Decay spectroscopy with MTAS and VANDLE

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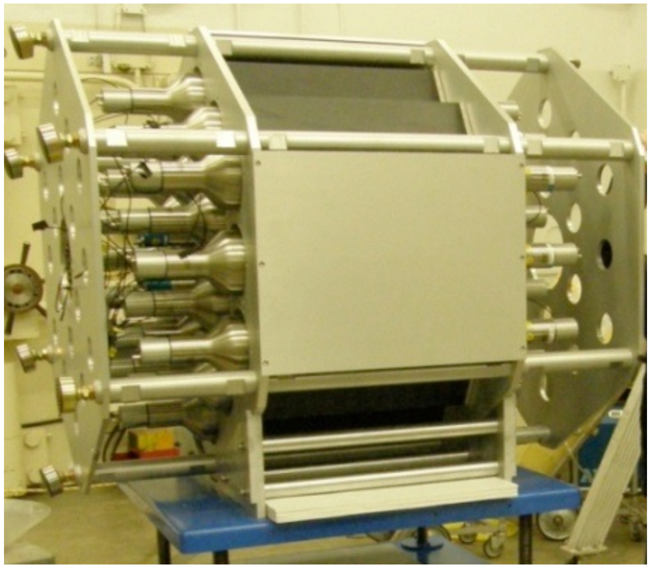
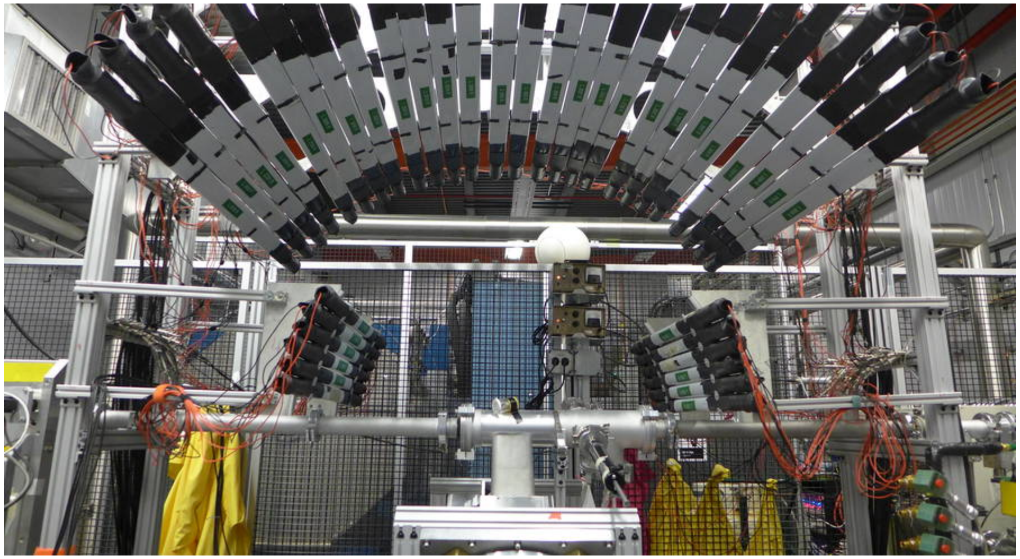
and others



MTAS = Modular Total Absorption Spectrometer



VANDLE = Versatile Array of Neutron Detectors for Low Energy

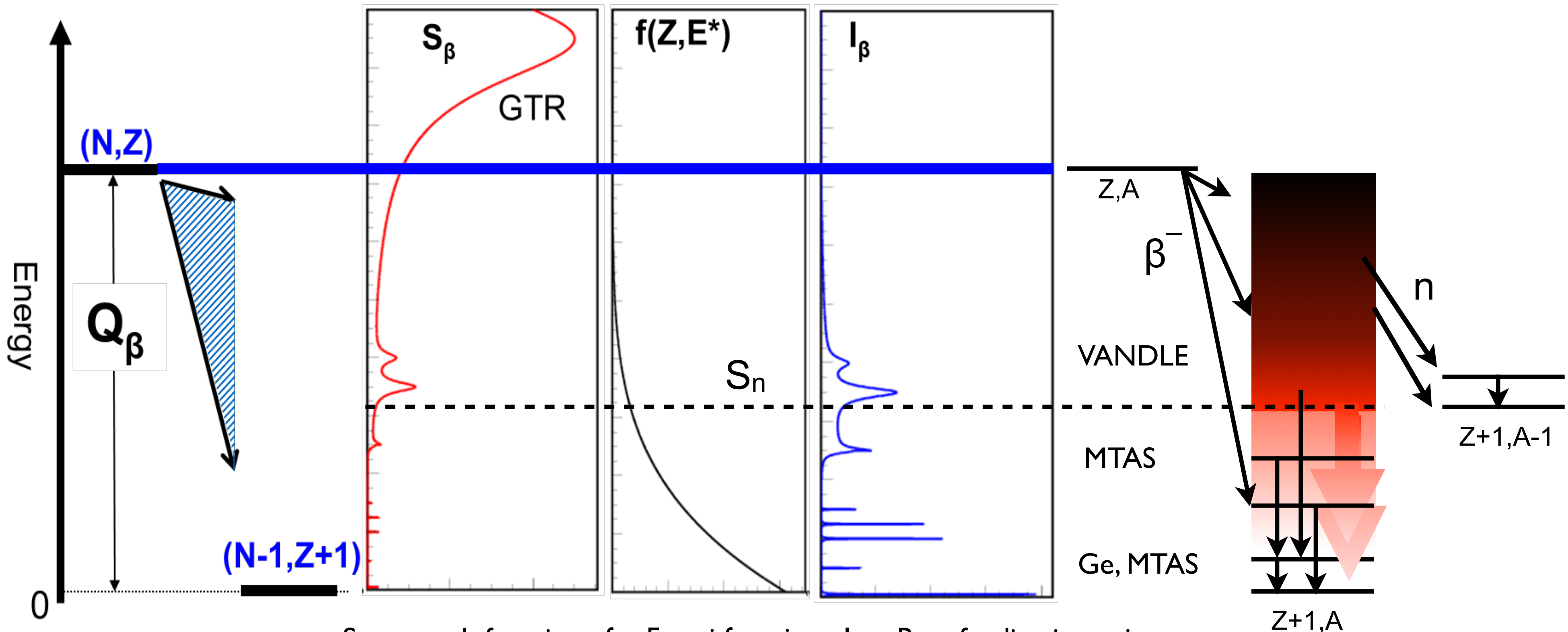
- Nuclear structure - beta strength below S_n
- Nuclear structure - energy "levels"
- Neutrino physics - anti-neutrino anomaly
- Nuclear energy - decay heat

- Nuclear structure - beta strength above S_n
- Nuclear structure - energy "levels"
- Nuclear structure - Gamow-Teller vs forbidden transitions
- Nuclear astrophysics - r-process
- Nuclear energy - neutron energy spectrum

Half-life, branching ratios, and intensities lead to beta strength function

$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)$$

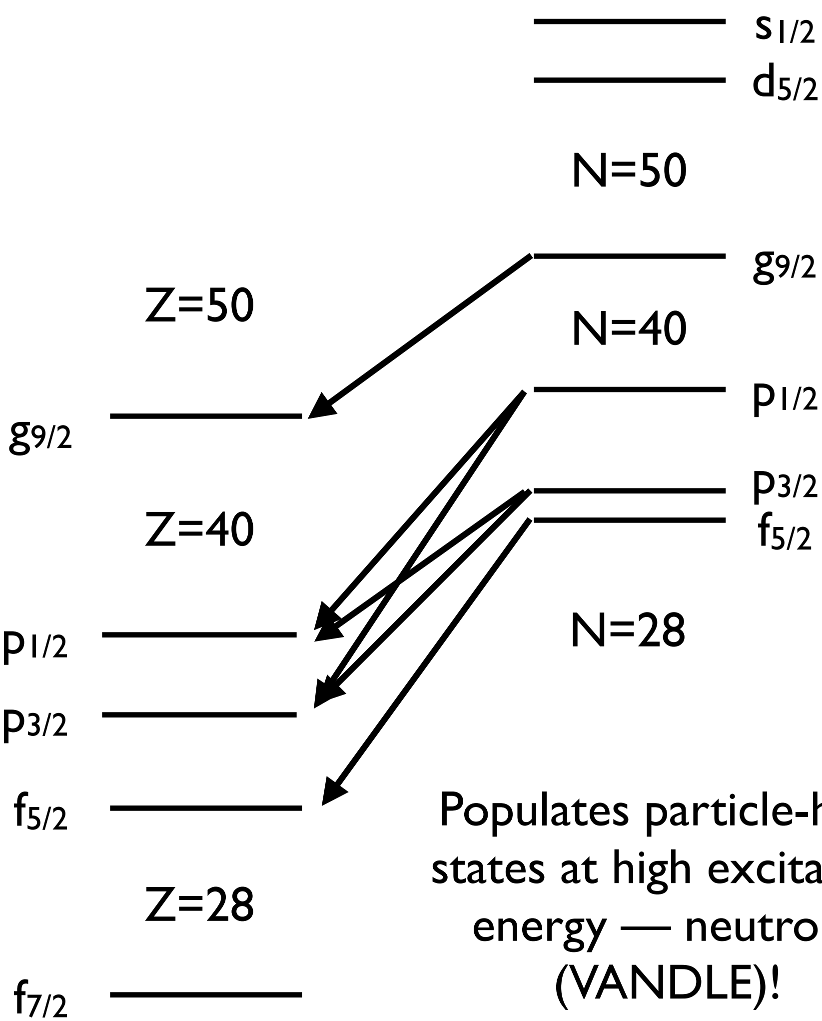
$$\beta^- \rightarrow \quad n = \; p + e^- + \bar{\nu}$$



S_β strength function (determined) f = Fermi function (calculated) I_β = Beta feeding intensity (measured)

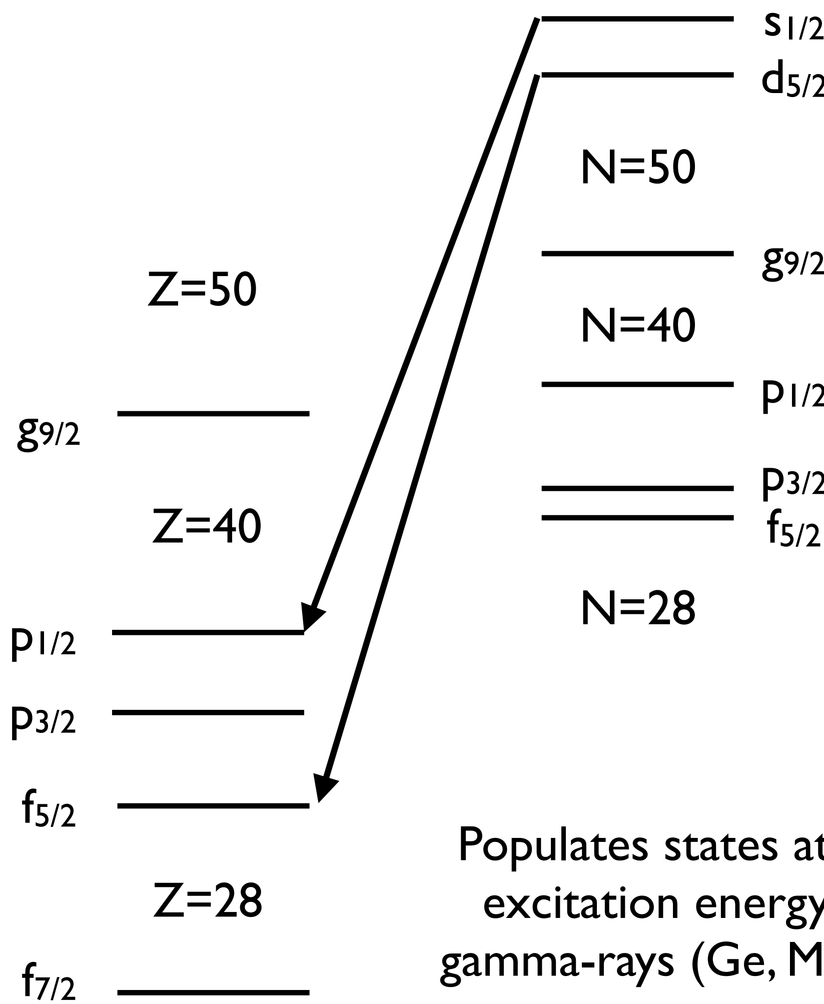
Exotic nuclei with large Q_β leads to competition

Gamow-Teller transitions
large strength, small beta energy
no parity change
no angular momentum change
spin change 0,1



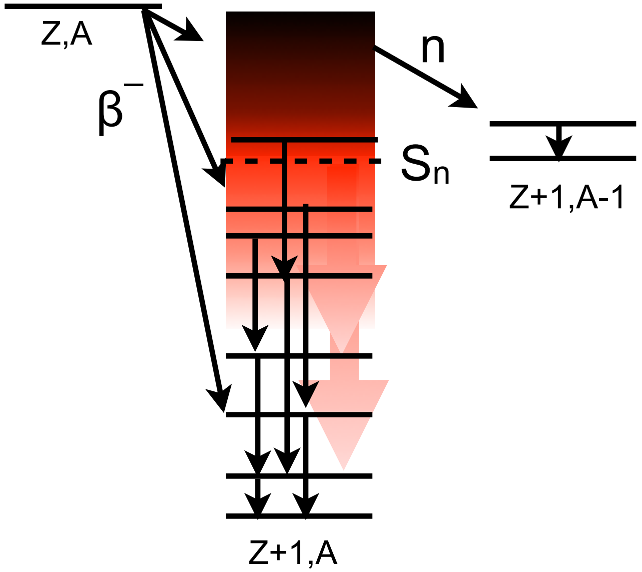
Populates particle-hole states at high excitation energy — neutrons (VANDLE)!

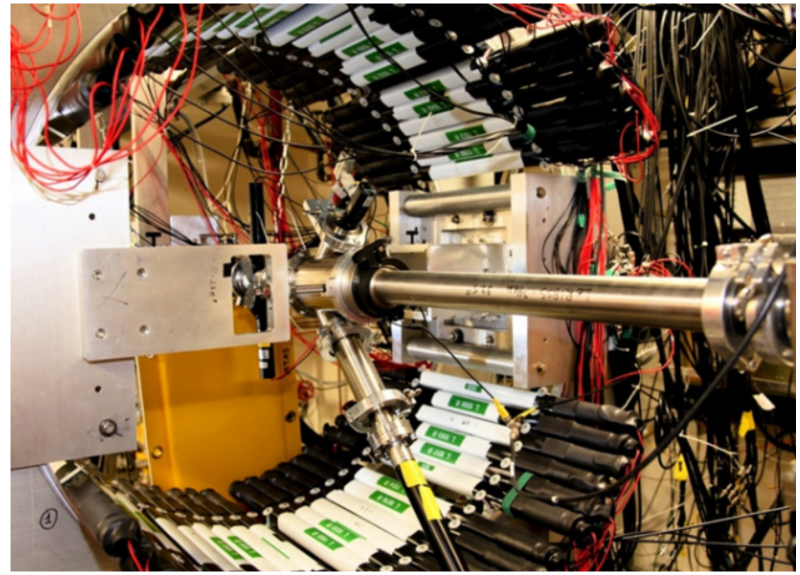
Forbidden transitions
small strength, large beta energy
parity change
angular momentum change
spin change 0,1,2



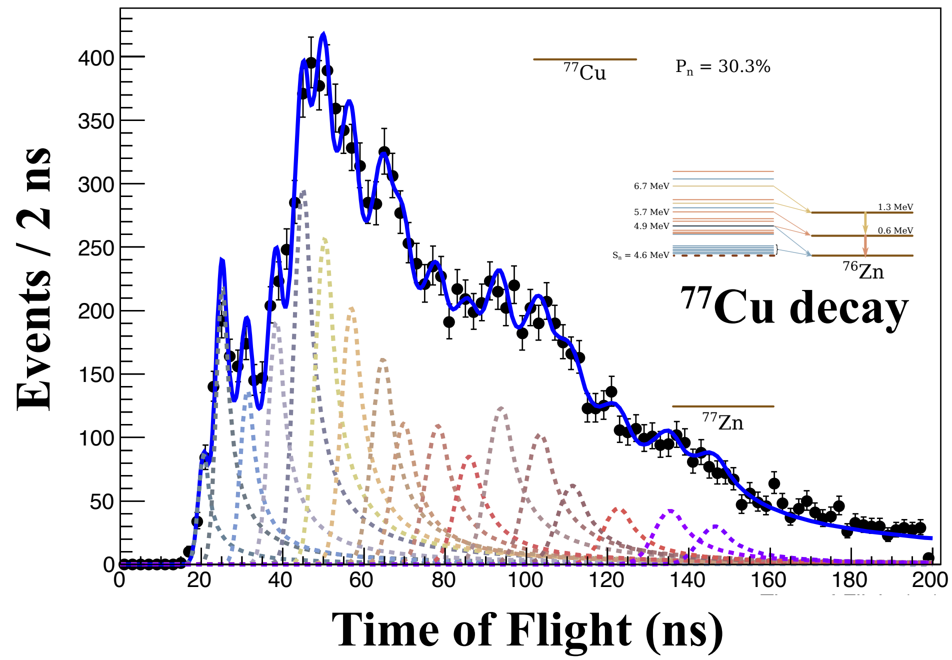
Populates states at low excitation energy — gamma-rays (Ge, MTAS)!

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/

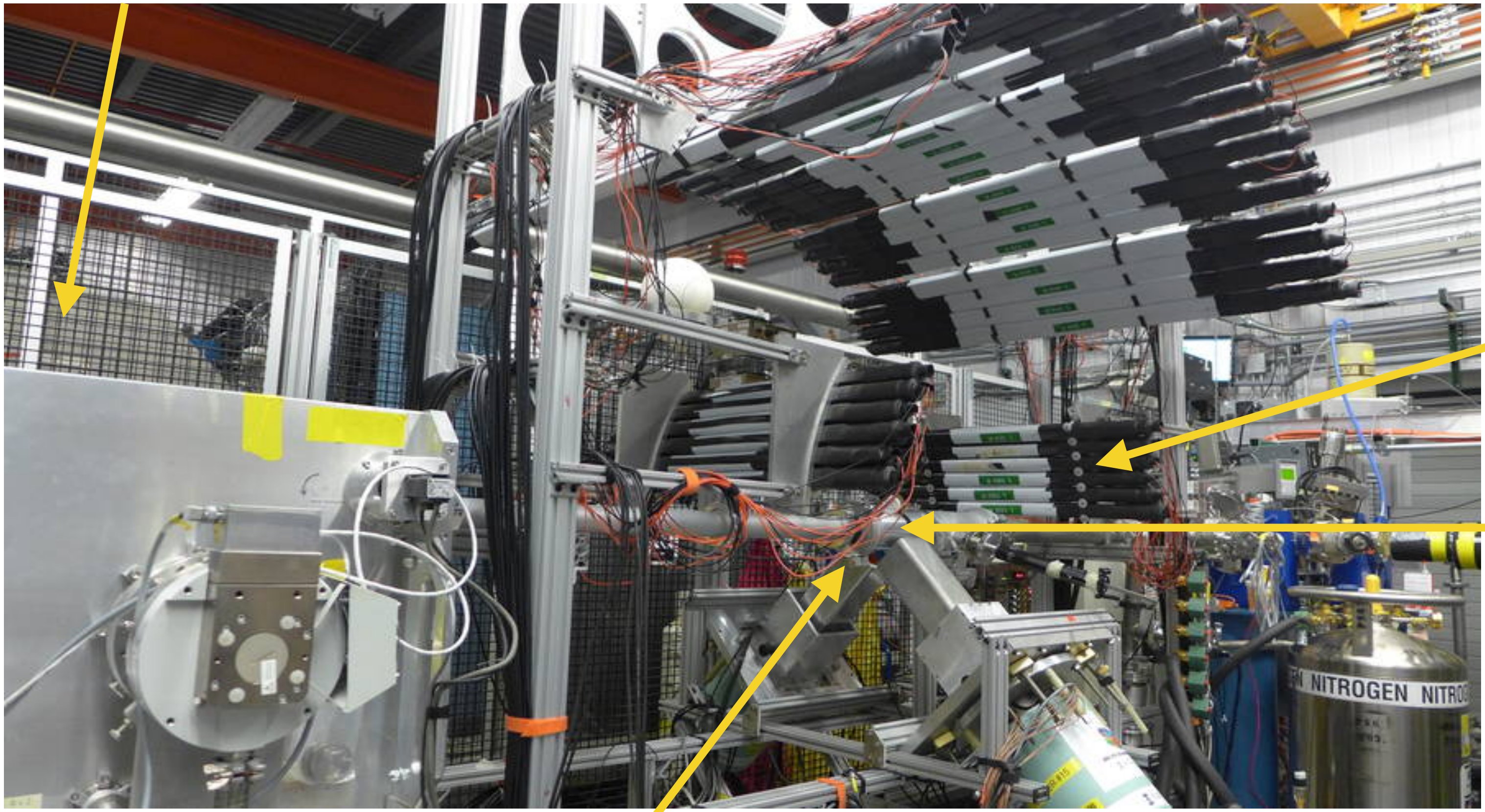
VANDLE @ CARIBU - Jan-Apr 2015

VANDLE can handle high neutron (thermal) background

CARIBU ^{252}Cf source

Medium Bars with 1.0 m flight path

New Frame: 20% of 4π



Small Bars with
0.5 m flight path

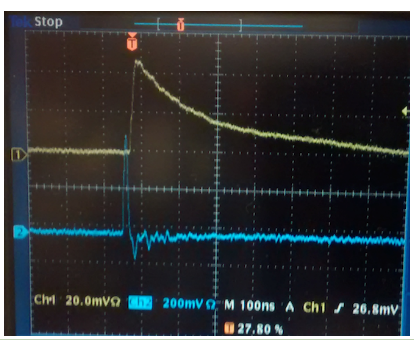
Beam line

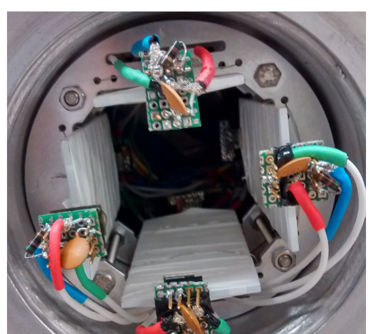
Tape drive

Plastic beta detectors with Si-PMTs

Clover detectors below beam line (no shadowing)

Oscilloscope scale:
Time: 100 ns
Upper: 20 mV
Lower: 200 mV

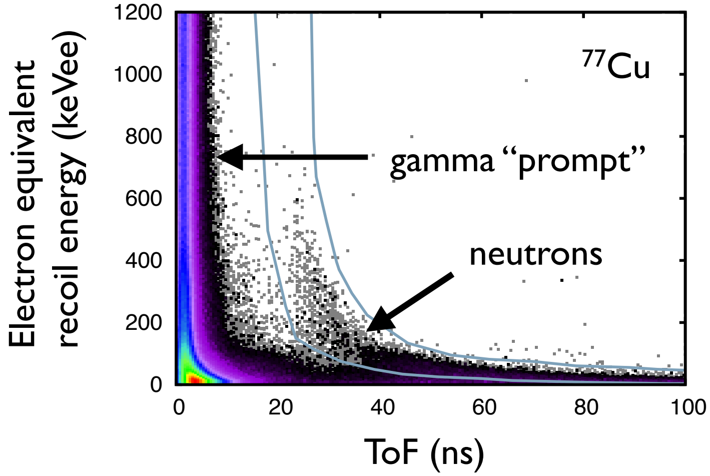




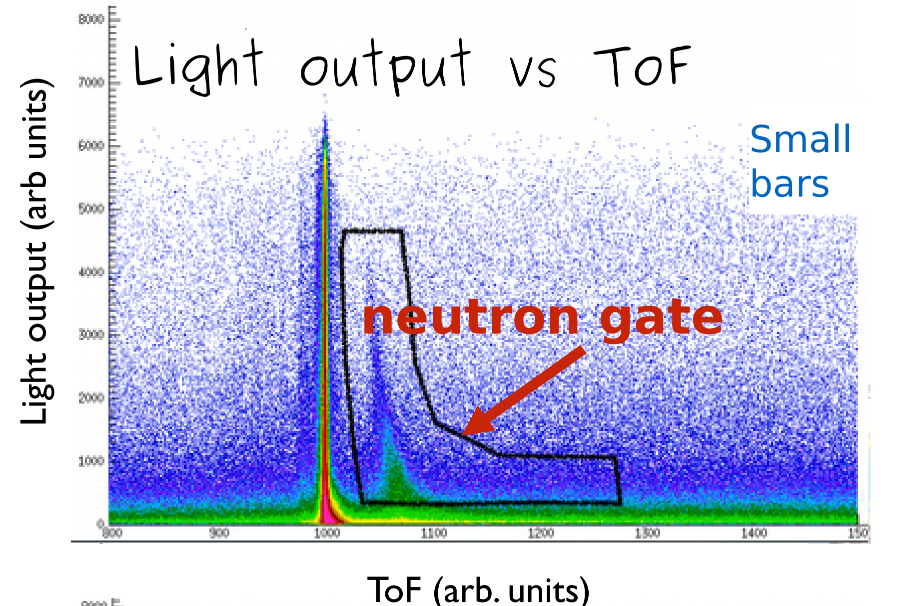
Slow and fast signals
1 ns resolution (was 3 ns)
Inside vacuum for low energy betas
Low noise Si-PMTs for low thresholds (~50 keV)
Total efficiency: ~70%

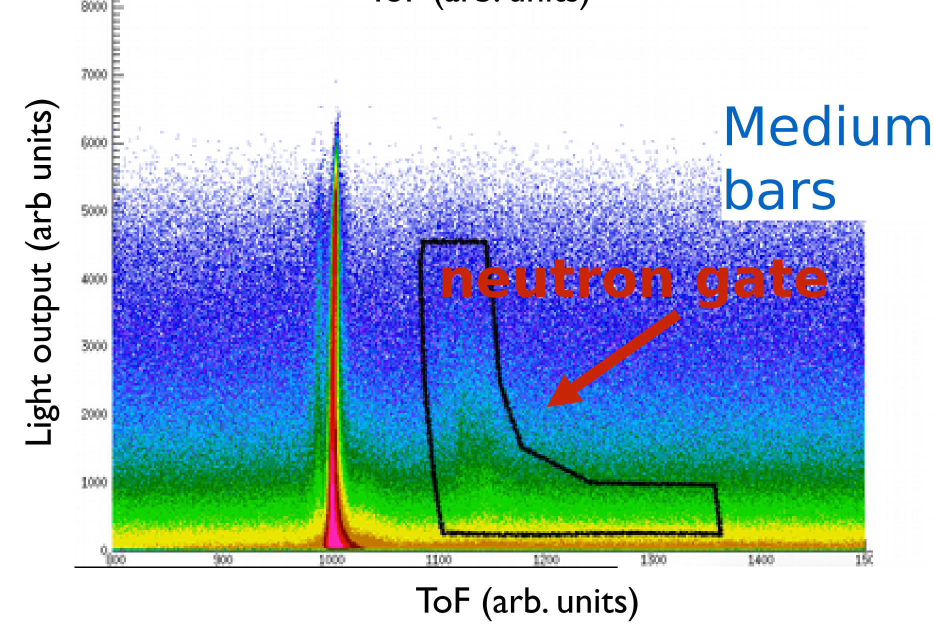
Neutron and neutron-gamma data

HRIBF data (extremely low background)



CARIBU data (high background)





New CARIBU data

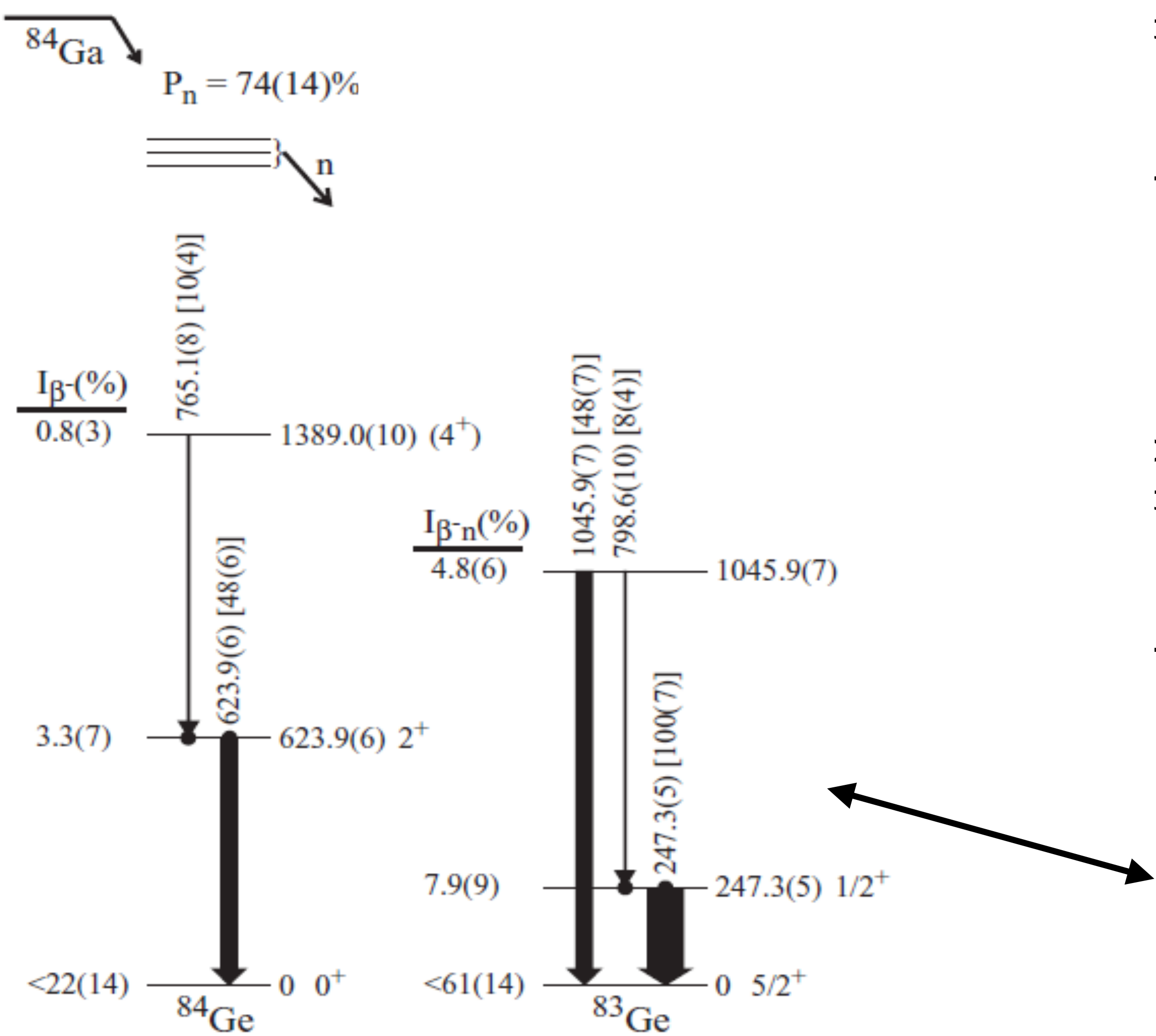
Longer ToF for medium bars easily visible
Will need to figure out best way to subtract background
Measured ^{135,136}Sb, ^{137}I, and ^{85}As (Jan-Apr 2015)
High gamma background due to n + ^{14}N

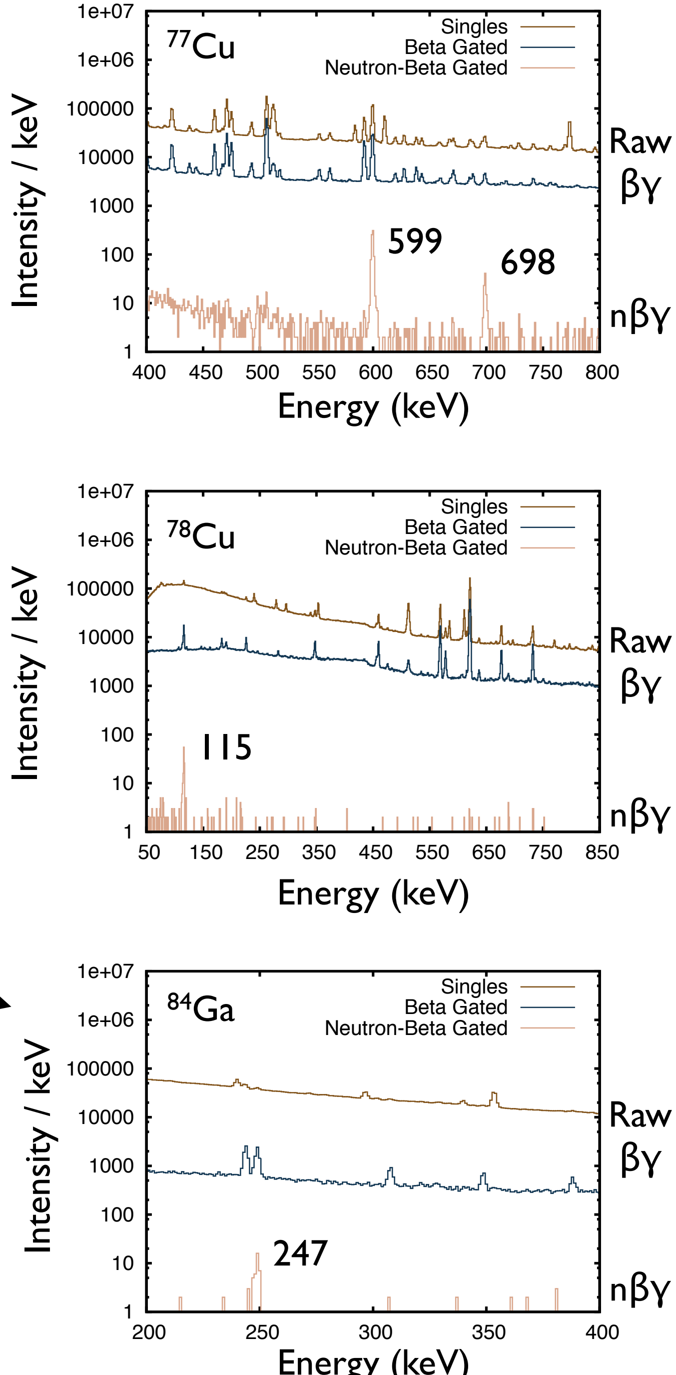
Expect SPES to be much more similar
to HRIBF in terms of data quality

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

Neutron-gamma data

The importance of pairing Ge with VANDLE - neutrons feed excited states in the daughter



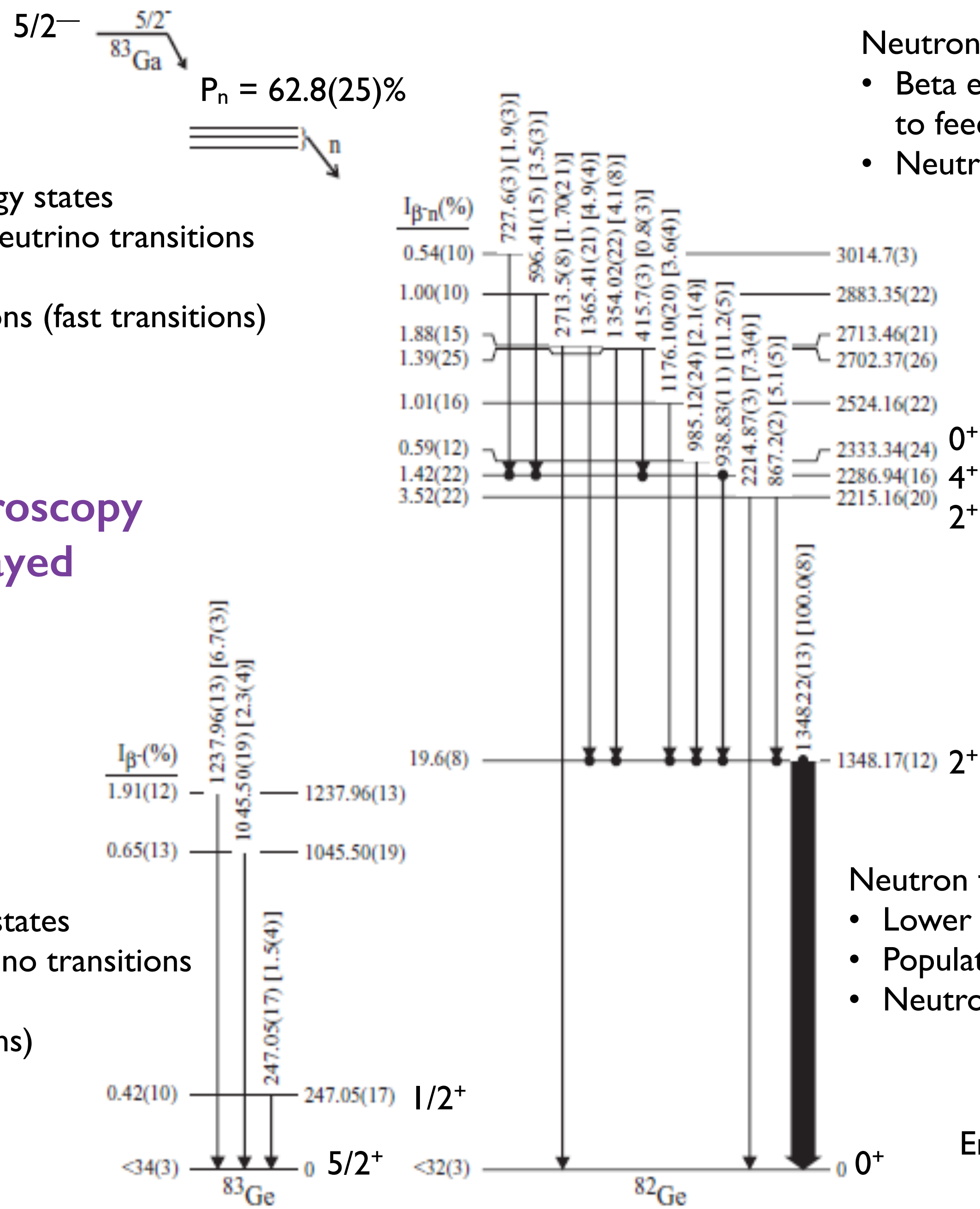


S. V. Paulauskas et al., NIM 737A, 22 (2014);

UTK Dissertation: http://trace.tennessee.edu/utk_graddiss/2606/

(M. Madurga et al., ^{84}Ga early analysis, 2013)

Neutron-gamma data example - decay of ^{83}Ga



Neutron feeding to high energy states

- Beta energy < Q_β - 6.6 MeV = 5.1 MeV to feed the highest 3.0 MeV state
- Neutrons of lower energy

Beta feeding to high energy states

- Lower energy beta + neutrino transitions
- Parity same
- Gamow-Teller transitions (fast transitions)
- Particle-hole states

Rich gamma spectroscopy following beta-delayed neutrons !

Neutron feeding to low energy states

- Lower energy beta + neutrino transitions
- Populate GT states above S_n
- Neutron changes parity (l=1 neutron)

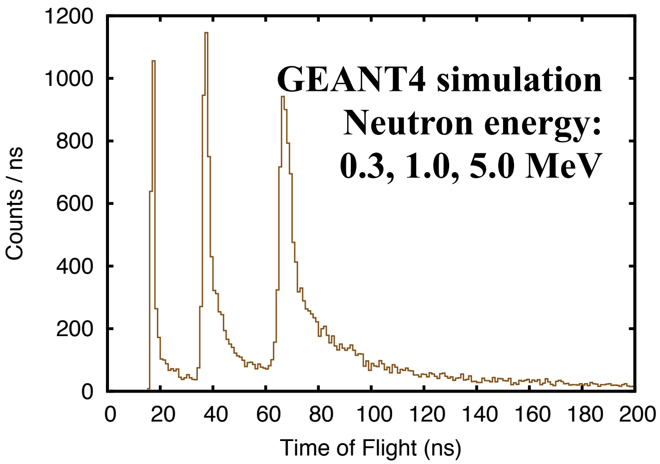
Beta feeding to low energy states

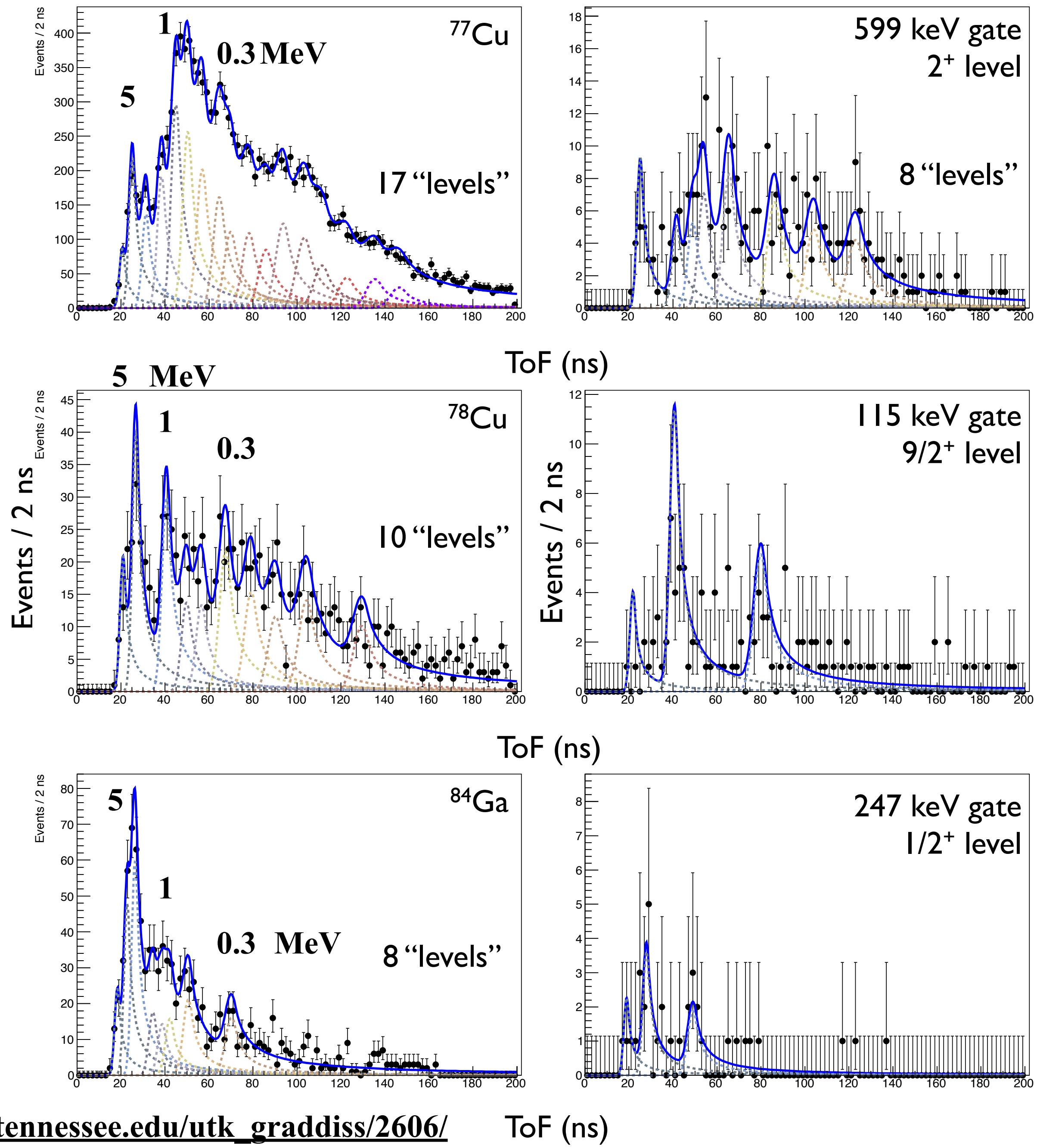
- High energy beta + neutrino transitions
- Parity changes
- Forbidden (slow transitions)

Energy scale for ^{82gs}Ge:
^{83gs}Ge + 3.6 MeV

VANDLE ToF projections and gamma-gated projections

- Spectra are fit with shapes derived from mono-energetic neutrons from Ohio U. tandem calibration run
- Detector timing resolution <250 ps for signals > 100 mV
- "Levels" may or may not be isolated states
- High energy neutrons indicate strong beta feeding well above neutron separation energy
- Neutrons do not necessarily feed ground state or just very low lying levels
- Differences in levels fed by neutrons indicate states are not completely mixed
- High energy neutrons indicate Gamow-Teller decay from closed neutron shell rather than first forbidden transitions

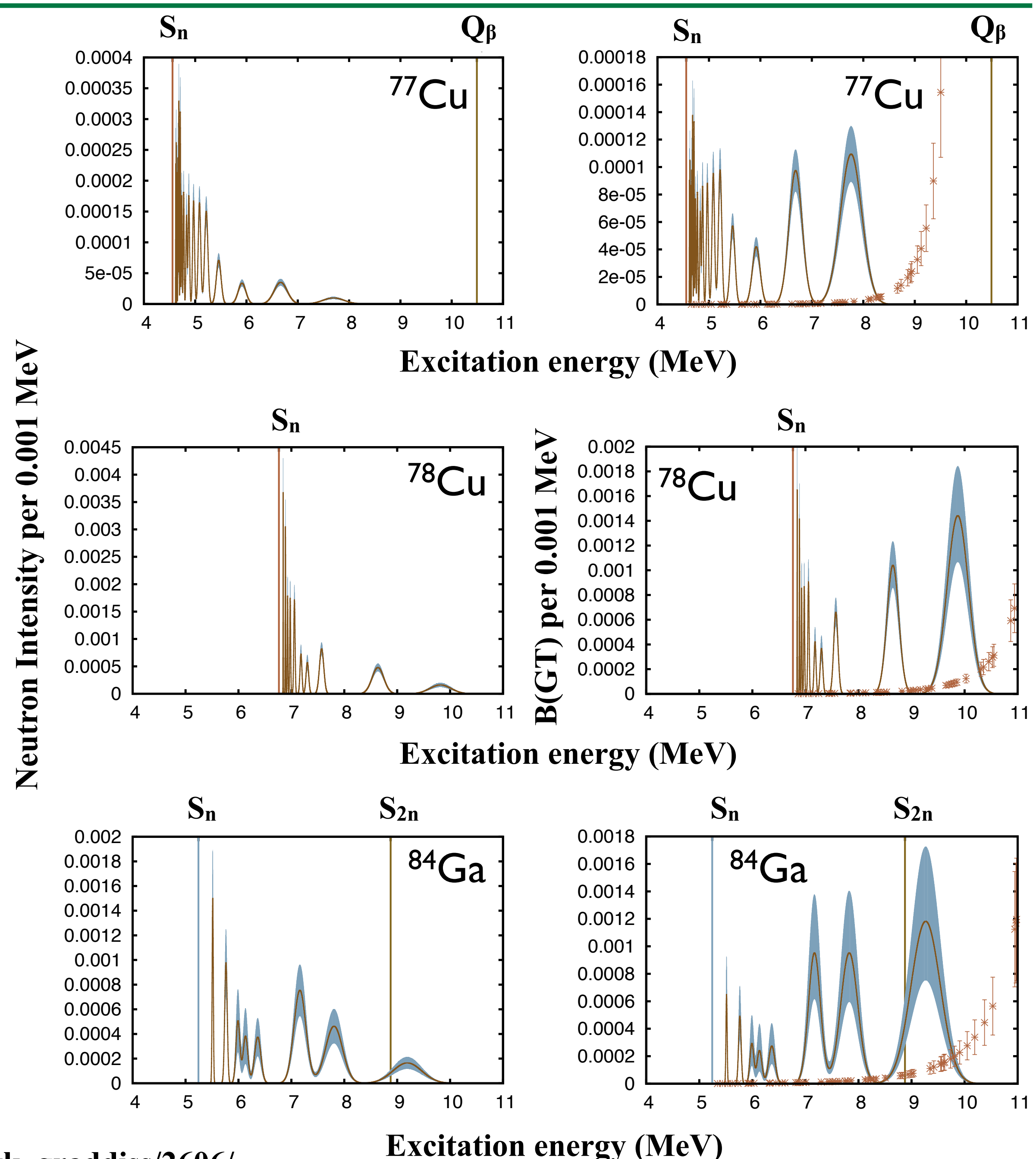




S. V. Paulauskas UTK Dissertation: http://trace.tennessee.edu/utk_graddiss/2606/
(M. Madurga et al., ^{84}Ga early analysis, 2013)

Intensities and Gamow-Teller Transition Strengths

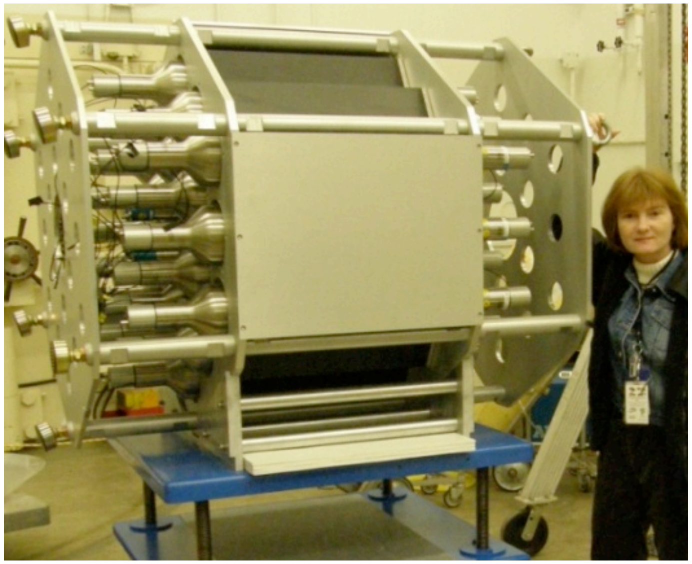
- Intensities derived from fits to the data allow feeding, branching ratios, and beta-delayed branching ratio to be deduced
- With the above, lifetimes and Gamow-Teller transition strength can be deduced
- Large width peaks are due to timing resolution
- Shaded areas give uncertainties due to statistics
- Stars (*) indicate sensitivity limits of what the B(GT) would be if only 10 neutrons had been detected
- B(GT) calculation assumes neutrons go to the ground state (not true!)
- Working on new calculations to reflect reality



Interpretation:
The large B(GT) matrix elements arise from the core neutron $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ orbitals below the N=50 shell closure decaying to $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ proton orbitals

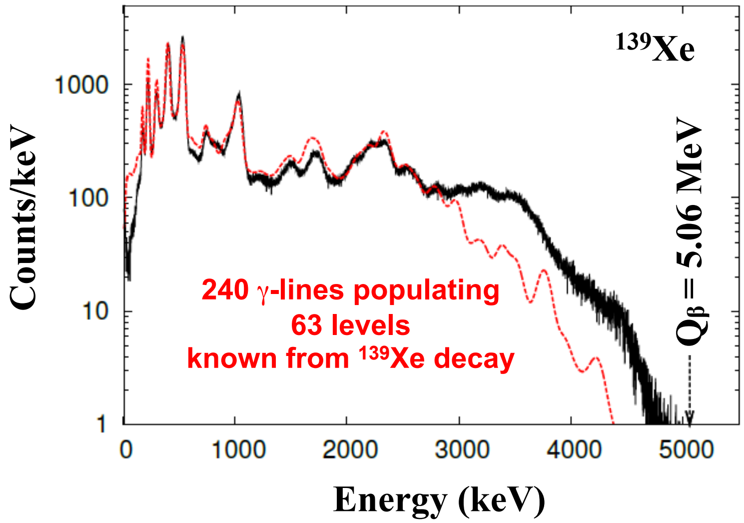
S. V. Paulauskas et al., NIM 737A, 22 (2014);
UTK Dissertation: http://trace.tennessee.edu/utk_graddiss/2606/

MTAS - Modular Total Absorption Spectrometer

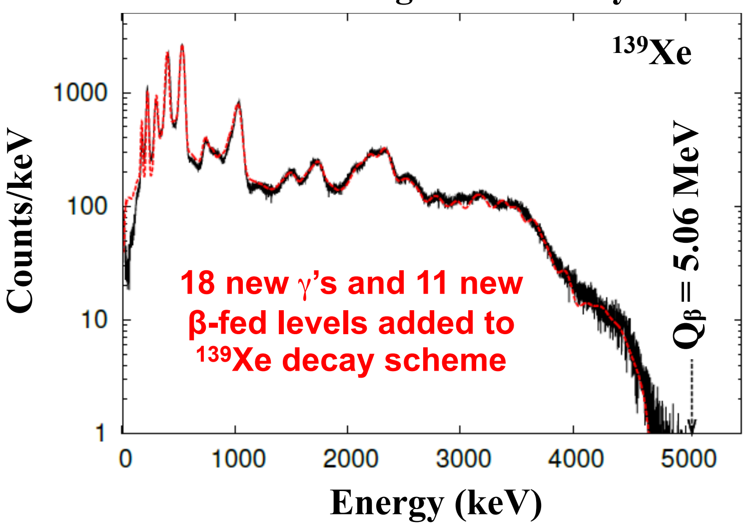


- Commissioned with beam in 2012 by measuring the decay of 22 isotopes - 7 highest priority of NEA
- Added more isotopes in 2015 using pure beams of Br, Rb, I, and Cs
- 19 detectors in full array achieve full energy peak efficiency of 71% at 4 MeV
- Includes segmented beta detectors with 70% efficiency
- Identifies levels in daughter nucleus fed in β-decay
- Large neutron capture signal at ~6.9 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

Full Data vs known levels in ENSDF

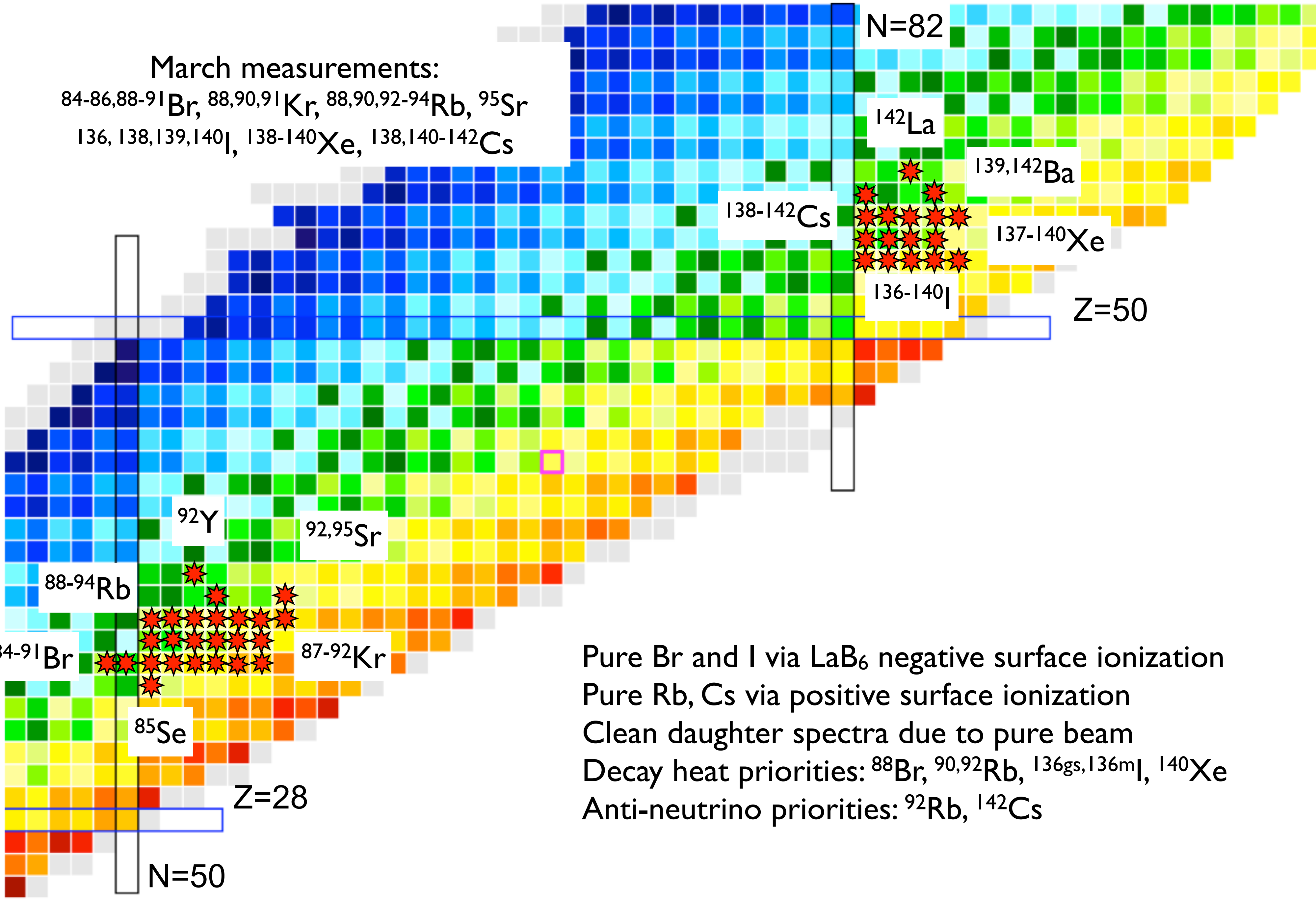


Full Data vs fit with augmented decay scheme



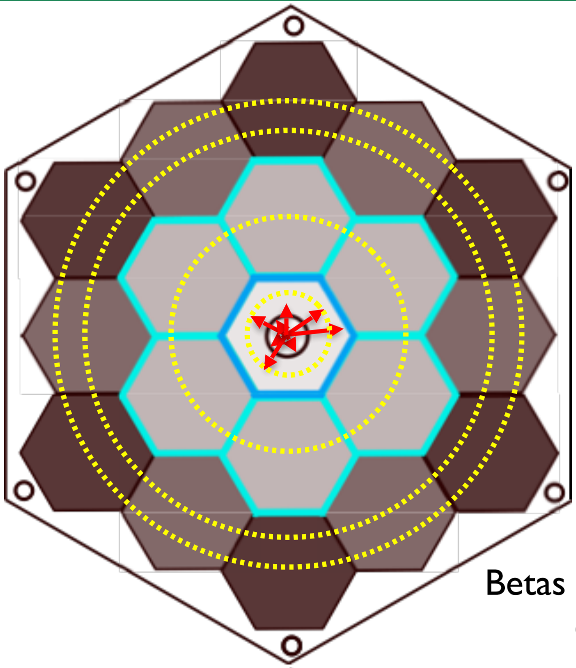
A. Fijalkowska et al., Nucl. Data Sheets 120, 56 (2014);
A. Fijalkowska, Dissertation, U. Warsaw, mid-2015 expected

Total Absorption Spectroscopy using MTAS



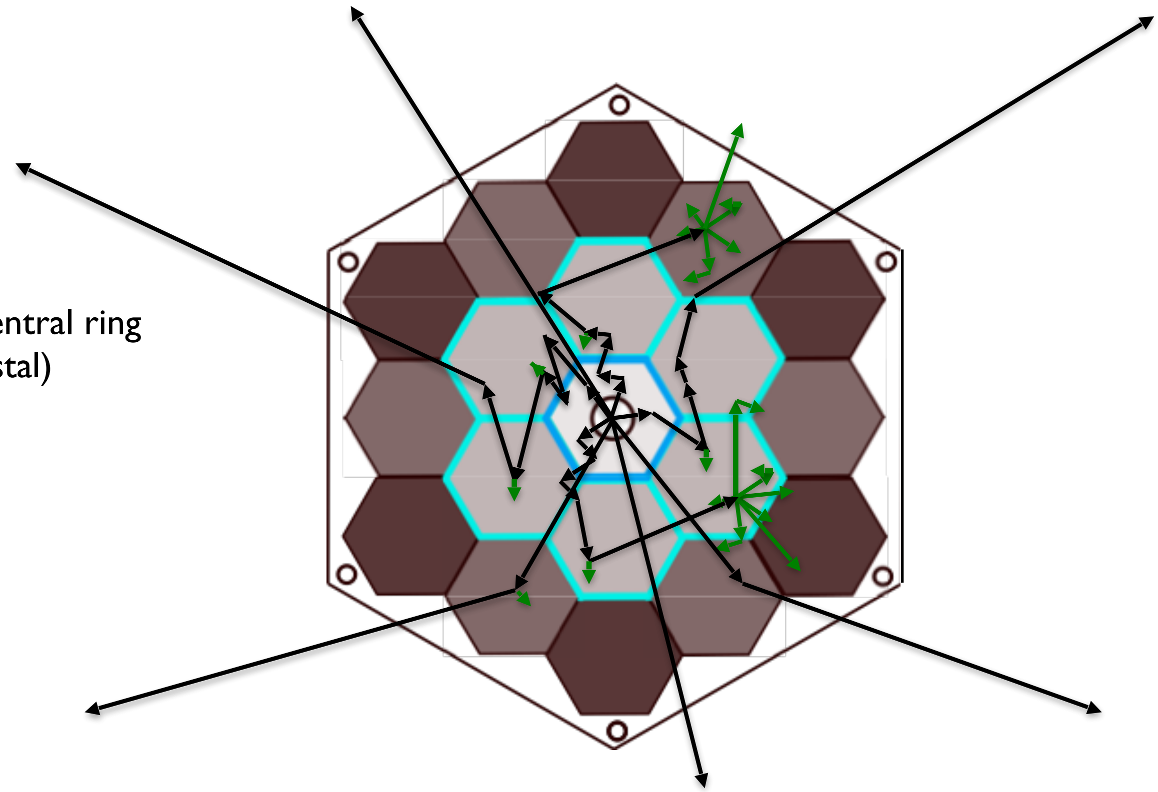
Pure Br and I via LaB_6 negative surface ionization
Pure Rb, Cs via positive surface ionization
Clean daughter spectra due to pure beam
Decay heat priorities: ^{88}Br, ^{90,92}Rb, ^{136gs,136m}I, ^{140}Xe
Anti-neutrino priorities: ^{92}Rb, ^{142}Cs

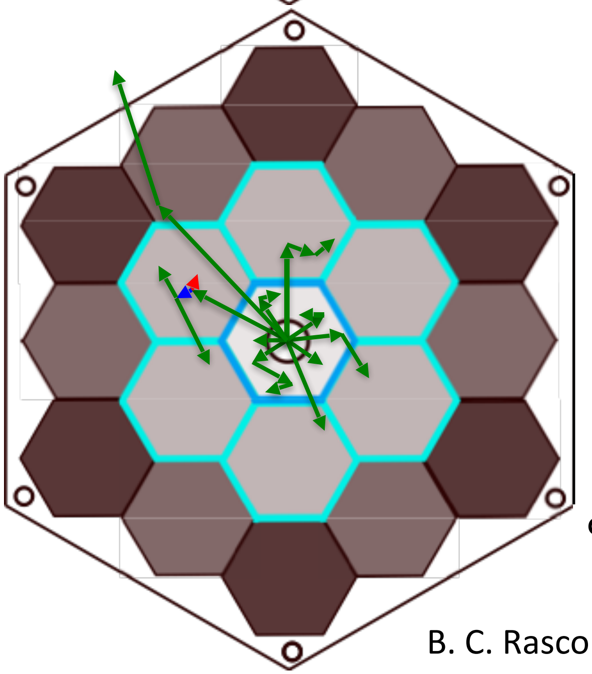
Understanding MTAS



MTAS has 4 layers (yellow dotted circles):
1 central module
3 rings of 6 detectors (inner, middle, outer)

Betas stay in central ring
(one crystal)





Gammas mostly in
central and inner rings

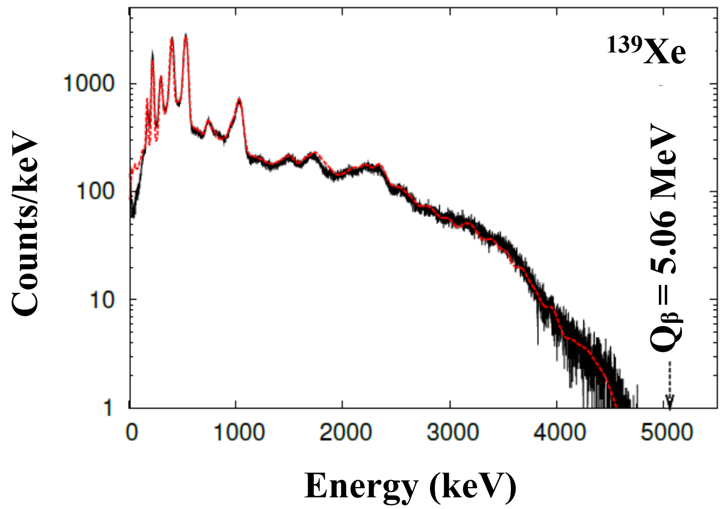
Neutrons events are throughout
Neutrons lose energy in the collisions
(n,n'γ) observed in MTAS
Capture rate proportional to NaI volume

B. C. Rasco et al., future paper
B. C. Rasco et al NIM A, in press: doi:10.1016/j.nima.2015.03.087

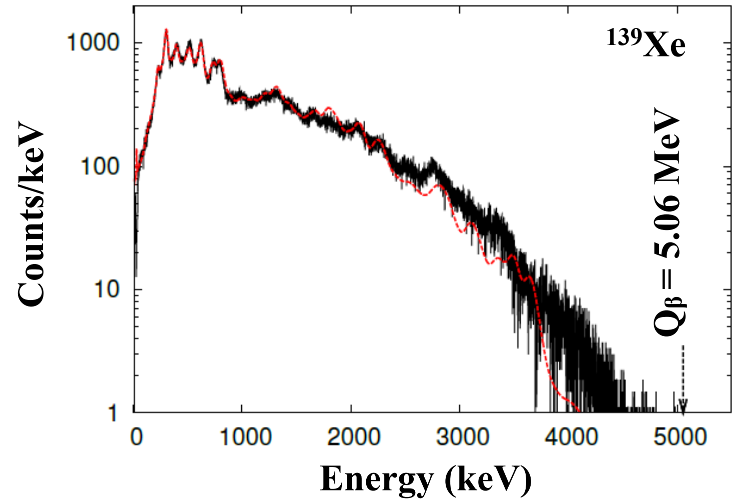
MTAS ^{139}Xe data - decay heat and beta strength

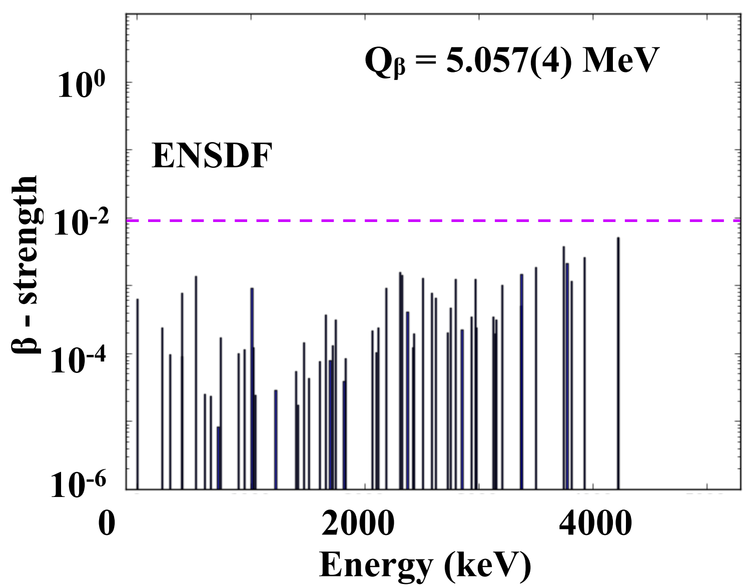
- Additional “pseudo” levels inserted to fit data
- Pseudo-levels may or may not be individual states
- Pseudo-cascades also inserted to fit data (M1, E1, E2)
- Ring data can be analyzed separately to get pseudo-levels and cascades closer to reality
- Data allows the beta strength to be determined
- Note the high strength as Q_β is approached - tail of Gamow-Teller resonance
- Typical results indicate more feeding to higher energy levels resulting in lower beta energy and more gammas released in decay heat

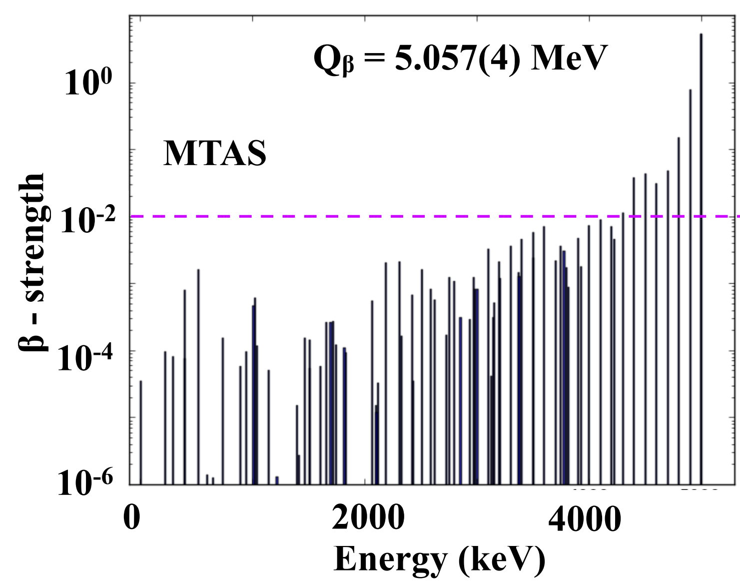
Central detector data and fit



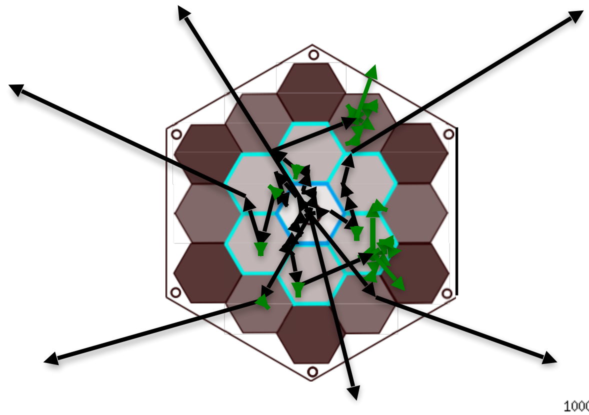
Inner ring data and fit



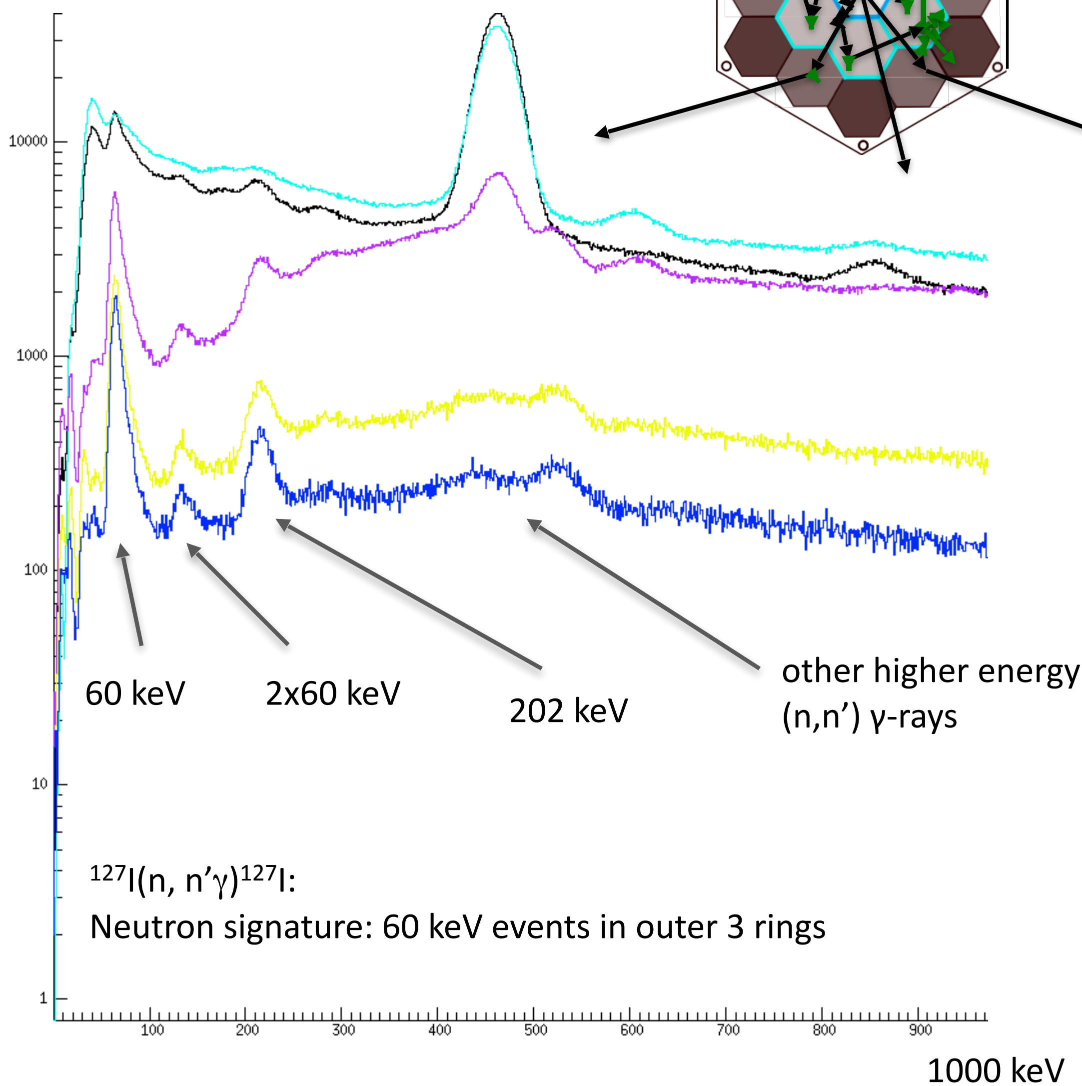


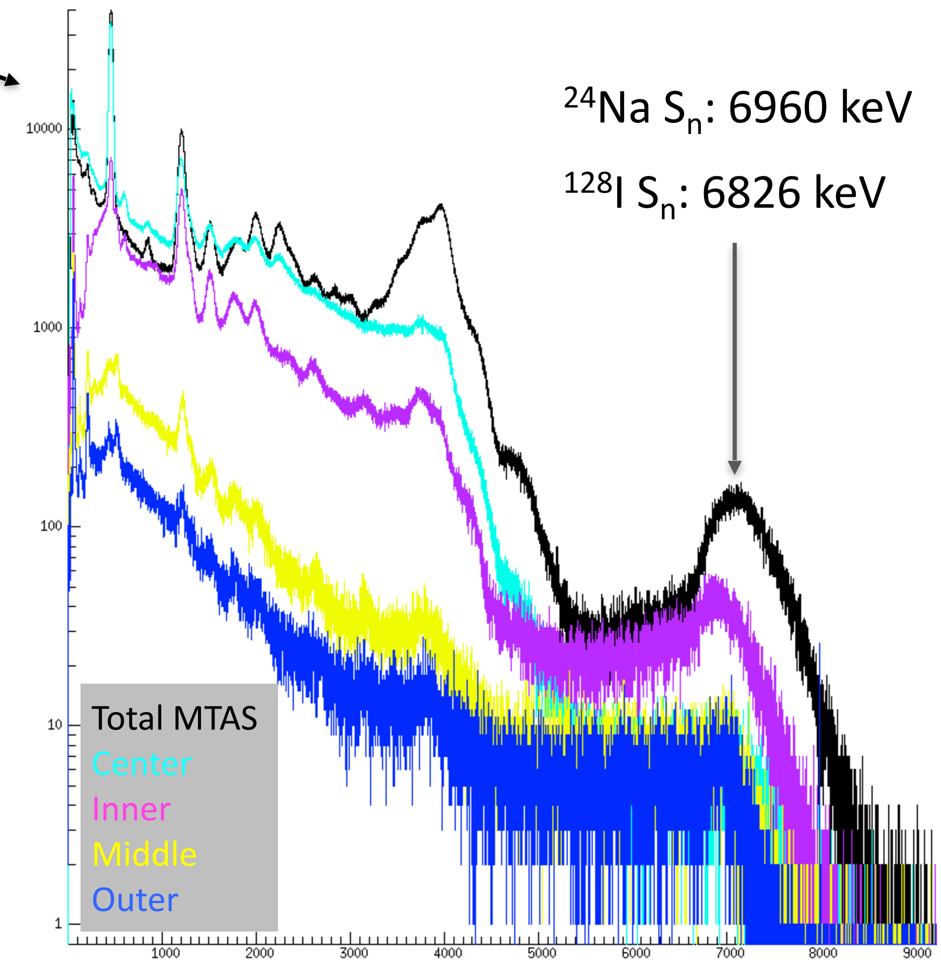


Understanding neutrons in MTAS - ^{137}I example



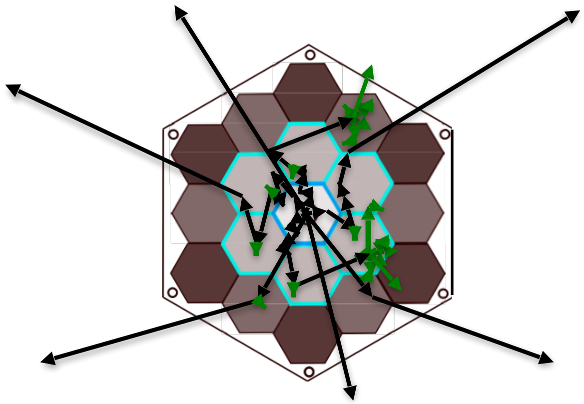
(n, n'γ) throughout MTAS
Multi-crystal construction
helps identify neutron events

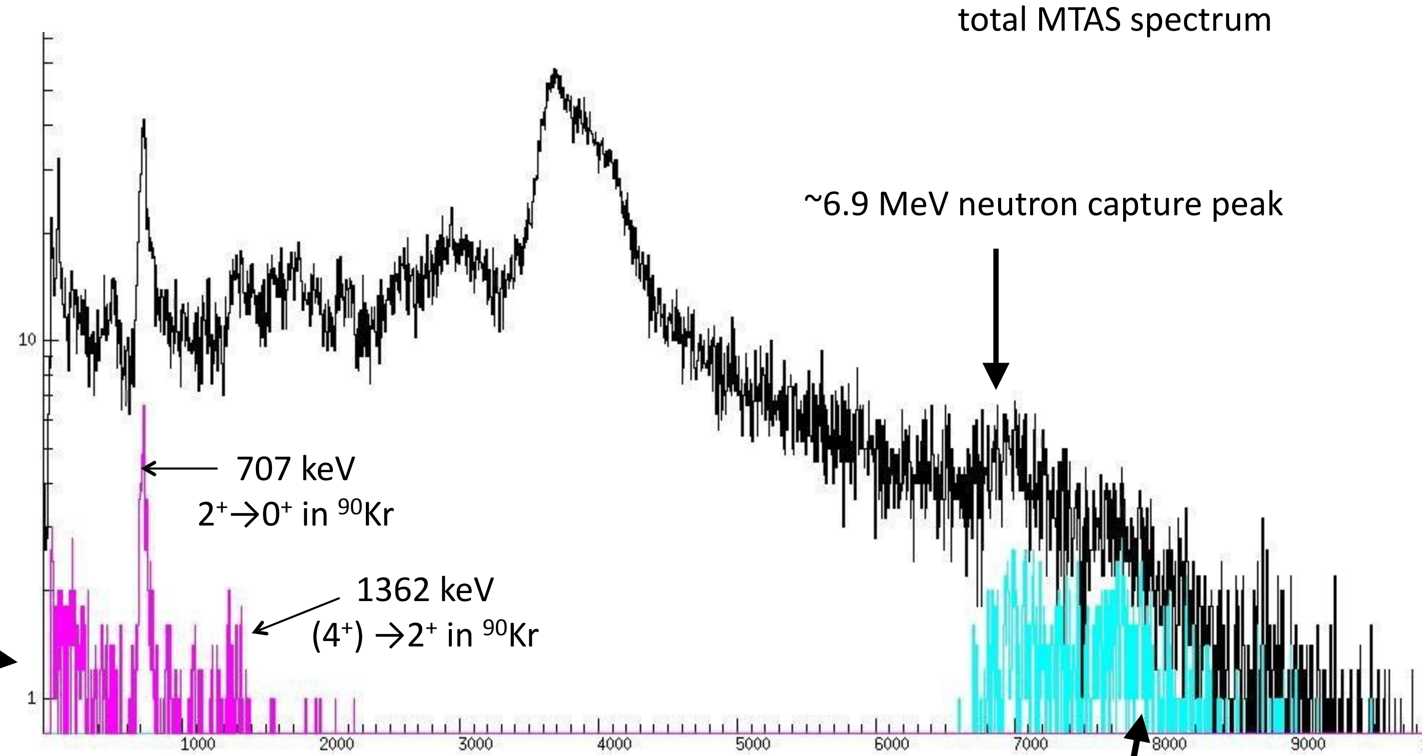




B. C. Rasco et al., future paper
B. C. Rasco et al NIM A, in press: doi:10.1016/j.nima.2015.03.087

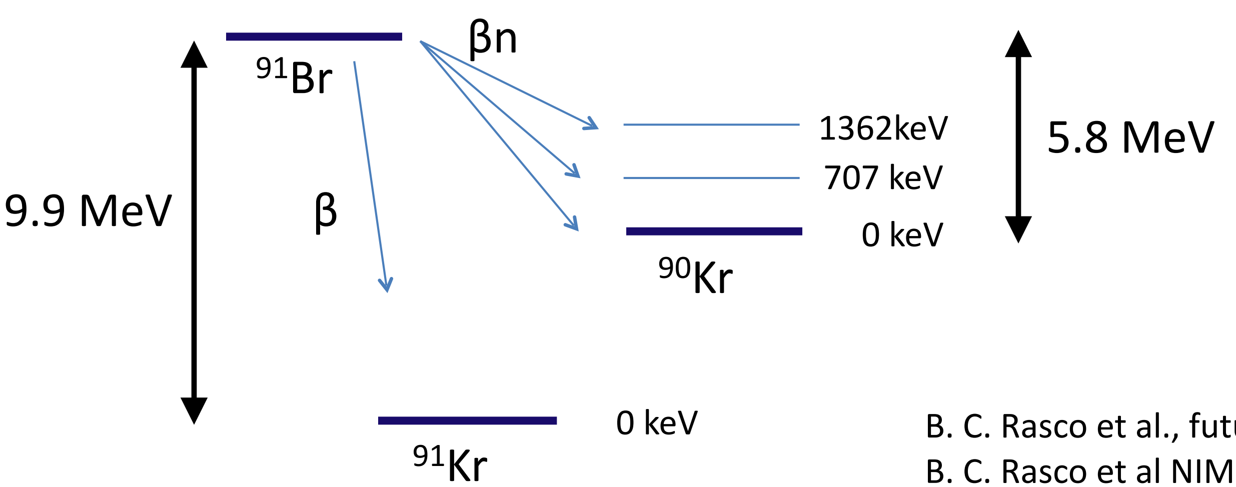
Understanding neutrons in MTAS — ring analysis: $^{91}Br \rightarrow {}^{90}Kr$





Energy spectrum of central crystal gated by neutron peaks in outer and middle detectors

Neutron capture + (n,n'γ) + daughter γ decay in outer and middle MTAS rings



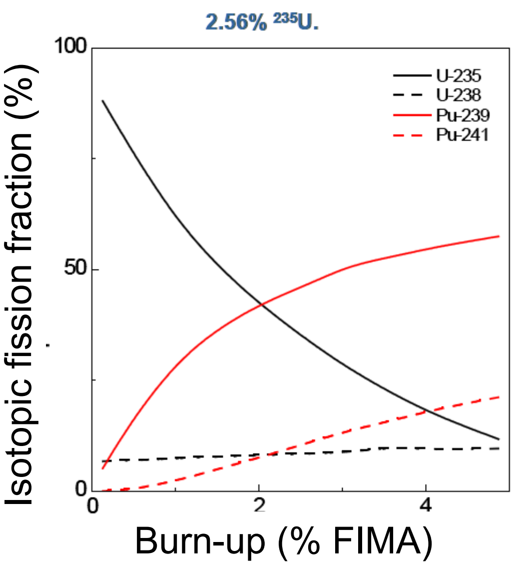
Gammas from βn likely to be low energy and confined in central crystal

B. C. Rasco et al., future paper

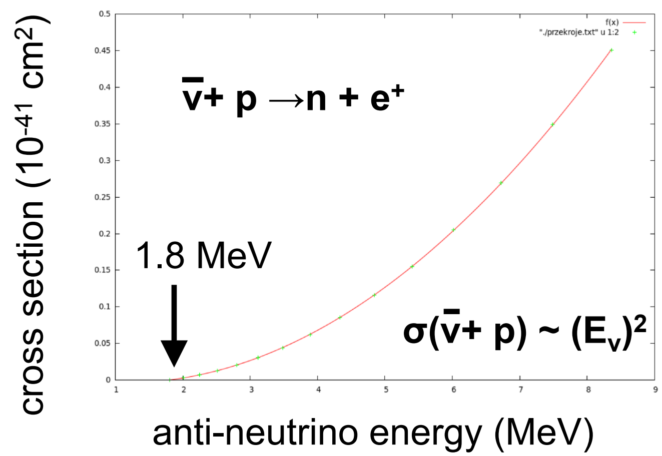
B. C. Rasco et al NIM A, in press: doi:10.1016/j.nima.2015.03.087

MTAS and anti-neutrino anomaly

- Neutrino detectors near nuclear reactors detect only 94.3(23)% of the expected anti-neutrinos
- Assumes fuel composition, fission yields, beta decay, and burn-up levels are known
- Based on "Schreckenbach data" of integral β-energy spectra for n + ^{235}U, n + ^{239}Pu, and n + ^{241}Pu
- Schreckenbach data augmented by later measurements (e.g. Haag et al. - n + ^{238}U) and data contained in ENSDF
- Anti-neutrinos above 1.8 MeV can interact with protons, i.e.., neutrino detectors
- Since betas and anti-neutrinos share the energy emitted in beta decay, knowledge of beta feeding and the beta-anti-neutrino energy relationship, determines the number of anti-neutrinos above threshold
- MTAS measurements determine the beta feeding

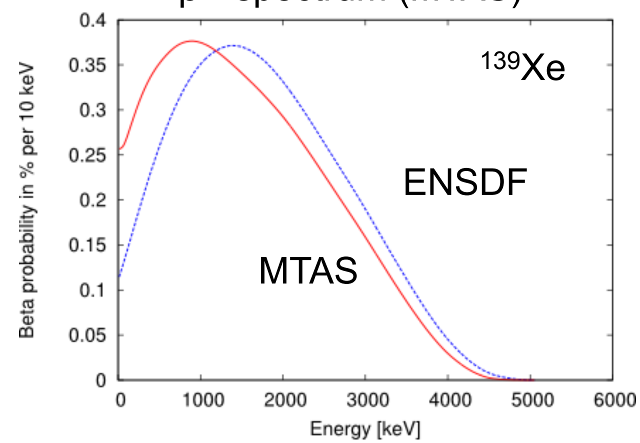


Iain Gauld (ORNL)
ORIGEN computer code (2014)

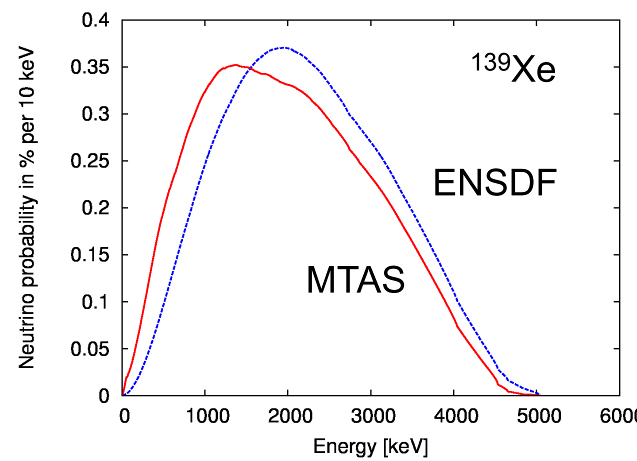


A. Strumia and F. Vissani,
Phys. Lett. B 564, 42, 2003

β− spectrum (MTAS)



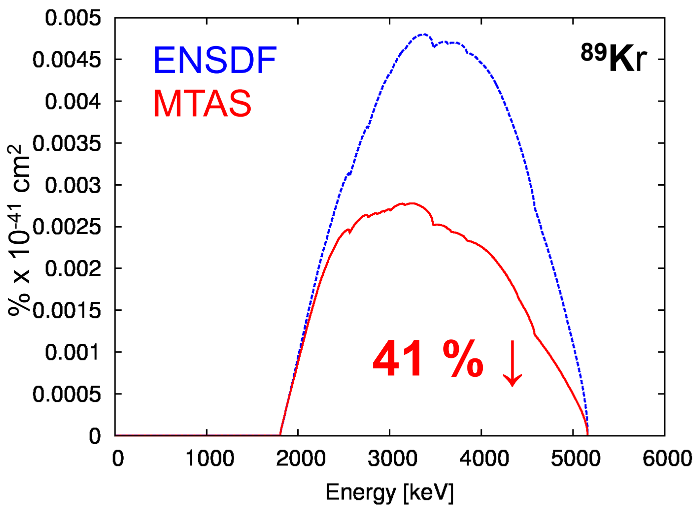
Anti-neutrino spectrum (derived)

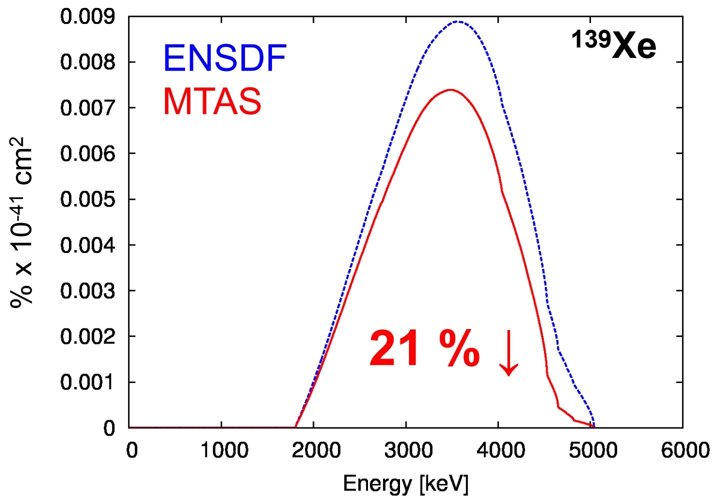


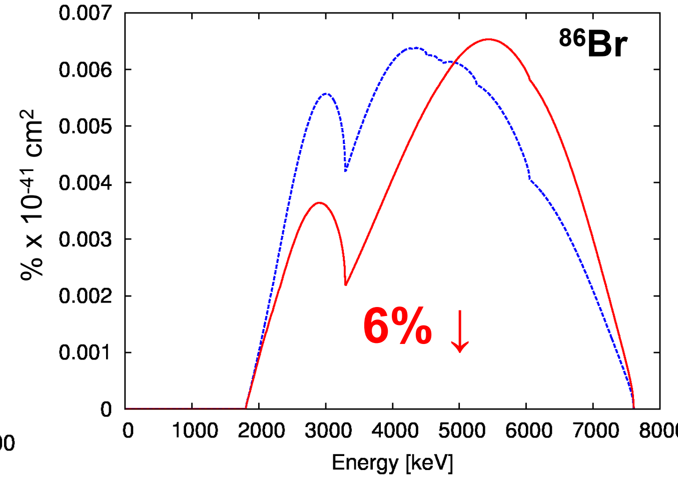
Average anti-neutrino energy shifted down 226 keV
Fijalkowska, Karny, et al. (2015)

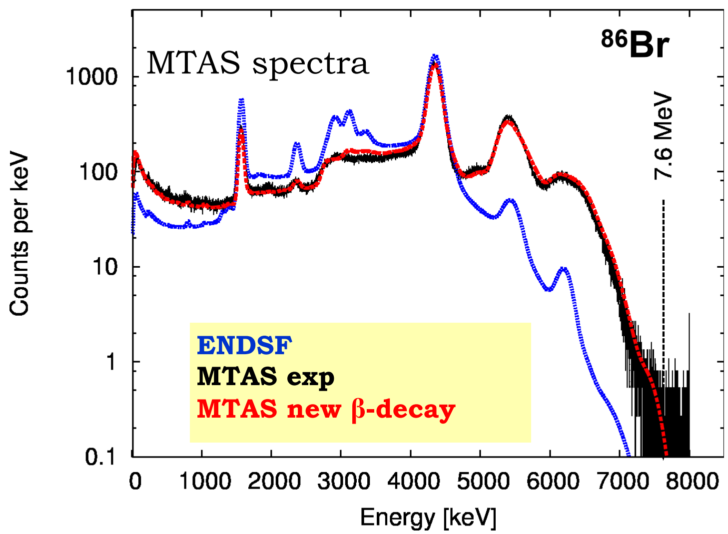
Some examples of MTAS impact on anti-neutrino anomaly

Anti-neutrino interactions on protons "turn on" at 1.8 MeV





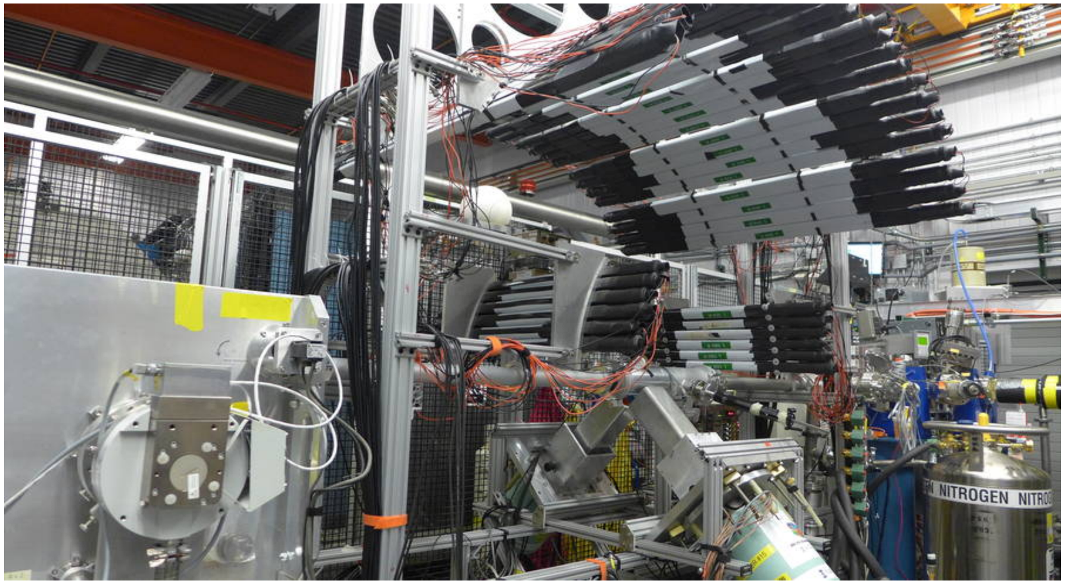


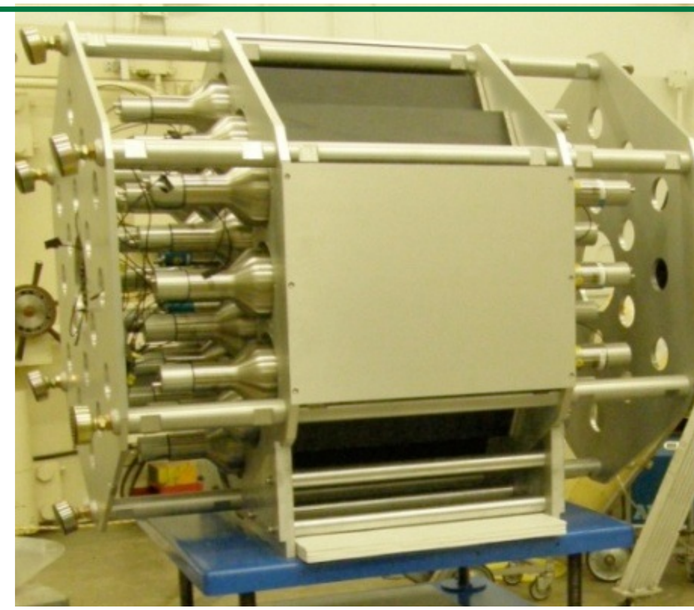


- Typically, we are finding more higher energy beta feeding and therefore, we deduce lower anti-neutrino energies
- There are cases, such as ^{86}Br where we find more ground state to ground state feeding and therefore, we deduce higher anti-neutrino energies
- In the final analysis of ^{86}Br, we find both and the net result is still lower anti-neutrino interactions

Seems likely that data from MTAS and other TAS detectors can resolve the anti-neutrino anomaly or at least, better define its magnitude

Conclusions





- MTAS and VANDLE are modern detector systems impacting the high energy regime of beta decay
- Data on fission fragments impact our knowledge of nuclear structure, nuclear astrophysics, nuclear energy, and neutrino physics
- VANDLE has shown significant numbers of high energy (> 2 MeV) neutrons are emitted in beta decay
- VANDLE (and 3Hen) has shown there can be rich gamma spectroscopy following neutron emission
- VANDLE is giving us insight into the beta decay strength function above the neutron separation energy
- MTAS has shown there are significantly more high energy levels being fed in beta decay than previously known (in ENSDF)
- MTAS detects neutrons and we are learning on how to analyze the data in the presence of beta-delayed neutrons
- MTAS gives us some indication that the anti-neutrino anomaly may be based on our inadequate knowledge of the beta decay of fission fragments
- Through these detector systems we are gaining insight into the true decay properties of neutron-rich fission fragments and this can impact our understanding of "real-world" systems such as nuclear reactors
- SPES, with its high beam intensities (and future isobar separator), will provide an excellent opportunity to continue this work in hopefully, low background conditions

Thanks to the collaborators

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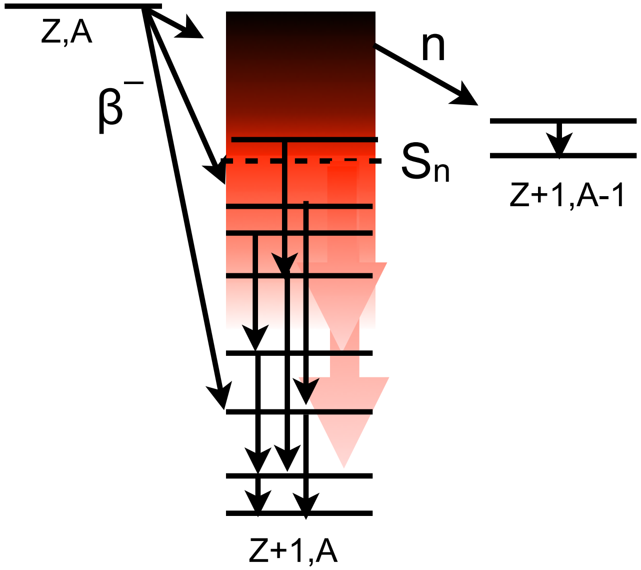
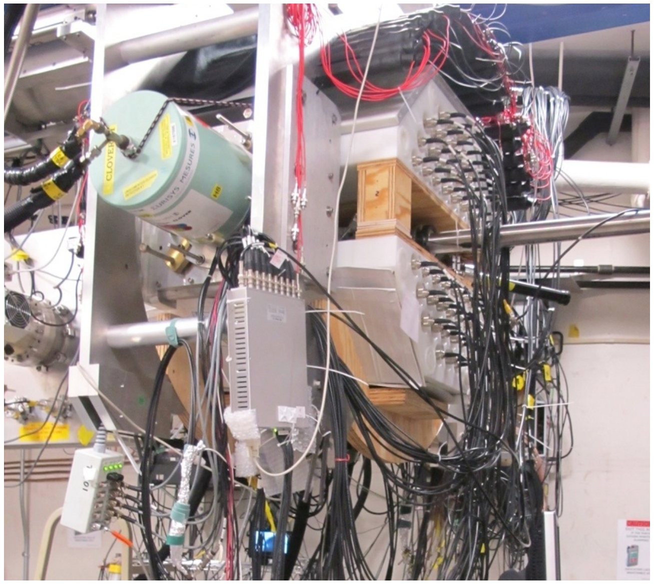
Names in bold lead some/most aspects of the projects
Underlined names are the people doing the data analysis

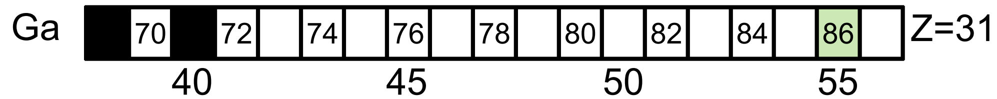
Measure the complete beta-strength function
3Hen - 3He ionization neutron counter

^{3}Hen Detector

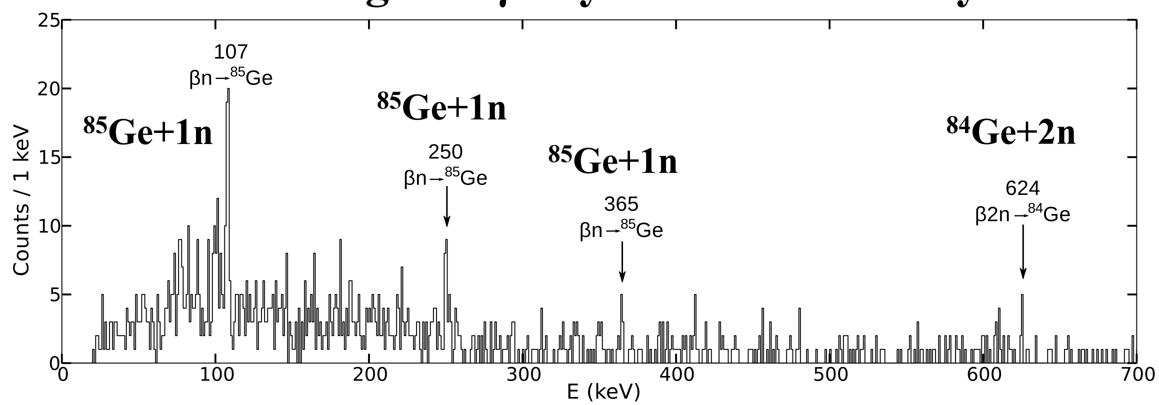




- **Commissioned with beam in 2012 by identifying the decay of ^{86}Ga**
- **Up to 74 detectors filled with 10 atm. of ^{3}He with efficiency of 80% between 0.001-1 MeV**
- **Used to count neutrons and detect the most exotic isotopes**
- **Can be "hybridized" (as shown - 48 detectors - eff. ~30%) and 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)**



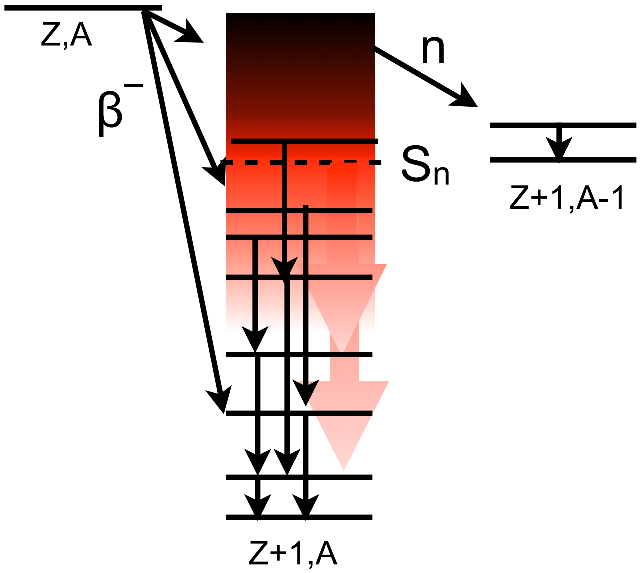
Neutron-gated γ-rays from ^{86}Ga decay



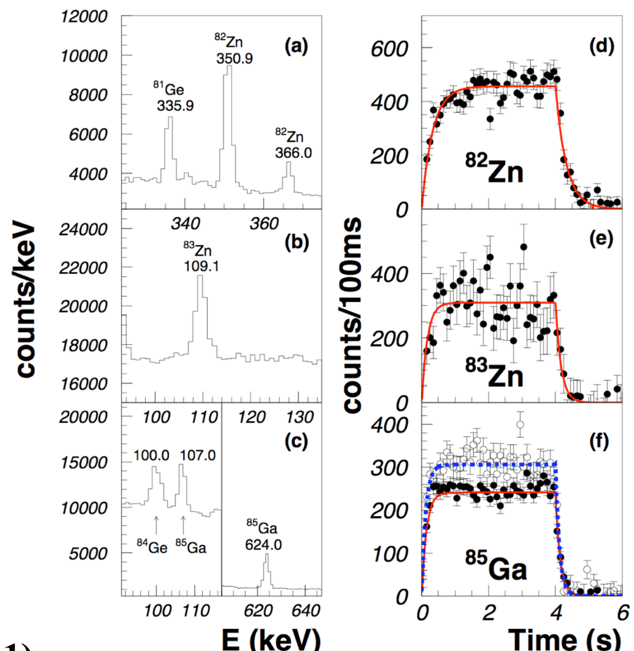
Note that Q_β ~ 15 MeV: even 3n + ^{83}Ga channel is open

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

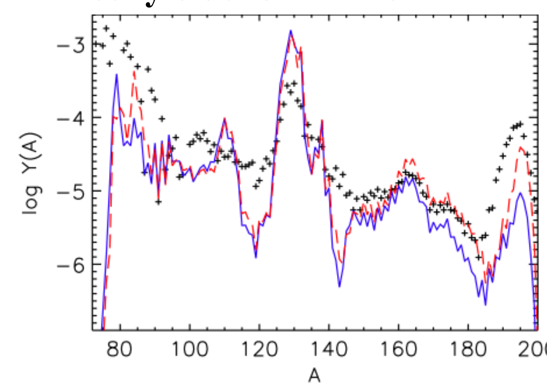
Measure the complete beta-strength function
LeRIBSS + CARDS - Clover Ge Array on a Low-energy Beam Line



- **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)

HRIBF yields = SPES Day 1 yields

Electron beam plasma source

- **Sn, Ge purity significant enhanced with molecular (S) transport**
- **contamination likely with such a "universal" source**
- **Zn, Cd, noble gases don't make negative ions**
- **RILIS has surface ionized contaminants (Cs, Rb, Sr, etc.)**
- **other elements enhanced with molecular transport: Sr, In, As,**