

Studies of radioactive nuclei and their role in the cosmos

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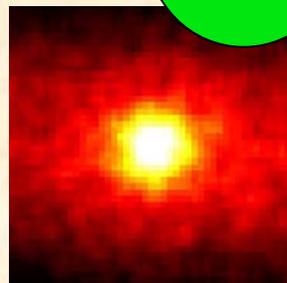
- Radioactive nuclei play an important role in astrophysics.
- Producing & accelerating these radioactive nuclei allows us to directly study nuclear reactions at the energies that are important in astrophysical objects.

^{18}F

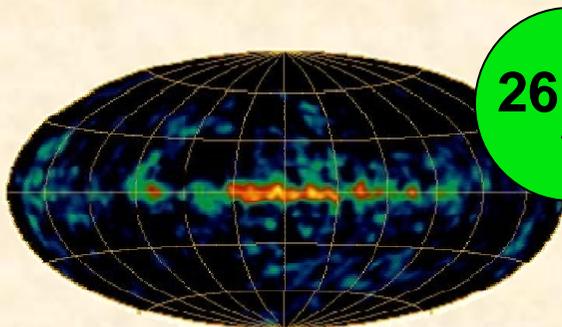


- $^{18}\text{F}(p,\alpha)^{15}\text{O}$
→ de Sereville *et al.*, #2.3
→ Chae *et al.*, #19.26
- $^{18}\text{F}(d,n)^{19}\text{Ne}$
→ Adekola *et al.*, #20.23
- $^{18}\text{F}(\alpha,p)^{21}\text{Ne}$
→ Lee *et al.*, #18.5

^7Be



- $^7\text{Be}(d,p)$
→ Angulo *et al.*, *ApJ* L105 ('05)
- $^7\text{Be}(p,\gamma)^8\text{B}$
- $^7\text{Be}(p,p^*)^7\text{Be}$
→ Yamaguchi *et al.*, #13.2



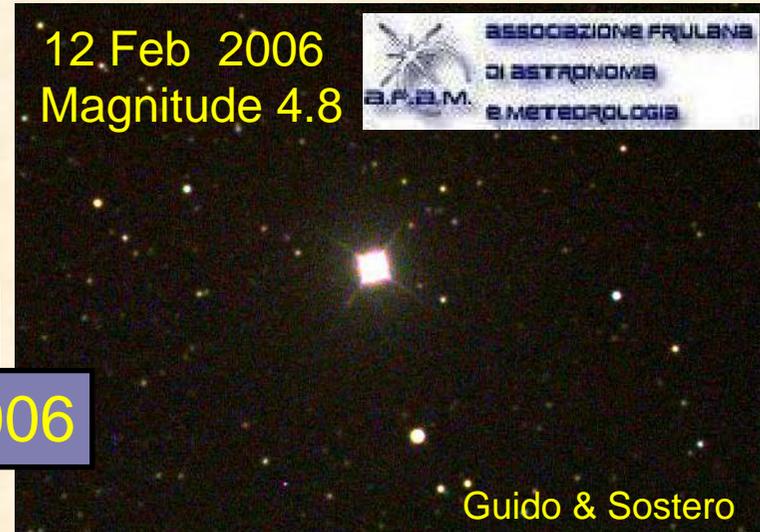
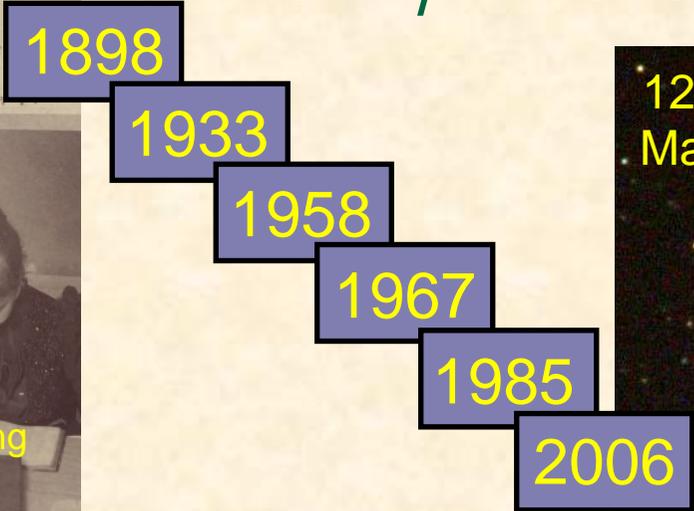
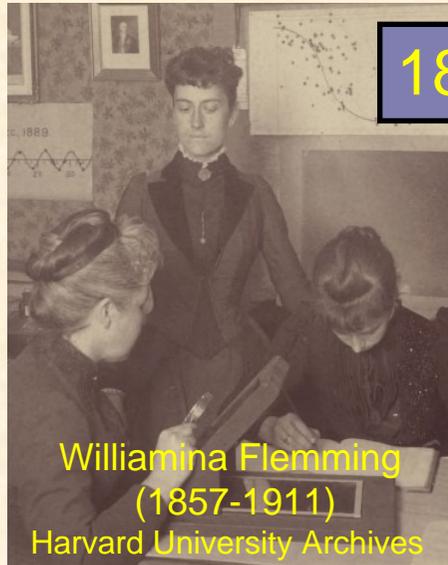
^{26}Al

- $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$
→ Ruiz *et al.*, #2.2
- $^{25}\text{Al}(p,p)^{25}\text{Al}$
→ Pearson *et al.*, #22.4

^{15}O

- $^{15}\text{O}(\alpha,\alpha)^{15}\text{O}$
→ Angulo *et al.*, #18.19

RS Oph returns



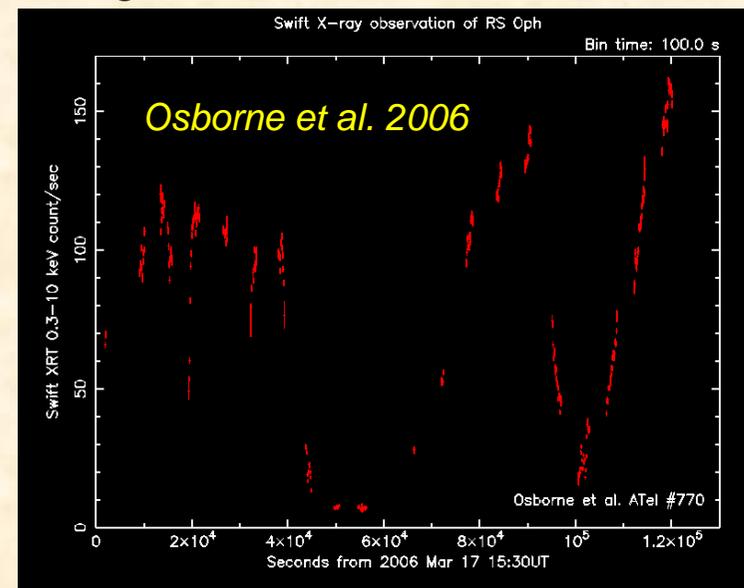
- Swift observations began less than 3 days after onset
- Simultaneous observations by 4 space orbiting observatories on Feb. 26



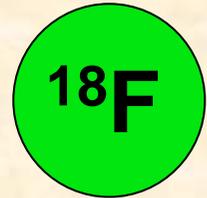
Swift



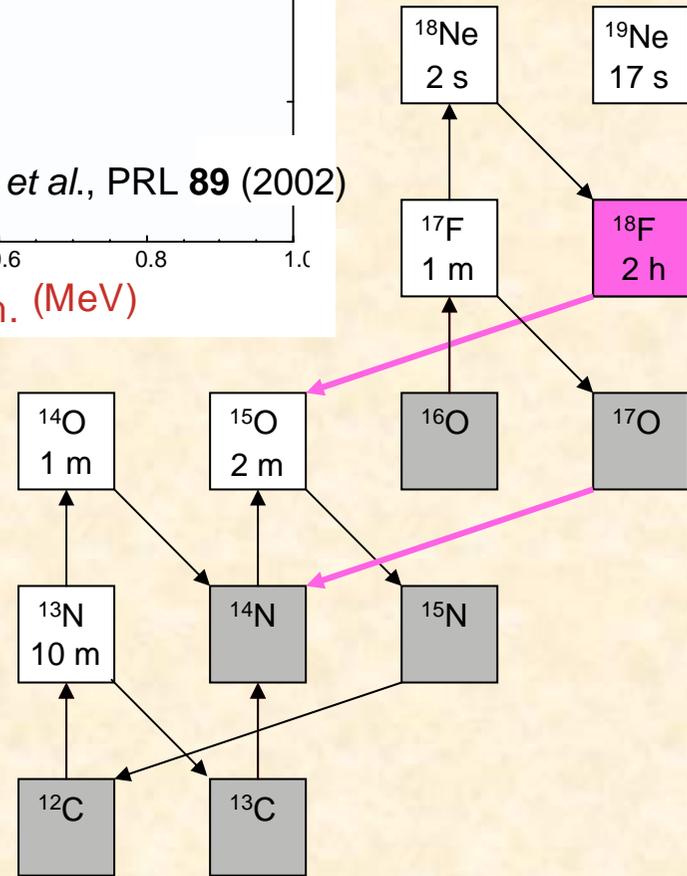
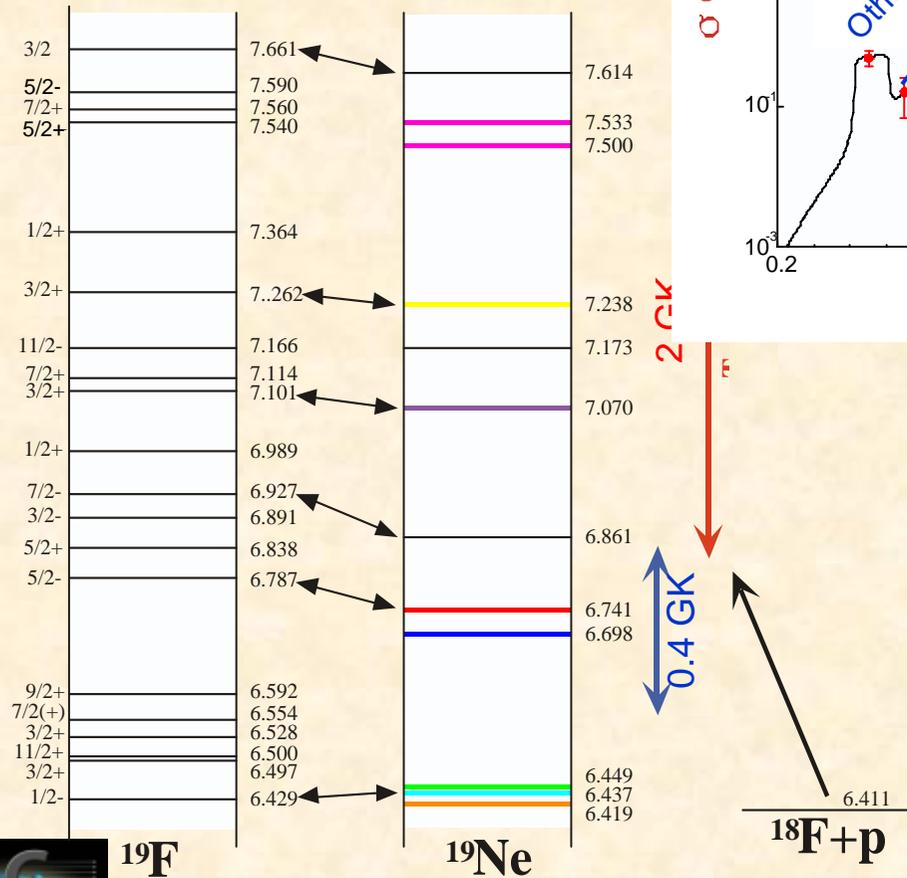
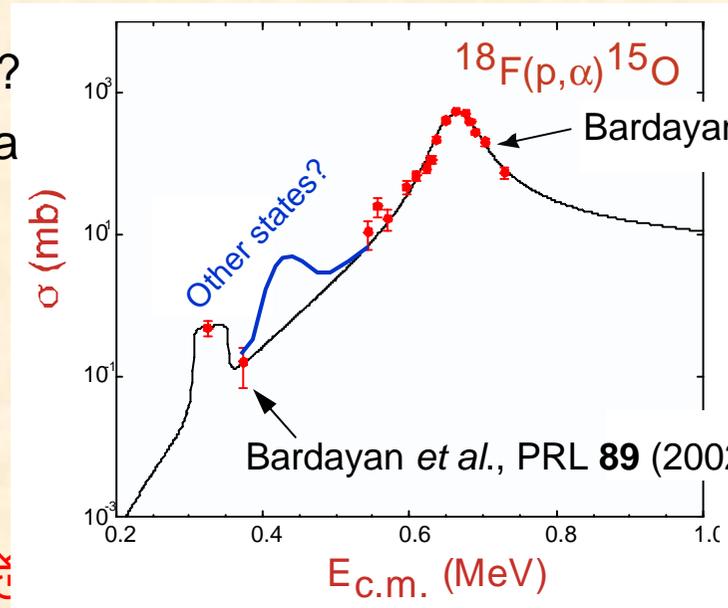
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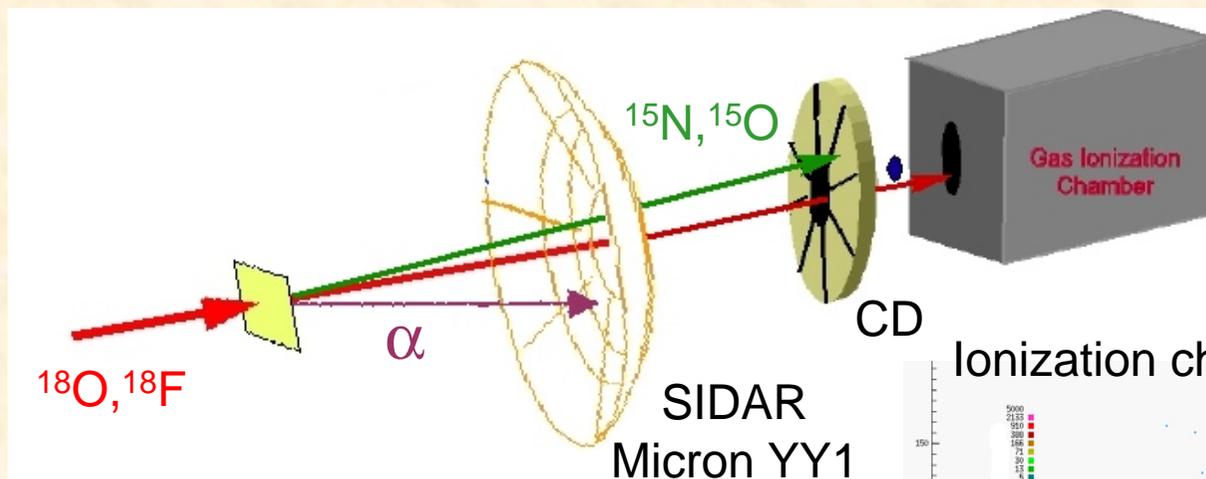
$^{18}\text{F}(p,\alpha)^{15}\text{O}$ in novae



- ^{15}N production
- Oxygen isotopic ratios: grains?
- Dynamics - helps power ejecta
- Source of γ rays

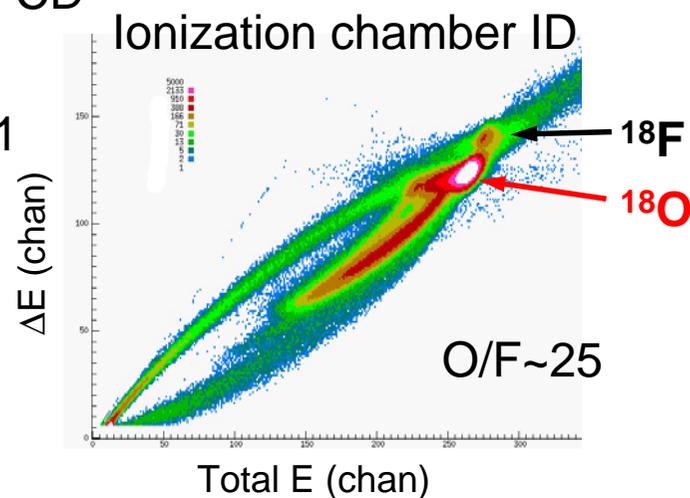
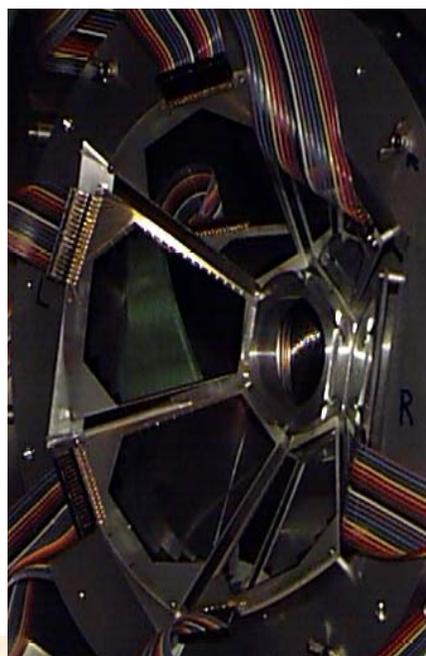
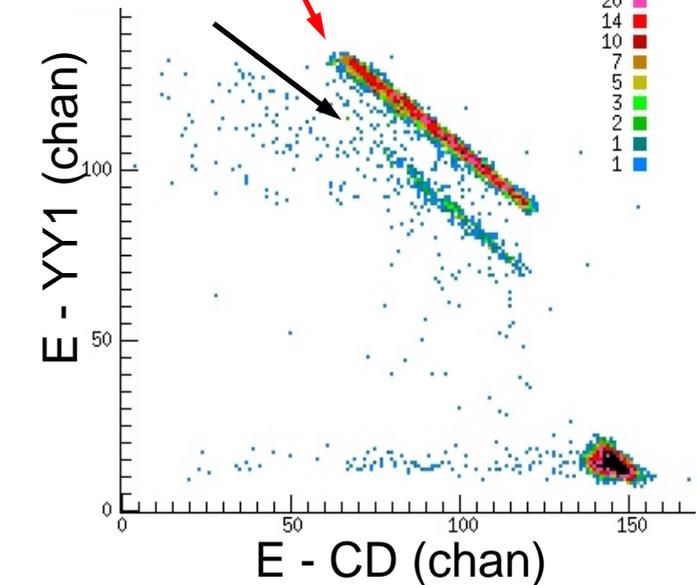


$^{18}\text{F}(p,\alpha)^{15}\text{O}$ at the HRIBF



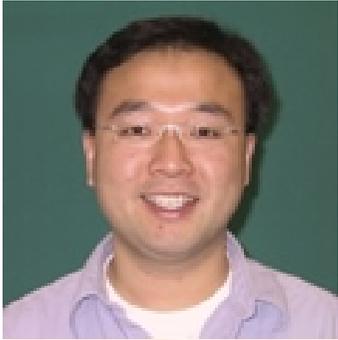
$^{18}\text{O}(p,\alpha)^{15}\text{N}$

$^{18}\text{F}(p,\alpha)^{15}\text{O}$



- Similar experimental approach as used in previous measurements at the HRIBF and CRC-Louvain-le-Neuve
- 5 energies measured at $E_{\text{cm}} > 660$ keV resonance



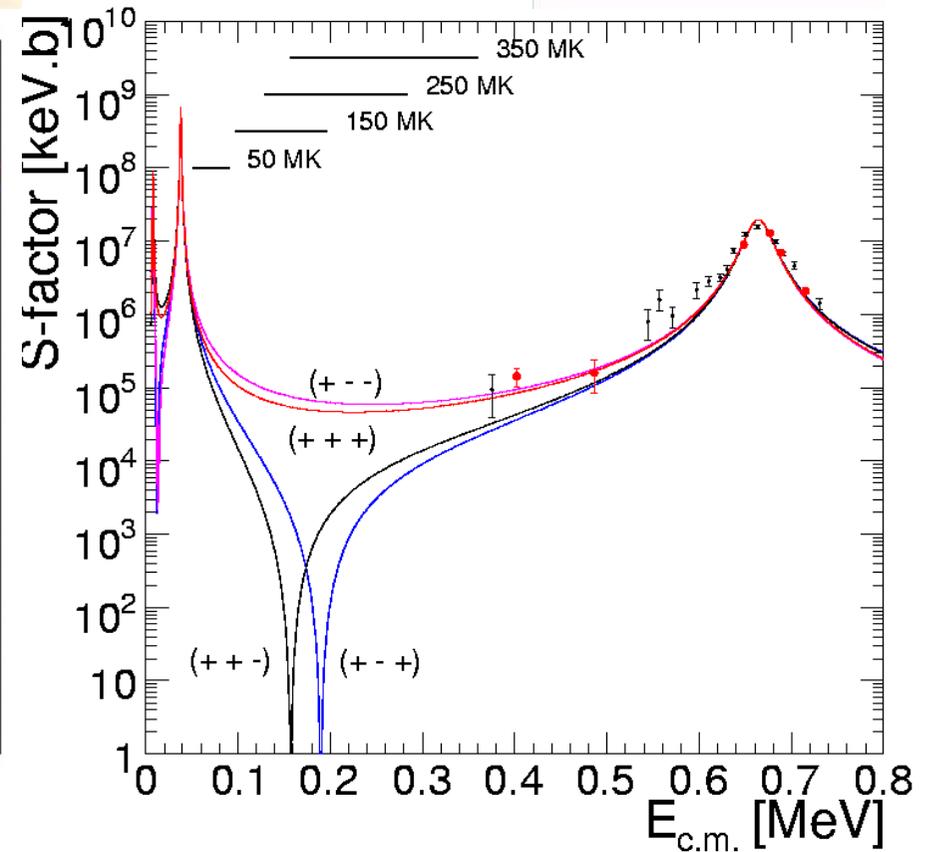
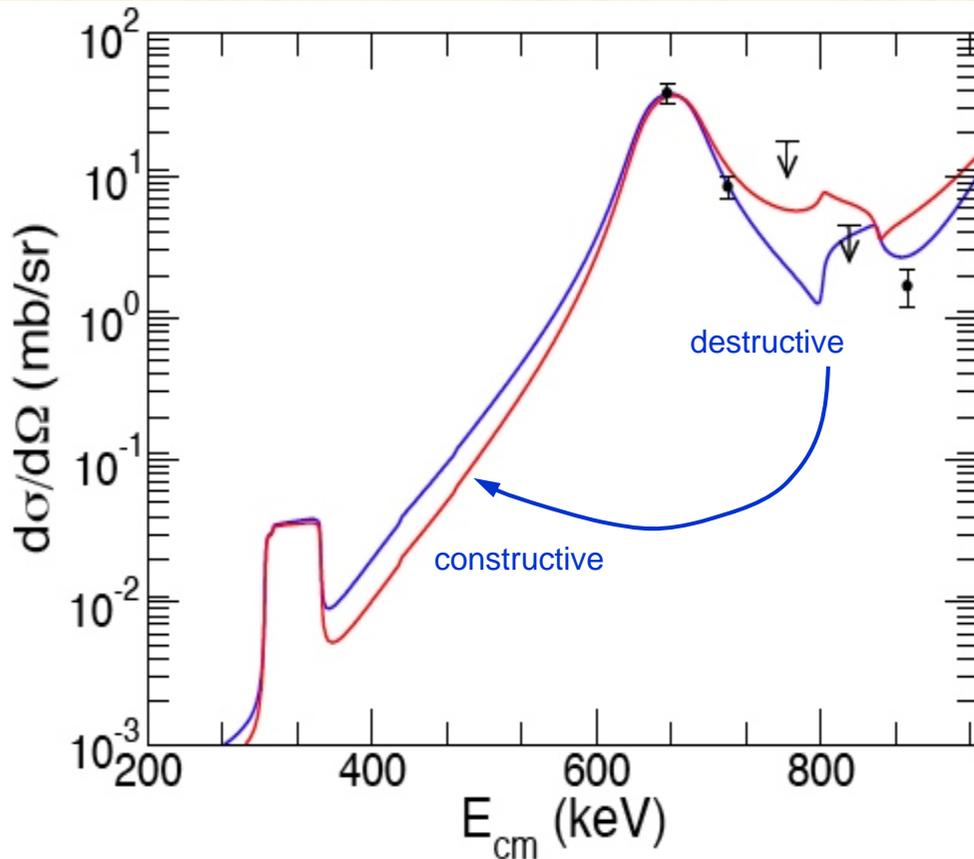


K.Y. Chae *et al.*,
PRC - in press,
Poster #19.26

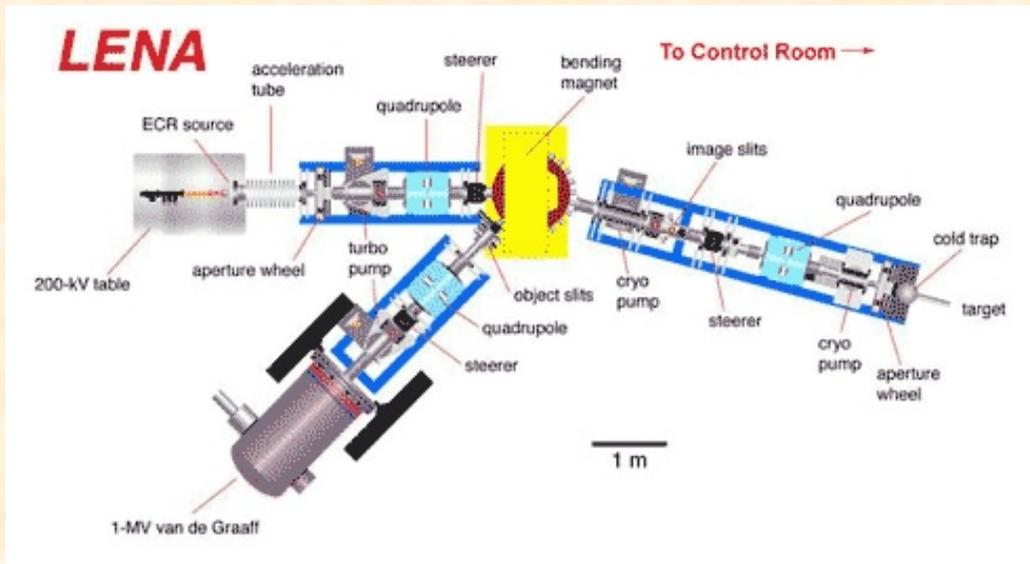
New $^{18}\text{F}(p,\alpha)^{15}\text{O}$ results

- Destructive interference measured above the 7.07 (3/2+) resonance.
- $\Gamma_p(827 \text{ keV}) < 1.2 \text{ keV}$
- $\Gamma_p(842 \text{ keV}) < 1.7 \text{ keV}$

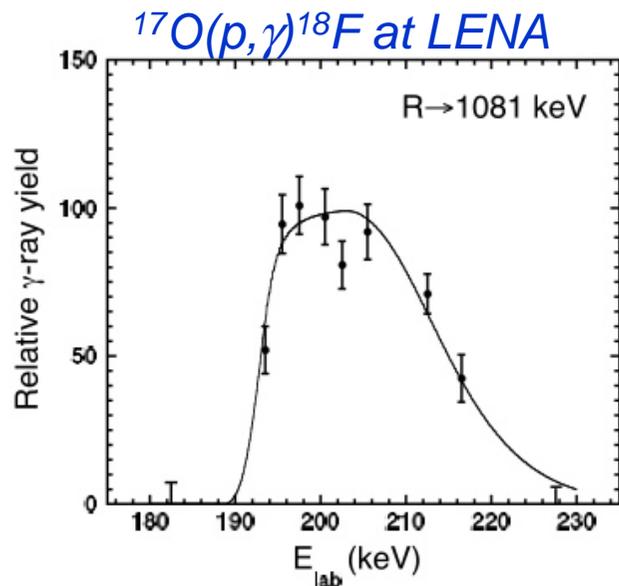
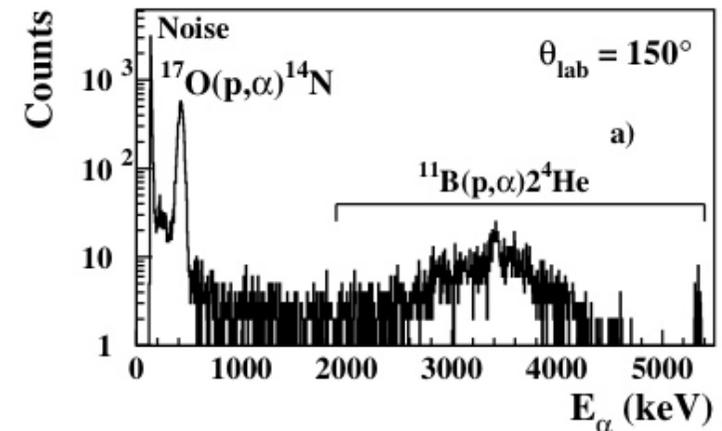
de Sereville *et al.*



The 180-keV resonance in $^{17}\text{O}+p$



$^{17}\text{O}(p,\alpha)^{14}\text{N}$ at CSNSM-Orsay

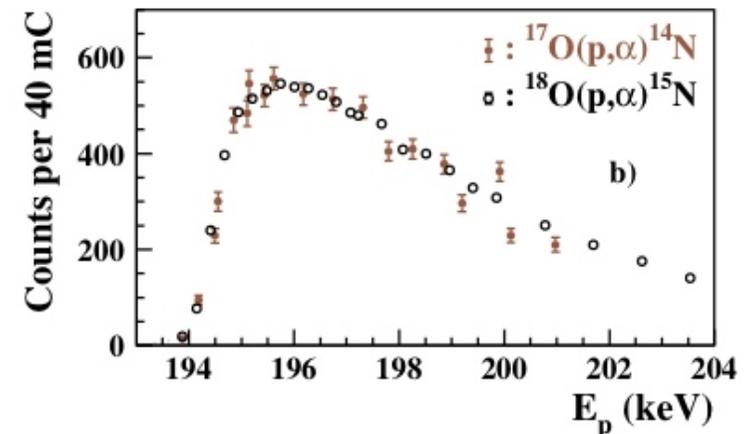


Fox *et al.*, PRC **71** (2005) 055801.

$^{17}\text{O}(p,\alpha)^{14}\text{N}$ rate
increased by
~100 times

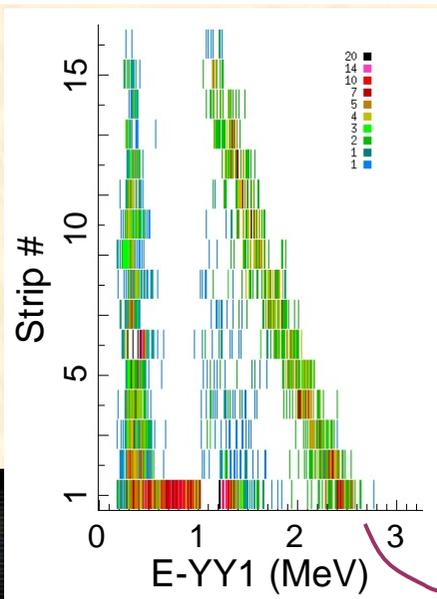
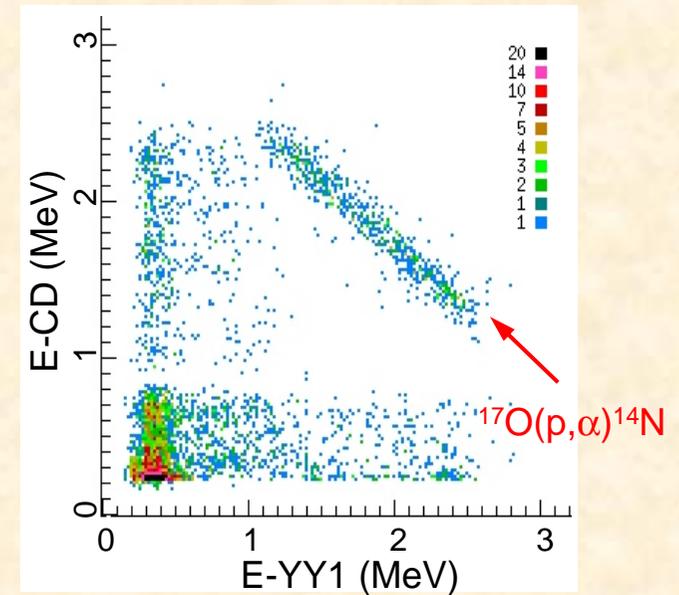
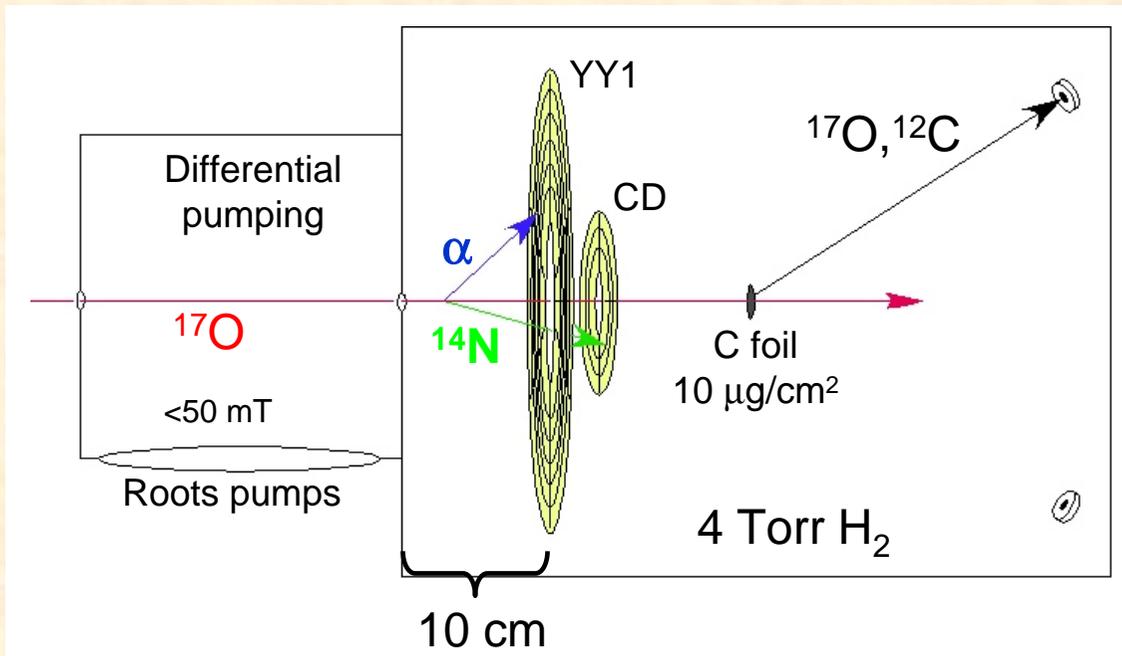
$$\frac{(p,\alpha)}{(p,\gamma)} \approx 700$$

^{18}F production
reduced by
~3-8 times in
novae

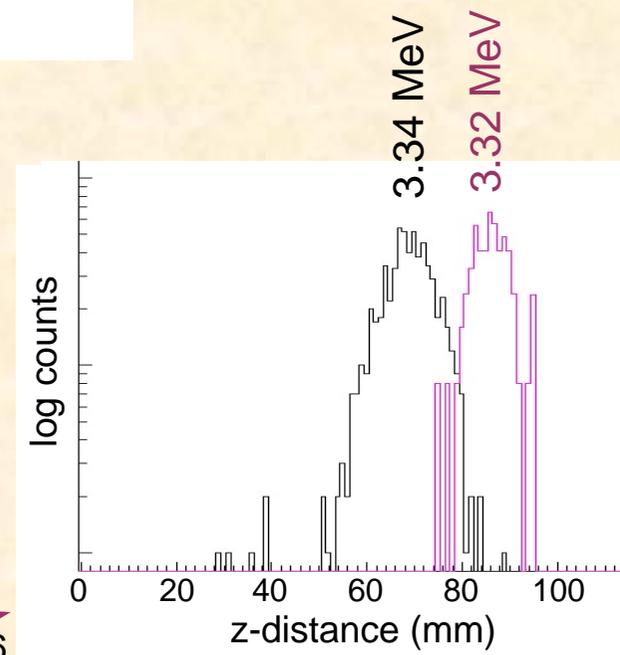


Chafa *et al.*, PRL **95** (2005) 031101.

Novel approach to (p, α) resonances



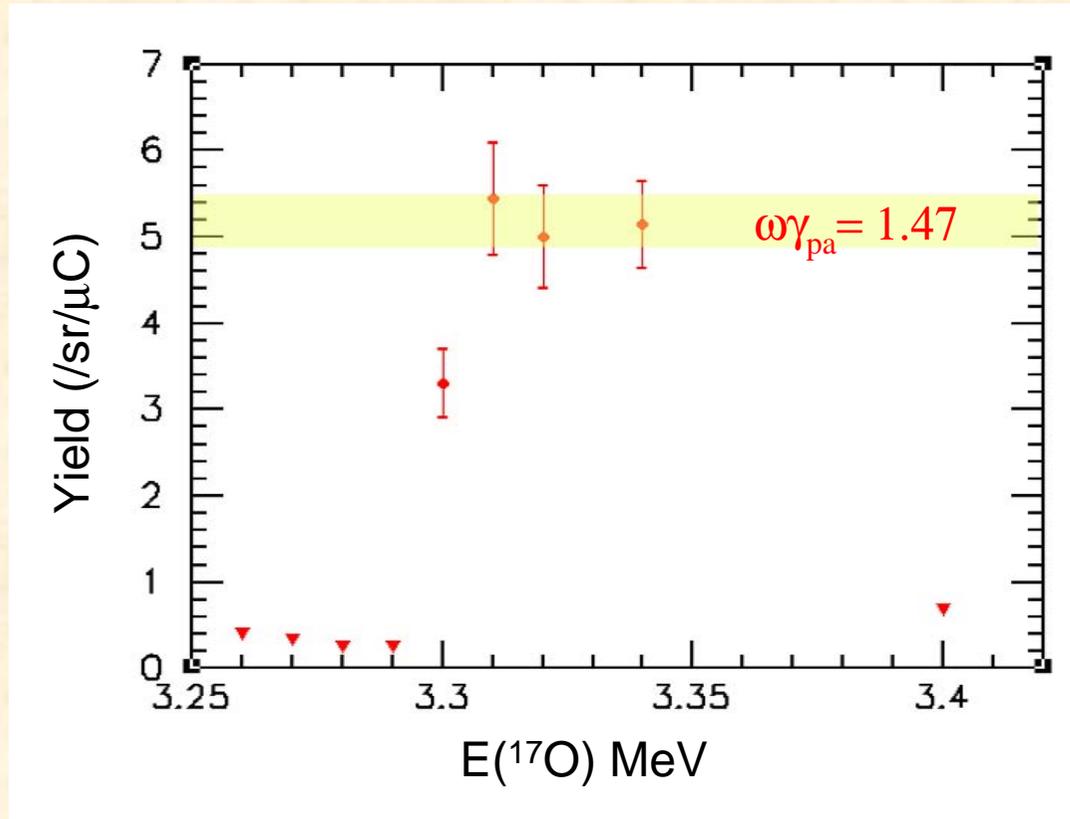
$E_\alpha \otimes \text{strip \#}$
 $\rightarrow \text{vertex}$



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Preliminary results $^{17}\text{O}(p,\alpha)^{14}\text{N}$

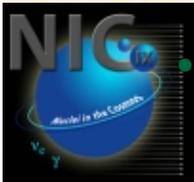


Chafa *et al.*
1.6 0.2 meV

- High sensitivity to narrow resonances
 - Yield 3x greater than with CH_2
 - Center-of-mass resolution < 1 keV
 - Background from beam contaminants greatly reduced

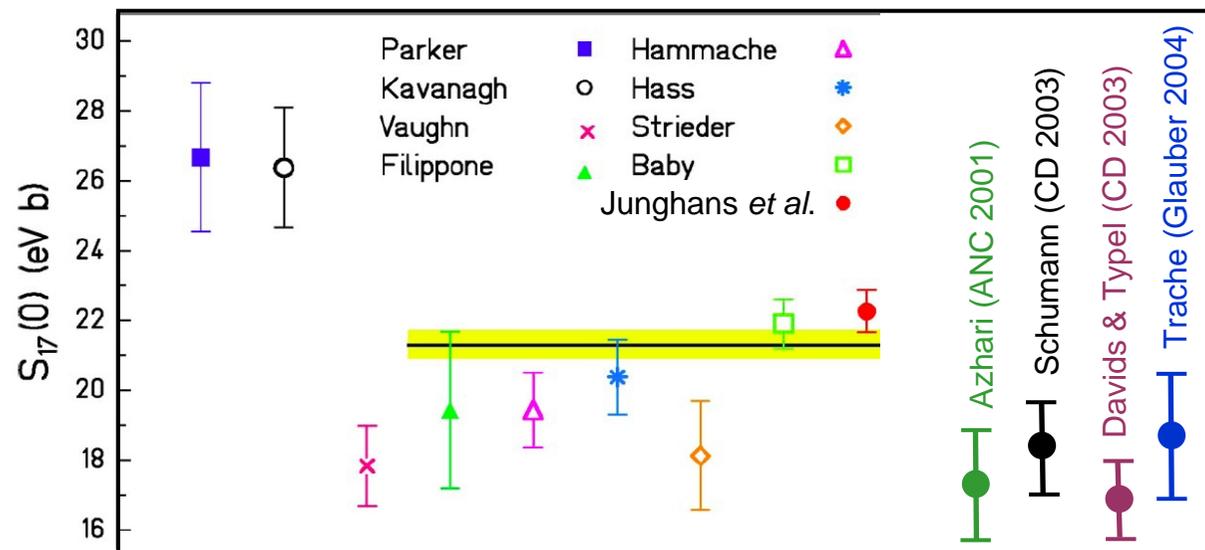
Next: will be applied to $^{18}\text{F}(p,\alpha)^{15}\text{O}$, e.g. $E_{\text{cm}} = 330$ keV, 287 keV

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Status of ${}^7\text{Be}(p,\gamma){}^8\text{B}$



Evaluated S_{17} (eV b)

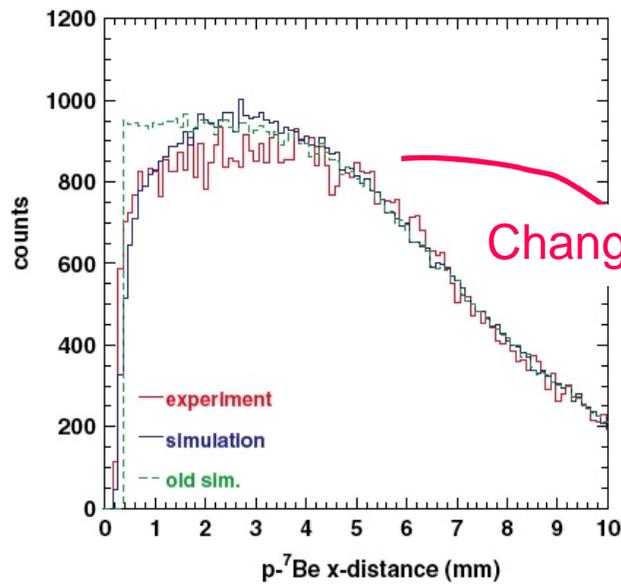
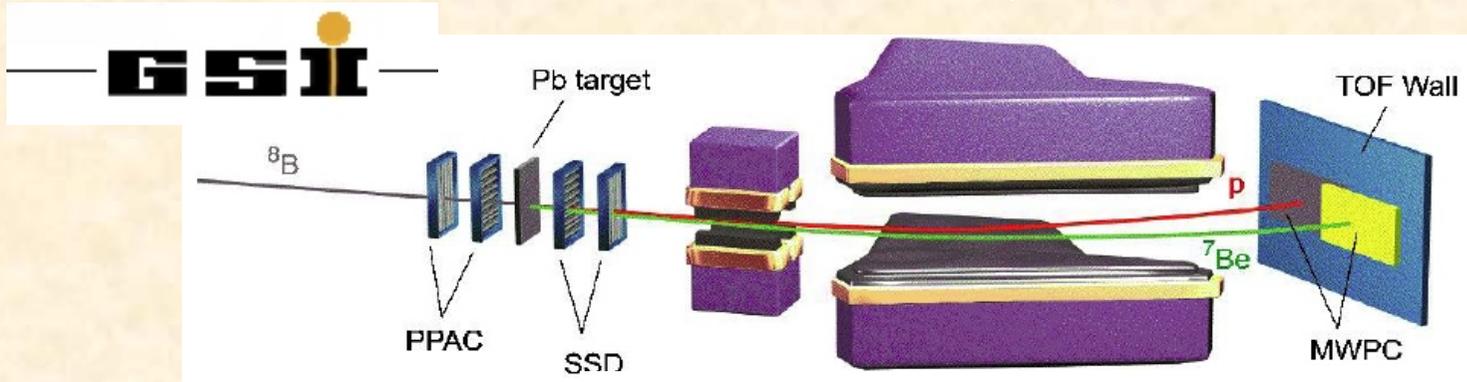
Junghans PRC 68 (2003) 065803.	$21.4 \pm 0.5 \pm 0.6$
Davids & Typel PRC 68 (2003) 045802.	$18.6 \pm 0.4 \pm 1.1$
Cyburt <i>et al.</i> , PRC 70 (2004) 045801.	$19.3 \rightarrow 21.4$ with $\sim 6\text{-}7\% \sigma$

- Precision has been significantly improved.
- Some questions remain.

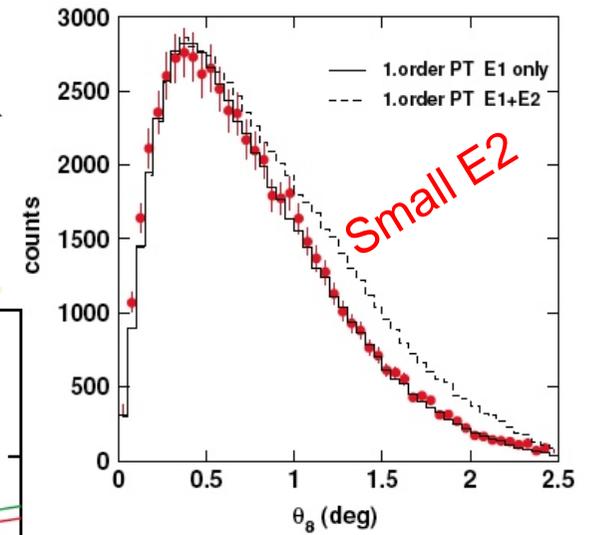
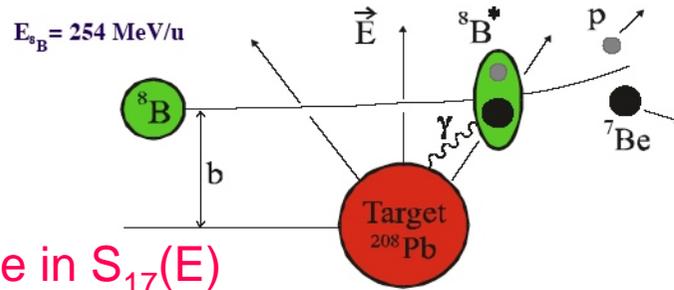


New Coulomb dissociation result

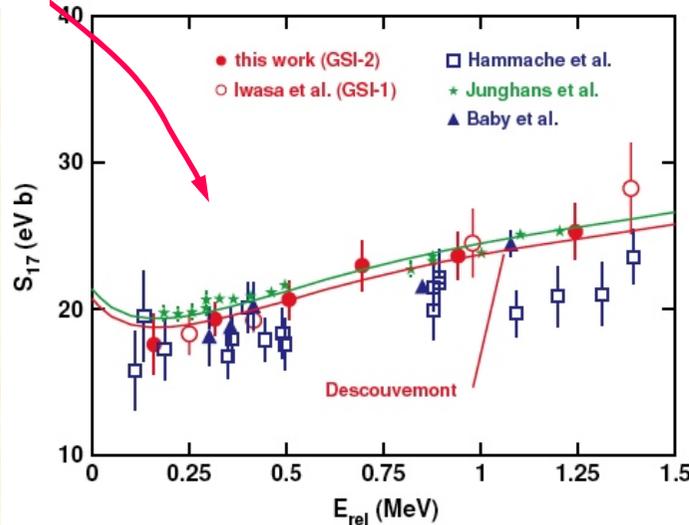
Schumann et al., PRC 73 (2006) 015806.



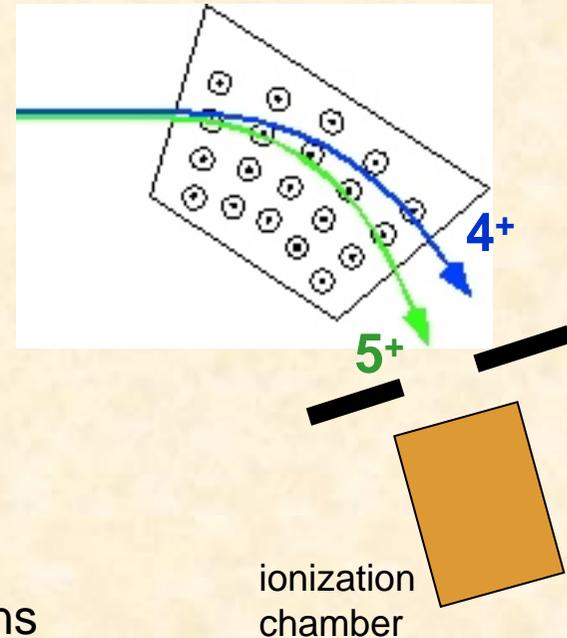
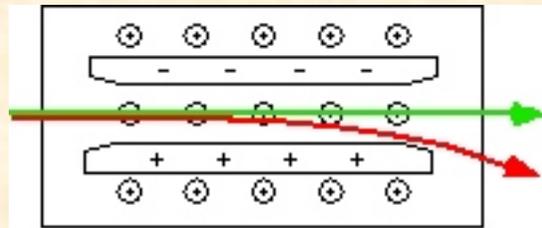
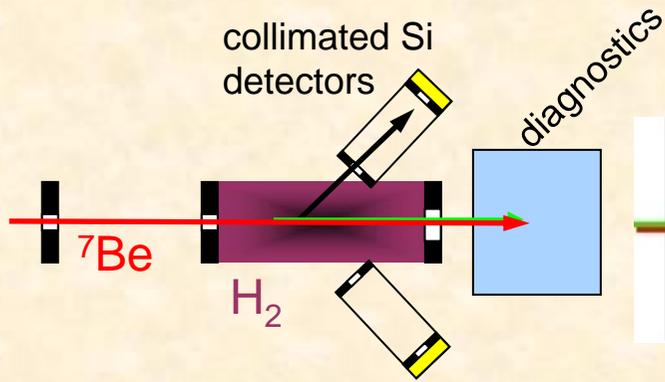
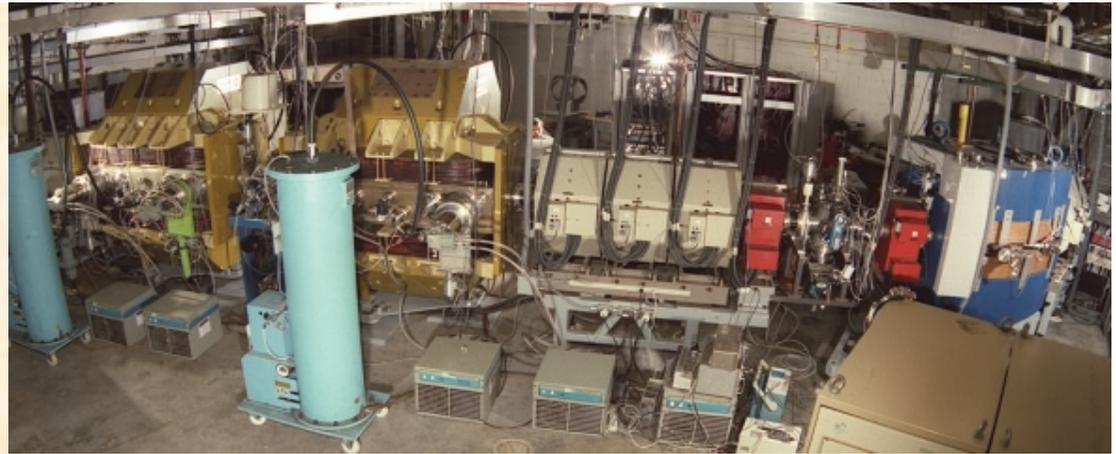
Change in $S_{17}(E)$



$20.6 \pm 0.8 \pm 1.2 \text{ eV b}$



$^1\text{H}(^7\text{Be},^8\text{B})$ at the HRIBF ala NABONA



$$\sigma = \frac{^8\text{B}}{I_7 \frac{H}{\text{cm}^2} \epsilon}$$

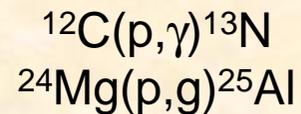
$$\bar{p}(^8\text{B}) = \bar{p}(^7\text{Be}) \pm 0.4\%$$

$$\theta(^8\text{B}) < 0.24^\circ$$

$$v(^7\text{Be}) = 1.14 v(^8\text{B})$$

- Accurate statistics
- **Different**, well-characterized systematic uncertainties

Transfer reactions
Fusion evaporation
Scattering reactions
Energy loss & stopping power

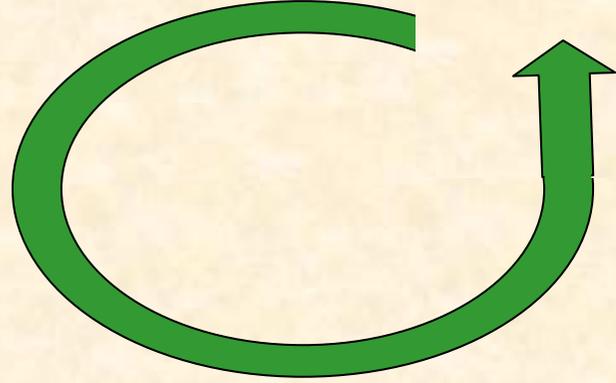


hrifb

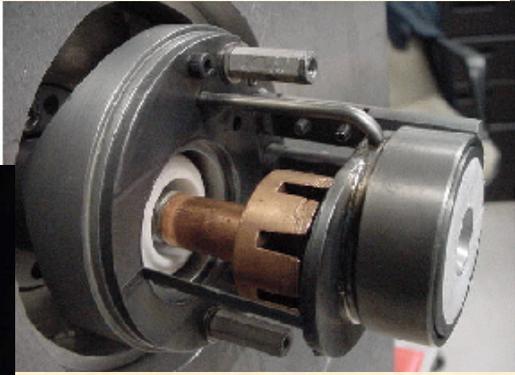
^7Be beam production



Li metal
12 MeV protons
 $\sim 10 \mu\text{A}$
 $^7\text{Li}(p,n)^7\text{Be}$
0.2 Ci

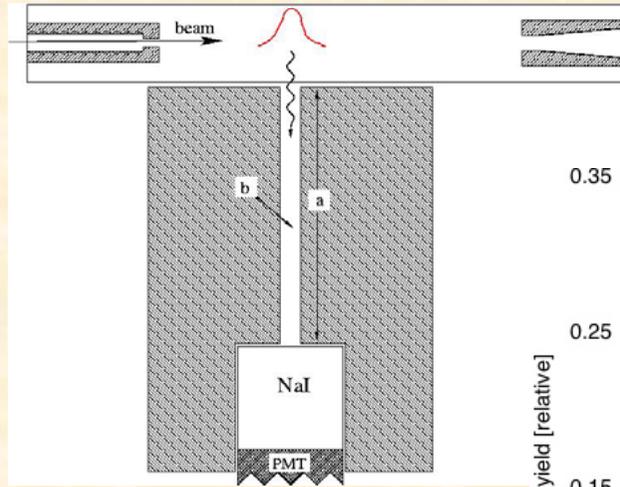
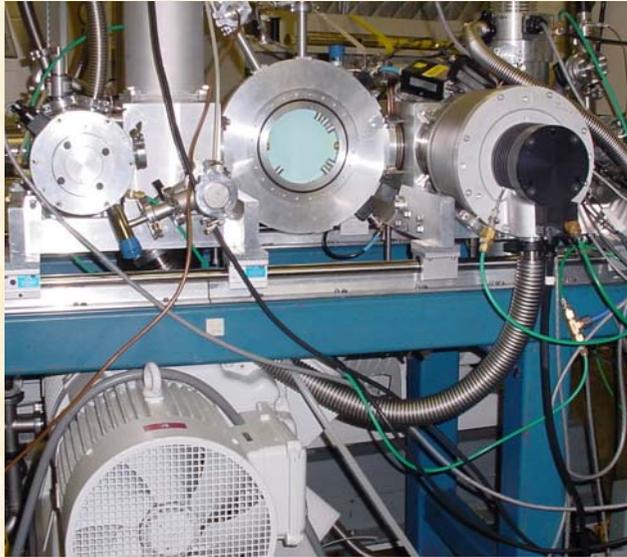


2×10^7 $^7\text{Be}/\text{s}$

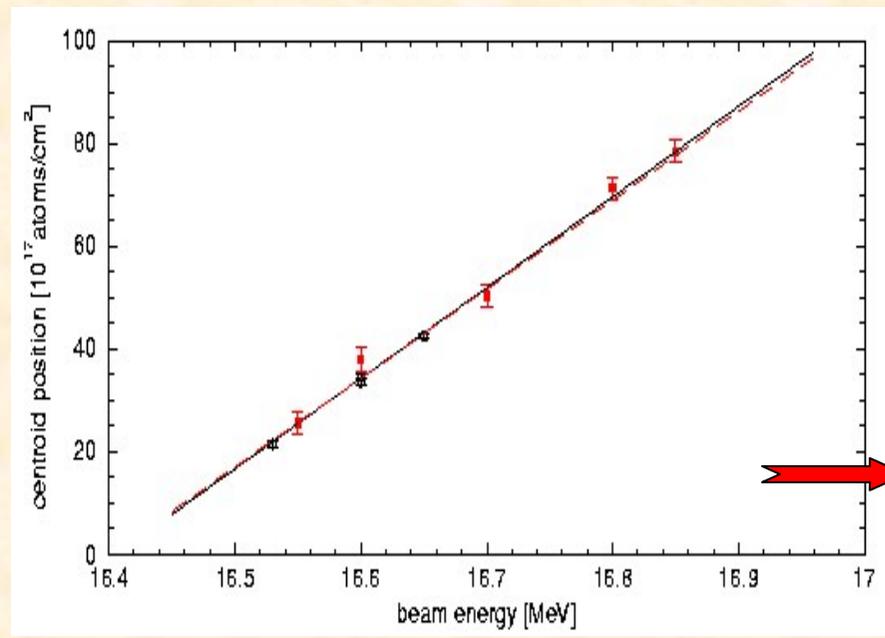
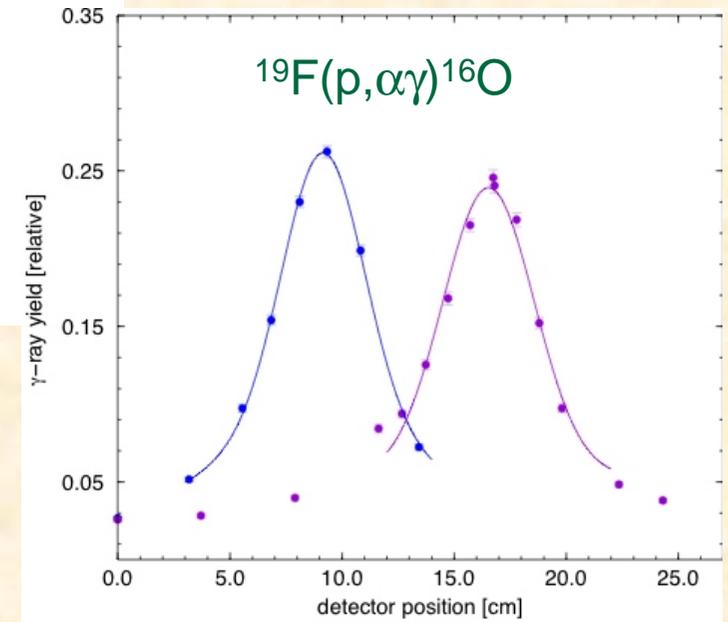


0.12 Ci

Windowless H_2 gas target



Si detector
 $\rightarrow \Delta E = 396 \pm 6$ keV



$$\epsilon = (57 \pm 2) \cdot 10^{-15} \text{ eV} \cdot \text{cm}^2$$

$$n = \Delta E / \epsilon$$

$$n_{5.5 \text{ Torr}} = (6.95 \pm 0.24) \cdot 10^{18} / \text{cm}^2$$



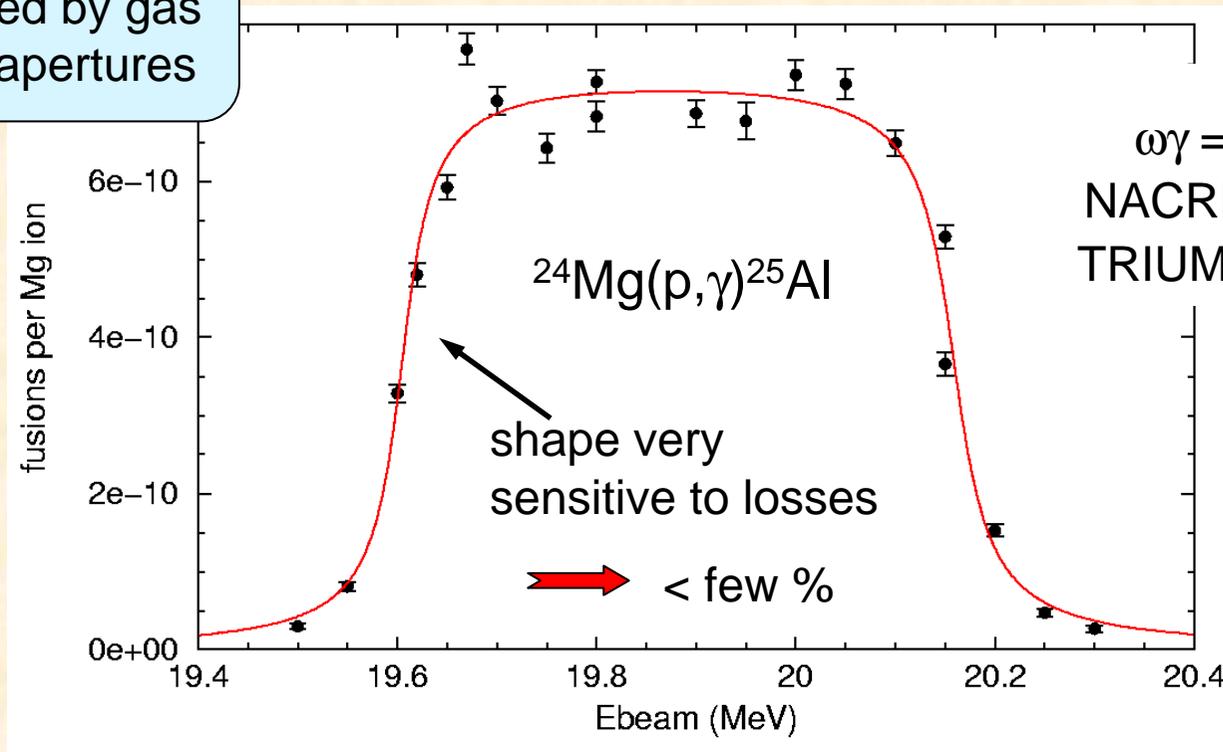
Stable capture reactions

Reaction	θ_{\max}	ΔE
${}^7\text{Be}(p,\gamma){}^8\text{B}$	0.24°	$\pm 0.9\%$
${}^{12}\text{C}(p,\gamma){}^{13}\text{N}$	0.39°	$\pm 1.4\%$
${}^{24}\text{Mg}(p,\gamma){}^{25}\text{Al}$	0.20°	$\pm 0.8\%$

→ broad resonance

→ narrow resonance scan

$\theta_{\text{lab}} < 0.63^\circ$
accepted by gas
target apertures

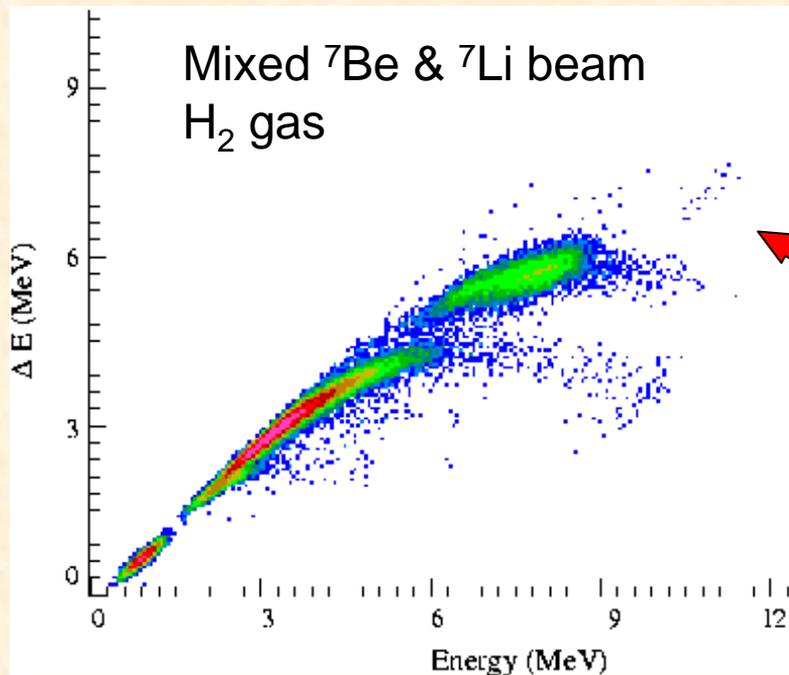


First ${}^7\text{Be}(p,\gamma){}^8\text{B}$ run at the HRIBF

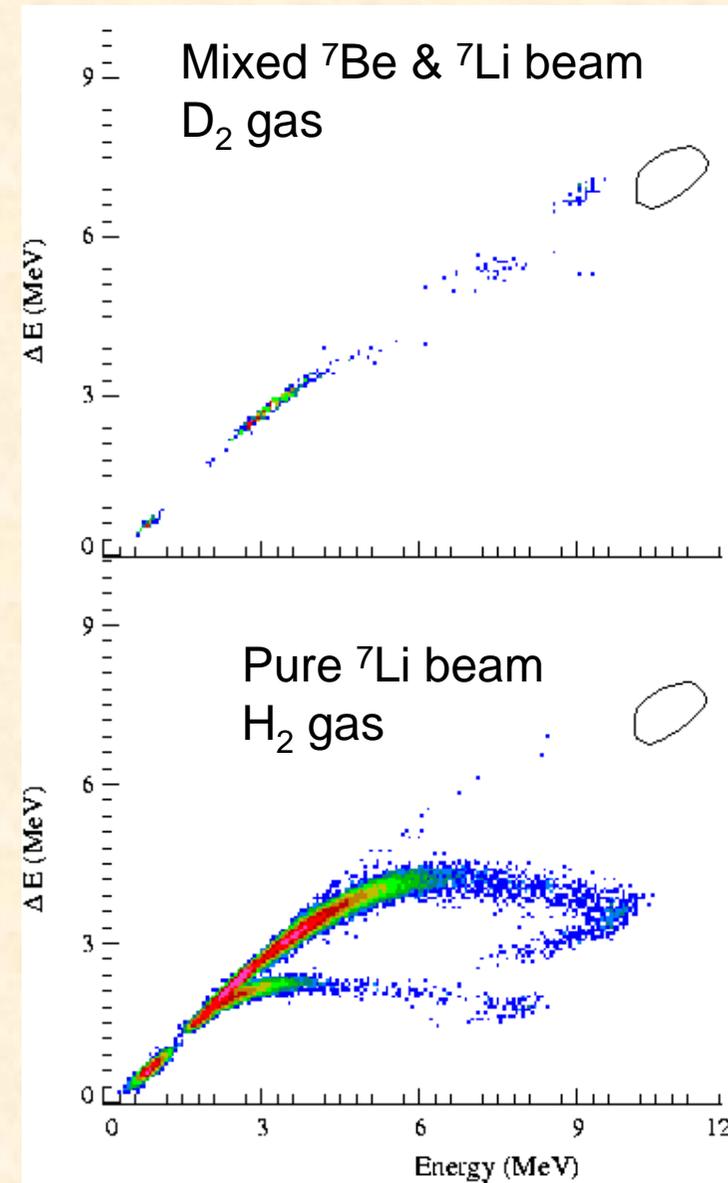
63.1 h

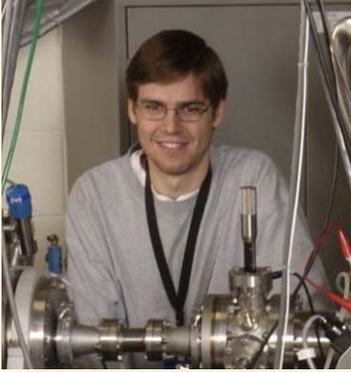
$\langle I \rangle = 1.52 \times 10^7$ ${}^7\text{Be}/\text{s}$

$E({}^7\text{Be}) = 11.96 \pm 0.02$ MeV



22 counts





R.P. Fitzgerald
Ph.D. UNC (2005)

Results from first run

Quantity	value	% uncertainty
${}^8\text{B}$ (counts)	22	21
p (counts)	3446	1.7
$p/{}^7\text{Be}$ (10^{10})	9.96	9
H/cm^2 (10^{18})	6.27	3
$\Phi(5+)$	0.944	2.3
ϵ	0.96	+4 / -6
σ (μb)	1.12	~24

New beam sampler



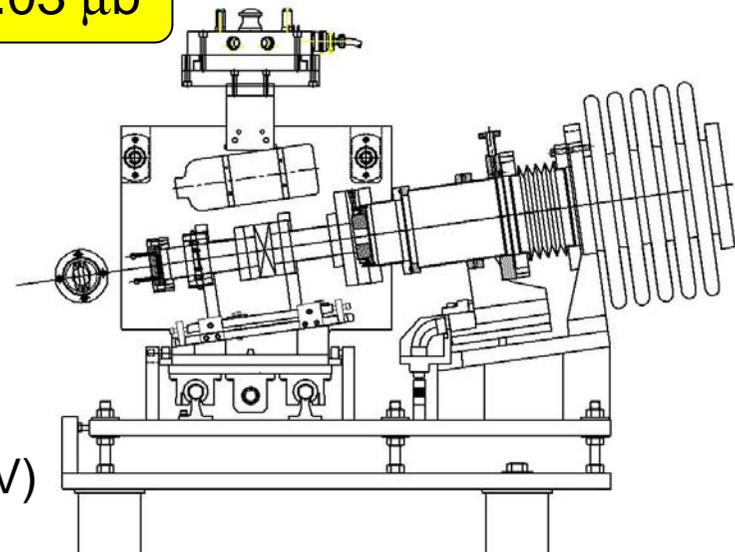
New stable beam studies (Seattle)

Junghans *et al.* $0.91 \pm 0.03 \mu\text{b}$

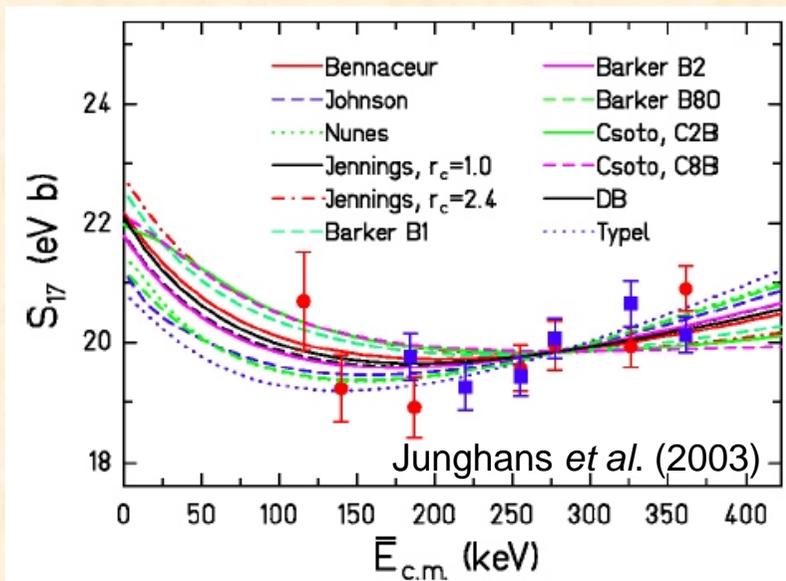
Working on increasing beam intensity

1. More activity: ORIC & Debrecan
2. Cathode geometry (~2x)
3. Low energy beam transport (?)

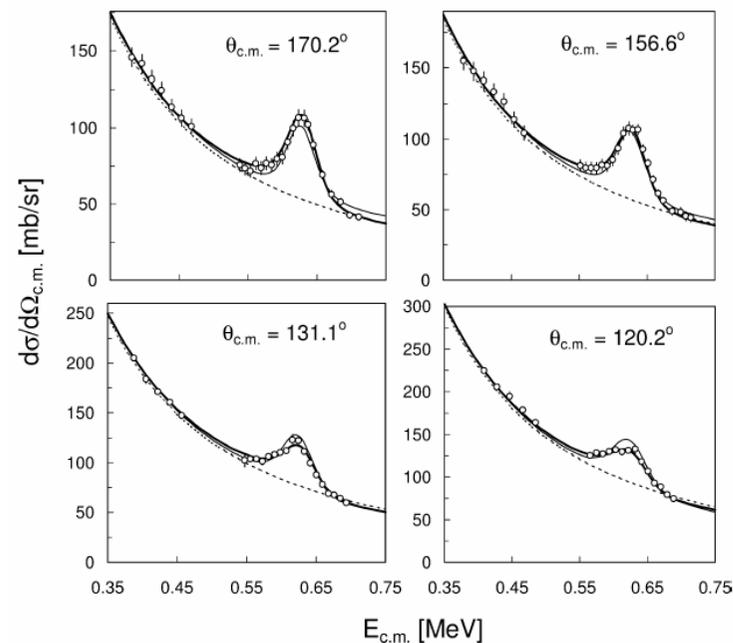
$8 \times 10^7 \text{ } {}^7\text{Be}/\text{s}$ (5x) \rightarrow ≈ 40 counts/day (1 MeV)
 ≈ 10 counts/day (0.3 MeV)



${}^7\text{Be}(p,\gamma){}^8\text{B}$ extrapolation



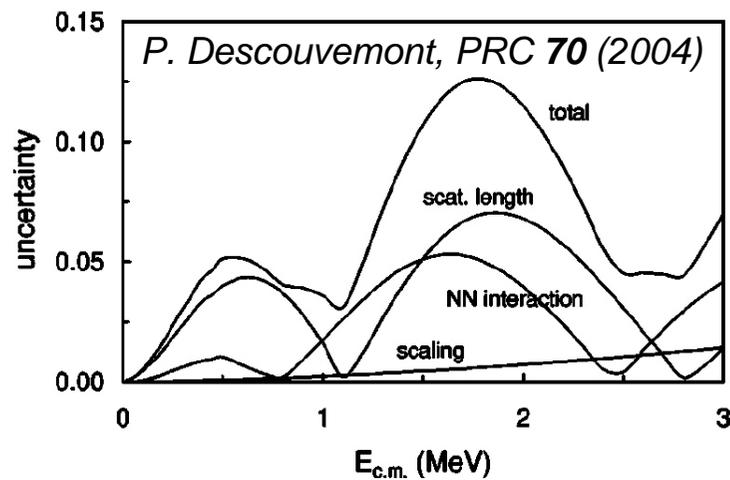
${}^7\text{Be}(p,p){}^7\text{Be}$ CRC-Louvain-le-Neuve



C. Angulo et al., NPA 716 (2003)

$${}^7\text{Be}+p: a_{01} = 25 \pm 9 \text{ fm}, \quad a_{02} = -7 \pm 3 \text{ fm}$$

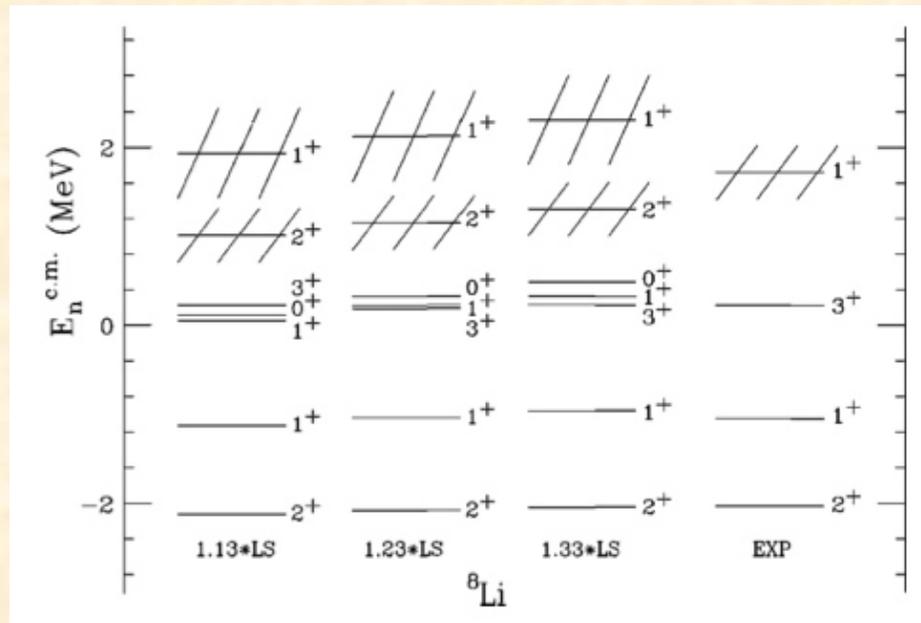
$${}^7\text{Li}+n: a_{01} = 0.87 \pm 0.07 \text{ fm}, \quad a_{02} = -3.63 \pm 0.05 \text{ fm}$$



- Uncertainty in shape of $d\sigma/d\Omega$ and ${}^7\text{Be}(p,\gamma)$ extrapolation to solar energies dominated by s-wave scattering lengths

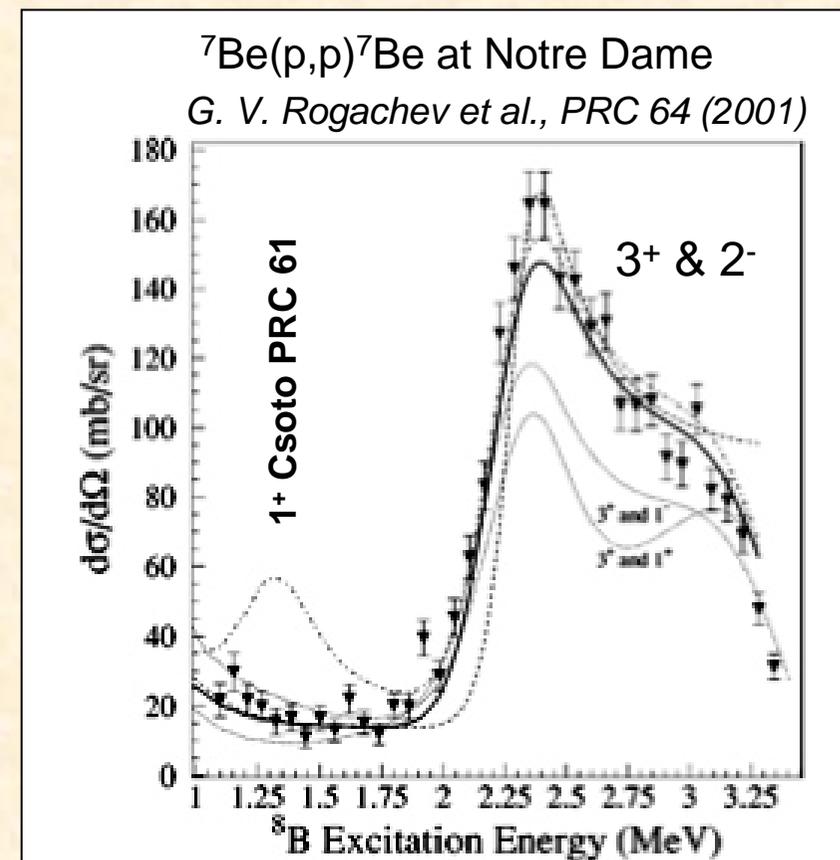
→ ~ 5% uncertainty in $S_{17}(0)$

^8B structure



- Proton and neutron in p orbitals
- 2^+ ground state
- Well-known 1^+ and 3^+ states
- Other positive-parity states expected from shell model

- New levels can significantly affect shape of $^7\text{Be}(p,\gamma)^8\text{B}$ cross section depending on properties
- No evidence yet for predicted positive parity resonances
- New structure in $^7\text{Be}+p$ scattering (TWINSOL) indicate broad 2^- level at high energies

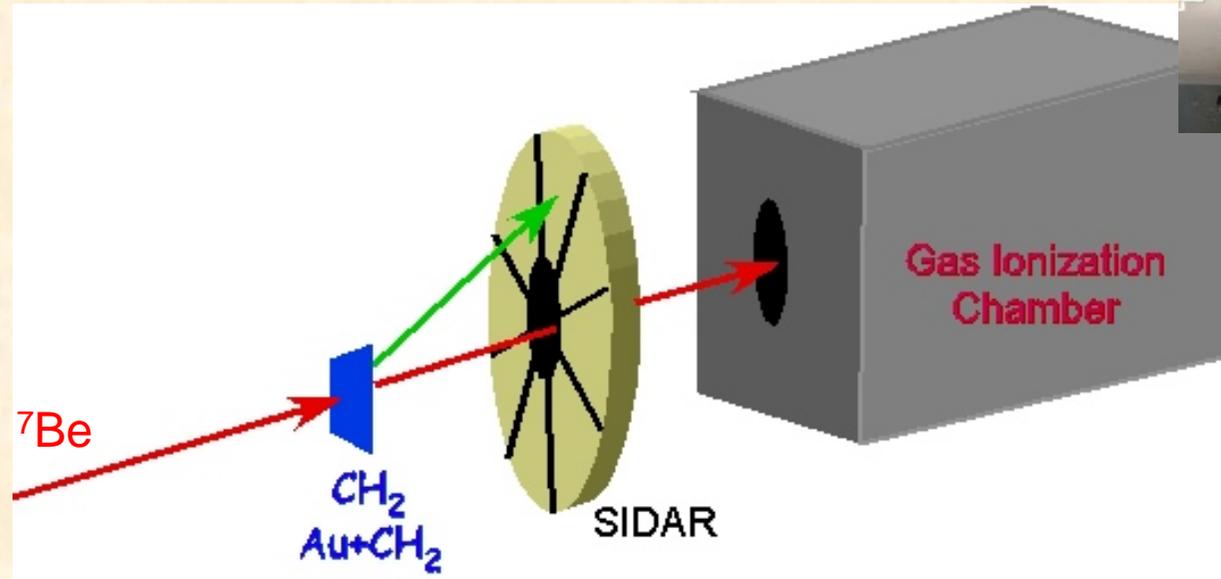




${}^7\text{Be}(p,p){}^7\text{Be}$



R.J. Livesay



Measured thick-target yield

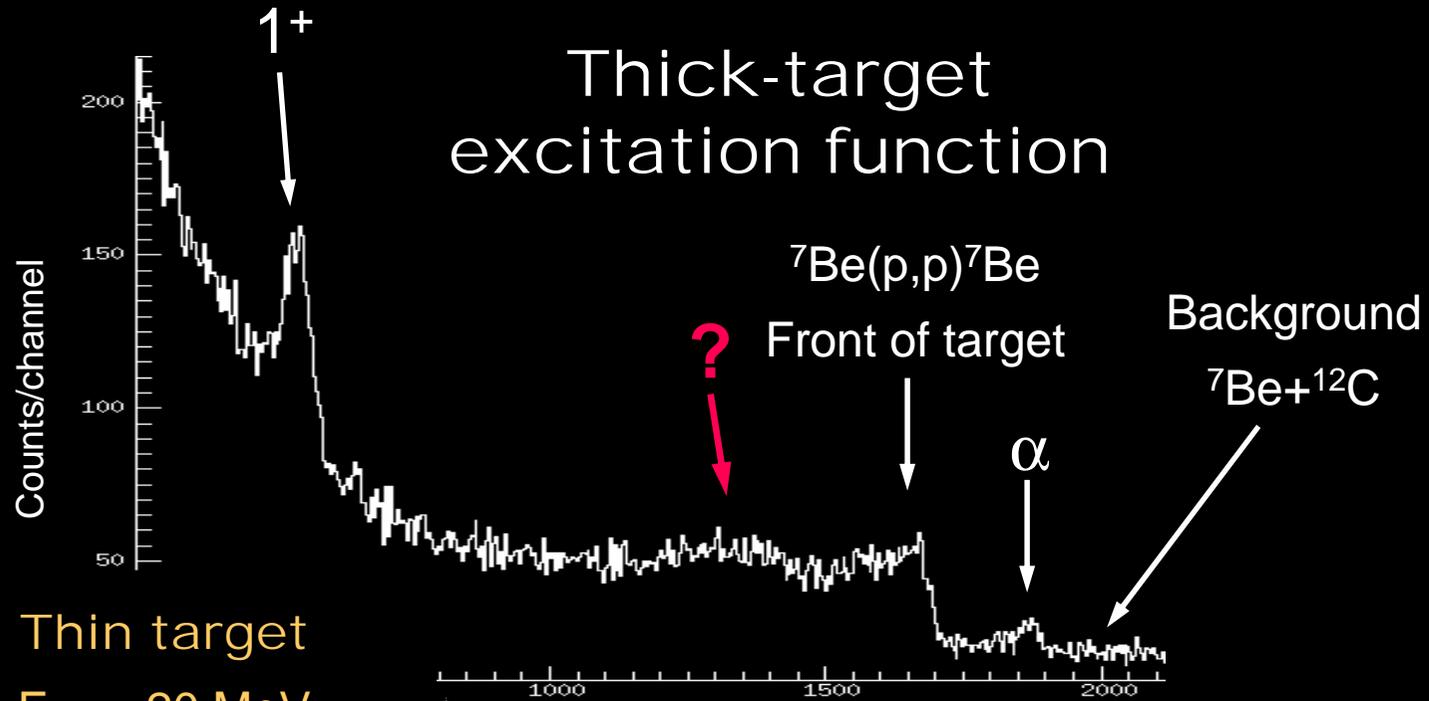
- 14 MeV beam of ${}^7\text{Be}$
- 4.3 mg/cm² CH₂

Measured thin-target excitation function

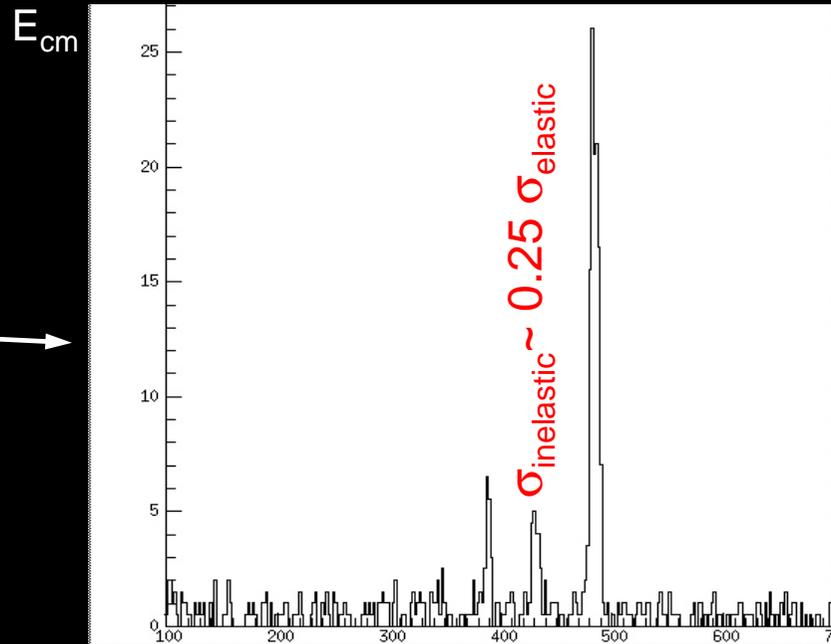
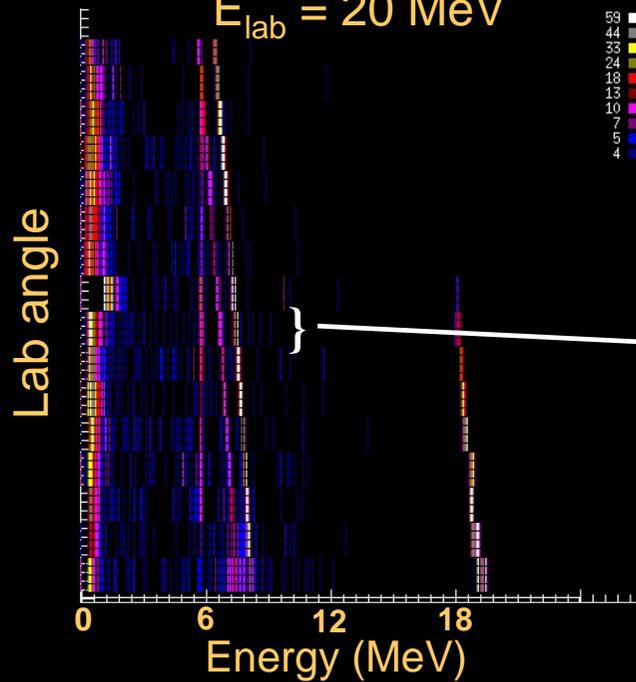
- 17 bombarding energies
- 100 μg/cm² CH₂ target
- $E_{\text{cm}} = 0.4$ to 3.3 MeV
- Normalization to ${}^7\text{Be}+\text{Au}$ scattering and to ${}^7\text{Be}+{}^{12}\text{C}$ scattering



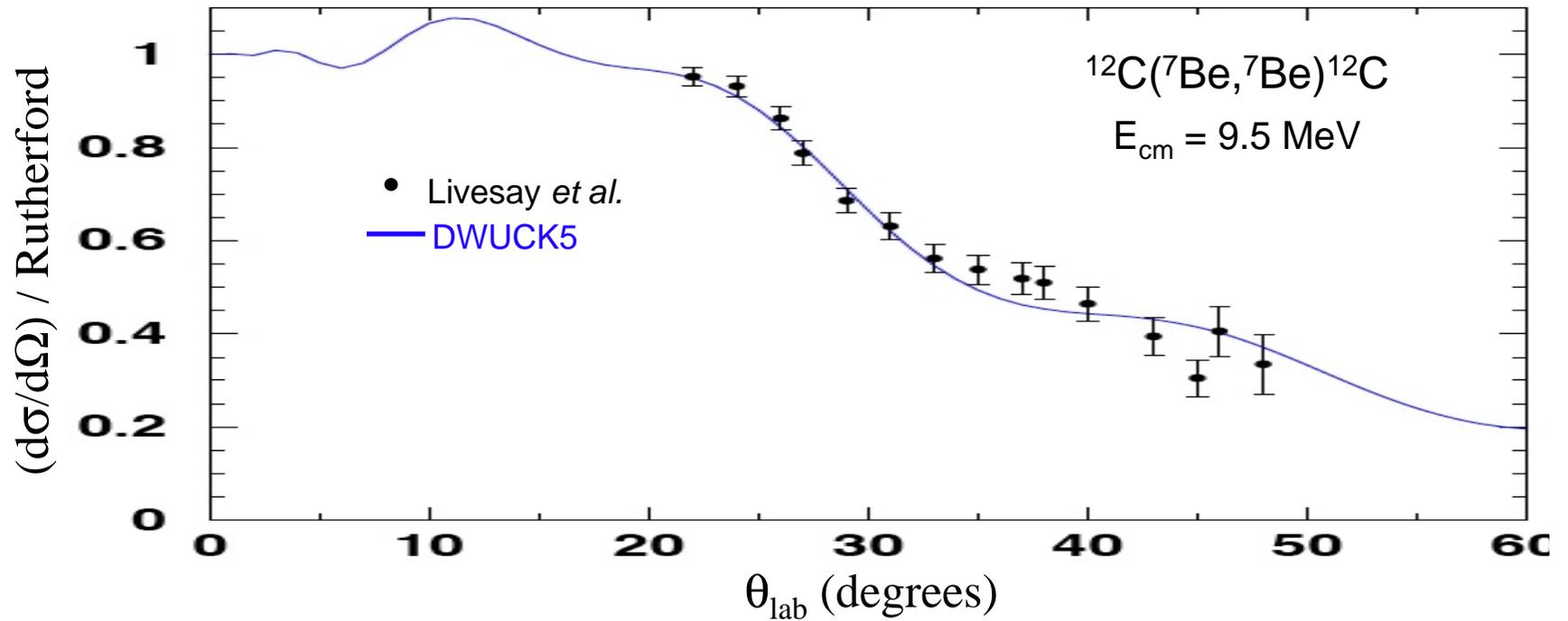
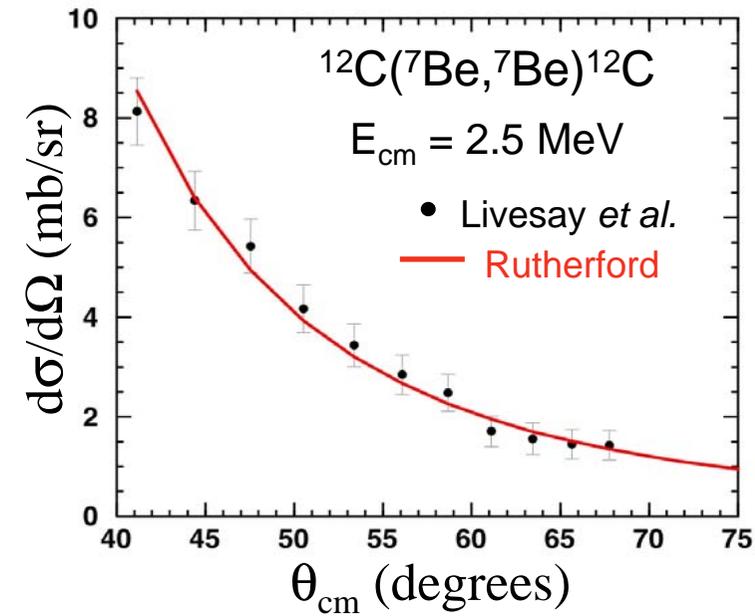
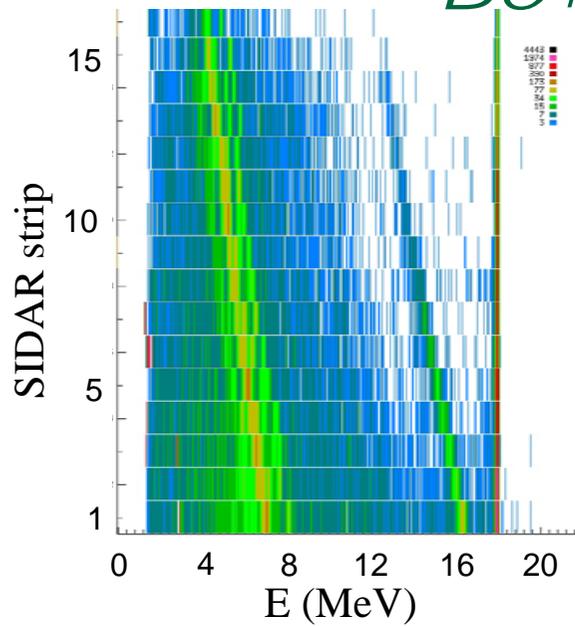
Thick-target excitation function



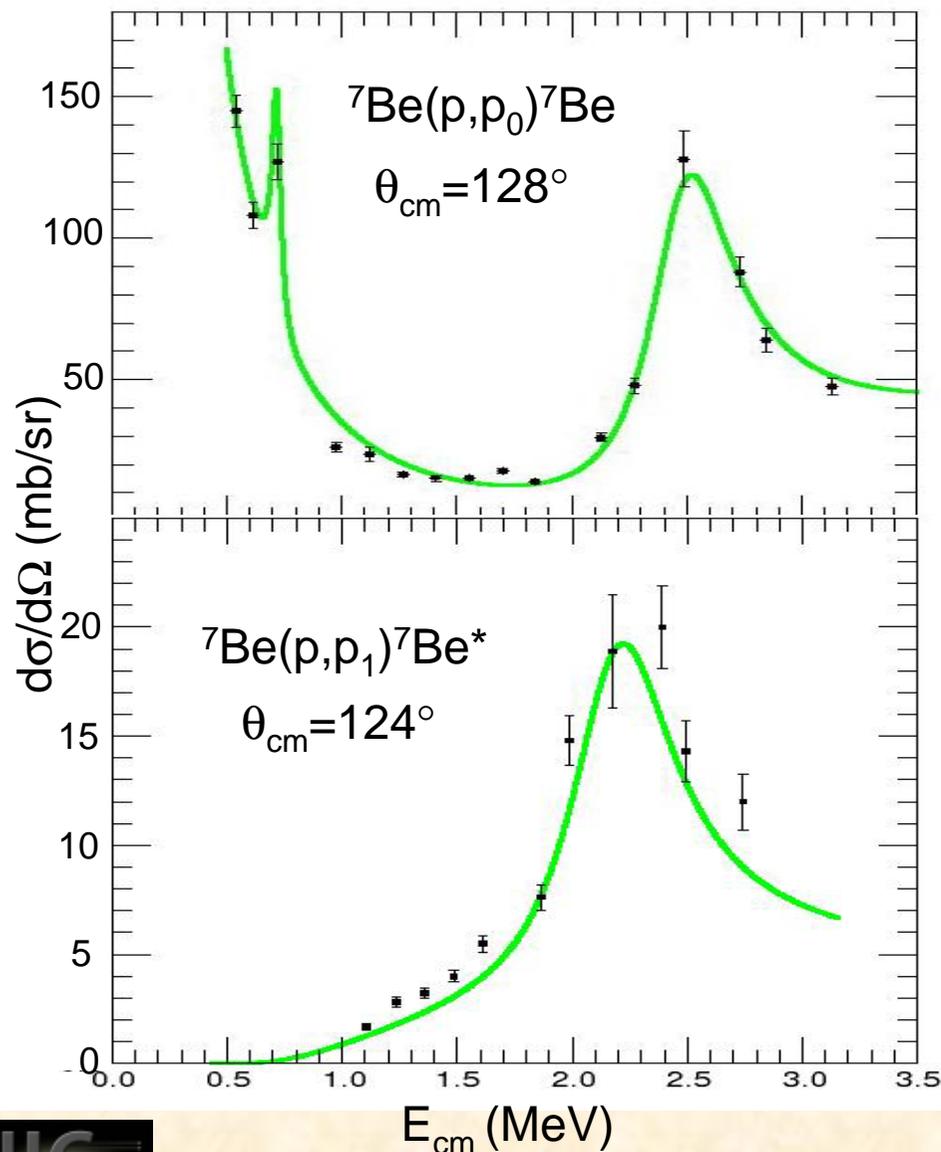
Thin target
 $E_{\text{lab}} = 20 \text{ MeV}$



${}^7\text{Be}+\text{Au}$ & ${}^7\text{Be}+{}^{12}\text{C}$ Scattering



Thin-target data



- New positive parity resonance observed in inelastic channel!
 - Not the known 3^+
 - $3^+ \rightarrow$ f-wave in inelastic
- $E_{cm} \sim 2.3$ MeV
- Best fit:
 - $J^\pi = 2^+$
 - $\Gamma \sim 600$ keV
 - $\Gamma_{p0} \sim \Gamma_{p1}$
- Possible $J^\pi = 0^+$ & $J^\pi = 1^+$?
- R-matrix analysis ongoing
- Accurate absolute normalization should allow accurate determination of phase shifts
- Resonance is too high in energy to significantly affect $S(0)$, but may explain some of the higher energy behavior





- New direct measurements and transfer reactions will continue to reduce the uncertainty on the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction rate.
- The $^7\text{Be}(p,\gamma)^8\text{B}$ cross section will be measured in inverse kinematics with an accuracy of better than 5%.
- Measurements with ^{25}Al radioactive ion beams will improve our understanding of the hot AlMg cycle and ^{26}Al production in novae.
- Many important reactions (e.g. $^{30}\text{P}(p,\gamma)^{31}\text{S}$, rp process waiting points) will remain experimentally out of reach and uncertain.



- A next-generation Rare Isotope Accelerator, as it was previously envisioned, is no longer under consideration.
- The USDOE has put a next-generation radioactive ion beam facility in its 5-year plan to Congress:
 - ~\$500M
 - PED funds ~ 2011
- First scientific results from a new U.S. radioactive ion beam facility.

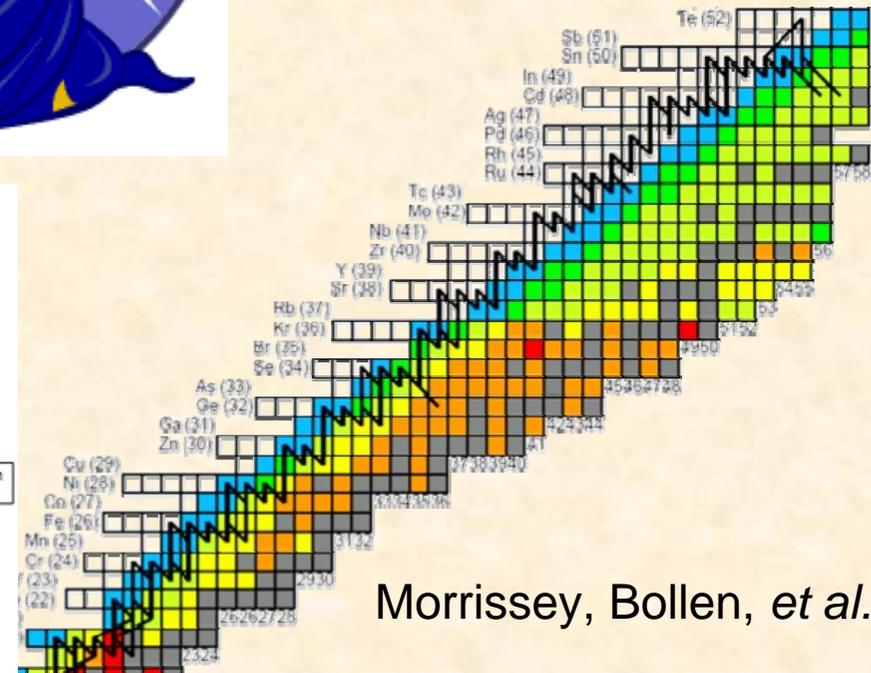
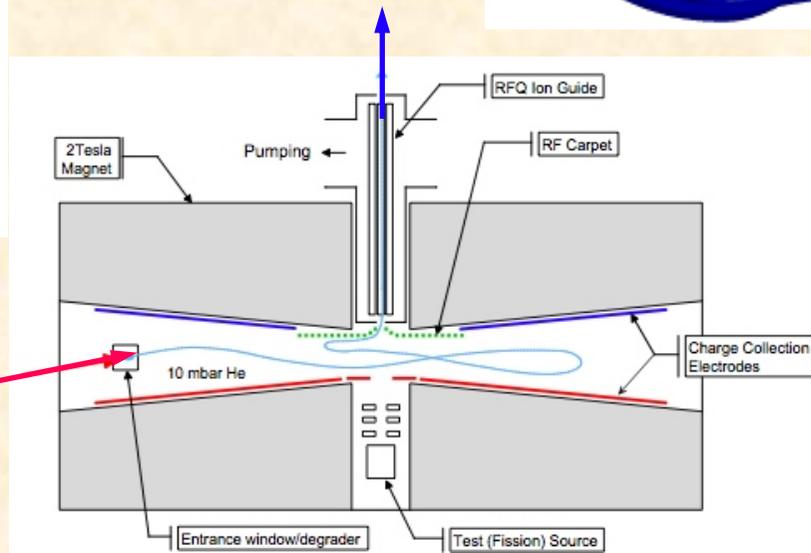




To accelerator



Fast Beam



Morrissey, Bollen, *et al.*

- Reaccelerated beams currently under development at MSU:
 - ^{30}P 10^8 s^{-1} → $^{30}\text{P}(p,\gamma)^{31}\text{S}$
 - ^{45}V 10^5 s^{-1} → transfer reactions
 - ^{68}Se 10^4 s^{-1} → p elastic scattering



Thanks to



K.Y. (Andy) Chae, Ryan P. Fitzgerald, R. Jake Livesay

A. Adekola, D.W. Bardayan, C.R. Brune, A E. Champagne,
C. Deibel, U. Greife, M.S. Johnson, K.L. Jones, R.L. Kozub, Z. Ma,
B.H. Moazen, C.D. Nesaraja, S.D. Pain, J.F. Shriner, Jr.,
M.S. Smith, D.W. Stracener, J.S. Thomas, D.W. Visser, C. Wrede

the HRIBF staff,

the U.S. DOE,

the organizers for a great conference,

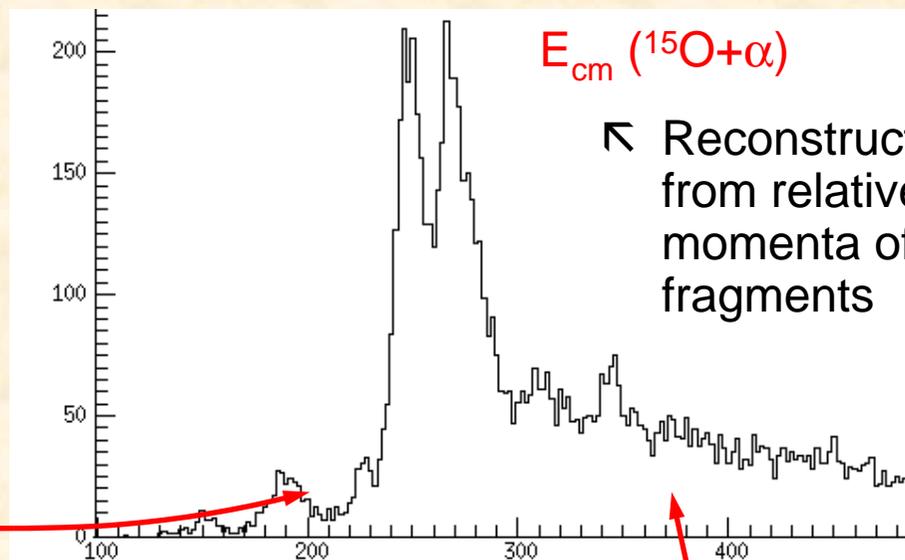
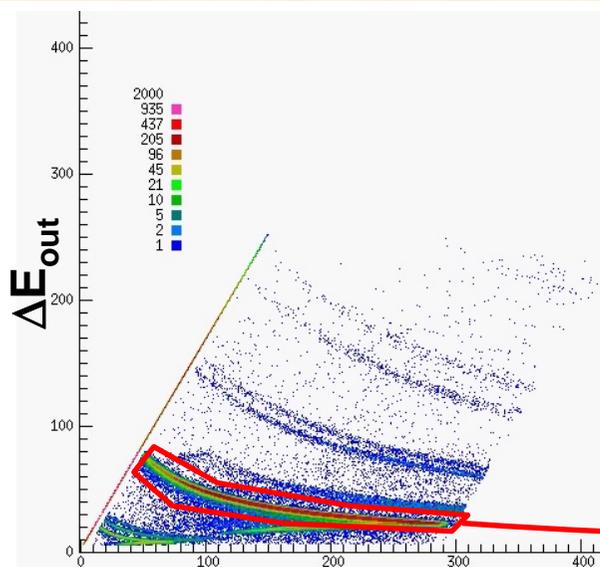
the organizers of the summer school,

and you for sticking around.





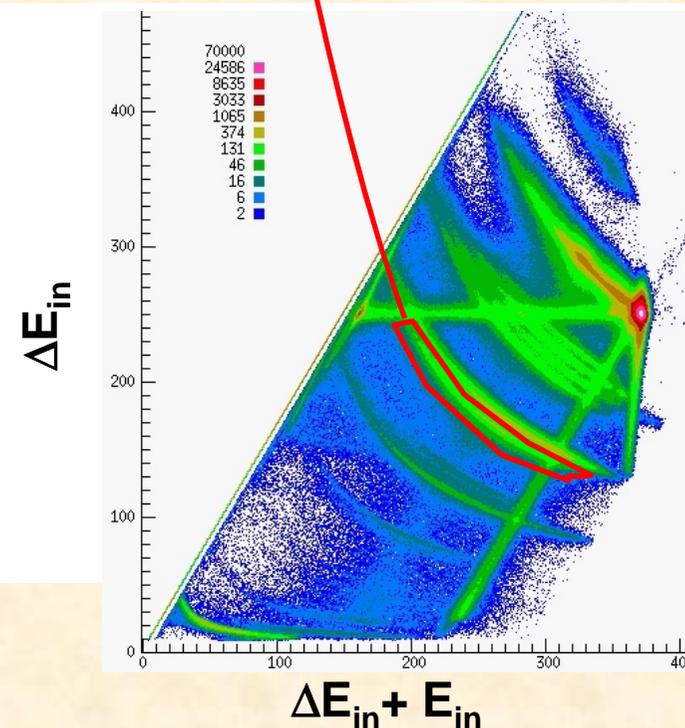
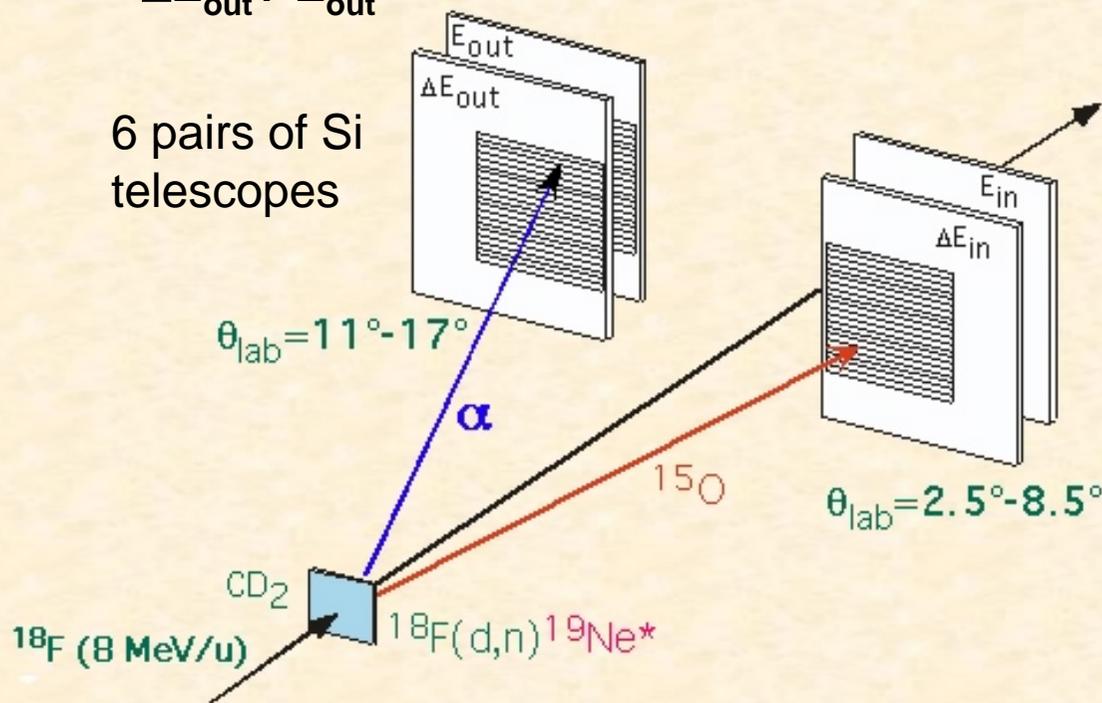
Adekola, Brune, *et al.*,
Poster #20.23



↖ Reconstruct E_{cm}
from relative
momenta of
fragments

$\Delta E_{out} + E_{out}$

6 pairs of Si
telescopes



$\Delta E_{in} + E_{in}$