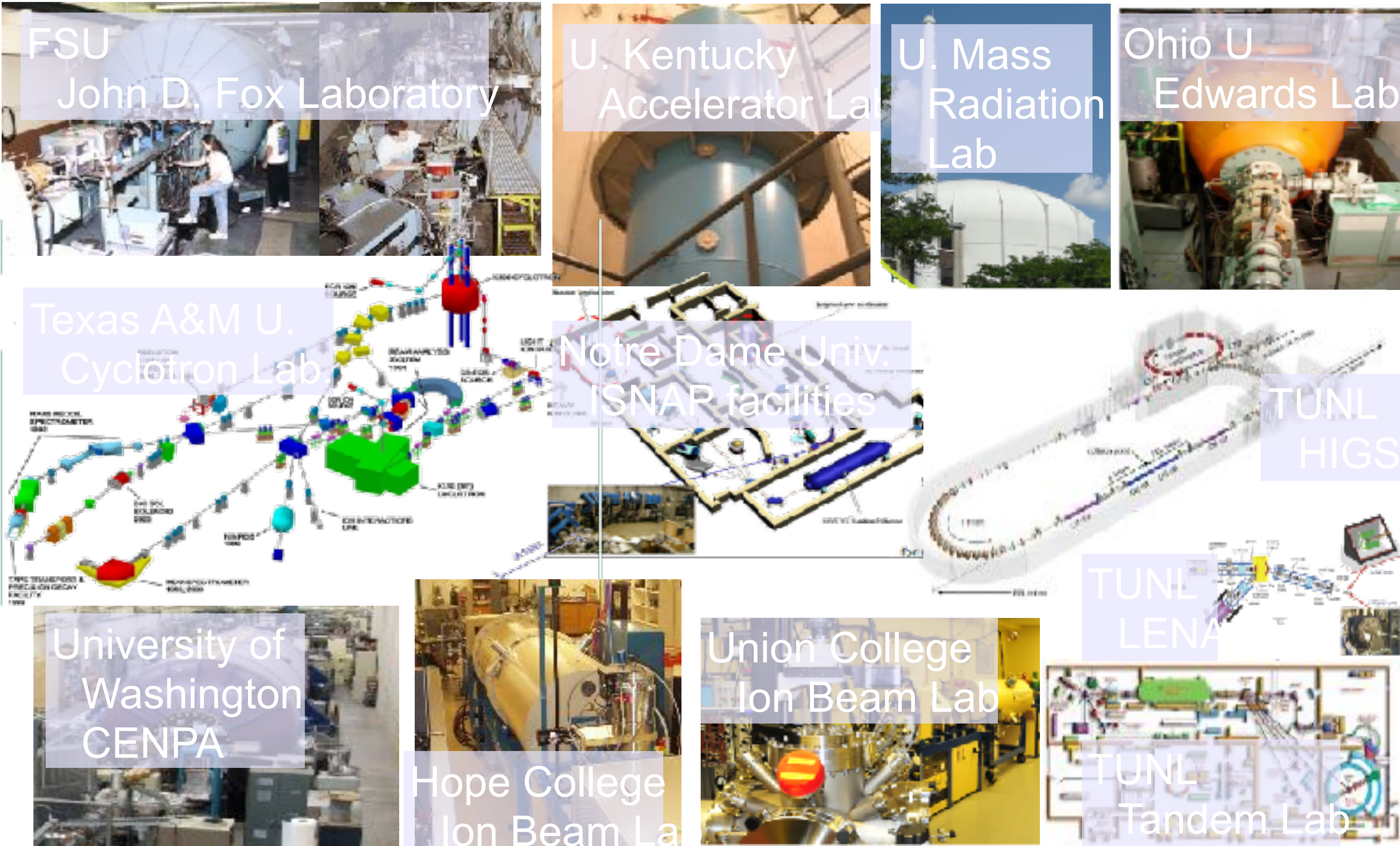
http://aruna.physics.fsu.edu

10 members

~200 users

ARUNA- Association for Research at University Nuclear Accelerators



FSU
John D. Fox Laboratory

U. Kentucky
Accelerator La

U. Mass
Radiation
Lab

Ohio U
Edwards Lab

Texas A&M U.
Cyclotron Lab.

Notre Dame Univ.
ISNAP facilities

TUNL
HIGS

TUNL
LENA

University of
Washington
CENPA

Hope College
Ion Beam La

Union College
Ion Beam Lab

TUNL
Tandem Lab

Operation and Budgets of ARUNA Laboratories

Three facilities are DOE Centers-Of-Excellence: Texas A&M Cyclotron, TUNL and U. Washington

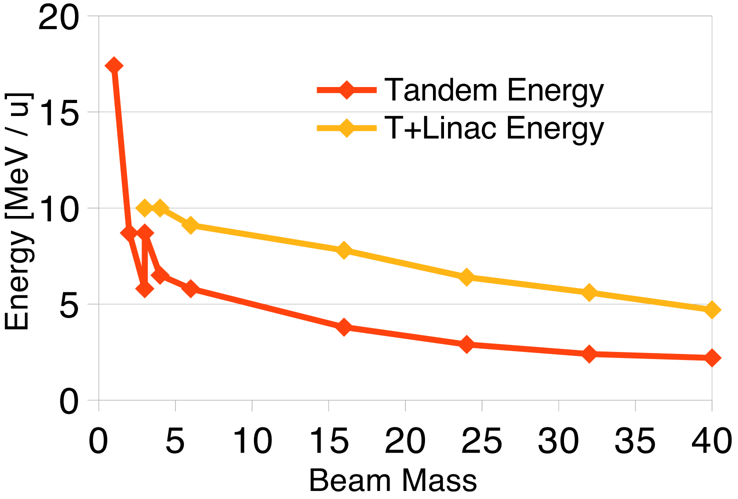
The others are funded through DOE or NSF through the Nuclear Physics core program.

The ARUNA facilities receive grant funding in excess of $15M

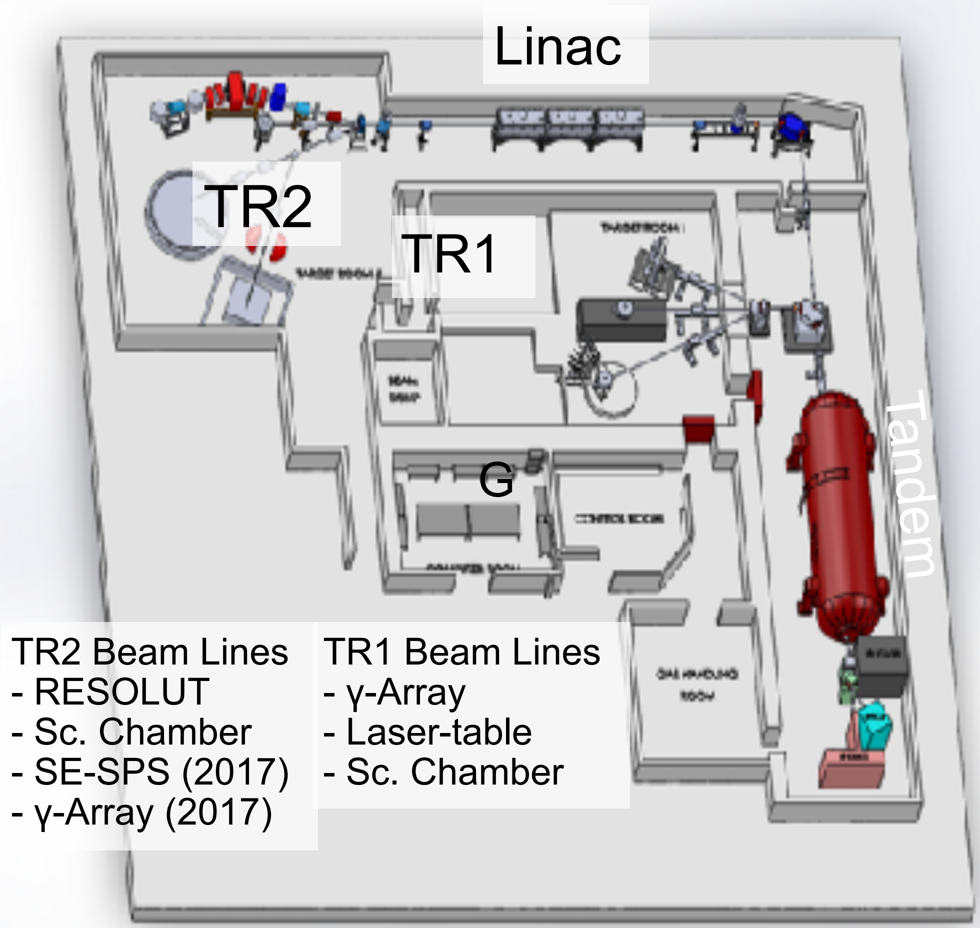
The hosting universities almost everywhere provide substantial support, which over-matches the operations cost in the form of staff positions, utilities and other contributions

Facilities and Research Highlights
The John D. Fox Accelerator Laboratory

- 9 MV Tandem + 8 MV Linac
- Beam Energy profile



- In-flight radioactive beams with Resolut
- Clover HPGe γ-array (TR1 → TR2)
- New: Super-Enge Split Pole Spectrograph

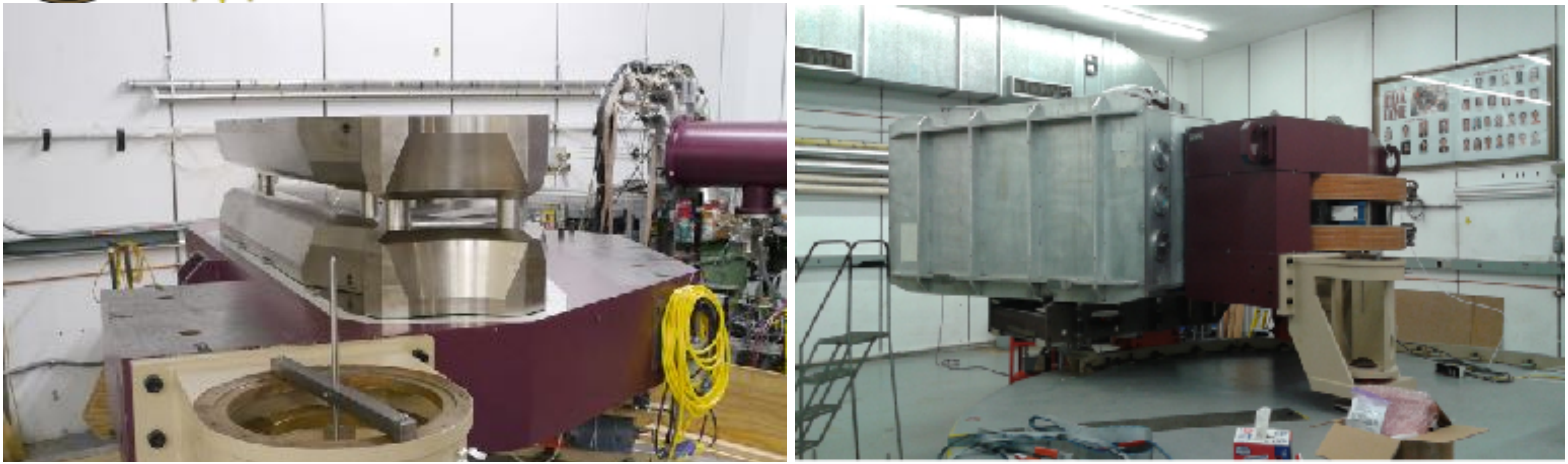


TR2 Beam Lines
- RESOLUT
- Sc. Chamber
- SE-SPS (2017)
- γ-Array (2017)

TR1 Beam Lines
- γ-Array
- Laser-table
- Sc. Chamber

Tandem: Pelletron-charged 9 MV FN-tandem
Linac: 14 Superconducting cavities
Niobium on Cu, Split-Ring (Atlas-design)

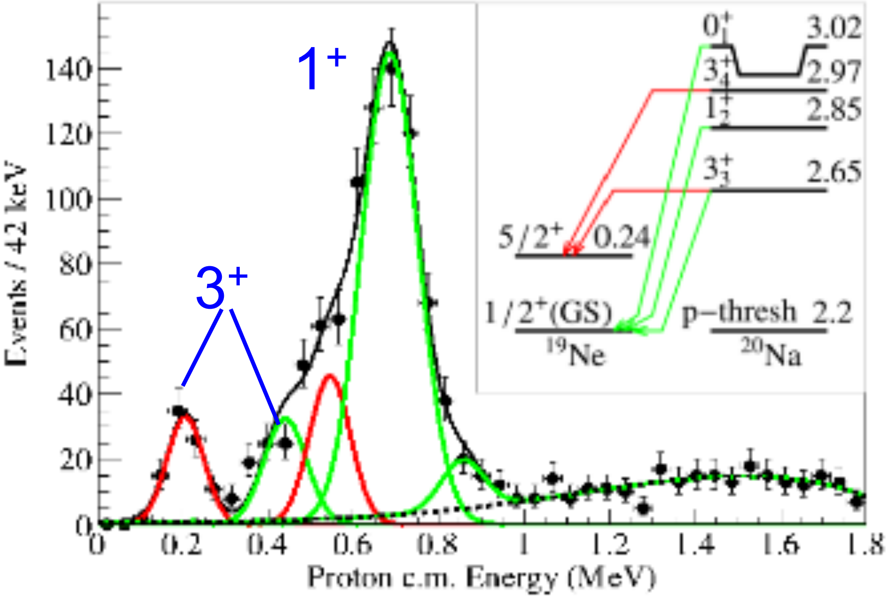
Super-Enge Split-Pole Spectrometer

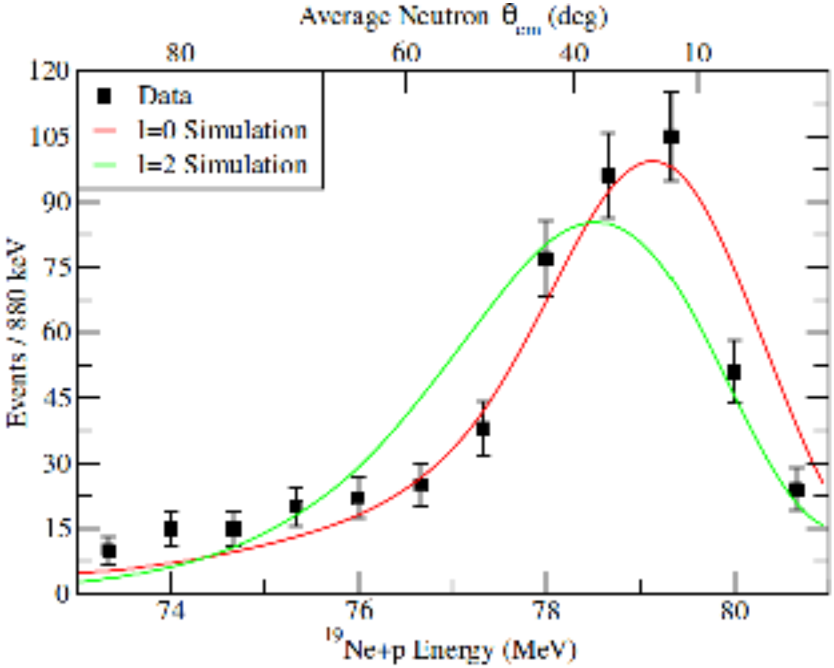


- SE-SPS installed at FSU, commissioning Fall 2017 LSU-FSU collaboration
- High resolution, large acceptance (12.8 msr)
- SABRE: Silicon detector array for coincident particle spectroscopy
- Spectroscopy of resonances for nuclear astrophysics, nuclear structure in the continuum
- Collaborators welcome

rp-Process: ^{20}Na Resonances Studied at FSU

- The ^{19}Ne(p,γ)^{20}Na reaction is the first (p,γ) reaction in rp-process nucleosynthesis.
- Measured (d,n) to resonances with a radioactive beam of ^{19}Ne at FSU's RESOLUT facility
- 670 keV 1+ (l=0) resonance, at higher energy than reported
- 440 keV 3+ (l=2) resonance with (l=0) excited state proton-branch
- Astrophysical (p,γ) rate is higher than assumed, because of ^{19}Ne excited state capture
- No “bottleneck” for X-ray bursts
- FSU graduate J. Belarge et al. PRL 117, 182701 (2016)

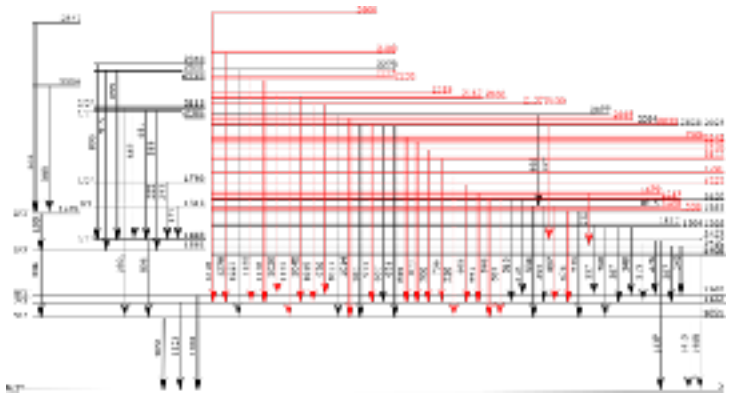


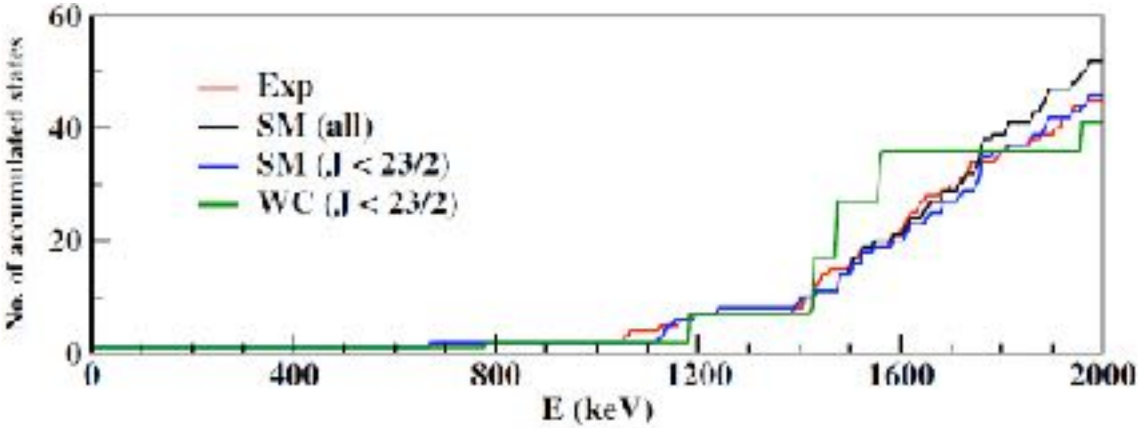


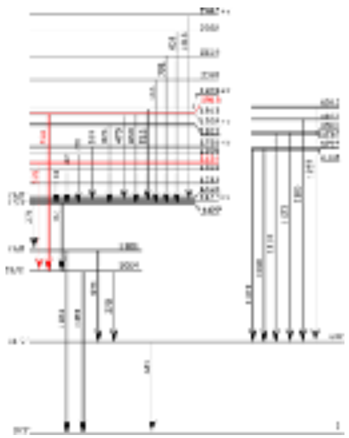
Undergraduate research at the Fox Lab - Results

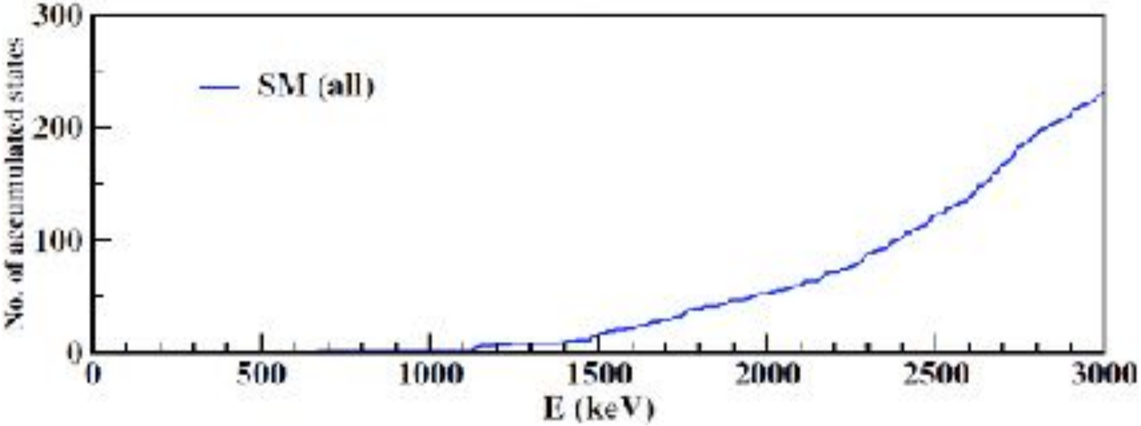
Complete spectroscopy of ^{211}Po via the (α,n) reaction (in press, Phys. Rev. C)

J.R. Cottle (Grinnell College) et al., FSU, MSU/NSCL, ORNL

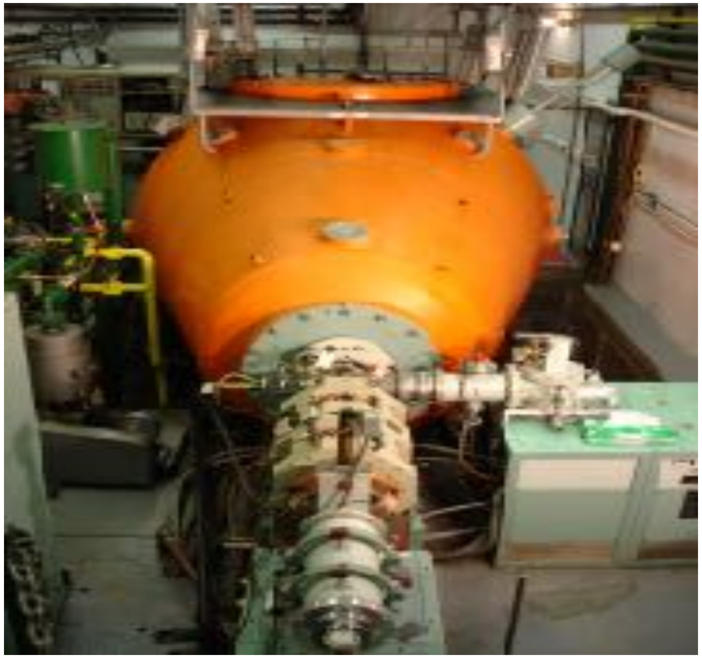






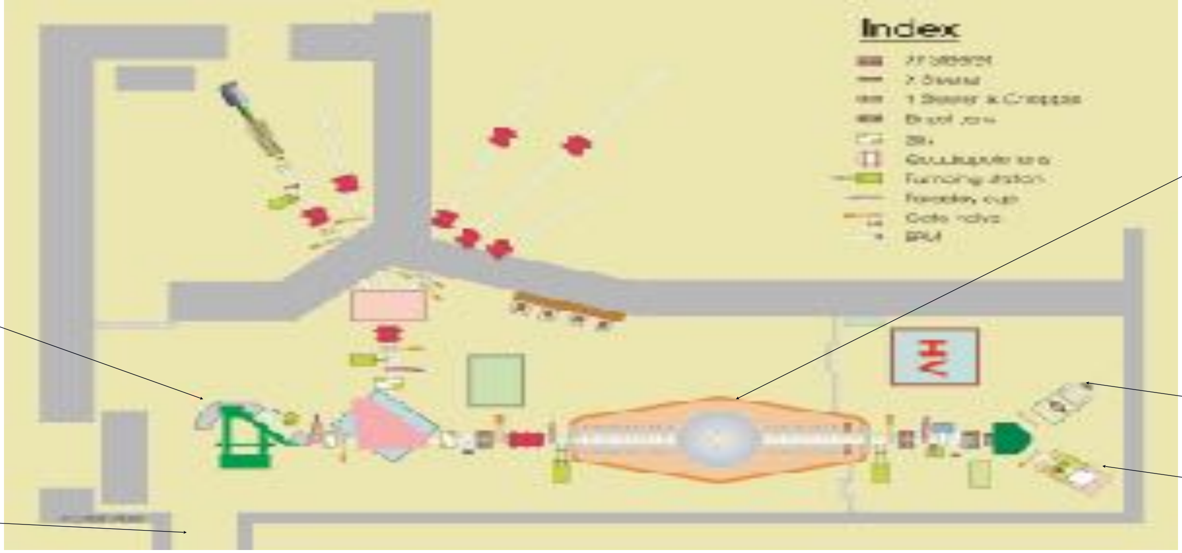


Edwards Accelerator Laboratory at Ohio University



Beam Swinger Facility

Target chamber



4.5-MV T-type tandem

Swinger Magnet
(-4° $\leq \theta_{lab} \leq$ 158°)

Cs Sputter Source

30-meter TOF Tunnel

Duoplasmatron He Source

Edwards Accelerator Laboratory at Ohio University

Research Areas: Nuclear Astrophysics, Nuclear Structure,
Surface Science, Applied Nuclear Science

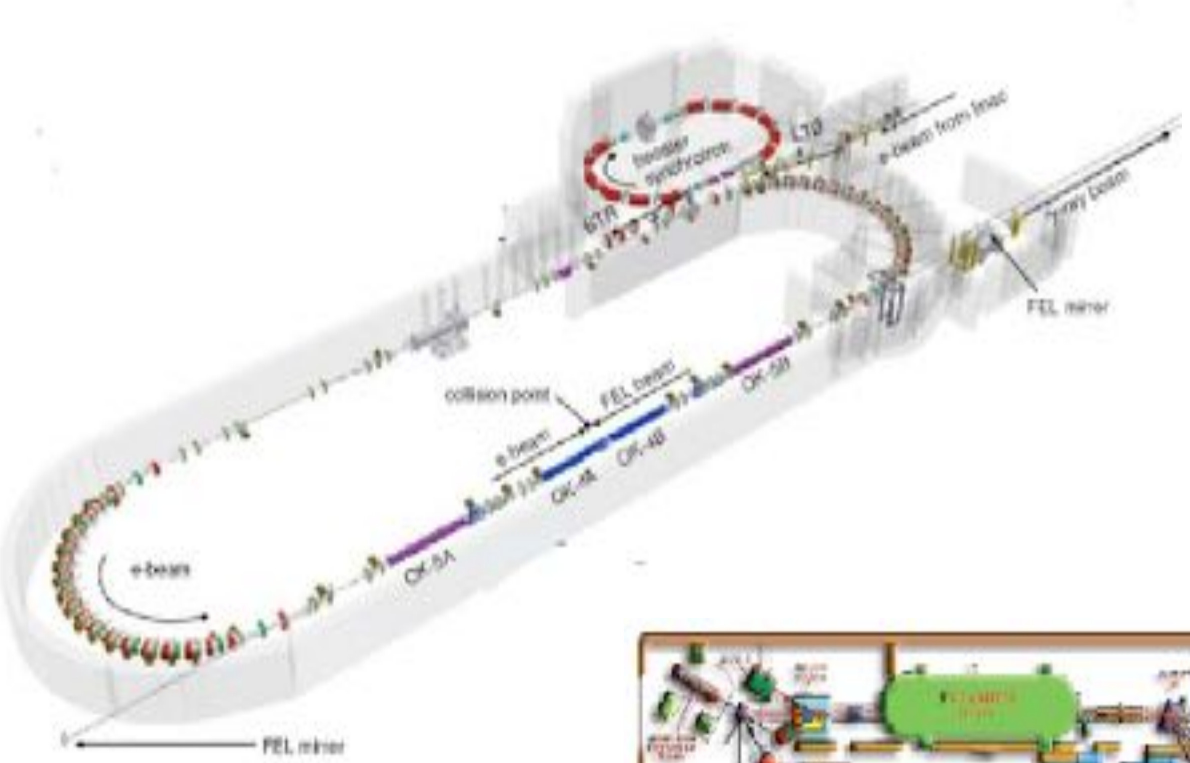
Senior Researchers: Carl Brune, Steve Grimes, Tom Massey,
Zach Meisel, and Alexander Voinov

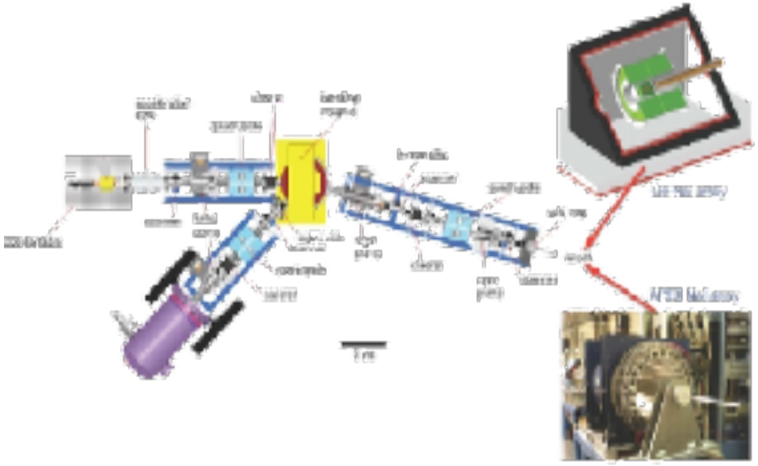
Research Highlight: Neutron Transport in Iron

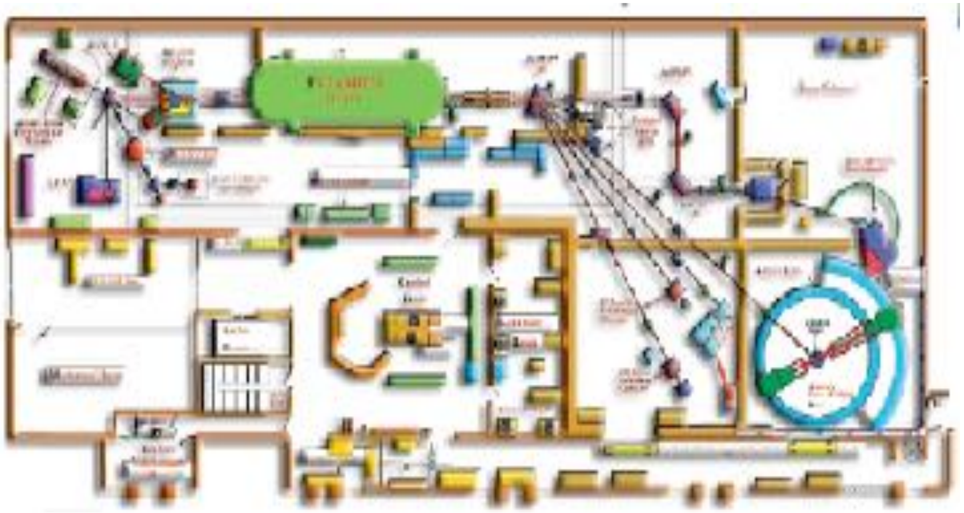
Ph. D. project of Sushil Dhakal who graduated in December 2016. A pulsed ~8 MeV source is located in the center of the sphere. Neutron time-of-flight is detected at a distance of 8 m. Experimental results are compared to Monte Carlo simulations using cross section libraries.

Our work indicates the neutron elastic scattering assumed in ENDF/B-VII is about 10% too large.

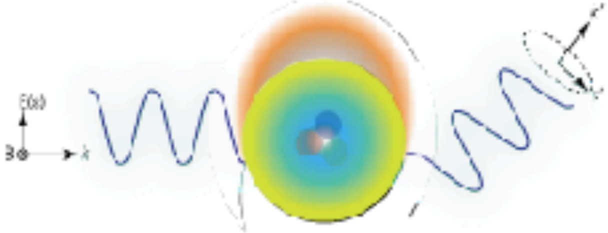
Facilities and Research Highlights
Triangle Universities Nuclear Laboratory



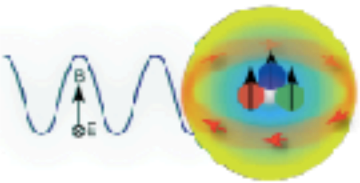




Measurement of polarizabilities via Compton Scattering provides stringent test of calculations that link the effective low-energy description of nucleons to QCD, and Lattice QCD predictions. At HIGS, we are measuring proton and neutron polarizabilities at unprecedented accuracies.



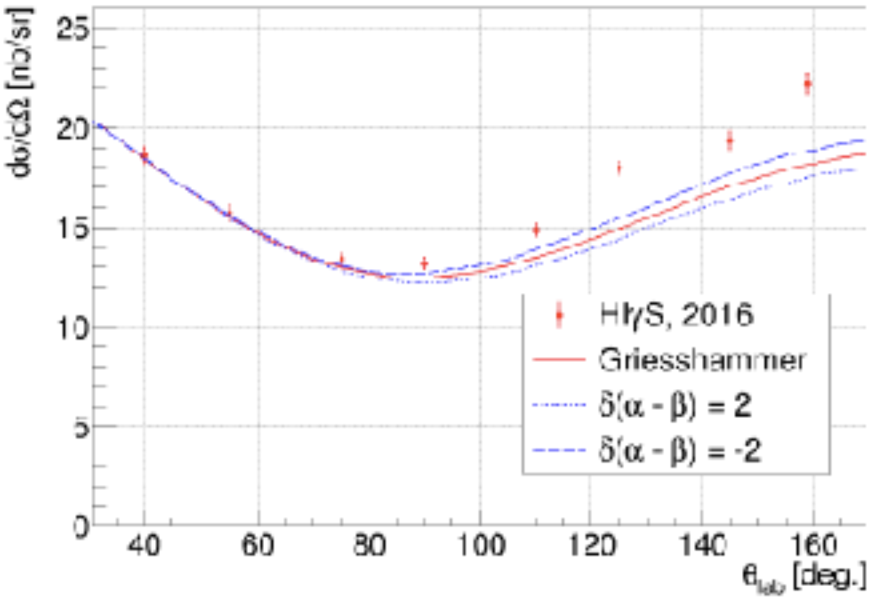
$$\vec{d} = 4\pi\alpha_{E1}(\omega)\vec{E}(\omega)$$



$$\vec{m} = 4\pi\beta_{M1}(\omega)\vec{B}(\omega)$$

The EM self-energy of the nucleon can be related to the measured elastic/inelastic cross sections; Largest source of uncertainty is from β_p β_n (where uncertainty from neutron dominates)

The Compton scattering setup at HIGS to measure proton's spin polarizabilities: Cryogenic target + NaI Array (HINDA)

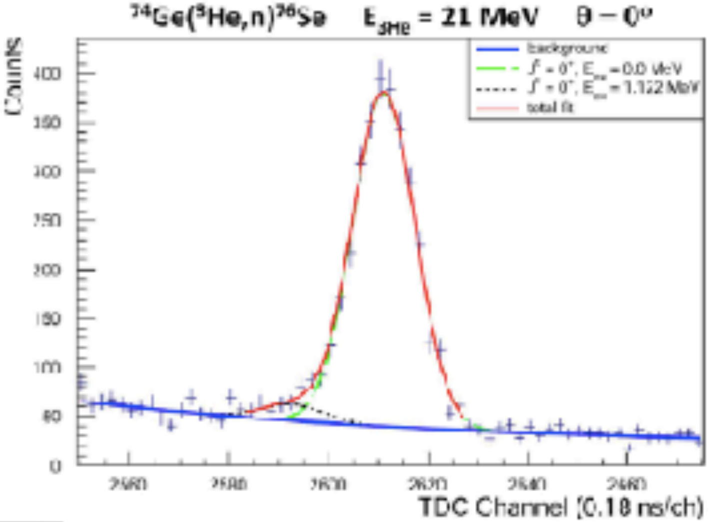


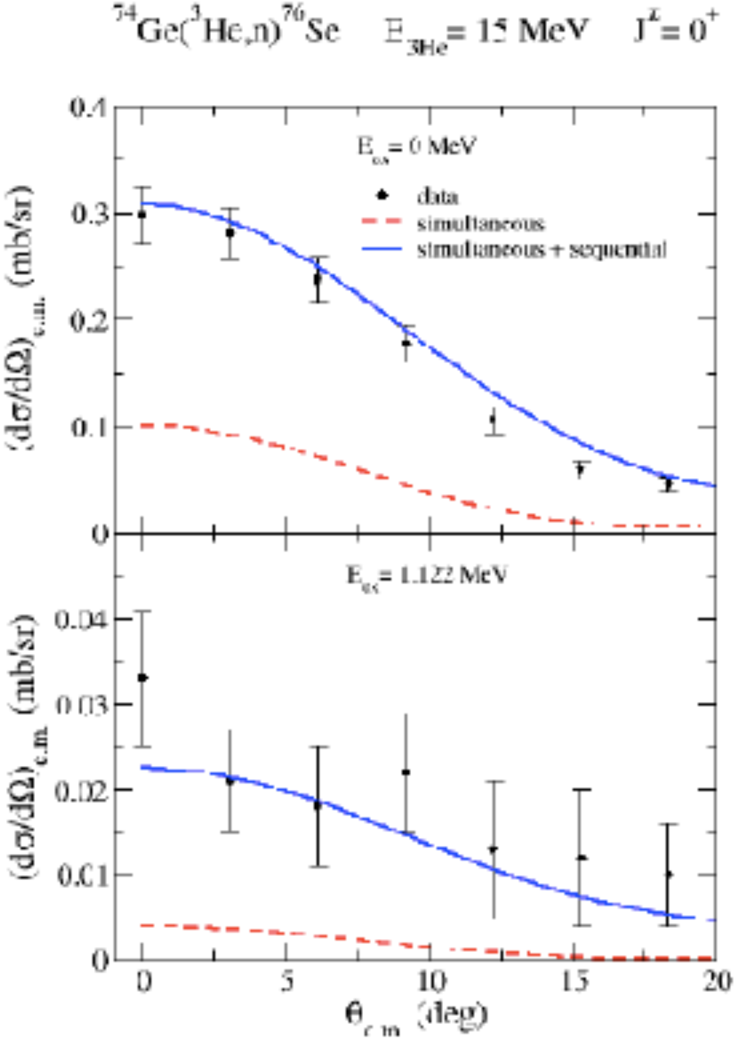
^{2}H Compton scattering cross section at 65 MeV. Measurement to separate inelastic channel is underway.

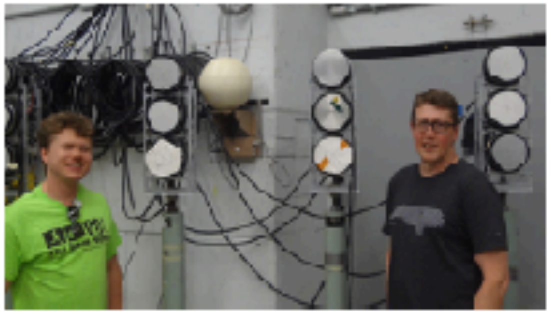
Rate for decay by exchange of virtual Majorana neutrinos:

$$\left[t_{1/2}^{(0\nu)}\right]^{-1} = G_1^{(0\nu)} \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2 \left(M^{(0\nu)}\right)^2$$

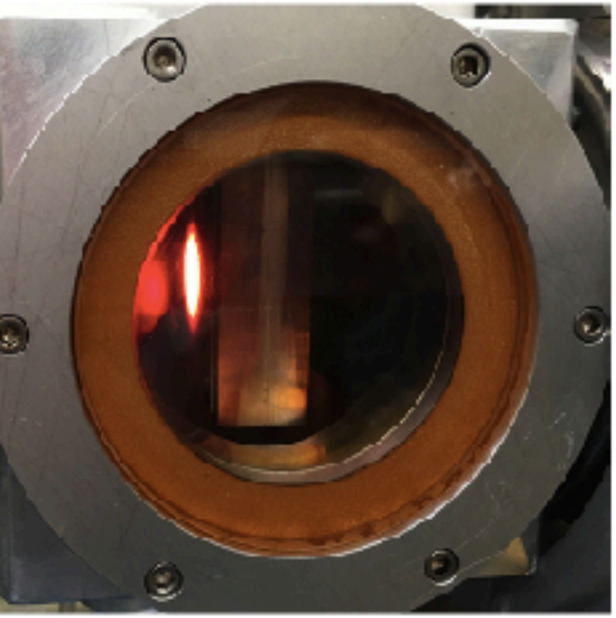
QRPA calculations of $(M^{(0\nu)})^2$ assume that the initial and final wavefunctions can be represented as a BCS condensate of the nucleons, an approximation that can be evaluated using two-nucleon transfer reactions





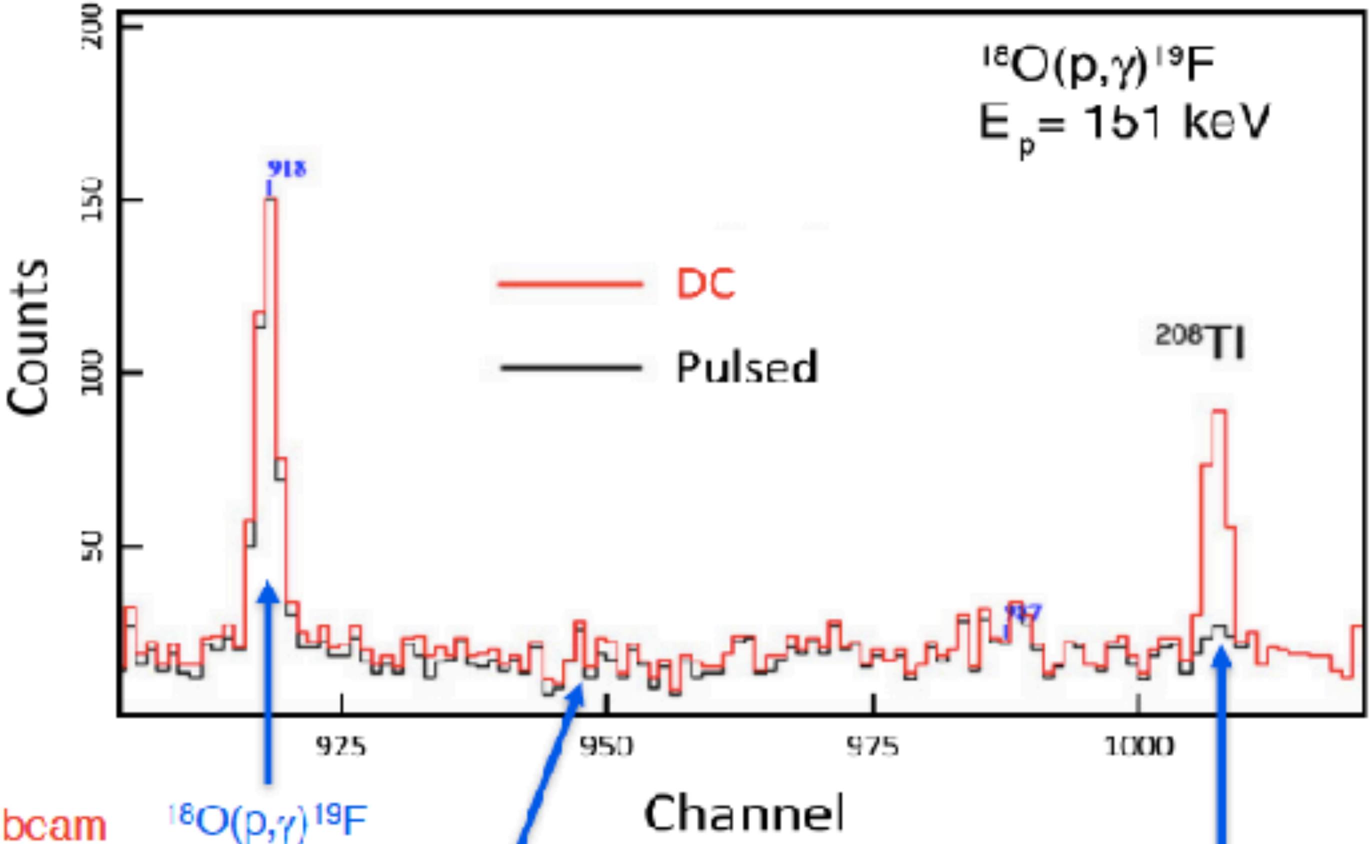


DWBA calculations performed by Alex Brown (MSU) using FRESCO: Ratio of first 0+ excited state to the ground state transition is consistent with the BCS approximation used in QRPA calculations of the $(M^{(0\nu)})^2$ for $0\nu\beta\beta$ of ^{76}Ge



H^+ beam on target:
~5 mA @ 200 keV
(most intense low-energy beam for nuclear astrophysics)

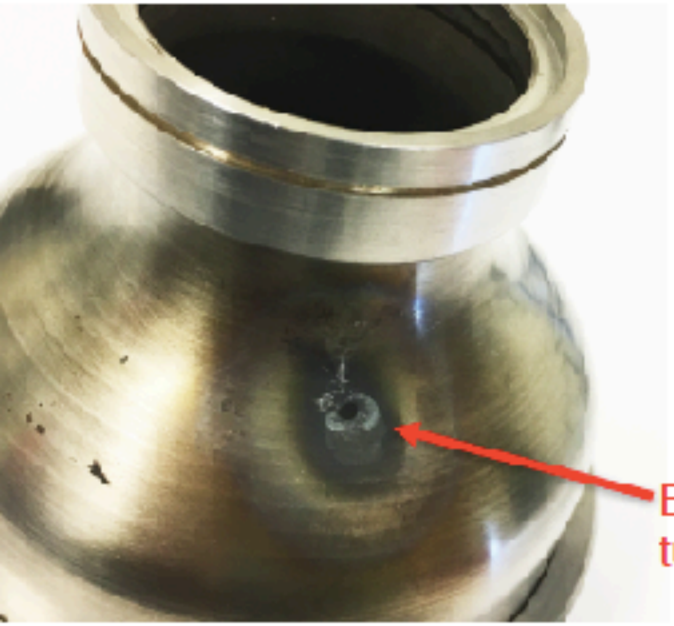
Background reduction via beam pulsing



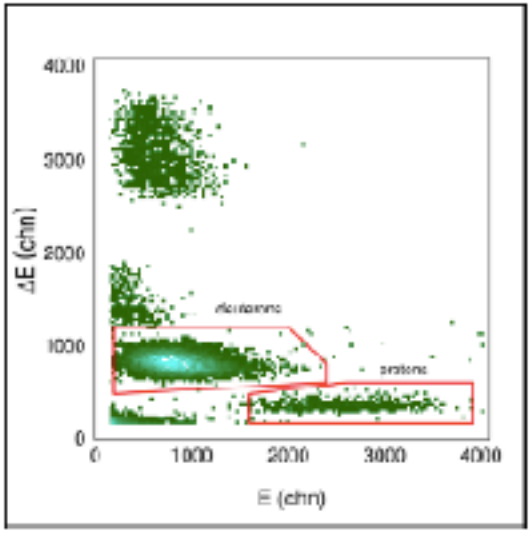
$^{18}O(p,\gamma)^{19}F$

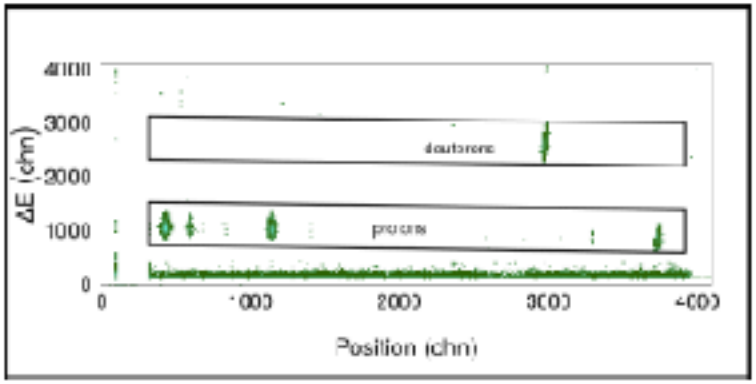
Comptons from higher-energy transitions

room backgroun



Bad beam tuning

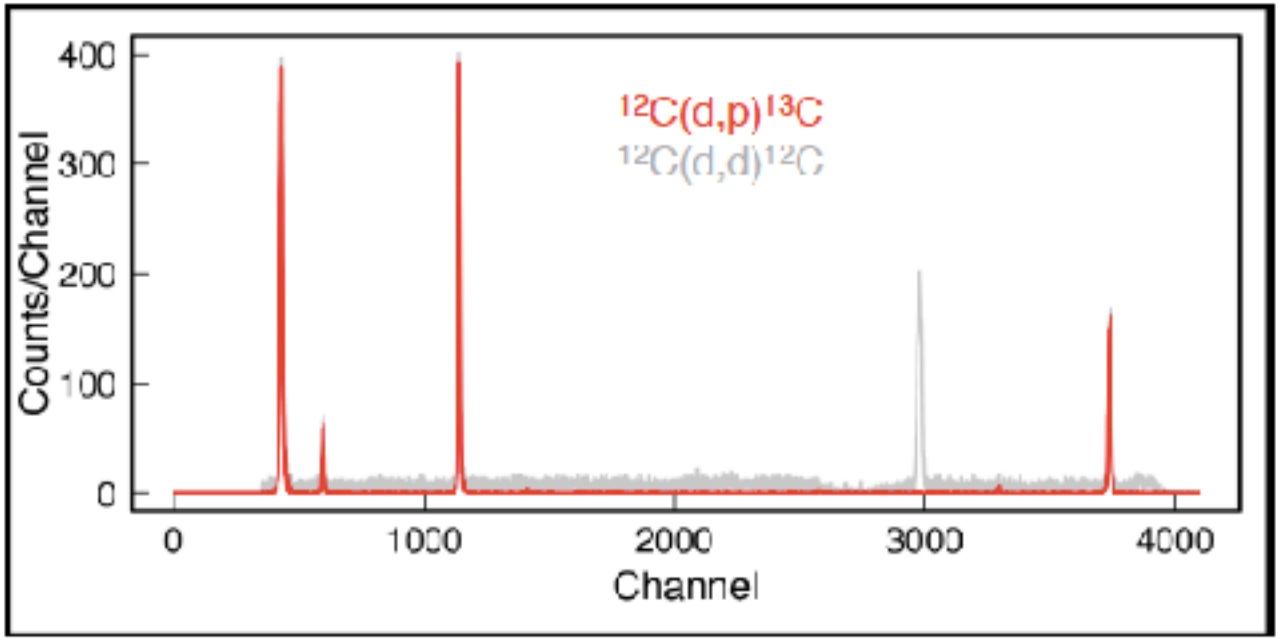




Spectrometer and detectors fully recommissioned

Upgrades to focal-plane detector:

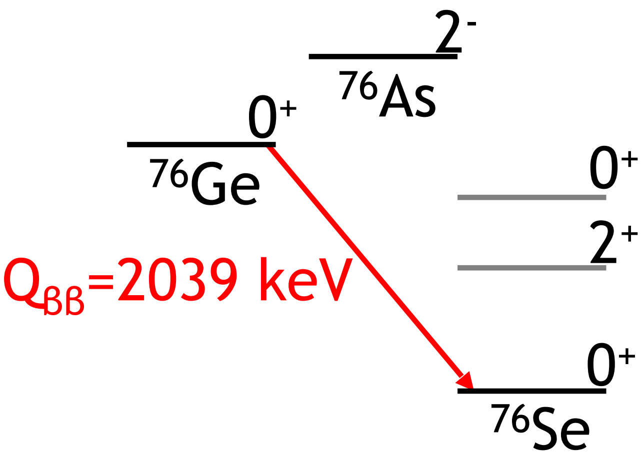
- Fiber readout
- Low-noise DL using in-house cremat pre-amps
- Sub-mm position resolution, robust operation



University of Kentucky Accelerator Laboratory

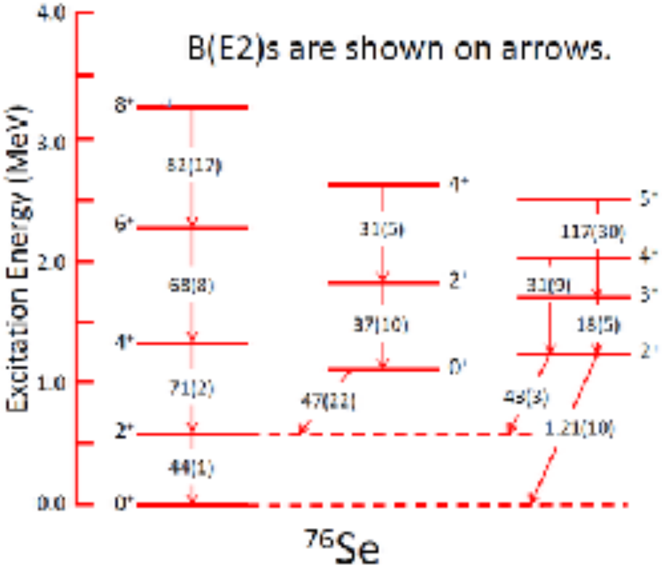
Nuclear Structure Relevant to Neutrinoless Double-β Decay: Detailed Studies of ^{76}Ge and ^{76}Se with the (n,n′γ) Reaction

7-MV Van de Graaff



- Monoenergetic fast neutrons
- Level Lifetimes by DSAM

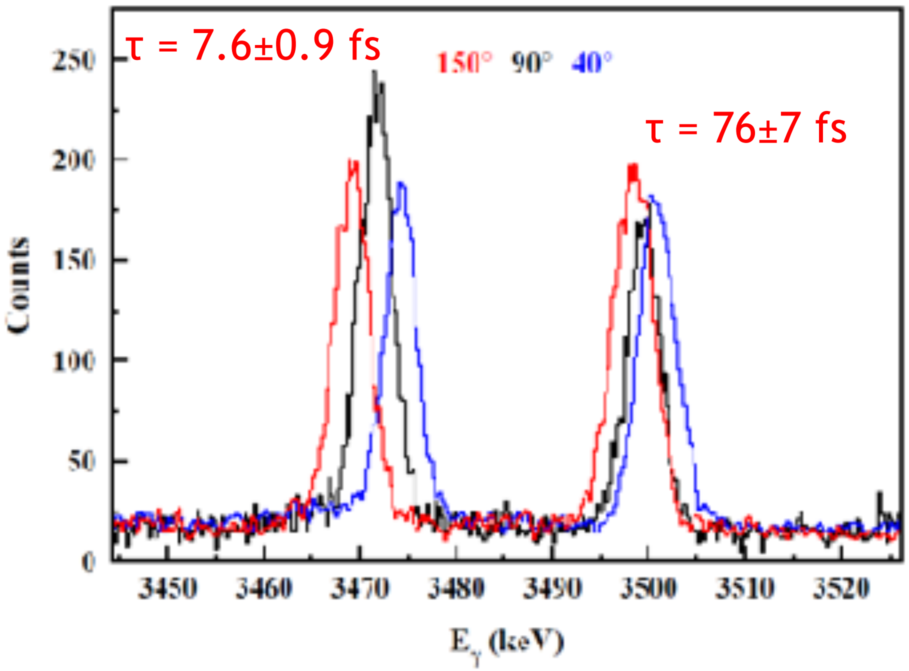
S. Mukhopadhyay *et al.*, in progress.



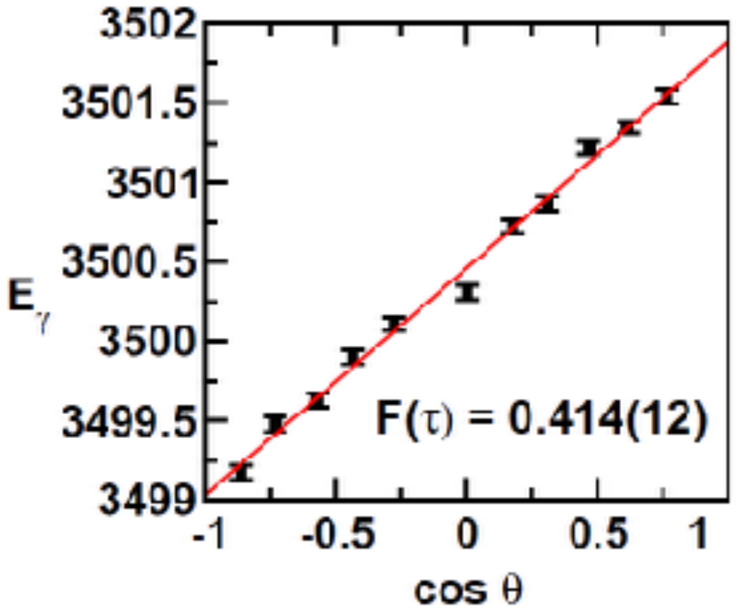
Association for Research at University Nuclear Accelerators

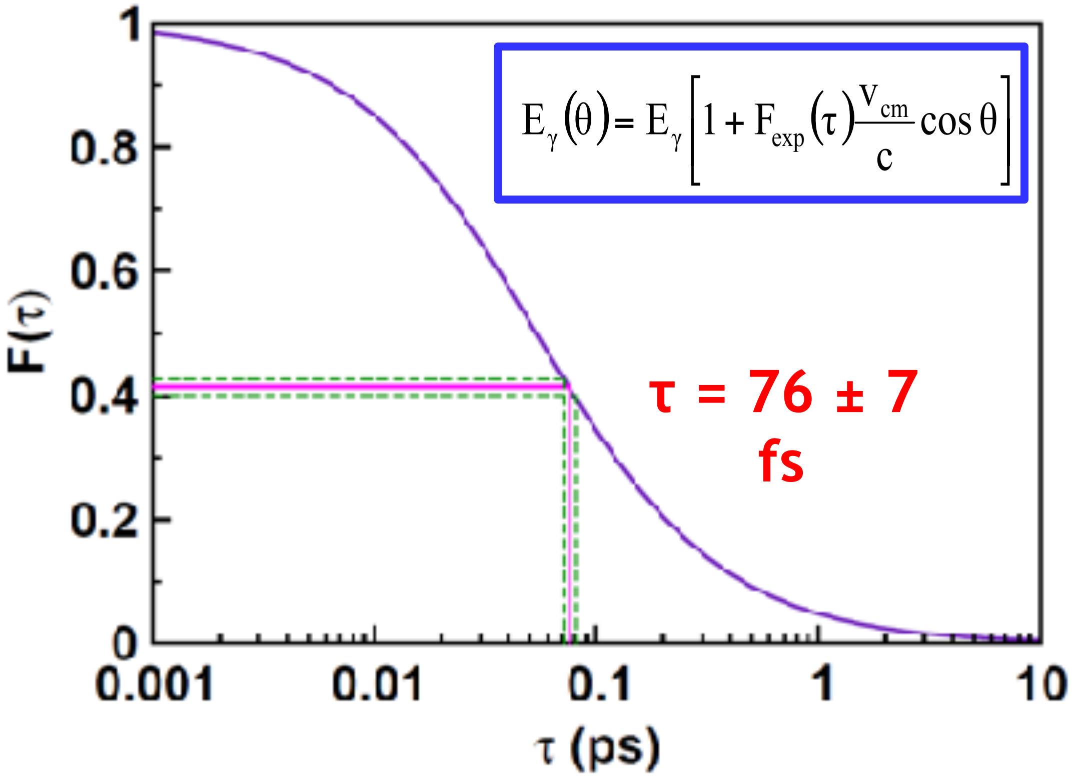
Nuclear Level Lifetimes by Doppler-Shift Attenuation following Inelastic Neutron Scattering

- Following neutron scattering, the nucleus recoils.
- The emitted γ rays experience a small Doppler shift.
- Level lifetimes in the femtosecond regime can be determined.


τ = 7.6±0.9 fs

τ = 76±7 fs

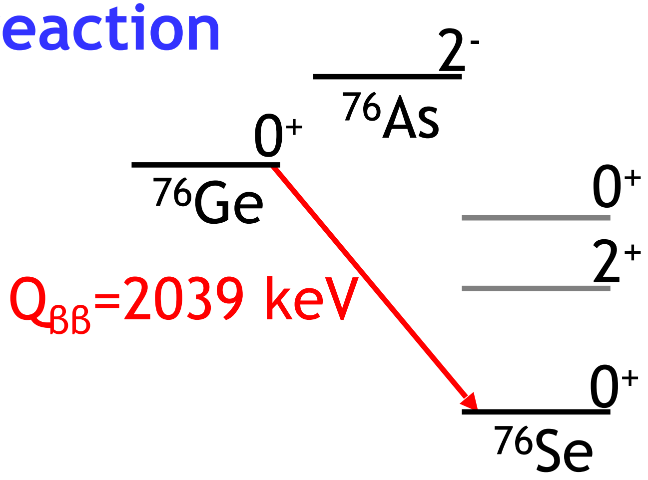

F(τ) = 0.414(12)


$$E_\gamma(\theta) = E_\gamma\left[1 + F_{exp}(\tau)\frac{V_{cm}}{c}\cos\theta\right]$$

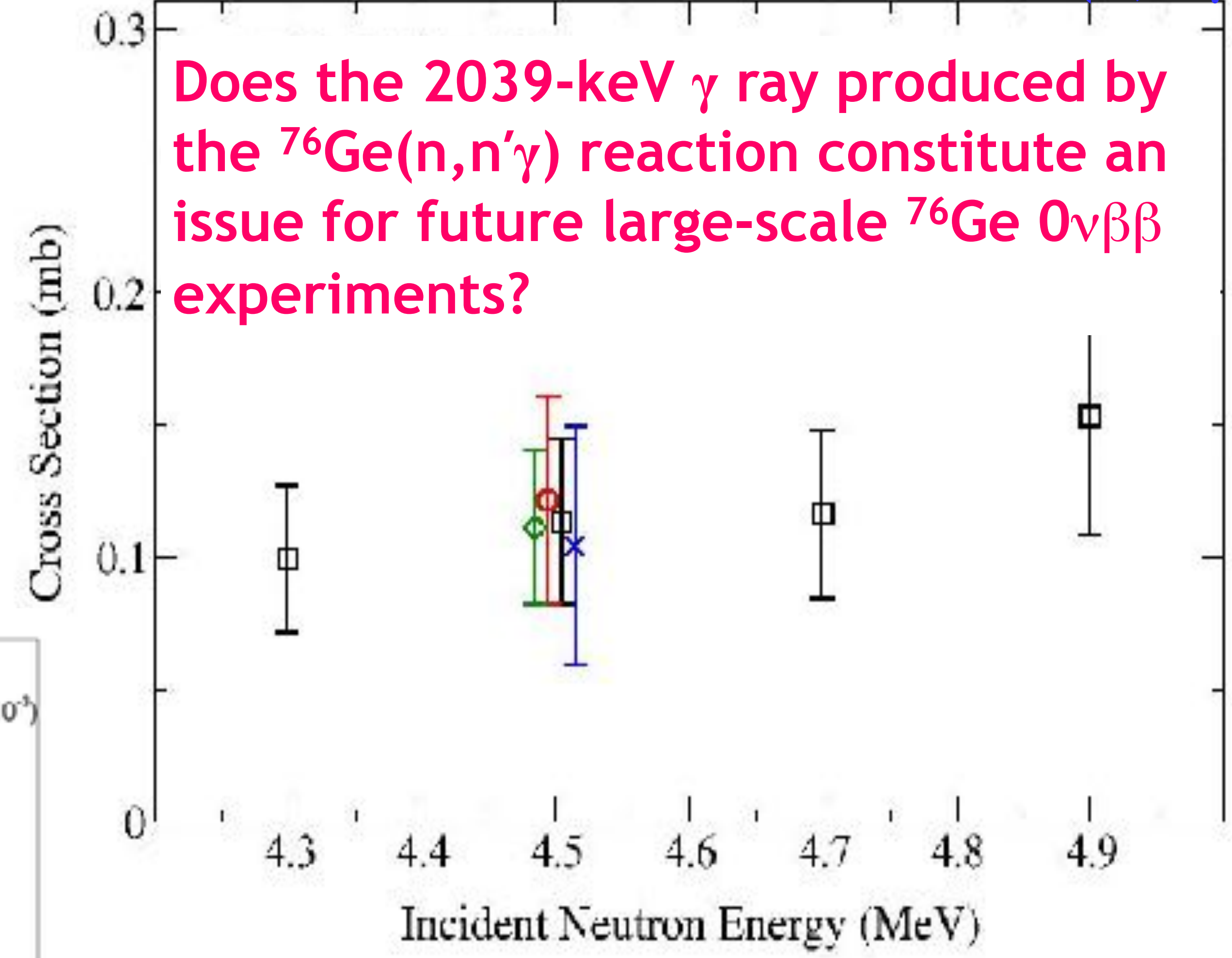
τ = 76 ± 7 fs

Fast-neutron-induced Background Near the Q value for $0\nu\beta\beta$

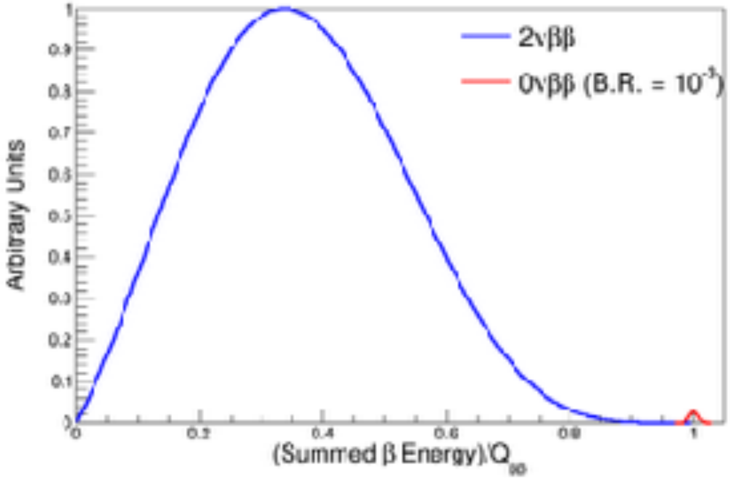
A detailed study of the nuclear structure of $^{76}\mathrm{Ge}$ via the $^{76}\mathrm{Ge}(n,n'\gamma)$ reaction



$Q_{\beta\beta}$=2039 keV



Does the 2039-keV γ ray produced by the $^{76}\mathrm{Ge}(n,n'\gamma)$ reaction constitute an issue for future large-scale $^{76}\mathrm{Ge}$ $0\nu\beta\beta$ experiments?



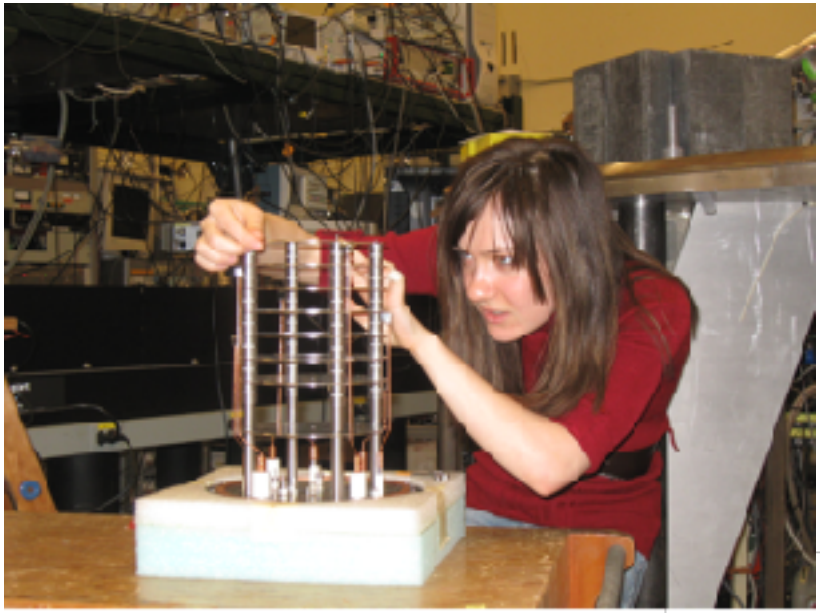
B.P. Crider *et al.*, Phys. Rev. C 92, 034310 (2015).

^{6}He β-ν angular correlation at U. of Washington

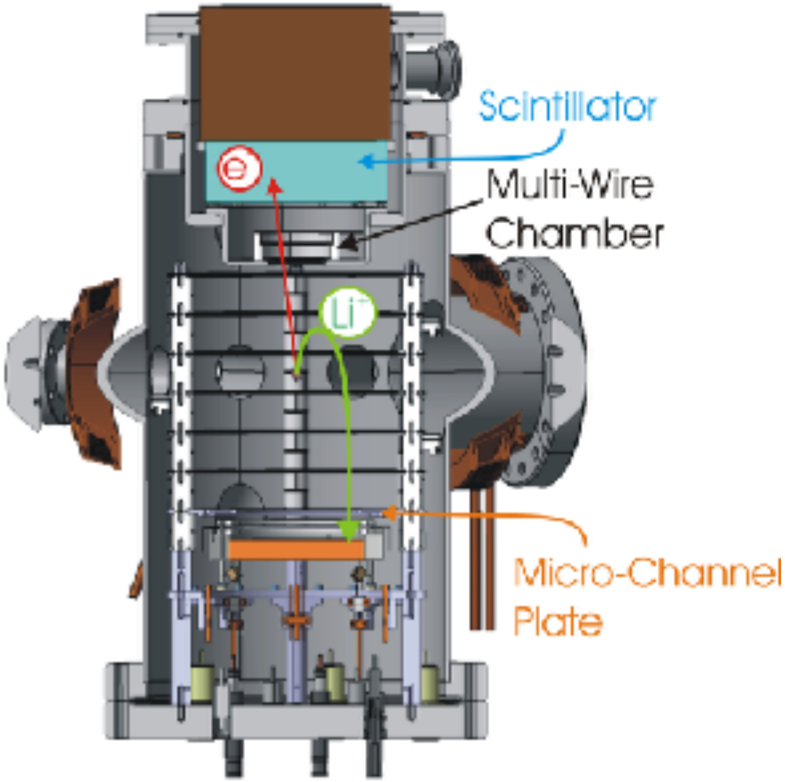
Y. Bagdasarova[1], K. Bailey[2], X. Fléchard[3], A. Garcia[1,*], R. Hong[1], A. Knecht[4], A. Leredde[2], E. Liennard[3], P. Mueller[2,*], O. Naviliat-Cuncic[5], T. O'Connor[2], M. Sternberg[1], H.E. Swanson[1], F. Wauters[1]

[1]*University of Washington*, [2]*Argonne National Lab*, [3]*LPC, CAEN, France*
[4]*PSI*, [5]*NSCL, Michigan State University*

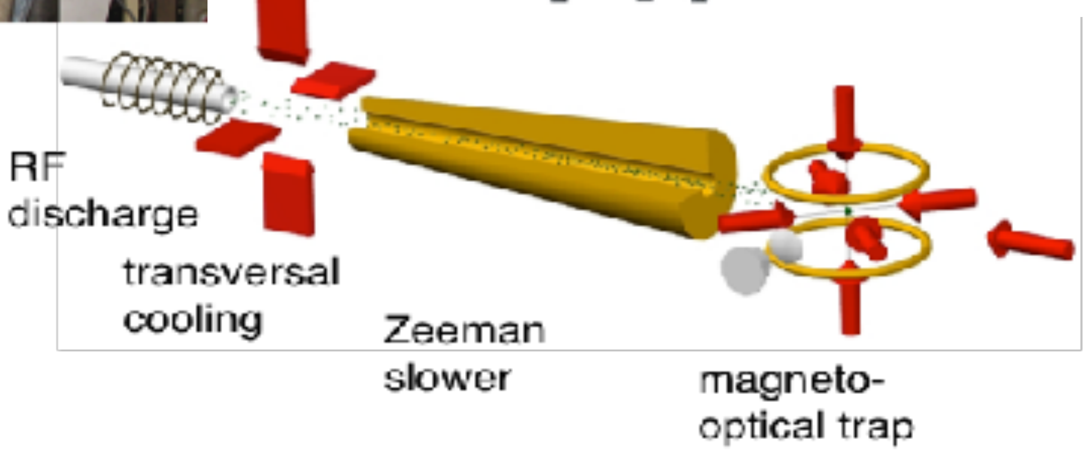
[*]Spokepersons



^{6}He Trap/Detector Chamber



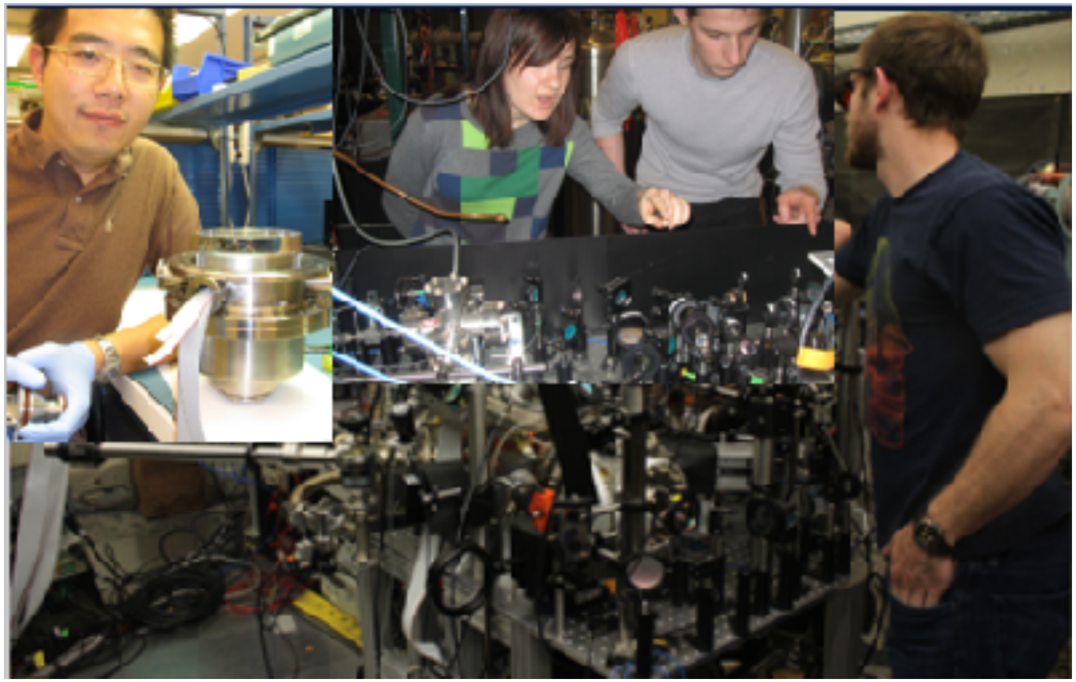
- Goal: measure "little a" to 0.1% in ^{6}He
  - pure Gamow-Teller decay
  - sensitive to tensor couplings
  - simple nuclear and atomic structure
- Laser cooling and trapping to prepare ^{6}He source (t ≈0.8 s)
- Detect electron and ^{6}Li in coincidence



^{6}He little-*a* measurement at U. of Washington

6He Source:
Reliable source of ~10^{10} ^{6}He's/s in low-background environment
A. Knecht et al. NIM A. **660**, 43 (2011)

Laser trapping and detection systems:
All systems working after much development.



First physics results:
Measurement of Li-ions charge distribution and comparison with atomic theory. Interesting discrepancies.
Submitted to PRC.

Status:

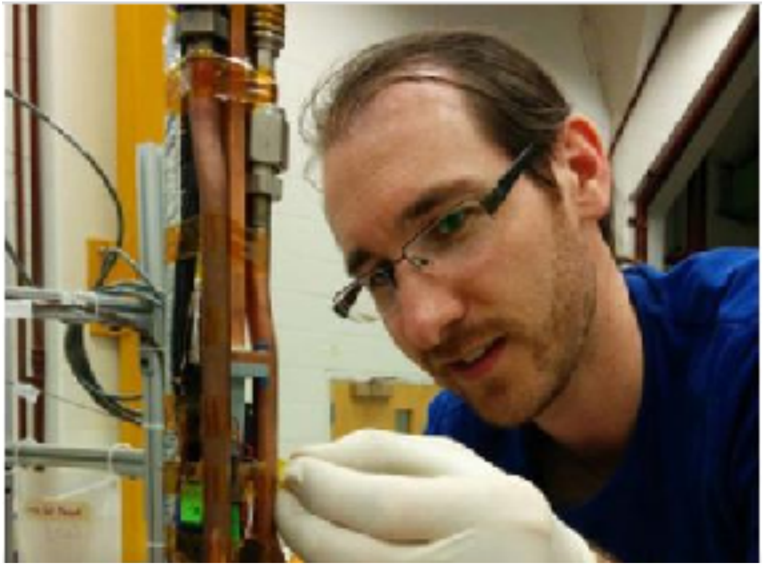
- Now efficiencies good for determination of little-a at the 1% level within 3 days.
- Presently working on systematic uncertainties.
- Aiming for $\Delta a/a$ <1% in near future.

^{6}He little-*b* measurement at U. of Washington

M. Fertl[1], A. Garcia[1], M. Guigue[4], P. Kammel[1], A. Leredde[2], P. Mueller[2], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[3], M. Sternberg[1], H.E. Swanson[1], B.A. Vandeevender[4], A. Young[3]

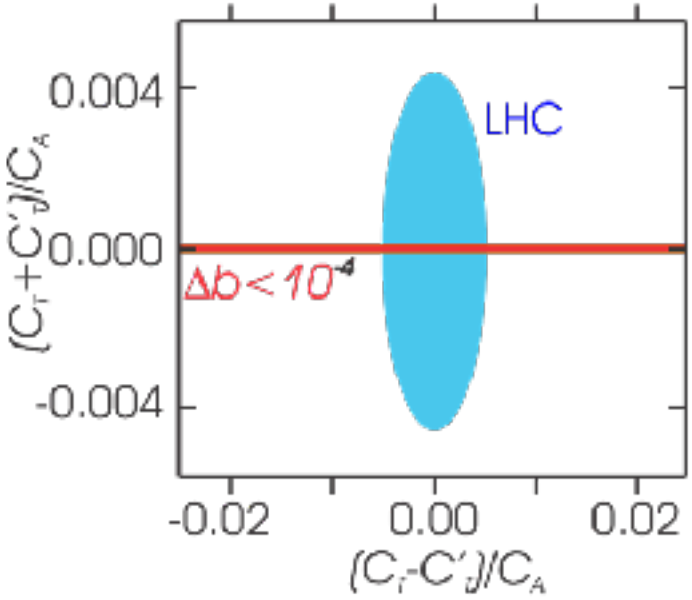
[1]*University of Washington,* [2]*Argonne National Lab,* [3]*North Carolina State University,* [4]*Pacific Northwest National Laboratory*

Use Cyclotron Radiation Electron Spectroscopy. Similar to Project 8 setup for tritium decay.



LRP: *…weak decay measurements with an accuracy of 0.1% or better provide a unique probe of new physics at the TeV energy scale, offering discovery potential complementary to muon and electron weak force measurements.*

- Goal: measure beta spectrum with high precision to search for "little b" deeper than 10^{-3} in ^{6}He.
- Most sensitive experiment ever proposed to search for chirality-flipping interactions. Sensitivity more than 1 order of magnitude higher than LHC!

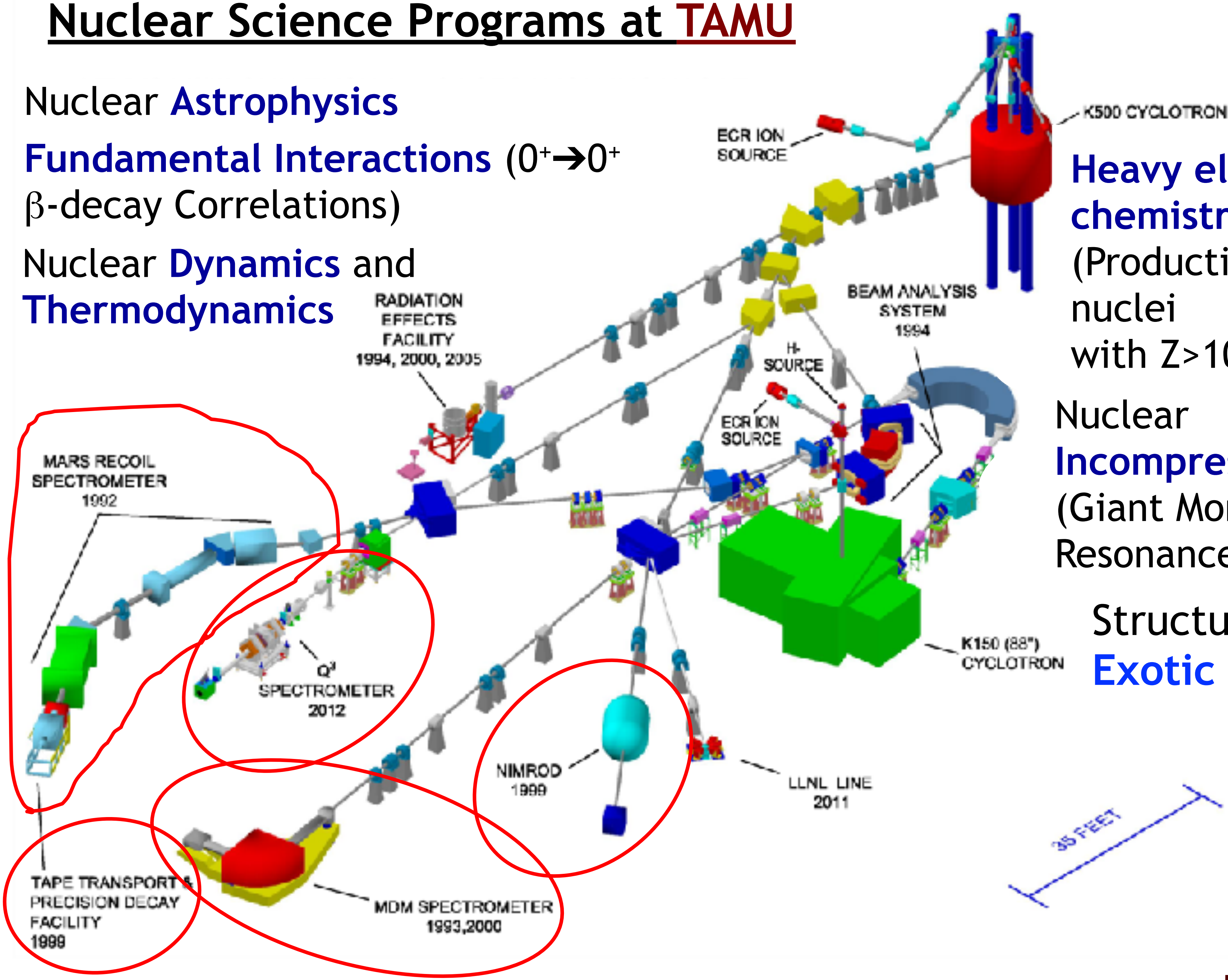


Nuclear Science Programs at TAMU

Nuclear **Astrophysics**

Fundamental Interactions ($0^+ \rightarrow 0^+$ β-decay Correlations)

Nuclear **Dynamics** and **Thermodynamics**



Heavy element chemistry (Production of nuclei with Z>100. . .)

Nuclear **Incompressibility** (Giant Monopole Resonance)

Structure of **Exotic nuclei**

PRECISE TEST OF INTERNAL CONVERSION THEORY

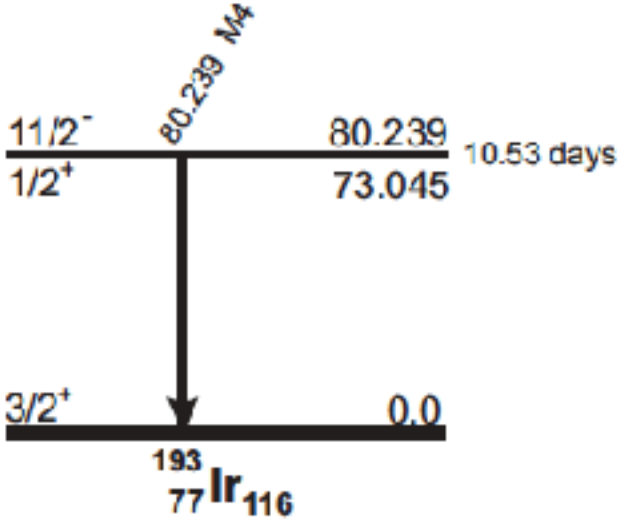
Method:

Measure γ ray and K x rays simultaneously in a single well-calibrated HPGe detector

$$\boxed{\alpha_K\,\omega_K = \frac{N_K}{N_\gamma}\,\frac{\varepsilon_\gamma}{\varepsilon_K}}$$

ω_K, the fluorescence yield, is known from systematics to 0.5%

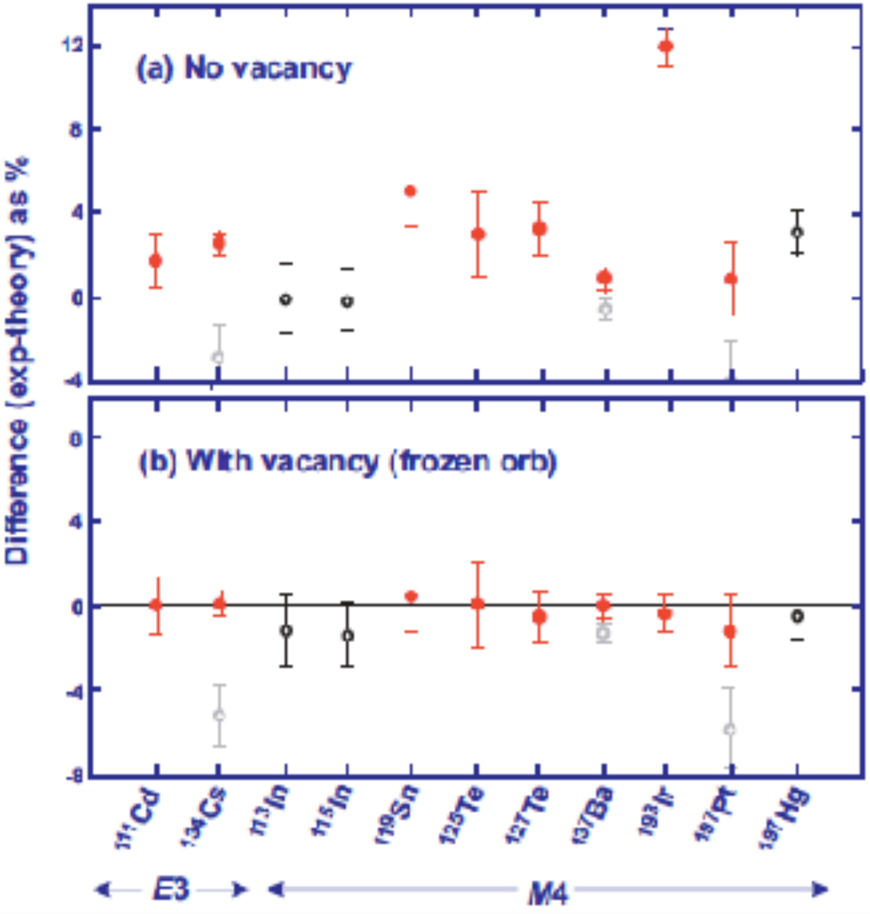
Example:



Result:

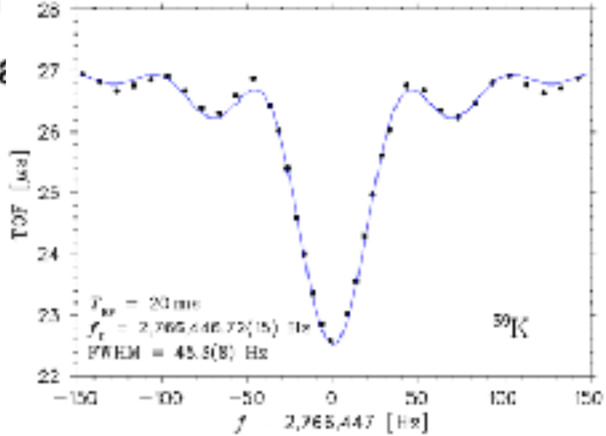
World data for α_K values measured to <2% precision. **Our results are in red.**

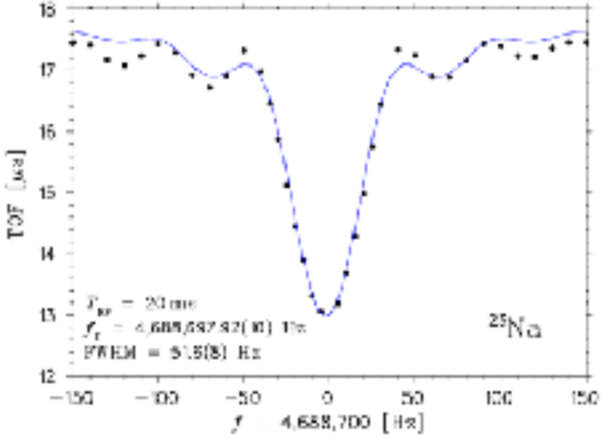
Demonstrates the need to include the atomic vacancy in calculations.

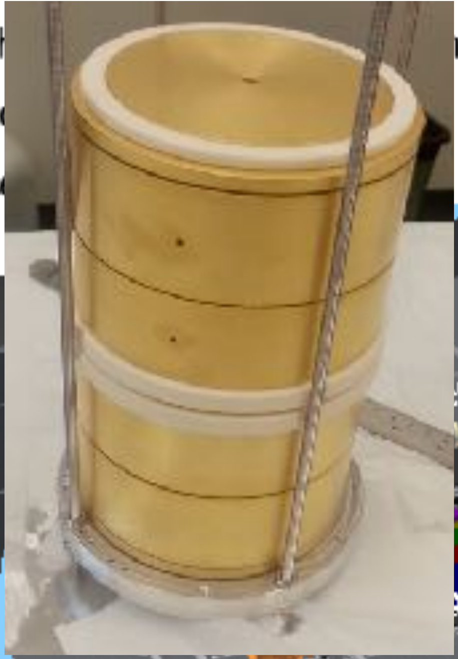


Texas A&M University Penning Trap (TAMUTRAP)

- Prototype trap: with d = 90 mm, it is th … ni
- Uniquely suited for studying β-delaye … c
- Ma … . las







Demonstrated ability to perform a 0.1 ppm mass measurement Aug 3rd (*very* preliminary)

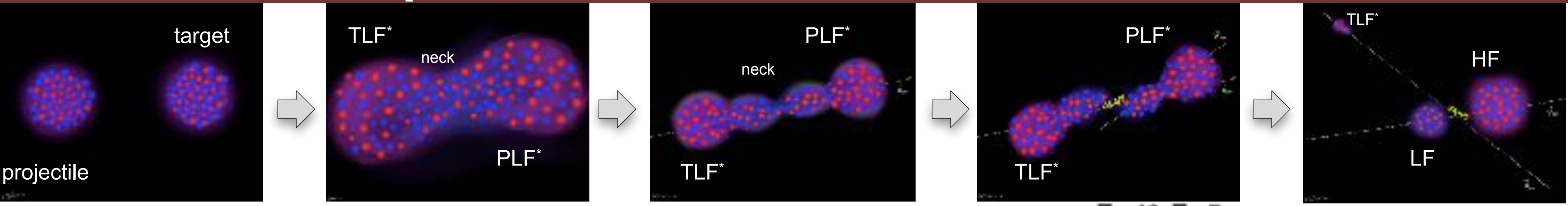
$$M_{^{23}\mathrm{Na}} = 21.414\,3212(12)\ \mathrm{GeV}$$

vs

$$\mathrm{AME} = 21.414\,3233\ \mathrm{GeV}$$

Equilibration Chronometry

Characterizing neutron-proton equilibration with sub-zeptosecond resolution



Motivation:

Constrain the nuclear equation of state.

Background:

N-Z equilibration should be directly observable in heavy ion reactions.

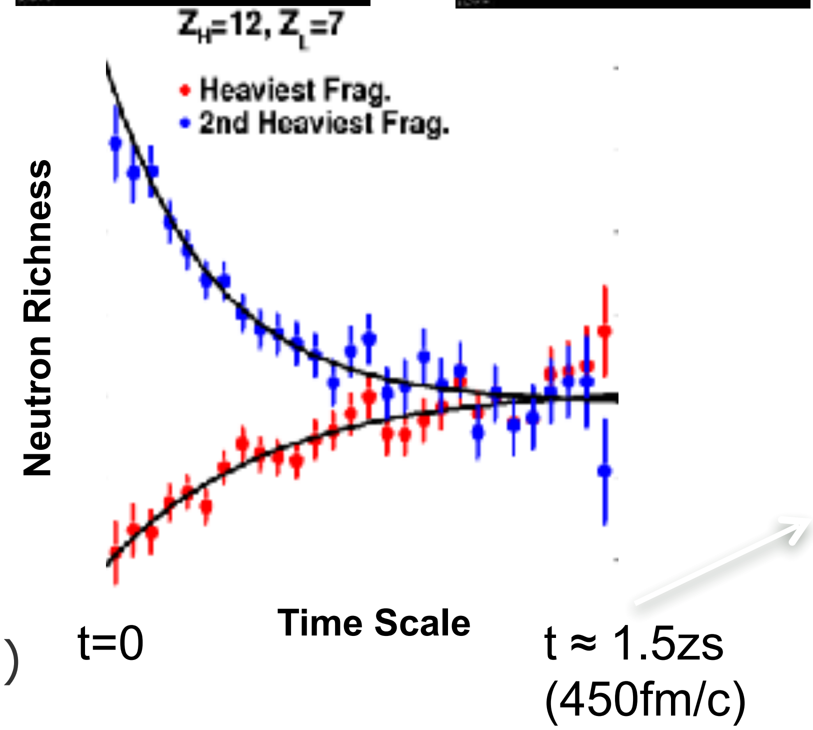
One fragment from binary split evolves in time.

Hypothesis:

The composition of the two fragments from a binary split should evolve toward each other with time.

Methods:

NIMROD 4π array.
First measurement of N-Z of both fragments.
Fine time resolution from alignment angle.



A. Jedele, et al., Phys. Rev. Lett. 118, 062501 (2017)

Results:

We observe N-Z equilibration as a function of time.
Equilibration curve is approximately exponential → First order kinetics
Zeptosecond timescale.

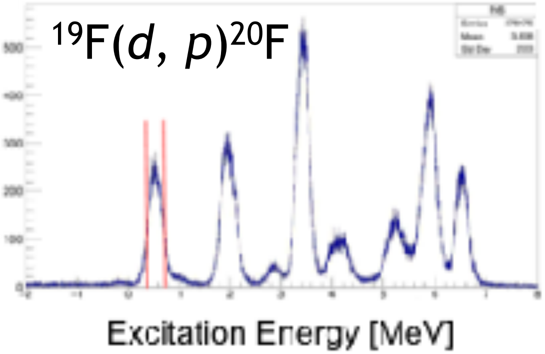
Reactions with RIBs

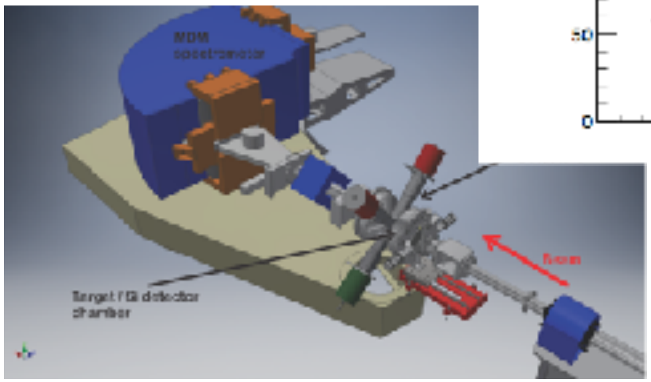
Nuclear Astrophysics with TIARA

- Indirect measurements of astrophysical radiative capture reactions using (d, p) and (6Li,d) at ~10A MeV.

- Commissioning and stable beam campaign in Fall 2016.

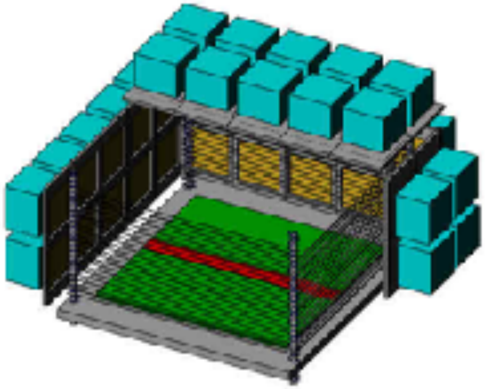
Classical novae	S-process
^{19}F(d, p)^{20}F	^{25}Mg(d, p)^{26}Mg
^{23}Na(d, p)^{24}Na	^{22}Ne(^{6}Li, d)^{26}Mg





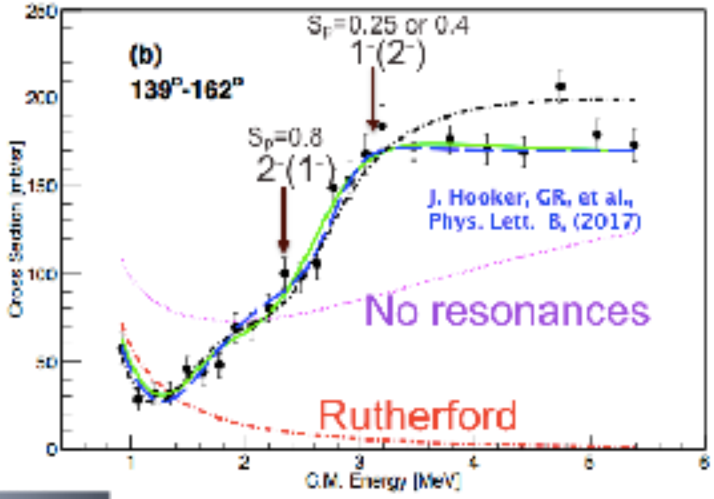
Active Target

TexAT



Structure of ^{10}N

Excitation function for ^{9}C+p elastic scattering



Extraction of Nh (Z = 113) Homolog In^{3+} Using Deep Eutectic Solvents

- Deep eutectic solvents are compounds with tunable chemical properties. Two solids are mixed to create a liquid.
- The slope gives us the speciation.
- DESs are being considered for application to Nh chemistry.

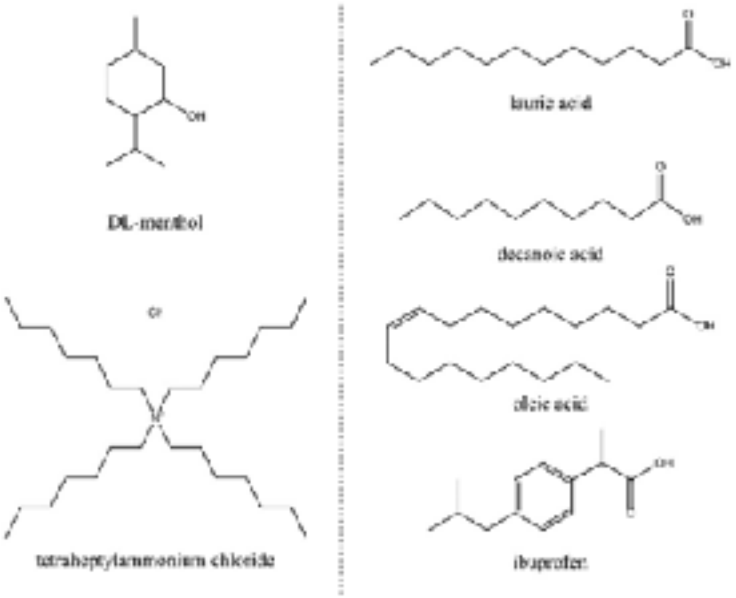


Fig. 1 Chemical structures of compounds used in this work for the preparation of the quaternary ammonium- and menthol-based mixtures (left – hydrogen bond acceptors, right – hydrogen bond donors).

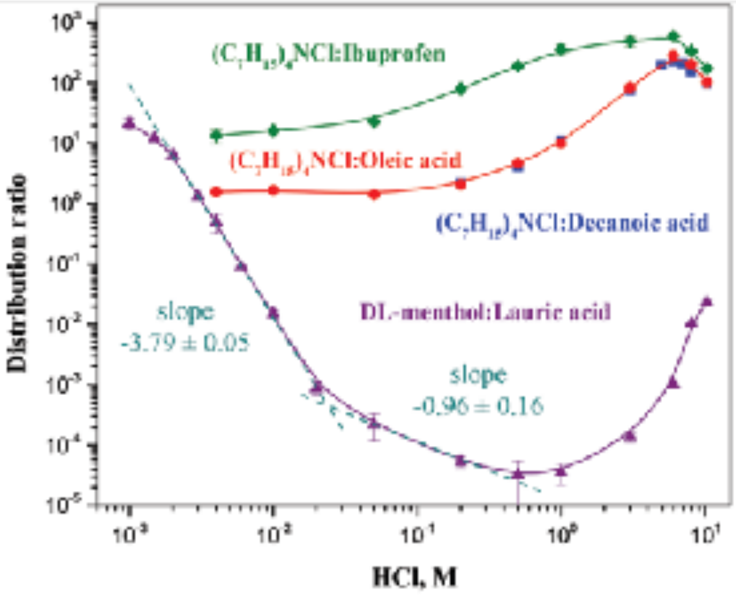


Fig. 3 Effect of aqueous hydrochloric acid concentration on the extraction efficiency of In into quaternary ammonium- and menthol-based hydrophobic mixtures. The solid lines are drawn to guide the eye.

E. E. Tereshatov *et al.*, Green Chem. **18**, 4616 (2016). doi:10.1039/c5gc03080c

Achievements 2013-2017

- Mapping the CNO and NeNa cycles

  $^{12}C(p,\gamma)^{13}N$, $^{14}N(p,\gamma)^{15}O$, $^{15}N(p,\gamma)^{16}O$, $^{17}O(p,\gamma)^{18}F$, $^{20}Ne(p,\gamma)^{21}Na$, $^{23}Na(p,\gamma)^{24}Mg$,

  Future measurements on $^{14}N(p,\gamma)^{15}O$ at CASPAR

- Closing in on neutron sources

  $^{22}Ne(\alpha,n)$ (via $^{26}Mg(\gamma,\gamma')$, $^{26}Mg(\alpha,\alpha')$, $^{22}Ne(^{6}Li,d)$ studies); completed

  Direct measurement of $^{10}B(\alpha,n)$, $^{11}B(\alpha,n)$, $^{13}C(\alpha,n)$ at NSL

  Future $^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$ at CASPAR

- Fusion and reactions in late stellar evolution

  $^{12}C+^{16}O$ for late stellar evolution and explosive oxygen burning with rebuilt SAND detector,

  Future measurement of $^{12}C+^{12}C$ at NSL and $^{20}Ne(\alpha,\gamma)$ at RHINO gas target

- The αp-process in X-ray bursts

  Completion of (p,t) studies in the sd-shell at RCNP Osaka for probing the compound nuclei of ^{18}Ne, ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, and $^{38}Ca(\alpha,p)$ reactions in preparation for RIB studies.

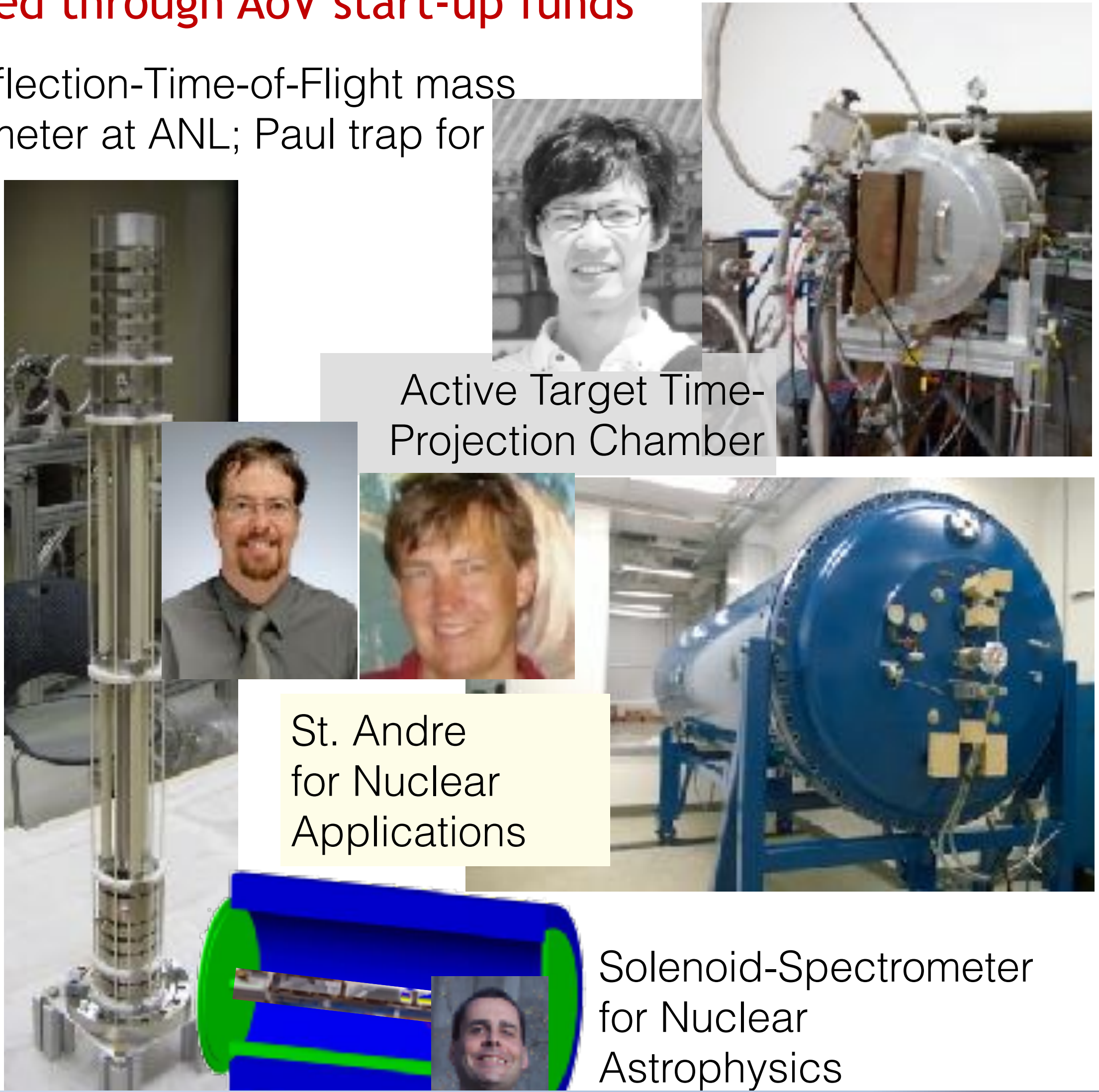
New Equipment developments

Financed through AoV start-up funds

Multi-Reflection-Time-of-Flight mass spectrometer at ANL; Paul trap for TwinSol

Gamma Summing Detector Array: HECTOR
(High EffiCiency TOtal absorption spectrometeR)

Enge Split-Pole Separator



Active Target Time-Projection Chamber

St. Andre
for Nuclear
Applications

Solenoid-Spectrometer for Nuclear Astrophysics

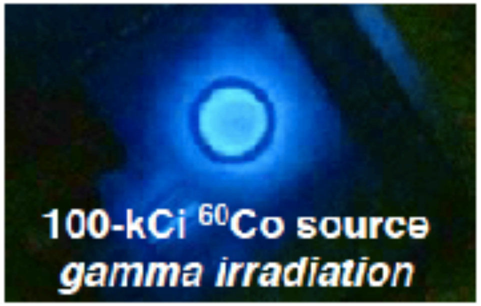
UMass Lowell Radiation Laboratory - Overview


Partha Chowdhury


Andrew Rogers

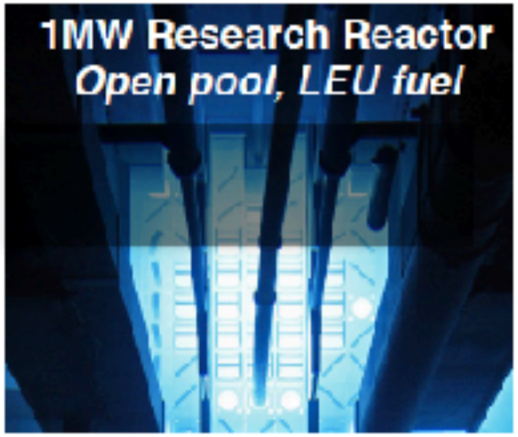

Kim Lister (emeritus)

\+ Incoming Faculty Fall 2017
Peter Bender
Marian Jandel

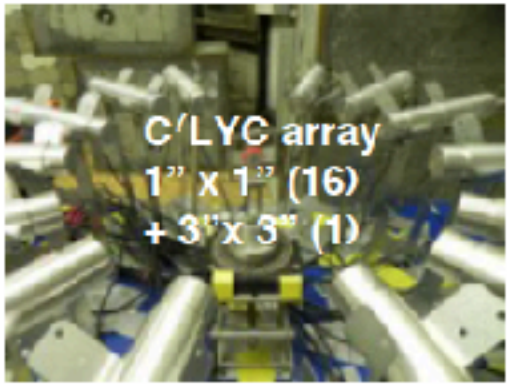

100-kCi ^{60}Co source
gamma irradiation

p, *d*, He, ... ions
100 μA DC beam
Sub-ns pulsing
Mono-energetic pulsed neutrons via ^{7}Li(p,n)
(goniometer, ToF)
Ion microprobe (PIXE and RBS)
General purpose scattering chamber


5.5 MV Van de Graaff
CN, single ended

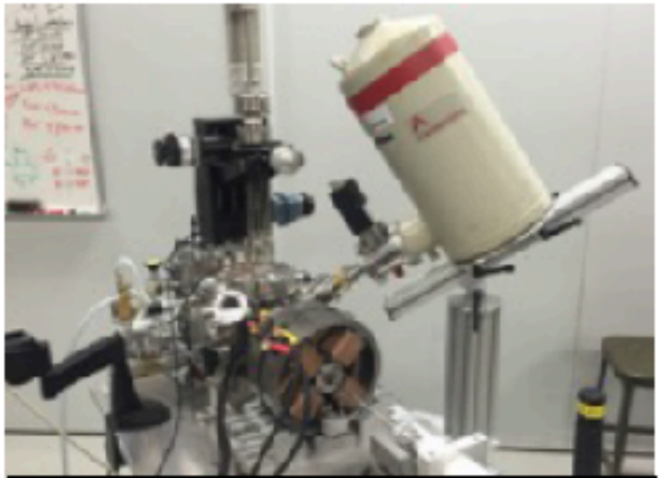

1MW Research Reactor
Open pool, LEU fuel

in-core sample (~10^{13} n/cm^2/s)
graphite thermal column (~10^{6} n/cm^2/s)
digital neutron radiography
hot cell, remote manipulators


C^7LYC array
1" x 1" (16)
\+ 3" x 3" (1)

Collaborators/Users: MIT/UMich/Penn State/GaTech, Yale, PHDS, CapeSym, RMD, Neutron Therapeutics,,...

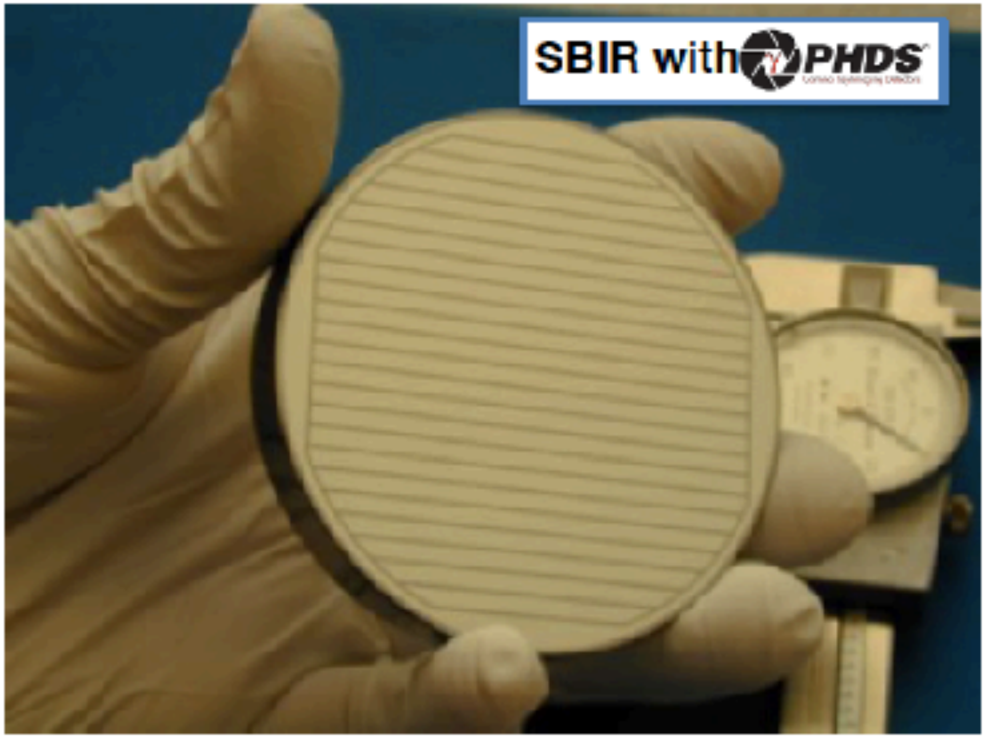

2 postdocs
~ 6 grads, 6 undergrads

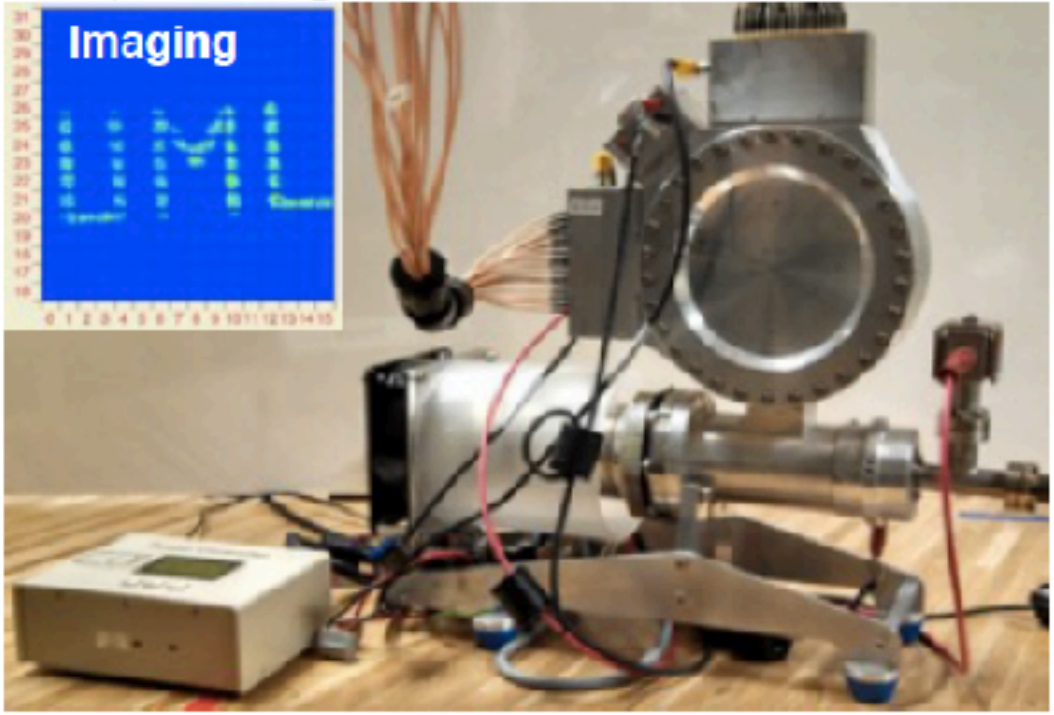

Proton microbeam and PIXE

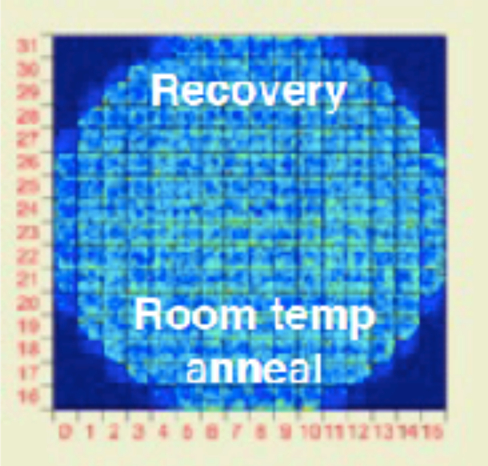

Compton-suppressed Ge array

NEW! Neutron Damage & Recovery: Segmented HPGe

- Segmented large planar Ge with new contact technology
- Applications in imaging and high count rate capabilities.
- **Neutron damage tests and "repairability" at UMass Lowell accelerator for in-beam physics**
- SBIR Phase2 grant with PHDS Co. to design a streamlined cryostat for an array tailored towards "in-beam" spectroscopy of superheavy elements.
- Controlled dose of mono-energetic neutrons from accelerator to induce lattice damage and charge trapping
- In-house annealing to assess robustness of contacts
- Repeat with higher doses to ascertain limits

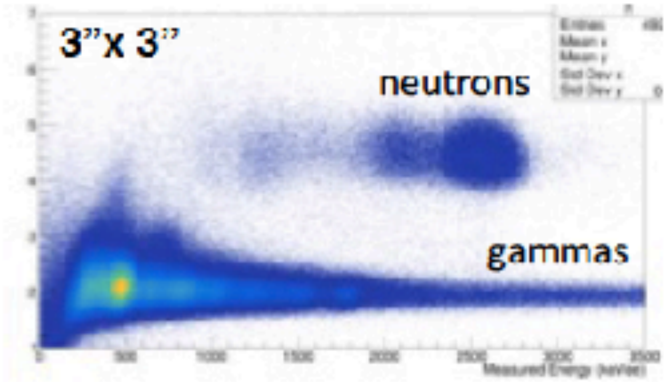




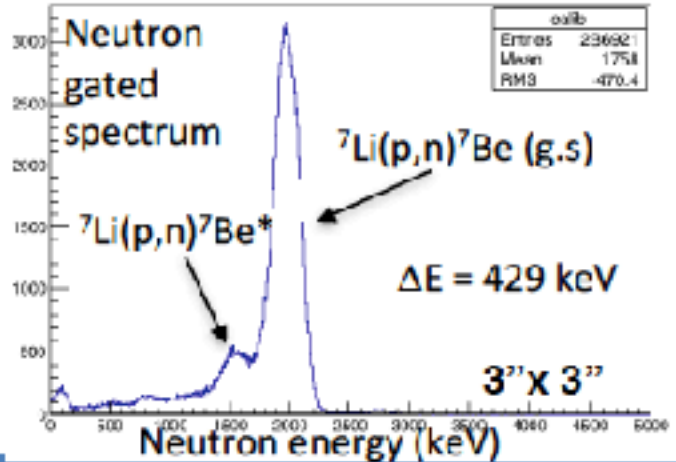


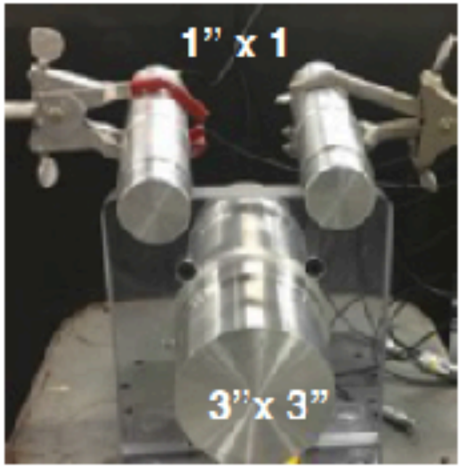
NEW! Fast Neutron Spectroscopy and Deuteron Beams

- 3"x3" + array of sixteen 1" x 1" C^7LYC scintillators
- Fast neutron detection via $^{35}Cl(n,p)$ reaction
- $^{35}Cl(n,p)$ cross-section measurements lacking in databases
- Large uncertainty in Monte Carlo simulations
- **Directly measure C^7LYC efficiency at accelerator**
- Mono-energetic neutrons produced via $^7Li(p,n)^7Be$ reaction
- Neutron production rate via ^7Be assay (52-day half-life)
- One ^7Be per neutron, 10% β-decay branch produces 479-keV γ-ray

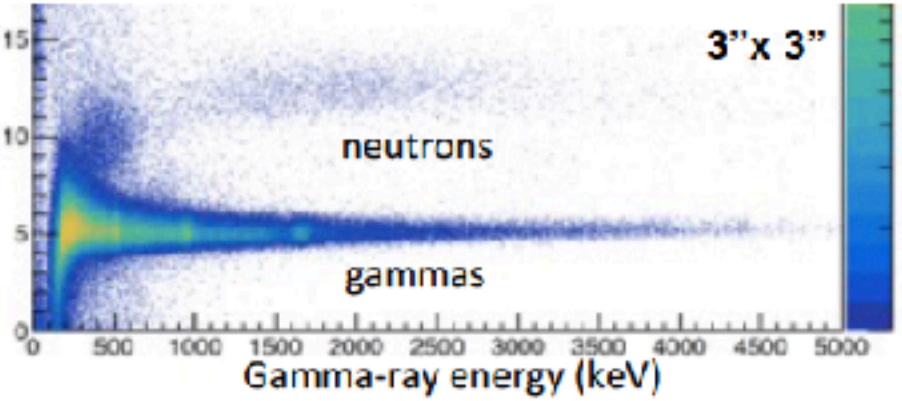


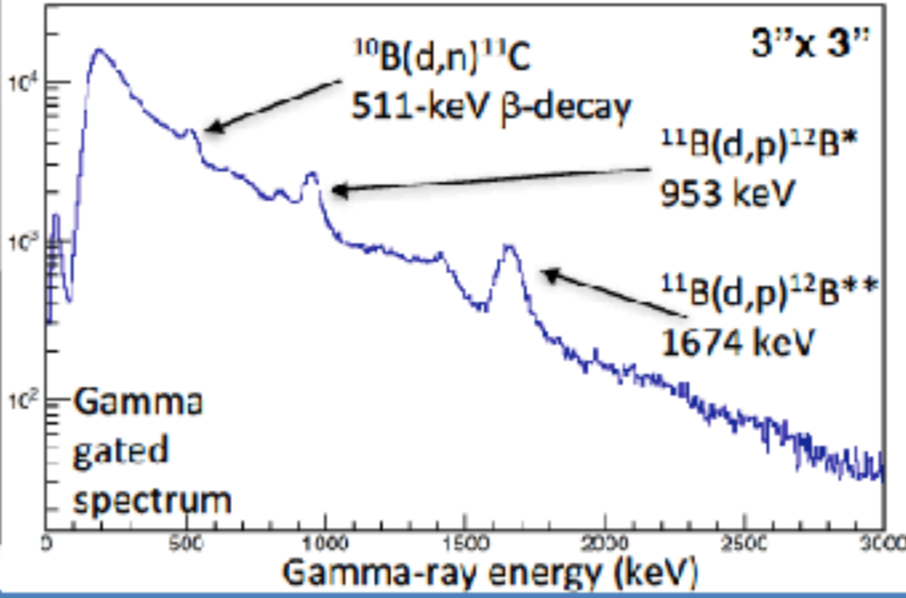

In-situ lithium target evaporator





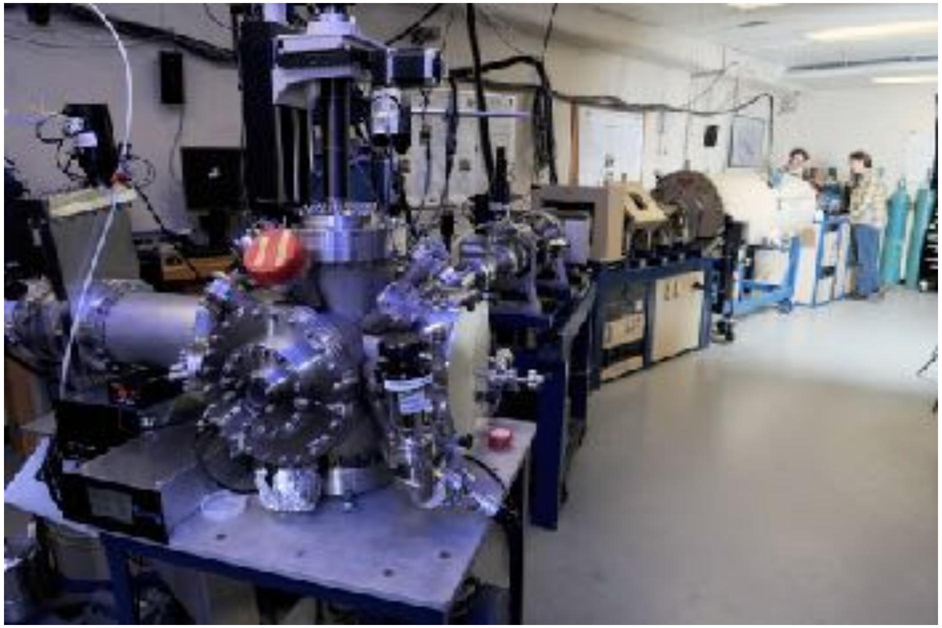
- **Beam tests with ~3 MeV deuterons**
- Natural Boron target
- $^{10,11}B(d,n)^{11}C$ reactions with C^7LYC
- Use dual gamma-neutron capability
- In-beam and decay spectra

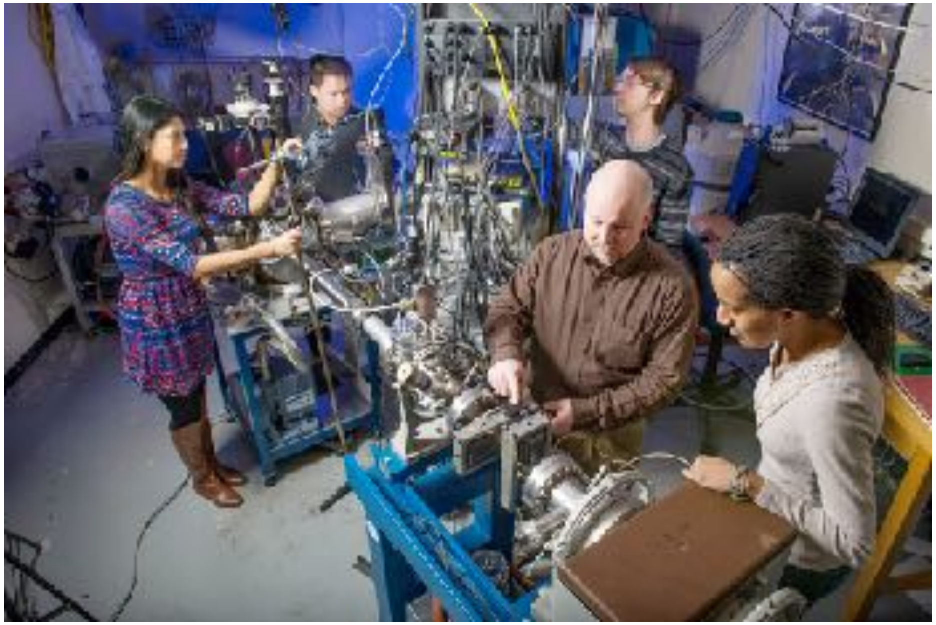




Union College Ion-Beam Analysis Laboratory (UCIBAL)

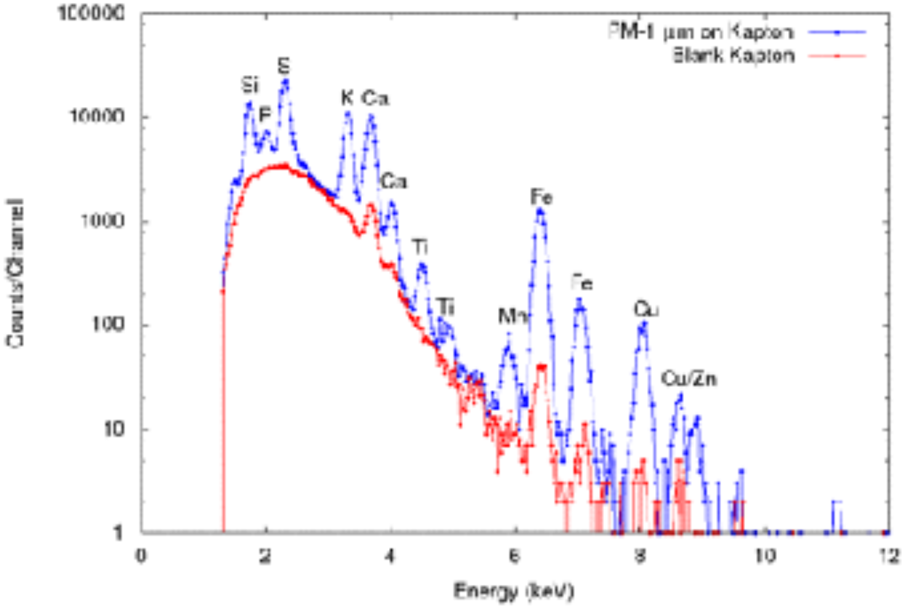
- Primary instrument is a 1.1-MV tandem Pelletron Accelerator
- Used in
  - Undergraduate research projects
  - First-Year Seminar in Physics
  - Advanced Laboratory
  - High school outreach
- Users in last 10 years
  - 4 Union College and visiting faculty
  - 250 undergraduate students
  - 153 high school students
  - 54 high school physics teachers

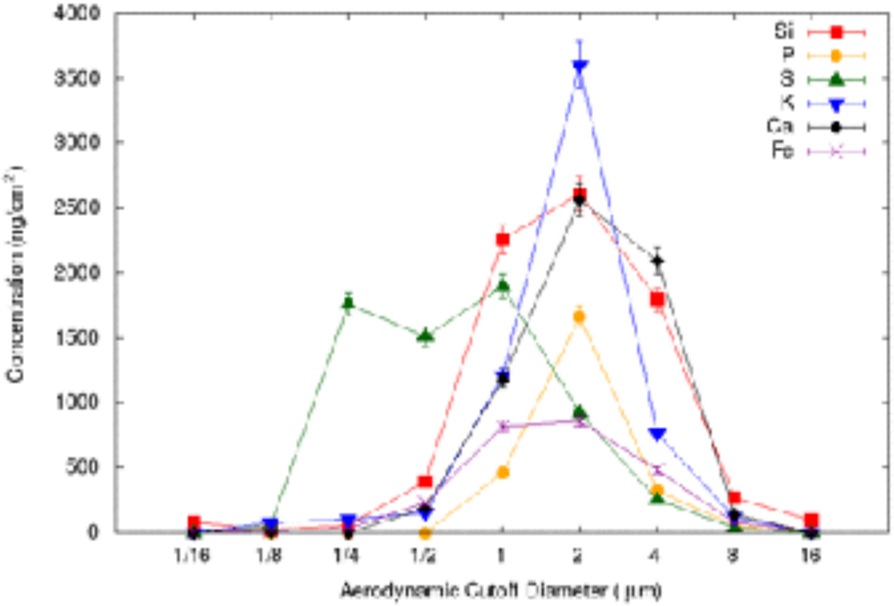




Research in UCIBAL

- Main emphasis on IBA of environmental samples
- Example: Characterization of atmospheric aerosols in the Adirondack Mountains [NIMB 350 (2015) 77]
  - PIXE analysis of airborne particulate-matter (PM) pollution as a function of particle size
  - Large concentrations of S measured in small particles that can travel great distances and contribute to the acid rain problem in the Adirondacks





Summary

1. ARUNA facilities do first rate science.
2. ARUNA facilities provide unique opportunities for new developments and testing that is not possible at big facilities.
3. ARUNA facilities attract students and help nuclear science compete for talent at the universities.
4. ARUNA facilities are flagships for universities and generate a lot of leverage support.
5. Scientists from ARUNA facilities are a major part of the user community of large facilities.
6. ARUNA facilities are an indispensable intellectual resource in the field.