Decay spectroscopy for nuclear astrophysics

Livius Trache

IFIN-HH Bucuresti-Magurele and
Cyclotron Institute, Texas A&M University

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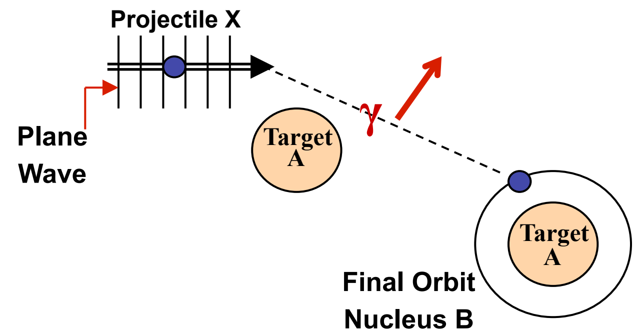
Radiative capture reactions



* Radiative capture reactions A(p,γ)B, A(α,γ), A(n,γ)

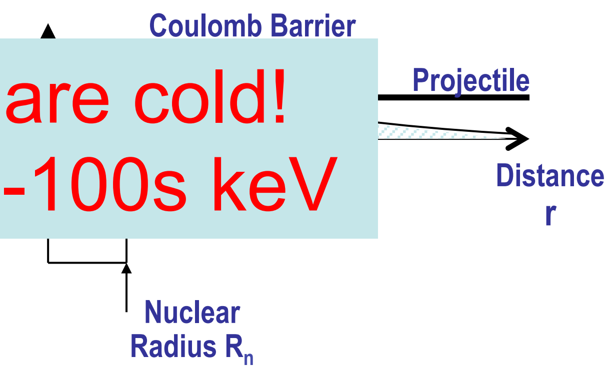
* **Non-resonant** or **resonant** reactions.

* At low energy, the probability that the incoming charged particle penetrates the Coulomb barrier:

$$P = \exp(-2\pi\eta), where \;\; \eta(E) = \frac{Z_1 Z_2 e^2}{h\nu}$$

* The cross section – astrophysical S-facto

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



Stars are cold!

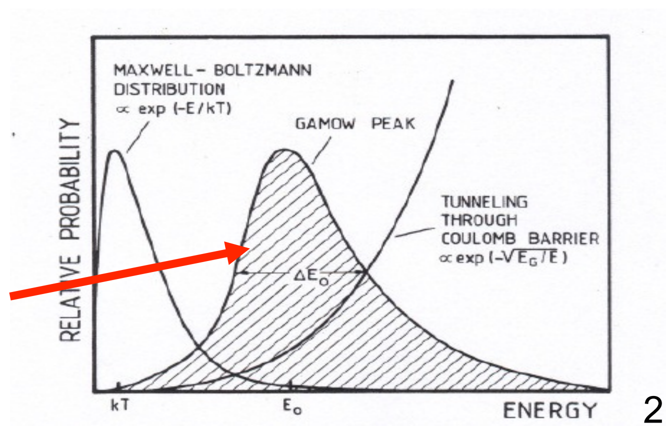
E_p=10s-100s keV

to determine

* Reaction rate per particle pair (i
distr):

$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty S(E)\exp\left(-\frac{E}{kT}-\frac{b}{E^{1/2}}\right)dE$$

- Reactions (that matter) take place in the Gamow energy window.
- Direct, or non-resonant part



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

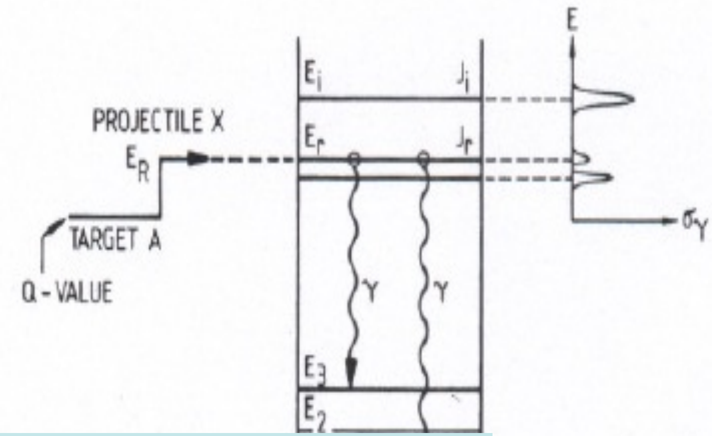
D Resonant Reaction Rates

* **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):

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



Stars are cold!
E_p=10s-100s keV

* The contribution to the reaction rate:

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

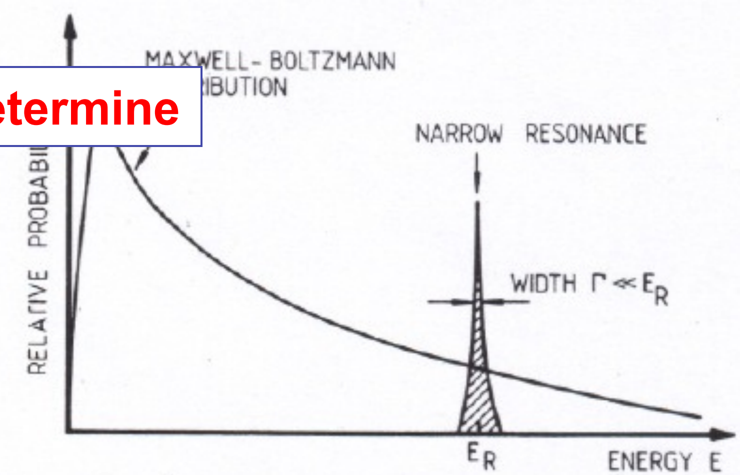
where

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

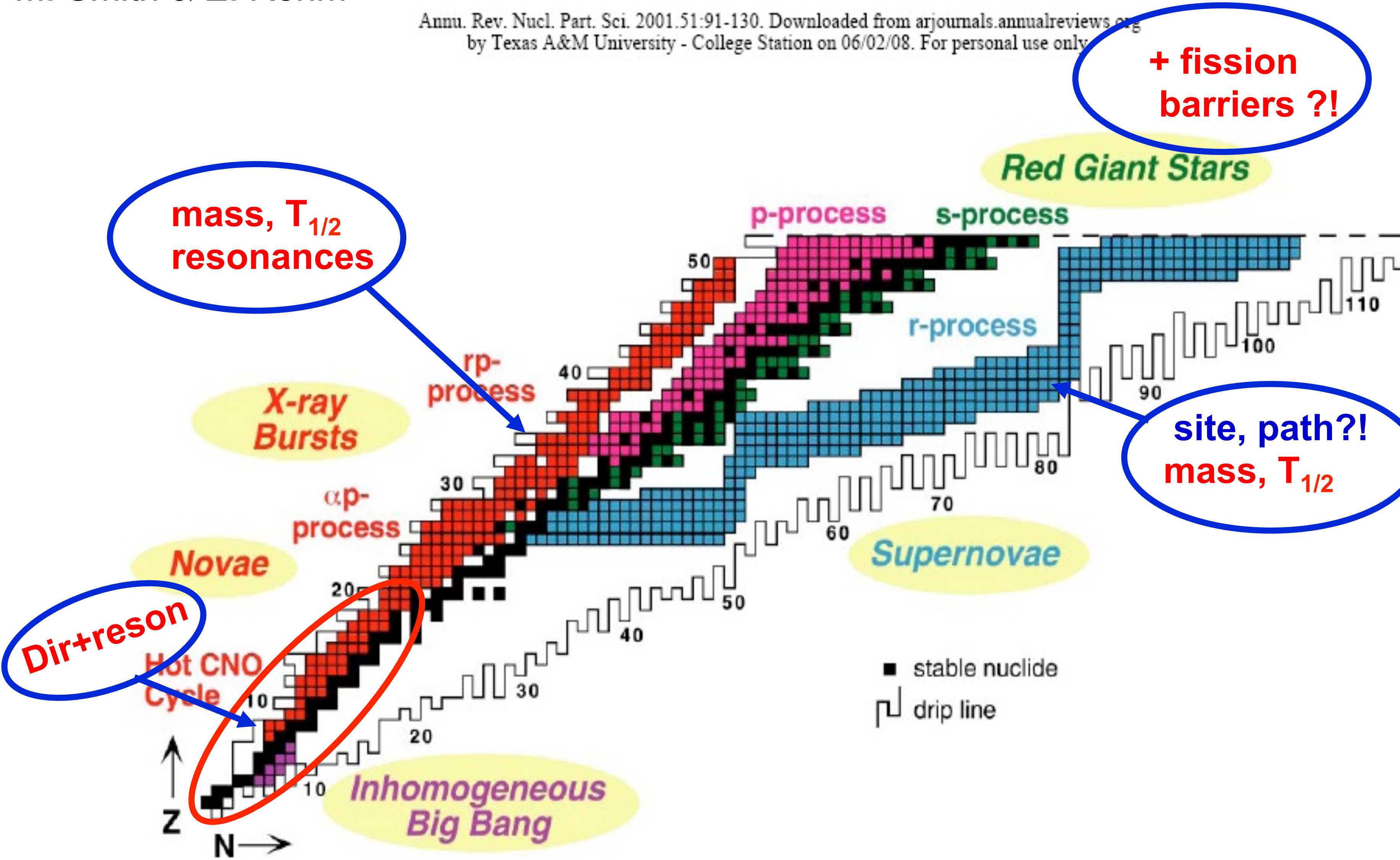
to determine

ωγ= resonance strength

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



M. Smith & E. Rehm



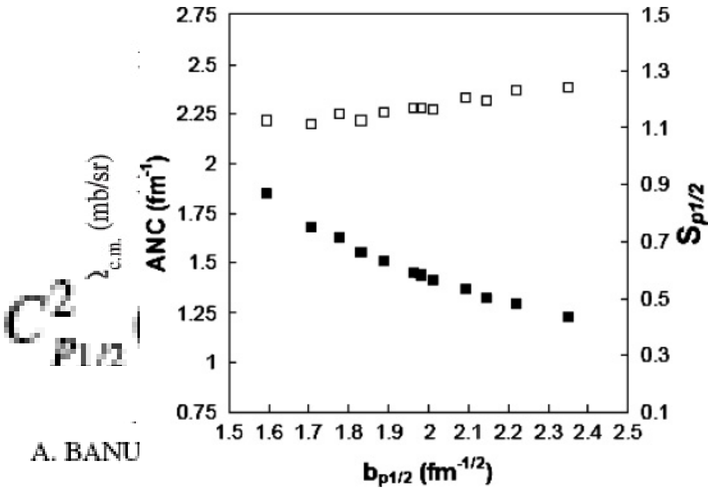
Two big problems:

1. **- reactions in stars involve(d) radioactive nuclei ⇒ use RNB**
2. **- very small energies and very small cross sections ⇒indirect methods**

Indirect methods in NPA

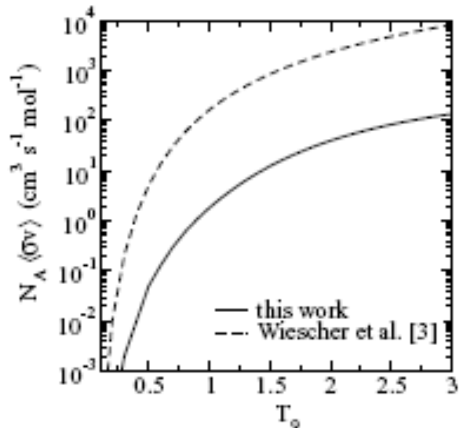
- Nuclear Phyiscs for Astrophysics (NPA):
  - evaluate energy and isotope production (which reactions?!)
  - evaluate reaction rates in cosmic processes
- Indirect methods in NPA with or w/o RNB
  - A. Coulomb dissociation
  - B. Transfer reactions (ANC method)
  - C. Breakup of loosely bound nuclei
  - D. Spectroscopy of resonances: β-decay, transfer reactions, resonant elastic scattering, etc…
    - Decay spectroscopy
  - E. Trojan Horse Method
  - …

$^{14}N(^{12}N,^{13}O)$ proton-transfer react ⇒ $^{12}N(p,\gamma)^{13}O$ (rap I,II proc)



C, S-factor 0-2 MeV
Reaction rate

fm^{-1}



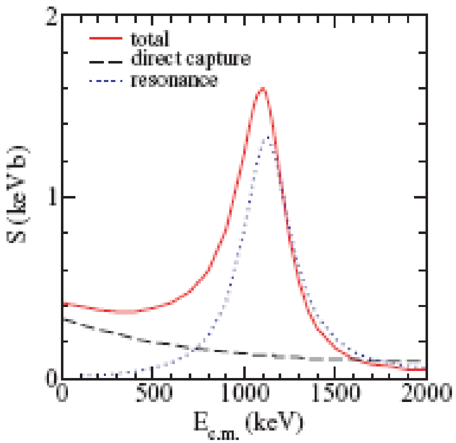


FIG. 8. (Color online) Astrophysical S factor of the $^{12}N(p,\gamma)^{13}O$ reaction as a function of the energy in the center-of-mass reference system. The dashed curve shows the direct capture component of the S factor, while the dotted curve is the resonant component. The solid curve is the total astrophysical S factor.

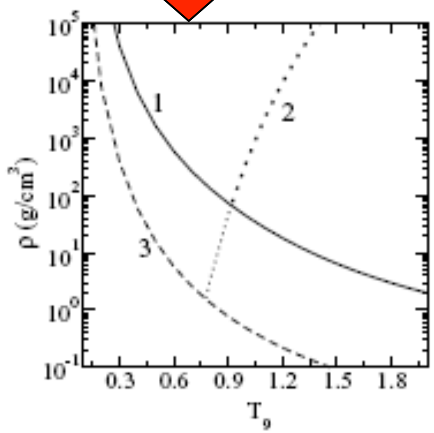
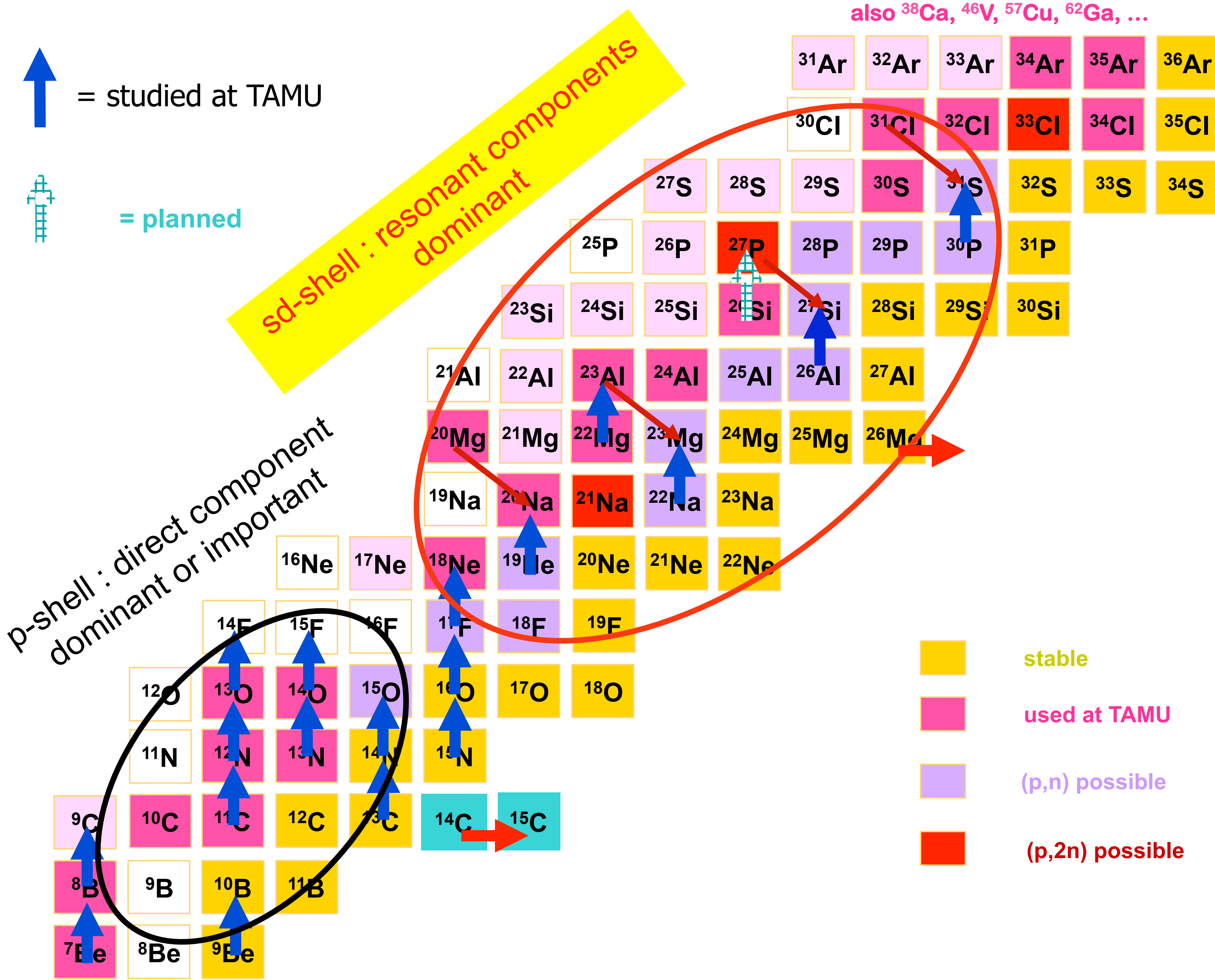


FIG. 10. Temperature and density conditions at which the $^{12}N(p,\gamma)^{13}O$ reaction may play a role. Curve 1 represents the equilibrium line between the rates for ^{12}N proton capture and ^{12}N β decay. Curve 3 illustrates the same result as determined from Ref. [3]. Curve 2 shows the line of equal strength between the rate of the ^{12}N radiative proton capture to ^{13}O and the rate for the inverse process, ^{13}O photodisintegration. See text for details.

A. Banu et al, Phys Rev C 79, 025805 (2009)

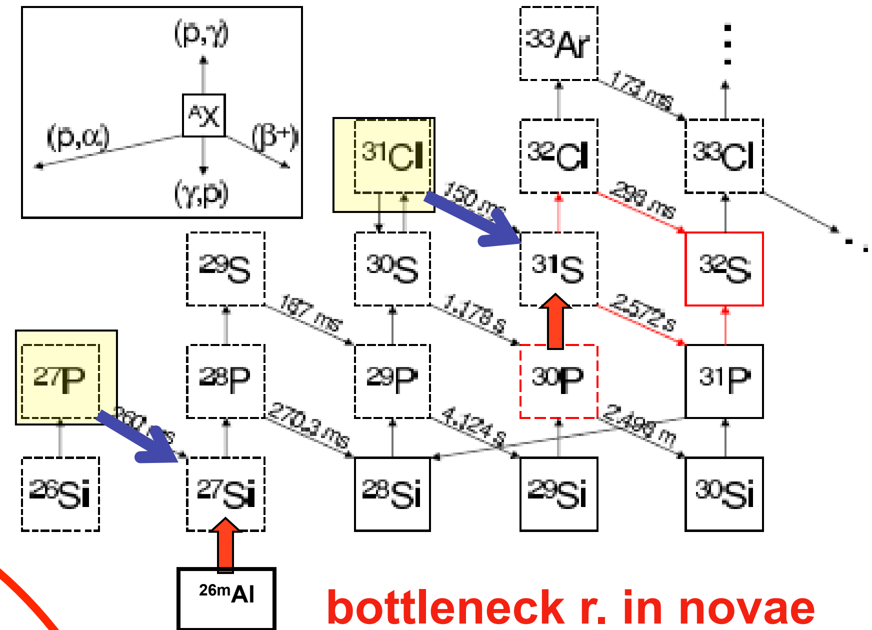


also ^{38}Ca, ^{46}V, ^{57}Cu, ^{62}Ga, ...
= studied at TAMU
= planned
sd-shell : resonant components dominant
p-shell : direct component dominant or important
stable
used at TAMU
(p,n) possible
(p,2n) possible
^{31}Ar ^{32}Ar ^{33}Ar ^{34}Ar ^{35}Ar ^{36}Ar
^{30}Cl ^{31}Cl ^{32}Cl ^{33}Cl ^{34}Cl ^{35}Cl
^{27}S ^{28}S ^{29}S ^{30}S ^{31}S ^{32}S ^{33}S ^{34}S
^{25}P ^{26}P ^{27}P ^{28}P ^{29}P ^{30}P ^{31}P
^{23}Si ^{24}Si ^{25}Si ^{26}Si ^{27}Si ^{28}Si ^{29}Si ^{30}Si
^{21}Al ^{22}Al ^{23}Al ^{24}Al ^{25}Al ^{26}Al ^{27}Al
^{20}Mg ^{21}Mg ^{22}Mg ^{23}Mg ^{24}Mg ^{25}Mg ^{26}Mg
^{19}Na ^{20}Na ^{21}Na ^{22}Na ^{23}Na
^{16}Ne ^{17}Ne ^{18}Ne ^{19}Ne ^{20}Ne ^{21}Ne ^{22}Ne
^{14}F ^{15}F ^{16}F ^{17}F ^{18}F ^{19}F
^{12}O ^{13}O ^{14}O ^{15}O ^{16}O ^{17}O ^{18}O
^{11}N ^{12}N ^{13}N ^{14}N ^{15}N
^{9}C ^{10}C ^{11}C ^{12}C ^{13}C ^{14}C ^{15}C
^{8}B ^{9}B ^{10}B ^{11}B
^{7}Be ^{8}Be ^{9}Be

D

Decay spectroscopy

Beta- and beta-delayed proton-decay



Explosive H-burning in novae

&

IAS in T_z=-3/2 nuclei

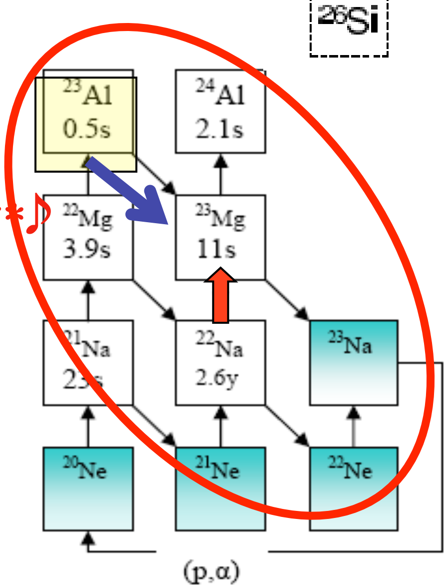
Isospin mixing

GT strength distribution

^{22}Na depletion in novae

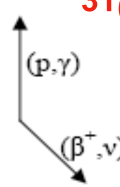
^{23}Al$\rightarrow {}^{23}Mg^* \Rightarrow {}^{22}Na(p,\gamma){}^{23}Mg^*$♪

& $^{22}Mg(p,\gamma){}^{23}Al$♪



bottleneck r. in novae

^{31}Cl$\rightarrow {}^{31}S^* \Rightarrow {}^{30}P(p,\gamma){}^{31}S^*$♪



See Jordi's list!

^{27}P$\rightarrow {}^{27}Si^* \Rightarrow$

$^{26m}Al(p,\gamma){}^{27}Si^*$♪

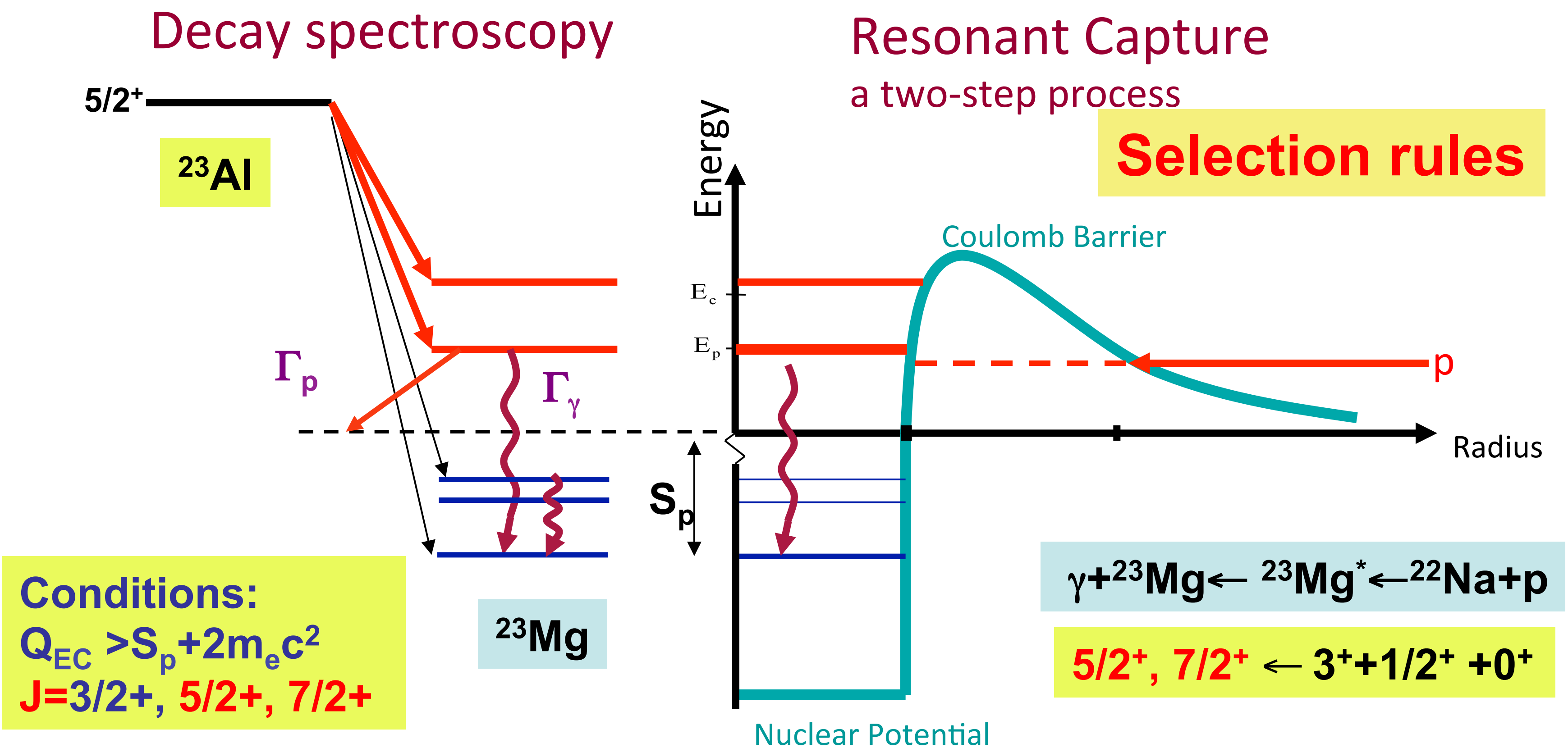
^{26}Al creation/destruction problem

Introduce the concept!

- Jordi's list:

Main nuclear data uncertainties in novae:

- $^{18}F(p,\alpha)^{15}O$
- THM ^{18}F RIB on H at TAMU
- $^{25}Al(p,\gamma)^{26}Si$
- ?! ^{26}P bp-decay ?!
- $^{30}P(p,\gamma)^{31}S$
  - Use ^{31}Cl $\beta\gamma$ and βp-decay at TAMU
  - Other spectroscopic studies: $(\alpha,n\gamma)^{31}S$ in Bucharest & ANL



Same compound system: ^{23}Mg

Resonant contributions to reaction rate:

Resonance strength

$\langle \sigma v \rangle_{res}$ …)$b_\gamma b_p$*Γ … tot

Lower proton energies most important, but very difficult:

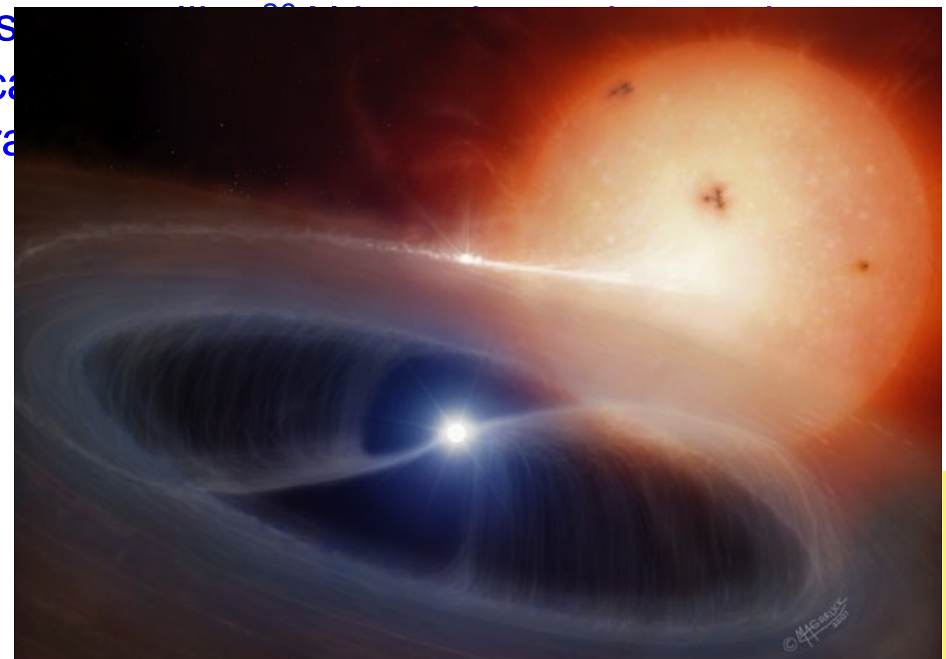
- lower branching
- increased exp difficulties (det windows, background, etc…)

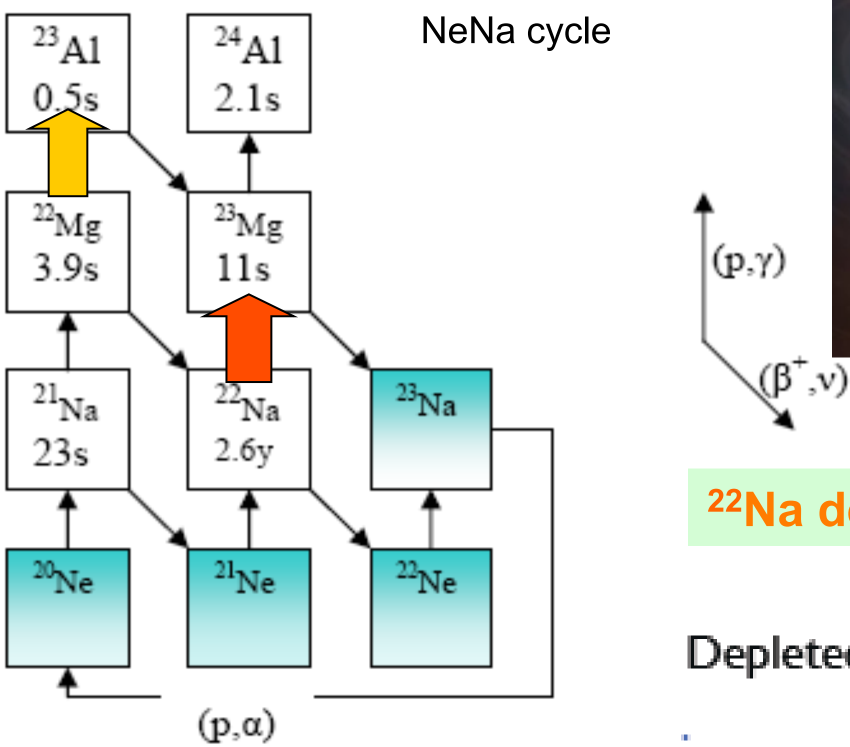
Need energy, J_r and resonance strength

Explosive H-burning in novae: "^{22}Na production"

- novae: explosive H-burning of accreting material in binaries star-WD. ~ 30/yr.
- γ rays from the decay of long-lived is
- E=1.275 MeV γ ray following the deca

but not observed by space gamma-ra



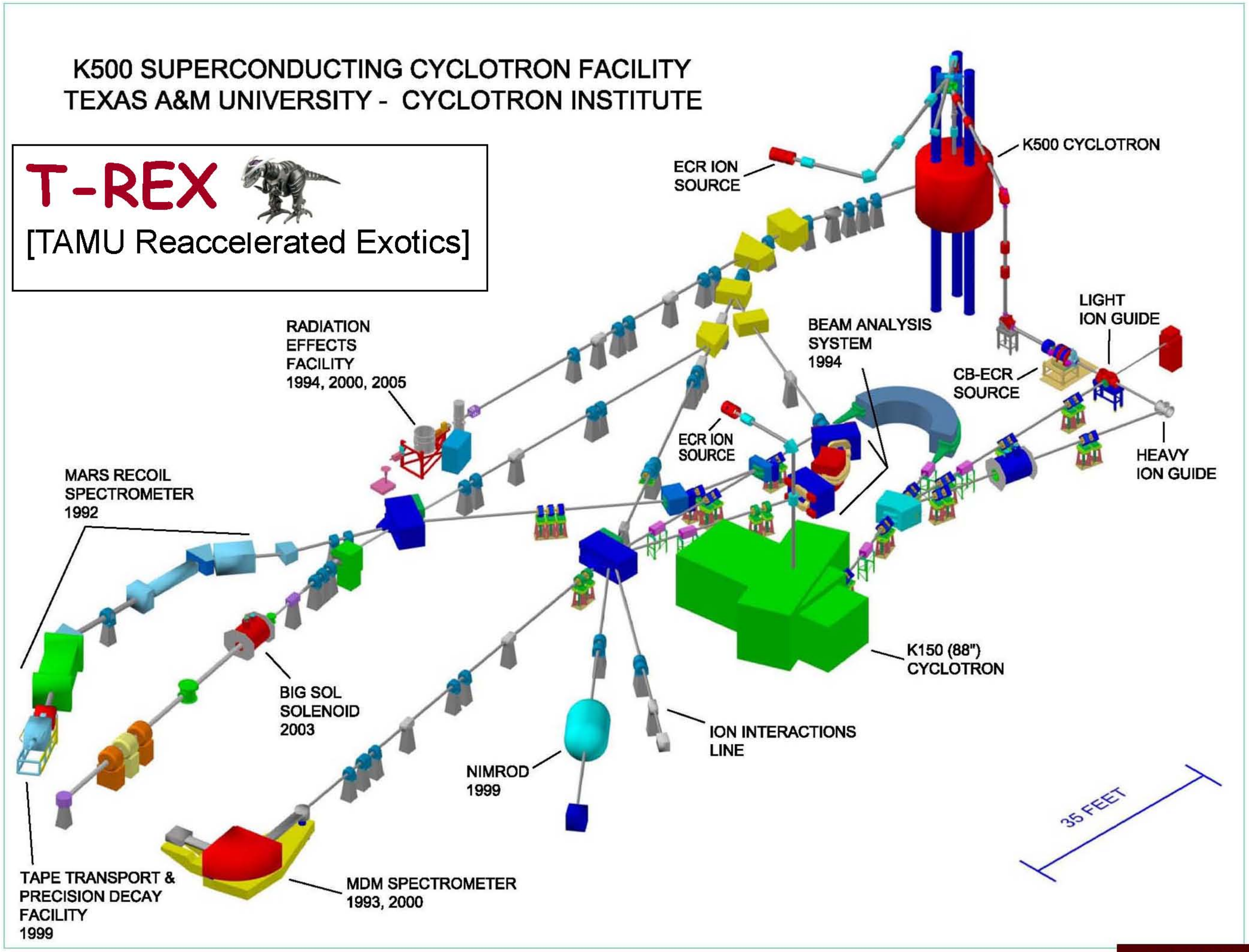


^{22}Na produced or depleted?!

^{22}Na depletion in novae: how does it happen?

Depleted via? { ^{22}Mg(p,γ)^{23}Al ↔ direct & res. capture
^{22}Na(p,γ)^{23}Mg ↔ resonant capture

- what are the stellar reaction rates for the **^{22}Mg(p,γ)^{23}Al** and **^{22}Na(p,γ)^{23}Mg**?



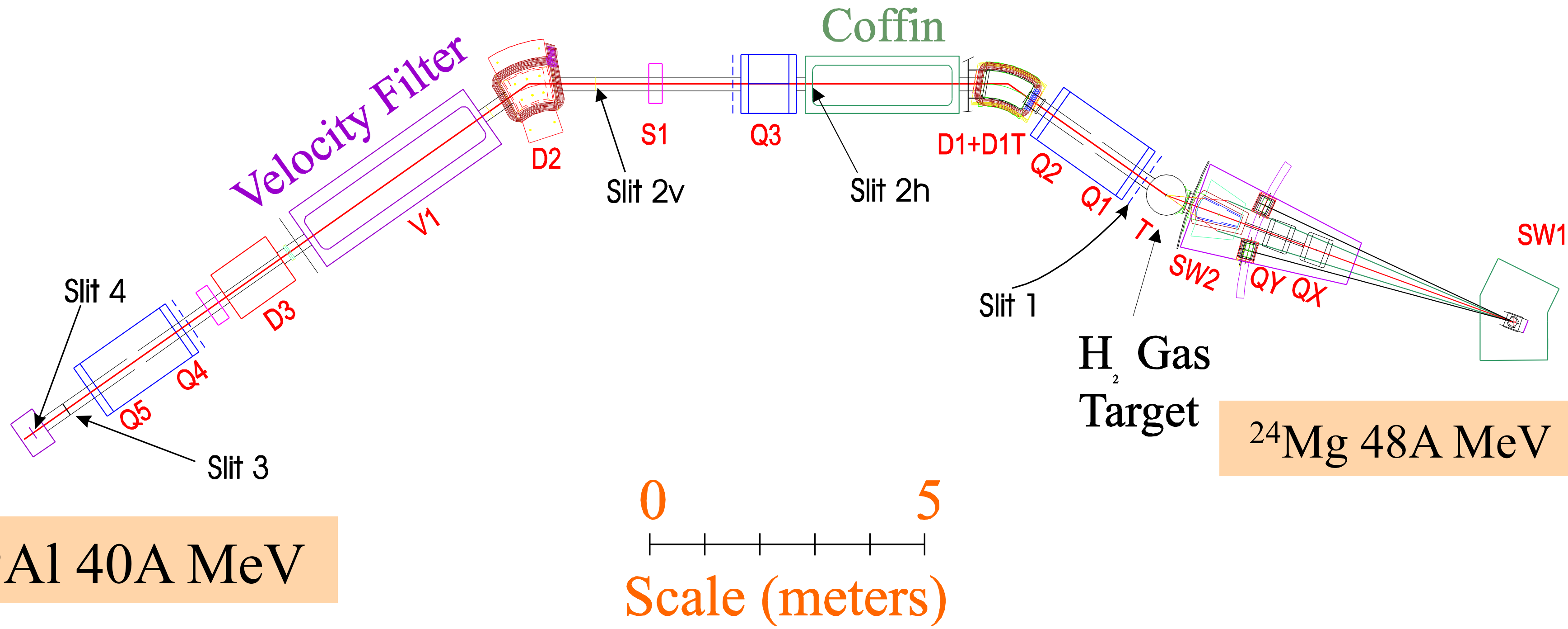
TEXAS A&M UNIVERSITY

^{23}Al

MARS

Momentum Achromat Recoil Separator

In-flight RB production



^{24}Mg 48A MeV

^{23}Al 40A MeV

Purity: 90%, or >99% after en degrader
Intensity: ~ 4000 pps
First time - very pure & intense ^{23}Al

Primary beam ^{24}Mg @ 48A MeV – K500 Cycl
Primary target LN_2 cooled H_2 gas p=1.6-2 atm
Secondary beam ^{23}Al @ 40.2A MeV

(p,2n) reaction

CYCLOTRON INSTITUTE
Texas A&M University

Isotope selection with MARS

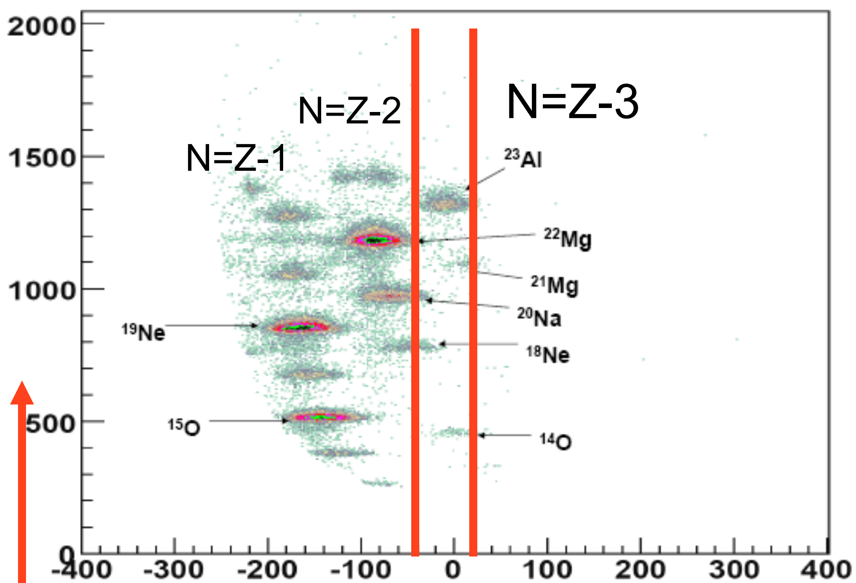


Fig. 16. △E vs Y position for ^{23}Al. Slits open and most nuclei passed and reach the MARS focal plane (target detector).

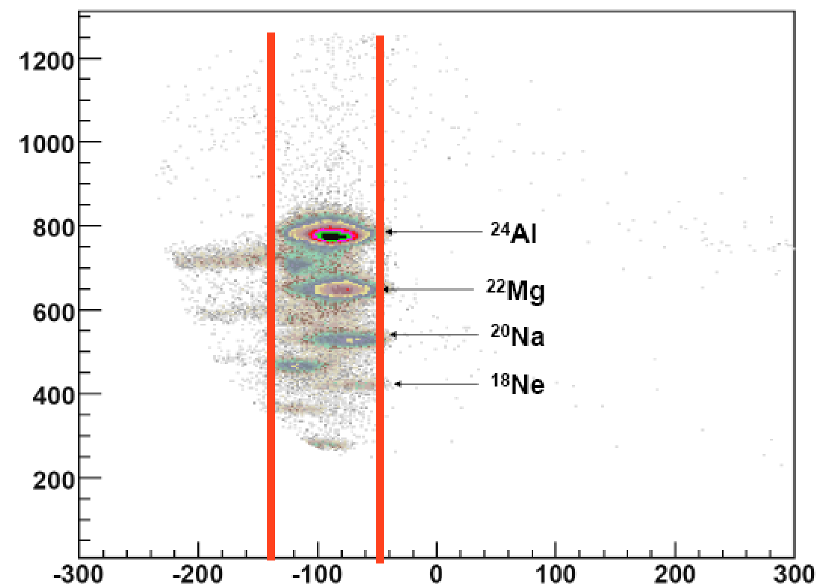


Fig. 18. △E vs Y position for ^{24}Al. Slit settings are listed at Table IV. Most impurity

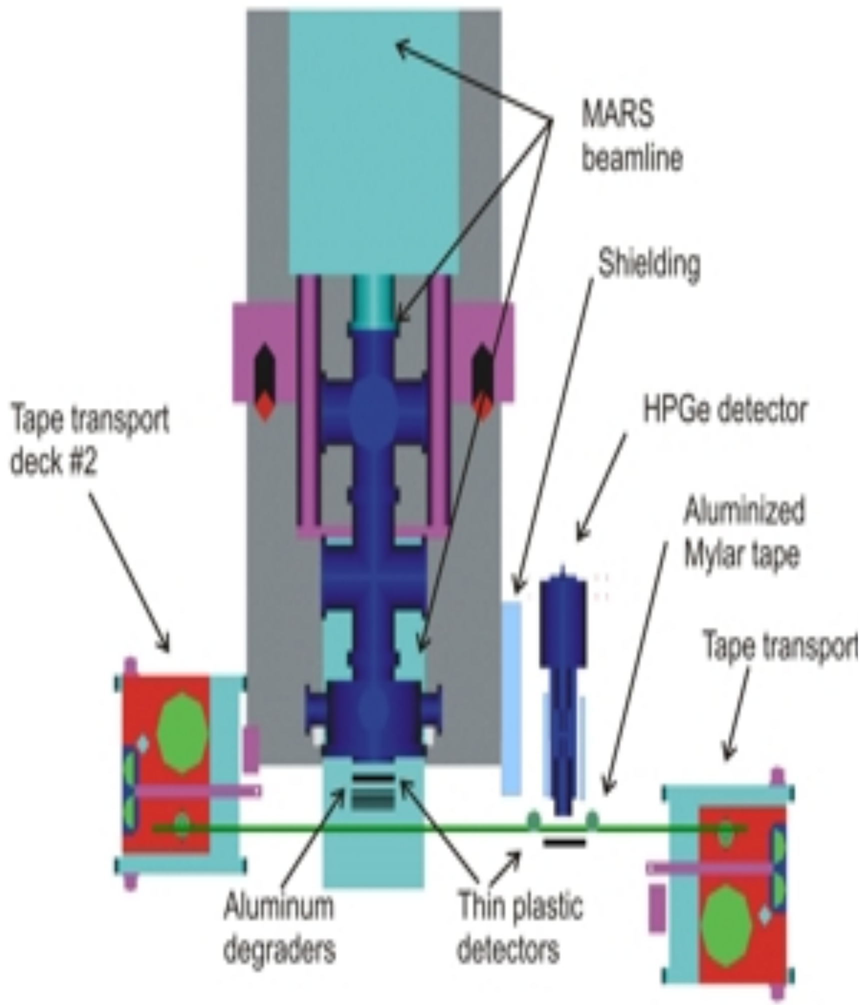
E

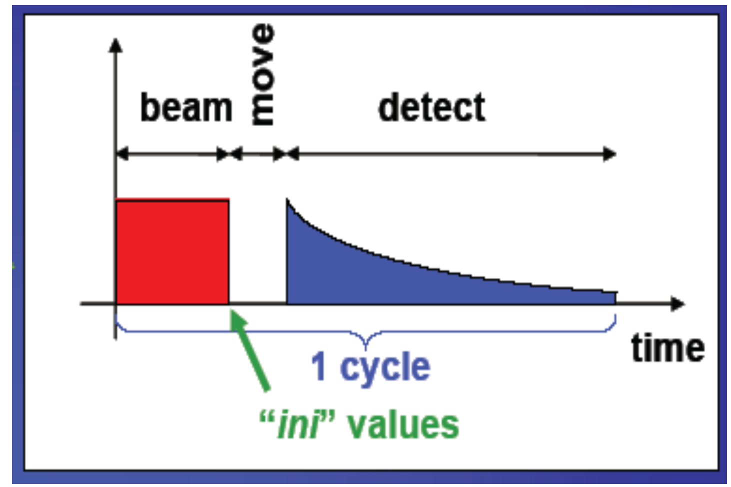
Pos ~ q/m

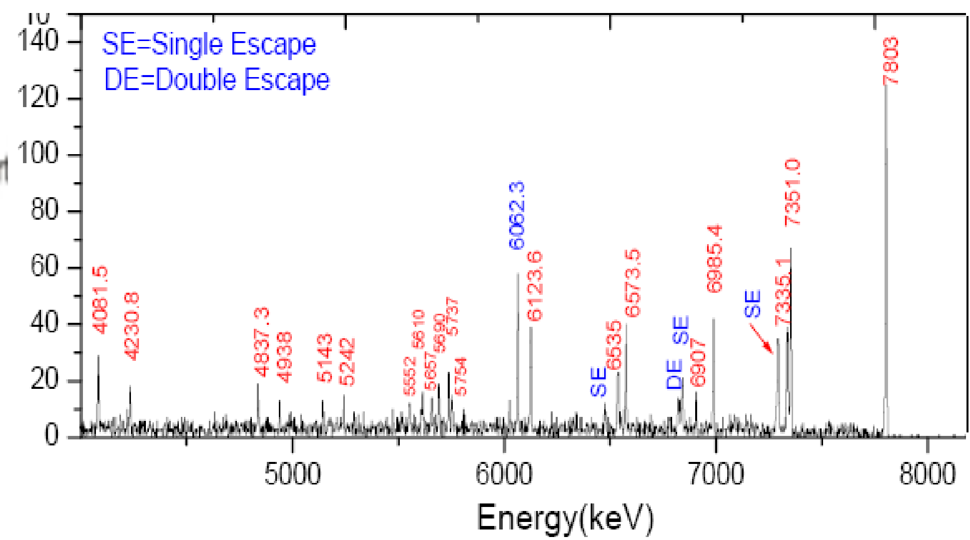
Final cut with focal plane **slits**

^{24}Al used for en and eff calibration of Ge detector to E_{γ}=8 MeV

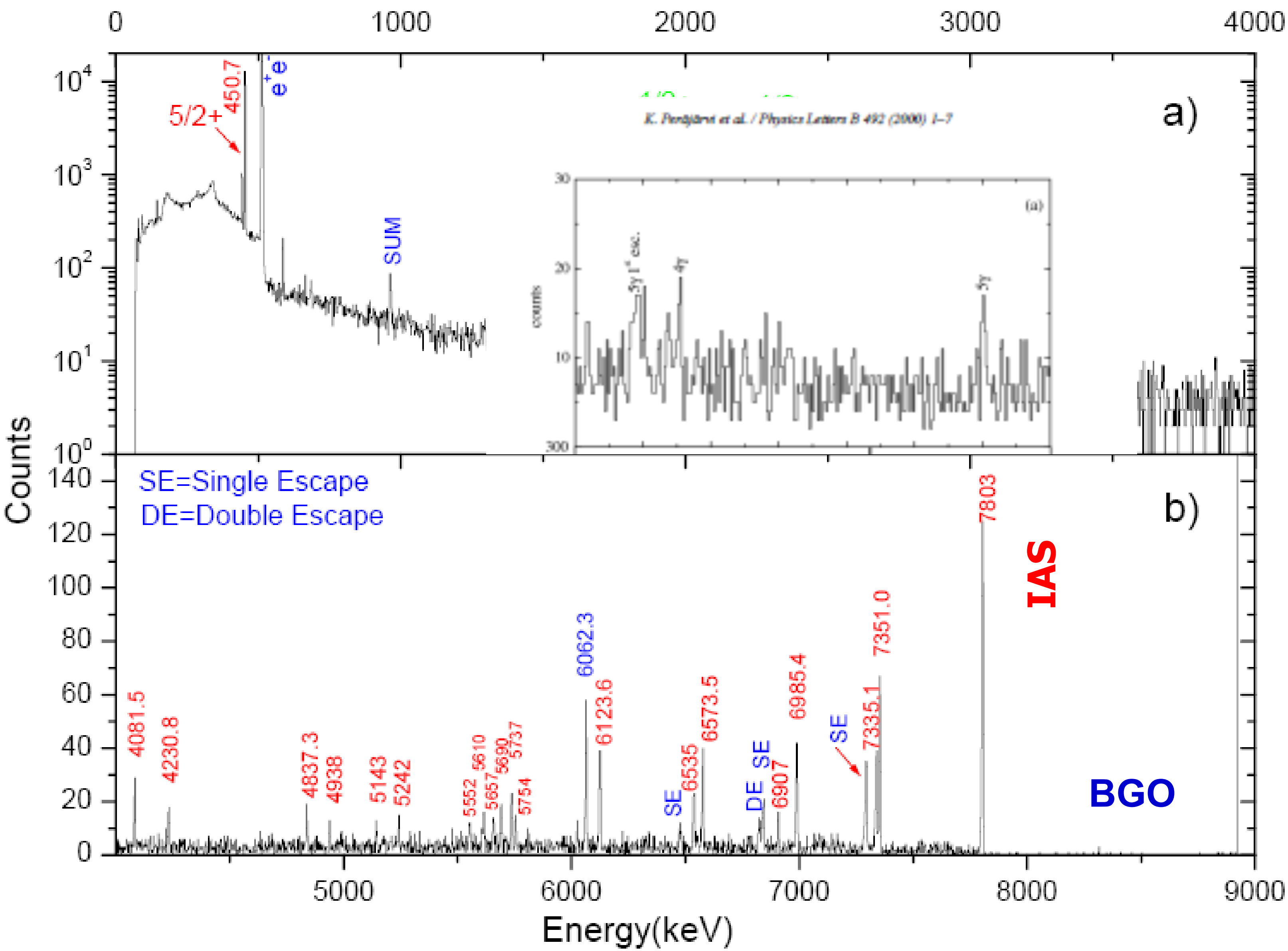
β decay study of pure RB samples







^{23}Al β-γ coincidence spectrum



^{23}Al β-decay results

- First clean and intense ^{23}Al source
- Found decay scheme
- established g.s. $J^{\pi}=5/2^{+}$ (not $1/2^{+}$) [VE Iacob ea, PRC 74, Oct 2006; also A. Ozawa ea, PRC 74, Aug 2006 from magn mom meas] ⇒ ^{22}Mg(p,γ)^{23}Al not important for depletion of ^{22}Na in novae
- absolute branching ratios (not easy or common!)
- measured $T_{1/2}$=446(4) ms (<1% accuracy) - w. γ-ray multiscaling
- and absolute log *ft*
- identified IAS E*=7802.9(5) keV by *logft=3.31(2) – meas!*
- used IMME to get new ^{23}Al mass ⇒ S_p(^{23}Al)=143(3) keV
  - Note: after mass meas in Jyvaskyla, became best IMME check! and S_p=141.11(43) keV
- Located IAS & state at E*=7787 keV – important resonance in ^{22}Na(p,γ)^{23}Mg

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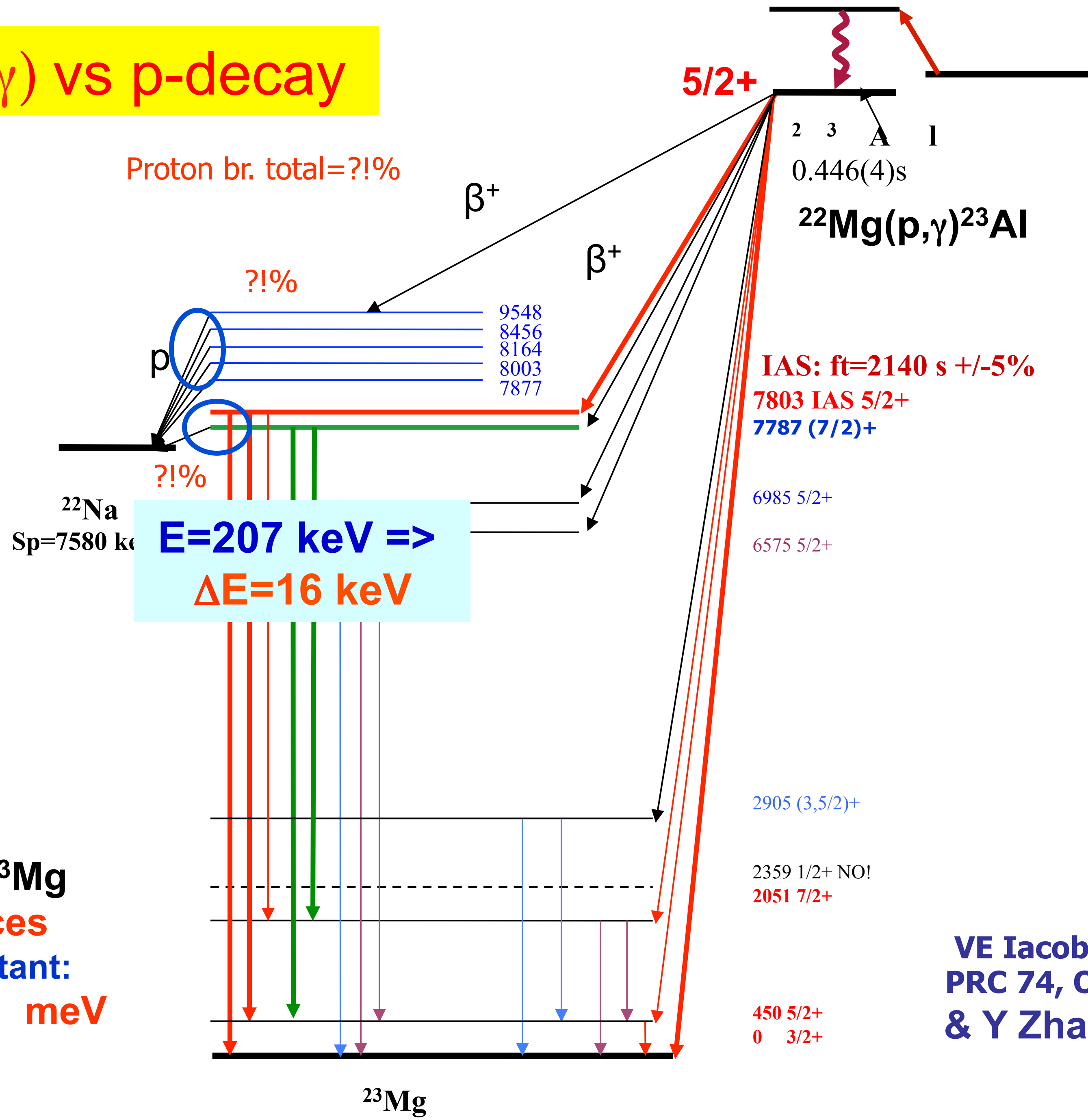
(p,γ) vs p-decay



$^{22}Na(p,\gamma)^{23}Mg$

resonances

Most important:

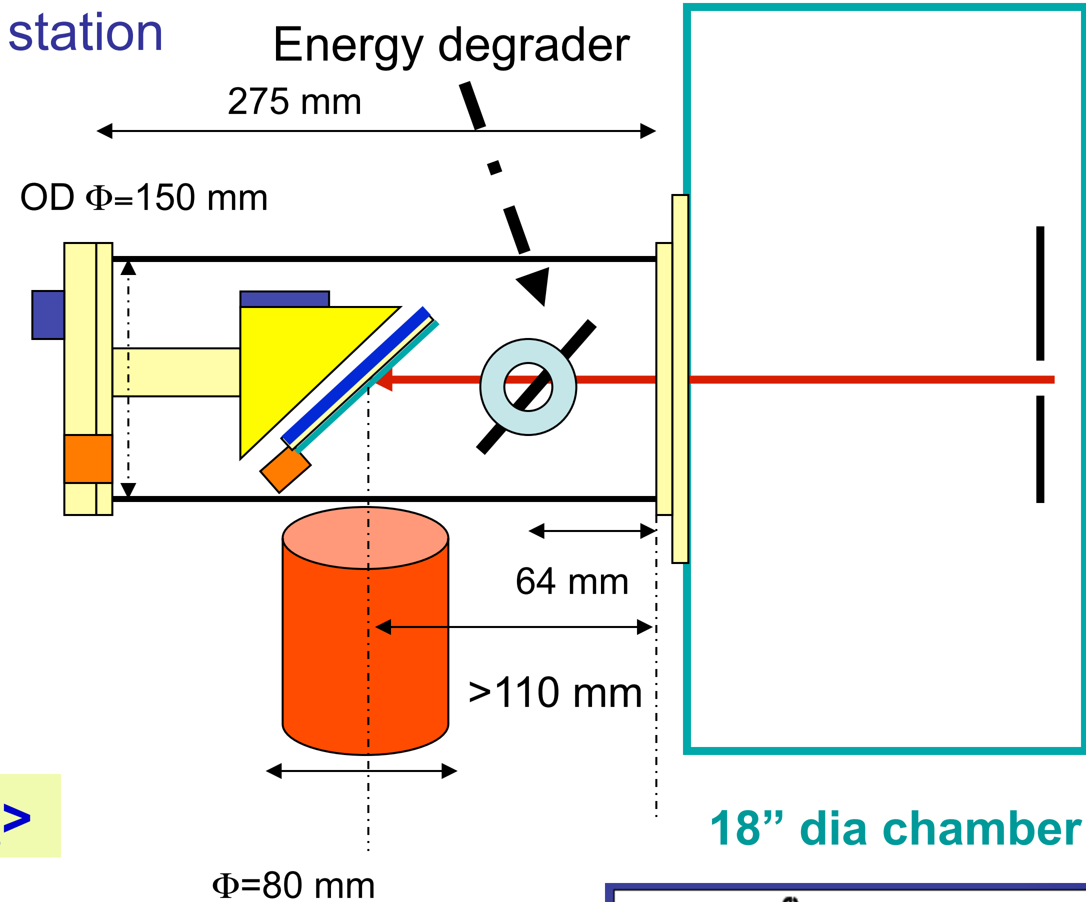
$\omega\gamma_{7787}$=__._?! meV

VE Iacob, et al., PRC 74, Oct. 2006

& Y Zhai thesis

Method: implantation in very thin Si detectors!

MARS implantation station

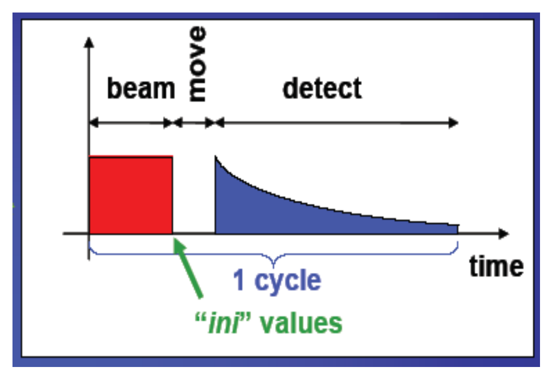


$E=E_p+kE_{recoil}+\langle\Delta E_\beta\rangle$

p-detector – v. thin DS Si strip 65 or 45 μm
W1-65 BB2-45

β-detector – thick Si det 1 mm

γ-detector – HPGe 70% effic

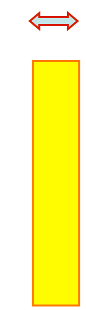


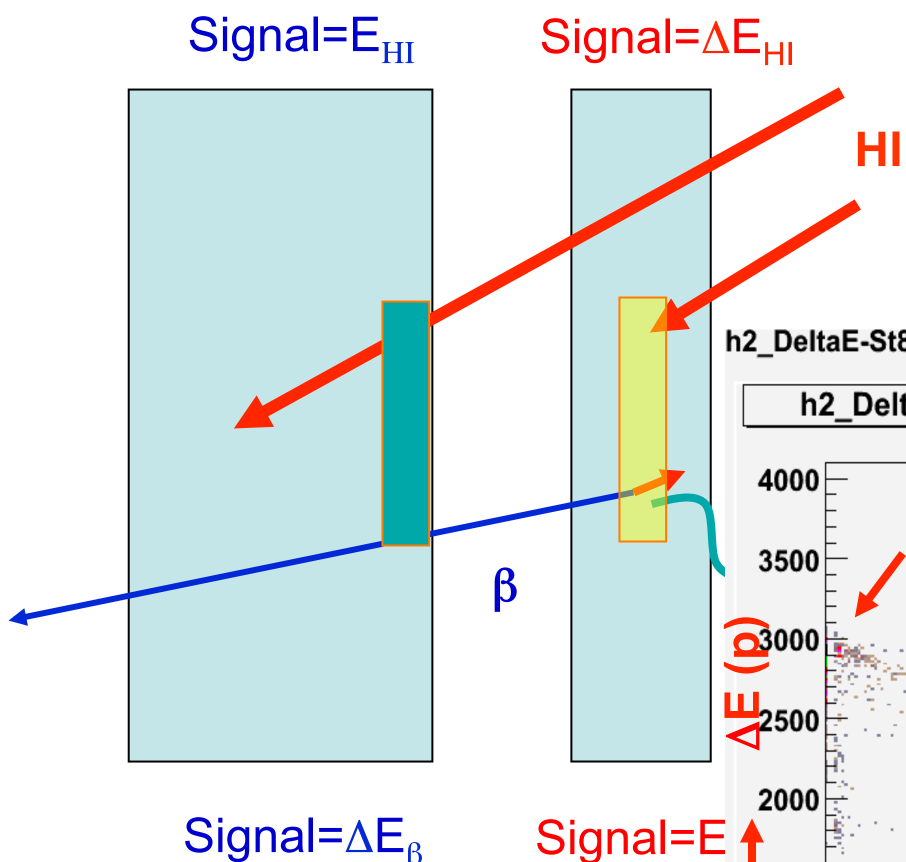
Pulsed beam

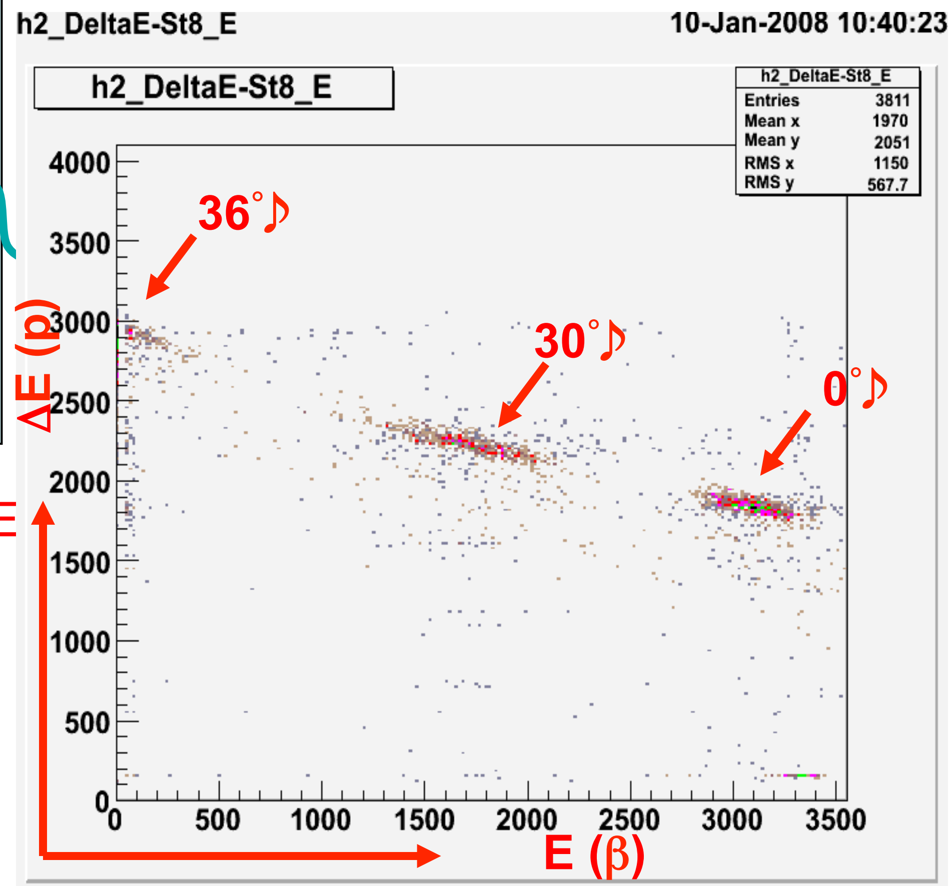
Si 1000 μm

Si strip 61 μm

"HI telescope mode" – control implantation







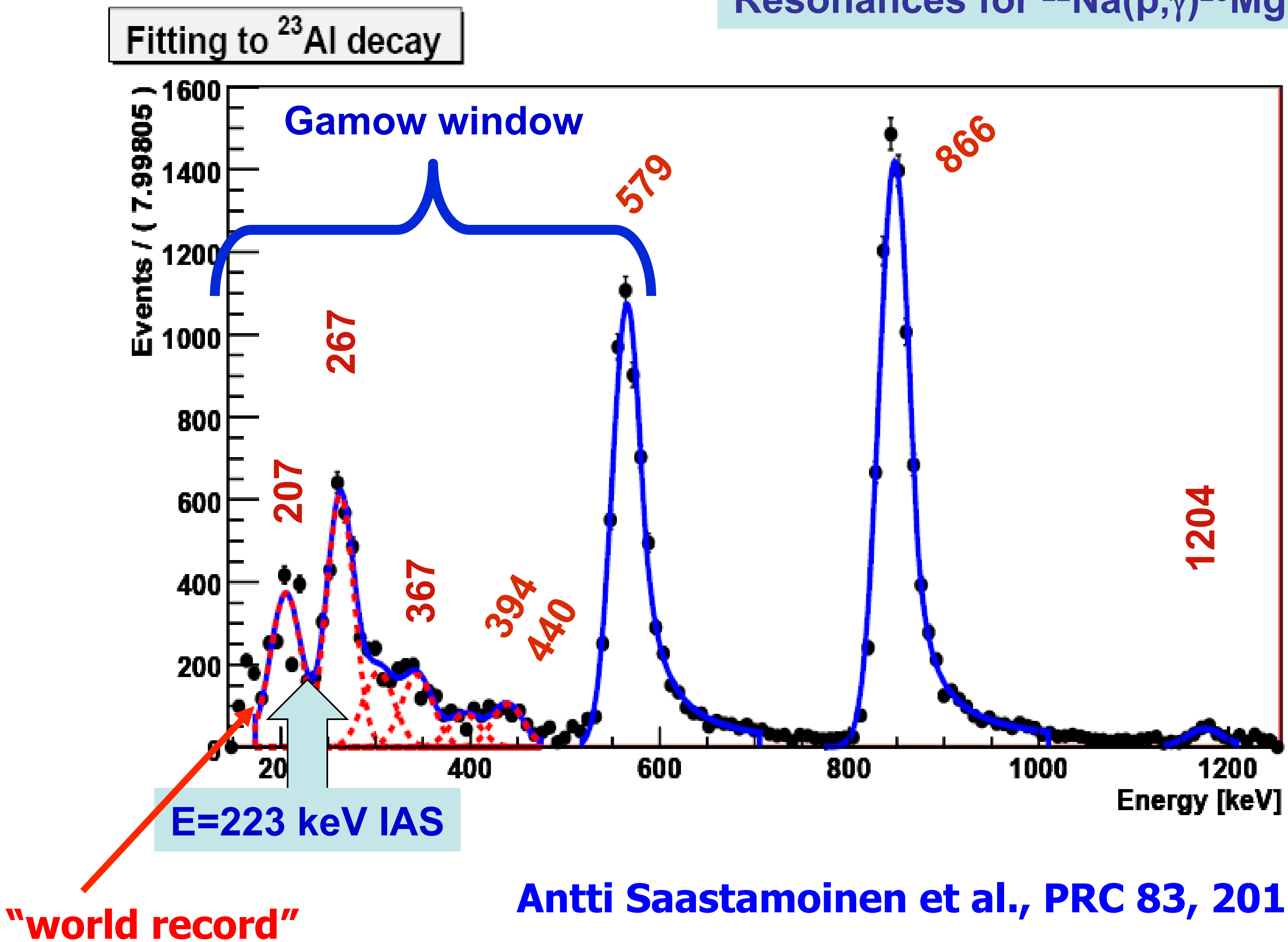
"β-proton mode"

measure simultaneously:

- β-proton and
- β–γ coinc.

^{23}Al β-delayed p-decay sp – after bkg subtraction

Resonances for ^{22}Na(p,γ)^{23}Mg

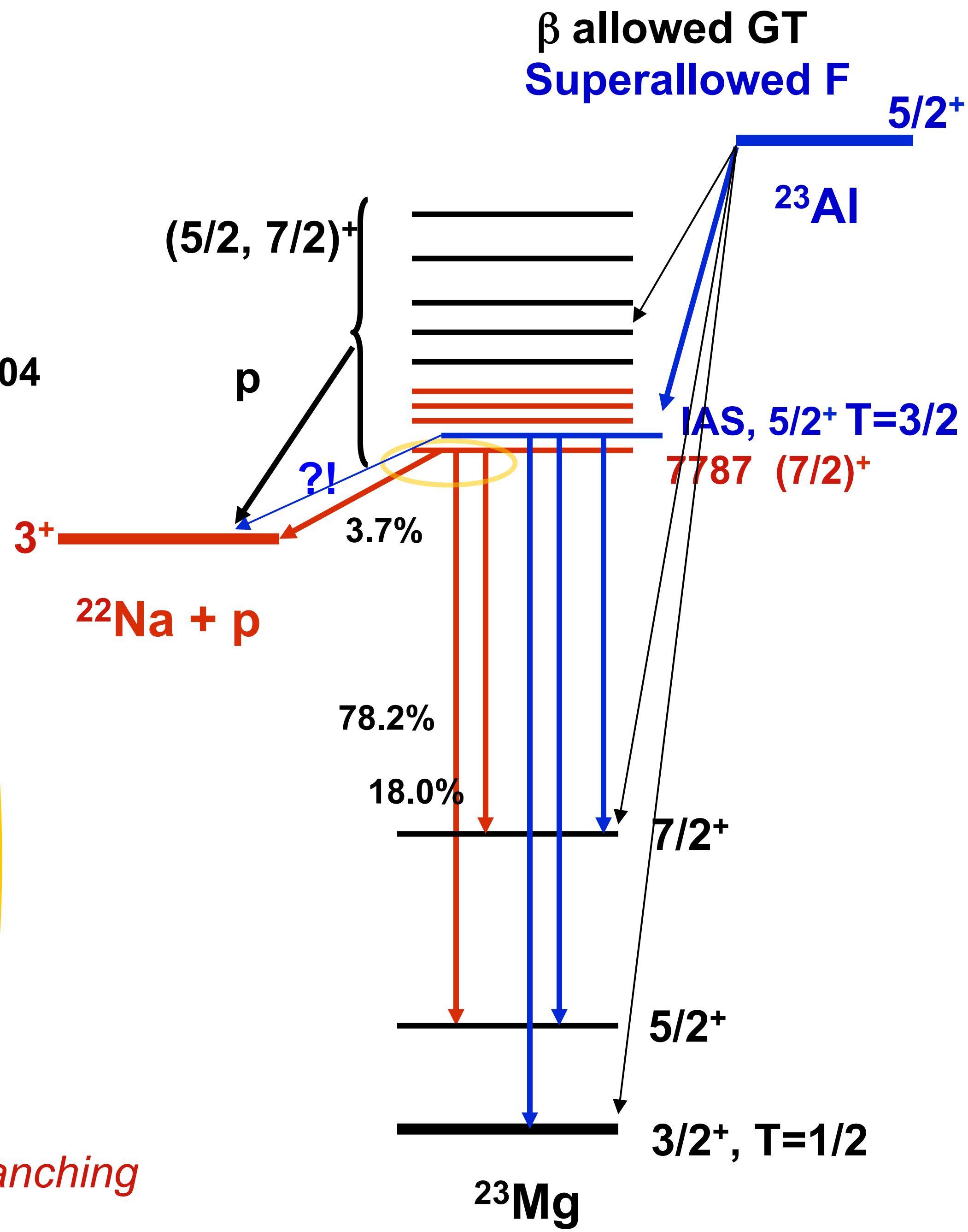


Antti Saastamoinen et al., PRC 83, 2011

$\omega\gamma=(2J+1)/(2j+1)(2I+1)b_\gamma b_p*\Gamma$

Most important resonance:
E_{res}=207 keV
$\omega\gamma$=1.4 meV (+.5,-.4)
Γ from τ=10(3) fs Jenkins ea, PRL 2004

	Eres (keV)	Eexc (keV)	br-p (of 100 beta)
	207	7787	0.14(3)%
IAS	223	7803	?!
	267	7848	0.18(4)%
	337	7917	0.03(1)%
	443	8024	0.02(1)%
	579	8160	0.28(1)%
	866	8447	0.41(1)%
	1204	8785	0.02(1)%
		total	1.22(5)%



*Rare case (2nd known!) s of γ & **p**-branching measured simultaneously !*

Full disclosure!

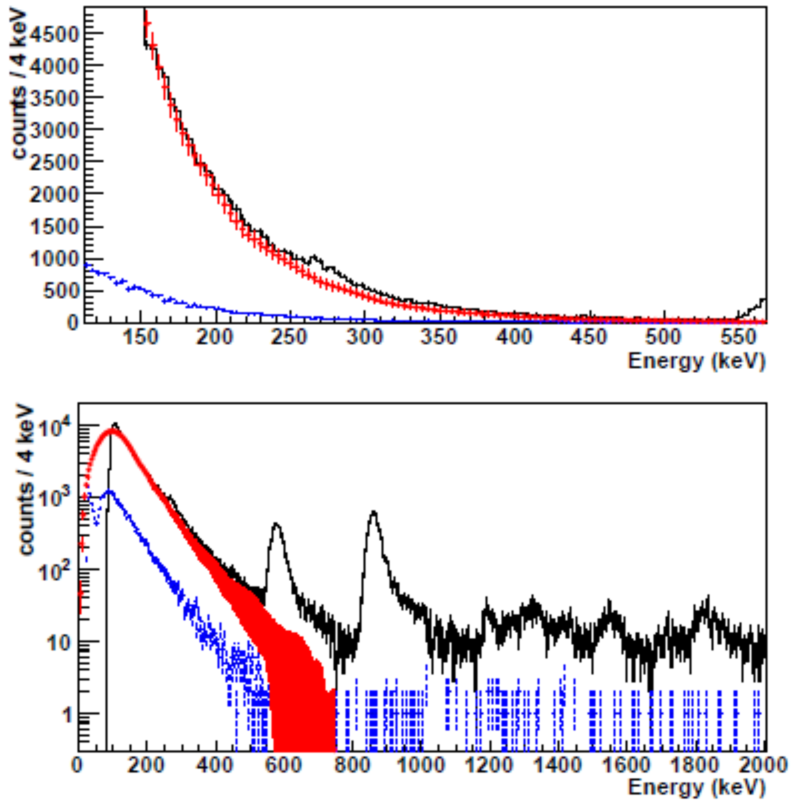
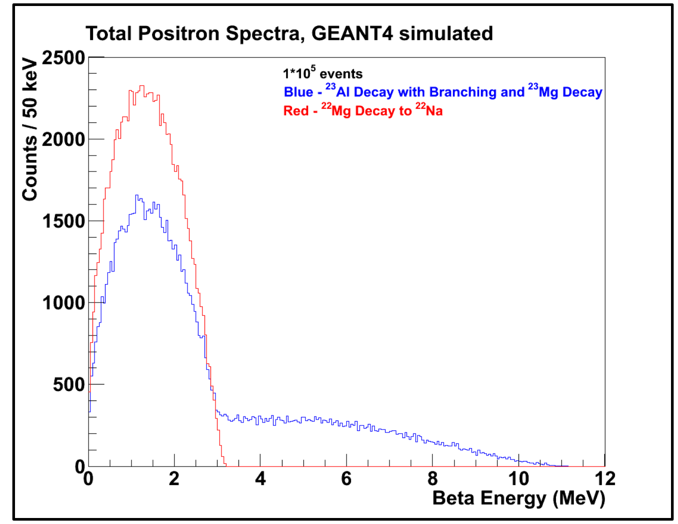
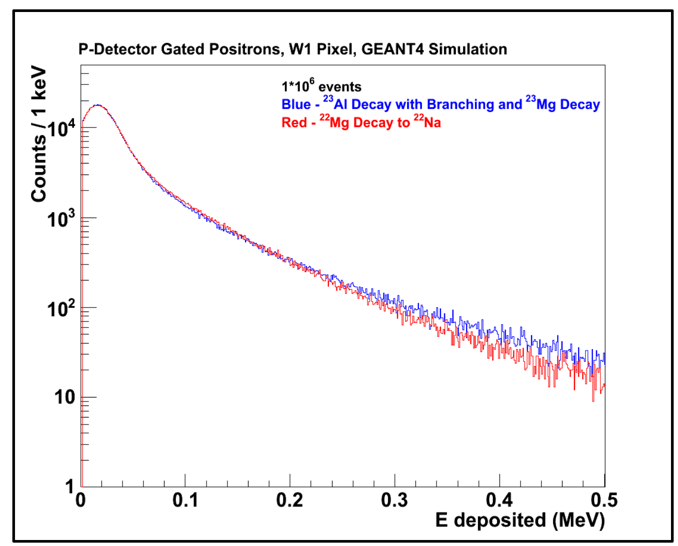


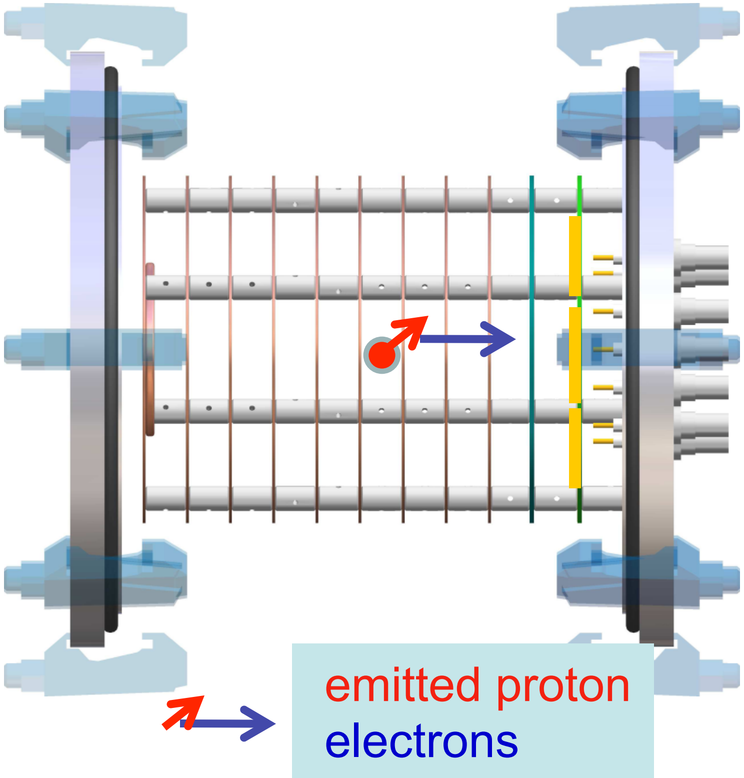
FIG. 7: (Color online) Full collected statistics for the ^{23}Al data (black, solid) and the ^{22}Mg data (blue, dashed). The energy is the total measured decay energy. Smoothed ^{22}Mg spectrum, scaled to match the ^{23}Al spectrum at 150 keV is shown with red dots and corresponding uncertainties. Upper 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.

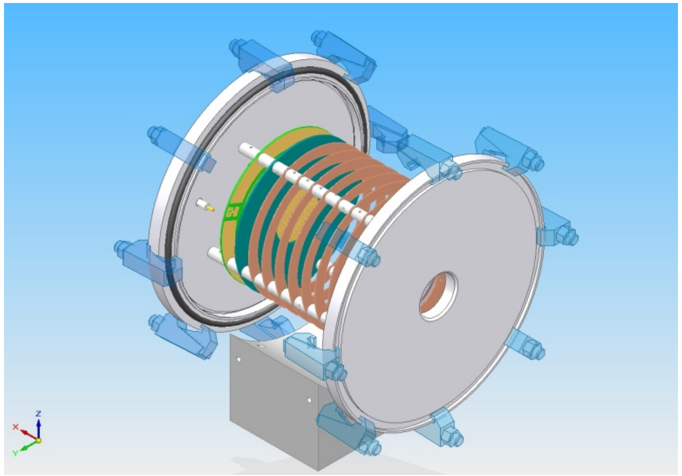


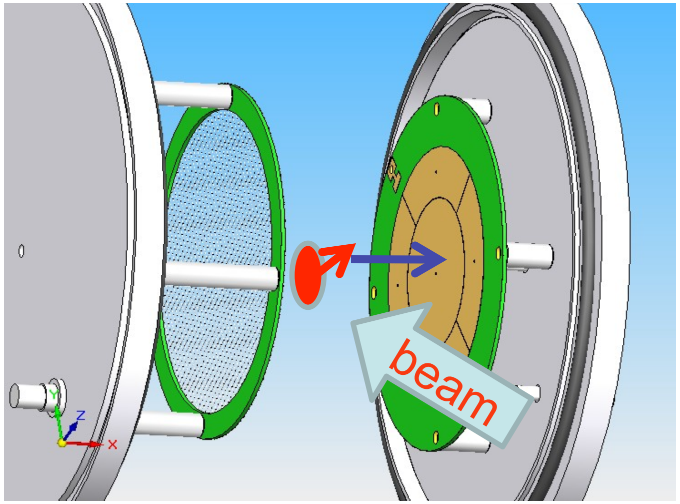


Background subtracted using decay of ^{22}Mg (not a proton emitter)

Solution: ASTROBOX







E Pollacco (CEA Saclay) proposed:

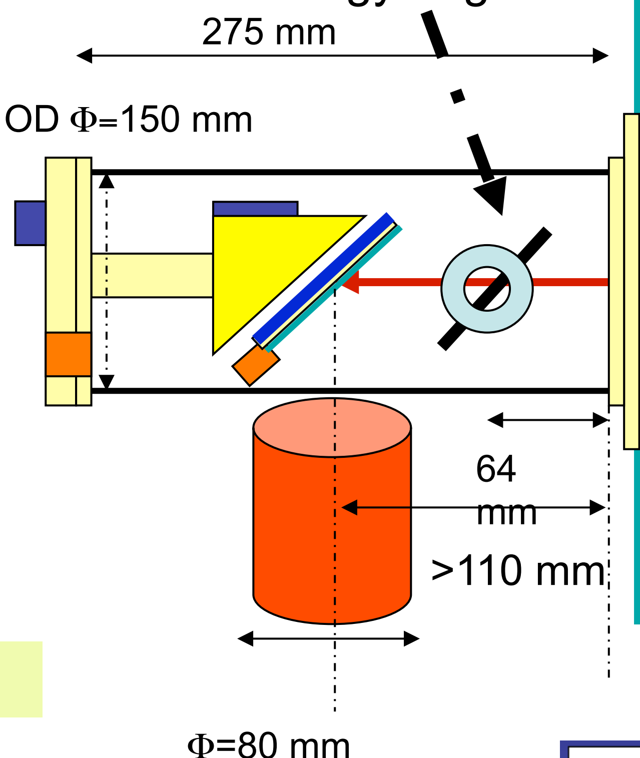
- Gas detector w MICROMEGAS
- Low proton energies (~1-200 keV), good resolution (5-10%)
- Reduced β background

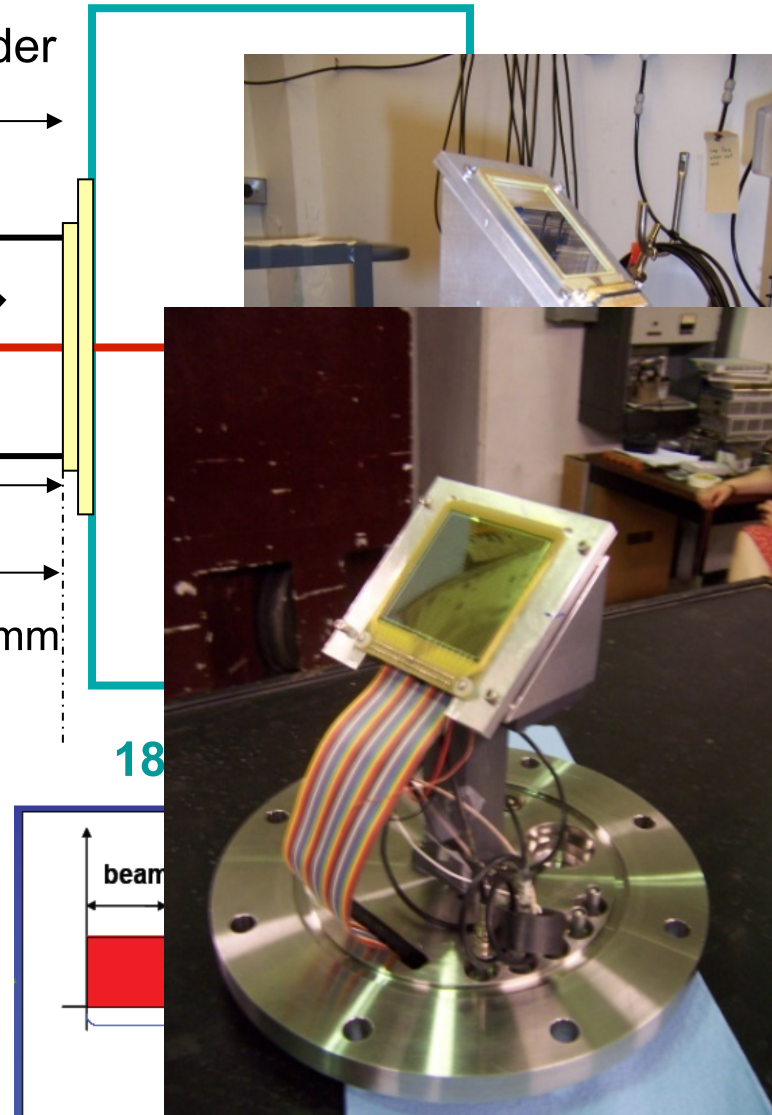
Experimental setup – 'Before'

MARS implantation station

thermocooler

connectors





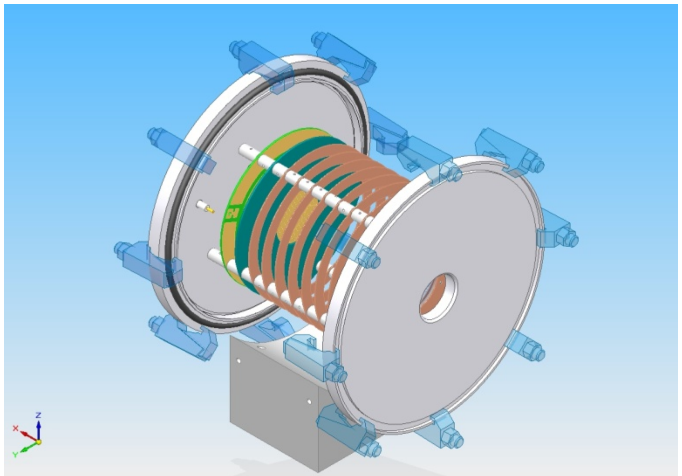
Pulsed beam

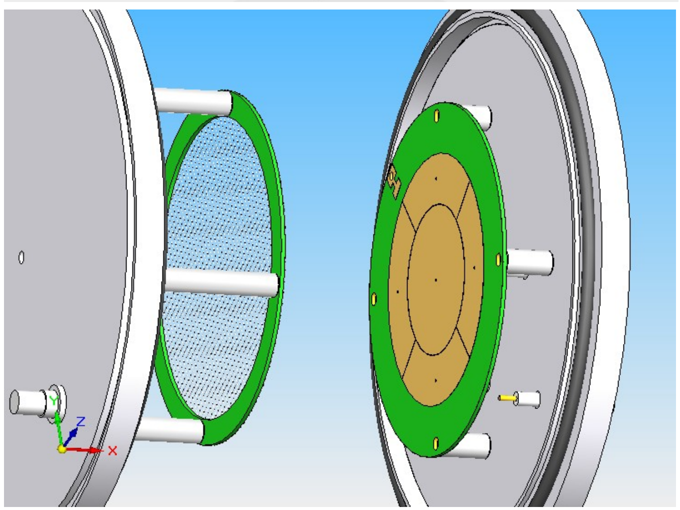
$E = E_p + kE_{recoil} + \langle \Delta E_\beta \rangle$

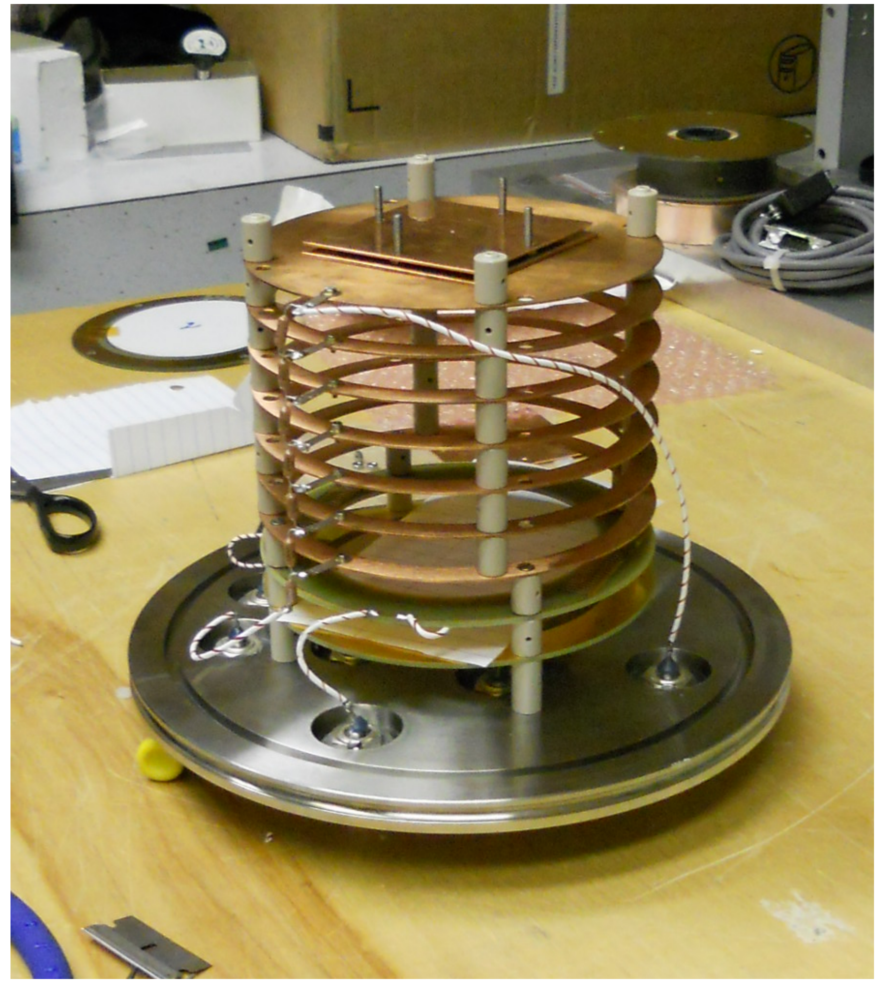
p-detector – v. thin DS Si strip 65 or 45 μm
W1-65 BB2-45

β-detector – thick Si det 1 mm
γ-detector – HPGe 70% effic

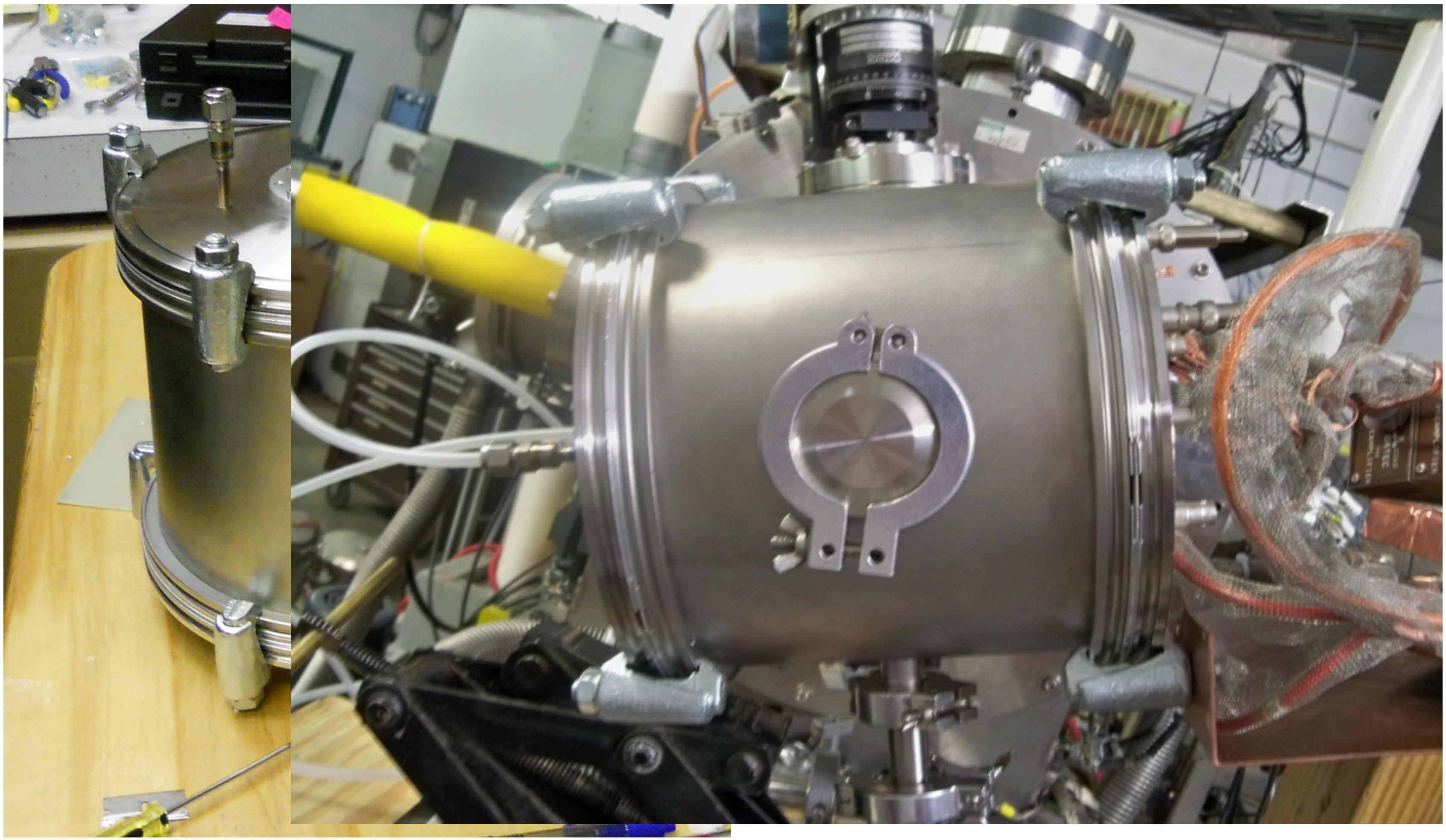
New detection setup - AstroBox

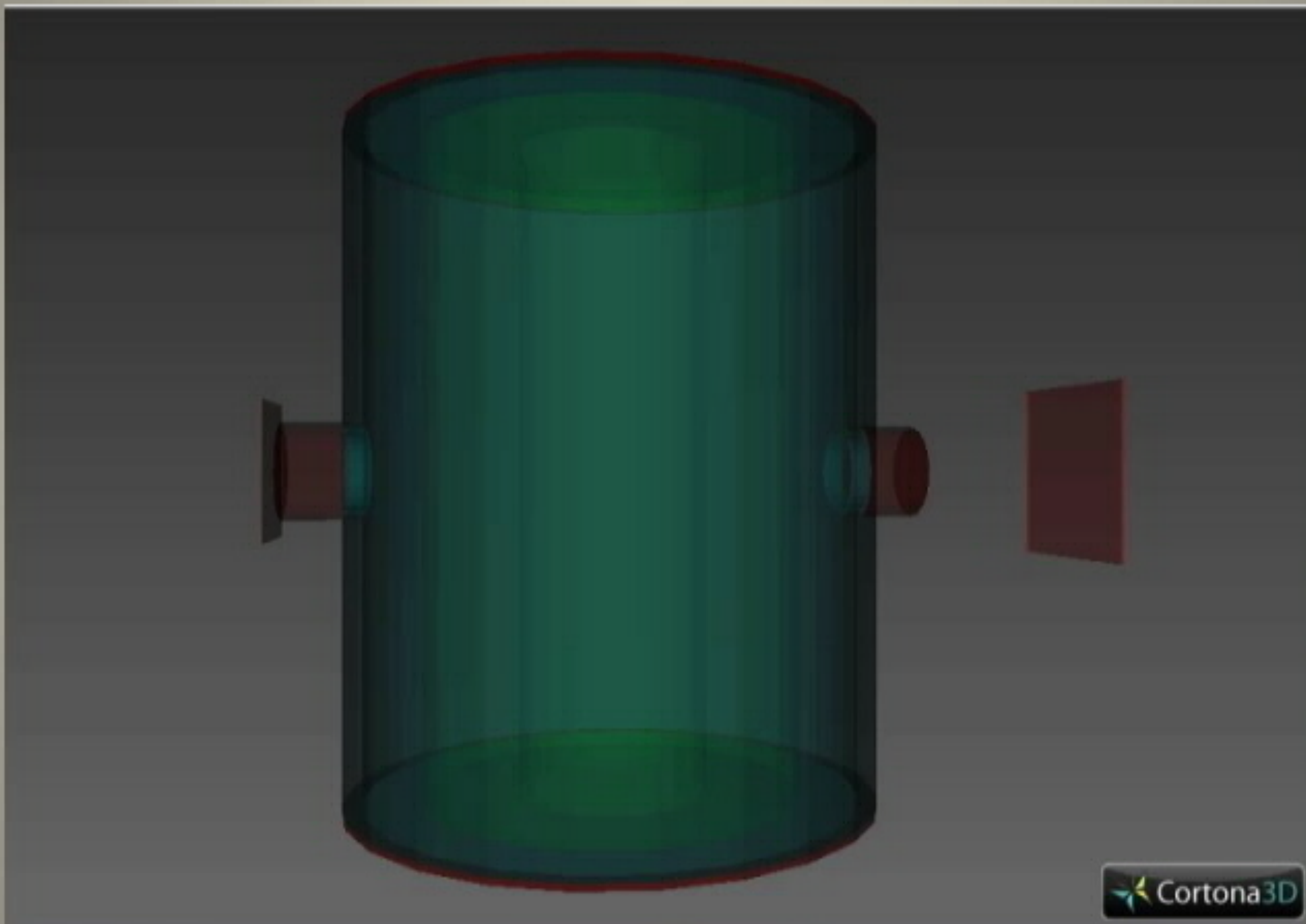






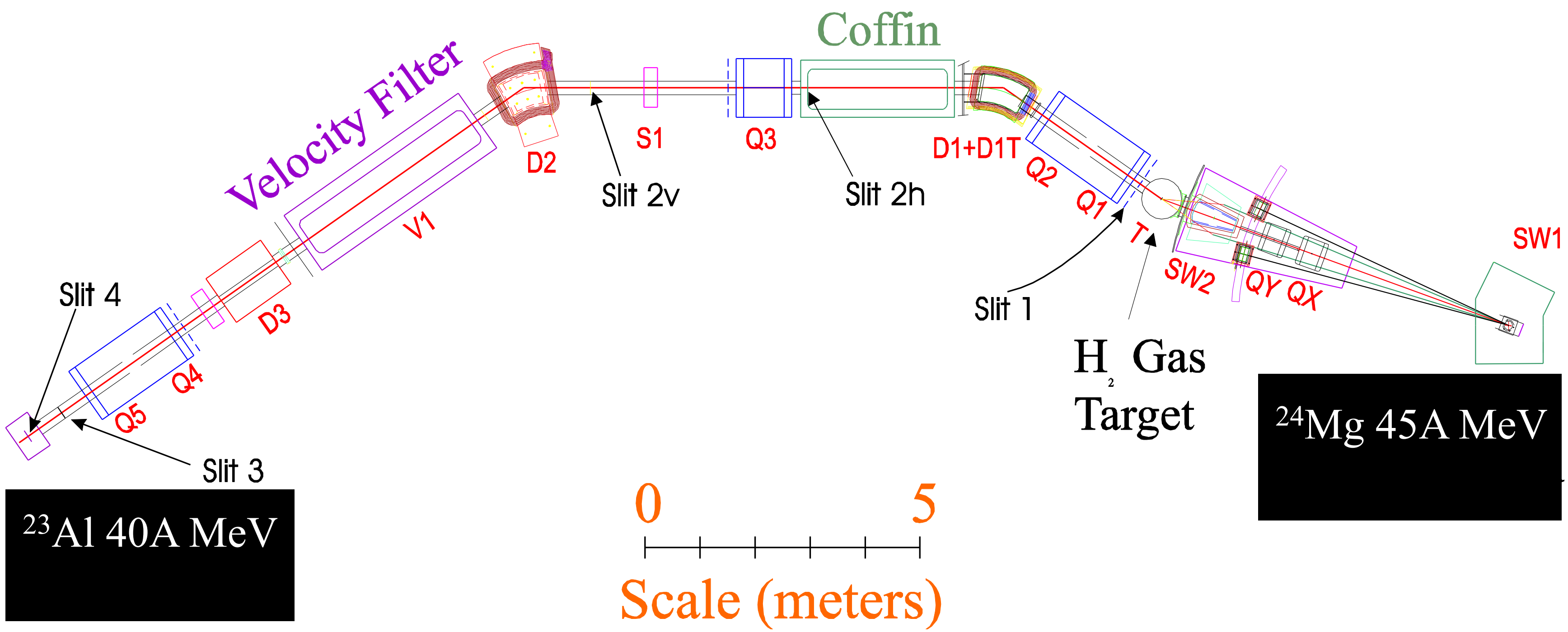
New detection setup - AstroBox




Cortona3D

28 fils au
pas de 2mm
Φ 50,4
Φ 50
5 tr meta
Φ 0.5mm
Φ 80
45°
139
Φ 110
B
op

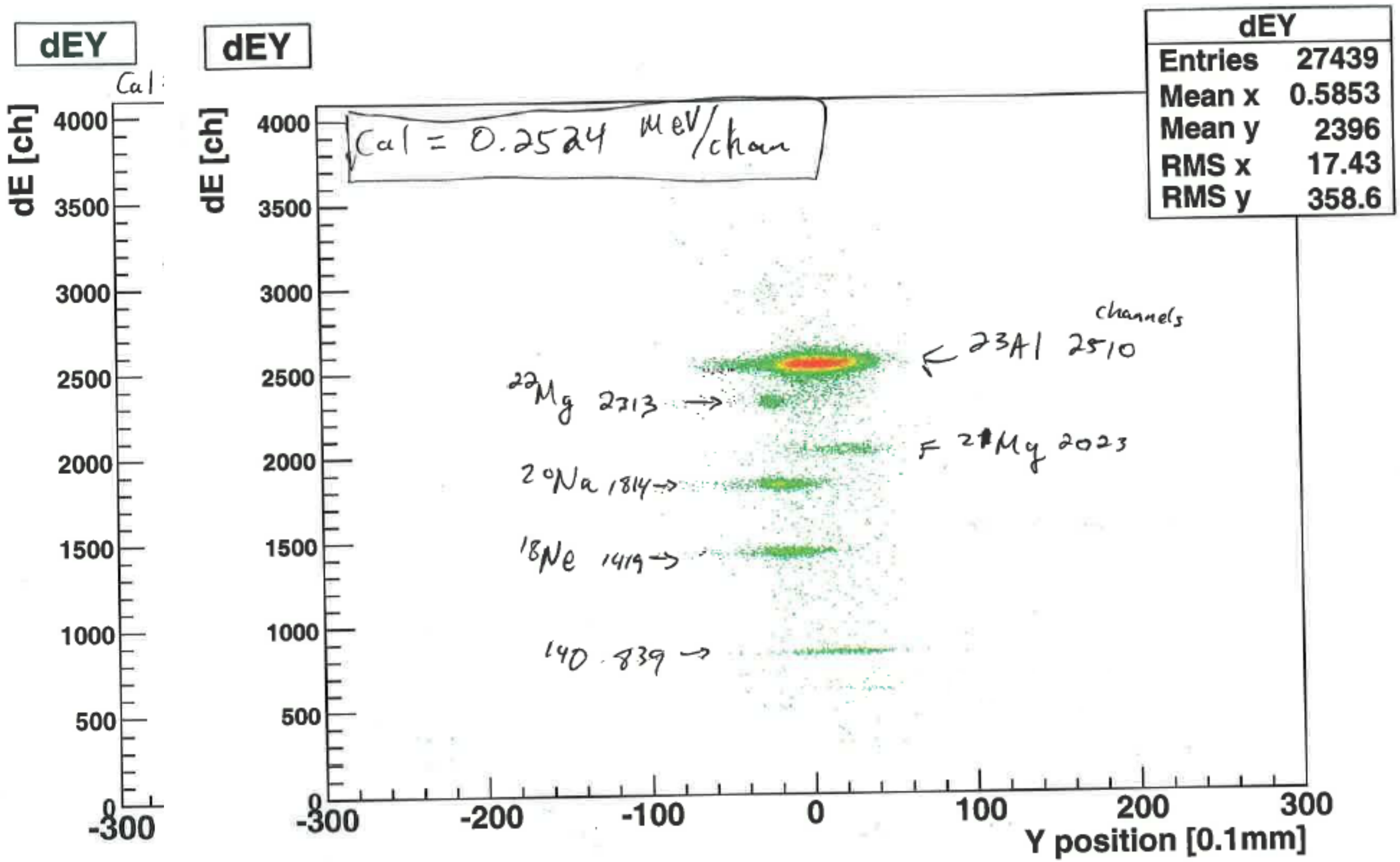
Momentum Achromat Recoil Separator

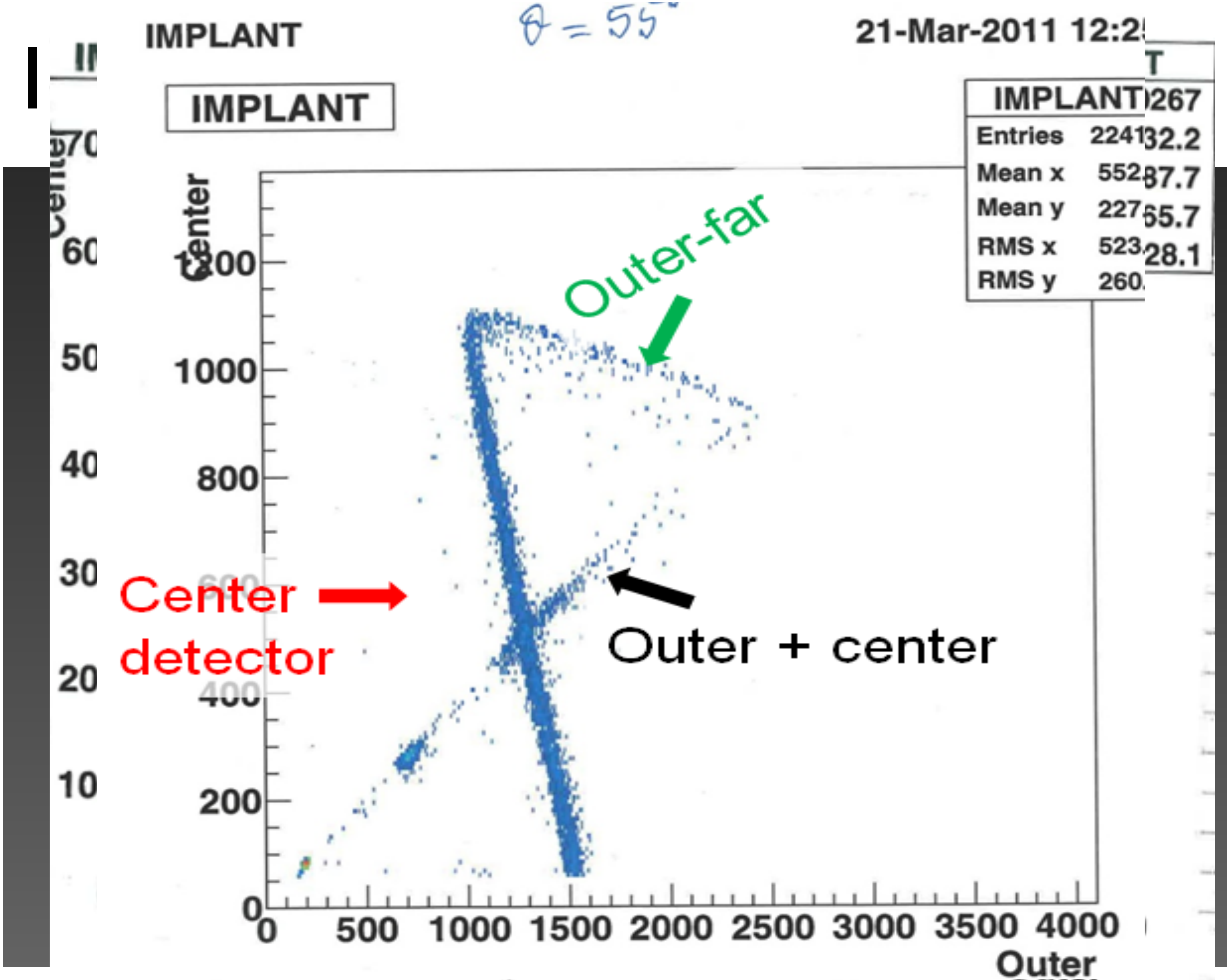


Purity: ~90%
Intensity: ~ 4000 pps
First time - very pure & intense ^{23}Al

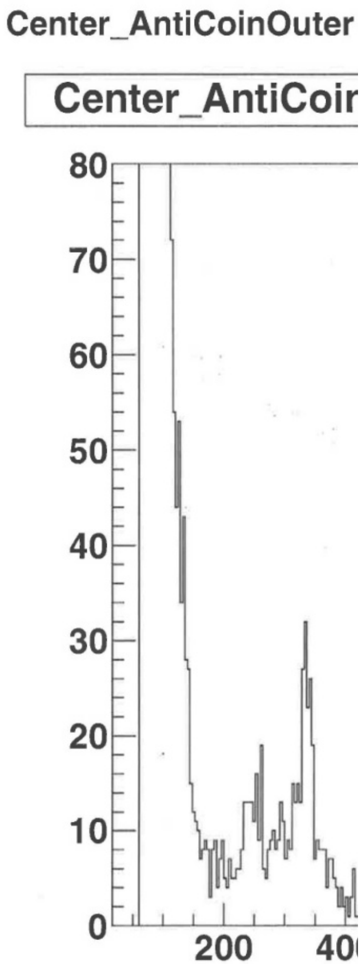
Primary beam ^{24}Mg @ 45A MeV – K500 Cycl
Primary target LN_2 cooled H_2 gas p=2 atm
Secondary beam ^{23}Al @ 40.2A MeV

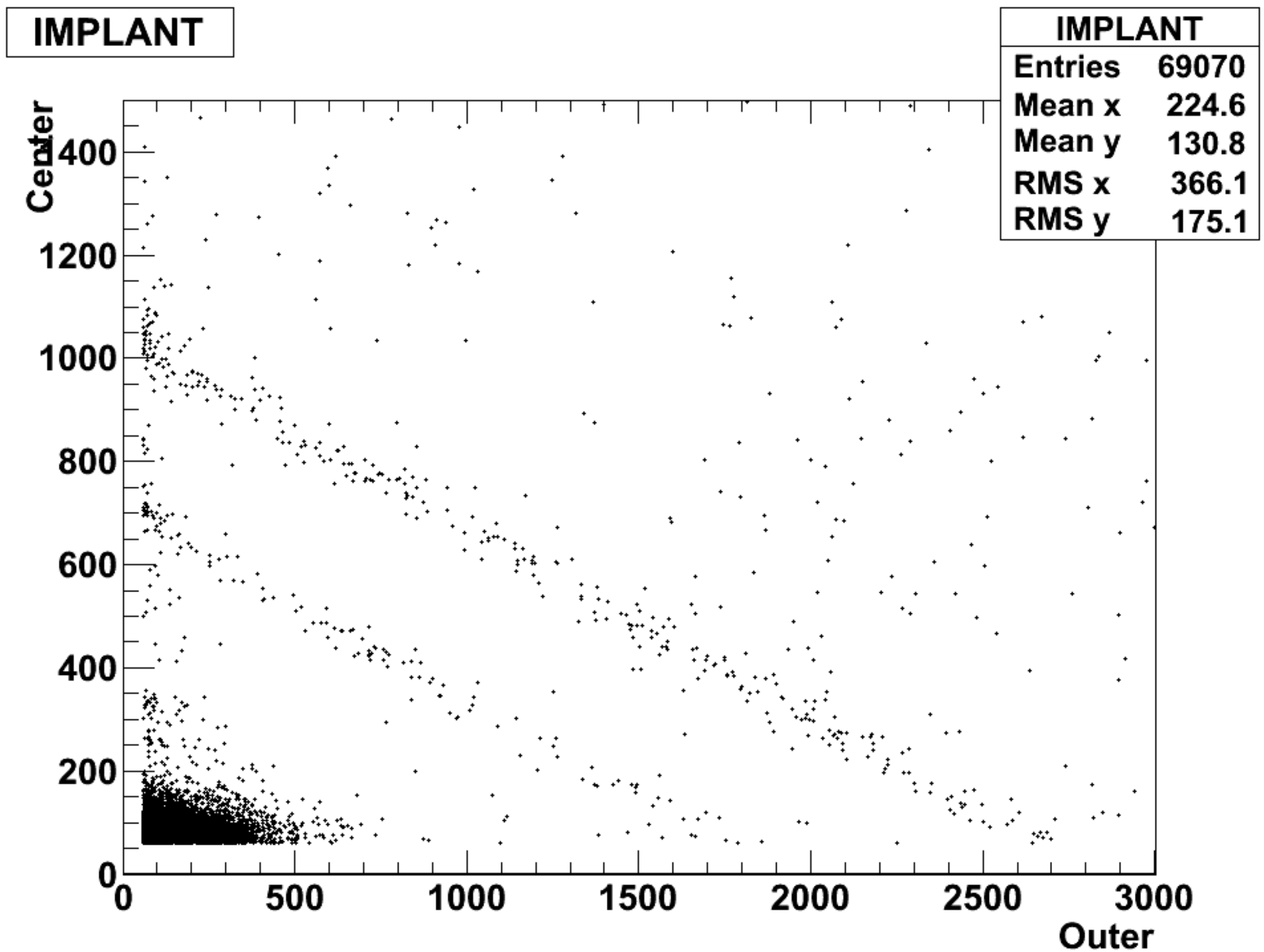
Isotope separation - MARS



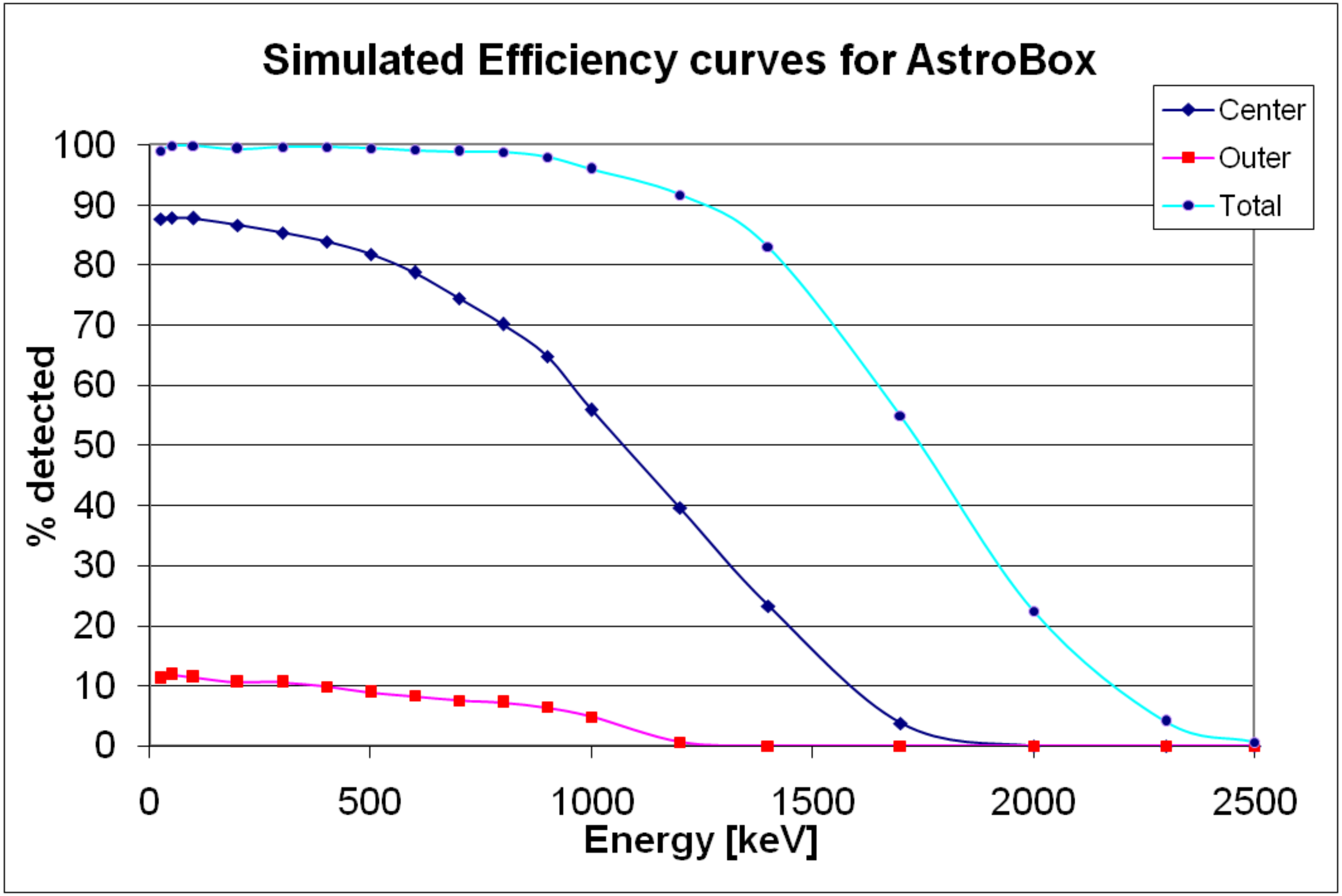

IMPLANT
θ = 55°
21-Mar-2011 12:2
IMPLANT
Entries
Mean x
Mean y
RMS x
RMS y
Center
Outer
Outer-far
Center detector
Outer + center

Measurements

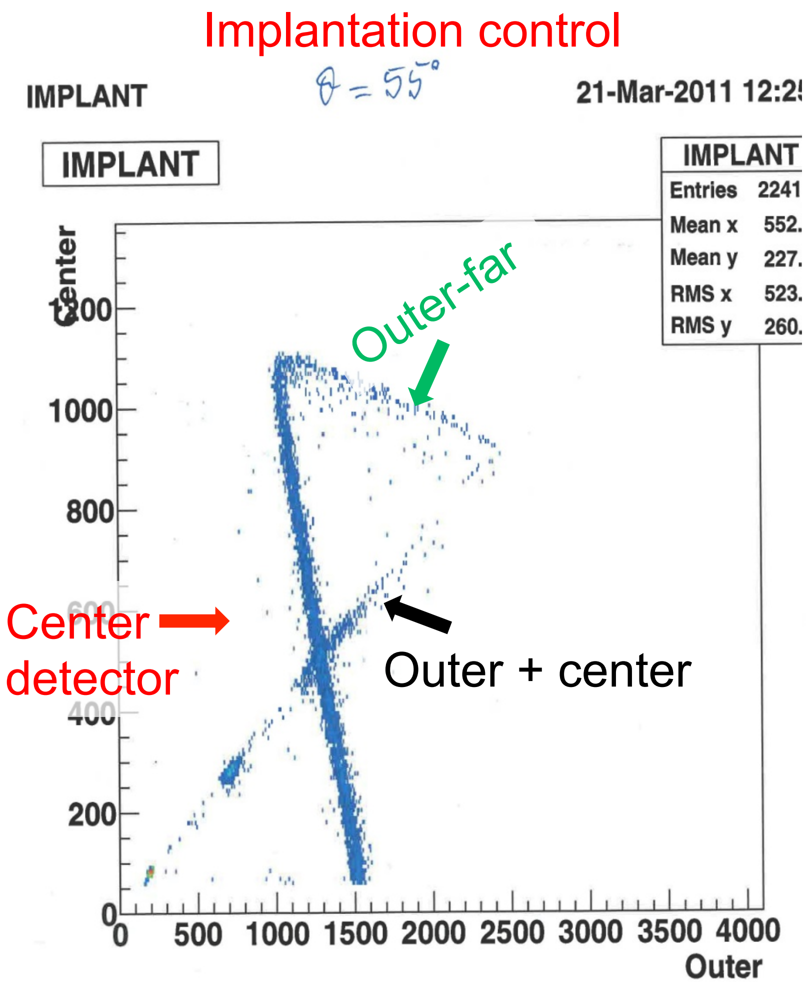


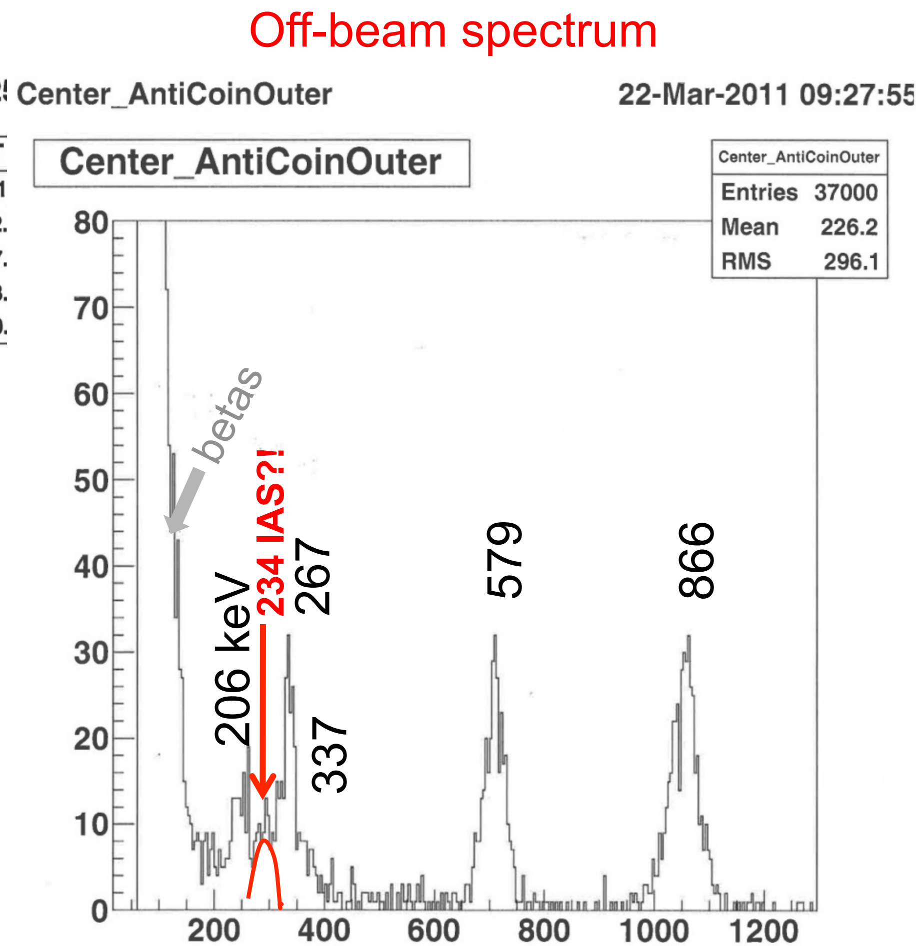


Results – Detection efficiency



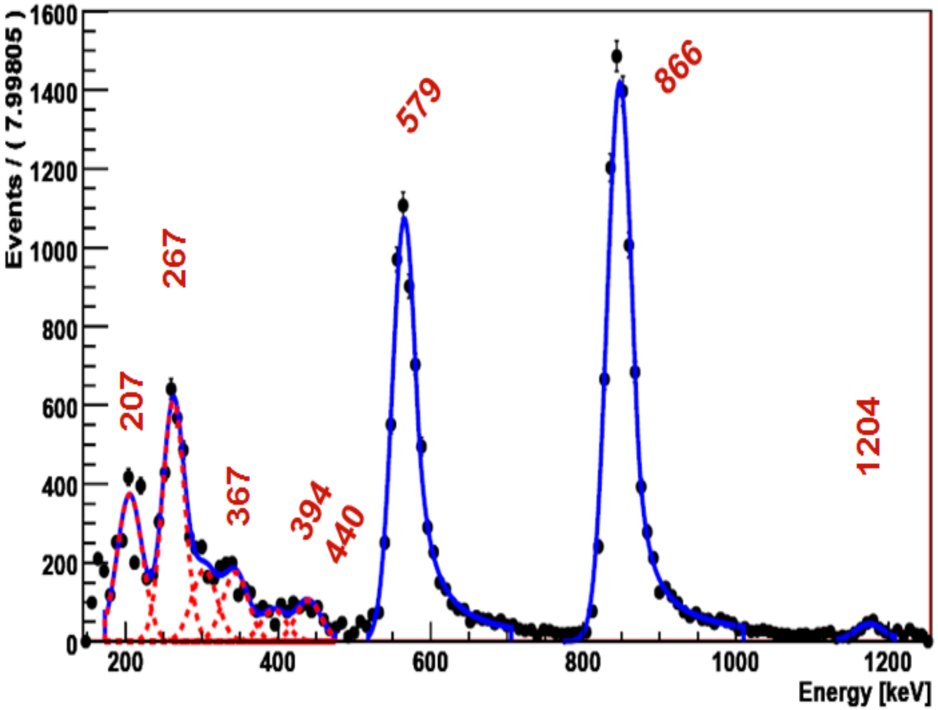
Run0311B: ^{23}Al βp-decay with ASTROBOX

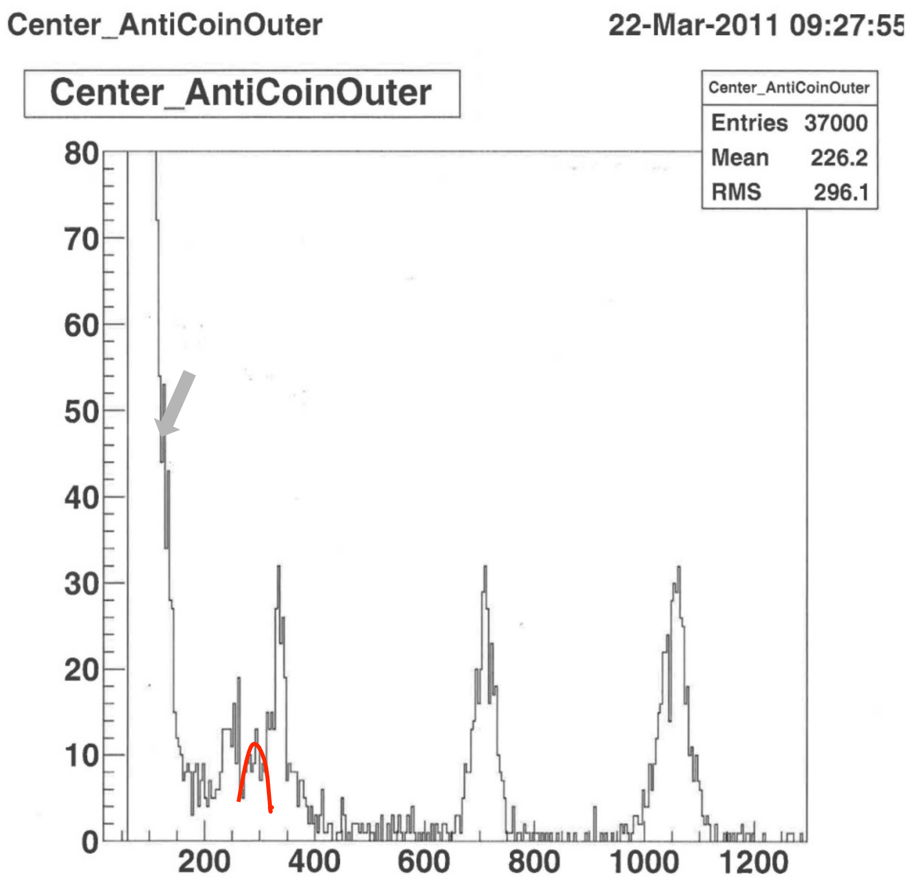




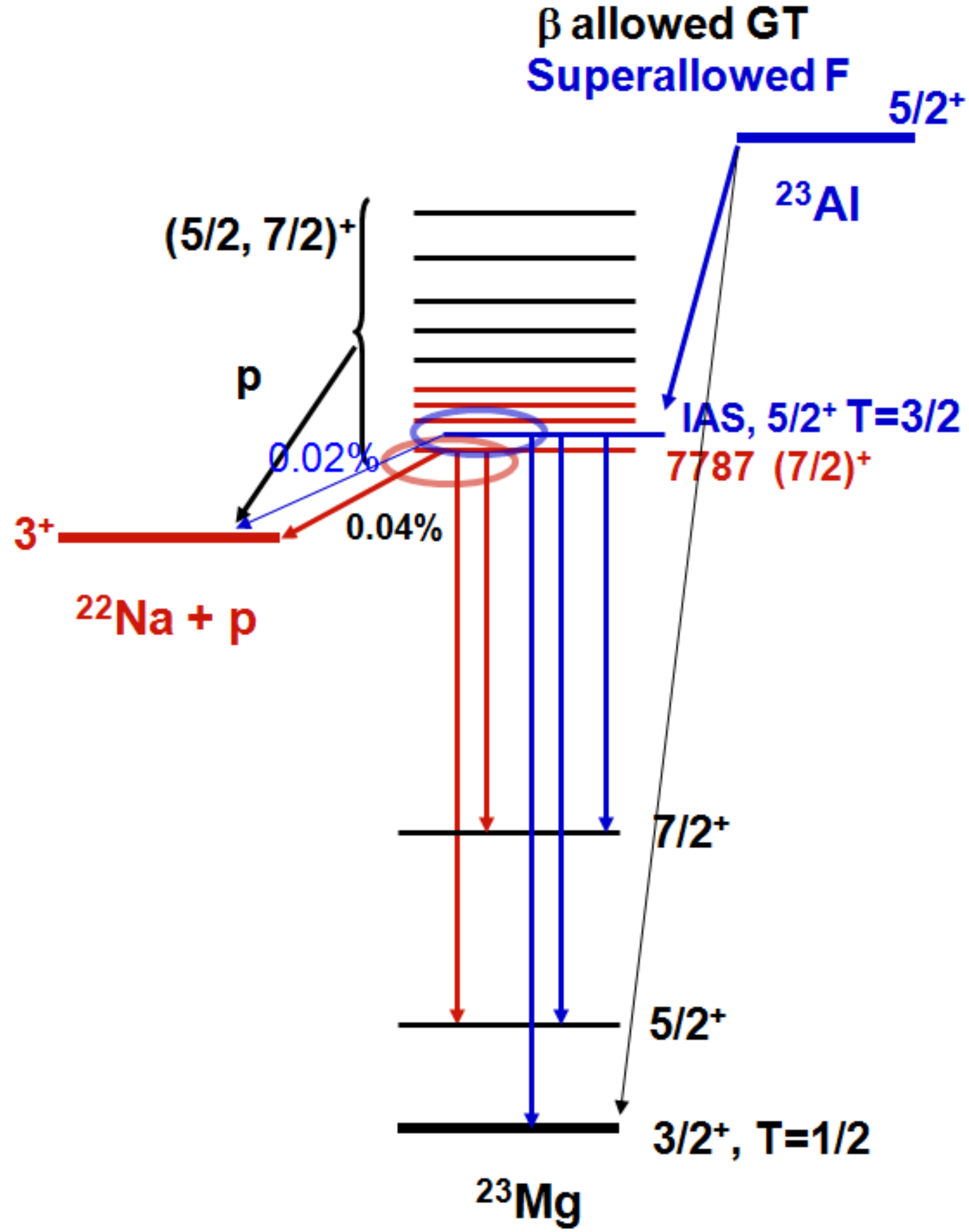
AstroBox - Results

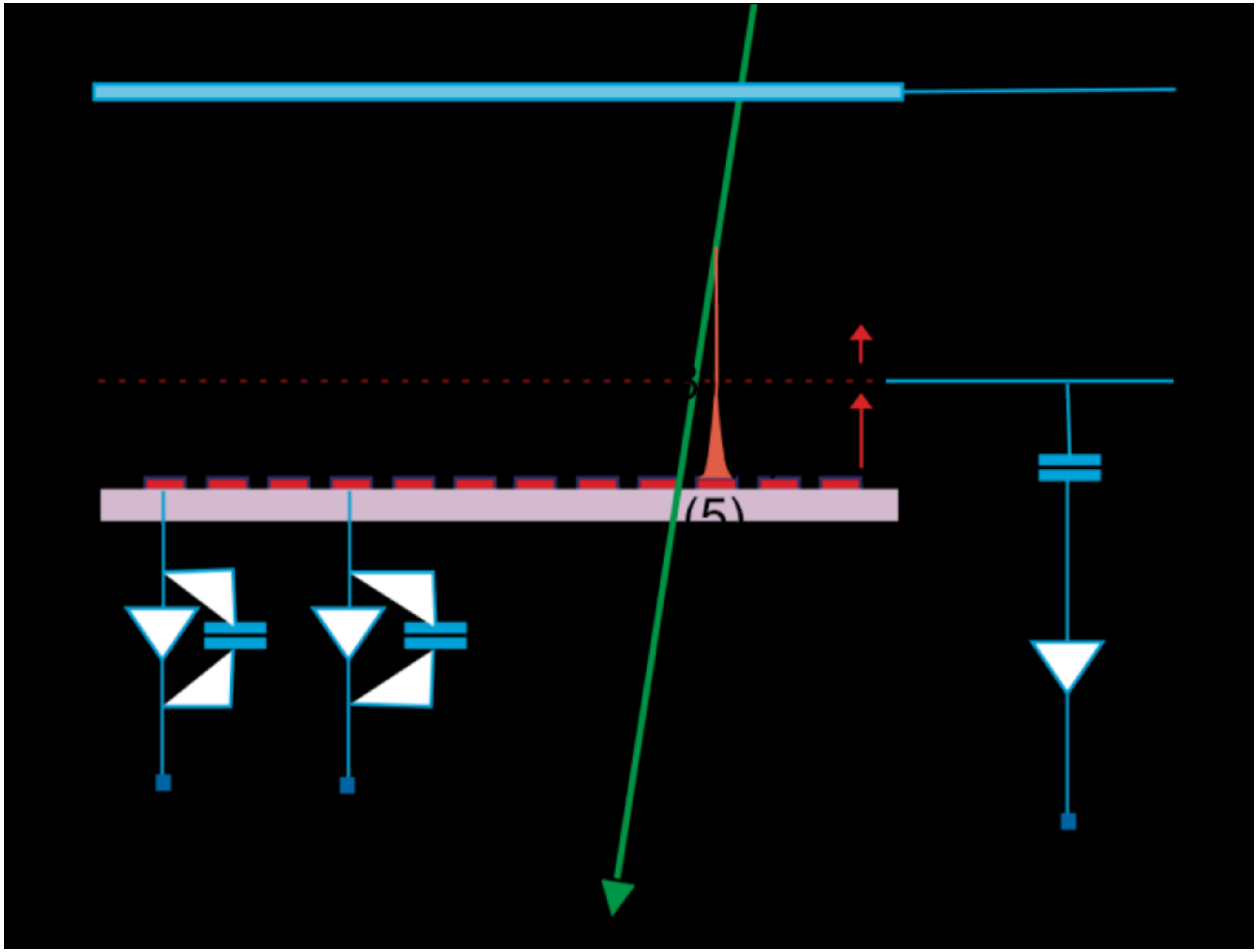
- Can go to E_p~80 keV
- Good peak separation
- Very sensitive – clear results within just ~2 hrs of statistics





	Eres (keV)	Eexc (keV)	br-p (of 100 beta)
	207	7787	0.04%
IAS	223	7803	0.02%
	267	7848	0.18%
	337	7917	0.06%
	443	8024	0.06%
	579	8160	0.39%
	866	8447	0.45%
		total	1.12(5)%



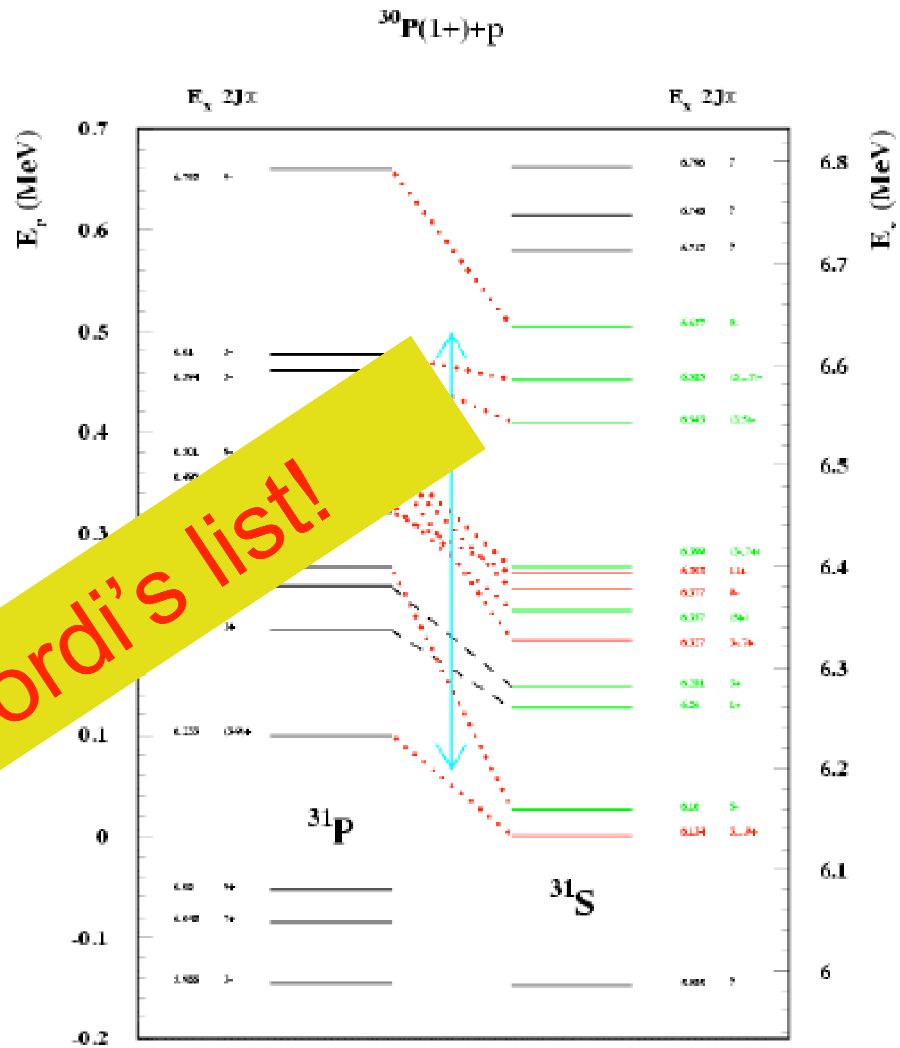

(5)

^{31}Cl

$^{30}P(p,\gamma)^{31}S$ rate

- ❑ No measured resonances
- ❑ Poor ^{31}S spectroscopy
- ❑ Rate from statistical (Hauser-Feshbach) model, inappropriate for this A and T
- ❑ Factor ~100 uncertainty (?
- ➢ Improved spectroscop *Jenkins et al. 2005;* *Kankainen et al. 20* *et al. 2007; Wrede et al. 2007*
- ➢ Rate ~H.F. but no measured $\omega\gamma$ or C^2S
- ➢ No ^{30}P beam !

See Jordi's list!

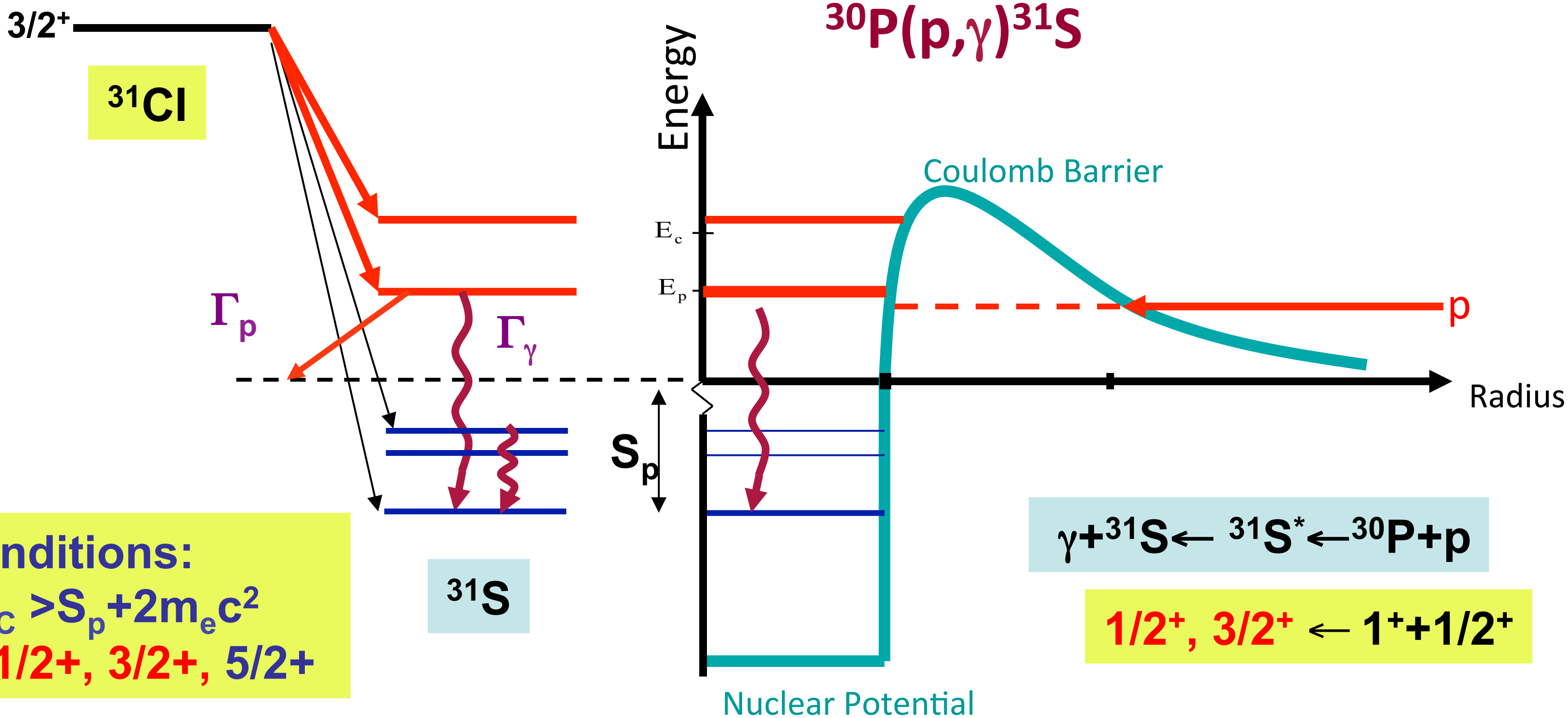


- ➢ Further experimental investigation of the $^{30}P(p,\gamma)^{31}S$ reaction

Novae will become the first explosive site where *all* nuclear reaction rates are derived from *experimentally measured cross sections* !

Decay of ^{31}Cl

Resonant Capture $^{30}P(p,\gamma)^{31}S$



Conditions:
$Q_{EC} > S_p + 2m_ec^2$
J=1/2+, 3/2+, 5/2+

Same compound system: ^{31}S

resonance strength:

$\Gamma_{tot} = \Gamma_p + \Gamma_\gamma$

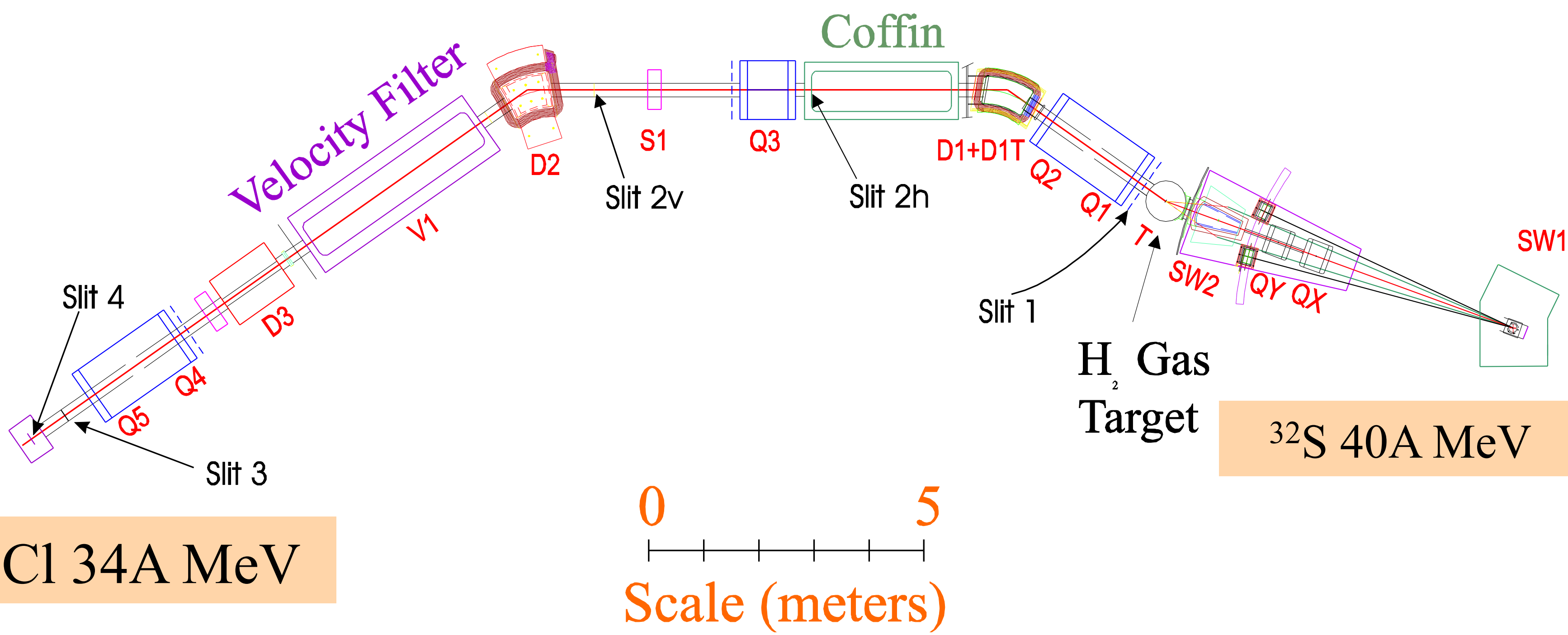
$\omega\gamma$ … Γ_γ … Γ_p

Lower proton energies most important, but very difficult:
- lower branching
- increased exp difficulties (det windows, background, etc…)

MARS

Momentum Achromat Recoil Separator

In-flight RB production



^{32}S 40A MeV

^{31}Cl 34A MeV

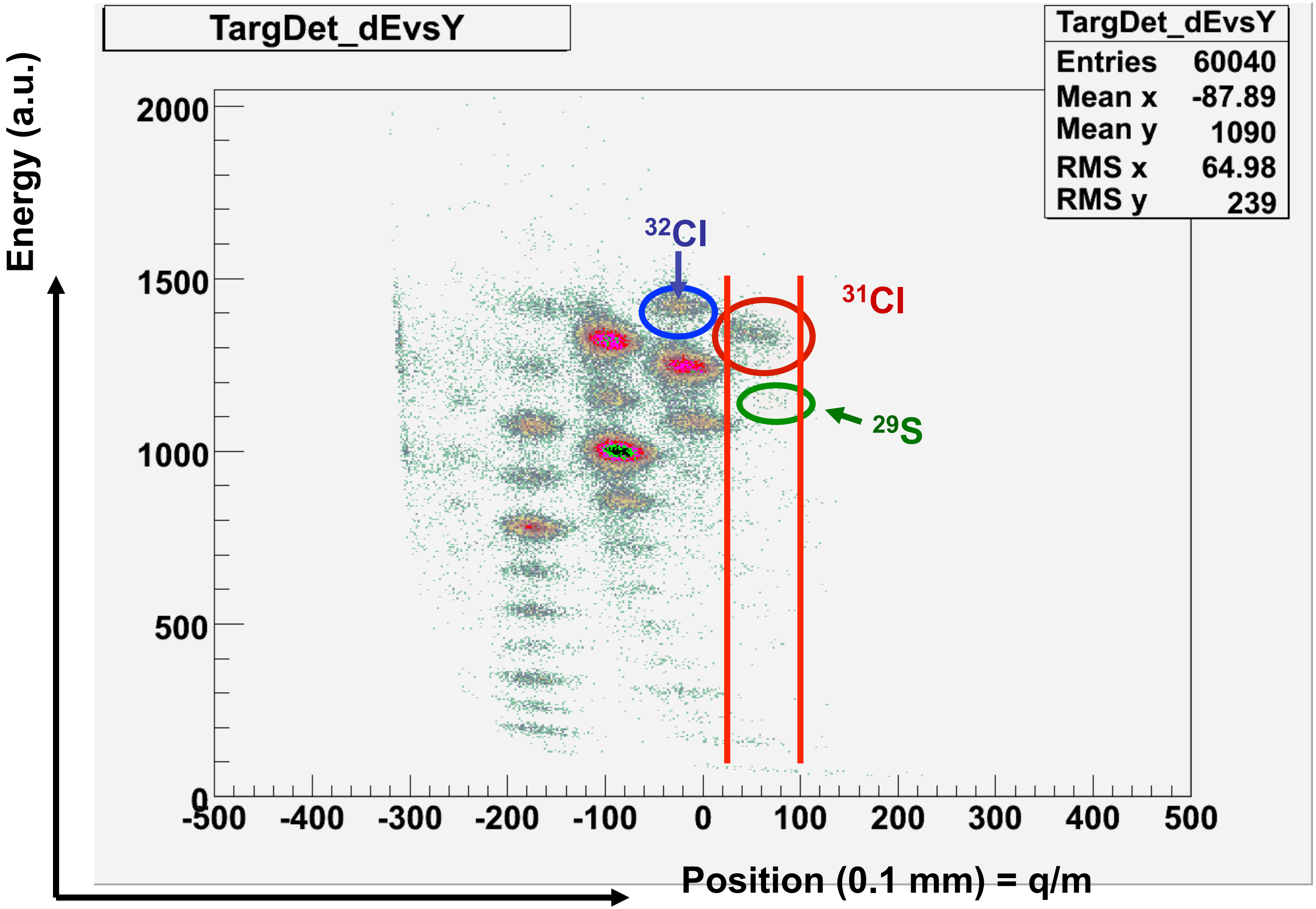
Purity: > 85 % (at target det)
Intensity: ~ 2-3000 pps
difficult - pure & intense ^{31}Cl

Primary beam ^{32}S @ 40A MeV – K500 Cycl
Primary target LN$_2$ cooled H$_2$ gas p=2 atm
Secondary beam ^{31}Cl @ 34 A MeV

(p,2n) reaction

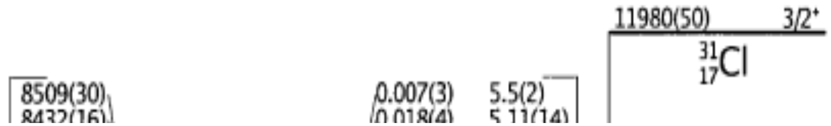
CYCLOTRON INSTITUTE
Texas A&M University

^{31}Cl production and separation



^{31}Cl β-decay - status 2006

A. Kankainen *et al.*: Excited states in ^{31}S studied via beta decay of ^{31}Cl



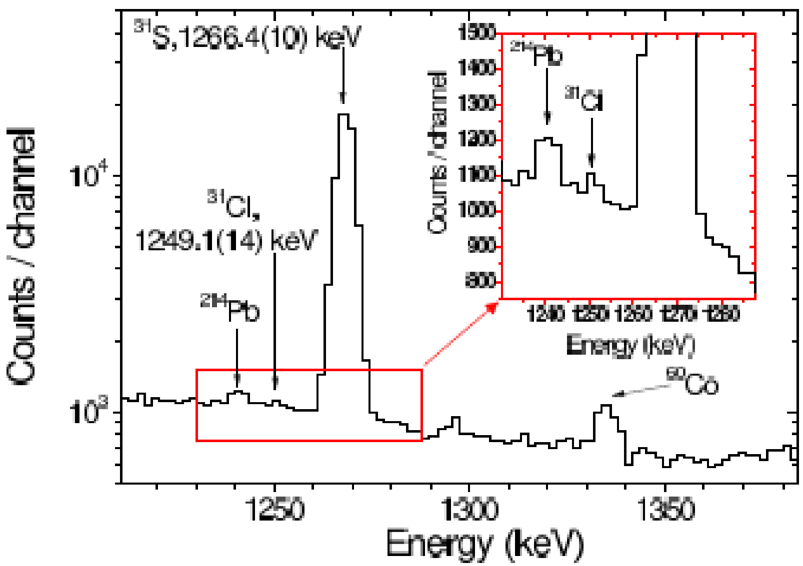


Fig. 5. The 1249.1(14) keV γ-peak in the spectrum of ^{31}Cl vetoed by the E2 silicon detector.

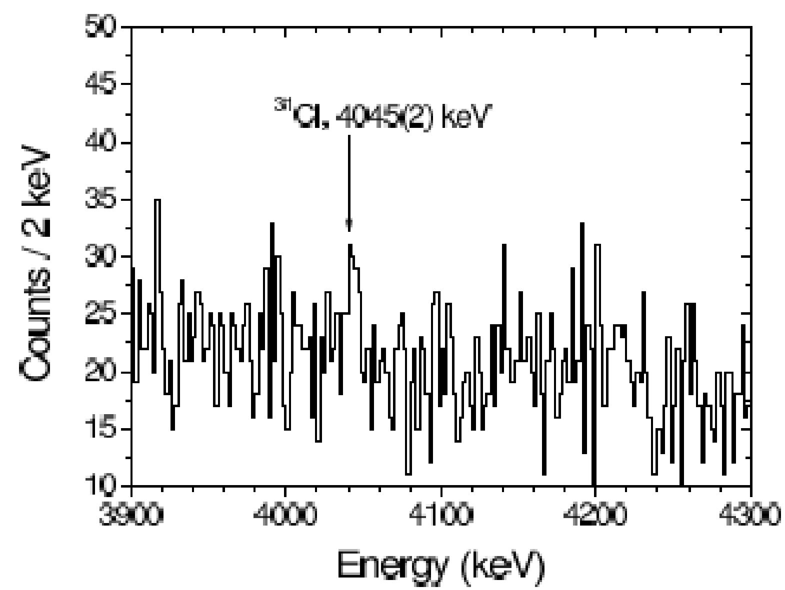
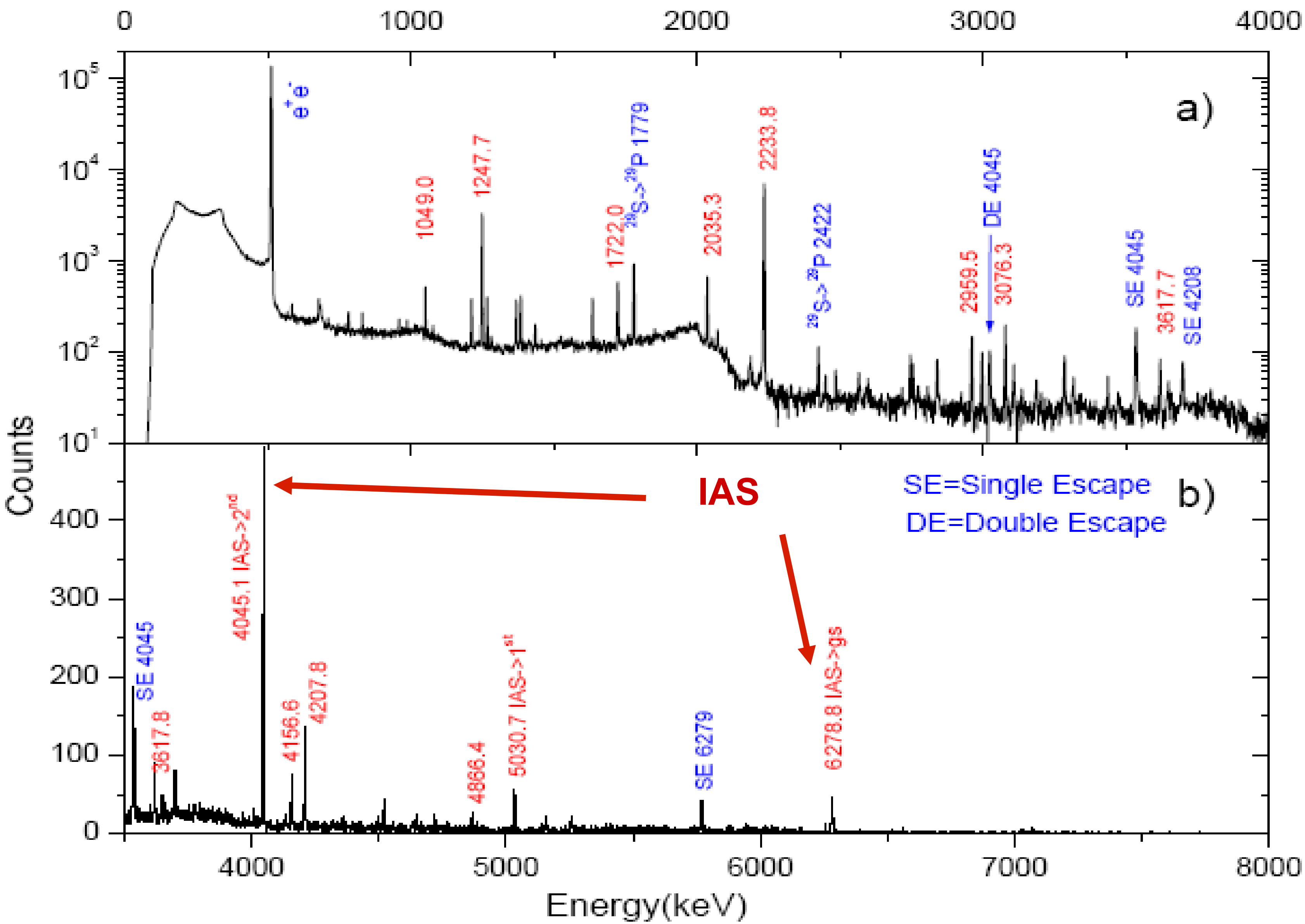
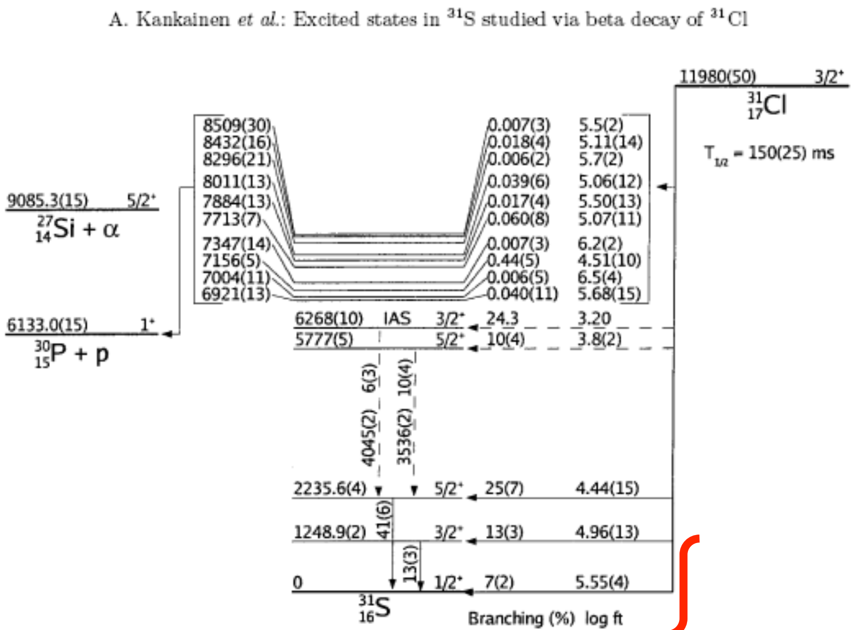


Fig. 7. The 4045(2) keV γ-peak in the spectrum of ^{31}Cl vetoed by the E2 silicon detector.

^{31}Cl βγ decay

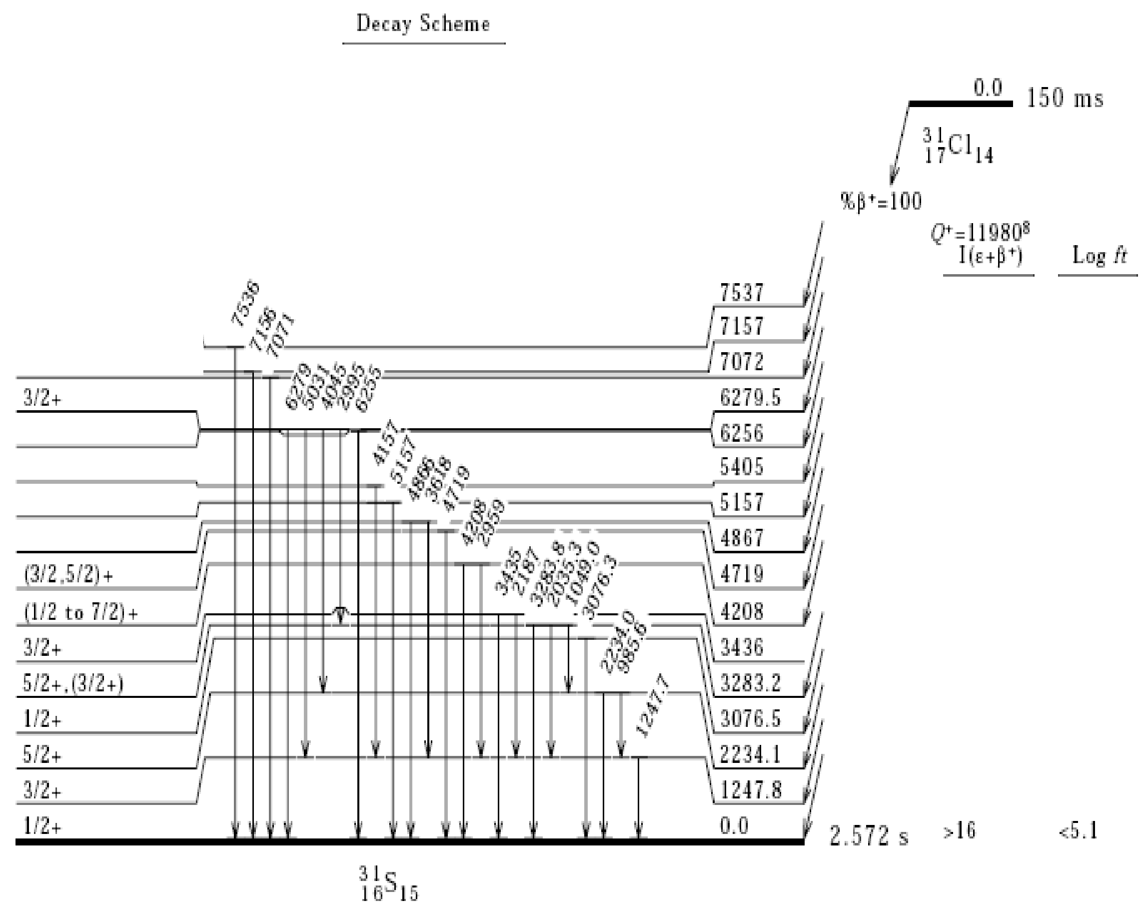


^{31}Cl β-decay - status 2006/present exp



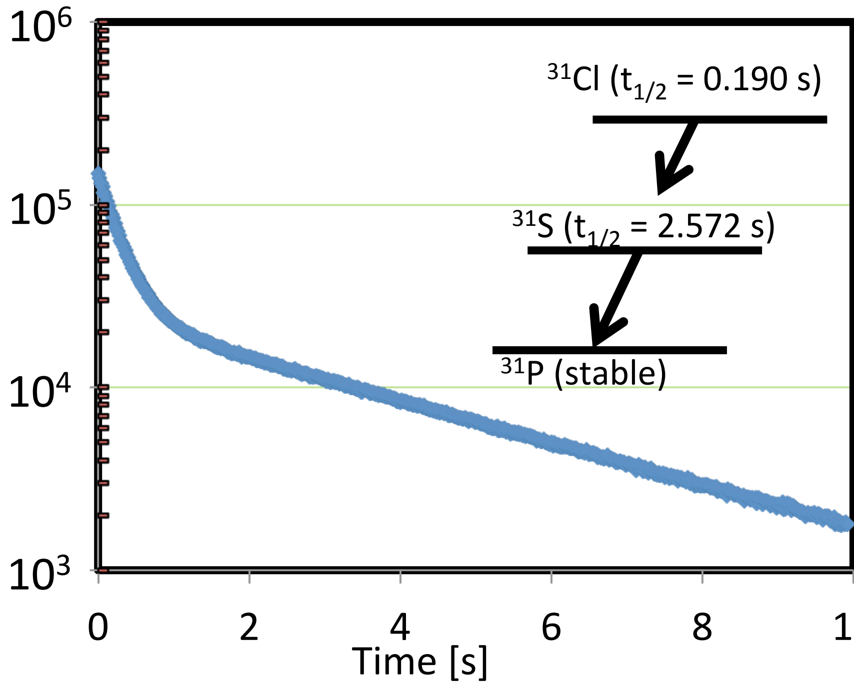
Old: $T_{1/2}$ **=150(25) ms**

New: $T_{1/2}$ = 190(1) ms

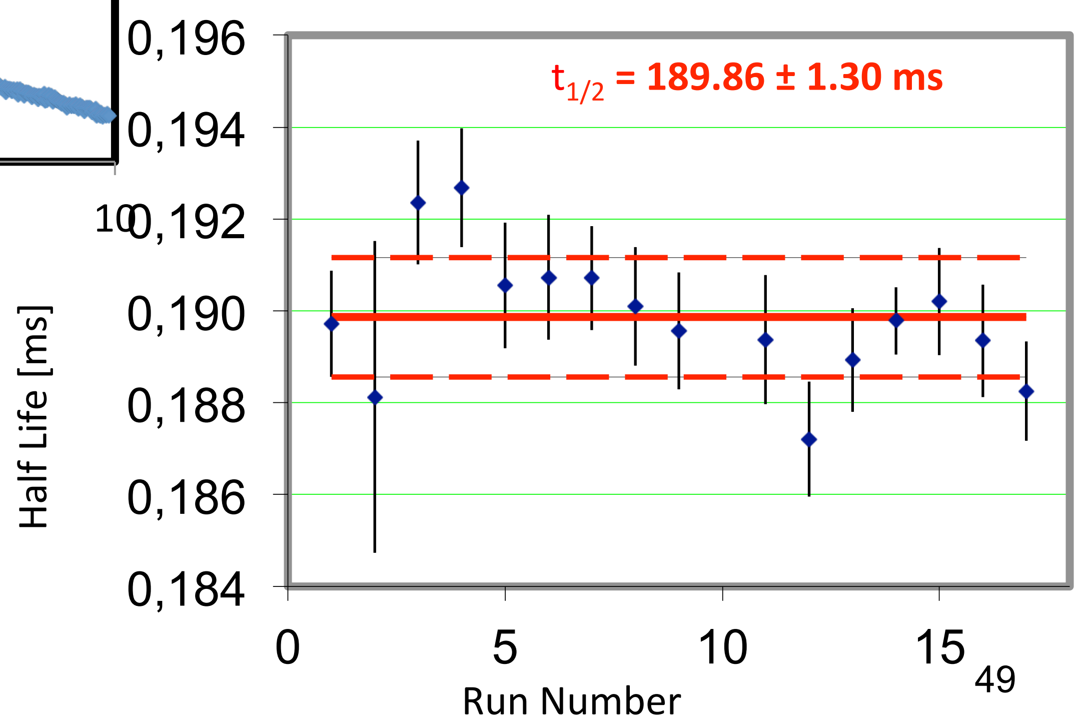


S_p=6.133 MeV

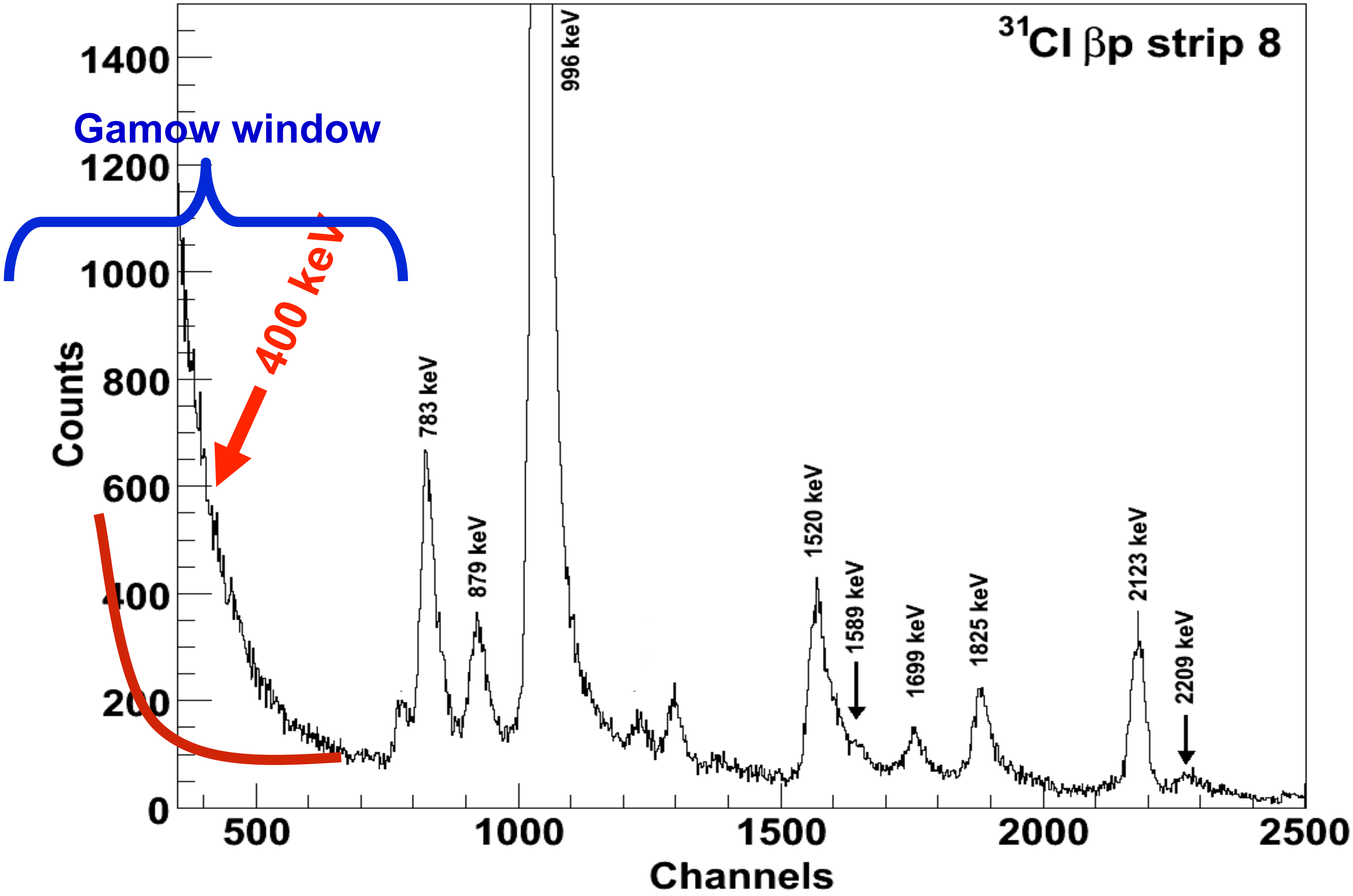
^{31}Cl Half-Life Stability versus Detection Settings



Run Apr09: more than 6×10^6 β$^+$ events (^{31}Cl & ^{31}S)

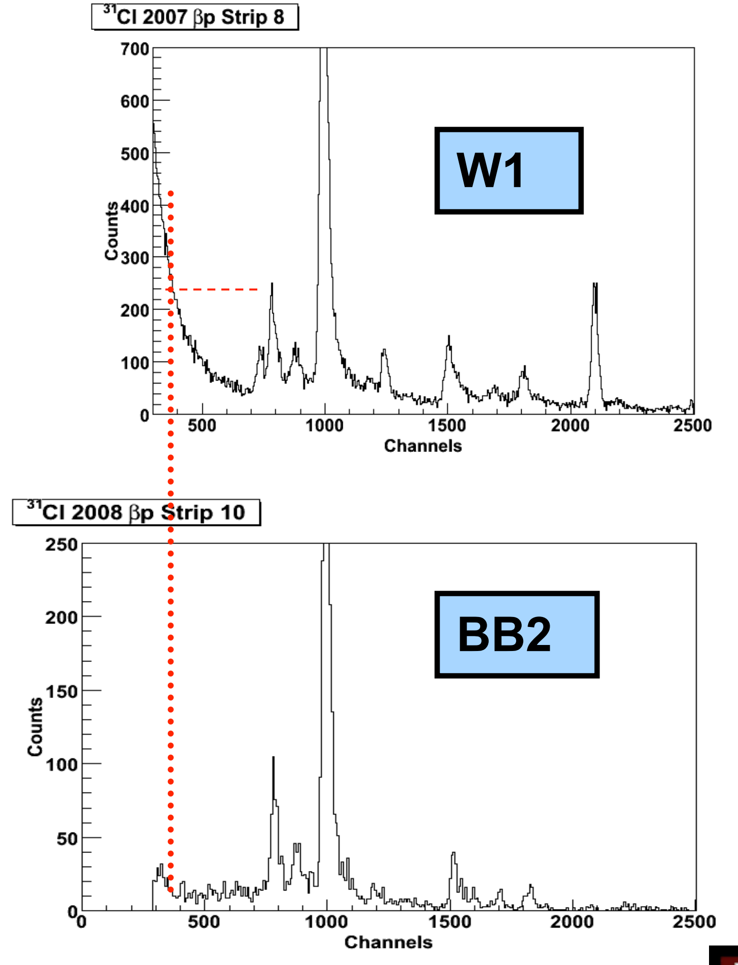


^{31}Cl proton-spectrum



Lowering β background:

- W1-65
  - Large amount of background in the regions of 500 keV or lower
- BB2-45
  - Only part of the statistics are shown, but
    - Resolution is visibly better
    - And the minimum energy threshold goes below 300 keV
    - Lose efficiency at E_p> 1.5 MeV
- Conclusions:
  - Thinner detector with thinner strips was better at measuring the proton energies as low as 2-300 keV

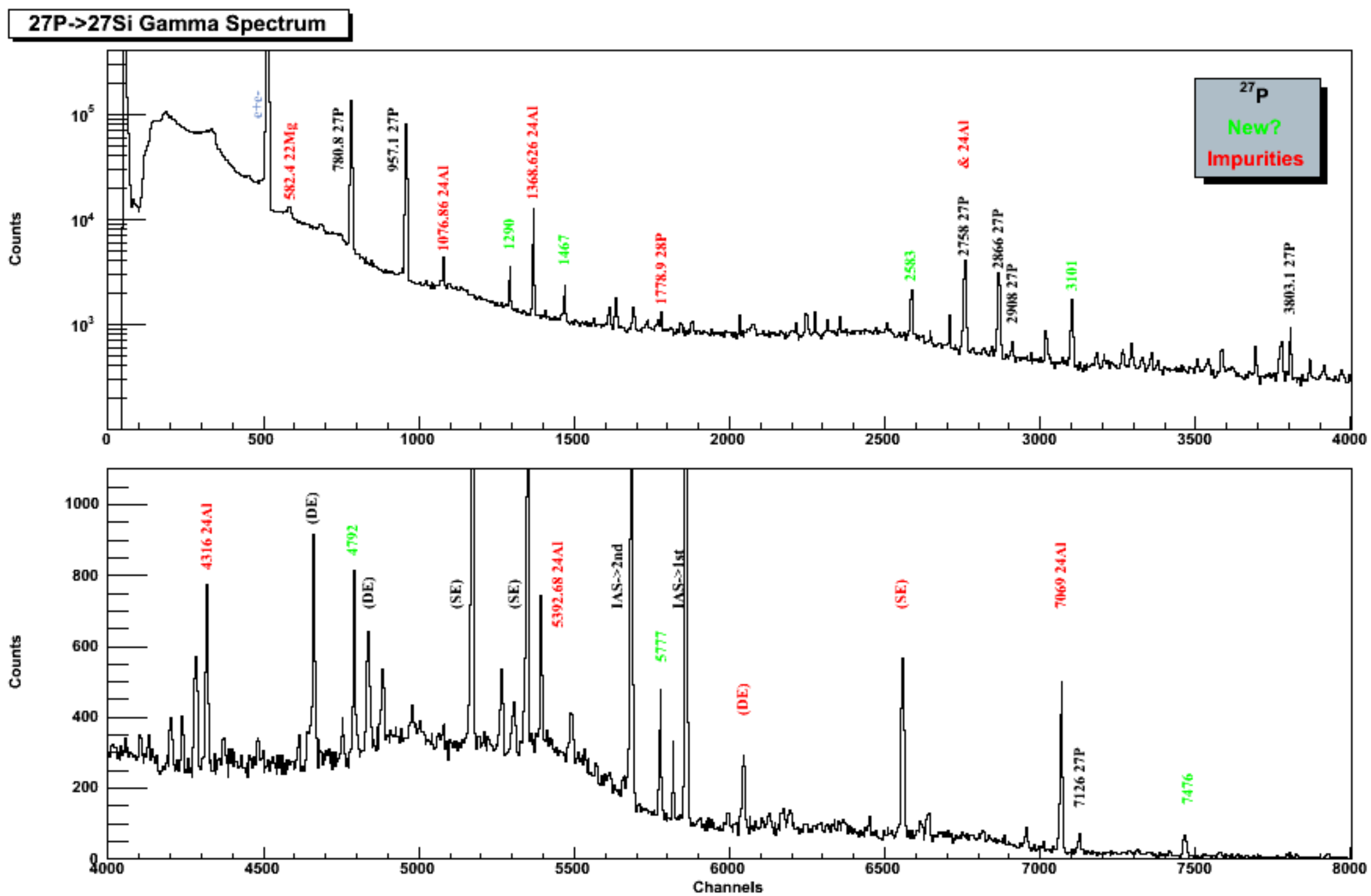


Un-fortunately: no new states here! And no AstroBox measurements. *Yet!*

^{31}Cl β-decay results

- First clean and intense ^{31}Cl source
- established β-decay scheme
- determined relative branching ratios
- measured $T_{1/2}$=190(1) ms (<1% accuracy)
- identified IAS E*=6279.5±0.3±1.5 (syst) keV and its decay
- used IMME to get new, more precise ^{31}Cl mass ME(^{31}Cl)=-7064(8) keV ⇒ Q_{EC}=11,980(8) keV and S_p(^{31}Cl)=289(8) keV (imp for ^{30}S(p,γ)^{31}Cl !)
- found precise energy of E^*=6256(1) keV ⇒ E_{res}=123(2) keV – important reson in ^{30}P(p,γ)^{31}S
- did not find IAS proton branching (at E_p=146 keV – very difficult !!)

^{27}P decay



Most recent: by Ellen Simmons et al.

Results β-delayed p-decay

- Technique works well – can go to E_p~100 keV and, maybe, lower
- Can work with lifetimes ~100 ms or less
- Very selective: can separate well beam cocktails (by implantation depths)
- Very sensitive: could obtain results for ^{21}Mg, ^{29}S at rates ~ 1-10 pps in 8 hrs
- Could study very weak branches (e.g. ^{20}Mg 50 pps)

Strengths:

- Good isotope separation (MARS)
- In-flight production: need 30-50 MeV/u (can be implanted)
- ASTROBOX opens new possibilities

Collaborators

- M McCleskey, E Simmons, A Spiridon, BT Roeder, G Tabacaru, RE Tribble, JC Hardy, VE Iacob, A Banu* *– Cyclotron Institute, Texas A&M University* *(* now at J Madison University, VA)*
- PJ Woods, T Davinson, G. Lotay *– Univ of Edinburgh*
- J Aysto, A Saastamoinen, A Jokinen *– Univ of Jyvaskyla*
- MA Bentley *– Univ of York*
- *E Pollacco et al. –CEA Saclay*