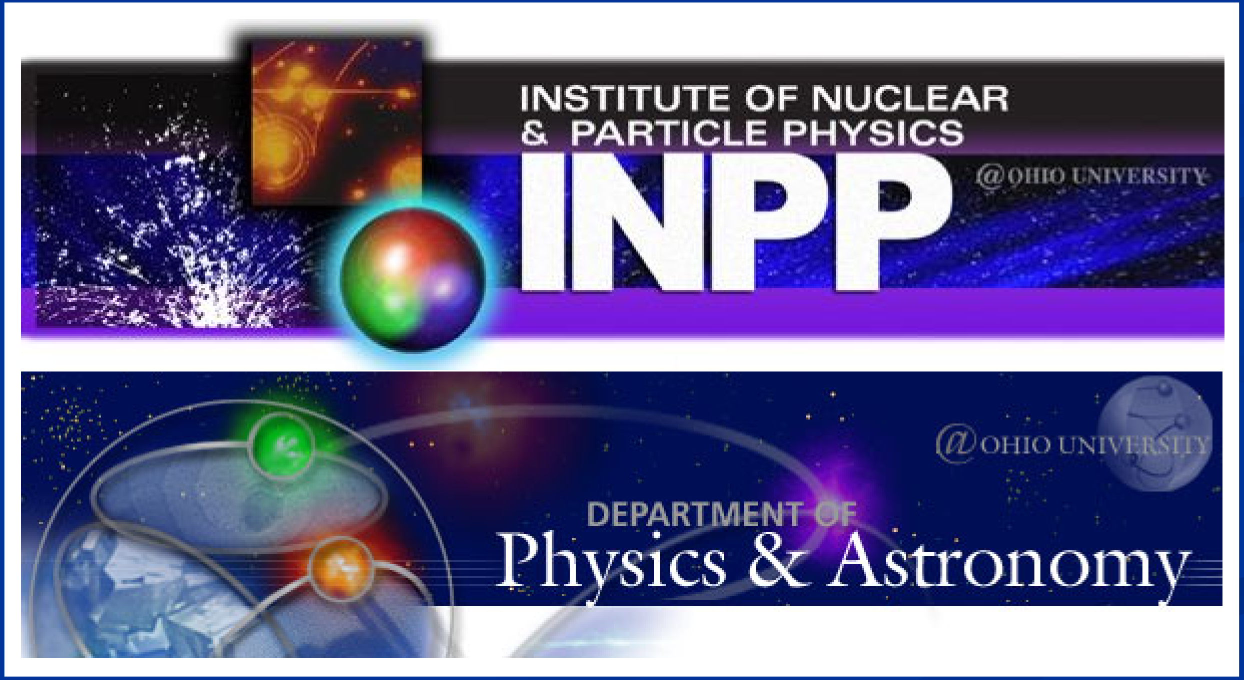
Nuclear Astrophysics - III

Carl Brune

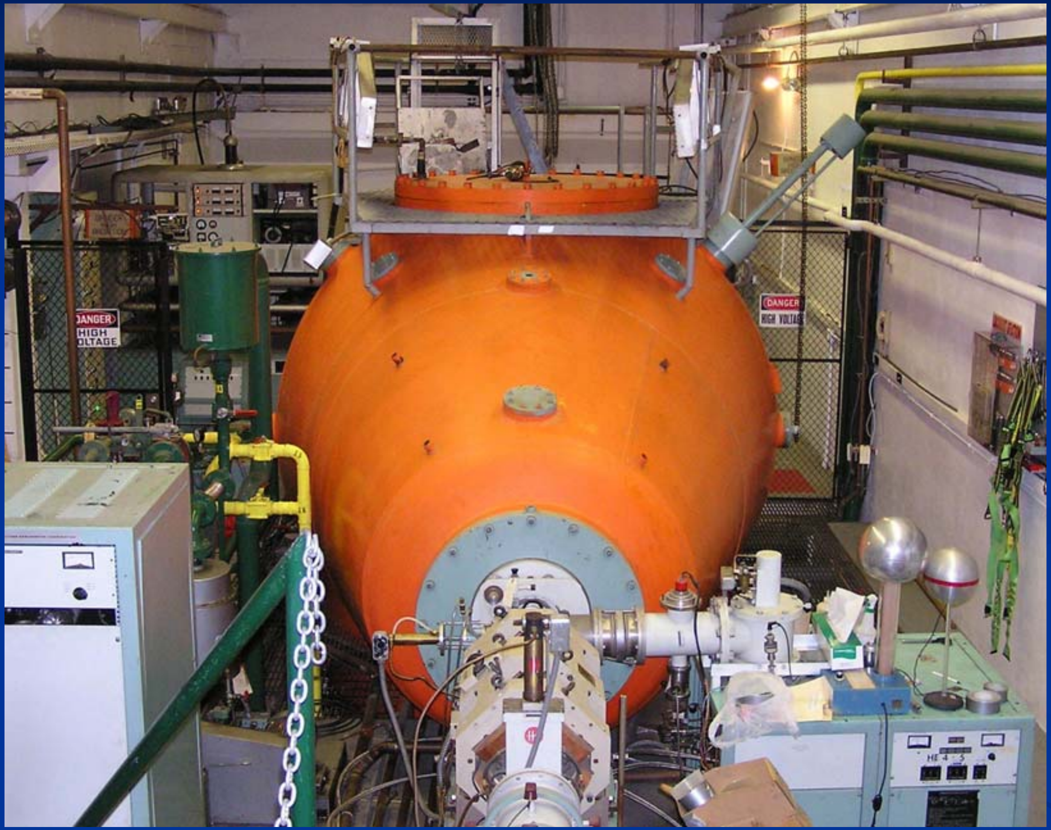


Plan for Today's Lecture

Some things we are doing presently with our low-energy stable beam accelerator at Ohio University:

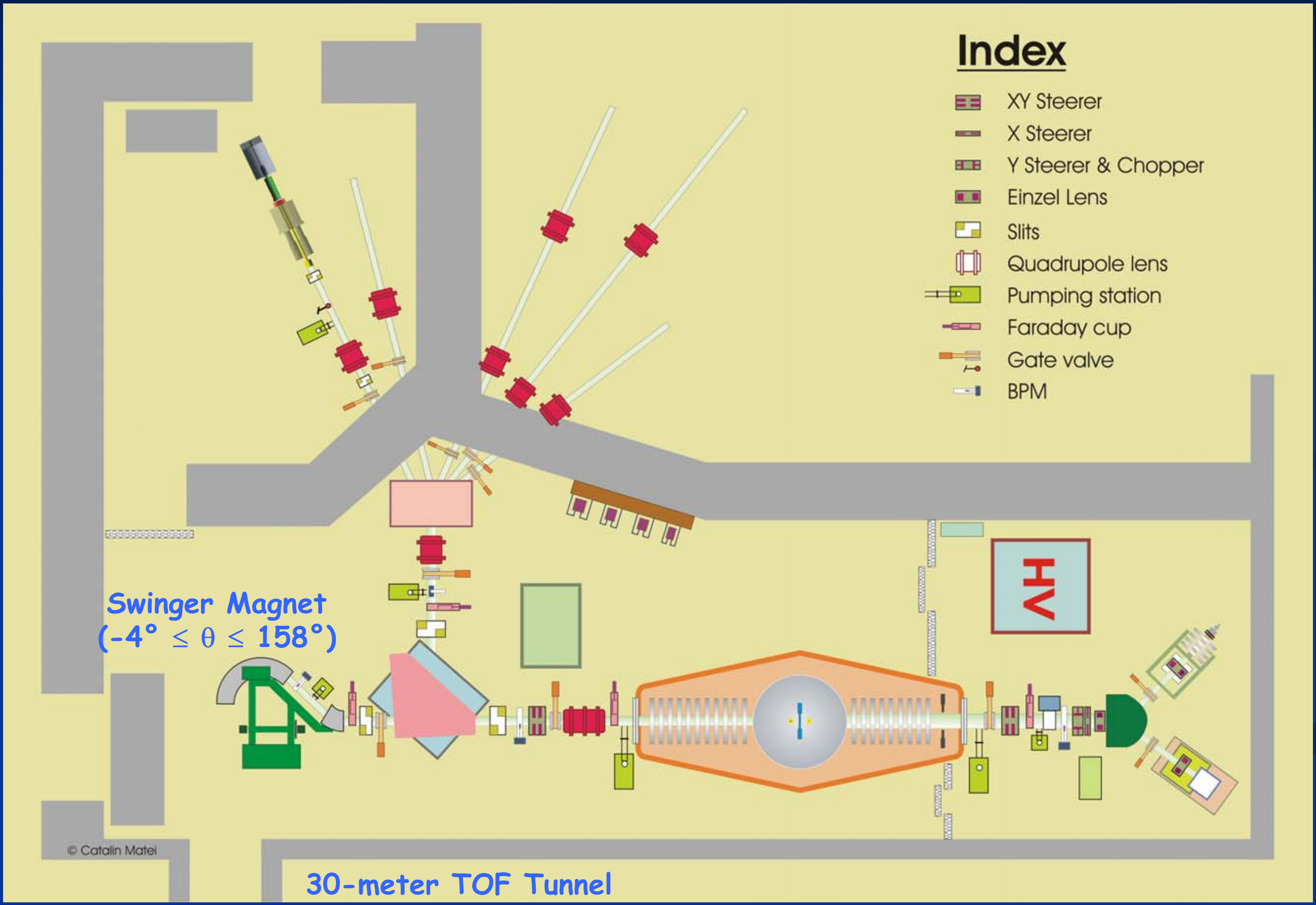
- (^{3}He,n) spectroscopy for nova nucleosynthesis
- Level densities
- Spectroscopic studies for $^{12}C(\alpha,\gamma)^{16}O$

Edwards Accelerator Laboratory



- 4.5-MV tandem accelerator
- p, d, ^{3,4}He, heavy ion beams
- 30 m time-of-flight tunnel

Edwards Accelerator Laboratory



The Origin of ^{26}Al in our Galaxy

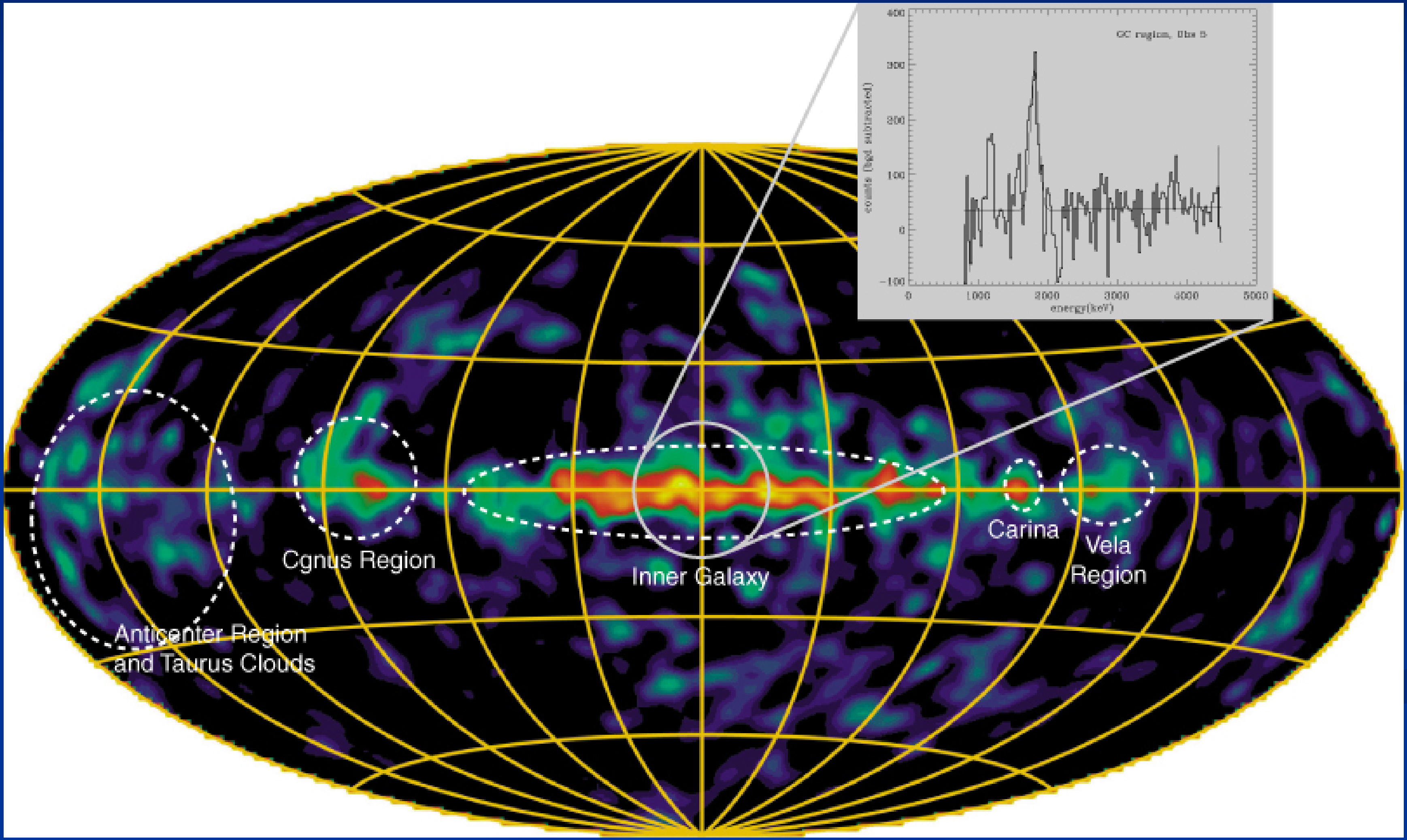
- source of 1809-keV gamma rays
- half-life = 0.73 million years

Novae are likely a significant source, via the sequence $^{24}Mg(p,\gamma)^{25}Al(\beta^{+})^{25}Mg(p,\gamma)^{26}Al$:

- Evidence from pre-solar grains
- Predicted by models (ONe novae)

^{26}Al is not produced if this sequence occurs: $^{24}Mg(p,\gamma)^{25}Al(p,\gamma)^{26}Si(\beta^{+})^{26m}Al(\beta^{+})^{26}Mg$

1809-keV flux distribution (COMPTEL on CGRO)



Neutron Time-of-Flight Technique

$$^{24}Mg + {}^{3}He \Rightarrow {}^{26}Si(*) + n$$

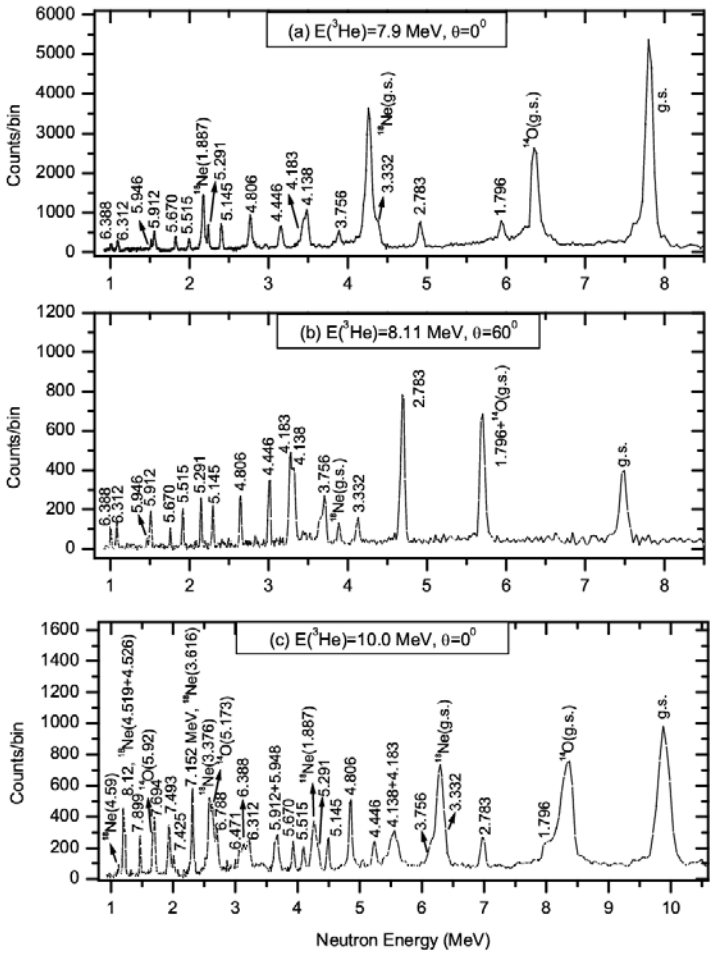
- time of flight ⇒ neutron energy
- kinematics ⇒ E_x in ^{26}Si
- $\Delta t \approx$ 2 ns
- long flight path, low E_n desirable
- NE-213 scintillator ⇒ neutron / gamma discrimination

Excellent energy resolution achievable !

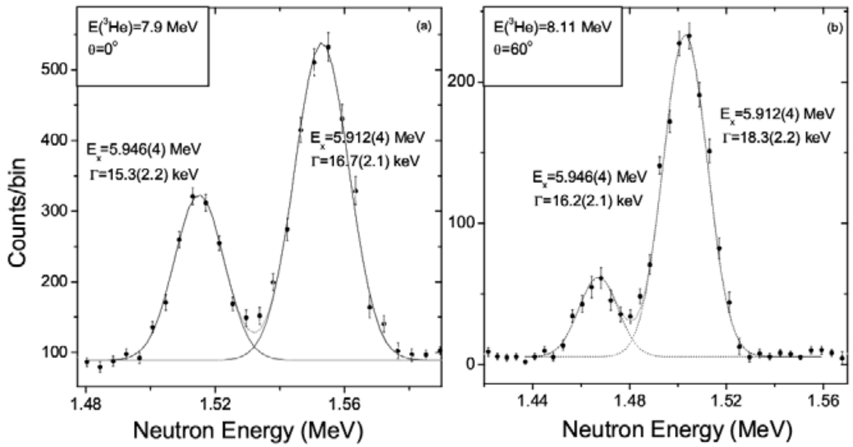
Neutron Energy Spectra

(Y. Parpottas)

full spectra



$^{24}Mg(^{3}He,n)^{26}Si(*)$

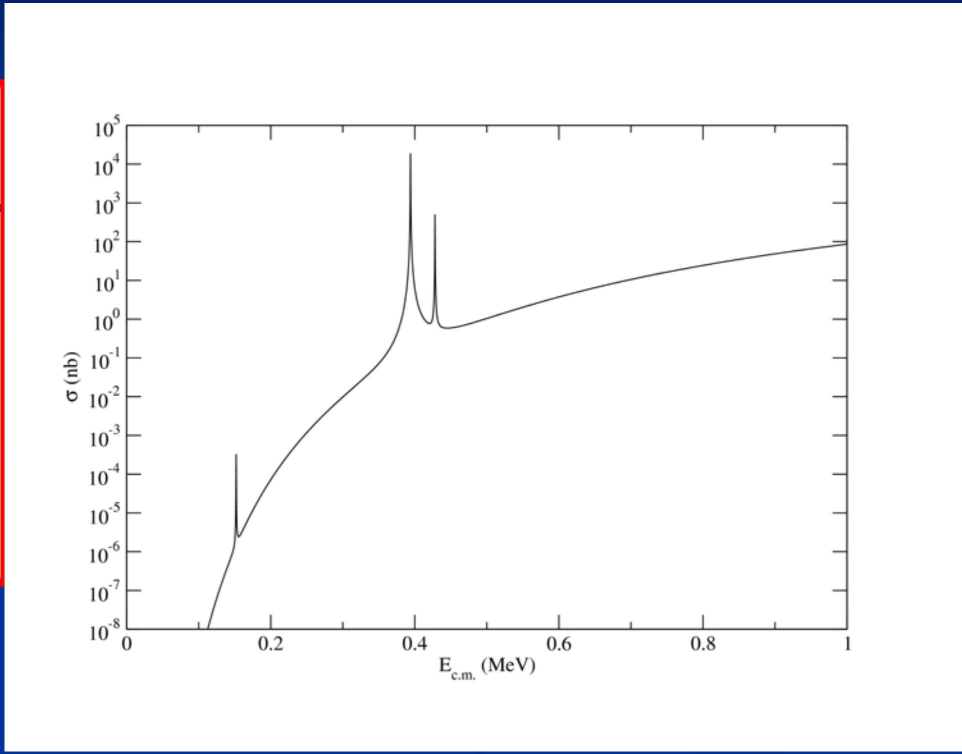


Key Result

Mirror nucleus leads us to expect 3^+ and 0^+ in this region.

Implications for $^{25}Al(p,\gamma)^{26}Si$

E_r (keV)	J^π	Γ_p (keV)
152	1^+	1×10^{-12}
394	3^+	3×10^{-3}
428	0^+	2×10^{-5}



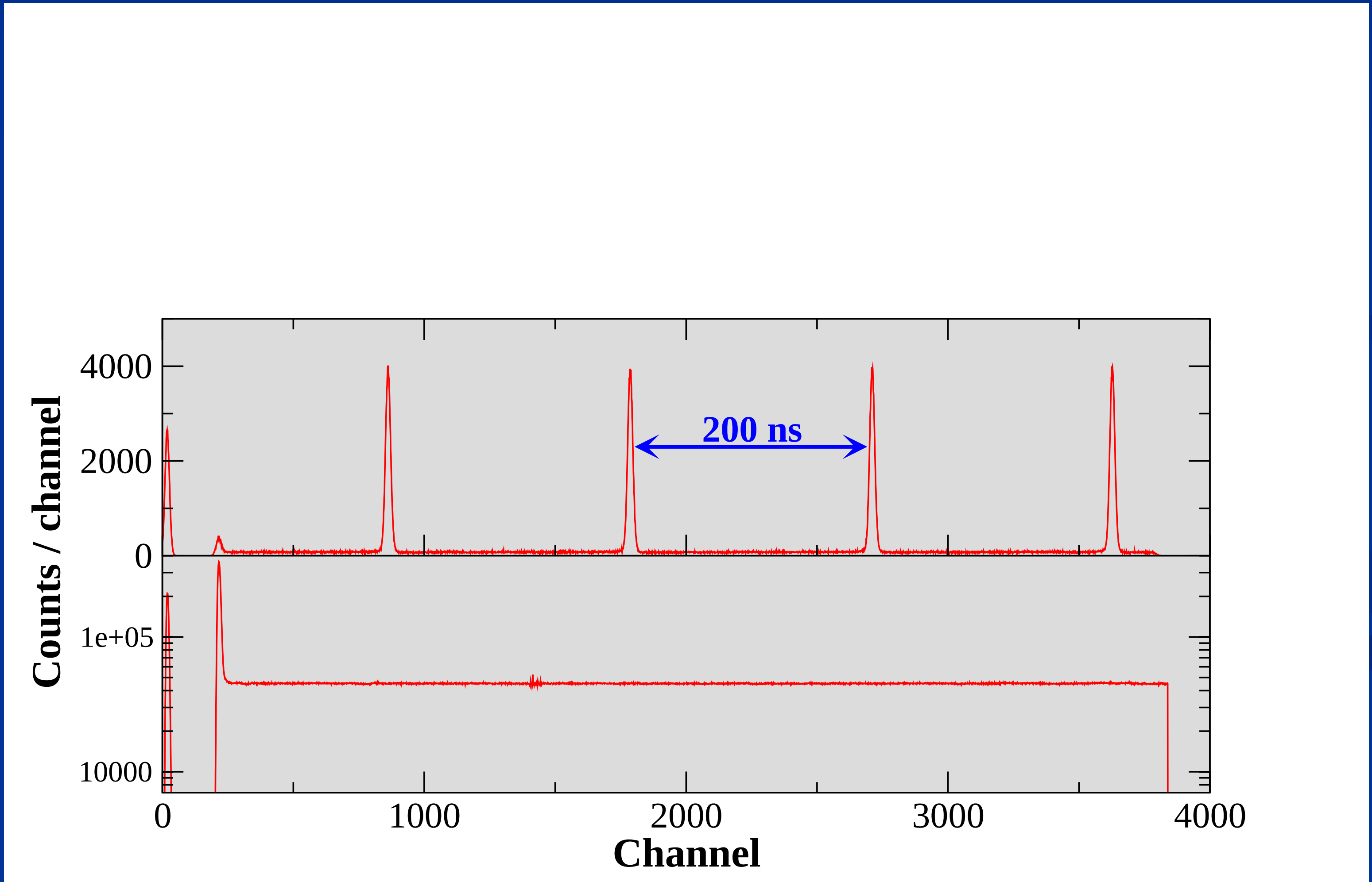
- Our reaction rate is a factor ~20 smaller at nova temperatures than previously thought.
- The J^π assignments should be verified.
- $^{28}Si(p,t)^{26}Si$ has been repeated at HRIBF to verify 0^+ assignments.

Implications for ^{26}Al production in Novae

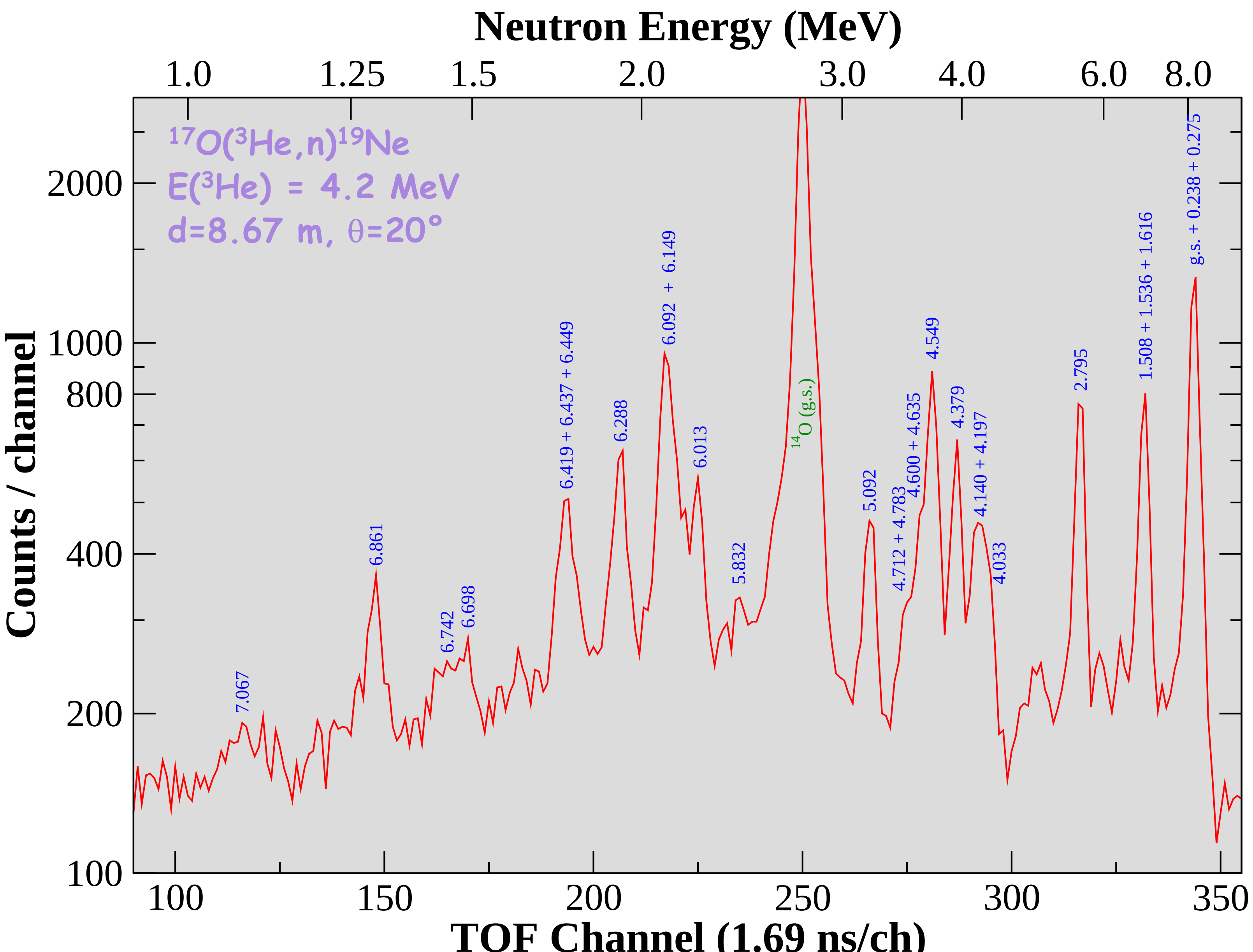
- Calculations using the previous reaction rate found that novae could produce up to 20% of the observed galactic ^{26}Al (Jose' et al.).
- Recent numerical studies (Iliadis et al. 2002) find less sensitivity to this reaction rate than expected.
- Other nuclear physics inputs have significant uncertainties.
- Recent data from SPI/INTEGRAL indicates other source may be more important.

Experiment: $^{17}O(^{3}He,n)^{19}Ne$

- Pulsed 4.2-MeV ^{3}He beam chosen to optimize efficiency and resolution
  - Q value of 4.2997 MeV with respect to ^{19}Ne ground state
  - Chopped and bunched at 1.25 MHz (800 ns) – pulse width 3-4 ns (FWHM)



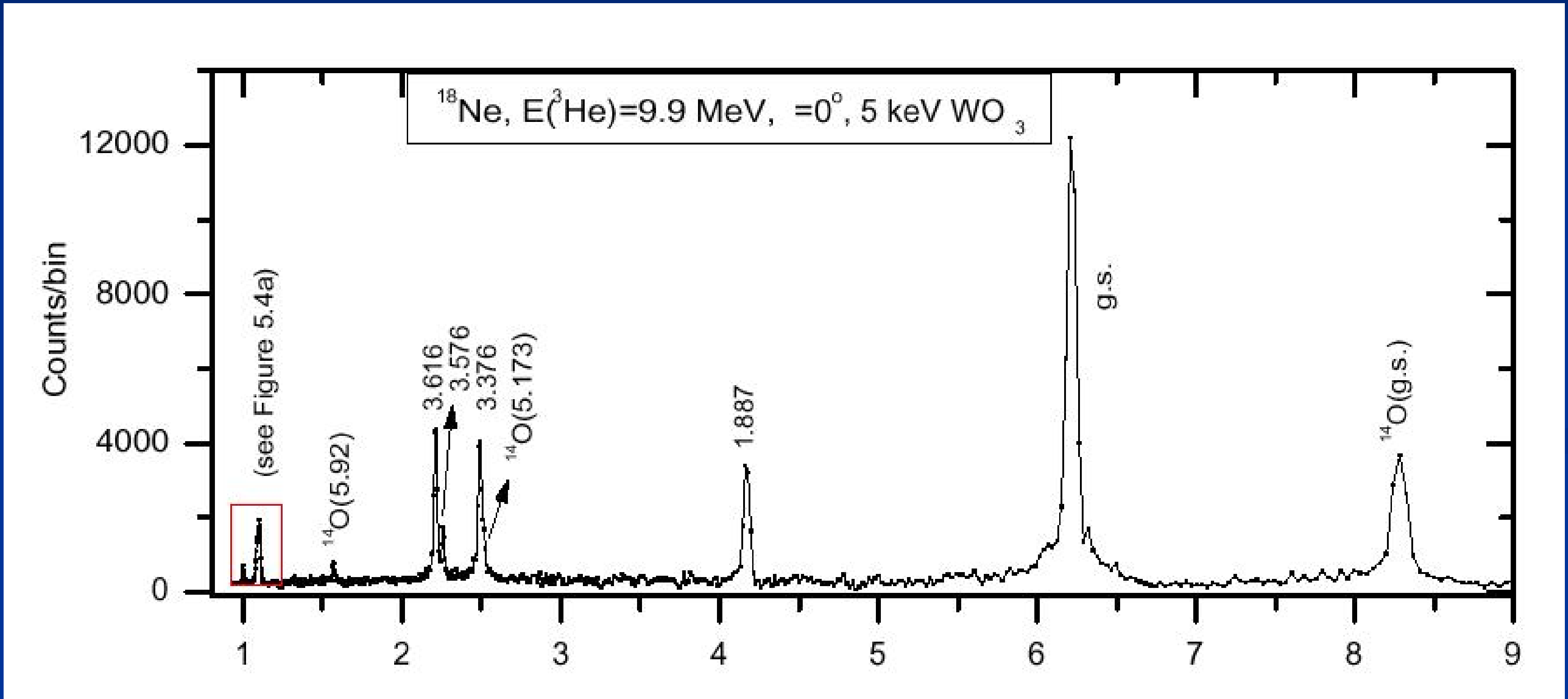
Preliminary Results



$^{16}O(^{3}He,n)^{18}Ne$

(Y. Parpottas)

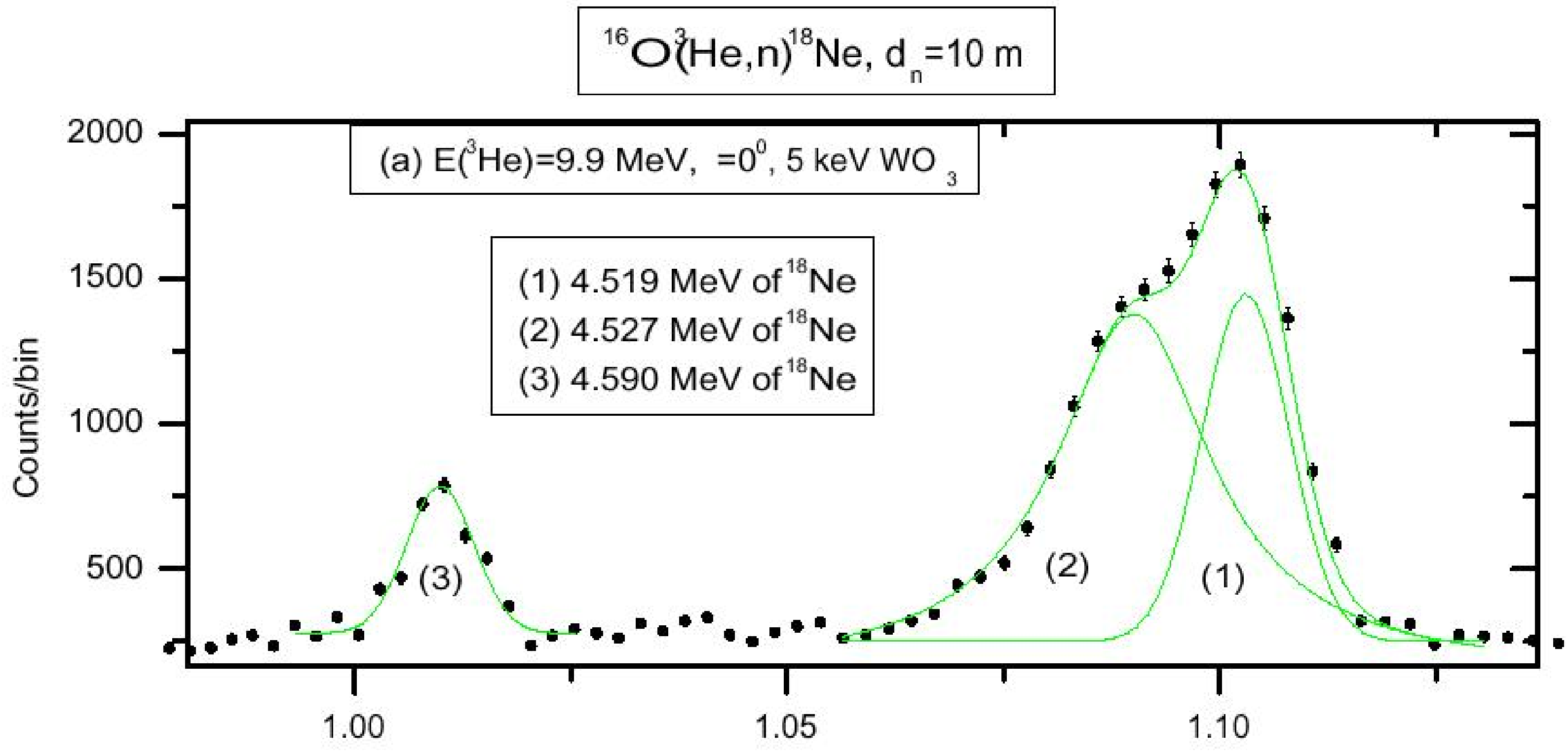
Relevant for the $^{17}F(p,\gamma)^{18}Ne$ Reaction



Neutron Energy (MeV)

$^{16}O(^{3}He,n)^{18}Ne$
(Y. Parpottas)

$\Gamma(4.527) = 17(4)$ keV



Neutron Energy (MeV)

Nuclear Reactions

Statistical (Hauser-Feshbach) Reactions

- Heavier (A>30) nuclei (except near closed shells or driplines)

Need:

- Level Densities
- Transmission Functions (optical potentials or strength functions)
- Understand systematics for both stable and unstable nuclei

Resolved Resonances

- need E_x, J^π, partial widths
- R-matrix analysis

Breit-Wigner Formula

$$\sigma(E) = \frac{2J+1}{(2J_1+1)(2J_2+1)} \frac{\pi}{k^2} \frac{\Gamma_1 \Gamma_3}{(E-E_R)^2 + \Gamma^2/4}$$

Nuclear Level Densities

Fermi Gas Form $\rho(u) \propto \dfrac{e^{2\sqrt{au}}}{u^{3/2}}$

$$a = \frac{\pi^2}{6} g$$

g: single-particle state density at the Fermi level

$$u = E_x - \delta$$

E_x is the excitation energy and δ is the shell and pairing correction

Normally Assume:

(1) $a = \alpha A$

where:

α = constant

$A = N + Z$

Recent Analysis of Al-Quraishi et al. (2001,2003) investigated:

(2) $a = \alpha_1 A \exp[-\beta(N-Z)^2]$

(3) $a = \alpha_2 A \exp[-\gamma(Z-Z_0)^2]$

Where Z_0 = Z of β-stable nucleus of mass A

Both equation (2) and equation (3) result in better fits than the normal assumption, equation (1). Additionally, equation (3) yields a better fit than equation (2).

The fitting was done for Nuclei with $20 \leq A \leq 110$. The nuclei used had sufficient information on the resolved levels to be used for level densities. This was also limited to both low energies and $|Z-Z_0| \leq 2$.

Need More Tests of Al-Quraishi Results

Energies > 3 MeV needed

More nuclei with $|Z - Z_o| \geq 2$

Investigate neutron spectra from:

$^{58}Fe(^{3}He,n)^{60}Ni$ — ^{60}Ni has $Z = Z_o$

$^{58}Ni(^{3}He,n)^{60}Zn$ — ^{60}Zn has $N = Z$

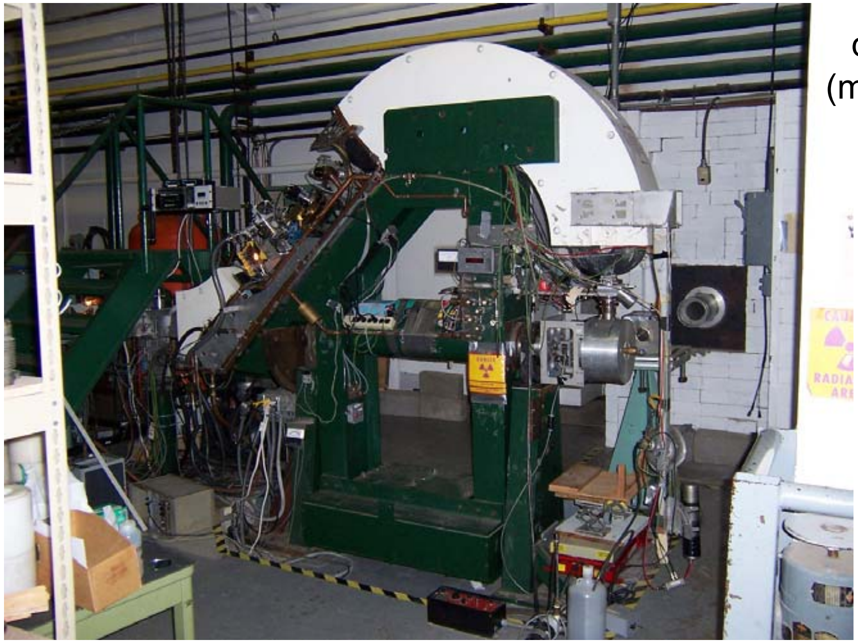
Thus, traditional form (Eq. 1) has level density $^{60}Ni \approx {}^{60}Zn$

Eq. (2) has level density $^{60}Ni < {}^{60}Zn$

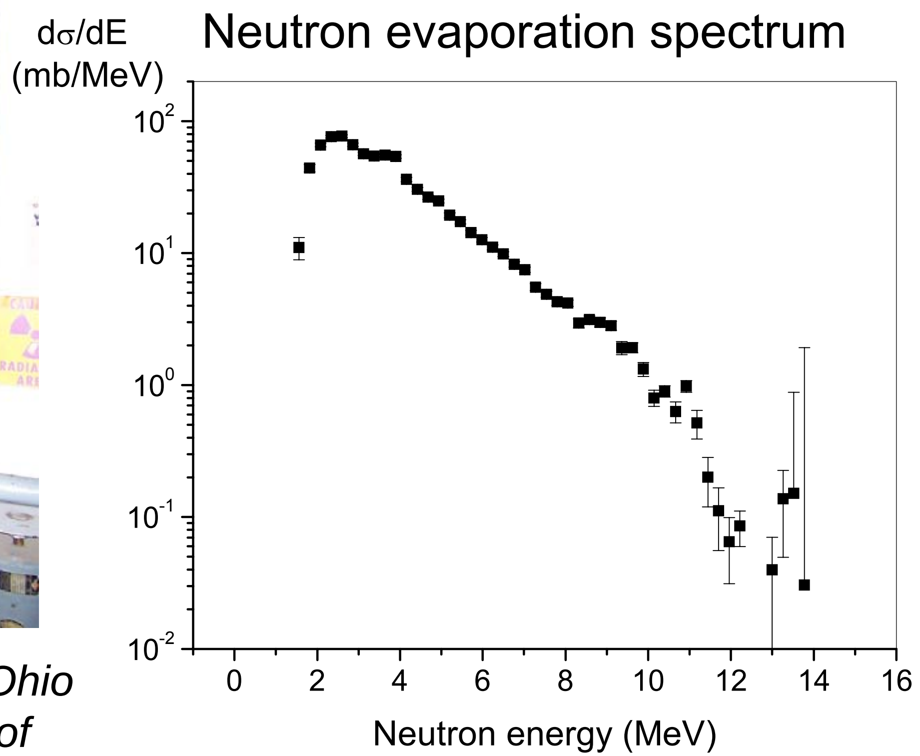
Eq. (3) has level density $^{60}Ni > {}^{60}Zn$

We are also investigating ($^{3}He,n\gamma$) which may allow the use of targets with natural abundance to be used.

Measurement of the level density of ^{56}Fe from ^{55}Mn(d,n)^{56}Fe reaction

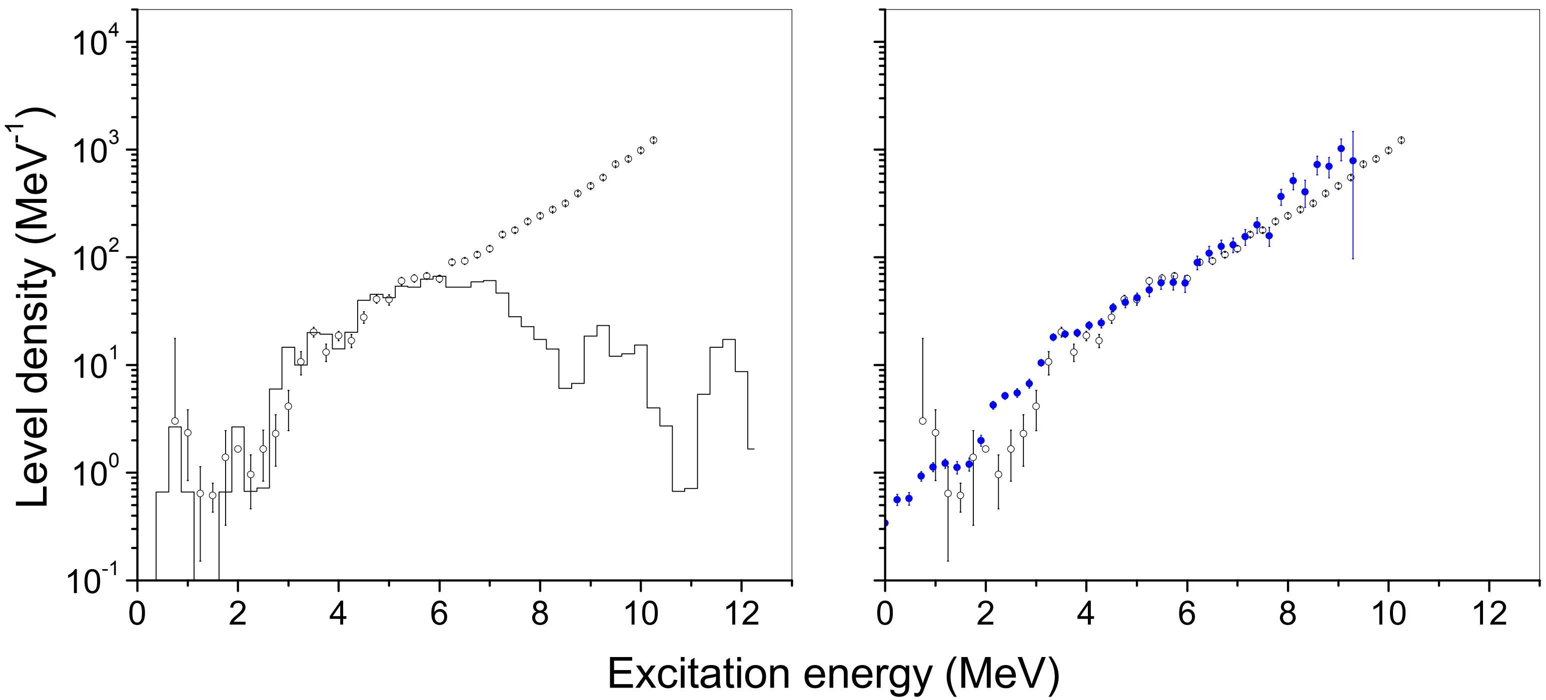


Swinger facility *of Edwards Accelerator (Ohio University) designed for the measurement of the energy and angular distributions of outgoing neutrons*



$$\rho(E) = \rho(E)_{input} \frac{(d\sigma / dE)_{meas}}{(d\sigma / dE)_{calc}}$$

Level density of ^{56}Fe from neutron evaporation spectra



- Level density from Oslo experiment
- Level density from $^{55}Mn(d,n)^{56}Fe$ experiment
- Level density of discrete low-lying levels

Evaporation Spectra Measured

- $^{45}Sc(d,n)$
- $^{51}V(d,n)$
- $^{45}Sc(^{3}He,n)$
- $^{55}Mn(d,n)$
- ^{58}Fe: $(^{3}He,n)$; $(^{3}He,p)$; $(^{3}He,\alpha)$
- ^{58}Ni: $(^{3}He,n)$; $(^{3}He,p)$; $(^{3}He,\alpha)$
- $^{59}Co(d,n)$

Future Plans

- Ohio: $^{46}Ti(^{3}He,n)$; $^{64}Zn(^{3}He,n)$; $^{70}Ge(^{3}He,n)$
- LBL: $^{12}C(^{76}Kr,p/\alpha)$; $^{12}C(^{76}Ge,p/\alpha)$; $^{12}C(^{76}Se,p/\alpha)$

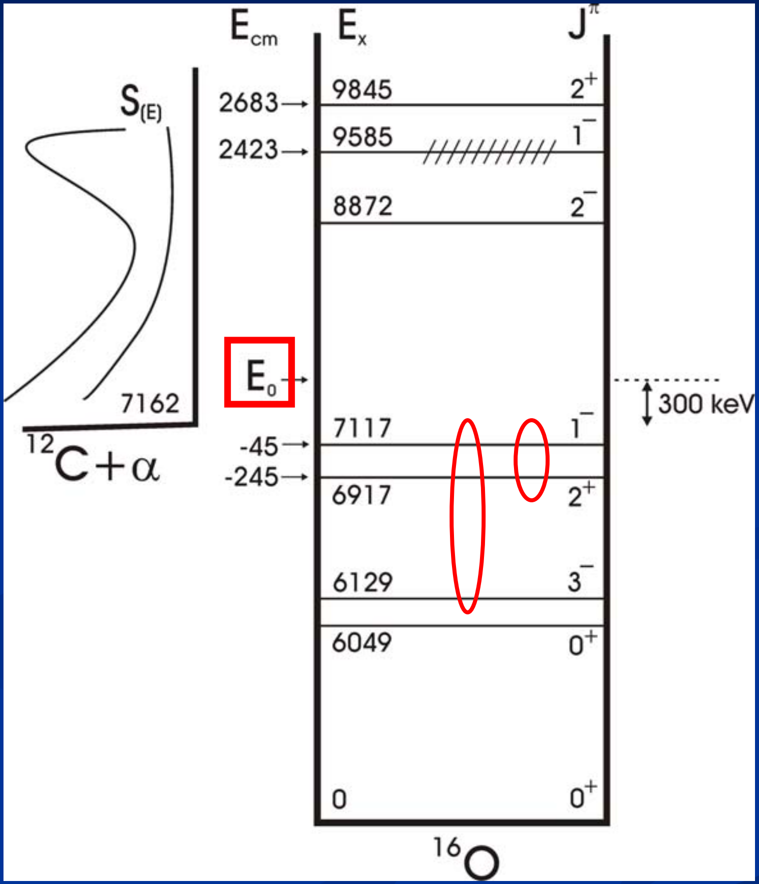
$^{12}C(\alpha,\gamma)^{16}O$ Cross Section

$^{12}C(\alpha,\gamma)$ - extrapolation to helium burning energies $E_0 \approx 300$ keV

$^{12}C(\alpha,\gamma)$ cross section

E1, E2 g.s. transitions most contributions

cascade transitions Up to 30% contribution

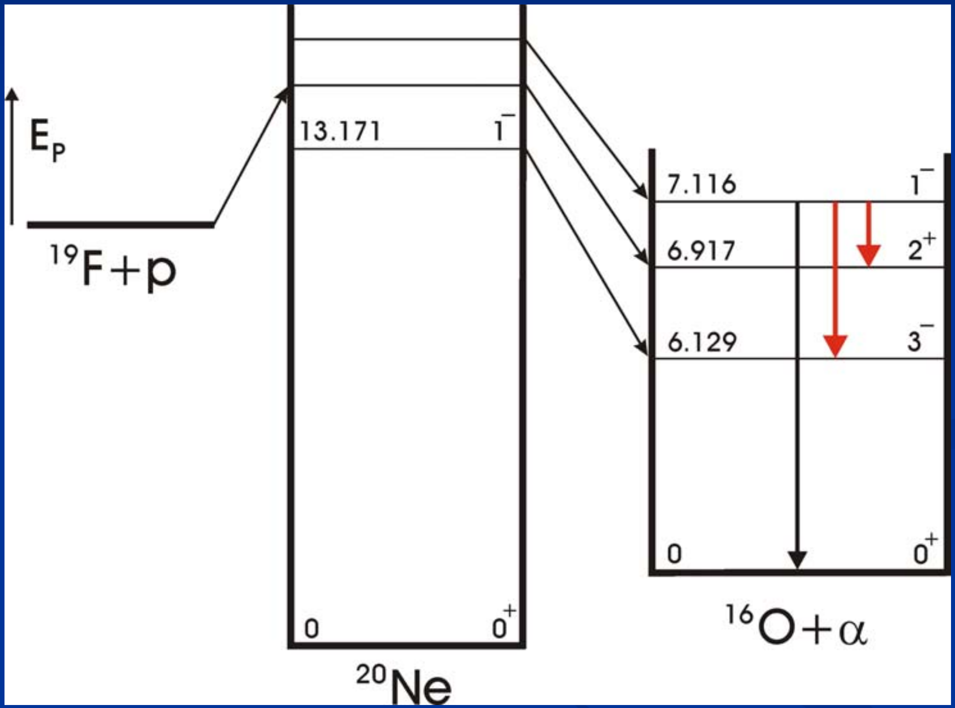


Determining the γ strength of the cascade transitions will result in a better extrapolation of the cascade and E2 ground state cross sections to low energies.

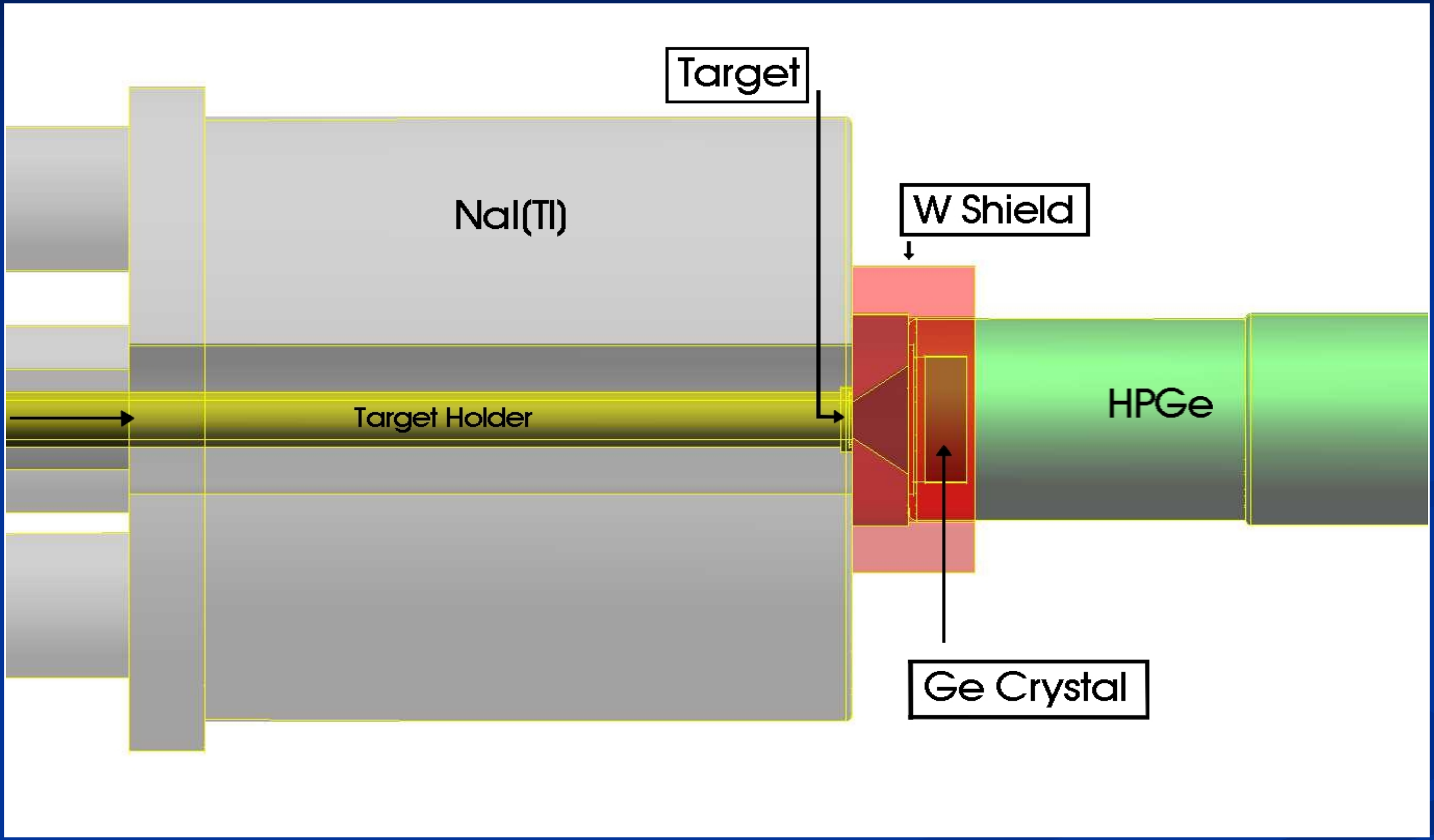
The Experiment

The 7.12-MeV excited state in ^{16}O is formed via the $^{19}F(p,\alpha)^{16}O$ reaction by bombarding targets of CaF_2 100μg/cm^2 thickness, evaporated on C backings.

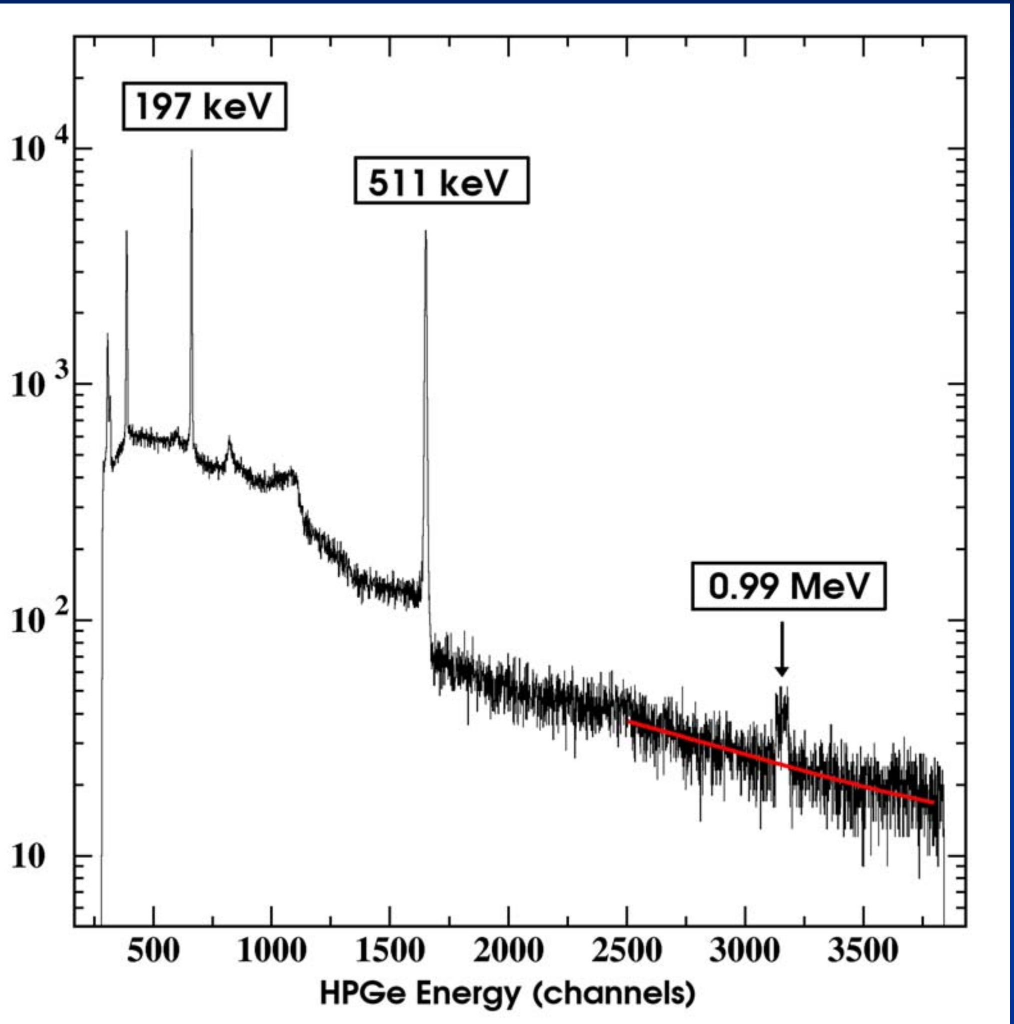
The energy of the proton beam was chosen at E_p=2.0025 MeV to maximize the relative population of the 7.12-MeV state.



Setup



Result for the 7.12→6.13-MeV transition



Fit selected region to extract background and count events of interest.

Calibrated sources and GEANT simulations used to estimate detectors efficiency

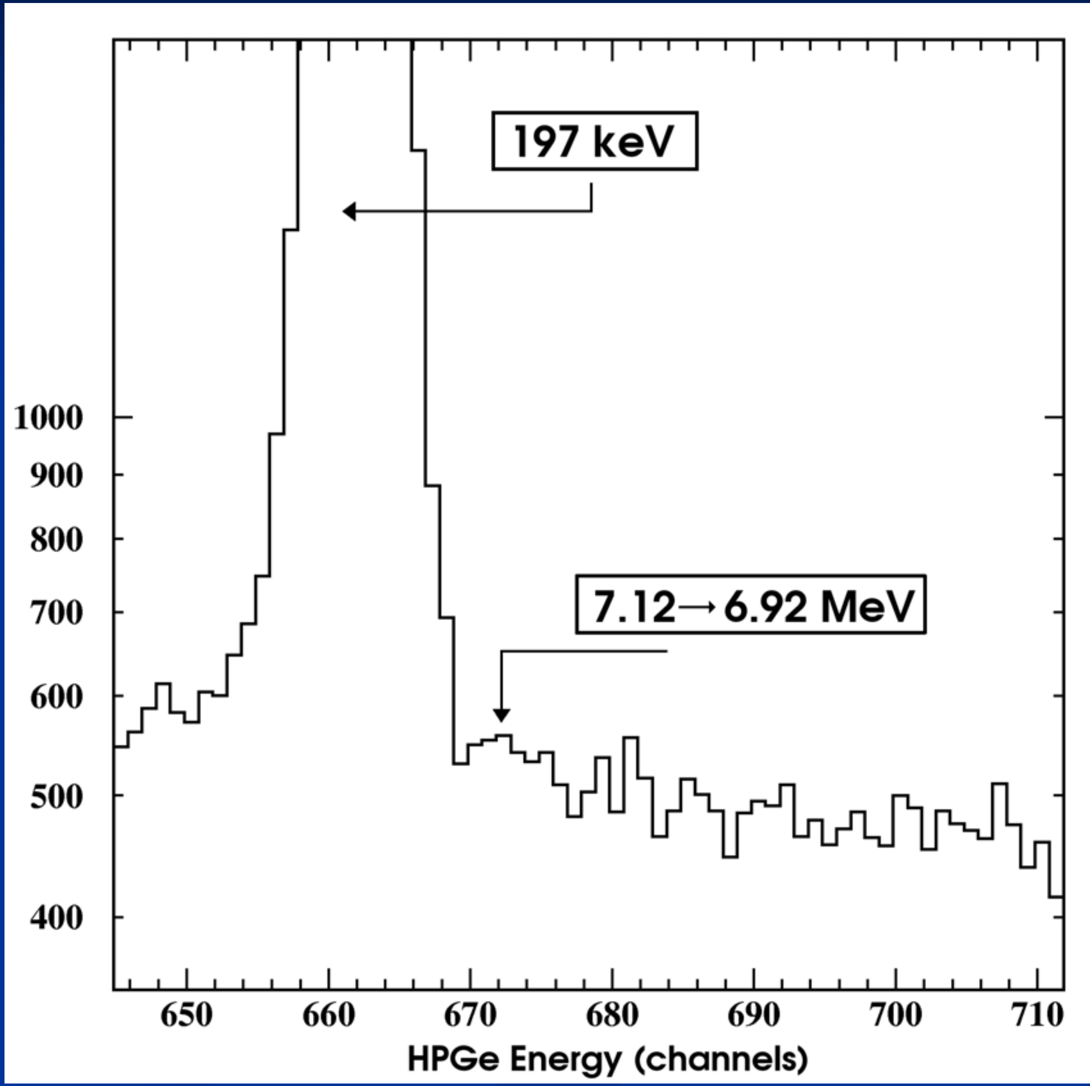
Calculate 7.12→6.13-MeV branching ratio:

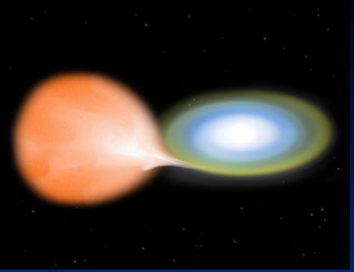
$$f = \frac{N_{1MeV} / \varepsilon_{HPGe}}{0.7 N_{NaI} / \varepsilon_{NaI}} = (8.3 \pm 0.4) \times 10^{-4}$$

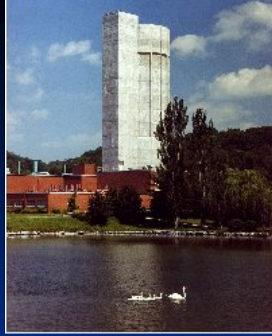
Result for the 7.12→6.92-MeV transition

A limit for this transition can be set with a 2-σ confidence level:

$$f_{7.12\to 6.92} \leq 1.2\times 10^{-5}$$





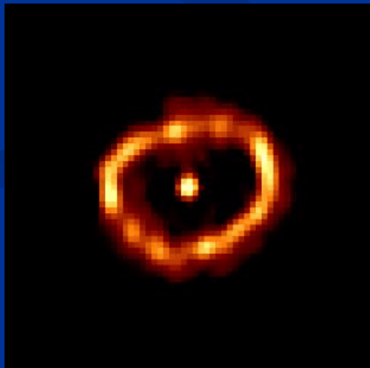


In Summary:

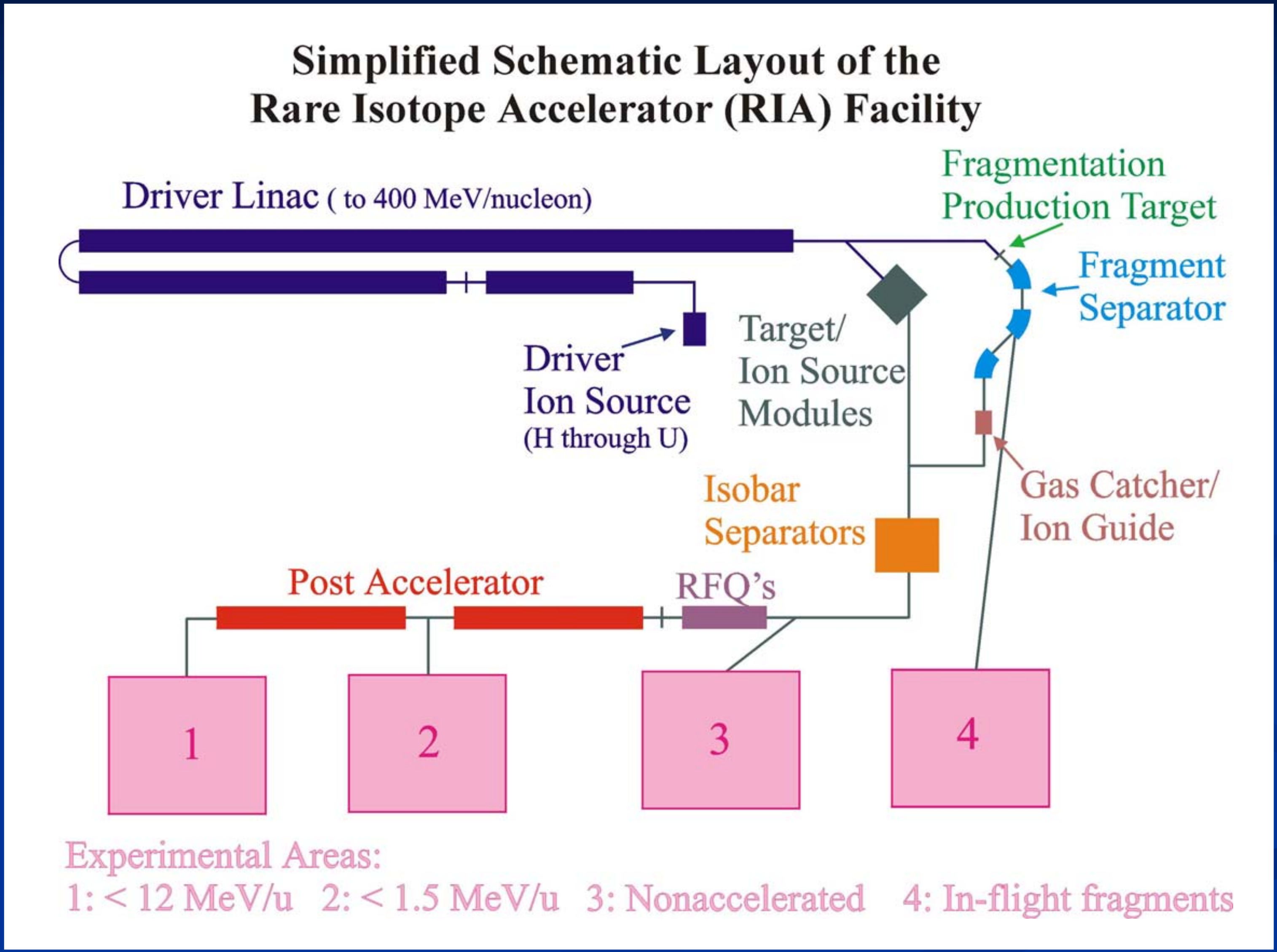
• Several reactions and nuclear astrophysics scenarios have been discussed over the past week.

• Many labs in North America are working on these questions with both stable beams (OU, UNC/Duke, Yale, Texas A&M,…) and radioactive beams (ORNL, NSCL, ANL, TRIUMF,…). Obviously this is a world-wide effort.

• We look forward to new data from ground- and space-based observatories and other probes of our universe.



Rare Isotope Accelerator

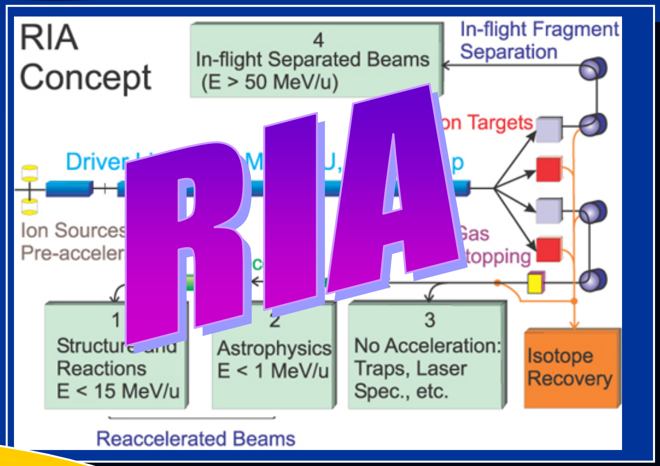


Nuclear Astrophysics at RIA

<10 MeV beams
- p-,α-,n-induced reaction rates (ANC,nucleon transfer, …)
- nuclear structure experiments

Neutron Facility
- n-capture on radioactive targets

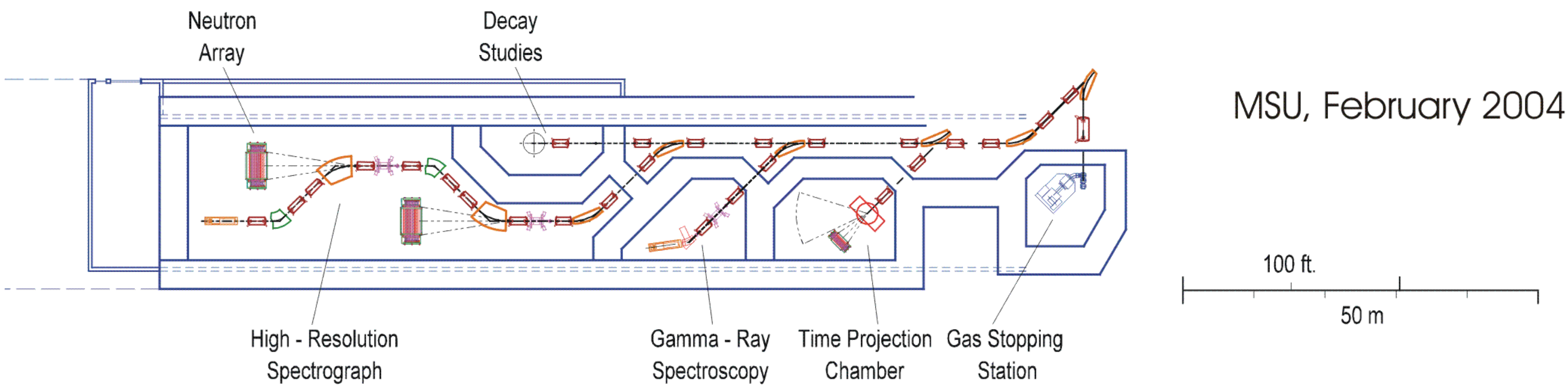
Stopped beams
- Masses
- β,βn,βp,p decays

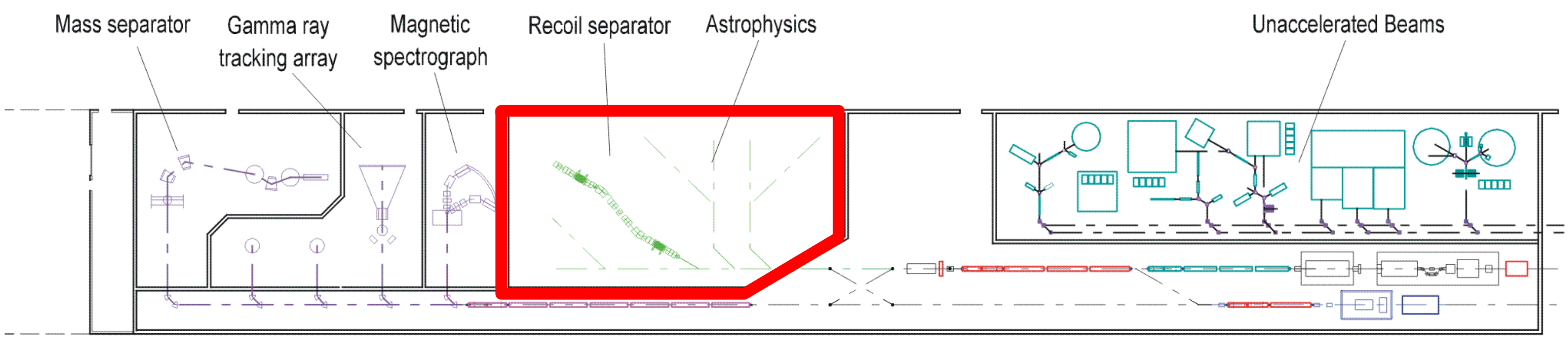


>100 MeV beams
- p-,α-,n-induced reaction rates (transfer/knockout, Coulomb breakup)
- β,βn,βp,p decays
- charge exchange reactions
- TOF mass measurements
- Nuclear structure experiments

<1 MeV beams
- p-, α-induced reaction rates (direct measurements)
- resonant scattering

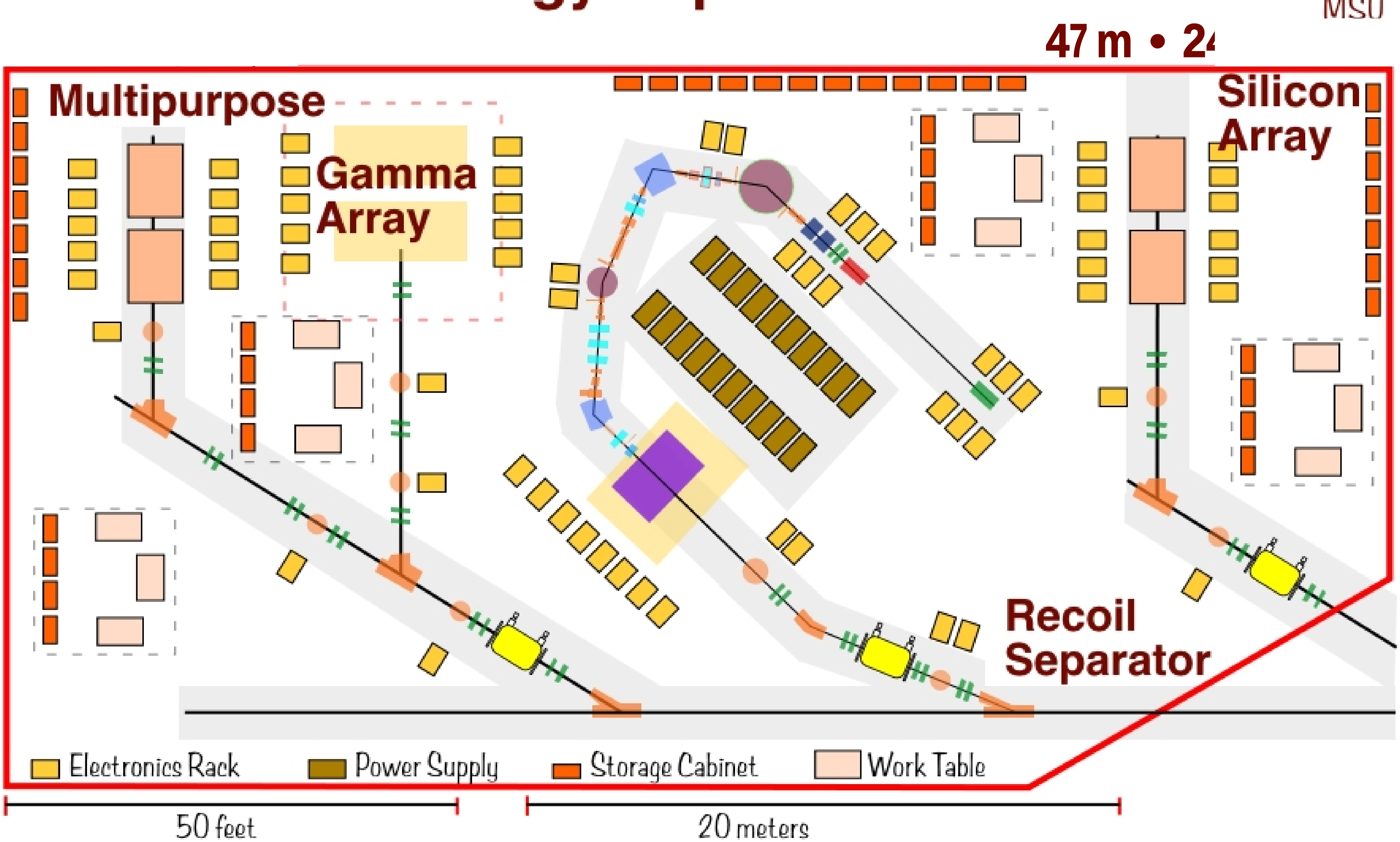
RIA Floor Plan





47 m • 24 m

Low Energy Experimental Hall



RIA Intensities