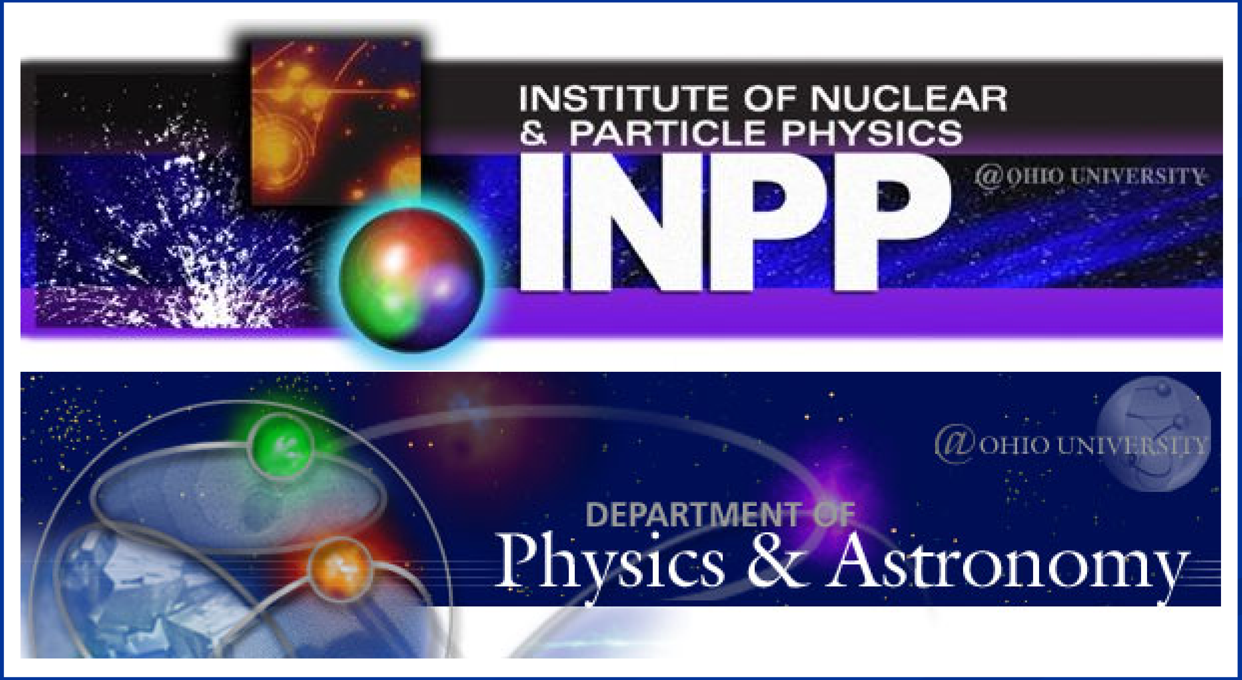
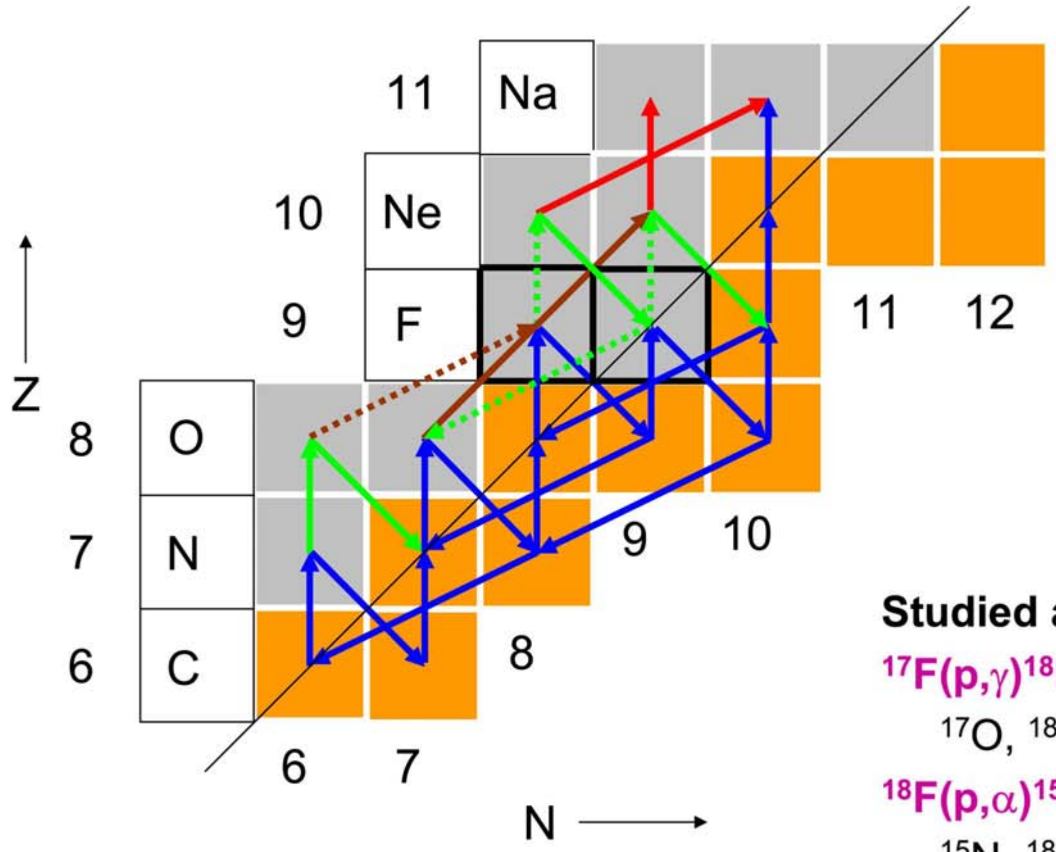
Nuclear Astrophysics - II

Carl Brune



Reactions in Stellar Explosions
(T ~ 10^7-10^9 K, varying densities)



↑ ~0.01 GK

↑ ~0.2 GK

↑ ~0.5 GK

↑ ~1 GK

Studied at HRIBF: ⇡

^{17}F(p,γ)^{18}Ne

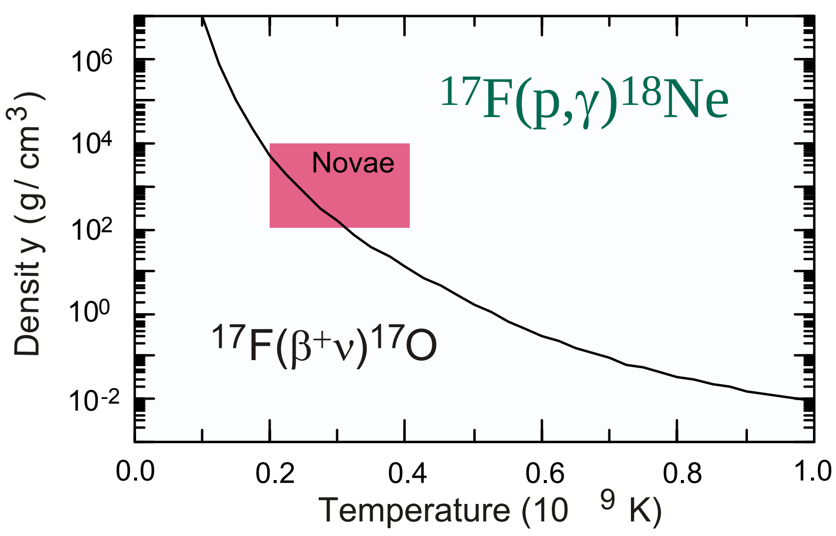
^{17}O, ^{18}F production

^{18}F(p,α)^{15}N and ^{18}F(p,γ)^{19}Ne

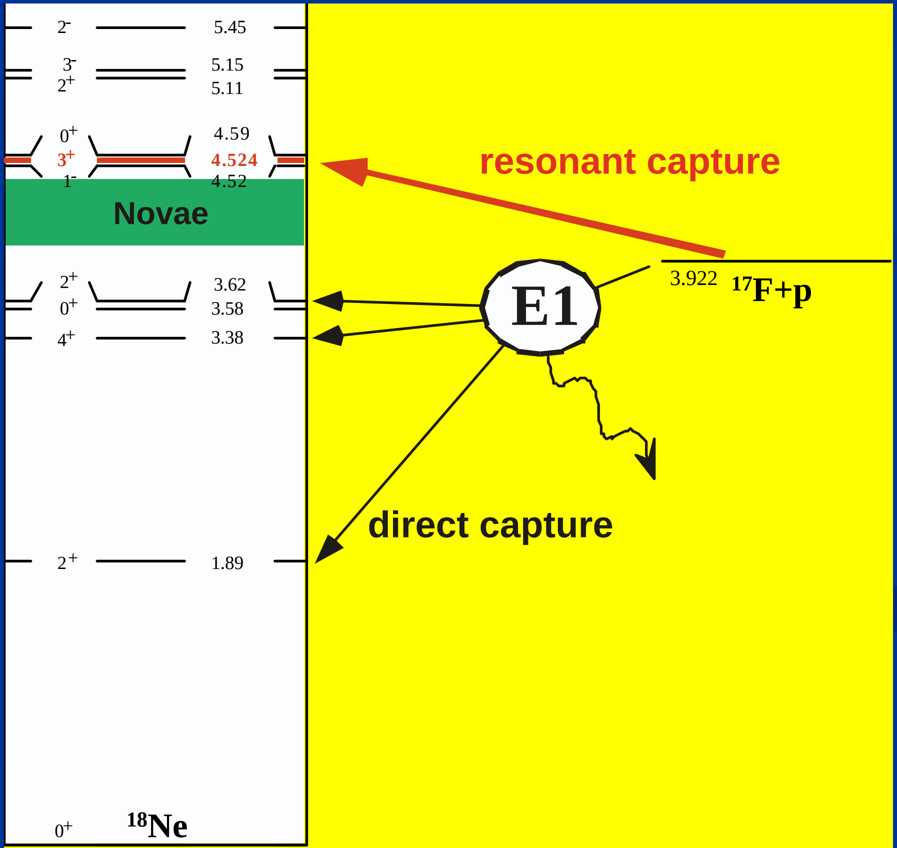
^{15}N, ^{18}F production

^{17}O/^{18}O ratios

The $^{17}F(p,g)^{18}Ne$ reaction rate

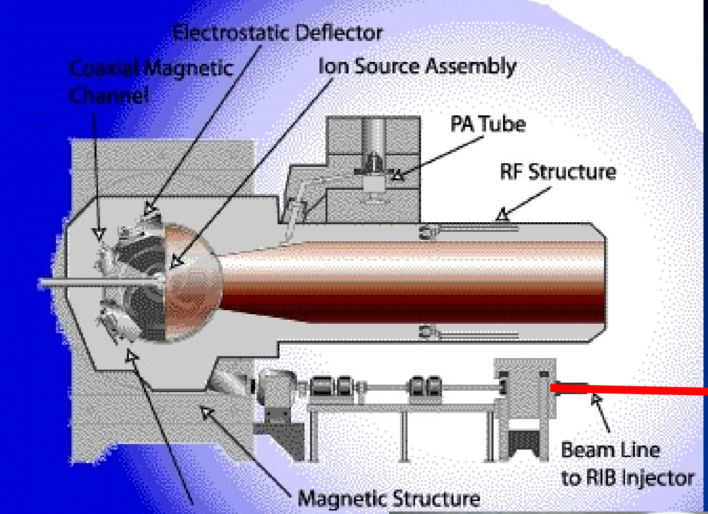


- Capture rate is comparable to the beta decay rate in novae.



- Two contributions to the rate:
  - Direct capture
  - 3+ resonance

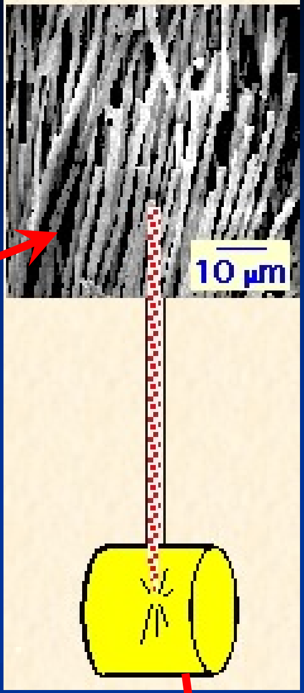
The Holifield RIB Facility at Oak Ridge National Lab



ORIC

p, d, or a

Hot, fibrous production target

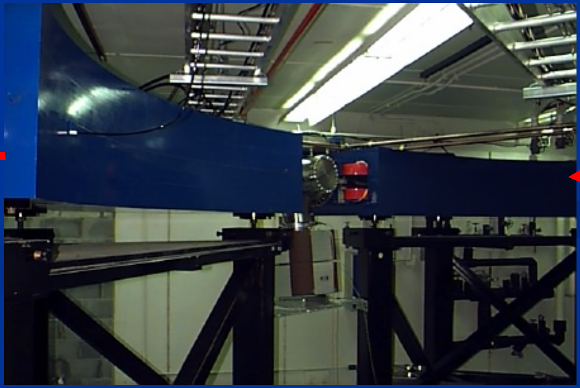


Ion source

25 MV tandem

RIB (300 keV)

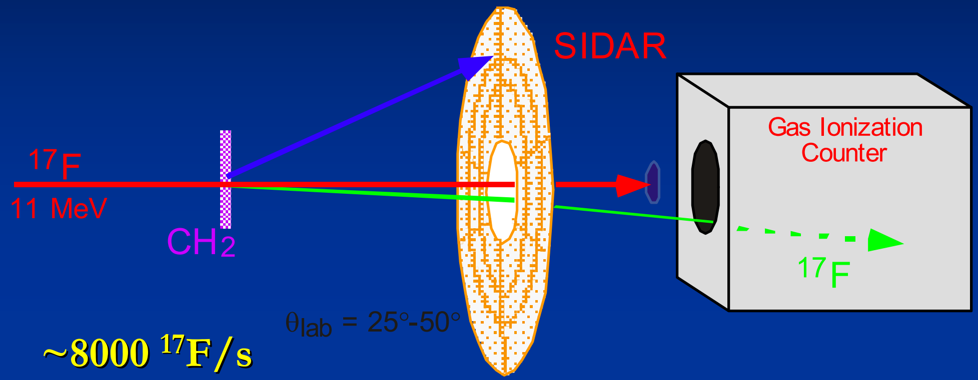
Mass analysis

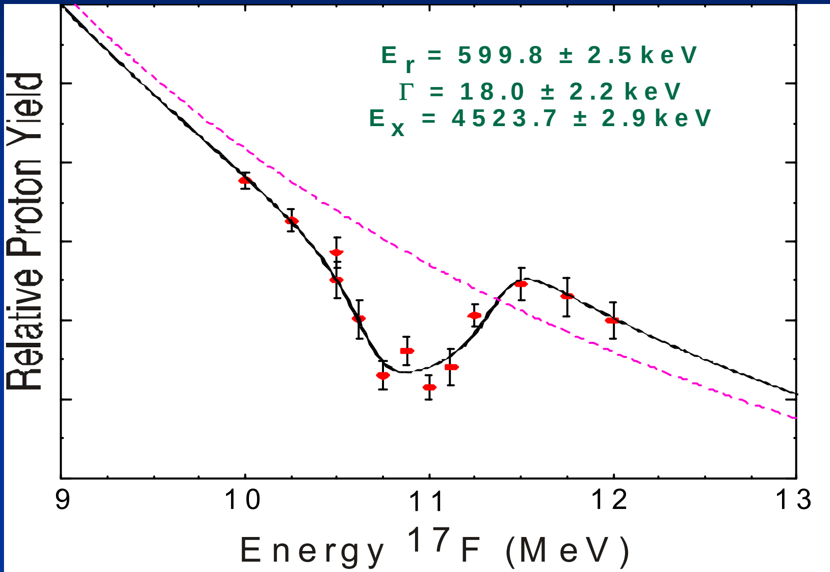


To experiments

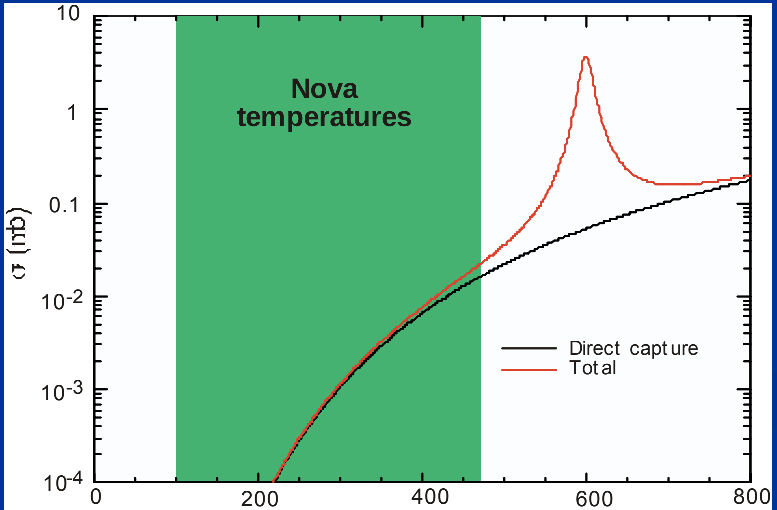
Energy and width of 3^+ measured via $^{17}F + p$ scattering

D. W. Bardayan *et al.*, Phys. Rev. C **62** (2000) 055804.
D. W. Bardayan *et al.*, Phys. Rev. Lett. **83** (1999) 45.

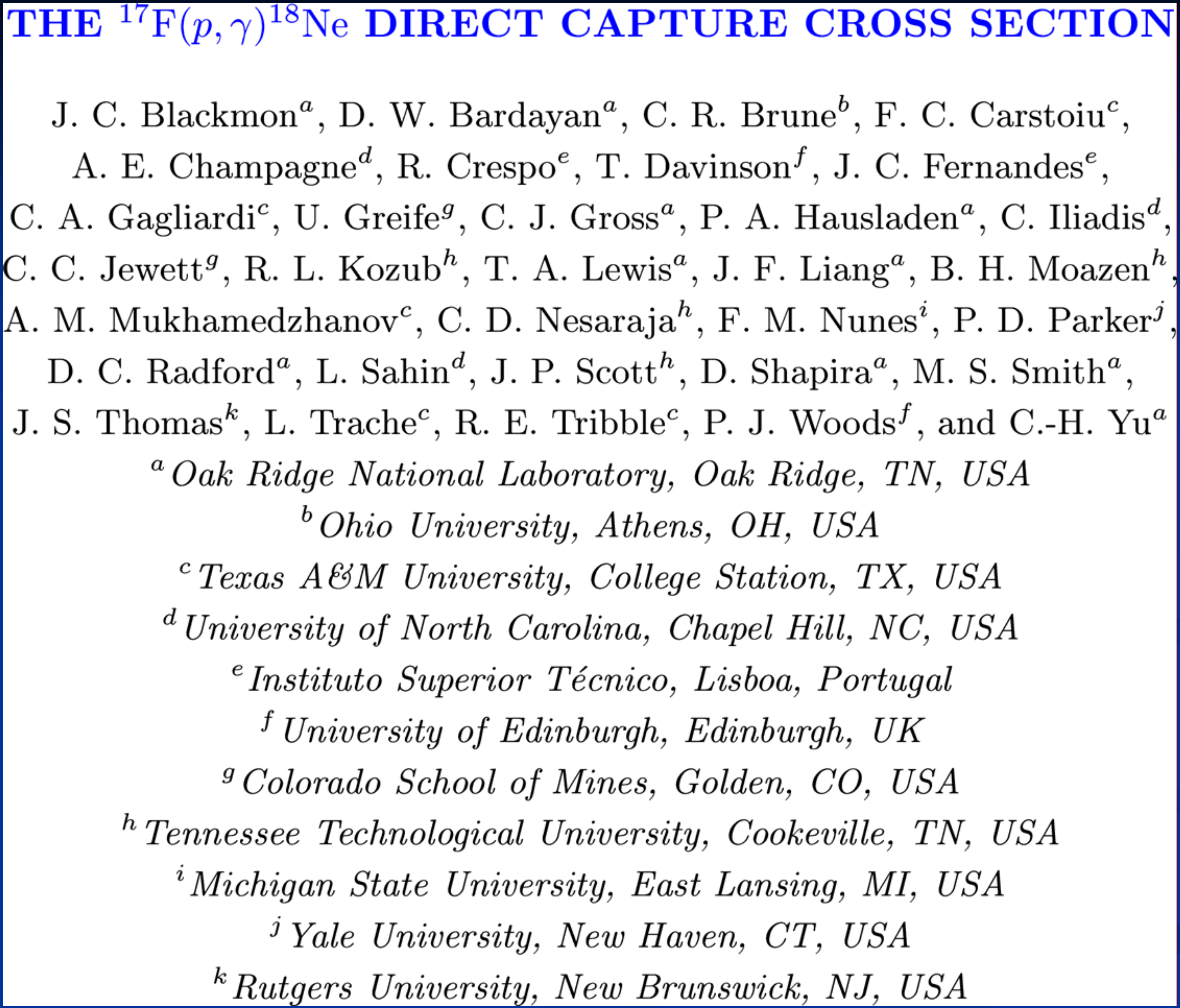




- ~8000 ^{17}F/s
- 48 μg/cm^2 polyropylene (CH$_2$) target
- Protons detected in large SIlicon Detector ARray (SIDAR)
- Heavy ions detected in coincidence by ionization counter



- 3+ resonance is too high in energy to contribute significantly to the rate at nova temperatures.
- Direct capture dominates, but cross section is unmeasured. Estimates based on ^{18}O.
- Direct capture cross section is too small to be measured at available ^{17}F intensities.



THE $^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}$ DIRECT CAPTURE CROSS SECTION

J. C. Blackmon[a], D. W. Bardayan[a], C. R. Brune[b], F. C. Carstoiu[c],
A. E. Champagne[d], R. Crespo[e], T. Davinson[f], J. C. Fernandes[e],
C. A. Gagliardi[c], U. Greife[g], C. J. Gross[a], P. A. Hausladen[a], C. Iliadis[d],
C. C. Jewett[g], R. L. Kozub[h], T. A. Lewis[a], J. F. Liang[a], B. H. Moazen[h],
A. M. Mukhamedzhanov[c], C. D. Nesaraja[h], F. M. Nunes[i], P. D. Parker[j],
D. C. Radford[a], L. Sahin[d], J. P. Scott[h], D. Shapira[a], M. S. Smith[a],
J. S. Thomas[k], L. Trache[c], R. E. Tribble[c], P. J. Woods[f], and C.-H. Yu[a]

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[e] *Instituto Superior Técnico, Lisboa, Portugal*
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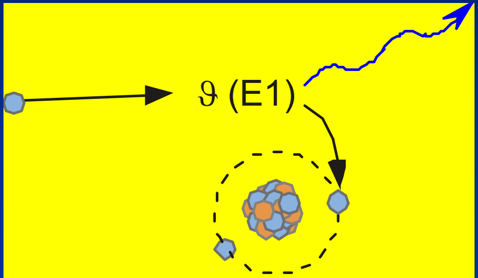
[k] *Rutgers University, New Brunswick, NJ, USA*

Direct capture cross section can be determined by measuring ANC's (or spectroscopic factors) from proton transfer reactions

- Direct capture occurs via an electromagnetic transition at large radii.



- The cross section can be accurately calculated from the Asymptotic Normalization Coefficients (ANC's) with little model dependence.

$$\sigma_{DWBA} \sim \left|\langle \chi_\beta \psi_\beta | \vartheta | \chi_\alpha \psi_\alpha \rangle\right|^2$$

$$\psi \sim \left(\frac{C}{b}\right)\varphi \quad \text{and} \quad \varphi \xrightarrow[r \gg R_A]{} b\,\frac{W}{r}$$

$$\frac{d\sigma}{d\Omega} = \frac{C_{Z+p}}{b_{Z+p}}\,\frac{C_{17F+p}}{b_{17F+p}}\,\sigma_{DWBA}$$

- The ANC's can be determined by measuring the cross section for peripheral proton transfer reactions.

Some Remarks on the “ANC Method”

- The idea to use transfer reactions (via spectroscopic factors) to constrain direct capture (DC) has been around since at least the early 1970s.
- Mukhamedzhanov and collaborators contributed the important observation that both the DC and transfer cross section depend mostly asymptotic tail of the bound state (ANC).
- For transfer reactions, the choices of kinematics and reaction can be exploited to reduce theoretical uncertainties. Experimental realities may limit the choices.
- Error analysis must consider model parameters (e.g. optical potentials) as well the reaction mechanism (e.g. 2-step processes, compound-nuclear processes).

Proton transfer reactions are difficult in inverse kinematics (new experimental techniques are required)

- For stable targets the (^{3}He,d) reaction can achieve ~15 keV resolution using a magnetic spectrograph.

- Inverse kinematics and low beam intensities (in the case of radioactive ion beams) produce several complications.

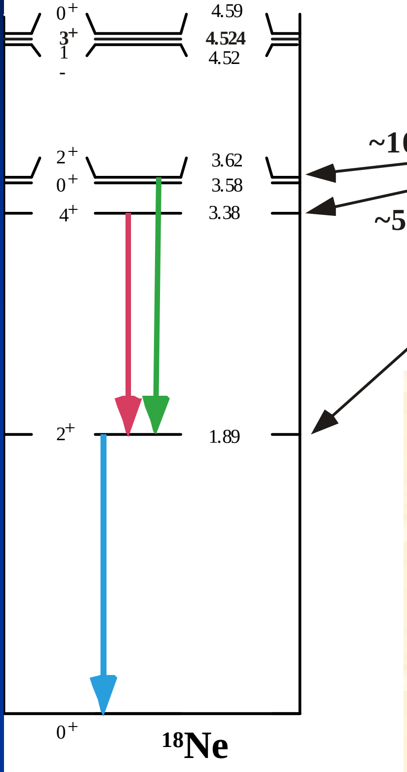
- (d,n): gas target? CD_2 target? Neutron detection?
- (^{3}He,d): gas target? Poor kinematics for detecting the deuteron.
- (^{7}Li,^{6}He) or (^{14}N,^{13}C)

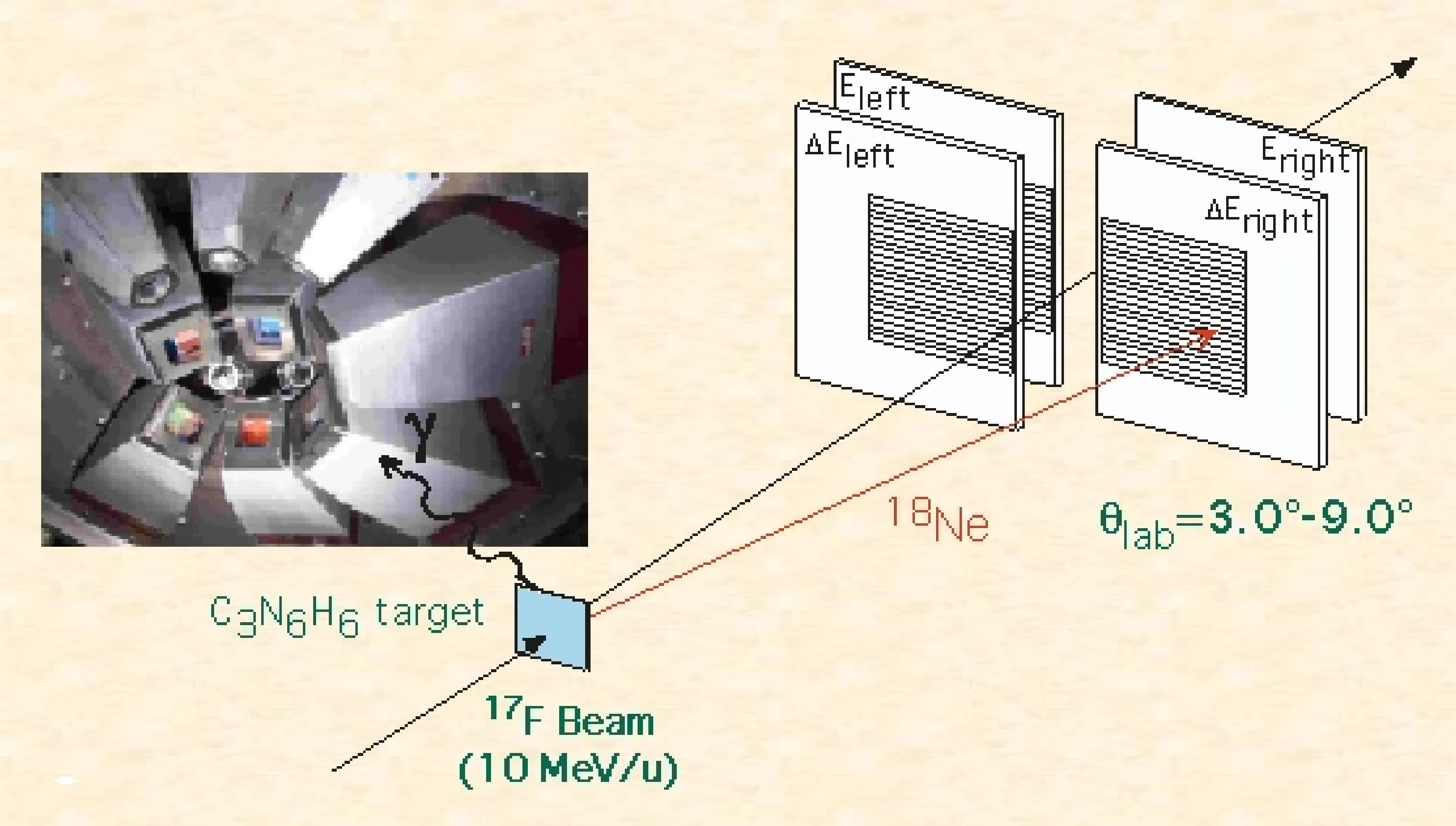
- The beam-like nucleus can be detected, but energy resolution tends to be poor.

- Gamma-ray tagging can be used for bound excited states.

$^{14}N(^{17}F,^{18}Ne^*)^{13}C$ at the HRIBF

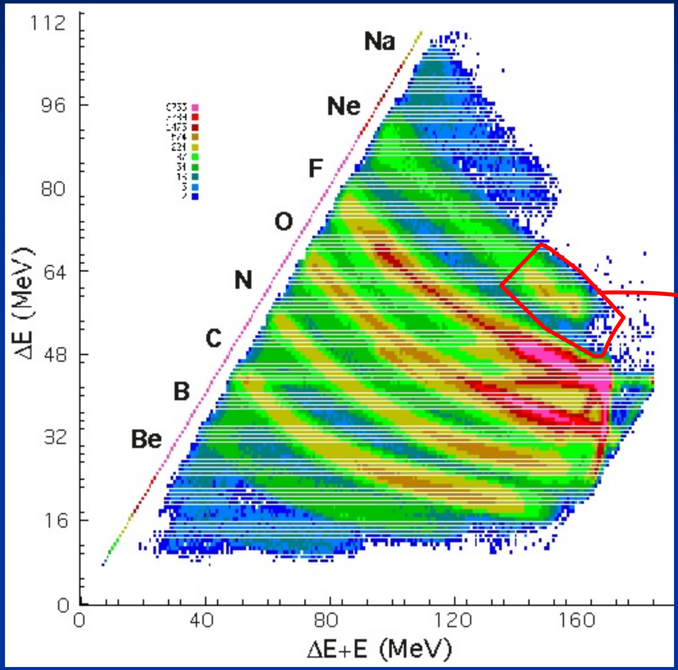
- The direct capture cross section is dominated by capture to excited states in ^{18}Ne.
- Gamma rays were detected by the CLARION array in coincidence with ^{18}Ne to resolve the states of interest.





Charged-particle spectra

Particle ID
Summed over whole detector

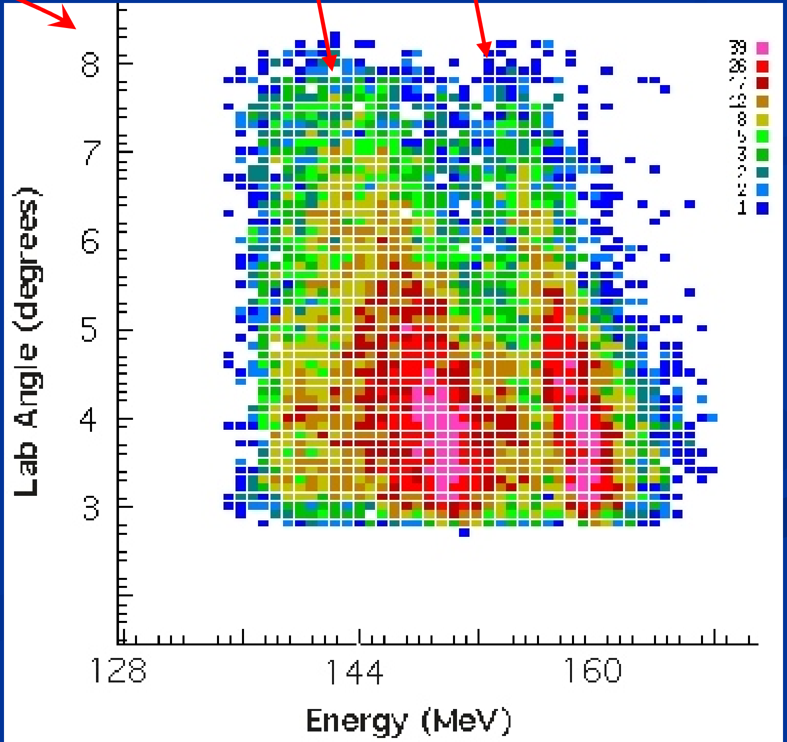


- Good Z separation, but (so far) poor isotopic separation in strip detector
- Charged-particle energy resolution is not good enough (yet) to separate any of the states of interest in ^{18}Ne.

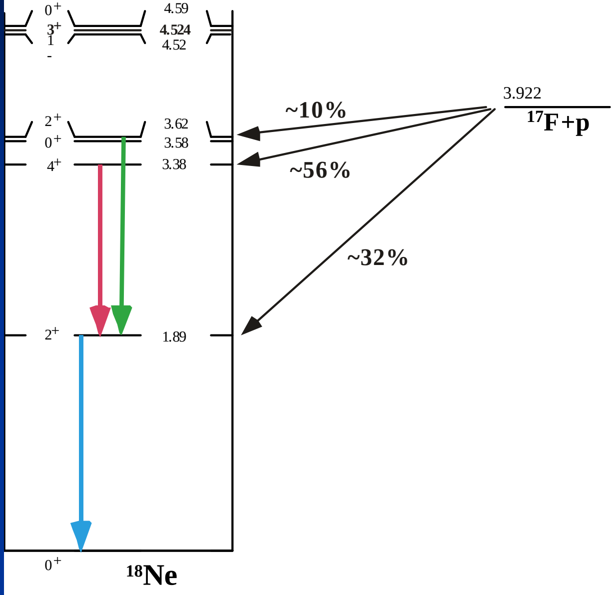
- ^{18}Ne is the strongest neon group, but populated two ways:

^{12}C(^{17}F,^{18}Ne*)^{11}B

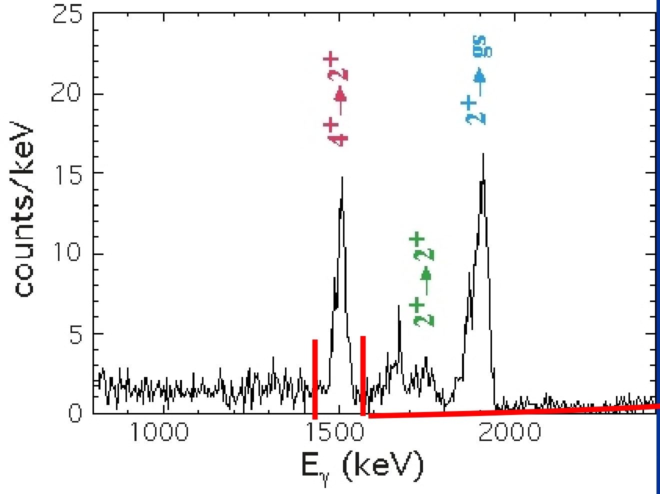
^{14}N(^{17}F,^{18}Ne*)^{13}C



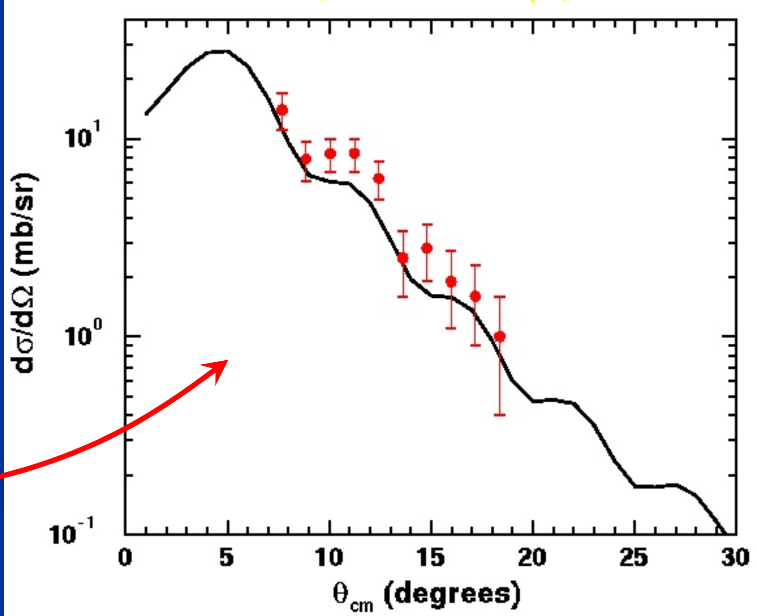
Gammas needed to resolve states



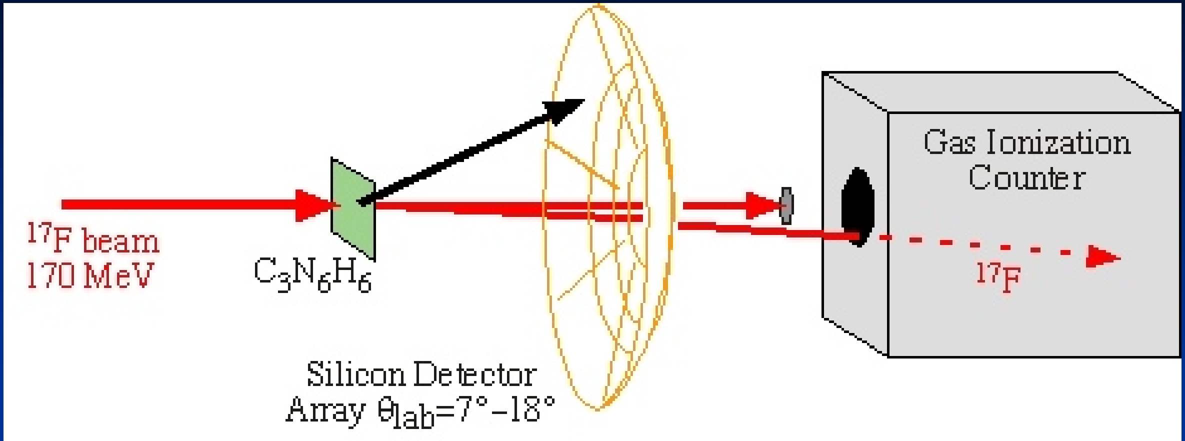
- data analysis in progress
- DWBA calculations with no free parameters
- S factor ~ 30% higher than shell model calculations
- Expect to accurately determine direct capture cross section within 10 %.

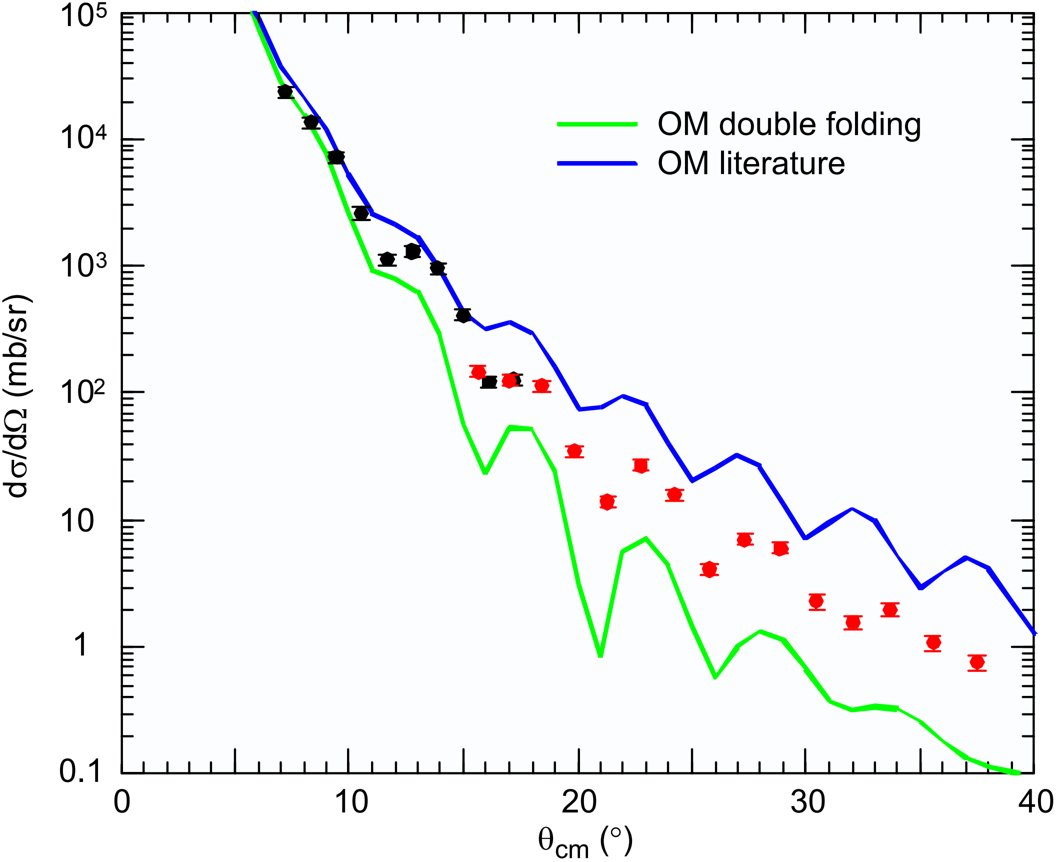


^{14}N(^{17}F,^{18}Ne$_{4+}$)^{13}C

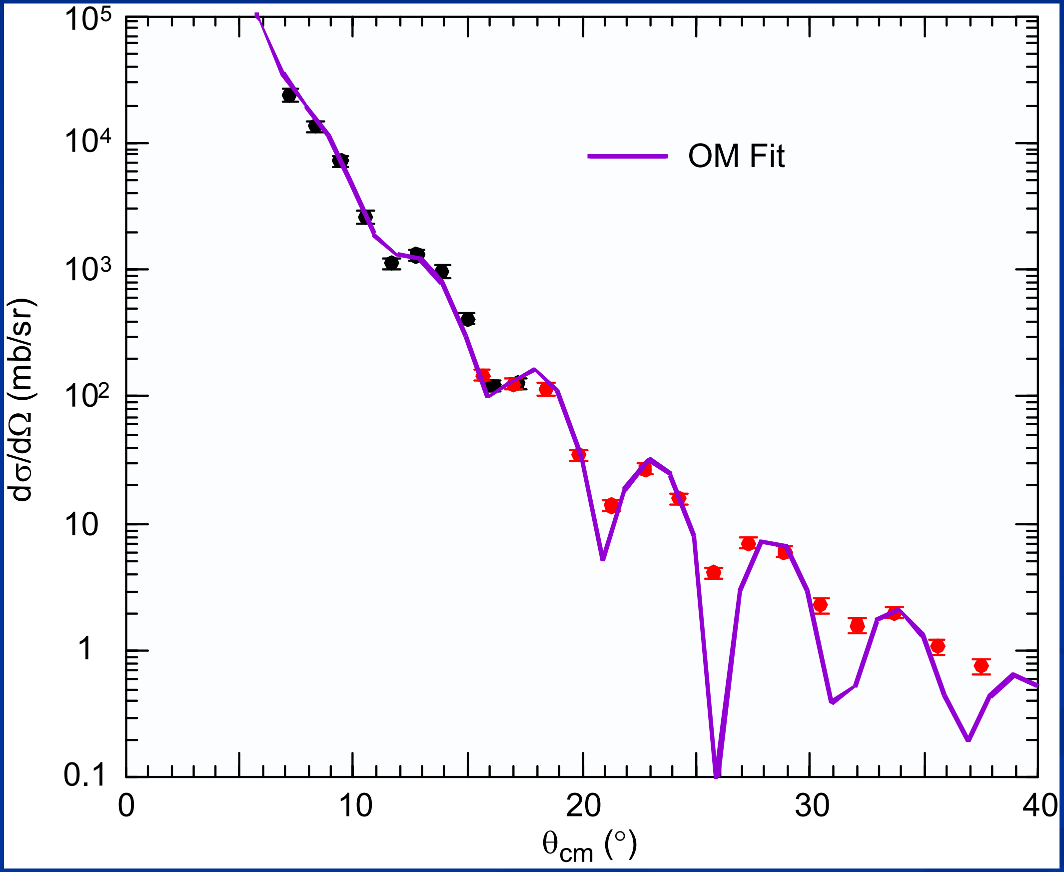


$^{14}N(^{17}F,^{17}F)^{14}N$ Measurement

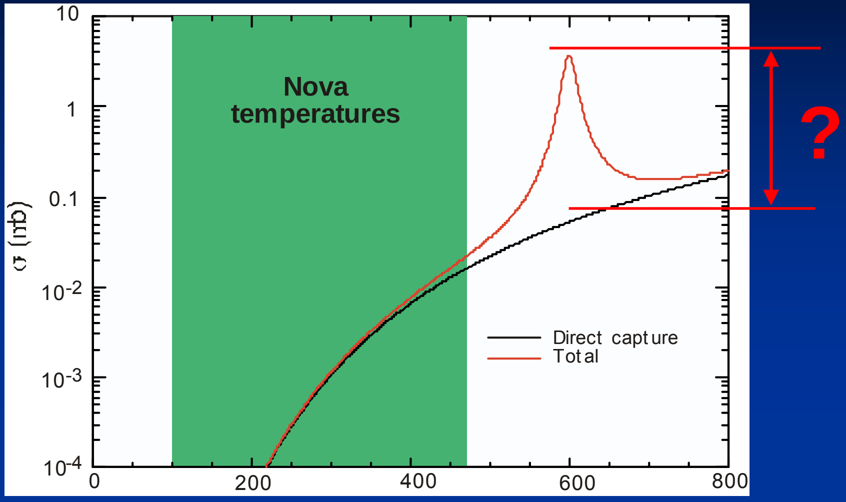




These data constrain the Optical Model parameters for the transfer reaction

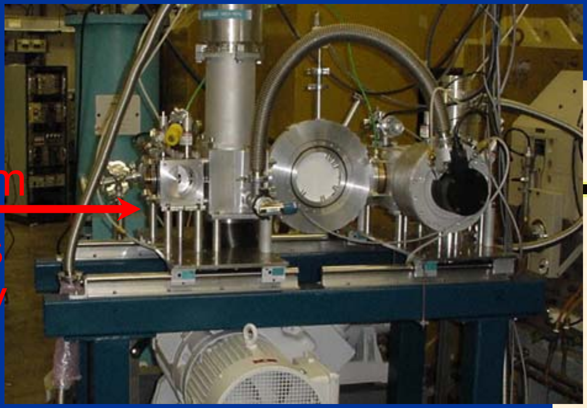


^{17}F(p,γ)^{18}Ne resonant cross section



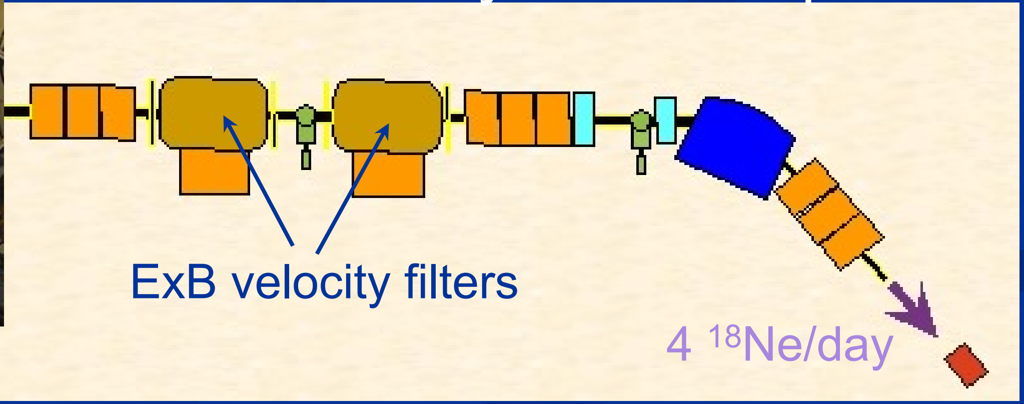
- Amplitude of 3^+ resonance is uncertain.
- Dominates the reaction rate at higher temperatures.
- We hope to measure the ^{17}F(p,g)^{18}Ne resonant cross section using a H_2 gas target and the DRS.

windowless H_2 gas target
10 mg/cm^2



^{17}F beam
10^7 pps
10 MeV

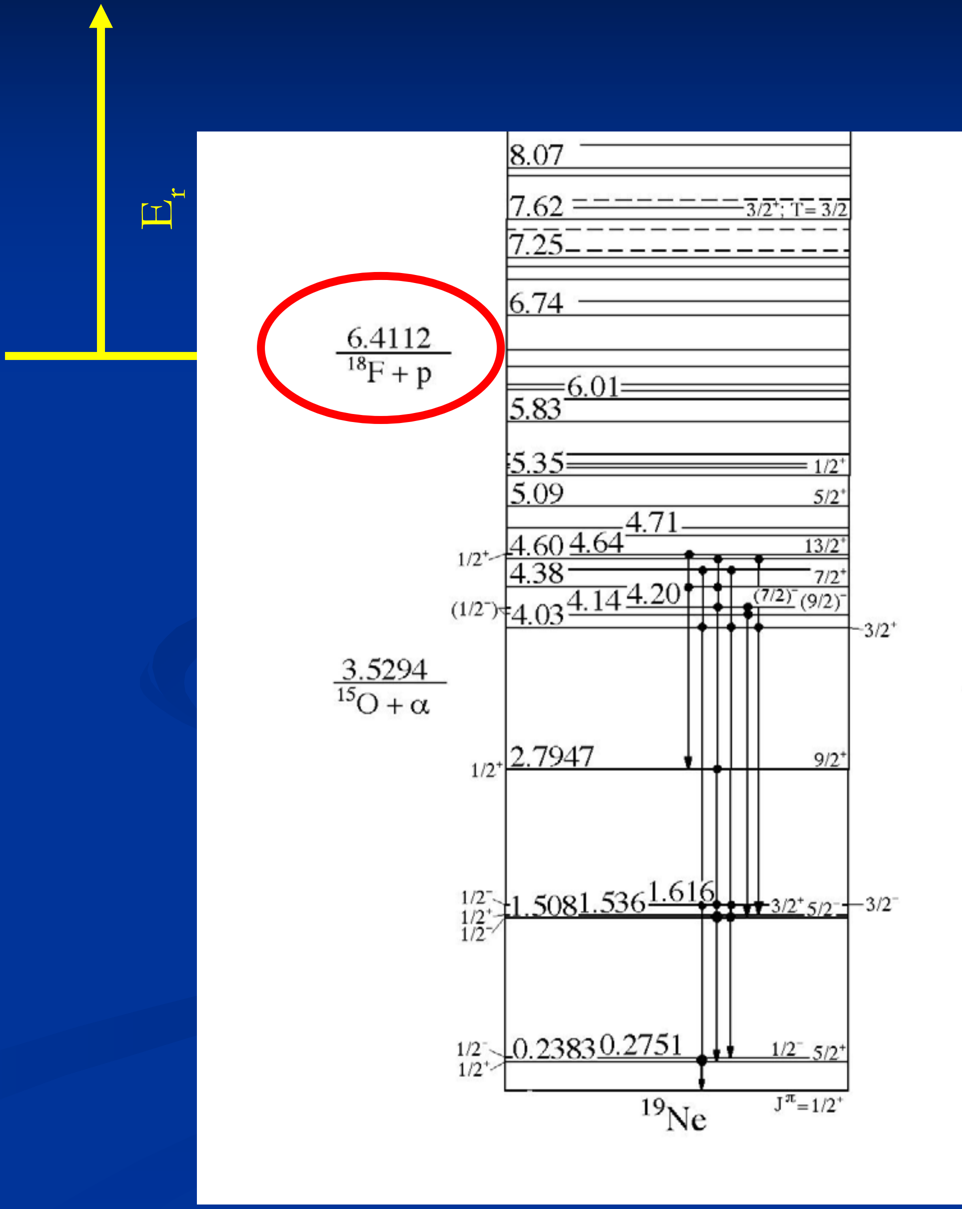
The Daresbury Recoil Separator



- ^{18}Ne from ^{1}H(^{17}F,^{18}Ne) reaction detected by gas ionization counter.

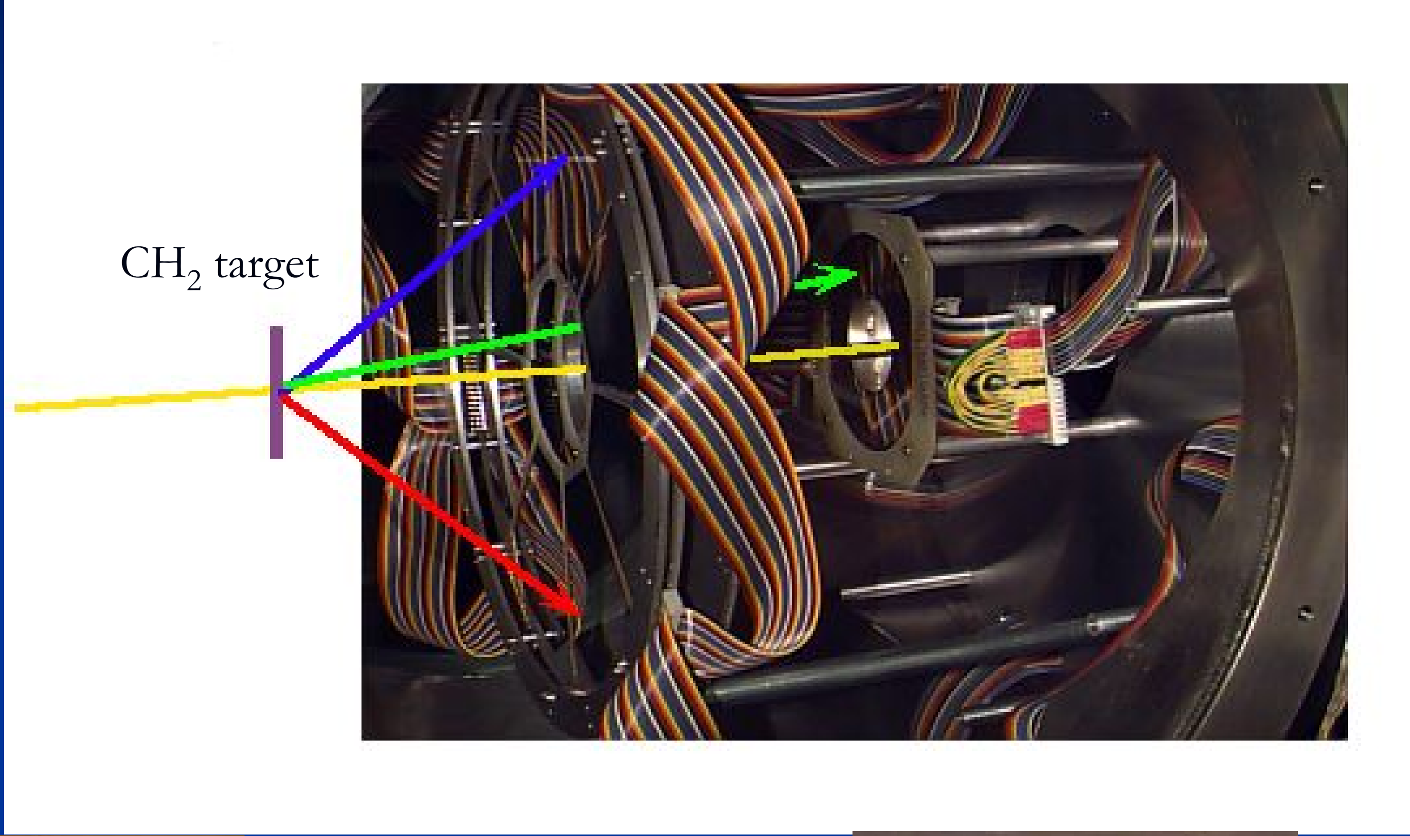
^{18}F(p,α)^{15}O and ^{18}F(p,γ)^{19}Ne

- Several resonances may be important for nova temperatures
- ^{18}F(p,α) can be measured directly, but not over the entire energy range needed for novae.
- Transfer reactions and mirror symmetry can also be used.

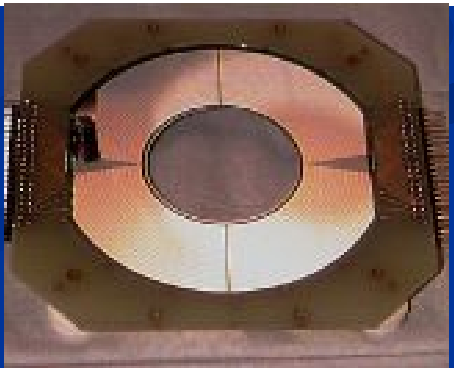


Experimental Approach

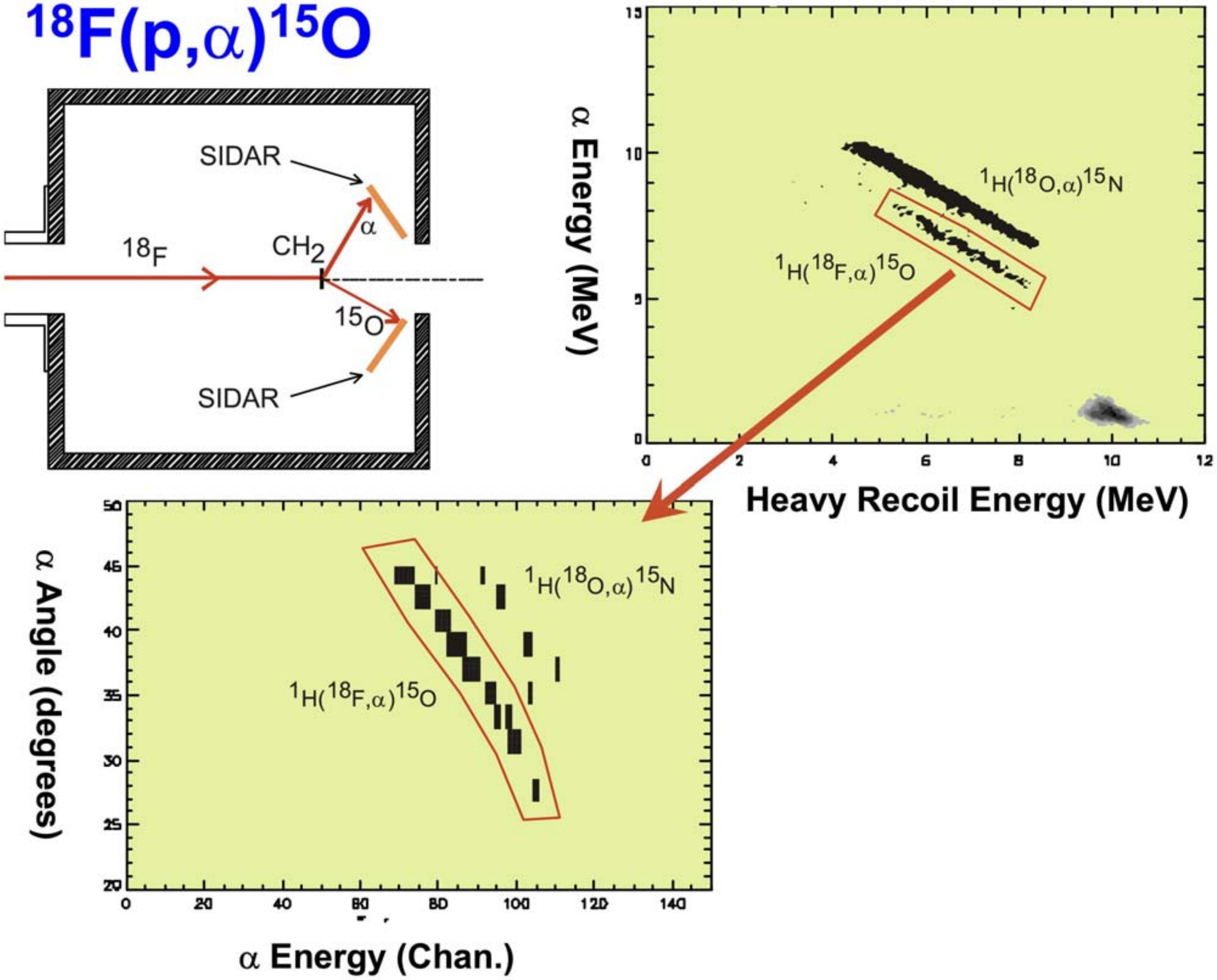
~5x10^5 ^{18}F/sec



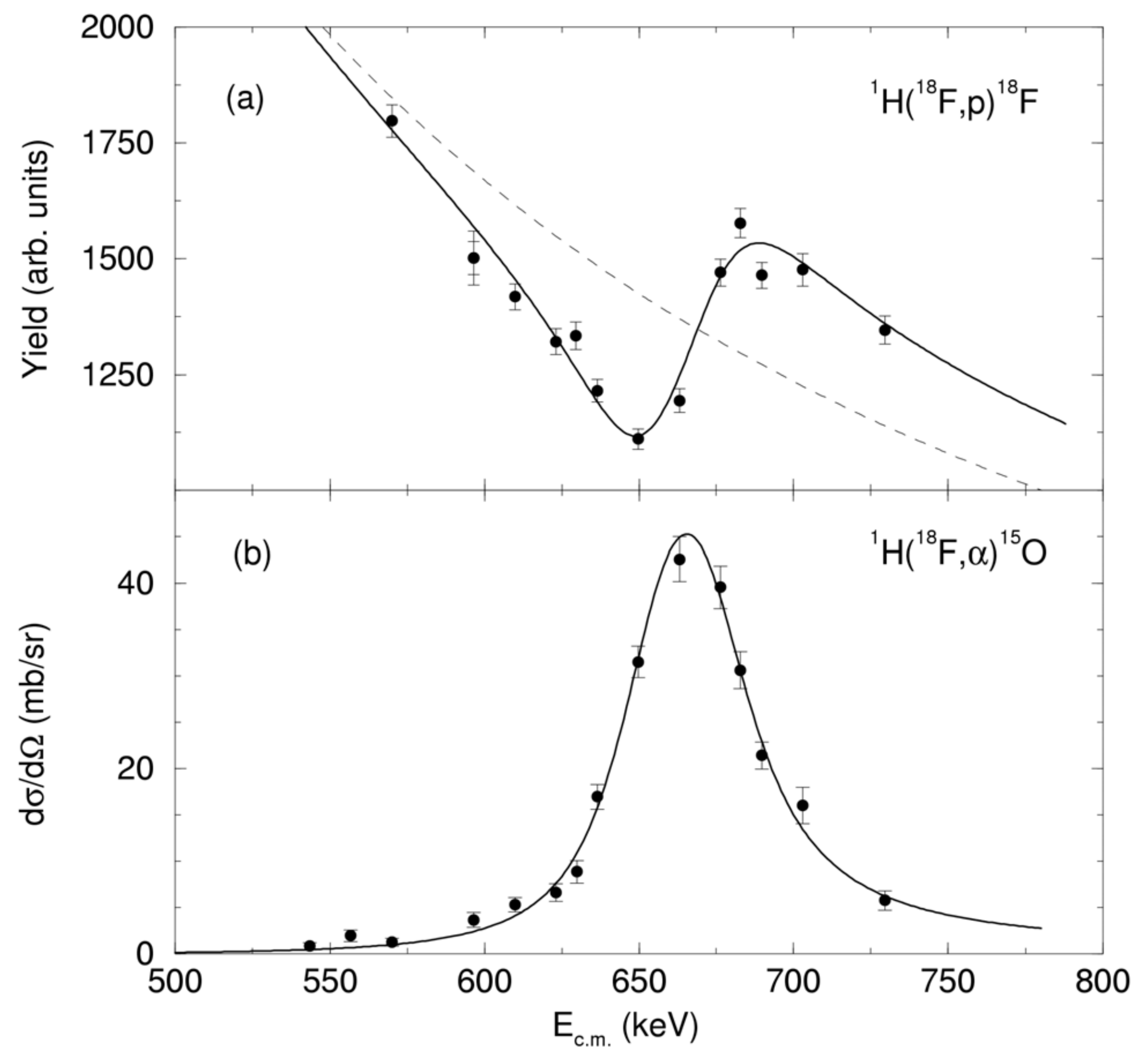
Si Strip Detectors



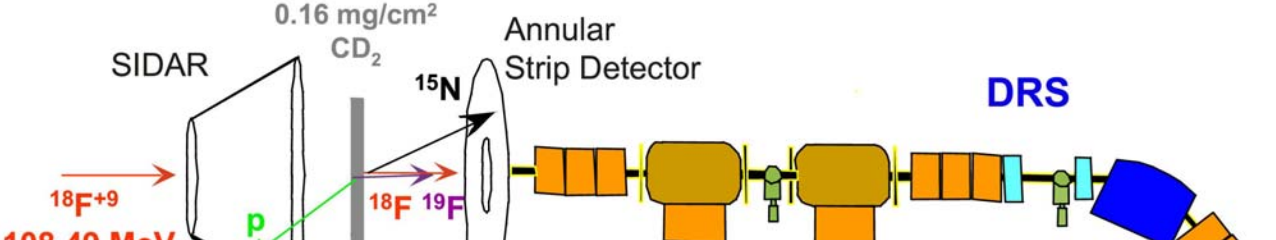
$^{18}F(p,\alpha)^{15}O$

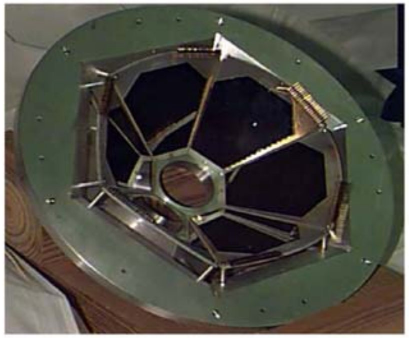


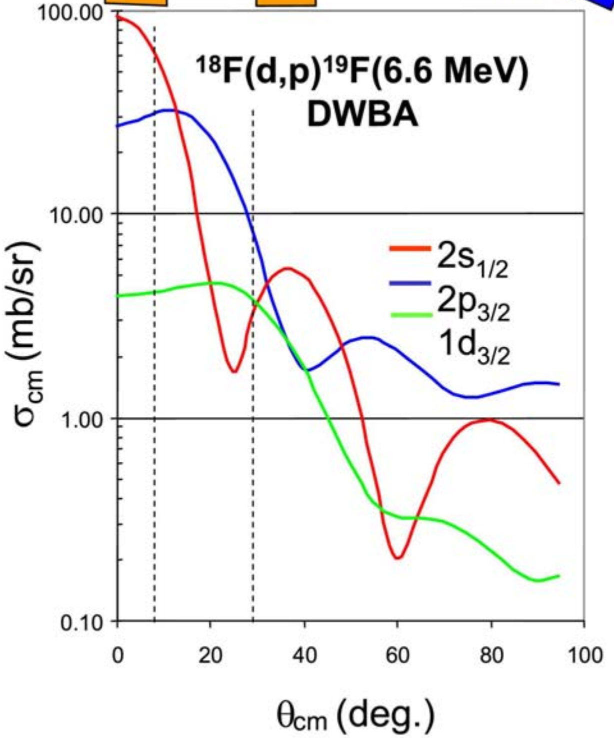
Results


(a)
$^1H(^{18}F,p)^{18}F$
Yield (arb. units)
2000
1750
1500
1250
(b)
$^1H(^{18}F,\alpha)^{15}O$
dσ/dΩ (mb/sr)
40
20
0
500
550
600
650
700
750
800
$E_{c.m.}$ (keV)

$^{2}H(^{18}F,p)^{19}F$ at the HRIBF (6 MeV/u)







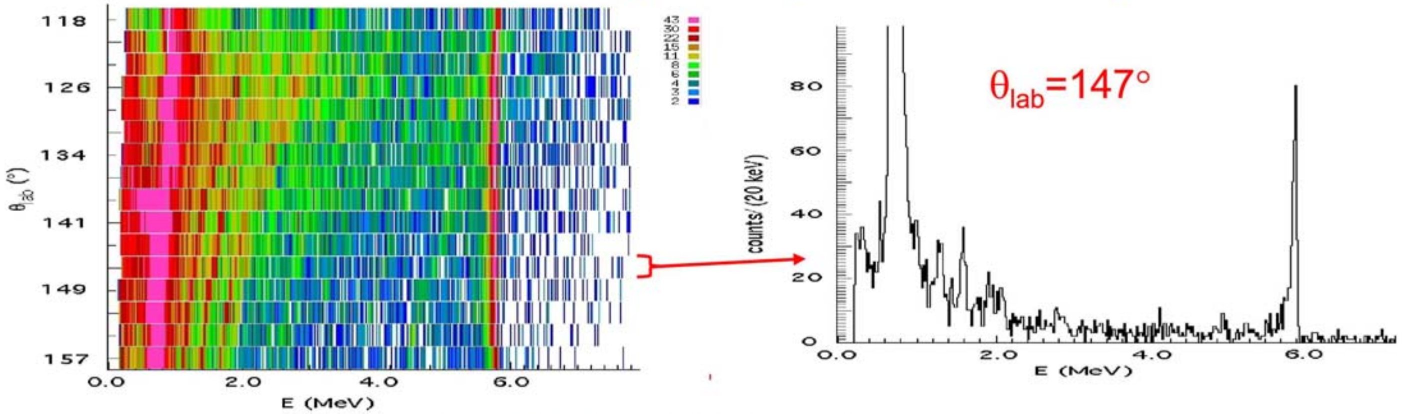
$\theta_{lab} \approx 116° - 160°$

$\theta_{cm} \approx 7° - 29°$

~ 3 days of data with

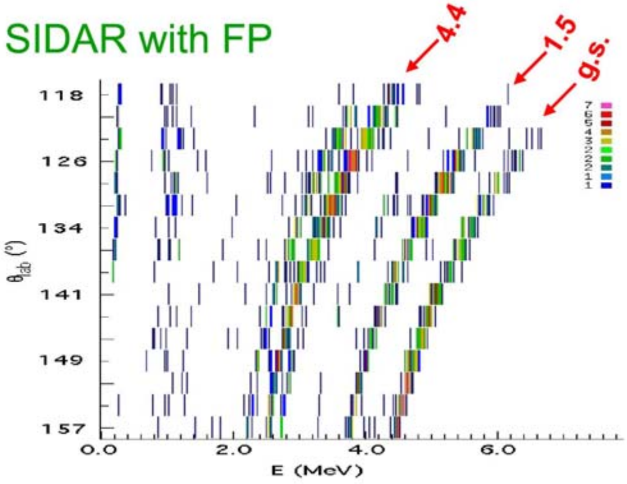
5 x 10^{5} ^{18}F/s on target.

SIDAR Singles Spectra (One Detector)

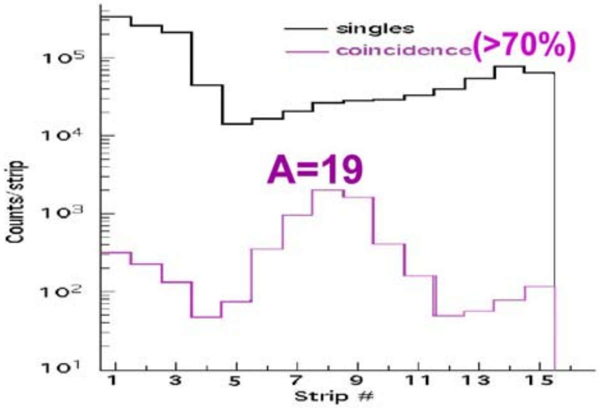


SIDAR-FP Coincidences

SIDAR with FP

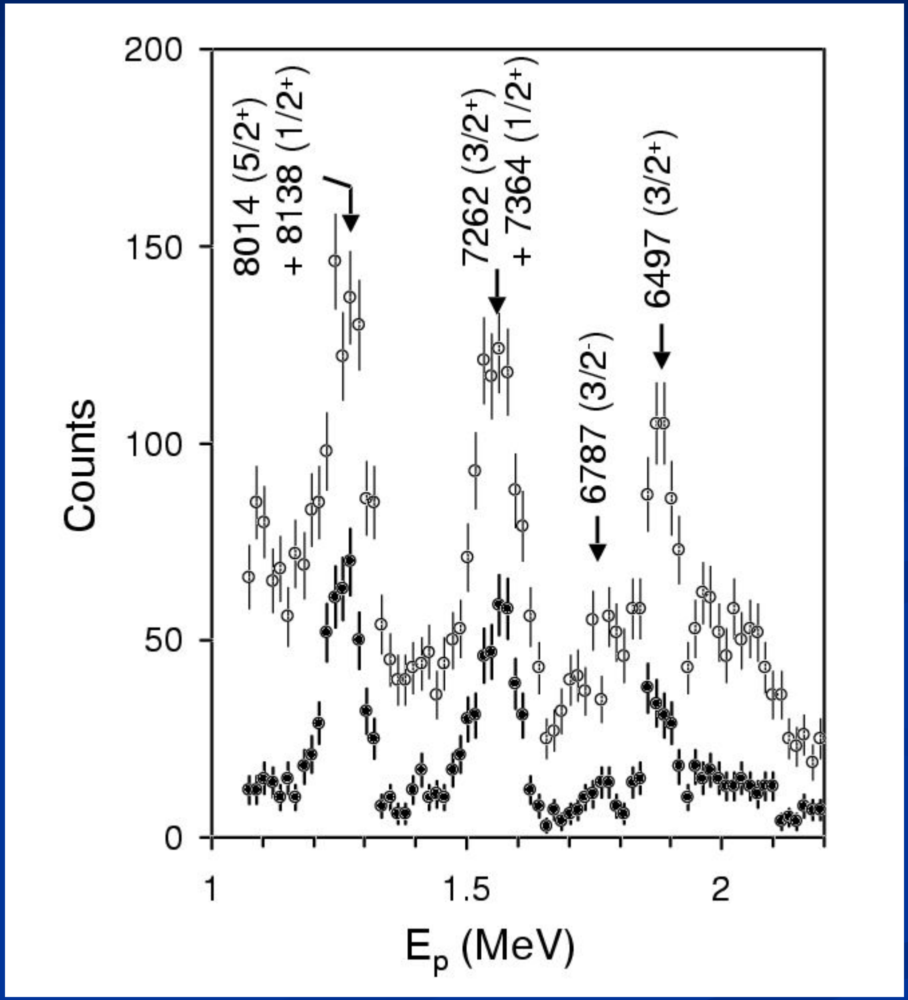


FP Position



Results

$^{18}F(d,p)^{19}F$
proton spectrum
$\theta_{lab} = 147^{o}$



Proton Transfer on ^{18}F

Appeared to be difficult…
but the ^{19}Ne states of interest break up into
$^{15}O+\alpha$ which provides a unique signature.

Our new approach to (d,n) and (d,p) :

$$^{18}F + {}^{2}H \Rightarrow {}^{19}Ne^{*} + n \Rightarrow {}^{15}O + \alpha + n$$

$$\Rightarrow {}^{19}F^{*} + p \Rightarrow {}^{15}N + \alpha + p$$

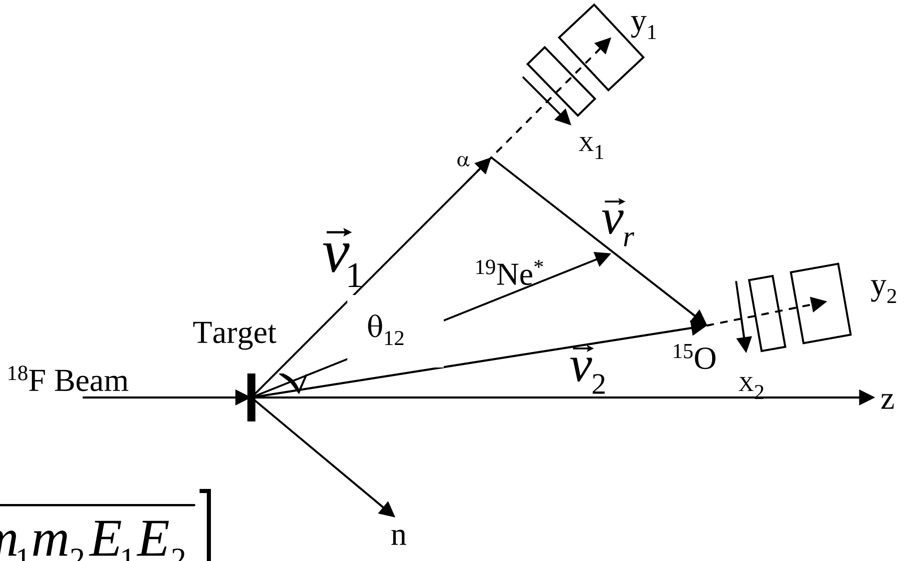
without detecting the n or p.

- **The ^{15}O and α are detected with position-sensitive Si strip detectors.**
- **The relative energy can thus be reconstructed.**
- **This approach is less sensitive to target thickness (720 $\mu g/cm^2$ was used).**
- **Work of my student: Remi Adekola**

Reconstructing the Relative Energy

Reaction:

$^{18}F + {}^{2}H \rightarrow {}^{19}Ne^{*} + n \rightarrow {}^{15}O + \alpha + n$



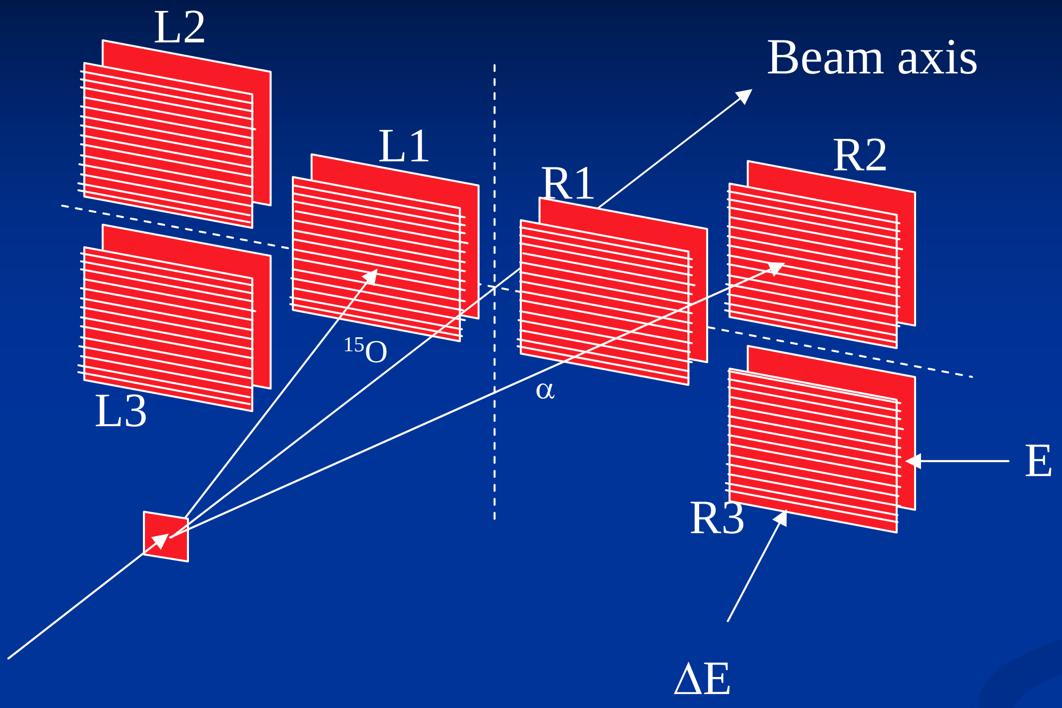
relative energy of the state

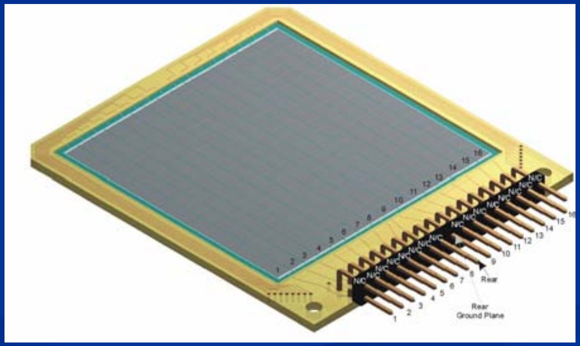
$$E_{rel} = \frac{1}{m_1 + m_2}\left[m_1 E_2 + m_2 E_1 - 2\cos\theta_{12}\sqrt{m_1 m_2 E_1 E_2} \right]$$

$$\boxed{E_x = E_{th} + E_{rel}}$$

$$Q = E_1 + E_2 + E_3 - E_A$$

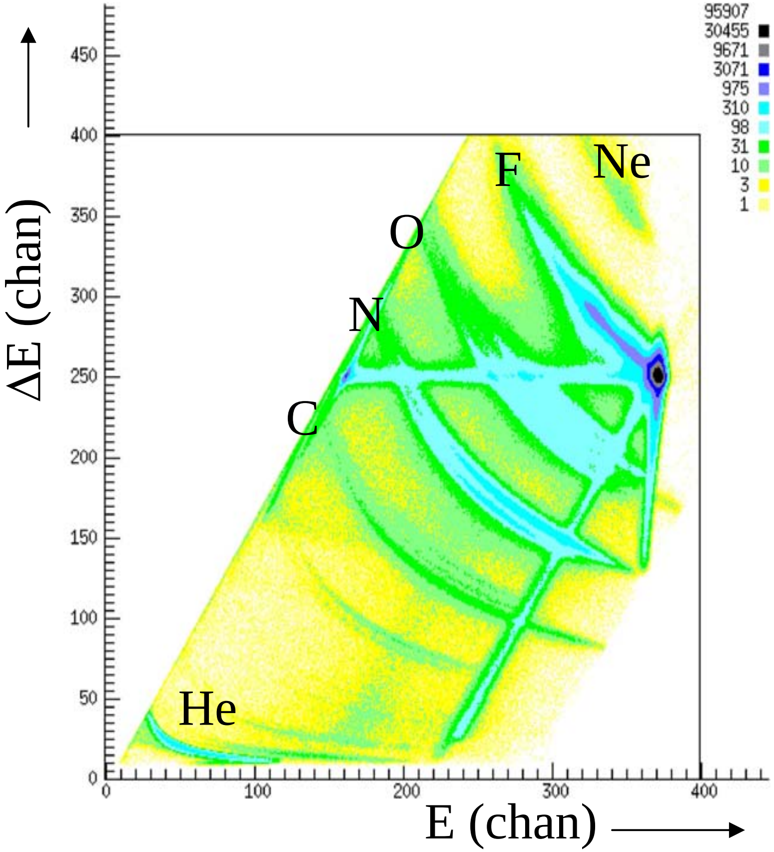
Detector configuration





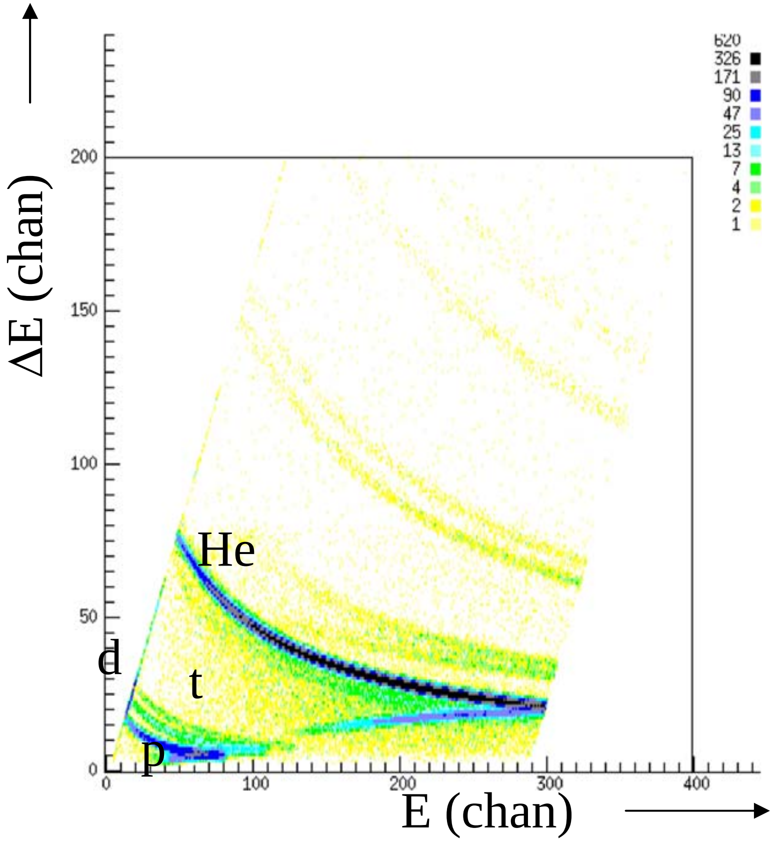
- Each telescope is 5 cm x 5 cm and located ~45 cm downstream from the target.
- Inner ΔEs are 65 μm; outers are 140 mm; E detectors are 1 mm.

Inner Telescope

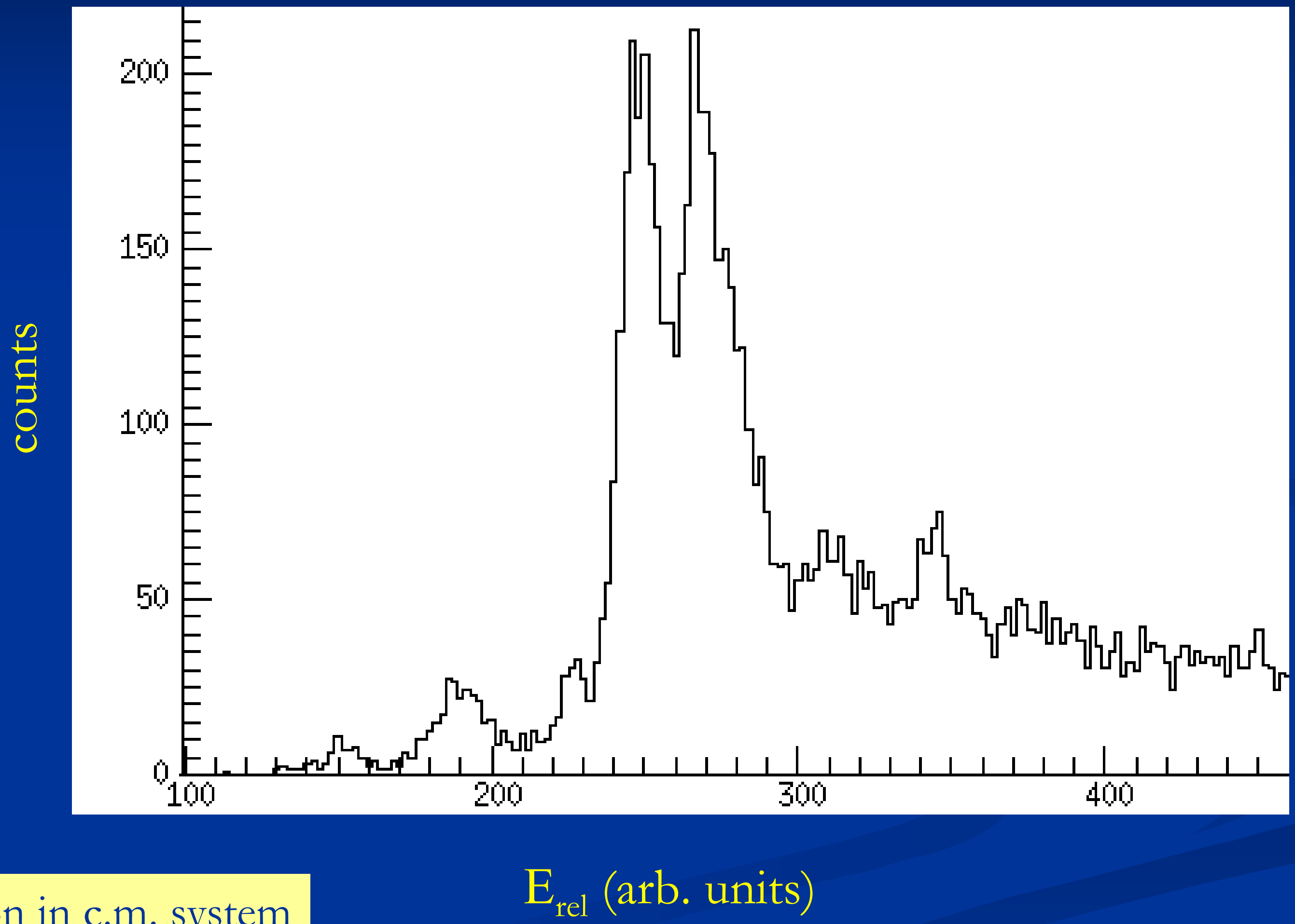


Particles identification histogram

Outer Telescope



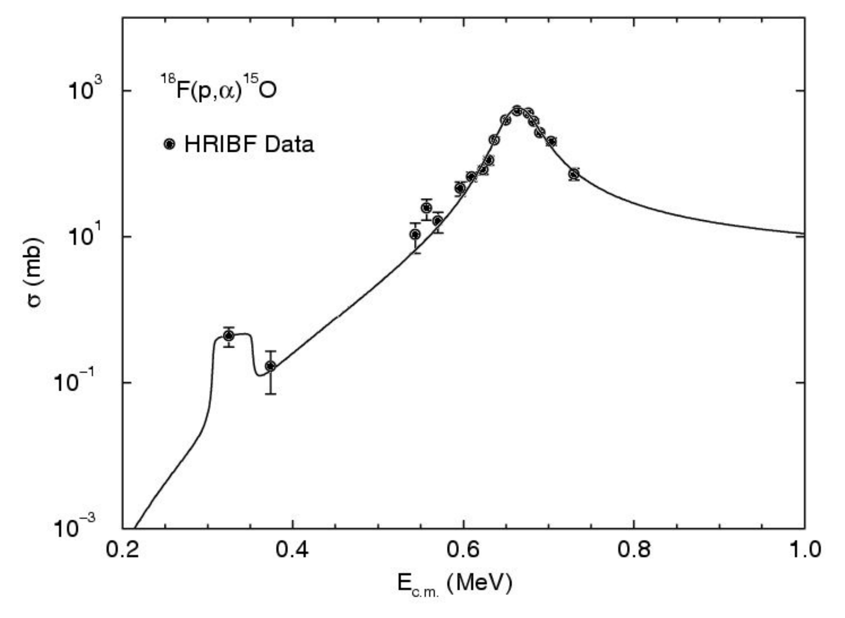
Preliminary Relative Energy Spectrum



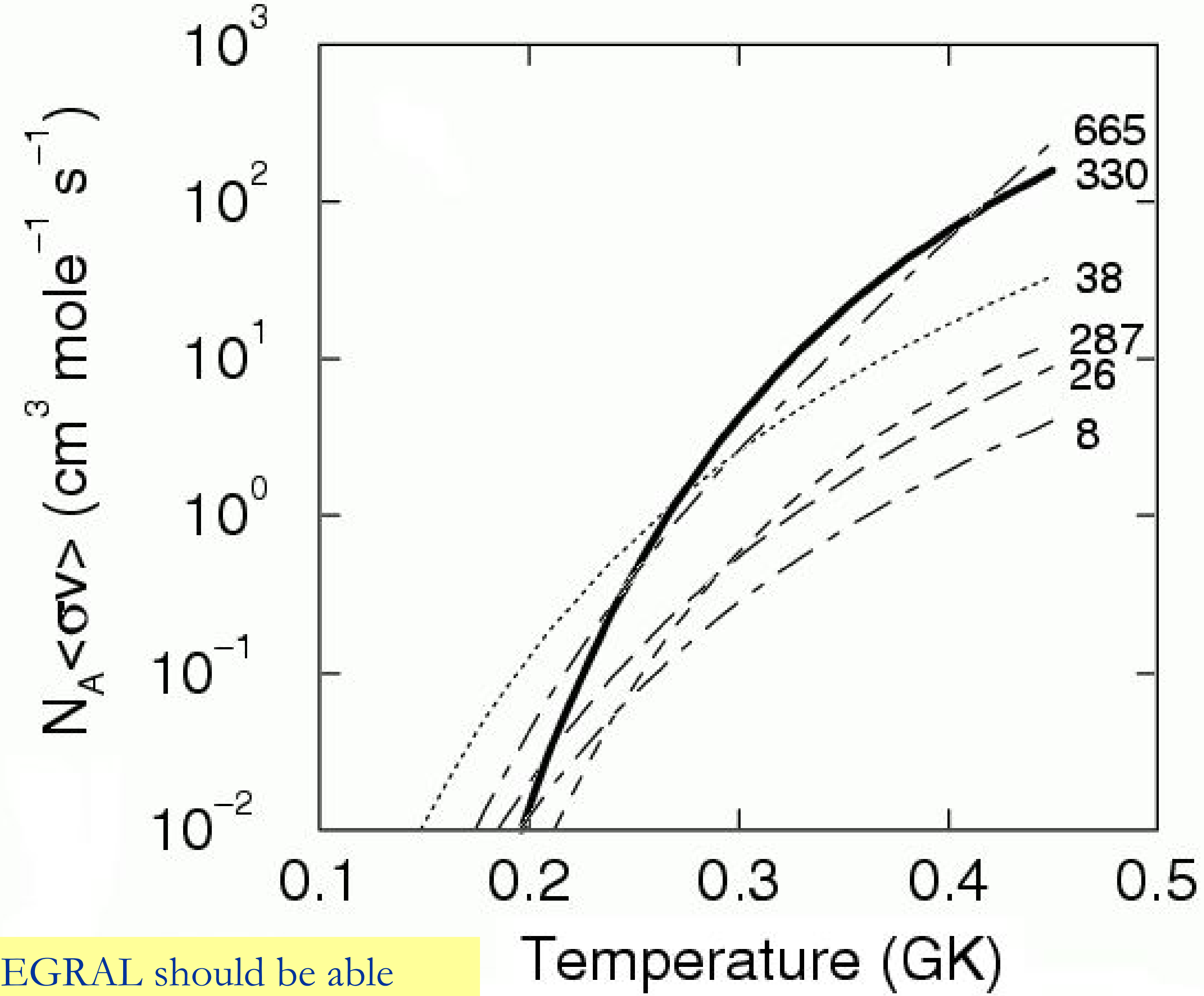
Energy resolution in c.m. system is ~70 keV.

Our Present Understanding

E_r (keV)	J^{π}	Γ_p (keV)
8	$3/2^+$	4×10^{-37}
26	$1/2^-$	3×10^{-20}
38	$3/2^+$	2×10^{-14}
287	$5/2^+$	4×10^{-5}
330	$3/2^-$	$2.2(0.7)\times10^{-3}$
665	$3/2^+$	$15.2(1.0)$

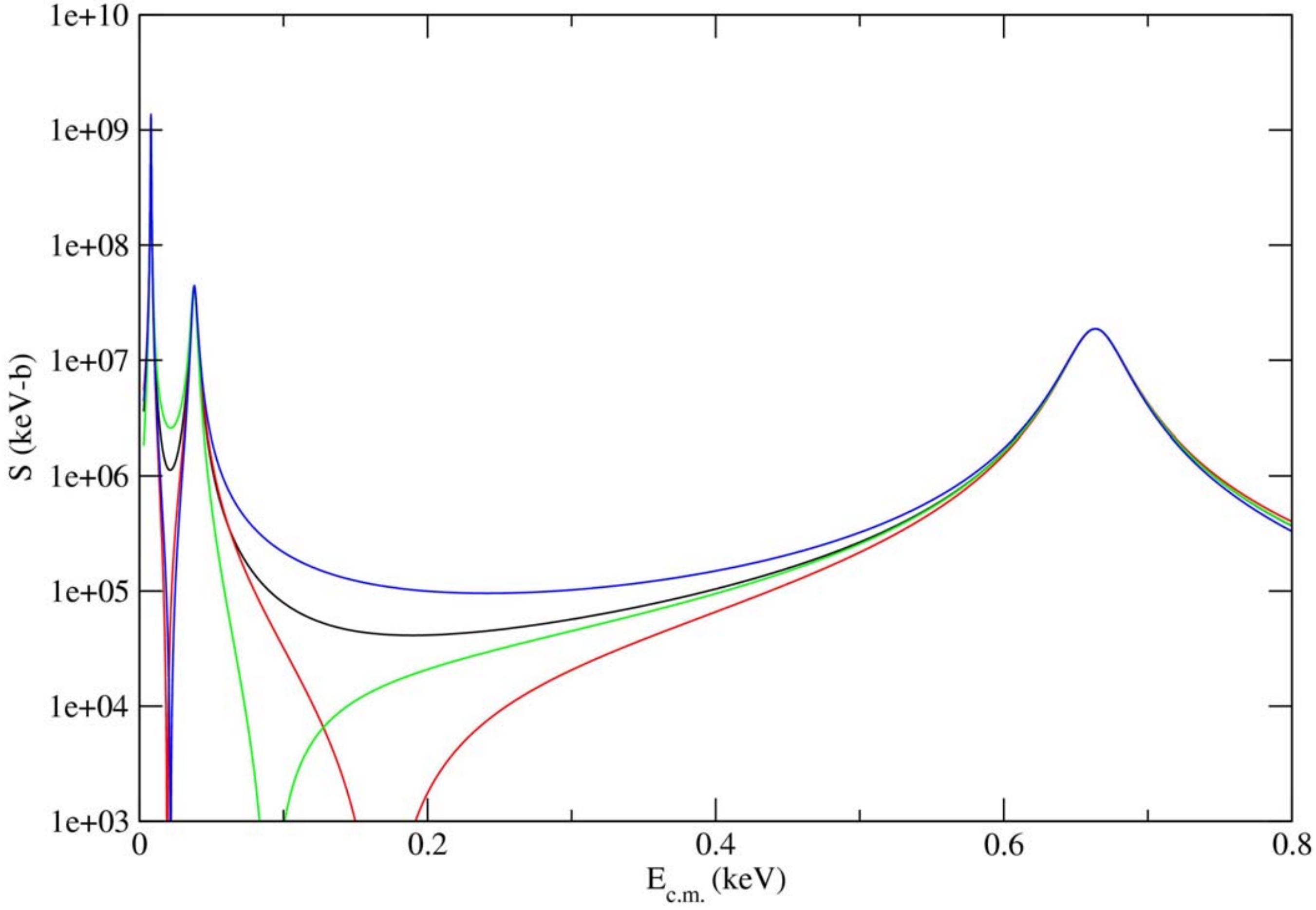


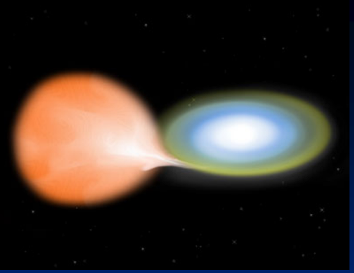
Reaction Rate



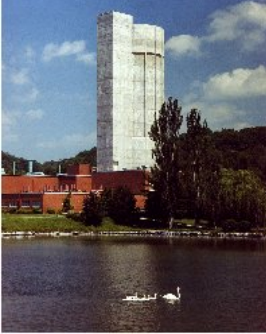
Note: SPI/INTEGRAL should be able to see 511-keV photons following a nova outburst provided it is with ~5kpc of earth.

Interfering 3/2⁺ Resonances





For the Future:



- **Complete analysis of proton transfer data.**
- **Measure $^{18}F(p,\alpha)^{15}O$ at lower energies?**
- **Measure spectroscopy with $^{17}O(^{3}He,n)^{19}Ne$.**

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