



FLORIDA STATE
UNIVERSITY

Experimental Techniques

Sergio Almaraz-Calderon

Florida State University

19th Exotic Beam Summer School
University of Notre Dame
June 6 -10, 2022



Experimental Techniques in Nuclear Physics ...

Nuclear Physics is a very broad field ...



- The type of experiment you need depends on what type of information you want to get



Experimental Techniques in Nuclear Physics ...

Nuclear Physics is a very broad field ...



- The type of experiment you need depends on what type of information you want to get

“ ... You can't always get what you want
But if you try sometime, you'll find
You get what you need ...”

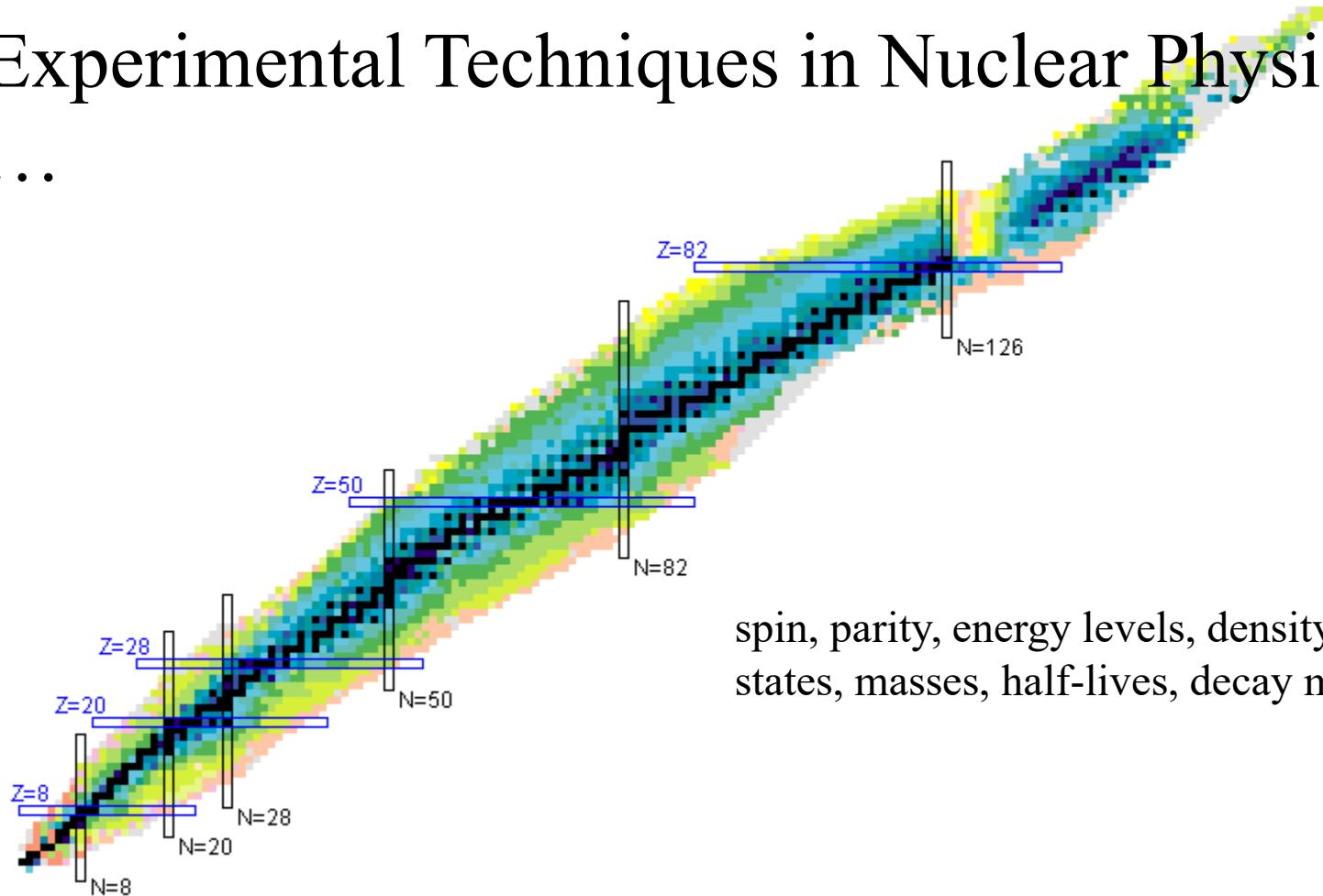
Mick Jagger/Keith Richards





Experimental Techniques in Nuclear Physics

...

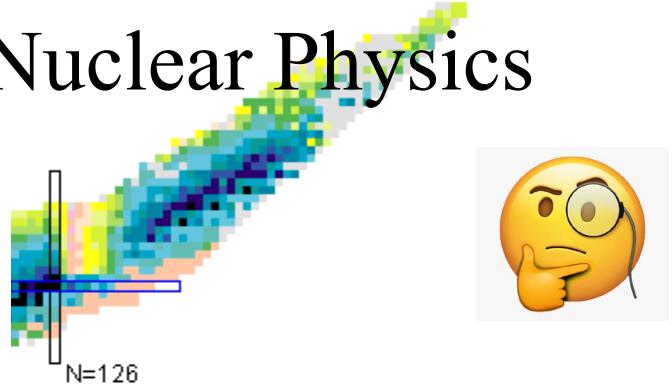


spin, parity, energy levels, density of states, masses, half-lives, decay modes, ...



Experimental Techniques in Nuclear Physics

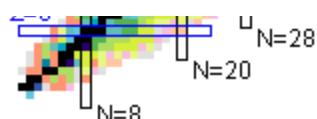
- (1) How did visible matter come into being and how does it evolve?
- (2) How does subatomic matter organize itself and what phenomena emerge?
- (3) Are the fundamental interactions that are basic to the structure of matter fully understood?
- (4) How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?



- What are the limits of nuclear existence and how do nuclei at those limits live and die?
- What do regular patterns in the behavior of nuclei divulge about the nature of nuclear forces and the mechanism of nuclear binding?
- What is the nature of extended nucleonic matter?
- How can nuclear structure and reactions be described in a unified way?

spin, parity, energy levels, density of states, masses, half-lives, decay modes, ...

- How did the elements come into existence?
- What makes stars explode as supernovae, novae, or X-ray bursts?
- What is the nature of neutron stars?
- What can neutrinos tell us about stars?



Nuclear Physics: Exploring the Heart of Matter, N.A.Sc. (2013)



Nuclear physics Experiments ... what do we want to measure? What information we want to obtain?

Nuclear properties: spin, parity, energy levels, density of states, masses, half-lives, decay modes, ...

Cross sections
Excitation functions
Capture rates ...

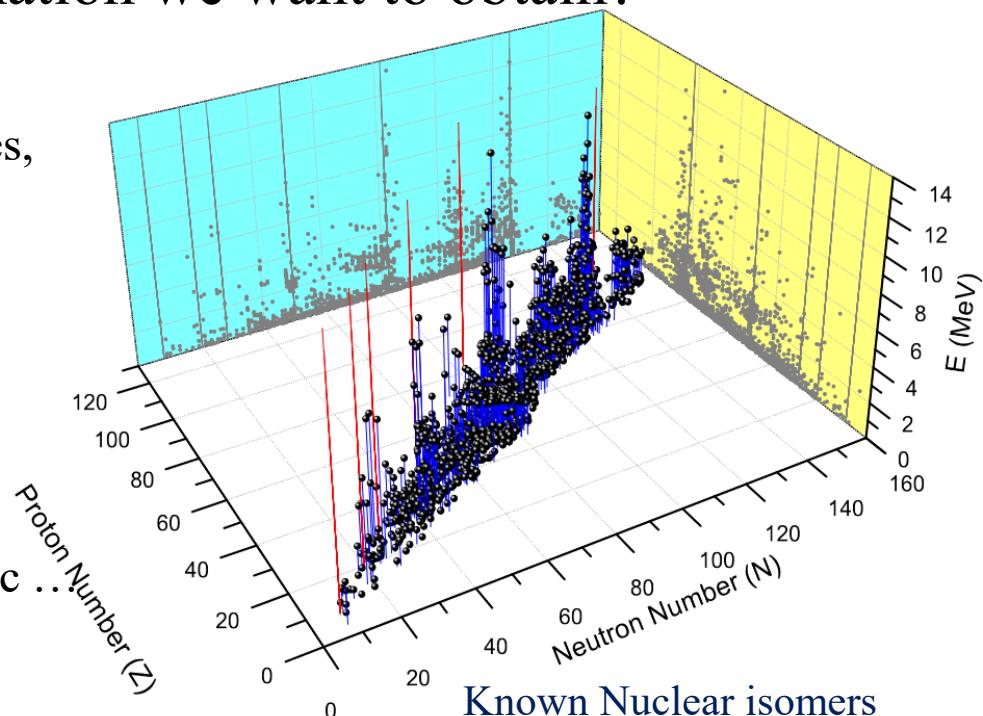
Beams: FRIB, ATLAS, ARUNA labs

Targets: radioactive, liquid, gas, cryogenic ...

Detectors:

Electronics/DAQ

...



Jain et al., Nucl. Data Sheets 128, 1 (2015)

Florida State University

Fox Accel. Lab.

Hope College

Ion Beam Analysis Lab.

Ohio University

Edwards Accel. Lab.

Texas A&M University

Cyclotron Institute

TUNL

Triangle Univ. Nuclear Lab

Union College

Ion Beam Analysis Lab.

Univ. of Mass.-Lowell

Radiation Lab.

University of Kentucky

Accel. Lab.

University of Notre Dame,

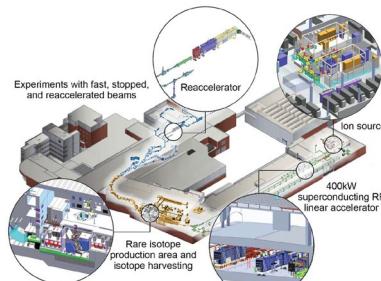
ISNAP, Inst. for Structure and
Nuclear Astrophysics

University of Washington

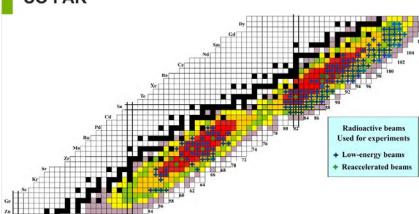
CENPA Center for
Experimental Nuclear Physics
and Astrophysics



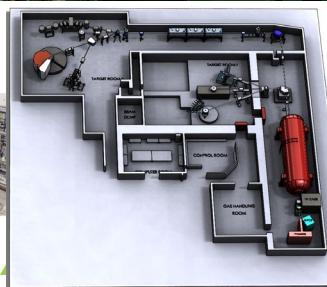
Beams → Facilities in the US



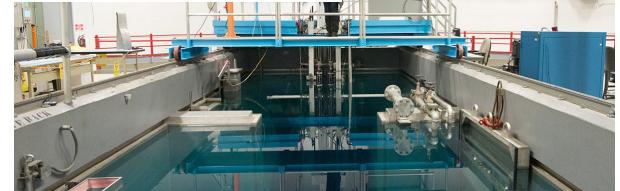
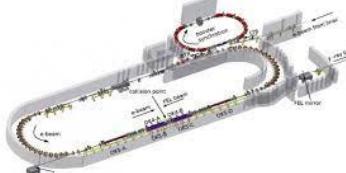
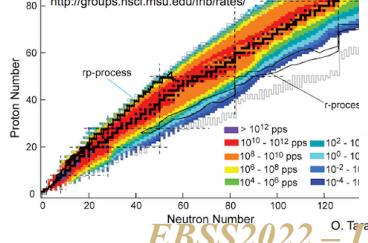
CARIBU BEAMS DELIVERED TO EXPERIMENTS SO FAR



All of these beams now available in the new low-background low-energy area (Area 1)



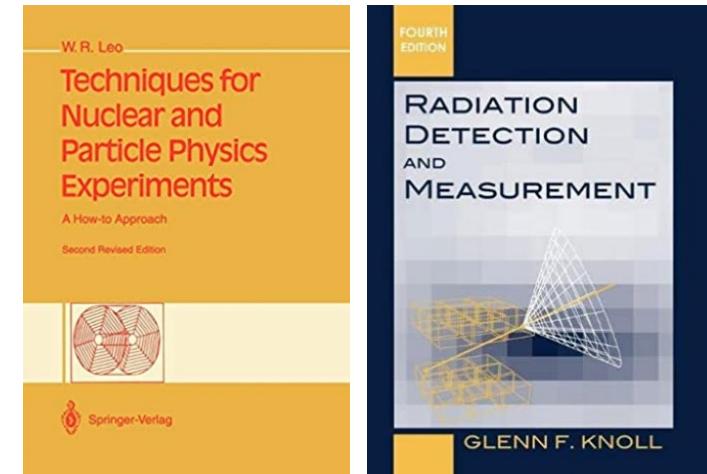
Separated fast beam rates
<http://groups.nscl.msu.edu/frib/rates/>





Detectors → Understanding Detectors: How does radiation Interact with matter?

- Heavy Charged particles: stopping power, Bethe formula, Bragg curve
- Electrons: energy loss, electron range, backscattering, positron interactions
- gamma-rays: photoelectric effect, Compton scattering, pair production
- Neutrons: ...

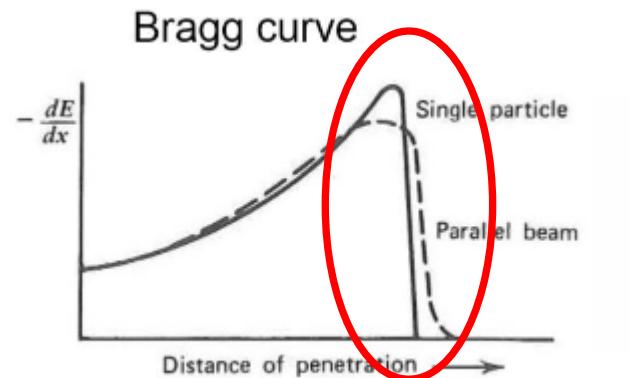




Detectors → Understanding Detectors: How does radiation Interact with matter?

- Heavy Charged particles: stopping power $-\frac{dE}{dx}$

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)}\right) - \beta^2 \right] \quad \text{Bethe-Bloch formula}$$

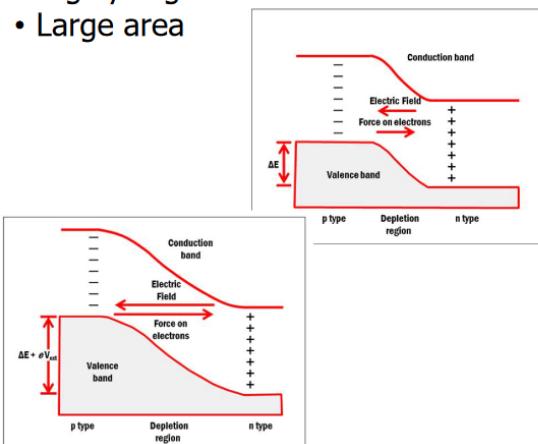




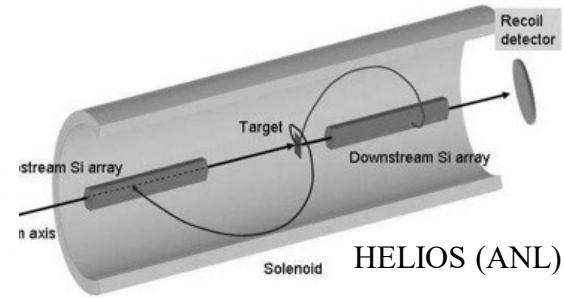
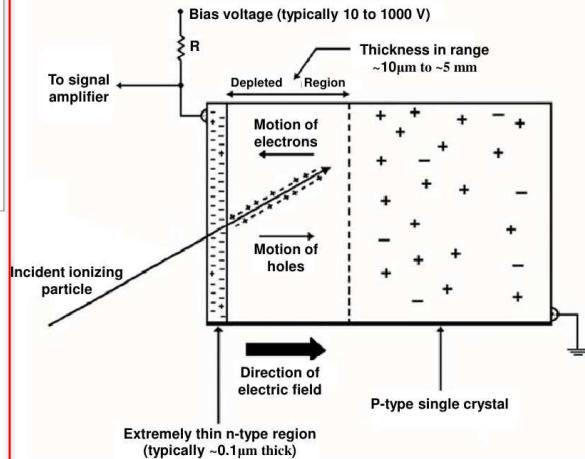
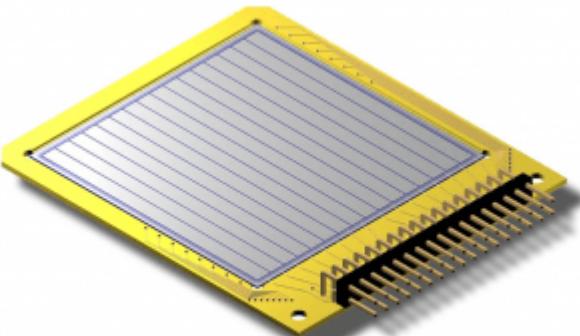
Selected types of charged-particle detectors:

Silicon arrays, ...

- Ionization energy = 3.62 eV
- Room temp (performance gains with cooling)
- Thin particle detectors (thicknesses $\sim 20\mu\text{m}$ ~ 2 mm)
- Highly segmented
- Large area



S. (Tony) Ahn (TAMU)



HELIOS (ANL)



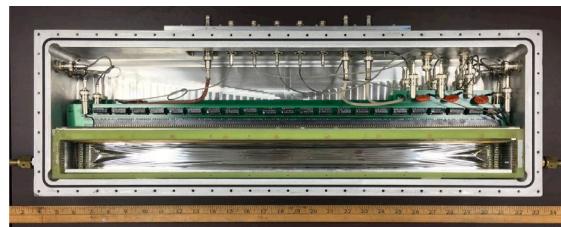
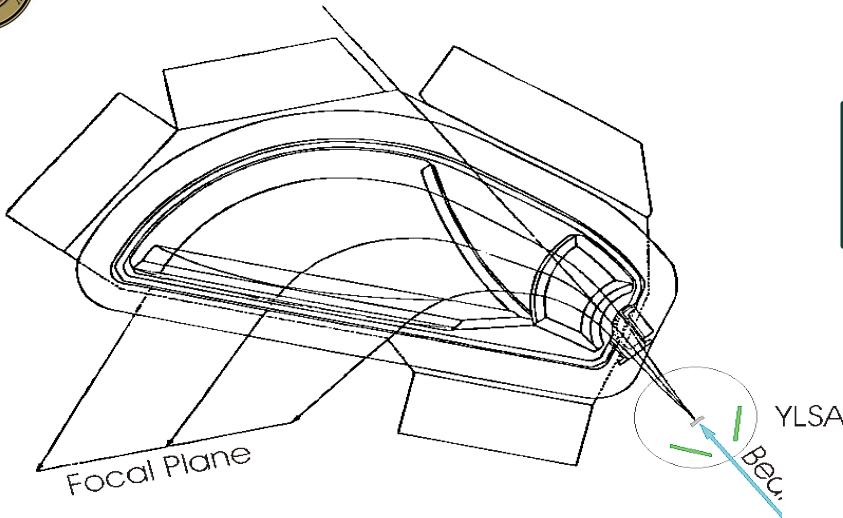
ORRUBA (ORNL)



SABRE (LSU)



Enge Split-Pole Spectrograph (SPS)

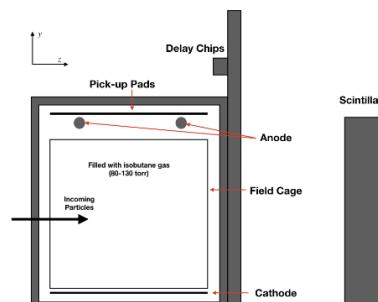


Position-sensitive
Ionization chamber

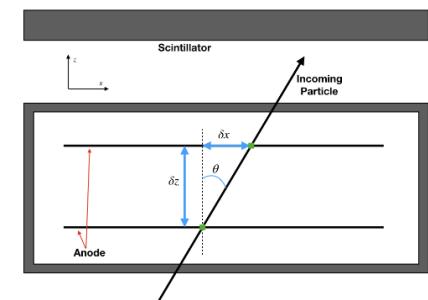
$$B\rho = \frac{\sqrt{2mE_{kin}}}{q}$$

Magnets don't lie!

12.8 msr acceptance
 $B_{\max} \sim 16.3$ kG
Radius of curvature: 51 -92 cm
Dispersion ~ 1.96
Resolving power = 1/4290



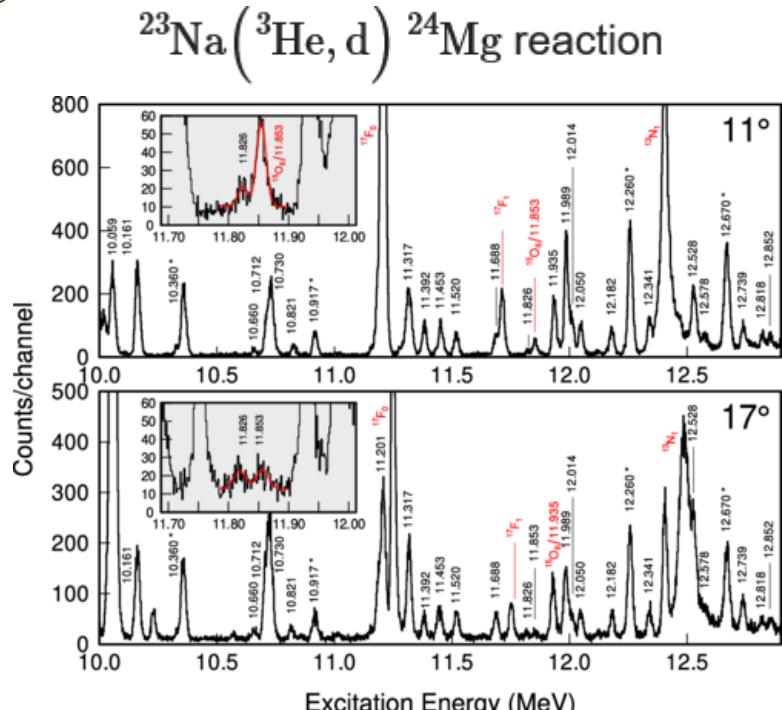
(a) Focal Plane Detector profile



(b) Focal Plane Detector top-down with tracking example

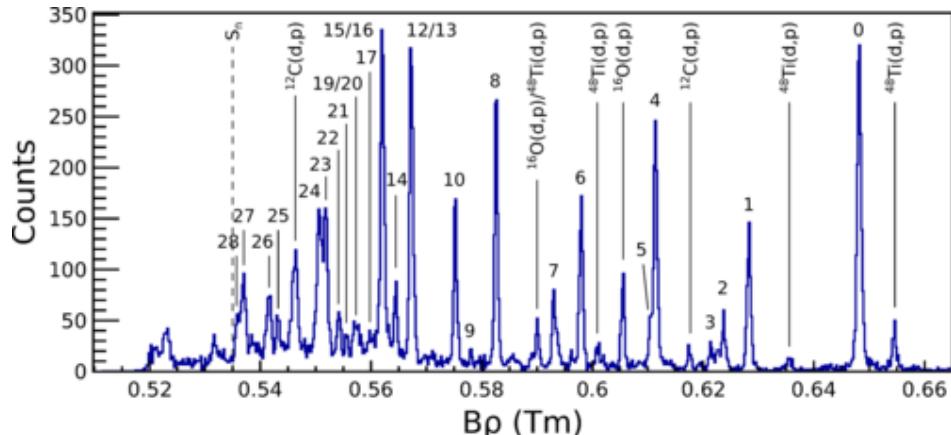
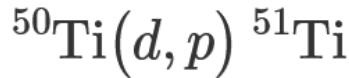


SPS @ TUNL



Marshall et al., PRC 104, L032801 (2021)

SPS @ FSU

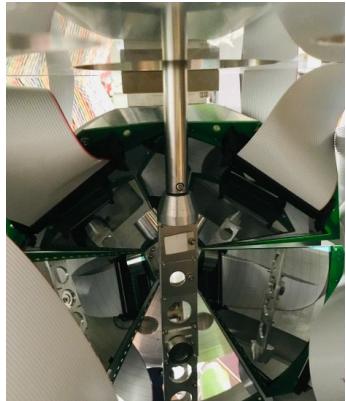


Riley et al., PRC 103, 064309 (2021)



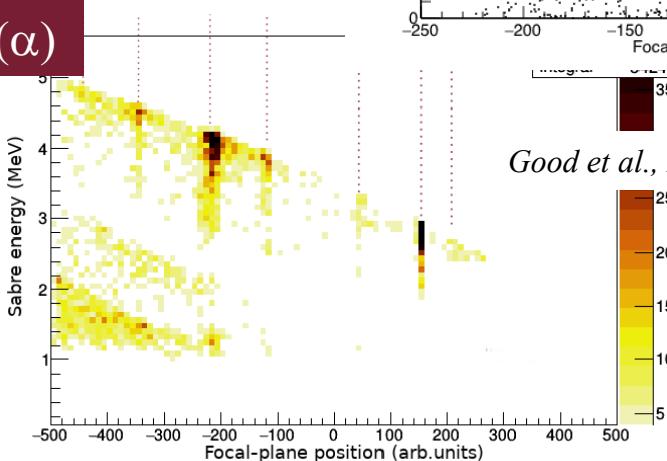
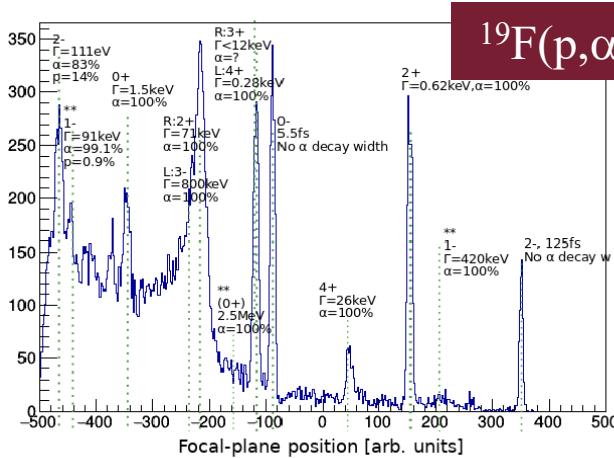
SABRE + SPS @ FSU

(C.M. Deibel, LSU group)



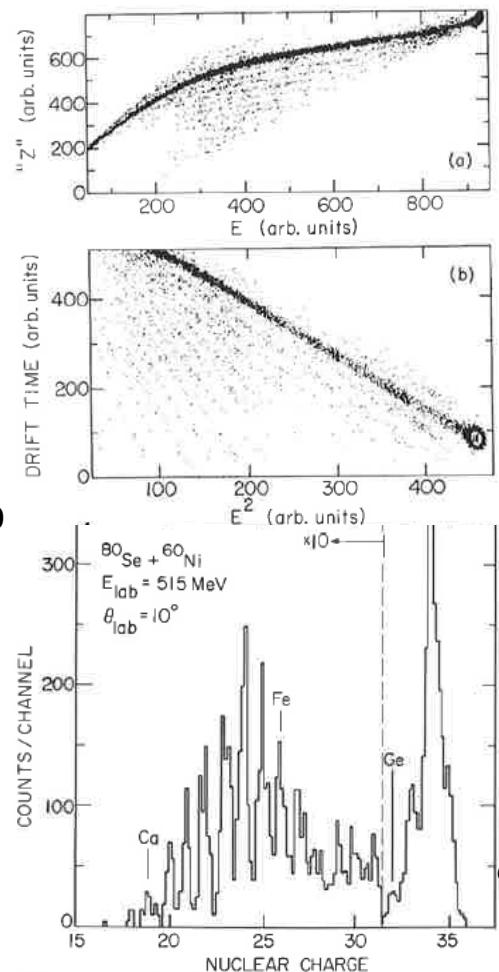
Lamp Shade Array,
large geometric efficiency ($\sim 30\%$)
Low thresholds,
digital.

Coincidences between
SABRE and SE-SPS





Range ~ $E^2/(mZ^2)$ Gases with high drift velocities



S. Almaraz-Calderon

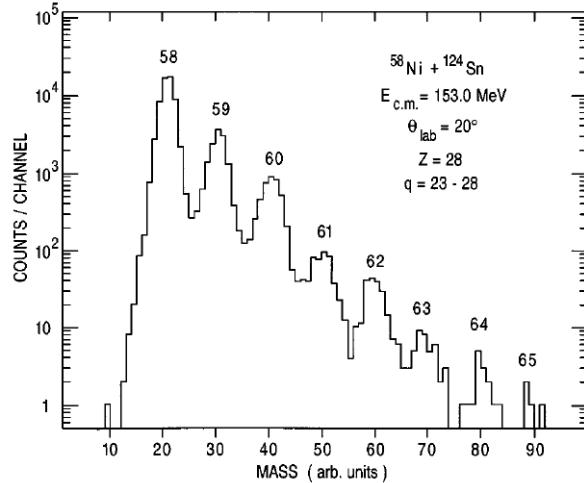
Heavy Ion Focal Plane @ SPS - ANL

Multineutron transfer in $^{58}\text{Ni} + ^{124}\text{Sn}$ collisions at sub-barrier energies

$$B\rho = \frac{\sqrt{2mE_{\text{kin}}}}{q}$$

C. L. Jiang *et al.*, PRC57, 2393(1998)

mass-identification



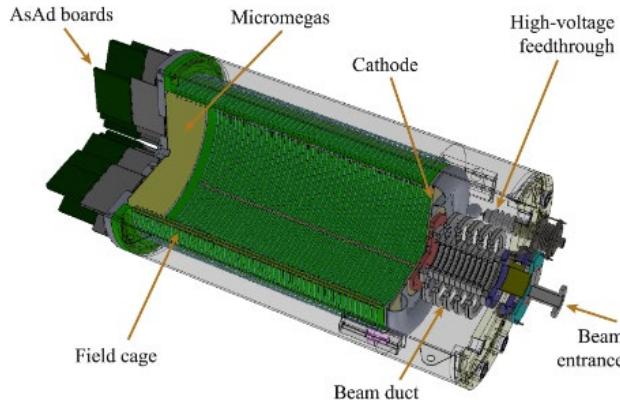
m/q (from TOF and Br)
 m/q^2 (from Br and E)

Rehm *et al.*, NIMA273, 262(1988)

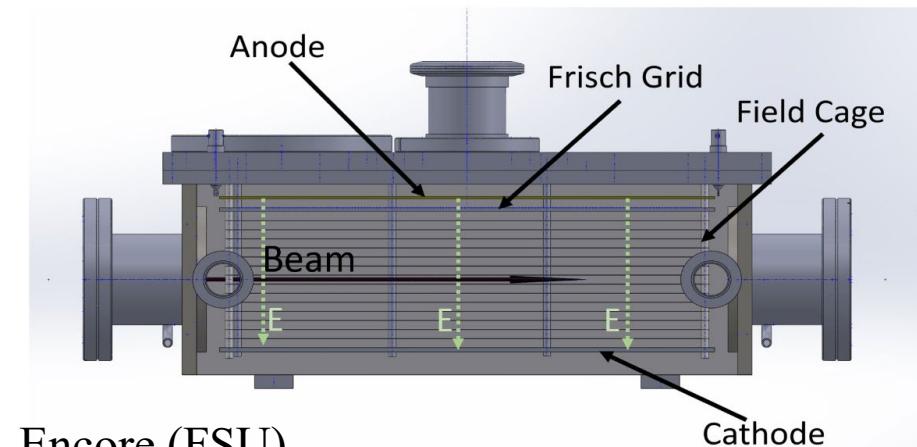


Active targets

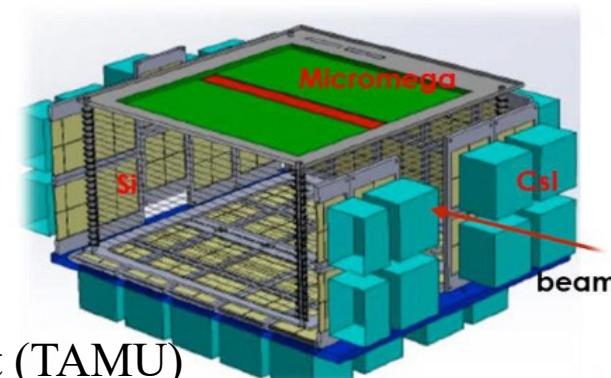
Active target detector that measures energy losses as the beams passes through the detector



AT-TPC (NSCL)



Encore (FSU)



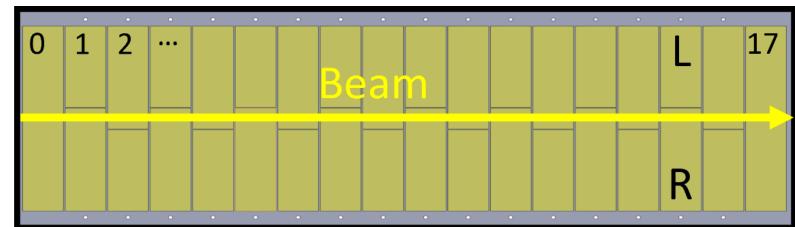
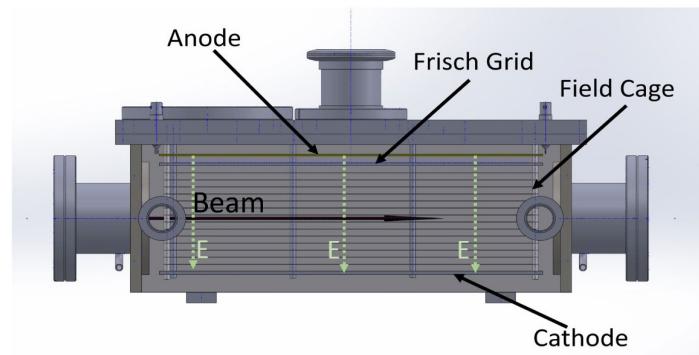
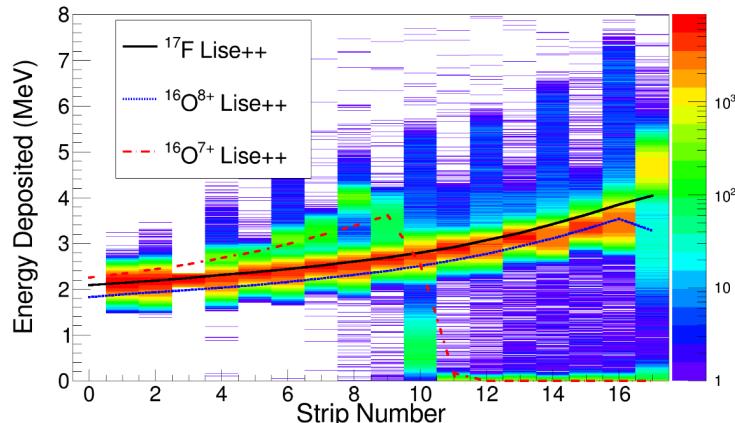
TexAt (TAMU)



Multi-Sampling Ionization Chambers (MUSIC-type)

- Self normalizing
- Efficient
- flexible
- Portable
- Rates of few kHz

$$-\frac{dE}{dx} \propto z^2$$



Various gasses, excitation function with a single energy,



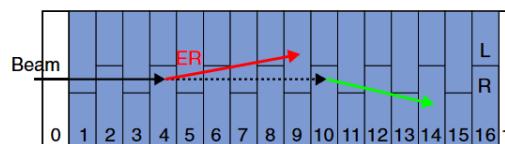
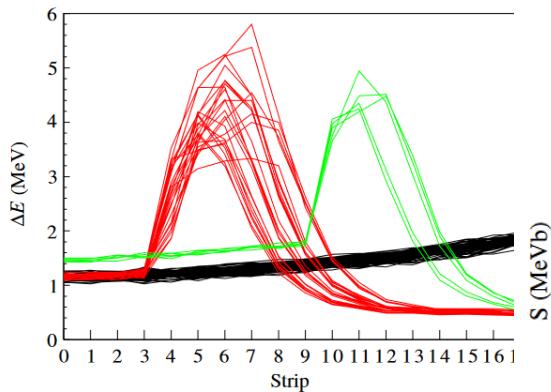
Fusion measurements

Carnelli et al., PRL 112, 192701 (2014)

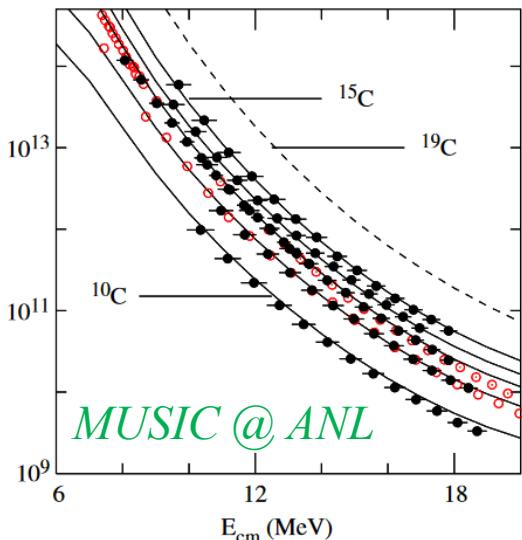
Asher et al., Eur. Phys. J. A 57, 272 (2021)

Asher et al., Phys Rev C 103, 044615 (2021)

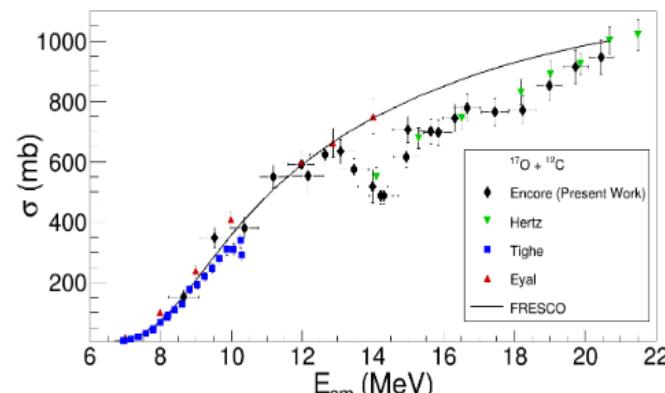
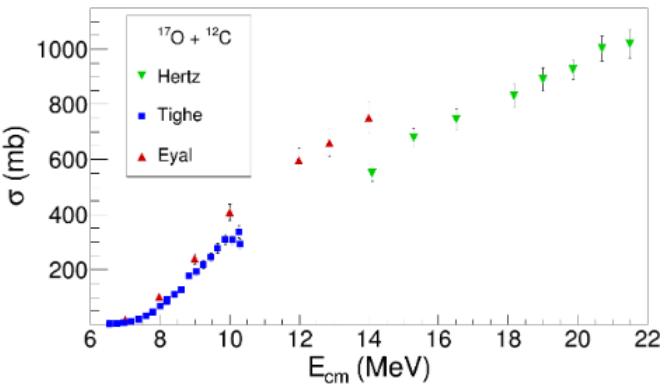
Carnelli et al., NIMA 799, 197 (2015)



Physics of X-ray Superbursts



$^{17}\text{O} + ^{12}\text{C}$: Fusion Oscillations

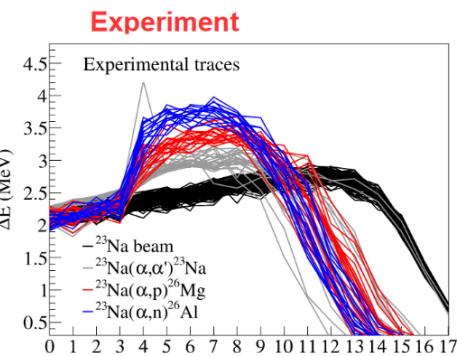
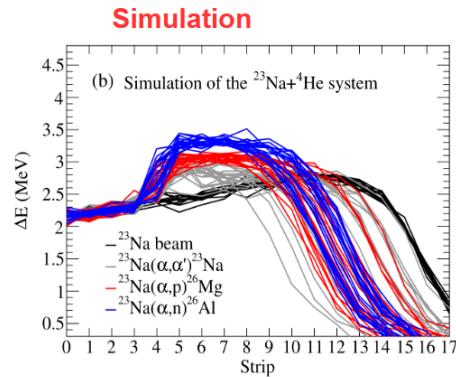


Encore @ FSU

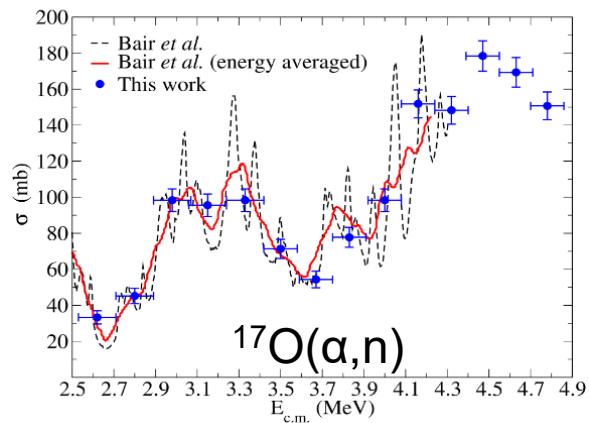


(α,p) & (α,n) reactions with MUSIC

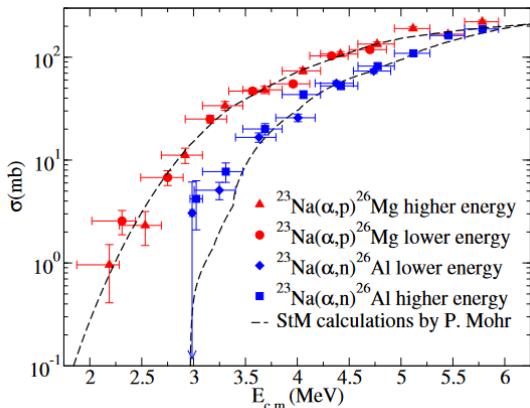
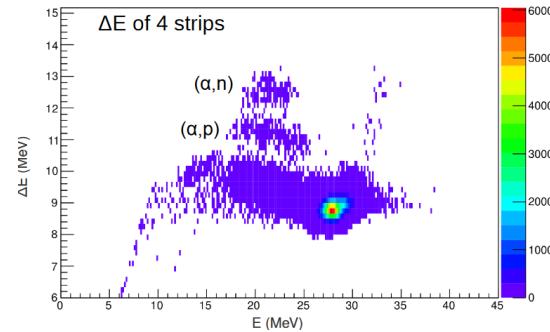
M. Avila (ANL)



Avila *et al.*, PRC.94.065804 (2016)



Avila *et al.*, NIMA, 859, 63 (2017)





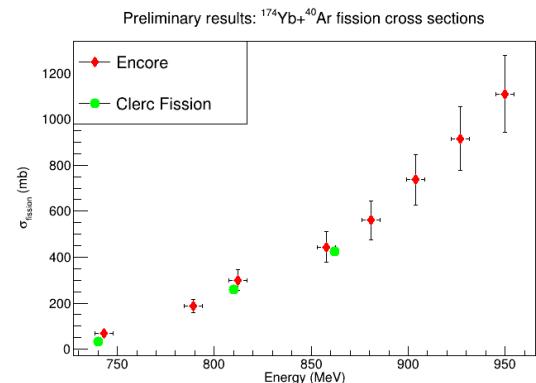
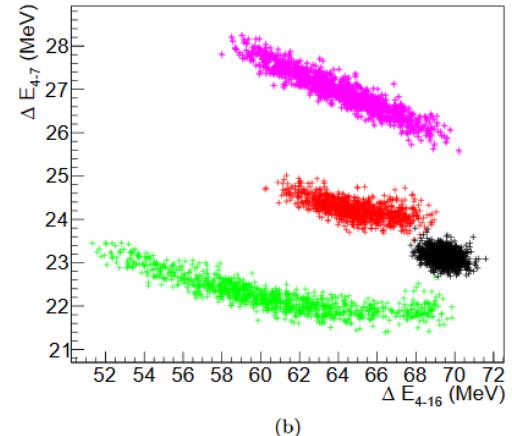
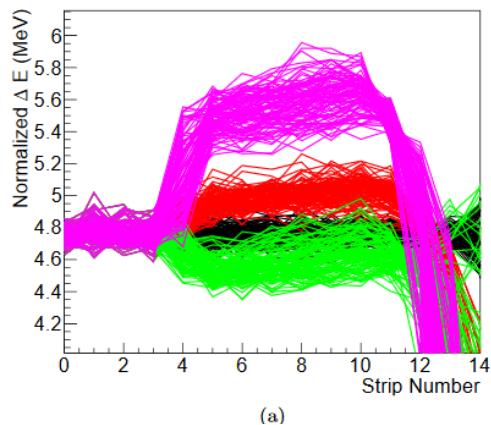
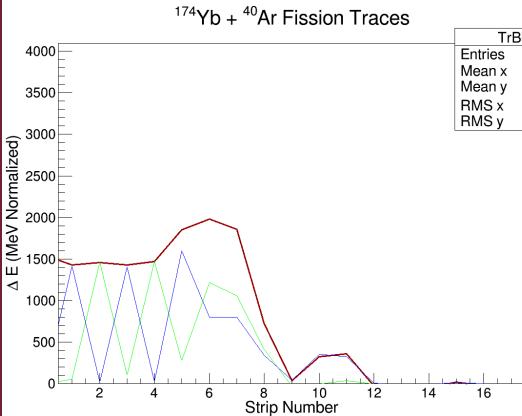
More MUSIC ...

(p, α) reactions

H. Jayatissa (ANL)

Fission reactions

E. Lopez-Saavedra (FSU)





Neutron detectors

how do you detect a particle with no charge??



VANDLE (UTK)



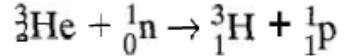
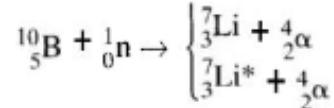
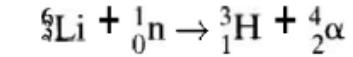
CATRiNA (FSU)



CZIYC (UMass-L)



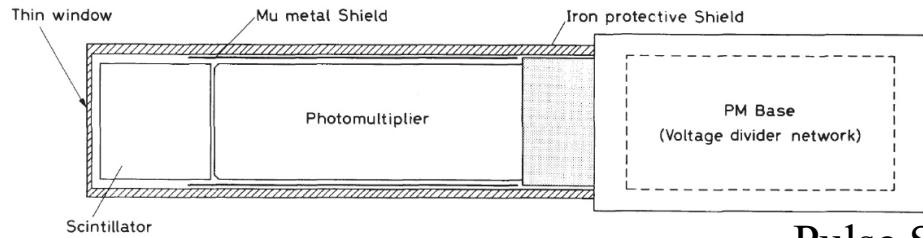
MONA-LISA (MSU)



HabaNERO (OU-ND)

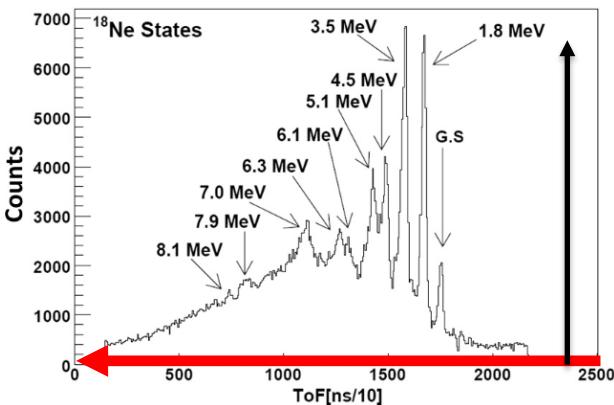


Liquid organic scintillators



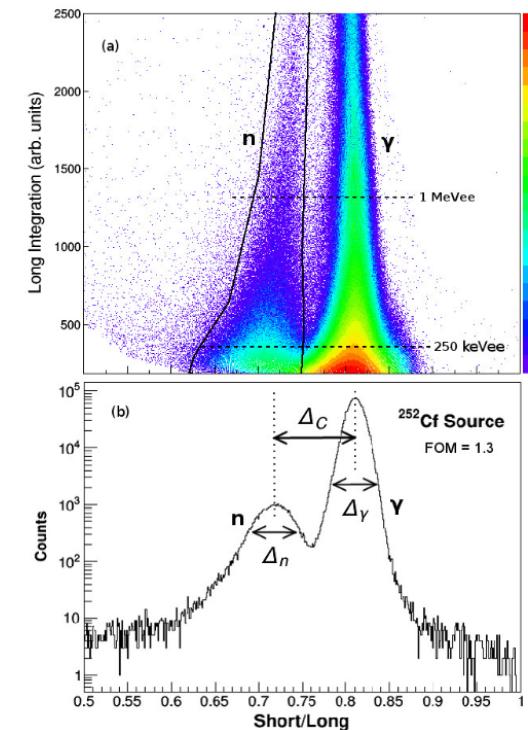
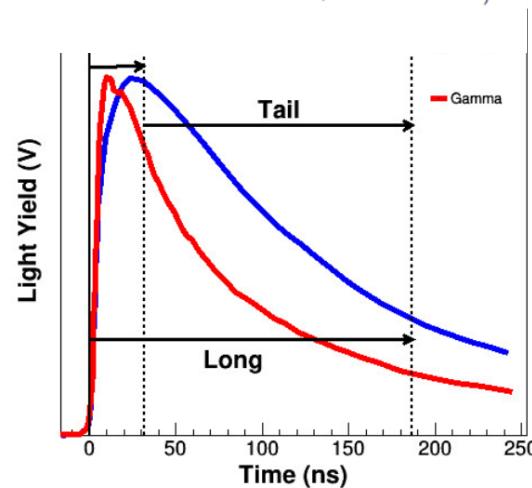
Pulse Shape Disc.

Time-of-flight: n/ γ difference



PRC 86, 029901 (2012).

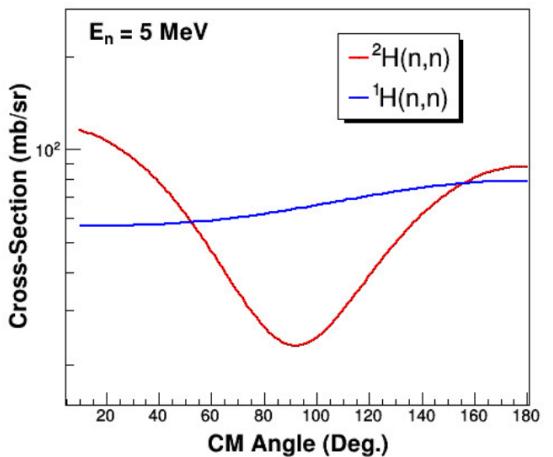
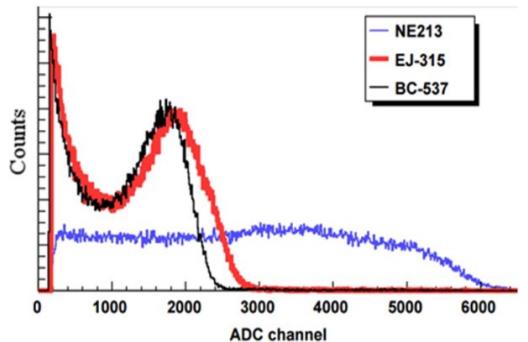
$$N = Ae^{-t/\tau_f} + Be^{-t/\tau_s},$$



Perello et al., NIMA 930, 196 (2019)

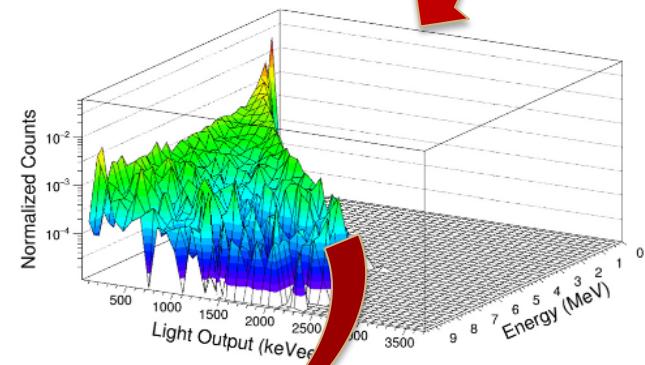
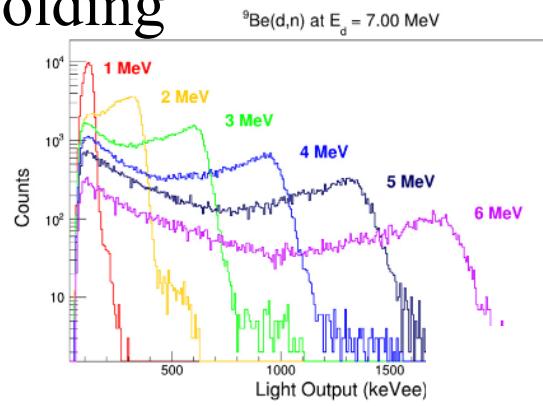
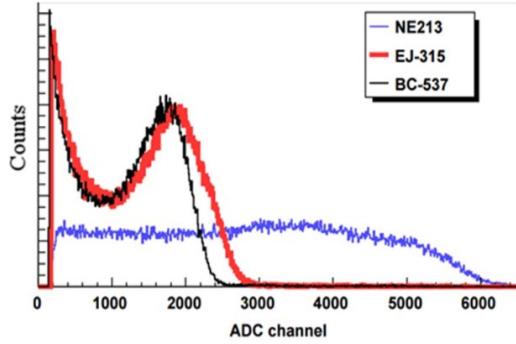


Deuterated neutron detectors (C_6D_6)

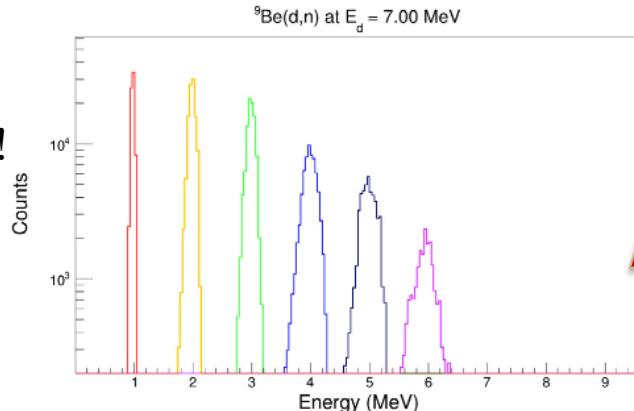




Neutron Spectrum unfolding



Neutron energies
independent of ToF!

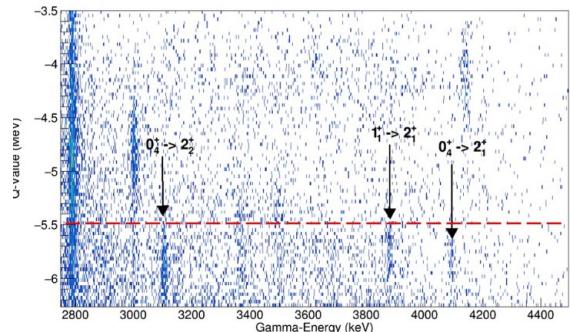
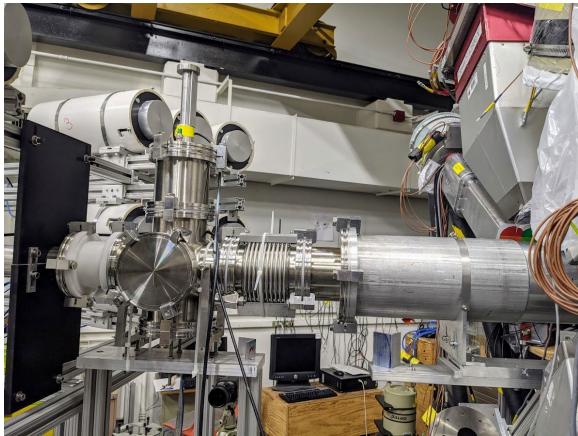
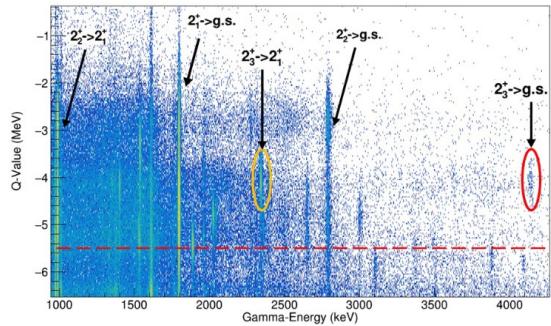
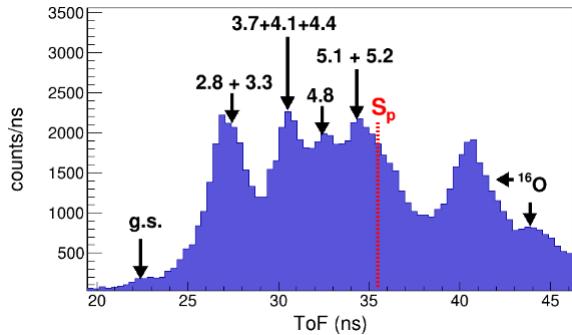


Morelock et al., NIMA 1034, 166759 (2022)



Neutron/Gamma coincidence measurements

$^{24}\text{Mg}(^3\text{He},\text{n}/\gamma)^{26}\text{Si}$ reaction



Perello et al., PRC 105, 035805 (2022)



We didn't talk about targets, electronics, DAQ, more detectors and many new and exciting developments in experimental techniques!

Be curious, excited, persistent! Keep up the good work!

Thanks!