

Neutron Scattering Cross Sections: (n,n') (n,γ) $(n,n'\gamma)$

Jeff Vanhoy

Current Team Members US Naval Academy, Annapolis, Maryland

University of Kentucky

Yongchi Xiao, postdoc
Erin Peters, instructor
Steven Yates, prof



Univ Dallas

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Jeff Vanhoy, prof



- UnivKY Lab Overview
- Primary Projects
- Secondary Projects
- Highlights

Special thanks to Anthony Ramirez,
currently @ LLNL.



University of Kentucky Accelerator Laboratory (UKAL)

- 7-MV single-ended Van de Graaff accelerator
- p, d, ^3He and α beams
- pulsed and bunched beam:
 - $f = 1.875$ MHz and $\Delta t \sim 1$ ns
- primarily conducts neutron-induced reactions and scattering experiments

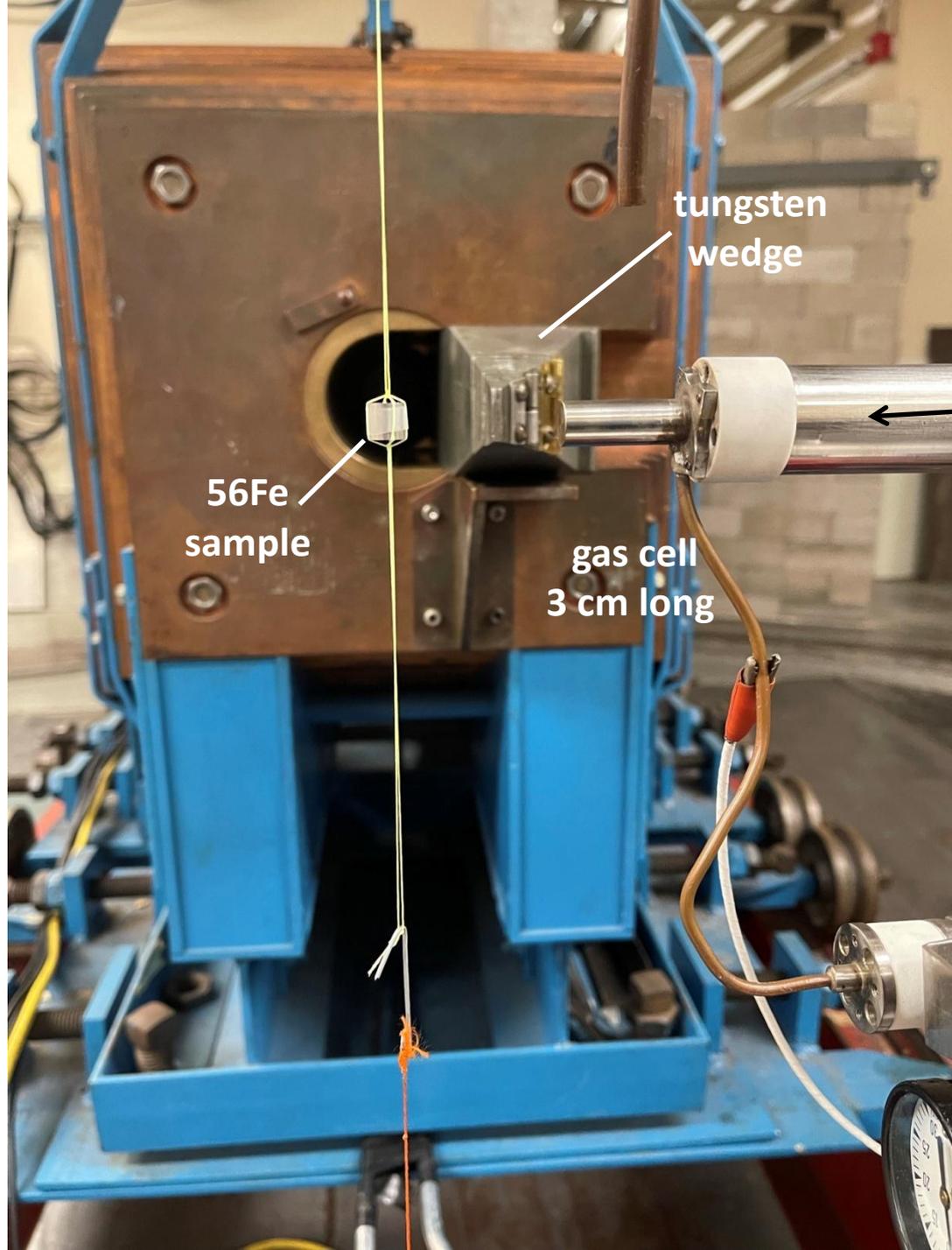


Basic Nuclear Science

- Nuclear structure via $(n, n'\gamma)$
 - Level Schemes and Transitions
 - Spectroscopic Information
 - DSAM Lifetimes

Applied Nuclear Science

- Cross section measurements
 - (n, n') - Elastic and inelastic cross sections
 - ^{23}Na , ^{56}Fe , ^{54}Fe , ^{12}C , $^{\text{nat}}\text{Si}$, $^{\text{nat}}\text{Li}$
 - $(n, n'\gamma)$ - γ -ray production cross sections
 - Level cross sections
- Detector development

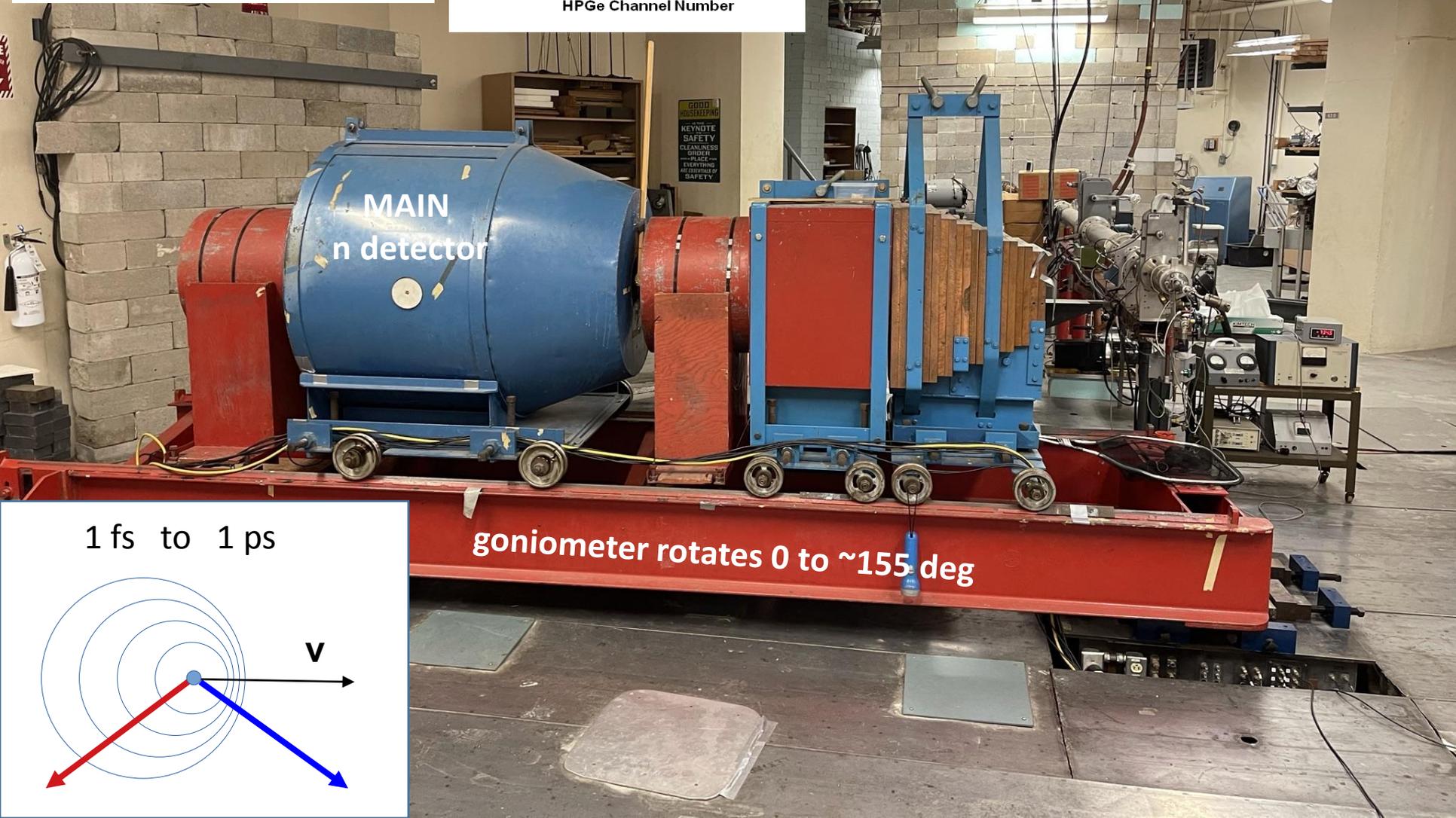
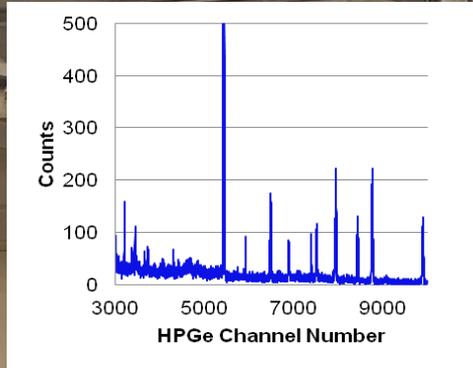
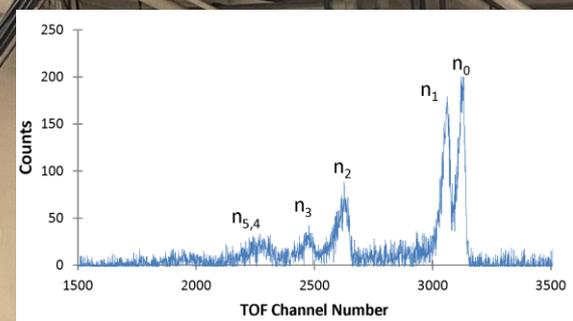


tungsten
wedge

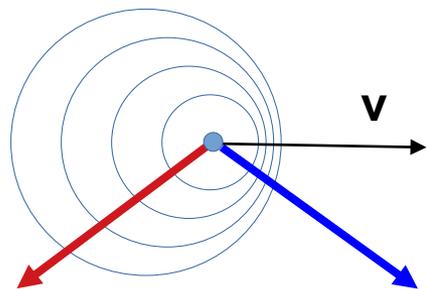
^{56}Fe
sample

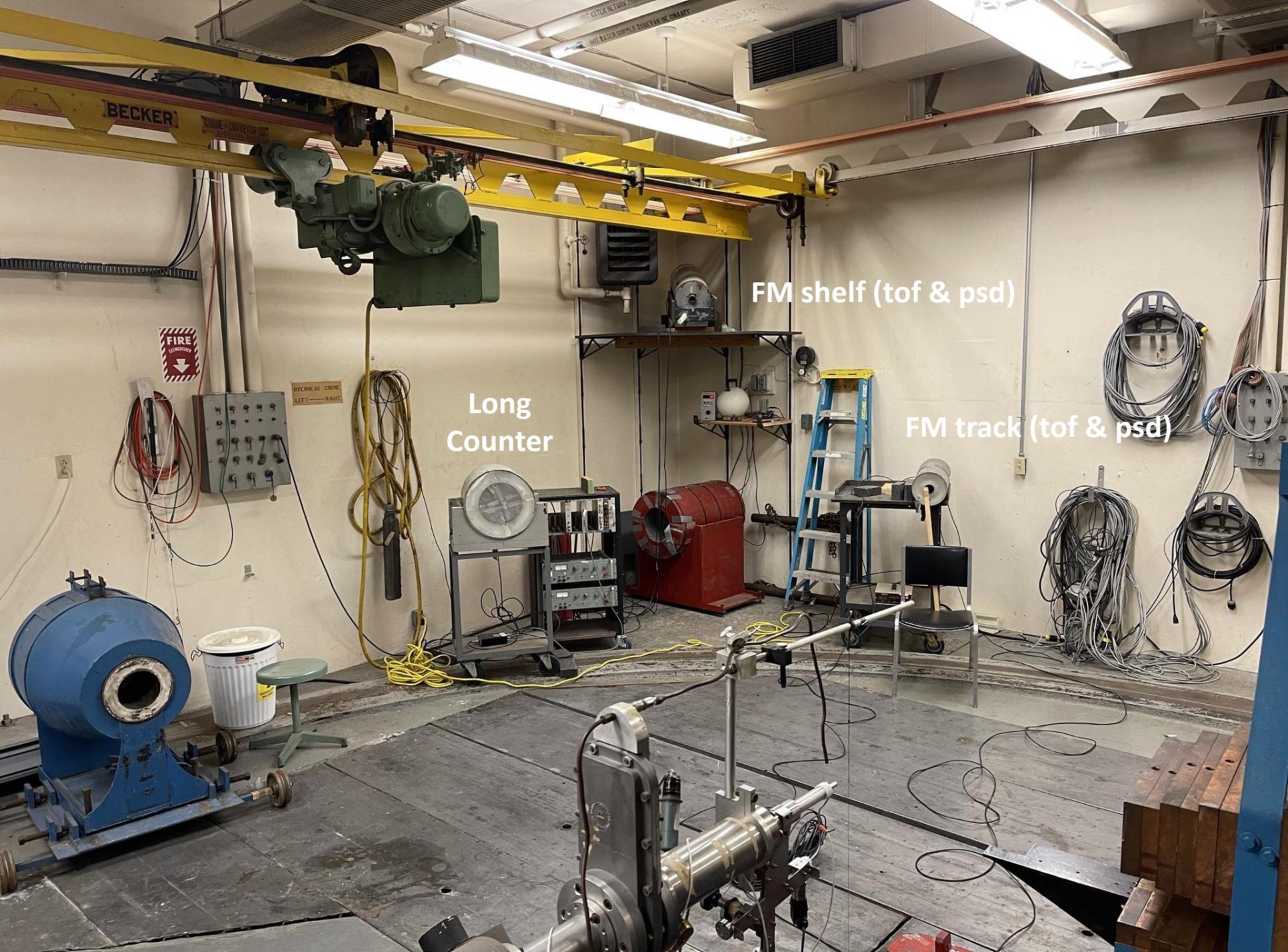
gas cell
3 cm long

pulsed
p, d, ^3He



1 fs to 1 ps





BECKER

CRANE - CONVECTOR CO.

FIRE
ALARM
PULL STATION

OVERHEAD CRANE
LEFT - RIGHT

Long
Counter

FM shelf (tof & psd)

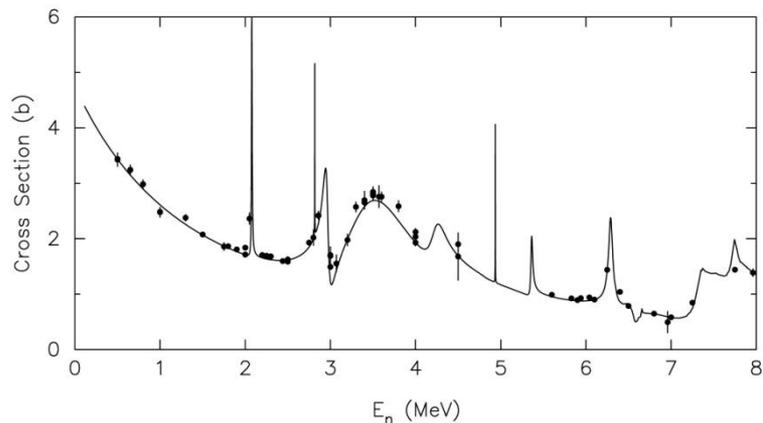
FM track (tof & psd)

HOT WATER RETURN ZONE
HOT WATER SUPPLY ZONE

Primary Projects

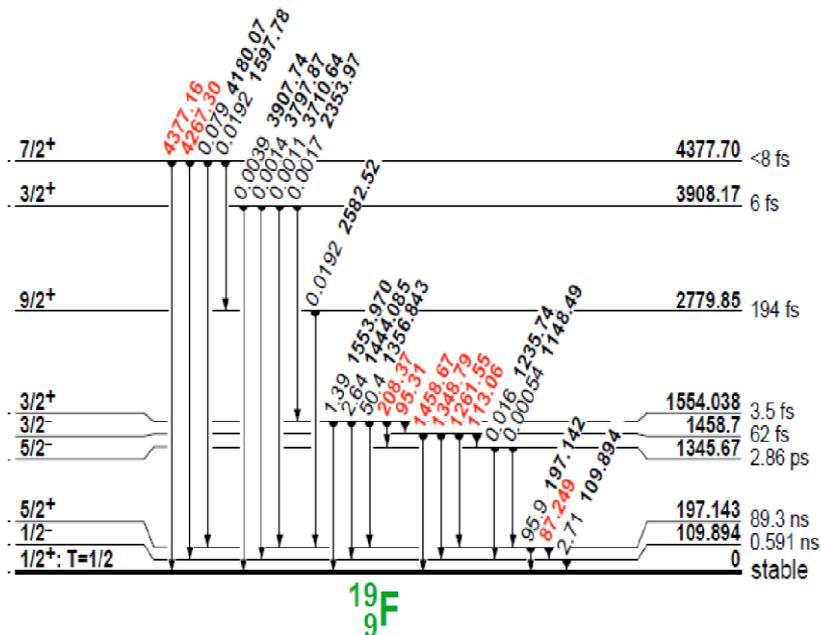
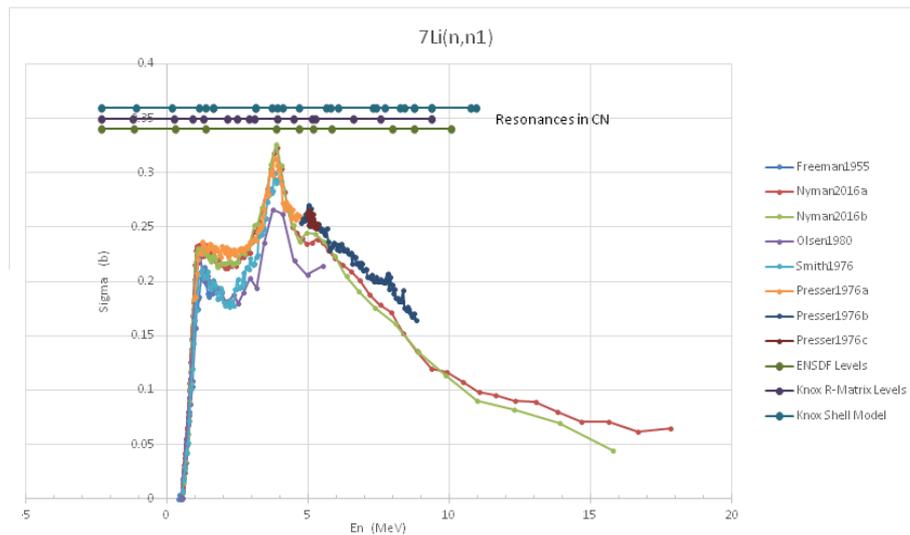
Carbon-12 is a component in

4-6 additional angular distribution measurements are needed in the range 5-8 MeV to assist with (n,n_1) resonance parameter analysis.



Lithium-7 is a component in

Resolve ambiguity above threshold for n_1
More ang distrib for resonance information



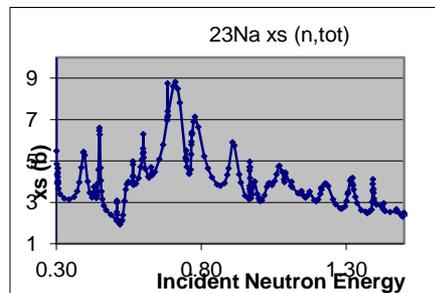
Flourine-19, Effectively no data since 1950s-1960s. Industrial manufacturers of compact molten salt reactors employ FLiBe as a base material and have called for an increased understanding of its properties..

Secondary Projects (if we have time)

Sodium-23 is a component in

Measurements below 1.3 MeV.

More ang distrib for resonance information



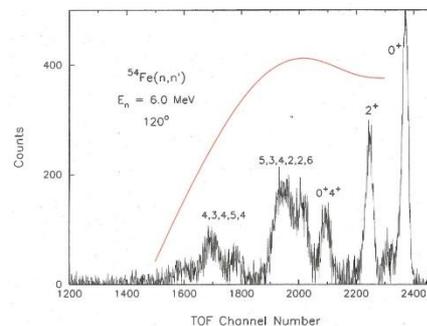
Magnesium-24 is a component in

More ang distrib for resonance information

Iron-56, one of the most ubiquitous materials,

Possible addn'l measurements upon request.

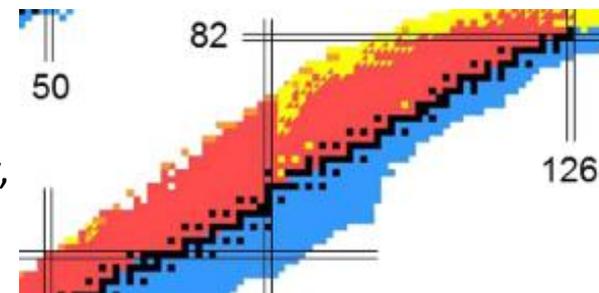
Conversion of existing HE data to neutron emission spectra.



Conversion of Previously Measured Angular Distribution Data to Differential Cross Sections.

The list includes most major stable isotopes of the elements

Na, Fe, Ge, Se, Zr, Mo, Ru, Pd, Cd, Sn, Te, I, Xe, Ba, Ce, Nd, Sm, Gd, Dy,



Neutron capture.

DANCE @ LANL: pulsed n beam w BaF detectors – total emission energy

130,132,134,136Xe proposed

FIPPS @ ILL: continuous n beam w HPGe – detailed γ -ray emissions btw levels

CdTe(n,γ)

100Ru(n,γ)



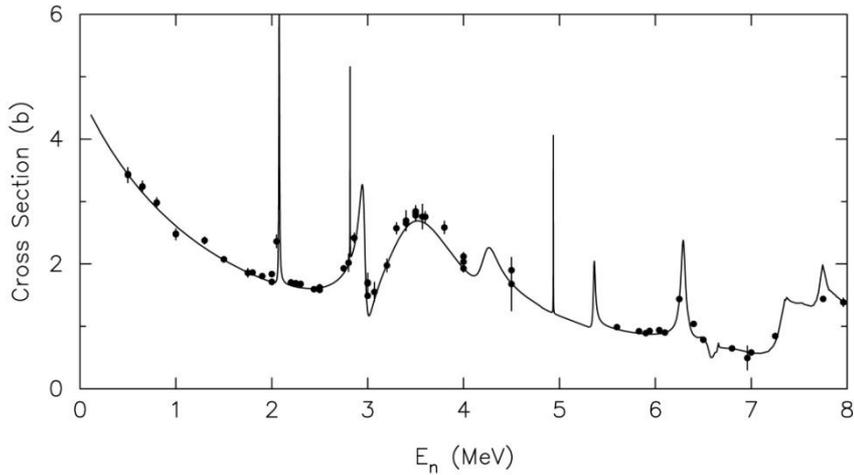
Sarah Evans Elizabeth Chouinard

On-site at Univ KY ~1 June to ~1 Aug

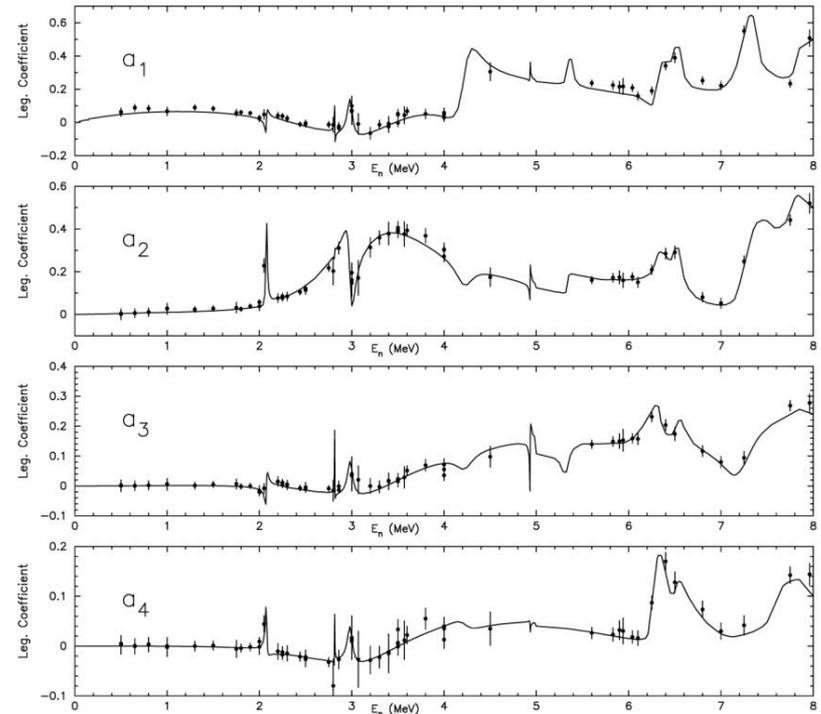
Participated in all Nucl Data & Nucl Structure expts

invited to join the Univ KY Nucl Phys REU sessions

(n,elas)



45 energies
64 elas diff xs
12 inelas diff xs



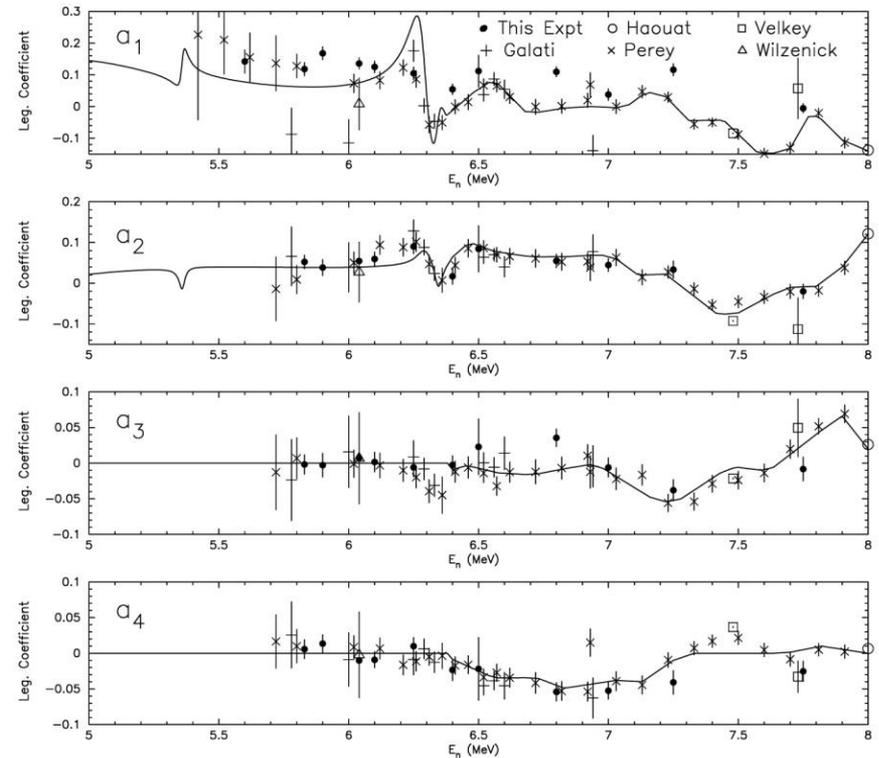
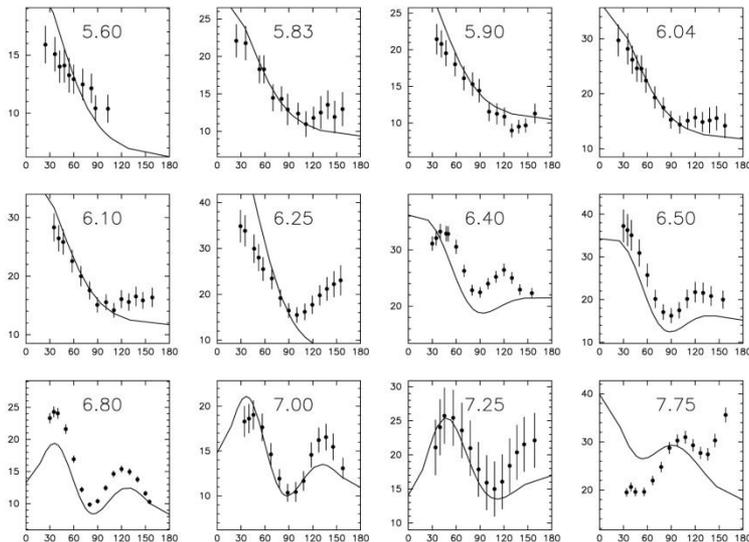
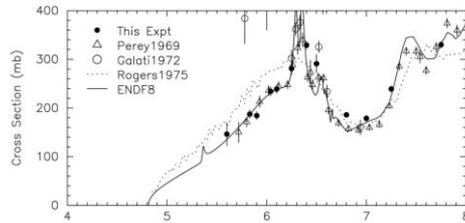


Sarah Evans Elizabeth Chouinard

low-energy (n, elas) 7 days
0.3, 0.2, 0.5 MeV

high energy (n, n_1) 11 days
6.4, 6.5, 6.8, 7.25, 7.75 MeV

(n, n_1)



Sarah Evans Elizabeth Chouinard

2 presentations

Exploring Innovation in Appalachia: an Undergrad Research Symposium @ UWV Aug 2011

Eliz placed 4th (i.e. honorable mention) out of 65 presentations

future plans

Sarah: senior
1 year gap
professional Frisbee player

Elizabeth: junior
another REU
1 year gap
graduate school physics



Determining Neutron Scattering Cross Sections of ¹²C

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¹University of Dallas, ²University of Kentucky, ³United States Naval Academy, ⁴Mississippi State University

ABSTRACT

At the University of Kentucky Accelerator Lab (UKAL), experiments were done to determine neutron elastic and inelastic scattering differential cross sections for ¹²C. The results of these measurements not only enhance our knowledge of how neutrons interact with a ¹²C nucleus but also provide valuable information for the next generation of nuclear reactors, i.e., Gen-IV reactors. Carbon and carbon materials serve as constituents in several of the Gen-IV reactor designs as fuel coatings, moderators, control rods, etc. In the experiments at UKAL, a 7-MeV model CN Van de Graaff accelerator was used to generate a pulsed proton beam which then interacted with tritium or deuterium to produce nearly monoenergetic neutrons through the ¹⁰B(p,n)¹⁰Be or the ¹¹B(d,p)¹¹B reactions. Using time-of-flight techniques, these neutrons scattered off a carbon sample and were detected with an E110110 scintillator detector. Angular distributions of 0.29, 0.51, 7.25, and 7.75 MeV scattered neutrons were deduced from the measurements. Results from these measurements, along with comparisons to theoretical data evaluations from the National Nuclear Data Center (NNDC) will be presented.

INTRODUCTION

Nuclear reactors produce many neutrons which scatter off nuclei either elastically or inelastically depending on the incident neutron energy. In elastic scattering, a neutron strikes a nucleus without exciting it whereas in inelastic scattering the nucleus is excited and releases gamma rays. Since scattered neutrons and gamma rays affect the energy and structural stability of a reactor, the nuclear reactor engineers must know the values of the different cross sections.

The main objective was to focus on the measurements at incident neutron energies of 7.25 and 7.75 MeV where both elastic and inelastic scattering occurs. The data evaluations were measured in their energy because measurements in this region are sparse. Additionally, the 2017 data set in Fig. 1 shows a sudden dip in the ¹²C cross sections around 0.2 MeV. Therefore, measurements were taken at $E_n = 0.29$ and 0.51 MeV to see if the apparent dip exists at $E_n < 0.29$ MeV and to attempt to verify the dip in the graph.

Fig. 1. Comparison of ¹²C cross sections of data sets from 2006 to 2017 (Graph from a personal communication from Yousou Yoon with data.)

The total cross sections are determined from the differential cross section data by adding the individual cross sections for all open channels (see Eq. 1). For the lower energies examined in this research, only the elastic cross section was needed whereas at higher energies, the elastic, inelastic, and total cross sections were needed to find the total cross section.

$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{capture} + \dots$ (1)

EXPERIMENT

Fig. 2. UKAL Van de Graaff accelerator of UKAL. The Van de Graaff is located on the left and without shielding on the right.

- The neutron scattering experiments were performed at UKAL.
- A CN Van de Graaff accelerator (Fig. 2) which operates at up to 7 MV generates a pulsed proton beam.
- The proton beam is focused and bent 90° in a horizontal direction.
- Neutrons are produced as the gas cell via a ¹⁰B(p,n)¹⁰Be reaction for $E_n = 0.29$ and 0.51 MeV and via a ¹¹B(d,p)¹¹B reaction for $E_n = 7.25$ and 7.75 MeV.
- The main detector in Fig. 3 and 4, an E110110 (4 MeV) or C1D1 (4 MeV) scintillator detector (Fig. 5), is rotated to various angles between 30° and 150° to determine the angular distribution.
- Pulse Shape Discrimination (PSD) and Time-of-flight (TOF) techniques are used to detect the neutrons.
- The efficiency of the main detector was determined by measuring the angular distribution from the T1p30 and D1d40 reactions from ¹⁹F via ¹⁹F(p,n)¹⁹O.

Fig. 3. The gas cell is located in the end of the sensitive and proton-neutron which are detected by the main detector.

Fig. 4. Schematic of the main detector and a deuterium detector (D1) extension about the ¹²C sample. (Picture from CASR 2014 Presentation with data.)

Fig. 5. Example of neutron detection using a scintillator detector (Picture from Liquid Scintillation Spectrometry Reference 3.17 revised.)

- The data were analyzed using SAN12 Etran.
- A background spectrum was taken and subtracted from the monitor spectrum to find the number of counts gathered by the main detector (Fig. 6)

Fig. 6. Graph showing the background (red) subtracted to find the main detector spectrum (blue).

- Neutron counts from the main detector and forward monitor spectra were used to find the efficiency (EFF) and the relative angular distribution (RAD). (See Eq. 2 and 3 and Fig. 7 and 8.)

$$EFF = \frac{N_{det}}{N_{std} \cdot T_{std} \cdot \Omega} \quad (2)$$

Distance Count for 0.4 and 0.5 MeV

Fig. 7. How the efficiency of the detector changes with incident neutron energy.

$$RAD = \frac{N_{det}}{N_{std} \cdot \Omega} \quad (3)$$

Fig. 8. Graph of the relative angular distribution of $E_n = 0.51$ MeV, which is used to find the differential cross sections.

- The differential cross sections $\frac{d\sigma}{d\Omega}$ were found by using Eq. 4, where T_{std} is the absolute normalization factor.

$$\frac{d\sigma}{d\Omega} = T_{std} \cdot RAD \quad (4)$$

RESULTS

The following graphs contain data from the experiment at UKAL and show the elastic and inelastic neutron scattering differential cross sections as a function of angle. These results are compared to NNDC/ENDF/VIII.0 evaluations.

Fig. 9. Elastic scattering differential cross section of ¹²C at $E_n = 0.51$ MeV compared to the 0.45, 0.50, and 0.55 MeV NNDC/ENDF/VIII.0 data. The results for $E_n = 0.51$ MeV in Fig. 9 do not agree well with the results from ENDF, but work is being continued to resolve this discrepancy. The issue also affects the 0.29 MeV data which is still under the process of evaluation.

Fig. 10. Elastic scattering differential cross section of ¹²C at $E_n = 7.25$ MeV compared to 7.25 MeV NNDC/ENDF/VIII.0 data.

Fig. 11. Inelastic scattering differential cross section of ¹²C at $E_n = 7.75$ MeV compared to 7.75 MeV NNDC/ENDF/VIII.0 data.

Fig. 12. Graph of the total cross sections of ¹²C. The red dots are for the 0.29, 0.51, 7.25, and 7.75 MeV data from UKAL. The blue dots are data from previous experiments at UKAL.

The total cross section values in Fig. 14 are found by integrating the differential cross sections. The total cross section values at 7.25 and 7.75 MeV in Fig. 13 agree fairly well with ENDF. However, the total cross section at 0.51 MeV in Fig. 13 does not agree with ENDF. This issue corresponds to the discrepancy in the differential cross section measurements seen in Fig. 9.

CONCLUSION

Preliminary results from this experiment consisted of angular distributions for incident neutron energies of 0.29, 0.51, 7.25, and 7.75 MeV as well as values for the total cross sections. The results will help the engineers in designing Gen-IV nuclear reactors. The 7.25 and 7.75 MeV measurements were in good agreement with ENDF whereas the 0.51 MeV measurements did not agree well for the 0.29 MeV data the relative angular distribution was found, but the differential cross sections have not yet been determined. Work is still in progress to resolve the issues with the 0.29 and 0.51 MeV data. These results will aid NNDC data evaluations in their calculations of theoretical parameters for neutron scattering from carbon.

REFERENCES

Carwin, W. R. (2008, August). *Generation IV Reactors Integrated Materials Technology Program Plan: Focus on Very High Temperature Reactor Materials*. nsl.gov. <https://info.nsl.gov/sites/publications/files/P242288.pdf>

Rand, P. (1997). *Neutron Interactions with Matter*.

ACKNOWLEDGMENTS

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Capture @ LANSCE: DANCE

<https://lansce.lanl.gov/facilities/lujan/instruments/fp-14/about.php>

completed

$^{112,114}\text{Cd}(n,g)$ – onsite 2019,2020

$^{110,111}\text{Cd}(n,g)$ – online 2020

attempted

$^{130,132}\text{XeF}_2$

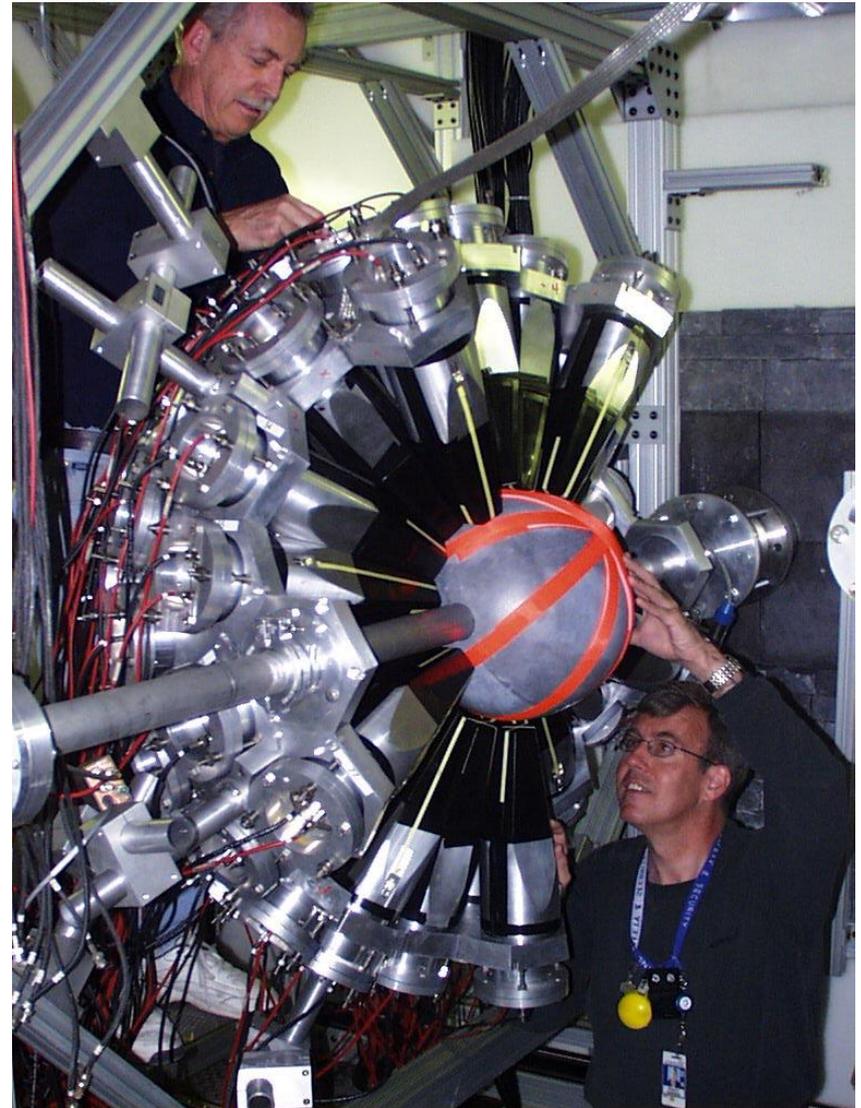
Much effort in design and construction of the XeF_2 target @ UnivKY

Scheduled 14 day Xe expt in Sept 2021

- LAMPF transformer fire
 - target stuck in beampipe
 - LiH absorber structural failure
- shifted to distant future

Mississippi State: Dipangkar Dutta
Jeff Winger

National Lab partners: Aaron Couture
Catherine Fry
Matt Mumpower
Chris Prokop



$4\pi \text{BaF}_2$ array

Inside of the DANCE ball. The large gray sphere in the center is a ^6LiH neutron absorber.

**Kofi
"TuTu"
Assumin-Gyimah**



Participated in all expts
DANCE onsite Aug-Dec 2021

114Cd

Ph.D. expected <Dec 2022

Finalized DANCE array calibration.
Corrections of & caused by target
Isolated 114Cd(n,g) yields

GEANT sim of thresholds & multiplicities
(w Milan Krticka & Standa Valenta)

**Stephan
Vajdic**



112,113Cd

Started – several months in.

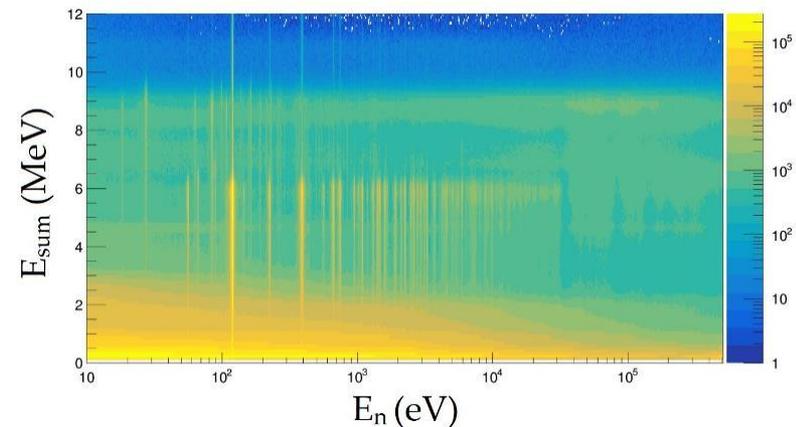
**Daniel
Araya**



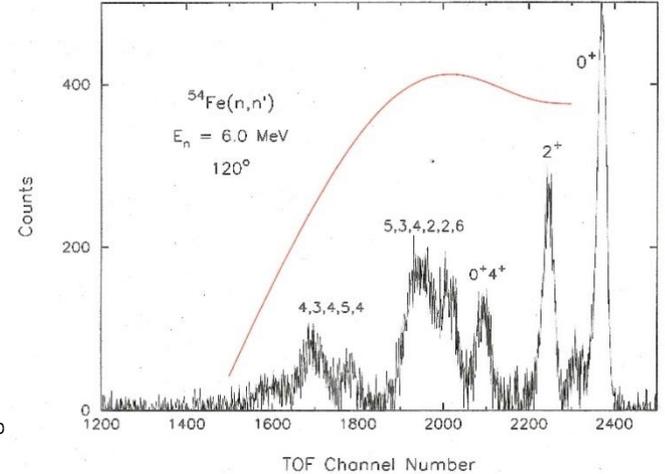
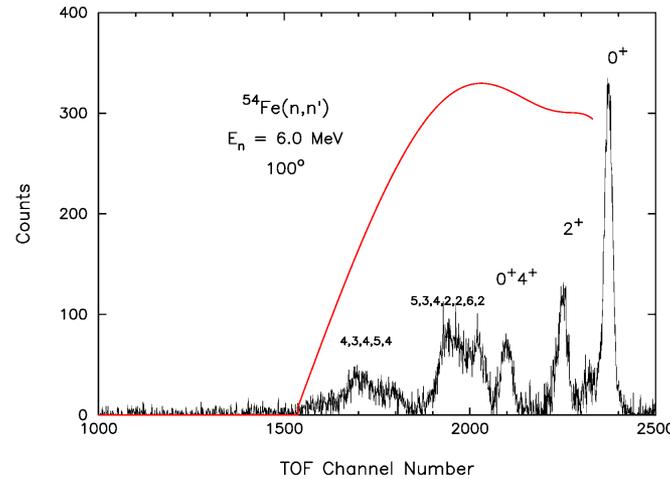
110,111Cd

Getting Started.

Example Raw Data: γ -energy deposited vs E_n



Avi Perkoff



knew C++, Learning python

Converting previous UnivKY ^{56}Fe , ^{54}Fe , ^{23}Na
nTOF spectra(θ) into energy spectra(θ)
(efficiency corrected and normalized)

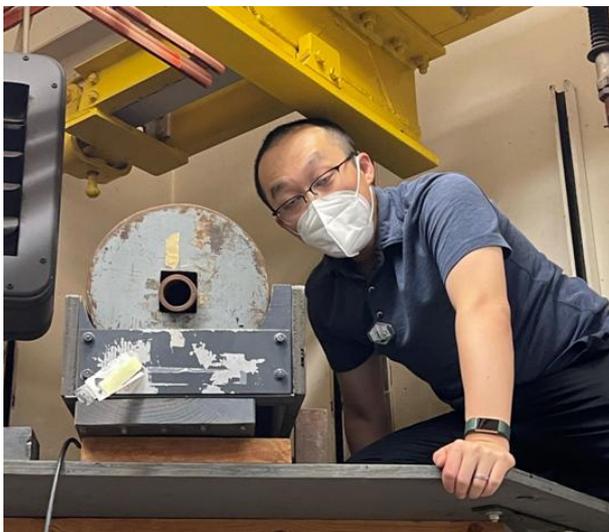
4 shifts (remotely) at a recent
 ^{130}Te CouEx measurement at ANL/ATLAS
w CHICO / GRETINA arrays

Graduates May 2022 → USMC Pilot



USMC assigned him to continue with the project until Aug 2022.

Yongchi Xiao



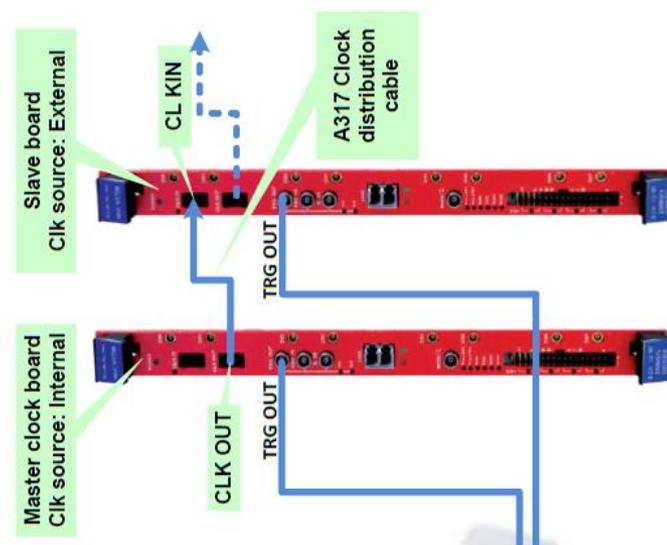
V1730 500 MS/s
scintillators nTOF
MAIN & FM
beam pulse

V1782 100 MS/s
HPGe
Long Counter

- + can record time-dependent γ -ray spectra
- + trapezoidal filter can be fine-tuned for each detector
- + can replay data & change your mind abt settings

- can't do detailed live-monitoring of data coming in
- time consuming development, testing, refining
- modules may not perform as expected,

CAEN may not have thought about some things

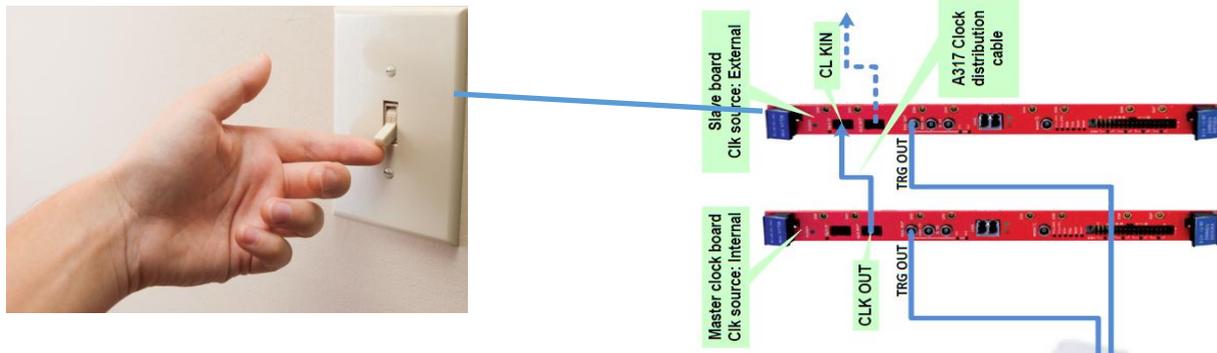


Presentation at 2021 DNP 11-14 Nov online

“Implementation and validation of a fully digital data acquisition system at the University of Kentucky Accelerator Laboratory”

• General Ideas

- Must do γ s in slow module and neutron in fast module
 - Fast module can't sufficiently amplify HPGe pulses
 - Fast module doesn't have adjustable trapezoidal filter required for γ s
- Time stamps btw modules **loose precision synchronization** when using fiber optic cables
- Can operate both modules with an external trigger, but require a **secondary on/off light switch to take data** after click CoMPASS 



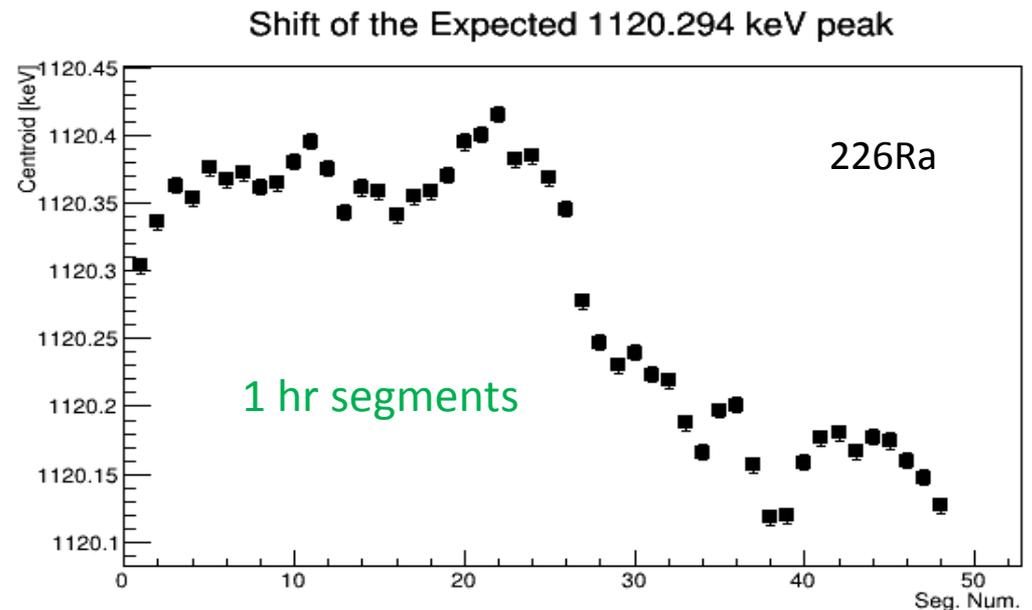
- Onboard-CFD vs RC-CR2 timing technique
 - The manual describes the techniques, but not how to customize them for specific needs.

- γ -ray detection in slower V1782 100MHz. We can:

- take UnivKY-style data w HPGe, BGO, LongCounter
 - w ext Ortec TAC for beam pulse timing info
- take ang distrib data for Doppler-shift lifetimes (comparable to analog system)
- fine tune BGO-Compton rejection during replay (better than previous analog system)
- measure time dependence of γ -ray background btw beam pulses
- do as-we-go corrections for HPGe gain drift (never possible before)

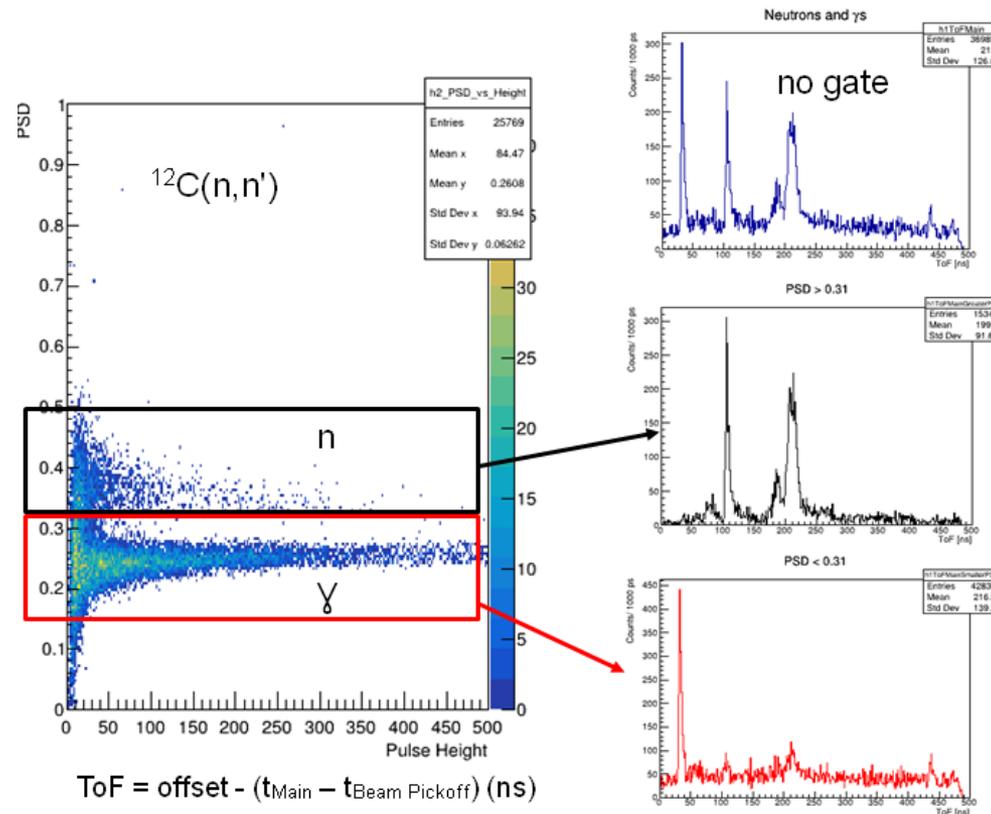
DSAM method requires centroids to $\sim 100^{\text{ths}}$ of keV.

Took 1 wk of real $\text{Li}(n,n_1\gamma)$ in Nov2021 to prep for ^{19}F isomer measurements.



- neutron detection in faster V1782 500MHz. We can:

- digitize the beam pulse (after valid event)
- take UnivKY-style neutron TOF data w
MAIN scintillator, Forward Monitors, & beampulse

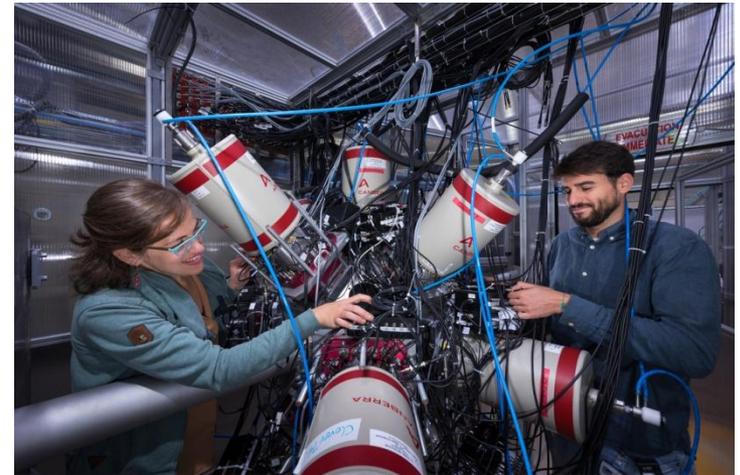
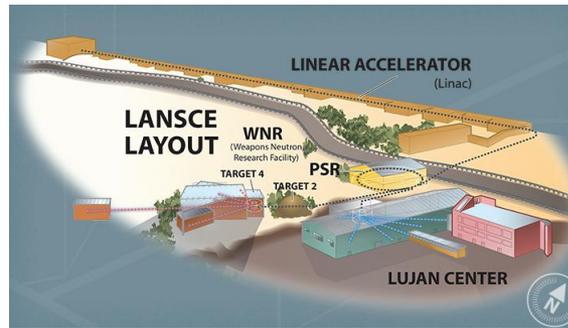


- fast module doesn't have adjustable trapezoidal filter

We've been working on γ -ray capabilities since ~June 2021

Other Projects

- Los Alamos LANSCE
 - DANCE – BaF2 array
 - Cd(n,γ) capture online ☹️
 - Xe(n,γ) to be rescheduled
- ILL Grenoble
 - FIPPS – clover array
 - Cd&Te capture online ☹️
 - 2-9July21, 9-21Sept21, 24-30Sept21
- ANL / ATLAS
 - CHICO & GRETINA
 - ^{130}Te CoulEx online & on-site 😊
 - 9-14Feb2021



<https://www.ill.eu/news-press-events/news/scientific-news/detail/improving-fipps-datasets-quality>



SUMMARY:

Weekly collaboration meetings.

Many UnivKY runs during summer 2021 to catch up from covid shutdown.

Pushing to get time-dependent $(n,n'\gamma)$ data functional – isomer in ^{19}F .

Need ^7Li metal ingot for good (n,n') -- 3*\$ + other issues

The team is working with many projects.



Supported by U.S. DoE FY20/21 awards SC0021424, SC0021243, SC0021175, SC000056

Supported by U.S. DoE FY22 awards unknown, SC0021243, SC0021175, unknown