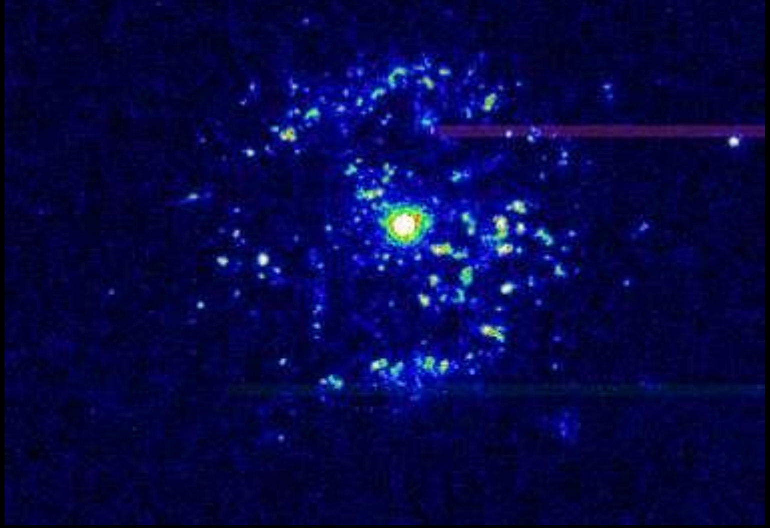
Nova Cygni

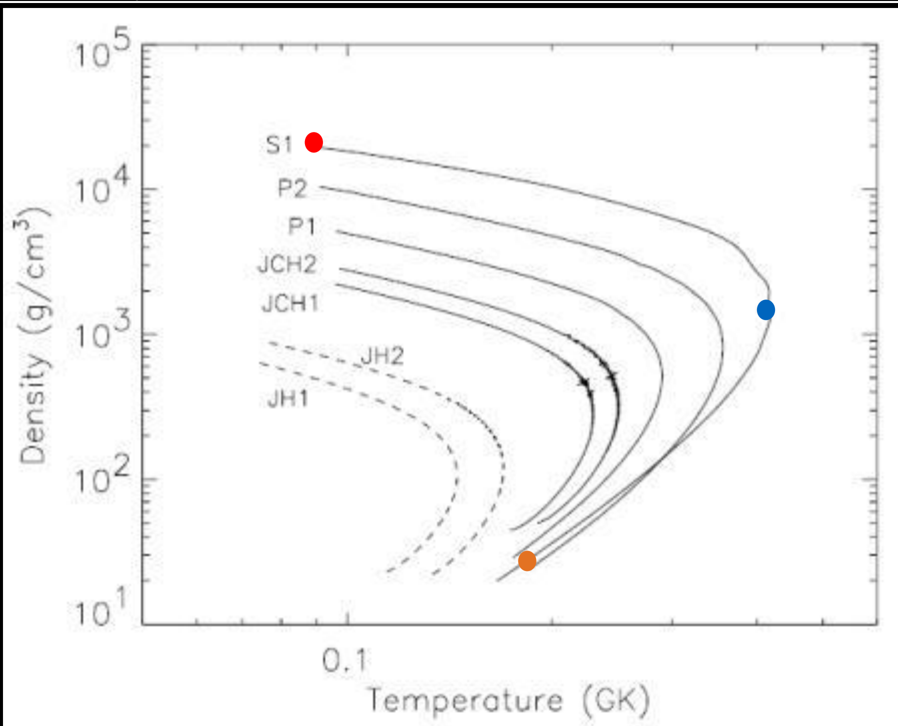
Nova T Pyxidis

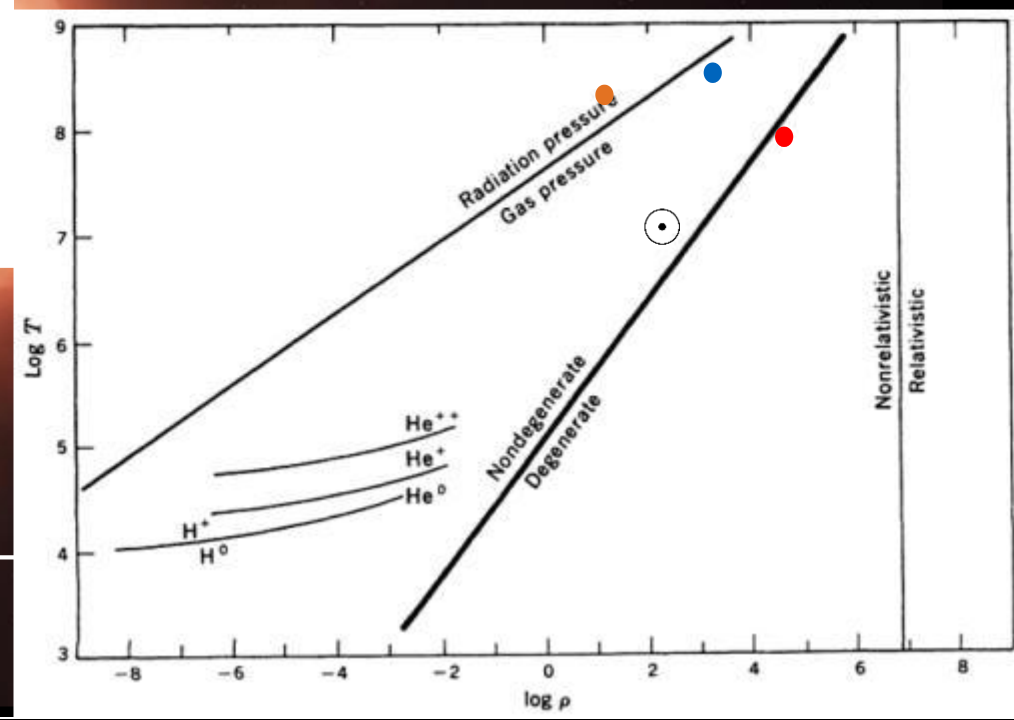


Oxygen-Novae: An Experimentalist’s Perspective

Measuring Nuclear Reaction Rates One Step at a Time

Shawn Bishop, TUM

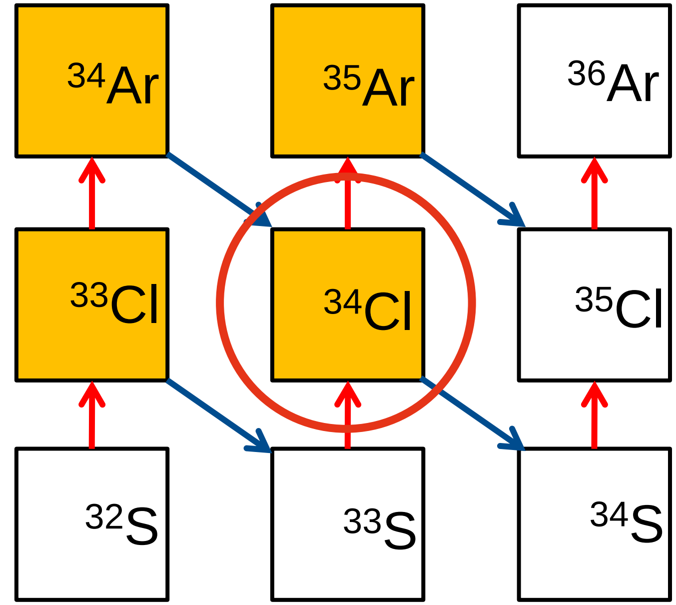


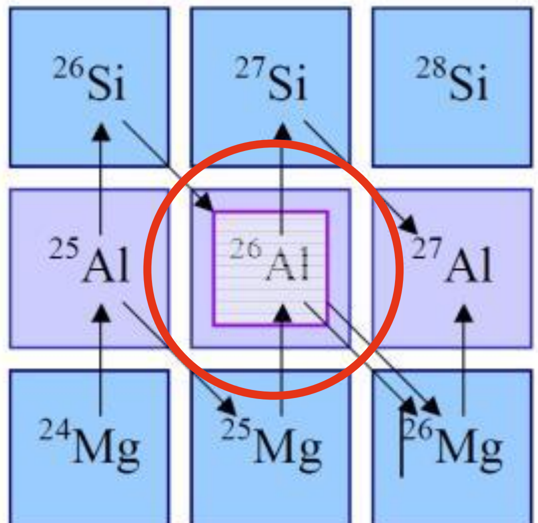


Transfer of H

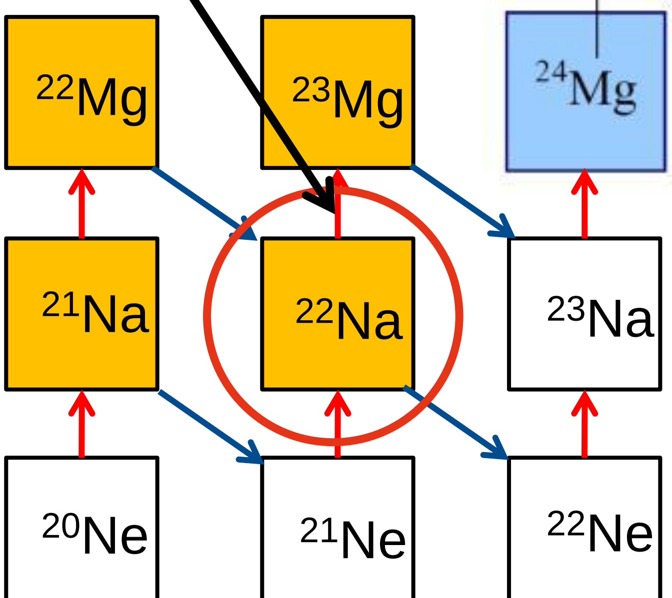
The Gamma-ray Emitters:

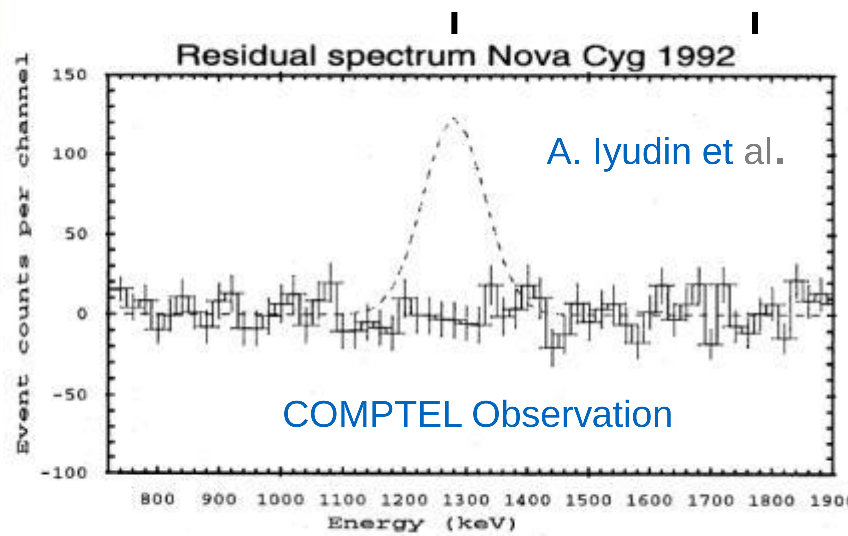
^{22}Na: $t_{1/2}$ = 2.6 yr, E = 1.28 MeV
^{26}Al: $t_{1/2}$ = 717 kyr, E = 1.81 MeV
^{34m}Cl: $t_{1/2}$ = 32 min,
1.18 MeV (14%), 2.13 MeV (42%), 3.30 MeV (12%)



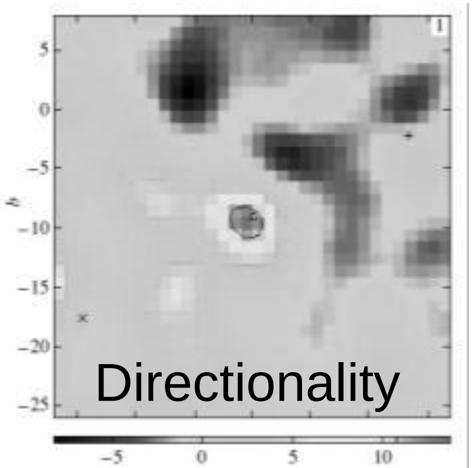


A. Sallaska et al., PRC **83**, 034611 (2011)





ISSN 1063-7729, Astronomy Reports, 2010, Vol. 54, No. 7, pp. 611–619. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © A.F. Iyudin, 2010, published in Astronomicheskiĭ Zhurnal, 2010, Vol. 87, No. 7, pp. 667–676.

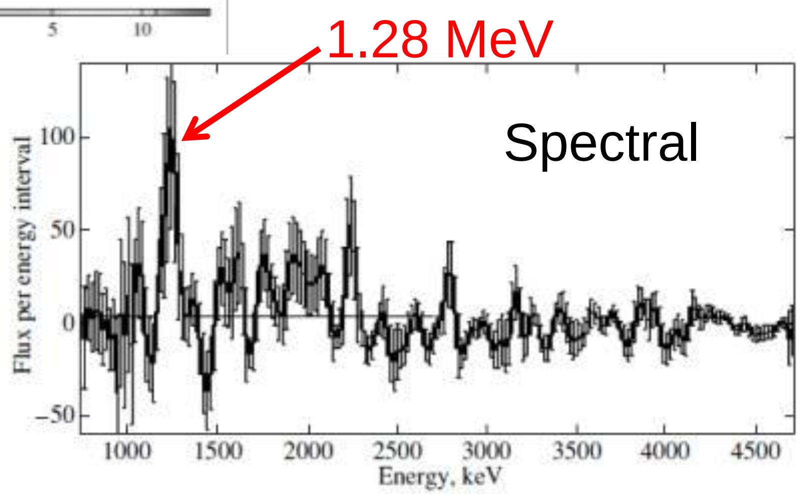


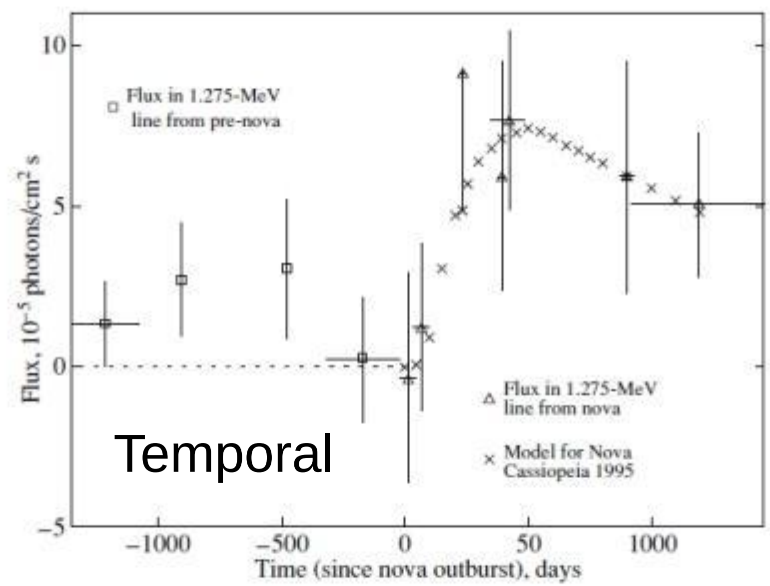
Observation of Line Emission of the Isotope ^{22}Na from a Classical Nova

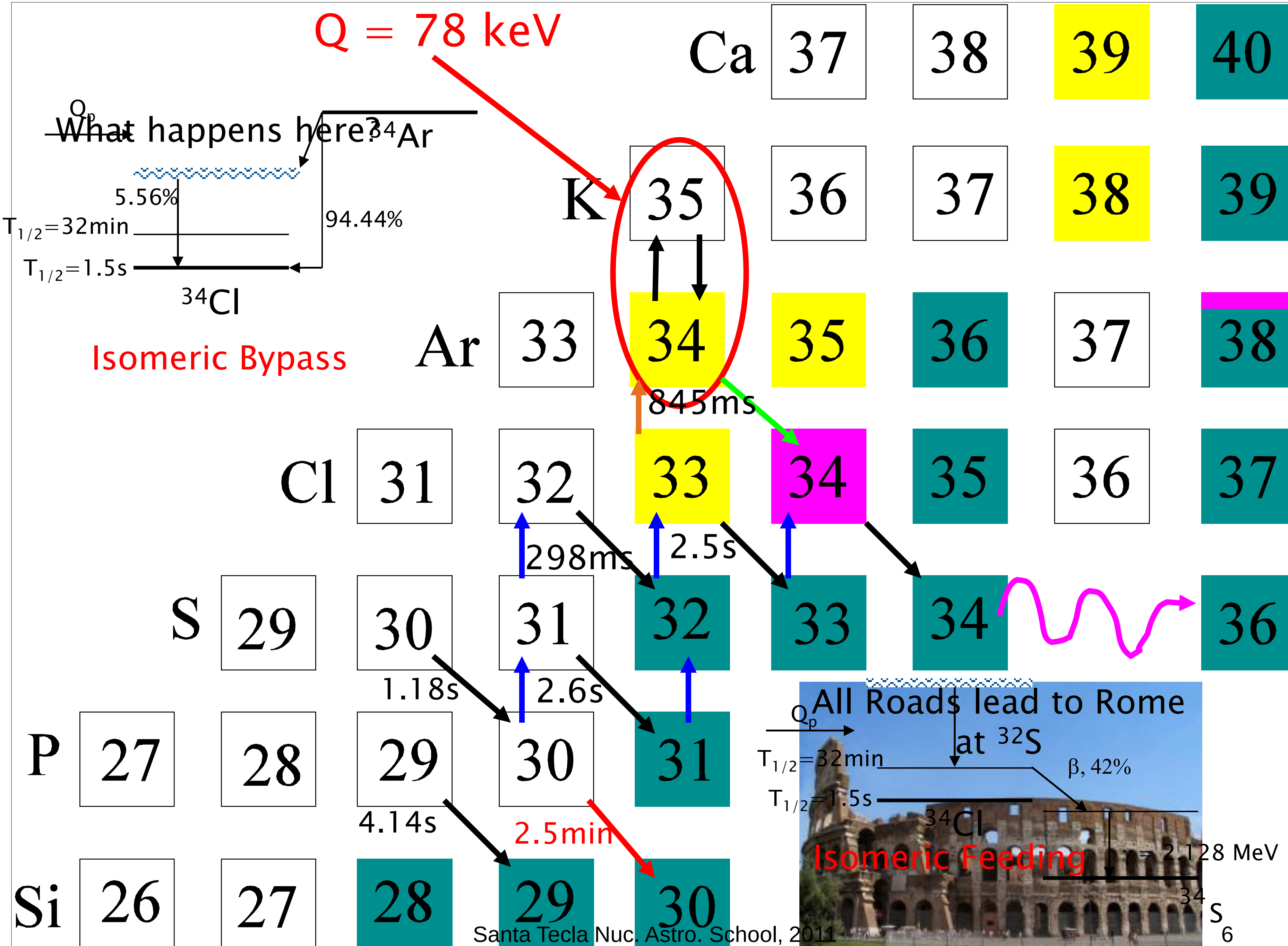
A. F. Iyudin

D.V. Skobel'tsin Nuclear Physics Research Institute,
M.V. Lomonosov Moscow State University, Moscow, Russia

Received August 26, 2009; in final form, February 5, 2010



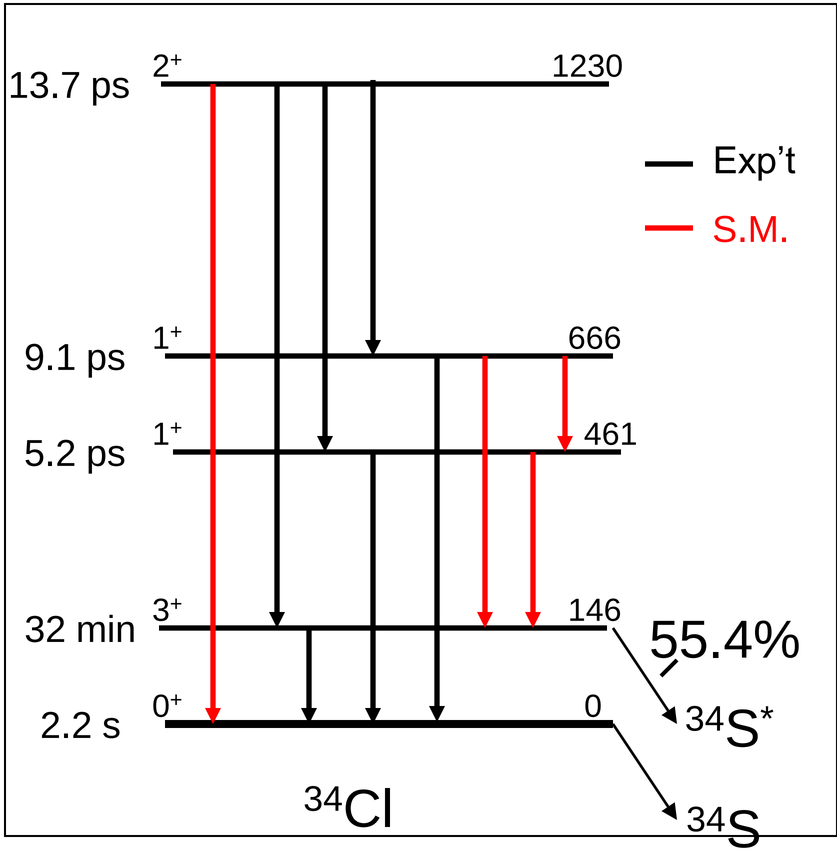



Q = 78 keV
What happens here?
Q_p
^{34}Ar
5.56%
94.44%
$T_{1/2}$=32min
$T_{1/2}$=1.5s
^{34}Cl
Isomeric Bypass
Ca 37 38 39 40
K 35 36 37 38 39
Ar 33 34 35 36 37 38
845ms
Cl 31 32 33 34 35 36 37
298ms
2.5s
S 29 30 31 32 33 34 36
1.18s
2.6s
P 27 28 29 30 31
4.14s
2.5min
Si 26 27 28 29 30
All Roads lead to Rome at ^{32}S
Q_p
$T_{1/2}$=32min
$T_{1/2}$=1.5s
β, 42%
^{34}Cl
Isomeric Feeding
γ = 2.128 MeV
^{34}S

A Thermonuclear Thermometer….

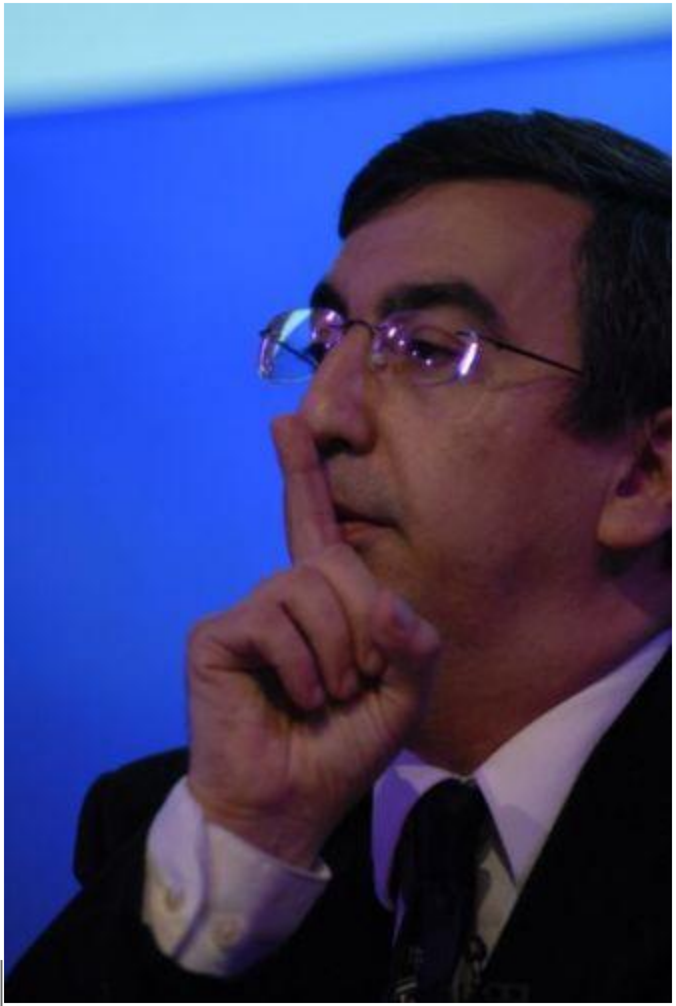
^{34m}Cl: A Thermonuclear Thermometer

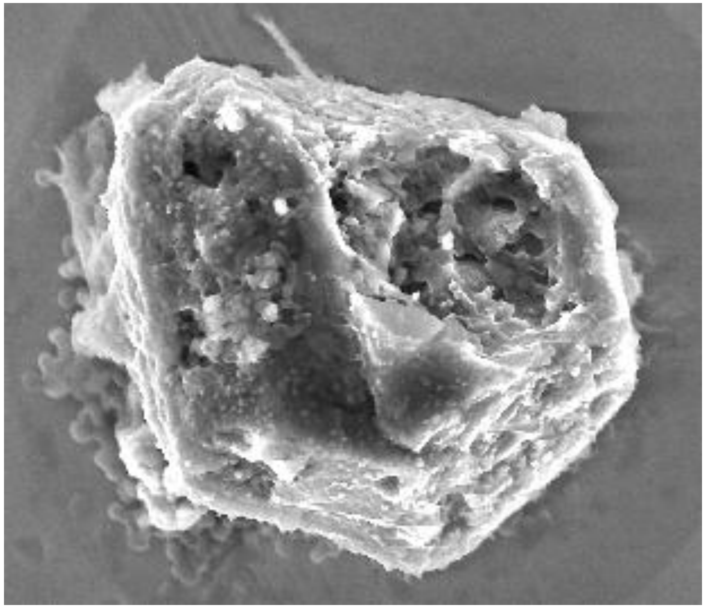
- 3^+ isomeric state gives rise to 2.12 MeV γ-line ¼ 42% per β decay
- Connected directly to ground by M3 transition (45.6% of the time)
- Radiation field can also connect isomeric state to ground state by induced transitions into higher states
  - If this is large enough, lifetime will be reduced from 32 min.
- System of coupled differential equations has been solved



A. Coc et al., PRC **61** (1999)

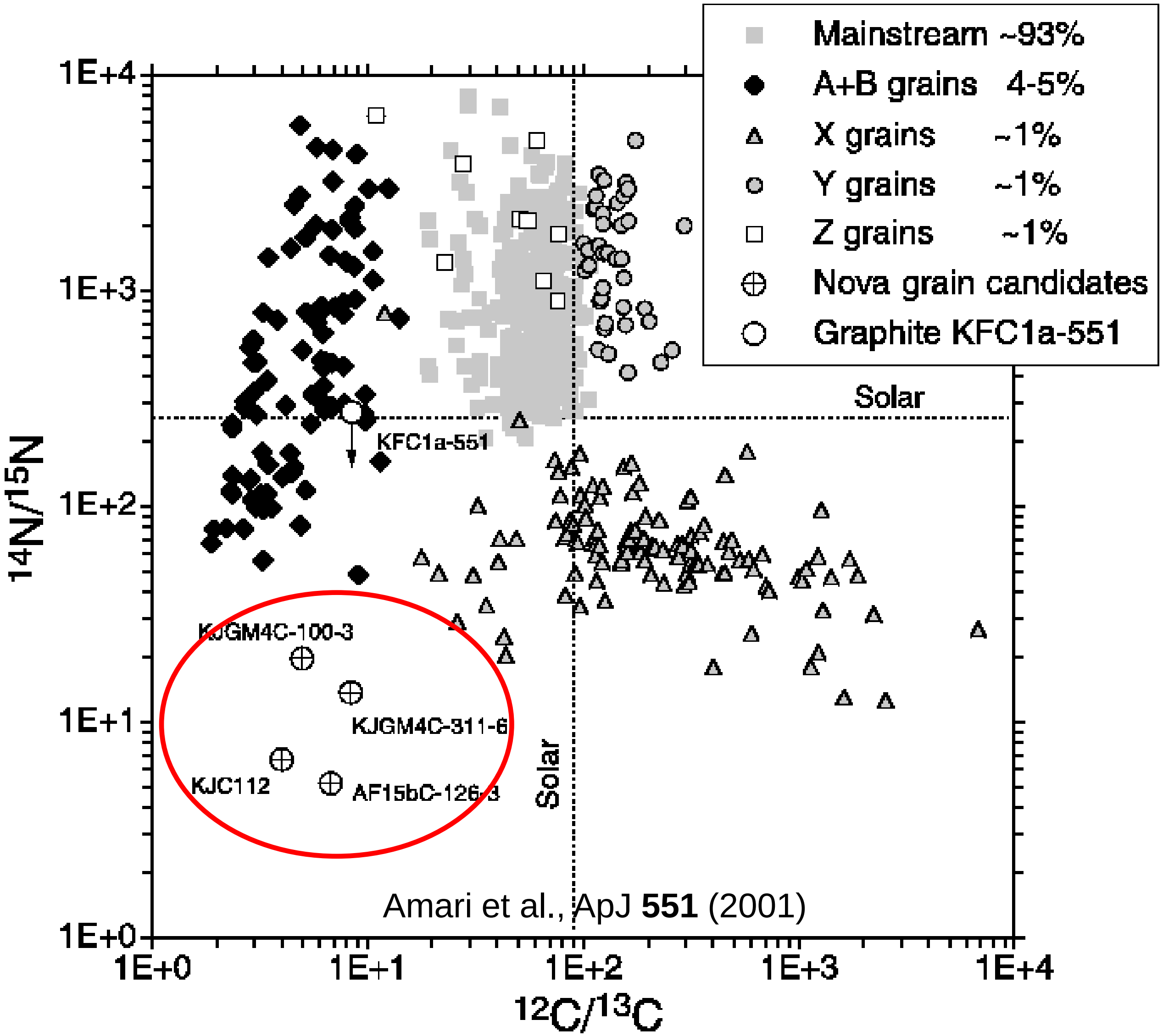
Presolar Grains from Novae



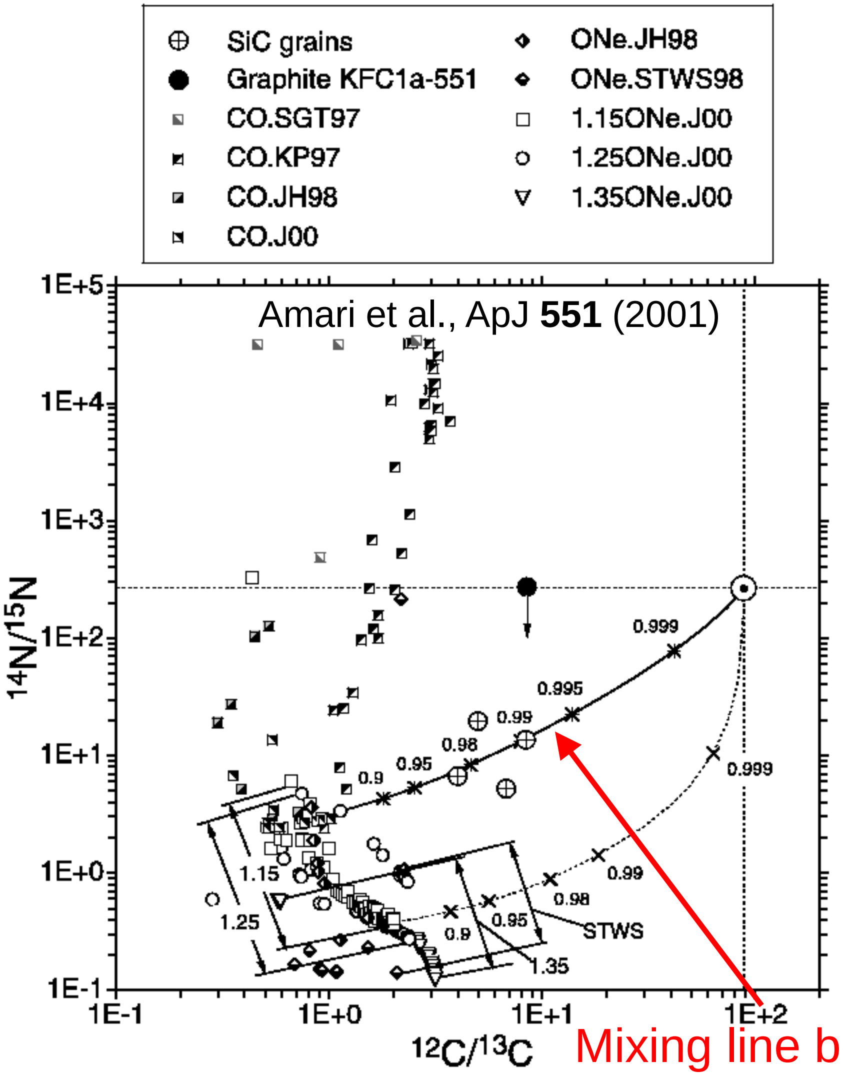


"Shhhhhh!!!!!!!!"

"Oh, no…. What's he about to say about my grains?!"



Amari et al., ApJ **551** (2001)



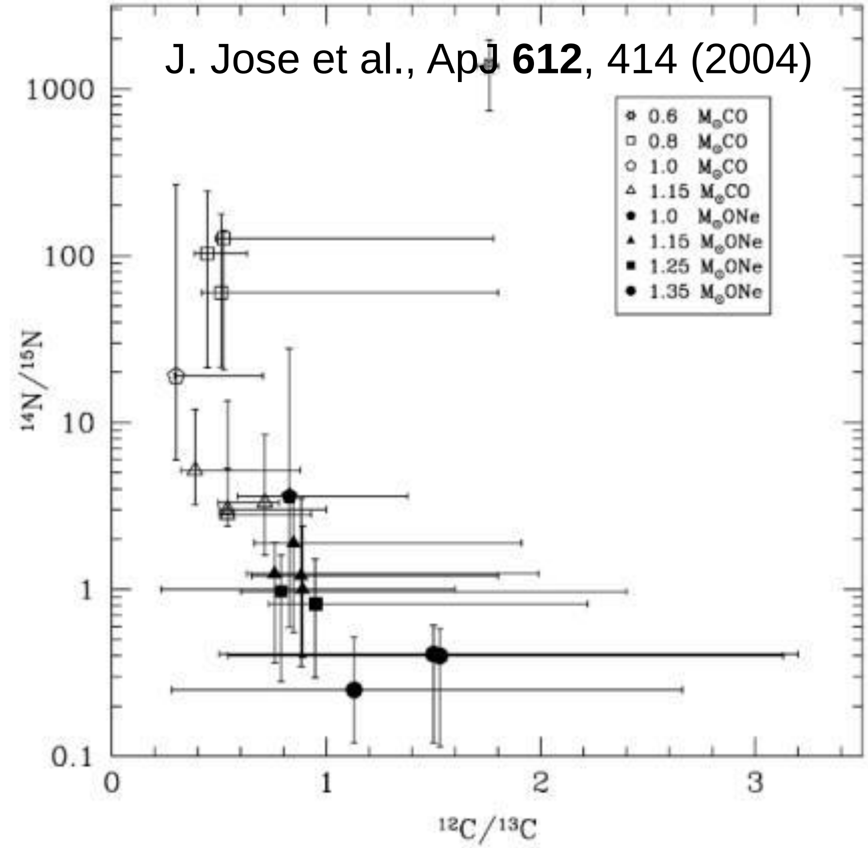


FIG. 4.—Nitrogen vs. carbon isotopic ratios, predicted by hydrodynamic models for both CO and ONe novae (see Tables 2 and 3 for details). Symbols represent mean mass-averaged ratios. Deviation bars, taking into account the gradient of composition in the ejected shells, are also shown for all models.

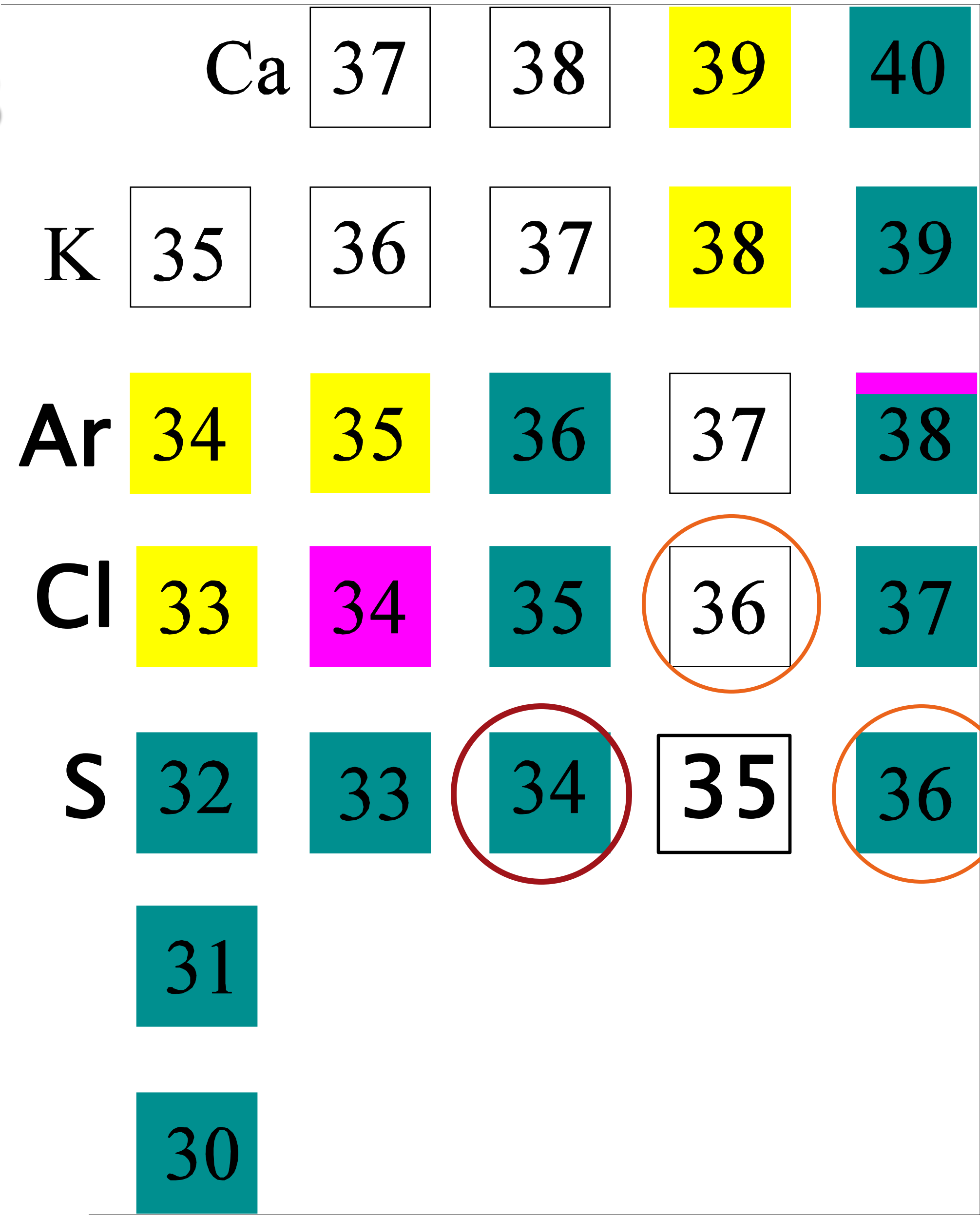
Mixing line between 1.25 M_0 ONe WD and isotopically-close solar material

Some Puzzles

- Calculations suggest grains are < 5% nova material → 95% coming from companion?
- Astro. observations indicate CO novae produce much more dust, hence, grains, than ONe. Yet, grains all appear to be from ONe novae!
- Most observed novae are CO-type, so why are grains all from ONe type?

If Companion is AGB

- ^{36}S is s-process: not nova
- AGB Star: $^{36}Cl(n,p)^{36}S$
- ^{34}S in nova from ^{34}Cl decay
- Sulfur measurements should be target of grains



Some Key Nuclear Reactions

- ^{34m}Cl is a “last chance” γ-emitter for novae nucleosynthesis
  - Bypassed: ^{33}Cl(p,γ)^{34}Ar
  - Produced: ^{33}S(p,γ)^{34m}Cl
  - Destroyed: ^{34m}Cl(p,γ)^{35}Ar
- Sulfur isotopes affected by these rates
  - Measurements of S in presolar grains would help confirm the novae origin
  - Could also help with mixing hypothesis

Reaction Rates:

Consider the schematic reaction: 1 + 2 → 3 + 4

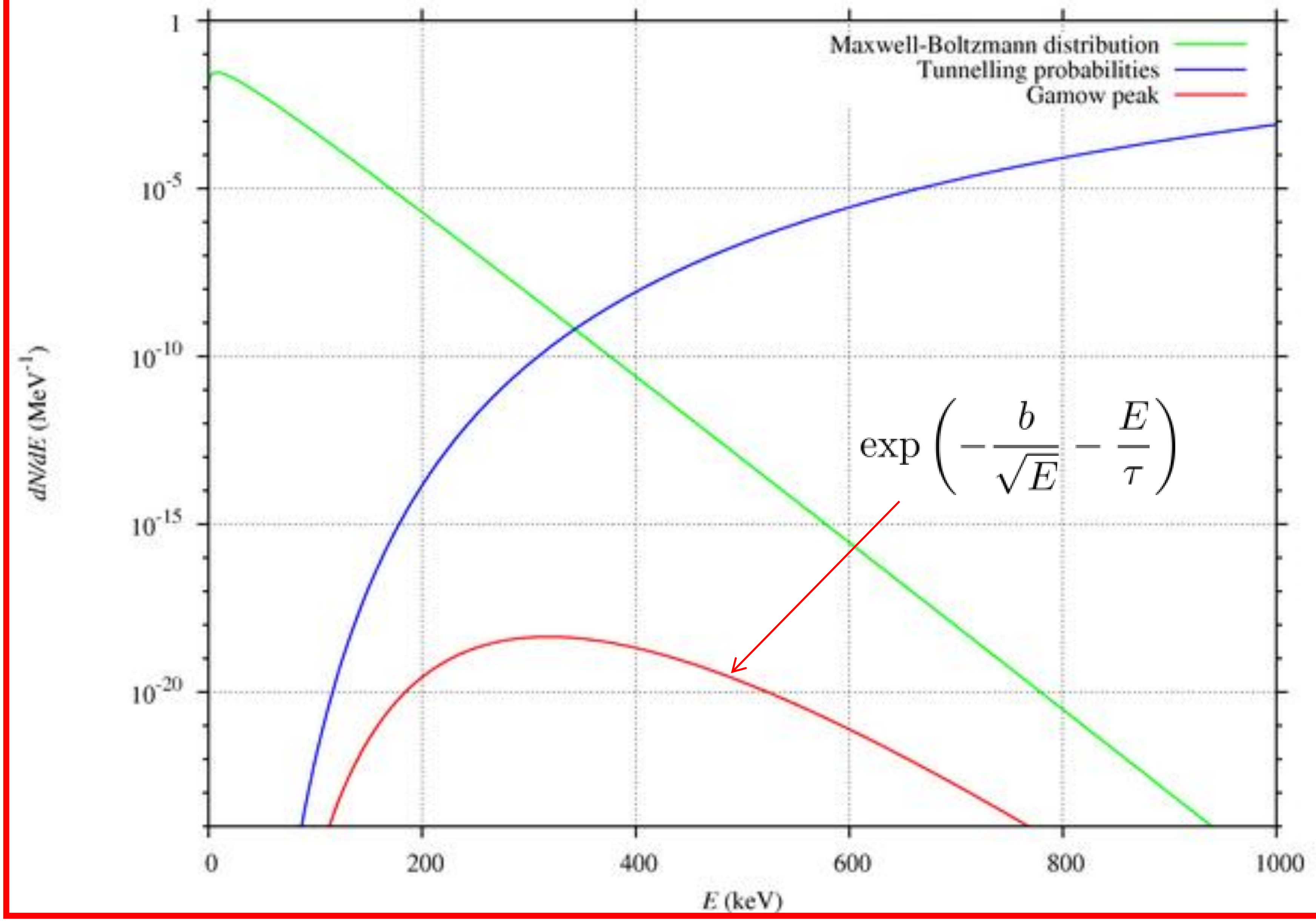
$$r_{12} = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{N_1 N_2}{1+\delta_{12}} \tau^{-3/2} \int_0^\infty E\,\sigma(E)\exp\left(-\frac{E}{\tau}\right) dE$$

In the case of pure (s-wave) tunnelling, the cross-section is parameterized by the well-known formula:

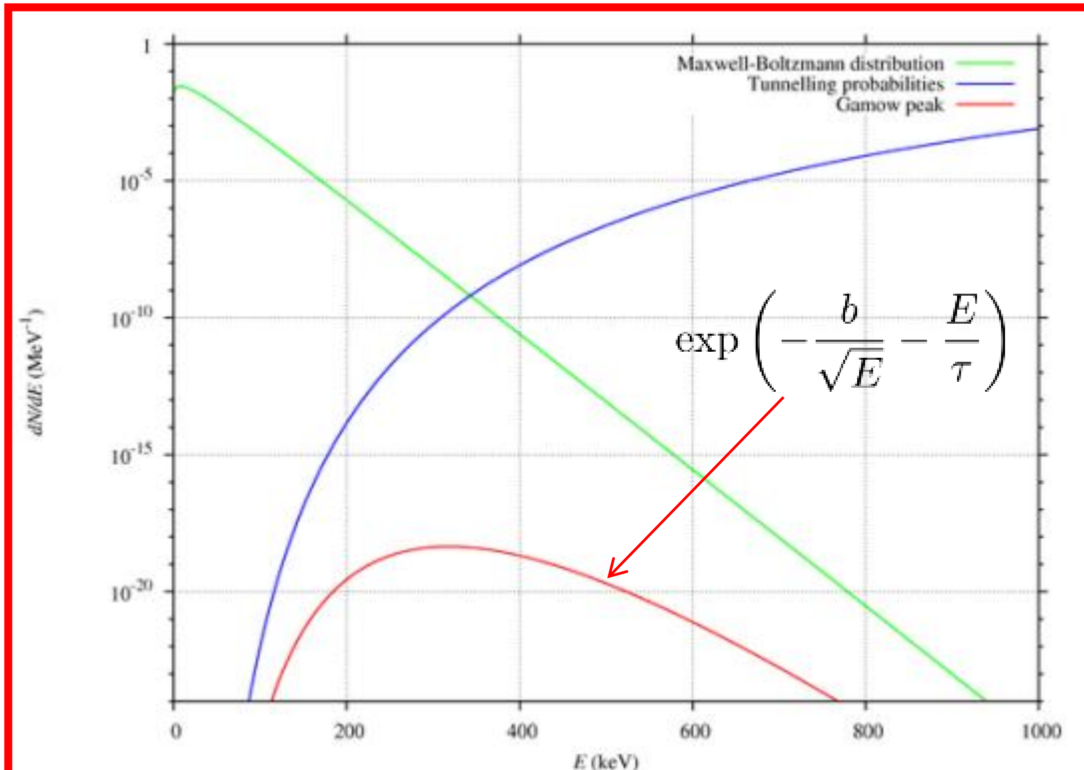
$$\sigma(E) = \frac{S(E)}{E}\exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right) = \frac{S(E)}{E}\exp\left[-2\pi\eta(v)\right]$$

$$r_{12} = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{N_1 N_2}{1+\delta_{12}} \tau^{-3/2} \int_0^\infty S(E)\exp\left(-\frac{b}{\sqrt{E}} - \frac{E}{\tau}\right) dE$$

$$b = 2\pi\frac{Z_1 Z_2 e^2}{h}\left(\frac{\mu}{2}\right)^{1/2} = 31.27 Z_1 Z_2 \mu^{1/2} \quad \mathrm{keV}^{1/2}$$


Maxwell-Boltzmann distribution
Tunnelling probabilities
Gamow peak
$\exp\left(-\frac{b}{\sqrt{E}}-\frac{E}{\tau}\right)$
1
10^{-5}
10^{-10}
10^{-15}
10^{-20}
dN/dE (MeV^{-1})
0
200
400
600
800
1000
E (keV)

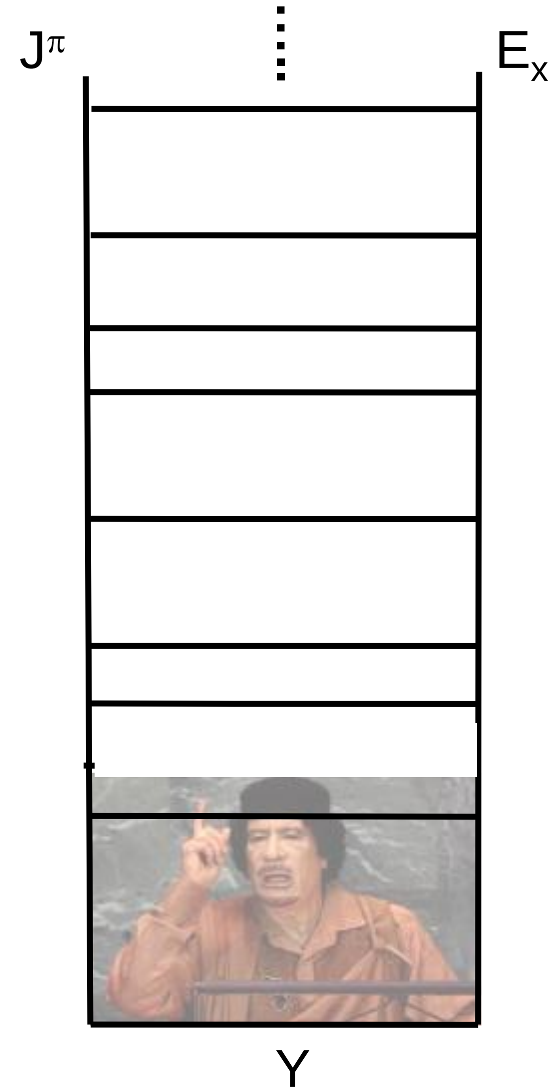
Resonant (p,γ) Reaction Considerations



ne of Y's
energy

nes can

2μ



Minimum E_x is when rel. energy E = 0. That minimum excitation energy is therefore the Q-value.

Resonant Reaction Rate

As before:

$$r_{12} = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{N_1 N_2}{1+\delta_{12}} \tau^{-3/2} \int_0^\infty E\,\sigma(E) \exp\left(-\frac{E}{\tau}\right) dE$$

Resonance cross section can be parameterized with a Breit-Wigner shape:

$$\sigma(E) = g\frac{\pi\hbar^2}{2\mu E} \frac{\Gamma_p \Gamma_\gamma}{(E-E_r)^2 + \Gamma^2/4}$$

Assume that both widths are small (total width is narrow) and they are constant (very weak energy dependence). Sub the above cross section into the integral, treating the Γ terms as constants:

$$r_{12} = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{\pi\hbar^2}{2\mu} \frac{N_1 N_2}{1+\delta_{12}} \tau^{-3/2} e^{-E_r/\tau} \frac{\Gamma_a \Gamma_b}{\Gamma} 2 \underbrace{\int_0^\infty \frac{\Gamma/2}{(E-E_r)^2 + \Gamma^2/4} dE}_{=\pi}$$

Resonant Reaction Rate (Single Resonance):

$$r_{12} = \left(\frac{2\pi}{\mu\tau}\right)^{3/2} \hbar^2 \frac{N_1 N_2}{1+\delta_{12}} \frac{2J_r+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma} e^{-E_r/\tau}$$

We have added the spin-statistical factors (now) to account for the fact that our theory up to this point has only considered spin zero particles (in entrance channel and exit channel) in the reaction.

More generally, for particles with spin, we have to multiply the cross section by the spin-statistical factor to account for the different permutations of spin alignments that are allowed.

J_r is the spin (intrinsic) of the resonance.
J_1 “ “ beam particle.
J_2 “ “ target particle.

We define $\omega\gamma = \frac{2J_r+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$ as the *resonance strength.*

Reaction Yield

Reaction yield dY, passing through target of thickness dx

$$dY = \sigma N_t dx$$

N_t is target number density

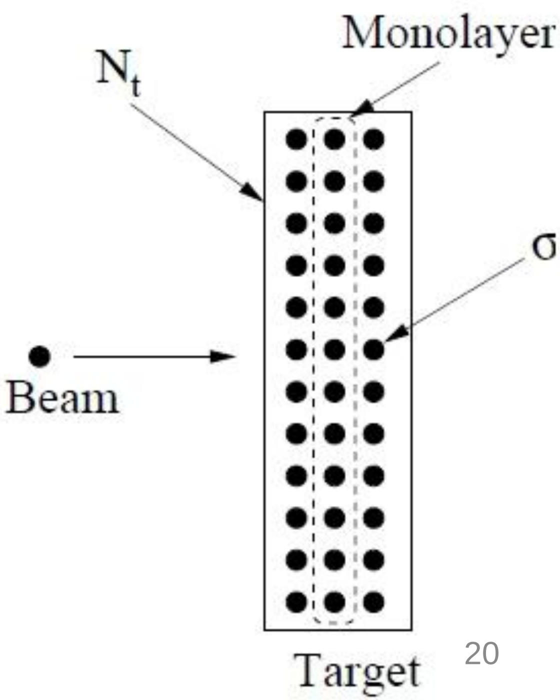
σ is the reaction cross section (energy dependent function)

In general, of course, targets are thicker than a mono-layer, and so the beam energy does change in a finite way, and so will the cross section. Thus, more generally, the reaction yield per incident beam particle is an integral over mono-layers:

$$Y = \int_{E}^{E-\Delta} N_t \sigma(E)\, dx$$

Use stopping power to integrate over E:

$$\epsilon(E_{lab}) = -\frac{1}{N_t}\frac{dE_{lab}}{dx}$$



$$Y = \frac{m_p + m_t}{m_t} \int_{E-\Delta}^{E} \frac{\sigma(E)}{\epsilon(E)}\, dE$$

Using: $$E_{cm} = \frac{m_t}{m_b + m_t} E_{lab}$$

Recall the Breit-Wigner cross section:

$$\sigma(E) = \frac{\pi \hbar^2}{2\mu E} \frac{2J_r + 1}{(2J_p + 1)(2J_t + 1)} \frac{\Gamma_p \Gamma_\gamma}{(E - E_r)^2 + \Gamma^2/4}$$

For proton, gamma and total widths considered as constants, and when the total resonance width $\Gamma \ll \Delta$ (narrow resonance, like a delta-function), then the above function can be integrated.

$$Y = \frac{\pi \hbar^2}{2\mu E_r} \frac{m_t}{m_b + m_t} \frac{2J_r + 1}{(2J_p + 1)(2J_t + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma/2} \epsilon^{-1} \times$$

$$\left[\arctan\left(\frac{E - E_r}{\Gamma/2}\right) - \arctan\left(\frac{E - E_r - \Delta}{\Gamma/2}\right)\right]$$

This is the *thick target yield curve*. It has a maximum at $E = E_r + \Delta/2$. At maximum, the yield is:

$$Y_{max} = \frac{\pi\hbar^2}{2\mu E_r}\frac{m_t}{m_b + m_t}\,\omega\gamma\,c^{-1}\ \arctan\left(\frac{\Delta}{\Gamma}\right)$$

And, as per our conditions on previous page, when $\Gamma \ll \Delta$ then:

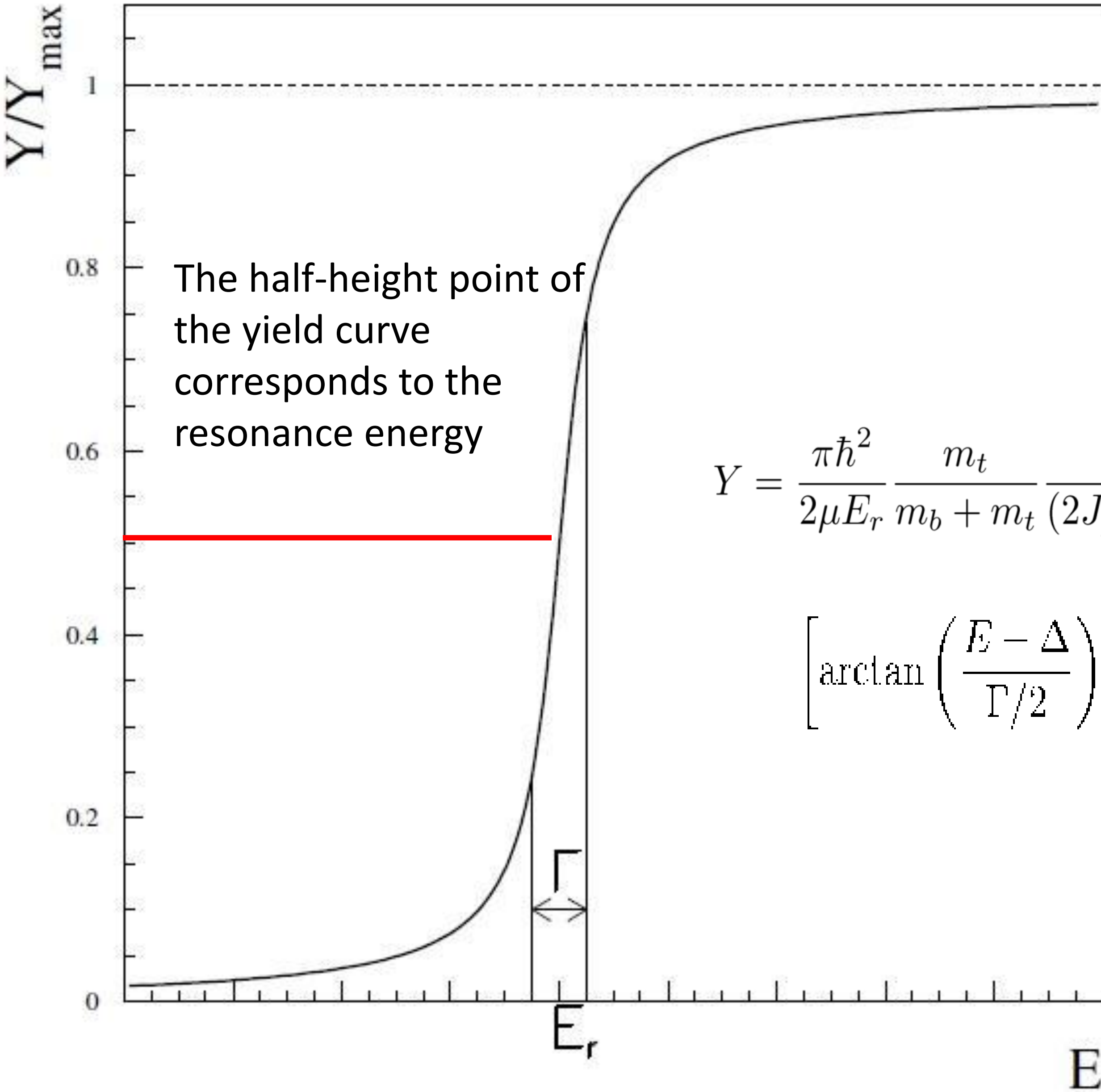
$$Y_{max} = \frac{\pi\hbar^2}{2\mu E_r}\frac{m_t}{m_b + m_t}\,\omega\gamma\,c^{-1}\ \arctan\left(\frac{\Delta}{\Gamma}\right)$$

$$Y_{max} = \frac{\pi^2\hbar^2}{4\mu E_r}\frac{m_t}{m_b + m_t}\,\omega\gamma\,c^{-1}$$

So:

Once we know the resonance energies of compound nucleus, and the stopping power in the target (can be measured), we can obtain the resonance strength from the maximum of the thick target yield curve.

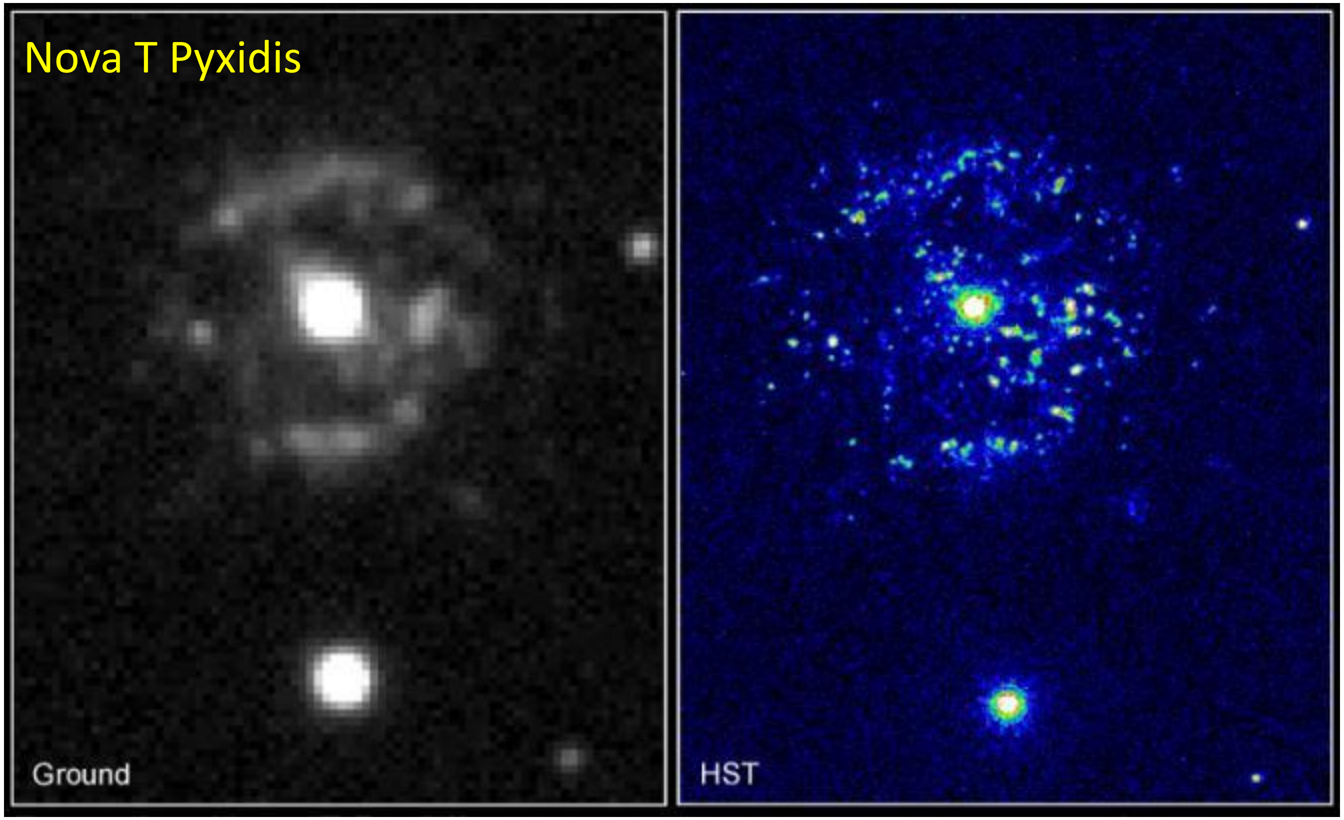
Thick Target Yield Curve



$$Y_{max} = \frac{\pi^2\hbar^2}{4\mu E_r}\frac{m_t}{m_b+m_t}\,\omega\gamma\,\epsilon^{-1}$$

$$Y = \frac{\pi\hbar^2}{2\mu E_r}\frac{m_t}{m_b+m_t}\frac{2J_r+1}{(2J_p+1)(2J_t+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma/2}\epsilon^{-1}\times$$

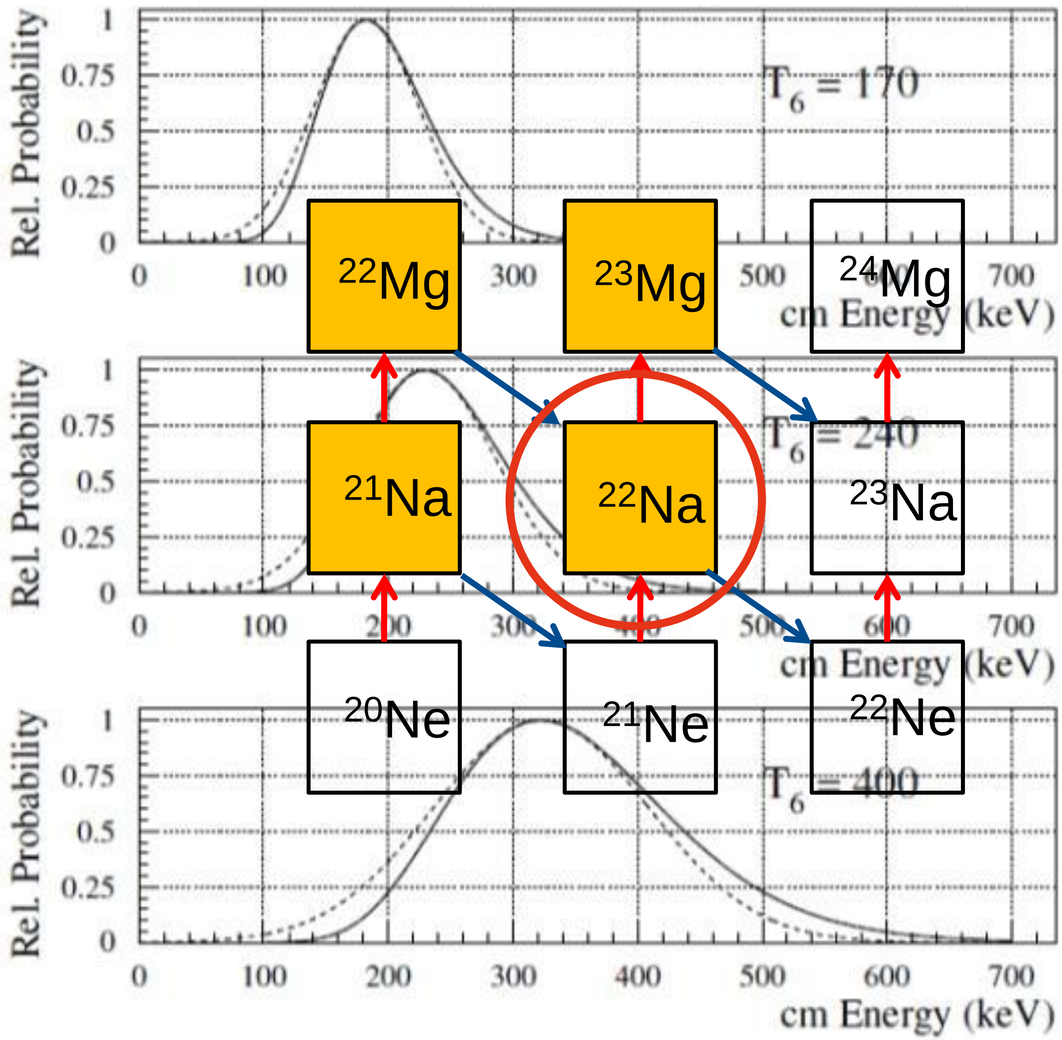
$$\left[\arctan\left(\frac{E-\Delta}{\Gamma/2}\right)-\arctan\left(\frac{E-E_r-\Delta}{\Gamma/2}\right)\right]$$

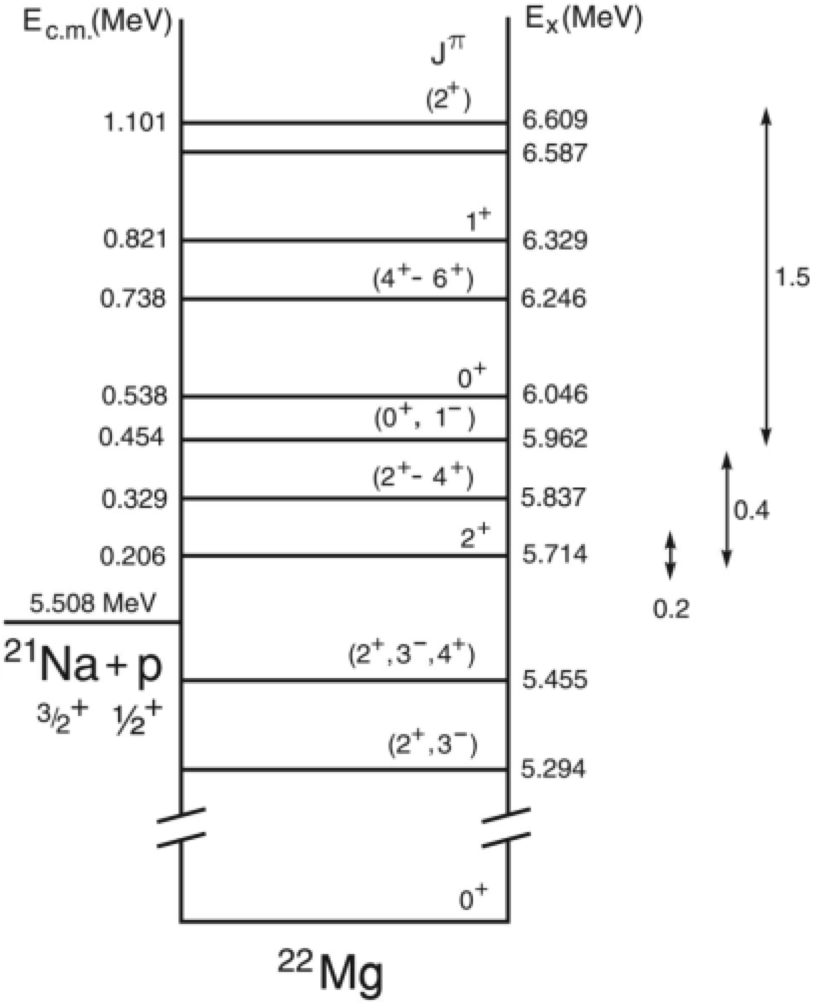


Measuring a Resonance Strength with a Radioactive Ion Beam

EXPERIMENTAL APPROACHES: THE DIRECT METHOD

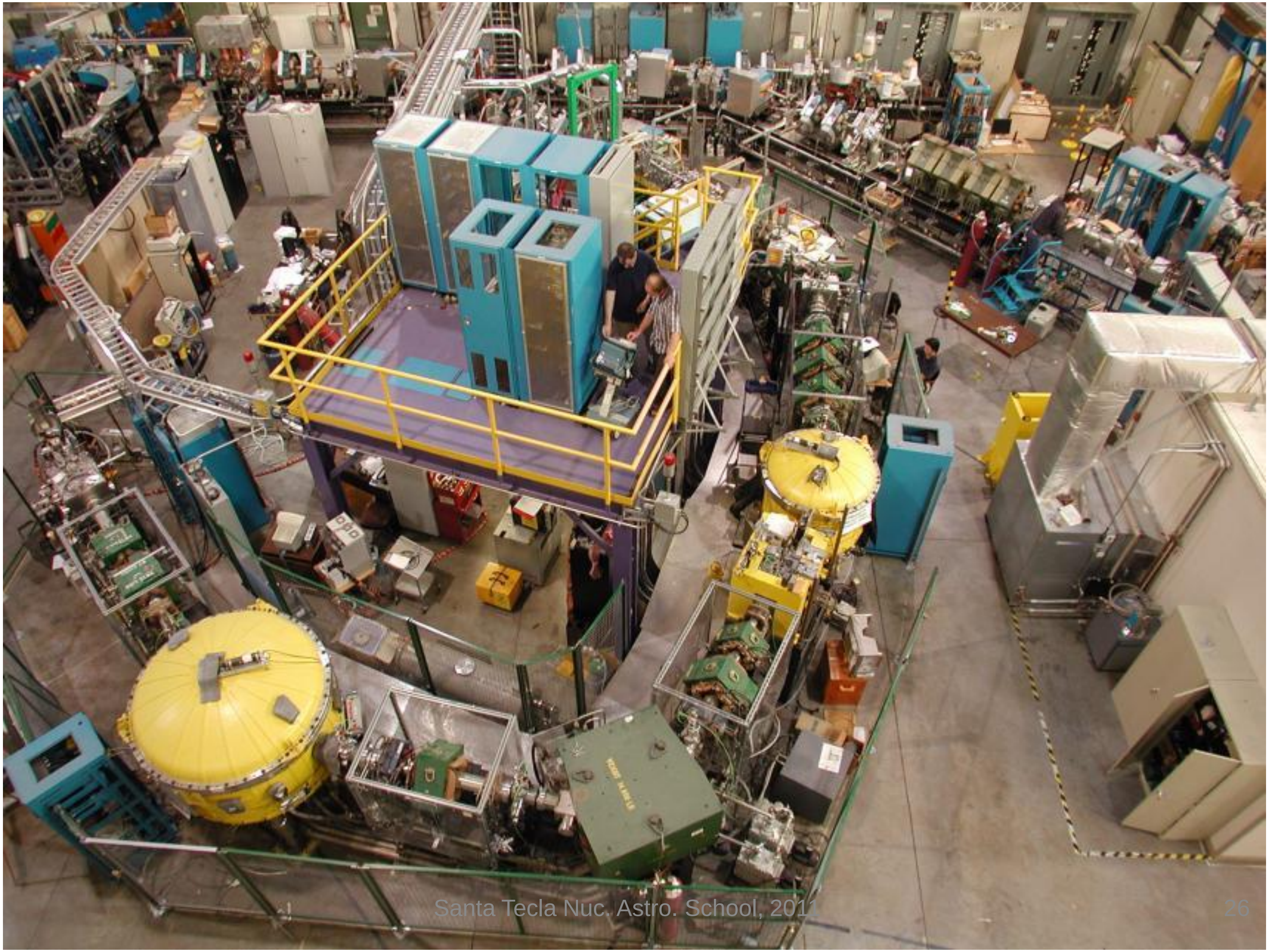
The Case for $^{21}Na(p,\gamma)^{22}Mg$





DRAGON Facility at TRIUMF, Canada

Detector of Recoils & Gamma-rays Of Nuclear reactions



It is clear that, for γ-ray emission collinear with the incident beam axis, the recoil nucleus will have maximum (minimum) kinetic energy for backward (forward) emission.

Therefore, the maximum/minimum momentum of the fusion recoils is given by:

$$p_r = p^* \pm p_\gamma = \sqrt{2m_b T_b}\left(1 \pm \frac{E_\gamma}{\sqrt{2m_b T_b}}\right)$$

Square both sides, and divide by $2m_r$ for the max/min recoil kinetic energy

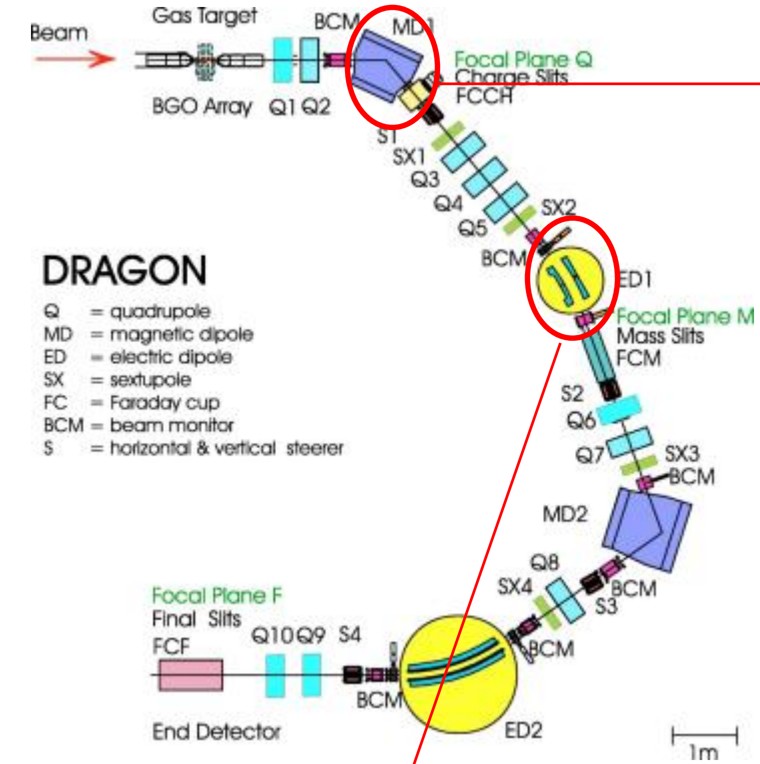
$$T_r = \frac{m_b}{m_r} T_b \left(1 \pm \frac{2E_\gamma/c}{\sqrt{2m_b T_b}} + \frac{E_\gamma^2/c^2}{2m_b T_b}\right)$$

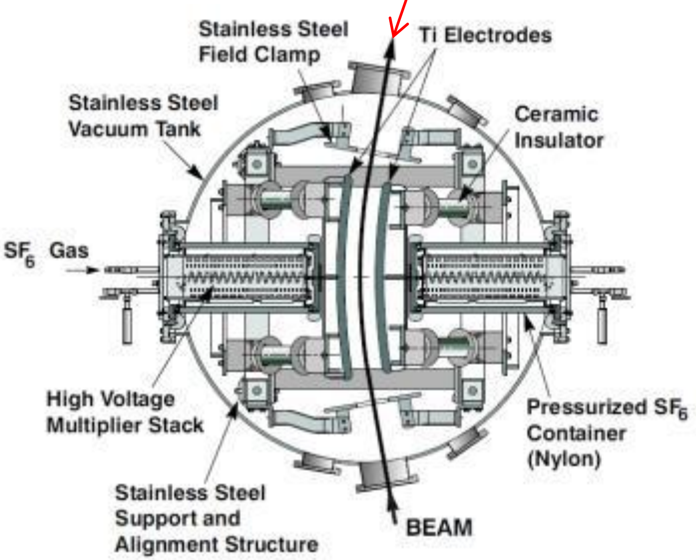
Around a few %

Order 10^{-4}

This result, written in this form, shows us that the fusion recoil particles will have max/min kinetic energies ~ several percent different from that of the unreacted beam particles.

How do we use these facts to separate the unreacted beam from the fusion particles?





Dipole magnet works on principle of Lorentz force. (ρ = bending radius)

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B} = qvB = m\frac{v^2}{\rho}$$

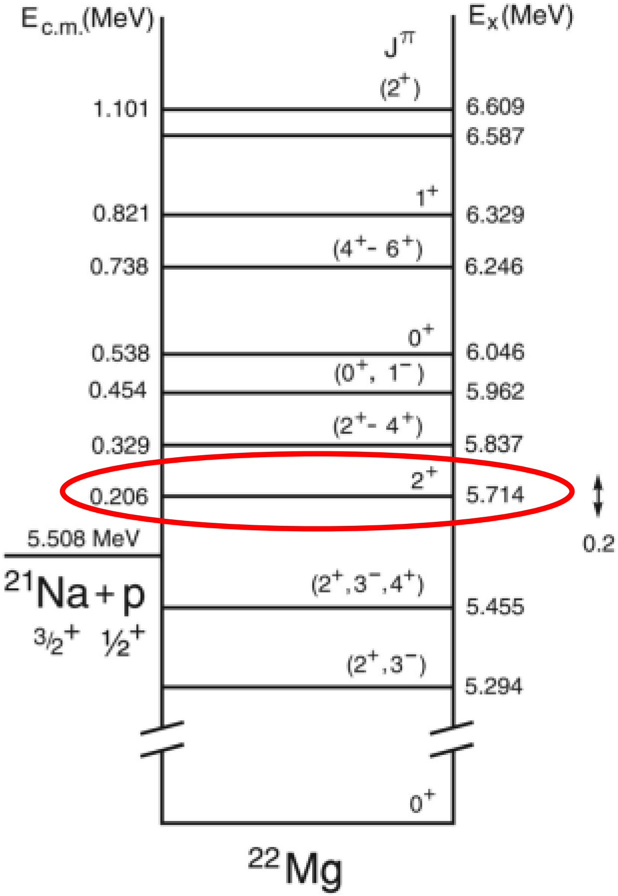
(circular trajectory)

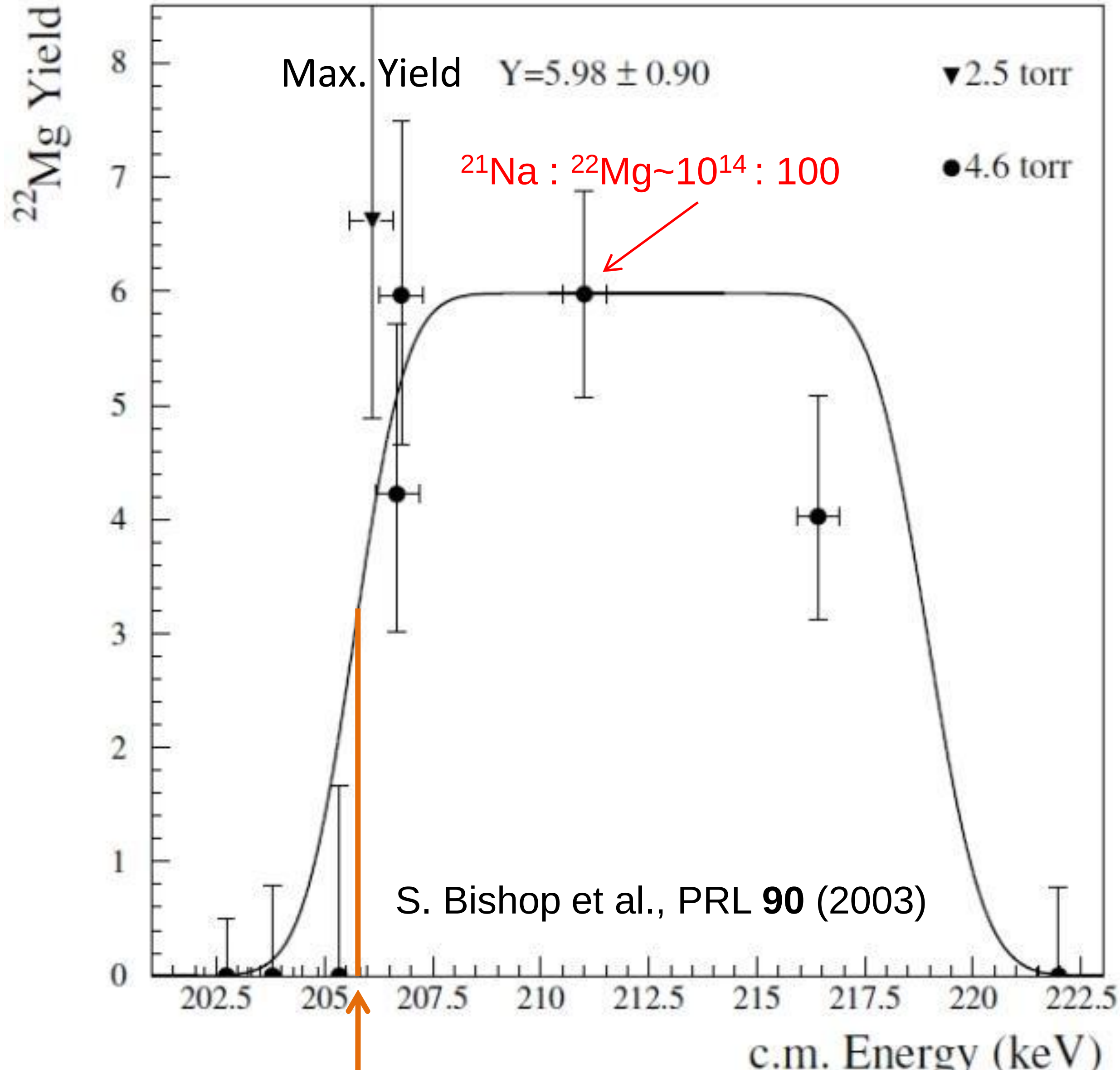
$$\Rightarrow p = qB\rho$$

Momentum selector, but in reaction, P is conserved. Will not separate beam from fusion product.

Separation happens with the electrostatic deflector:

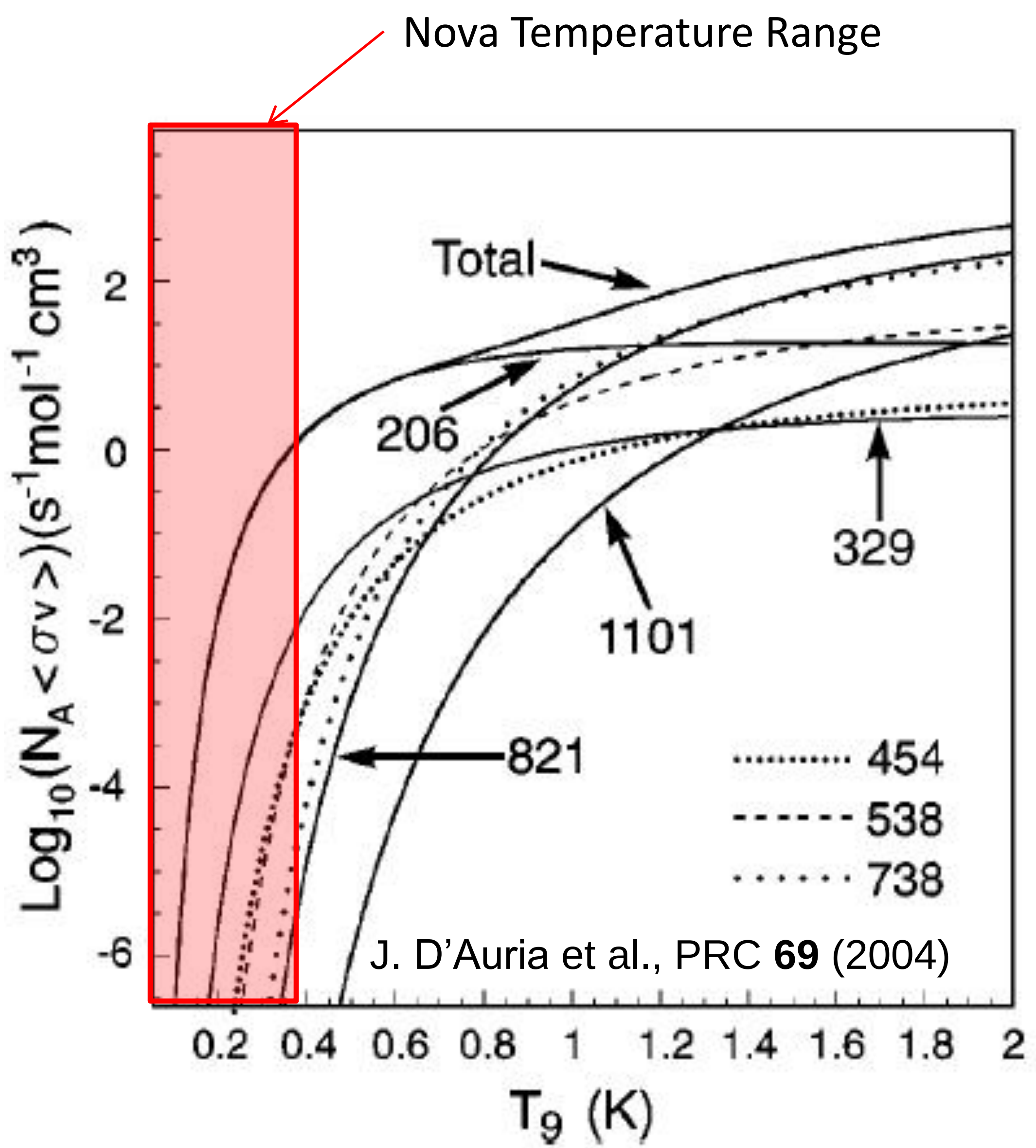
$$q\mathcal{E} = m\frac{v^2}{R} \Rightarrow T = \frac{q\mathcal{E}R}{2}$$

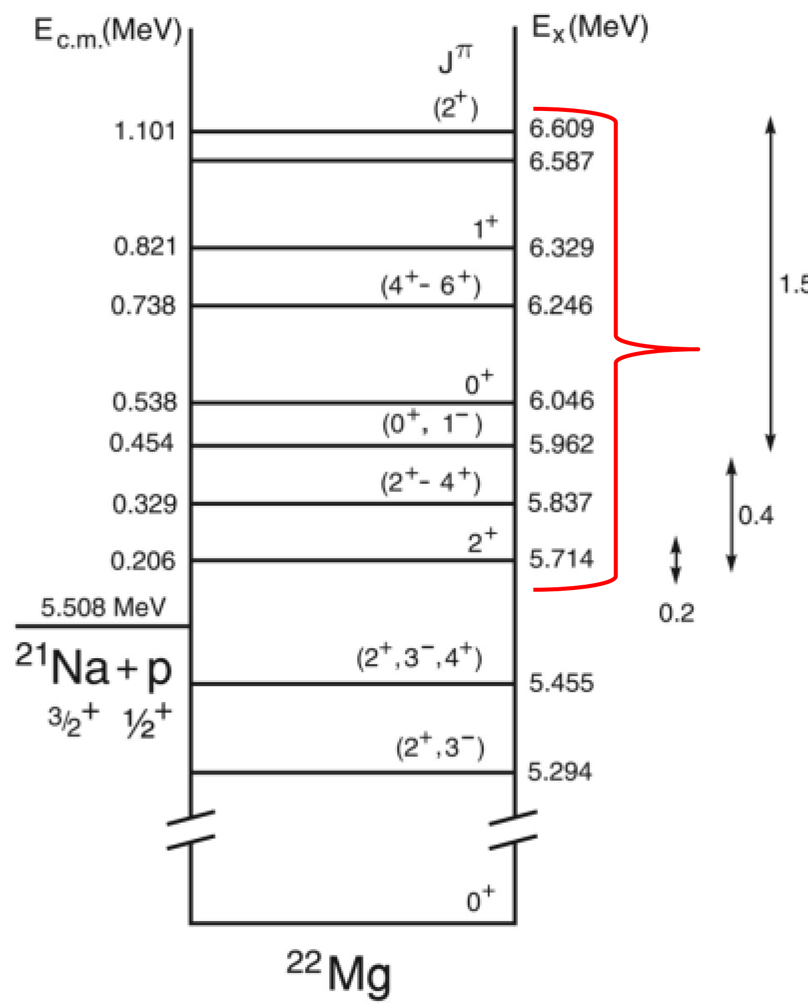




Resonance Energy = $205.7 + 0.5$ keV

$$\omega\gamma = 1.07 \pm 0.21 \text{ meV}$$


Nova Temperature Range
Total
206
329
1101
821
454
538
738
J. D'Auria et al., PRC 69 (2004)
$\log_{10}(N_A\langle\sigma v\rangle)(s^{-1}mol^{-1}cm^3)$
2
0
-2
-4
-6
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
T_9 (K)


$E_{c.m.}$(MeV)
E_x(MeV)
J^π
(2^+) 1.101 6.609
6.587
1^+ 0.821 6.329
(4^+-6^+) 0.738 6.246
0^+ 0.538 6.046
$(0^+, 1^-)$ 0.454 5.962
(2^+-4^+) 0.329 5.837
2^+ 0.206 5.714
5.508 MeV
$^{21}Na + p$
$3/2^+$ $1/2^+$
$(2^+,3^-,4^+)$ 5.455
$(2^+,3^-)$ 5.294
0^+
^{22}Mg
0.2
0.4

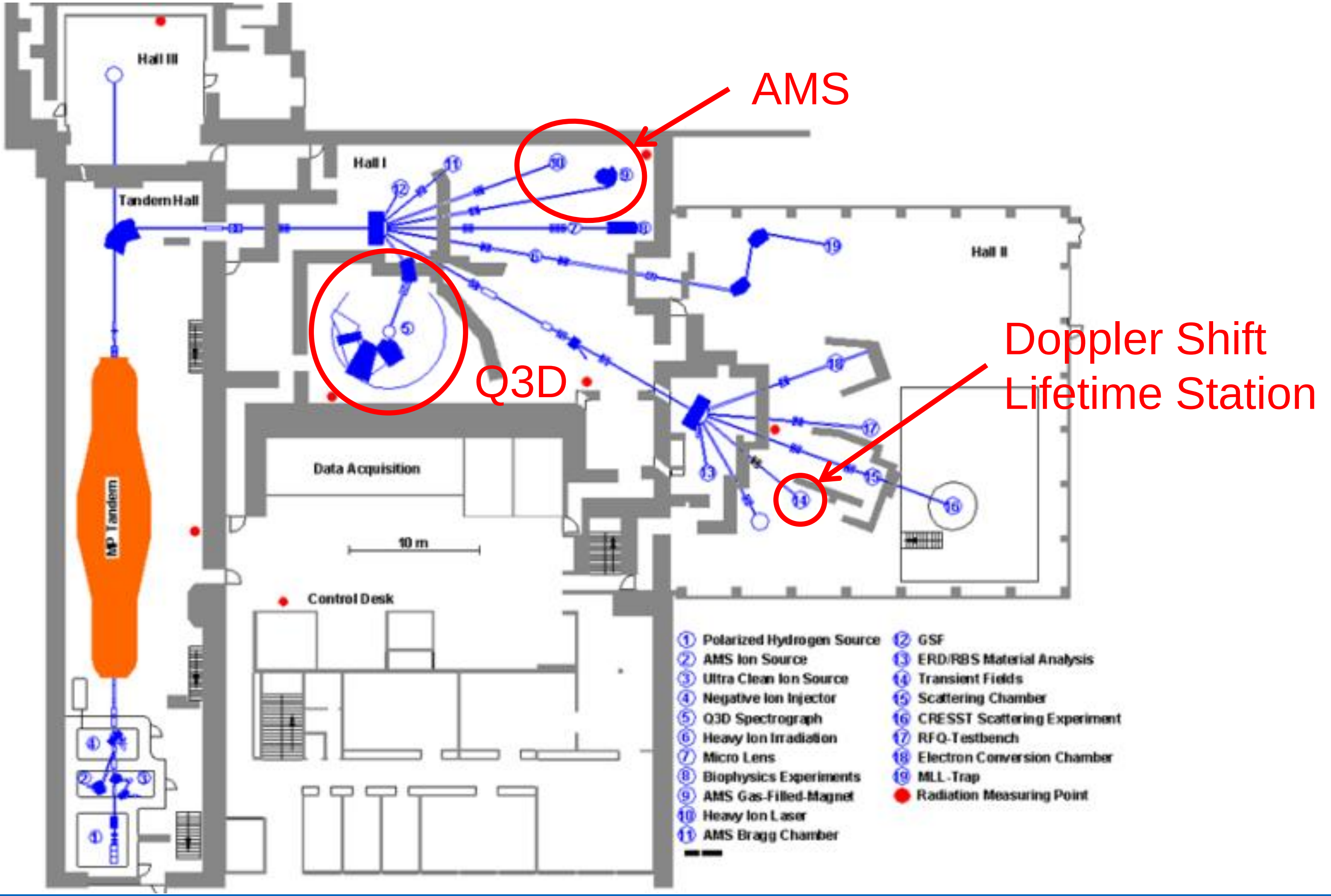
Measuring Astrophysical Rates one Step at a Time

STABLE BEAMS

MLL Overview

- 14 MV Terminal voltage
- Pulsed beam
  - 200 ns between pulses
  - Pulse width ~ 1 ns
- Cesium sputtering ion source
  - Negative ion beams
  - No Nobel gas ion beams (except ^{3,4}He)
- Isobaric separation at $90°$ bending magnet

Accelerator Laboratory: Overview

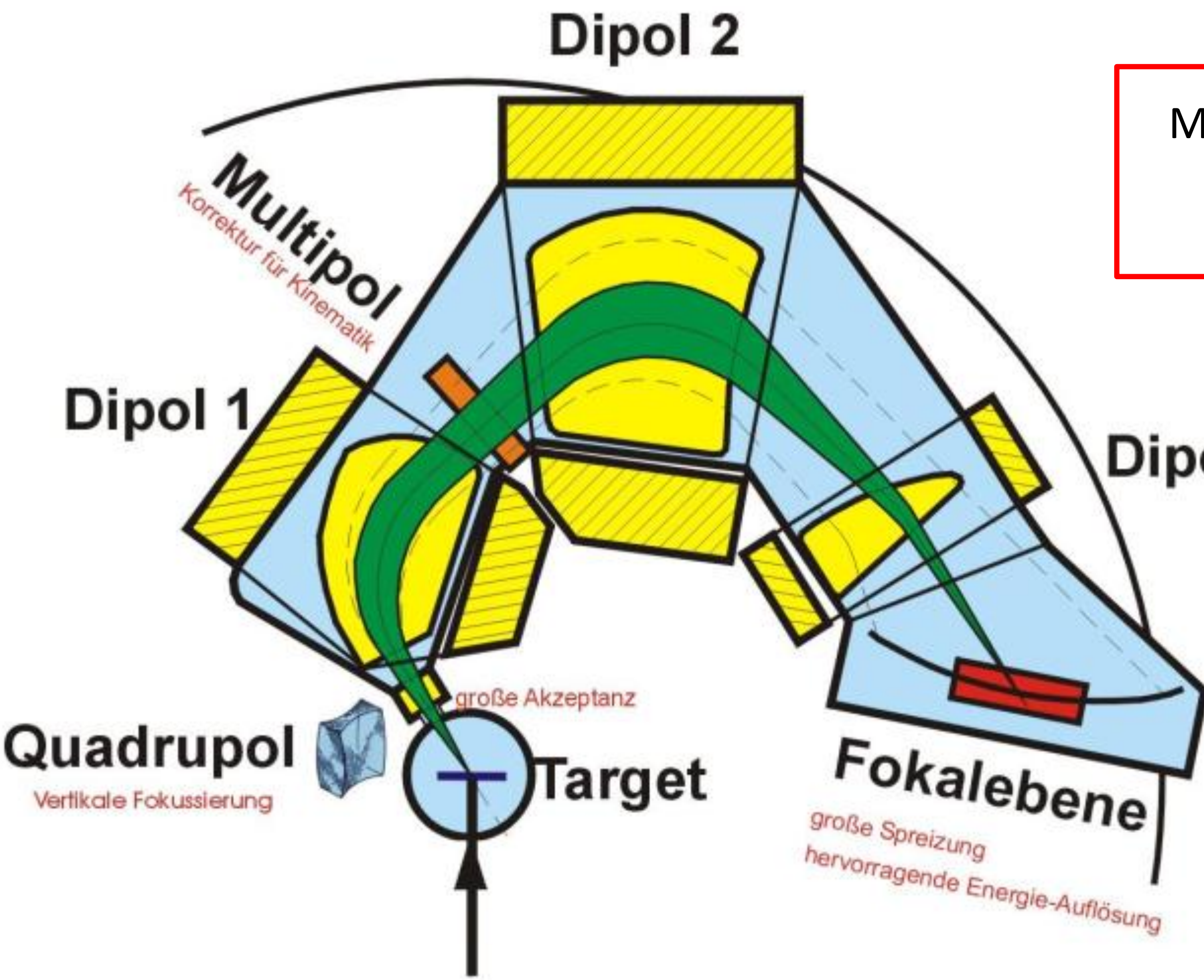


$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu k T}\right)^{3/2} \hbar^2 \sum_i \omega\gamma_i e^{-\frac{E_i}{kT}}$$

- Extracting exp(-E_i/kT)

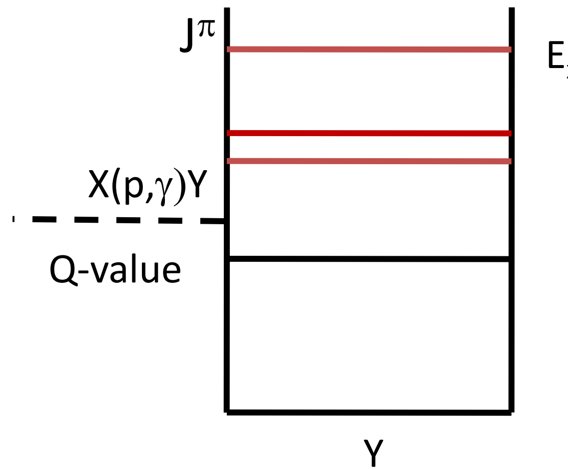
MAPPING EXPLOSIVE REACTION RATES: THE Q3D

Q3D High Resolution Spectrograph at TUM



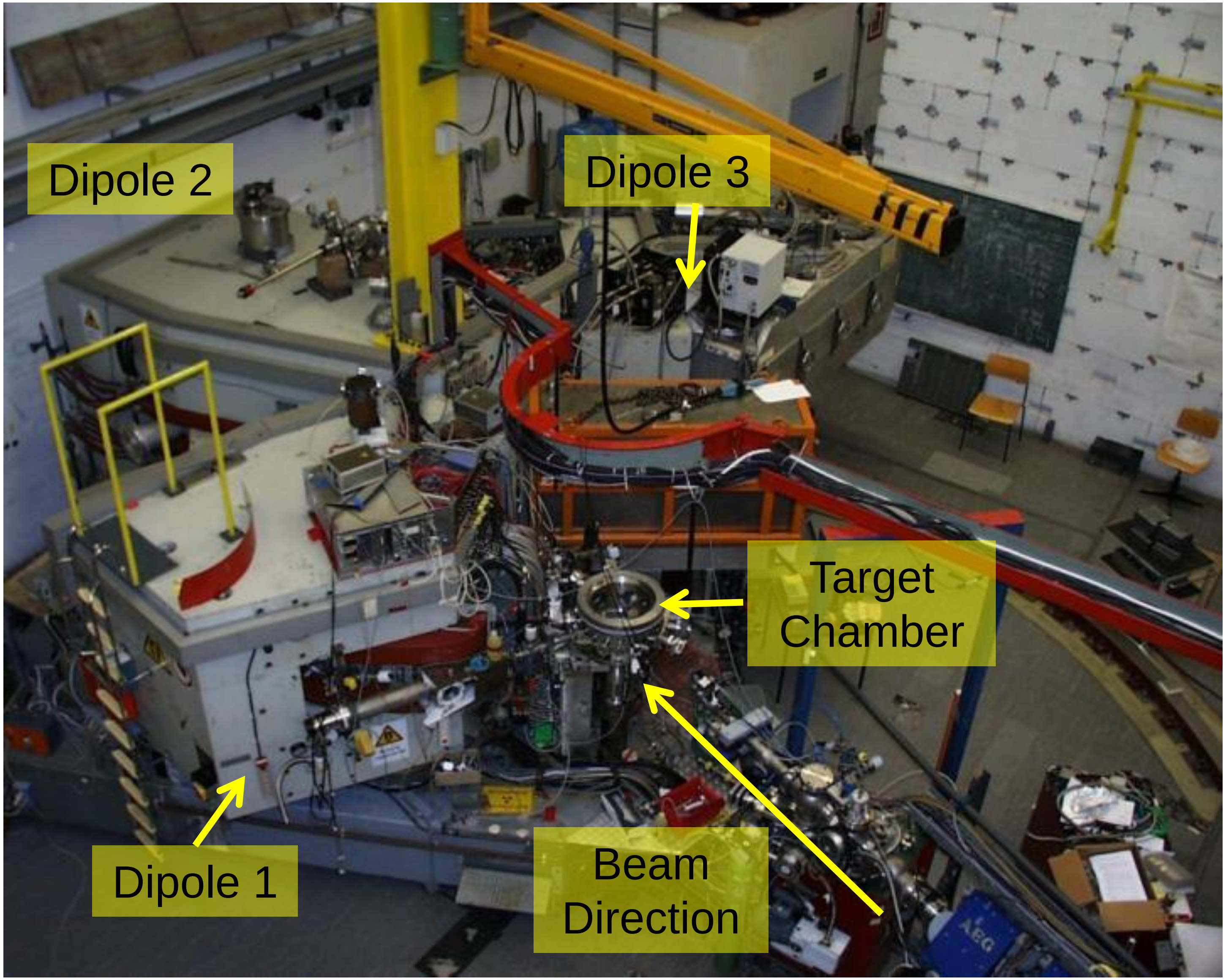
Momentum resolution:

$$\Delta p/p \approx 10^{-4}$$



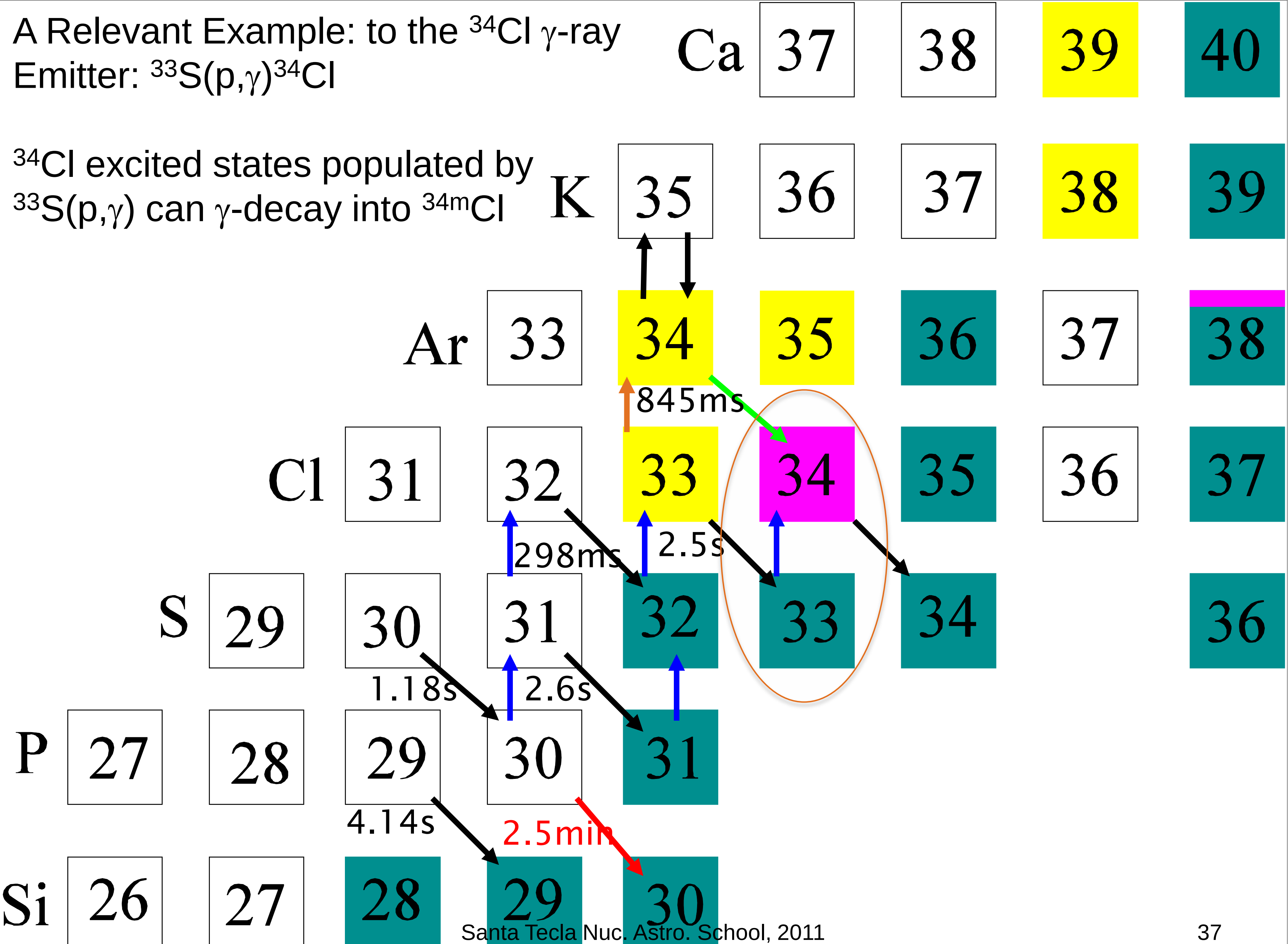
Used to search for, and study, excited states of nuclei by populating those states using one-step transfer reactions: X(^{3}He,t)Y, as an example

Position of triton along Focal Plane is a measure of the excitation energy.

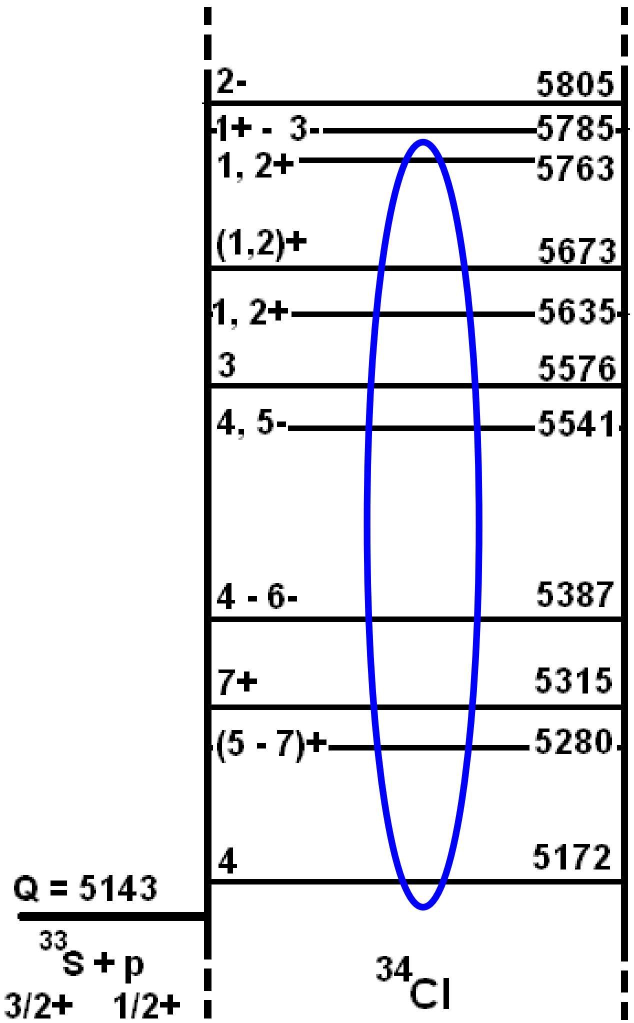

Dipole 2
Dipole 3
Target Chamber
Dipole 1
Beam Direction

A Relevant Example: to the ^{34}Cl γ-ray Emitter: ^{33}S(p,γ)^{34}Cl

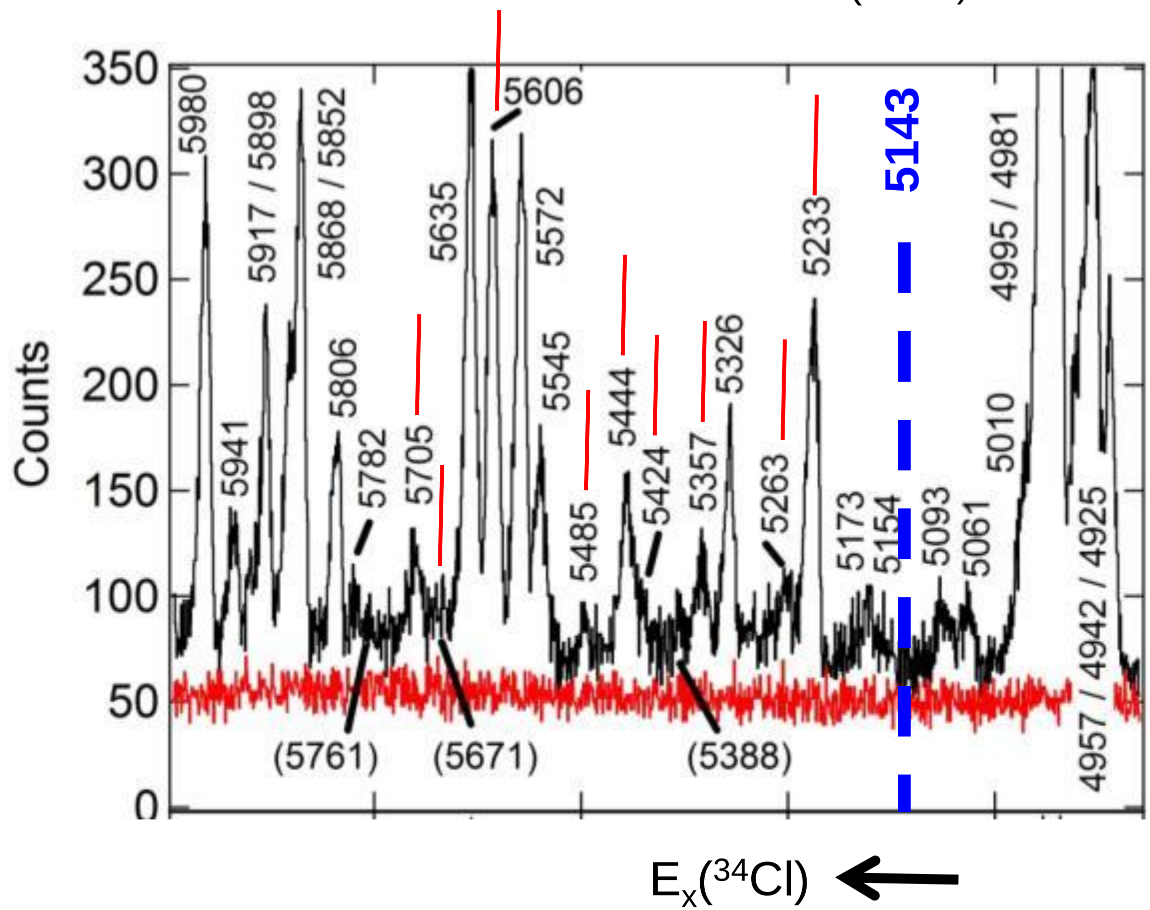
^{34}Cl excited states populated by ^{33}S(p,γ) can γ-decay into ^{34m}Cl



$^{34}S(^3He,t)^{34}Cl$, E_{He} = 25 MeV, θ = 15°



Parikh et al. PRC **80** (2010)



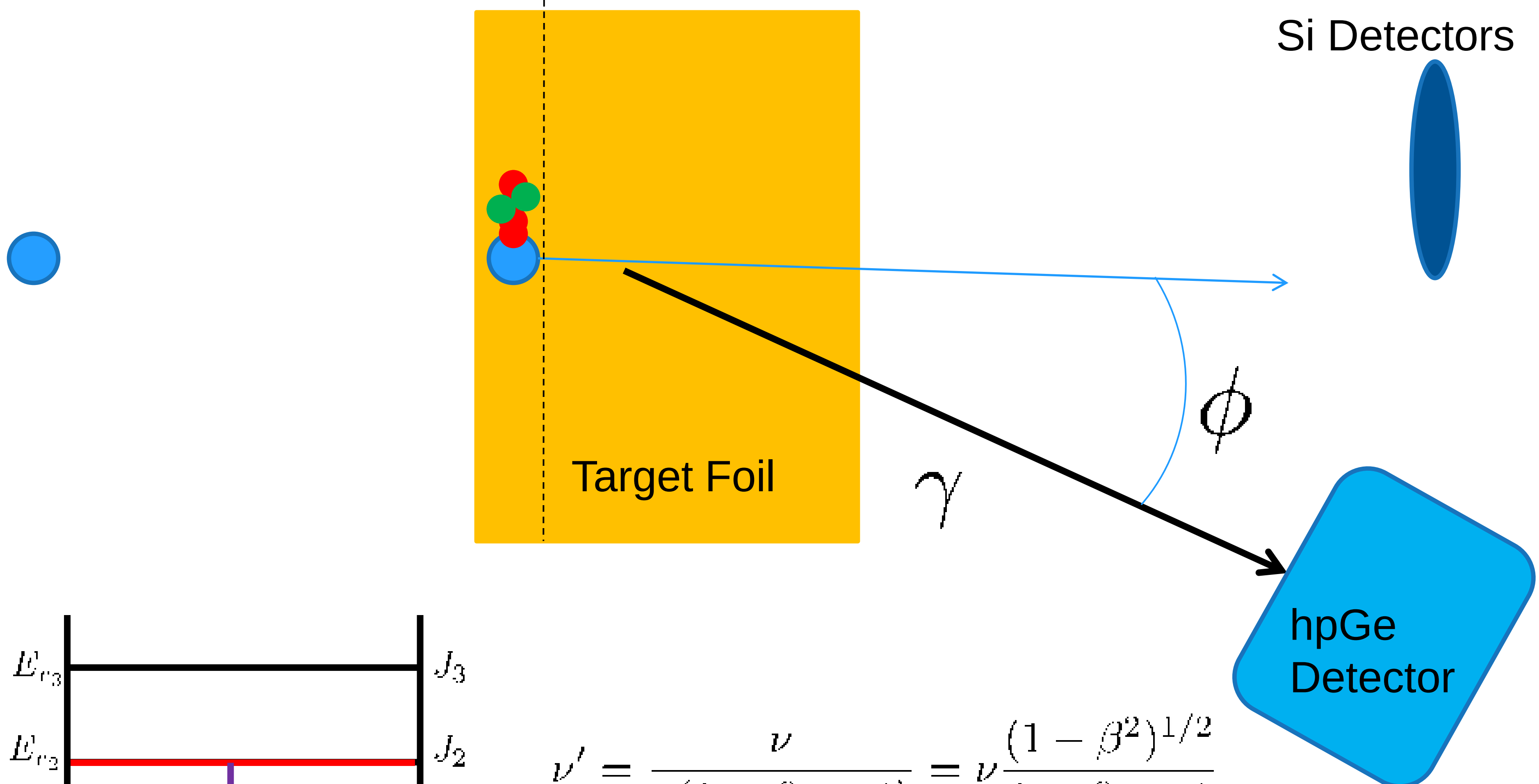
Ag$_2$S Target

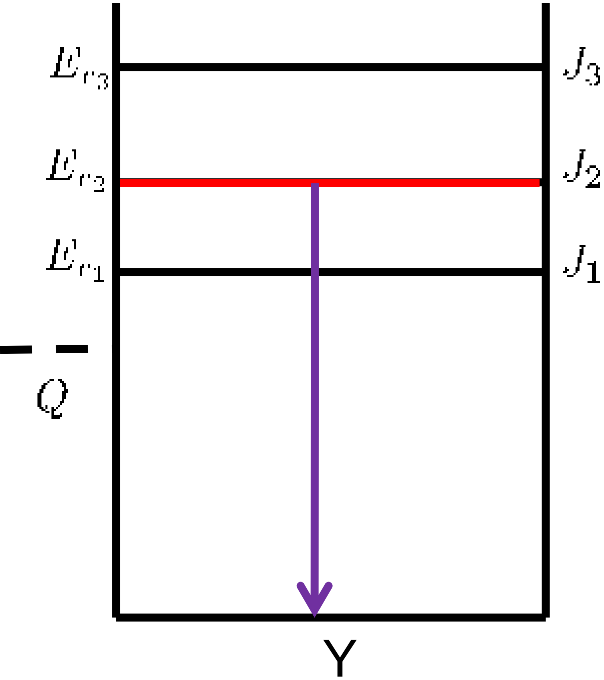
$$\omega\gamma = \frac{2J_i + 1}{(2J_p + 1)(2J_X + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma} = g(1 - B_p)B_p \frac{\hbar}{\tau}$$

$$B_p = \Gamma_p / (\Gamma_p + \Gamma_\gamma)$$

- Extracting the $\hbar/\tau$ term

DOPPLER LIFETIME STATION



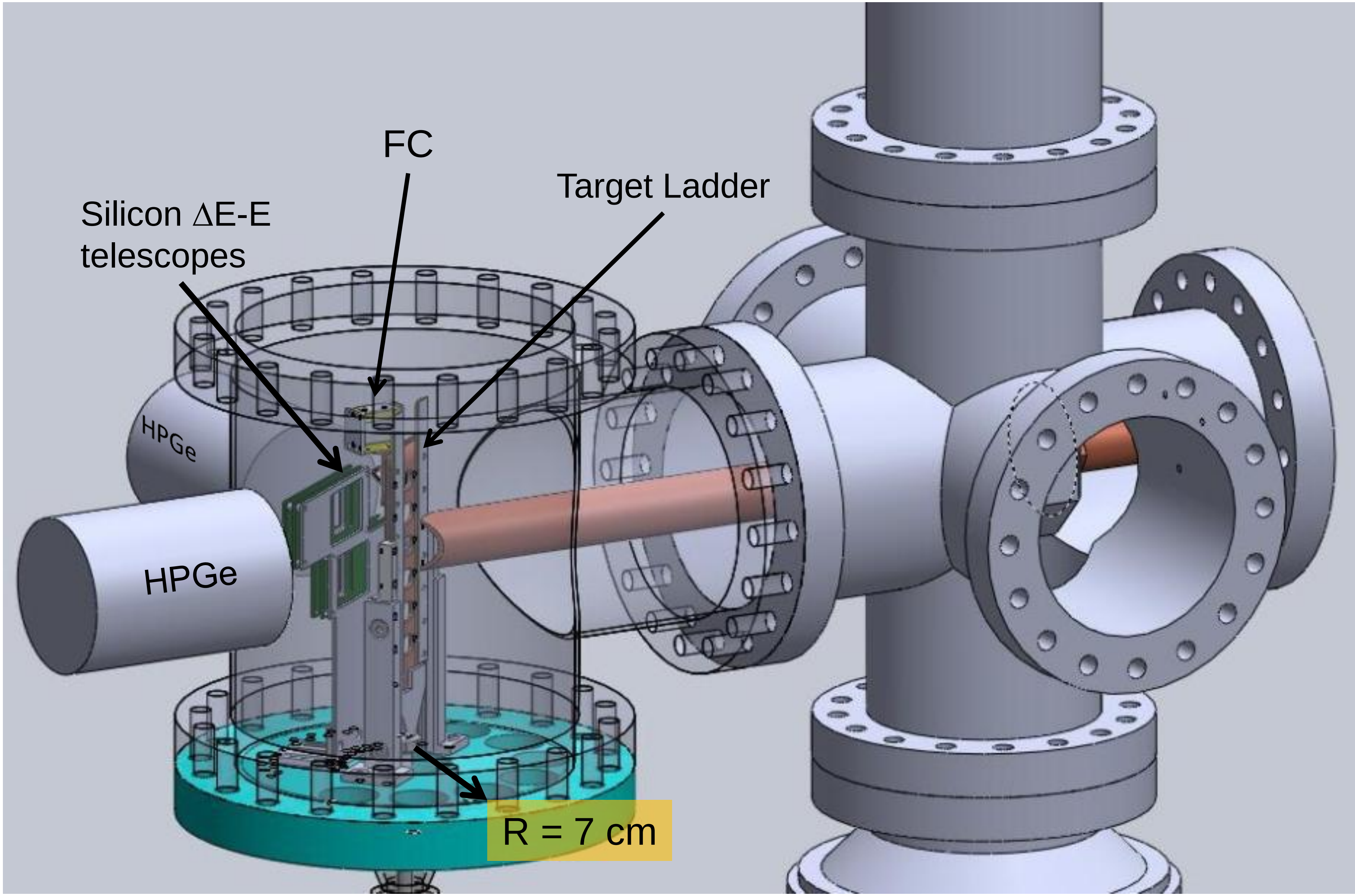


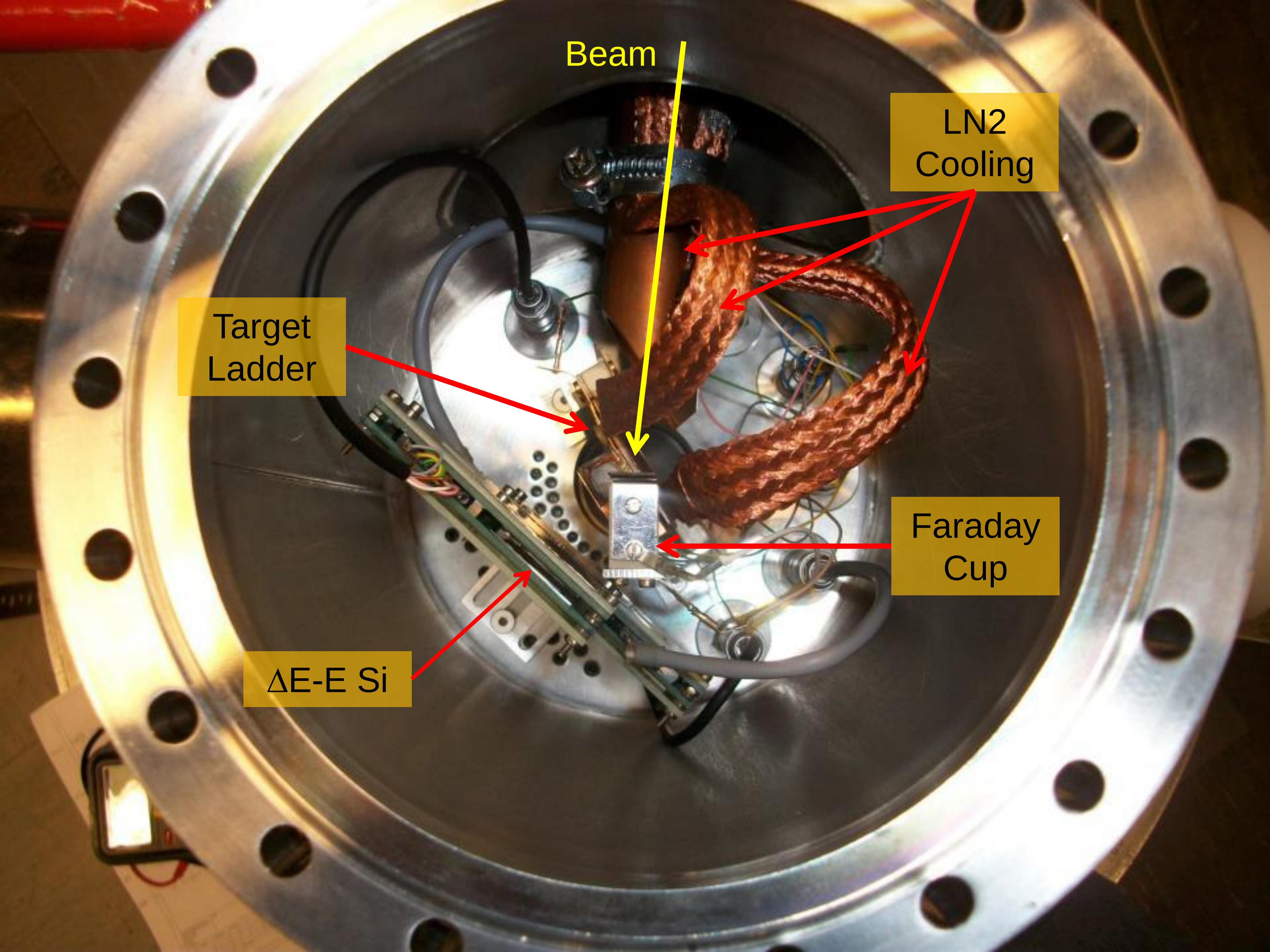
$$\nu' = \frac{\nu}{\gamma(1-\beta\cos\phi)} = \nu\frac{(1-\beta^2)^{1/2}}{1-\beta\cos\phi}$$

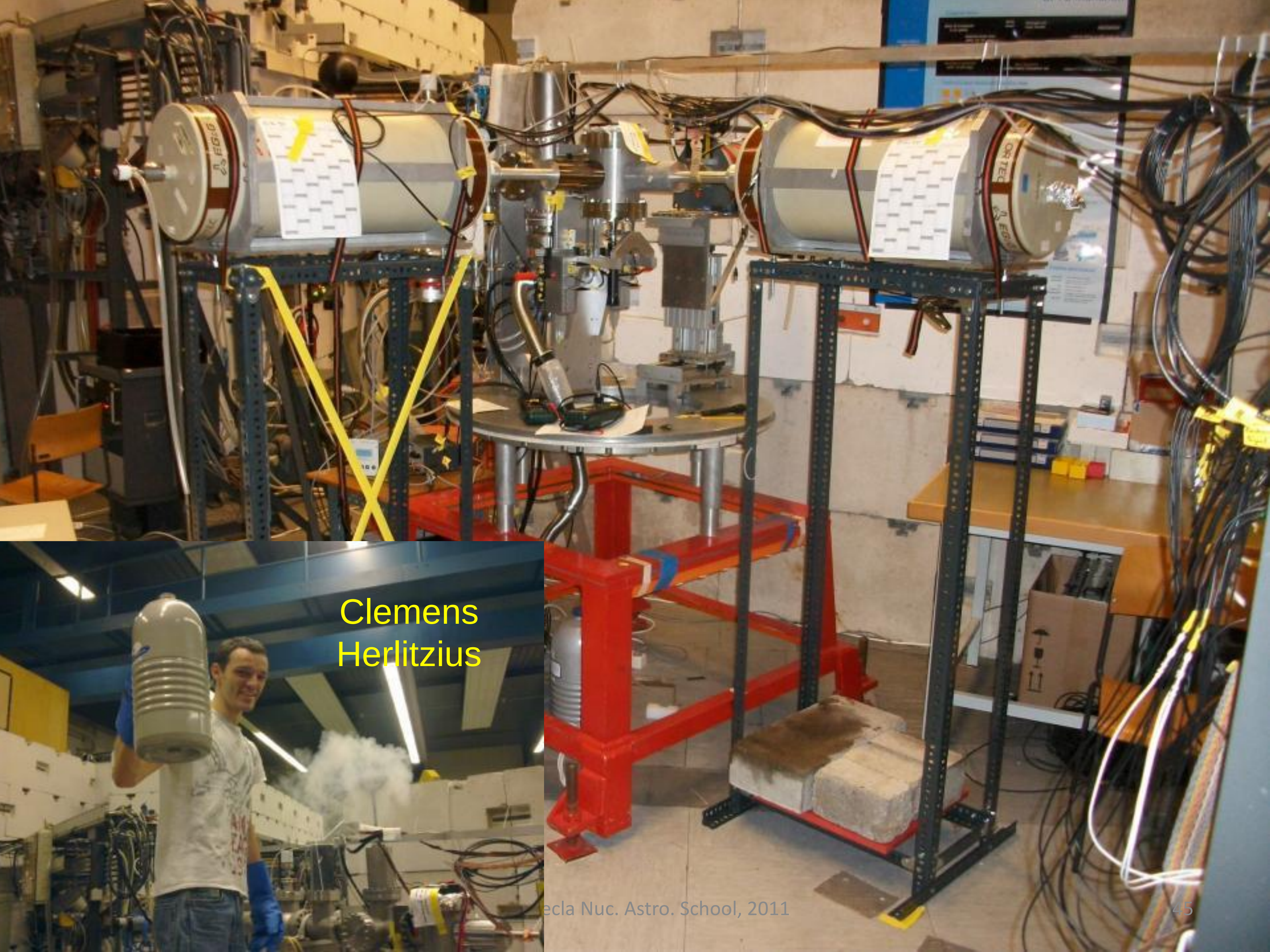
$$\Rightarrow E'_\gamma = E_\gamma \frac{(1-\beta^2)^{1/2}}{1-\beta\cos\phi}$$

$$\approx E_\gamma(1 - 1/2\beta^2 + \ldots)(1 + \beta\cos\phi + \ldots)$$

$$\approx E_\gamma(1 + \beta\cos\phi)$$

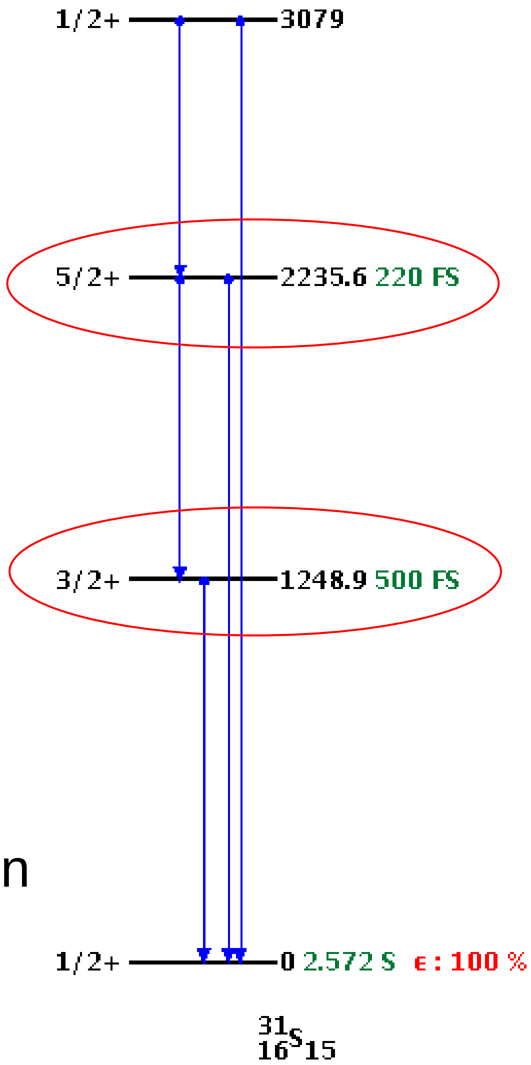

FC
Target Ladder
Silicon ΔE-E
telescopes
HPGe
HPGe
R = 7 cm


Beam
LN2 Cooling
Target Ladder
Faraday Cup
ΔE-E Si

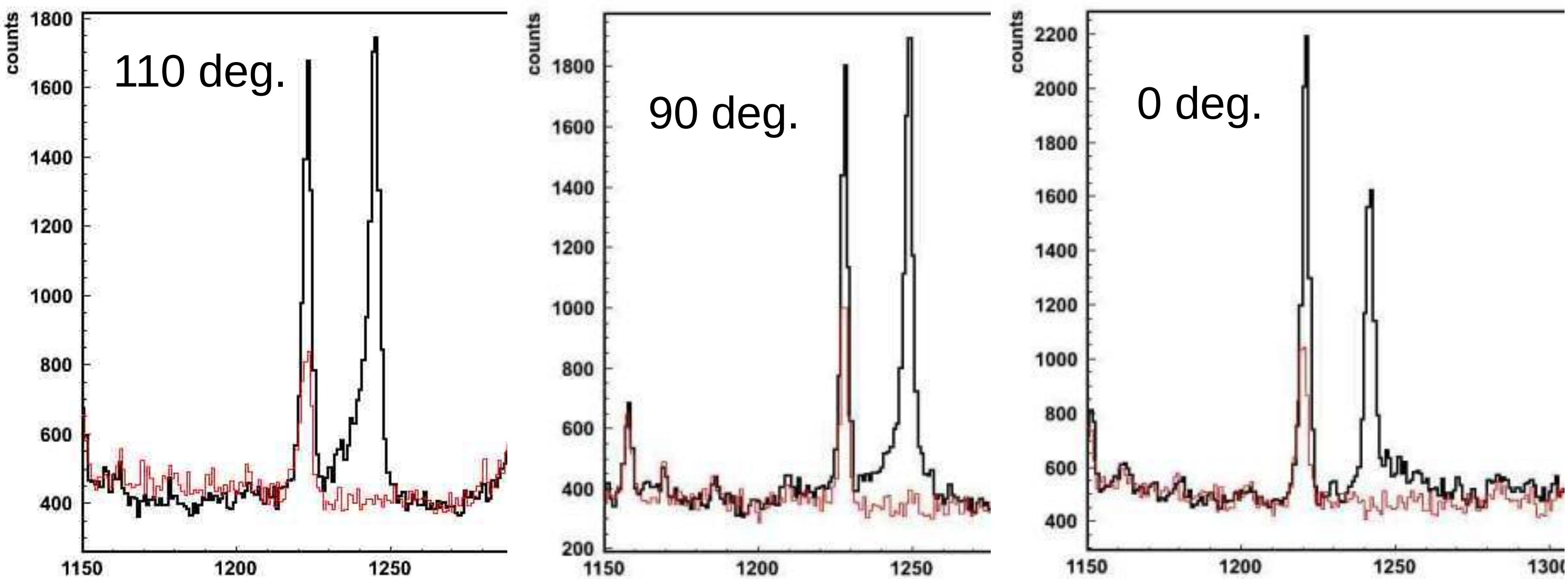

Clemens
Herlitzius

Commissioning Aug. 2011

- Chose the $^{32}S(^{3}He,\alpha)^{31}S$ reaction
  - 1st and 2nd excited states previously observed
  - Lifetimes known
  - ^{32}S beam energy: 85 MeV
- Level energy-spacing large
  - Gammas easily distinguishable
  - Alpha particles well-separated kinematically
- Target:
  - Au foil, 6 micron thick
  - 1st 0.3 micron implanted with ^{3}He at FZ Dresden
- Analysis presently underway



Preliminary Doppler Shifted Spectra



Approximately 50% of total data

Summary

- Nova reaction rates important
  - Gamma-ray yields
  - Potential for future detectability
  - Presolar grain provenance and mixing hypothesis
    - ^{33}S overproduction
    - ^{36}S content
- Methods
  - Direct, as it happens in explosion
  - Indirect: using stable-beam reactions to obtain resonance properties for rate
- TUM
  - Commissioned Doppler station

Summary Continued

- October 2011:
  - Try to get some lifetimes and/or strengths of ^{34}Cl resonances in the Gamow Window for $^{33}S(p,\gamma)^{34}Cl$