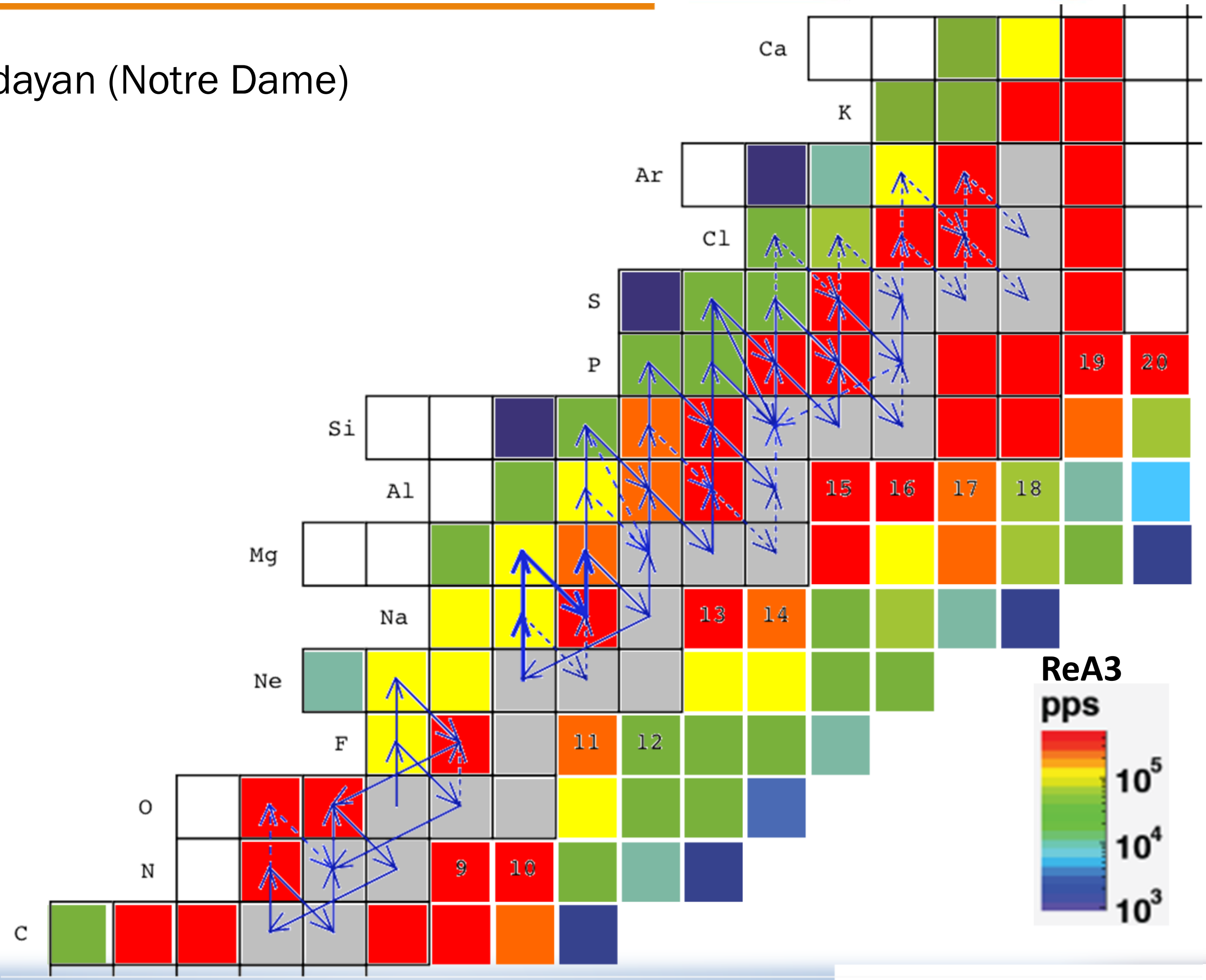
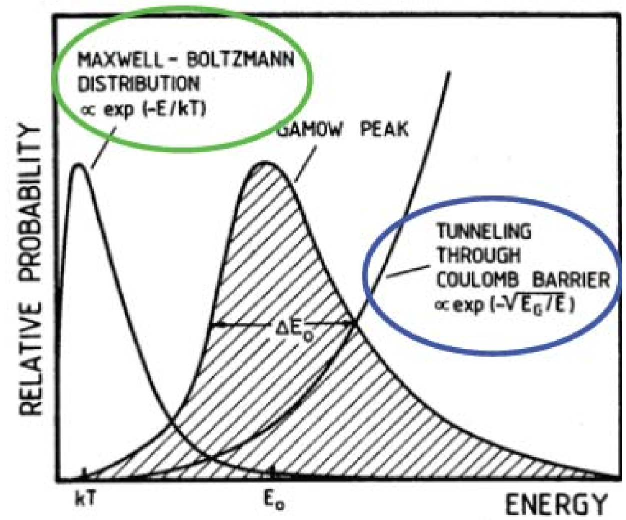
Proton-transfer reactions on exotic nuclei as a probe of nucleosynthesis

D. W. Bardayan (Notre Dame)



Direct vs. Indirect measurements

- Reaction rate combines
  - thermal velocity distribution in stellar plasma (Maxwell-Boltzmann distribution)
  - probability of tunneling through Coulomb barrier (nuclear cross section)



Rolfs & Rodney (1988)

- For resonant reaction rates:
  - exponentially dependent on resonance energy: E_r
  - linearly dependent on resonance strength: $\omega\gamma$

- Measure reaction rates:
  - directly
  - indirectly

If resonance is narrow

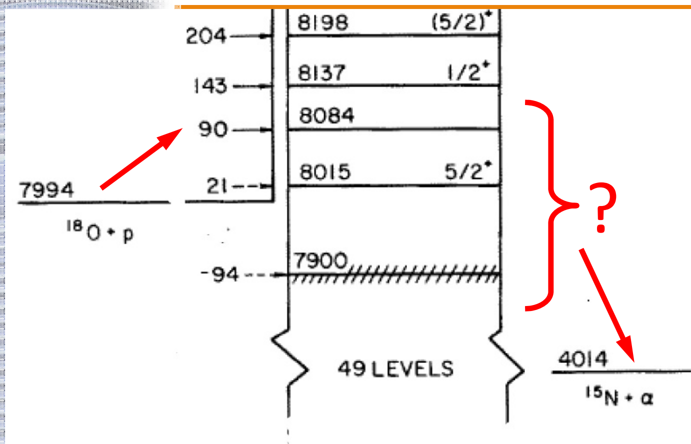
$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu} kT \right)^{3/2} \hbar^2 (\omega\gamma) e^{-E_r/kT}$$

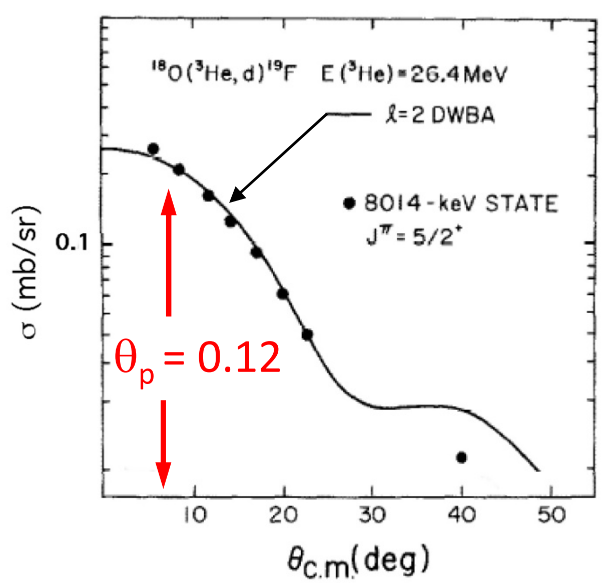
E_r & J^π are most important

$$\omega\gamma = \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{\Gamma}$$

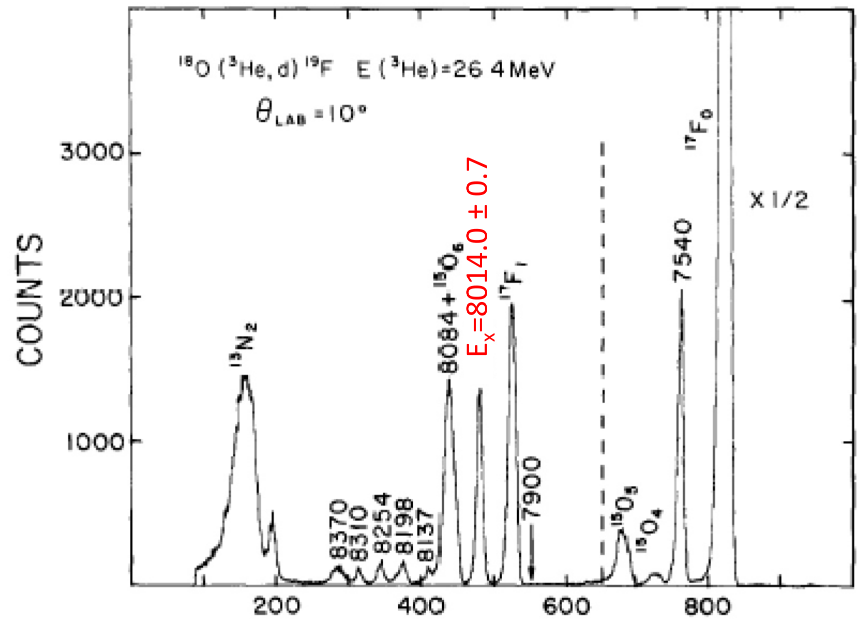
“resonance strength”

(^{3}He,d) on stable targets to determine (p,γ) rates





Champagne and Pitt (1986)



$$\Gamma_p = 2\left(\frac{\hbar^2}{\lambda\mu R}\right)\left(\frac{\theta_p^2}{F_\ell^2 + G_\ell^2}\right) \Longrightarrow \Gamma_p = 2\times10^{-19}\ \text{eV}$$

1 mA p + ^{18}O → 1 event / 3x10^5 years

↖ Well established techniques with stable beams

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Experimental approaches with exotic beams

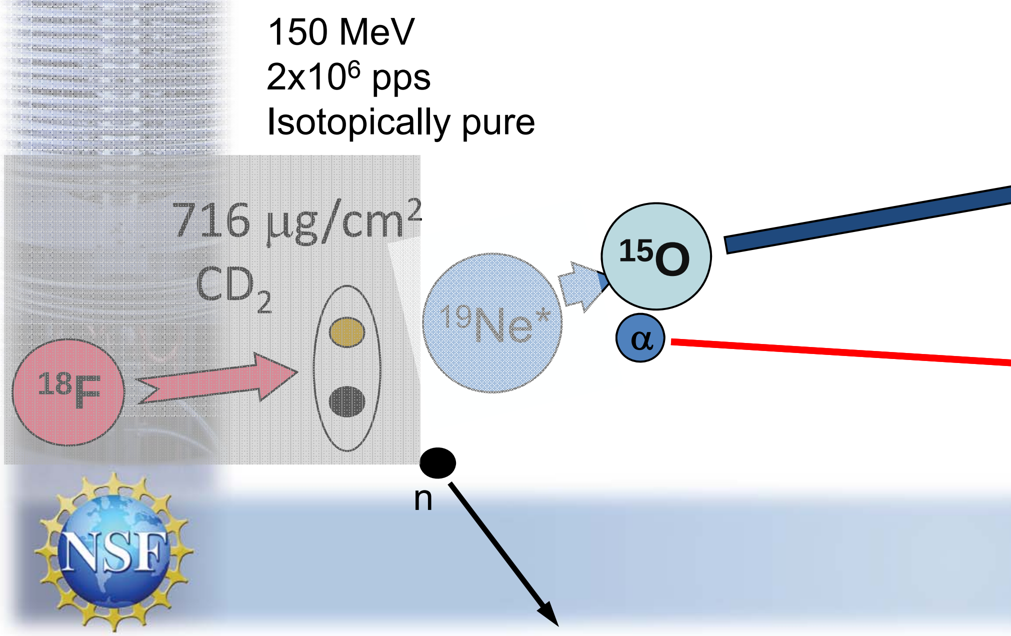
- Challenges
  - Beams are lower intensities and frequently contaminated
  - Inverse kinematics limits resolution
  - "Best" proton transfer reactions have difficult target/detector issues.
- (d,n) reactions
  - (CD_2) target are relatively easy to use
  - Background from spectator C atoms
  - Neutron detection difficult. Groups avoid at all costs.
- (^{3}He,d) reactions
  - Localized targets of ^{3}He hard
  - ^{3}He expensive
  - d detection easy

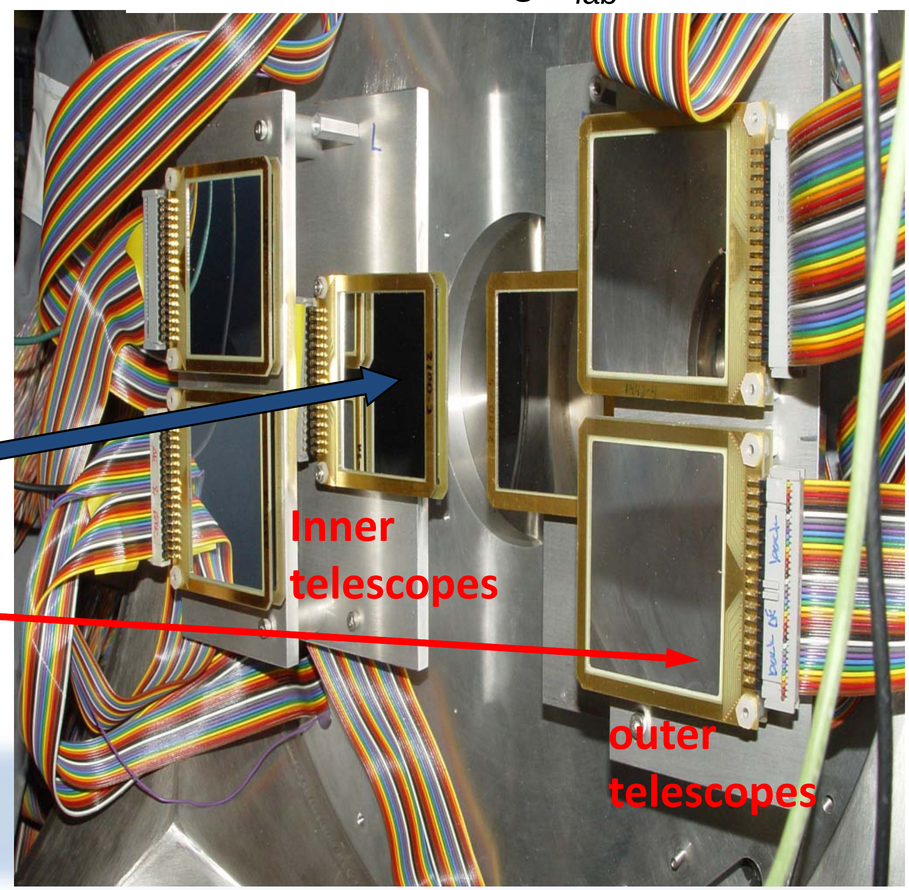
$^{18}F(d,n)^{19}Ne \rightarrow {}^{15}O + \alpha$

A. Adekola et al., PRC 83, 052801(R) (2011).

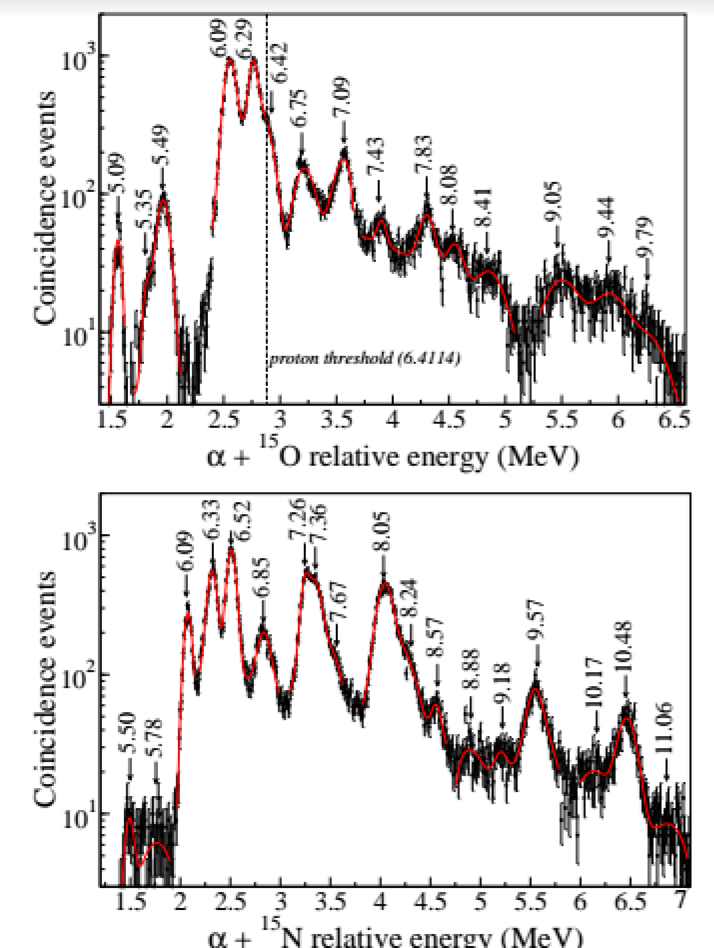
- Laboratory: ORNL Holified Radioactive Ion Beam Facility
- Beam: $^{9+}F^{18}$
  - Energy 150 MeV
  - Intensity ~ 2 x 10^6 ions/s
  - Run time 117 hrs
- Target: 716 $\mu g/cm^2$ CD_2

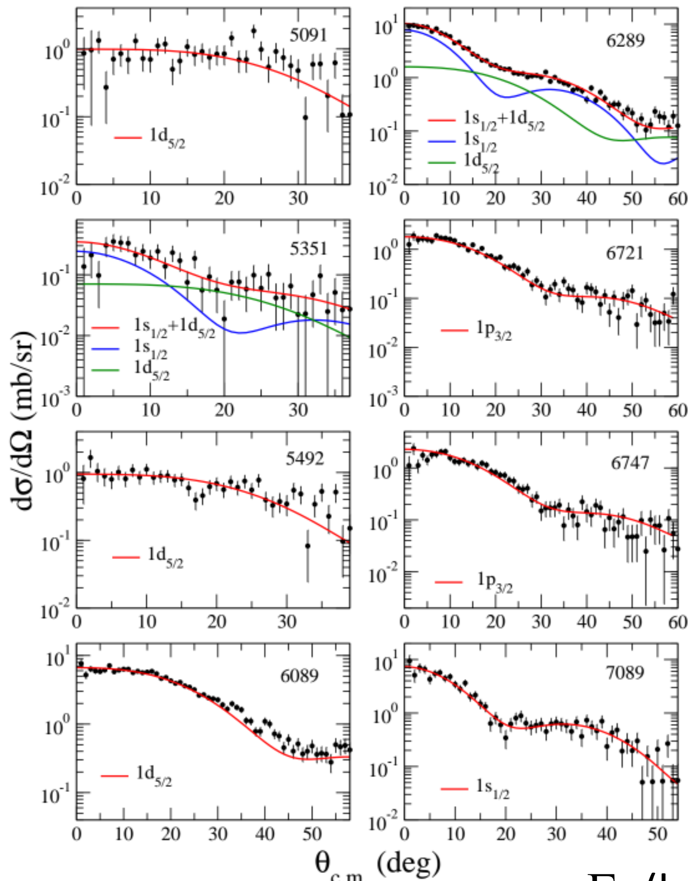
Six position sensitive silicon-strip detectors covering θ_{lab}~2°-17°





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

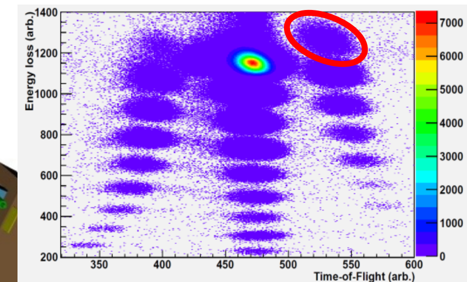




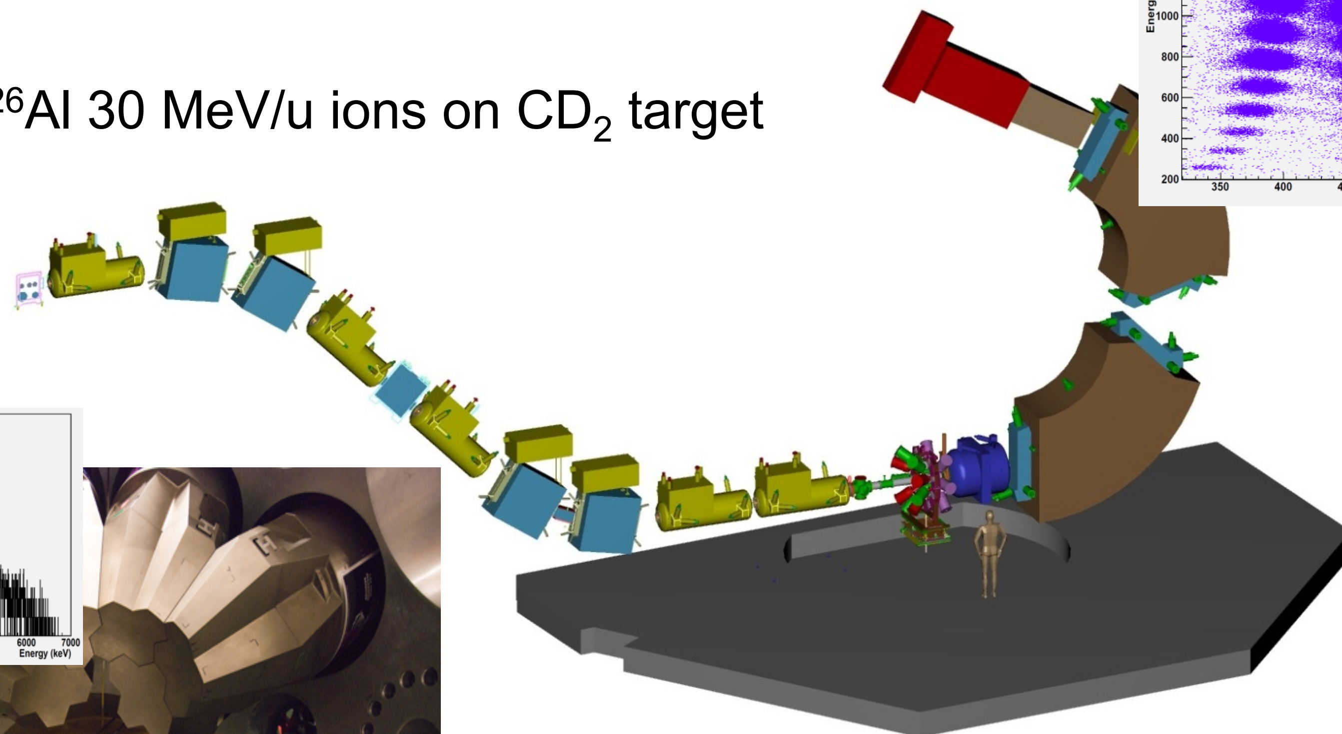
E_x (keV)	J^{π}	Γ_p (keV) Present work	Ref [8]
6419	$3/2^-$	$1.27(4) \times 10^{-38}$	$2.2(4) \times 10^{-37\,a}$
	$1/2^-$	$2.54(4) \times 10^{-38}$	
6449	$3/2^+$	$2.35(4) \times 10^{-15}$	$4.0(4.0) \times 10^{-15}$
6741	$3/2^-$	$7.3(6) \times 10^{-3}$	$2.22(68) \times 10^{-3}$
7076	$3/2^+$	$13.5(7)$	$15.2(1.0)$

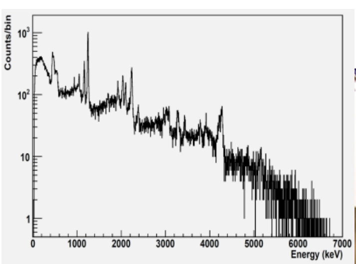
[a] Previous workers assumed $J^{\pi} = 3/2^+$ for the state.

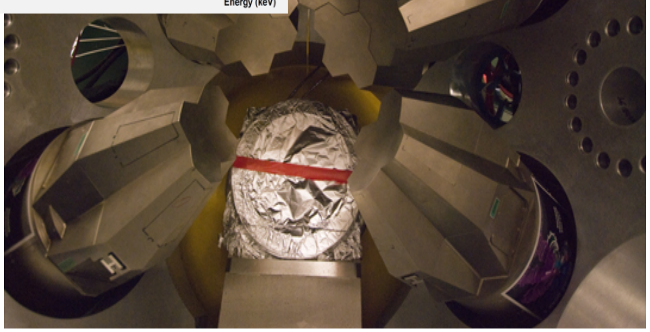
New technique for (d,n) studies of (p,γ) resonance strengths with GRETINA γ-array and S800 spectrometer
PJW, H Schatz et al., NSCL, April 2013



~10^6 ^{26}Al 30 MeV/u ions on CD_2 target



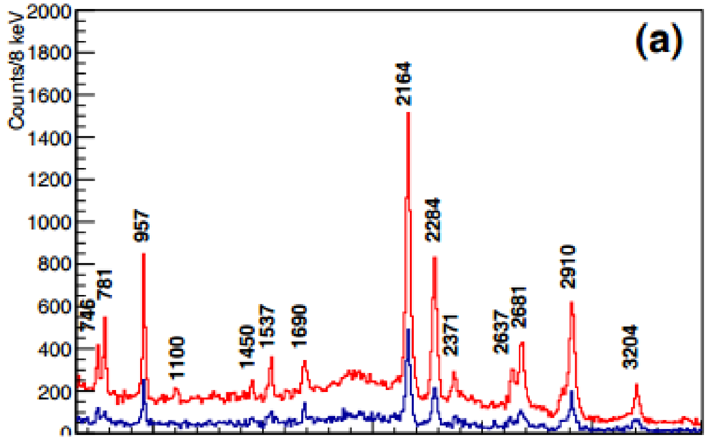


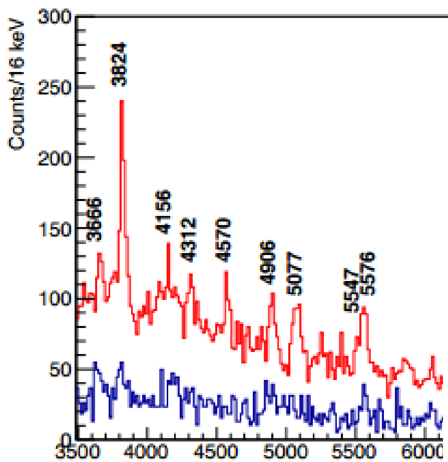


Measure $\sigma(d,n)_{INT}$ → Γ_p for strong resonances

slide courtesy of P. Woods

^{27}Si gamma spectrum



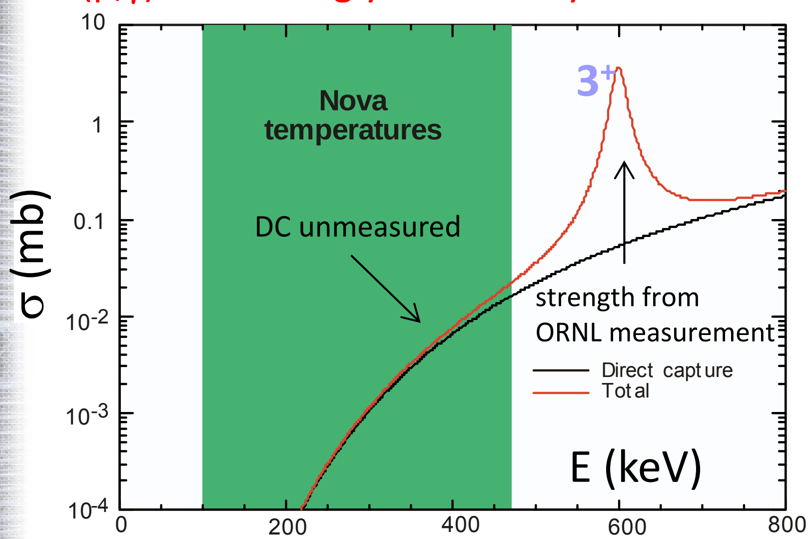


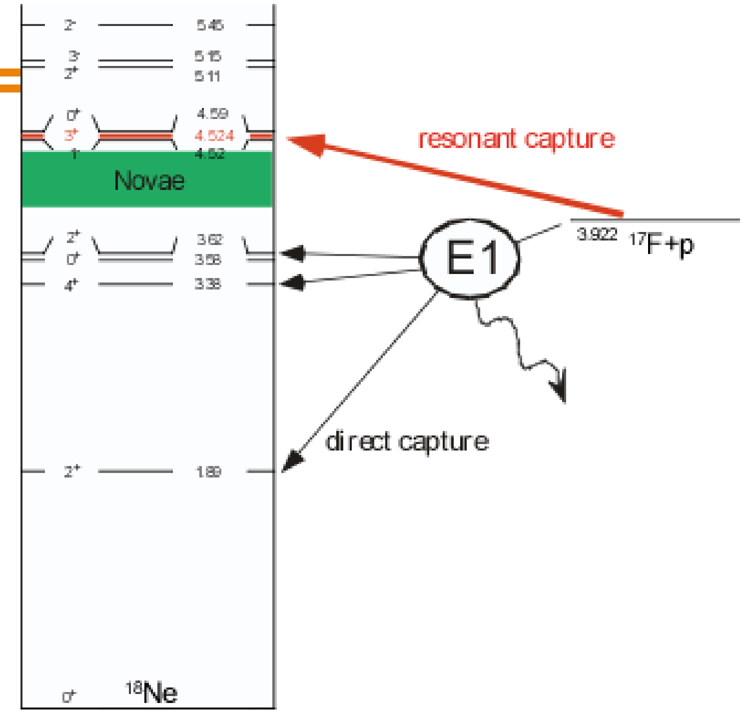
A. Kankainen et al., Eur. Phys. J. A 52, 6 (2016).

E_x (keV)	E_{res} (keV)	J^π	l	σ_{exp} (μb)	σ_{theor} (μb)	$C^2S(d,n)$	$C^2S(^3\mathrm{He},d)$	$C^2S(d,p)$	C^2S_{SM}
5547.3(1)		$9/2^+$	2	520(110)	850	0.61(13)			0.44/0.42
6734.0(2)		$11/2^+$	2	390(90)	1104	0.35(8)			0.50/0.50
7129.0(2)		$13/2^+$	2	630(130)	1262	0.5(1)			0.77/0.74
7590.1(9)	126.9(9)	$9/2^+$	0	≤ 37	375	≤ 0.10	≤ 0.002	0.0093(17)	0.011/0.017
			2	≤ 37	757	≤ 0.05	–	0.068(14)	0.053/0.052
7651.9(6)	188.7(6)	$11/2^-$	1	280(70)	1260	0.22(5)	0.16	0.14(3)	0.067
			3	280(70)	2517	0.11(3)	0.49	–	0.480
7739.3(4)	276.1(4)	$9/2^+$	0	70(30)	370	0.19(9)	0.087	–	0.019/0.011
			2	70(30)	746	0.10(5)	0.124	–	0.0092/0.011
		$9/2^-$	1	70(30)	982	0.07(4)	0.064	–	0.038
			3	70(30)	2070	0.035(16)	0.199	–	0.11

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

$^{17}F(p,\gamma)^{18}Ne$ strongly affected by unmeasured DC rate.



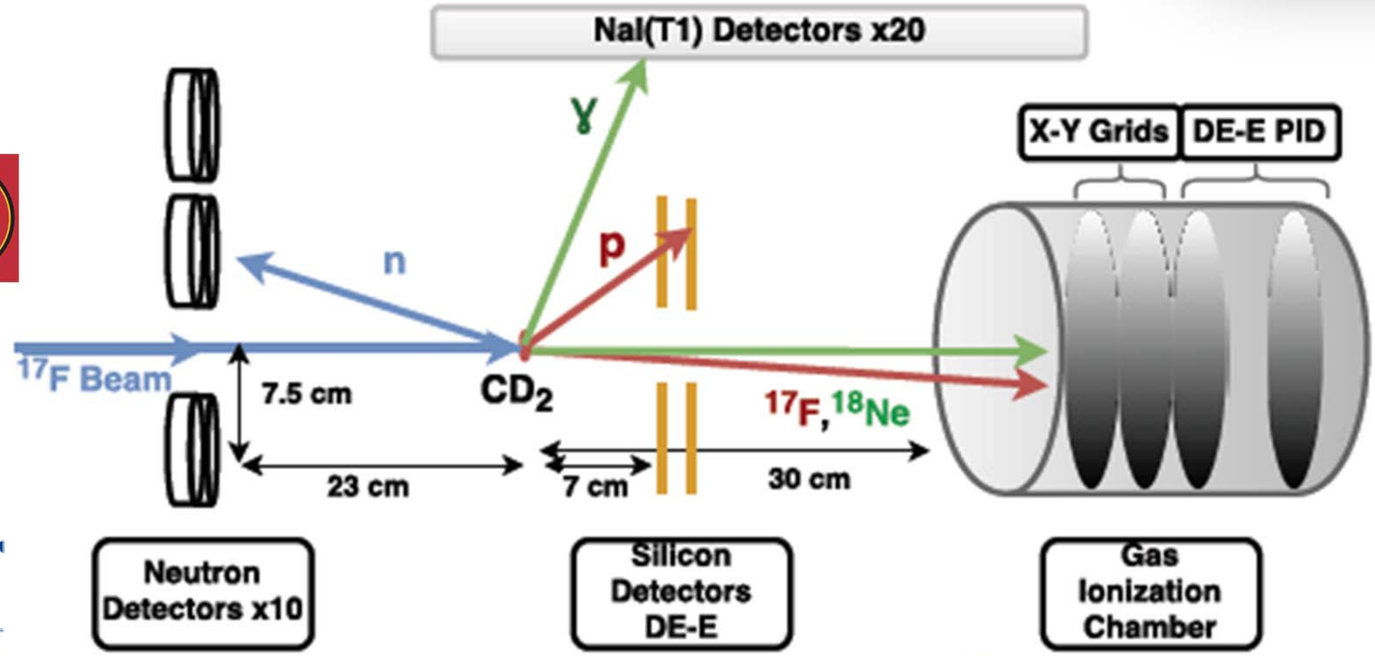


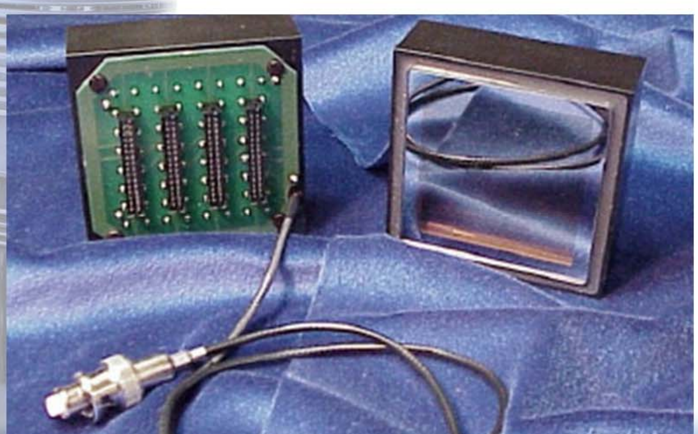
$$\sigma_{DC} = \sum_l C^2S\, \sigma_{theo}(l)$$

Need C^2S to calculate DC rate.

Will use the $^{17}F(d,n)$ reaction to measure the needed spectroscopic strengths.

(d,n) proton transfer using ResoNeut





$^{17}F(d,n)^{18}Ne^{*} \rightarrow (p)^{17}F$

$^{17}F(d,n)^{18}Ne^{*} \rightarrow (\gamma)^{18}Ne$

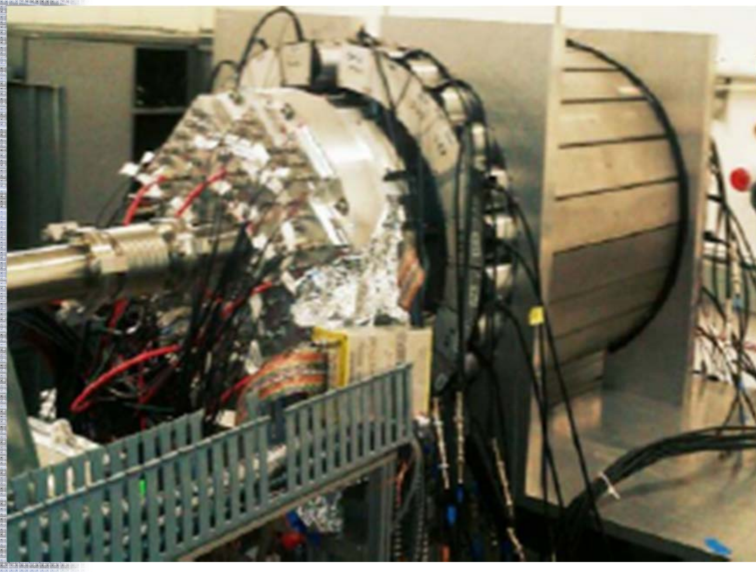
⇒ $^{17}F(p,\gamma)^{18}Ne$ reaction rate

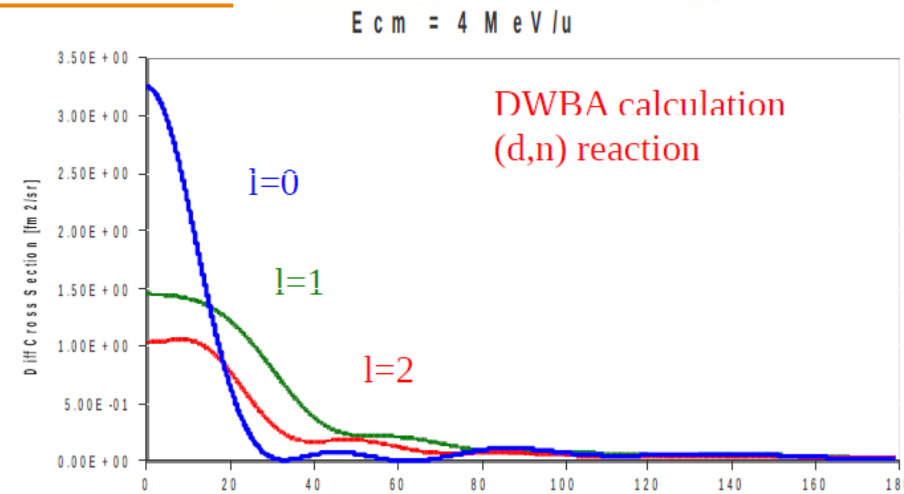
S. Kuvin *et al.*

ResoNeut= P-Terphenyl + Planacon PMT

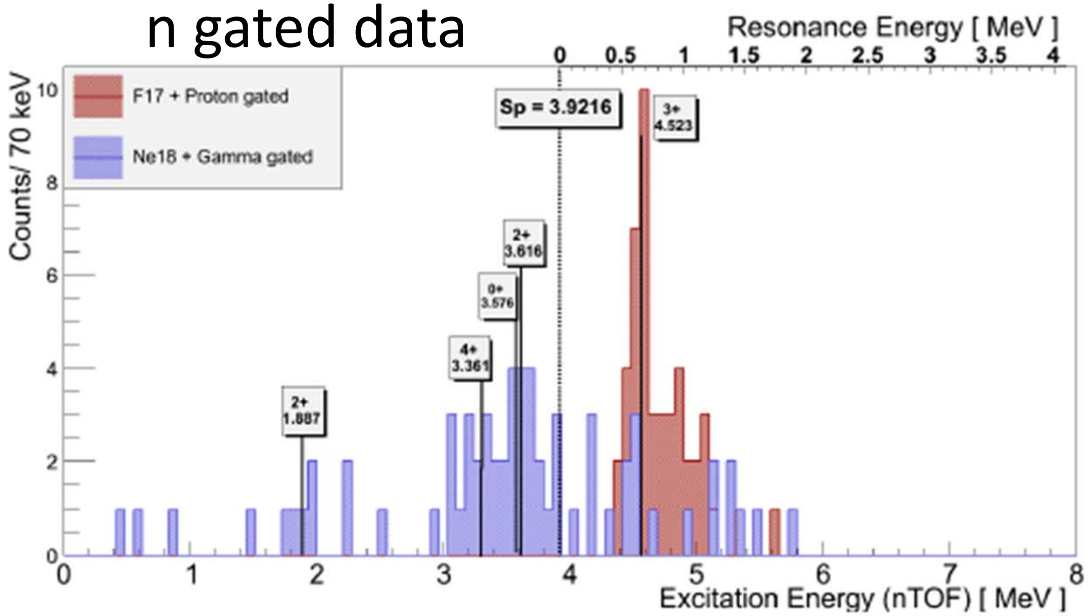
slide courtesy of J. Blackmon

$^{17}F(d,n)$ at ResoNeut





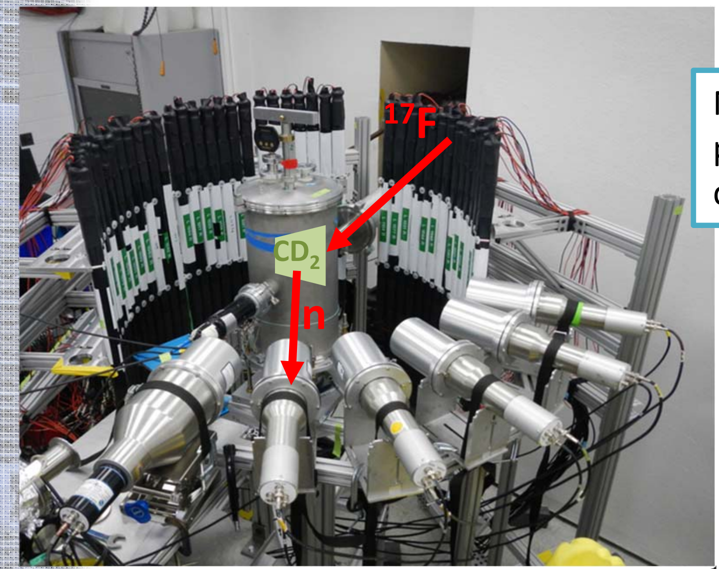
n gated data



slide courtesy of I. Wiedenhoever

$^{17}F(d,n)^{18}Ne$ at Notre Dame

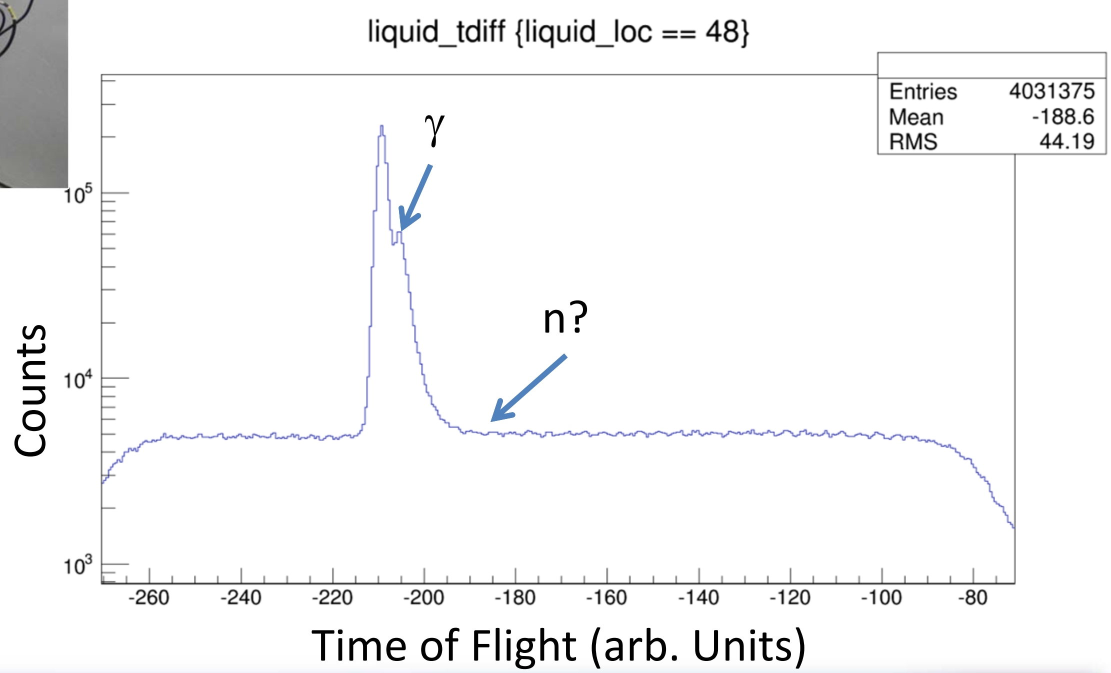
– P. O'Malley et al.



Neutrons detected in array of VANDLE plastic scintillators and U. Michigan deuterated Benzene detectors.

Start on n detection
Stop on delayed beam stop

2 γ flashes from beam on target and beam stop (i.e., the scintillator).



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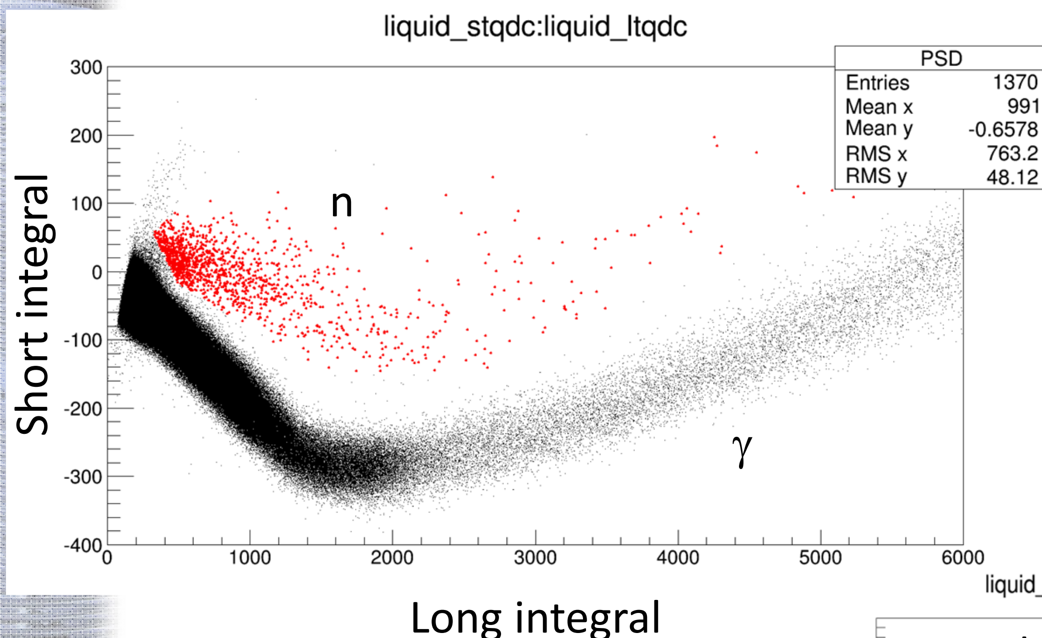
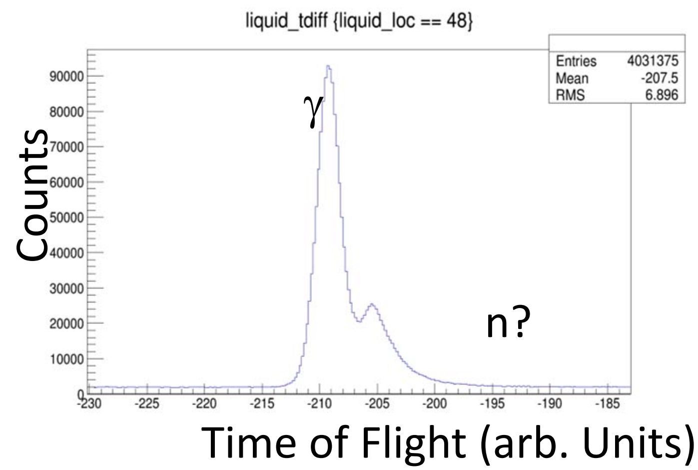
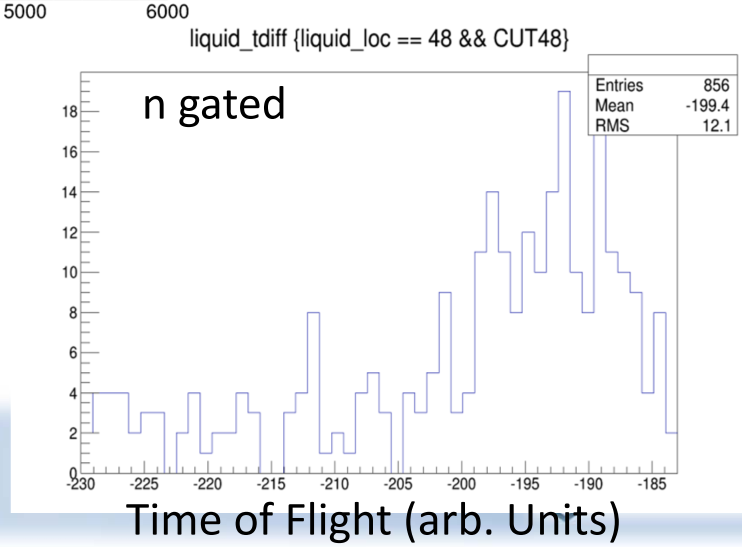
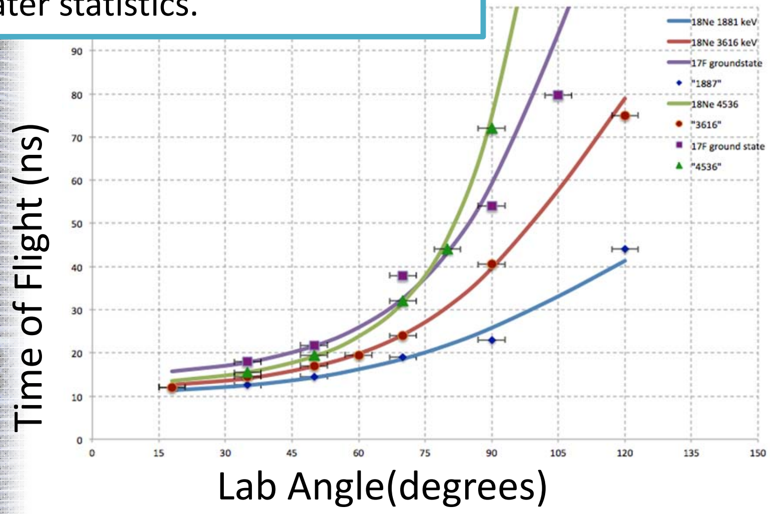


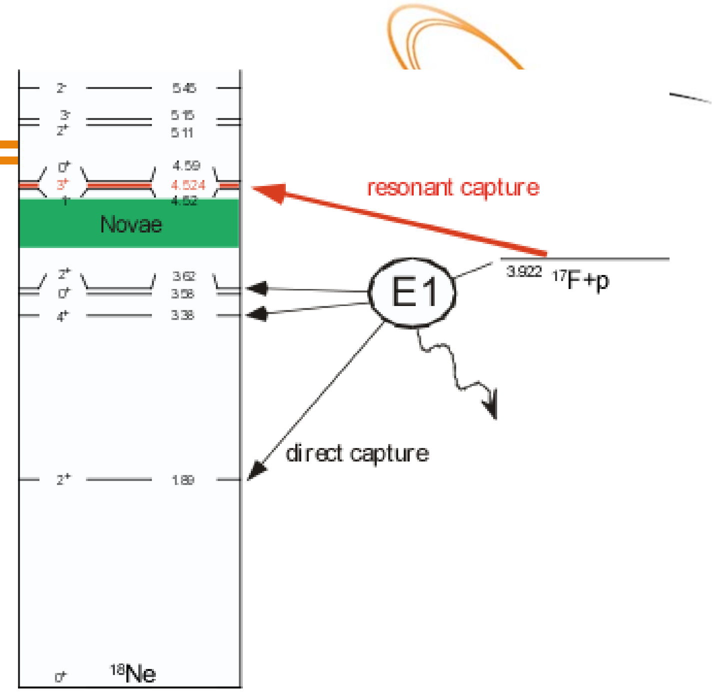




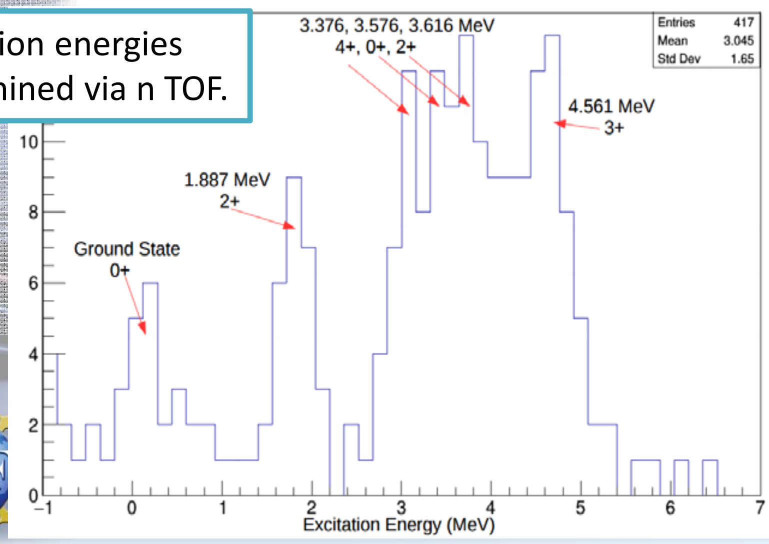
$^{17}F(d,n)^{18}Ne$

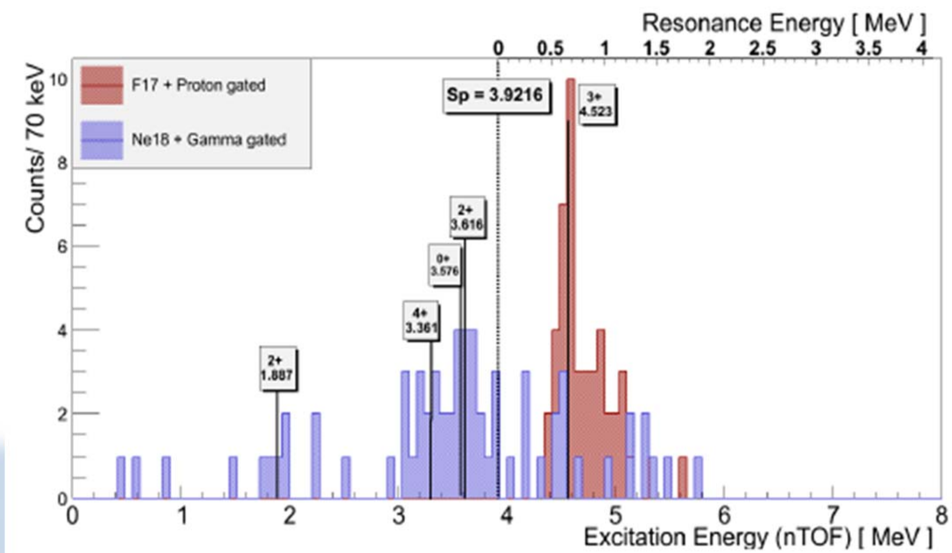
Small interference from $^{16}O(d,n)$. Will repeat with pulsed beam and greater statistics.





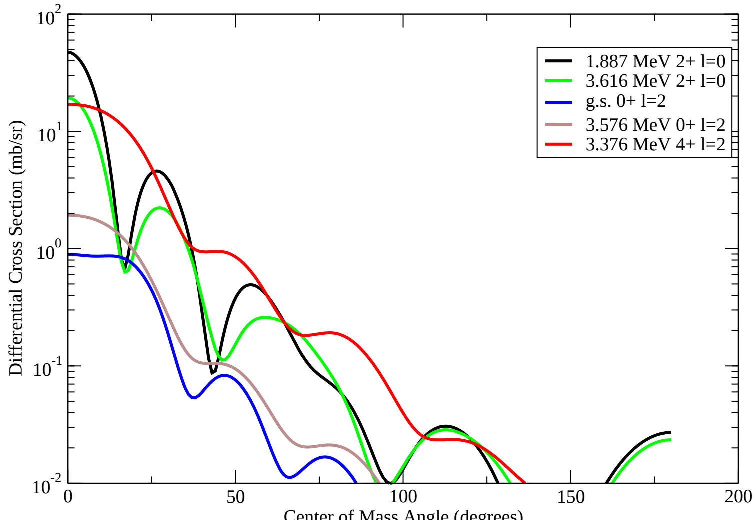
Excitation energies determined via n TOF.



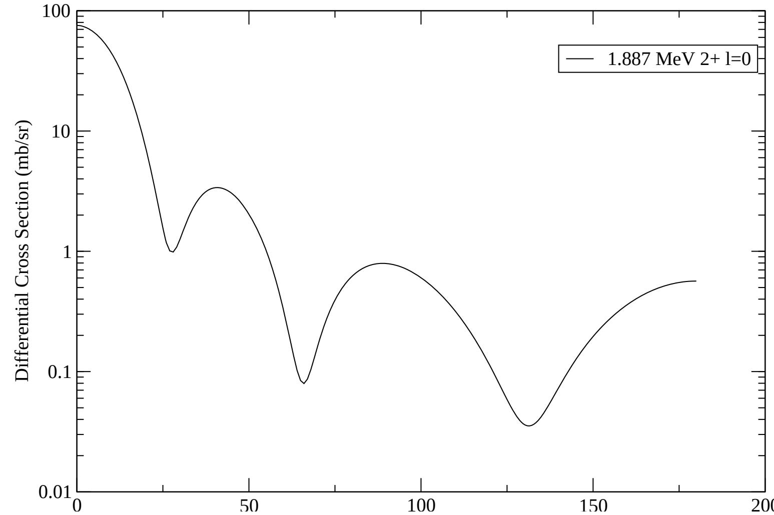


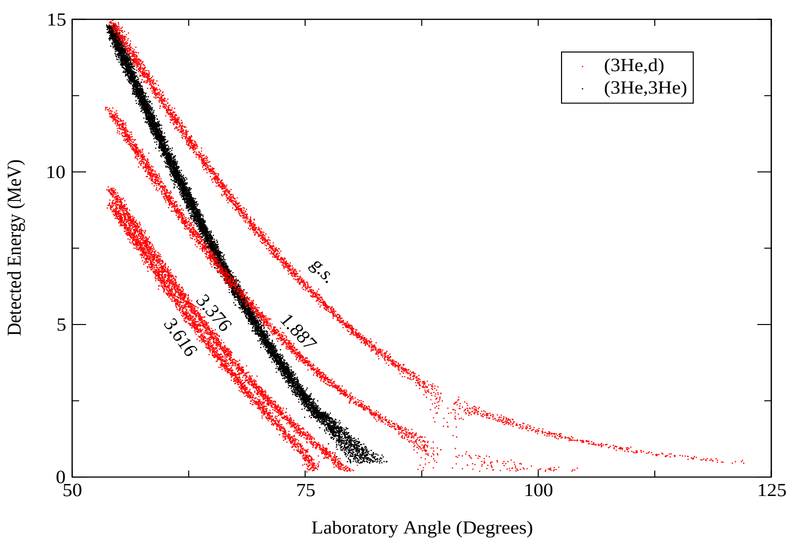
(d,n) or (^{3}He,d)?

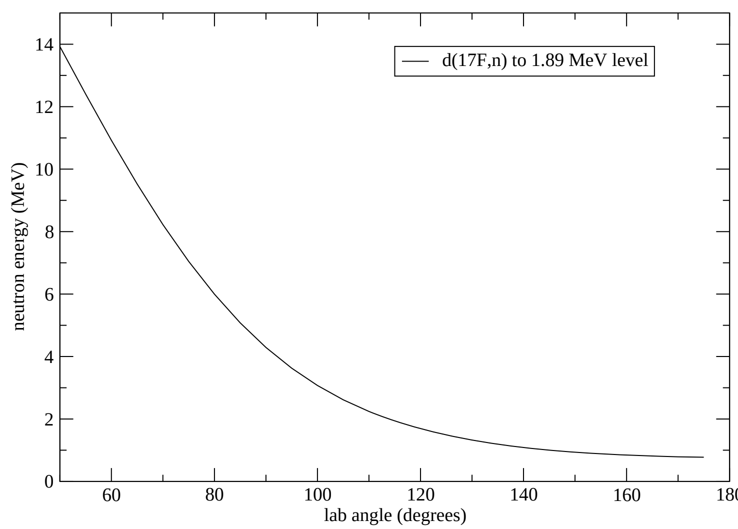
(^{3}He,d) on ^{17}F at 5 MeV/u



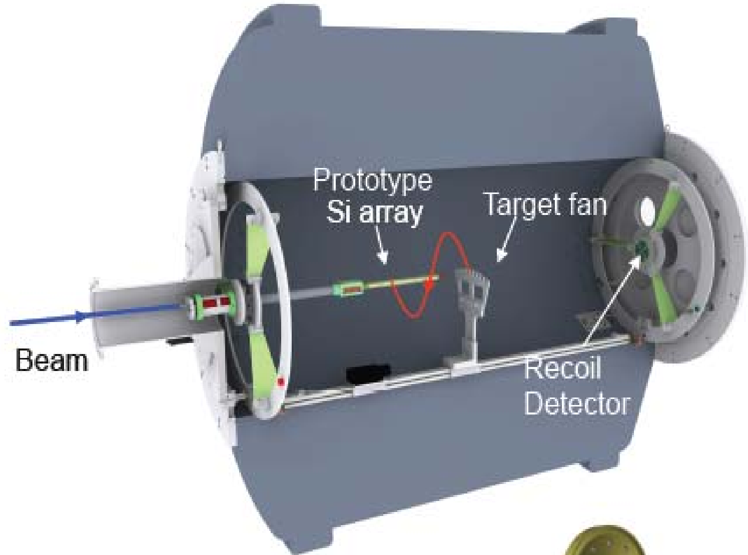
(d,n) on ^{17}F at 5 MeV/u





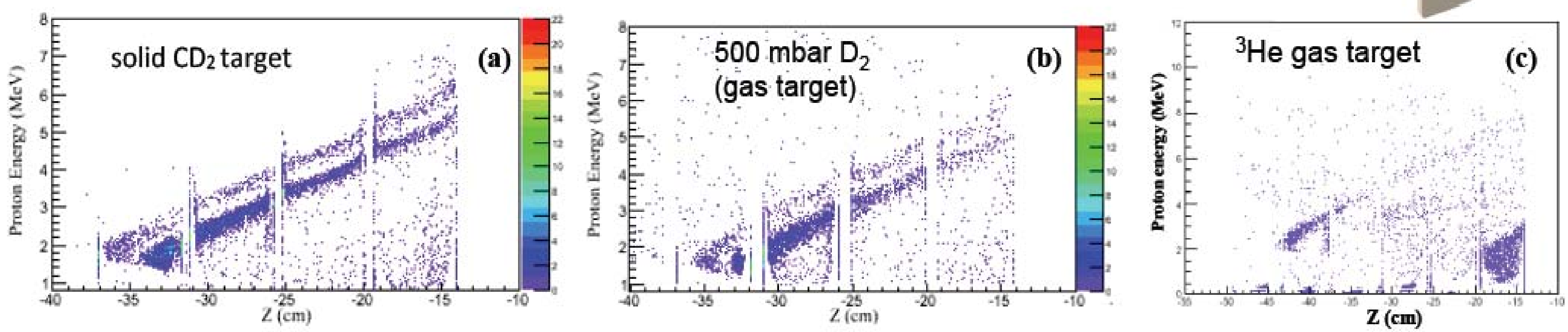


(^{3}He,*d*) in HELIOS



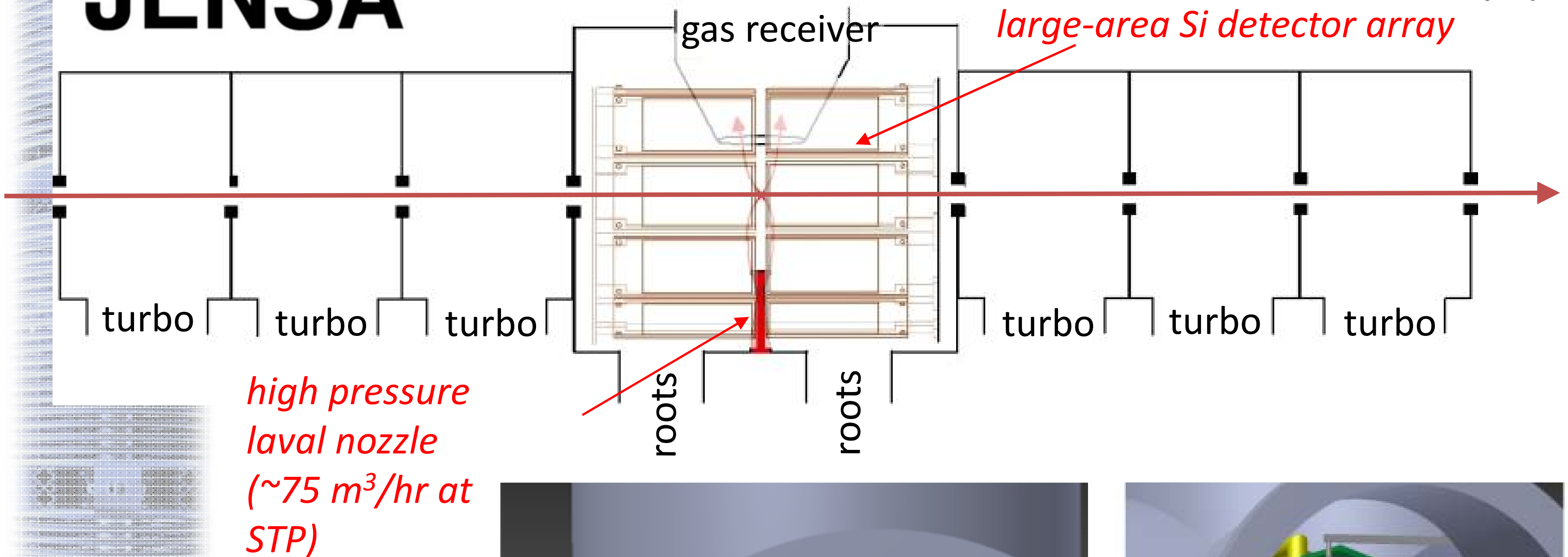
- HELIcal Orbit Spectrometer (HELIOS)
  - particle ID via time-of-flight
  - no kinematic compression → better resolution
  - high geometrical efficiency

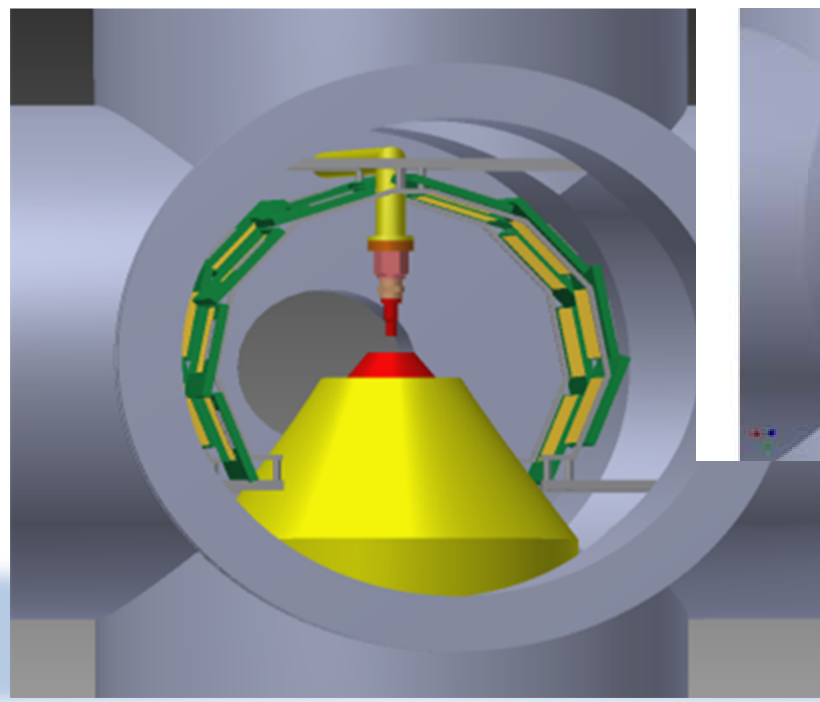
- Measurements of (*p*,*γ*) resonances using target coupled with HELIOS via (^{3}He,*d*)
  - ^{14}C(^{3}He,*d*)^{15}N used as commissioning experiment for gas target
  - resolutions of better than 275-keV FWHM achieved . . . improvements to come

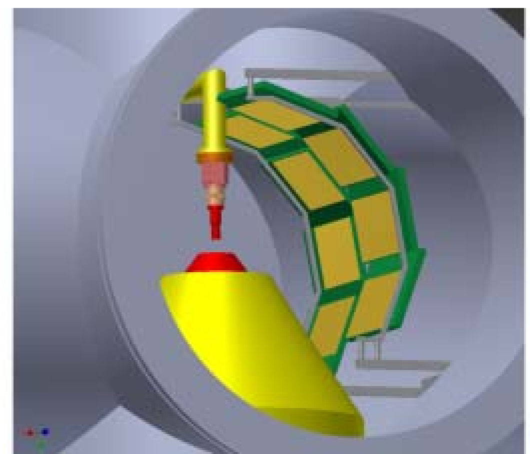


slide courtesy of C. Deibel

JENSA







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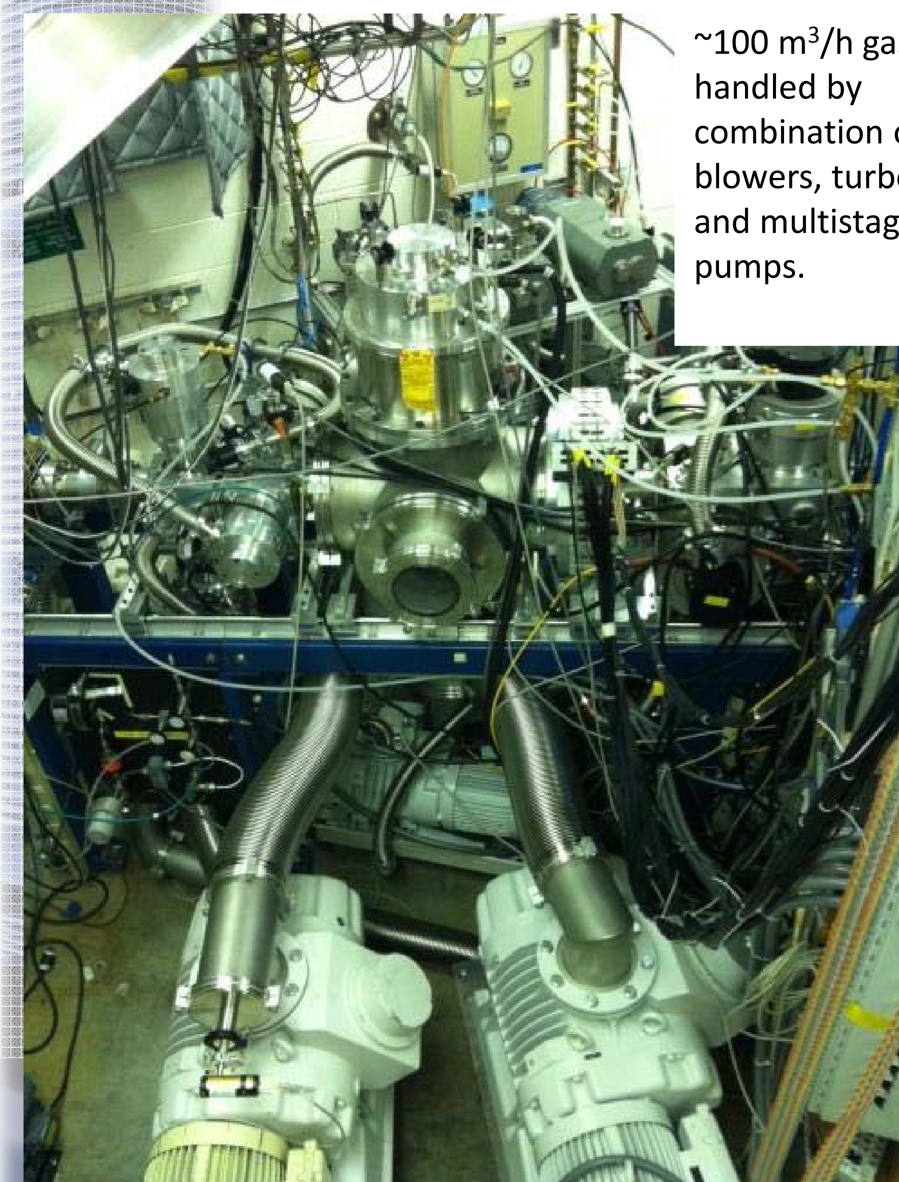
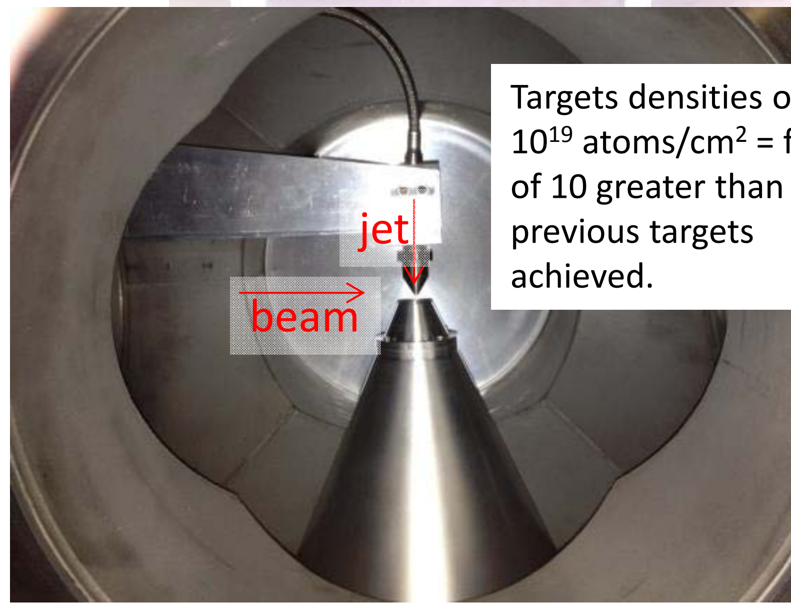
JENSA Constructed at ORNL



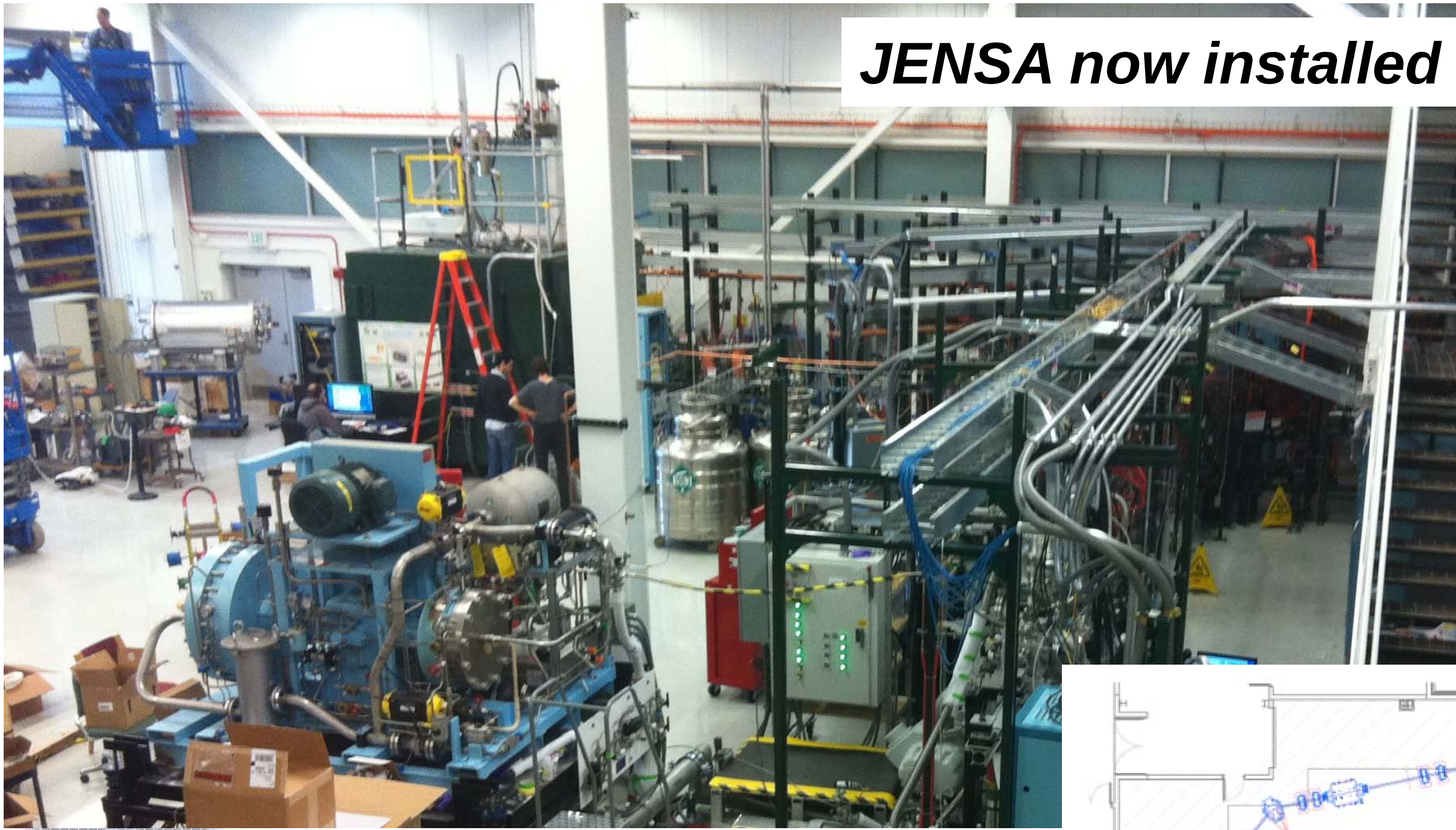
~100 m^3/h gas flow handled by combination of roots blowers, turbo pumps, and multistage dry pumps.

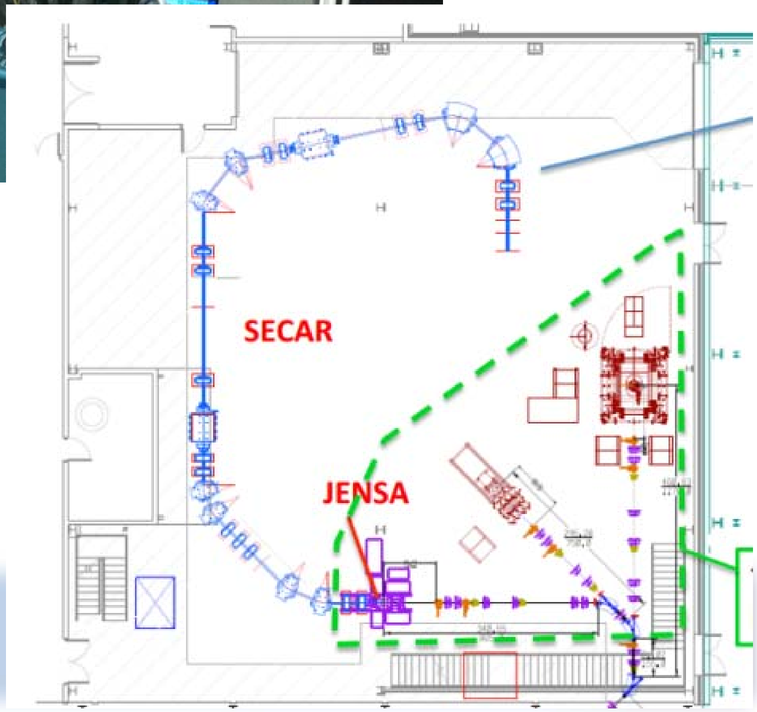
Final compression performed by industrial compressor.



Targets densities of 10^{19} atoms/cm^2 = factor of 10 greater than previous targets achieved.

JENSA now installed at ReA3





Conclusions/Questions

- Are we wasting out time?
  - Are proton-transfer reactions a reasonable alternative to direct (p,g) measurements?
  - Do we need full angular distributions?
  - Are angle-integrated cross sections enough?
- Is there a preference (d,n), (^{3}He,d), etc…?
  - Is the theory sufficiently developed?
  - How do we do it?
- What else needs to be measured?
  - Is elastic scattering data needed?
- Help!