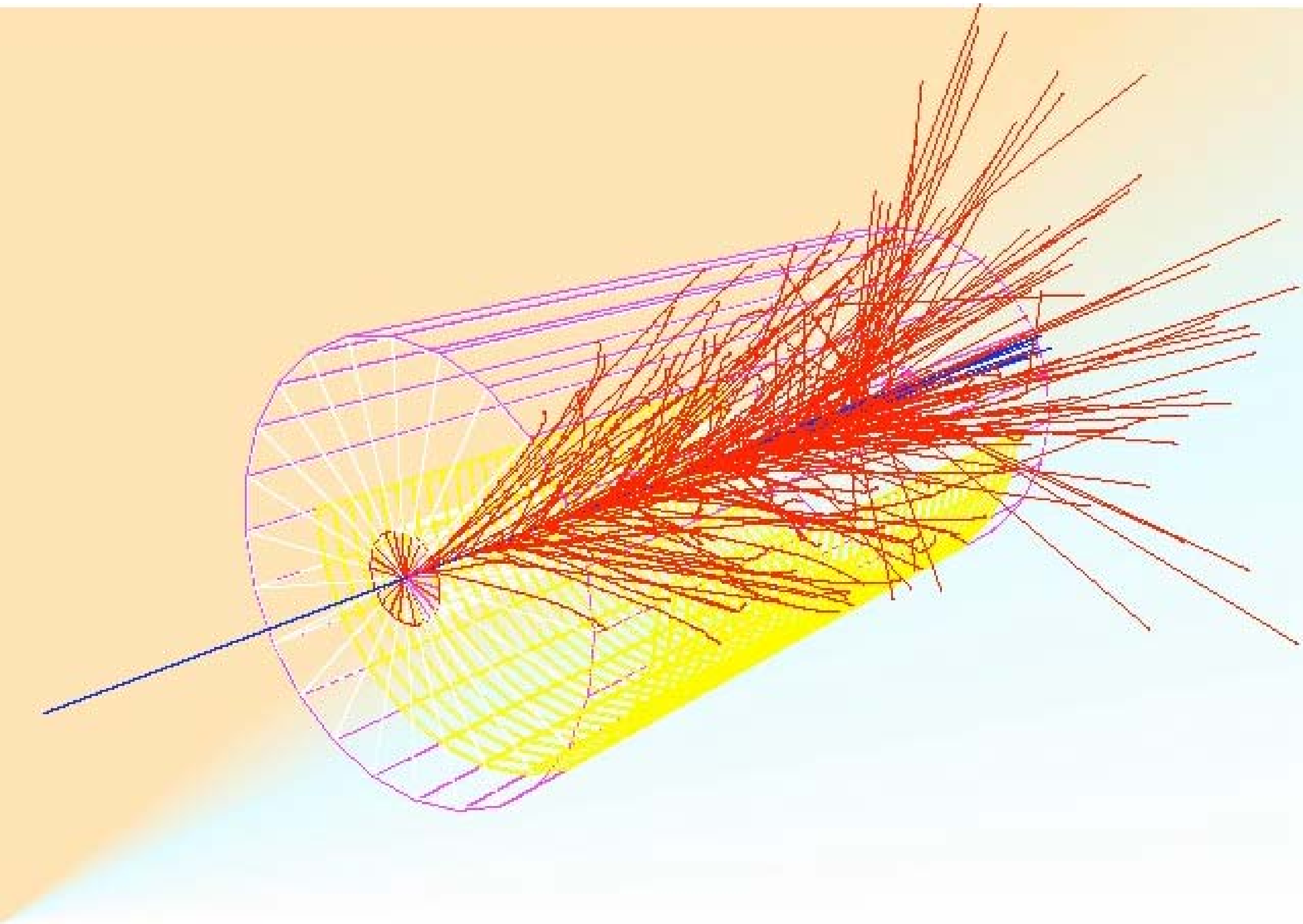


Tactic: electric field calculations

Field shaping with potential rings



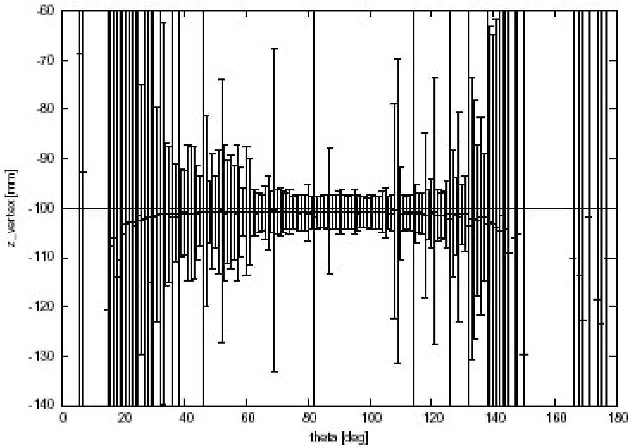
Tactic: GEANT simulations



$^{8}Li(\alpha, n)^{11}B$

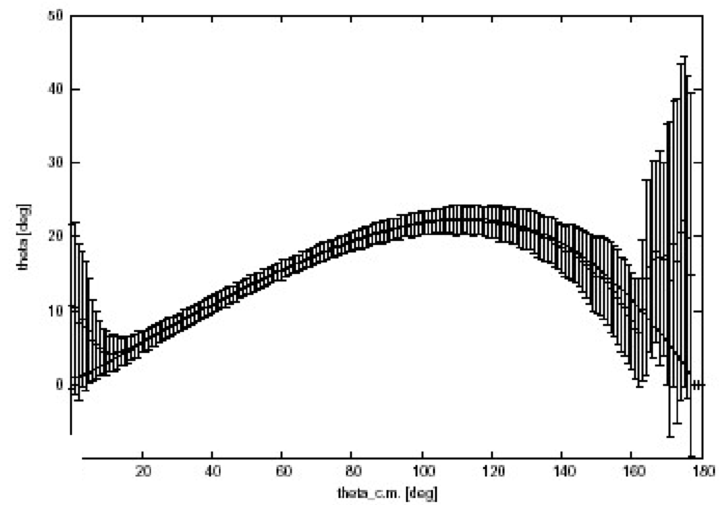
Ground state transition simulation.

TACTIC GEANT simulations

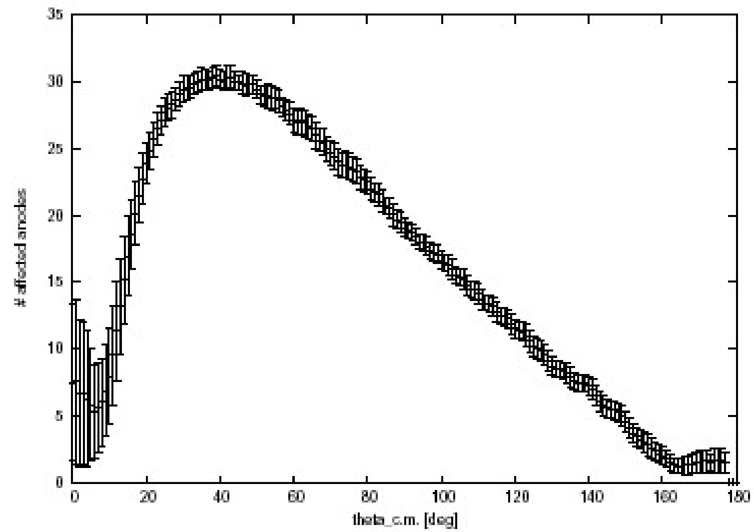


Vertex reconstruction

$^{8}Li(\alpha,n)^{11}B$

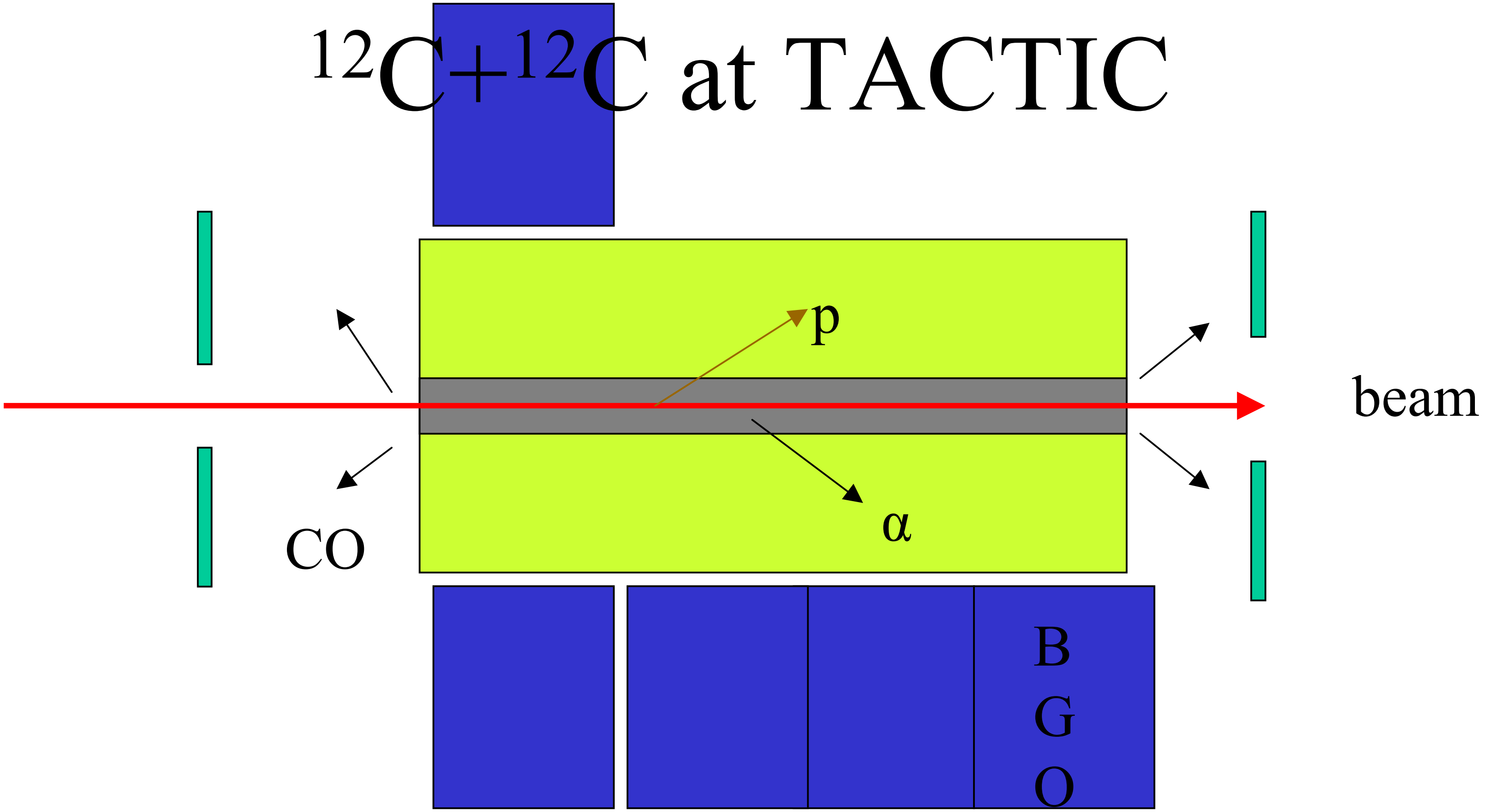


Angle reconstruction



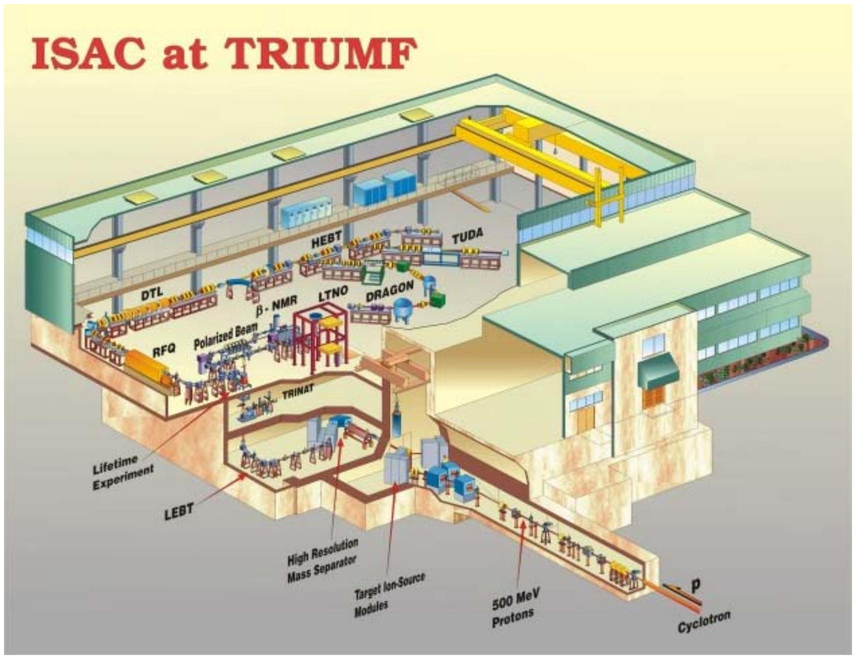
Number of anodes hit

$^{12}C+^{12}C$ at TACTIC



Windowless gas target

ISAC



Isotope Separator and ACelerator

Funded in 1995, first

radioactive beam (le) in 1998, first

accelerated beam in 2000.

Target and Target Hall

target hall

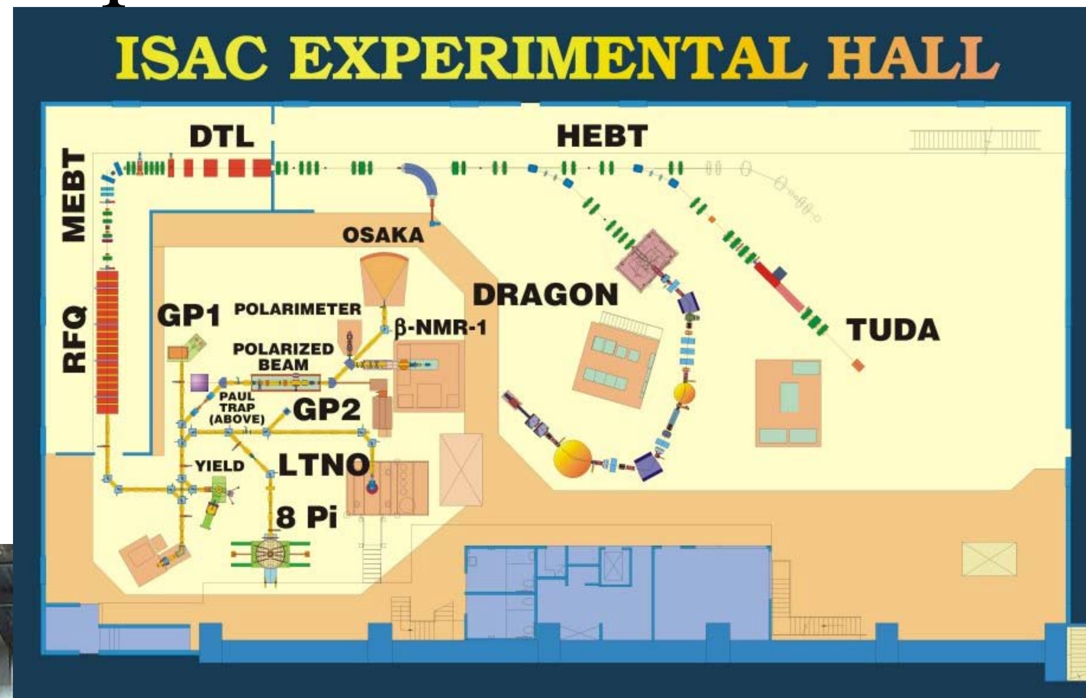
target plug

Isol principle

target assembly and extraction

ISAC-experimental hall

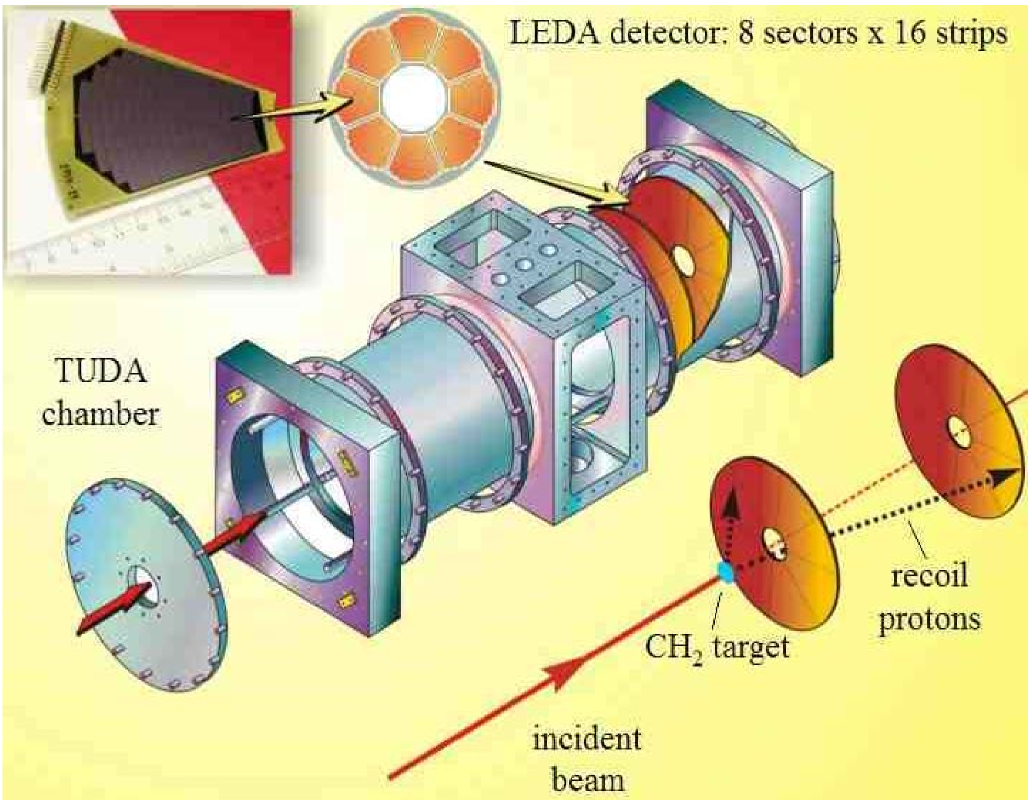
plan view

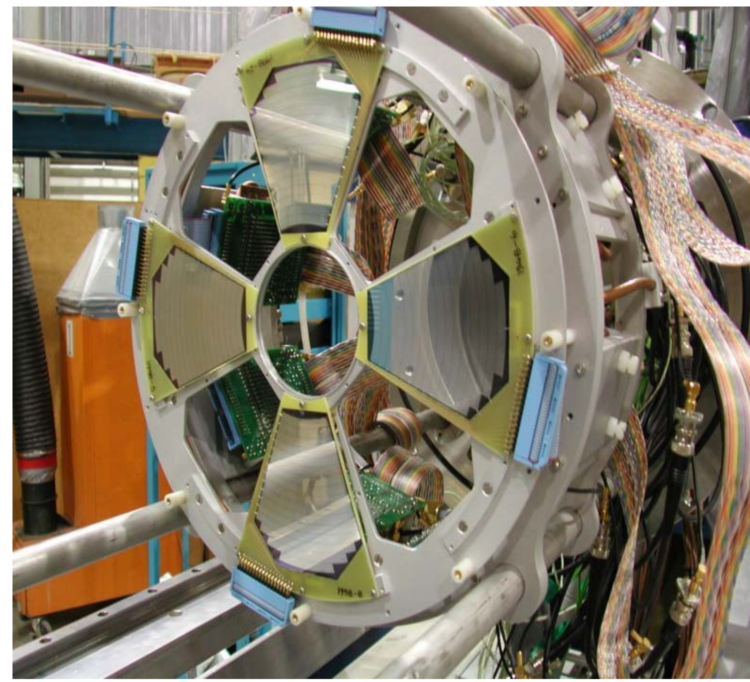


fish eye photograph

TUDA

TRIUMF UK Detector Array

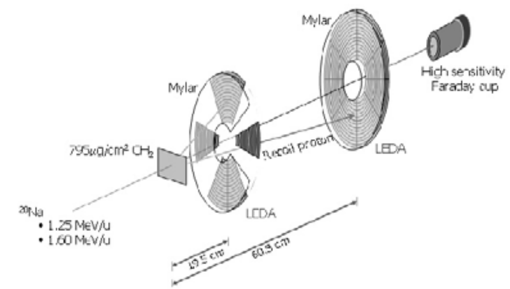




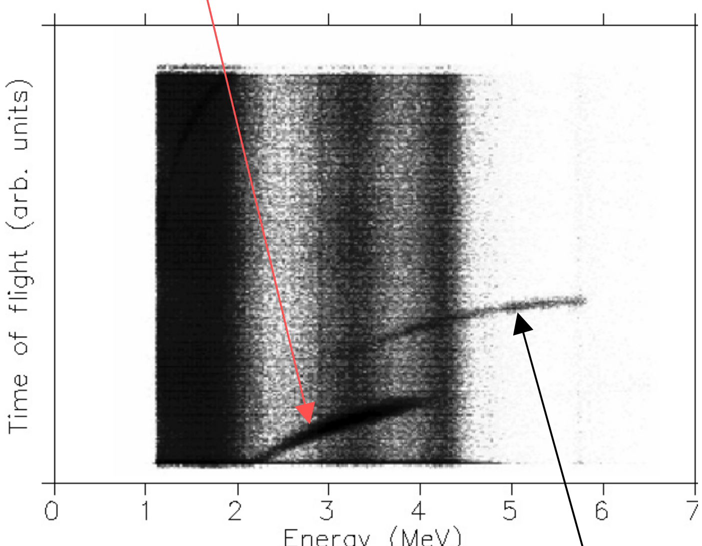
http://tuda.triumf.ca

Elastic scattering experiments

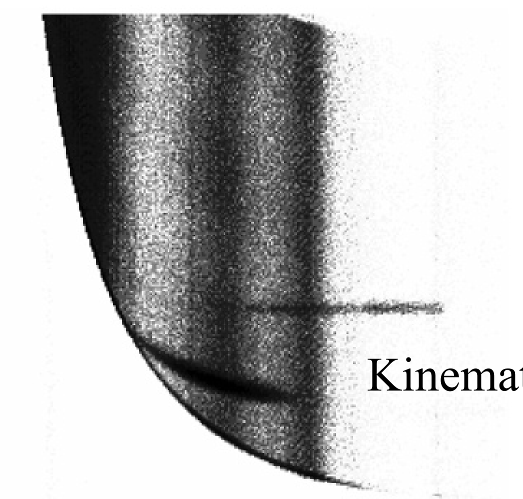
^{20}Na(p,p)^{20}Na, Energy-TOF spectra



Heavy ions



Proton events



Kinematic correction

CH_2 target

Multichannel *R*-matrix

The most general expression in *R*-matrix theory is given by the following:

$$\frac{d\sigma_{\alpha,\alpha'}}{d\Omega_{\alpha'}} = \frac{1}{(2I_1+1)(2I_2+1)} \sum_{ss'} (2s+1) \frac{d\sigma_{\alpha s,\alpha' s'}}{d\Omega_{\alpha'}}$$

The latter cross section can be written as a sum over a Coulombterm, a resonance term and an interference term:

$$\frac{d\sigma_{\alpha s,\alpha' s'}}{d\Omega_{\alpha'}} = \frac{\pi}{(2s+1)k_\alpha^2} \times (CT + RT + IT)$$

The Coulombterm is nearly identical to the scattering amplitude shown previoulsy. The resonance term is:

$$RT(\alpha s, \alpha' s') = \frac{1}{\pi} \sum_L B_L(\alpha s, \alpha' s') P_L(\cos(\theta_{\alpha'}))$$

Multichannel *R*-matrix

with

$$B_L(\alpha s,\alpha' s') = \frac{1}{4}(-)^{s-s'} \sum_{J_1 J_2 \ell_1 \ell_2 \ell'_1 \ell'_2} \overline{Z}(\ell_1 J_1 \ell_2 J_2, sL)\overline{Z}(\ell'_1 J_1 \ell'_2 J_2, sL)(T^{J_1}_{\alpha s\ell_1,\alpha' s'\ell'_1})(T^{J_2}_{\alpha s\ell_2,\alpha' s'\ell'_2})^*$$

with the *Z* coefficients of above and the transition matrix *T* as:

$$T^{J_1}_{\alpha s\ell,\alpha' s'\ell'} = e^{2i\omega_{\alpha\ell}}\delta_{\alpha s\ell,\alpha' s'\ell'} - U^{J_1}_{\alpha s\ell,\alpha' s'\ell'}$$

with the scattering matrix *U* of above. The interference term is then:

$$IT(\alpha s) = -\delta_{\alpha s\ell,\alpha' s'\ell'} \frac{1}{\sqrt{4\pi}} \sum_{JL} (2J+1) 2\,\mathrm{Re}[i(T^{J_1}_{\alpha s\ell,\alpha' s'\ell'})^* C_{\alpha'}(\theta_{\alpha'}) P_L(\cos\theta_{\alpha'})$$

With *C* being the Coulombterm.

Multichannel *R*-matrix

The scattering matrix can be expressed in *R*-matrix as:

$$U_c^J = e^{i(\Omega_c + \Omega_{c'})}\{\delta_{cc'} + 2iP_c^{1/2}\sum_{\lambda\mu}\gamma_{\lambda c}^J \gamma_{\mu c}^J A_{\lambda\mu}^J P_{c'}^{1/2}\}$$

The summation runs over states. It is

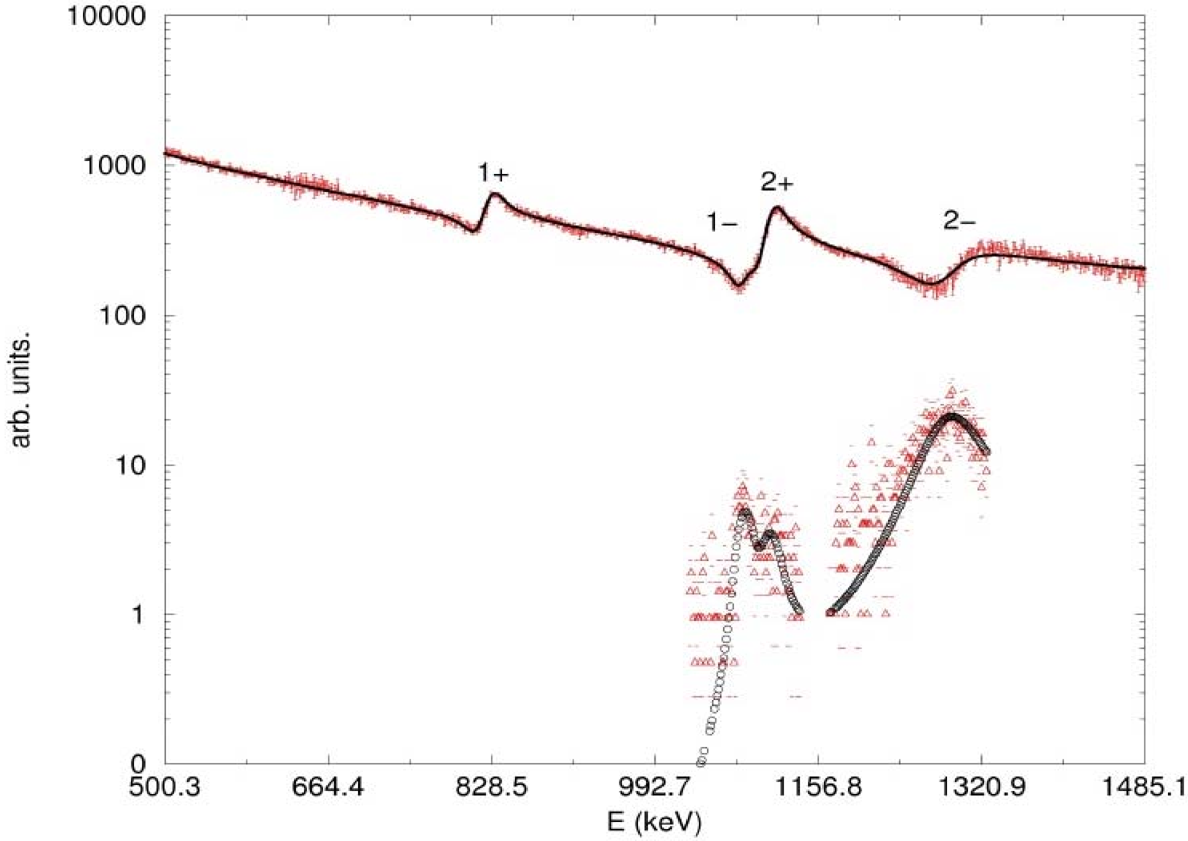
$$\Omega_c \equiv \omega_c - \phi_c \qquad \phi_c = \arctan(\frac{F_c}{G_c})$$

And the inverse of the state matrix:

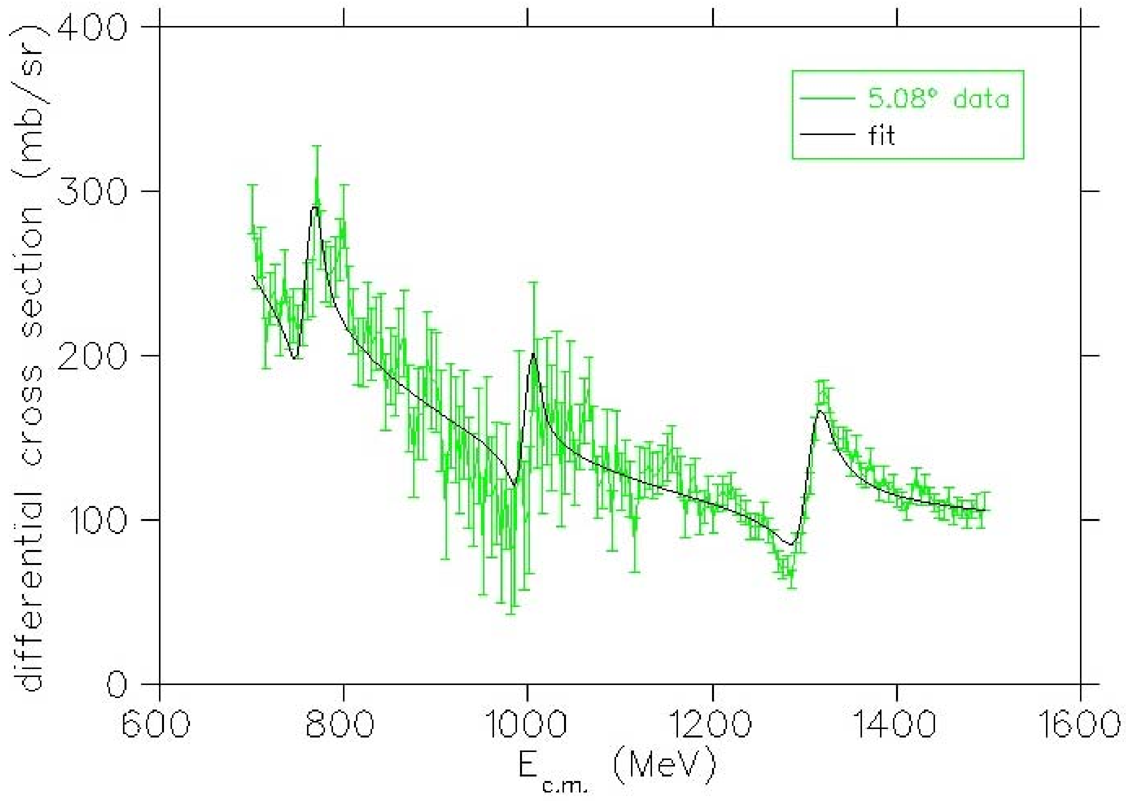
$$(A^{-1})_{\lambda\mu}^J = (E_\lambda^J - E)\delta_{\lambda\mu} - \sum_c \gamma_{\lambda c}^J \gamma_{\mu c}^J (S_c - B_c + iP_c)$$

Results of $^{21}Na(p,p)^{21}Na$

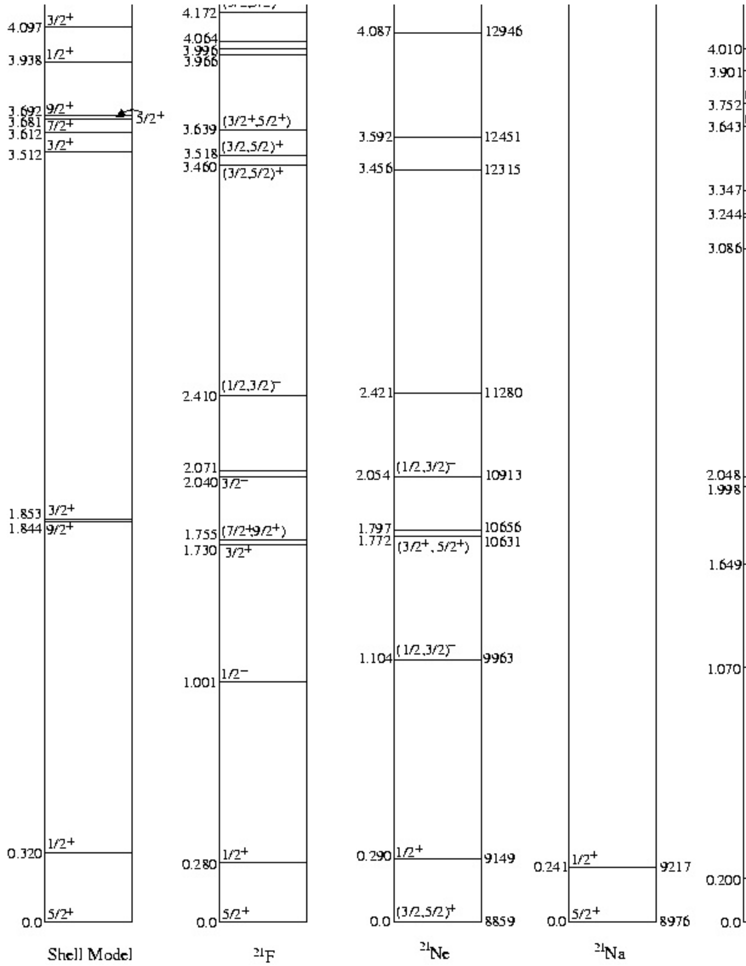
Elastic
and
inelastic
channel



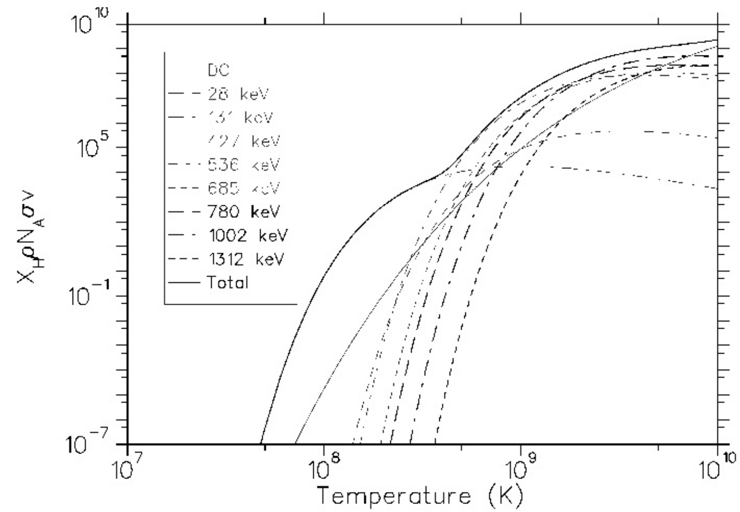
Results of $^{20}Na(p,p)^{20}Na$



Results of ^{20}Na(p,p)^{20}Na



Stellar reaction rates



Analogue nuclei, T=3/2

Test of gas target for E870

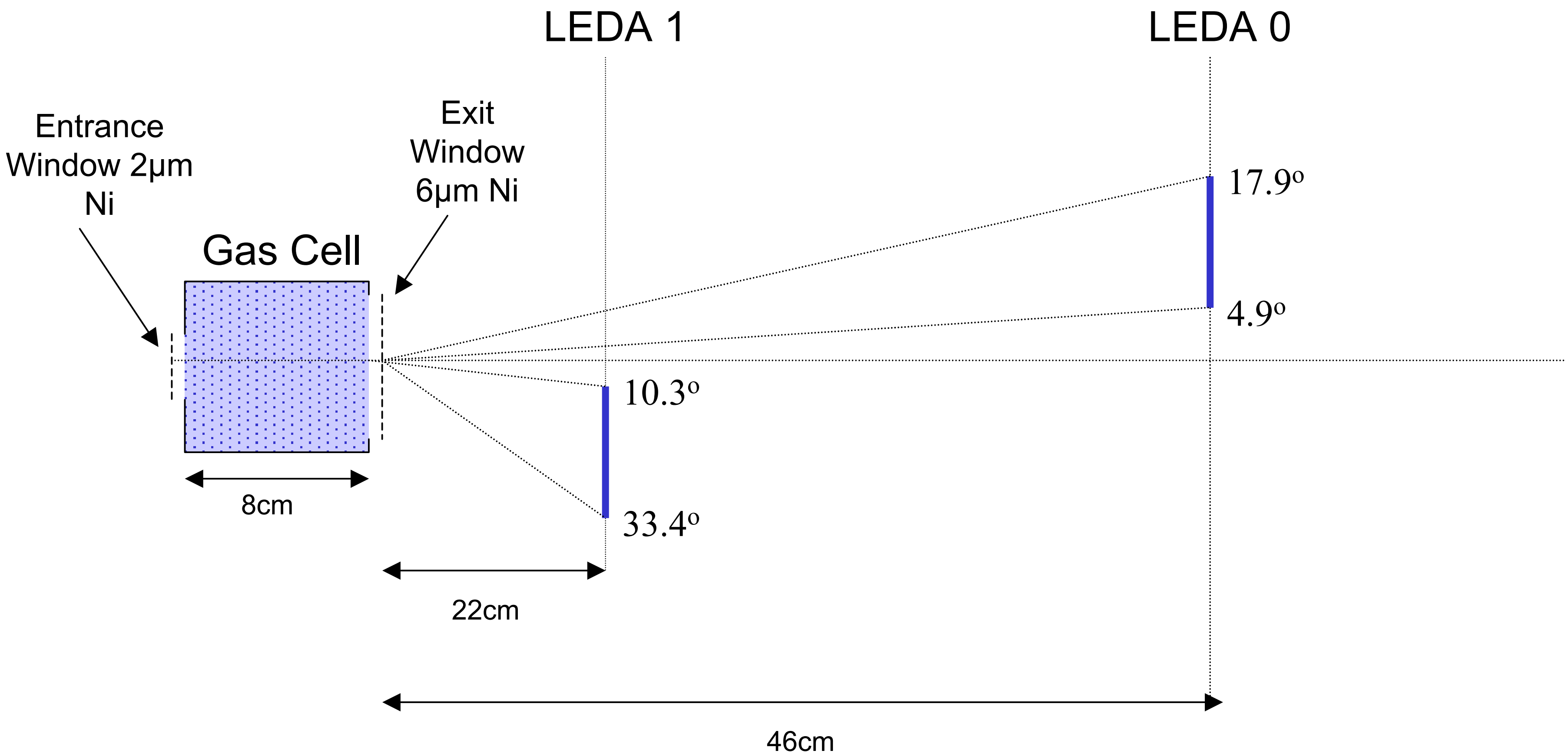
E870 is a measurement of the **$^{18}Ne(\alpha,p)^{21}Na$** reaction, a key to breakout from the Hot-CNO cycle in X-ray bursters.

The measurement requires a helium gas target and this measurement was designed to test this target and the analysis technique

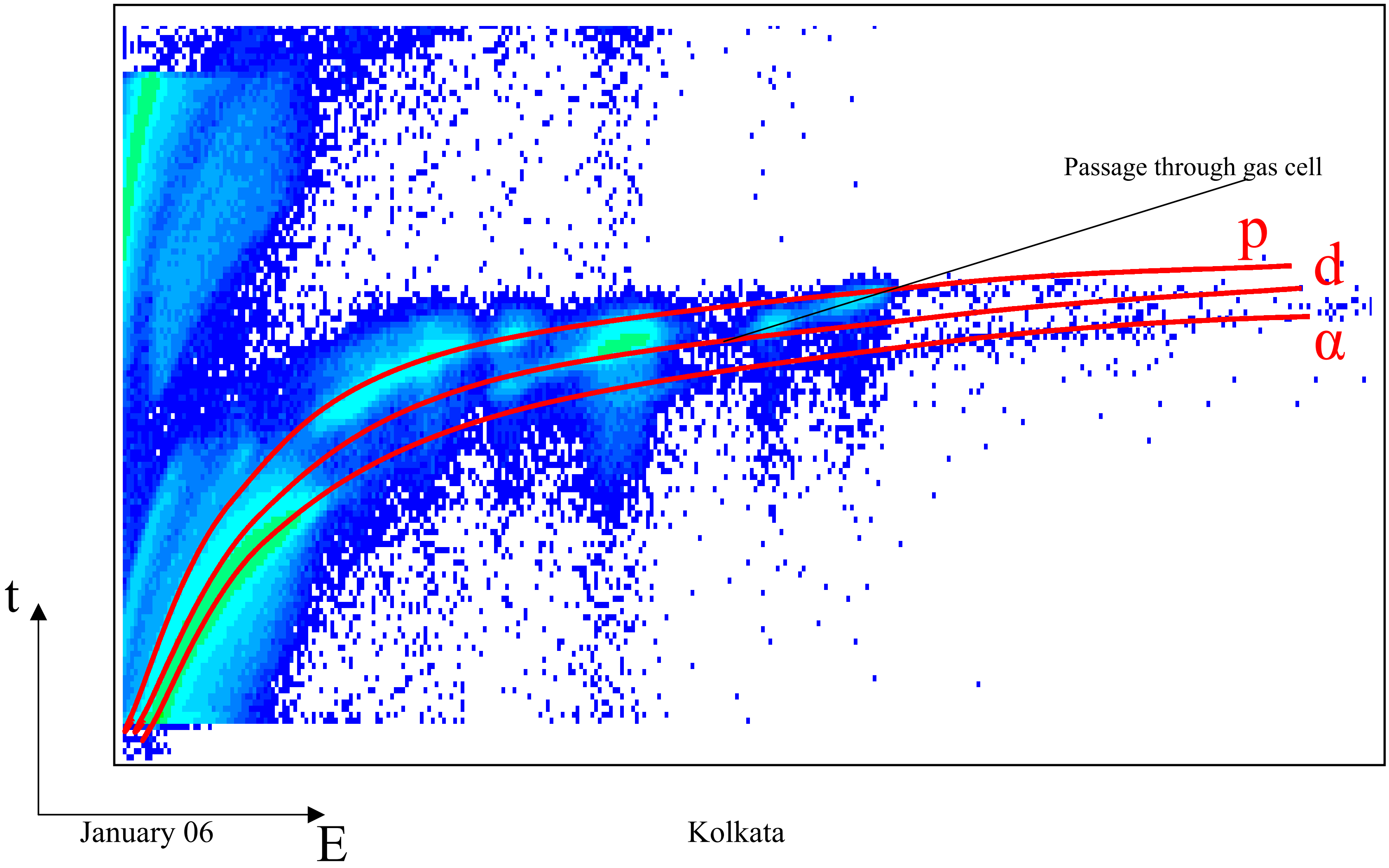
The test was performed using the $^{10}B(\alpha,p)^{13}C$ reaction which has similar kinematics and similar energy protons to the ^{18}Ne measurement

One week of running using the TUDA chamber and two LEDA detector sectors

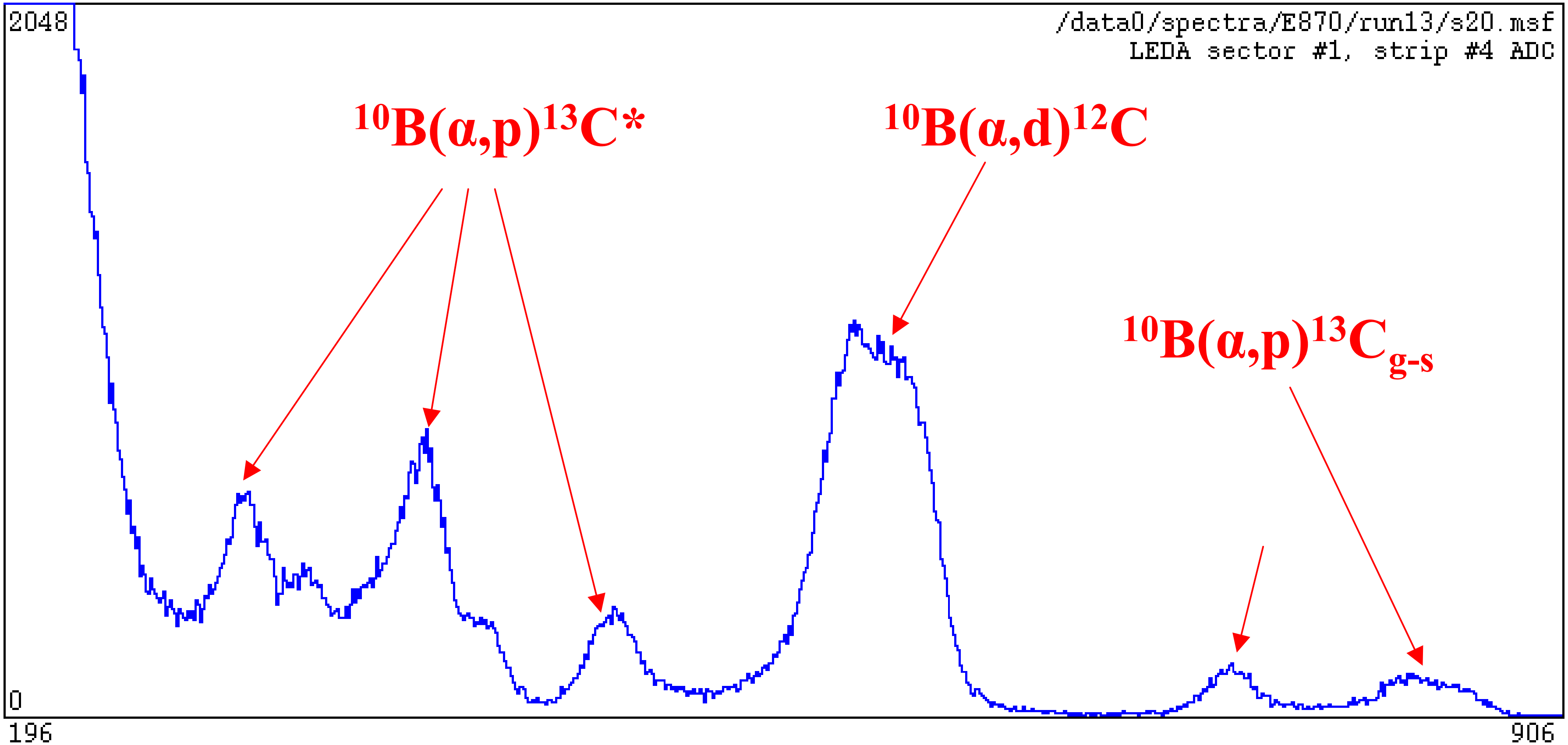
Test setup


LEDA 1
LEDA 0
Entrance Window 2μm Ni
Exit Window 6μm Ni
Gas Cell
17.9°
4.9°
10.3°
33.4°
8cm
22cm
46cm

Energy-TOF spectra

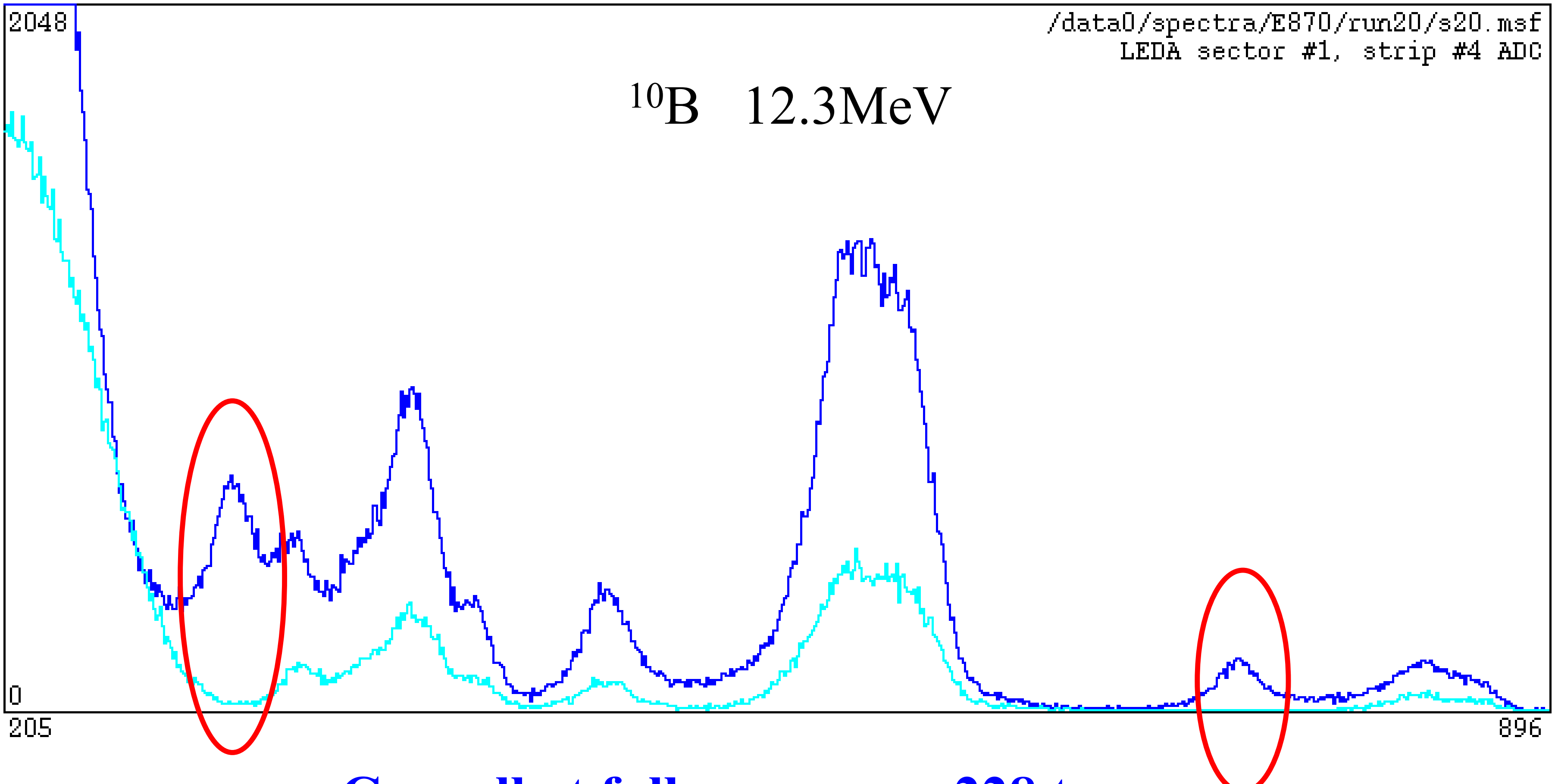


`Proton' cut spectrum



^{10}B 12.3MeV Gas Cell at full pressure (228 torr)

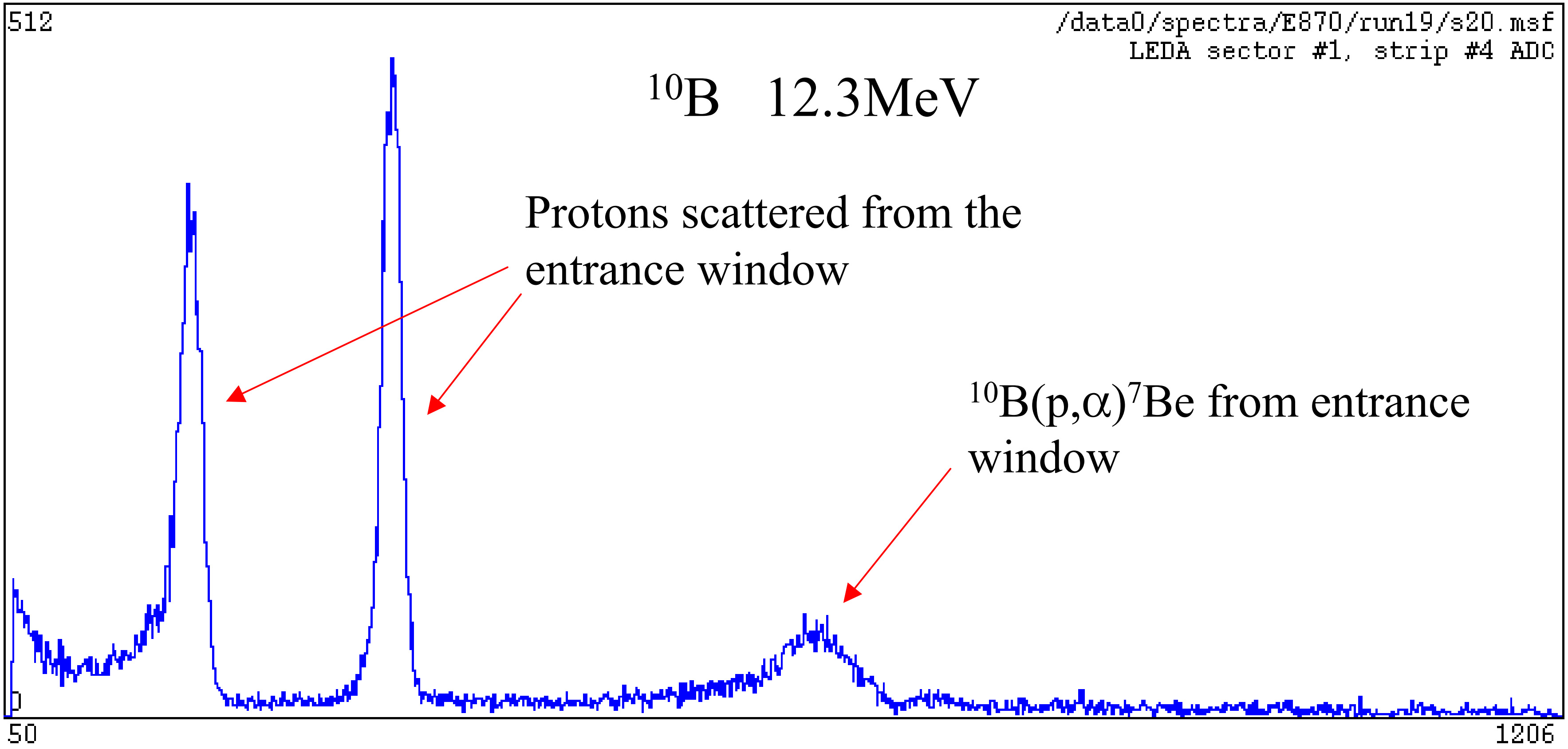
Reducing pressure



Gas cell at full pressure = 228 torr

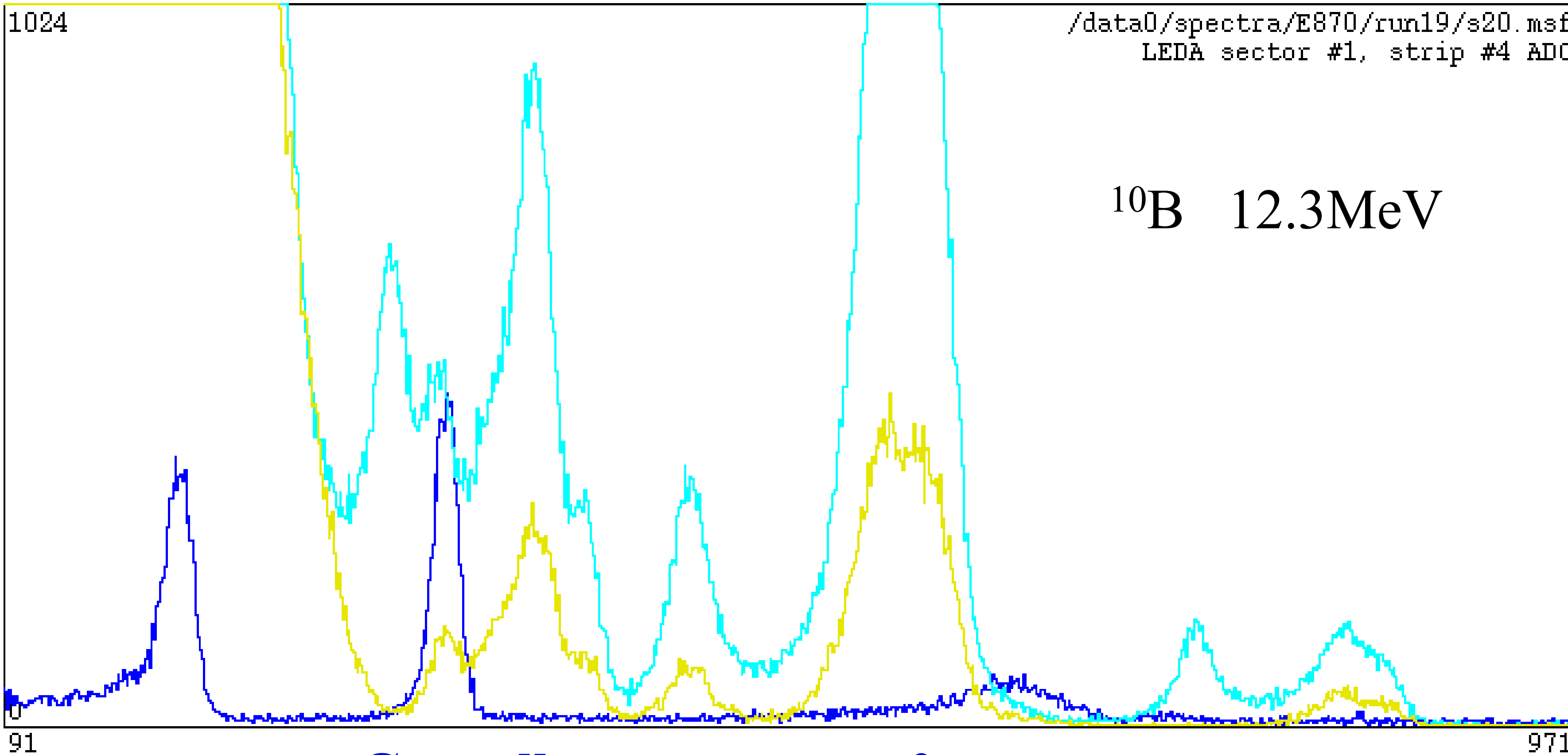
Gas cell at half pressure = 114 torr

Background



Gas Cell at vacuum

Background-data overlay



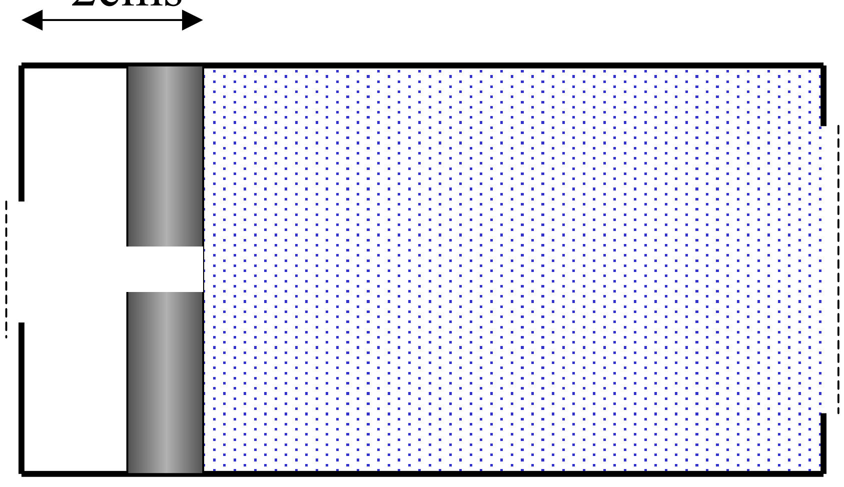
Gas cell at vacuum = ~0 torr

Gas cell at half pressure = 114 torr

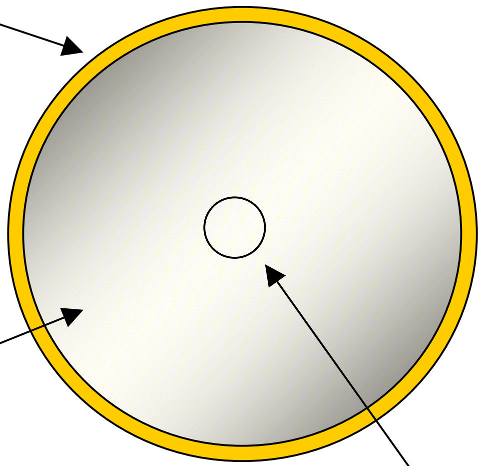
Gas cell at full pressure = 228 torr

Background reduction tool

Position in gas cell:



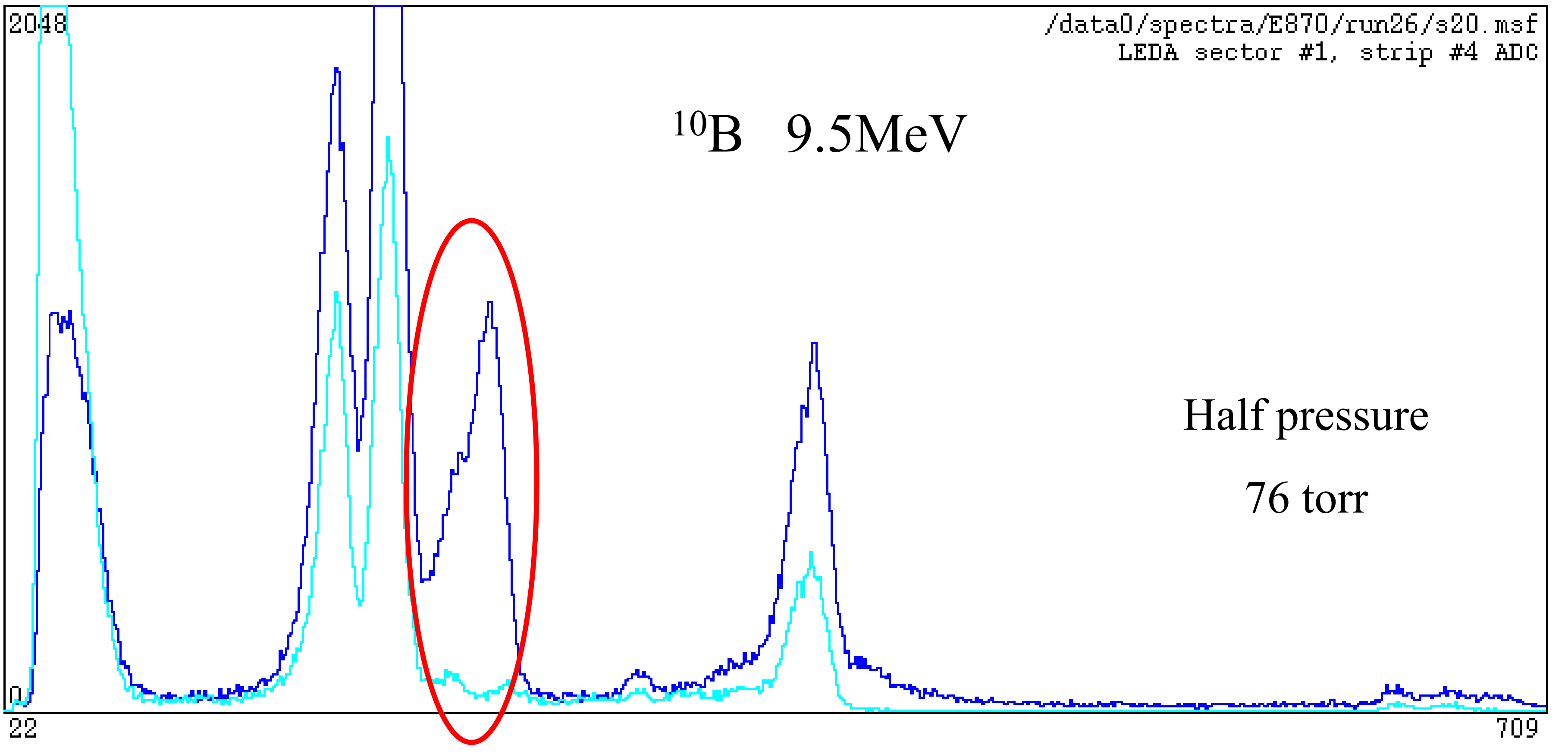
Front face view:



BaRT

(**Ba**ckground **R**eduction **T**ool)

Overlay with/without BaRT



Gas Cell without BaRT

Gas cell with BaRT

The $^{21}Na(p,\gamma)^{22}Mg$ Reaction

- First direct radioactive beam measurement of the reaction rate, populating the 5.714 MeV level in ^{22}Mg
- Measured resonance energy and the resonance strength
  - $E_{cm} = 205.7 \pm 0.5$ keV
  - $\omega\gamma = 1.03 \pm 0.21$ meV

S. Bishop *et al*., PRL **90**, 162501 (2003).

DRAGON
Summary of $^{21}Na(p,\gamma)^{22}Mg$

Resonance Strengths and Energies

E_x (keV)	E_{cm} (keV)	Γ (keV)	ωγ (meV)
5714	205.7 ± 0.5		1.03 ± 0.21
5837	329		≤ 0.29
5962	454 ± 5		0.86 ± 0.29
6046	538 ± 13		11.5 ± 1.4
6246	738.4 ± 1.0		219 ± 25
6329	821.3 ± 0.9	16.1 ± 2.8	556 ± 77
6609	1101.1 ± 2.5	30.1 ± 6.5	368 ± 62

J.M. D'Auria *et al*., PRC **69**, 065803 (2004).

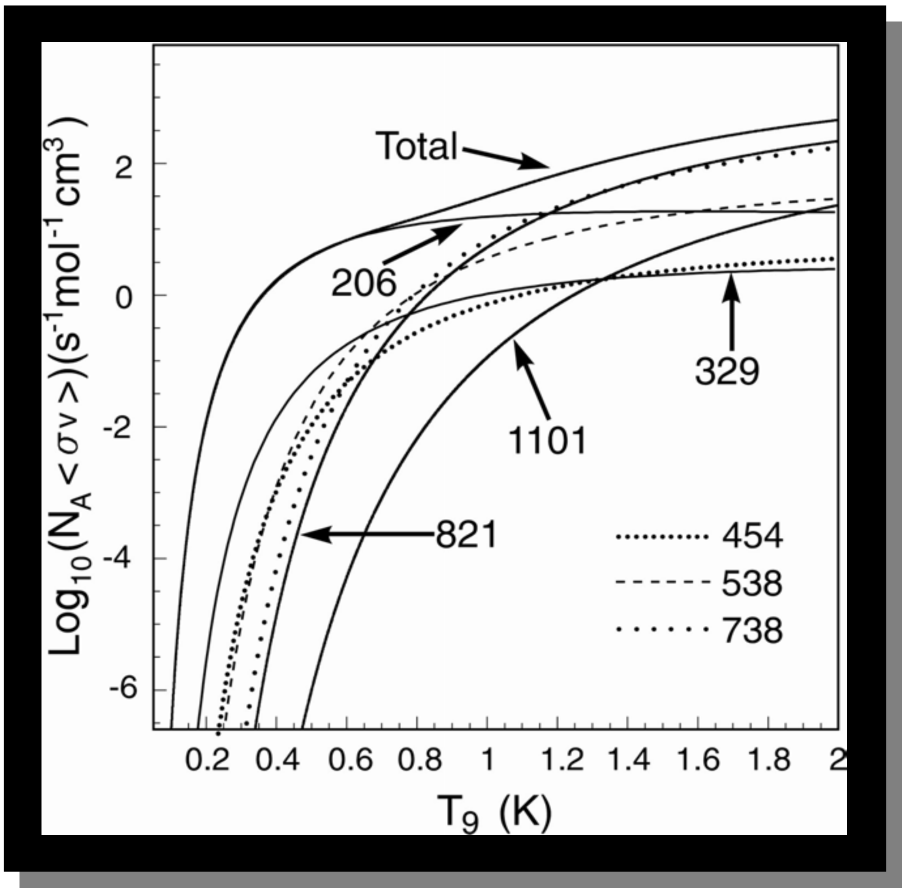
γ-γ Correlation Analysis

- Received 10^9 ^{21}Na per second from ISAC onto H_2 gas target
- Detect multiple gammas in the BGO array
- Propose decays and spin assignments, guided by analogue states in the mirror nucleus ^{22}Ne
- working on using our GEANT simulation to possibly extract branching ratios

C.C. Jewett, Ph.D. thesis, Colorado School of Mines.

The three Resonances

Contributions to the Reaction Rate



- Extended the measurements to other states, deduced their contributions to the reaction rate and their impact on ^{22}Na production in ONe novae and x-ray bursts

J.M. D'Auria *et al*., PRC **69**, 065803 (2004).

^{22}Mg γ-γ Analysis Results

^{22}Mg			Mirror Nucleus ^{22}Ne[b]	
E_x (keV)[a]	Level (keV)	Proposed J$^{\pi}$	Level (keV)	J$^{\pi}$
1101.1 ± 2.5	6609	2+	6817	2+
821.3 ± 0.9	6329	1+	6853	1+
738.4 ± 1.0	6246	4+	6345	4+
~1079	6587			

[a] J.M. D'Auria *et al*., PRC **69**, 065803 (2004).
[b] R.B. Firestone, Table of Isotopes, 8th Edition, 1996.

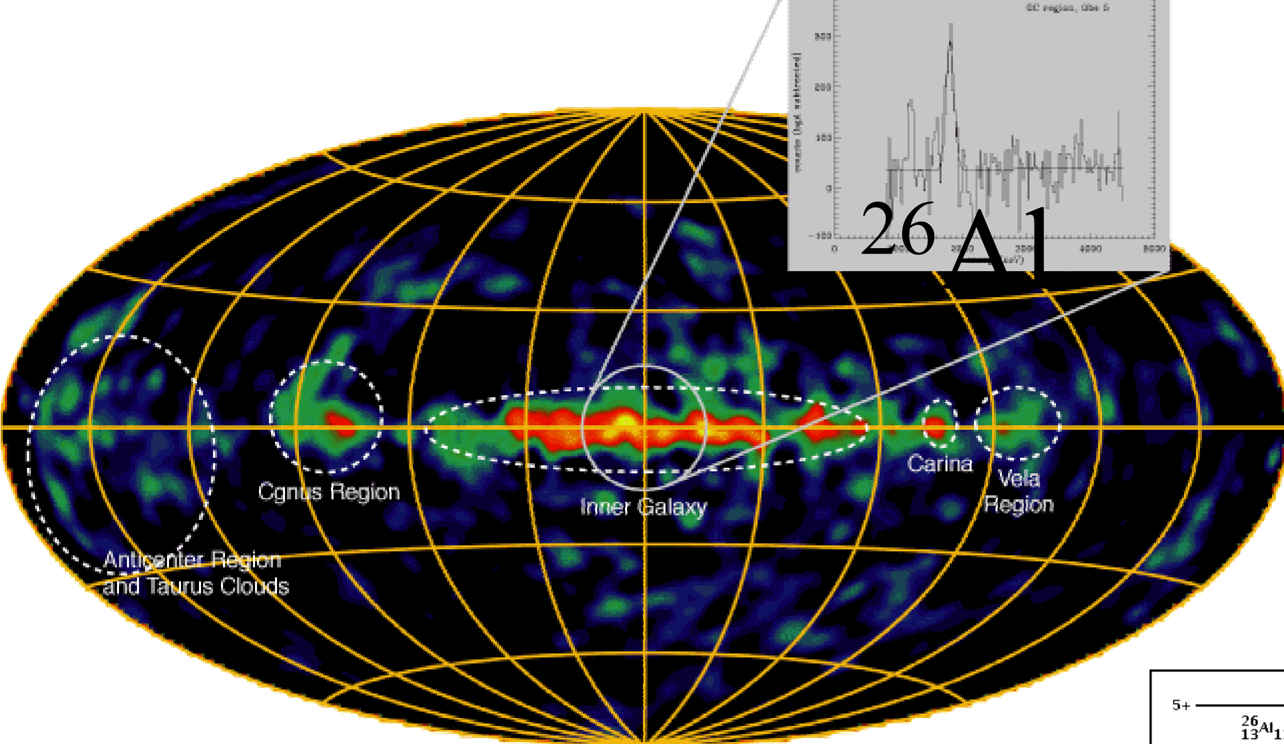
Consistent with results from the TUDA group:

C. Ruiz *et al*., PRC **65**, 042801(R) (2002).
C. Ruiz, Ph.D. Thesis, University of Edinburgh (2003).

Revisiting the 1101 keV resonance

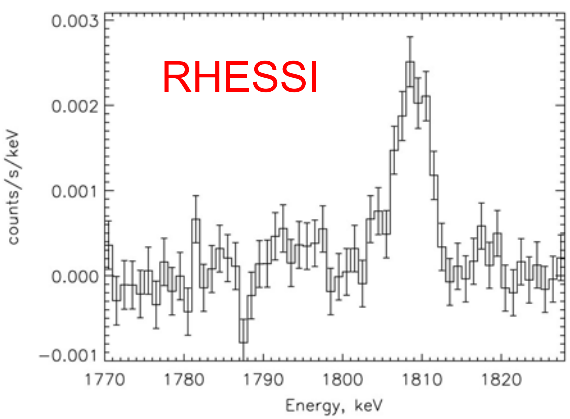
- Different gamma distribution at the low-energy tail
- TUDA suggested ~1080 keV
- Extended our measurements down to lower energy
  - See resonance
  - Twice as intense

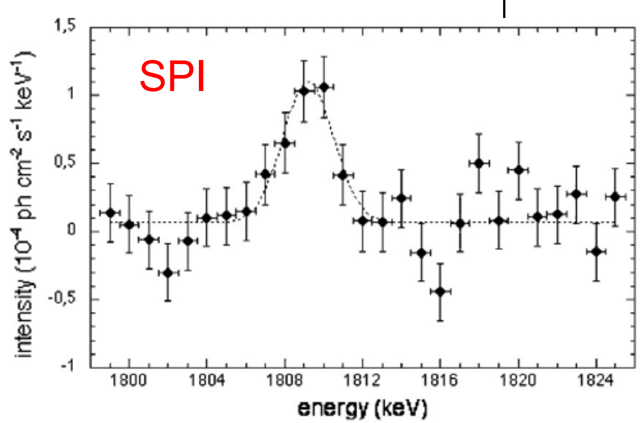
C.C. Jewett, Ph.D. thesis, Colorado School of Mines.

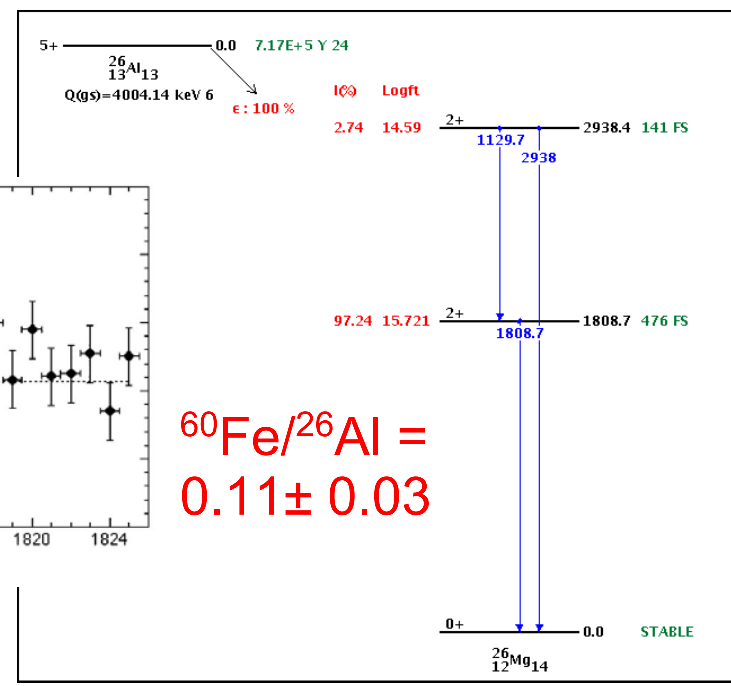


- $t_{1/2}$ = 717,000 yr
- E_γ = 1809 keV

- COMPTEL → $2M_\odot$
- RHESSI, INTEGRAL
- SN II, Wolf-Rayet
  - SNII H-Shell and O-Ne shell
- AGB, Novae (ONe)?







$^{60}Fe/^{26}Al$ = 0.11± 0.03

January 06

Kolkata

- José, Coc, Hernanz (1999)
  - 0.4 $M_{\odot}$ ^{26}Al from ONe Novae

- For Novae –

  ^{21}Na(p,γ)^{22}Mg,

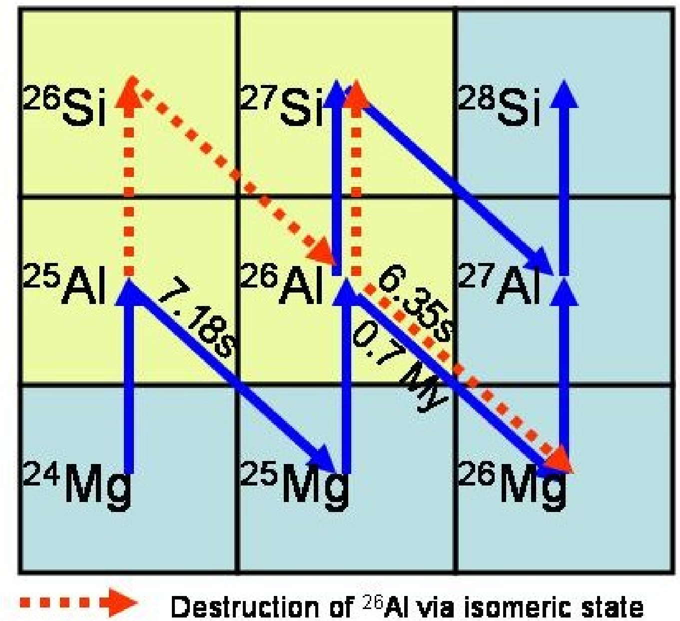
  ^{25}Al(p,γ)^{26}Si,

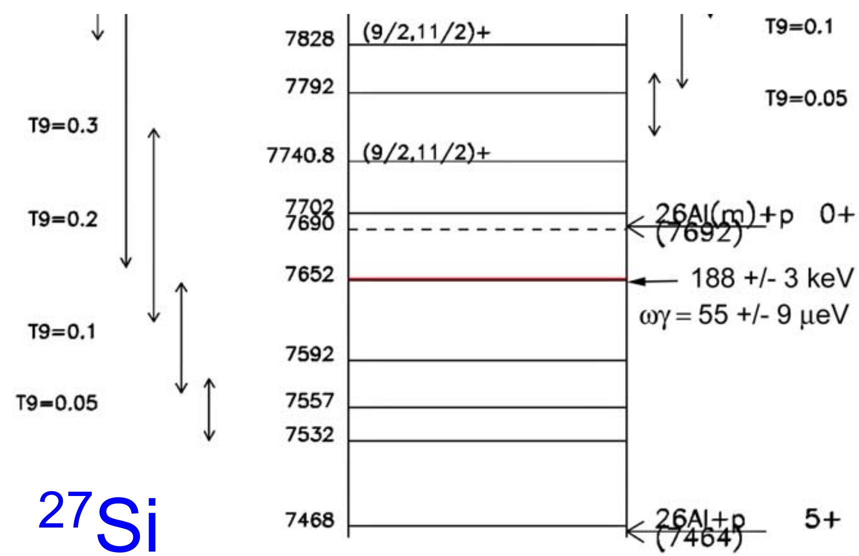
  ^{23}Na(p,γ)^{24}Mg,

  ^{22}Na(p,γ)^{23}Mg

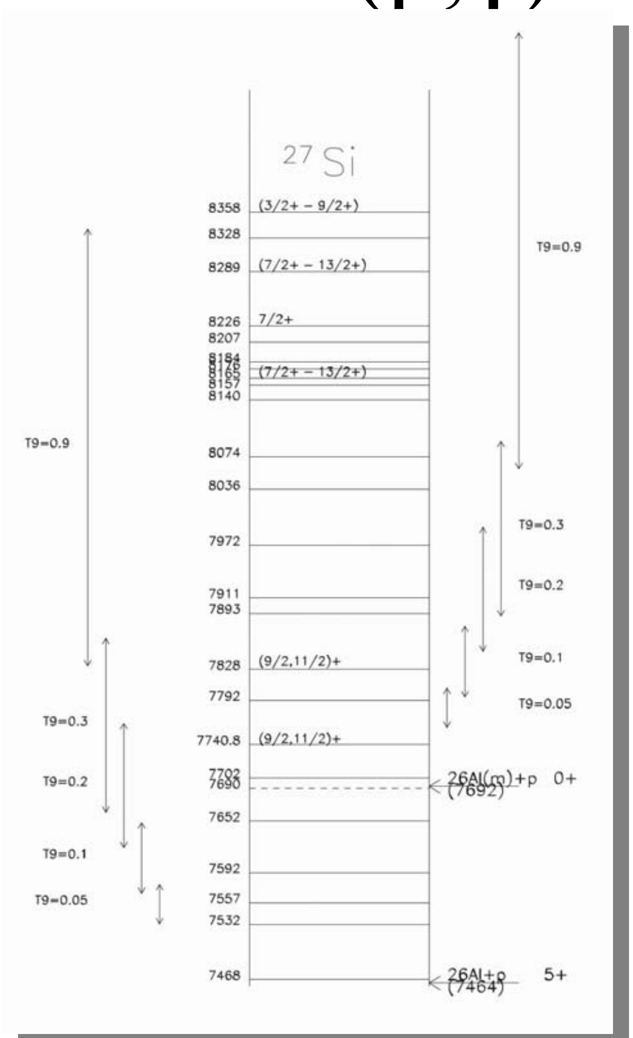
- SNII – above plus

  ^{26m}Al(p,γ)^{27}Si + others



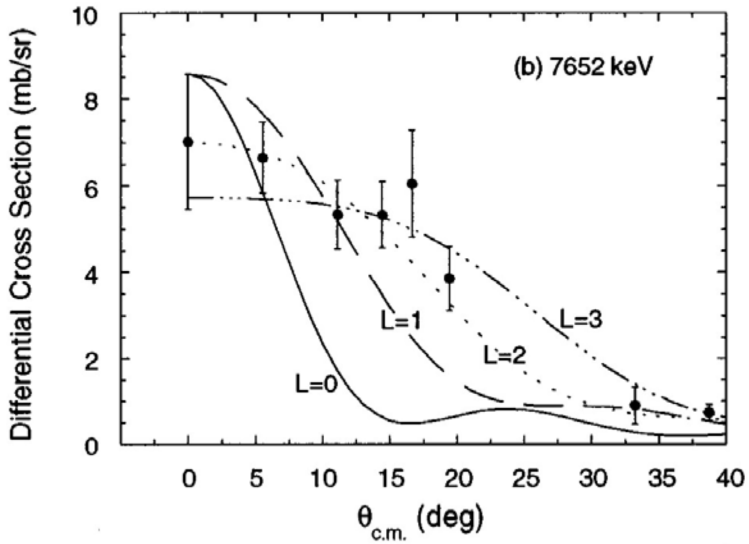


$^{26}Al(p,\gamma)^{27}Si$ - 188 keV resonance



- 7652 keV level
- Dominating resonance in ^{26}Al+p for novae
- A change in ωγ by 1/3 would change the final abundance of ^{26}Al by a factor of 2
- Weak, poorly-known resonance
  - High 0.29 meV
  - Low 10^{-5} meV
  - Adopted value 0.064 meV
- DRAGON has used the 7828 keV level (363 keV resonance) for commissioning

- Schmalbrock 86: $^{28}Si(^{3}He,\alpha)^{27}Si$
- Wang 89: $^{27}Al(^{3}He,t)^{27}Si$ l ≥ 2
- Vogelaar 96 (89): $^{26}Al(^{3}He,d)^{27}Si$ no unique l-transfer
- Vogelaar thesis 89: resonance strength + branching ratios



Preliminary finding of a about 60% lower resonance strength.

^{27}Si