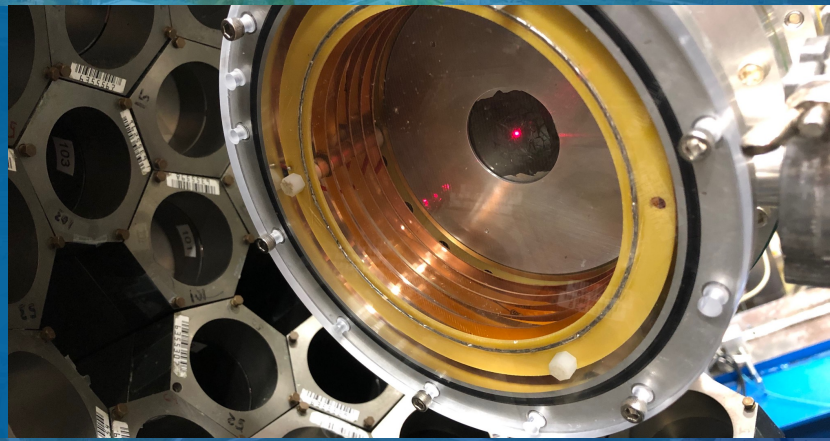
NOVEMBER 22, 2024

FRAGMENT-CORRELATED γ-RAY EMISSION FROM ^{252}CF(SF)

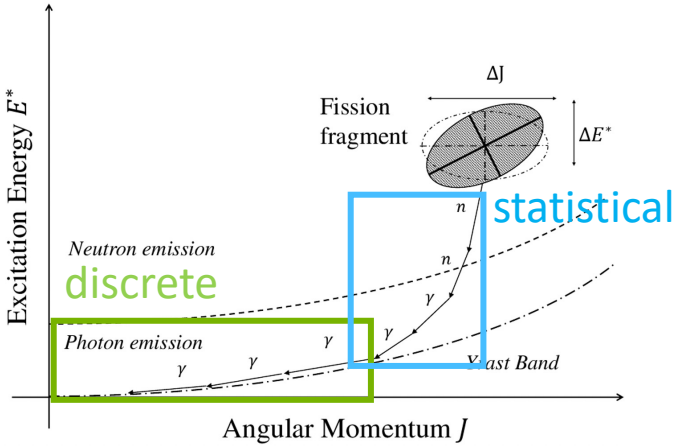


IVAN TOLSTUKHIN
Argonne National Laboratory

FIESTA 2024
Los Alamos, NM

BACKGROUND AND MOTIVATION

- The excited fragments decay by emission of both n and γ-rays
  - Neutrons emitted dissipating much of the fragment excitation energy
  - γ-rays emitted after no more neutrons can be emitted dissipating much of the angular momentum (J)
    - Information on both the nuclear reaction process and the structure of the exotic nuclei that are decaying.



S. Marin PRC 104, 024602 (2021)

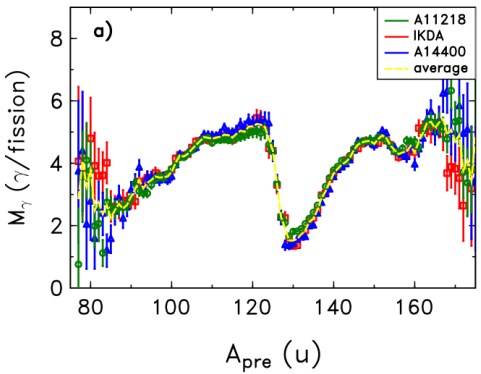
- **There is a shortage of experiments studying fragment initial conditions (E^*, J)**
- **Generation of angular momentum**
  - Long-standing puzzle of angular momentum generation "Why do fragments with angular momentum emerge from a fragment with no angular momentum?"
- **Accurate models of fission**
  - Phenomenological codes of fission fragment emissions are routinely used in nuclear technologies

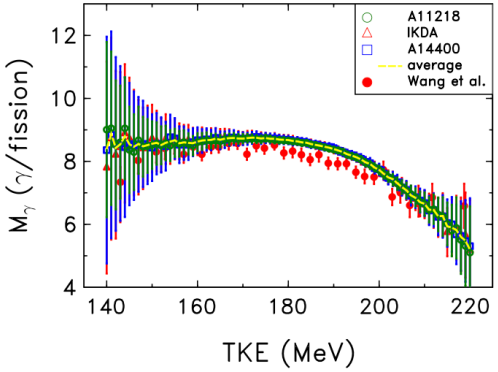
FISSION GAMMA-RAY MEASUREMENTS

M. Travar Phys. Lett. B 817, 136293 (2021)

Measured fission γ-ray multiplicity in coincidence with fragment mass & TKE

- Confirmed γ-ray sawtooth
- TKE dependence

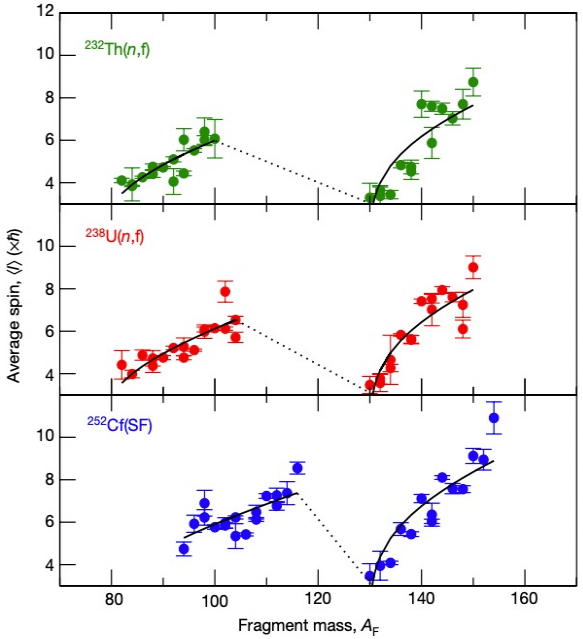




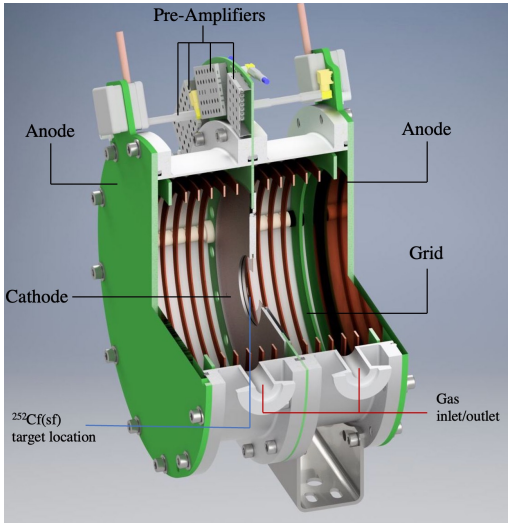
J.N. Wilson Nature 590, 566-570 (2021)

Measured feeding of levels to extract fragment spins

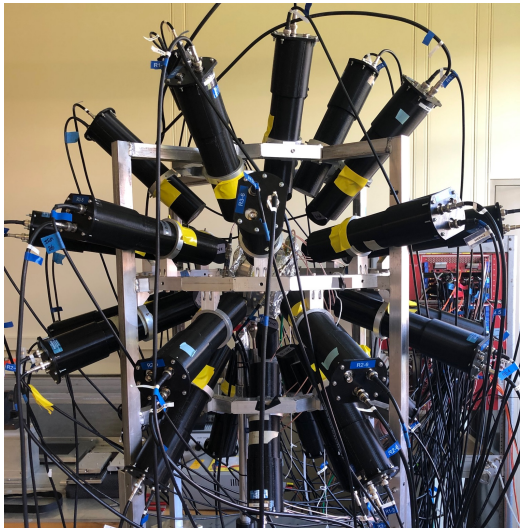
- First observation of spin sawtooth,
- No sensitivity to fragment energy



FS-3 EXPERIMENTAL CAMPAIGN



+



Twin Frisch-grid ionization chamber (TFGIC):

- Fragment properties:
  - kinetic energy, TKE
  - Mass, A
  - Polar angle, $\cos\theta$

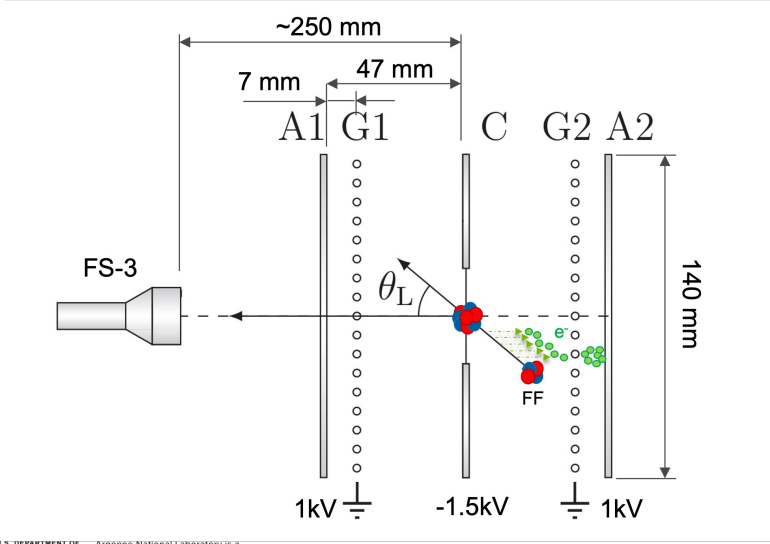
Fission Sphere-3 (FS-3):

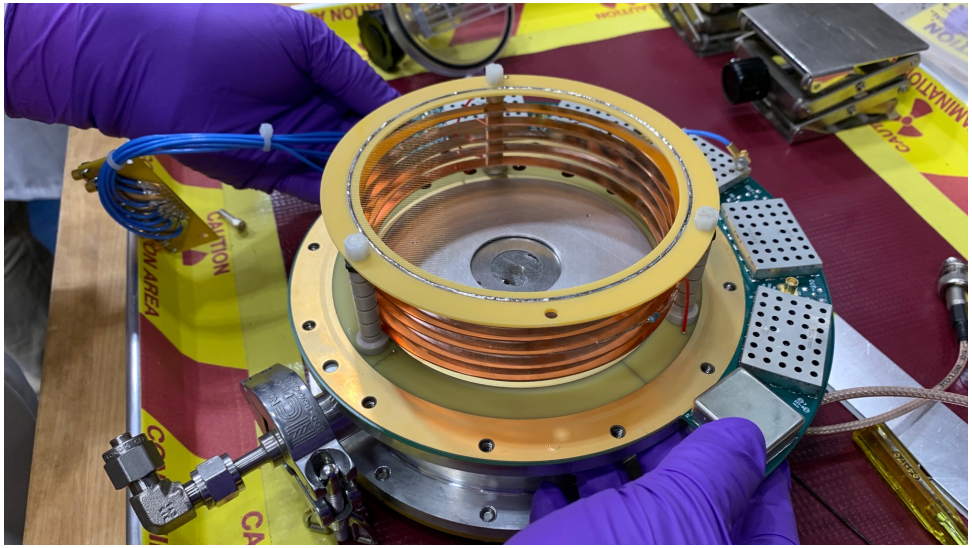
- stilbene scintillators for neutron and gamma detection
- Developed by University of Michigan

FISSION CHAMBER

Twin Frisch Gridded Ionization Chamber (TFGIC):

- The two sides of the chamber measure fragments energies and polar angles
- ^{252}Cf(SF) source on 100 μg/cm^2 C backing in the middle of the chamber





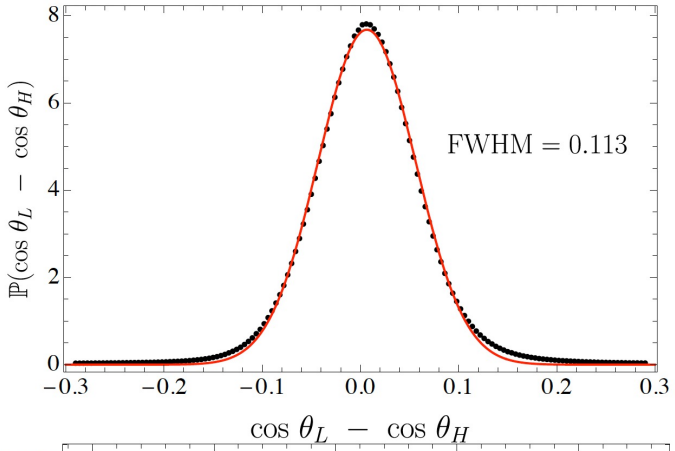
- Flangeless to reduce attenuation of n and γ-rays
- Gas-filled with P-10 (10% Ar, 90% CH4)
  - 950 torr with continuous flow ~ 100 cc/min
- DAQ based on CAEN 1st generation digitizer V1740

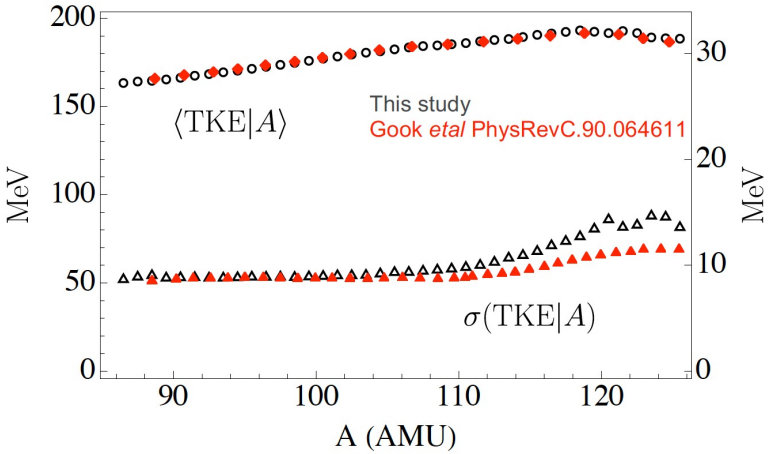
S. Marin, I. Tolstukhin etc., NIMA 1048, 168027 (2023)

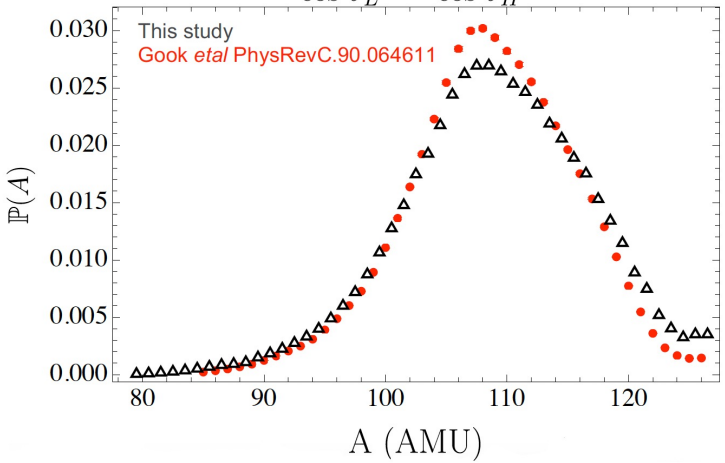
TFGIC PERFORMANCE

- Ratio of grid/anode signal to extract polar angels
- 2E method to determine the masses of FF, based on the fragments E and the law of conversation of J
- TFGIC performance comparable to literature values:
  - Angular resolution of cosθ ~ 0.05
  - Energy resolution on TKE of 3-4 MeV
  - Mass resolution of 4-5 AMU

S. Marin, I. Tolstukhin etc., NIMA 1048, 168027 (2023)



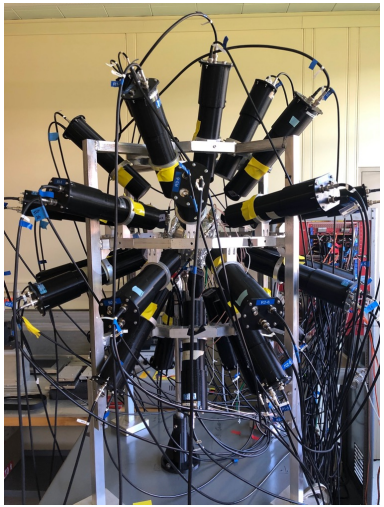




→ **Allow measurement of excitation energy with resolution of ~5 MeV**

FISSION SPHERE-3

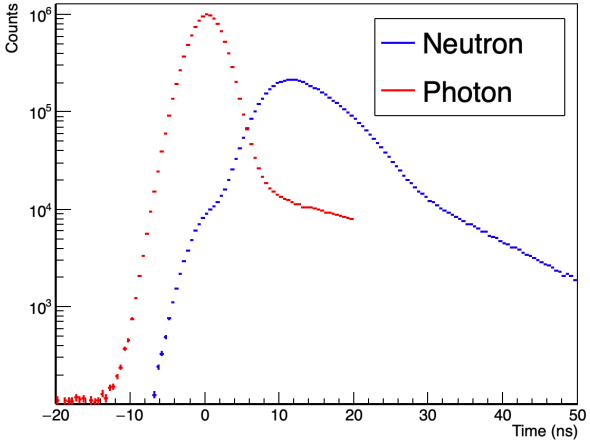
The FS-3 array is a multiplicity-oriented detection array
- 40 trans-stilbene detectors
- 5.08 cm x 5.08 cm
- 2'' PMT ElectronTube 9214B
- PSD capable for n-γ discrimination

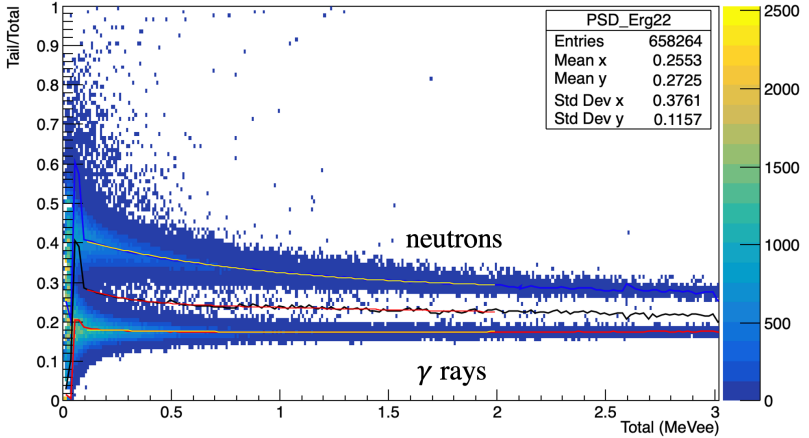


S. Marin, I. Tolstukhin etc.,
NIMA 1048, 168027 (2023)

The response of the FS-3 is similar to Chi-Nu at LANL
- Improved PSD and energy resolution allow to push threshold to 30 keVee

ToF with respect to the cathode time
- $\sigma_\tau \approx 5$ ns
- Using PSD and ToF for particle ID

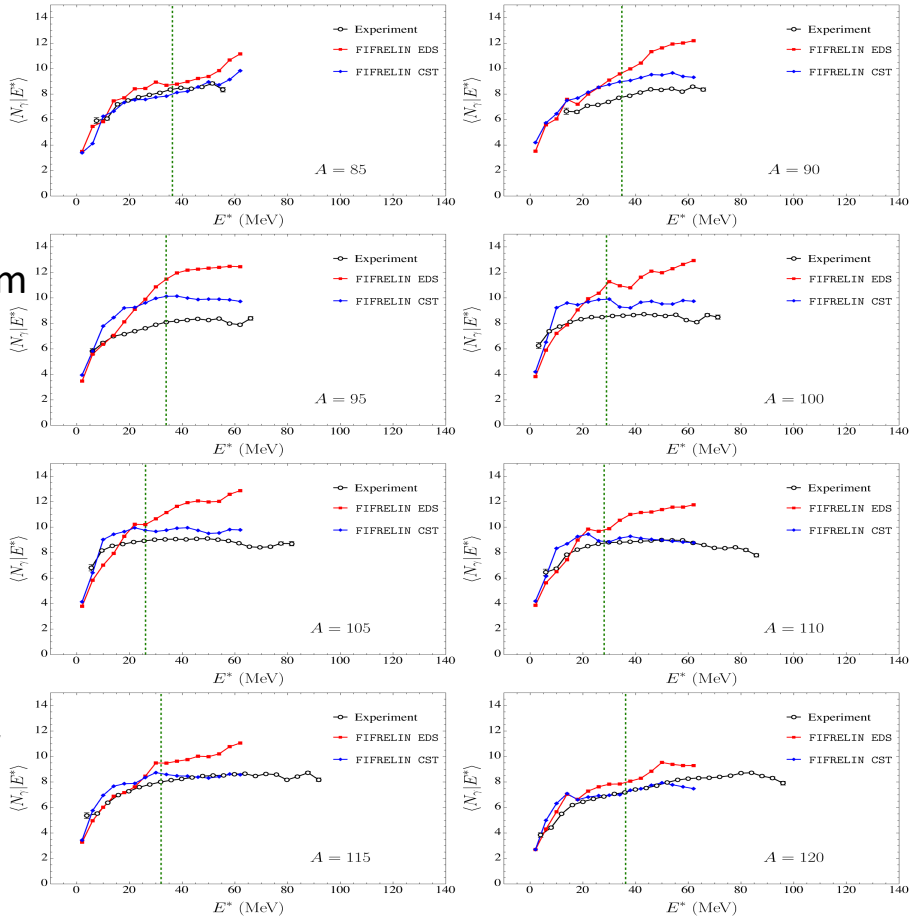




TOTAL GAMMA-RAY MULTIPLICITY

- Fragment excitation energy determined from experiment observables: $E^* = Q(A) - TKE$
- Gamma-ray multiplicity indicative of angular momentum
- At high excitation energies, angular momentum does not increase with E^*
- the mean γ-ray multiplicity increases up to a value of approximately 8 γ rays.

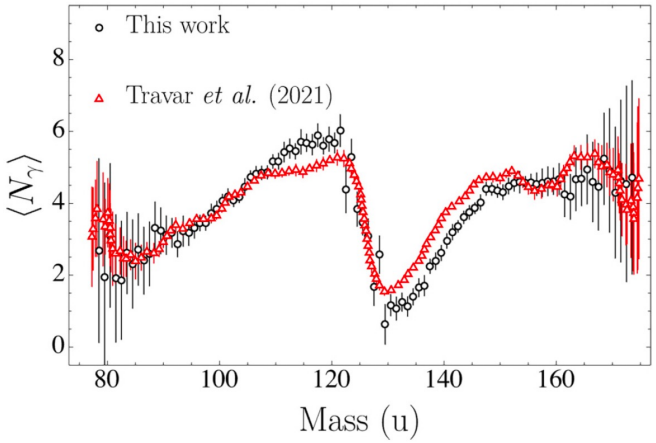
- Spin-energy correlations are expected from statistical considerations:
  - Is the energy available for angular momentum generation the same as E*
  - Does a larger portion of AM carry out by neutrons and statistical γ rays?



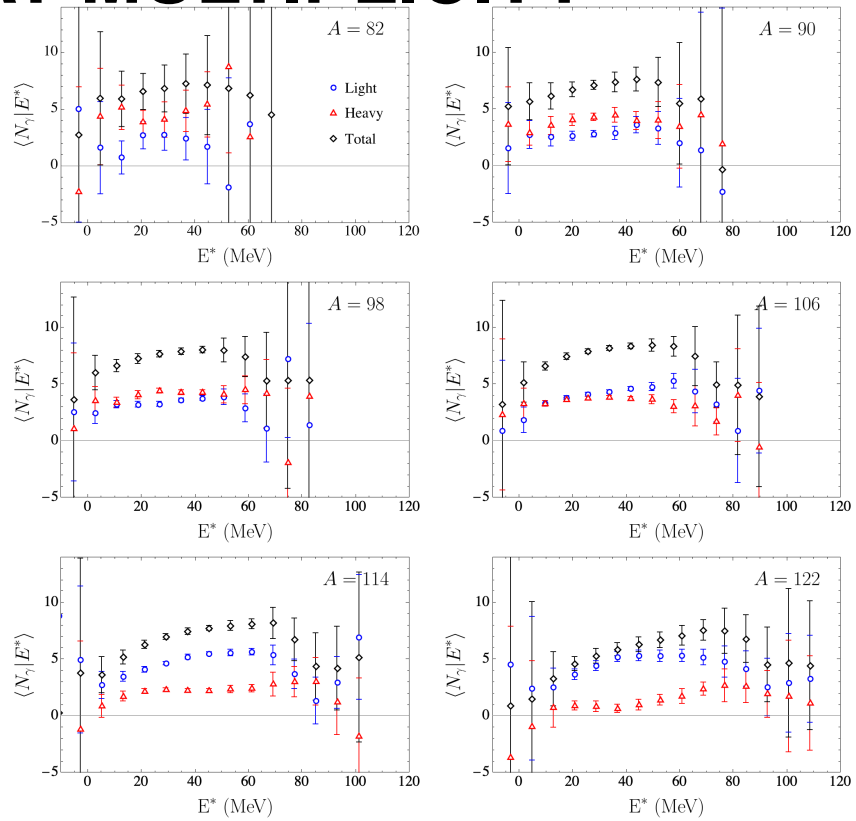
S. Marin, I. Tolstukhin etal., PRC 109 (5), 054617, 2024

INDIVIDUAL GAMMA-RAY MULTIPLICITY

- Maier-Leibniz Doppler Shift analysis to separate γ ray multiplicities emitted by the light and heavy fragments (only 2 FS-3 detectors used)
- Individual mean γ-ray multiplicities as a function of fragment mass
  - ✓ Sawtooth pattern in the γ-ray multiplicity distribution align with recent findings by Travar et al.



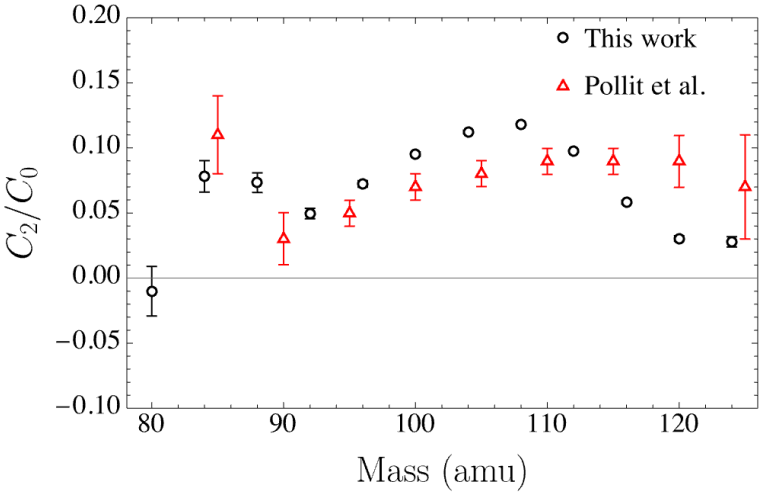
S. Marin, I. Tolstukhin etal., PRC 109 (5), 054617



- ✓ γ-ray yield from the light and heavy fragment changes at different rates with E*

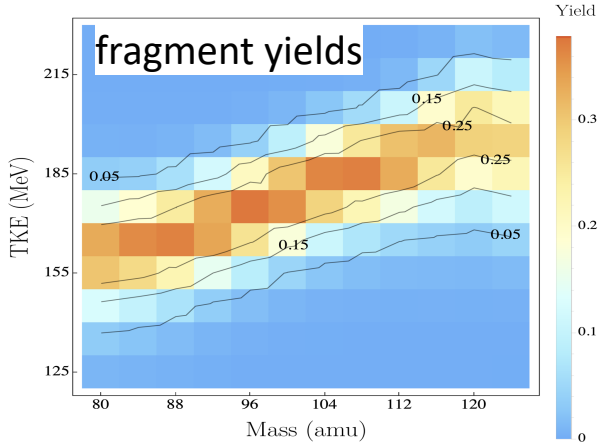
GAMMA-RAY ANGULAR DISTRIBUTION

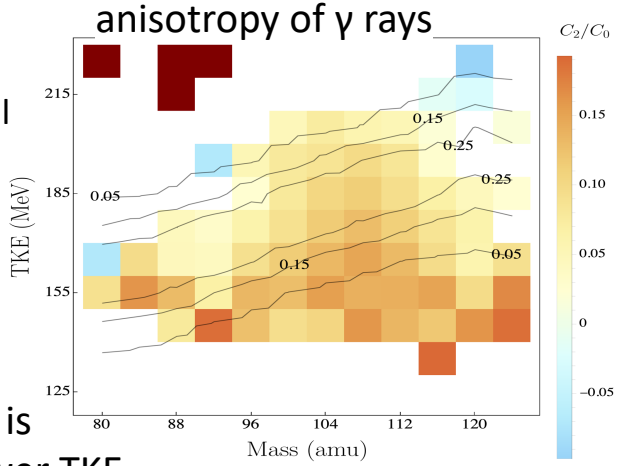
- Angular distribution of γ rays often represents the most direct probe of AM in nuclear system
- Our measurement indicates a significant modulation of the γ-ray anisotropy (C_2/C_0) with fragment mass
- It could be an indication of a different degree of the polarization of the fragments' AM



$$\sum_{i=0}^{l_{max}} C_i P_i(\cos\theta)$$

P_i - Legendre polynomial
C_i - amplitude

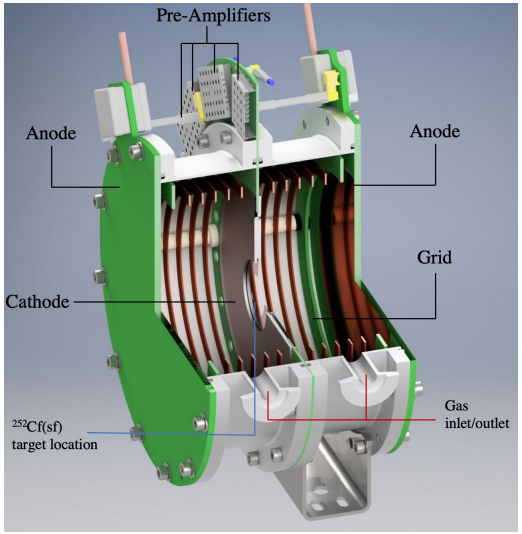




S. Marin, I. Tolstukhin etal., PRC 109 (5), 054617

- The anisotropy of γ rays is more pronounced at lower TKE

GAMMASPHERE EXPERIMENTAL CAMPAIGN



+

Twin Frisch-grid ionization chamber (TFGIC):

- Fragment properties:
  - kinetic energy, TKE
  - Mass, A
  - Polar angle, $\cos\theta$

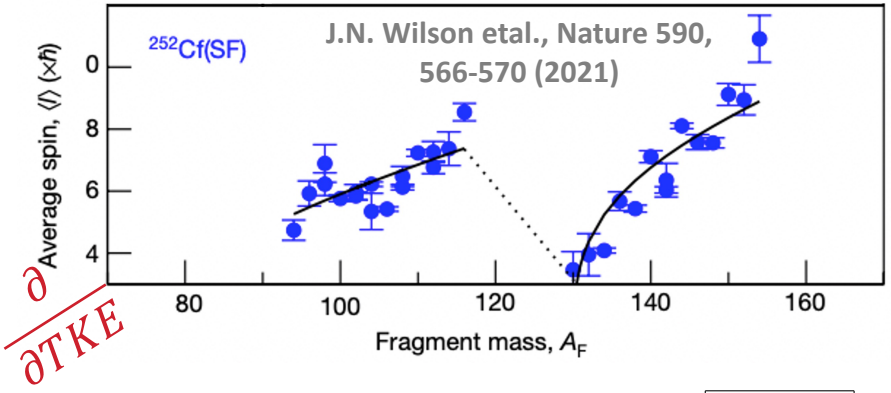
Gammasphere:

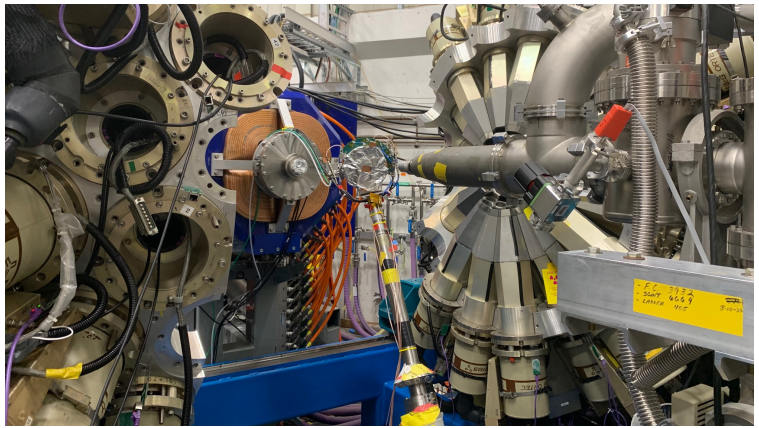
- ATLAS @ ANL
- high-purity germanium detectors with BGO suppression shields
- high-multiplicity spectroscopy in 4π

I-Y Lee, Nuclear Physics A, 520, 641-655(1990)

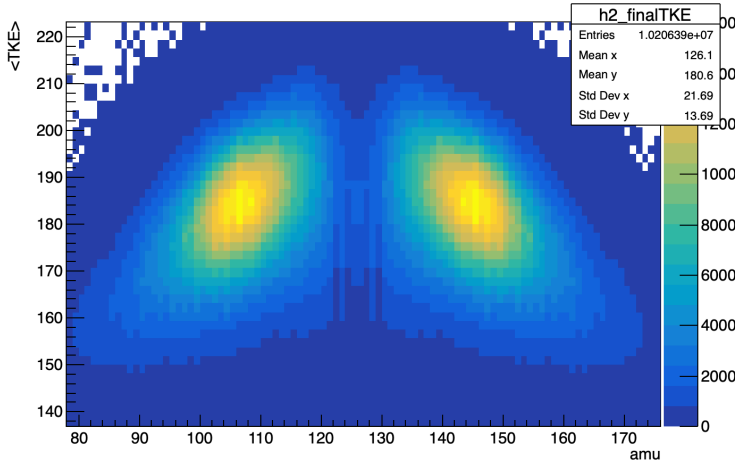
GAMMASPHERE EXPERIMENT

- We conducted an experiment similar to Wilson et al., with the addition of a TFGIC
  - Twin Frisch-grid ionization chamber provides fragment A, TKE
  - Gammasphere provides high-resolution and multiplicity measurement of γ-ray cascade





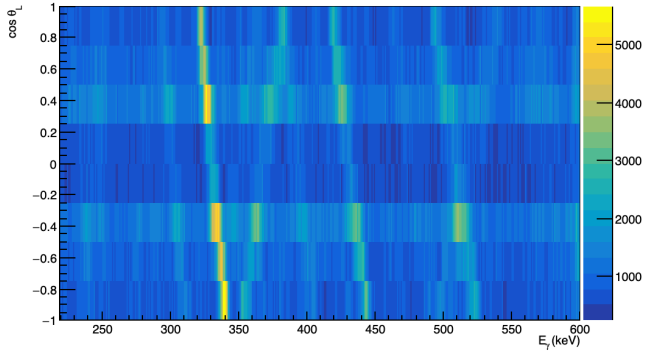
Fission chamber inside Gammasphere



Fragment mass vs. TKE for a single 30m run

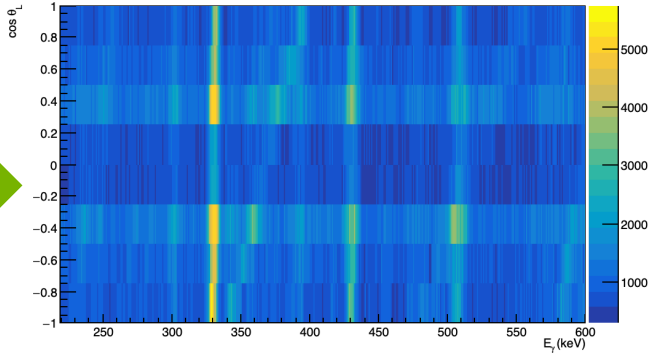
EXPERIMENTAL ANALYSIS (^{144}Ba)

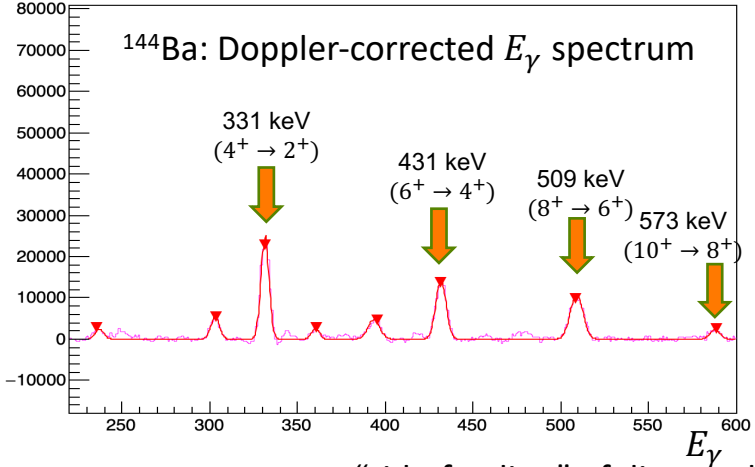
Fragment mass-gated E_γ spectrum with Doppler-shifted ground-state band transitions



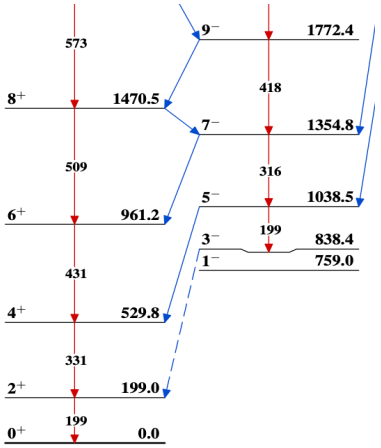
Most prompt γ rays are emitted from accelerated fragments

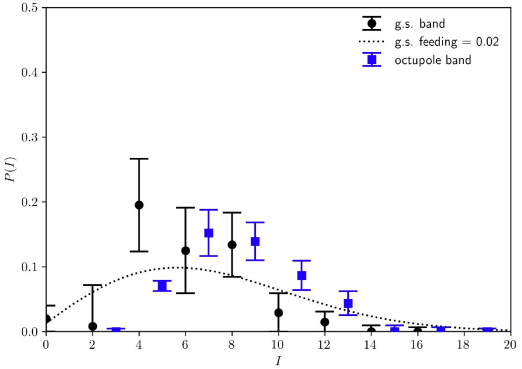
Doppler corr.





+





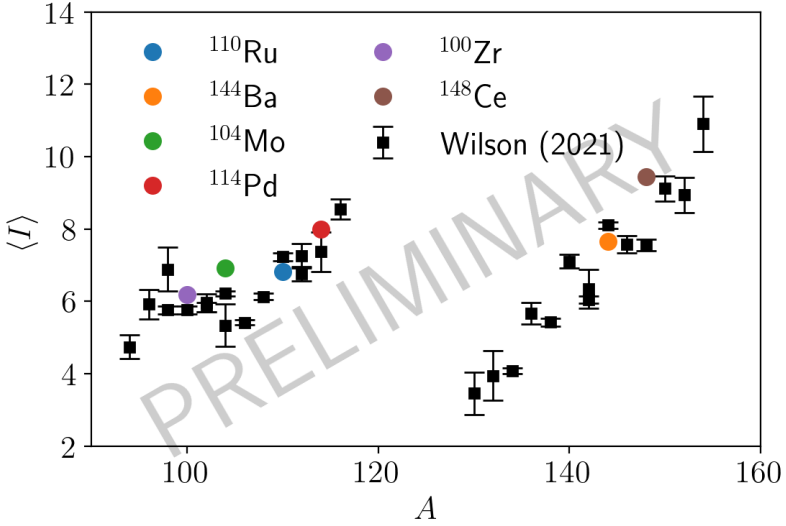
"side-feeding" of discrete levels determined based on observed intensity balance of known gamma transitions

Spin distribution reconstruction for each TKE bin

EXPERIMENTAL RESULTS

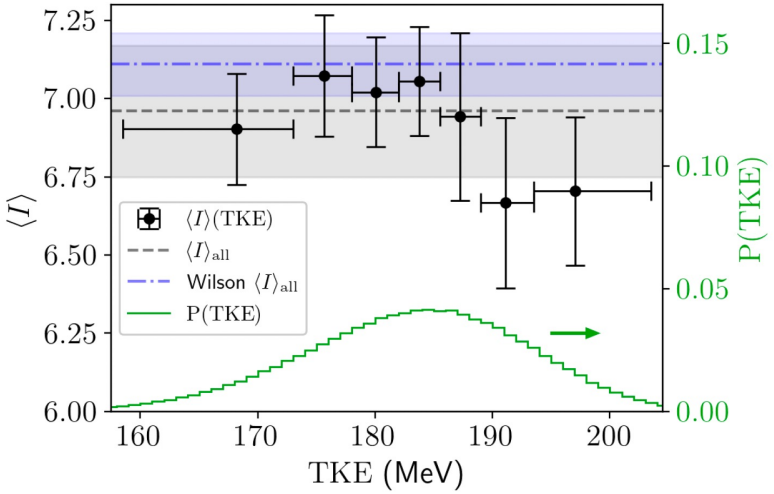
- 130 kBq ^{252}Cf Source (~4000 fissions/s)
- 240 h of livetime at ATLAS
  - 3.5×10^{9} fission events

- Without cutting on TKE, we expect to reproduce the spin sawtooth from Wilson et al.



N. Giha, S. Marin, I. Tolstukhin etal., submitted to PRC

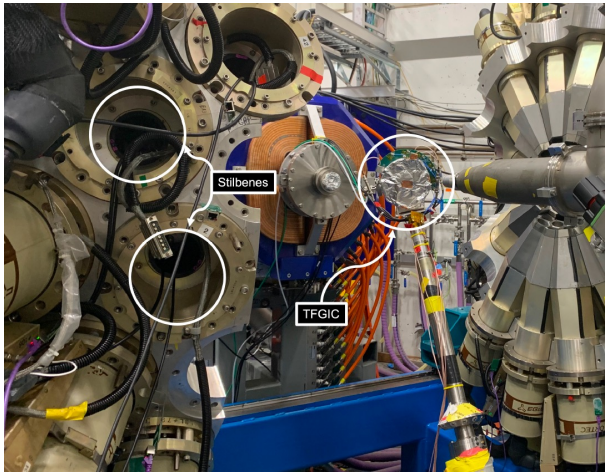
Average post-statistical spin vs. TKE for ^{144}Ba



- Statistical γ -ray and n emission do not destroy correlation between initial and post-statistical spin

- Analysis is underway to construct a "TKE-dependent spin sawtooth", or $\langle J\rangle\,(A, TKE)$

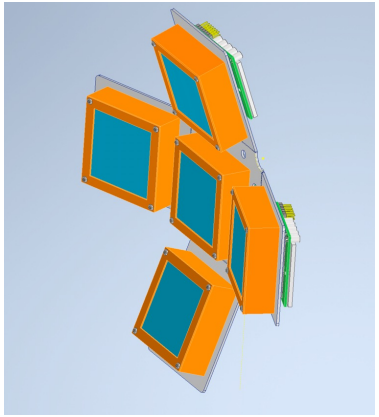
FUTURE PROGRAM AT ANL



Extend Gammasphere analysis:

- angular correlations of gammas and angular momentum direction in fission
- Gammasphere was also instrumented with 12 stilbene detectors
  - neutron-gamma correlations and energy-angle distribution of neutrons —> Resulting in fission neutron observables (multiplicity, spectra, angle)

Argonne NEutron Gamma Array



Development of modular array for neutron-gamma measurements:

- EJ-276D PSD plastic scintillator 50x50x10-20 mm^3
- ARRAYJ-60035-64P SiPM: 64 6x6 mm2 SiPM array combined with fast preamp (~1 ns rise time)
- On-board signal processing with CAEN VX2730 digitizer - 32 Ch. 14 bit 500MS/s
- Current status:
  - 10 detectors
  - Preamp prototyping and testing

CONCLUSION

New experimental results on ^{252}Cf(sf) from a recent experiment performed using a combination of a TFGIC and organic scintillators and Gammasphere

- The multiplicity of γ rays does not increase steadily with fission fragment excitation energy
  - could be an indication of a saturation of the AM

- Separated the average emission of γ rays for the light and heavy fragment
  - Could indicate the presence of complex modes of AM generation

- γ-ray anisotropy dependence on a mass and TKE

- The result of experiment with the Fission chamber and Gammasphere will help to Investigate the dependence of angular momentum on excitation energy

- The results of this experiment can be used to validate and improve nuclear-dynamic models of fission, and predict the scission configurations

ACKNOWLEDGES

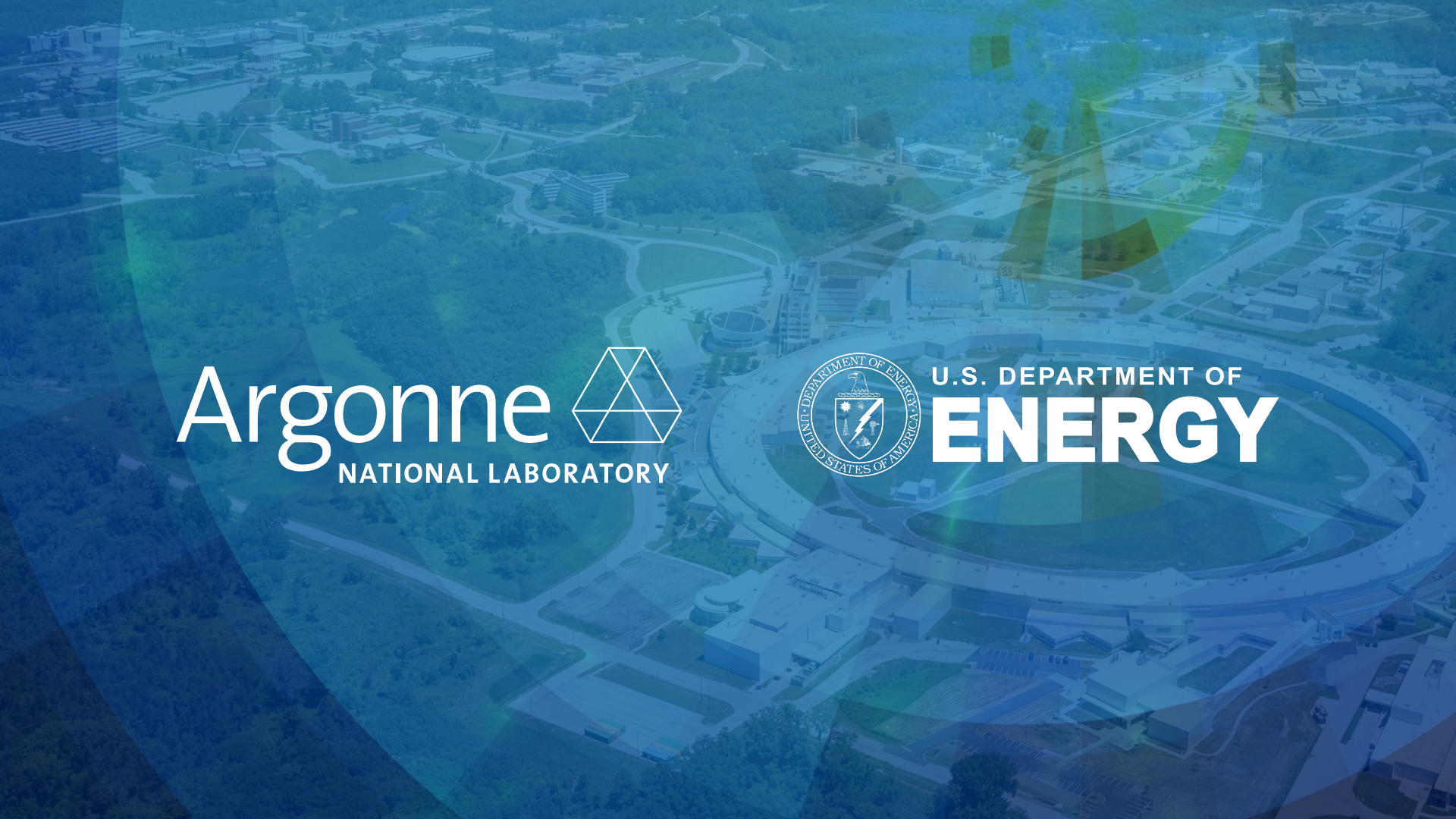
IAT
B. P. Kay
M. B. Oberling
F. Tovesson

N. P. Giha (now at IJCLAB, Orsay)
S. Marin (now at CERN)
S. A. Pozzi

D. L. Duke

W. D. Loveland

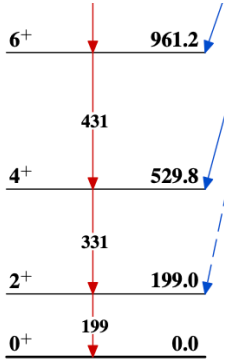
This work was in part supported by the Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D), National Nuclear Security Administration, US Department of Energy. This work was funded in-part by the Consortium for Monitoring, Technology, and Verification under Department of Energy National Nuclear Security Administration award number DE-NA0003920. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract Number DE-AC02-06CH11357.

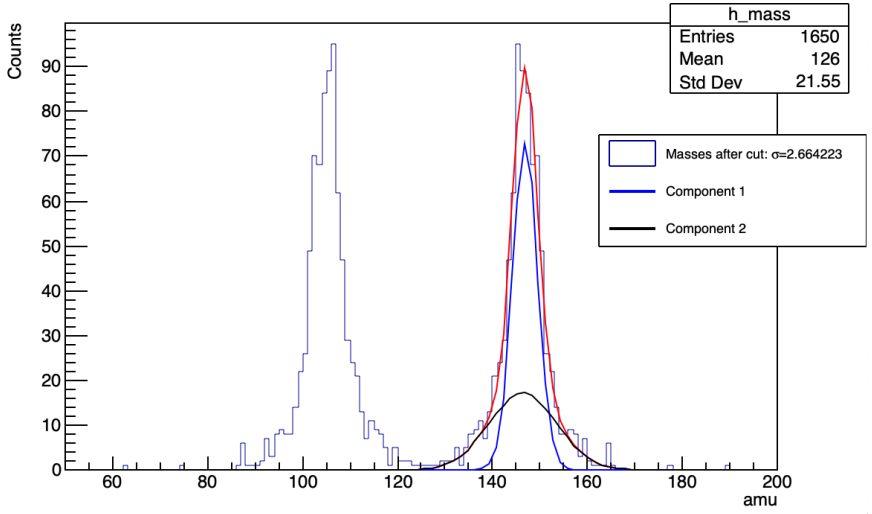

Argonne
NATIONAL LABORATORY
U.S. DEPARTMENT OF
ENERGY

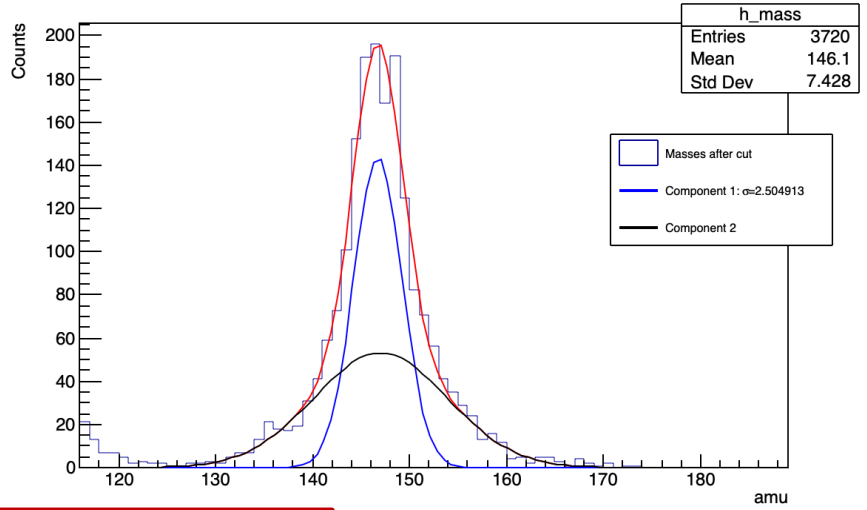
BACKUP: CHAMBER MASS RESOLUTION

Gammasphere allows us to extract the mass resolution for specific fragments:

- Uniquely identify fragment with gamma lines
- Check the reconstructed (pre-neutron) masses of those events
- 2E method previously reported FWHM ~ 4-5 amu







$$\text{FWHM} \approx 2.355\sigma \approx 6 \text{ amu}$$

BACKUP: GAMMASPHERE CALIBRATION

- The full energy peak efficiency was calibrated by placing a sealed 195.8 kBq ^{226}Ra source inside the TFGIC