Aruna-Laboratories: FSU
John D. Fox Accelerator Laboratory

- Founded in 1959
- Today:
  9 MV Tandem accelerator
  8 MV SC Linac booster
  RESOLUT in-flight RIB facility
- Founding member of ARUNA,
  the Association for Research with
  University Nuclear Accelerators
- Programs in
  Gamma-spectroscopy
  RIB-Resolut: With LSU: ANASEN,
  RESONEUT (d,n) neutron detection
  with IU: Fusion measurements

ARUNA- White paper at http://aruna.physics.fsu.edu

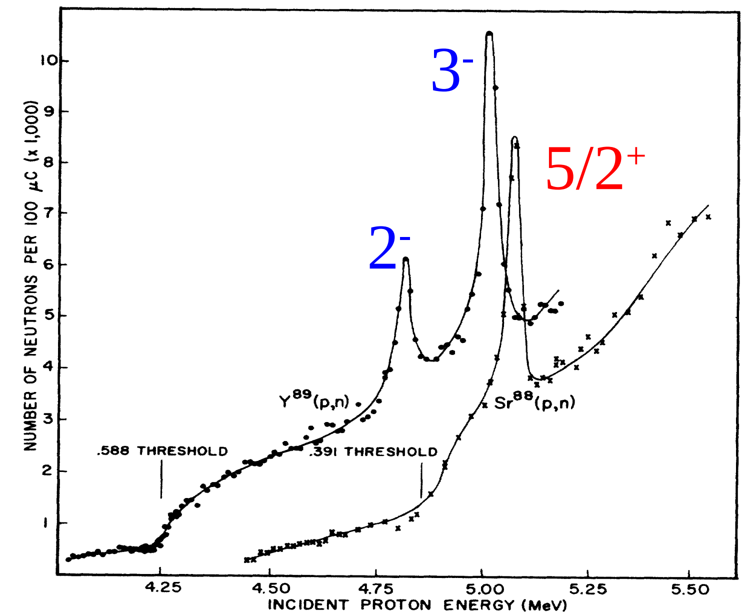
Exotic Beam Summer School 2015: was at FSU

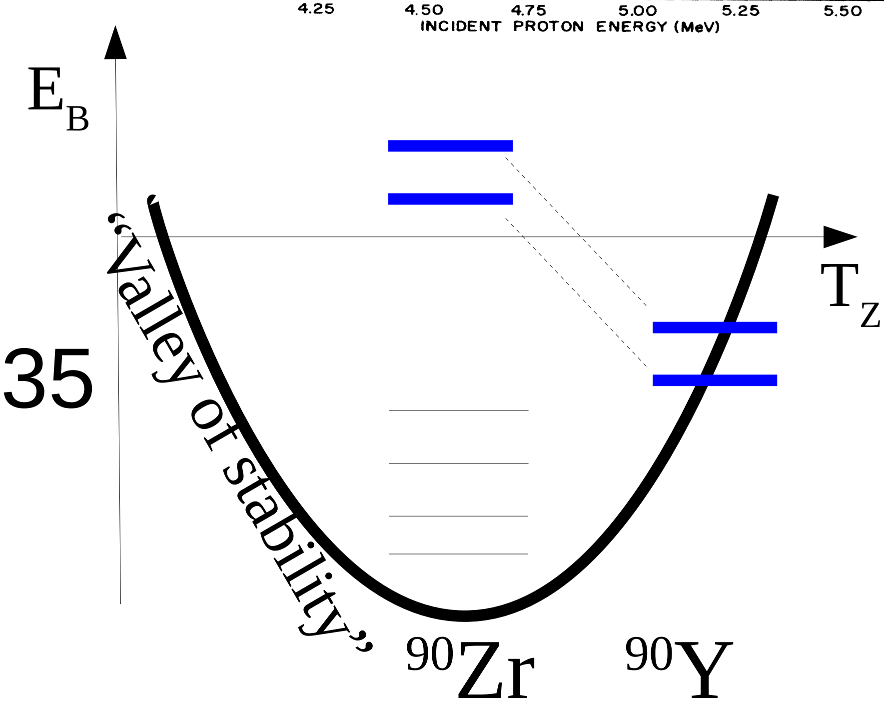
FSU Timeline: The early years

- 1959 6MV EN tandem accelerator
  The 3rd Tandem van-de-Graaff
  in the world.
  1964 … Precision is king:
  Isobaric Analog States
- 1970
  9MV FN Tandem vdG accelerator

1964: Isobaric Analog States
J.D. Fox, C.F.Moore, D.Robson, PRL 12,198

- Found sharp! unbound states
  2^-, 3^- in ^{90}Zr
  and $5/2^+$ in ^{89}Y
- Analogs to 2^- (g.s.) , 3^- in ^{90}Y
  and $5/2^+$ (g.s.) in ^{89}Sr
- States are 10 keV wide,
  Tandem delivers
  ~5 MeV +- 3 keV beam
- Theory: 1965
  D. Robson Phys.Rev. 137, 535
- Conference on
  “Isobaric Spin” in TLH, 1966





FSU People in Low-energy Nuclear Physics and Nuclear Astrophysics

- Faculty Experiment
  S. Almaraz-Calderon
  P. Cottle
  (K. Kemper)
  M. A. Riley
  S.L. Tabor
  I. Wiedenhöver
- Faculty Theory
  J. Piekarewicz
  A. Volya



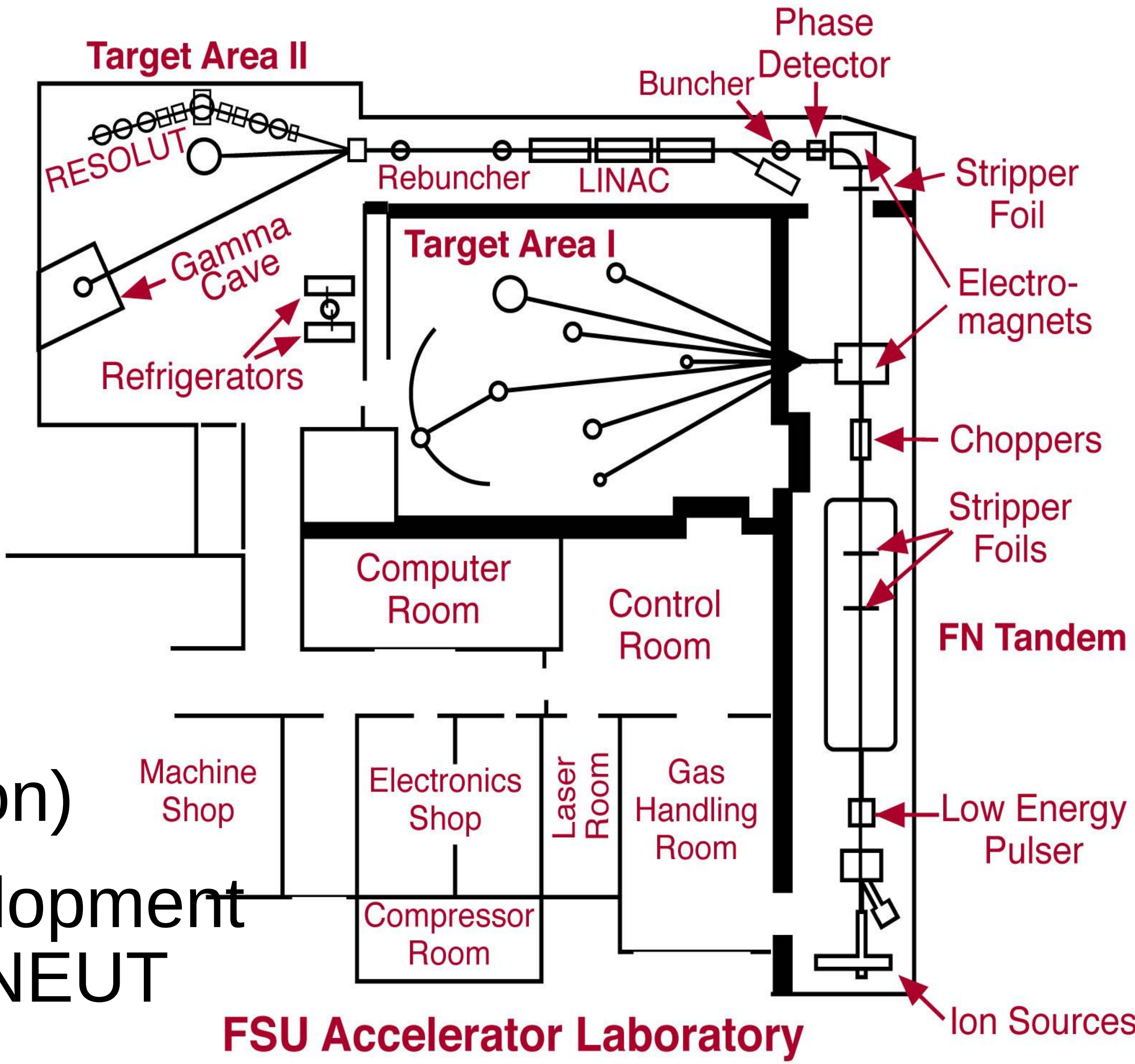





The John D. Fox Laboratory

Tandem-Linac programs in

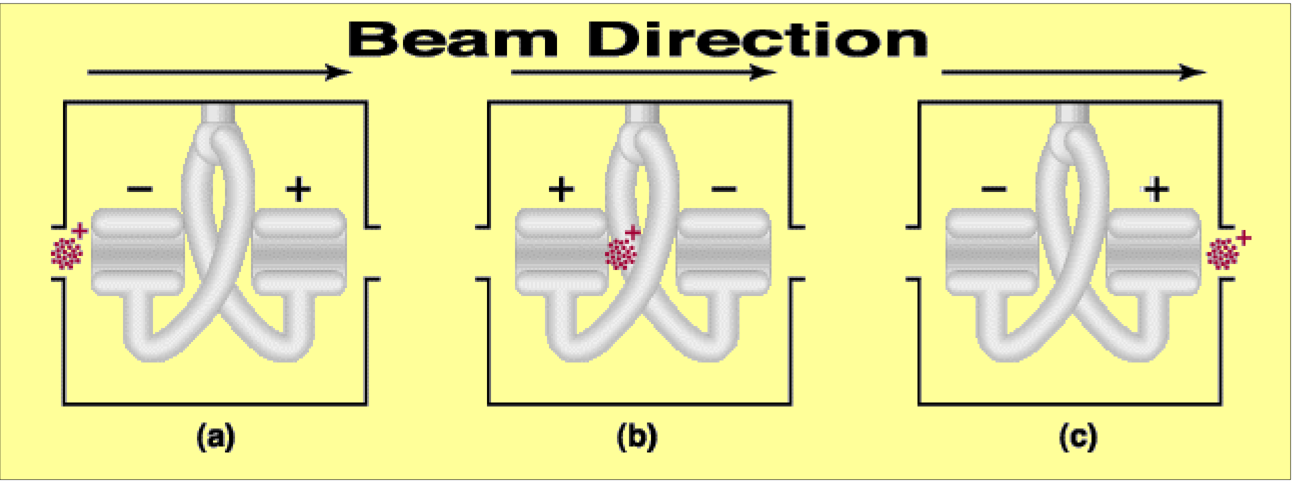
- Gamma-Ray spectroscopy (S.L. Tabor, M.A. Riley P. Cottle)
- In-flight RIB (I. W., Sergio Almaraz-Calderon)
- Instrument-development ANASEN, ResoNEUT

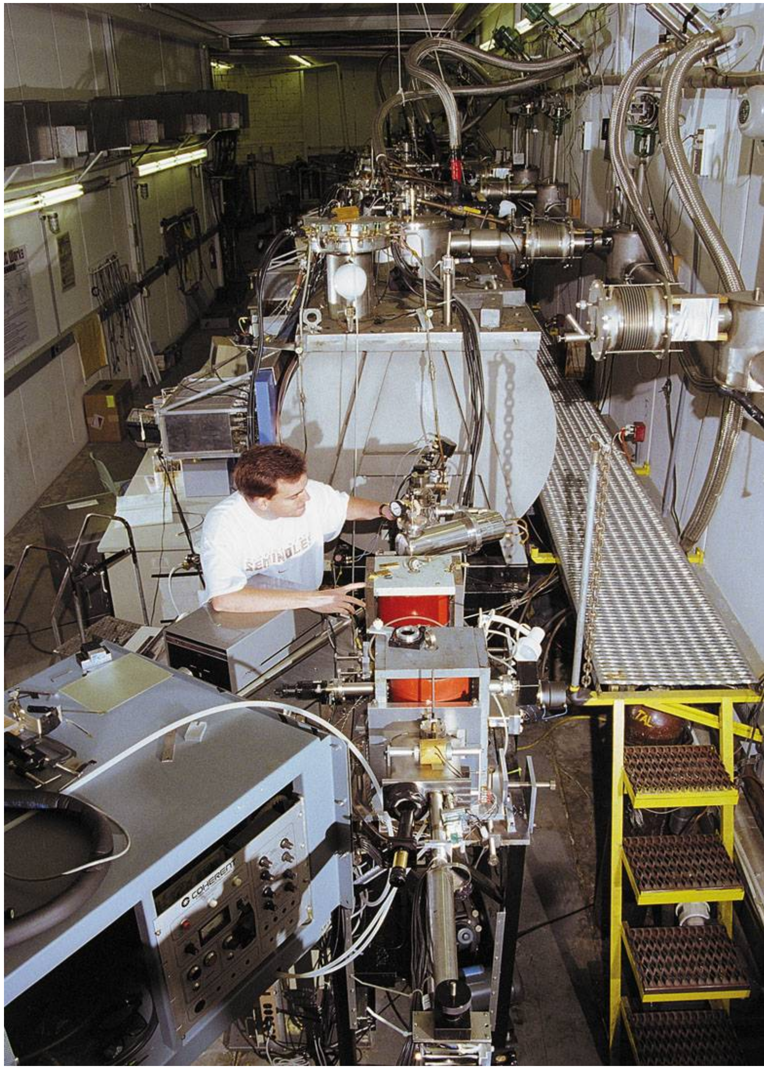


9MV Tandem Accelerator (1970)

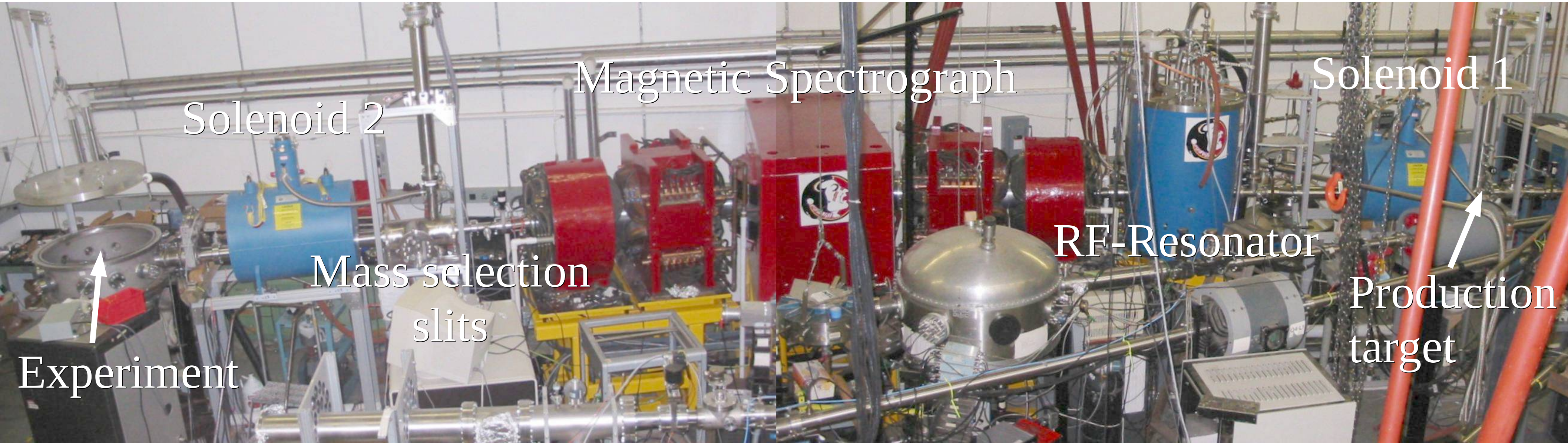
Superconducting Linear Accelerator

- Superconducting Linear Accelerator: Commissioned in 1986
- 14 Superconducting Resonators of Atlas v/c~0.1 split-ring type
- Beams up to S, 4-8 MeV/u



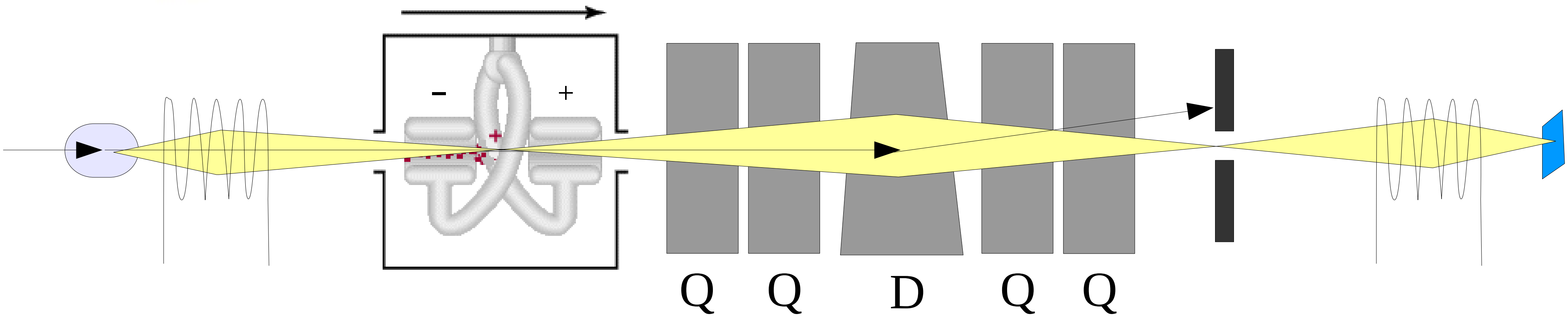


RESOLUT: A radioactive beam facility at FSU



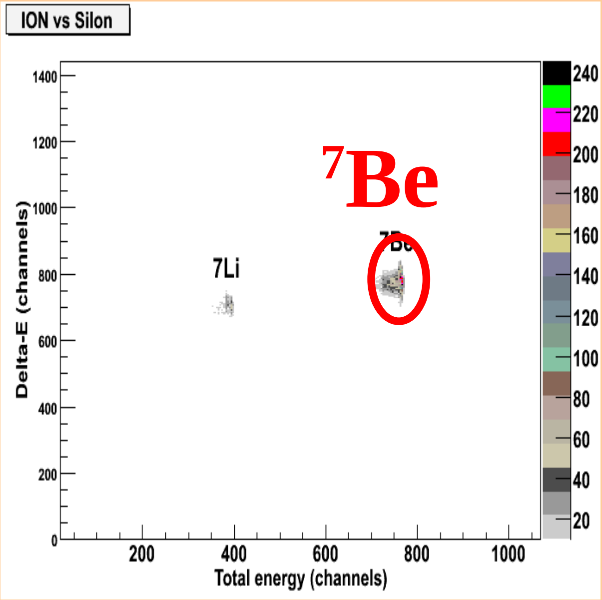
- In-flight production of radioactive beams in inverse kinematics
- Combination of superconducting RF-resonator with high acceptance magnetic spectrograph to create mass spectrometer
- Beam energy resolution ~0.5%

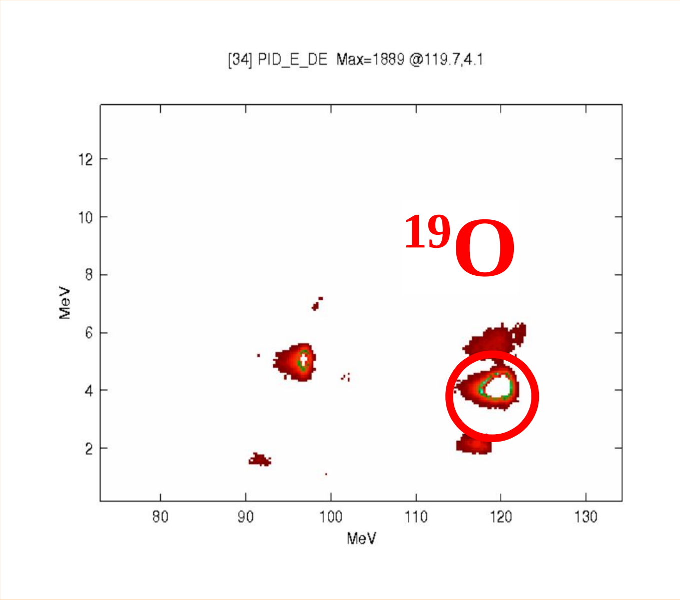
RESOLUT: In-flight production of radioactive beams

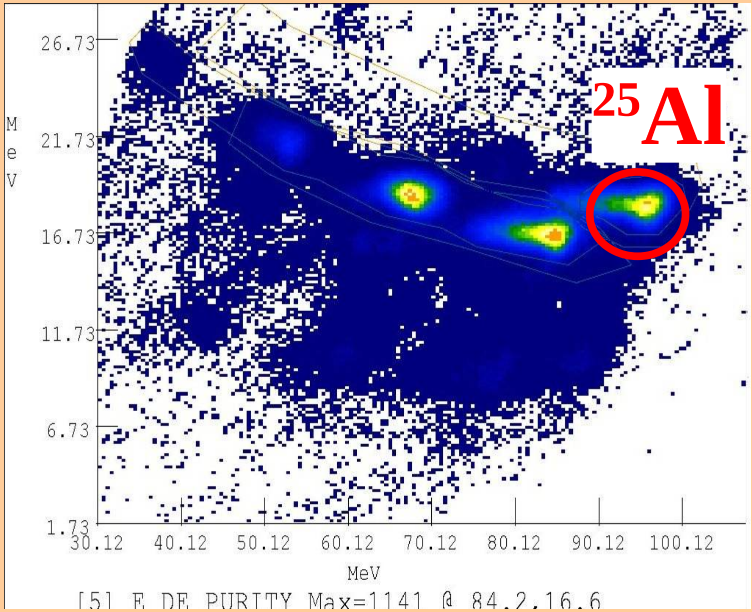


- Production target: gas cell (H_2, D_2, He^3, He^4)
- Production reaction: inverse kinematics
- E.g. $(^{24}Mg(d,n)^{25}Al)^{-1}$, ^{24}Mg at ~6 MeV/u
- ^{25}Al: angles +/- 3º, energies +/- 5 %
- RESOLUT acceptance: θ+/- 3º, energy +/- 2%

RESOLUT operation: RIB used in Experiments





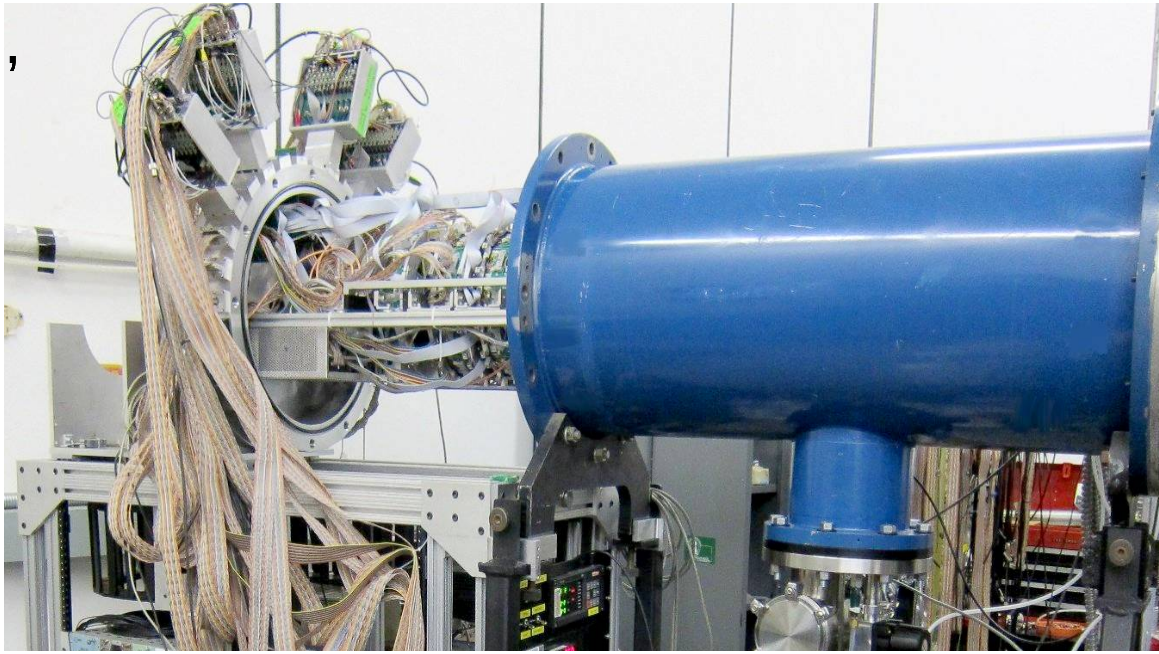


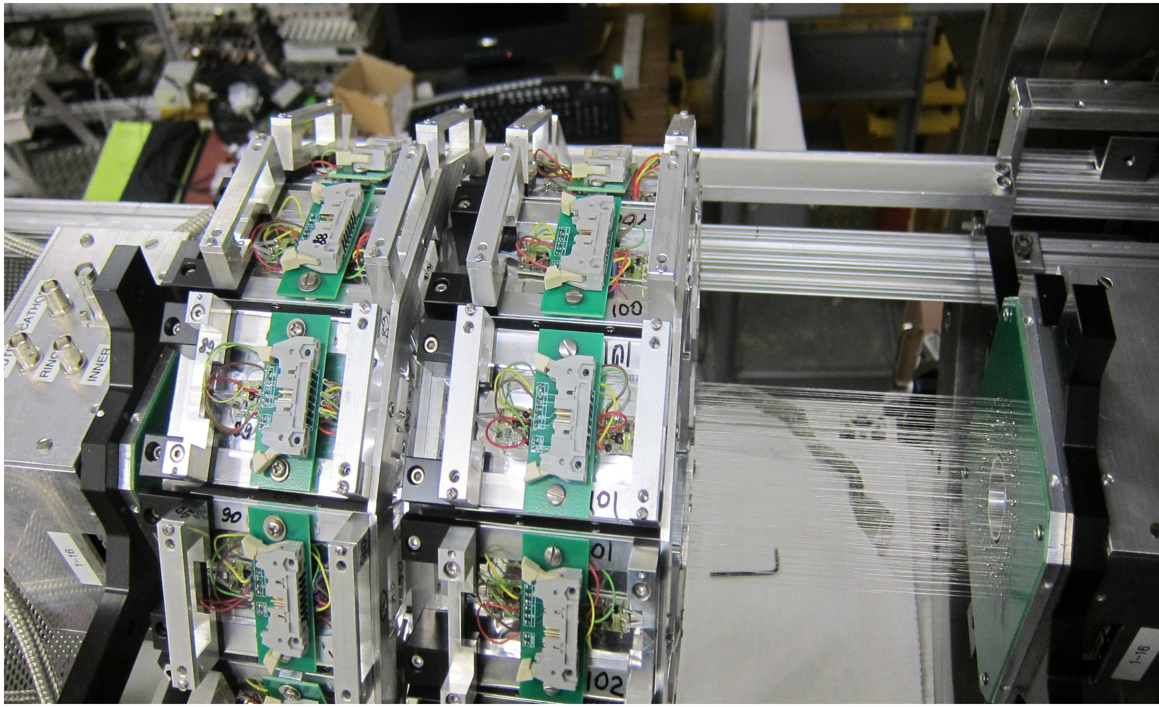
^{7}Li(d,^{3}He) ^{6}He 18-29 MeV, ~1· 10^{4} pps (40% pure)
^{7}Li(p,n) ^{7}Be 25-35 MeV, ~2· 10^{5} pps (80% pure)
^{7}Li(d,p)^{8}Li 20-30 MeV ~5 · 10^{4} pps (90% pure)
^{7}Li(^{3}He,n)^{8}B 30-45 MeV ~1 · 10^{4} pps (10% pure)
^{7}Li(^{3}He,n)^{10}N 27-55 MeV ~1 · 10^{3} pps (10% pure)
^{18}O(d,n)^{17}F 80 MeV ~2 · 10^{5} pps (80% pure)
^{18}O(d,p)^{19}O 95 MeV ~5 · 10^{4} pps (90% pure)
^{18}O(^{3}He,n)^{18}Ne 70 MeV ~2· 10^{4} pps (25% pure)
^{24}Mg(d,n)^{25}Al, 98 MeV, ~2· 10^{4} pps (35% pure)

- Beams are purified off-line through tof-tracking and gating

Instrument Development: ANASEN

- Active-target detector for (p,p), (α,p) and (d,p) reactions with exotic beams
- NSF-MRI grant
  J. Blackmon (LSU),
  G. Rogachev,
  I. Wiedenhöver (FSU)
- To be used
  at FSU's RESOLUT facility
  and MSU's ReAX facility
- Developed and commissioned at FSU
- Radioactive beam experiments (FSU)
  He-6(α,α') B-8(p,p')
  O-19(d,p) , C-10(p,p')
  Ne-18(α,p)
- ReA-3 K-37(p,p)





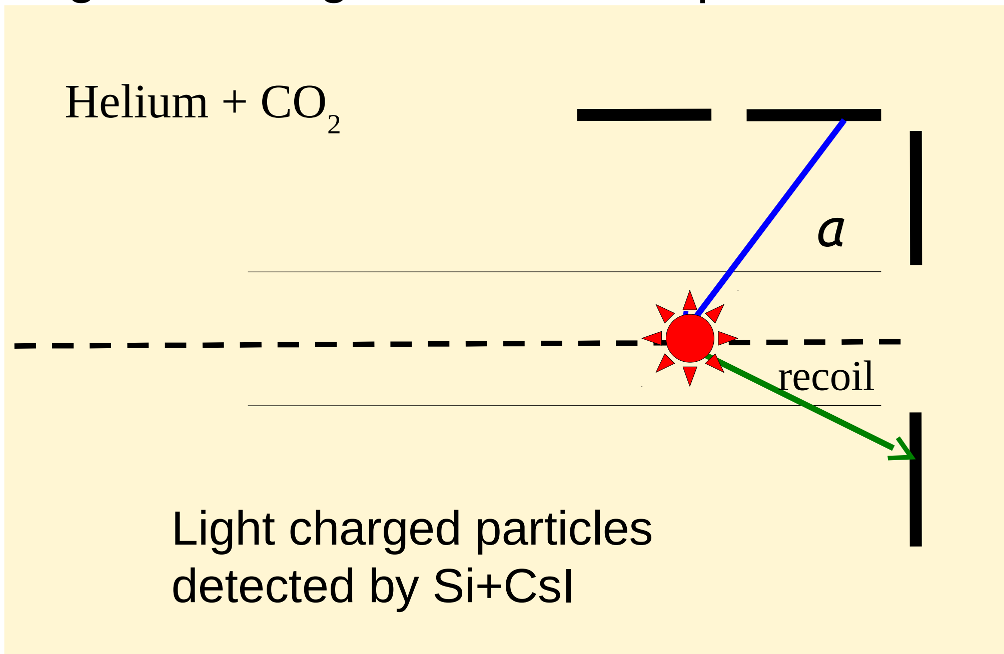
ANASEN: ^{6}He+α scattering
FSU Grad.Student A. Kuchera

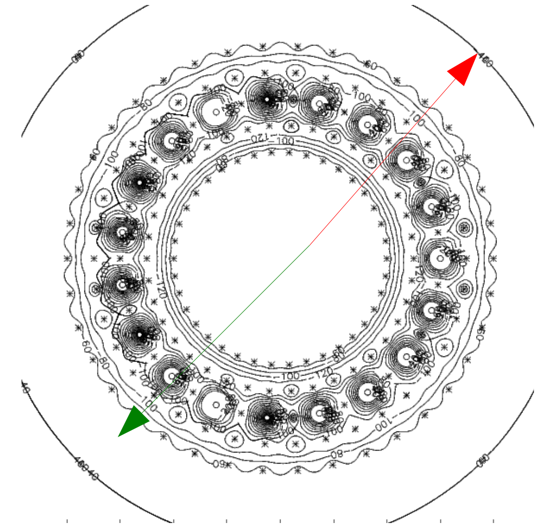
With TAMU & INFN-Canania

^{6}He beam from RESOLUT

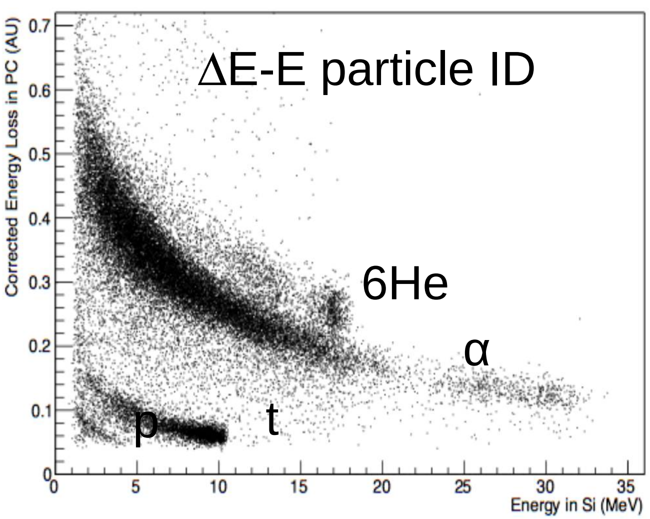
7 bombarding ^{6}He energies used to map between Ex=9.1-17 MeV in ^{10}Be

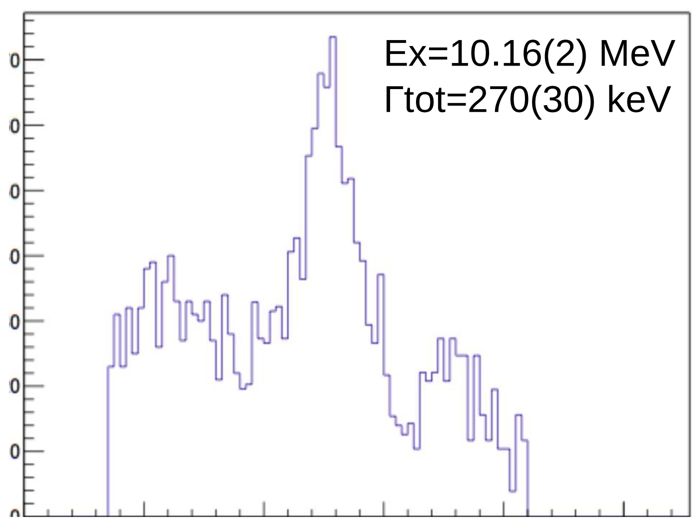
^{6}He (enters through Window)

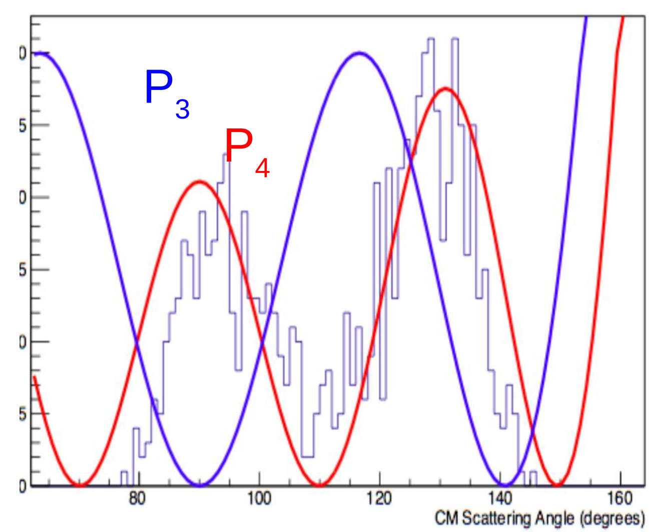




Angular distribution => **4^{+}**



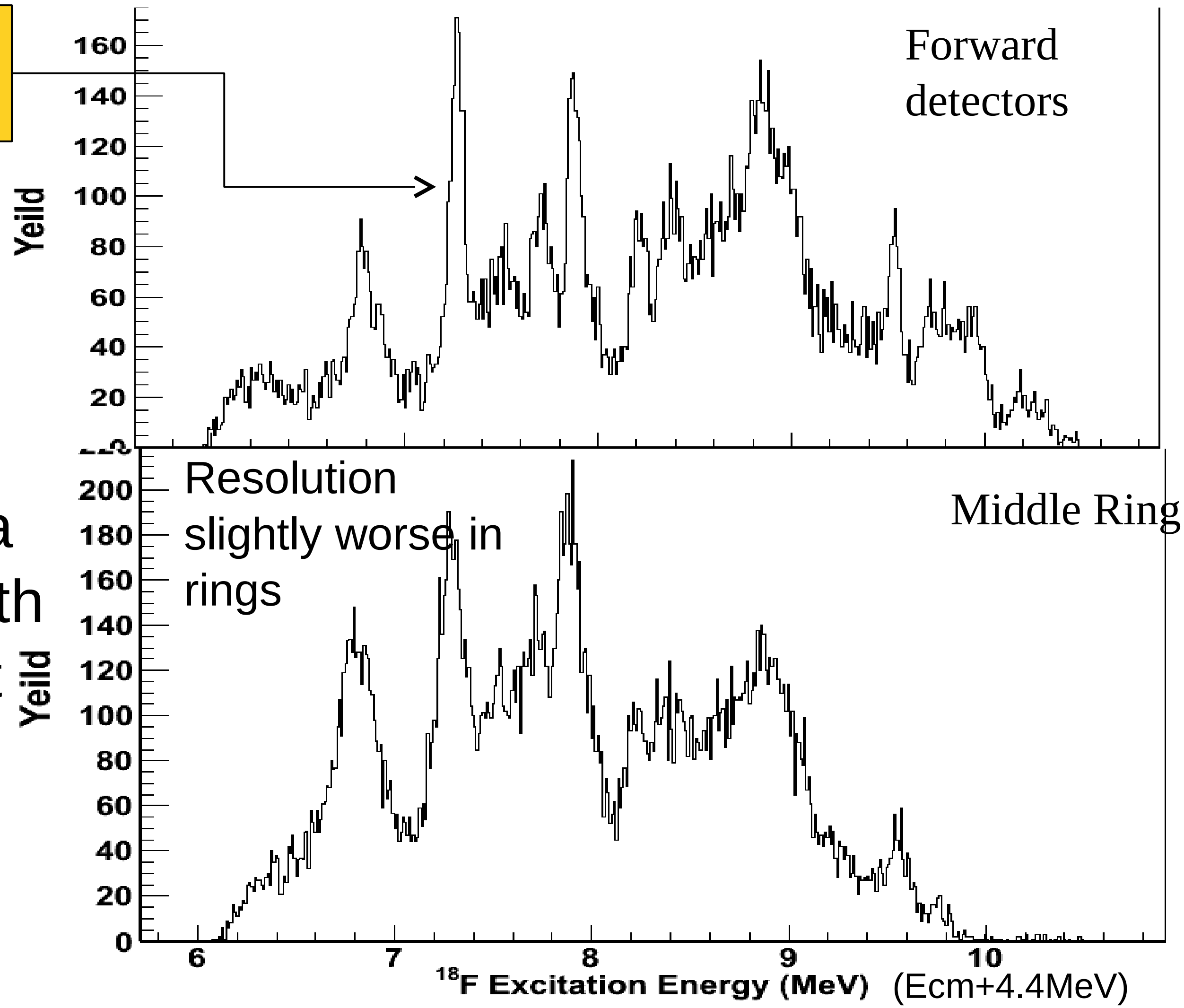




^{18}F excitation function measured with ANASEN

6 hr of data
<10^6 ions/s

ΔEcm(FWHM) as small as 70 keV



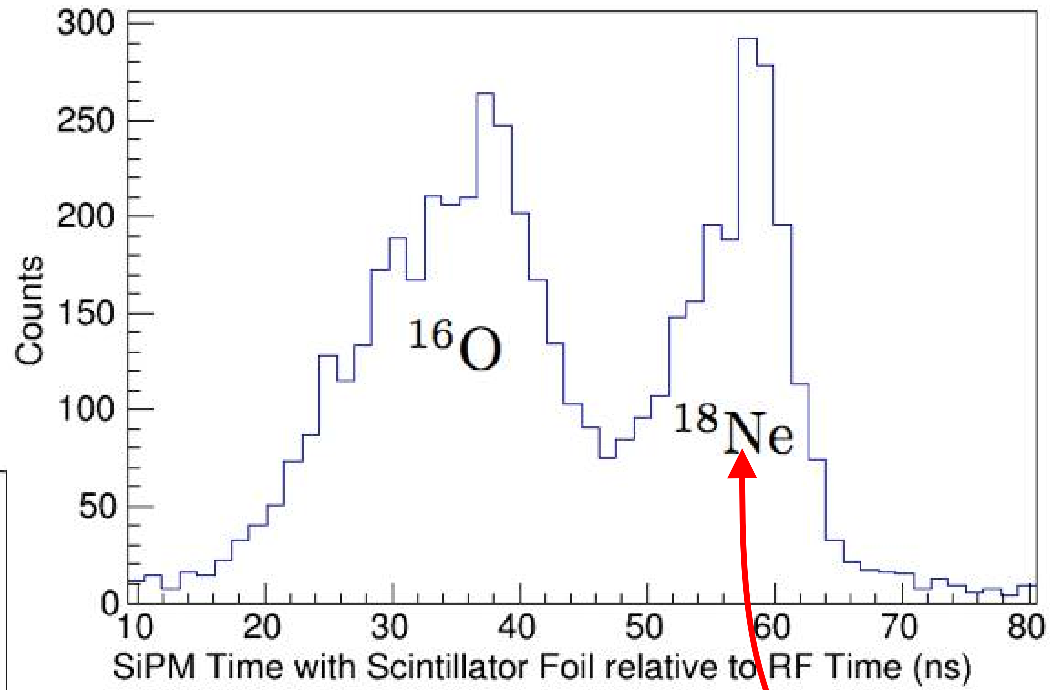
- Next: Analyzing $^{18}Ne(\alpha,p)^{21}Na$ Measured with RESOLUT at FSU

J.C. Blackmon

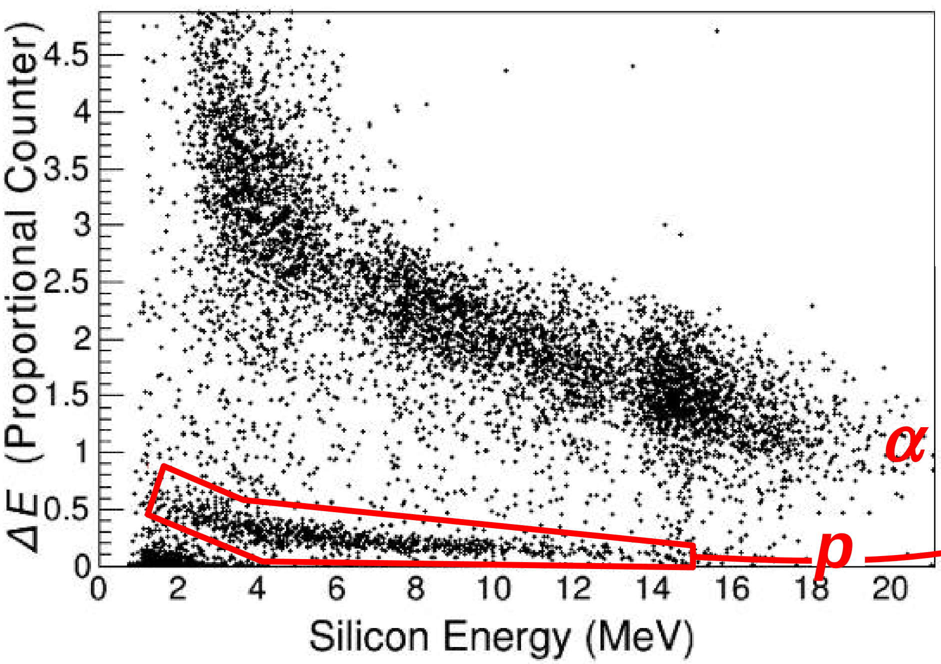
$^{18}Ne+\alpha \rightarrow ^{21}Na+p$ with ANASEN & RESOLUT

- 56 MeV ^{18}Ne
  - ~ 10^4 ^{18}Ne/s
  - **6%** purity (94% ^{16}O)
  - ~ 5 day run
- Scintillator-SiPM for TOF
  - Relatively clean ID
  - Increases beam emittance

Incident ion particle ID via Scint-RF TOF



Light ion particle ID via *ΔE-E*

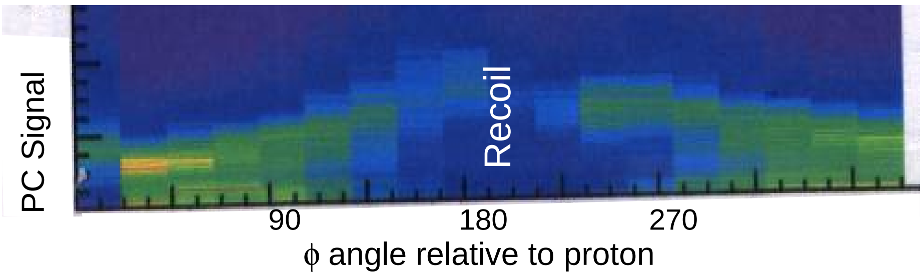


Reconstruct excitation function . . .

Resolution Issues and Improvements

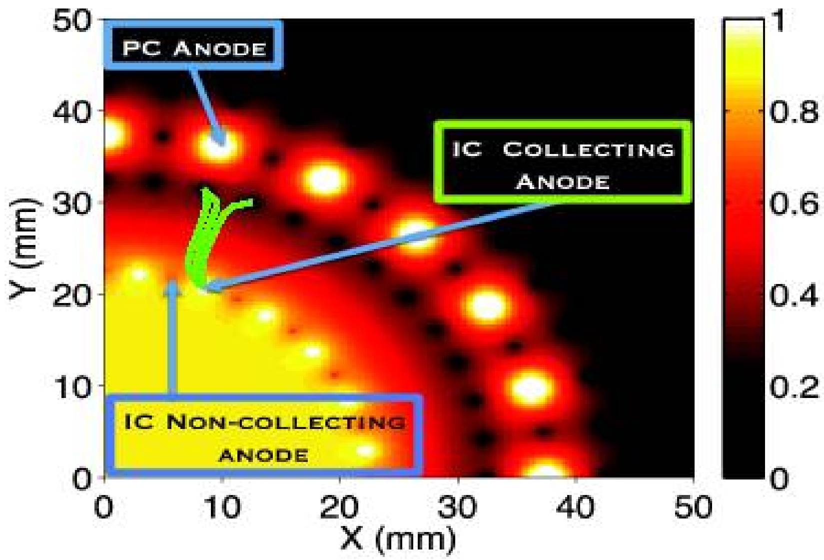
Issues:

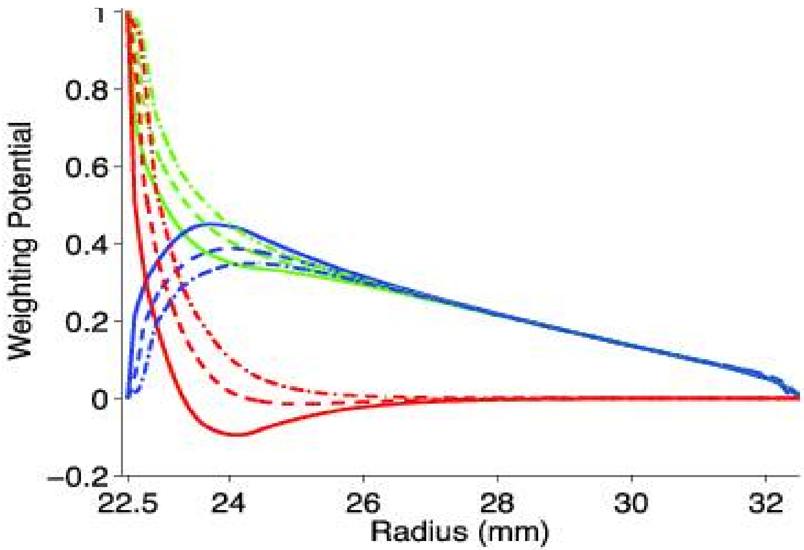
- Resolution significantly worse than in ^{14}N test
- Straggling of ^{18}Ne beam in scintillating foil and increased energy resolution of in-flight beam
- Recoiling heavy ions in PC region



Improvements:

- MCP-RF timing for Particle ID
- Thinner in-flight production target
- Active target redesign – Version 2.0
  1. 19 $\rightarrow$ 24 anode wires in PC
  2. Incorporate separate heavy ion detection capability
  3. Caen 1730 digitizers for PC waveform analysis
  4. New two stage preamplification





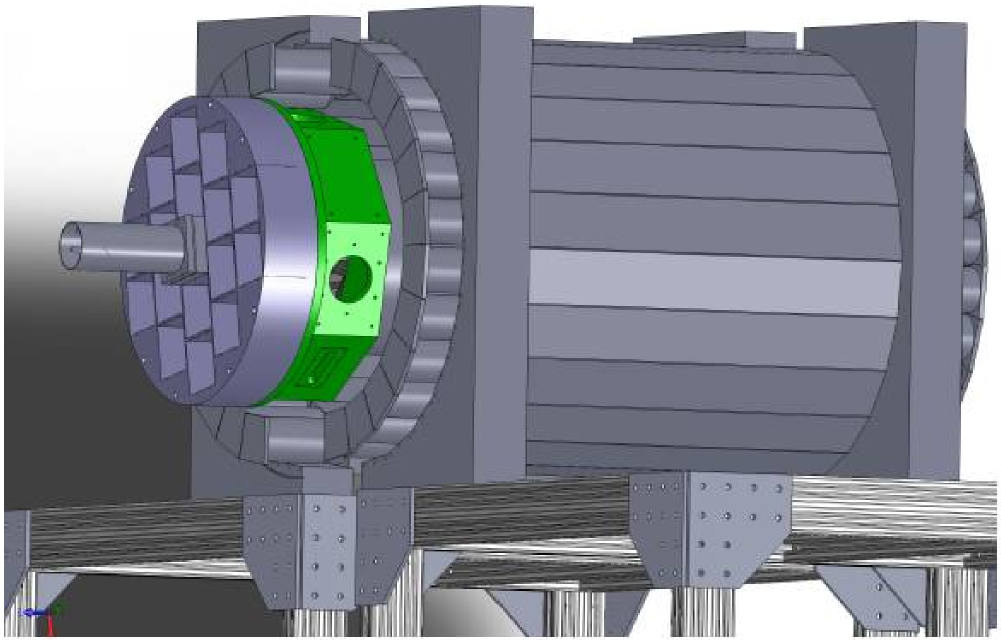
… and at ReA-3

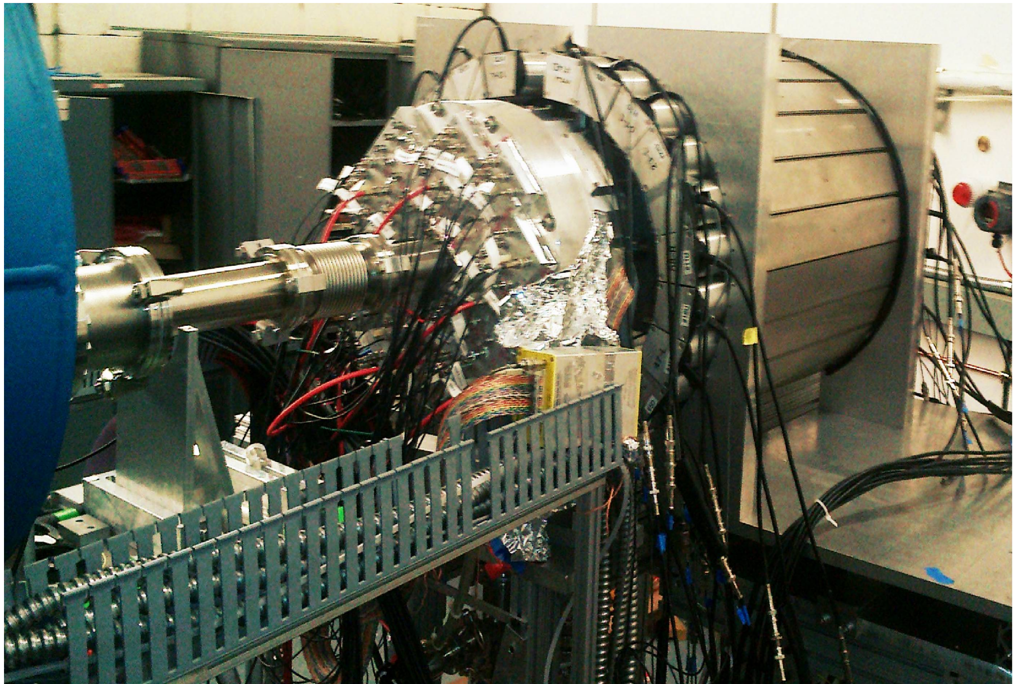
The ResoNeut Setup

Optimized for
(d,n) experiments studying astrophysical rp-process resonances

Array of 12 para-Terphenyl scintillators with
<60 keV n-threshold and
γ / n discrimination
8 detectors from NSF MRI (RUI) to U. North Florida

+20 NaI detectors
+DSSD-telescopes
+Recoil Ion-chamber
(J. Blackmon, C. Deibel, LSU)

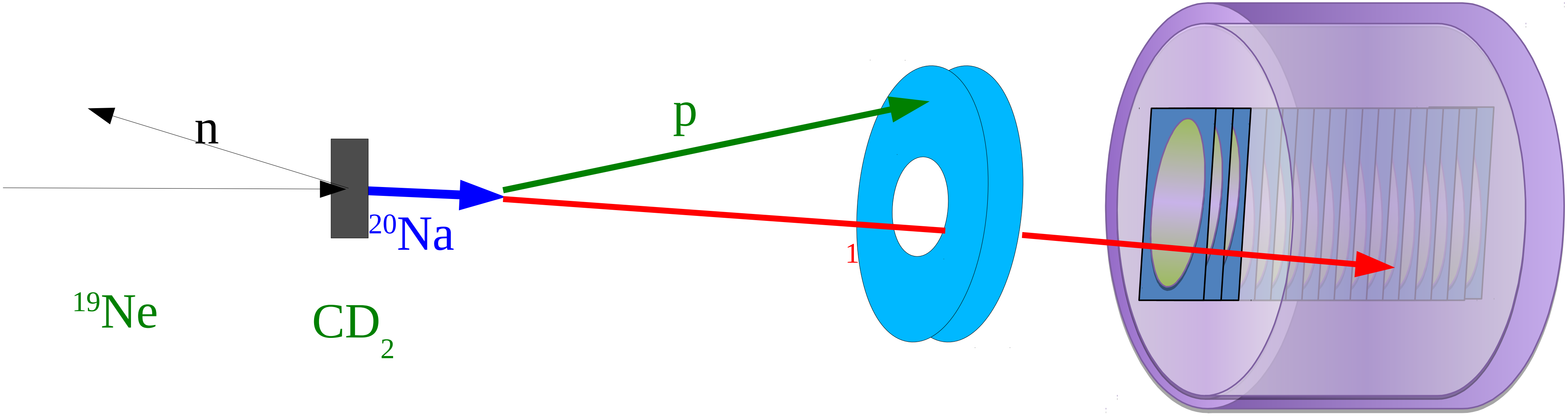




The detection scheme

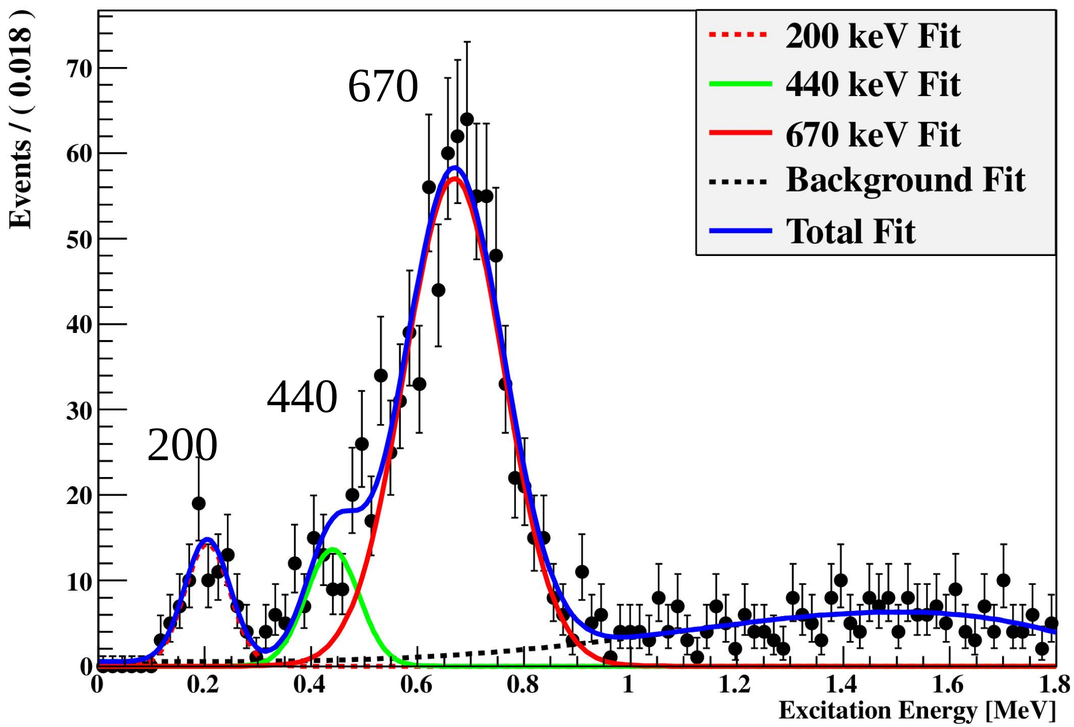
$$^{19}\mathrm{Ne}(d,n)^{20}\mathrm{Na}^{*} \rightarrow {}^{19}\mathrm{Ne}+p$$

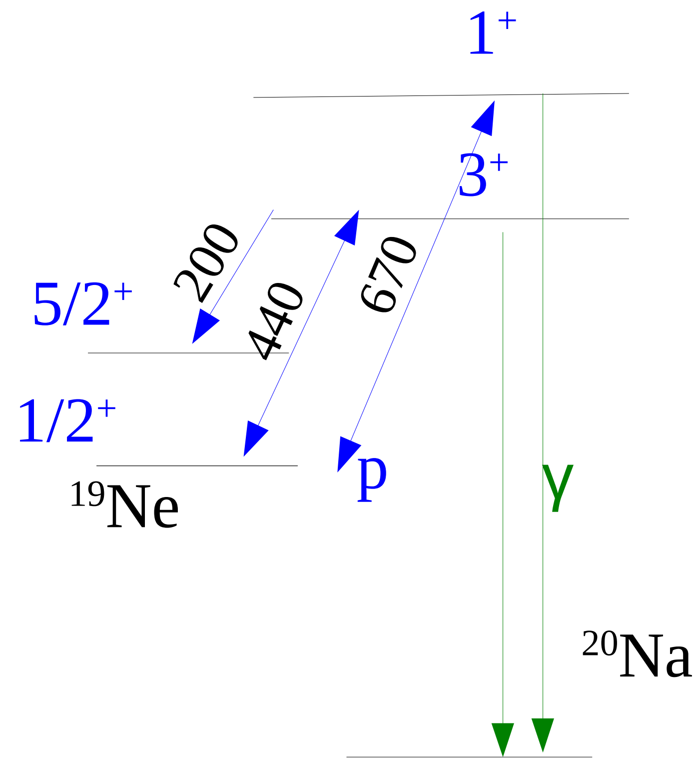
- Narrow ^{20}Na recoil cone
- ^{20}Na-resonances
  decay by p-emission in narrow decay cone



- The (d,n) reaction favors l=0,2 transfer
- The proton-decay favors l=0 decay

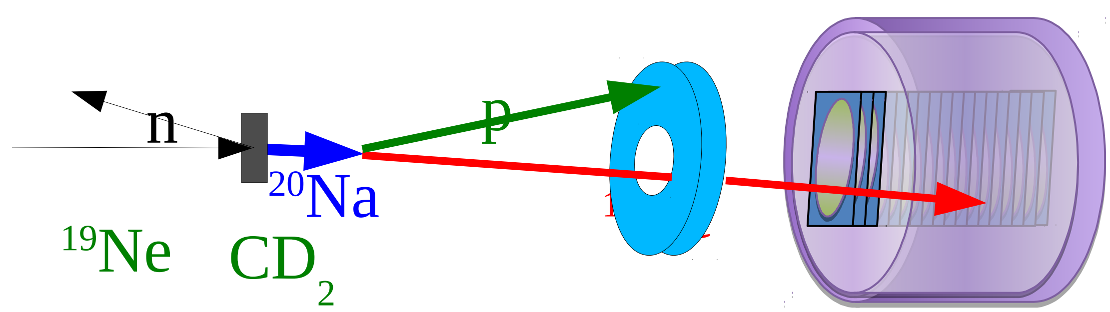
$^{19}Ne(d,n)^{20}Na$ (p) ^{19}Ne
FSU Grad. Student J. Belarge

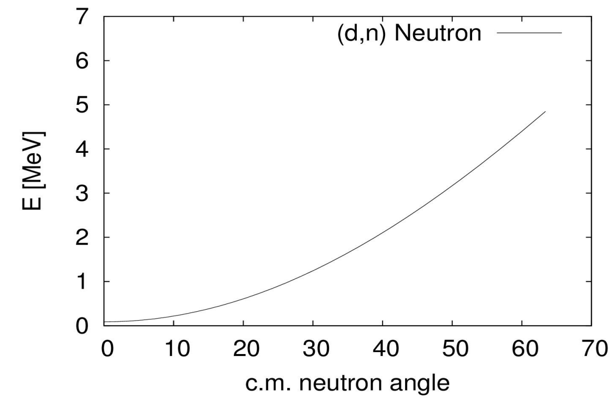


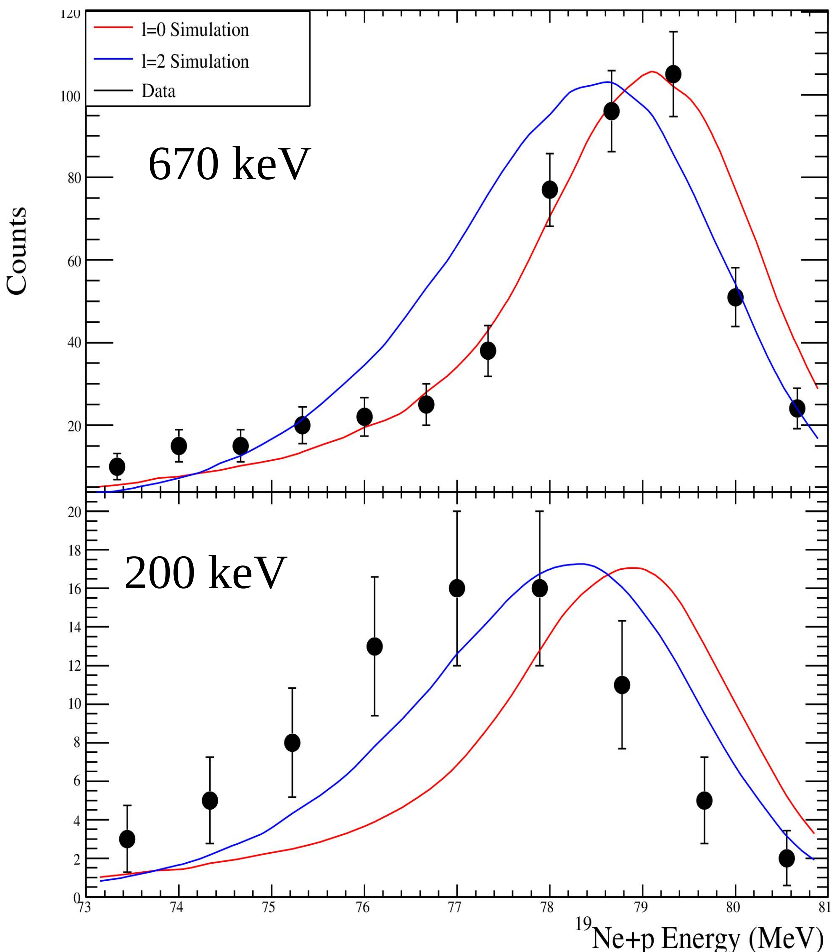


- Beam: ^{19}Ne at 87 MeV $4*10^4$ pps
- Reconstruct p-resonance spectrum through recoil+proton invariant mass
- 440, 670 keV resonances known
- Additional 200 keV peak is “inelastic” l=0 proton-emission towards $5/2^+$ state

Angular Momentum



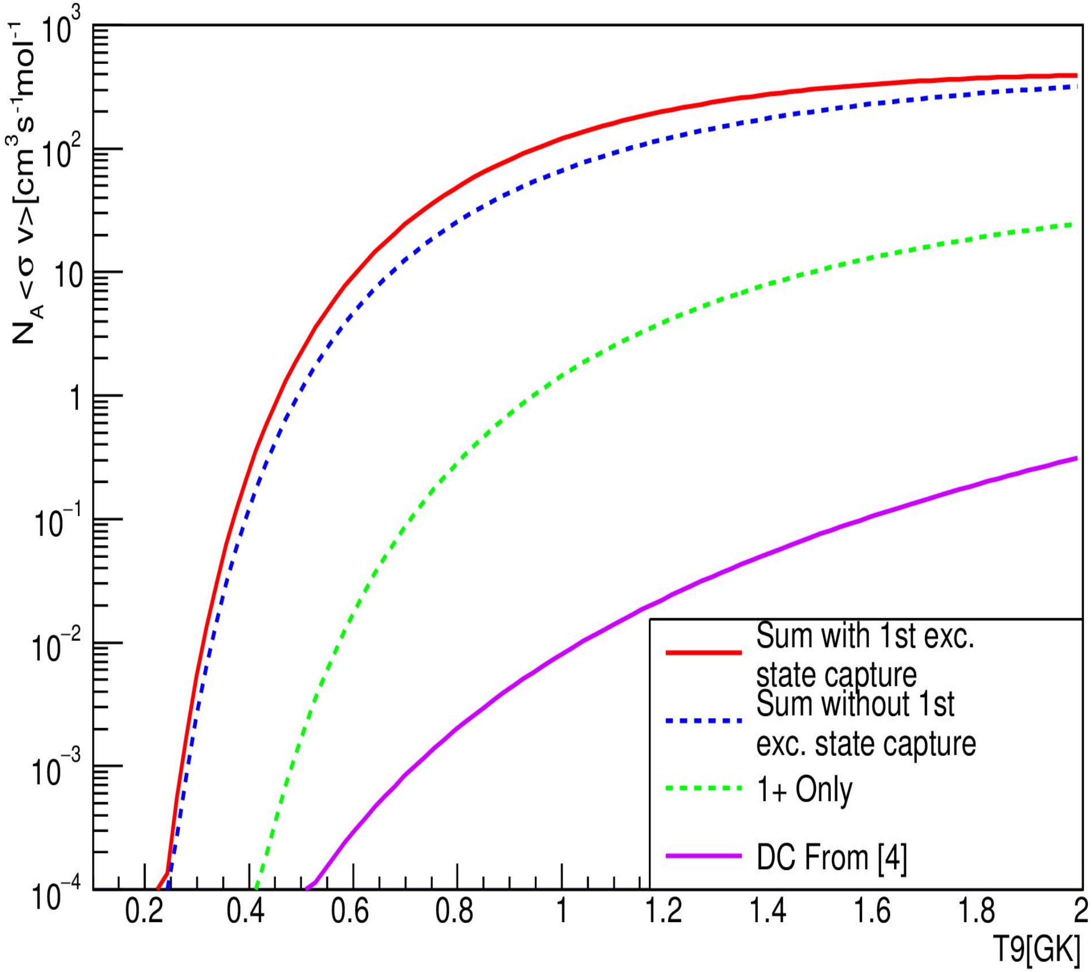




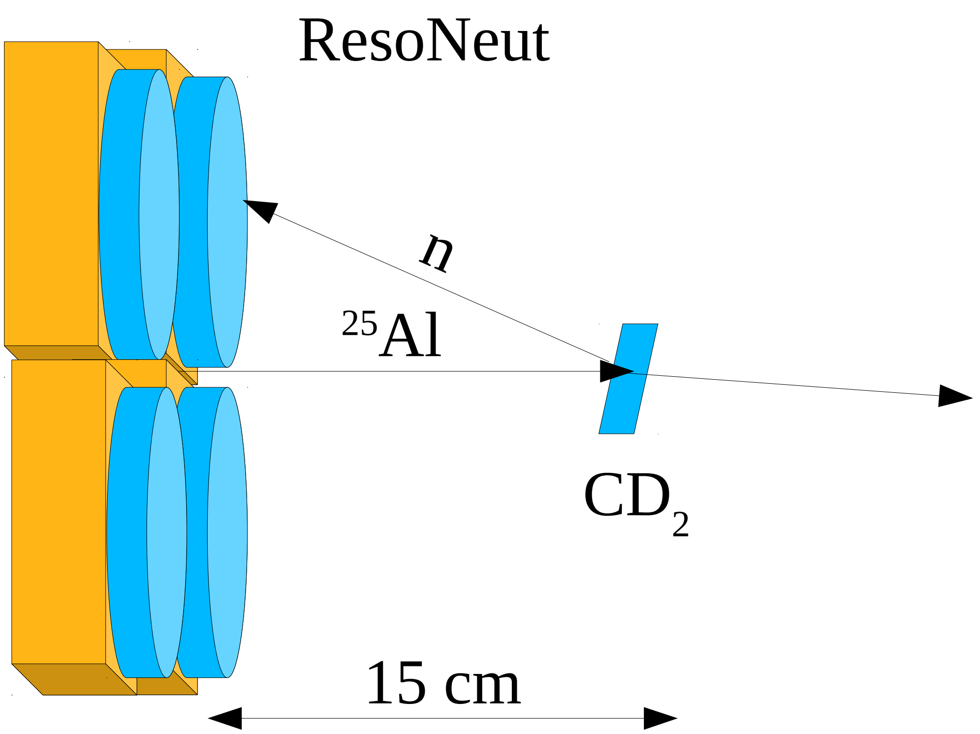
- Determine angular distribution of neutron through "missing energy"
- compare to CRC-model of (d,n) reaction
- 670 keV is l=0
- 200 keV shows l=2
- is interpreted as l=2 population in (d,n), with l=0 proton emission

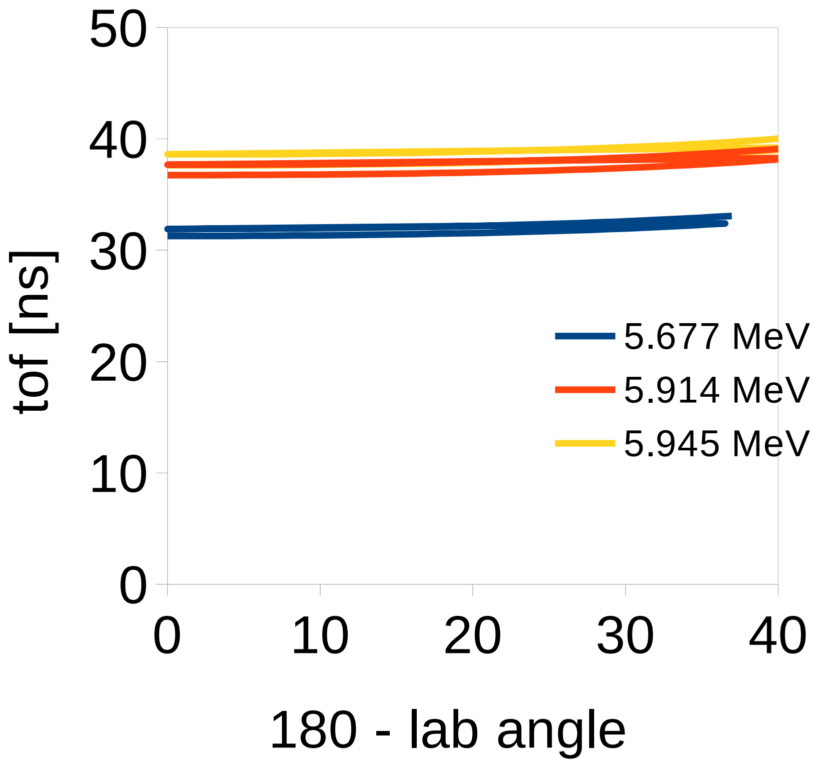
Resonance (p,γ) Rates

- The 3^+ resonance at 440 keV creates an efficient path for the ^{19}Ne(p,γ) reaction
- The excited-state capture contributes a factor 2 over the entire temp. range
- => ^{19}Ne(p,γ) is no bottleneck



How to measure (d,n) in inverse kinematics better

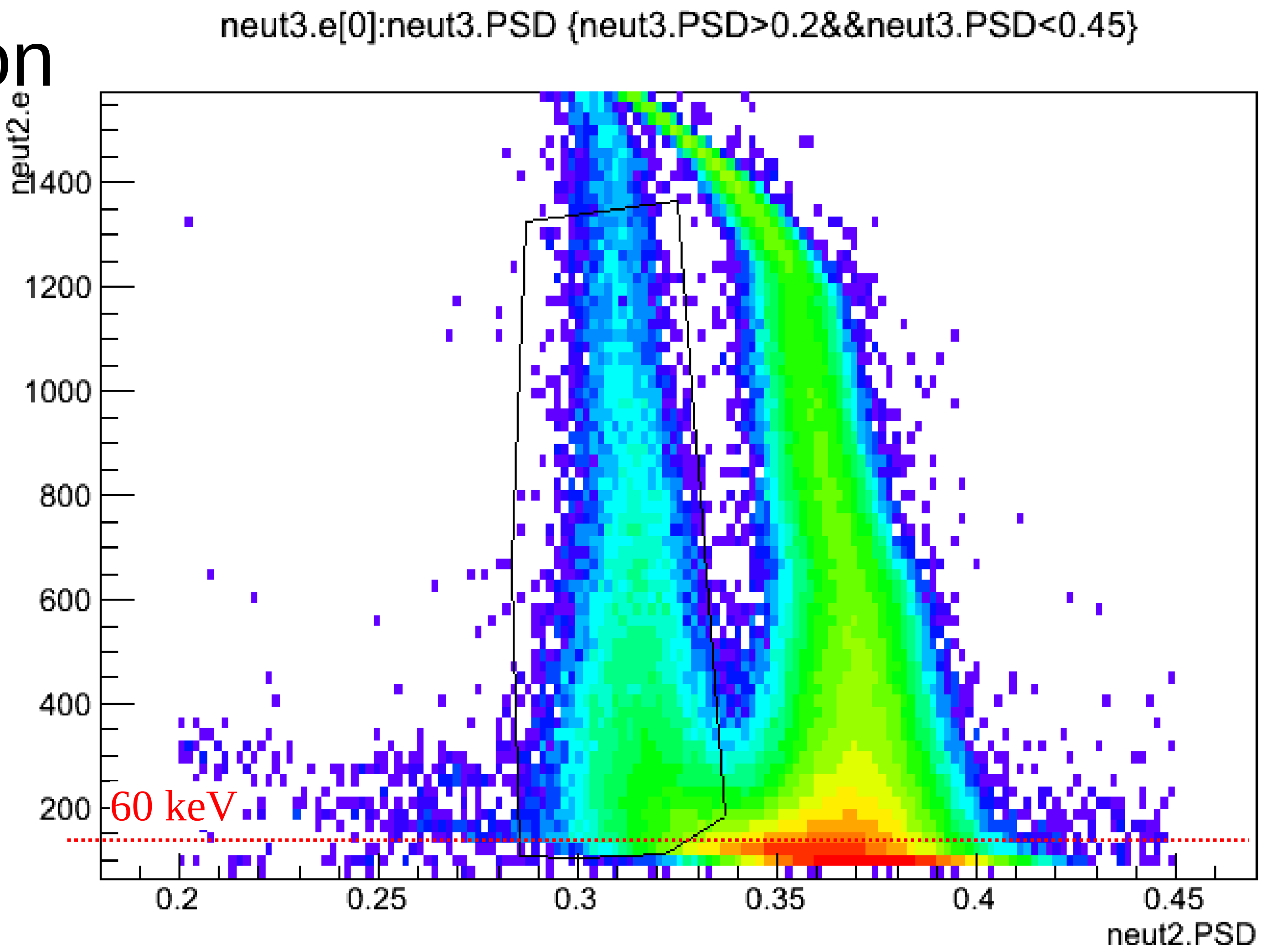




- 89-120 keV Neutrons (5.914 resonance)
- Resolution~50 keV for a 0.1 mg/cm^2 target
- Time of flight is an almost angle-independent signal
- Very compact neutron-setup covers “forward” peak

Detector-performance: (n/γ) discrimination

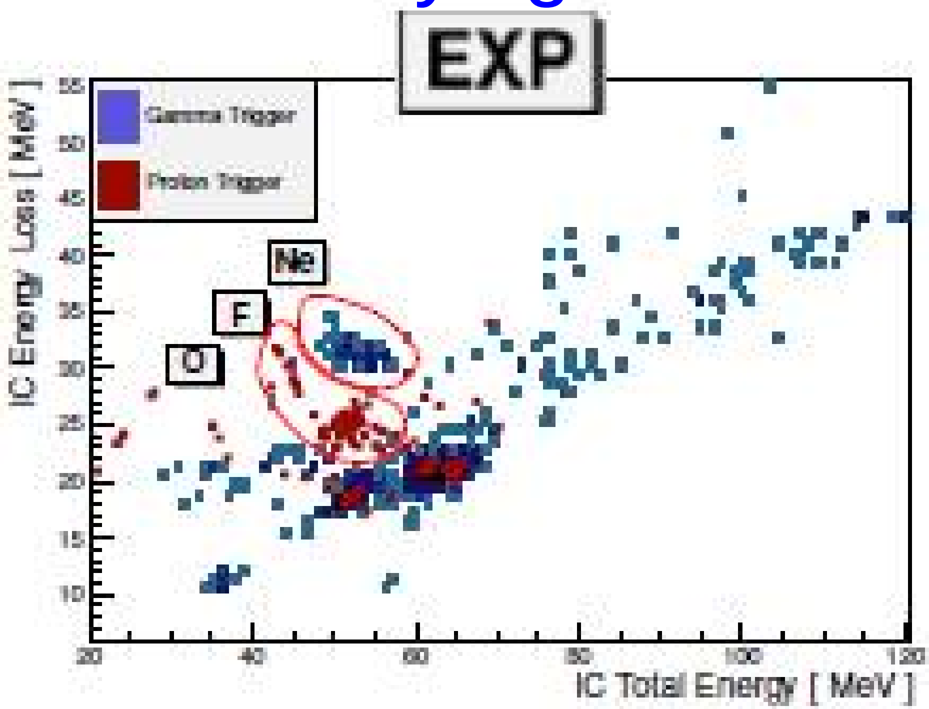
- Gated integration pulse-shape analysis 5ns / 25 ns
- charge-ratio (x-axis) vs charge (y-axis)
- Neutrons (left) separated almost down to threshold of ~80 keV proton

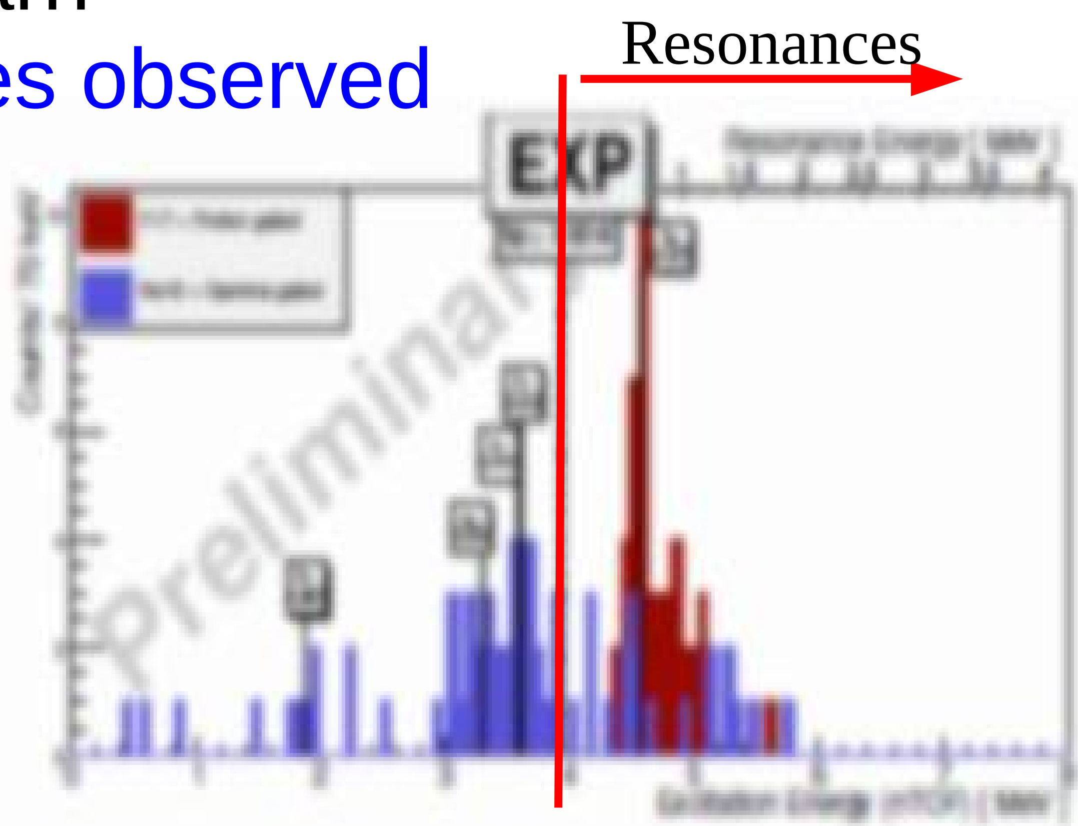


- Add X-ray absorbers for total separation

Development of (d,n) tof-spectroscopy
FSU Grad. Student S. Kuvin

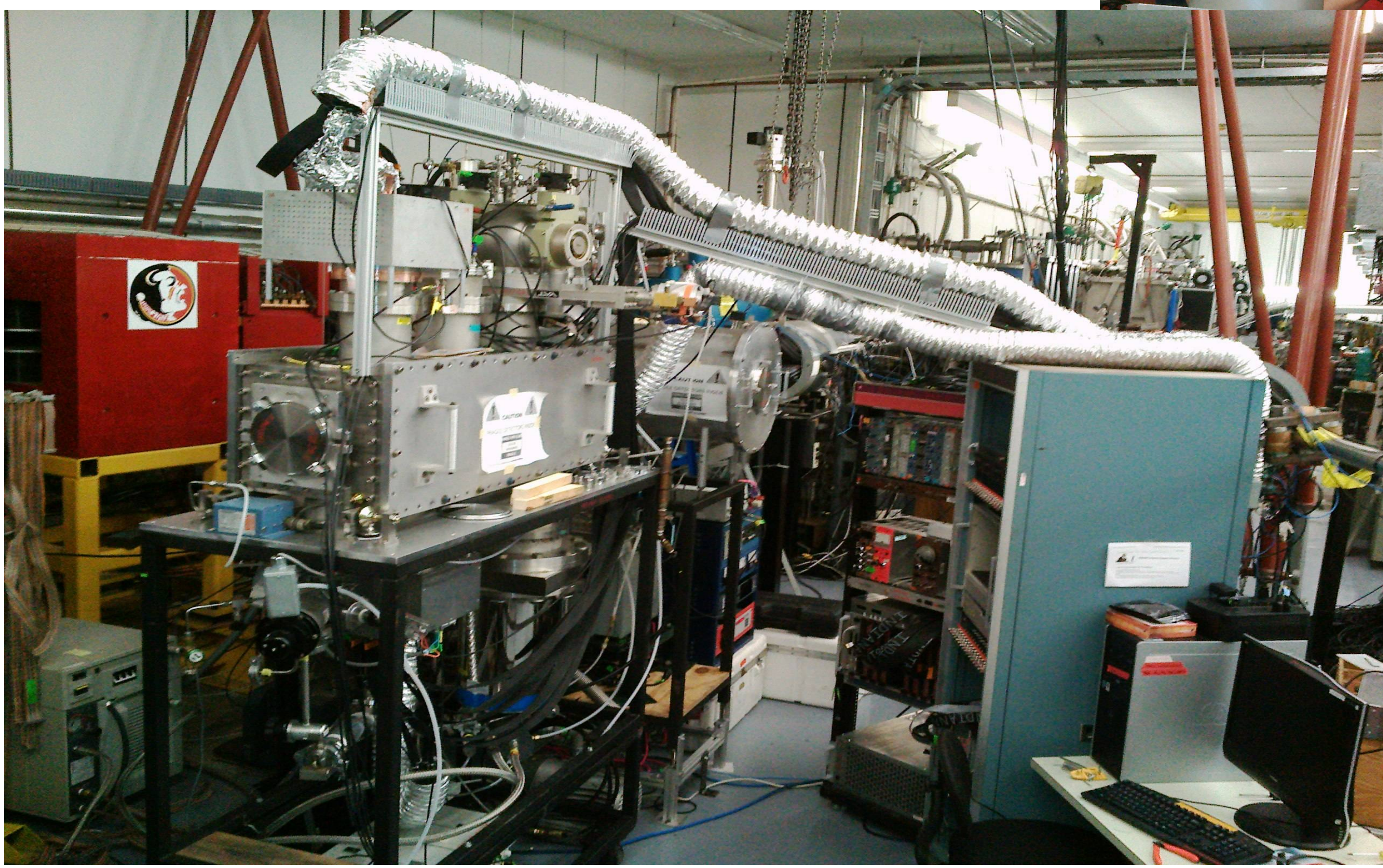
^{17}F(d,n)^{18}Ne time-of-flight measurement
gated on proton-decay + ^{17}F recoil
vs. γ-decay + ^{18}Ne recoil
4.53 MeV 3^+, 16 mbarn consistent with (p,p) and (p,γ)
5.07 MeV 2^+ state, 2 mbarn
No lower lying resonances observed





R. de Souza, S. Houdan , Indiana University

TOF – E fusion experiment
1/2014: Development of Setup with
^{18}O stable beams
6/2015: Measurement of RIB
^{19}O + ^{12}C, ^{17}F + ^{12}C
fusion excitation function



Fusion studies: $^{19,18}O+^{12}C$

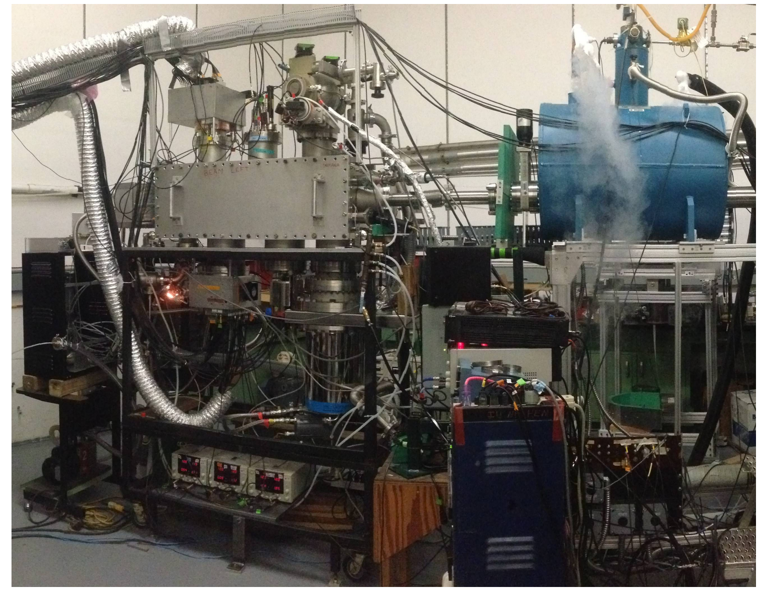
INDIANA UNIVERSITY

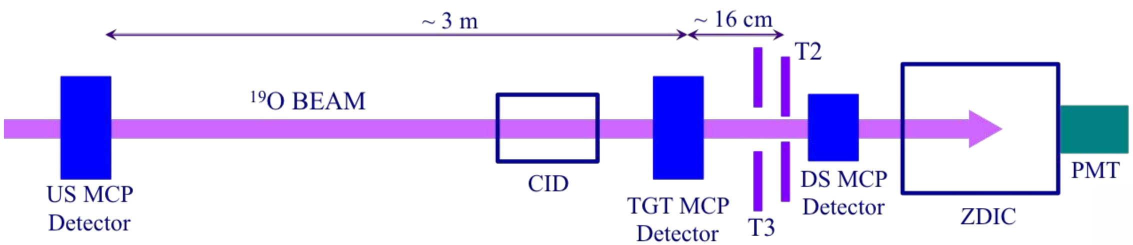
$^{18}O(d,p)^{19}O$, ^{18}O @ ~75 MeV

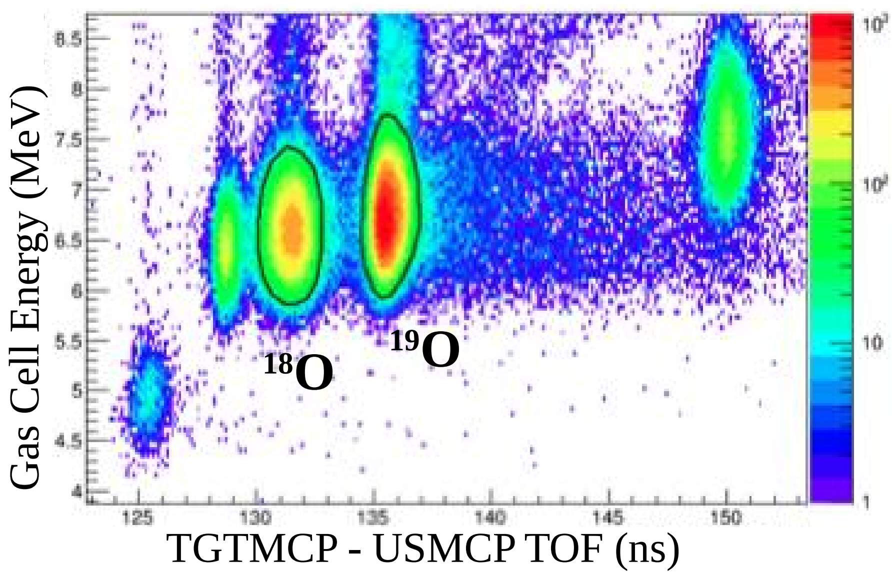
Beam on target: ~1-2x10^4 pps

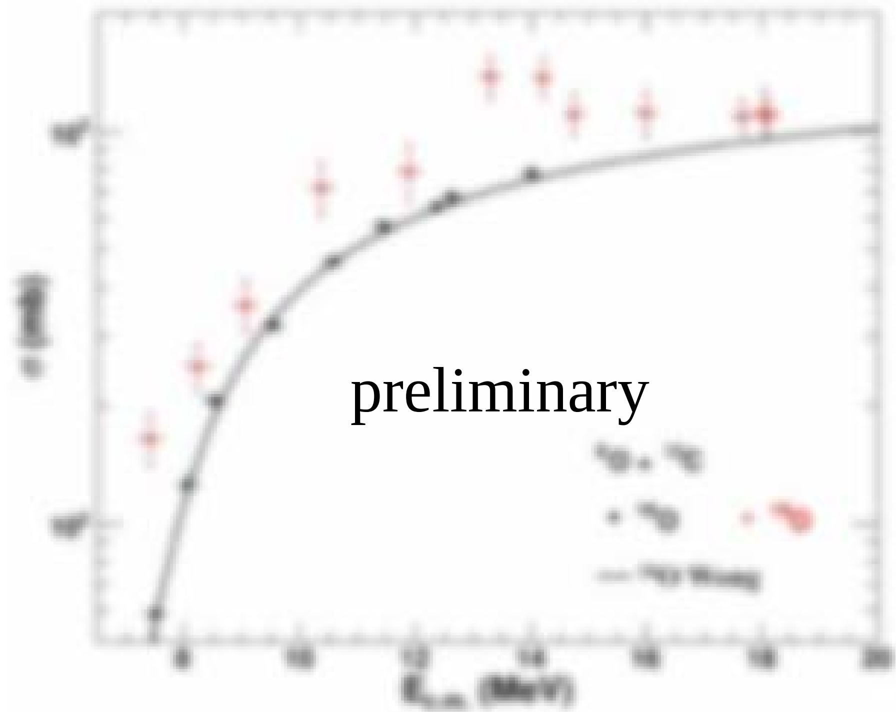
Beam purity: 25 - 50 % ^{19}O

Target: 100 μg/cm^2

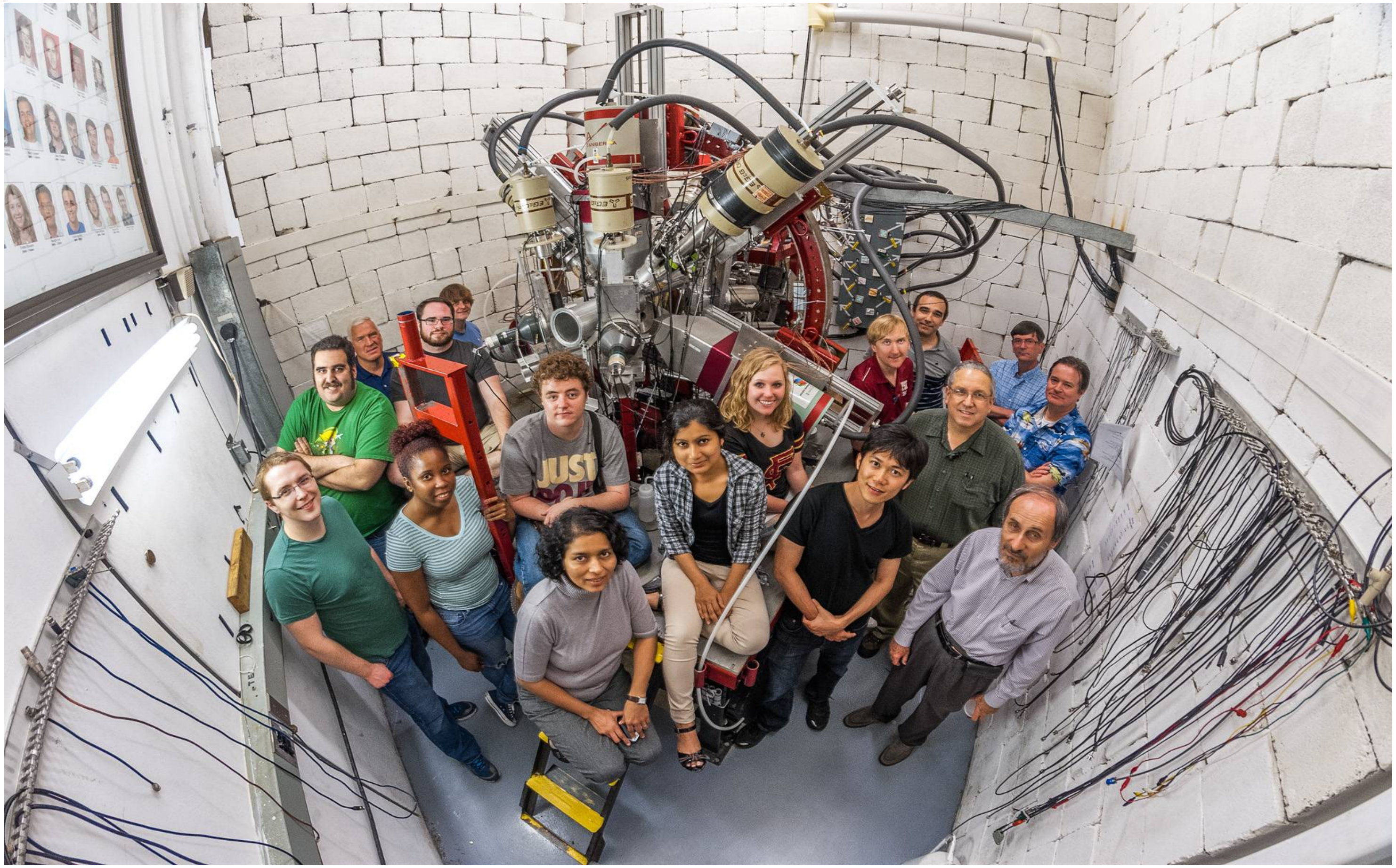








The “Gamma Gang” 2015

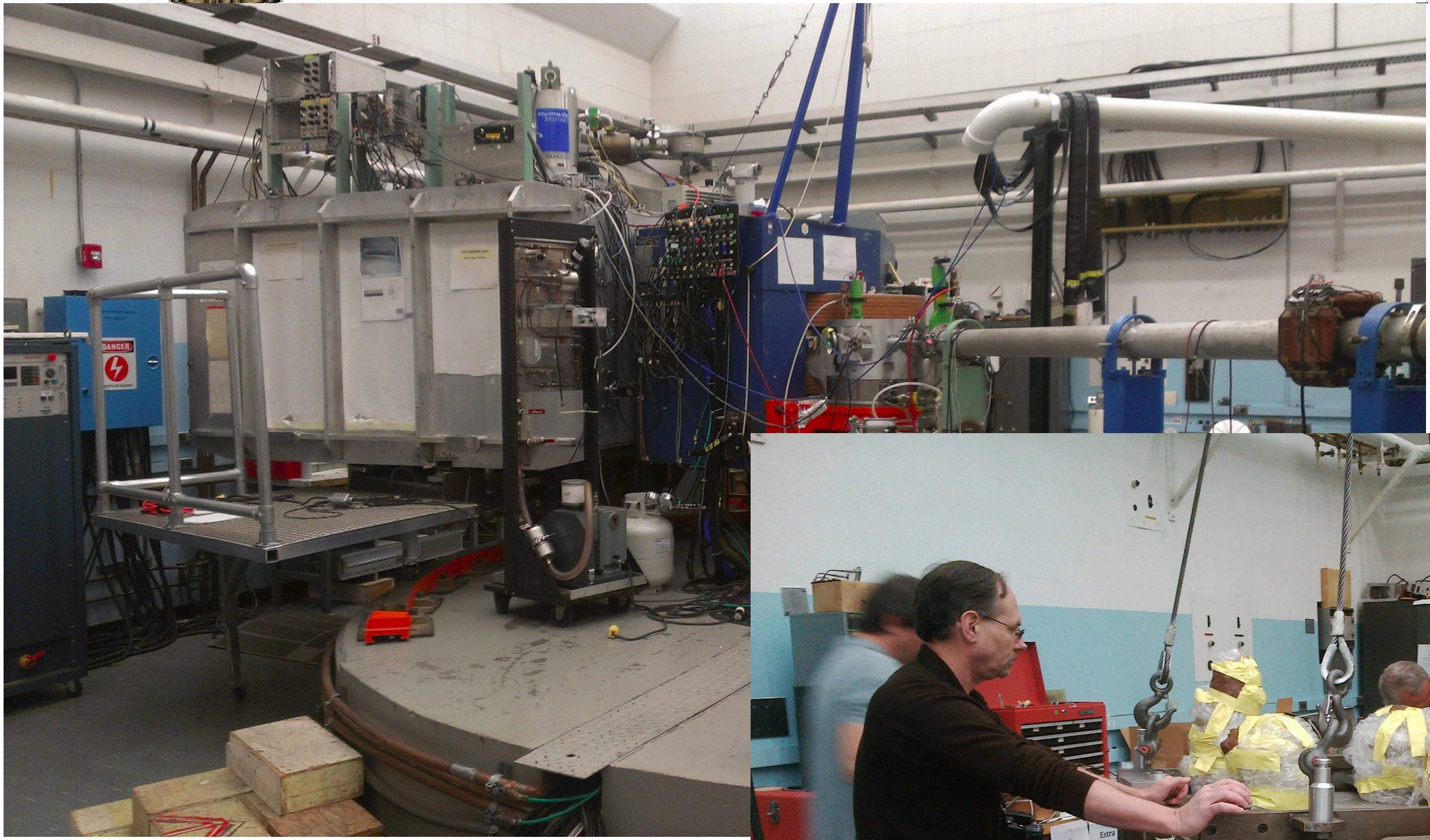


Compton-suppressed Germanium-detector array
three Clovers and ~ten single-crystal detectors
Digital DAQ
Spring 2015: Campaign   of 7 1/2 weeks of experiments
with ^{14}C and ^{3}He beams

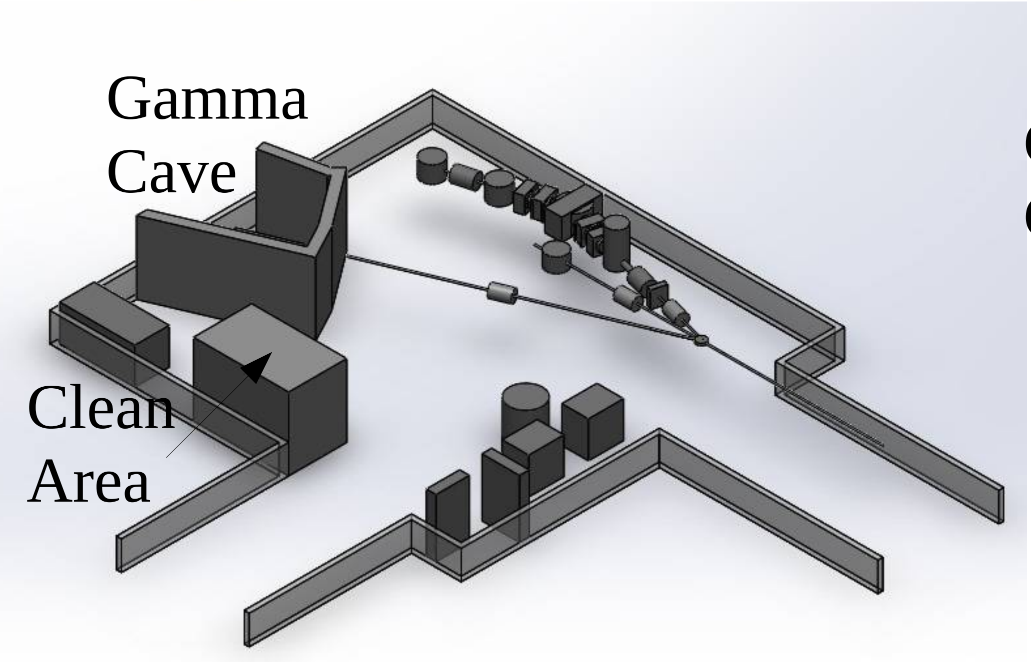
Yale SPS: 2014 MRI grant from NSF

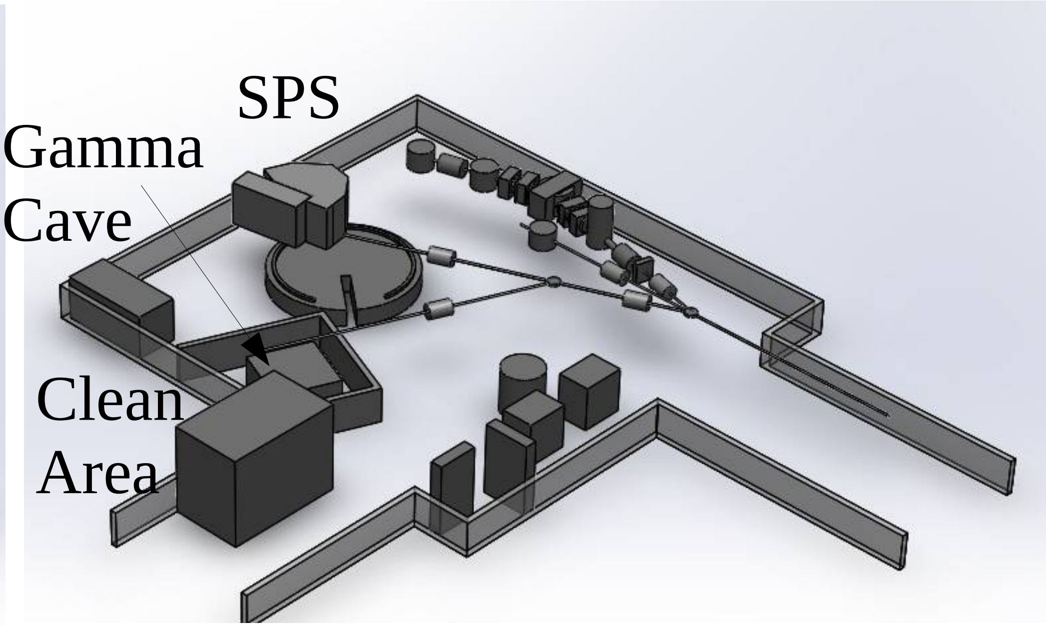
- Yale SPS and related detectors were moved to TLH in November 2013, using 80000 USD of FSU/ LSU funds
- Collaboration with C. Deibel, J. Blackmon (LSU)
- All components are at FSU /LSU
  - High resolution spectroscopy of resonances and orbital excitations through (d,p), (d,^{3}He), (^{3}He,d),, (^{3}He,t), (^{7}Li,t), (^{6}Li,d), (^{12}C,^{6}He)
  - For nuclear astrophysics and nuclear structure
  - FSU accelerator can reach 9~MeV/u for all these beams
  - Spectroscopy of resonances, coincident α/p/n/γ decay branching ratios
- System development over three years

Dismantling the SPS@Yale (Nov 2013)



SPS at FSU





Relocate "Clean Area" Spring 2015
Perform Gamma-campaign Spring 2015,
Relocate Gamma-setup and "Cave", July 2015
Build Concrete Pedestal with pile foundation, Dec. 2015
Assembly of SPS, Spring-Summer 16
Commissioning experiments in 2016/17

Making Space for SPS

The future: Linac upgrade project

- The current linac has
  12 accelerating resonators for β=0.1
- The original design anticipated an upgrade to 20 resonators, including four with β=0.07
- We acquired the missing resonators, including cryostats and electronics from Kansas State
- We have been offered additional resonators from ATLAS, which will be used to swap low-performing ones in current lineup
- The upgraded linac will easily support RESOLUT operations up to mass 40
- It will allow more reliable operations (not everything is at the limit)

The future: Linac Upgrade Project

- Tandem 8.7 MV
- Realistic Resonator fields ~2.5 MV/m and 2 MV/m
- Beam acceleration profiles; (MeV/u)

	Current Linac	Upgrade Stage 2	Upgrade Stage 3	Complete Upgrade
^{16}O	7.8 6.8	8.8 8.0	10.2 9.3	10.7 9.8
^{24}Mg after prod. target	6.4 4.6	7.4 5.8	8.8 7.4	9.5 8.1
^{32}S after prod. target	5.6 3.1	6.4 4.3	7.9 5.9	8.8 7.4
^{40}Ca after prod. target	4.7	5.5	6.9 4.4	7.9 5.6

Summary: The John D. Fox Superconducting Accelerator Lab

- The John D. Fox Laboratory is a busy place, which supports active programs in Nuclear Structure and Nuclear Astrophysics
- We have established an in-flight facility for radioactive beam experiments with ~4 MeV/u and mass <=30
- We are bring the ex-Yale Enge Split-Pole Spectrometer back to life, which will support a new research program in resonance spectroscopy
- Our lab is an ideal place to develop world-class instruments for ReAX and FRIB
- Our laboratory continues to be a talent-magnet