Decay spectroscopy techniques to study neutron-rich fission fragments at ATLAS

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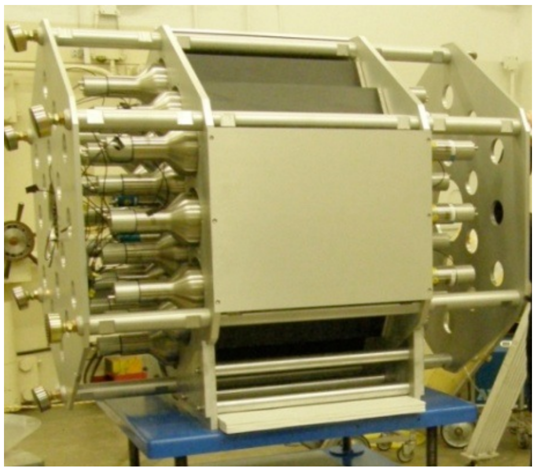
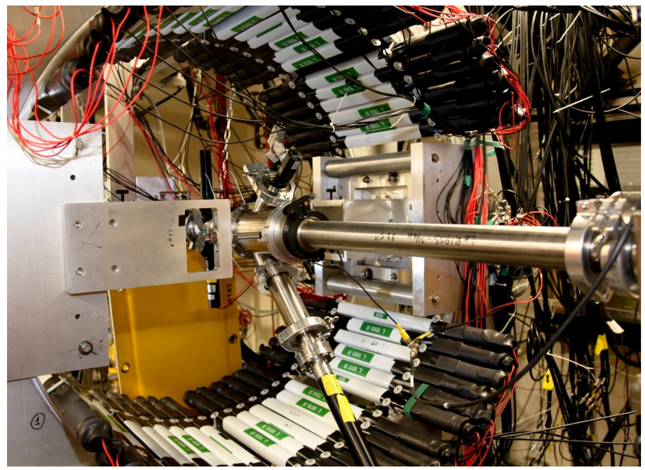
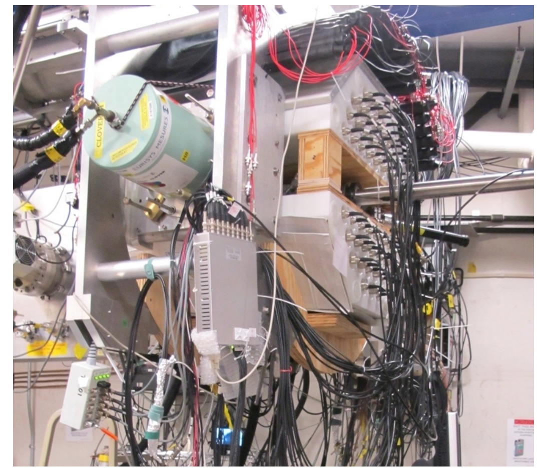


MTAS = Modular Total Absorption Spectrometer



VANDLE = Versatile Array of Neutron Detectors for Low Energy

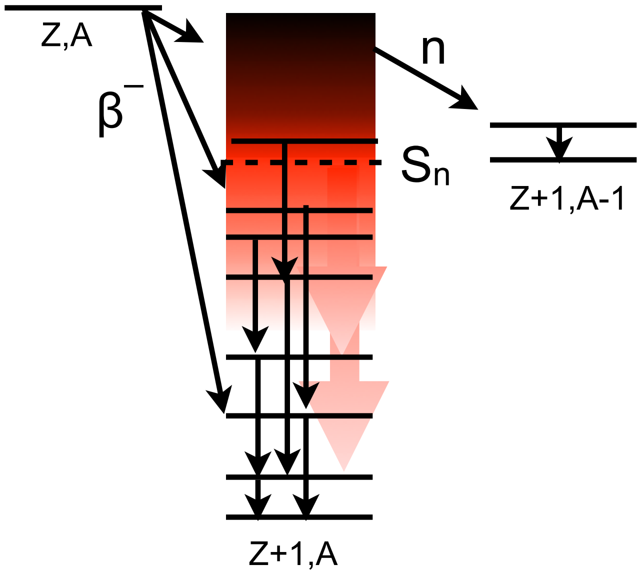


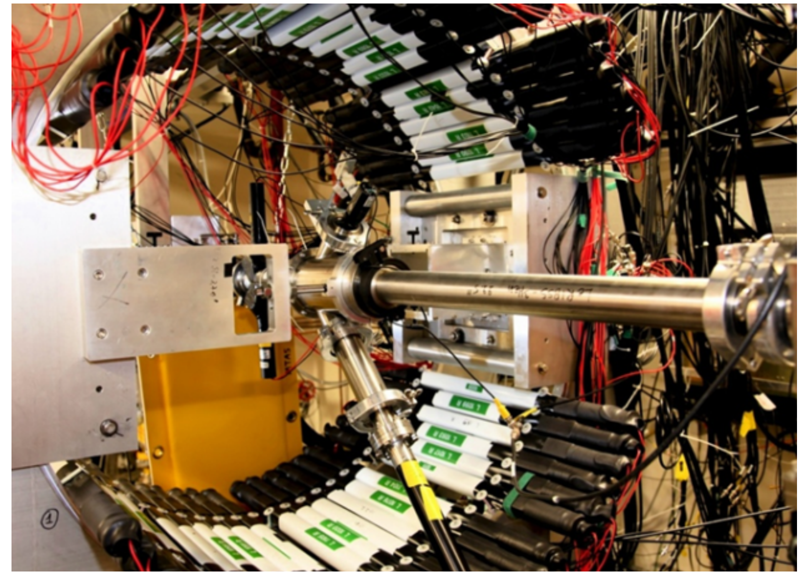
3Hen = Helium-3 Neutron Detectors
Hybrid-3Hen = 3Hen + Clover Ge

The physics of neutron-rich fission fragments

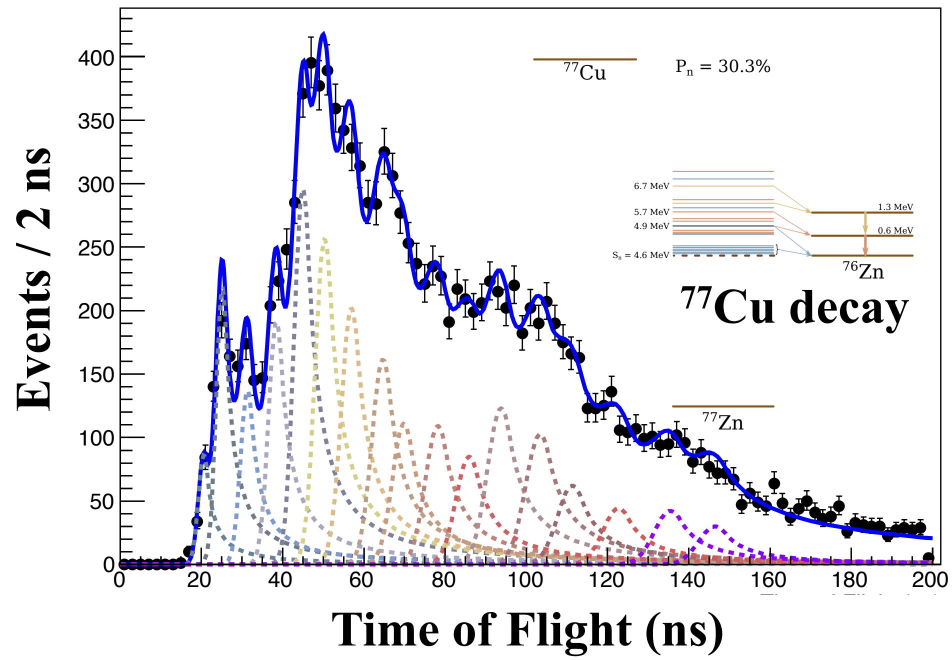
- nuclear structure evolution as N >> Z
- spectroscopy near and above the neutron separation energy
- rapid-neutron capture half-lives and beta-delayed neutron branchings
- societal impact in better data for modeling neutron-rich environments such as nuclear reactors
- more detailed understanding of the anti-neutrino spectra from reactors

Measure the complete beta-strength function
VANDLE - Neutron energies via time-of-flight





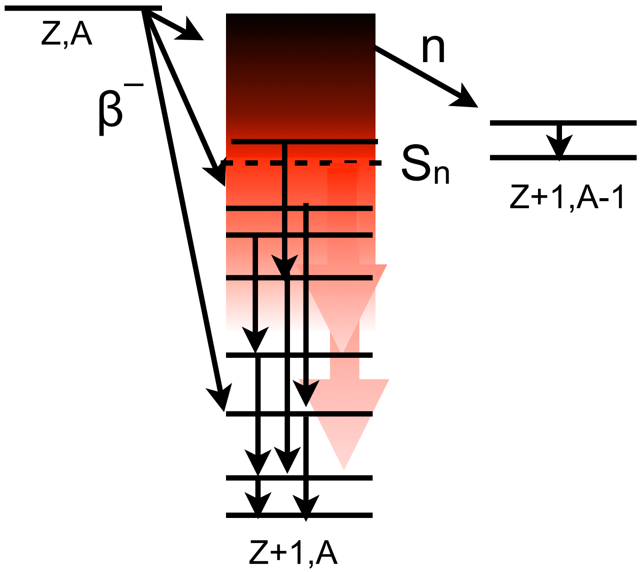
- **Commissioned with beam in 2012 with nearly 30 fission fragments measured**
- **48 detectors in barrel array achieve efficiency of 12% at 1 MeV; calibrated with mono-energetic neutrons at Ohio**
- **Used to measure neutron energies via time-of-flight (~50 cm flight path as shown); now 100 cm flight path**
- **Can be "hybridized" to be compatible with other detectors such as Ge - neutron feeding as high as 1 MeV in daughter**
- **Results indicate significant intensity of ~2 MeV neutrons (higher than expected) in the decay of some isotopes - ^{77}Cu, ^{84}Ga, ^{136}Sb**
- **High energy neutrons indicate Gamow-Teller decay from closed neutron shell rather than first forbidden transitions**

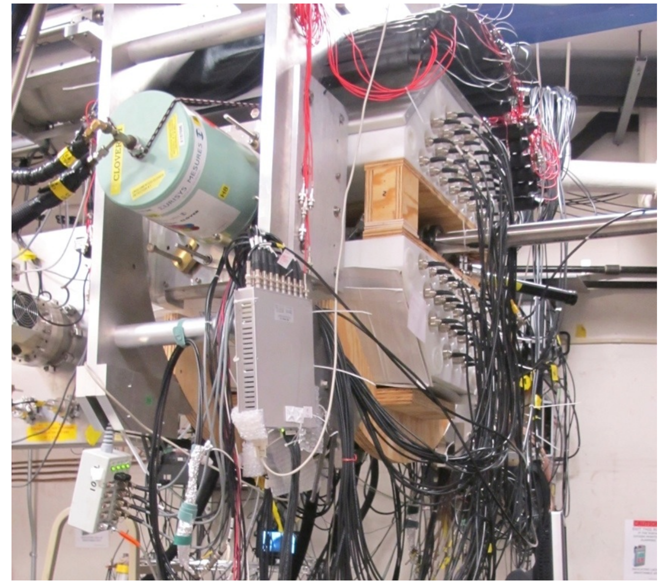


S. V. Paulauskas et al., NIM 737A, 22 (2014); UTK Dissertation: http://trace.tennessee.edu/utk_graddiss/2606/

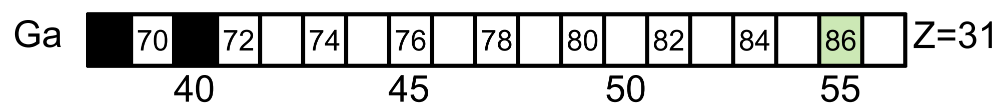
Measure the complete beta-strength function
3Hen - 3He ionization neutron counter

^{3}Hen Detector

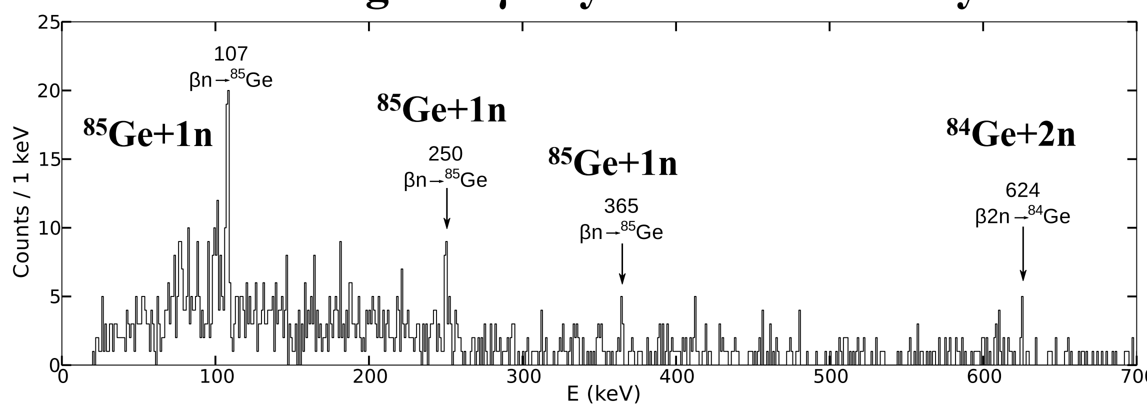




- Commissioned with beam in 2012 by identifying the decay of ^{86}Ga
- Up to 74 detectors filled with 10 atm. of ^{3}He with efficiency of 80% between 0.001-1 MeV
- Used to count neutrons and detect the most exotic isotopes
- Can be "hybridized" (as shown - 48 detectors - eff. ~30%) and used with other detectors such as Ge and used as a gating detector
- Results revealed large 2n decay branch and strong competition between 1n (60%) and 2n (20%) emission: Miernik et al., PRL 111, 172501 (2013)
- 1-3 ions per second (RILIS) at HRIBF (RIKEN ~0.15 at 10 pnA ^{238}U 345 MeV/u beams)



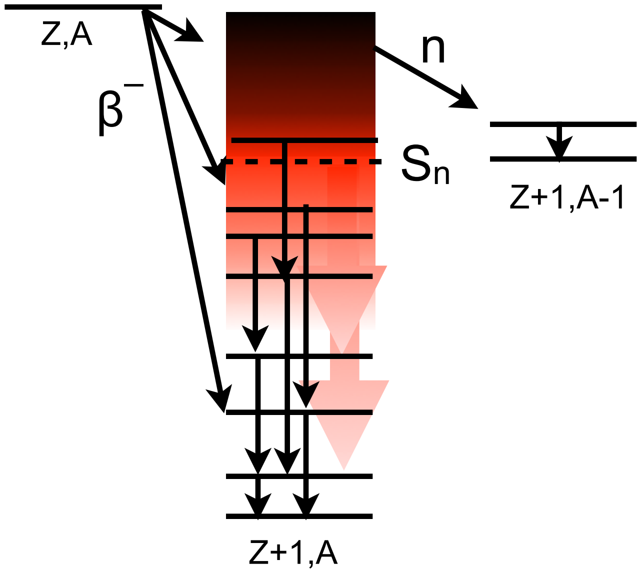
Neutron-gated γ-rays from ^{86}Ga decay

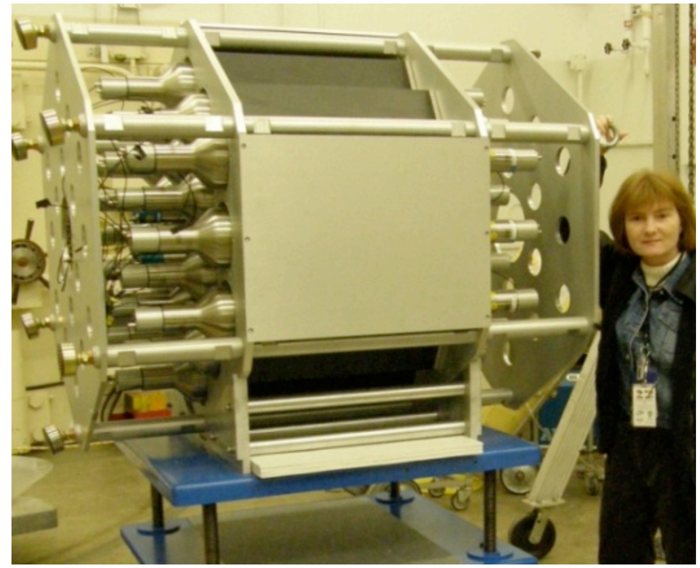


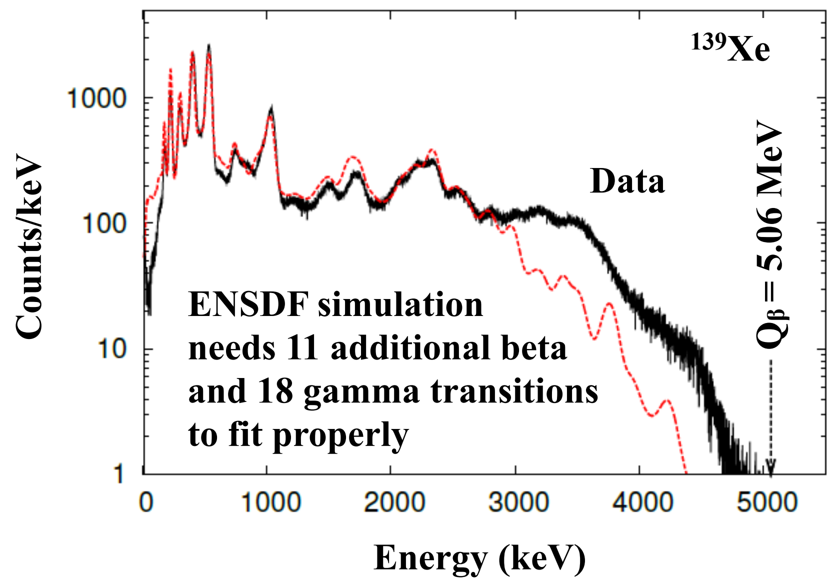
Note that Q_β ~ 15 MeV: even 3n + ^{83}Ga channel is open

K. Miernik et al., PRL 111, 132502 (2013)

Measure the complete beta-strength function
MTAS - Modular Total Absorption Spectrometer



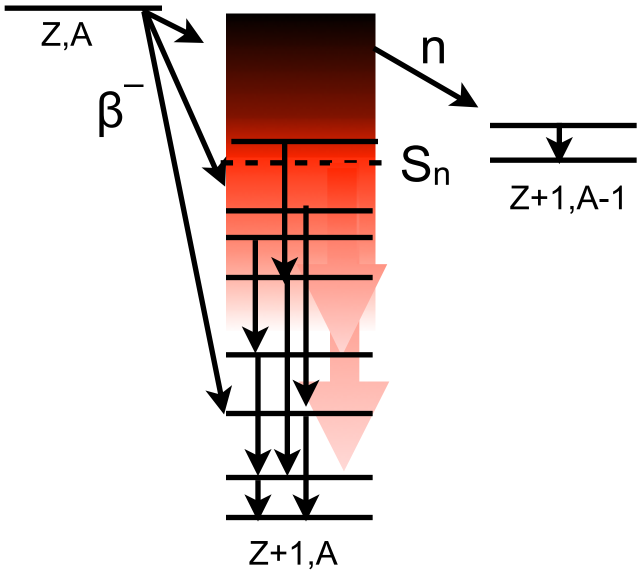




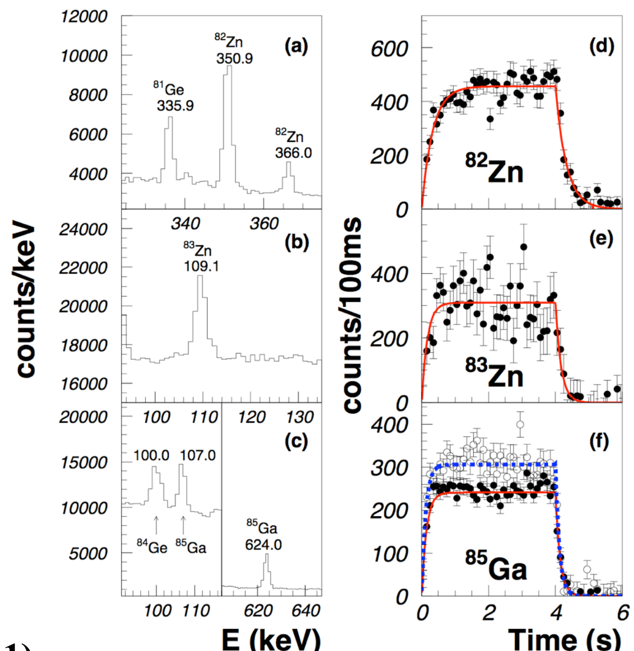
- Commissioned with beam in 2012 by measuring the decay of 22 isotopes - 7 highest priority of IAEA
- 19 detectors in full array achieve full energy peak efficiency of 71% at 4 MeV
- Includes segmented beta detectors with 70% efficiency
- Identifies levels in daughter nucleus fed in β-decay
- Large neutron capture signal at ~7 MeV on Na and I
- Results are used to determine the decay heat released by fission products: typically we found a 20-40% increase in average gamma energy
- Higher lying beta feeding = lower beta energies = lower anti-neutrino energies from reactors

A. Fijalkowska et al., Nucl. Data Sheets, in press;
A. Fijalkowska, Dissertation U. Warsaw 2014-15

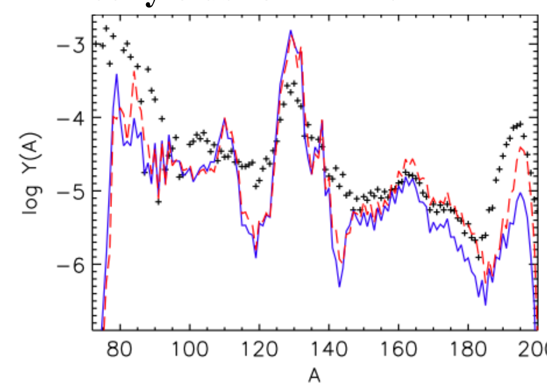
Measure the complete beta-strength function
LeRIBSS + CARDS - Clover Ge Array on a Low-energy Beam Line



- **Commissioned with beam in the 2008**
- **4 Ge detectors downstream from high-resolution mass analyzer (M/ΔM ~ 10,000)**
- **Can be "hybridized" and combined with other detectors**
- **Close geometry achieves 6% efficiency at 1.33 MeV and 34% at 81 keV**
- **Results expanded many decay schemes and corrected half-lives**



r-process abundances - Half-lives measured and systematics extended in A~80 affect yields for A>140

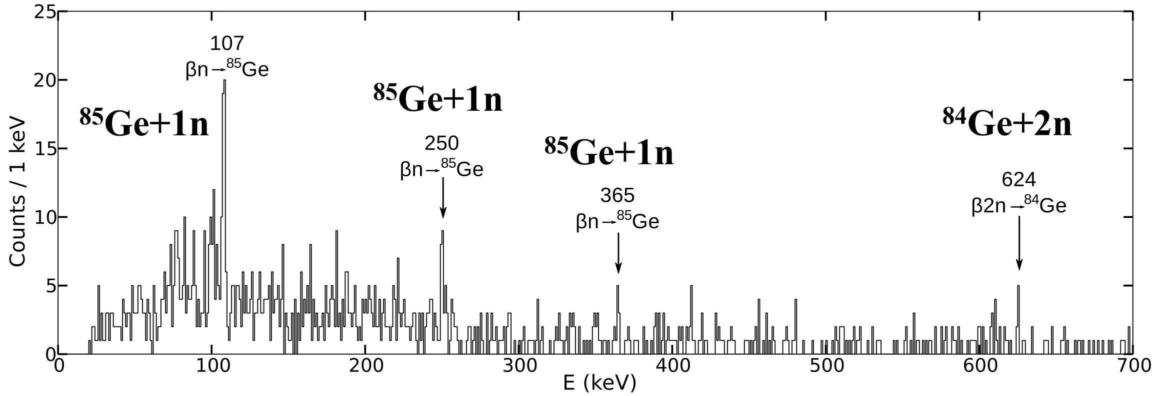


Measured (+) and calculated r-process abundances with parameters adjusted based on our new data on $^{82-83}$Zn and ^{85}Ga (red). The blue curve is based on unmodified parameters.

Madurga et al., Phys. Rev. Lett. 109, 112501 (2011)

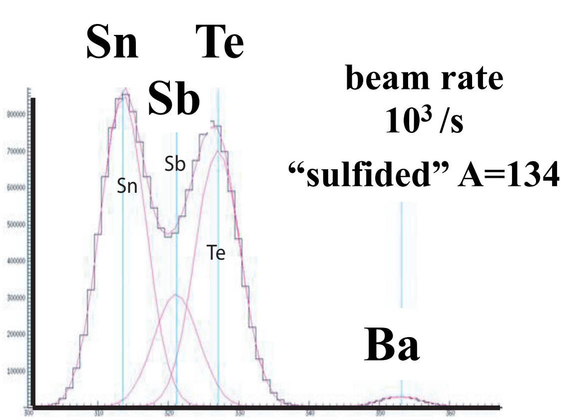
High mass resolution doesn't do it alone

Neutron-gated γ-rays from ^{86}Ga decay



- Attempted 2-3 times using positive and negative ions (electron beam plasma source with and without Cs charge exchange
- Required laser ionization to suppress ^{86}Br
- Mass difference between ^{86}Ga and ^{86}Br: 1945:1
- Beam intensity ^{86}Ga:^{86}Br 1: >10^7 per second

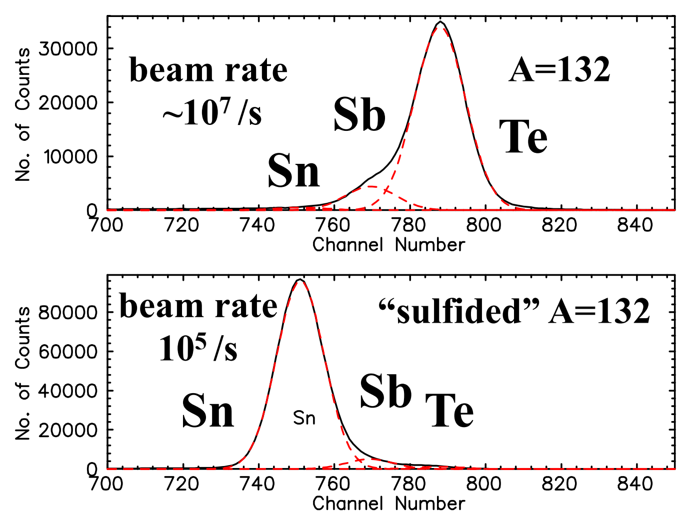
Energy losses in an ion chamber



Projection along DE

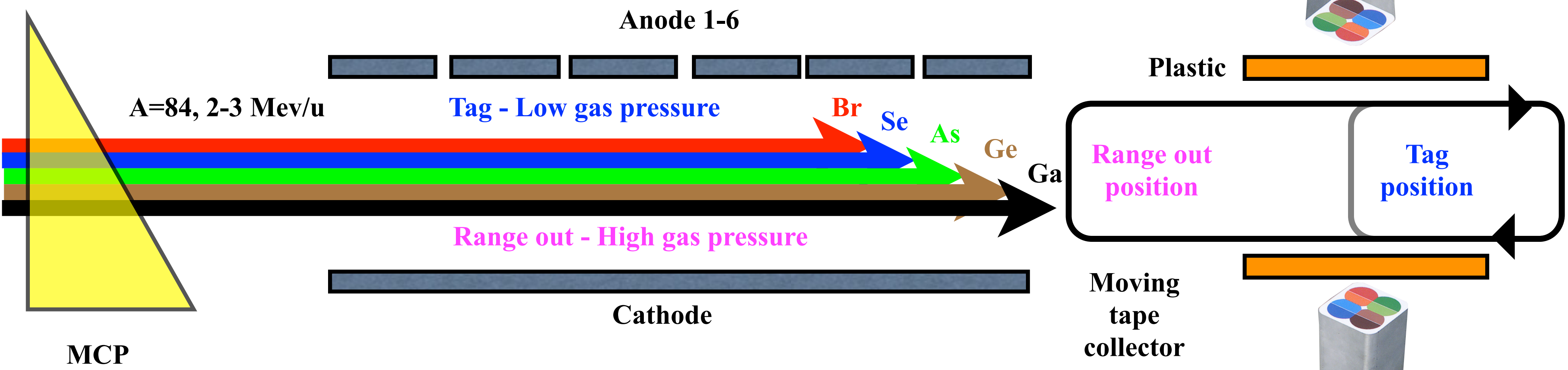
- Molecular transport of SnS followed by break-up in the charge exchange cell
- Even with factors of ~10^5 suppression, Sb and Te remain in the beam
- Mass difference between ^{134}Sn and ^{134}Te: 7684:1
- Mass difference between ^{132}Sn and ^{132}Te: 14236

Energy losses in an ion chamber



Living with contaminated beams: accelerate and range-out

1 MCP provides fast timing of heavy ion beam and near 100% efficiency
1 Ionization chamber provides Z identification - 100% efficiency
2 Hemispheric plastic detectors outside vacuum chamber detects betas and removes background - efficiency:
35-48% (β-energy dependent)
4 Clover Ge detects gamma-rays - efficiency:
22% @ 90 keV
8.5% @ 600 keV
5% @ 1332 keV



Ionization chamber provides ability to adjust quickly the isobaric separator ➡ M/ΔM~4000
High gas pressure ranges out high-Z ions but requires tape at window and movement to measuring station
Low gas pressure tags ions and allows implantation at measuring station
Acceleration costs intensity: factors 10-13 for acceleration; 2-∞ for charge exchange

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Different gas pressure regimes

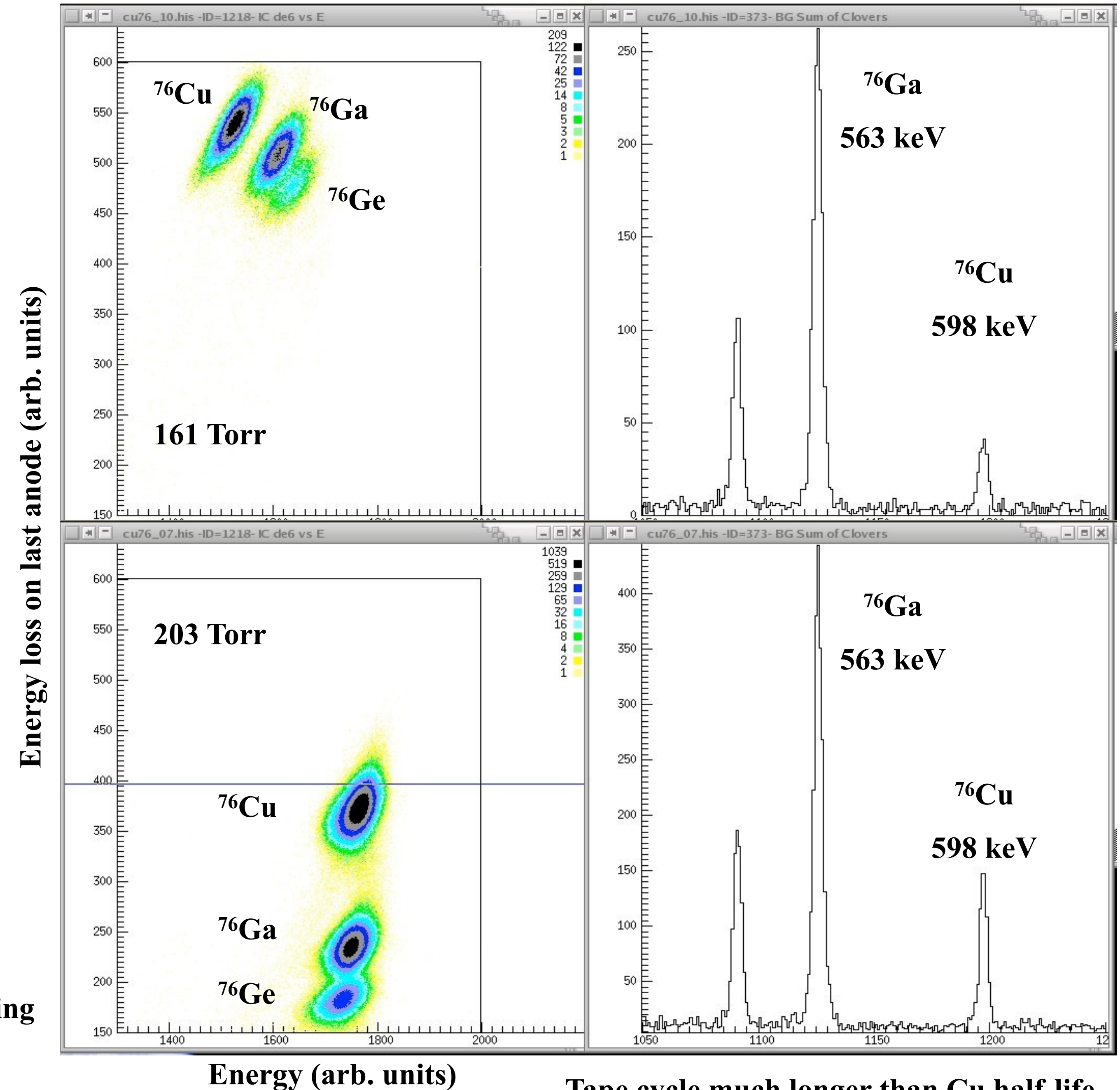
Low gas pressure (100-160 Torr)

- Identify isobars
- Measure full beam rates
- Implant at measuring point for shortest half-lives
- Small sample size possible

High gas pressure (~ 200 Torr)

- Best isotope identification
- Limit ion implantation to tape
- Adjust isobar magnet to reduce unwanted ions
- Range out the lower Z components
- Implant at window and move sample to measuring point
- Large losses unless tape positioned at exit window

Absolute values (P_n) possible with ion counting
Winger et al., PRL 102, 142502 (2009)



Tape cycle much longer than Cu half-life

Experimental hall requirements based on largest equipment

VANDLE
- Assume beam height at least 1.25 meters
- VANDLE barrel has 1 meter time-of-flight so ~2 meters on either side of beam line
- VANDLE prefers to be far away from concrete and other materials that scatter neutrons

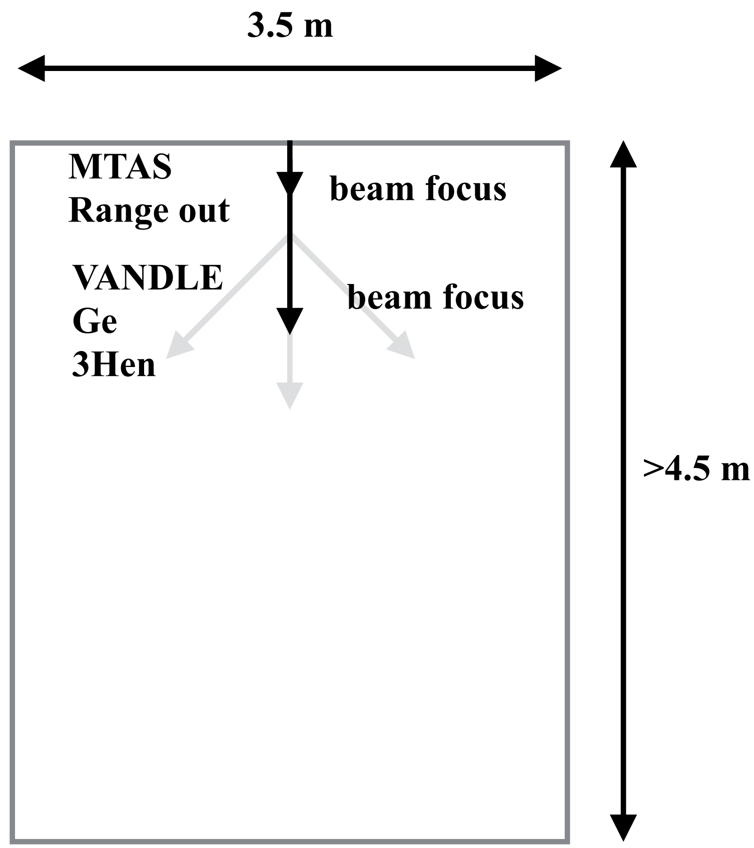
MTAS

- Array and shielding weighs approximately 7 tons.
- Although on wheels path to experimental hall should not have stairs, trench coverings, etc.
- Shielding is ~2.5 meters long. Since the tape extends all the way through array and shielding, similar amount of room is necessary behind MTAS

Ranging out accelerated line (use depends on beam purity)

- Same as the low energy hall with a little extra length to accommodate ion chamber upstream

Beam conditions
- DC or nearly so
- Beam deflector - time (seconds) variable
- Constant energy, low emittance
- Although not necessary, 300+ keV beams could be appealing for implantation timing on sub-200 ms activities



Consider multiple beam lines - can a beam deflector be used to serve 2 experiments at once?

- Multiple techniques for enhanced purity beams
- Small circular beam sizes (1-2 mm radius)
- User access to small step changes of isobar settings