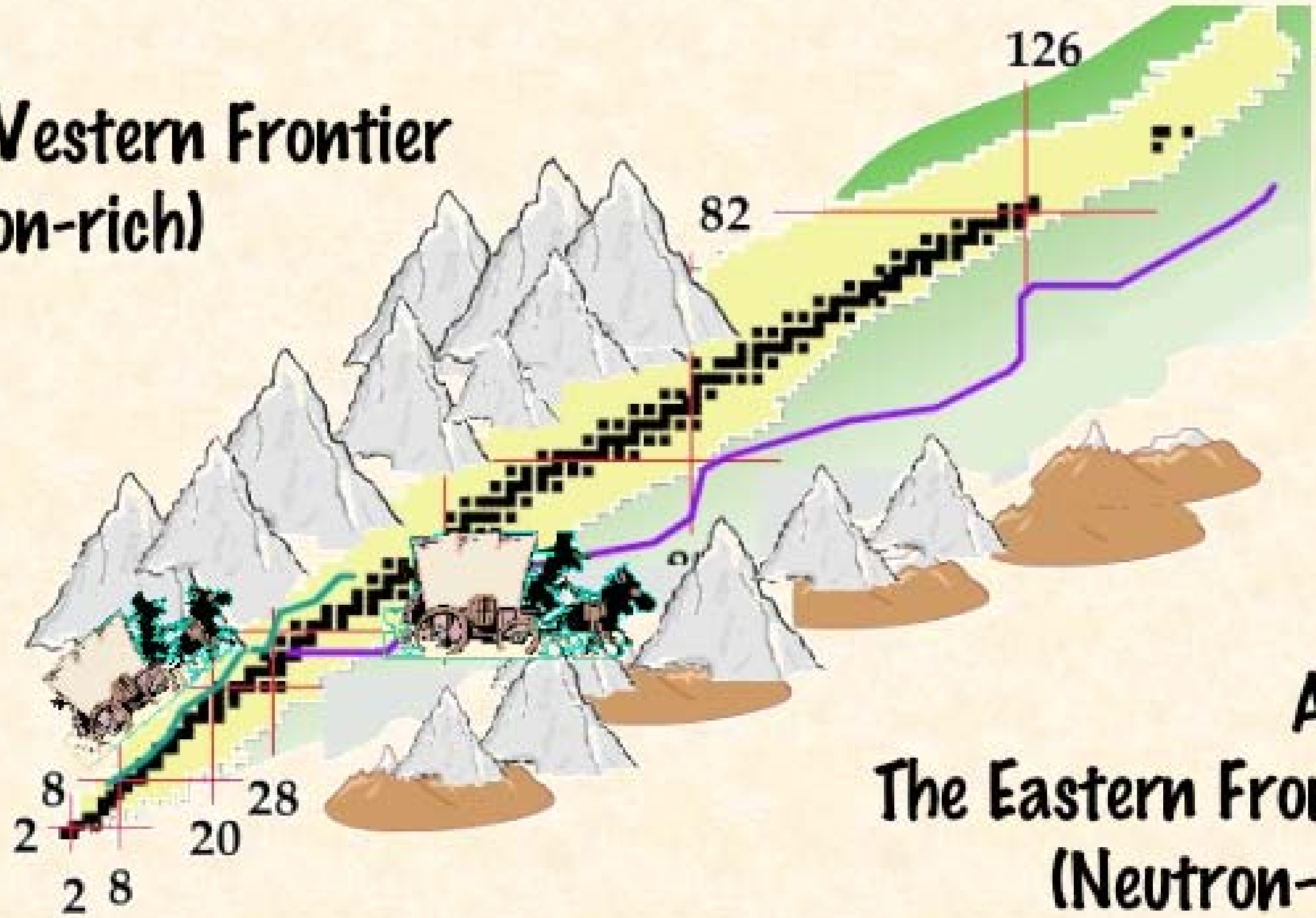
Laboratory Measurements at the Frontier

Jeff Blackmon, Physics Division, ORNL

Act I
The Western Frontier
(Proton-rich)

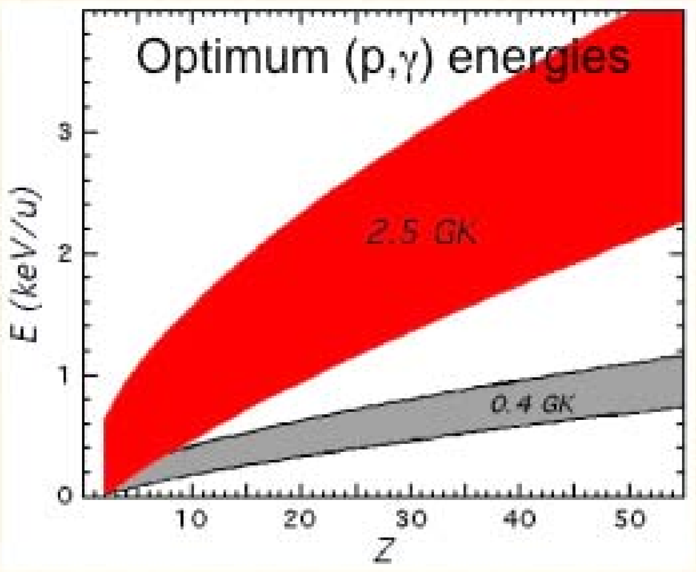


Act II
The Eastern Frontier
(Neutron-rich)

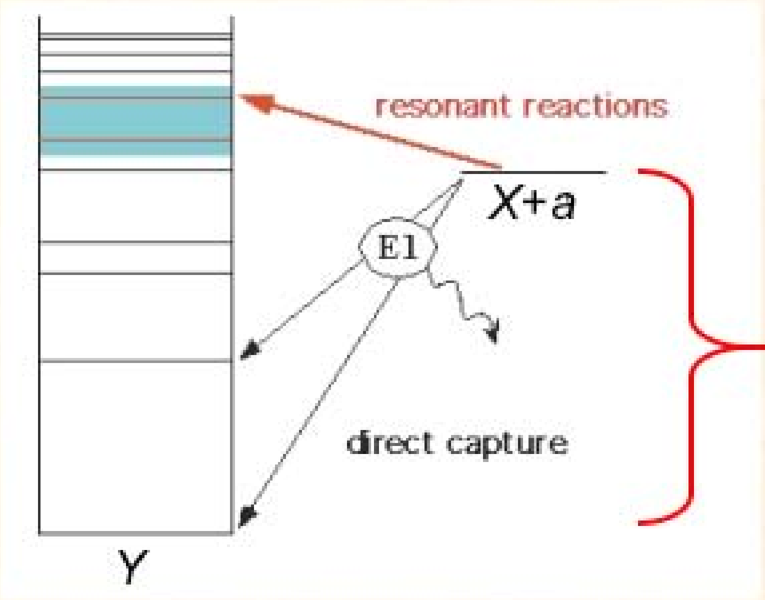
The western frontier

Energies are high: T, Z

Broader range of energies



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



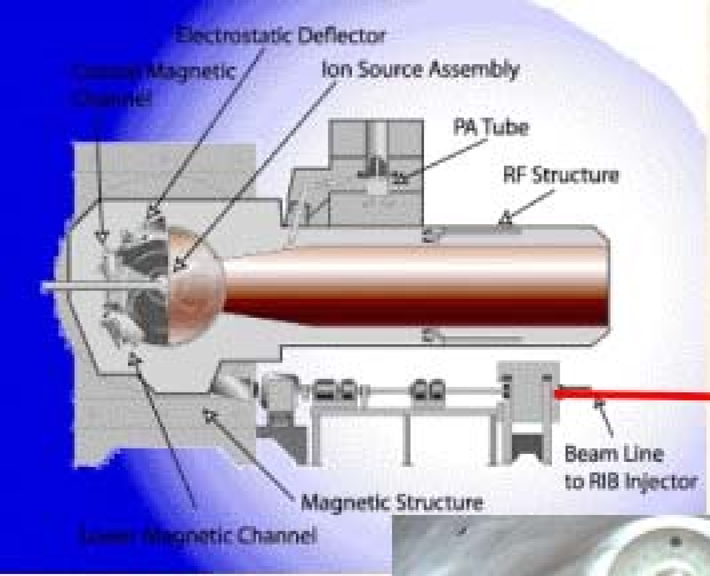
Lower binding energy for radioactive nuclei

Lower level density & broad states

$\rightarrow E_x$, J^π, Γ_a or $C^2 S_a$

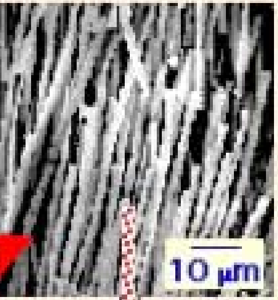
Direct capture can play a role in some cases

ISOL
(e.g. Holifield RIBF)

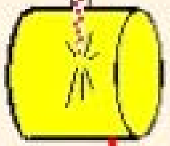


ORIC

p, d, or α



Hot, fibrous production target



Ion source

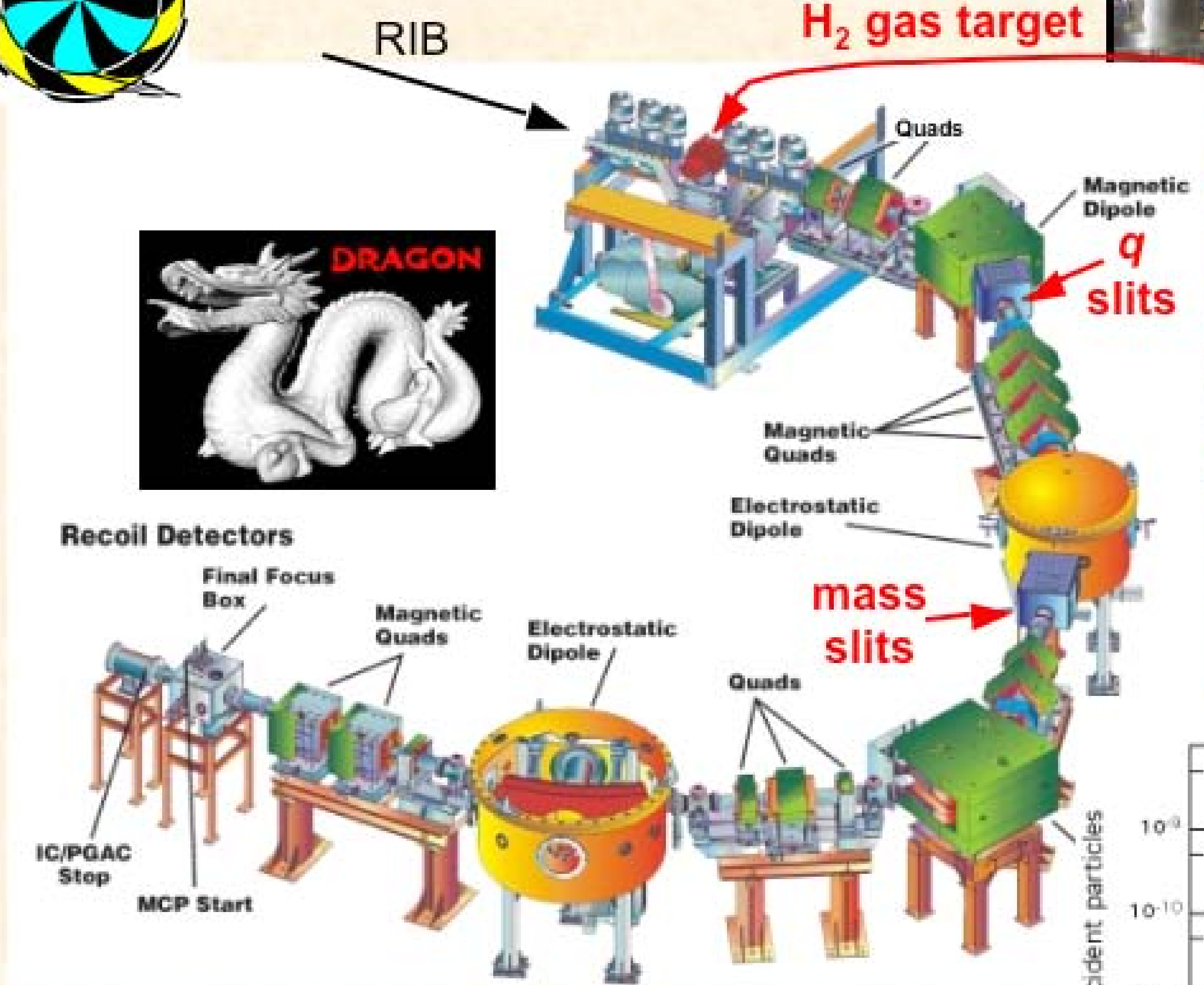
RIB (300 keV)

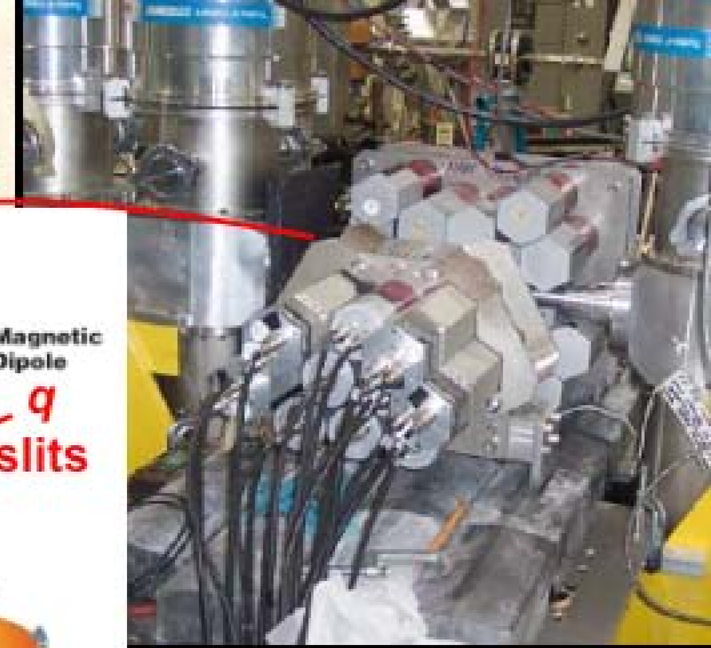
Mass analysis

25 MV tandem

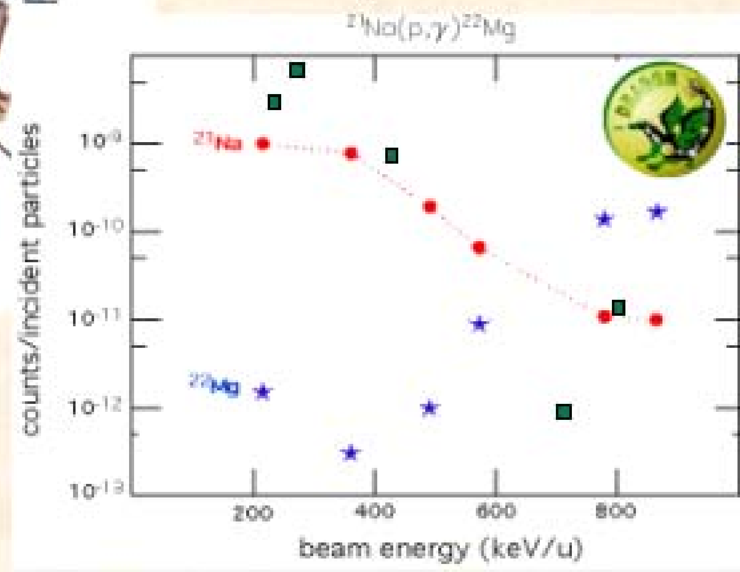
To experiments

(p,γ) at ISAC





30 BGO detectors surround the target recoil+γ coincidences



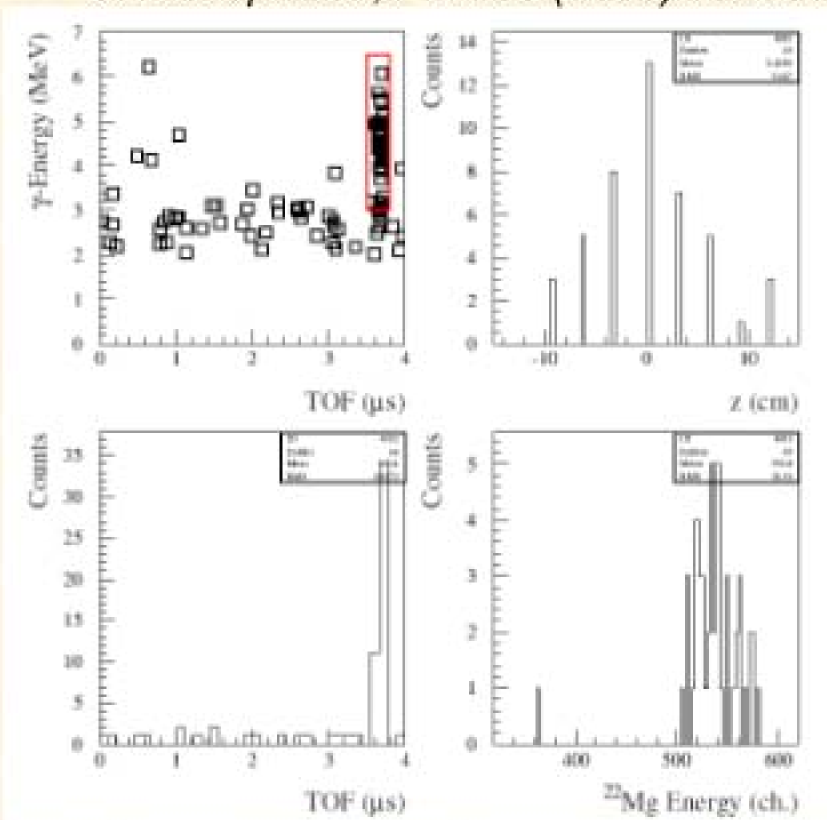
D. A. Hutcheon et al., NIM ***A498*** *(2003) 190.*
S. Engel et al., NIM A, in press.

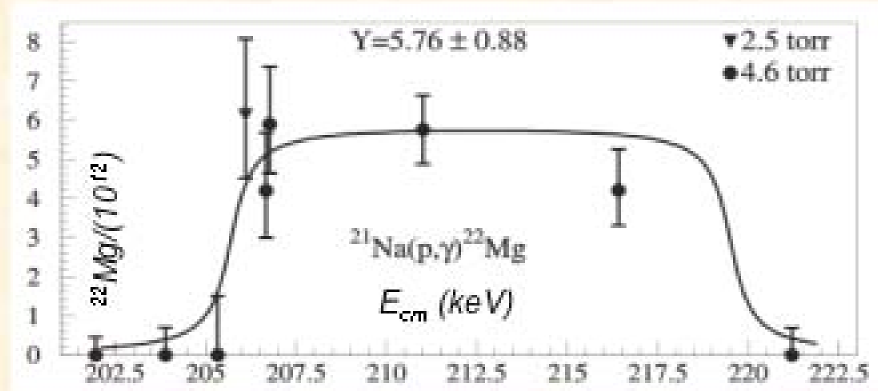
DRAGON results

$^{21}Na(p,\gamma)^{22}Mg \rightarrow {}^{22}Na$ (E_γ = 1.275 MeV)

$^{26}Al(p,\gamma)^{27}Si \rightarrow {}^{26}Al$ (E_γ = 1.809 MeV)

*J. D'Auria et al., PRC **69** (2004) 065803.*
*S. Bishop et al., PRL **90** (2003) 162501.*





→ New mass for ^{22}Mg (δ=6 keV)

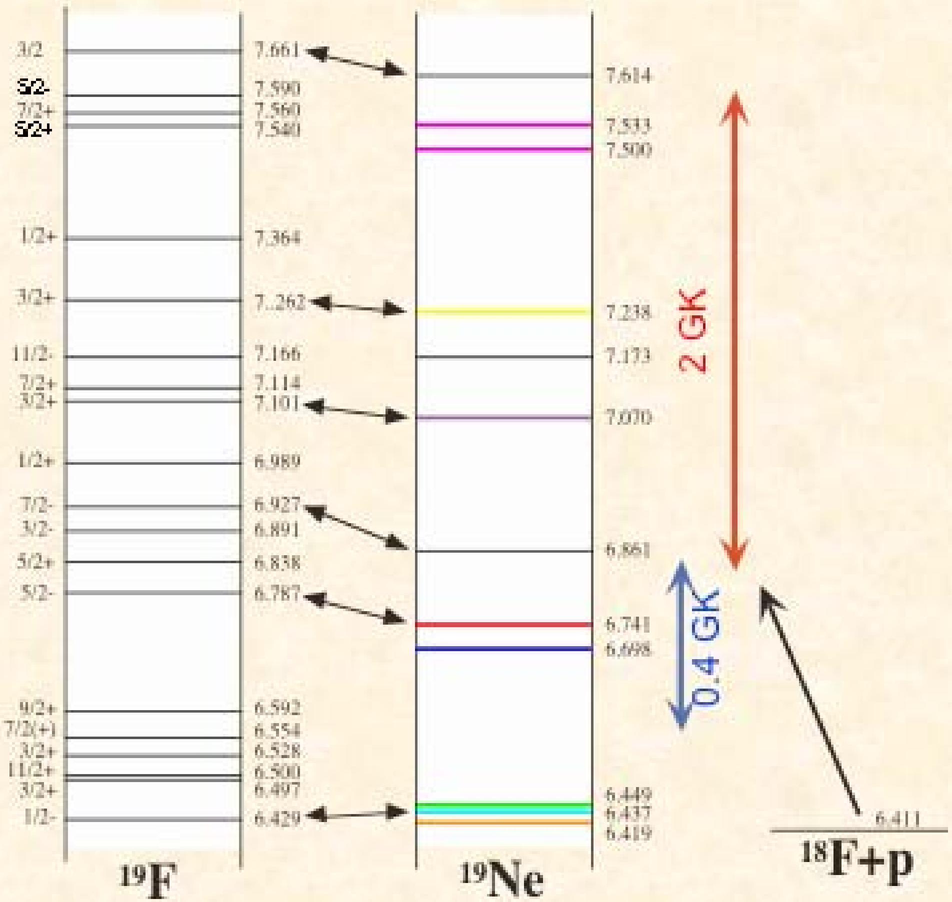
Now measuring the 188 keV resonance in $^{26}Al(p,\gamma)^{27}Si$

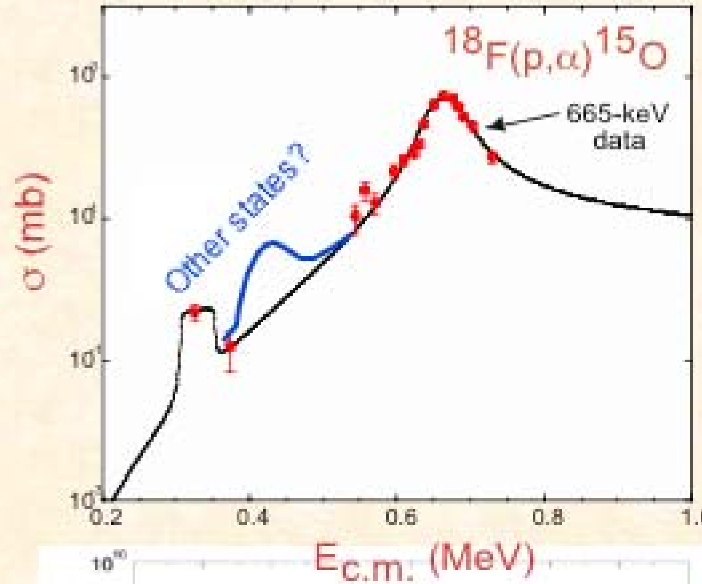
10^8 ^{26}Al/s on target

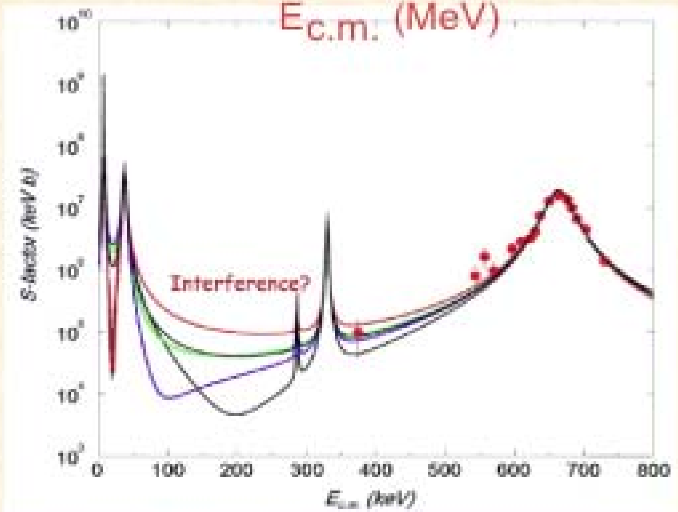
$^{18}F(p,\alpha)^{15}O$ at the HRIBF

The most important reaction for understanding positron annihilation γ-rays from novae

D.W. Bardayan et al, PRL ***89*** *(2002) 262501.*







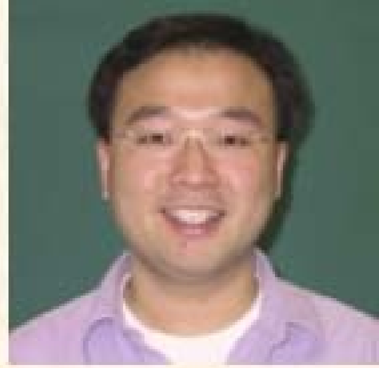
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

JINA Frontiers

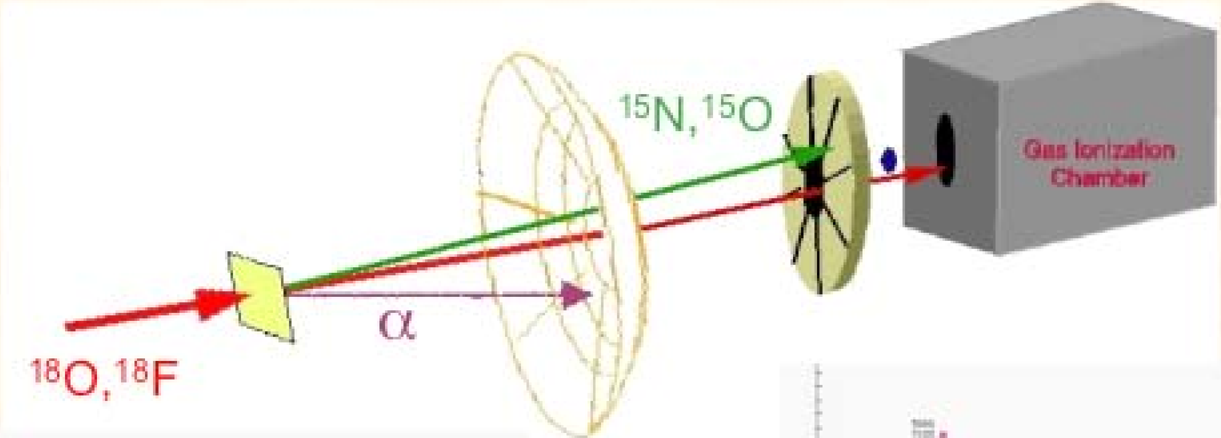
UT-BATTELLE

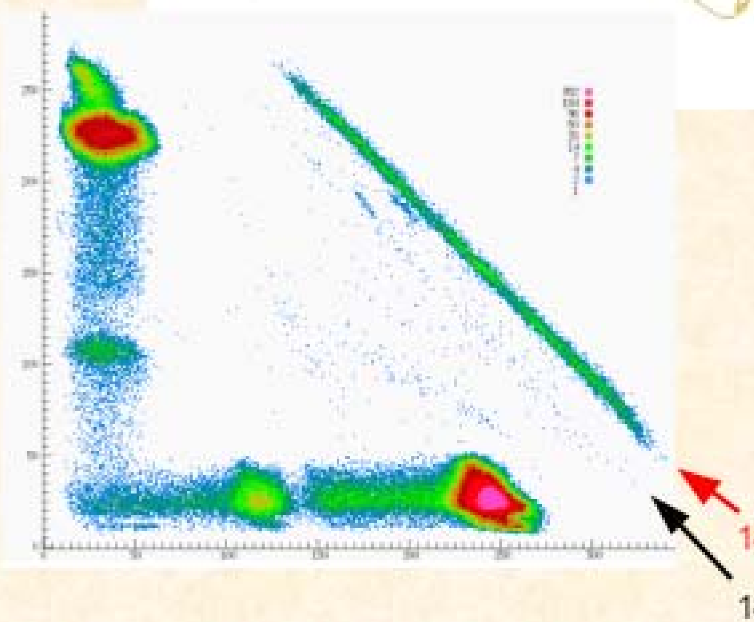
$^{18}F(p,\alpha)^{15}O$

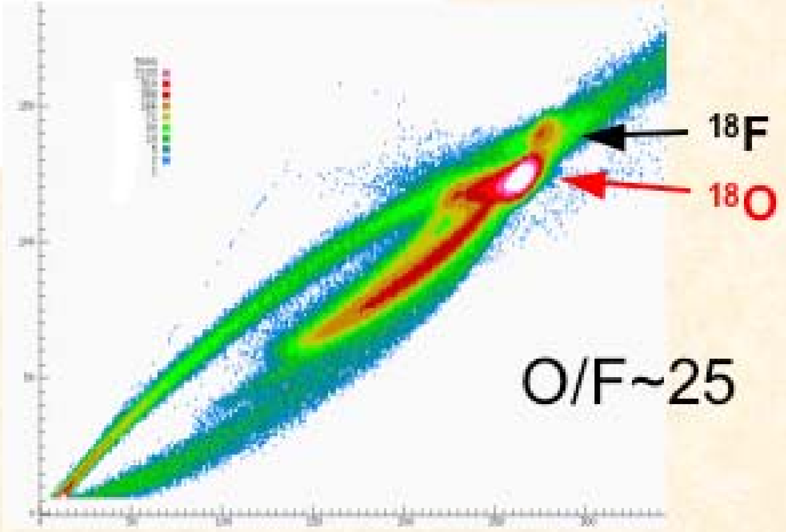
Goal: Improved beam intensity and efficiency



Andy Chae
Ph.D. Dissertation
Univ. Tennessee

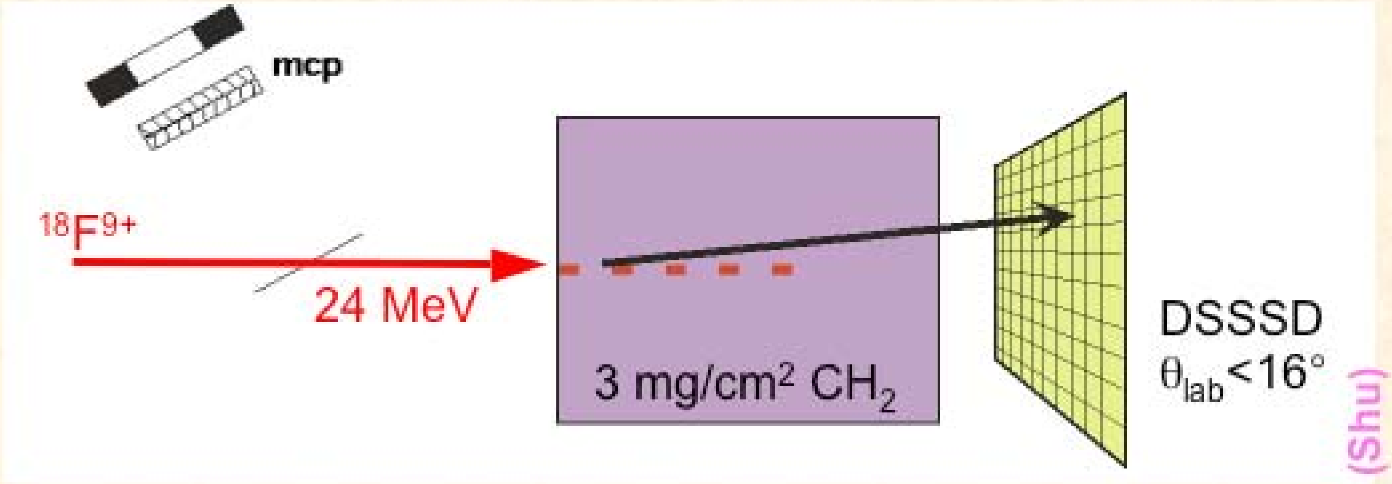




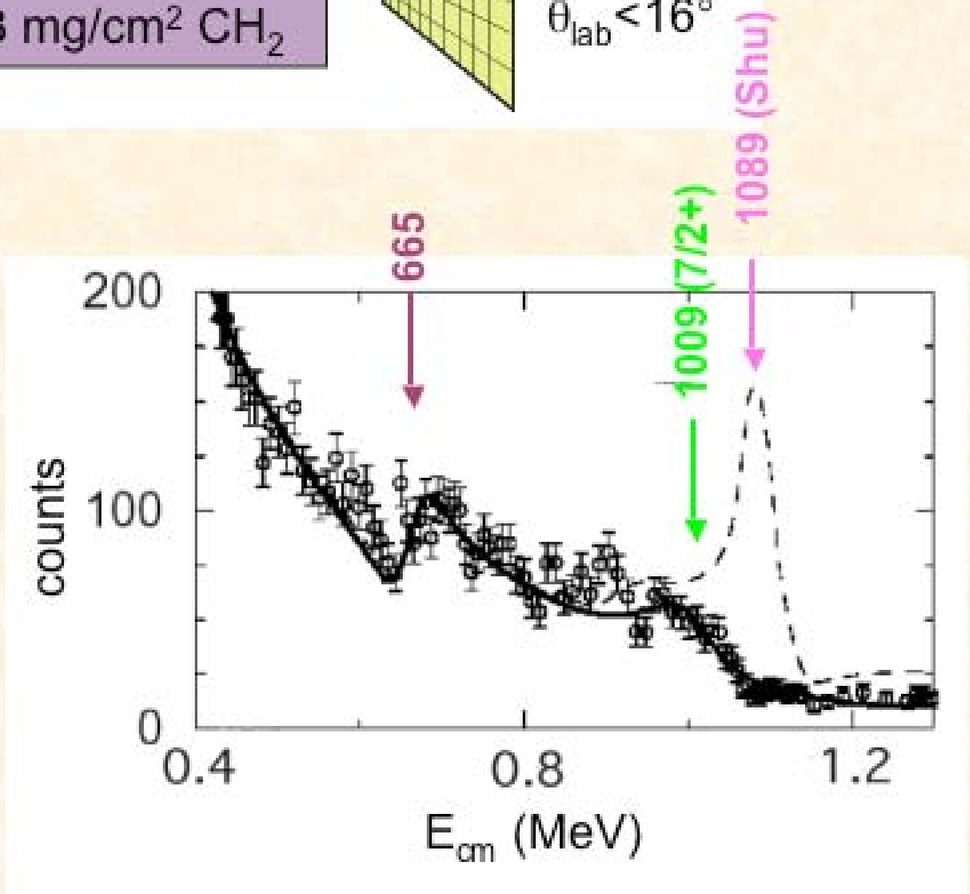


$^{18}F+p$ elastic scattering at the HRIBF

D.W. Bardayan et al., Phys. Rev.C 70 (2004).

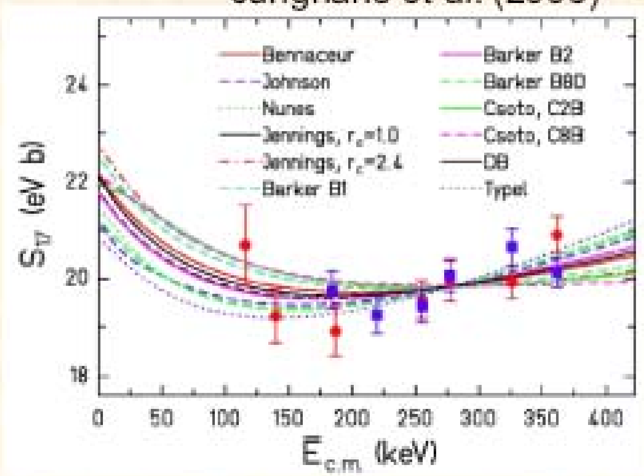


- New $7/2^+$ resonance at E_x=7.42 MeV
- Significant upper limits set on potential resonances with E_{cm} > 665 keV
- The 665 and 1009 keV resonances dominate the reaction rate at higher temperatures ($T>4x10^8$ K).
- However, elastic scattering is not sensitive to narrow resonances at lower energies that likely dominate the rate in novae.

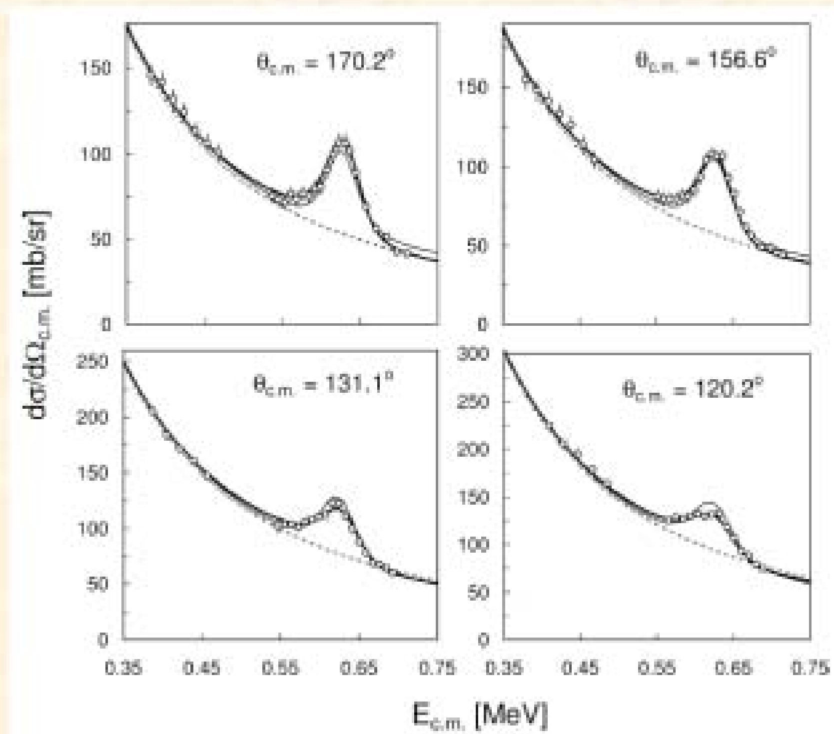


$^7Be(p,p)^7Be$ and Extrapolation of $^7Be(p,\gamma)^8B$

Junghans *et al.* (2003)



- Need very precise value for ^{7}Be(p,γ)^{8}B at low energy to better interpret solar neutrino observations (Super-K, SNO).
- Accurate s-wave phase shifts would help better constrain the extrapolation.

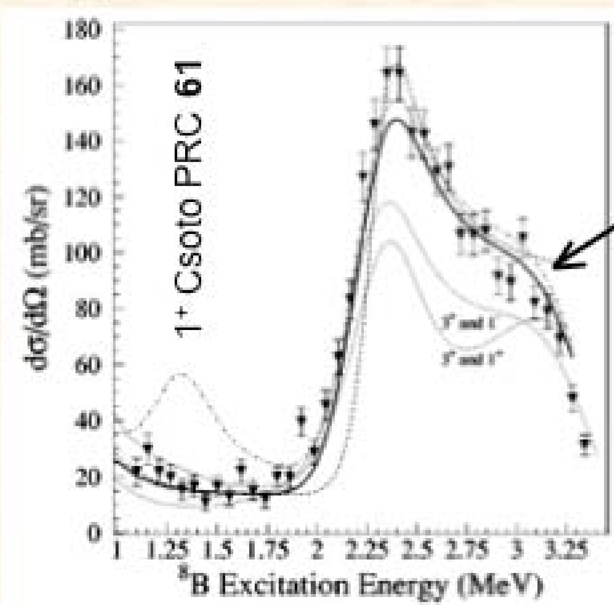


a_{01} = 25 ± 9 fm, a_{02} = -7 ± 3 fm

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

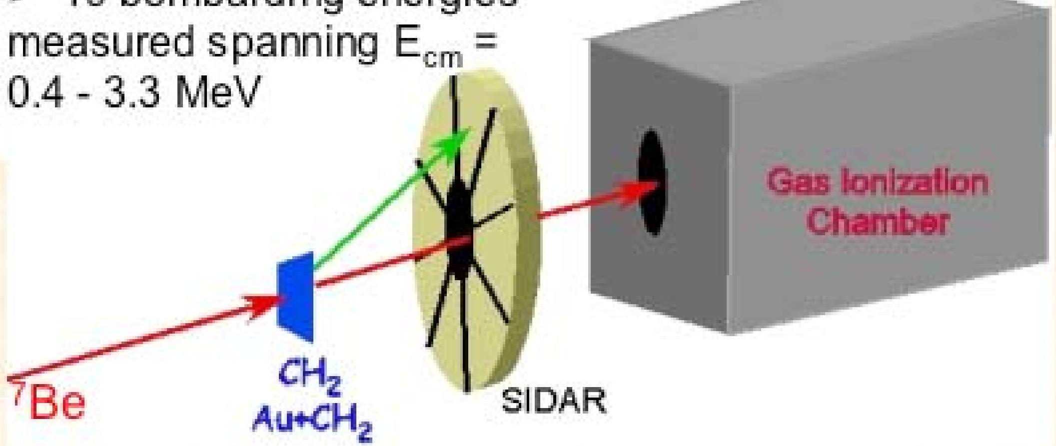
- Influence of broad resonances?

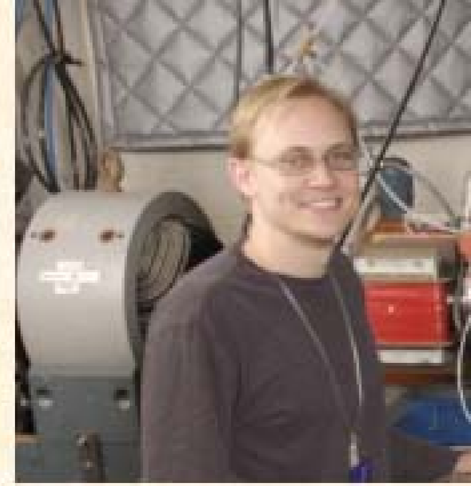
G V Rogachev *et al.*, PRC **64** (2001)



$^7Be(p,p)^7Be$ at the HRIBF

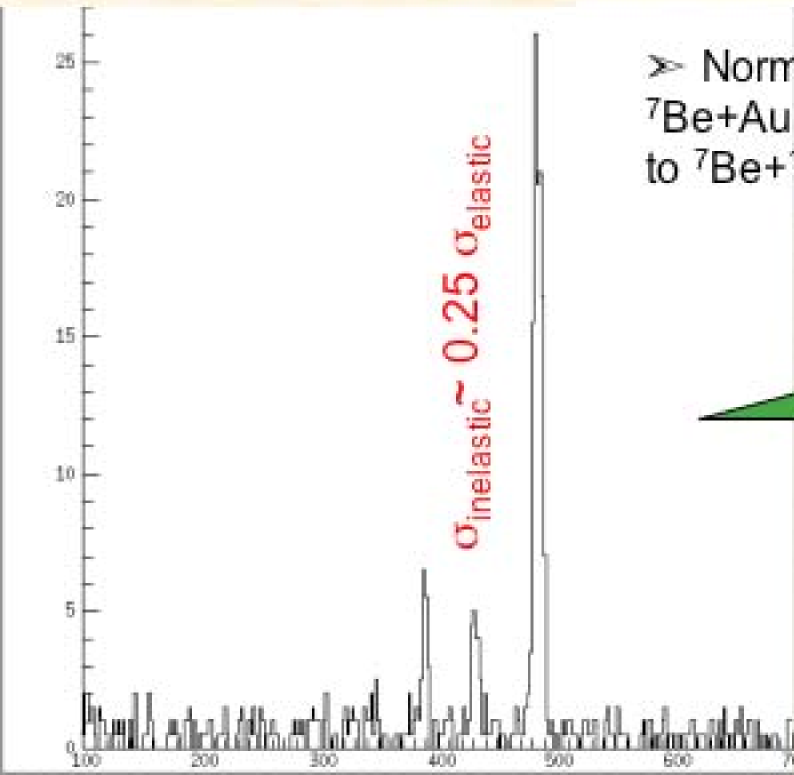
➢ 19 bombarding energies measured spanning E_{cm} = 0.4 - 3.3 MeV

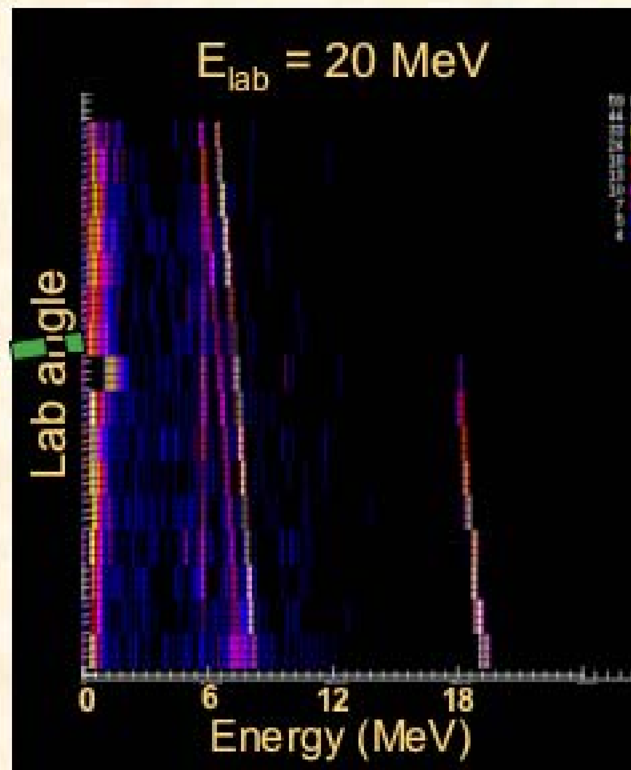




Jake Livesay
Ph.D. Dissertation

➢ Normalization to ^7Be+Au scattering and to $^7Be+^{12}C$ scattering





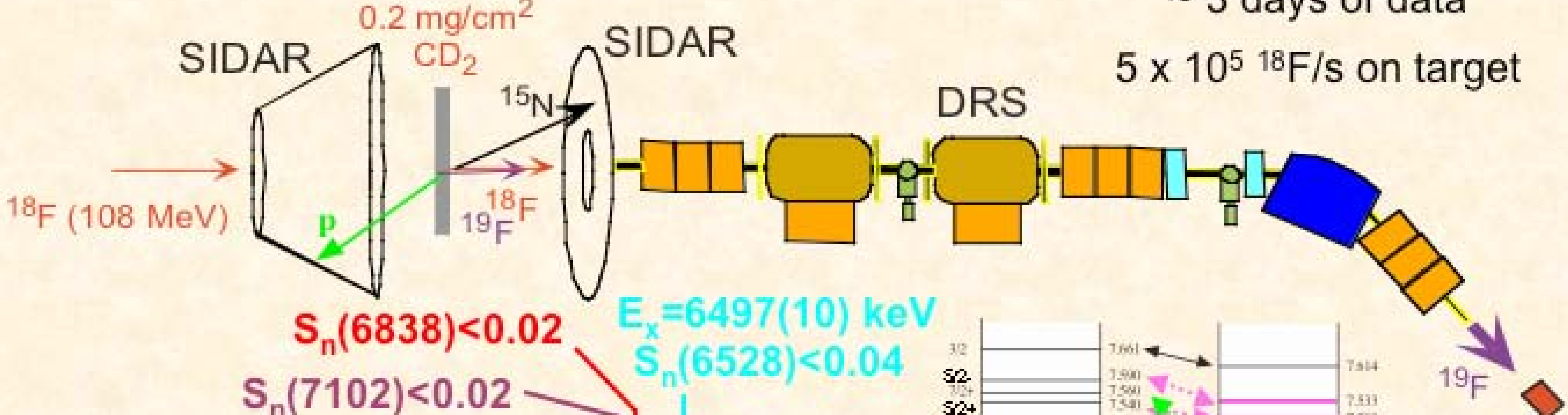
Transfer Reactions → Resonant properties

$^{18}F(d,p)^{19}Ne$ - Neutron single-particle strengths of mirror levels for $^{18}F(p,\alpha)^{15}O$.

R.L. Kozub et al., Phys. Rev. C ***71*** *(2005) 032801.*

~ 3 days of data

5×10^5 ^{18}F/s on target



E_x=6497(10) keV

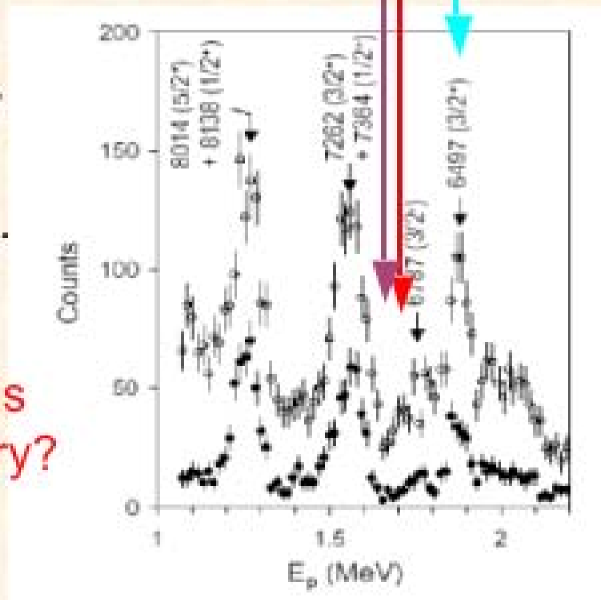
$S_n(6528)<0.04$

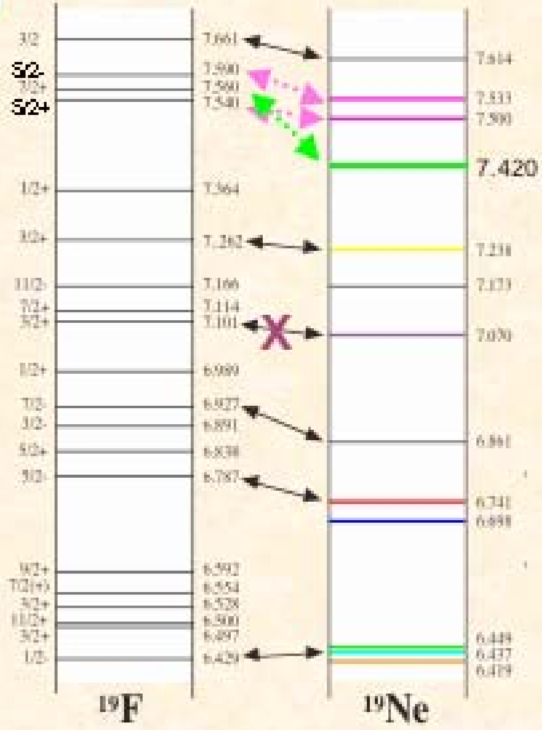
$S_n(6838)<0.02$

$S_n(7102)<0.02$

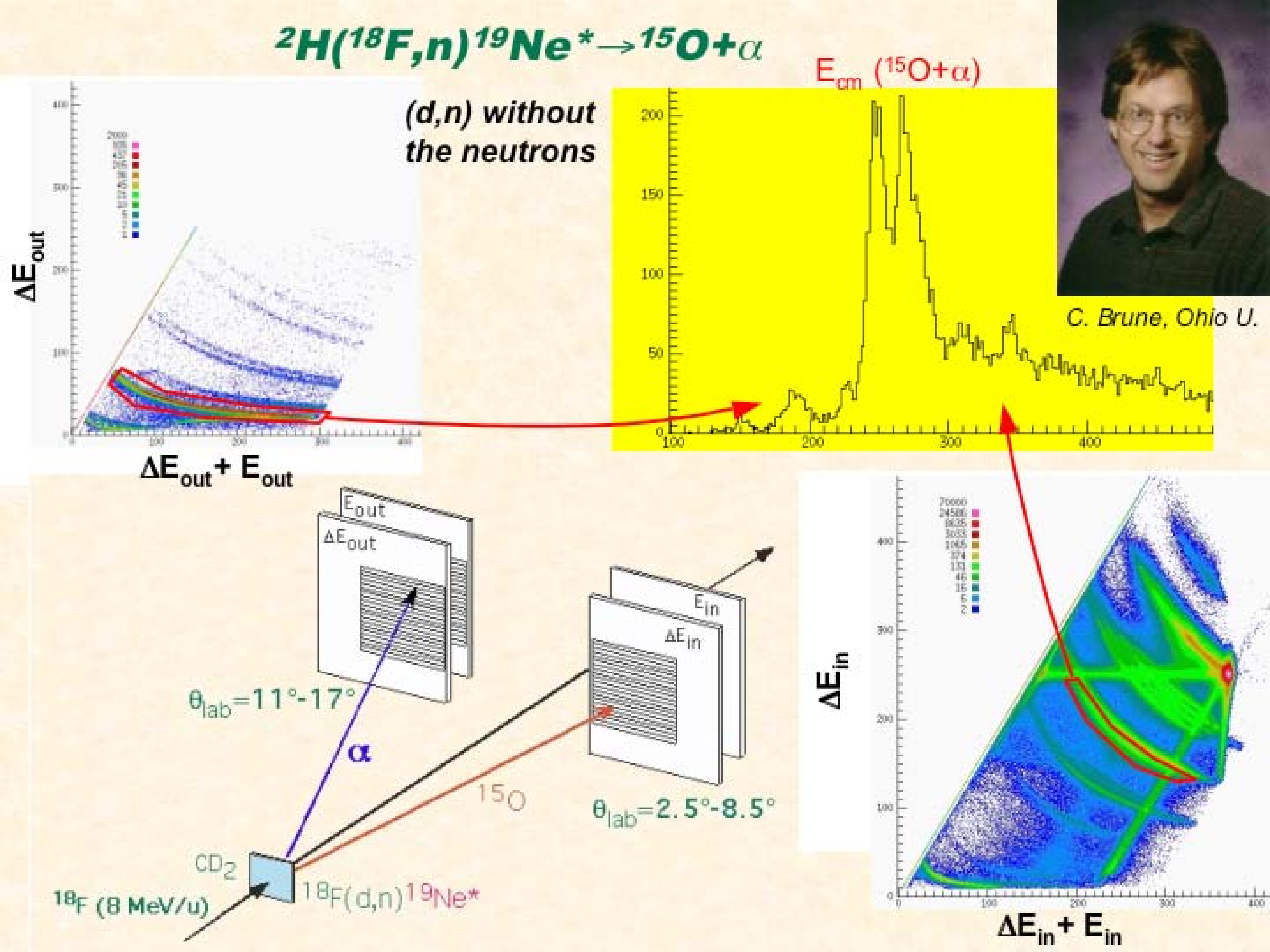
→ Significantly lower $^{18}F(p,\alpha)$ reaction rate …

But how good is mirror symmetry?





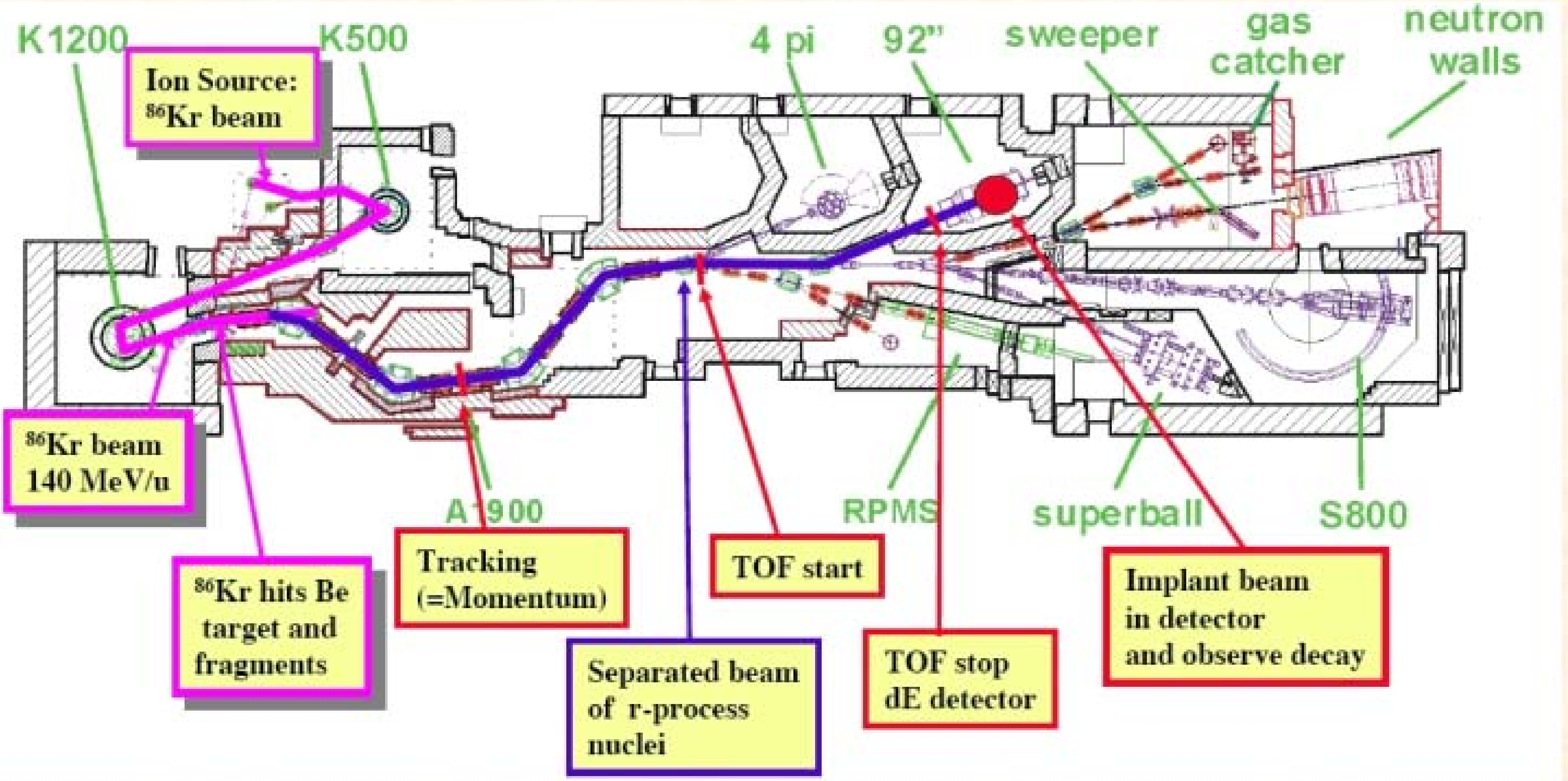
$^{2}H(^{18}F,n)^{19}Ne^{*} \rightarrow ^{15}O+\alpha$



Projectile Fragmentation (e.g. NSCL)

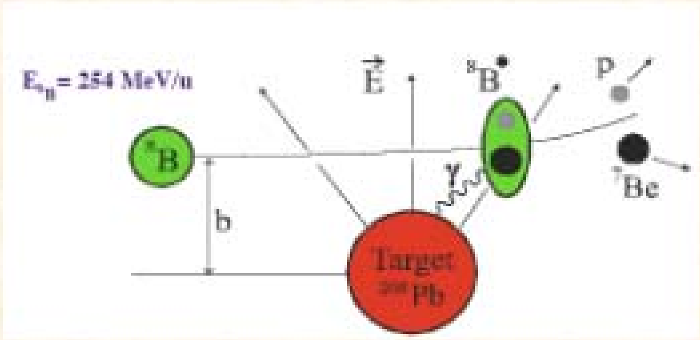
The Joint Institute for Nuclear Astrophysics
H. Schatz

The National Superconducting Cyclotron Laboratory at MSU



Sümmerer

Coulomb dissociation

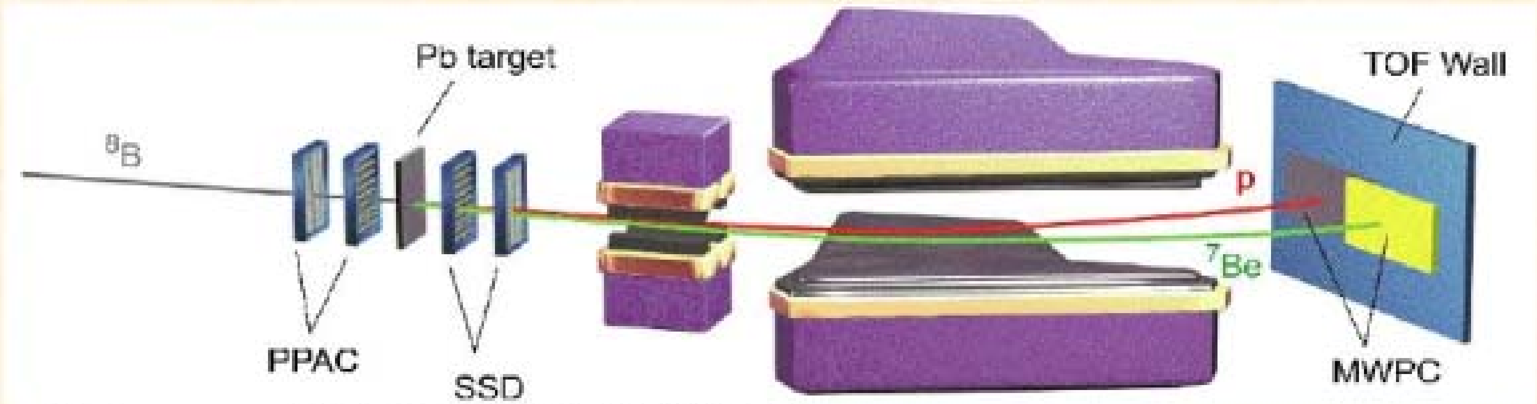


Measure inverse to capture reaction using RIB on a γ target.

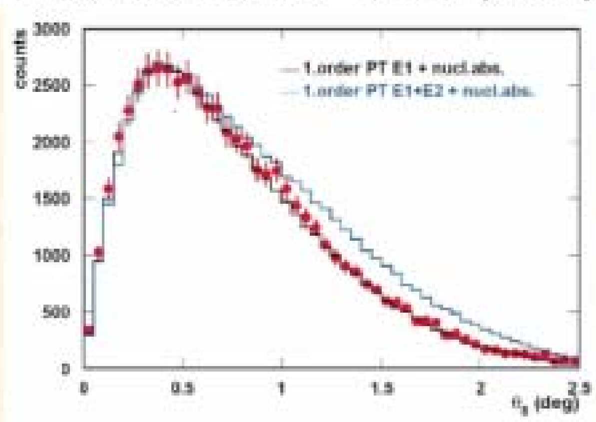
<u>Complications</u>

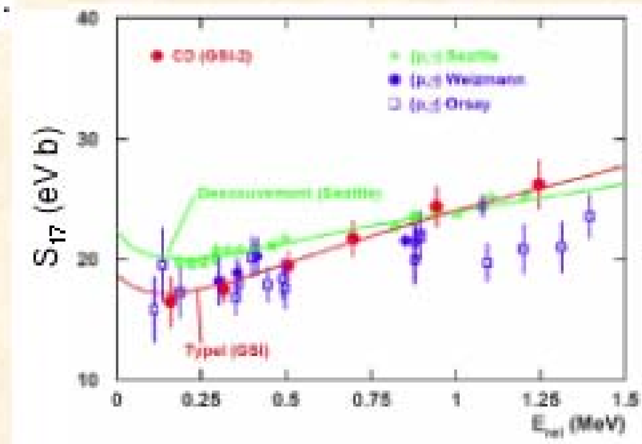
multipolarities

nuclear contribution



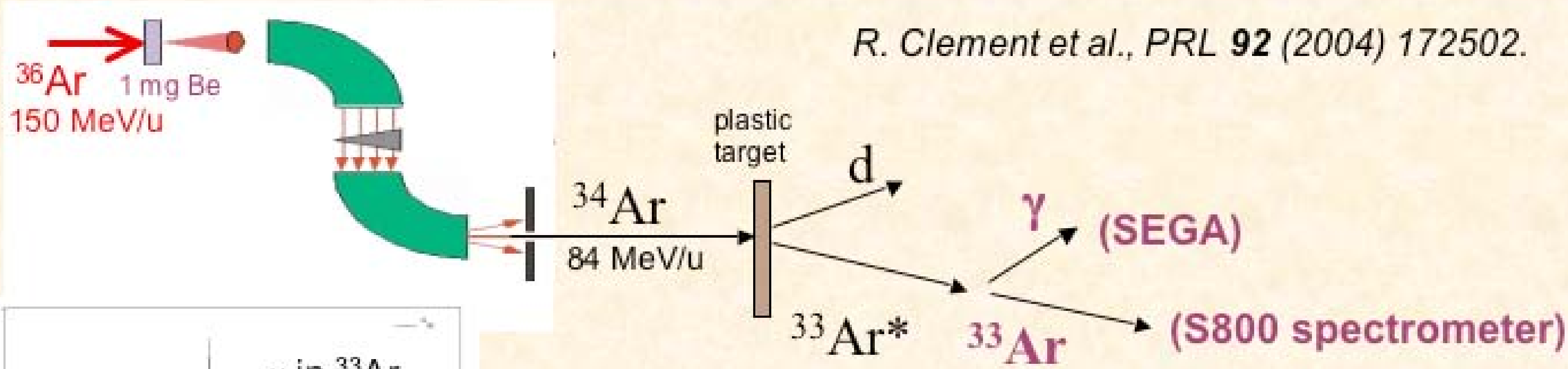
Schumann et al., PRL 90 (2003) 232501.

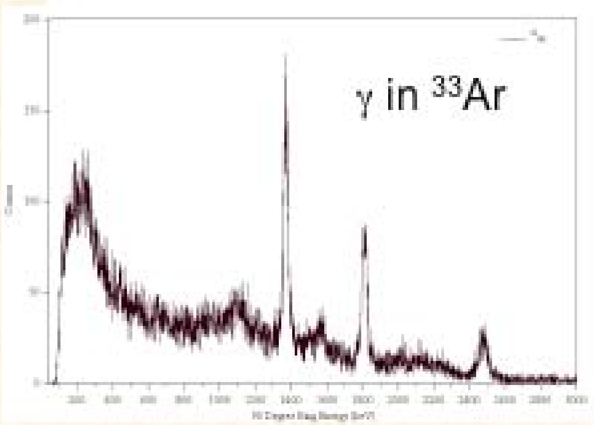




(p,d) in inverse kinematics at MSU/NSCL

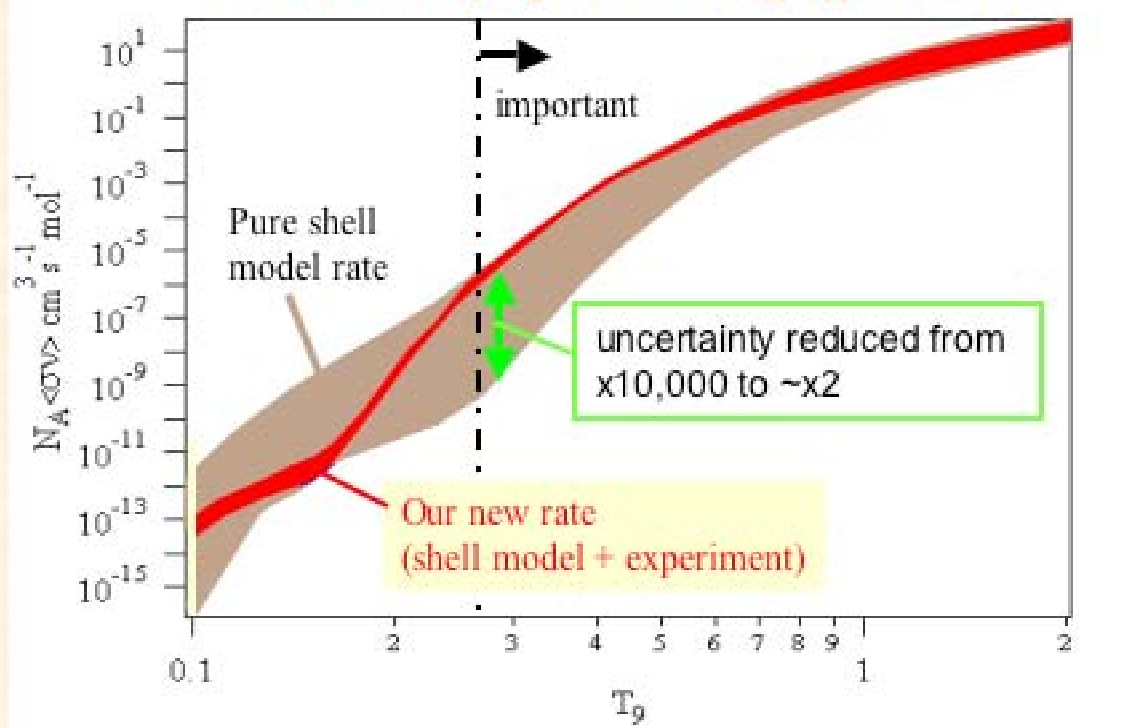
R. Clement et al., PRL **92** (2004) 172502.

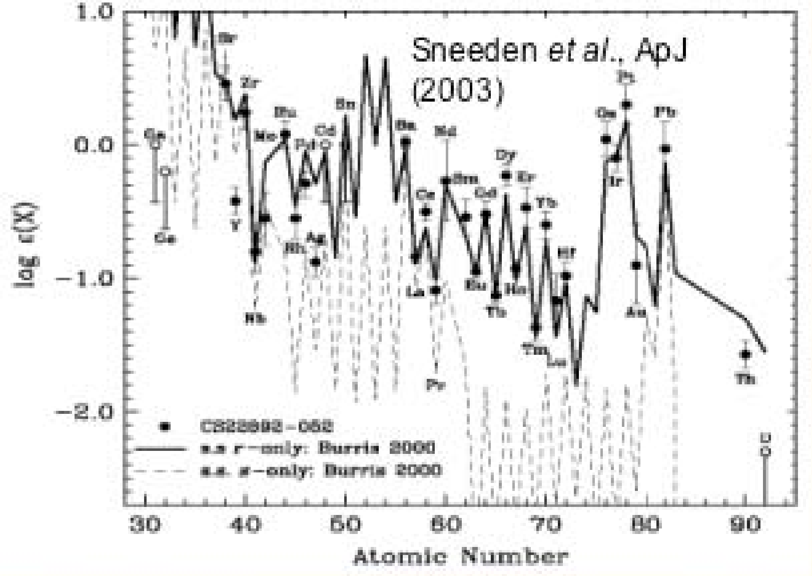




level energies in ^{33}Ar are resonance energies in ^{32}Cl+p

New astrophysical ^{32}Cl(p,γ)^{33}Ar rate



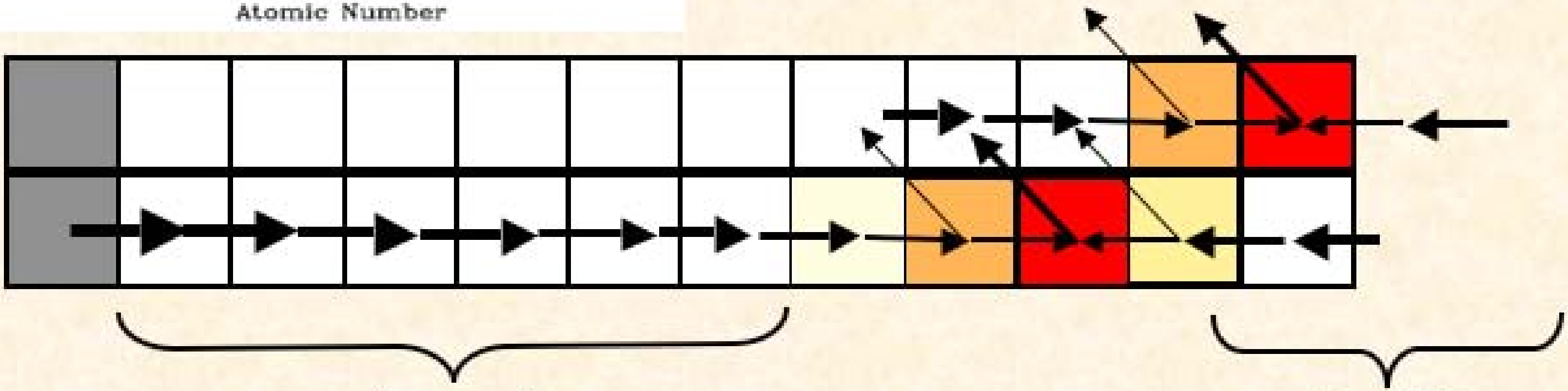


The eastern frontier

Tremendous new data from metal poor halo stars are helping us understand the r process

2 different r processes?

Need better data on neutron-rich nuclei



Large S_n
$(n,\gamma) >> (\gamma,n) >> t_{1/2}$

Small S_n
$(\gamma,n) >> (n,\gamma) >> t_{1/2}$

Masses, half-lives and decay properties (P_n) are crucial

However, only a few dozen r process nuclei have been created so far → 1000's left

Basic nuclear structure information is also crucial: E(2+), B(E2), Single-particle levels

Mass measurements

thanks to D. Lunney

2 modes:

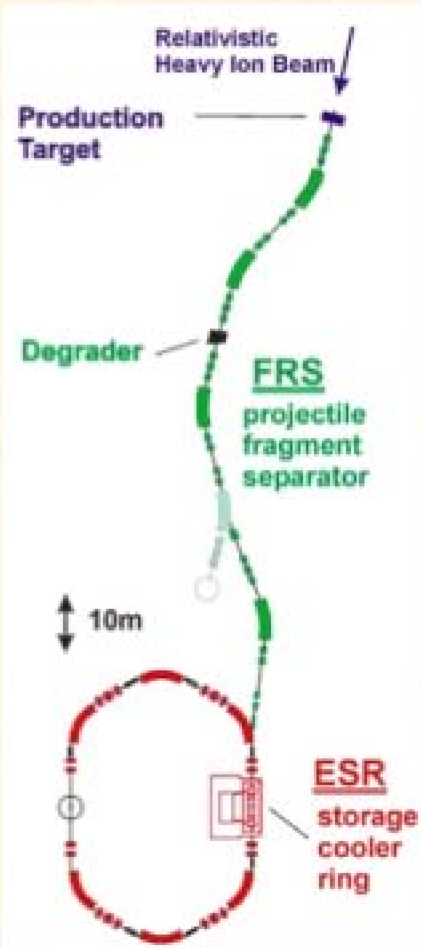
Schottky - slow, more precise
isochronous - fast, less precise

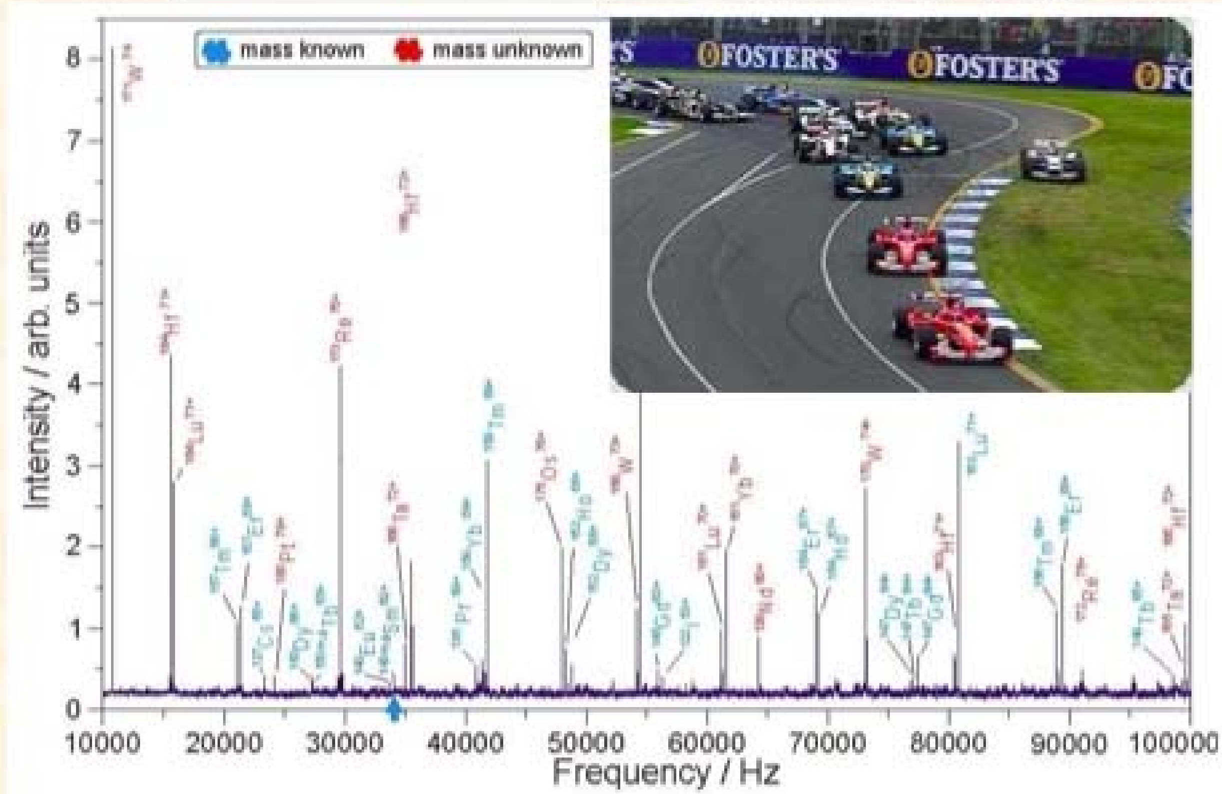
Yu. Litvinov et al., NPA ***734*** *(2004) 473.*

G. Munzenberg et al., Prog. Nucl. Part. Phys. ***53*** *(2004) 351.*

Experimental Storage Ring:

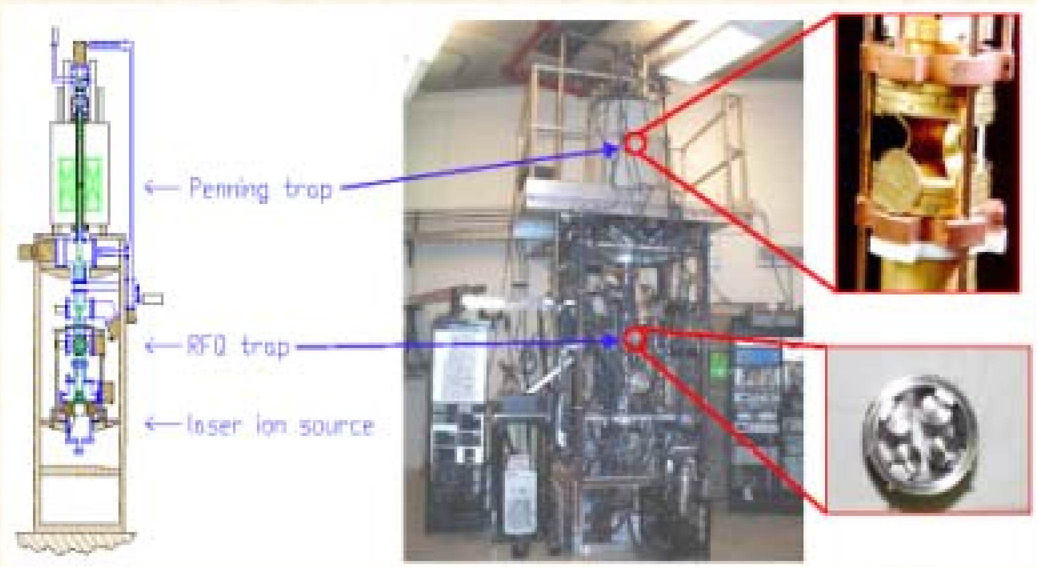
$$\Delta m/m = \gamma_t^2 \, \Delta f/f + (\gamma_t^2 - \gamma^2)\, \Delta v/v$$

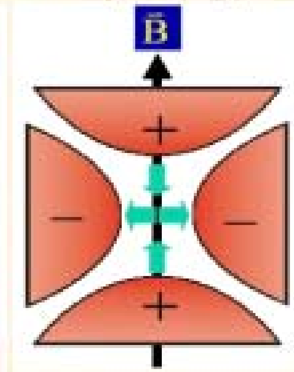


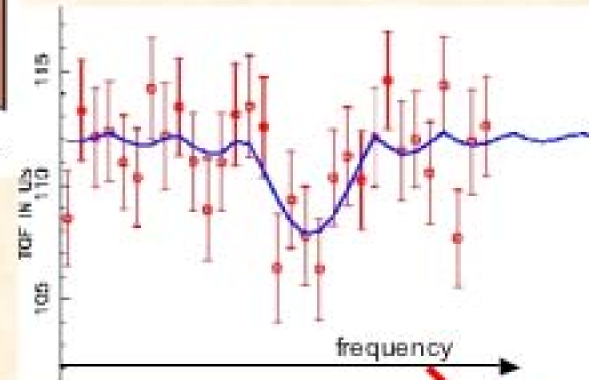


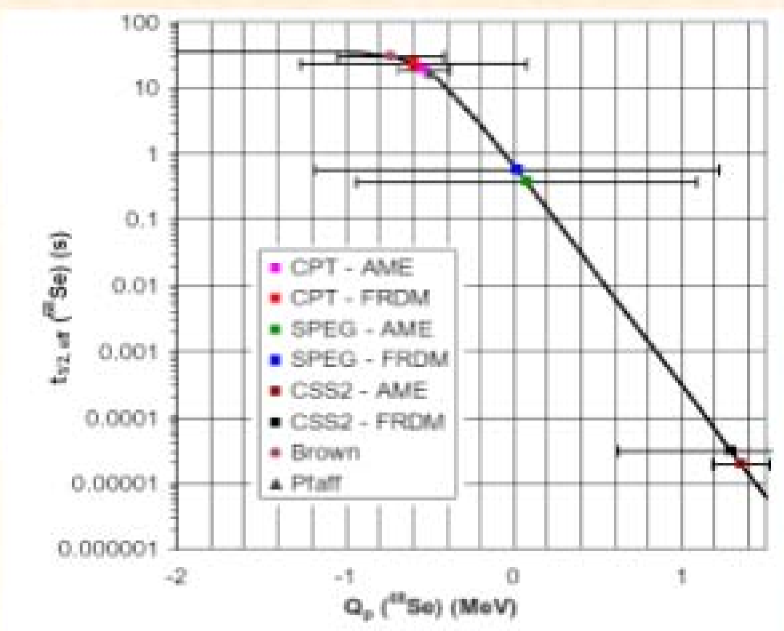
Mass measurements with traps

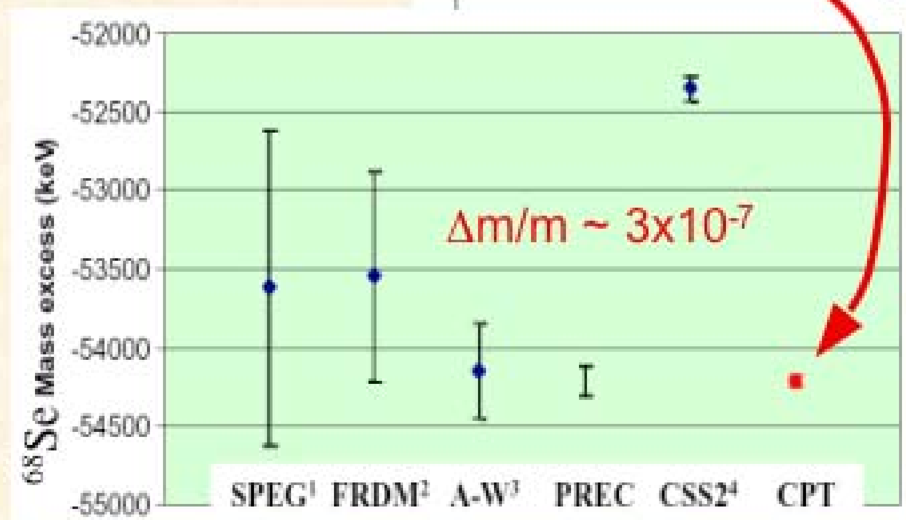
J. A. Clark *et al.*, PRL **92** (2004) 192501.









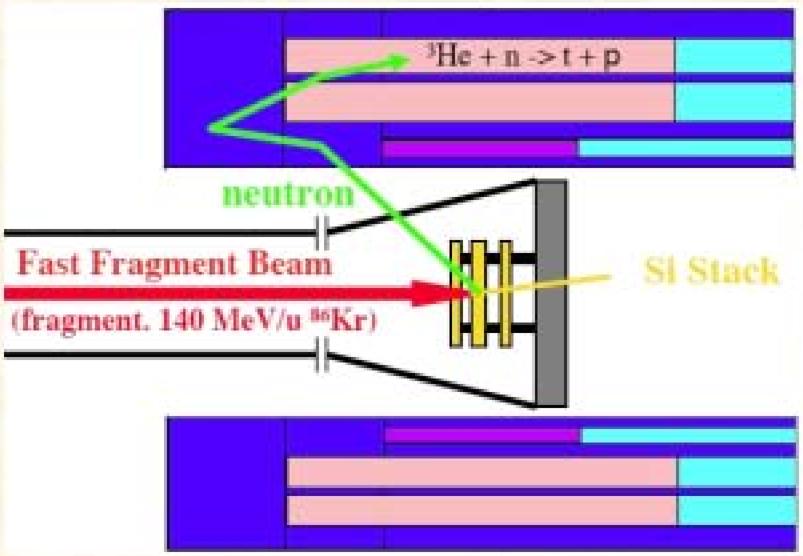


➢ ^{64}Ge and others measured!

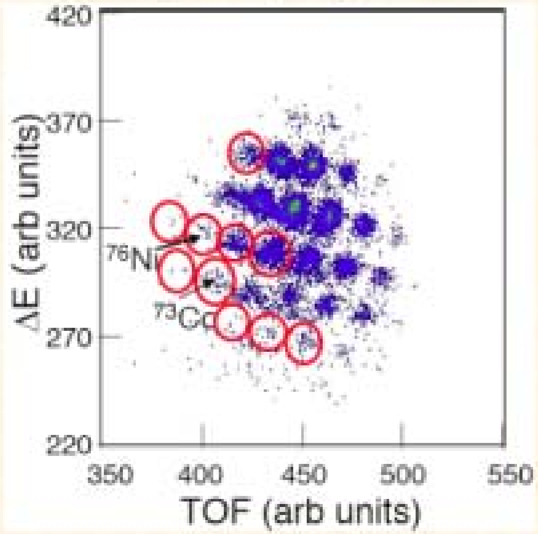
H. Schatz

Decay studies near ^{78}Ni at MSU/NSCL

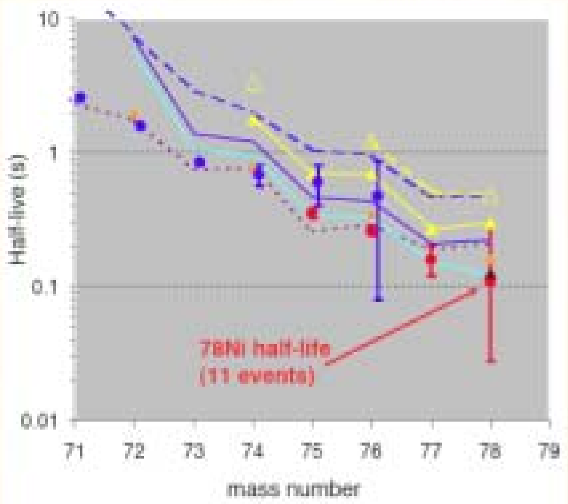
P. T. Hosmer et al., PRL ***94*** *(2005) 112501.*



Many isotopes are studied at once, uniquely identified

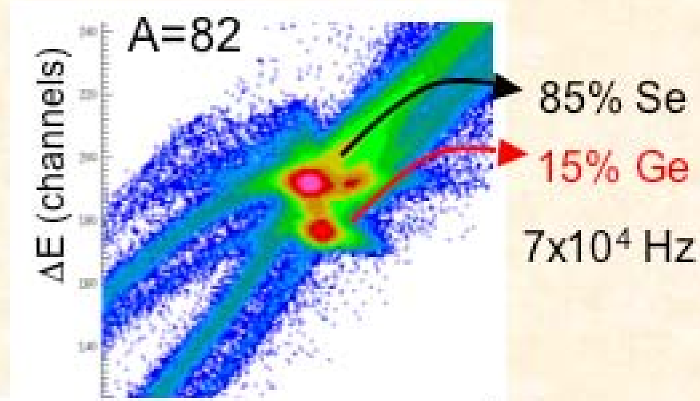


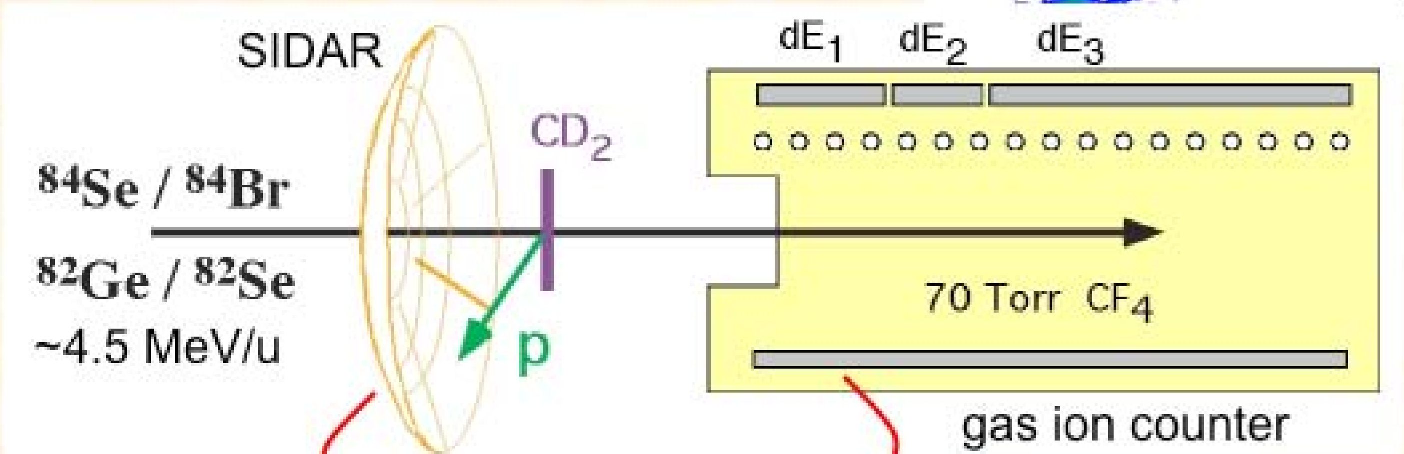
Decay correlated with time, location of implant

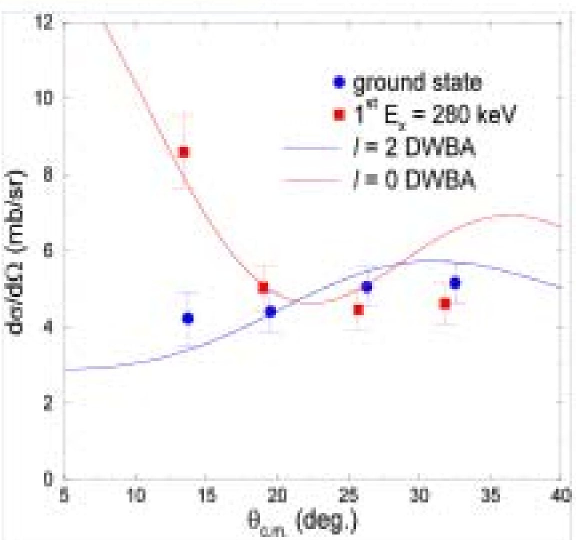


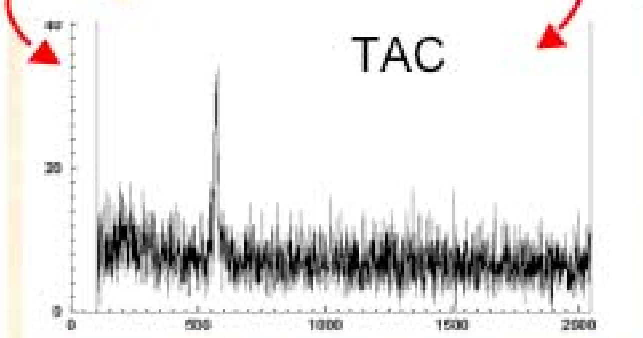
(d,p) on N=50 Nuclei

Jeff Thomas
Ph.D. Dissertation
Rutgers Univ. 2005









$Q = 1.47(\pm 0.02_{stat} \pm 0.07_{sys})$ MeV

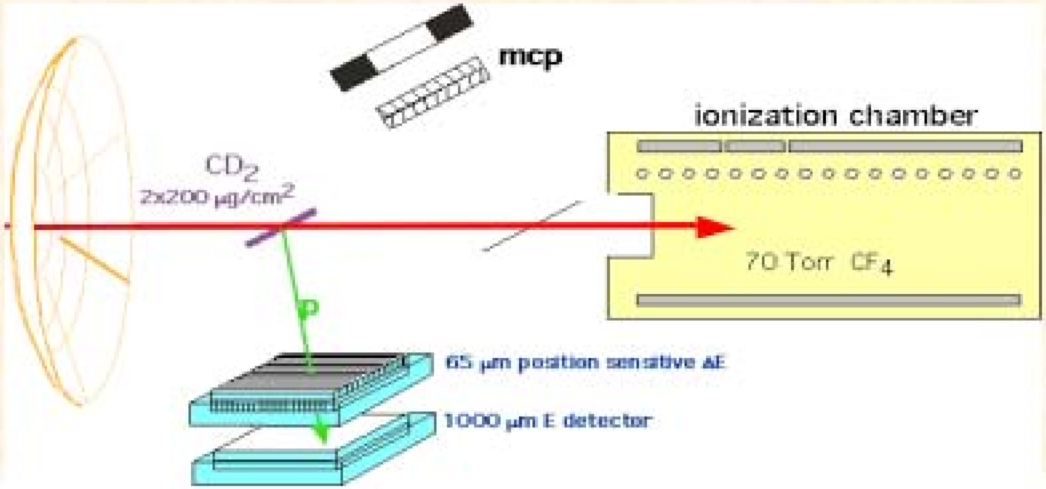
$1^{st}\ E_x = 280\ (\pm 20)$ keV

$Q_{(n,\gamma)}(^{82}Ge) = 3.69 \pm 0.07$ MeV

$^{82}Ge(n,\gamma)$ Q-value is lower than any stable nucleus heavier than ^{15}N

Nuclei near ^{132}Sn: $^{124}Sn(d,p)^{125}Sn$ test case

K.L. Jones *et al.*, *PRC* ***70*** *(2004) 067602.*



Complications

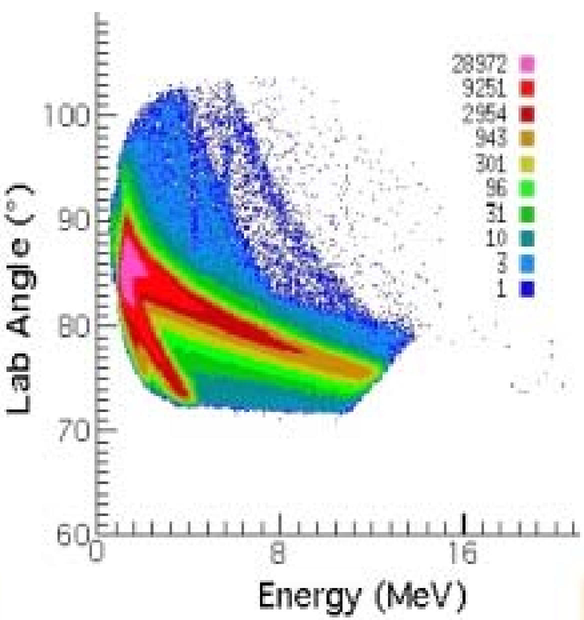
More inverse

$\theta_{lab} < 90°$

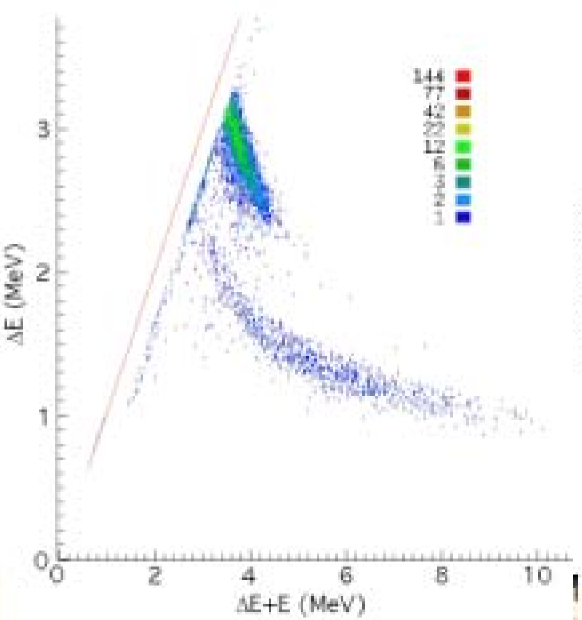
$dE/d\theta$ larger

E limited ~V_c

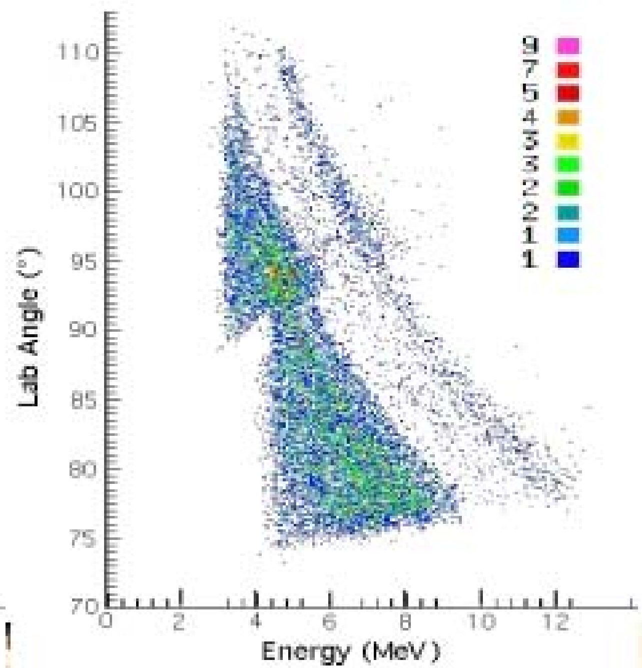
Singles



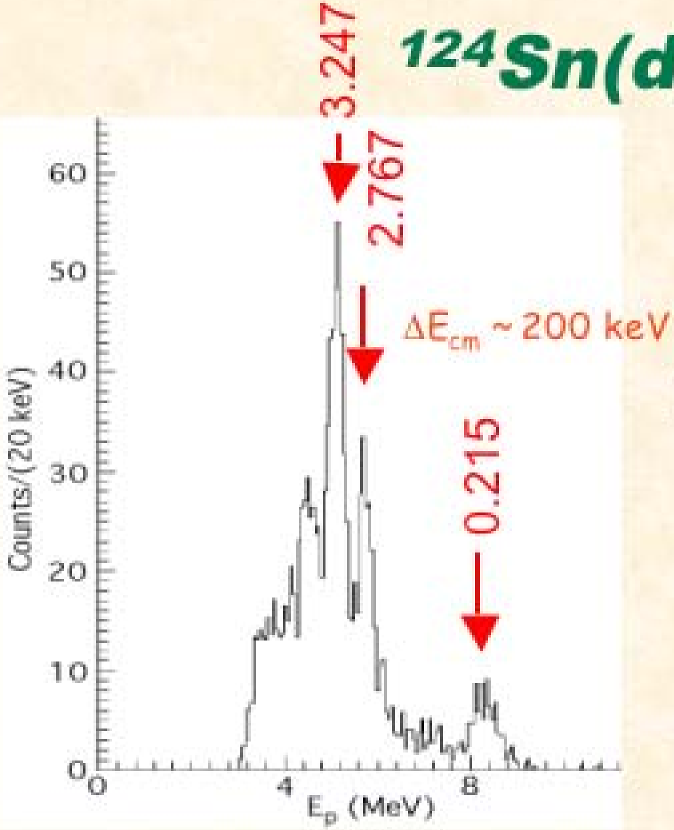
PID



Proton gated



$^{124}Sn(d,p)$ results

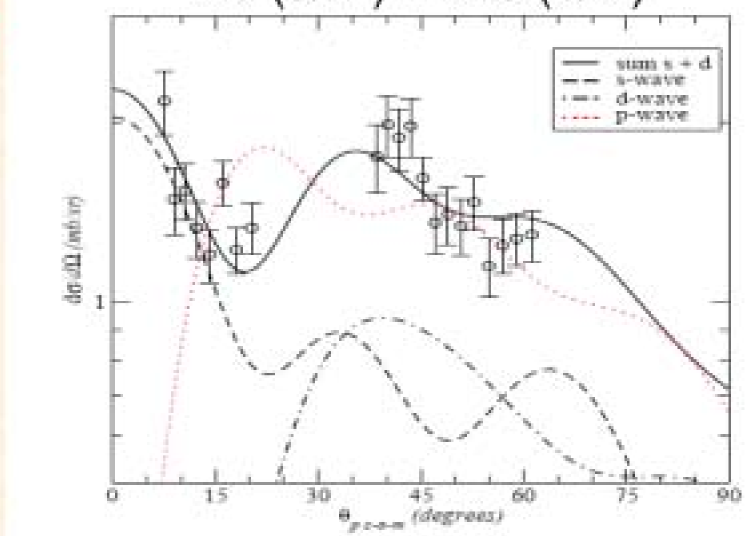


Fair energy resolution

Reliable ℓ and S_n

Need good efficiency

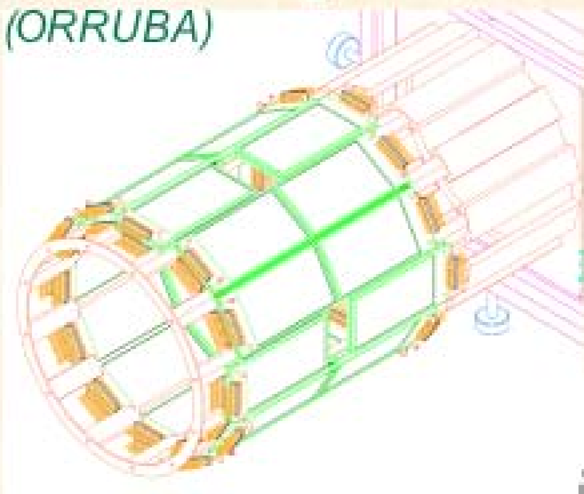
20 (3/2$^+$) + 215 (1/2$^-$)



Neutron spectroscopic factors

	This Work	Stromich et al.	Bingham and Hillis
$3/2^+$	0.44	0.53	0.44
$1/2^-$	0.33	0.32	0.33
$7/2^+$	0.46	0.52	0.54

Oak Ridge - Rutgers Univ. Barrel Array (ORRUBA)

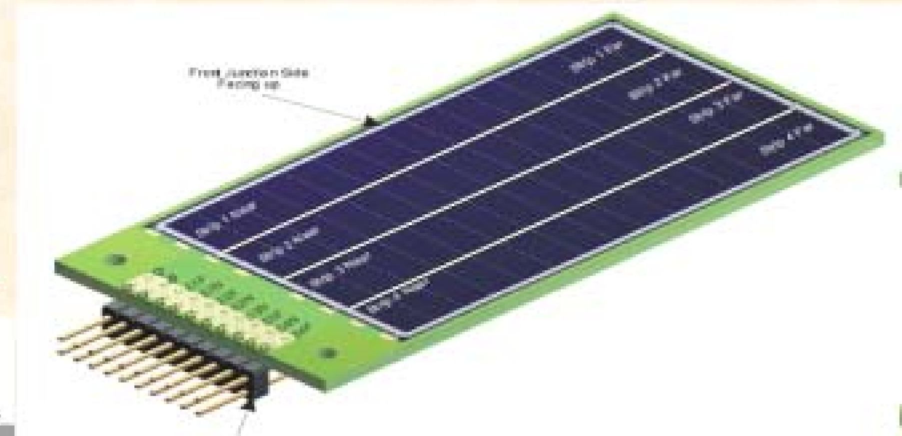


Rutgers

Department of Physics and Astronomy

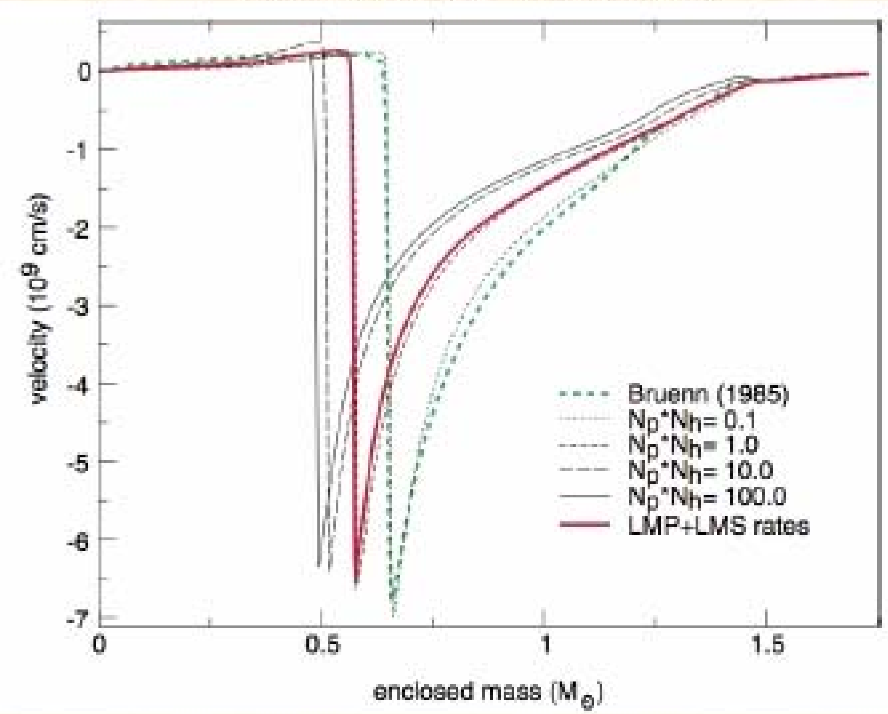
ORAU

OAK RIDGE ASSOCIATED UNIVERSITIES



Supernovae dynamics

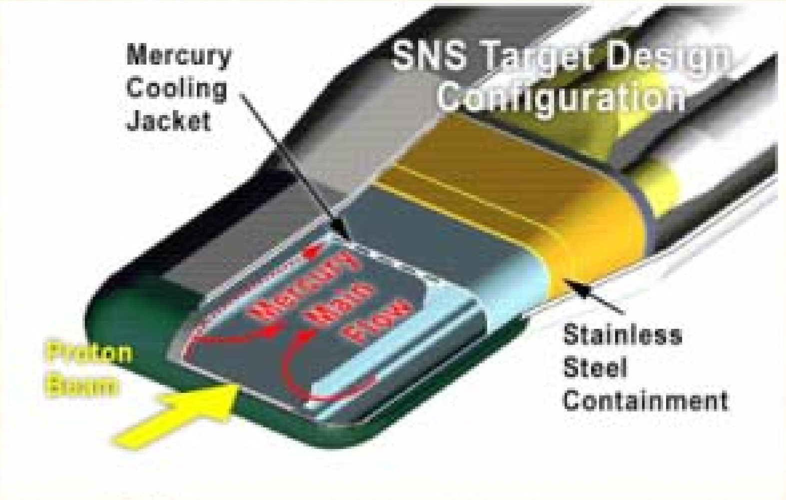
Effect of e-capture rates on formation of the shock



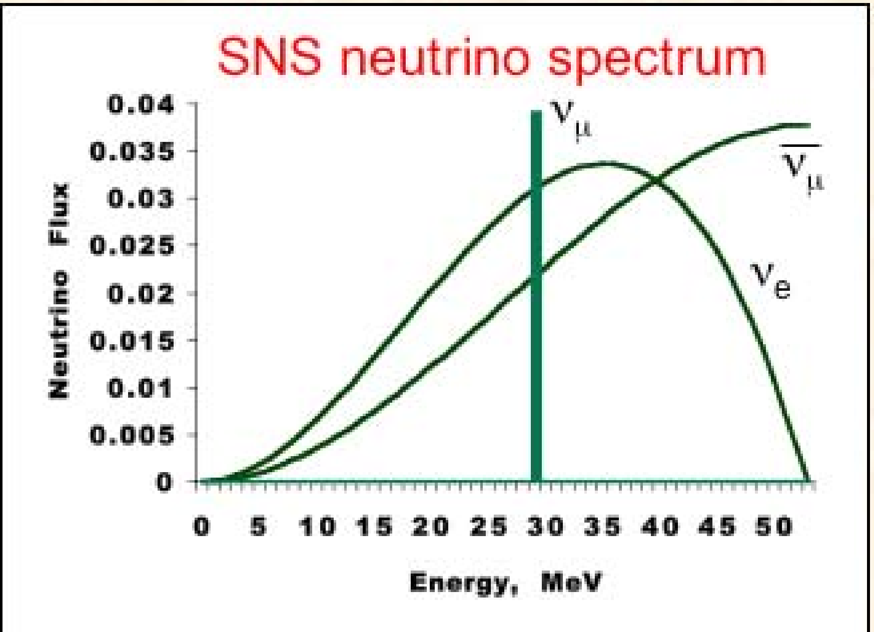
Only ν_e+^{12}C cross section has been measured with good precision (10%)

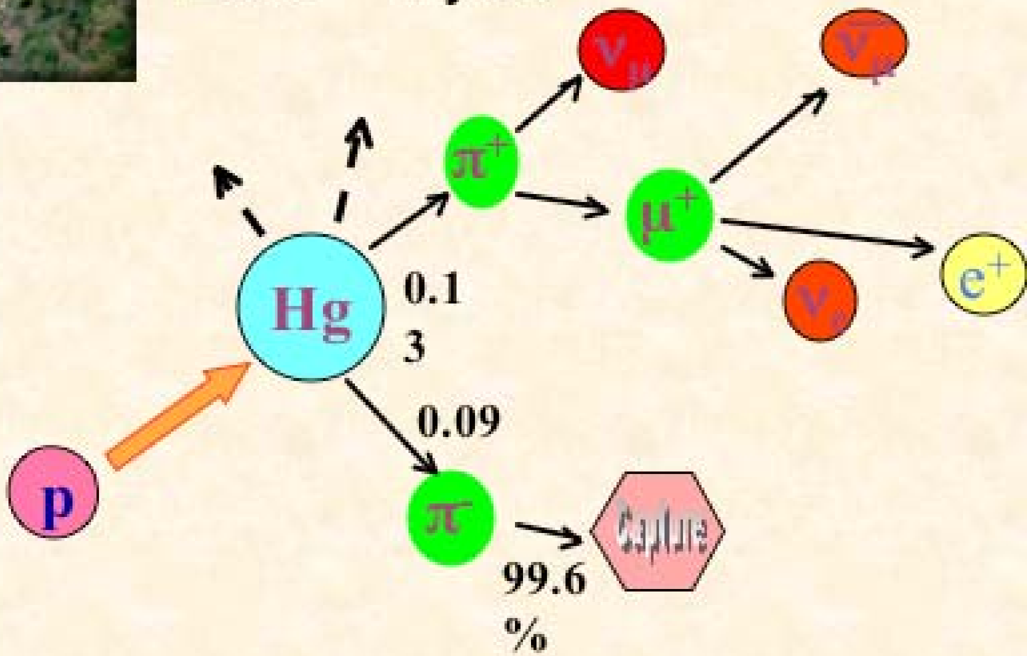
- Weak interactions play a crucial role in supernovae.
- Electron capture rates affect the formation of the shock wave.
- Neutrino interactions play a role in driving the explosion.
- Neutrino induced reactions can alter nucleosynthesis.
- Electron capture rates (the inverse of neutrino absorption) are critical for core collapse.
- Neutrino cross sections are not well understood -- sensitive to nuclear structure:
  - GT strengths
  - first-forbidden contribution

The Spallation Neutron Source



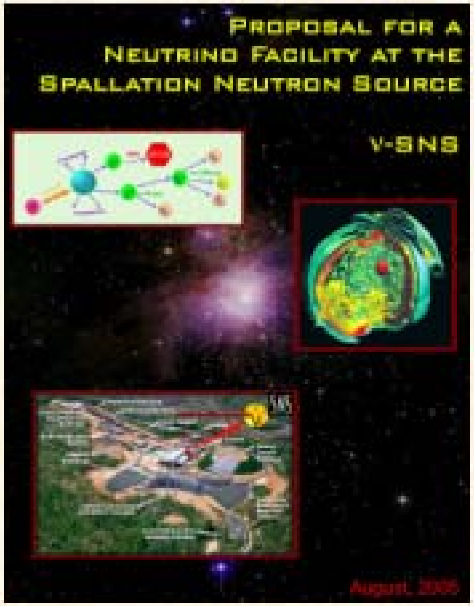
$2x10^{22}$ ν/year

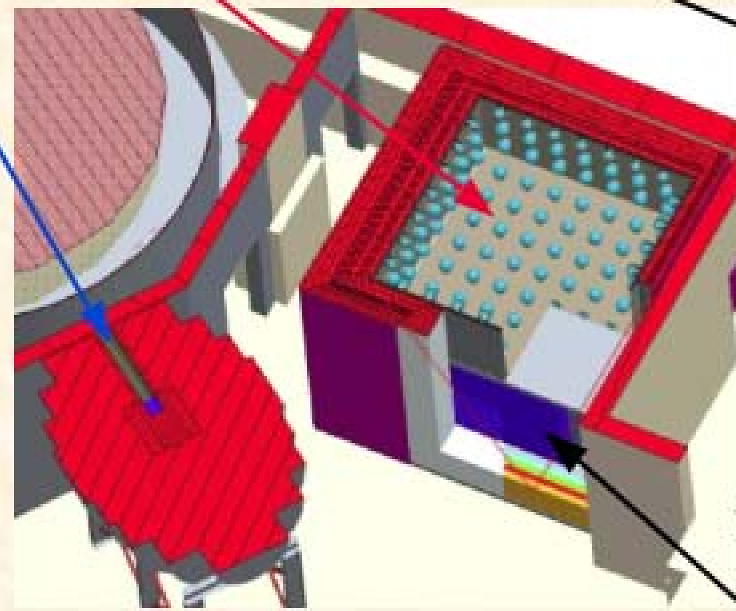




νSNS

- A proposal has been submitted to DOE to construct a facility for neutrino studies at the Spallation Neutron Source.
- Collaboration >40 scientists



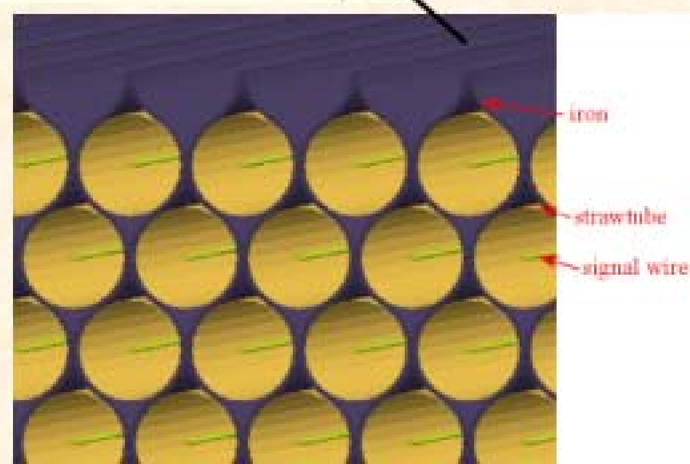


Shielded facility & 2 Detectors proposed

Homogeneous (scintillator, water, D_2O)

Segmented (Fe, Al, Pb, etc.)

> 10^3 ν_e events/yr/detector



http://www.phy.ornl.gov/nusns

Conclusion

There are lots of exciting discoveries being made at the frontiers of nuclear stability.

Radioactive beam facilities are pushing the boundaries of the frontier.

Experimental approaches are being developed to increase the discovery potential on the frontier.

Many thanks to all my collaborators and colleagues.