Measurements of the Astrophysically Important $^{40}Ca(\alpha,\gamma)^{44}Ti$ Reaction Rate

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JINA Frontiers Meeting

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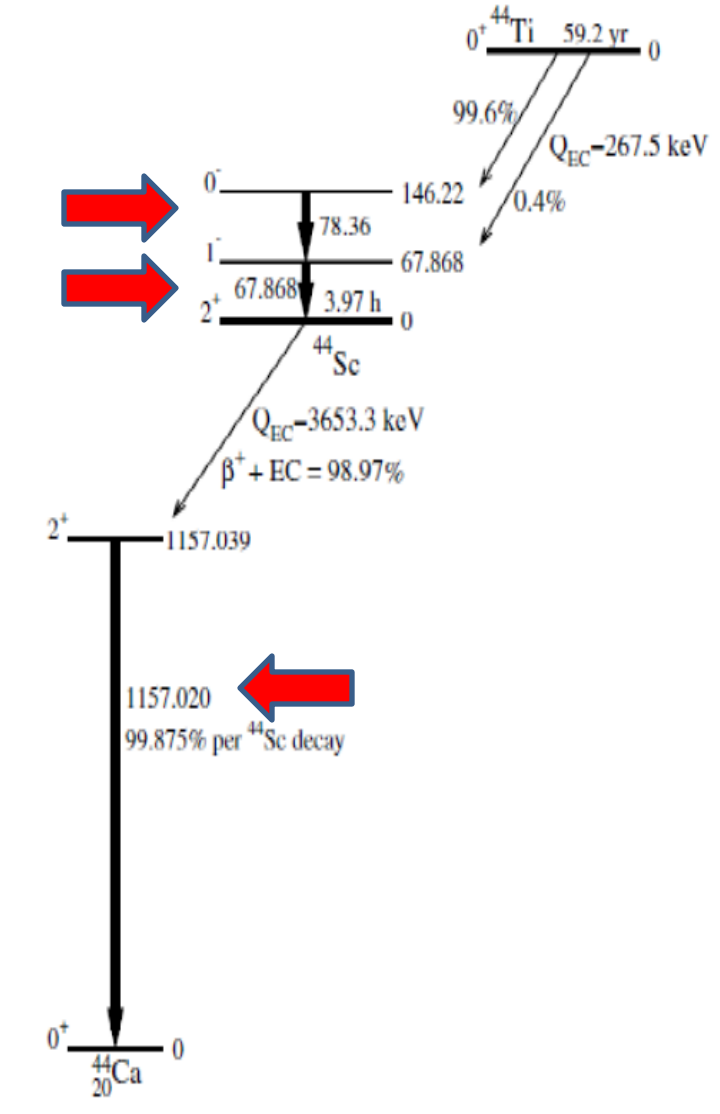
Why study ^{44}Ti at all?

- Recent observations of live ^{44}Ti highlight its use as a probe for SNRs (eg Cas A, COMPTON / INTEGRAL)
- Relatively short half-life ($t_{1/2}$=58.9 yrs)
- Created in CC SN which enrich the ISM
- Observational & modeling differences (1.6×10^{-4} $M_{\odot}$)
  - Larger by x 2-10 than predicted
  - Mass cut dependence
  - Reaction rate discrepancies

Getting to know ^{44}Ti

- First unstable nucleus of the α-chain
- Relatively short lived ($t_{1/2}$=58.9 ± 0.3 yrs), *Ahmad et al*
- Detectable through 68, 78 and 1157 keV γ-lines
- Predominantly created through ^{40}Ca(α,γ)^{44}Ti reaction
- Produced in the inner layers of SN explosions, during α-rich freeze-out



Previous measurements

Prompt γ measurements in 1970's

- Simpson *et al.*, *Phys. Rev. C* 4 (1971)
- Cooperman *et al.*, *Nucl. Phys. A* 284 (1977)
- Dixon *et al.*, *Phys. Rev. C* 15 (1977); *Can. J. Phys.* 58 (1980)

$$\Sigma\omega\gamma = 12 \text{ eV}$$

Recent AMS measurements

- Nassar *et al.*, *Phys. Rev. Lett.* 96 (2006)

$$\omega\gamma_{int} = 24 - 60 \text{ eV}$$

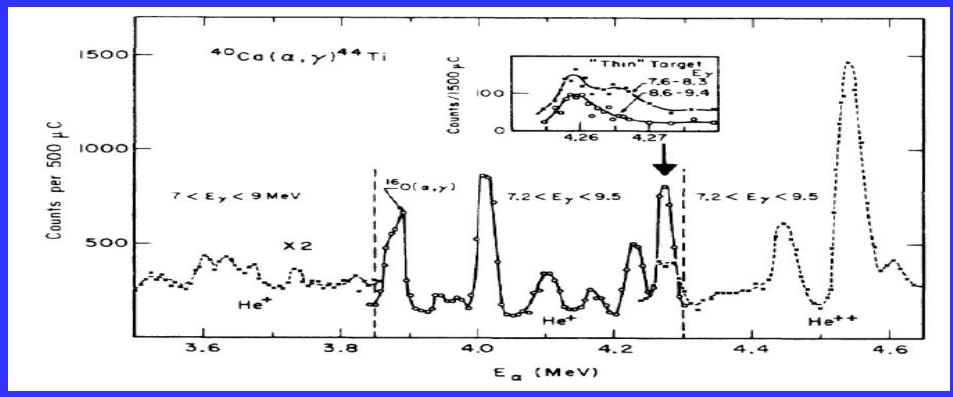
Factor of ~ 2 - 5

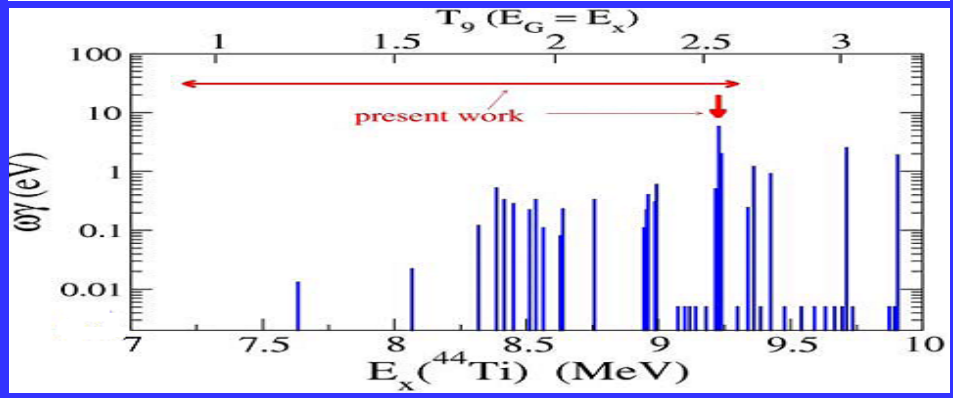
Factor of ~ 12.5

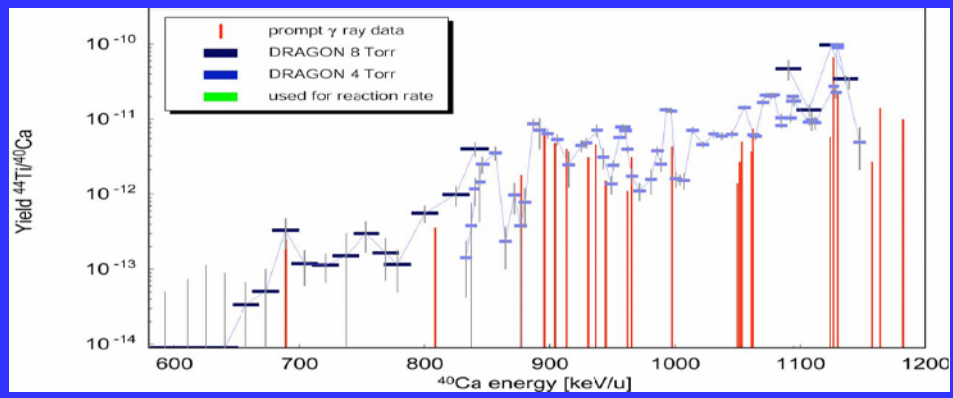
Recoil mass separator measurements

- C. Vockenhuber et al., Phys. Rev. C 76 (2007) 035801

$$\omega\gamma_{int} = 150 \text{ eV}$$







Experimental Approaches

Direct γ-Counting

- Performed at DTL, Bochum
- He incident on Ca target
- Direct γ-decay counting
- 4π Summing technique
- Yield curve measured

AMS Counting

- Gas cell activation, catcher implantation
- Chemical separation
- Ion acceleration and AMS measurement
- Discrete resonance strengths

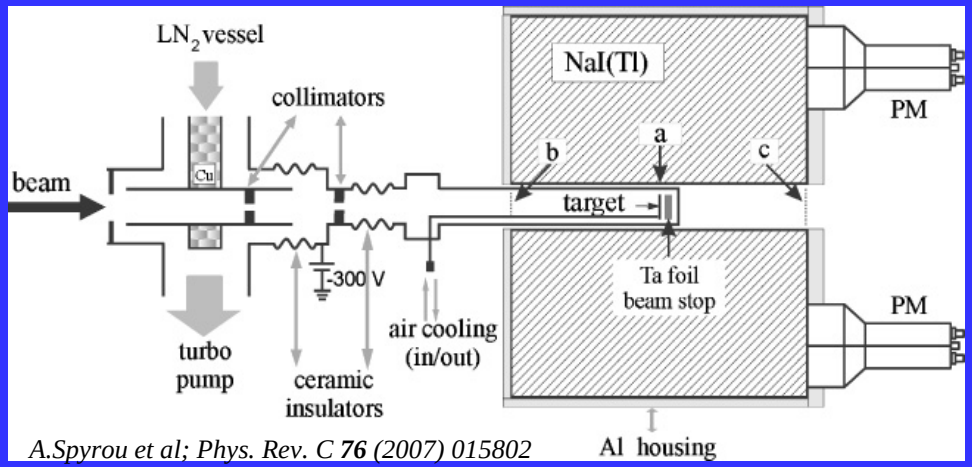
Experimental Set-up

Dynamitron Tandem Laboratory – Ruhr-Universität Bochum, Germany

RUBION
Zentrale Einrichtung für Ionenstrahlen und Radionuklide

- 12 x 12 in NaI(Tl) detector
  - *35 mm central bore hole*
- Covering ~98 % of 4π
- With $E_{res} \approx 2$ % at 10 MeV

- 2^+ He beam, 3 – 4.6 MeV
- ~ 2 eμA on target



*A.Spyrou et al; Phys. Rev. C **76** (2007) 015802*

- Ca targets on Cu backing
- Evaporated on-site, rapidly installed
- Both thin (110 nm) and thick (530 nm) targets used

γ-summing background

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$$= Y_5 + Y_4 + Y_2$$
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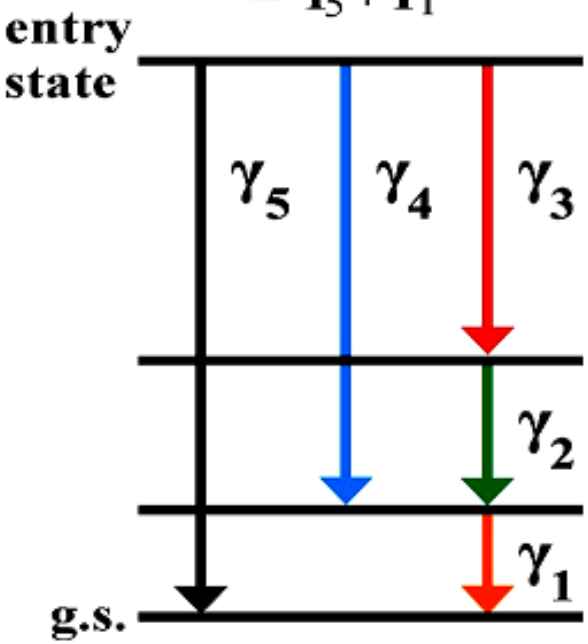
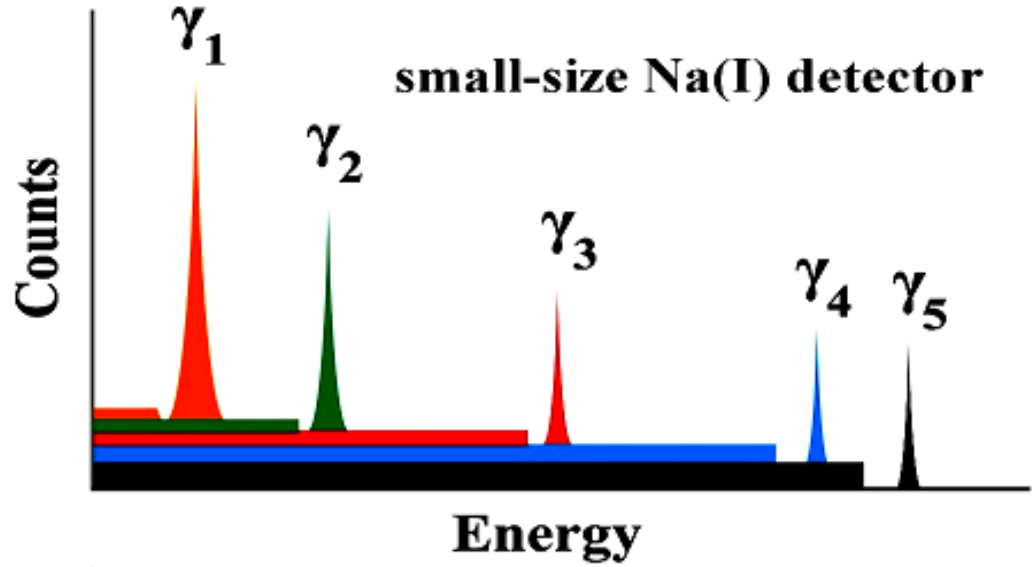
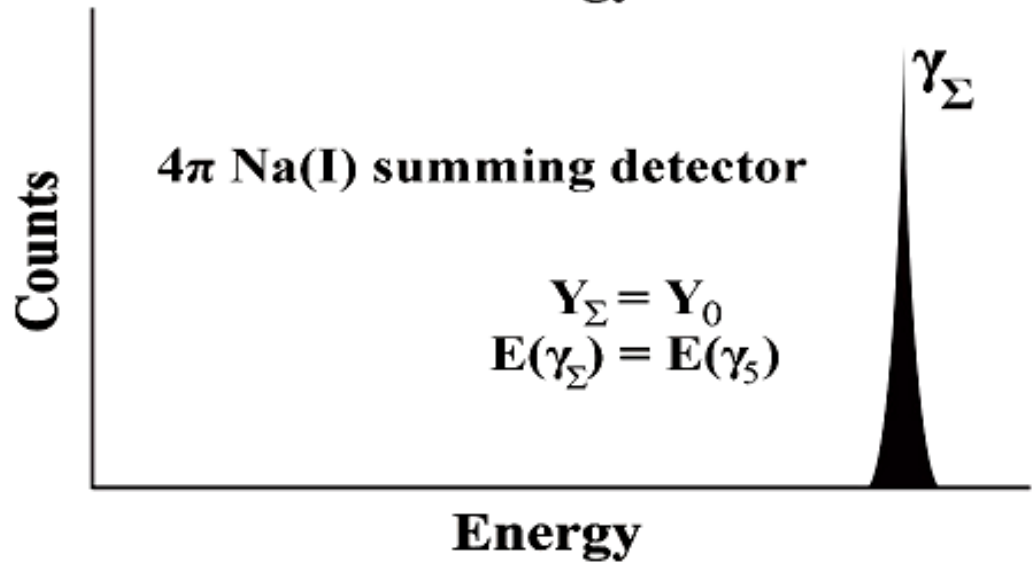




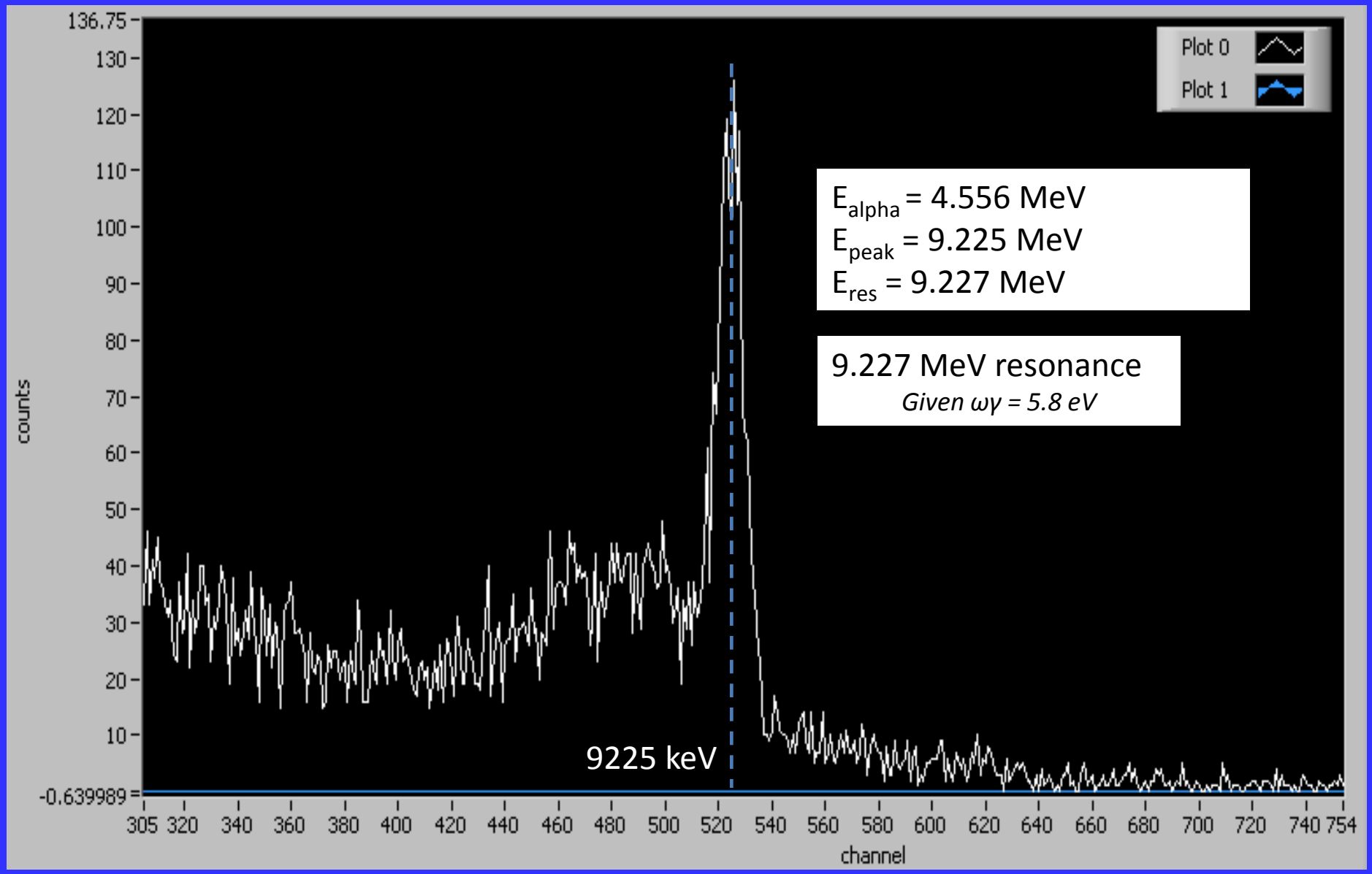


Advantageous long response time and large volume

Typical crystal decay time ≥ 250 ns

*A.Spyrou et al; Phys. Rev. C **76** (2007) 015802*

Experimental reality



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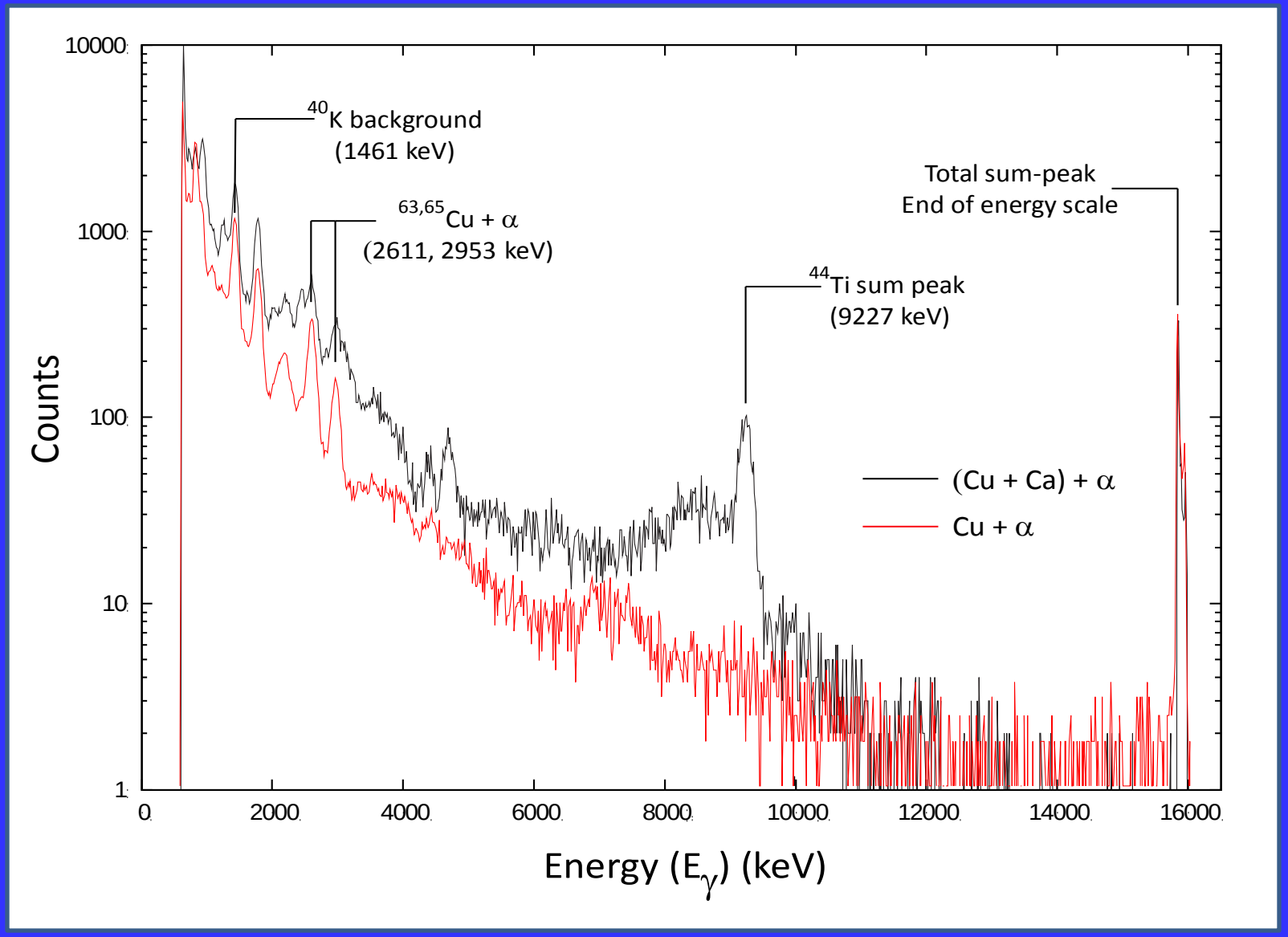
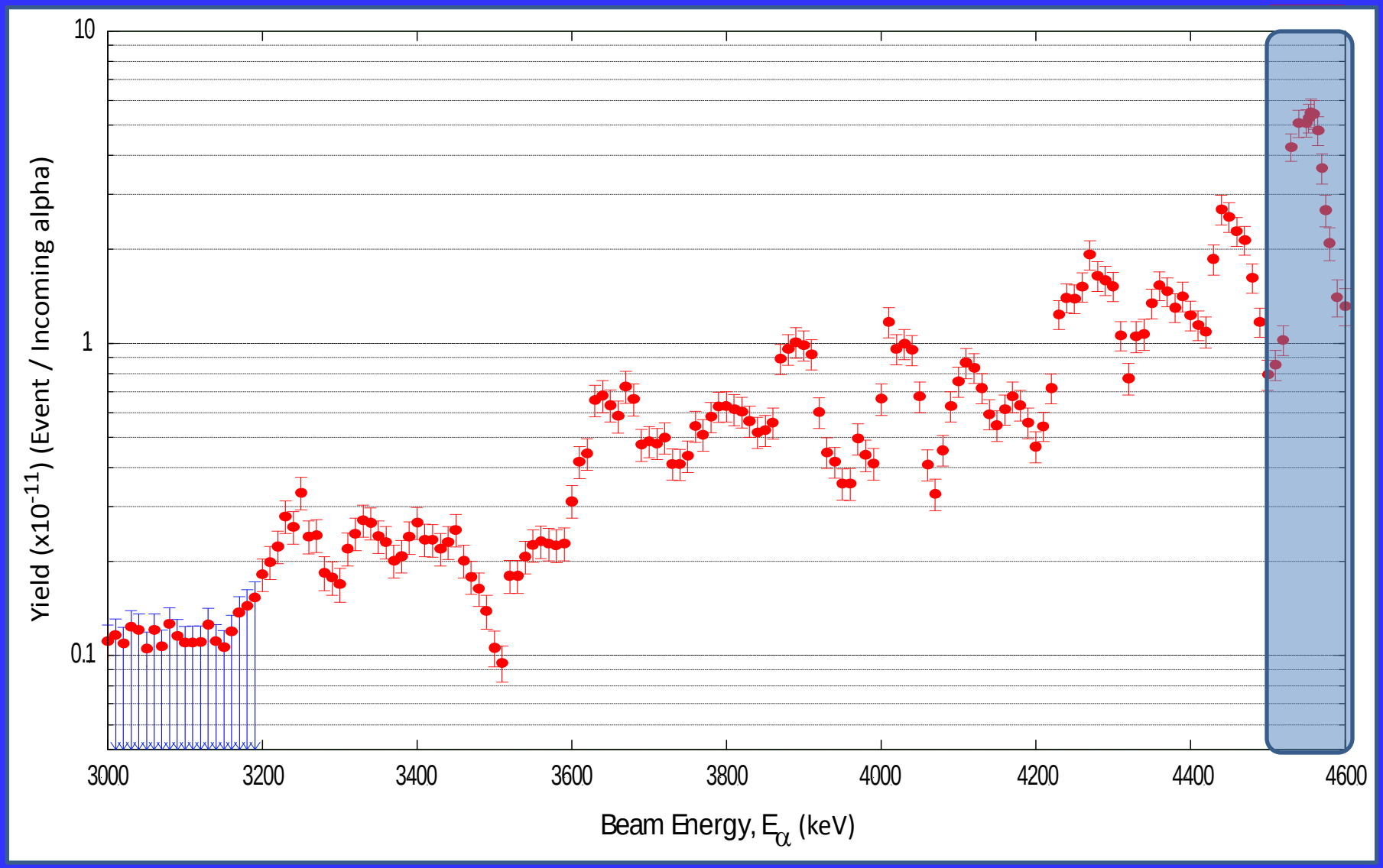
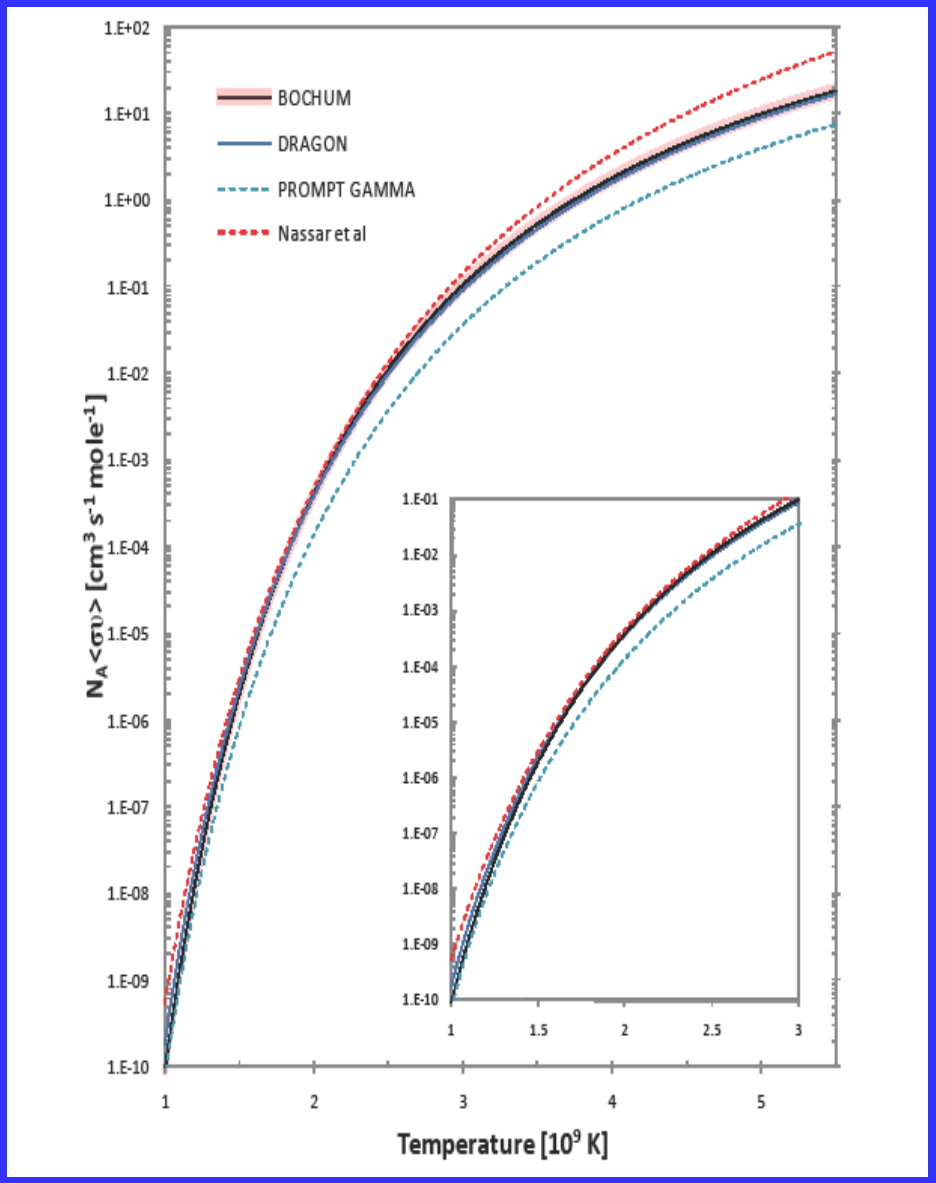
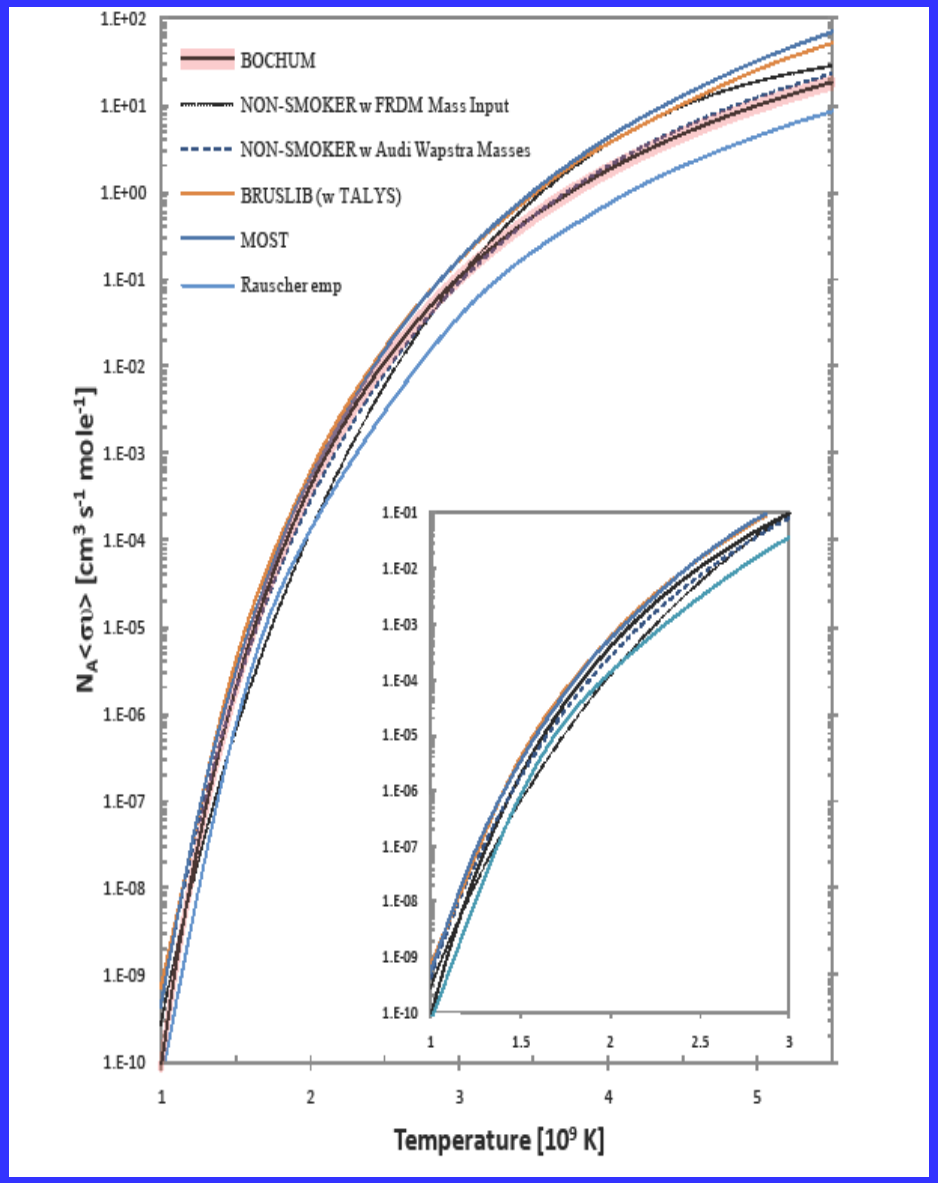


Yield curve & resonance structure



Reaction rate comparison





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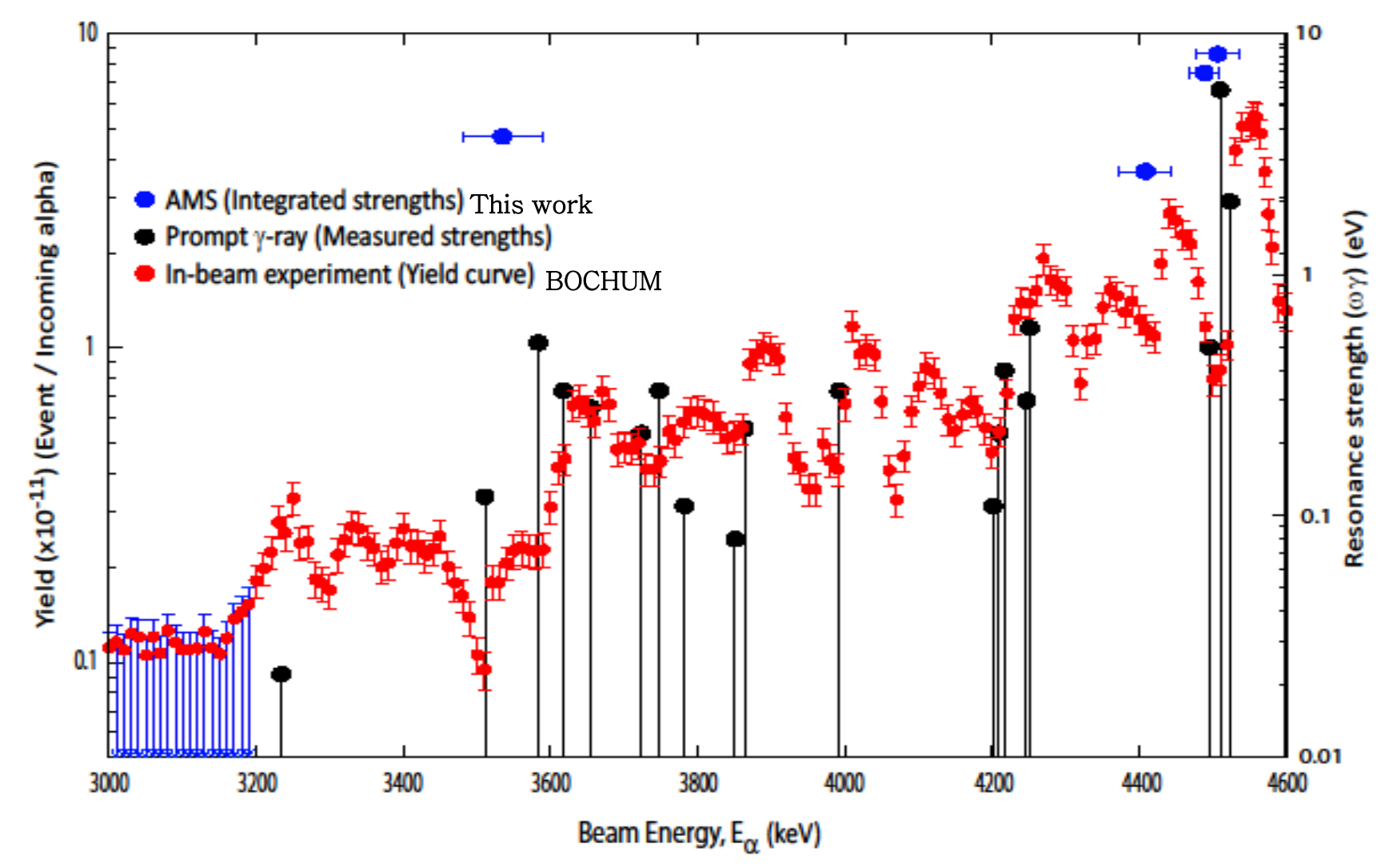


Have we fixed anything?

- To be honest…yes and no
- New measurements support previous RMS data
  - 40 % increase in ^{44}Ti yield
- Still not in-line with observed yields
- More data needed…

- Less confusion about reaction rate
- Rate increase from prompt γ measurements
- Onus moves towards SN modeling

With Thanks To:

Direct γ-Counting

H-W. Becker[2], A. Best[1], J. Görres[1], M. Wiescher[1]

AMS Counting

M. Bowers[1], P. Collon[1], W. Lu[1], M. Paul[3], C.Schmitt[1]

[1] NSL, Notre Dame

[2] Ruhr-Universität Bochum,

[3] Racah Institute of Physics, Hebrew University

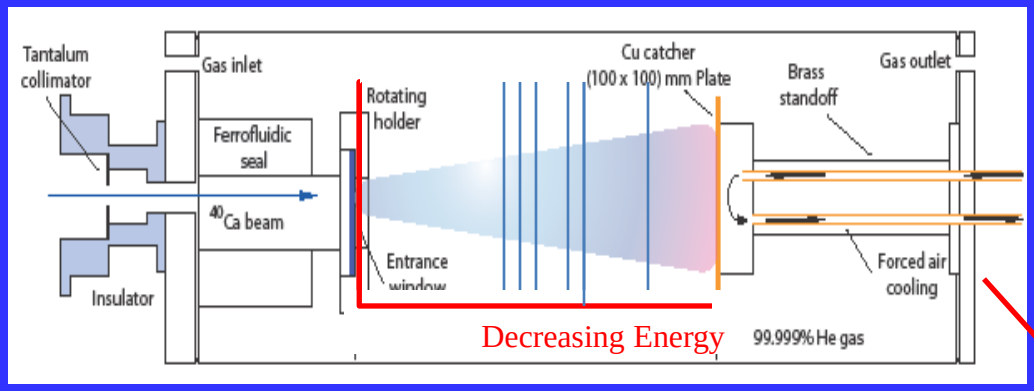
TABLE 4

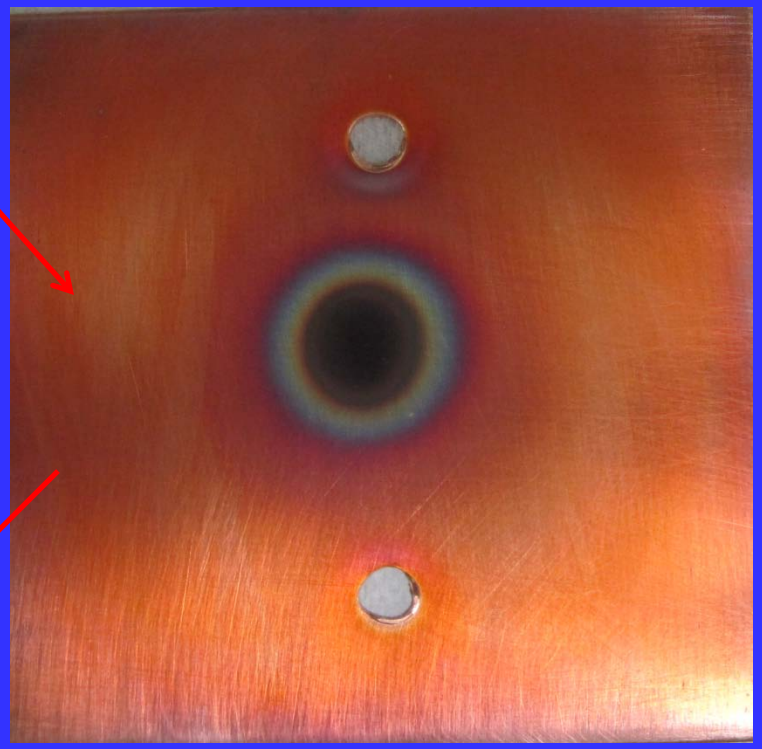
ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$

	Reaction Rate Multiplied by 1/100		Reaction Rate Multiplied by 100	
Rank	Reaction	^{44}Ti Change (percent)	Reaction	^{44}Ti Change (percent)
1	^{44}Ti(α, p)^{47}V	+173	^{45}V(p, γ)^{46}Cr	−98
2	α(2α, γ)^{12}C	−100	α(2α, γ)^{12}C	+67
3	^{40}Ca(α, γ)^{44}Ti	−72	^{44}Ti(α, p)^{47}V	−89
4	^{45}V(p, γ)^{46}Cr	+57	^{44}Ti(α, γ)^{48}Cr	−61
5	^{57}Ni(p, γ)^{58}Cu	−47	^{57}Co(p, n)^{57}Ni	+25
6	^{57}Co(p, n)^{57}Ni	−33	^{40}Ca(α, γ)^{44}Ti	+22
7	^{13}N(p, γ)^{14}O	−16	^{57}Ni(n, γ)^{58}Ni	+10
8	^{58}Cu(p, γ)^{59}Zn	−14	^{54}Fe(α, n)^{57}Ni	+9.4
9	^{36}Ar(α, p)^{39}K	−11	^{36}Ar(α, p)^{39}K	+5.5
10.....	^{12}C(α, γ)^{16}O	+3.5	^{36}Ar(α, γ)^{40}Ca	+5.3

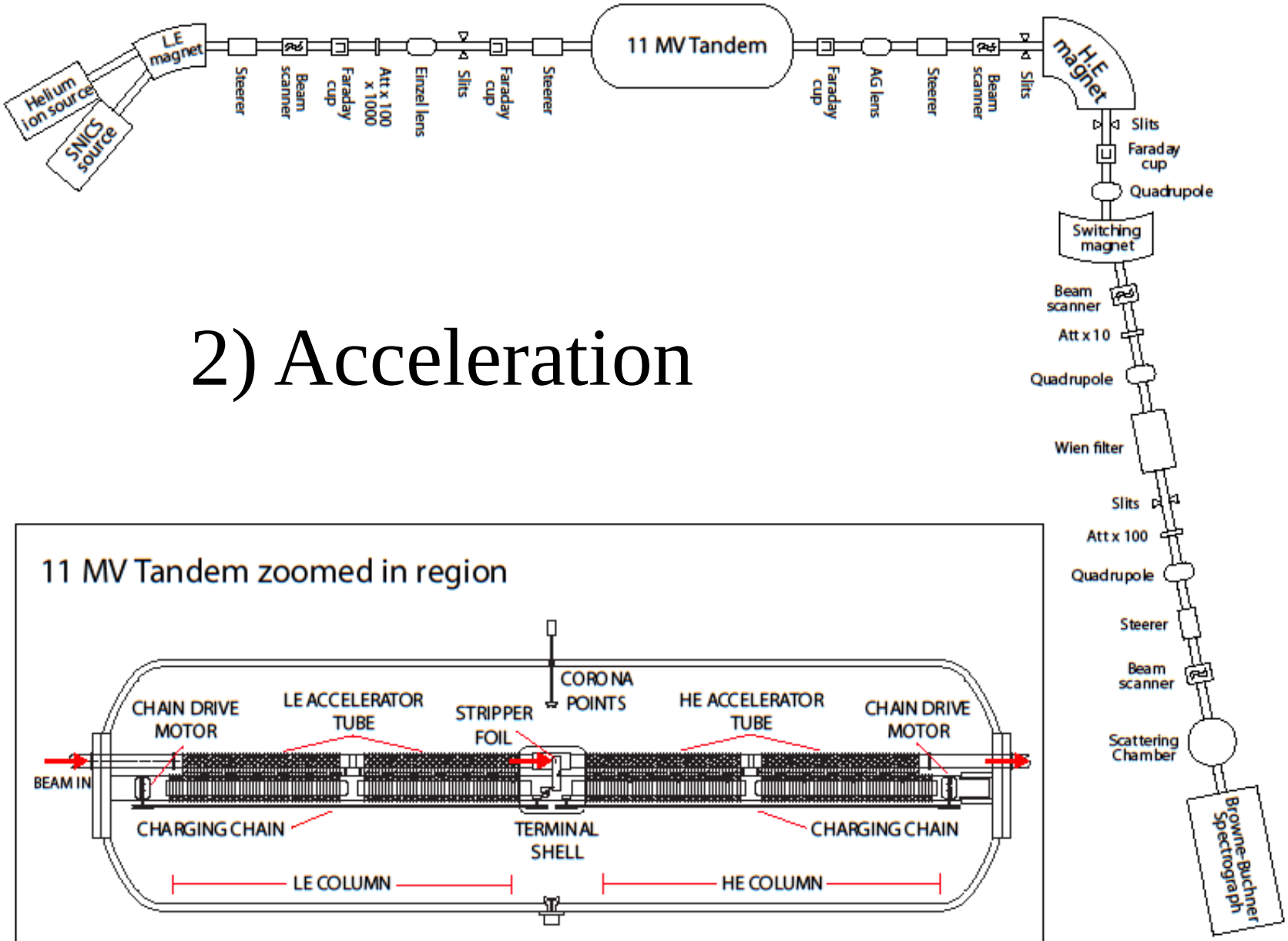
Experiment 1 of 2 – AMS at the NSL

1) Sample activation & preparation





2) Acceleration

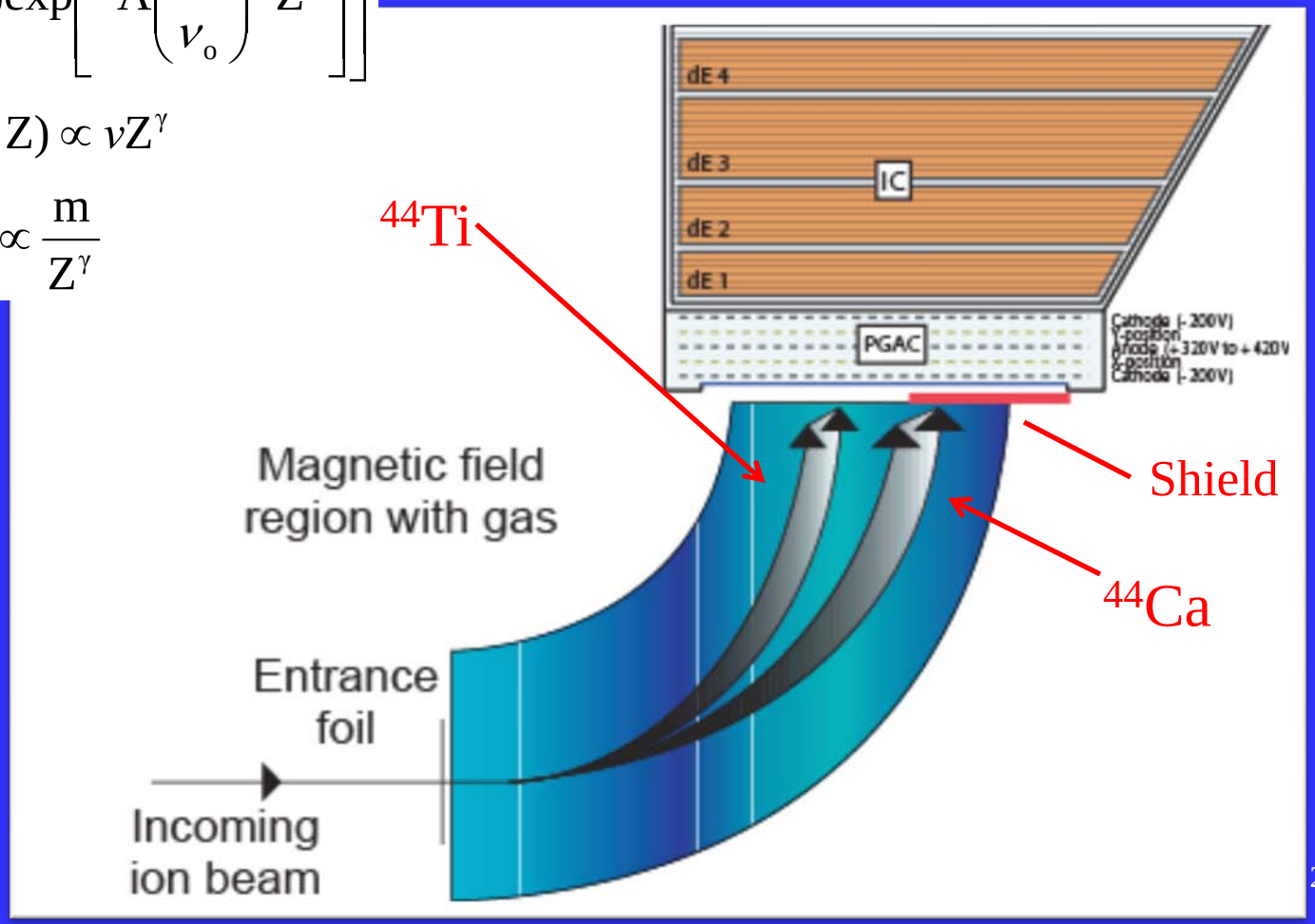


3) Separation & the GFM approach

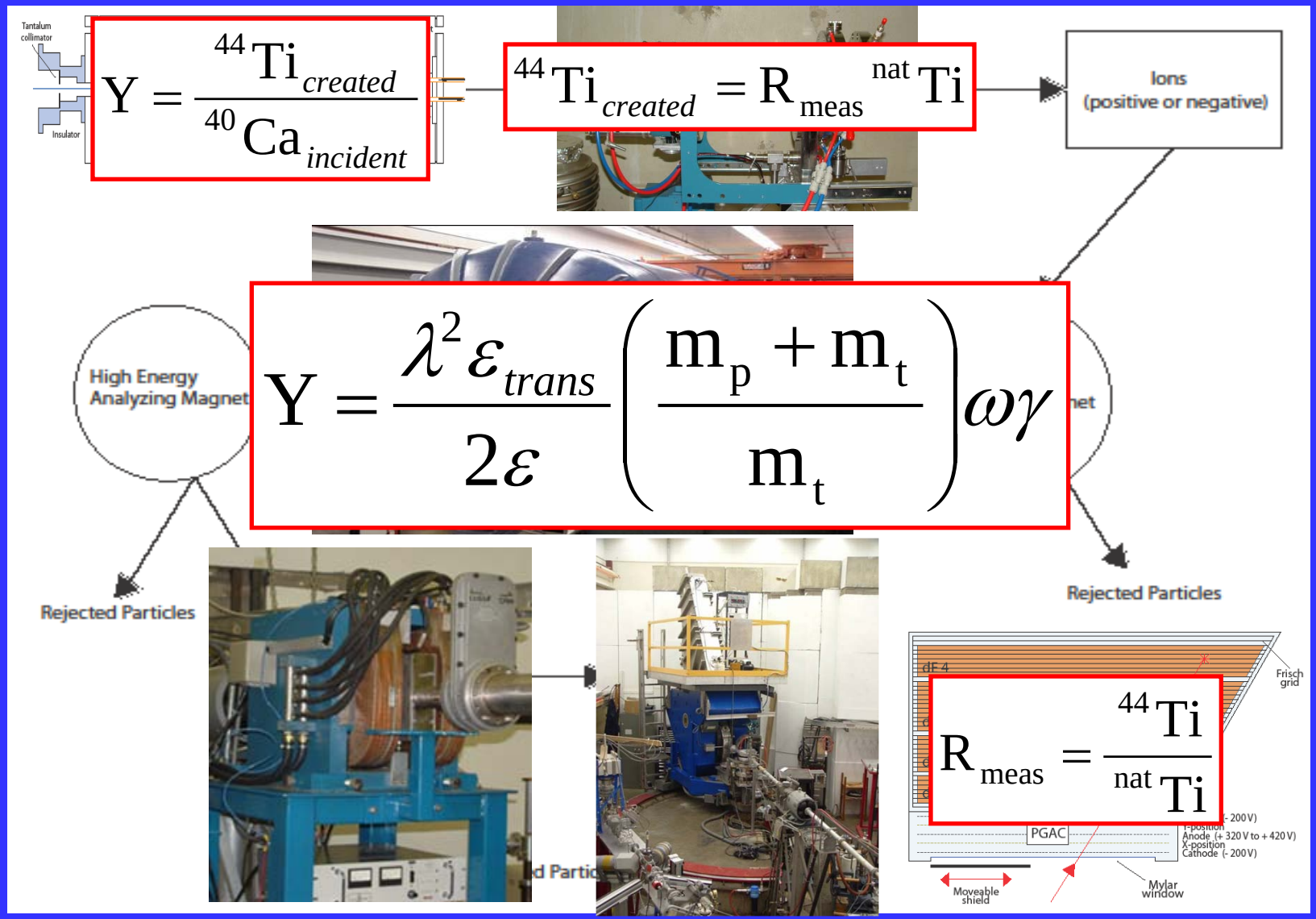
$$Q_{ave} = Z\left[1-(1.08)\exp\left[-A\left(\frac{\nu}{\nu_o}\right)^{\delta} Z^{\gamma}\right]\right]$$

$$Q_{ave}(\nu, Z) \propto \nu Z^{\gamma}$$

$$B\rho \propto \frac{m}{Z^{\gamma}}$$



AMS experimental approach – 3 stage



$$Y = \frac{{}^{44}\mathrm{Ti}_{created}}{{}^{40}\mathrm{Ca}_{incident}}$$

$${}^{44}\mathrm{Ti}_{created} = R_{meas}\,{}^{nat}\mathrm{Ti}$$

$$Y = \frac{\lambda^2 \varepsilon_{trans}}{2\varepsilon}\left(\frac{m_p + m_t}{m_t}\right)\omega\gamma$$

$$R_{meas} = \frac{{}^{44}\mathrm{Ti}}{{}^{nat}\mathrm{Ti}}$$

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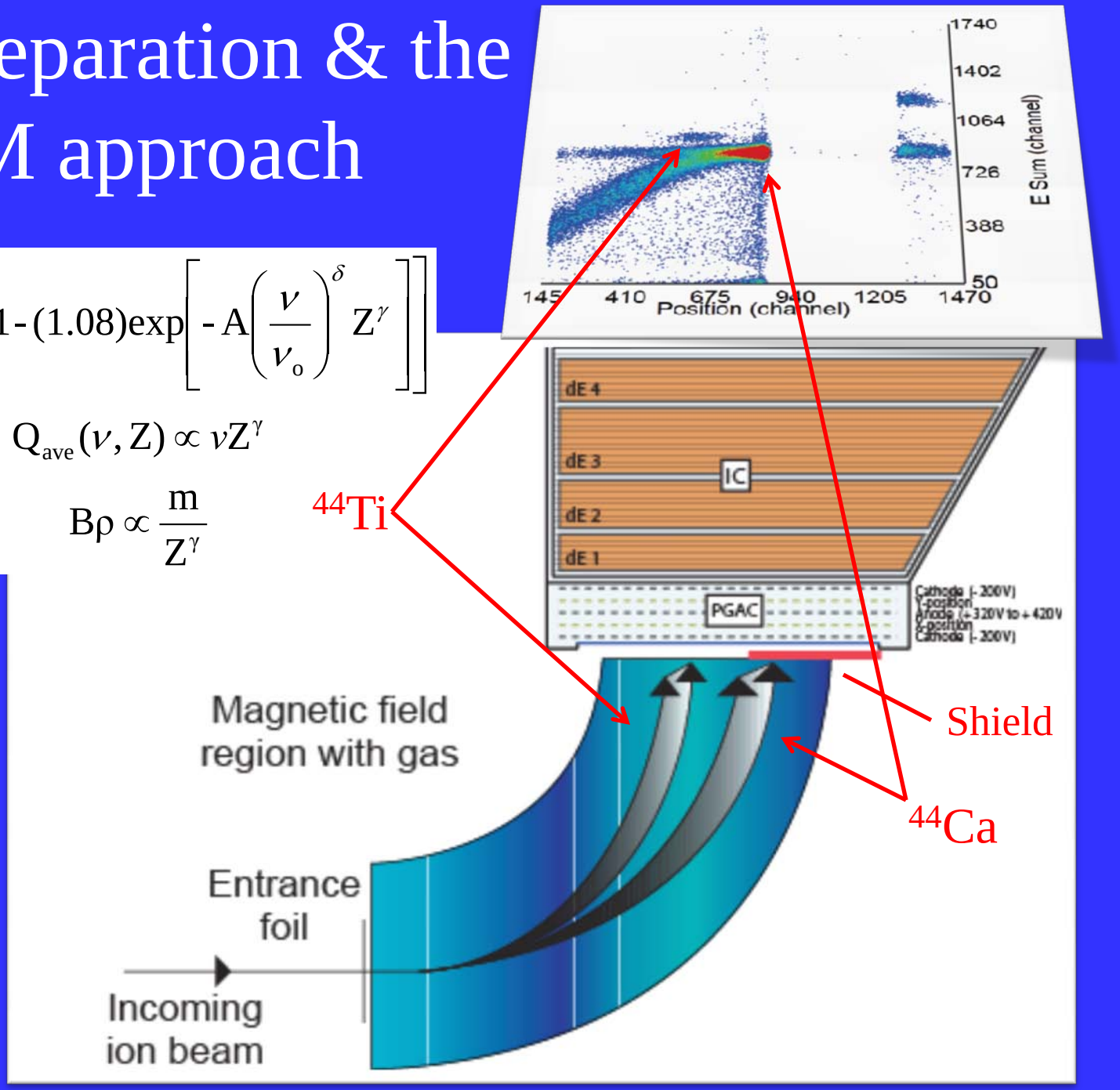
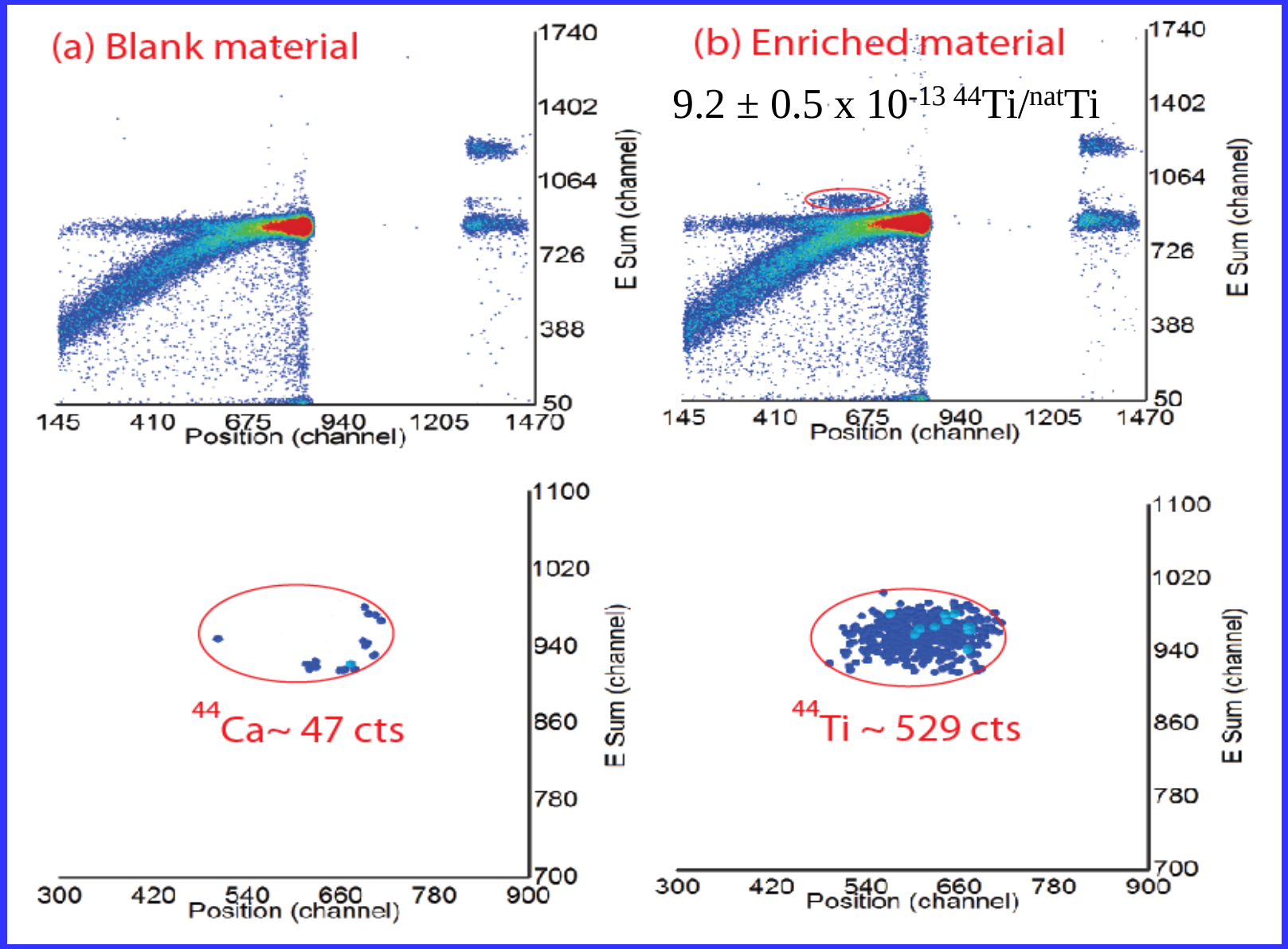


Detection and ^{44}Ti



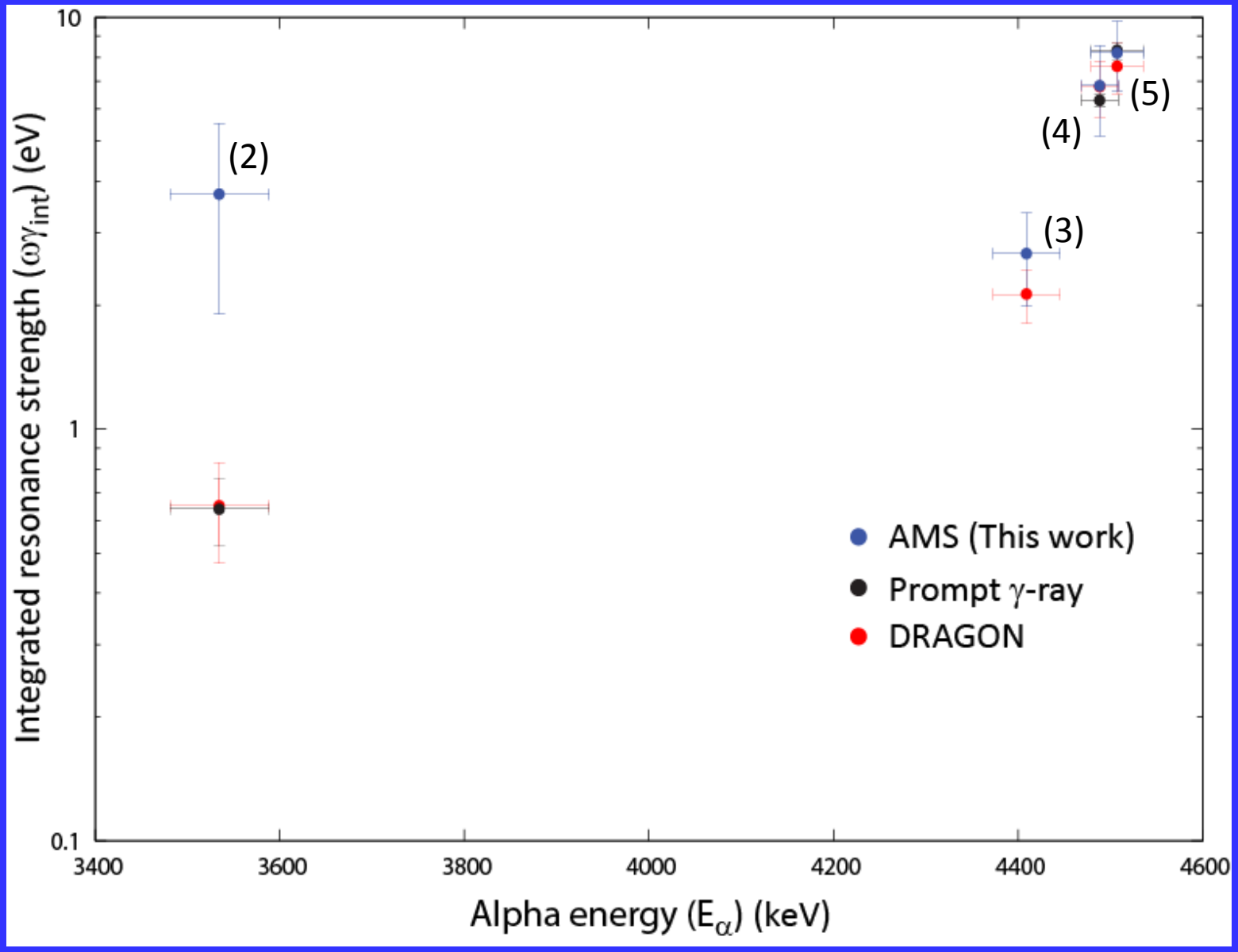
System sensitivity

- Measured
  - Sample 2 = 5.7×10^{-15} $^{44}Ti/^{nat}Ti$, $\omega\gamma_{int} = 3.7 \pm 1.8$ eV
  - Sample 3 = 2.2×10^{-14} $^{44}Ti/^{nat}Ti$, $\omega\gamma_{int} = 2.7 \pm 0.7$ eV
  - Sample 4 = 2.0×10^{-14} $^{44}Ti/^{nat}Ti$, $\omega\gamma_{int} = 6.8 \pm 1.1$ eV
  - Sample 5 = 4.7×10^{-14} $^{44}Ti/^{nat}Ti$, $\omega\gamma_{int} = 8.2 \pm 0.4$ eV

Current sensitivity ~ 4.5×10^{-15} $^{44}Ti/^{nat}Ti$

1.0×10^{-15} ~

Resultant measurements



Experiment 2 of 2 – γ measurement at Bochum

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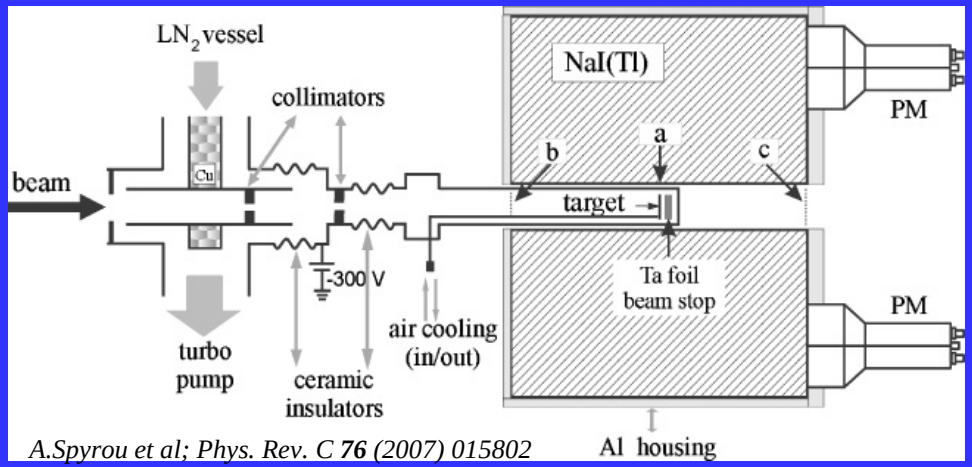

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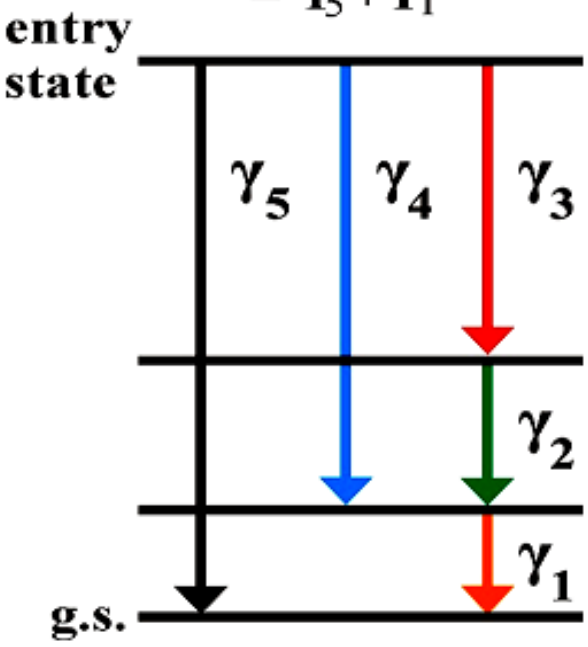

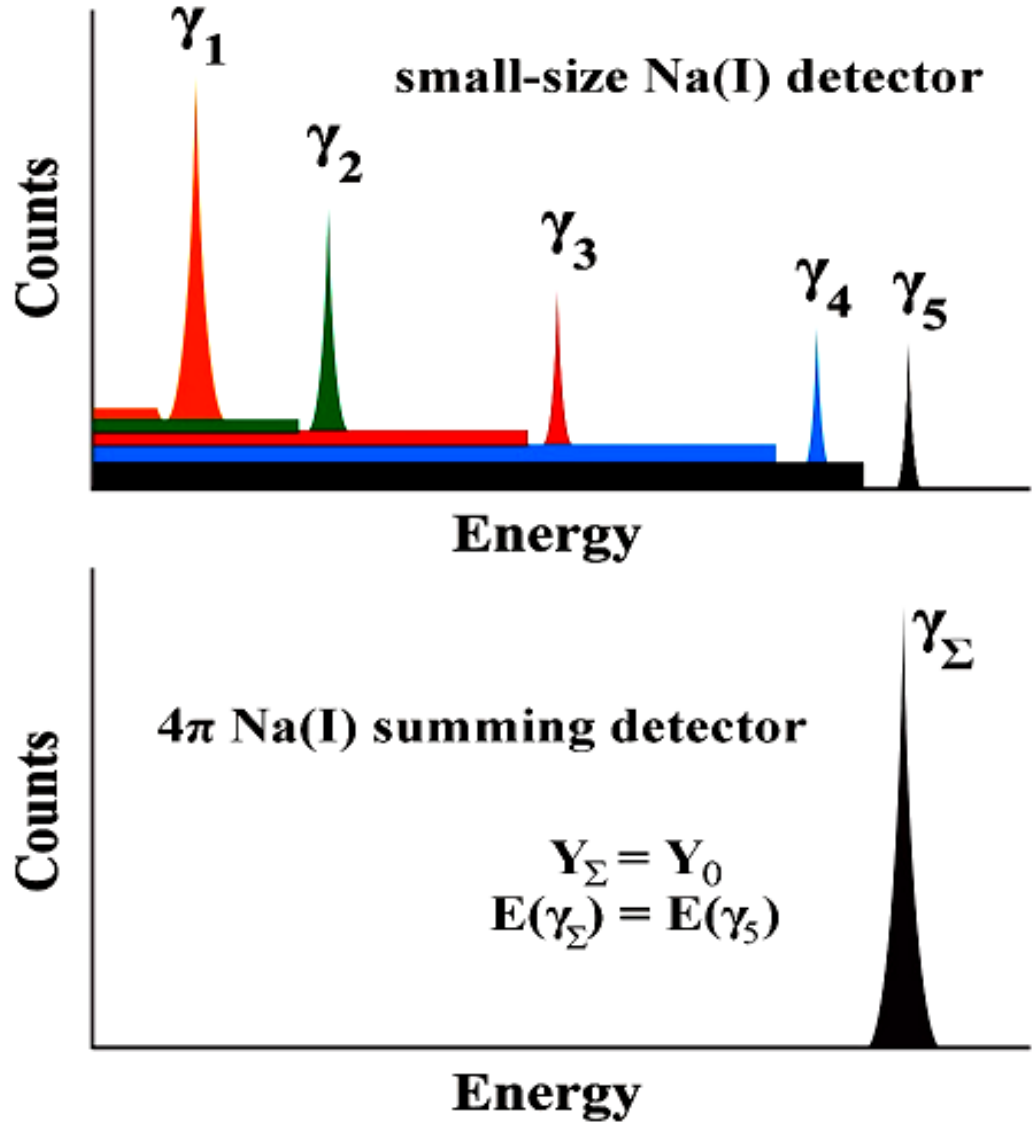

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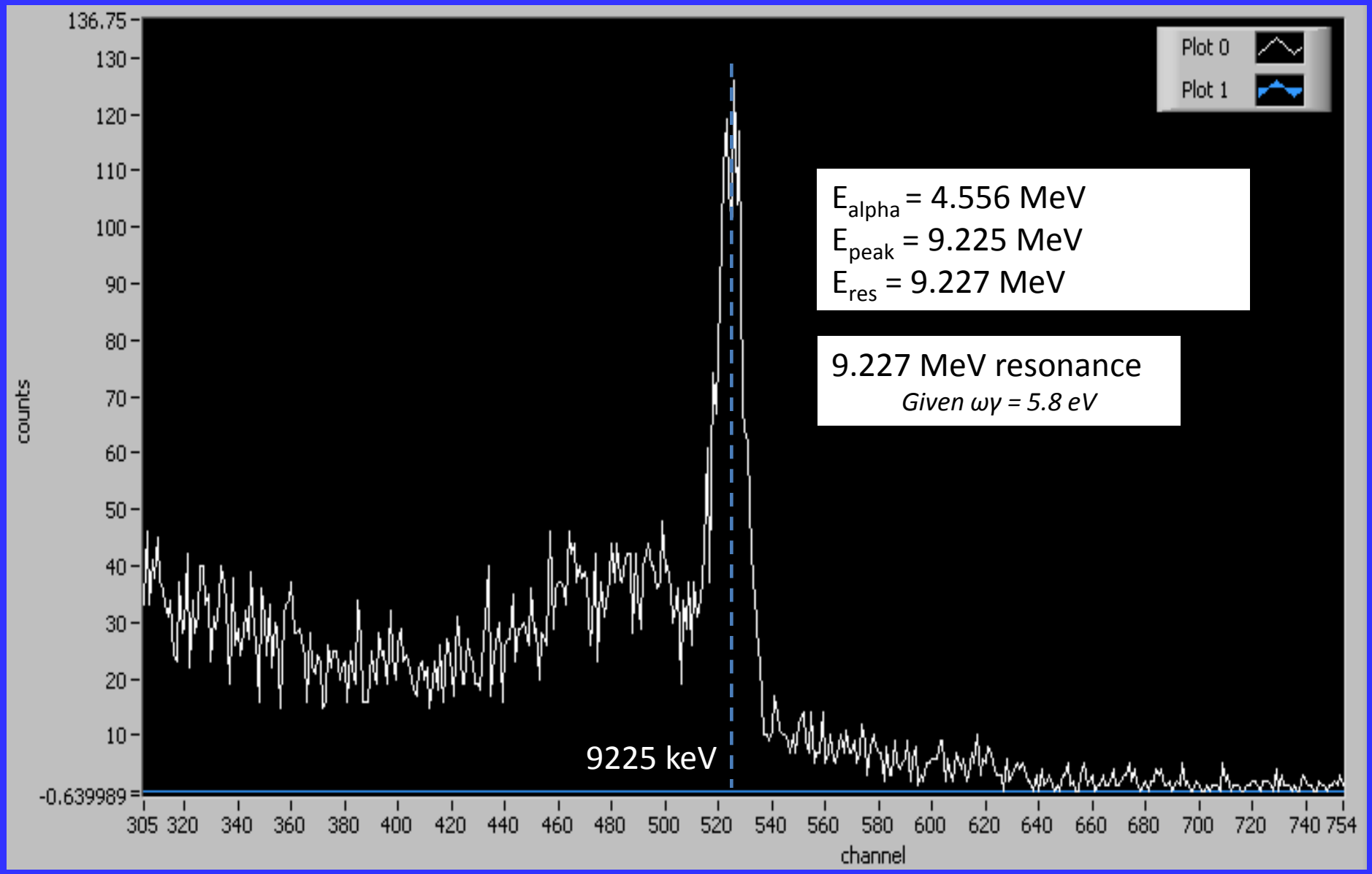
Experimental reality



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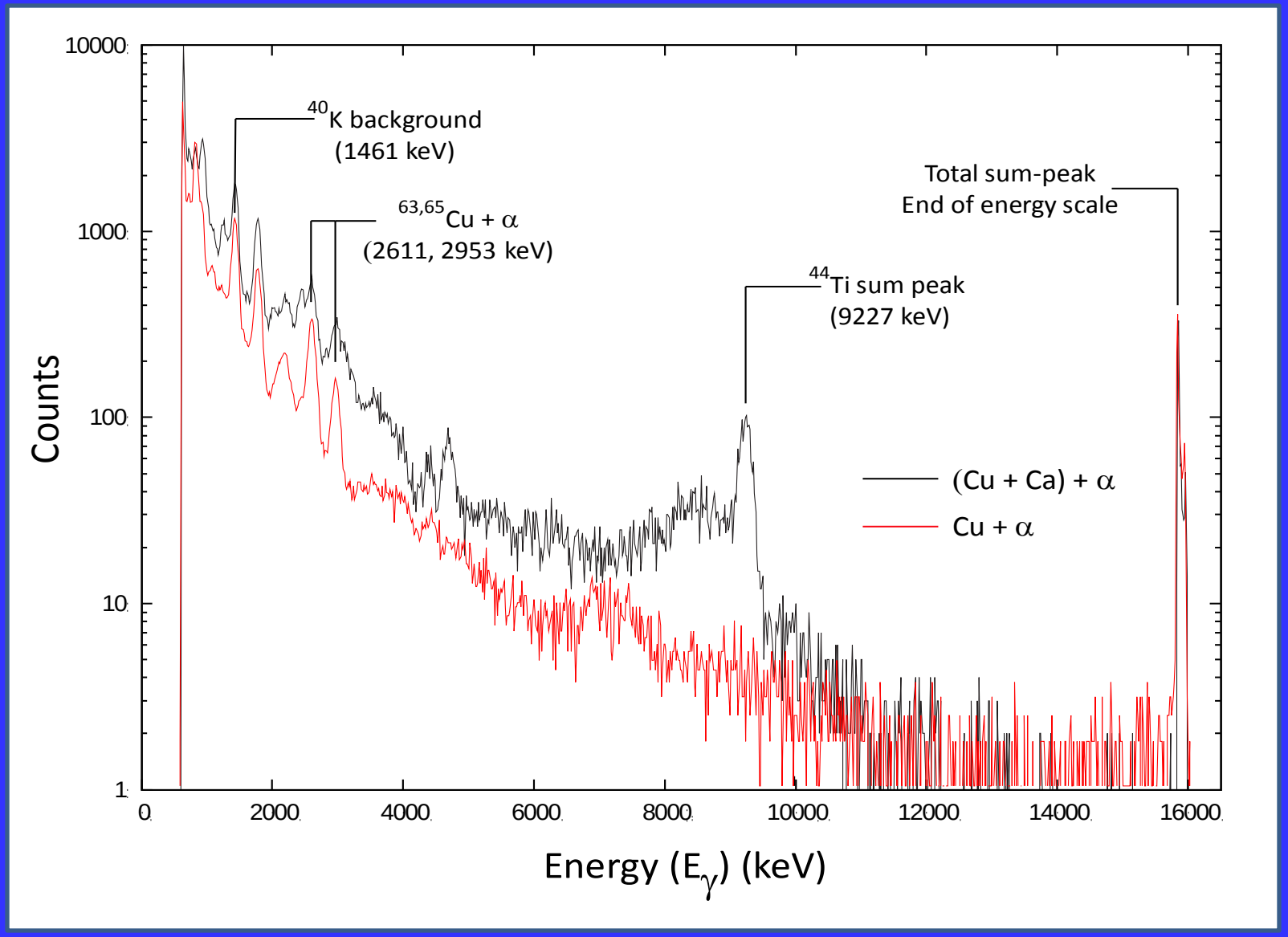
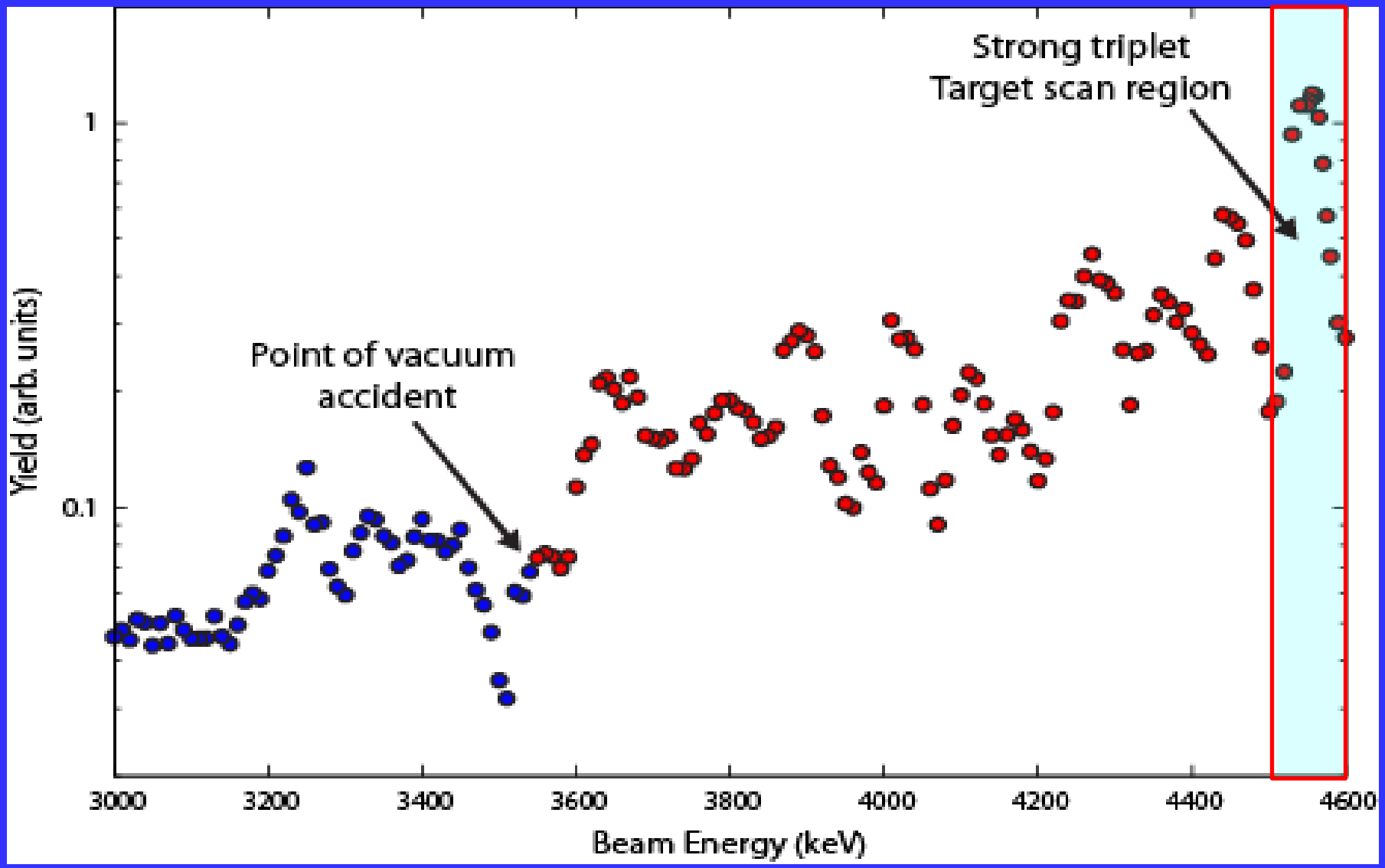


Yield curve & resonance structure



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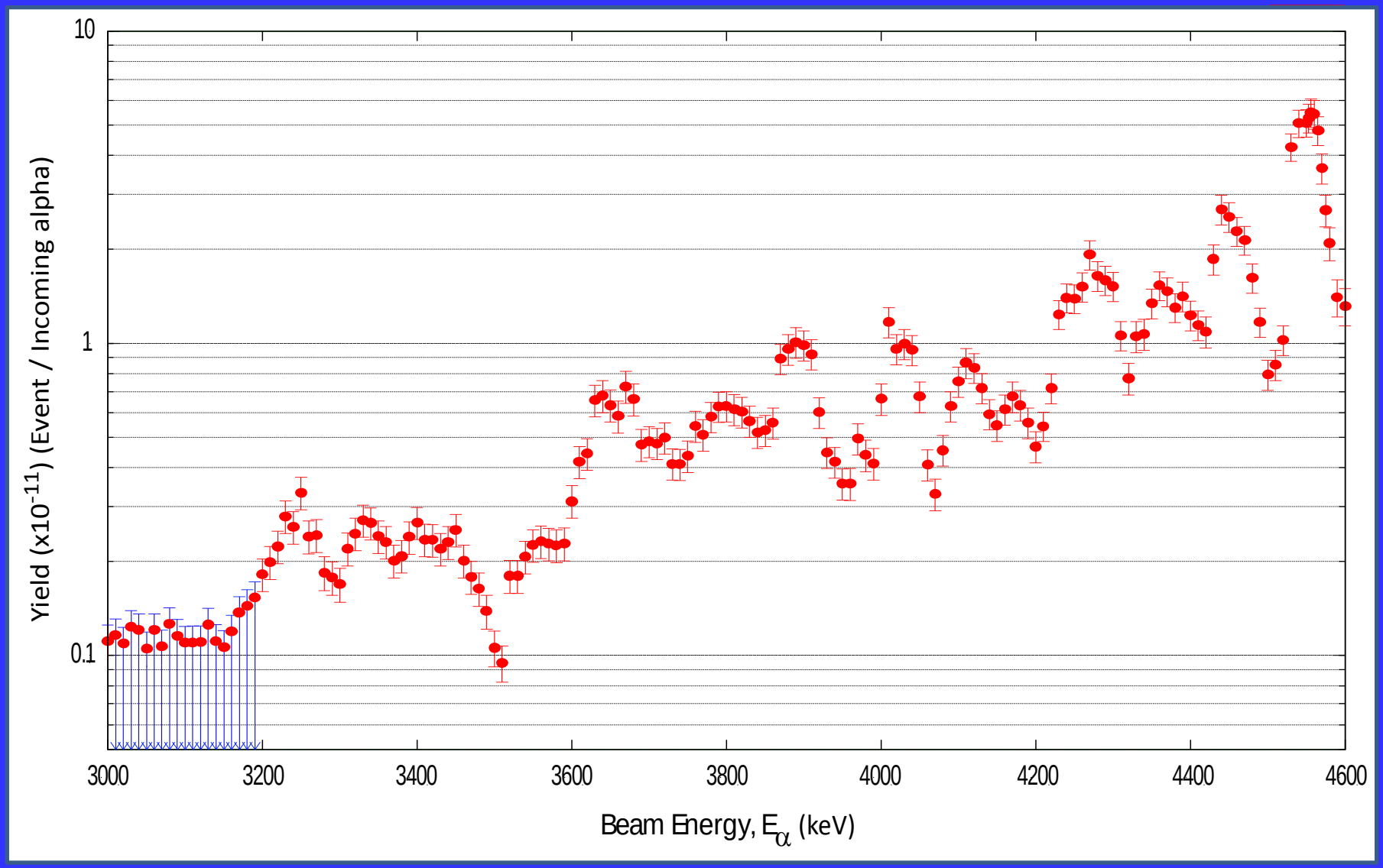


Astrophysical reaction rate

- So far we only have the number of ^{44}Ti events

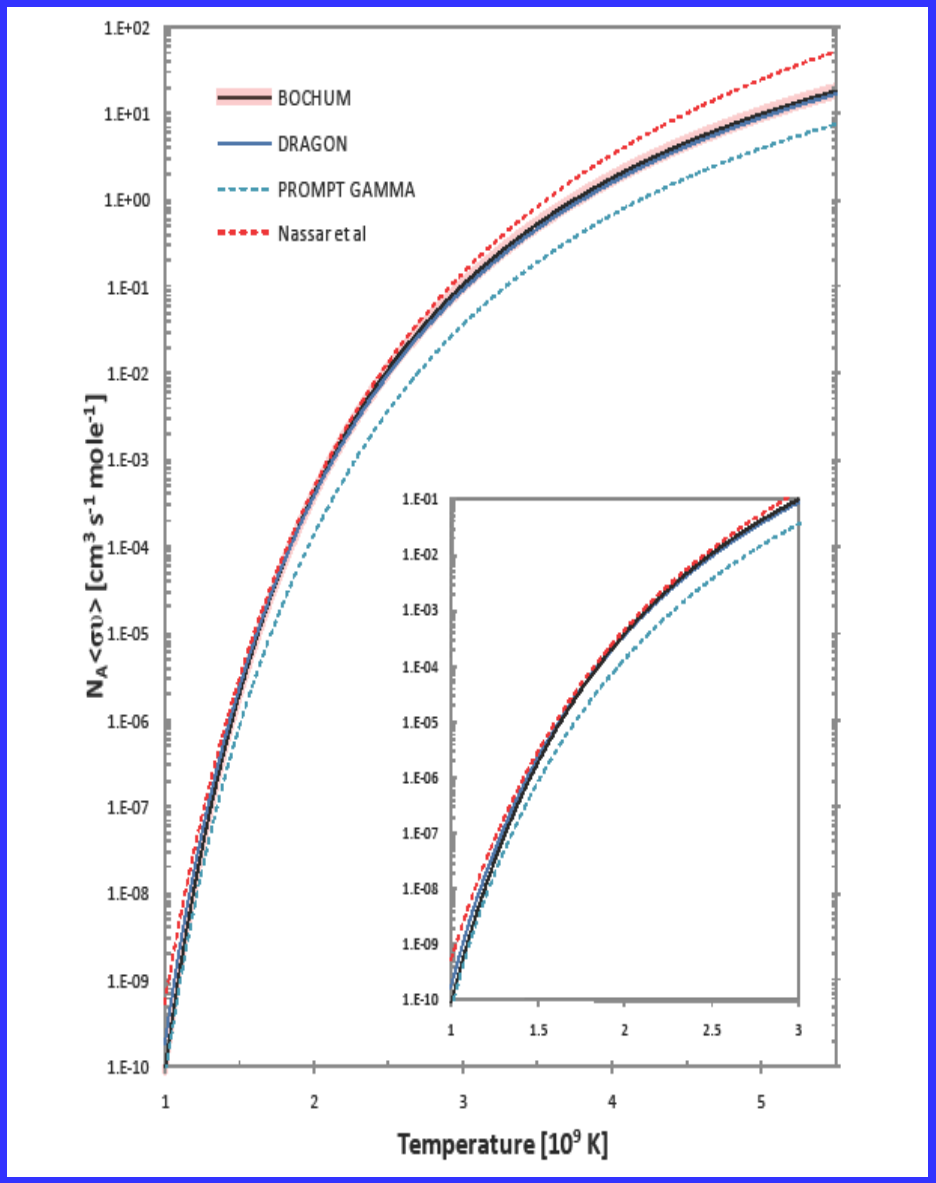
$$Y = \frac{^{44}\mathrm{Ti}}{\alpha}$$

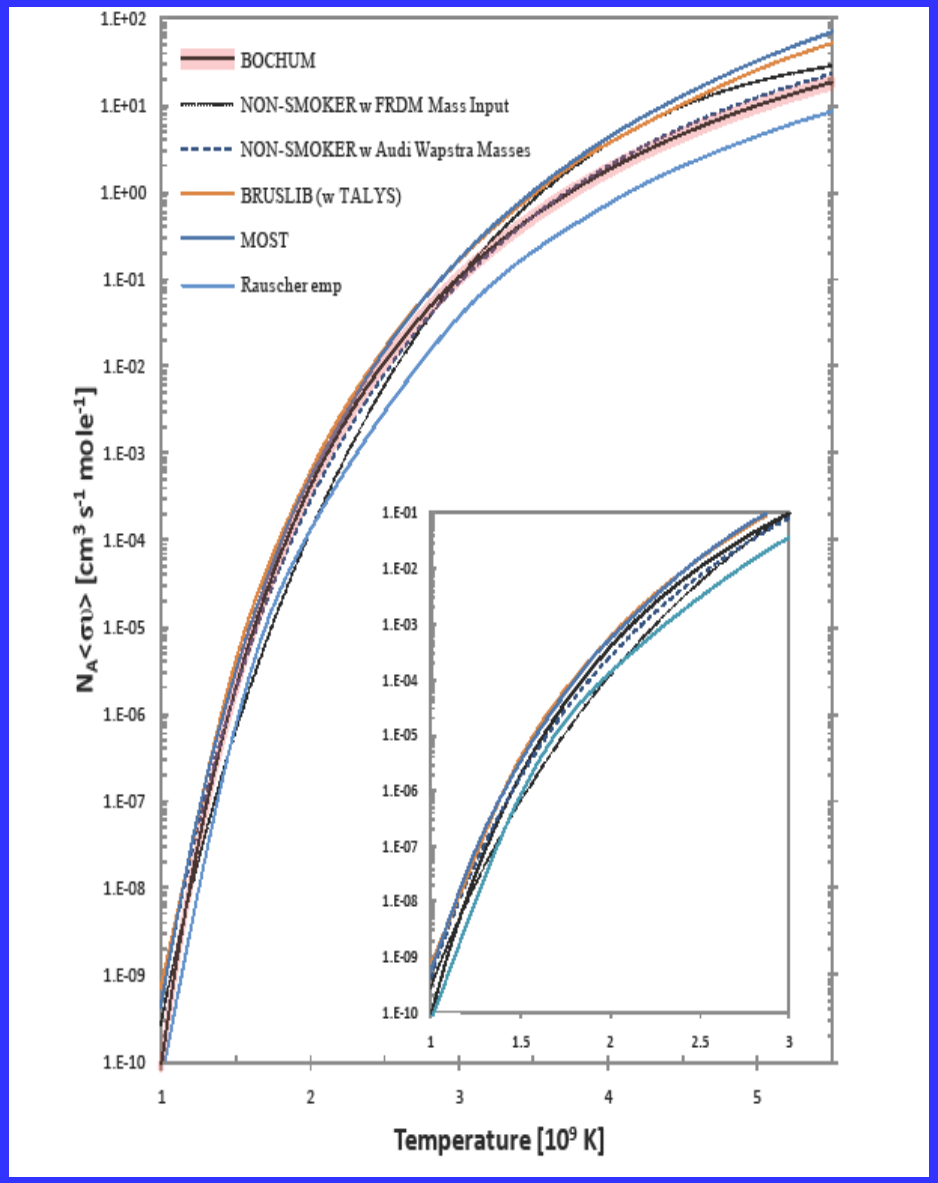
$$Y = \frac{\lambda^2 \varepsilon_\Sigma}{2\varepsilon}\left(\frac{m_p + m_t}{m_t}\right)\omega\gamma$$

$$\omega\gamma = \frac{2J_R + 1}{(2J_t + 1)(2J_p + 1)}\frac{\Gamma_t \Gamma_\gamma}{\Gamma}$$

$$N_A\langle\sigma v\rangle = 1.54\times10^{11}(\mu T_9)^{-3/2}\omega\gamma \exp\left(-11.605\frac{E_R}{T_9}\right)$$

Reaction rate comparison





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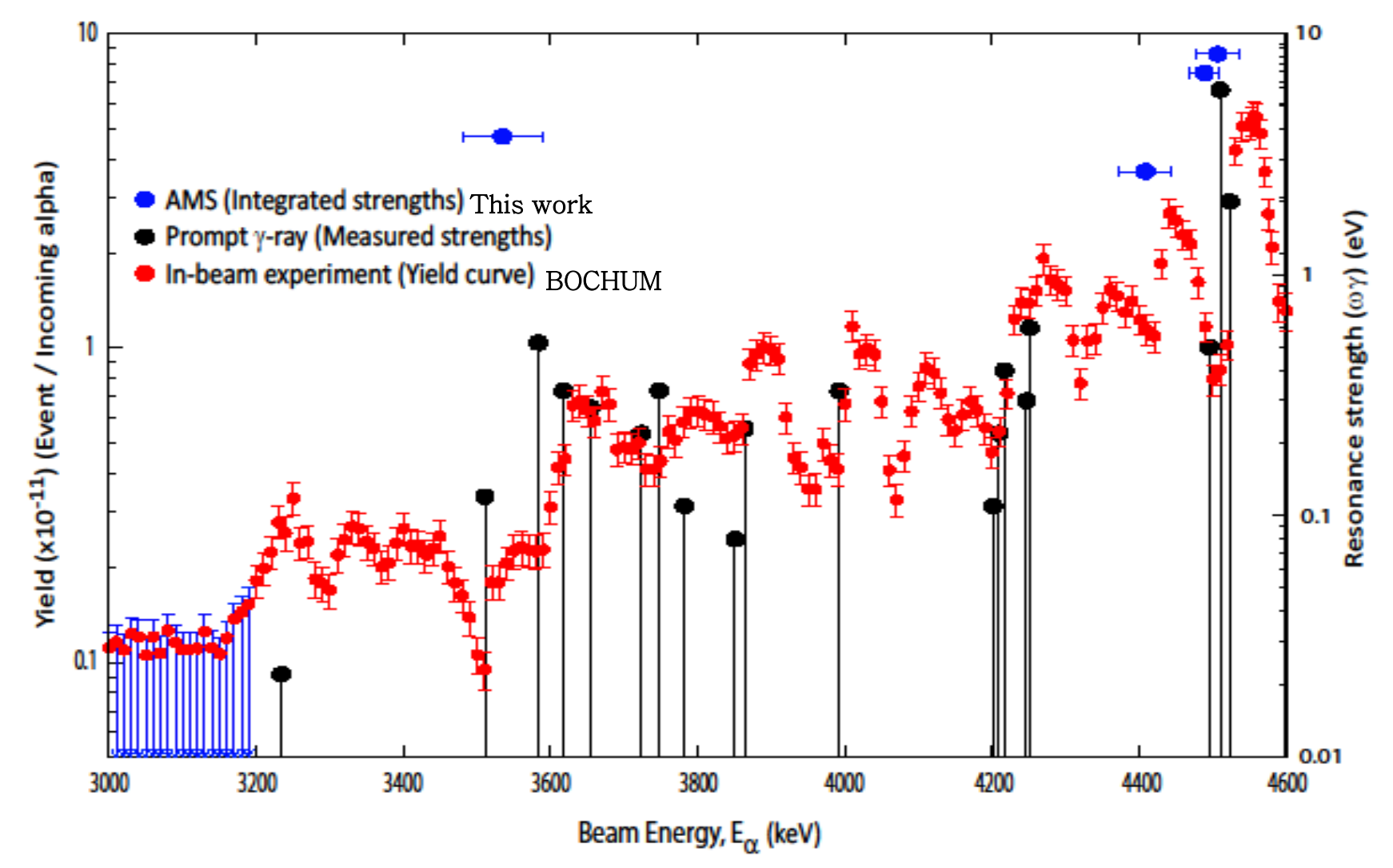

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Conclusions

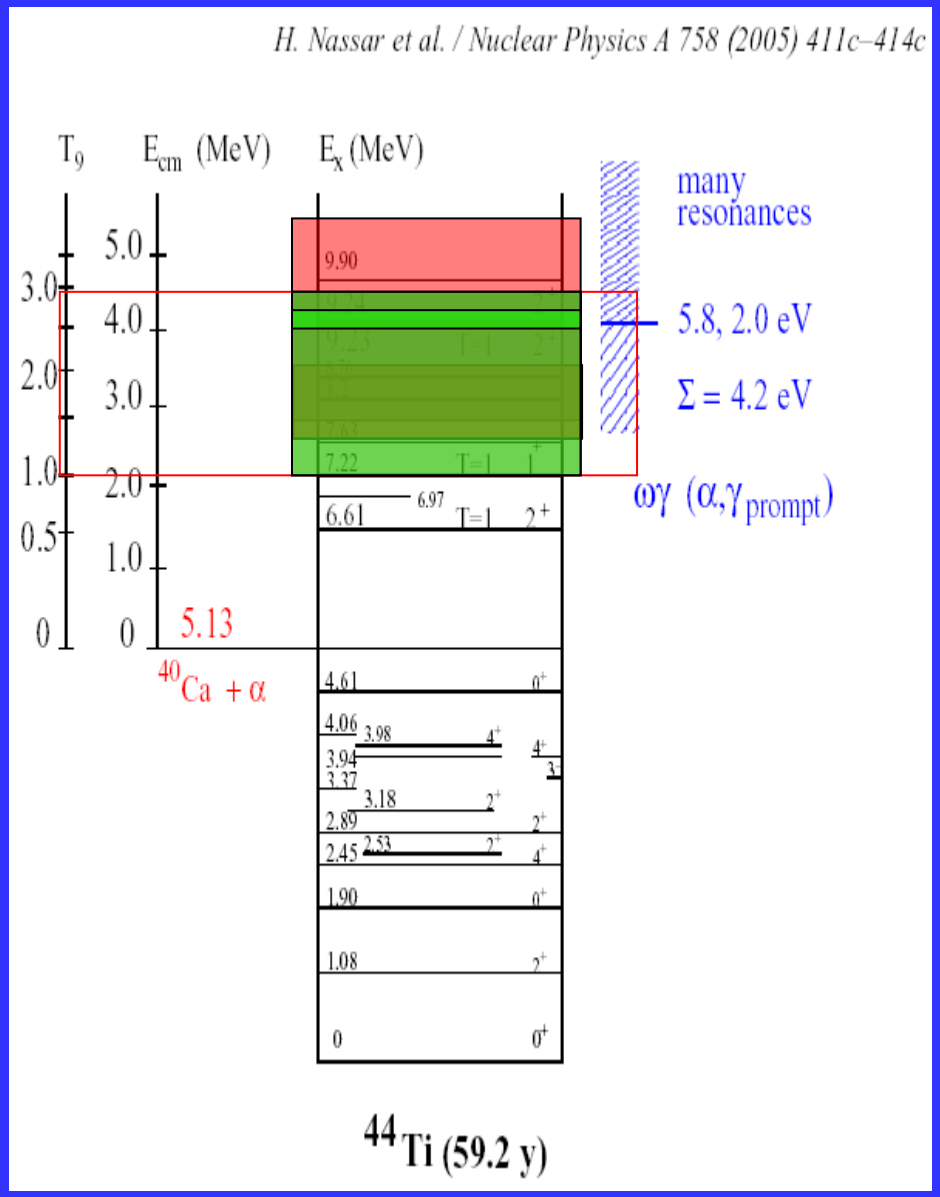
- New AMS system is viable
- AMS limited to small E steps for nuclear astro.
- Further effort should give ~ 10^{-16} sensitivity

- Less confusion about reaction rate
- Rate increase from prompt γ measurements
- Onus moves towards SN modeling

After thoughts

- AMS system
  - Further chemical separation of calcium
  - Further investigate copper catcher
  - Better transmission
- In-beam experiment
  - More intense α-beam, & thinner targets
  - Further low energy measurements
  - Possible higher energy measurements
- Something called St.George ???

Ranges of interest



Prompt γ measurements

- *12 resonances measured 7.627 – 8.767 MeV*
- *Expanded later to 8.577 – 10.527 MeV*

AMS activation and measurements

- *Initial strong doublet activation, 9.23 & 9.24 MeV*
- *Integrated measurement over astrophysical region*
  - *7.3 – 9.3 MeV*

Recoil Mass Separator measurement

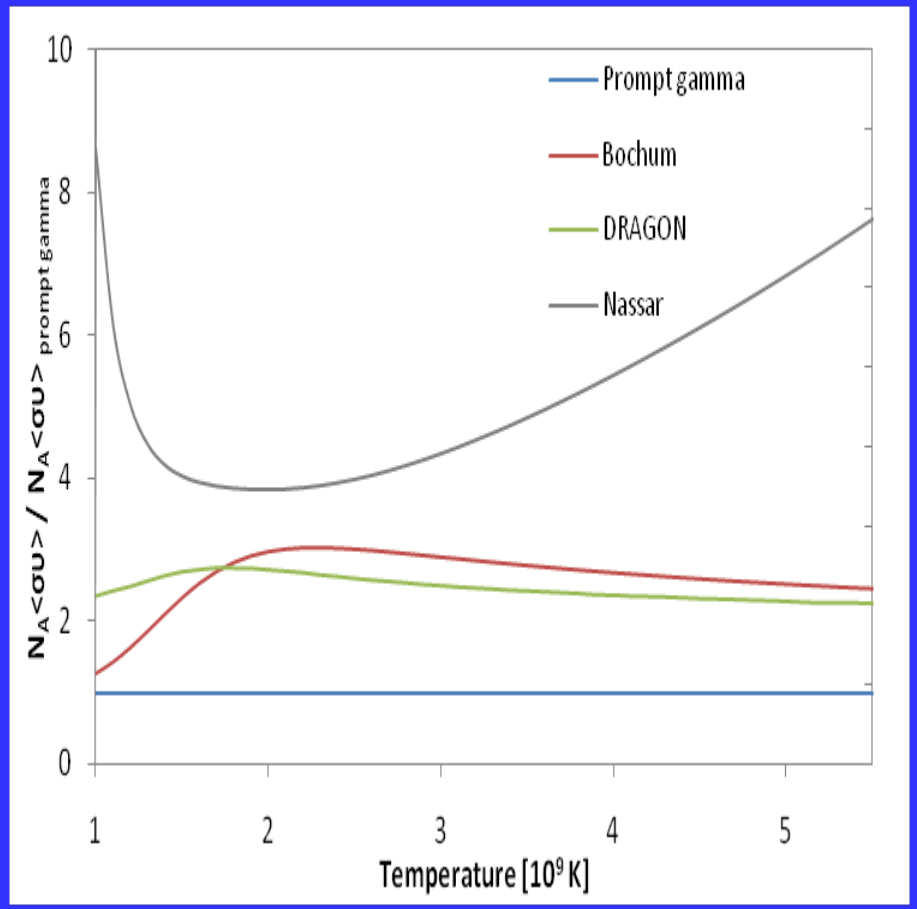
- *>100 energy steps covering 7.329 – 9.326 MeV*
  - *Utilizing both thin and thick targets*

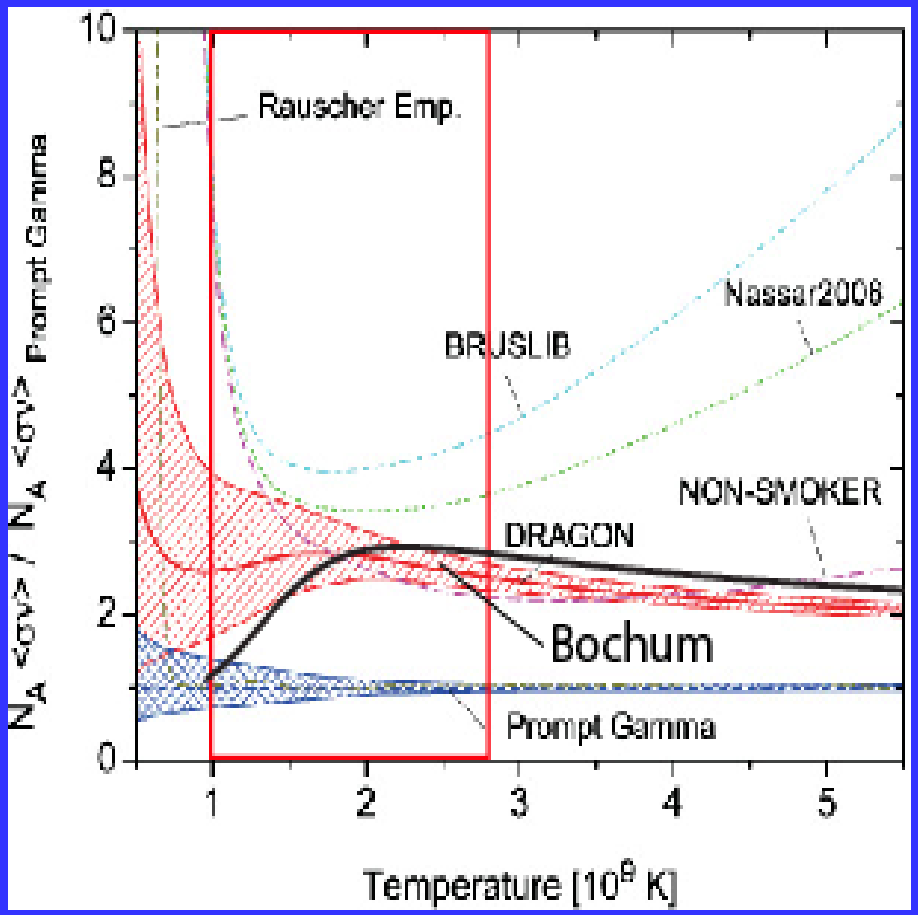
Measurements for this work

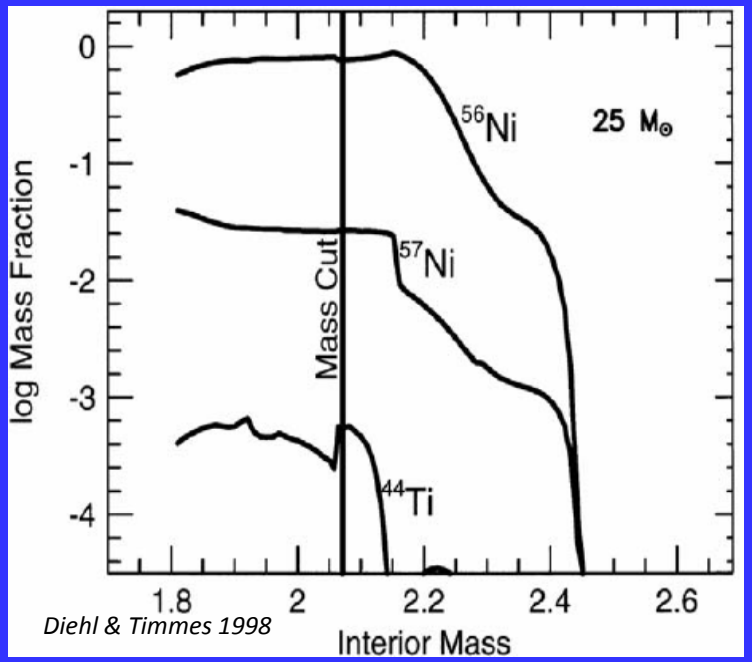
- *In beam measurements 7.854 – 9.308 MeV*
  - *>150 energy steps with thick and thin target*
- *Four AMS activation and measurements*

Accidents Will Happen

Reaction rate relations







Diehl & Timmes 1998