TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

^{22}Ne(p,γ)^{23}Na and the origin of ^{23}Na

Annika Lennarz
Postdoc | Division of Physical Sciences | TRIUMF

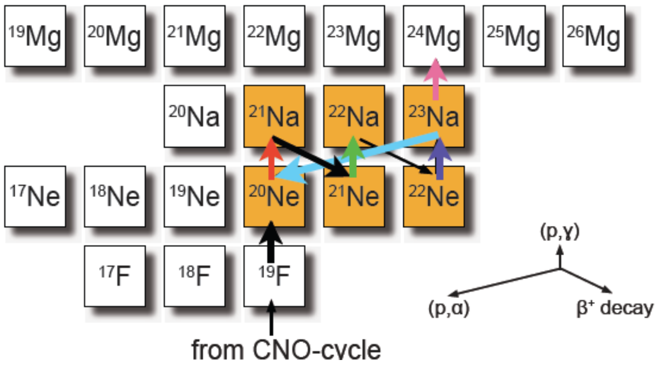
WNPPC, Banff
February 18th, 2017

^{22}Ne(p,γ)^{23}Na reaction affects ^{23}Na abundance in various stellar sites:

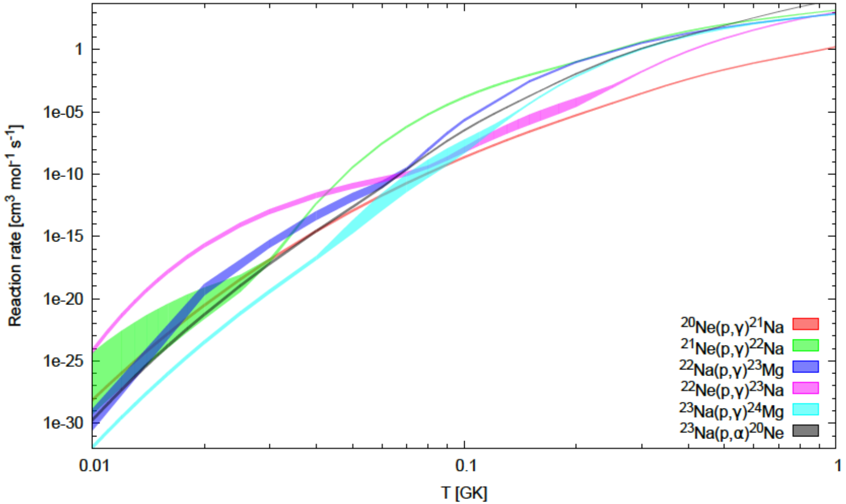
- **Hot-bottom burning** (HBB) in AGB stars (M>4$M_{\odot}$)
- Convective carbon-shell burning in **massive stars** (competes with ^{22}Ne(α,n)^{25}Mg)
- **Nova** nucleosynthesis (0.15 < T < 0.45 GK)

*Increased interest in abundance prediction since discovery of **Na-O anti-correlation** in red giant stars of globular clusters*

NeNa cycle



$^{20}Ne(p,\gamma)^{21}Na(e+\ \nu)^{21}Ne(p,\gamma)^{22}Na(e+\ \nu)$**$^{22}Ne(p,\gamma)^{23}Na$**$(p,\alpha)^{20}Ne$

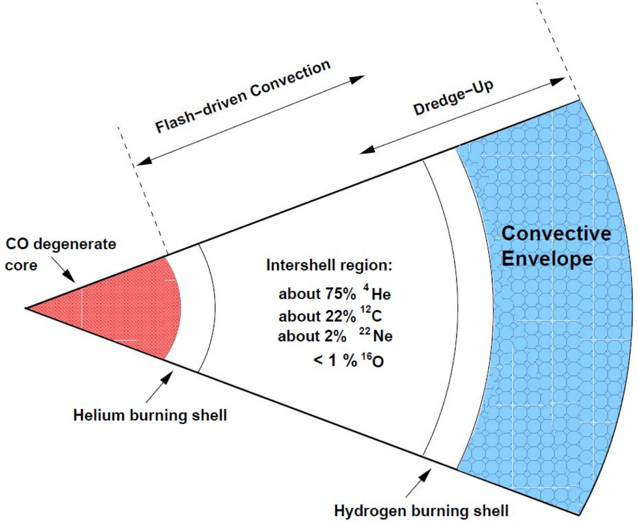


Based on Illiadis et. al. Nucl. Phys. A 841, 251 (2010)

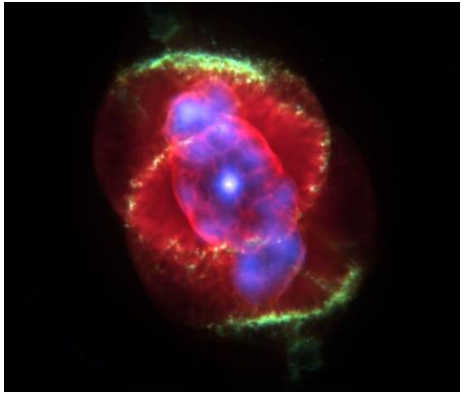
- NeNa cycle of H-burning (T>0.07 GK)
- Low contribution to energy budget
- **BUT:** Importance for stellar **nucleosynthesis**
- Affects **abundance** of elements between ^{20}Ne & ^{27}Al
- Rate of NeNa cycle determined by $^{20}Ne(p,\gamma)^{21}Na$
- Highest uncertainty in $^{22}Ne(p,\gamma)^{23}Na$

Hot bottom burning

- AGB stars ($M>4M_\odot$): **HBB** occurs at base of convective envelope
- 60 MK < T < 100 MK material is processed via **CNO, NeNa & MgAl** cycles:
  - Increase Na & Al surface abundances
  - Decrease Mg abundance
- Oxygen depletion via ON cycle
- **Mixing** with surface through convection
- **Ejection** in strong stellar winds

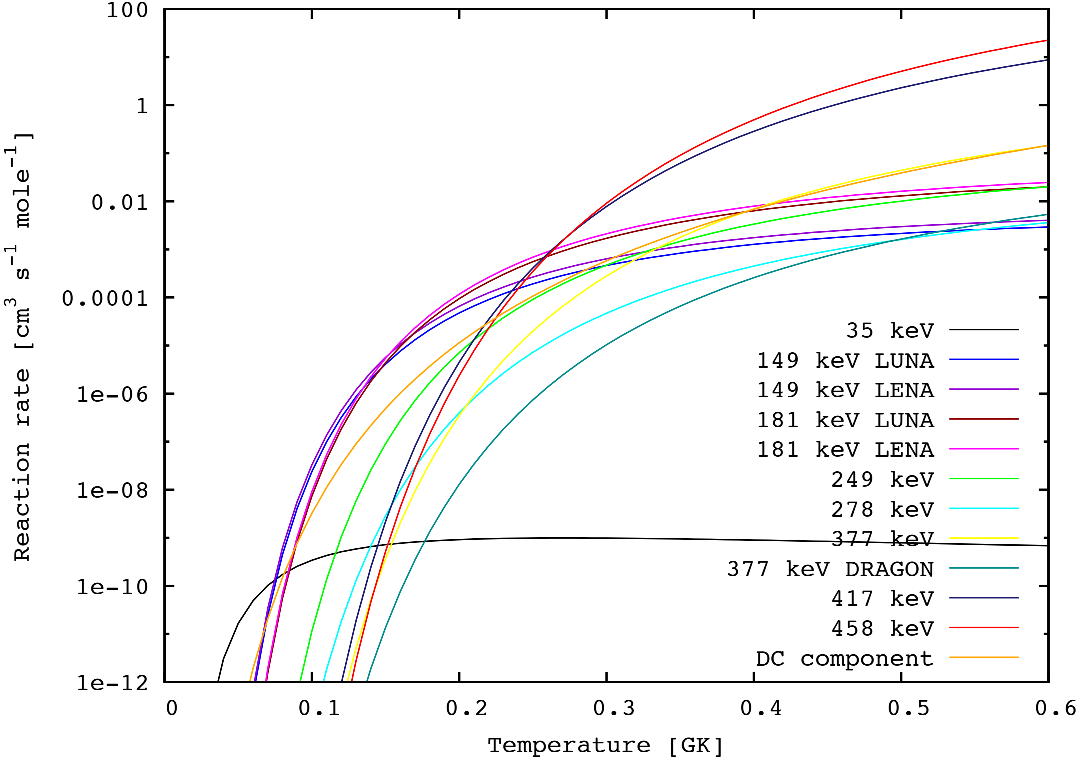


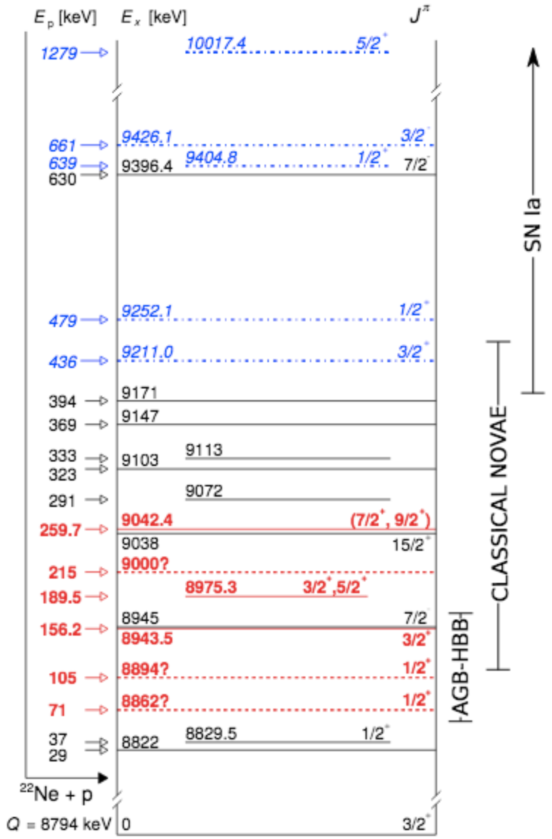
→ ***Anomalies** in O, Na, Mg, Al **abundances** in GC stars as a result of "pollution" from AGB stars undergoing HBB?*



→ ***Abundance patterns** → **study nucleosynthesis pathes in all cycles!***

^{22}**Ne(p,γ)**^{23}**Na** *is considered reaction with* ***highest uncertainty*** *on reaction rate in NeNa cycle*





$^{22}Ne(p,\gamma)^{23}Na$ reaction rate

- Uncertainties in $\omega\gamma$ for (until recently unobserved) **low-energy resonances**
- → **Discrepancies** between compilations by up to a factor of 1000 (T~0.08GK)
- → Abundance **variations** for nuclides between ^{20}Ne & ^{27}Al by up to 2 orders of magnitude!

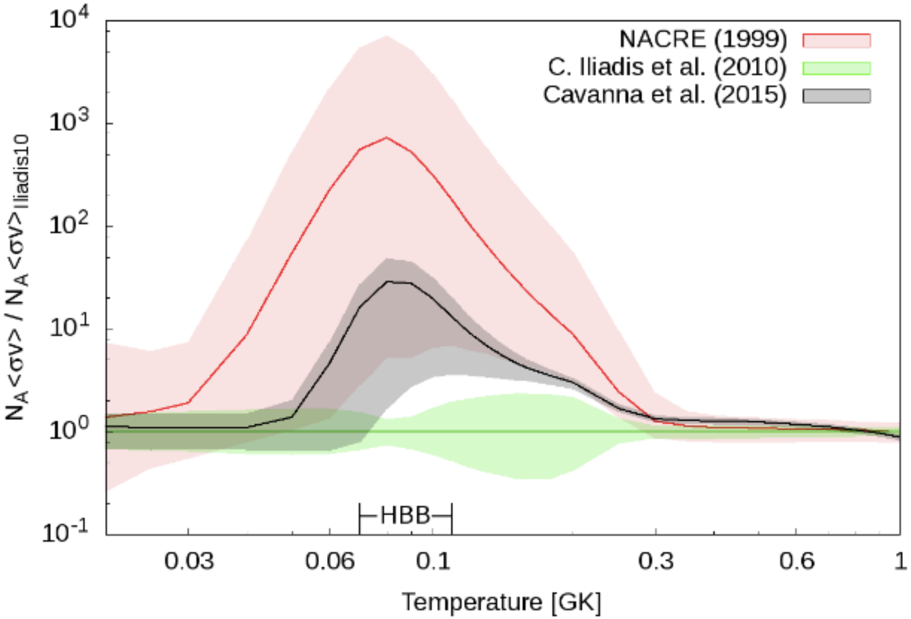
***First data** on several low-energy resonances published by LUNA group*

$\omega\gamma(E_{cm}$=149 keV) = **($1.48(10) \times 10^{-7}$)** eV

$\omega\gamma(E_{cm}$=181 keV) = **($1.87(6) \times 10^{-6}$)** eV

$\omega\gamma(E_{cm}$=249 keV) = **($6.89(16) \times 10^{-6}$)** eV

(Cavanna et. al. PRL 115, 252501 (2015))



Slemer et. al. arXiv:1611.07742v1 (2016)

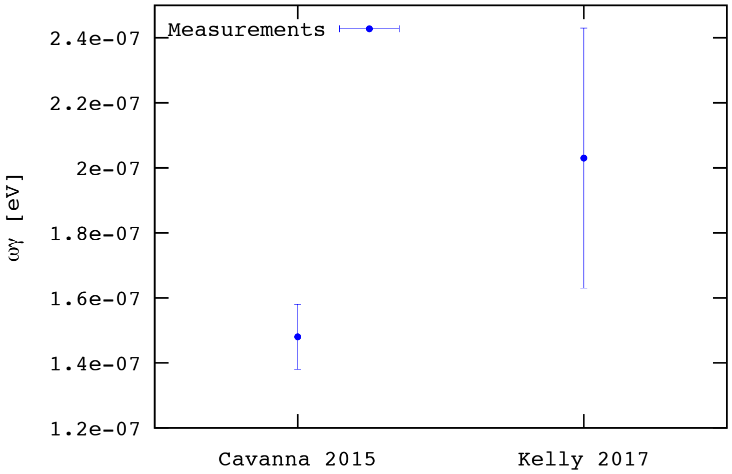
→ *Confirmation with different method needed!*

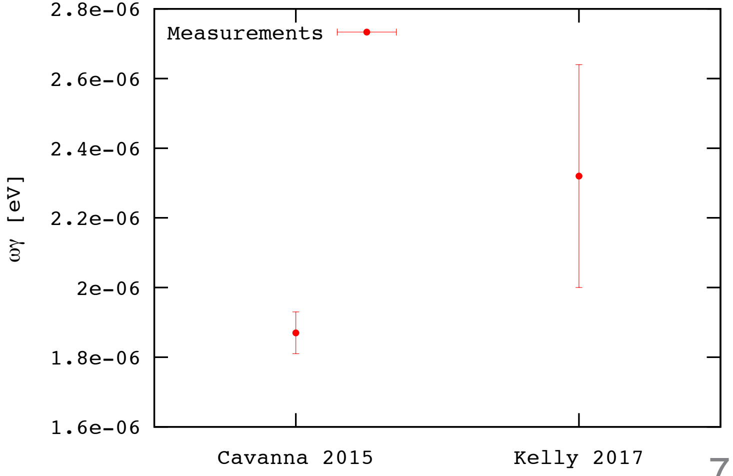
Previous measurements of low-energy resonances

Recent measurement of low-energy resonances by Kelly et. al. (PRC **95**, 015806 (2017)) at Laboratory for Experimental Nuclear Astrophysics (LENA)

- $\omega\gamma(E_{cm}$=178 keV) = (**2.32(32) x 10^{-6}**) eV
- $\omega\gamma(E_{cm}$=151 keV) = (**2.03(40) x 10^{-7}**) eV

} **Not in agreement** with LUNA result!



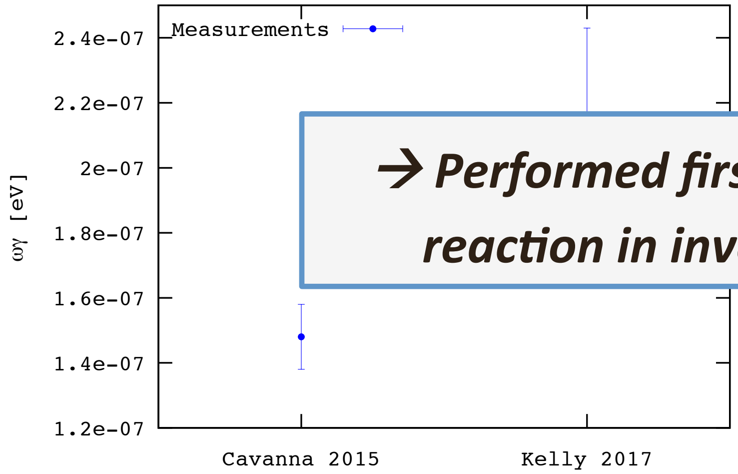


Previous measurements of low-energy resonances

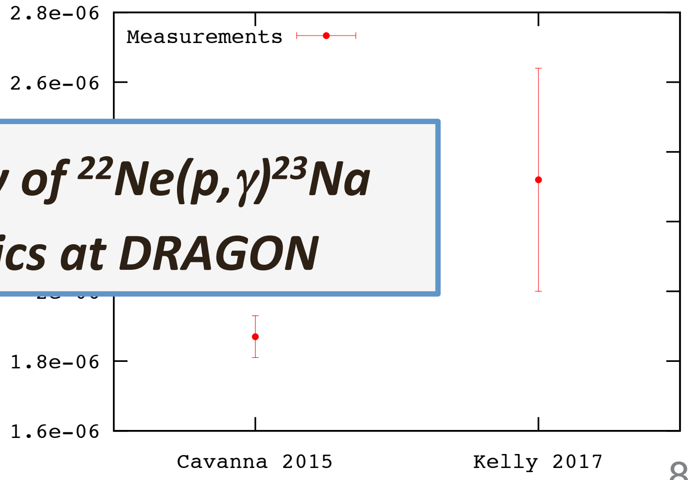
Recent measurement of low-energy resonances by Kelly et. al. (PRC **95**, 015806 (2017)) at Laboratory for Experimental Nuclear Astrophysics (LENA)

- $\omega\gamma(E_{cm}=178\text{ keV}) = (\mathbf{2.32(32) \times 10^{-6}})\text{ eV}$
- $\omega\gamma(E_{cm}=151\text{ keV}) = (\mathbf{2.03(40) \times 10^{-7}})\text{ eV}$

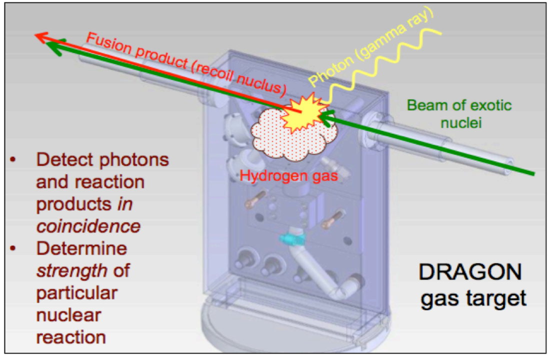
} **Not in agreement** with LUNA result!

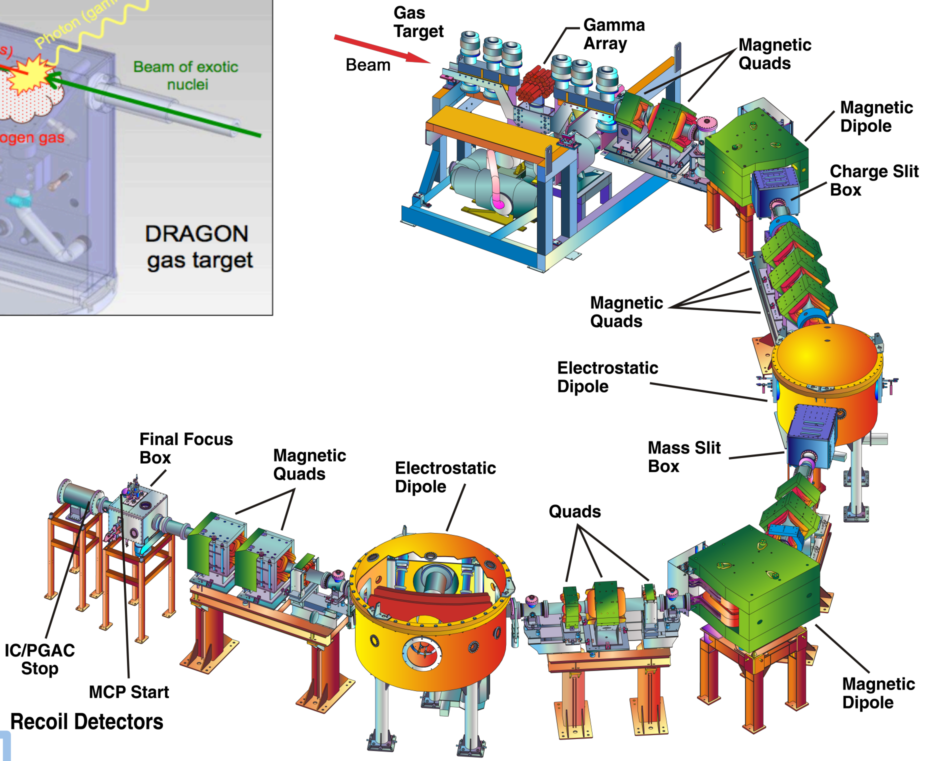


→ ***Performed first direct study of $^{22}Ne(p,\gamma)^{23}Na$ reaction in inverse kinematics at DRAGON***



1. Windowless gas target
2. BGO γ-detection array
3. MEME mass separator
4. Recoil detection system





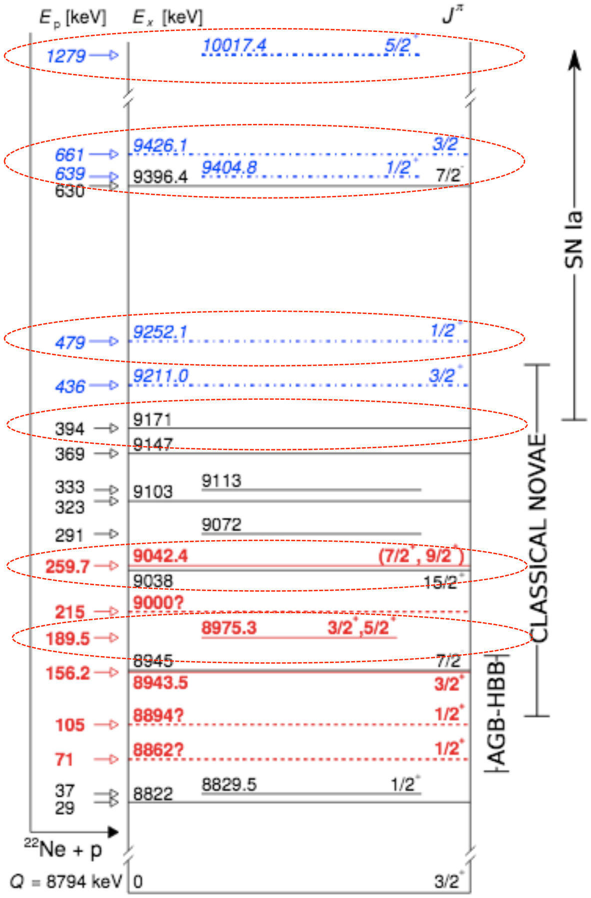
$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

#reactions per incident ion

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

$^{22}Ne(p,\gamma)^{23}Na$ at DRAGON

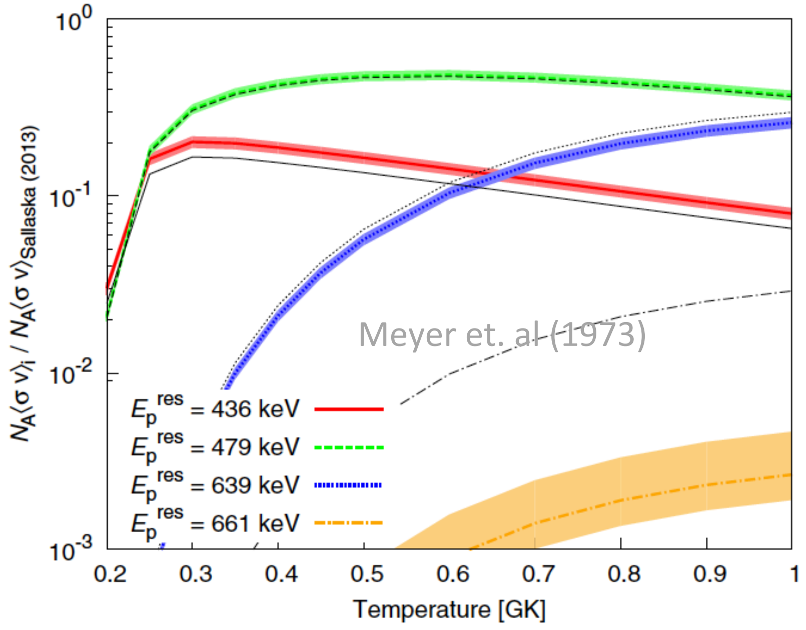
- **High** beam **intensities** (MCIS, **$2x10^{12}$ pps** at DRAGON)
- **First direct** measurement in **inverse kinematics**
  - E_{cm}=1222 keV
  - **E_{cm}=632 keV**
  - E_{cm}=612 keV
  - **E_{cm}=458 keV**
  - E_{cm}=377 keV
  - E_{cm}=322 keV
  - **E_{cm}=249 keV**
  - **E_{cm}=181 keV**
  - E_{cm}=149 keV (**lowest energy** received at DRAGON)
  - Direct capture measurements E_{cm}=200 keV to 400 keV



E_{cm}= 632 keV – Previous measurements

- **$\omega\gamma$=0.032$_{-0.009}^{+0.024}$ eV** (Depalo et. al. PRC 92, 045807 (2015))
- **$\omega\gamma$=0.35(1) eV** (Meyer & Smit, NPA 205, 177 (1973))

Order of magnitude deviation!



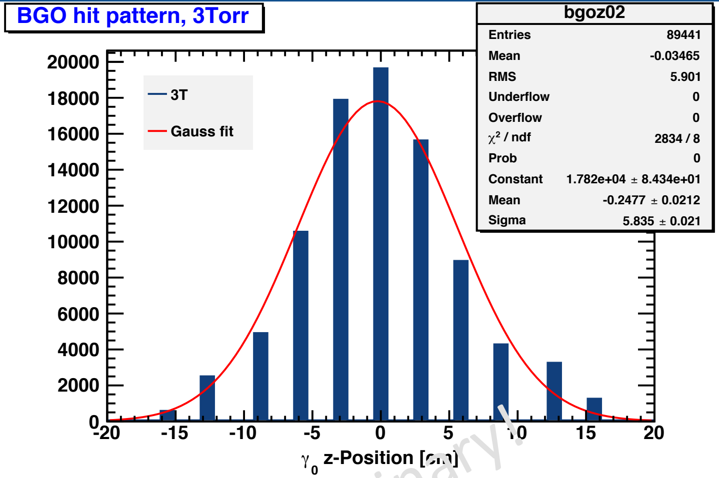
Depalo et. al. PRC 92, 045807 (2015)

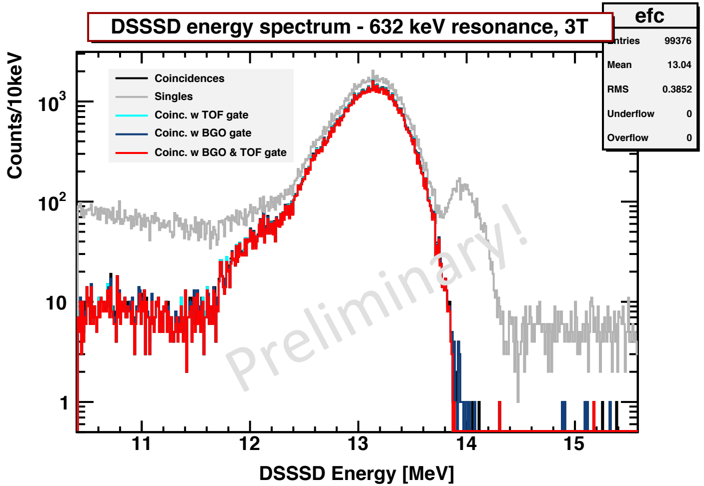
→ Contribution to reaction rate <1%

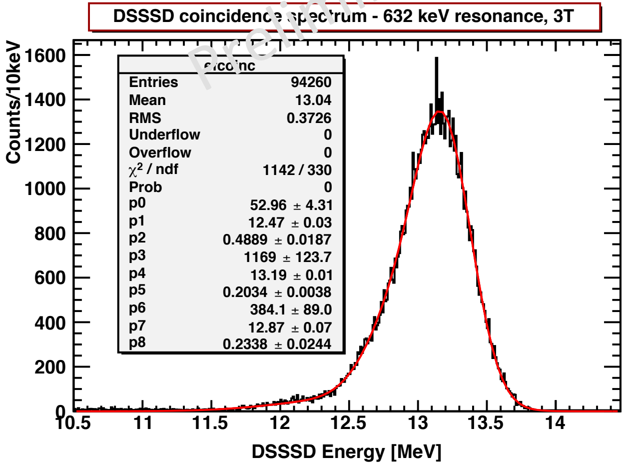
- Is this resonance completely **negligible?**
- Worth confirming with different direct method

E_{cm}=632 keV – DRAGON measurement

- Yield measurements at **3** different **pressures**
- Contribution from strong 612 keV resonance excluded (γ-ray spectrum & pressure variation)
- Resonance centered in target at 3 Torr
- High statistics

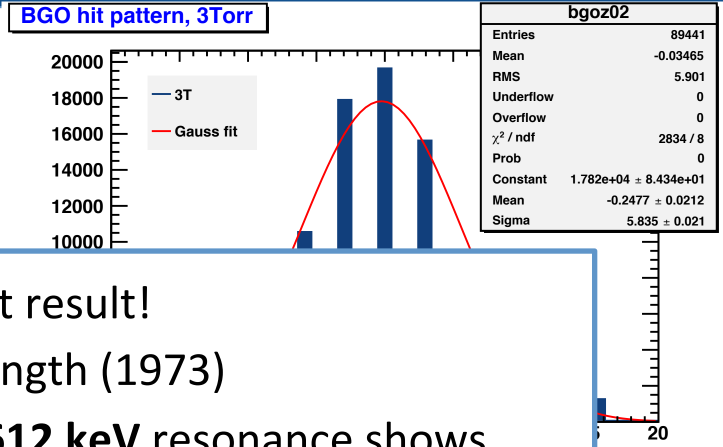




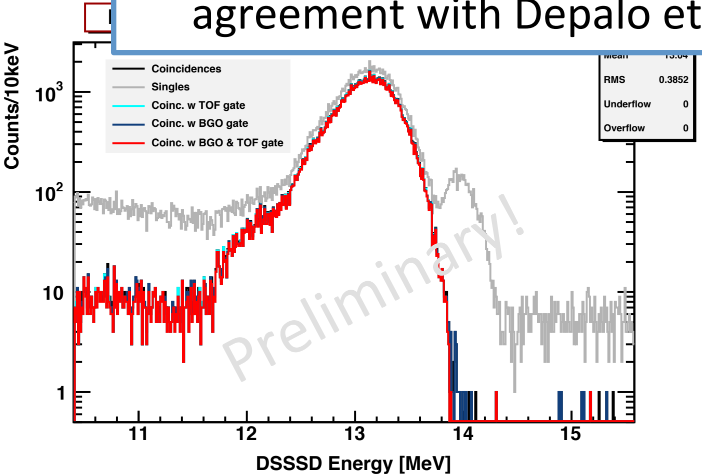


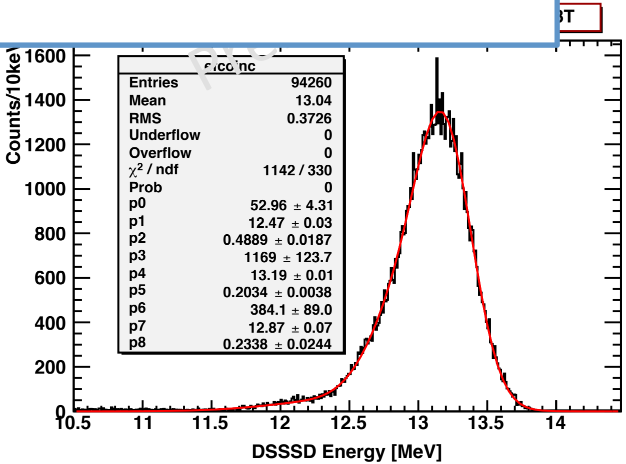
E_{cm}=632 keV – DRAGON measurement

- Yield measurements at **3** different **pressures**
- Contribution from strong 612 keV resonance excluded (γ-ray spectrum & pressure variation)
- Resonance
- High statisti



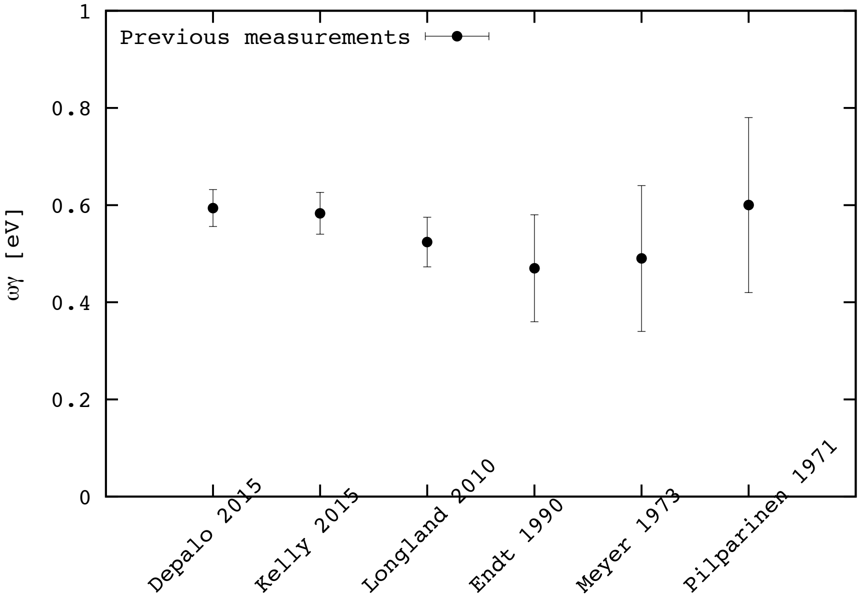
- **DRAGON:** **<u>ωγ deviates</u>** from recent result!
- **<u>Even stronger</u>** than previous lit. strength (1973)
- **Reference** measurement of strong **612 keV** resonance shows agreement with Depalo et. al. (2015)





E_{cm}=458 keV – Previous measurements

6 previous measurements (2 in 2015)



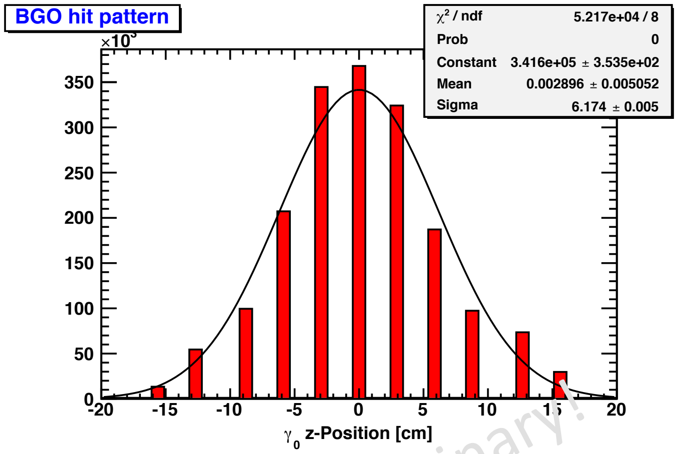
Relevance:

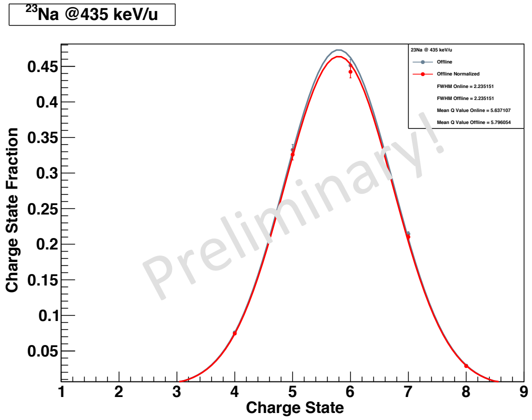
- **Significant contribution** to ^{22}Ne(p,γ)^{23}Na reaction rate
- Standard ***reference resonance***
- ^{22}Ne-Ta target stoichiometries (^{22}Ne(α,n)^{25}Mg & ^{22}Ne(α,γ)^{26}Mg)

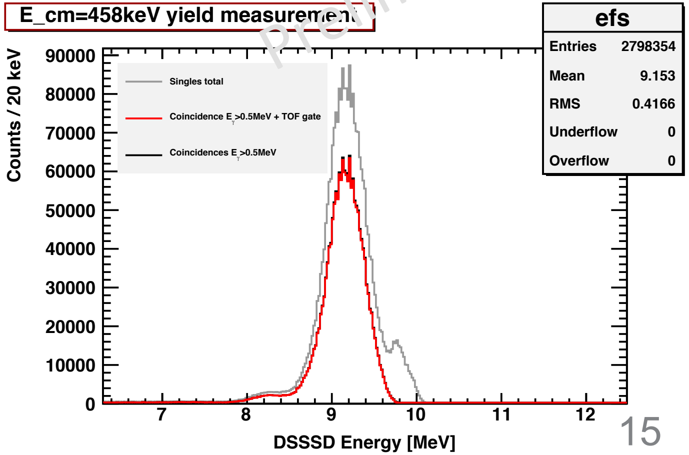
- Recent ωγ**=0.583(43) eV** (Kelly et. al. PRC 92, 035805 (2015) at van de Graaff acc. (LENA))
- Recent ωγ**=0.594(38) eV** (Depalo et. al. PRC 92, 045807 (2015) at HZDR, relative to 1.222 MeV resonance

E_{cm}= 458 keV – DRAGON measurement

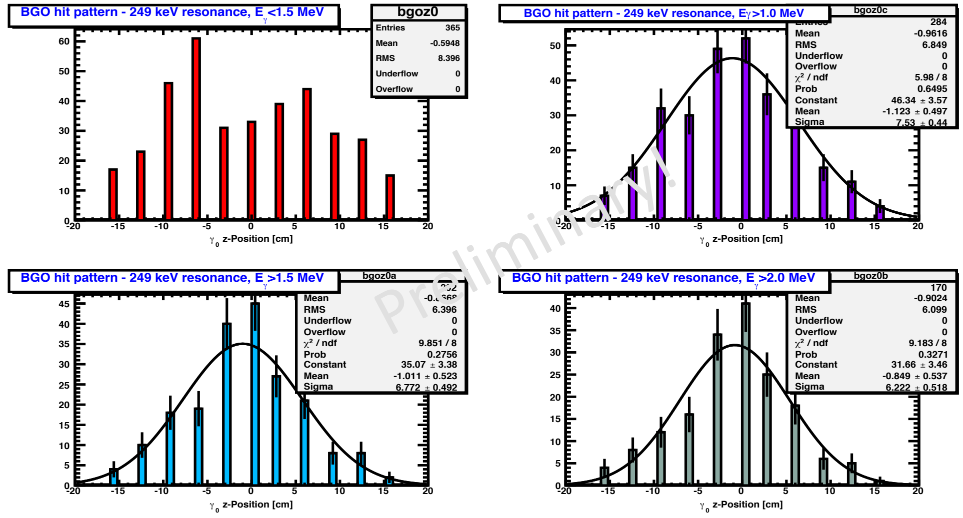
- ~7 hrs of data → High statistics
- High beam suppression with $q_{max}=6^+$ ($q_{beam}=4^+$)
- Measured charge-state distribution and stopping power
- Analysis (**preliminary!**) → $\omega\gamma$ is **lower** than reported recently & closer to Longland et. al. value!





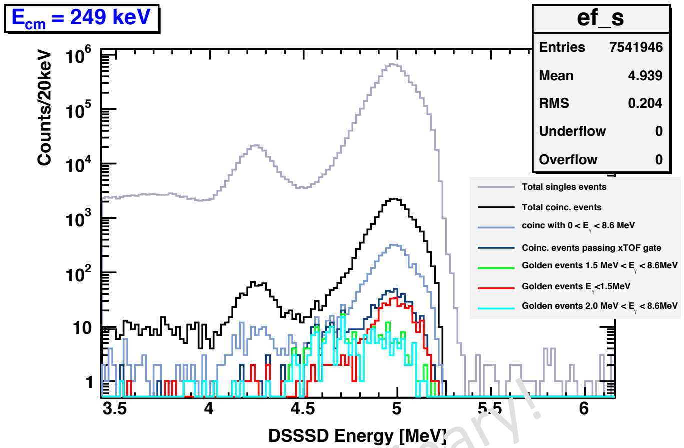


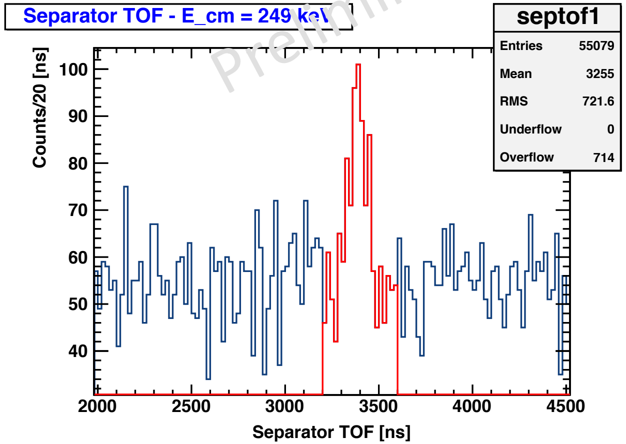
Low-energy resonance E_{cm}=249 keV



Final level [keV]	Ig [%]
440	45.4(0.9)
2076	18.7(0.6)
2704	10.9(0.5)
3848	13.3(0.5)
3914	1.8(0.4)
5927	3.6(0.2)
6042	2.6(0.2)
6355	1.5(0.2)
6820	2.2(0.2)

- BGO gates + simulation to reduce background rate
- Analysis (preliminary) shows agreement with latest value from Depalo et. al.

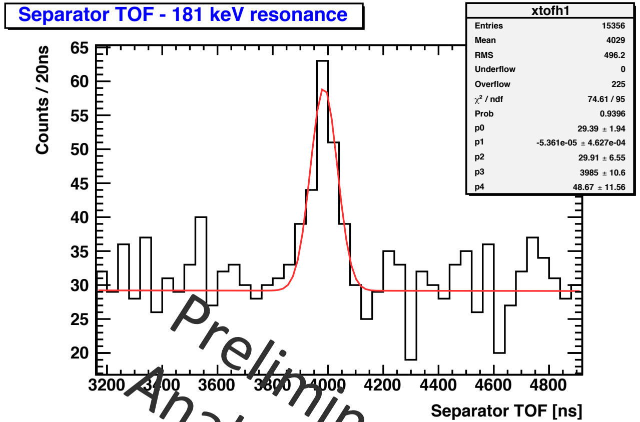


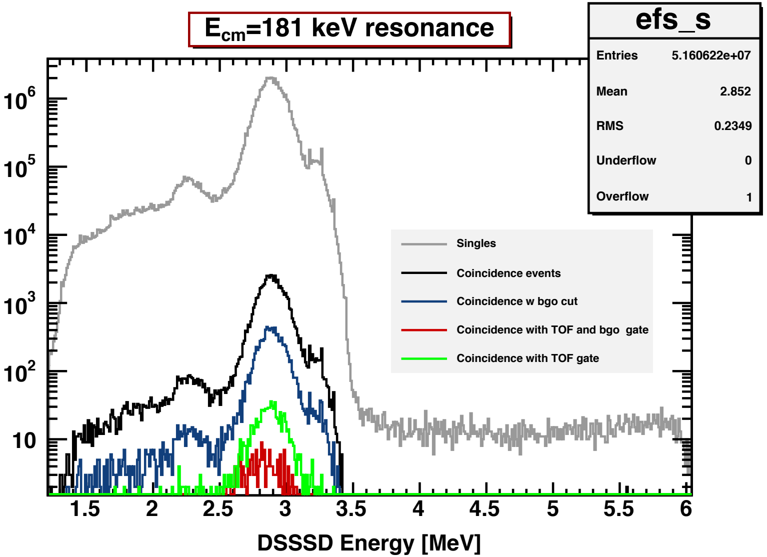


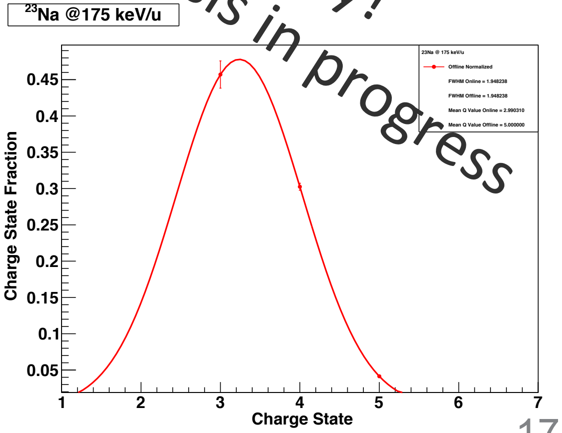
E_{cm}=181 keV

Challenging measurement…

- Low resonance strength between 1.8×10^{-6} eV and 2.3×10^{-6} eV
- **Second lowest energy** ever received at DRAGON
- Recoil cone angle at **limit of geometric acceptance**
- **Increased beam emittance** → Higher **background** level







Summary

- ***Direct*** study of **^{22}Ne(*p*,*γ*)^{23}Na capture rate** with DRAGON in ***inverse kinematics***
- Relevant for nucleosynthesis of nuclides from ^{20}Ne to ^{27}Al
- DRAGON collected data for **9 on-resonance** measurements + DC measurements

Preliminary analysis:

- Deviation for **632 keV** ωγ from HZDR result **BUT** agreement for 612 keV res.
- **458 keV** ωγ lower than 2015 results (HZDR & LENA)
- **249 keV** resonance strengths in agreement with previous result
- Analysis of **181 keV** low-energy resonance (ωγ possibly lower) and DC contribution in progress

It stays interesting!

TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Many thanks to the DRAGON collaboration!

TRIUMF: Alberta | British Columbia | Calgary | Carleton | Guelph | Manitoba | McGill | McMaster | Montréal | Northern British Columbia | Queen's | Regina | Saint Mary's | Simon Fraser | Toronto | Victoria | Western | Winnipeg | York

TRIUMF

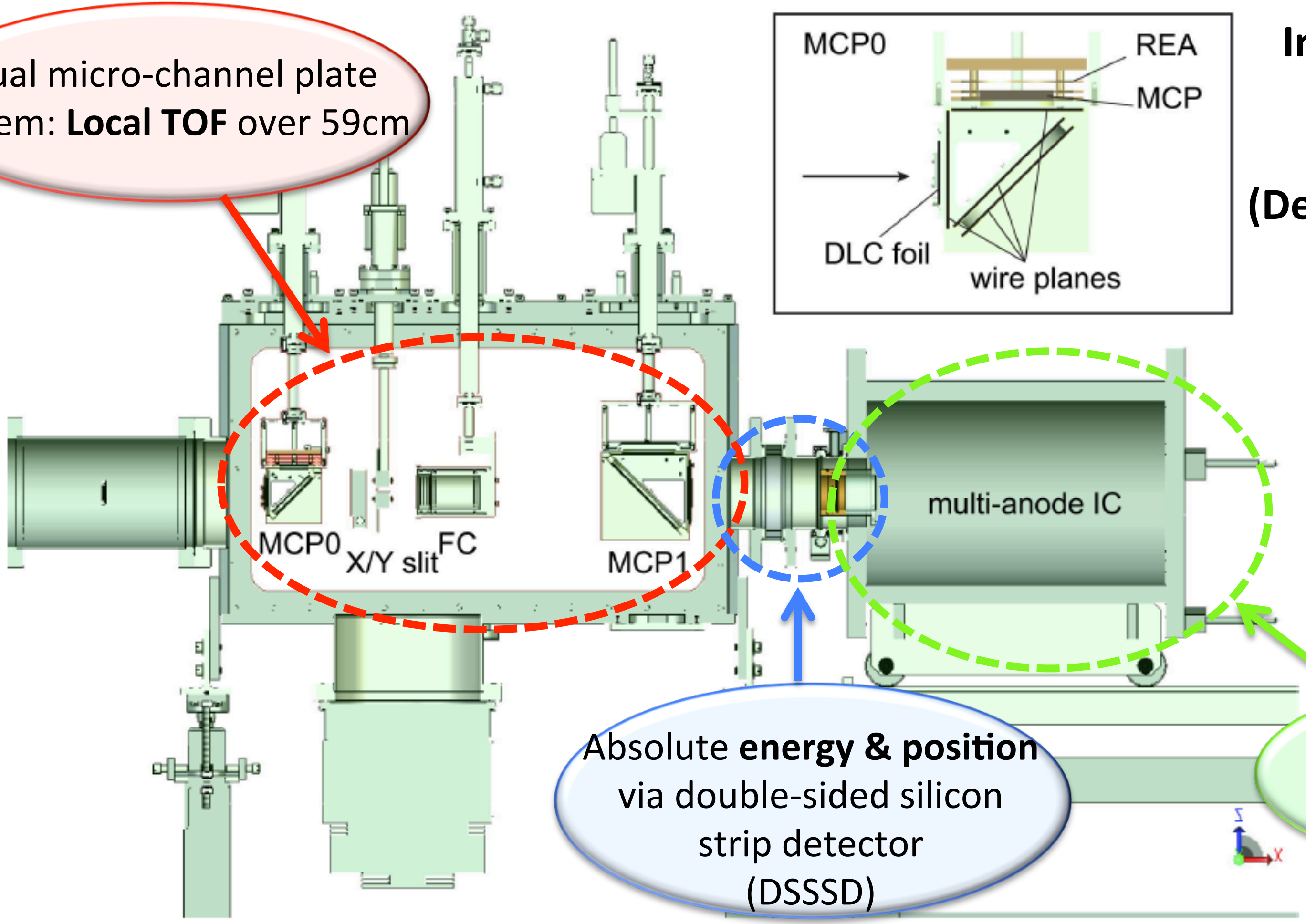
Canada’s national laboratory
for particle and nuclear physics
and accelerator-based science

Thank you!
Merci!

TRIUMF: Alberta | British Columbia | Calgary | Carleton | Guelph | Manitoba | McGill | McMaster | Montréal | Northern British Columbia | Queen’s | Regina | Saint Mary’s | Simon Fraser | Toronto | Victoria | Western | Winnipeg | York

Follow us at TRIUMFLab

Particle detection – end detectors



Interchangeable end detectors
IC or DSSSD
(Depending on reaction)

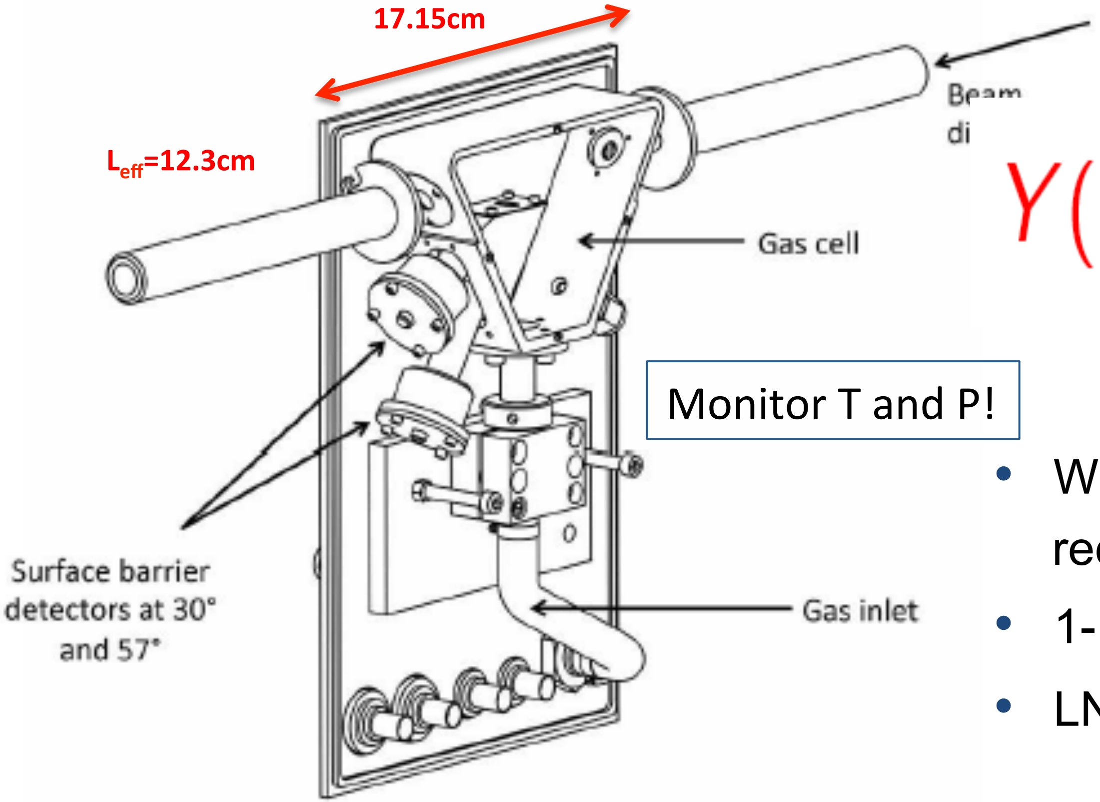
- Particle ID
- Local TOF
- ΔE/E, Total E

ΔE-E in ionization chamber for **Z-identification**

DRAGON Objectives:

- Study energy range relevant to AGB stars and novae for temperatures between 0.1 GK and 0.4 GK
- Direct measurement of **E_{cm}= 149, keV, 181 keV, 249 keV** resonances
- Re-measure “well-known” reference resonances (E_{cm}=458, 612, 632, 1222 keV)
- Provide more stringent limits on cross sections between 200 and 400 keV (also **Direct capture** contribution)

DRAGON gas target

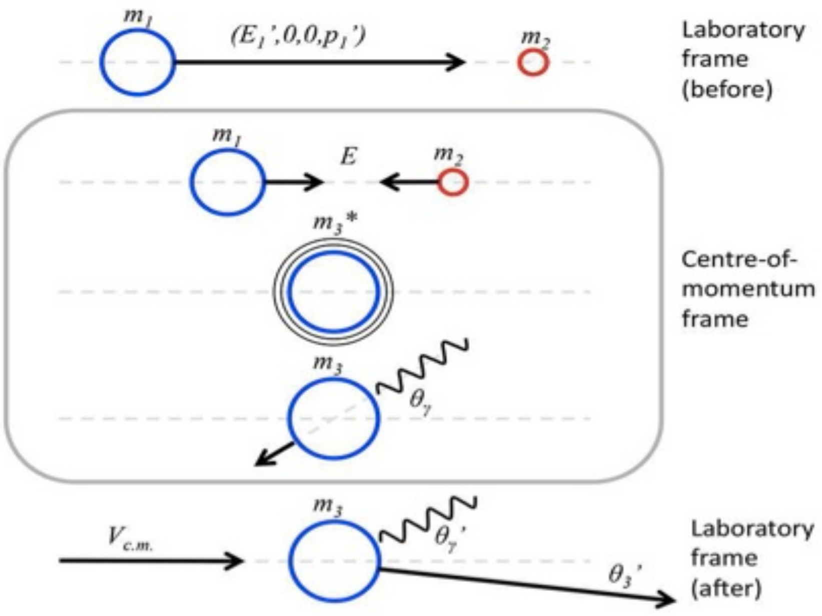


Monitor T and P!

$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

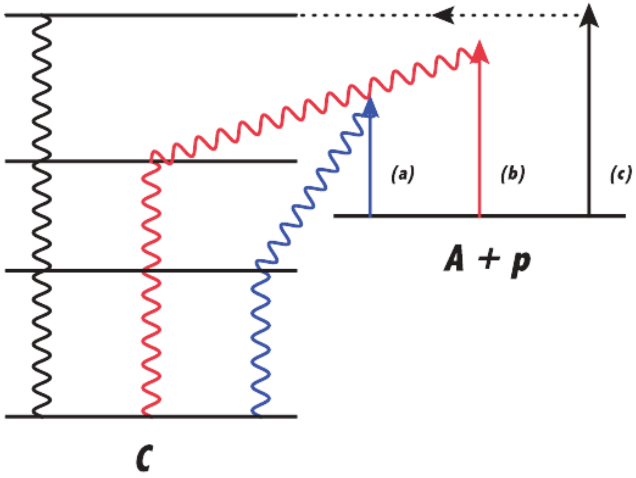
- Windowless, differentially pumped, recirculating **gas target** (H_2 or He)
- 1-10mbar (pumping constraints)
- LN_2 cooled zeolite cleaning trap

Radiative capture in inverse kinematics



Important consideration:
If ratio m_{beam}/m_{target} is large, recoil energy can only be relatively small amount lower than beam energy!

- (p,γ) and (α,γ) reactions
- Mainly resonant capture:
  A + b = C + γ
- σ in pb or μb range



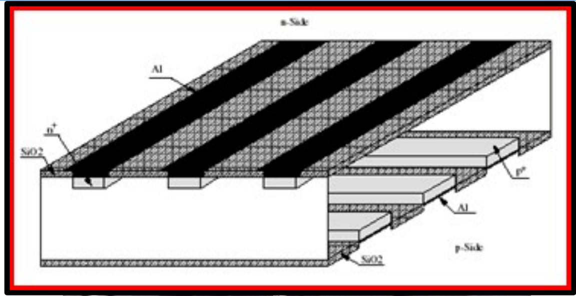
Figures from C. Ruiz et. al., Eur. Phys. A 50, 99 (2014)

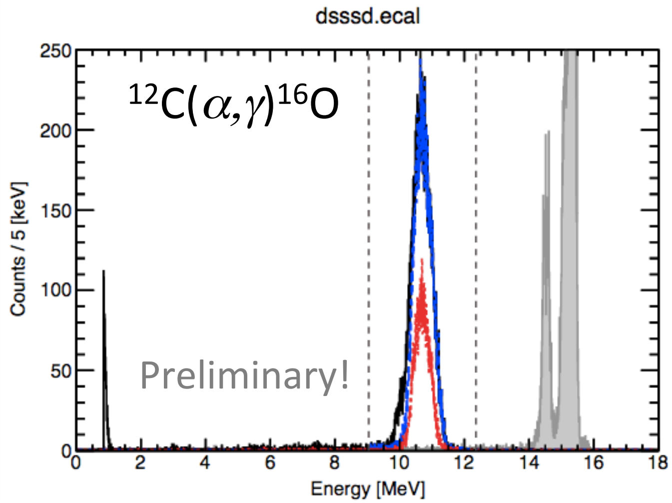
Particle detection - DSSSD

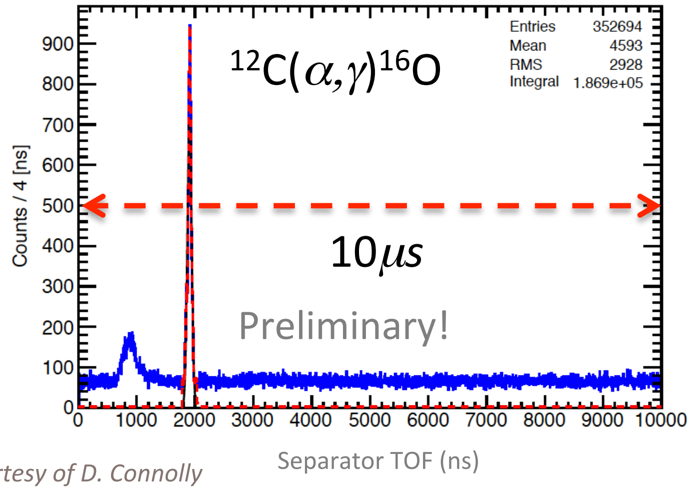
- Good energy resolution (charged particle detection)
- Timing (10ns) resolution superior to IC
- Combine with fast signal (prompt γ-detector)

  → **Precise TOF measurements**
- **BUT:** Sensitive to radiation damage!

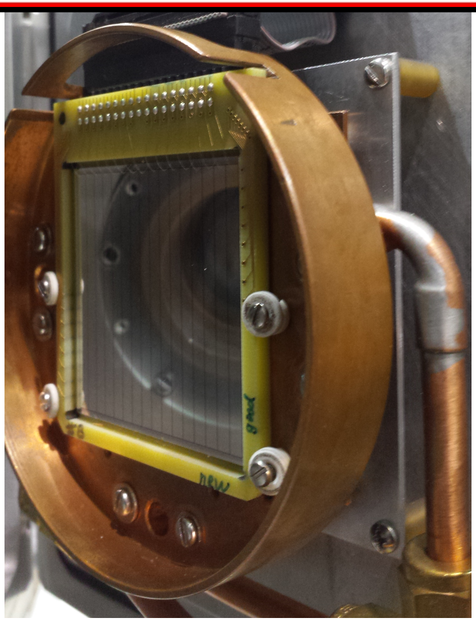
2D position resolution



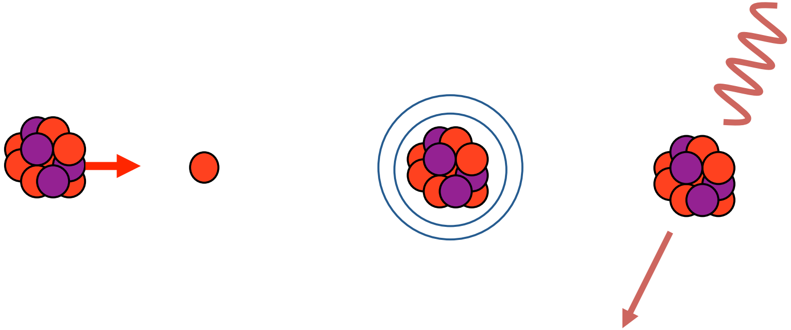


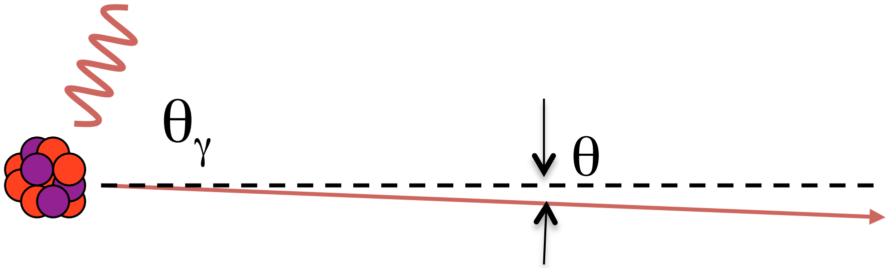


Figures courtesy of D. Connolly



Defines range of reactions that can be measured!





- **Maximum** possible **recoil angle** when E_γ is maximized for $E_\gamma = Q+E_{c.m.}$
- AND emission perpendicular to incident beam direction **($\theta_3=\pi/2$)**
- **Nominal acceptance** (w.r.f to zero):

  21 mrad & +/- 4% in E

Non-relativistic limit:

$$\tan\theta'_{3,\max} \cong \frac{Q+E_{c.m.}}{\sqrt{2\frac{m_1}{m_2}(m_1+m_2)E_{c.m.}}}$$

$$\frac{d\theta'_3}{dE}=0;\ E_{cm}=Q$$

Momentum spread:

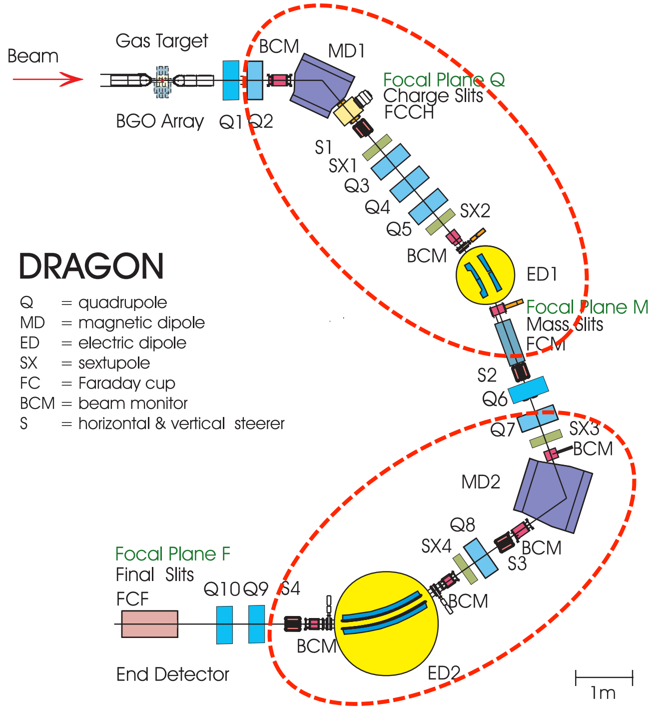
$$\frac{\Delta p'_3}{p'_3} \cong \frac{E_{\gamma,\max}}{p'_1} \cong \theta'_{3,\max}$$

Needs to accept momenta with →

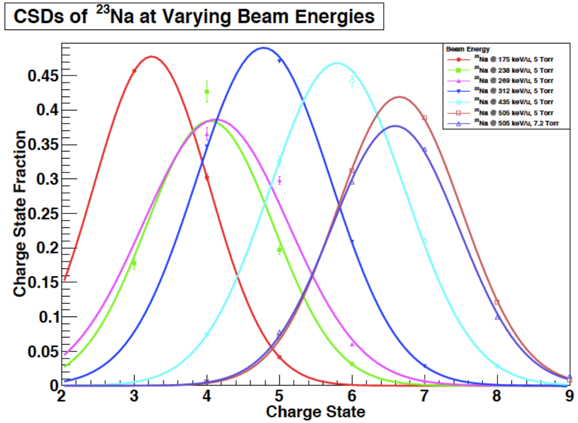
$$\Delta p'_3\left(1\pm\frac{\Delta p'_3}{p'_3}\right)$$

DRAGON – charge selection

- 21m length (target to focal plane)
- Ion optical configuration: **M-E-M-E design**



$$F = \frac{dp}{dt} = q(\varepsilon + \upsilon \times B)$$



Charge selection

- Beam & recoils emerge in **range of charge states**
- **Initial charge selection** prevents ions in non-selected q from striking smooth electrodes at glancing angles
- Spacial separation in focal plane

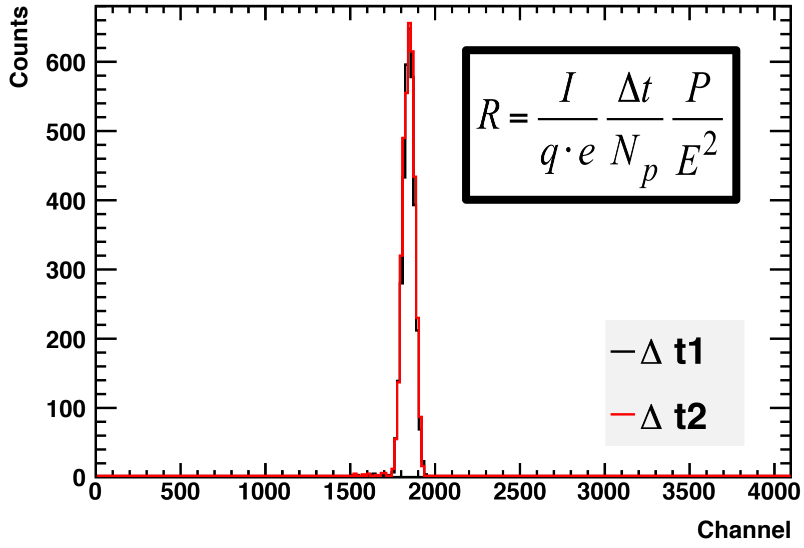
$$\Delta\rho / \rho \approx \Delta q / q$$

	MD1	MD2
ρ	1.00 m	0.813m
ϕ	50°	75°

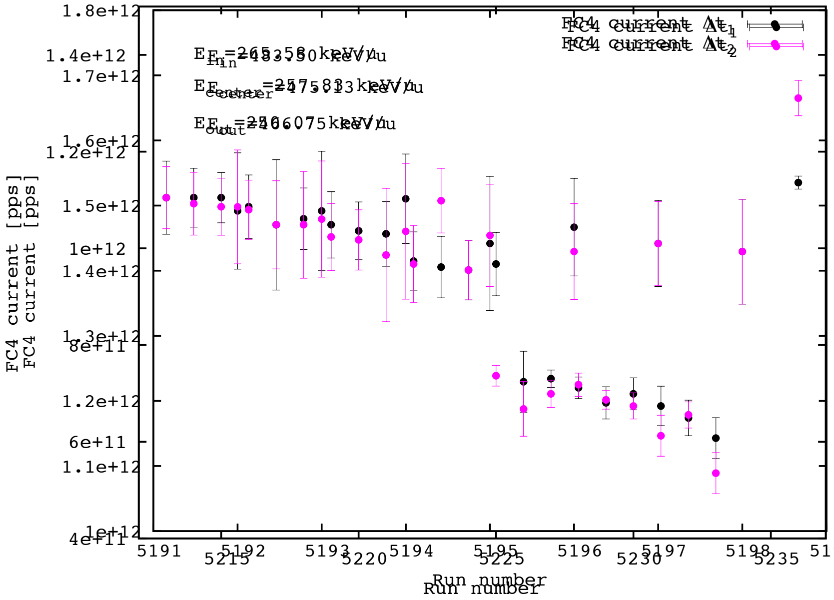
All measurements of cross sections or resonance strengths require knowledge of the number of particles incident on the target!

Options:

① Elastic scattering of beam ions on target (surface barrier detectors) + cup readings



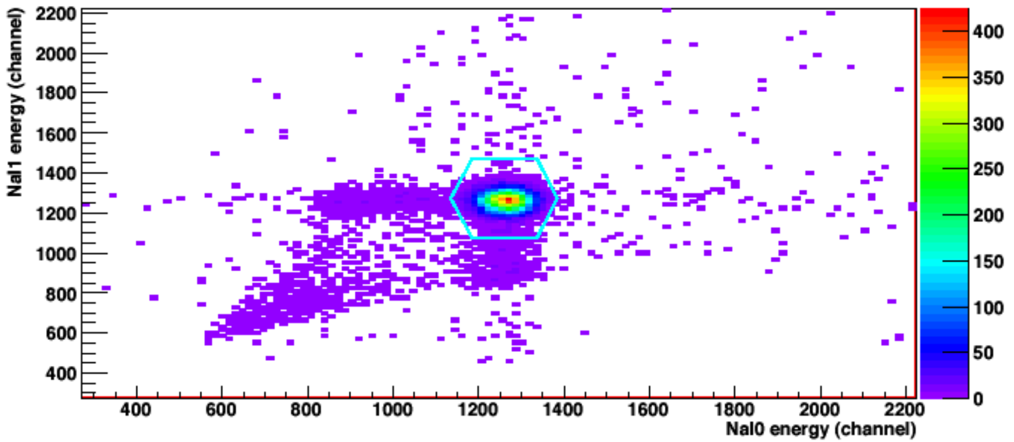
\+



All measurements of cross sections or resonance strengths require knowledge of the number of particles incident on the target!

Options:

② Monitor prompt γ-radiation & β^+-decay via annihilation (NaI)



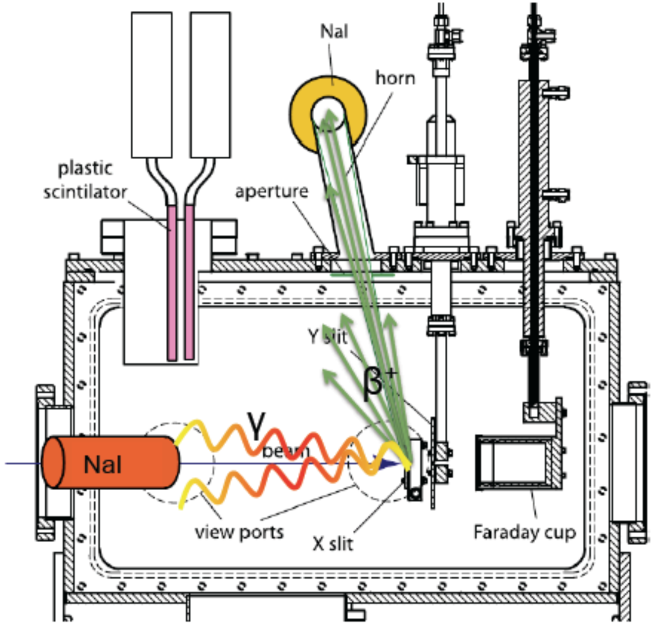
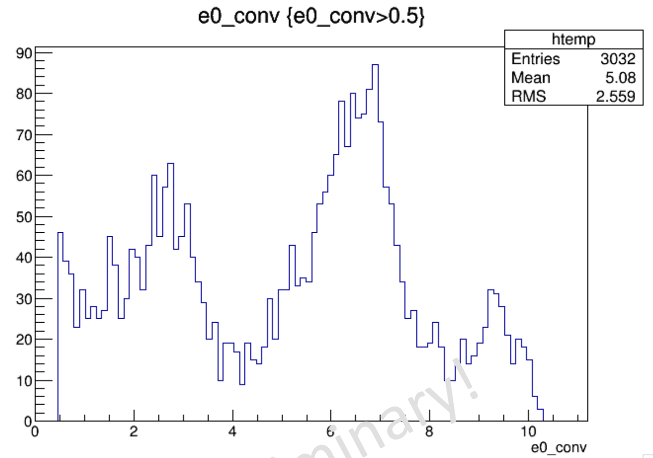
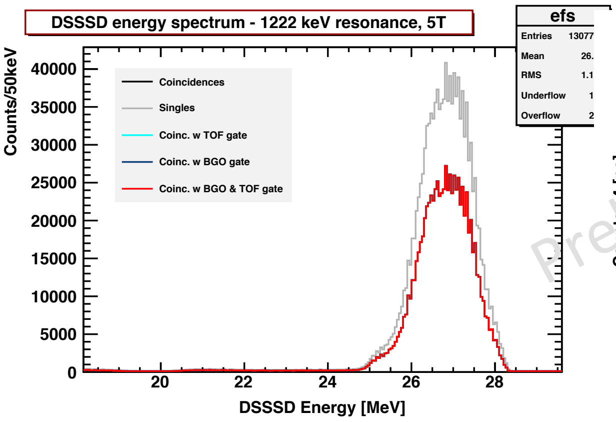


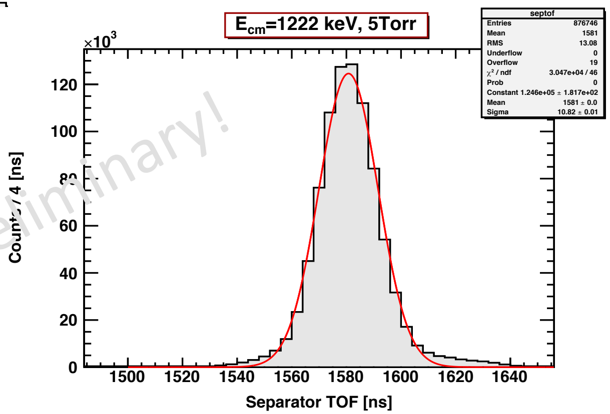
Figure from C. Ruiz et. al., Eur. Phys. A 50, 99 (2014)

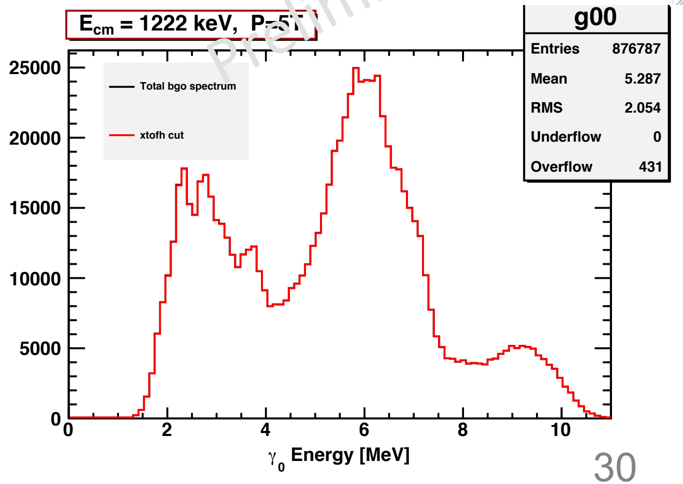
E_{cm}=1222 keV

- Used as **reference** for LUNA to determine **target stoichiometry**
- → Re-measured strong reference resonance (**ωγ=10.8(7) eV**)
- Measurements at 2 charge states (q=8⁺, q=9⁺) & 2 intensities
- Strong resonance, high statistics, low background
- Is it stronger?
- Cross check bgo efficiency simulation with coincidence and singles spectra









E_{cm}=458 keV

- Option to cross-check simulated BGO efficiency with data
- Consistent results using singles & coinc. spectra