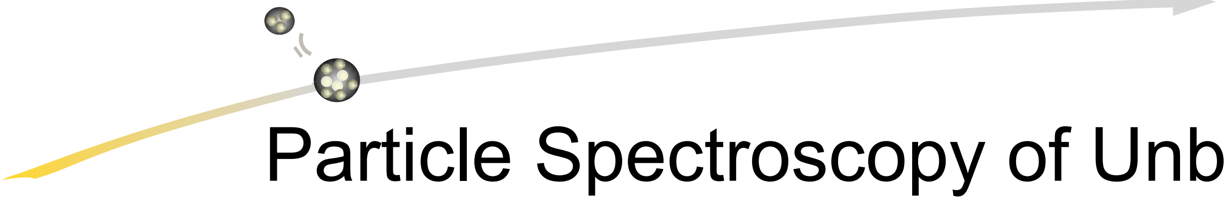


Particle Spectroscopy of Unbound States for Nuclear Astrophysics

Jeff Blackmon
Louisiana State University

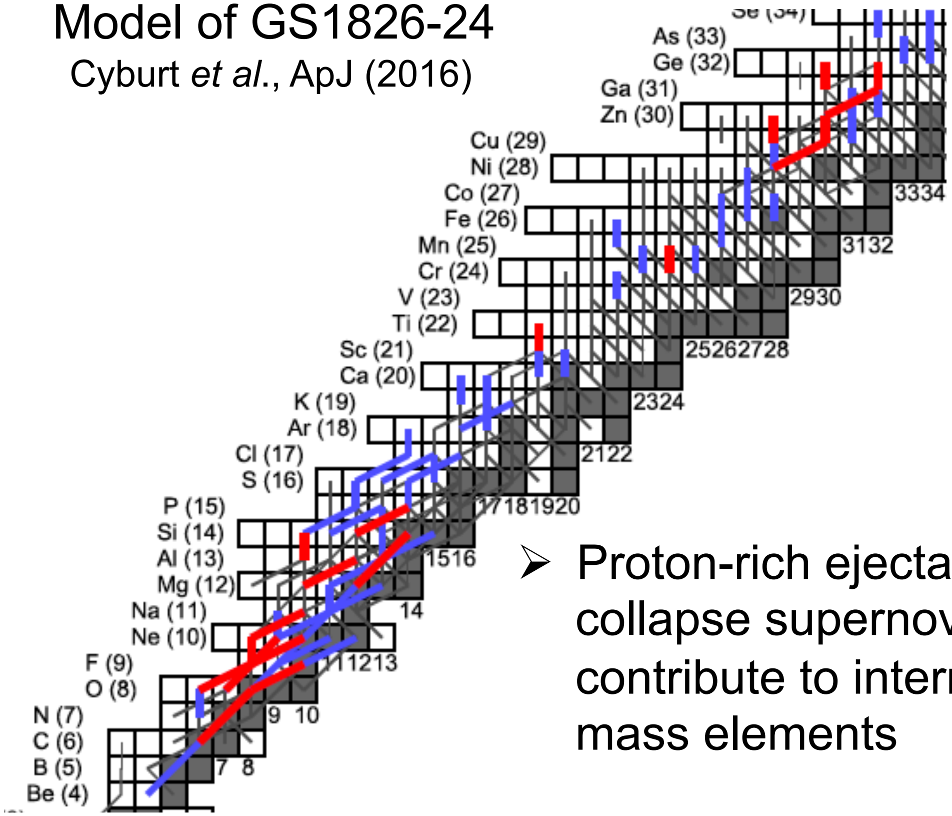
- Reaction rates for novae, X-ray bursts & supernovae
- Γ_p: (p,γ) & (p,α) rates via the (d,n) and (d,p) reactions
  - $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$ *(Adekola et al.)*
  - $^{26}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ *(Pain et al.)*
  - N=Z: the future: $^{30}\mathrm{P}$ *(Pain et al.)*
  - $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ *(Belarge et al.)*
  - $^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}$ *(Kuvin et al.)*
- Γ_α: (α,p) reaction rates
  - The SE-SPS
  - $^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ and $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$
  - $^{14}\mathrm{O}(\alpha,p)^{18}\mathrm{Ne}$ and $^{18}\mathrm{Ne}$:$^{18}\mathrm{O}$ symmetry
- Concluding remarks

Explosions in proton-rich environments

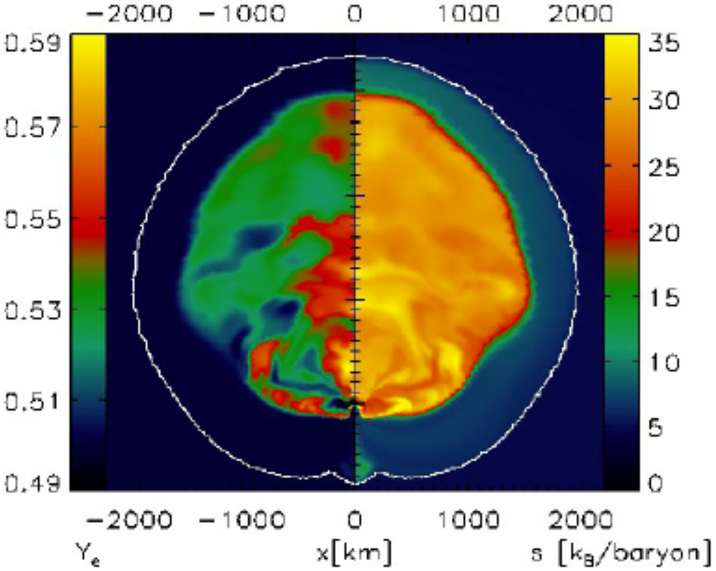
- ➢ Cataclysmic binaries
  - Novae
  - X-ray bursts
- ➢ Certain nuclear reactions (on p-rich nuclei) influence observables

Model of GS1826-24

Cyburt *et al*., ApJ (2016)



- ➢ Proton-rich ejecta of core-collapse supernovae may contribute to intermediate mass elements



Müller, Janka et al.

Reaction rates and resonances

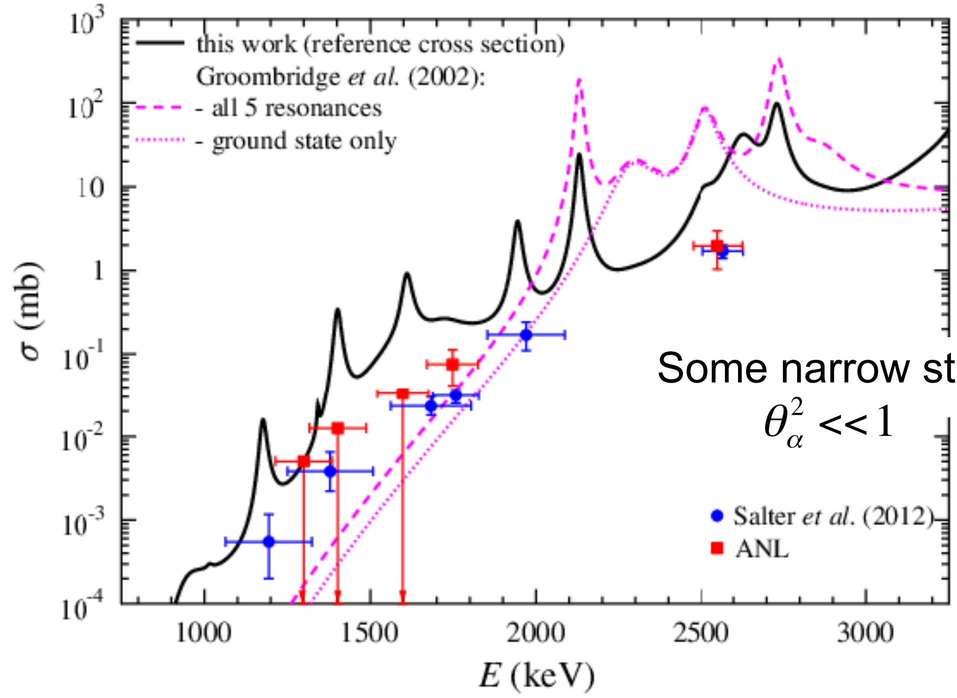
- Hydrogen and helium induced reactions are dominated by resonances near threshold
- Direct measurements are challenging
- Easier: indirectly determine resonance properties
  - E_r, J^π, Γ_p, Γ_α, Γ_γ Reaction theory!

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}}(kT)^{3/2}\int_0^\infty \sigma E e^{-E/(kT)}dE$$

States near p threshold are narrow

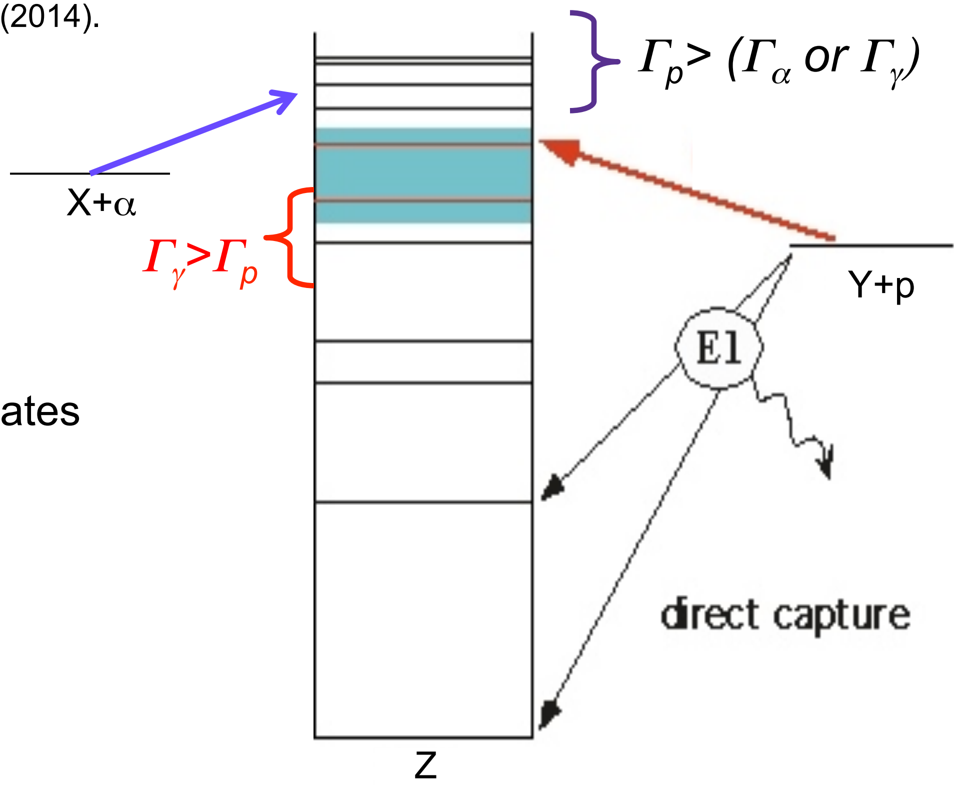
Branching ratios are observable!

^{18}Ne(α,p)^{21}Na Evaluation: Mohr, Longland and Iliadis, PRC (2014).



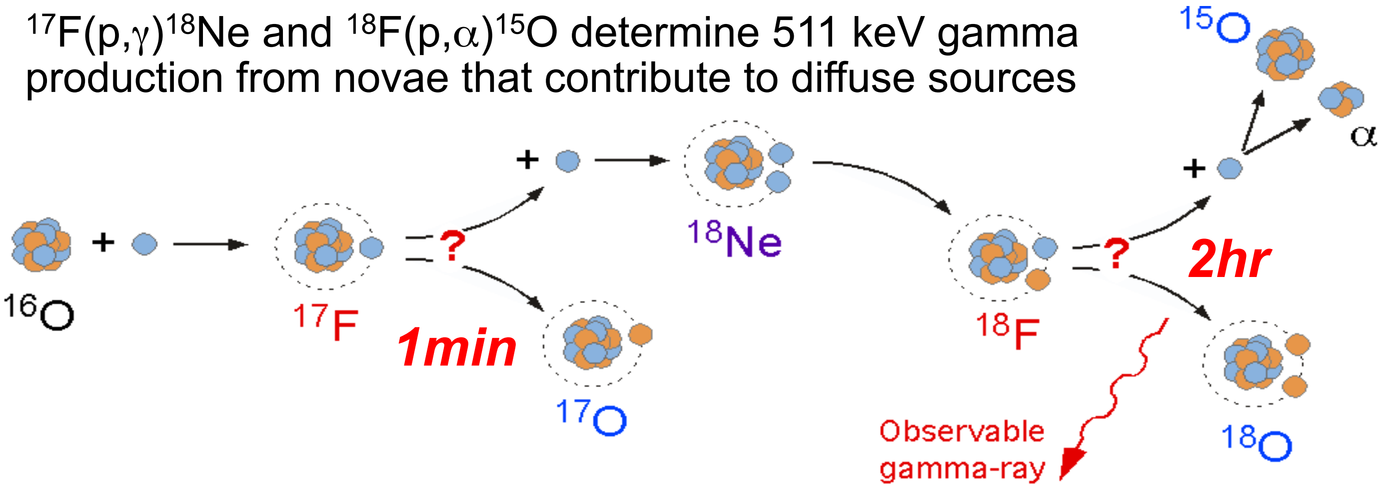
Some narrow states

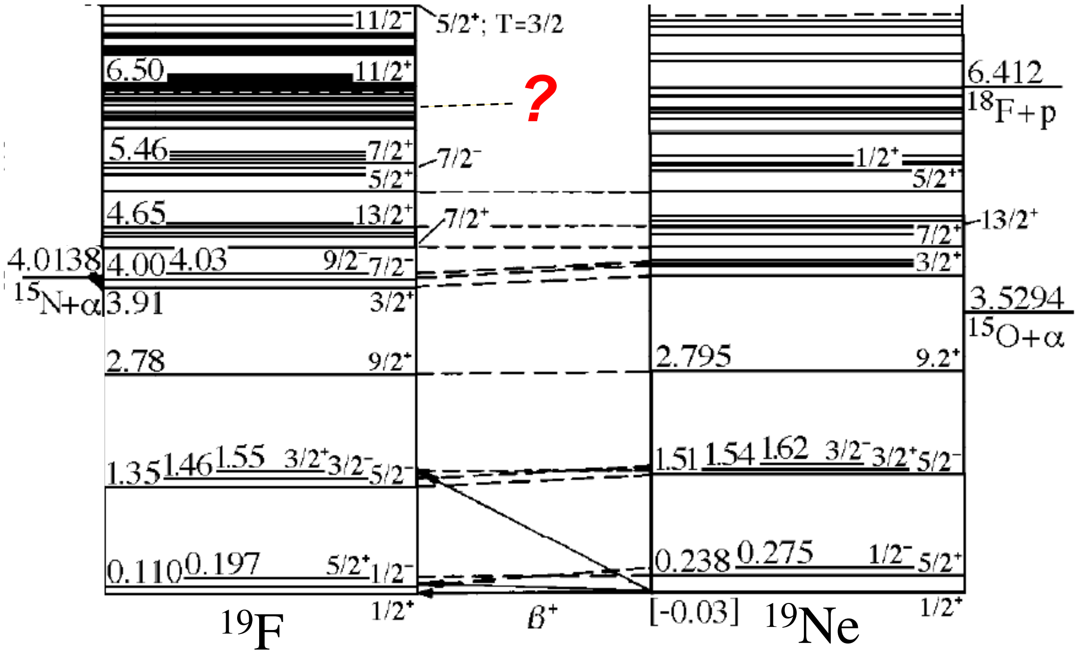
$\theta_\alpha^2 << 1$

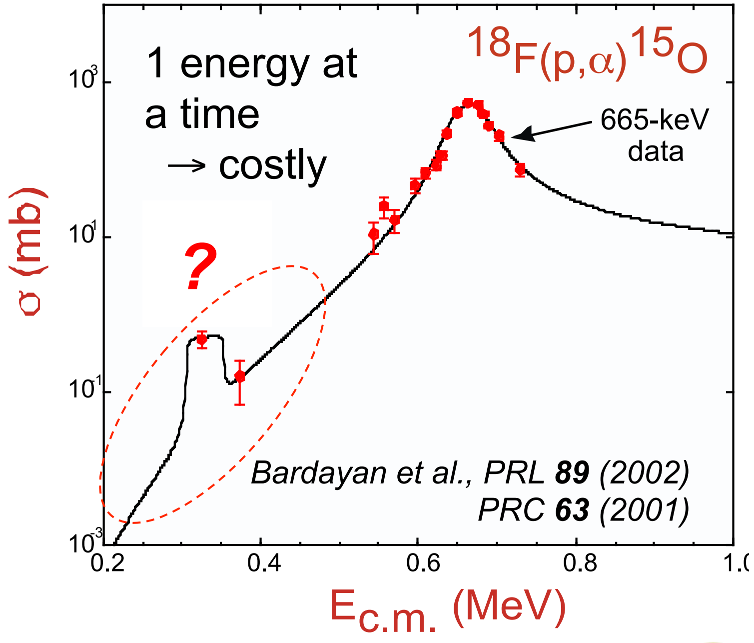


$^{18}F(p,\alpha)^{15}O$ & Novae

- $^{17}F(p,\gamma)^{18}Ne$ and $^{18}F(p,\alpha)^{15}O$ determine 511 keV gamma production from novae that contribute to diffuse sources







1 energy at a time → costly

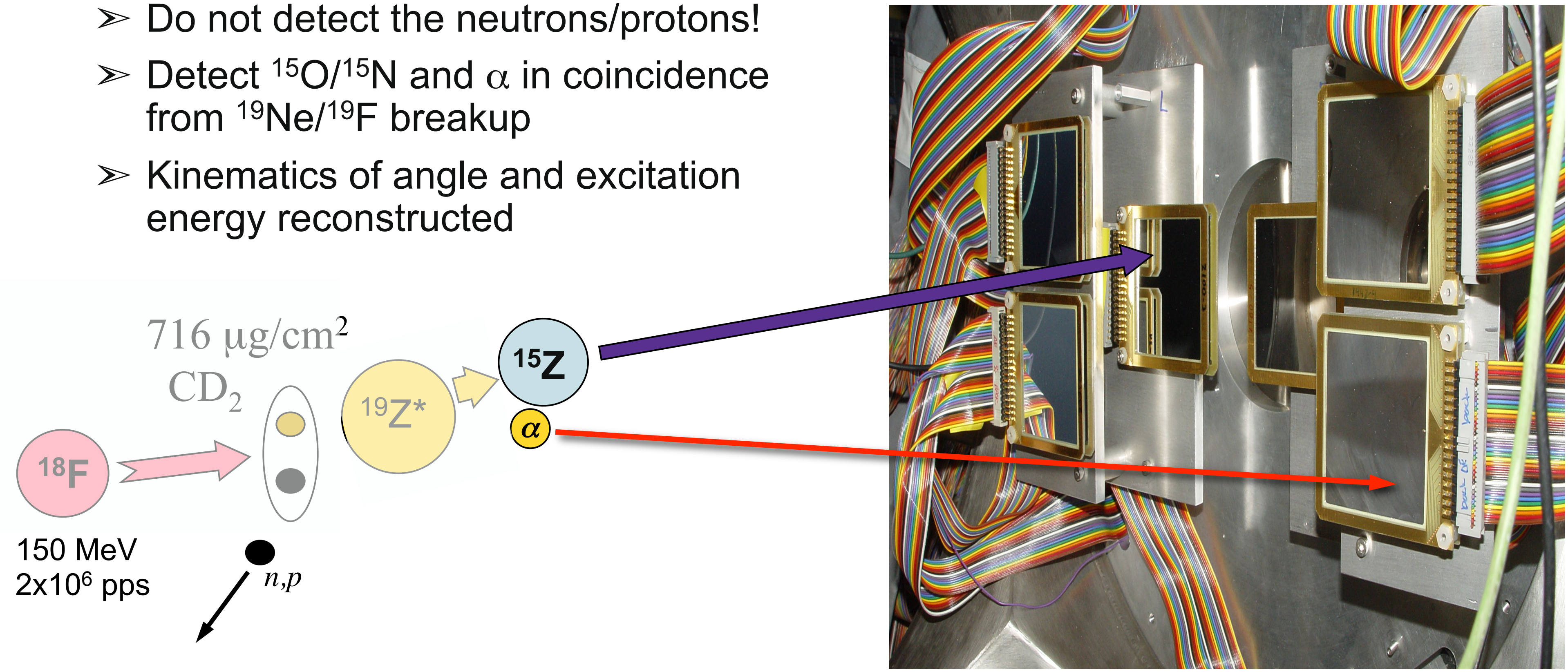
Bardayan et al., PRL ***89*** *(2002)*
PRC ***63*** *(2001)*

$^{18}F(d,n)^{19}Ne \rightarrow {}^{15}O+\alpha$

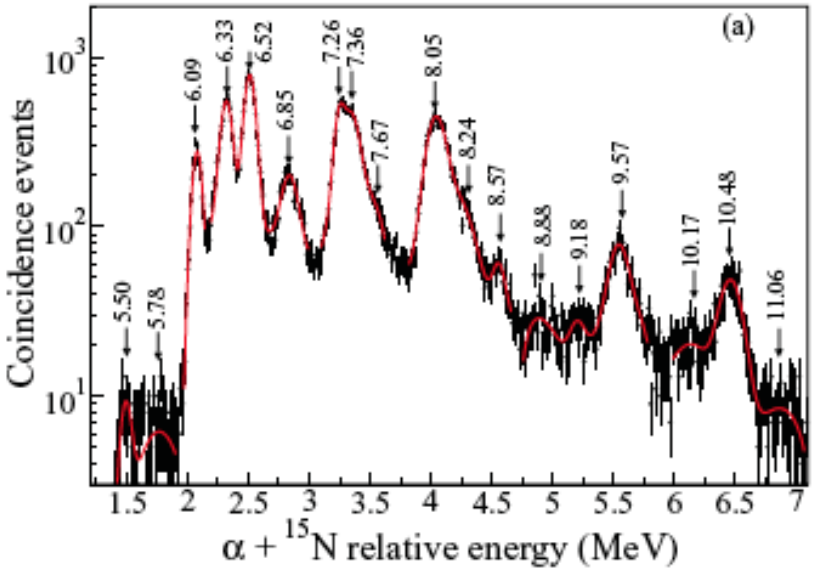
Adekola *et al.*, PRC **83, 84, 85** (2011-12).

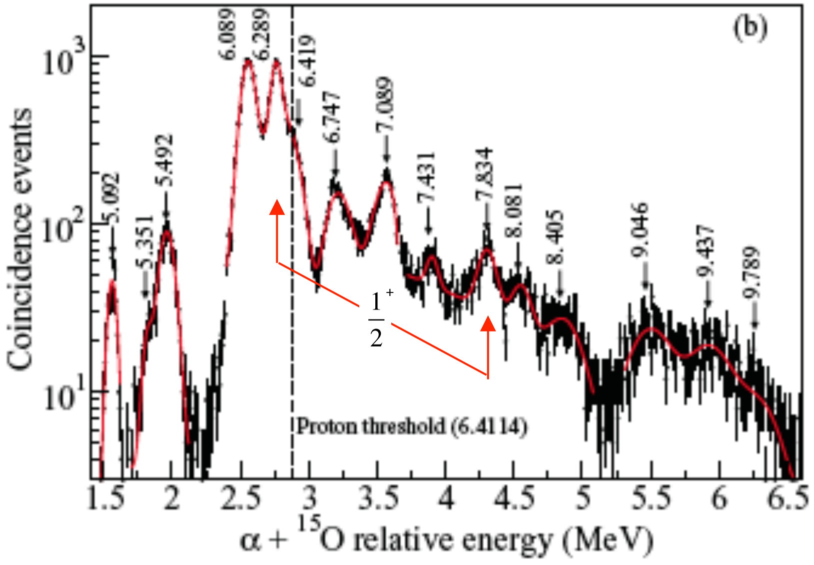
- Use ^{18}F(d,n)^{19}Ne reaction to populate the states of interest in ^{19}Ne
- ^{18}F(d,p)^{19}F simultaneously measured
- Do not detect the neutrons/protons!
- Detect ^{15}O/^{15}N and α in coincidence from ^{19}Ne/^{19}F breakup
- Kinematics of angle and excitation energy reconstructed

Six position sensitive silicon-strip detectors covering θ_{lab}~2°-17°

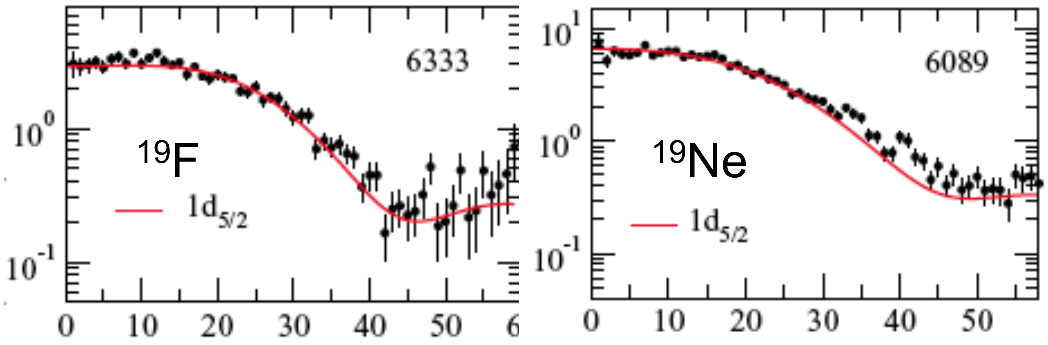


$^{18}F(d,n)^{19}Ne \rightarrow {}^{15}O+\alpha$ & $^{18}F(d,p)^{19}F \rightarrow {}^{15}N+\alpha$





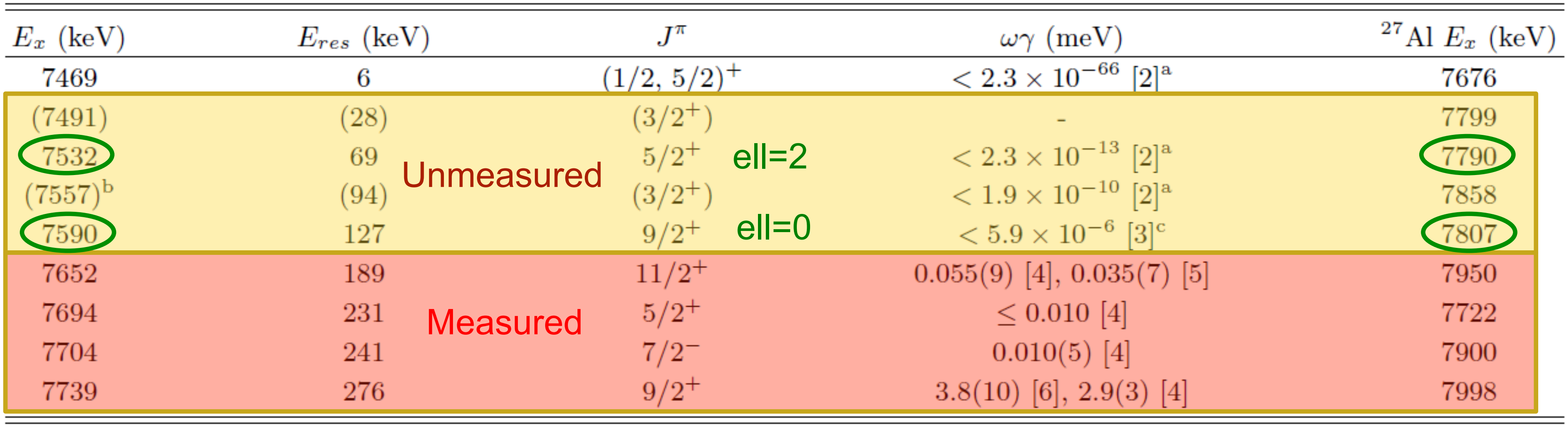
- ➢ Simultaneous mirror measurements



^{19}F			^{19}Ne		
E_x (keV)	ℓ	$(2J+1)S_n$	E_x (MeV)	ℓ	$(2J+1)S_p$
6331	2	1.95(3)	6089	2	2.36(3)
6255/6497/6528	0	0.64(2)	6289	0	0.92(3)
6787	1	0.37(2)	6741	1	0.50(2)
7262/7364	0	0.67(2)	7076	0	1.47(5)

- ➢ Efficiency complicated
- ➢ Definitive mirror assignments still often not clear
- ➢ Reaction models to the continuum
- ➢ Interference between levels

$^{26}Al(p,\gamma)^{27}Si$ and Galactic ^{26}Al



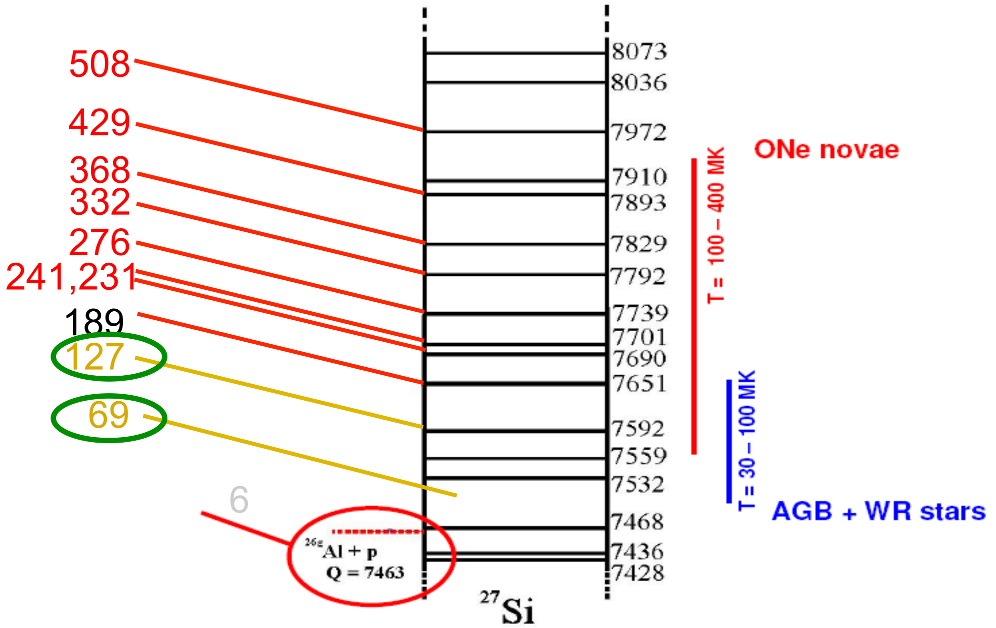
E_x (keV)	E_{res} (keV)	J^{π}	$\omega\gamma$ (meV)	^{27}Al E_x (keV)
7469	6	$(1/2, 5/2)^+$	$< 2.3 \times 10^{-66}$ [2][a]	7676
(7491)	(28)	$(3/2^+)$	-	7799
7532	69	$5/2^+$	$< 2.3 \times 10^{-13}$ [2][a]	7790
(7557)[b]	(94)	$(3/2^+)$	$< 1.9 \times 10^{-10}$ [2][a]	7858
7590	127	$9/2^+$	$< 5.9 \times 10^{-6}$ [3][c]	7807
7652	189	$11/2^+$	0.055(9) [4], 0.035(7) [5]	7950
7694	231	$5/2^+$	≤ 0.010 [4]	7722
7704	241	$7/2^-$	0.010(5) [4]	7900
7739	276	$9/2^+$	3.8(10) [6], 2.9(3) [4]	7998

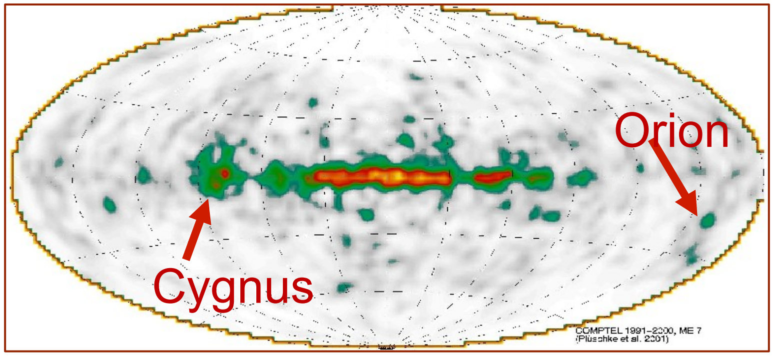
Unmeasured

ell=2

ell=0

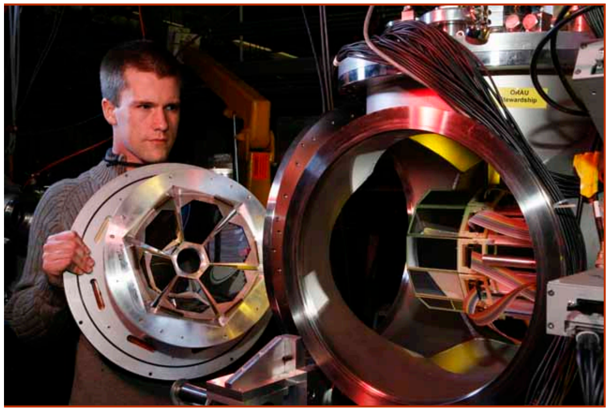
Measured

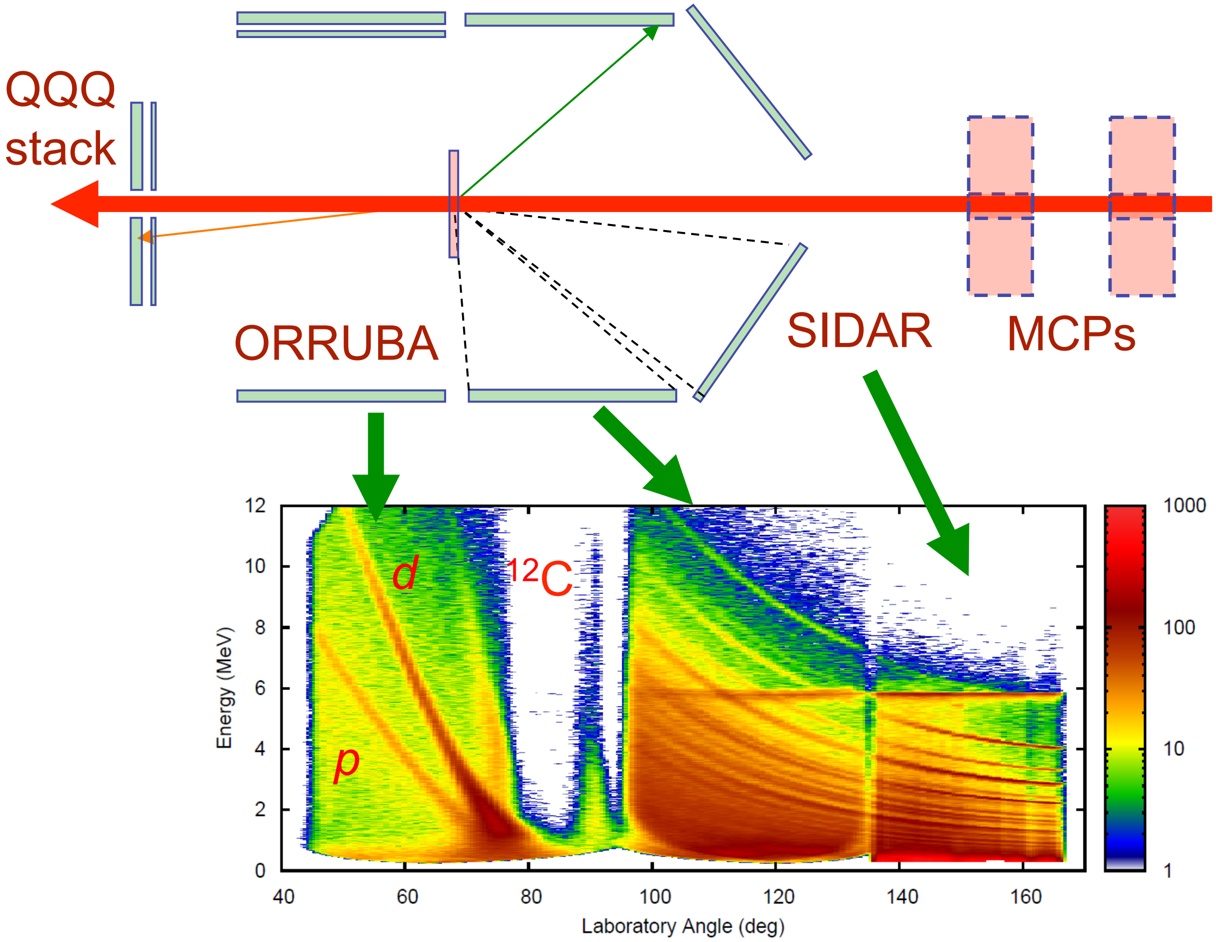




- Strengths of 69 and 127 keV resonances major uncertainty in $^{26}Al(p,\gamma)^{27}Si$ rate

$^{26}Al(d,p)^{27}Al$ to Mirror States

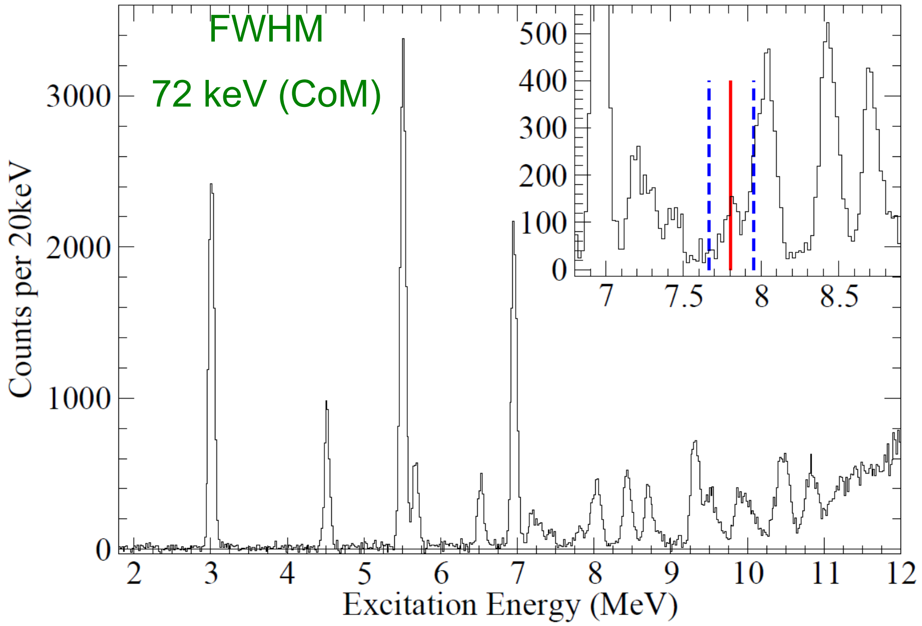


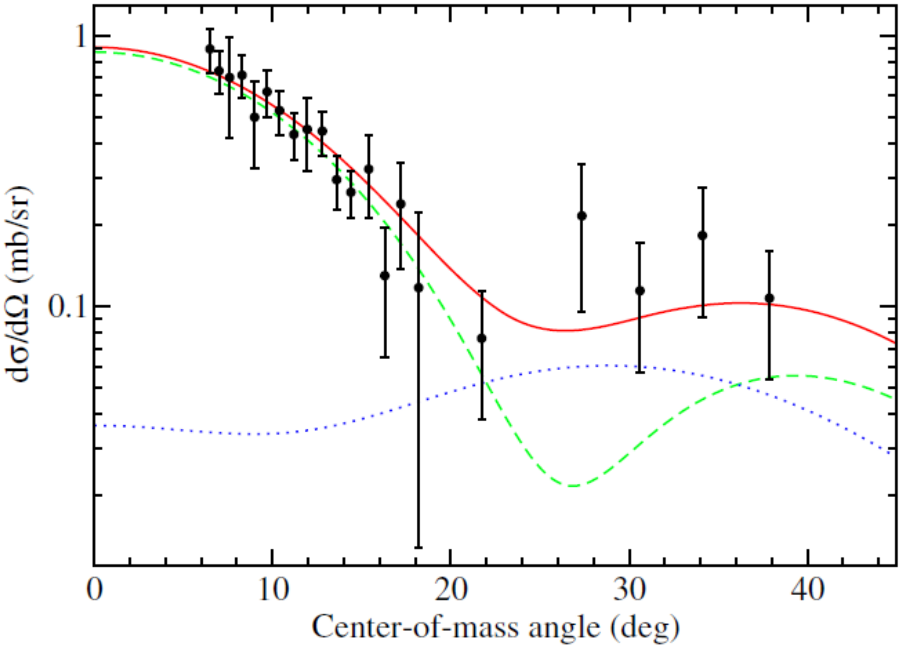


- 117 MeV ^{26}Al
- 5×10^6 pps
- 150 $\mu g/cm^2$ CD_2
- MCP normalization (200 kHz)

Neutron spectroscopic factors in ^{27}Al

7805(12) keV (127-keV mirror)





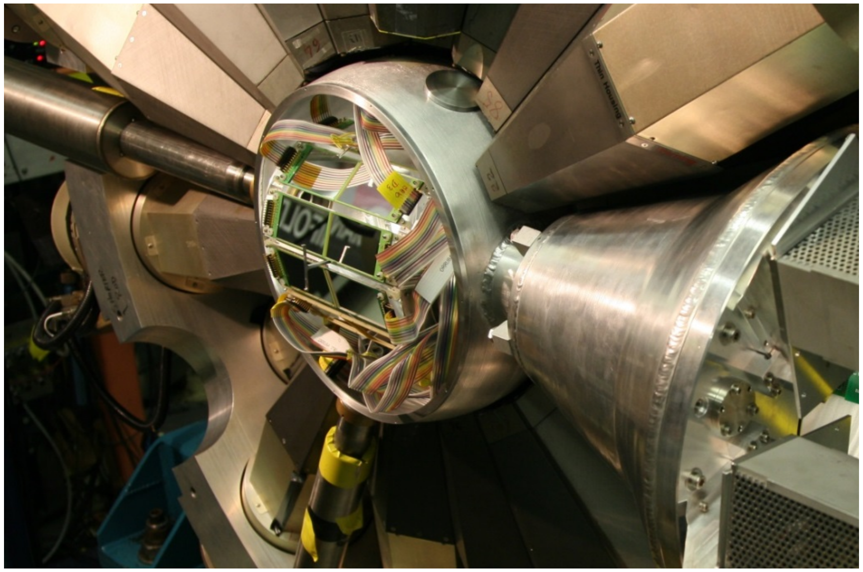
	^{27}Al	^{27}Al	^{27}Al^{a}	^{27}Si^{a}	^{27}Si	Γ_{sp}	Γ_{p}	$\omega\gamma$
J^{π}	E_x (keV)	$C^2S_\nu^{exp}$	$C^2S_\nu^{th}$	$C^2S_\pi^{th}$	C^2S_π	(meV)	(meV)	(meV)
$9/2^+$	7807	0.0102 ± 0.0021	$0.0112^{-0.0002}_{+0.0007}$	$0.0094^{+0.0016}_{-0.0024}$	$0.0085^{+0.0024}_{-0.0031}$	6.70×10^{-3}	$5.7^{+1.6}_{-2.1} \times 10^{-5}$	$2.6^{+0.7}_{-0.9} \times 10^{-5}$
$5/2^+$	7790	≤ 0.061	$0.0100^{+0.0006}_{-0.0002}$	$0.0088^{+0.0010}_{-0.0022}$	≤ 0.054	2.06×10^{-10}	$\leq 1.1 \times 10^{-11}$	$\leq 3.0 \times 10^{-12}$

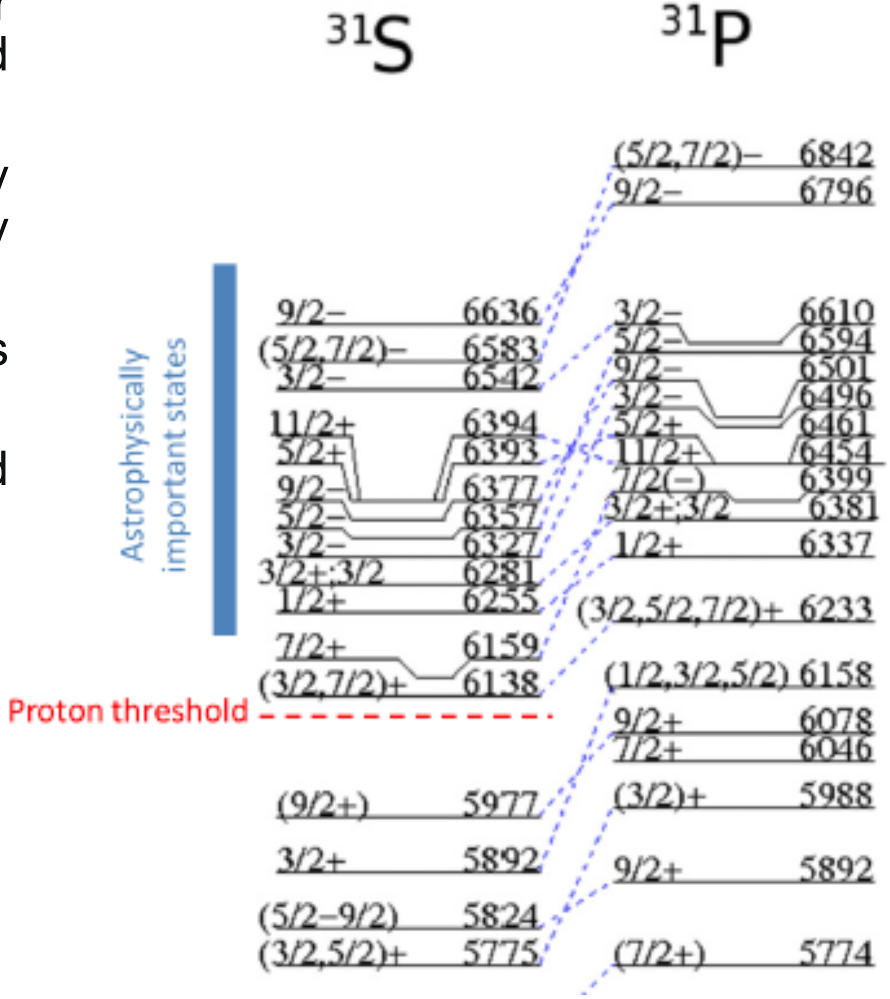
[a] From SMEC calculations using the USD-b effective interaction, using a continuum coupling constant of −650 MeV fm^3.

- ➢ Quantifying uncertainties in reaction models and mirror symmetry?

^{30}P(d,pγ)^{31}P with GODDESS

- ^{30}P(p,γ)^{31}S: Most important reaction for understanding enrichment of S and heavier elements in nova ejecta
- Large uncertainty but high level density and only a few resonances will likely contribute
- Proton singles and p-γ coincidences with ^{30}P(d,pγ) and GODDESS?
- Limitations from reaction model and mirror symmetry?

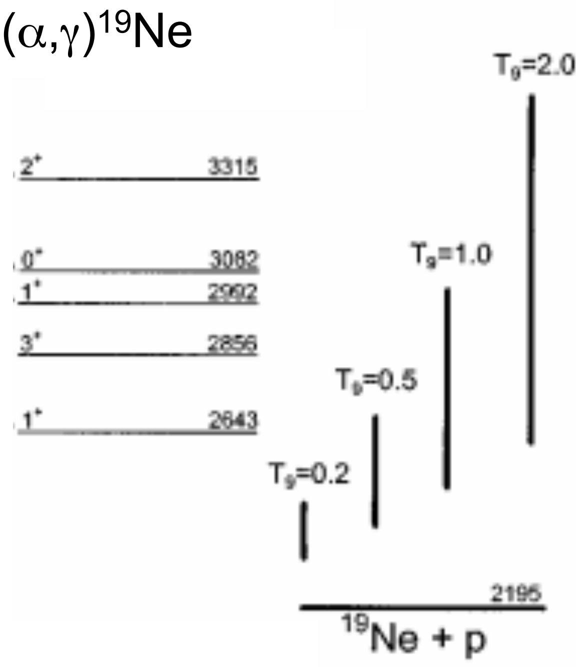




How good is this picture?

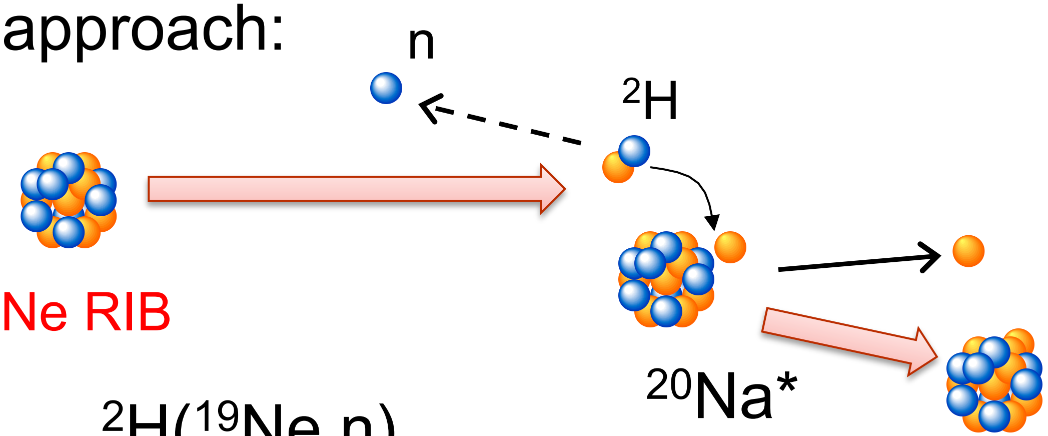
$^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$

- $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is a limiting reaction for CNO breakout
- $^{19}Ne(p,\gamma)^{20}Na$ reaction should be much faster than $^{15}O(\alpha,\gamma)^{19}Ne$
- Spin assignments of states in ^{20}Na are not clear
- Uncertainty in $^{19}Ne(p,\gamma)^{20}Na$ rate is large



Vancraeynest *et al.*,
PRC (1998)

Our approach:

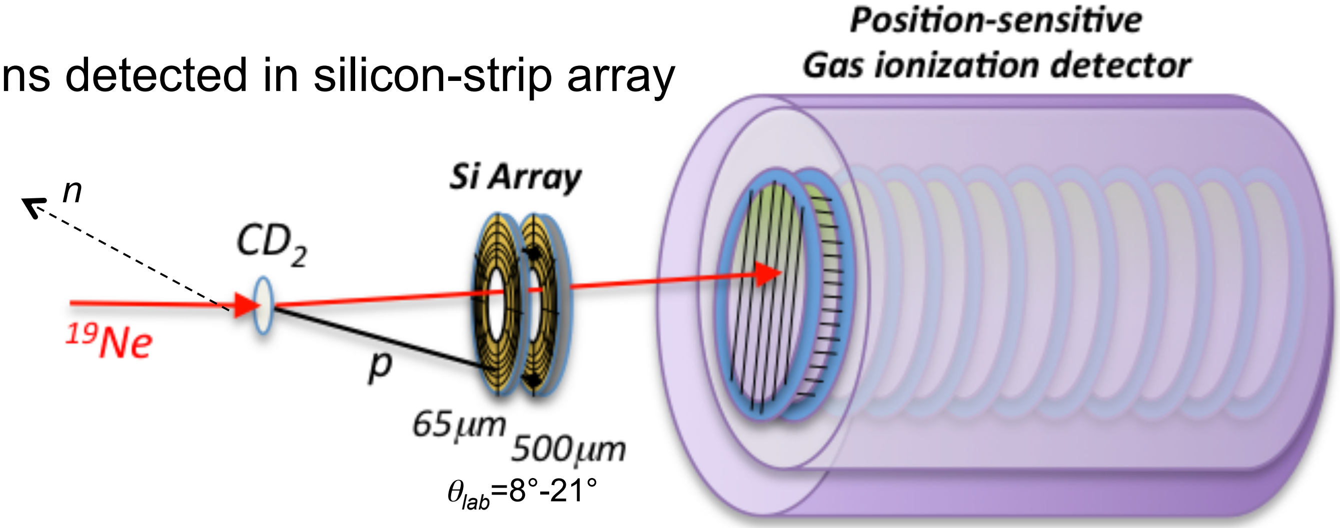


$^{2}H(^{19}Ne,n)$

- Forget about the low energy neutron
- Detect ^{19}Ne and p with high spatial and energy resolution

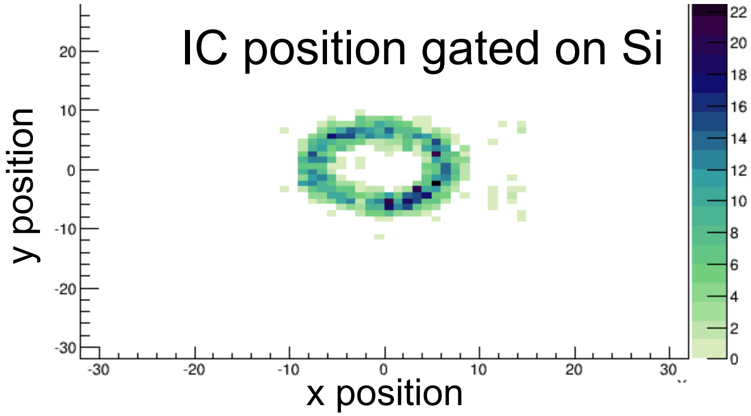
$^{19}Ne(d,n)^{20}Na \rightarrow ^{19}Ne+p$ Approach

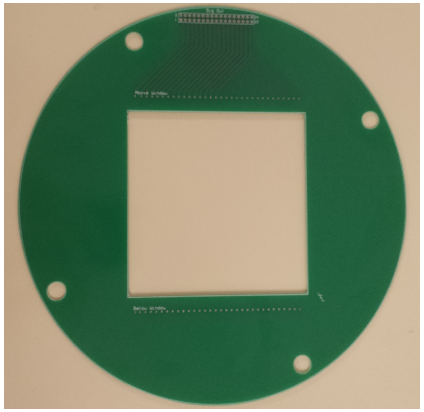
- Protons detected in silicon-strip array

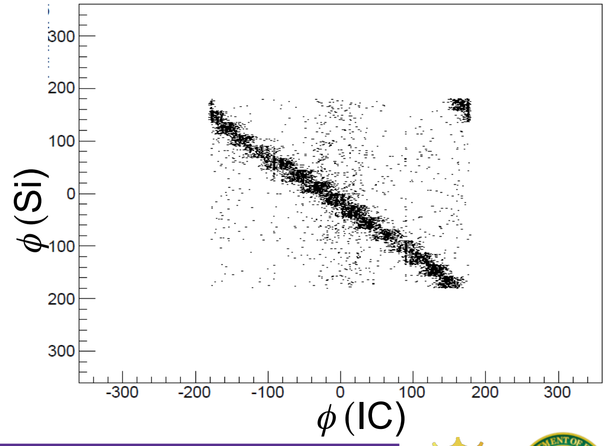


- Beam and recoiling heavy ions detected in position-sensitive, gas ionization detector

Results from $^{12}C(p,p)$ test experiment

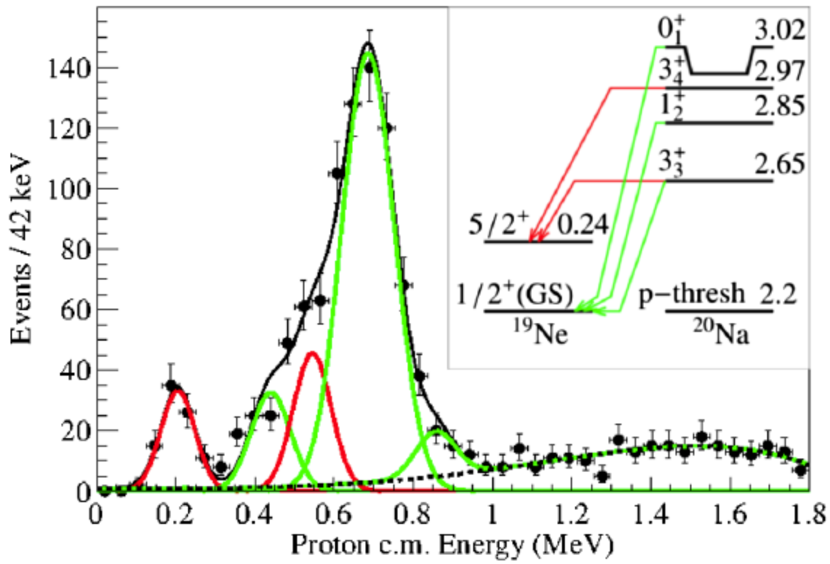


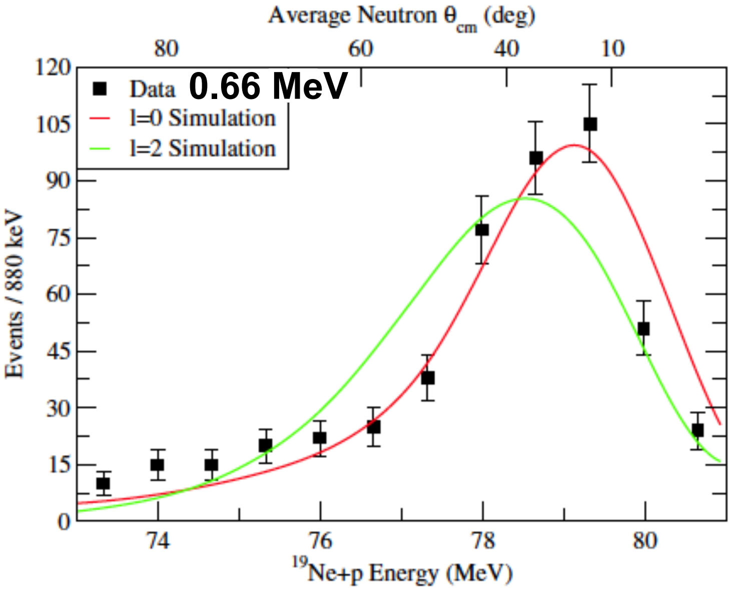


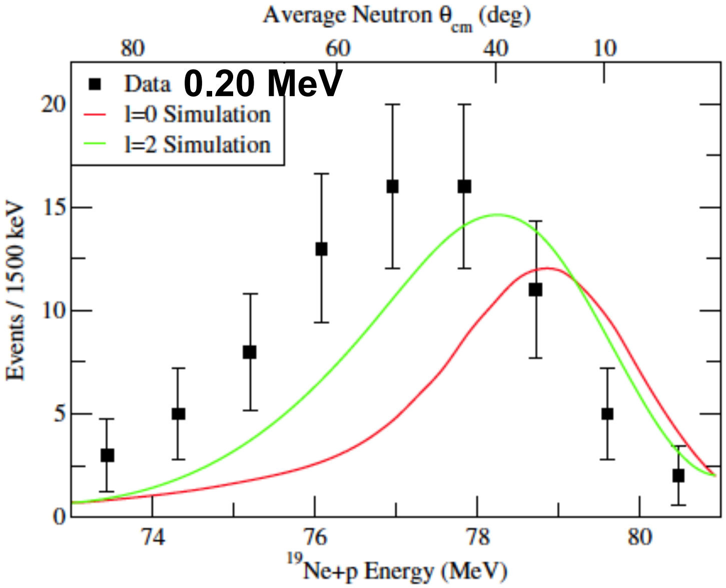


^{19}Ne(d,n)^{20}Na→^{19}Ne+p Results

- Reconstructed E_{cm} spectrum and angular distributions
- 2.65 MeV state has equal decay branching to g.s. and $\frac{5^+}{2}$
- Thermal population of the first-excited ^{19}Ne state contributes to the ^{19}Ne(p,γ) reation rate



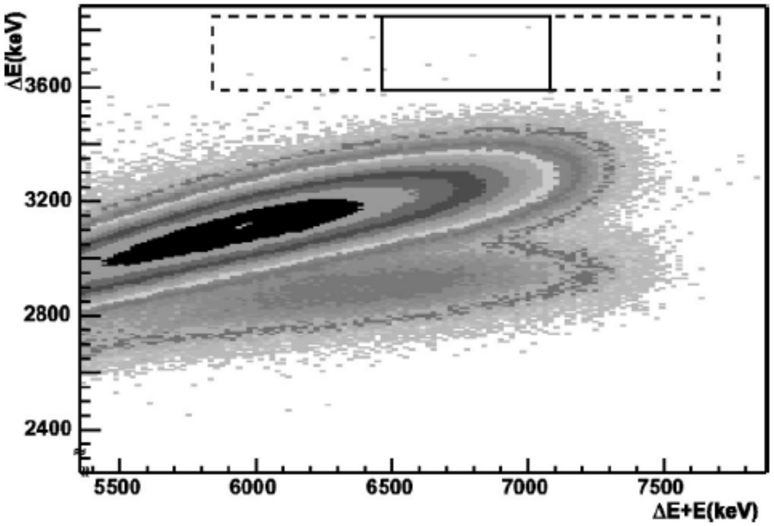




$^{19}Ne(p,\gamma)^{20}Na$ Reaction Rate

- With J^{π} established, it is hard to reconcile direct (p,γ) limits with lifetime measurements in the mirror ^{20}F.

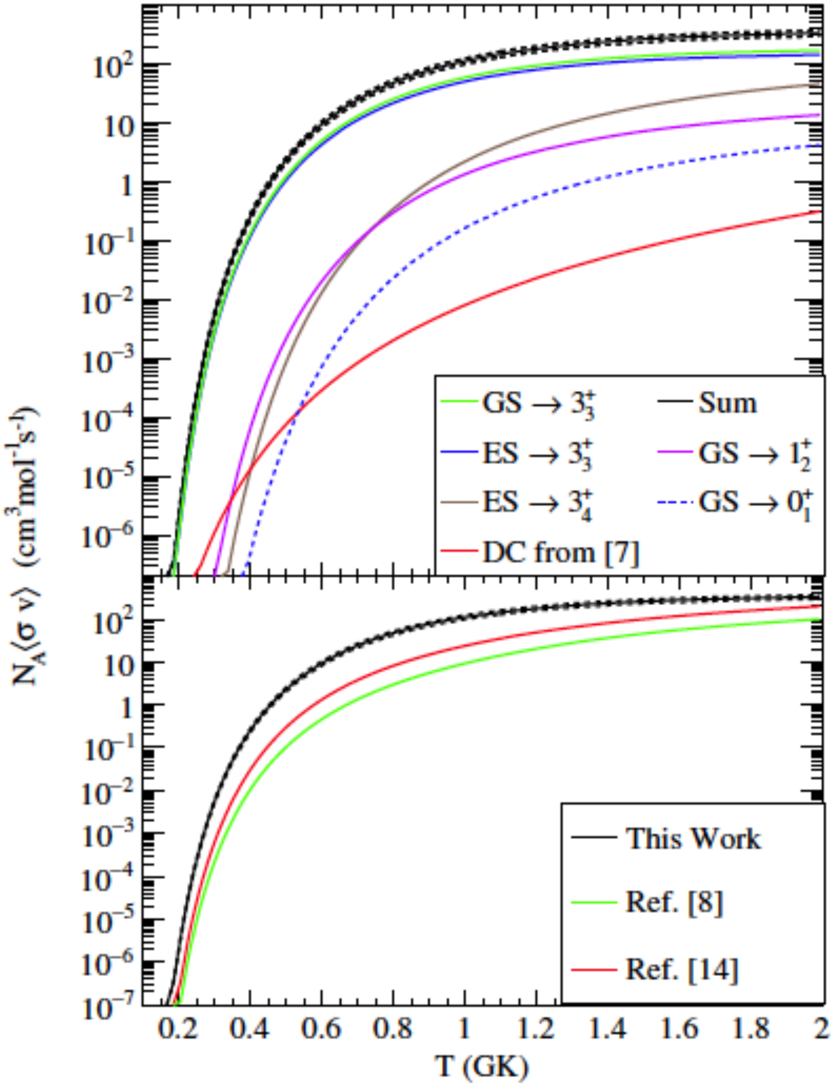
Couder *et al.*, *PRC* (2004): $\omega\gamma_{440} < 15$ meV



Lifetime measurements → $\omega\gamma_{440} = 74$ meV

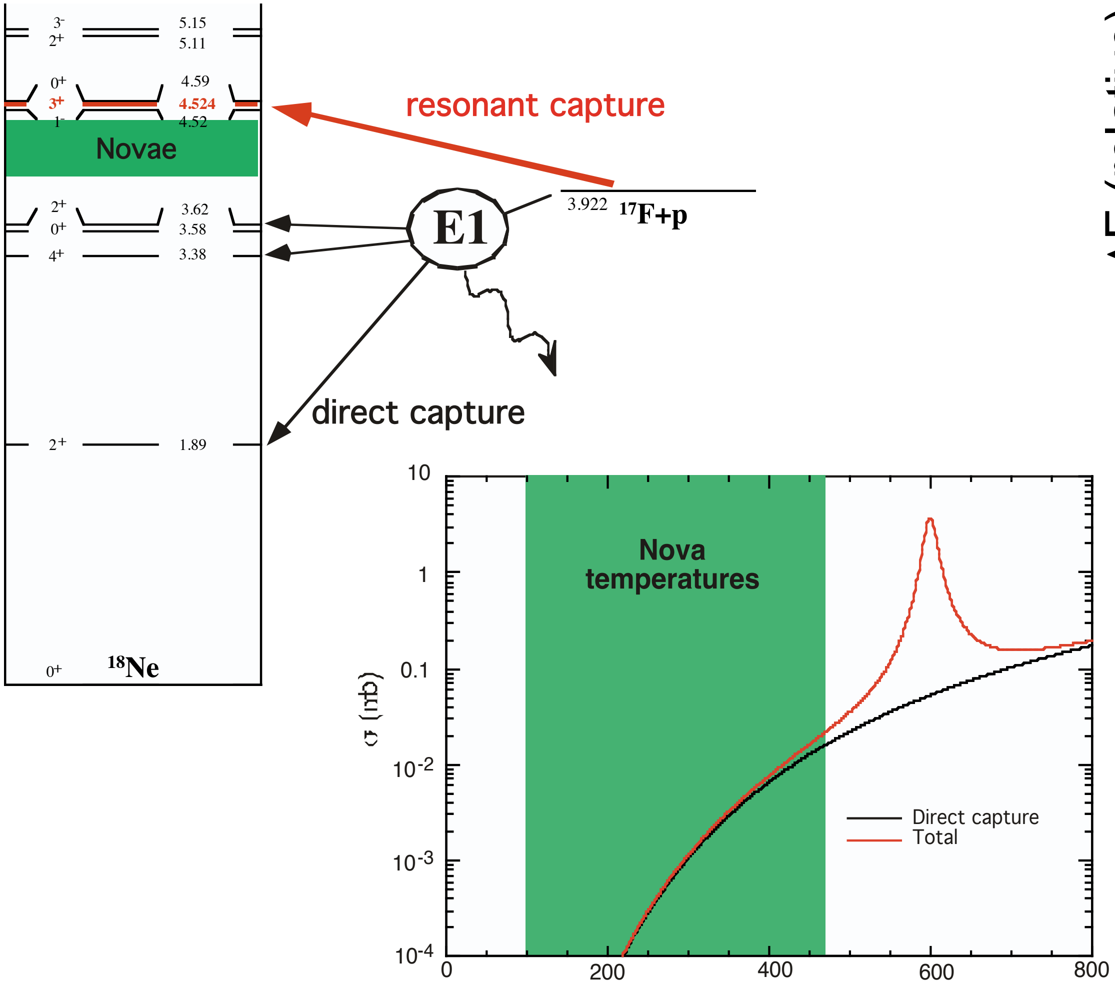
- Using Γ_{γ} from mirror and reactions on the excited state increases the reaction rate significantly more than already expected.

Belarge *et al.*, *PRL* ***117*** (2016)

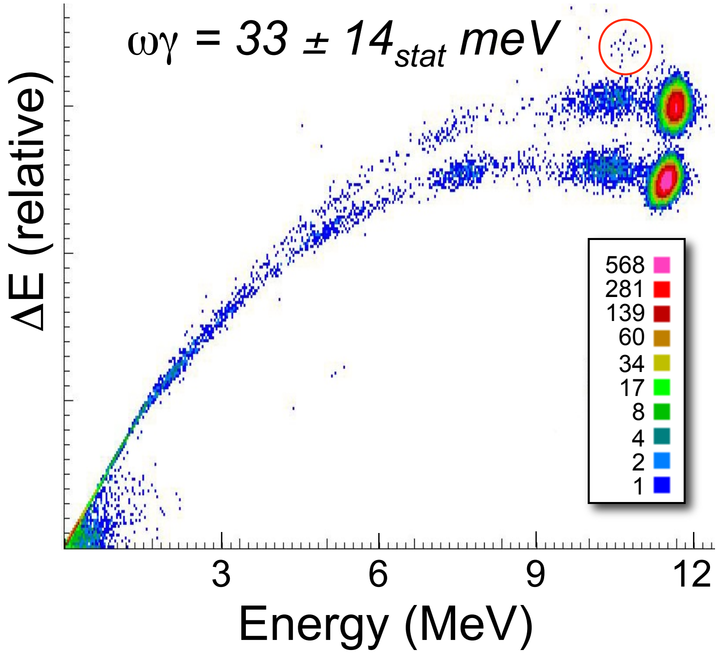


$^{17}F(p,\gamma)^{18}Ne$

- Most important resonance directly measured
- Largest uncertainty is direct capture



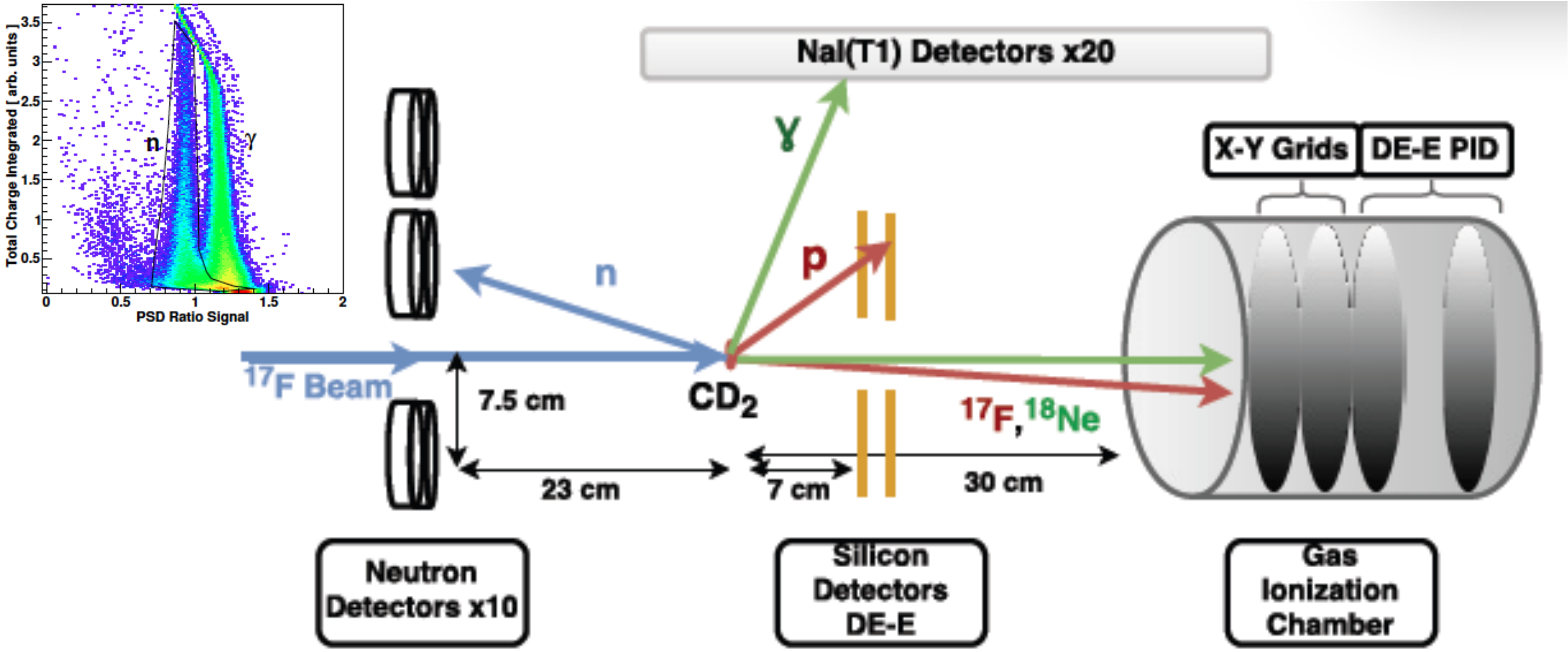
Chipps *et al.*, PRL (2009)

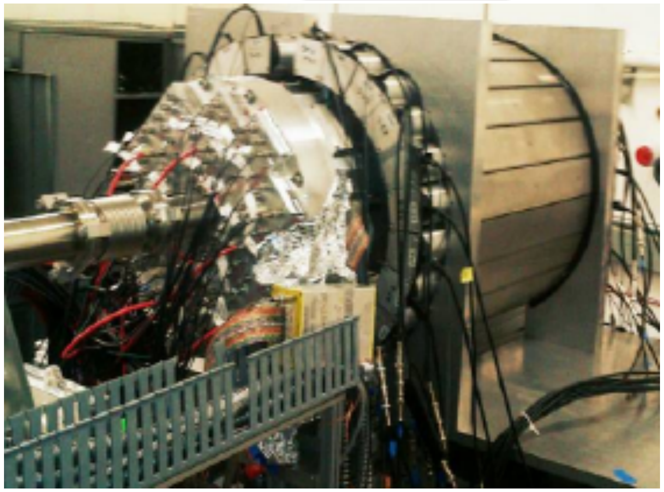


$\omega\gamma = 33 \pm 14_{stat}$ meV

- Need new approach for bound(ish) states

^{17}F(d,n) using RESONEUT





^{17}F(d,n)^{18}Ne* → (p)^{17}F

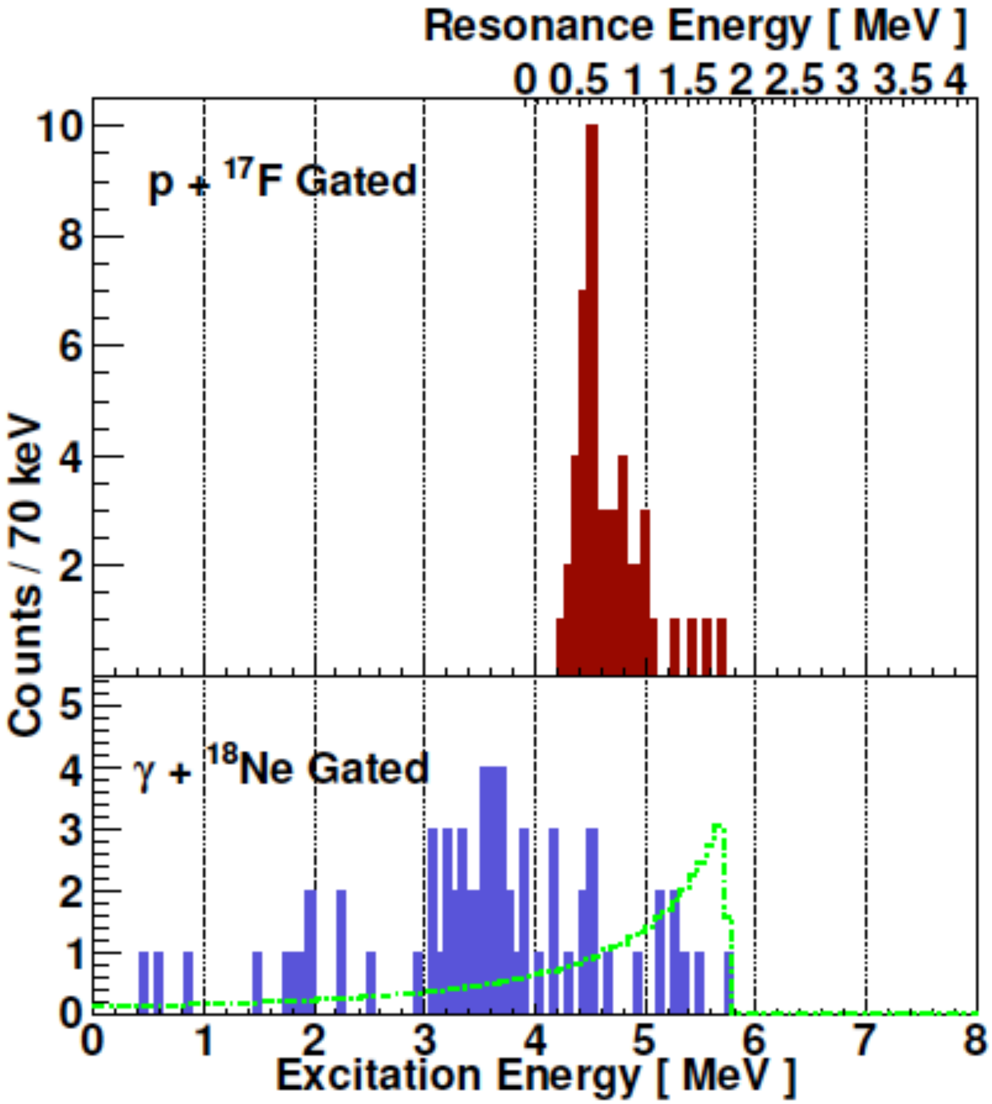
→ (γ)^{18}Ne

⇒ ^{17}F(p,γ)^{18}Ne reaction rate

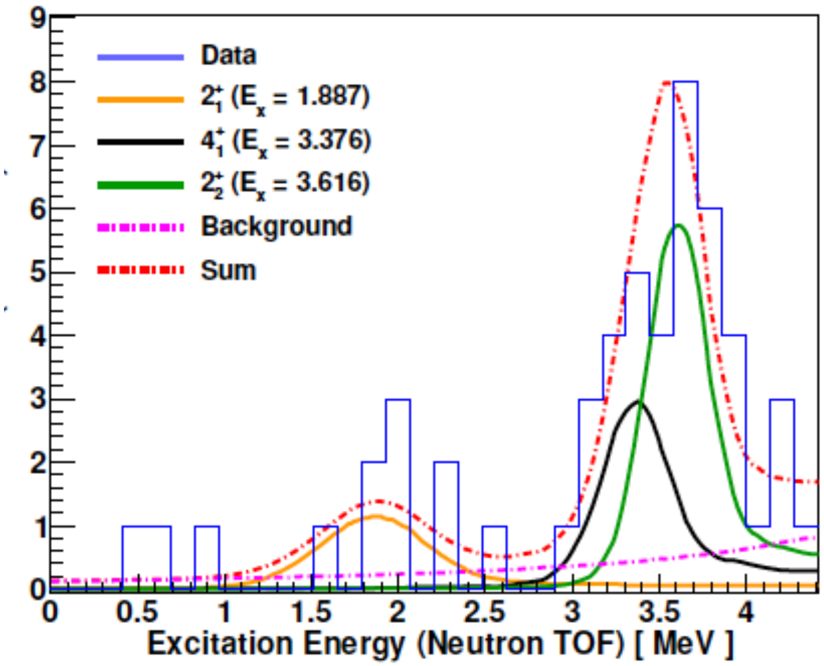
S. Kuvin *et al.*

ResoNeut= P-Terphenyl + Planacon PMT

^{17}F(d,n)^{18}Ne data



- Good neutron TOF resolution
- Proton unbound states agree with HRIBF measurements
- Bound states are observed above background allowing ANCs to be extracted

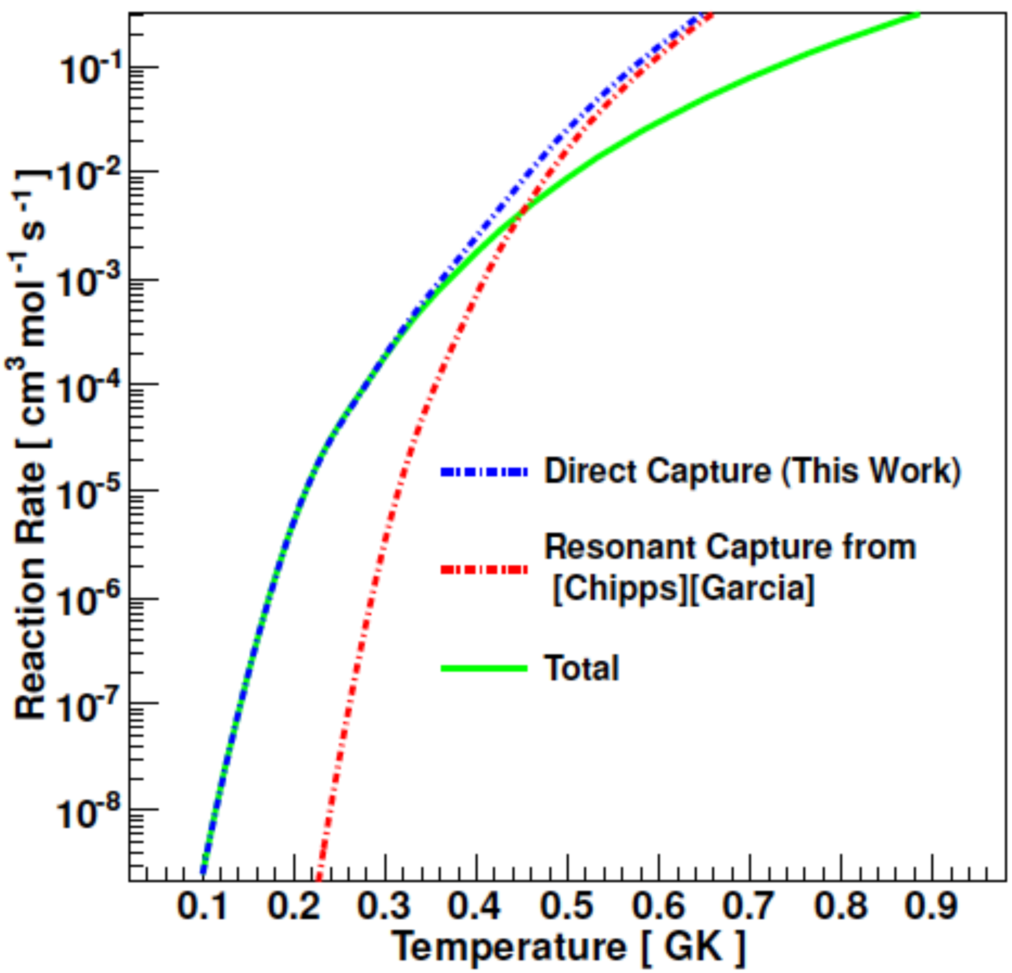


$^{17}F(p,\gamma)^{18}Ne$ Preliminary Results

- Asymptotic Normalization Coefficients (ANCs) allow accurate determination of the direct capture cross section
- We find the ANCs to be in good agreement with those in the ^{18}O mirror
- Uncertainties in the reaction rate significantly reduced at nova and X-ray burst temperatures

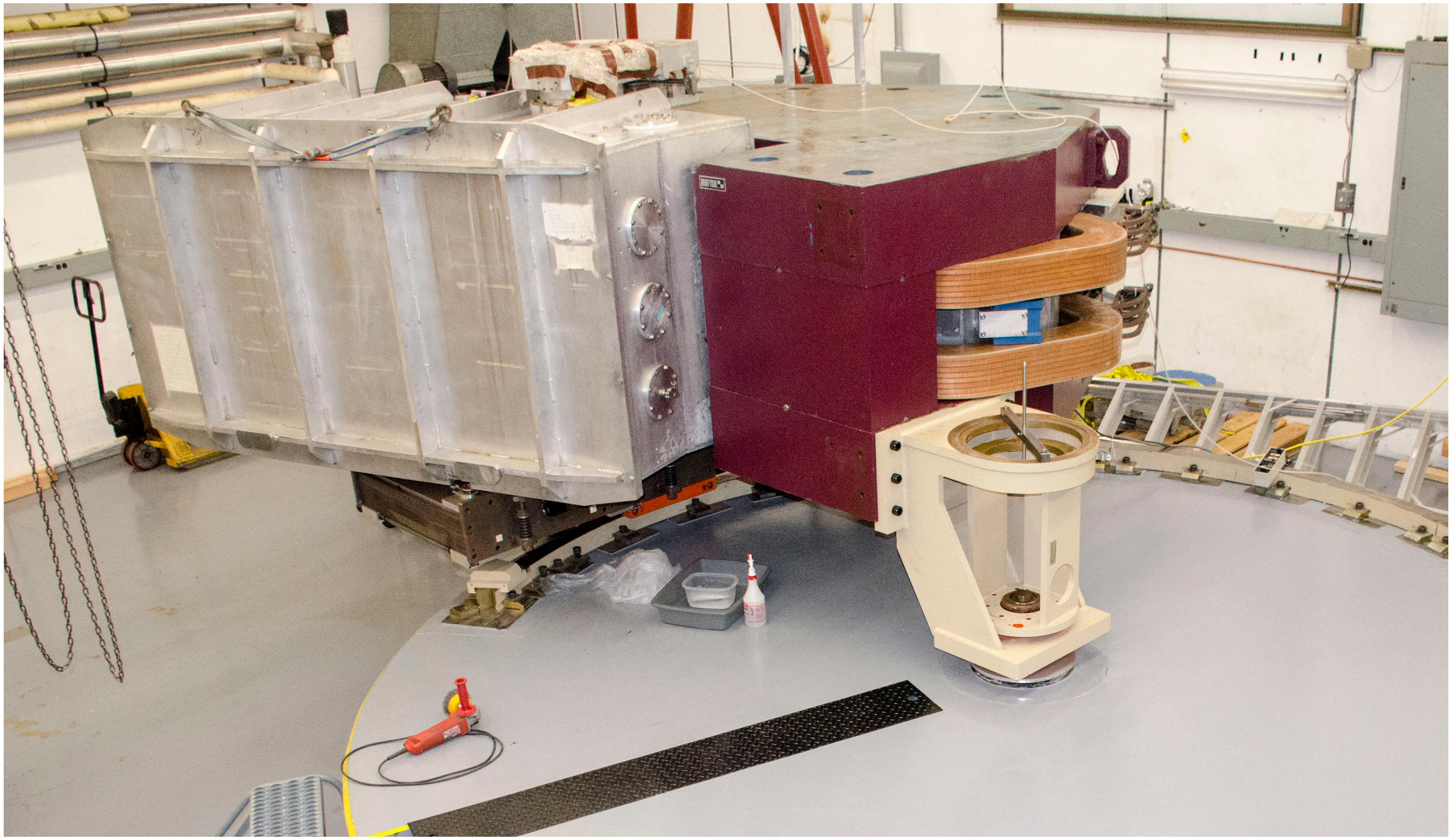
			Mirror		
E_x(MeV)	J^π	nlj	C^2S [a]	ANC [b]	ANC [c]
0	0^+	1d5/2	1.22	12.2(12)	-
1.888	2^+	2s1/2	0.21	14.9(21)	16(8)
	2^+	1d5/2	0.83	2.85(32)	2.6(13)
3.376	4^+	1d5/2	1.57	2.73(35)	2.8(11)
3.576	0^+	1d5/2	0.28	-	-
3.616	2^+	2s1/2	0.35	117(20)	148(56)
	2^+	1d5/2	0.66	2.46(33)	3.1(12)

[a] Li et al.[14]
[b] Abdullah et al.[20]
[c] This work

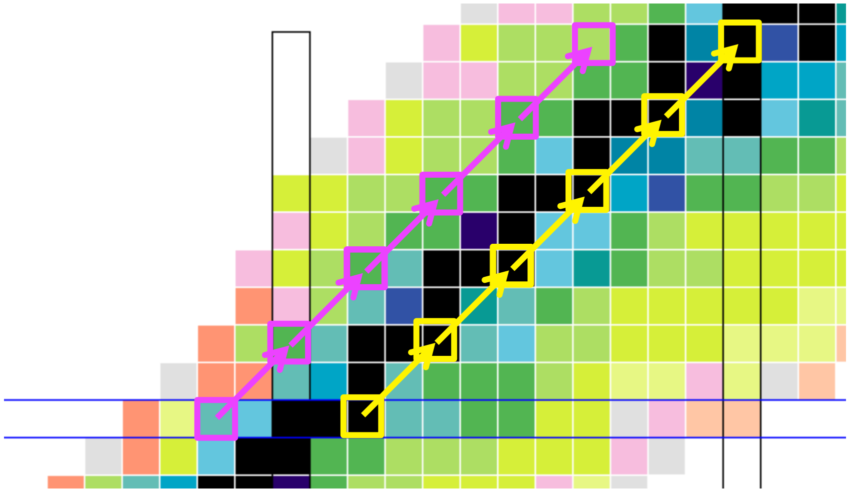


SE-SPS at FSU

- Former Yale large-acceptance Enge SPS now being installed at Fox Superconducting Accelerator Laboratory at FSU
- Experiments starting this year!

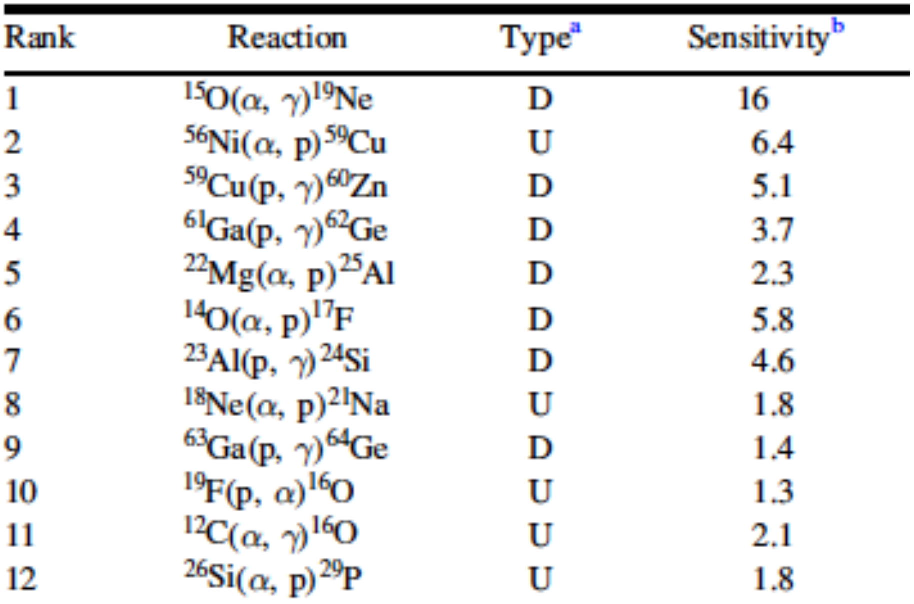


(α,p) reaction rates & X-ray bursts



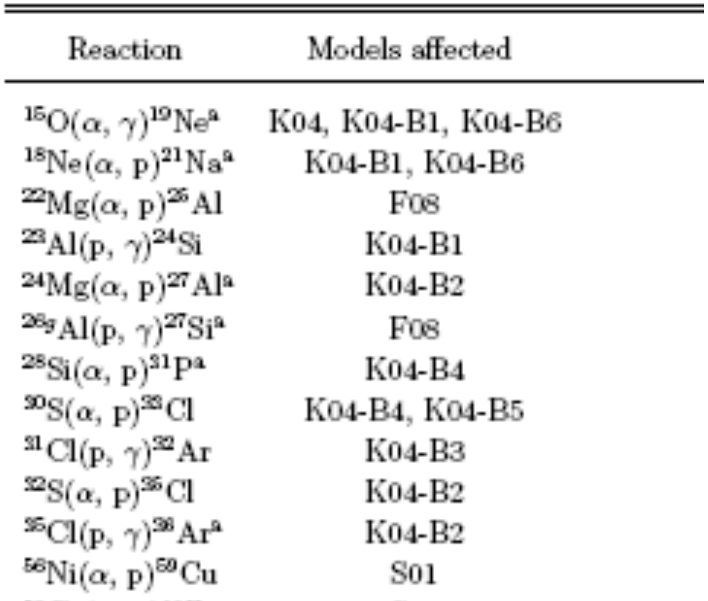
- (α,p) reactions on T_z=+1 nuclei are important reactions in X-ray bursts
- Uncertainties dominated by alpha widths of resonances
- We will measure alpha decay branching ratios with Enge+SABRE
- Mirror reactions on stable nuclei, e.g. (^{6}Li,d) and (α,α) – but is it meaningful?

Cyburt et al., APJ (2016)



Rank	Reaction	Type[a]	Sensitivity[b]
1	^{15}O(α, γ)^{19}Ne	D	16
2	^{56}Ni(α, p)^{59}Cu	U	6.4
3	^{59}Cu(p, γ)^{60}Zn	D	5.1
4	^{61}Ga(p, γ)^{62}Ge	D	3.7
5	^{22}Mg(α, p)^{25}Al	D	2.3
6	^{14}O(α, p)^{17}F	D	5.8
7	^{23}Al(p, γ)^{24}Si	D	4.6
8	^{18}Ne(α, p)^{21}Na	U	1.8
9	^{63}Ga(p, γ)^{64}Ge	D	1.4
10	^{19}F(p, α)^{16}O	U	1.3
11	^{12}C(α, γ)^{16}O	U	2.1
12	^{26}Si(α, p)^{29}P	U	1.8

Parikh et al., APJ (2008)



Reaction	Models affected
^{15}O(α, γ)^{19}Ne[a]	K04, K04-B1, K04-B6
^{18}Ne(α, p)^{21}Na[a]	K04-B1, K04-B6
^{22}Mg(α, p)^{25}Al	F08
^{23}Al(p, γ)^{24}Si	K04-B1
^{24}Mg(α, p)^{27}Al[a]	K04-B2
^{26g}Al(p, γ)^{27}Si[a]	F08
^{28}Si(α, p)^{31}P[a]	K04-B4
^{30}S(α, p)^{33}Cl	K04-B4, K04-B5
^{31}Cl(p, γ)^{32}Ar	K04-B3
^{32}S(α, p)^{35}Cl	K04-B2
^{35}Cl(p, γ)^{36}Ar[a]	K04-B2
^{56}Ni(α, p)^{59}Cu	S01

Alpha spectroscopic factors in ^{19}F:^{19}Ne

- ~10x discrepancy in alpha spectroscopic factors for mirror states of astrophysical importance?

^{19}F wavefunctions? $\begin{cases} {}^{12}C \otimes {}^{7}Li \\ {}^{11}B \otimes {}^{8}Be \\ {}^{14}N \otimes {}^{5}He \\ {}^{15}N \otimes {}^{4}He \end{cases}$

“One can see that the disagreement exceeds one order of magnitude.”

de Oliveira *et al.*, *PRC* ***55*** (1997)

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1

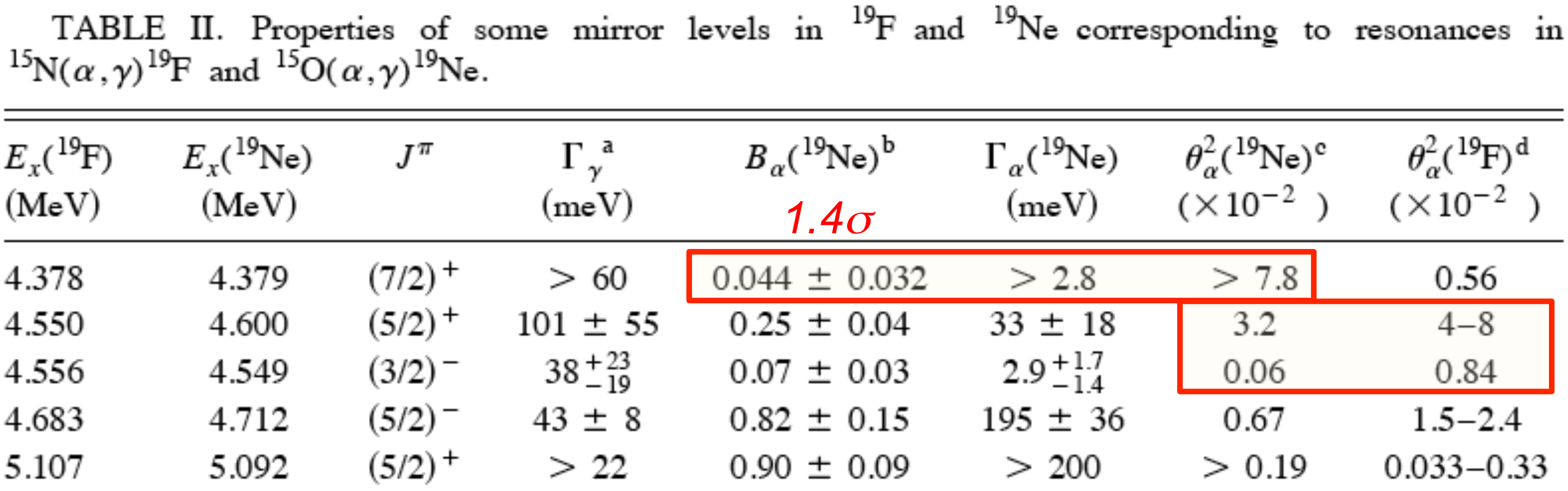
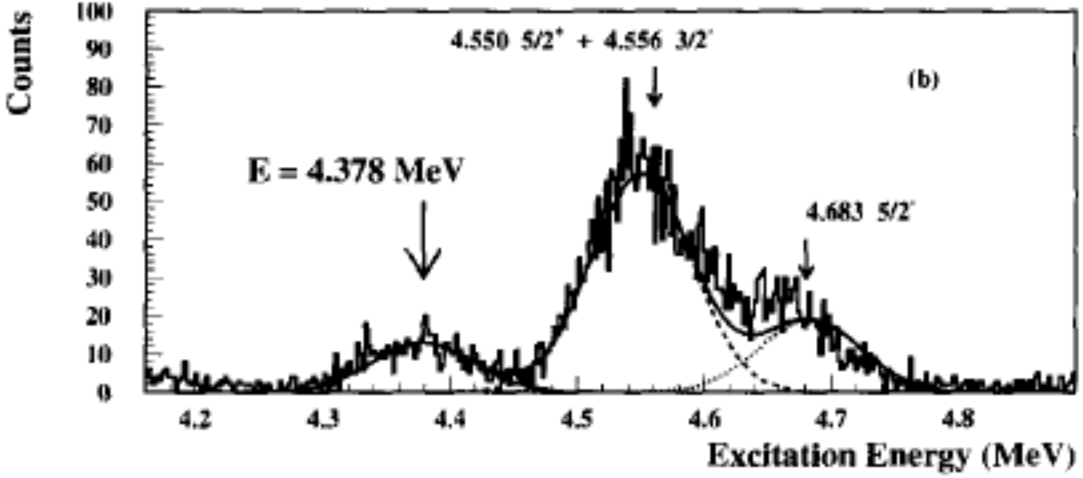


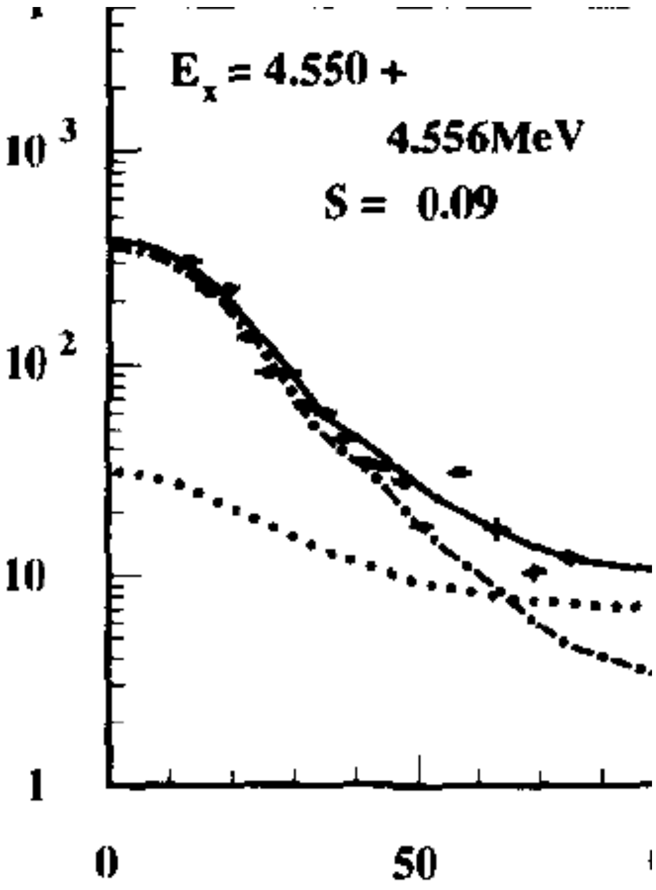
TABLE II. Properties of some mirror levels in ^{19}F and ^{19}Ne corresponding to resonances in ^{15}N$(\alpha,\gamma)^{19}$F and ^{15}O$(\alpha,\gamma)^{19}$Ne.

$E_x(^{19}\mathrm{F})$ (MeV)	$E_x(^{19}\mathrm{Ne})$ (MeV)	J^π	Γ_γ [a] (meV)	$B_\alpha(^{19}\mathrm{Ne})$ [b] 1.4σ	$\Gamma_\alpha(^{19}\mathrm{Ne})$ (meV)	$\theta^2_\alpha(^{19}\mathrm{Ne})$ [c] ($\times 10^{-2}$)	$\theta^2_\alpha(^{19}\mathrm{F})$ [d] ($\times 10^{-2}$)
4.378	4.379	$(7/2)^+$	> 60	0.044 ± 0.032	> 2.8	> 7.8	0.56
4.550	4.600	$(5/2)^+$	101 ± 55	0.25 ± 0.04	33 ± 18	3.2	4–8
4.556	4.549	$(3/2)^-$	38^{+23}_{-19}	0.07 ± 0.03	$2.9^{+1.7}_{-1.4}$	0.06	0.84
4.683	4.712	$(5/2)^-$	43 ± 8	0.82 ± 0.15	195 ± 36	0.67	1.5–2.4
5.107	5.092	$(5/2)^+$	> 22	0.90 ± 0.09	> 200	> 0.19	0.033–0.33

Maybe not as bad as it appears?

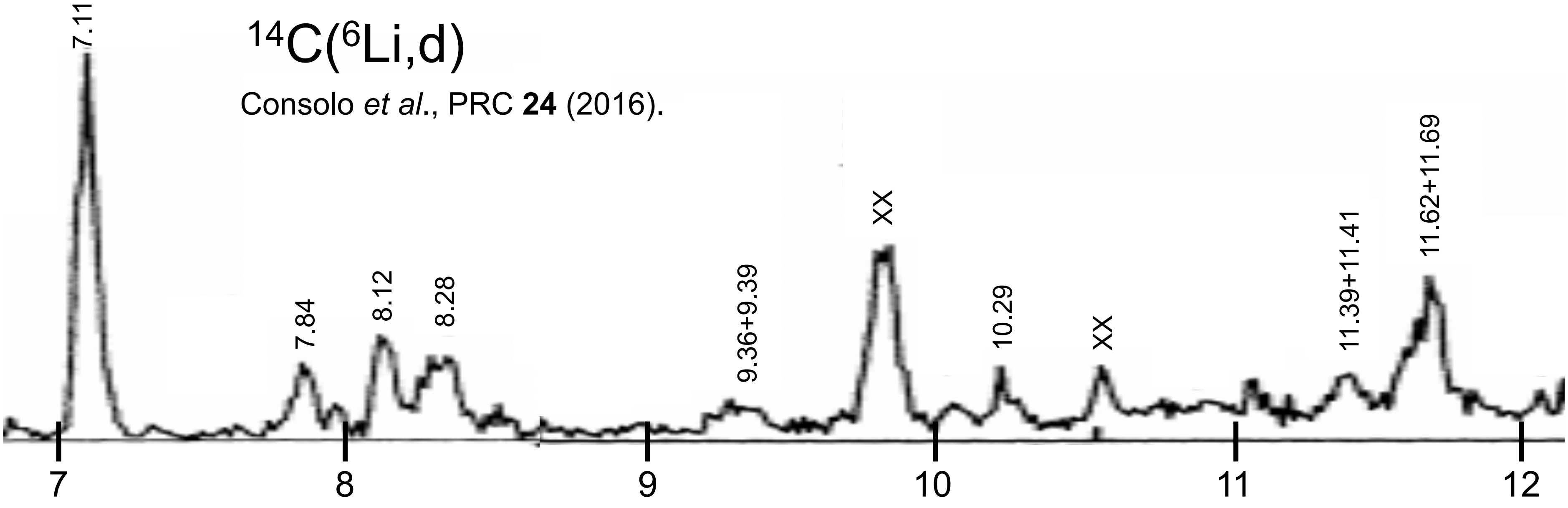
$^{15}N(^7Li,t)^{19}F$ de Oliveira *et al.*, NPA **597** (1996)





- ➢ 4.550 and 4.556 states not resolved
- ➢ Dominated by 4.550 strength – but to what degree?
- ➢ Only weak constraints on 4.556 level

α cluster states in ^{18}O

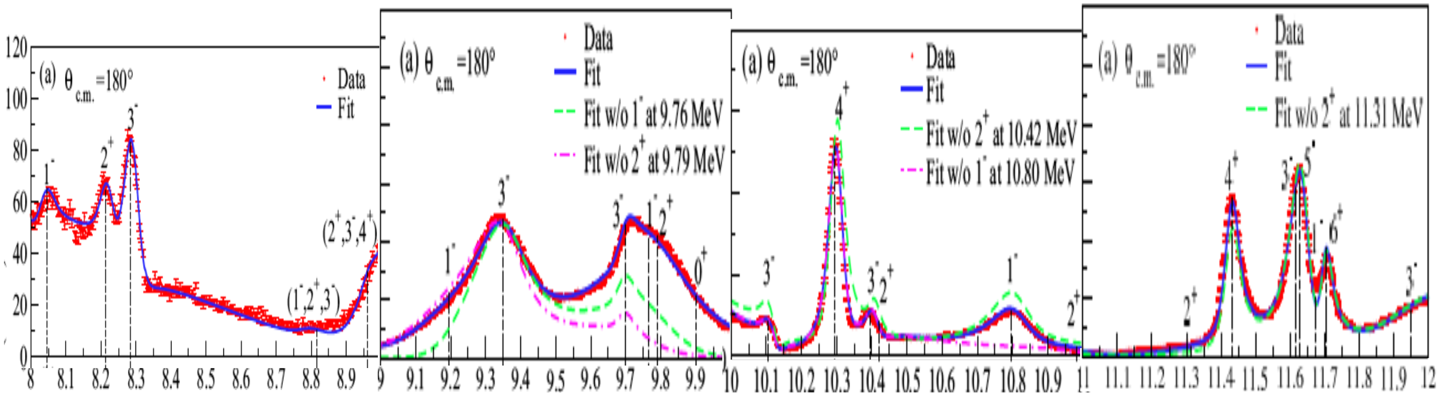


^{14}C(^{6}Li,d)

Consolo *et al.*, PRC **24** (2016).

^{14}C(α,α)

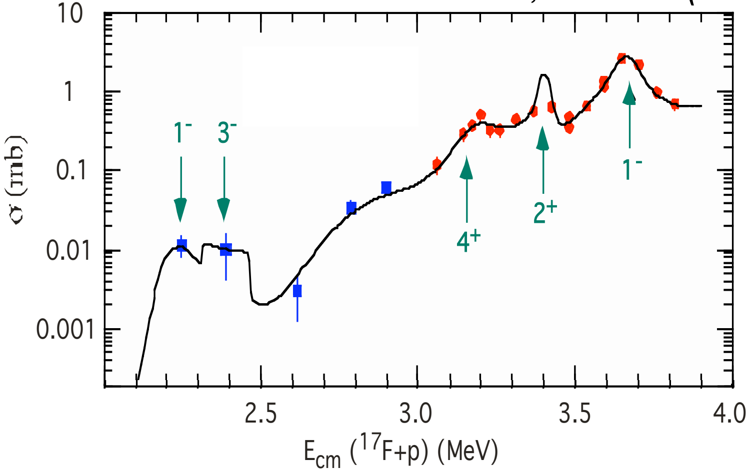
Avila *et al.*,
PRC **90** (2016).



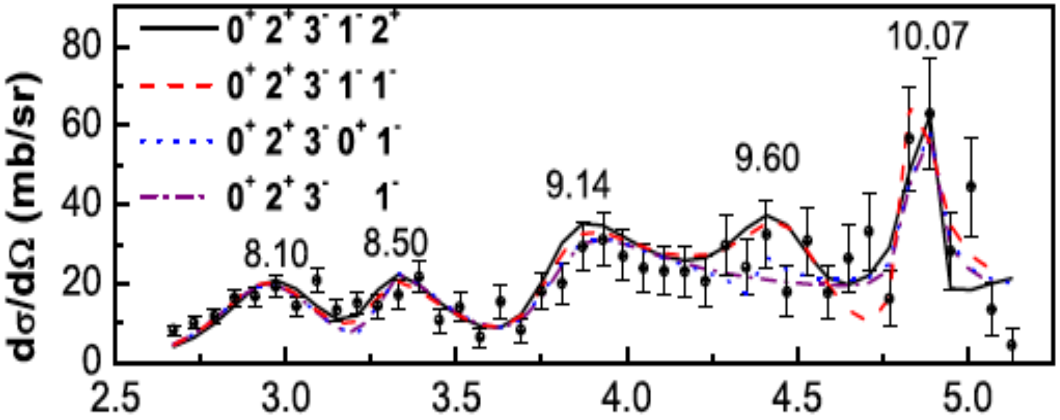
α widths in ^{18}Ne

^{17}F(p,α)^{14}O

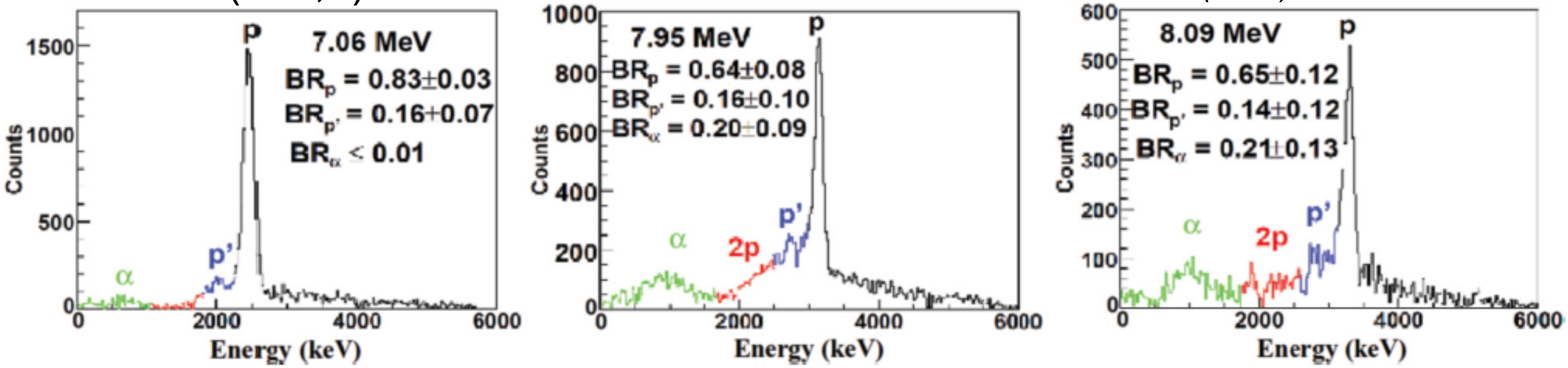
*Blackmon et al., NPA **688** (2001)*
*Harss et al., PRL **82** (1999)*



^{14}O(α,p)^{17}F *Kim et al., PRC **92** (2015)*



^{16}O(^{3}He,n)^{18}Ne→^{14}O+α *Almaraz-Caldaron et al., PRC **86** (2012)*



^{18}O:^{18}Ne Comparison?

^{14}O(α,p)

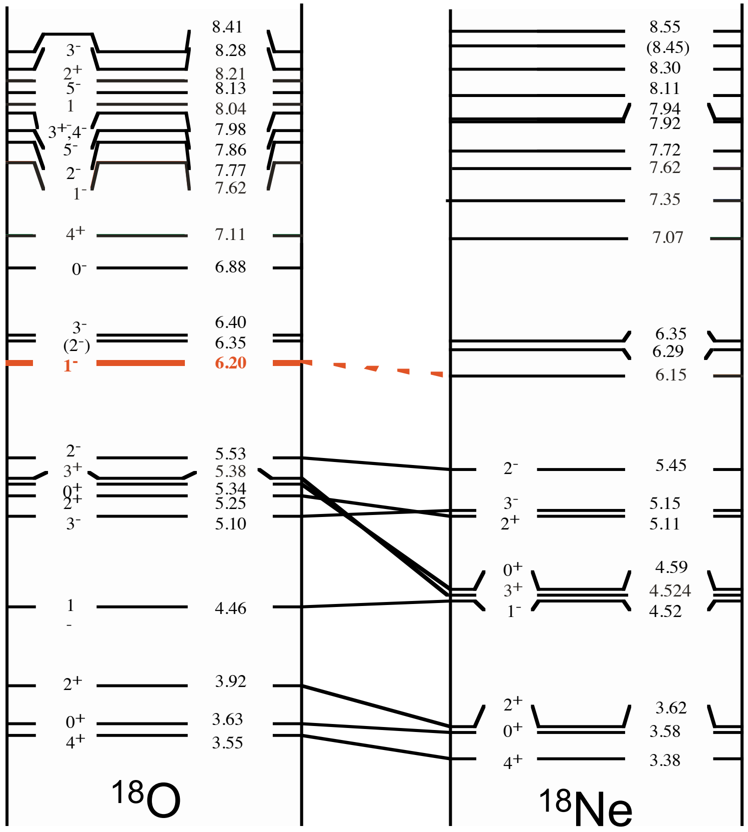
E_x		Γ_α (keV)
7.35	(1^-)	3.1 (2)
7.60	(0^+)	1.5 (5)
7.72	(2^+,3^-)	1.9 (3)
8.10	(0^+)	40 (5)

^{17}F(p,α)

6.15	(1^-)	0.008 (3)
7.10	(1^-)	0.30 (8)
7.35	(4^+)	1.9 (3)
7.60	(1^-,2^+,3^-)	0.5–1.2

^{16}O(^{3}He,n)

7.95	(3^-)	11 (7)
8.09	(3^-)	6 (4)



- Probably the only state with a clear mirror assignment is 6.20 ⇔ 6.15 (1-) level
- Most important resonance for ^{14}O(α,p)^{17}F

  2 eV from ^{14}C(^{7}Li,t)
  8 eV from ^{17}F(p,α)
- Limitation of mirror symmetry?

Concluding remarks

- Reactions on proton-rich nuclei are important
  - (p,γ)
  - (α,p)
  - (n,p)

- Direct measurements are very difficult
  - Small cross sections
  - Low radioactive ion beam intensities

- Indirect approaches are crucial

- Reliable reaction models into the continuum are important
  - Often narrow states near threshold

- Mirror reactions are much easier experimentally
  - But how reliable are any comparisons?