Updates on the Modular Total Absorption Spectrometer

B.C. Rasco – ORNL Physics Division

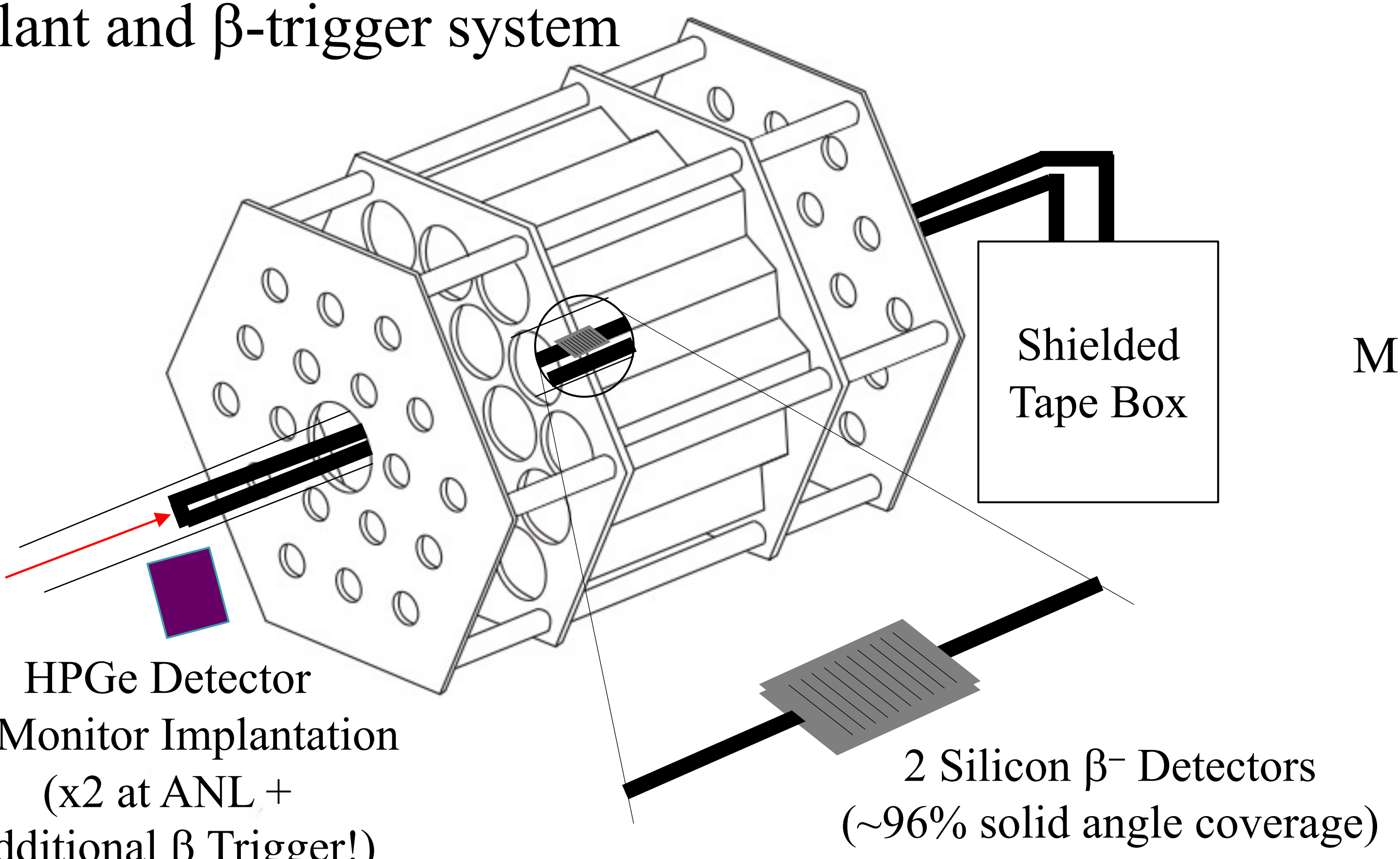
January 18, 2023

International Atomic Eenergy Agency - Wien

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

MTAS – Modular Total Absorption Spectrometer

MTAS implant and β-trigger system



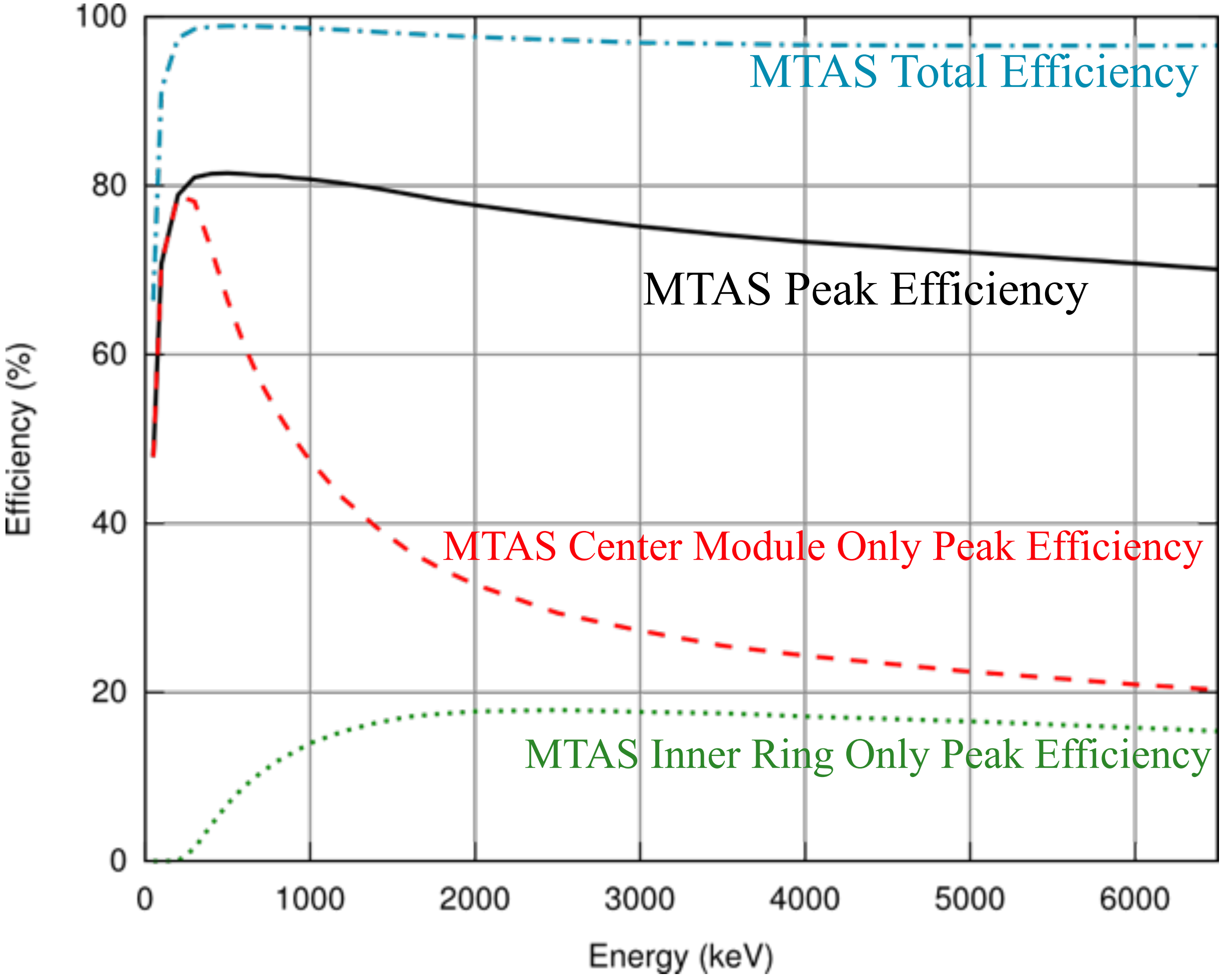
MTAS and auxilliary detectors use UTK/ORNL DAQ

M. Karny, *et al.*, NIM A, 836, 83-90 (2016)
B.C. Rasco, *et al.*, NIM A, 788, 137-145 (2015)

B.C. Rasco, *et al.*, Phys. Rev. Lett. **117**, 092501 (2016)
A. Fijałkowska, *et al.*, PRL **119**, 052503 (2017)
B.C. Rasco, et al., PRC (2017)
P. Shuai, et al., PRC (2022)
B.C. Rasco, et al., PRC (2022)
M. Wolińska-Cichocka submitted to PRC (2023)

Modular Total Absorption Spectrometer Efficiency

Single γ-ray Efficiency of MTAS

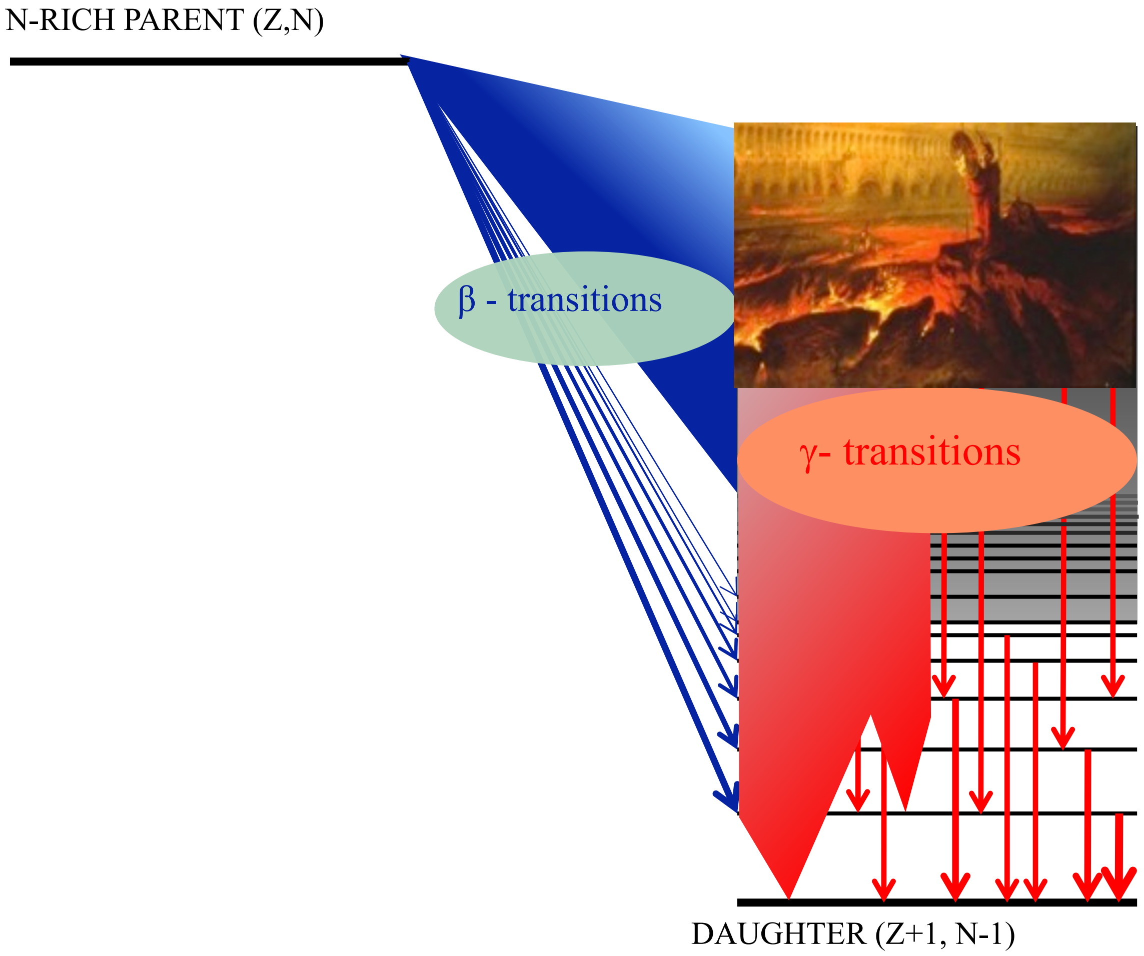


Karny, *et al.*, NIM A, 836, 83-90 (2016)

Peak Efficiency is
All γ-Ray Energy Detected

Total Efficiency is
Any γ-Ray Energy Detected

Why Total Absorption Spectroscopy Needed?



J.C. Hardy, *et al.*, **PLB 71**, (1977)

Pandemonium Effect

Using low efficiency detectors
can bias β-feeding patterns

This problem is made worse if there
is a high density of states
that decay via multiple γ-rays
to the ground state

For β decays, low efficiency
measurements can lead to an
overestimation of lepton (β,ν) energy
and an
underestimation of γ-ray energy
per β decay

Why Total Absorption Spectroscopy Needed?

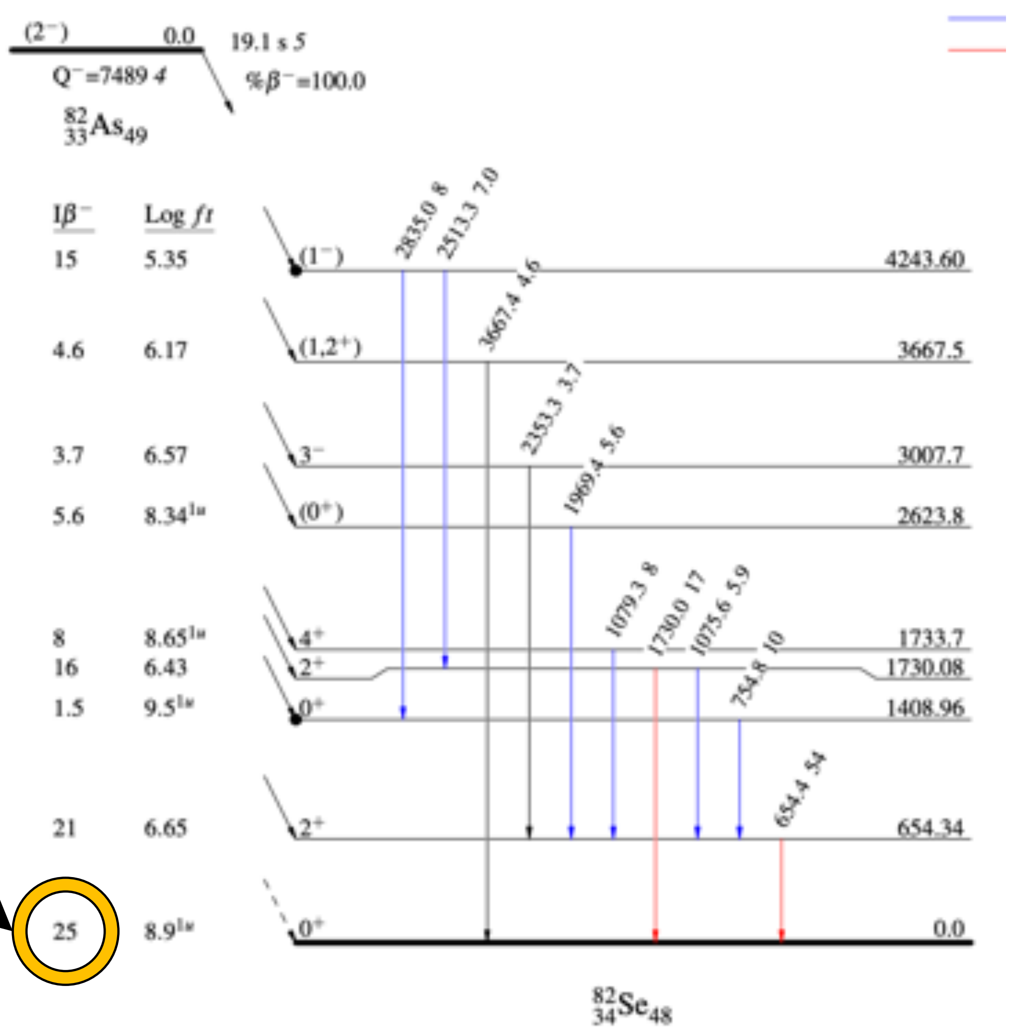
Ground-State to Ground-State Feeding

Large ground-state to ground-state feeding leads to large uncertainties on absolute γ-ray intensities. This is not always reported.

^{82}As: 25(25)% GS-GS (<50%?)

^{86}Se: < 20% GS-GS
^{104}Mo lowest feeding: 86(21)% or 77(19)%
^{106}Mo: < 18% GS-GS
^{138}I: 26(5)% GS-GS (Deduced by Evaluator)
^{144}Cs: No Experimental GS-GS Data

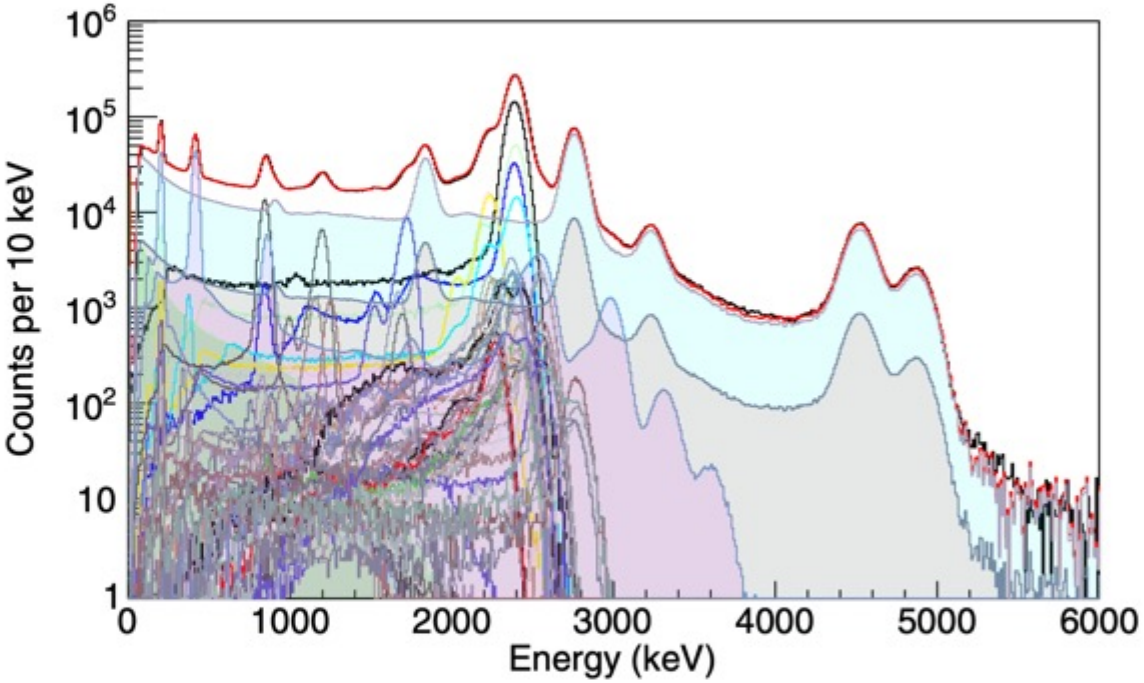
Plus many more ground-state to ground-state feedings with large uncertainties.



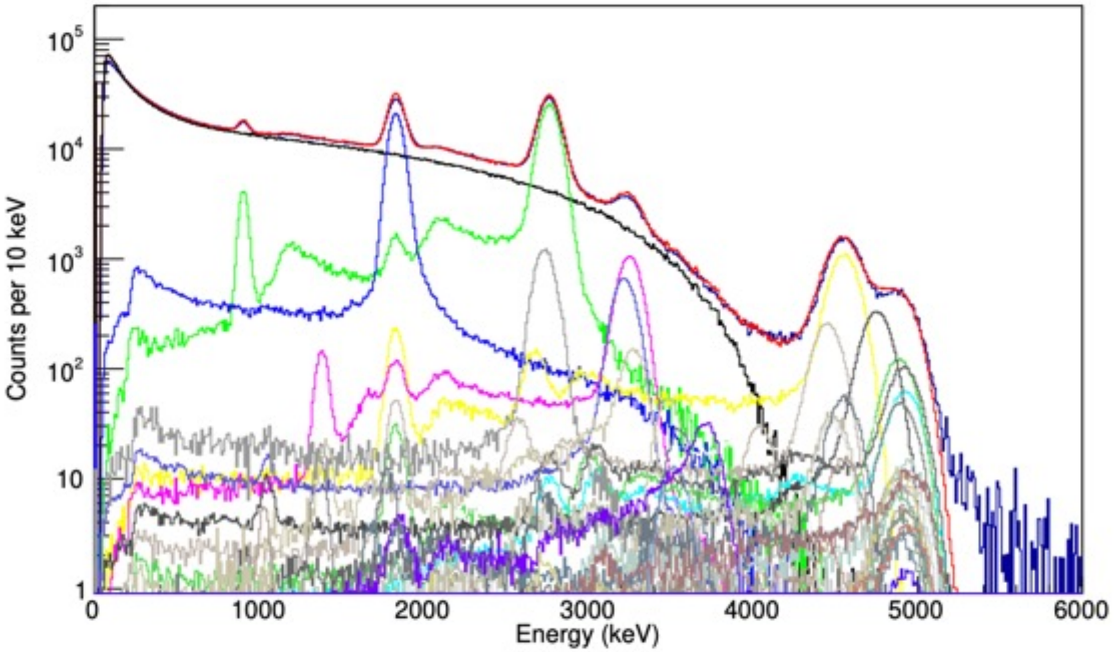
OAK RIDGE National Laboratory

^{88}Rb and ^{88}Kr β Decays

^{88}Kr (^{88}Rb and ^{87}Kr)



^{88}Rb



^{88}Kr results largely consistent with current ENSDF. ^{88}Kr difficult to isolate, but both contaminants, ^{88}Rb and ^{87}Kr, were easily and cleanly isolated independently and can be scaled using the Bateman Equation.

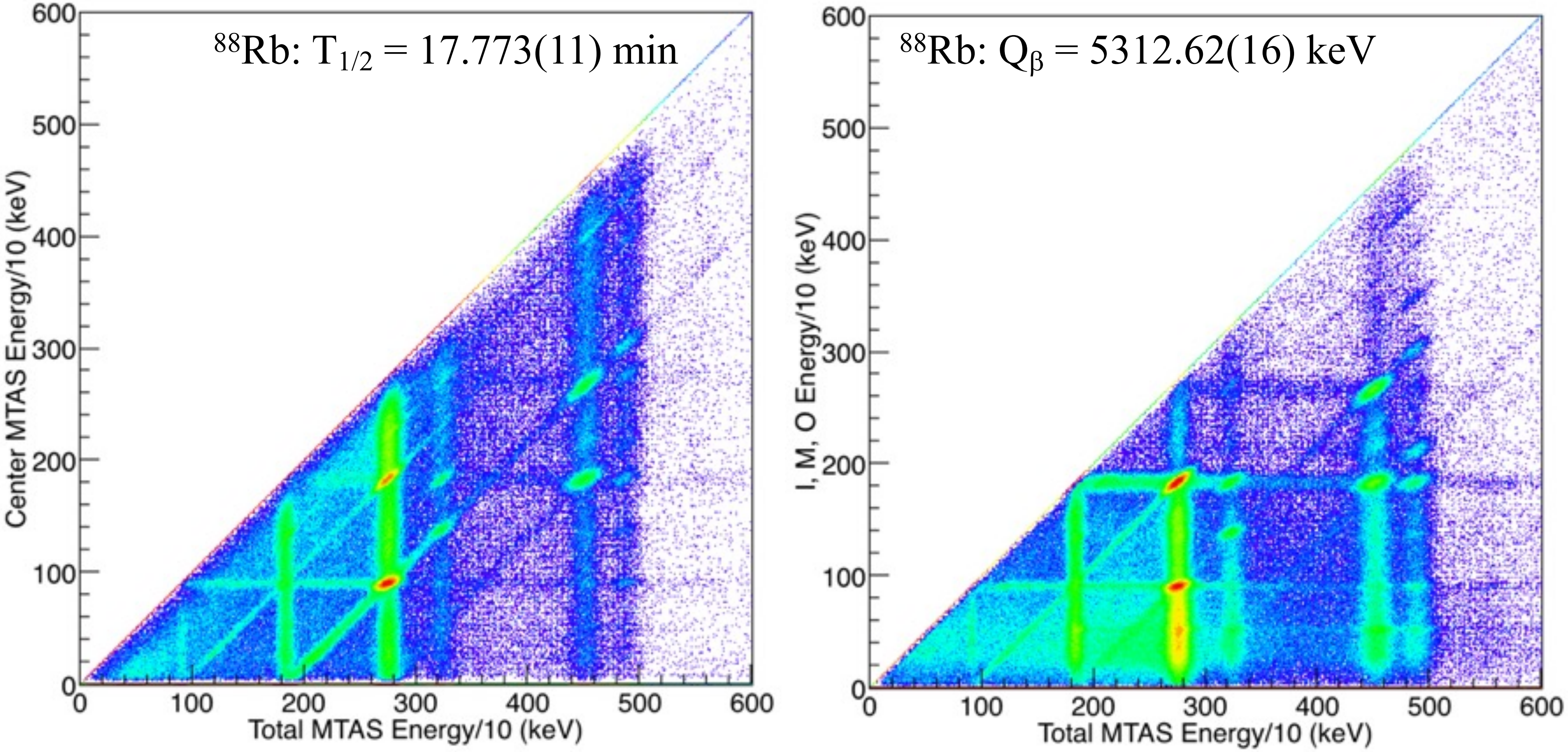
^{88}Rb results largely consistent with current ENSDF. But current ENSDF ground-state to ground-state feeding biased by one measurement with likely statistical only errors reported.

P. Shuai, *et al.*, PRC 105, 054312 (2022)

^{88}Rb and ^{88}Kr β Decays

Multiple γ rays: ^{88}Rb 2D Decay Path Information
Fit at the same time as the total MTAS spectrum.

Gating on total energy and looking at the individual modules gives individual γ decays from that level.

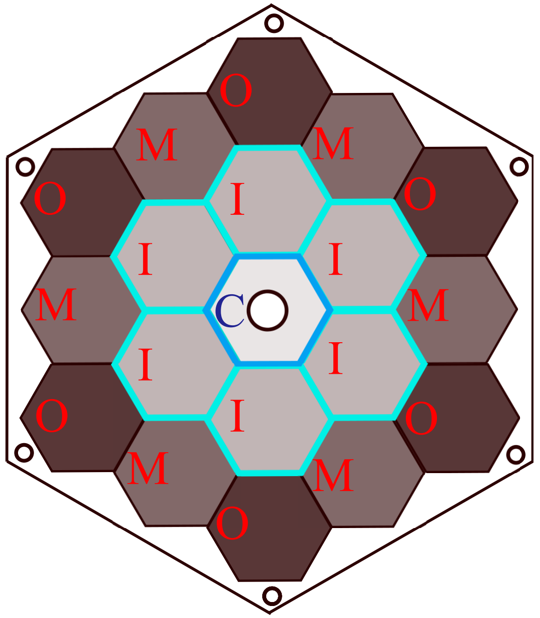


^{88}Rb: $T_{1/2} = 17.773(11)$ min

^{88}Rb: $Q_\beta = 5312.62(16)$ keV

P. Shuai, *et al.*, PRC 105, 054312 (2022)

Can easily identify individual high energy γ rays!

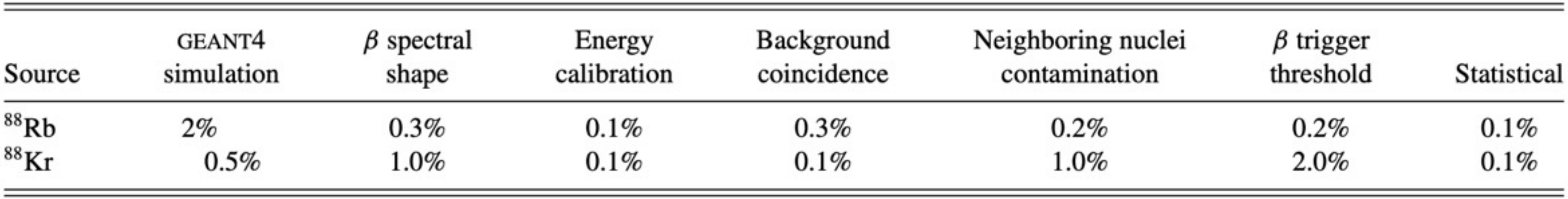


Sharing between modules gives individual γ-ray information.

^{88}Rb and ^{88}Kr β Decays

Compare the ground-state to ground-state systematic uncertainties for ^{88}Rb, $I_{\beta gs}$ = 78.5(2.0)%, and ^{88}Kr, $I_{\beta gs}$ = 13.5(1.0)%.

^{88}Kr and ^{88}Br Ground-State Systematic Uncertainties



Source	GEANT4 simulation	β spectral shape	Energy calibration	Background coincidence	Neighboring nuclei contamination	β trigger threshold	Statistical
^{88}Rb	2%	0.3%	0.1%	0.3%	0.2%	0.2%	0.1%
^{88}Kr	0.5%	1.0%	0.1%	0.1%	1.0%	2.0%	0.1%

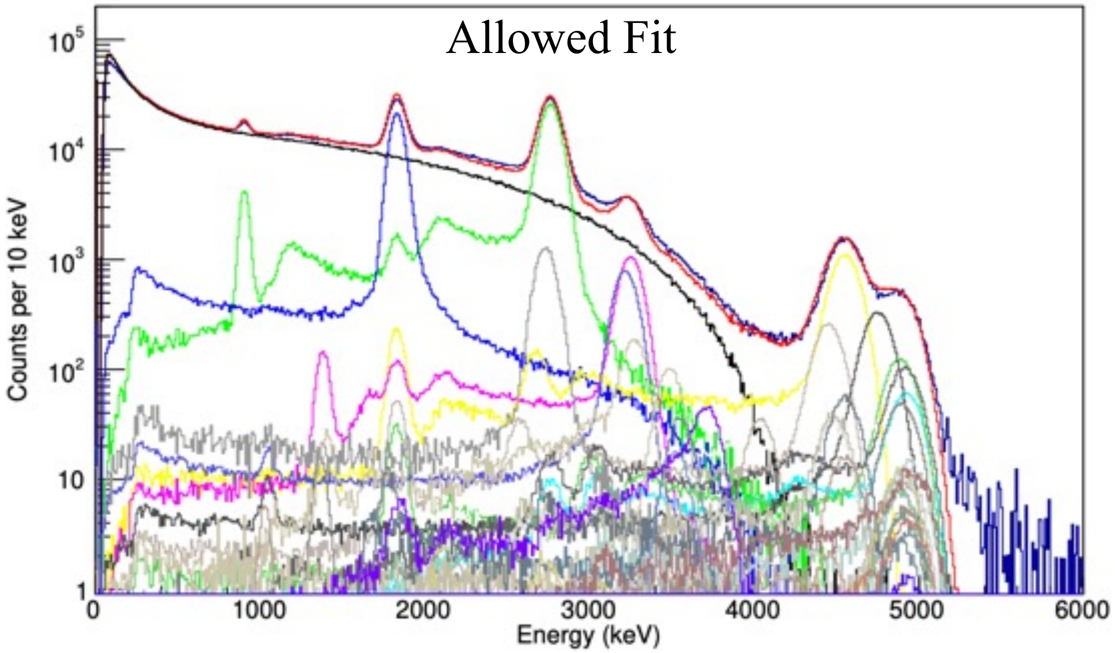
P. Shuai, *et al.*, PRC 105, 054312 (2022)

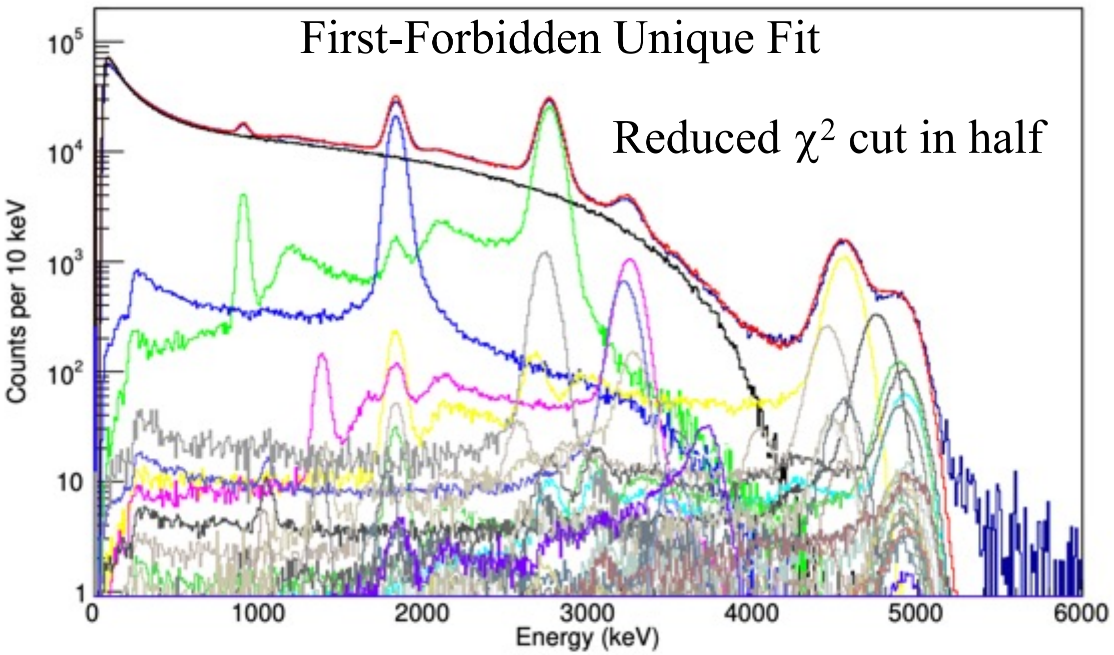
^{88}Rb and ^{88}Kr β Decays

First Steps Towards Isolating Individual β Transitions in Complex β Decays

Identifying First-Forbidden Unique from Allowed with the Modular Total Absorption Spectrometer

Identification of individual β shapes from complex β decays is possible
ORNL's Modular Total Absorption Spectrometer (MTAS) is a very efficient β and γ-ray detector.
The MTAS detector can distinguish a first forbidden unique β decay and an allowed β decay.


Allowed Fit


First-Forbidden Unique Fit

Reduced χ^2 cut in half

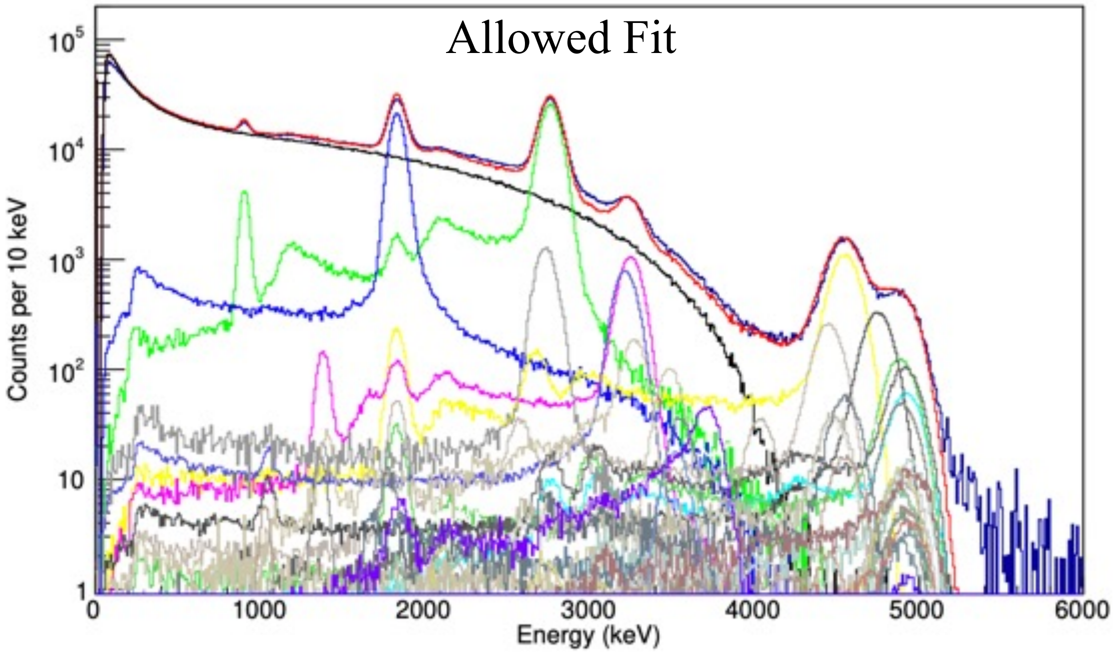
P. Shuai, *et al.*, PRC 105, 054312 (2022)

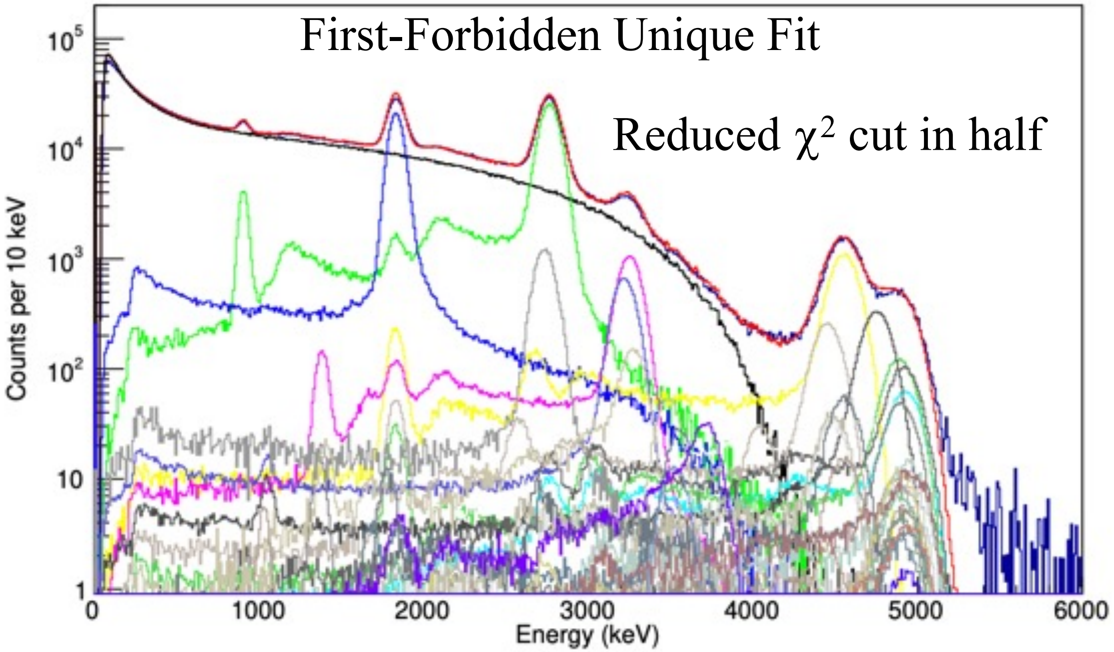
^{88}Rb and ^{88}Kr β Decays

First Steps Towards Isolating Individual β Transitions in Complex β Decays

Identifying First-Forbidden Unique from Allowed with the Modular Total Absorption Spectrometer

Leads to the suggestion we can identify and measure β-shape factors
We have been funded with a Nuclear Data Funding Opportunity to do this
and the work is ongoing.

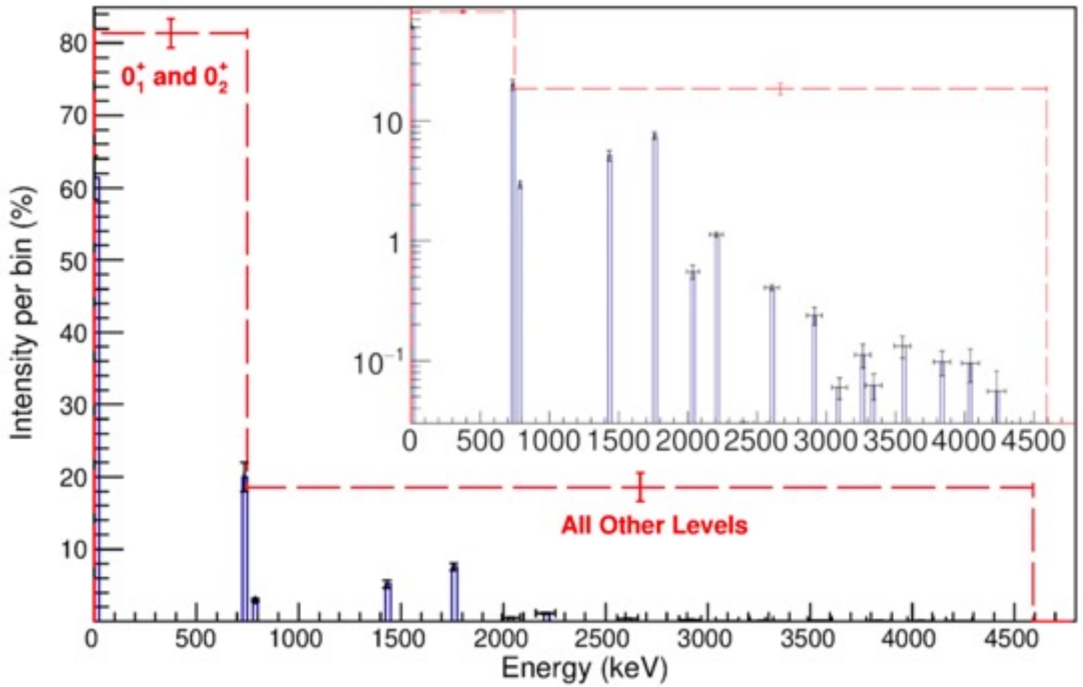

Allowed Fit


First-Forbidden Unique Fit

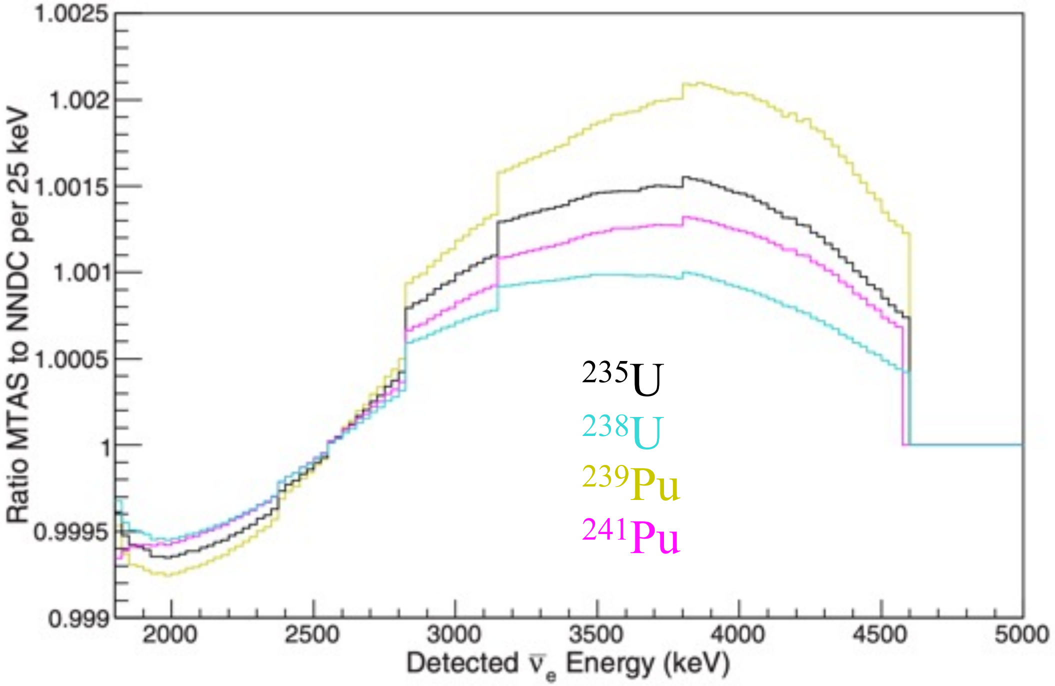
Reduced χ^2 cut in half

P. Shuai, *et al.*, PRC 105, 054312 (2022)

^{98}Nb β Decay - Impact of Increased Precision



^{98}Nb Impact on Detected Antineutrino Change by Fuel Type



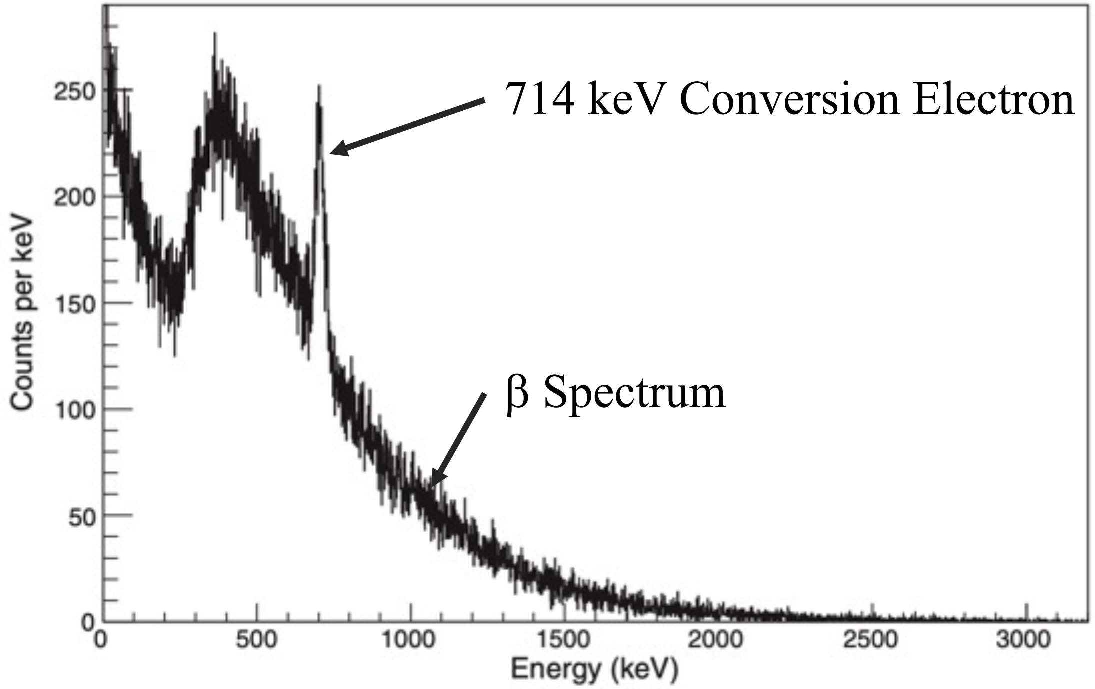
MTAS ^{98}Nb ground-state to ground-state feeding, $I_{\beta gs} = 61(3)\%$, in agreement with ENSDF ^{98}Nb ground-state to ground-state feeding, $I_{\beta gs} = 57(6)\%$, but 2x improvement in precision.

This leads to about a 5% increase in the number of detected antineutrinos from each ^{98}Nb β decay.

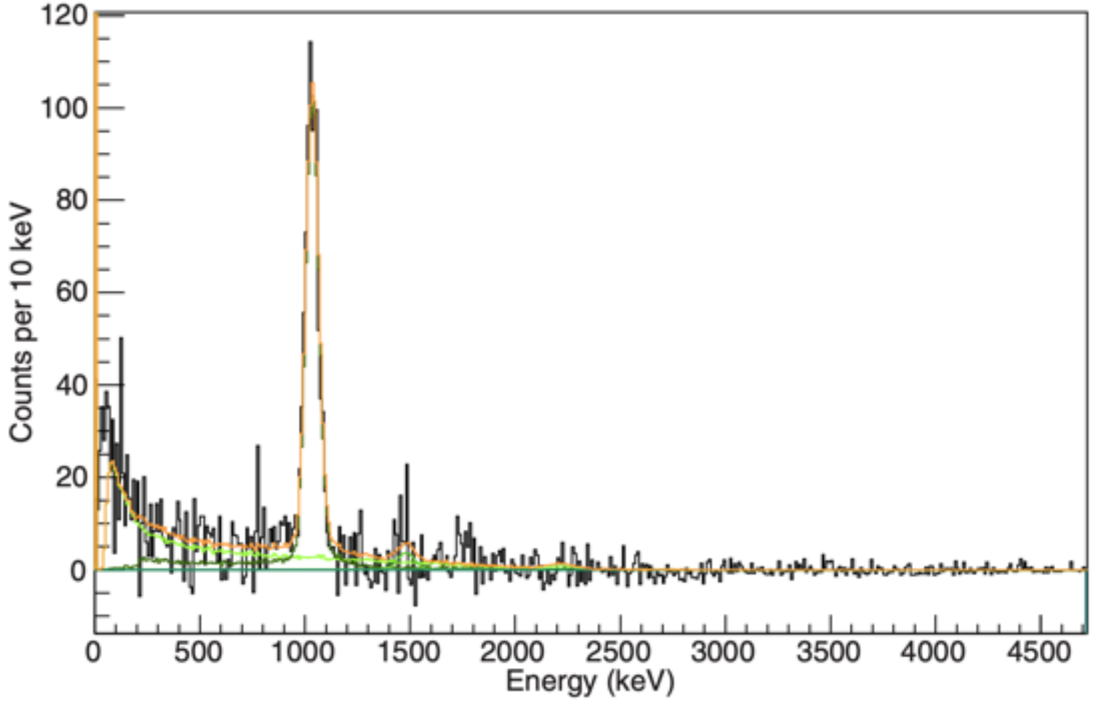
B.C. Rasco, *et al.*, PRC 105, 064301 (2022)

^{98}Nb β Decay - Isolating $0^+ \rightarrow 0^+$ Conversion Electrons

Individual Silicon Strip Detector



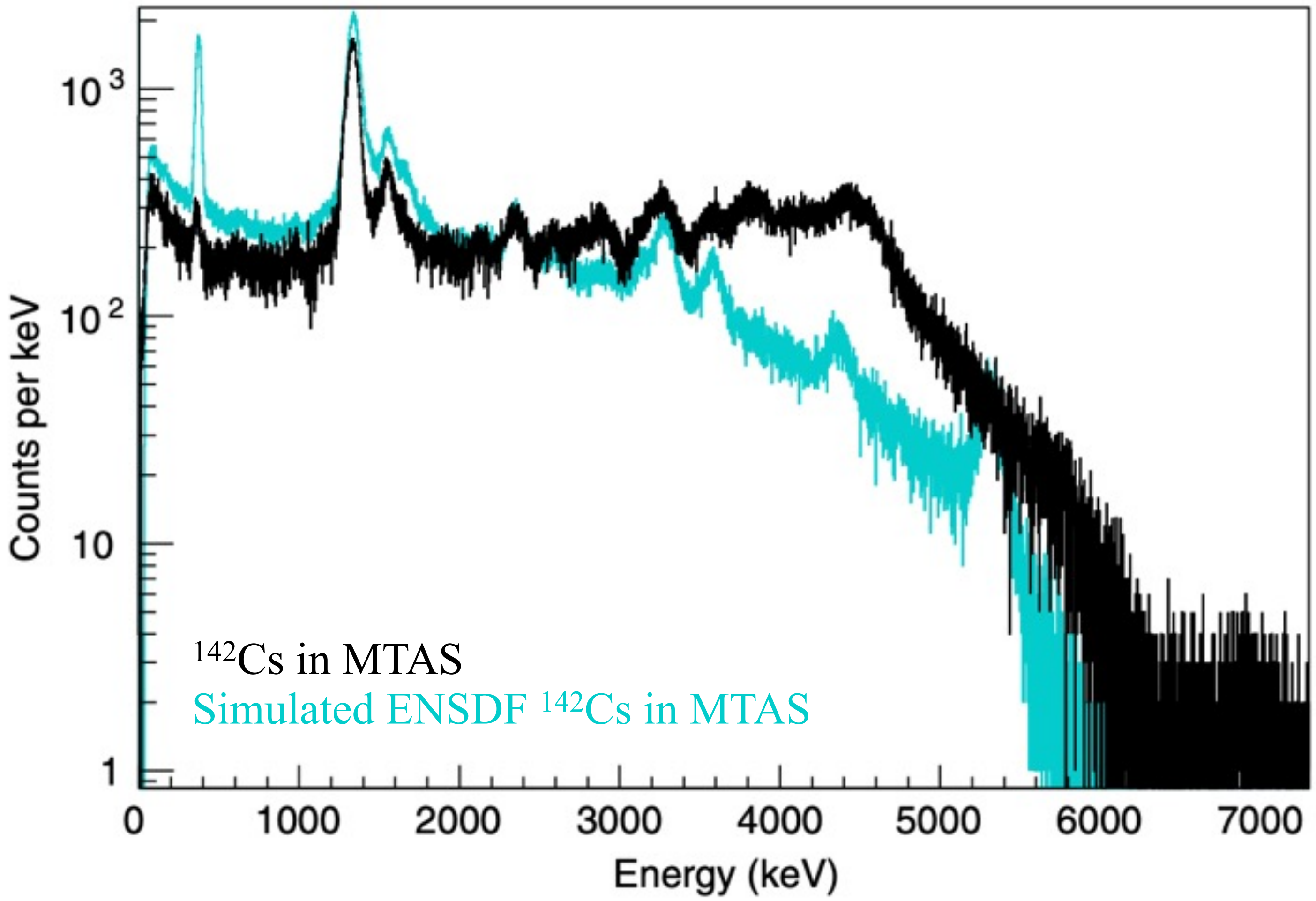
MTAS Signal Gated on Peak in Silicon



MTAS ^{98}Nb feeding to first excited 0^+ level, $I_{\beta 0+}$ = 20(2)%, in agreement with
ENSDF ^{98}Nb feeding to first excited 0^+ leve, $I_{\beta gs}$ =20(4)%,
but 2x improvement in precision.

B.C. Rasco, *et al.*, PRC 105, 064301 (2022)

^{142}Cs, ^{142}Ba, and ^{142}La β Decays



Pandemonium Effect in Action

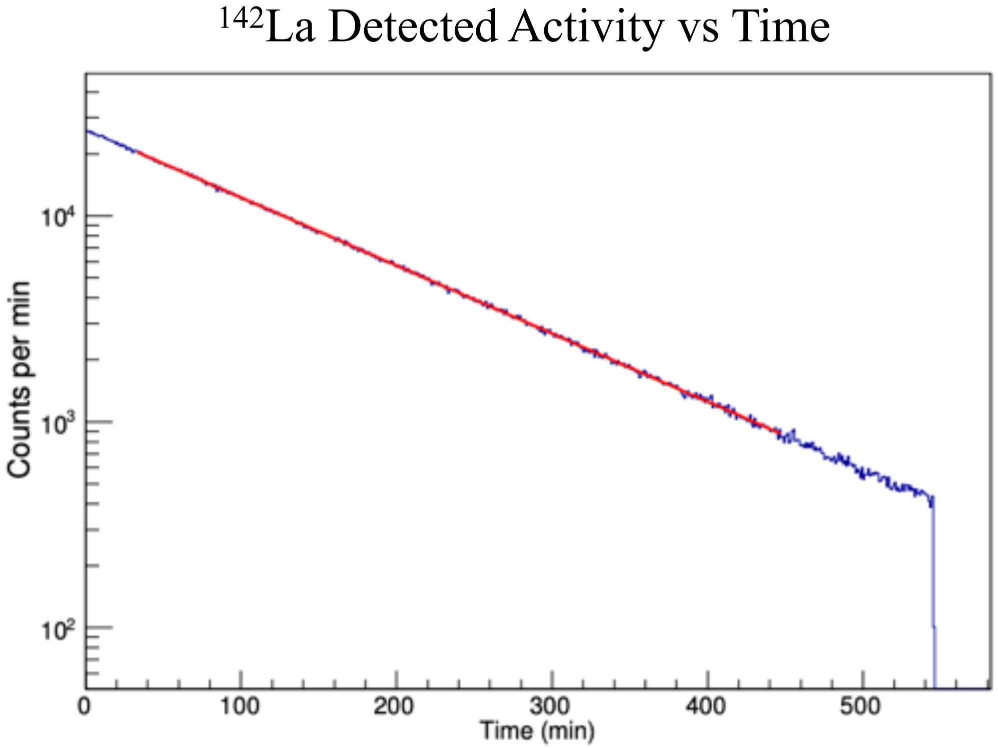
Log Scale! So big differences.

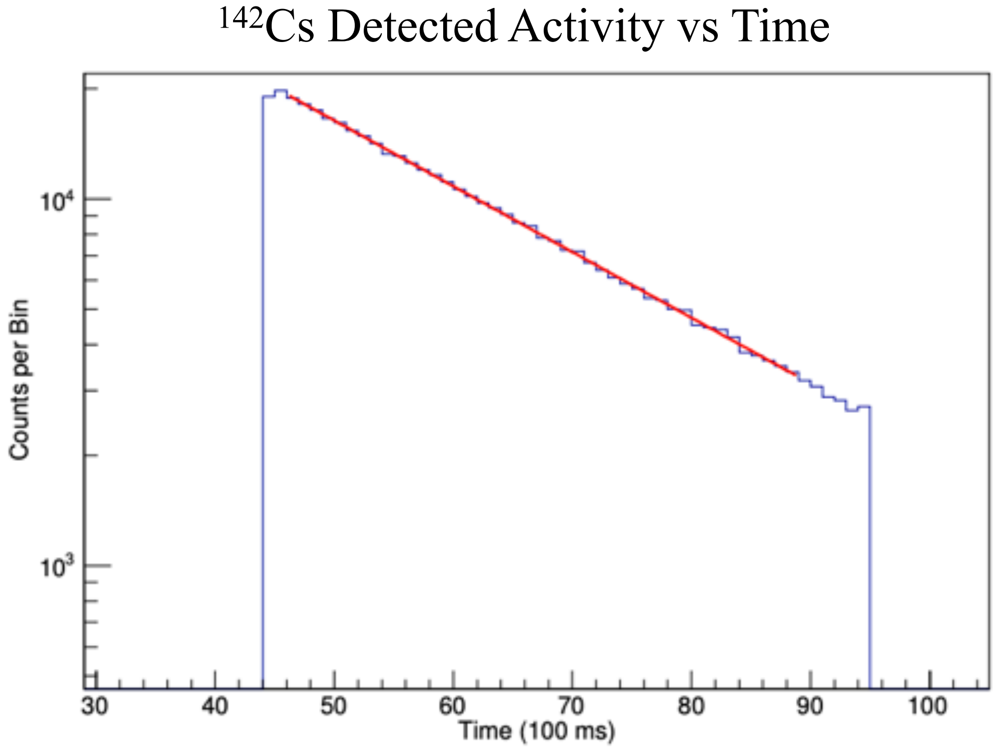
Large increase to high energy level feedings detected.

β-Feeding to first excited state shrinks from 7.2+-1.2% to almost zero.

B.C. Rasco, *et al.*, Phys. Rev. Lett. **117**, 092501 (2016)
M. Wolińska-Cichocka, *et al.*, Submitted to PRC (2023)

^{142}Cs, ^{142}Ba, and ^{142}La β Decays





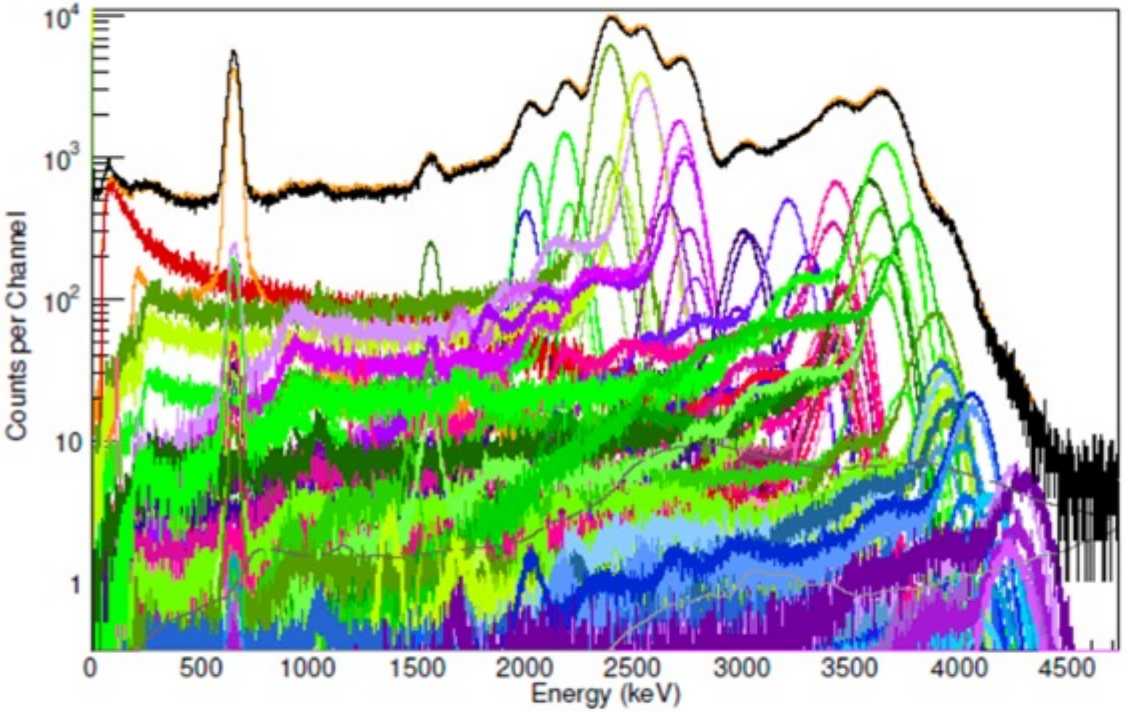
^{142}Cs and ^{142}La β Decays Improved Half-life Precision by ~2x and ~5x, Respectively.

Nuclei	Q_β [51]	GS Spin [49]	$T_{1/2}$ ENSDF	$T_{1/2}$ MTAS
^{142}Cs	7328(8) keV	0^-	1.684(14) s	1.678(8) s
^{142}Ba	2182(8) keV	0^+	10.6(2) min	10.5(15) min
^{142}La	4509(6) keV	2^-	91.1(5) min	91.2(1) min
^{142}Ce^a		0^+	$> 5 \times 10^{16}$ yr	

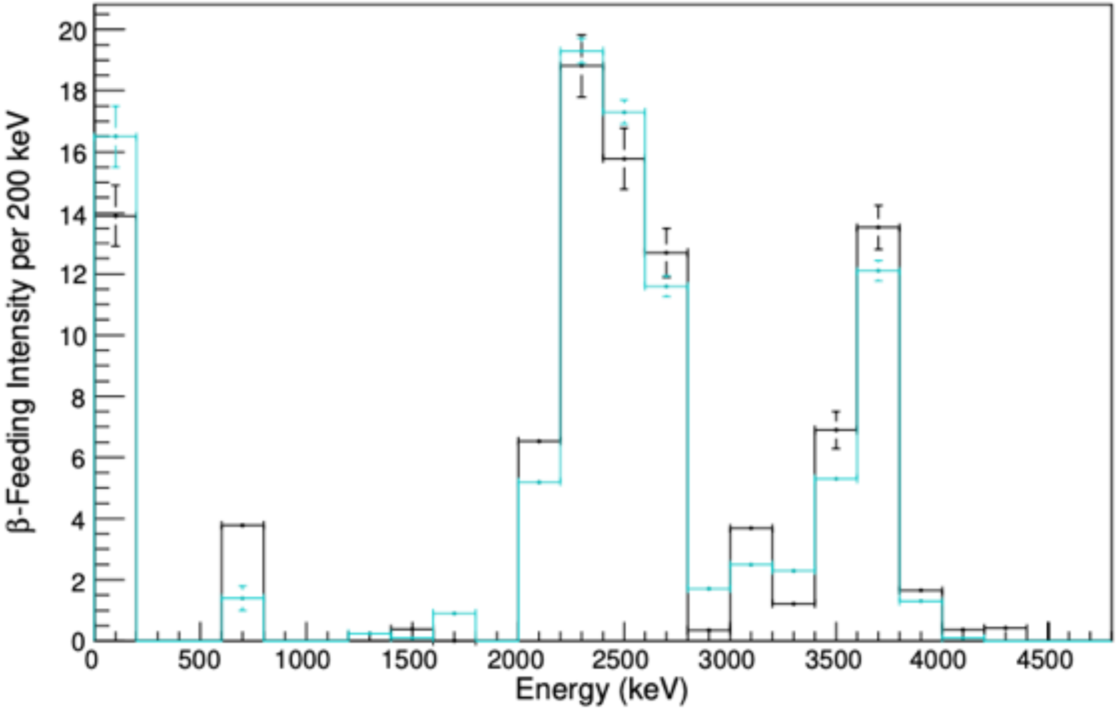
M. Wolińska-Cichocka, *et al.*, Submitted to PRC (2023)

^{142}Cs, ^{142}Ba, and ^{142}La β Decays

^{142}La Fit



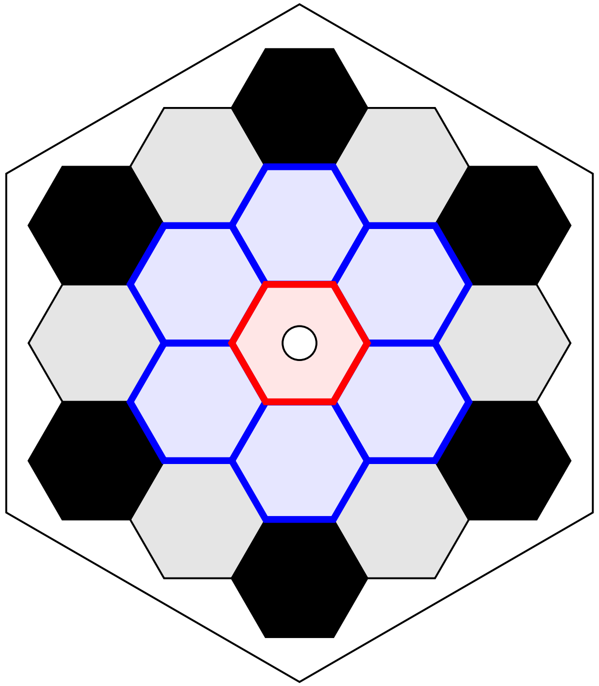
^{142}La β-Feeding Intensities

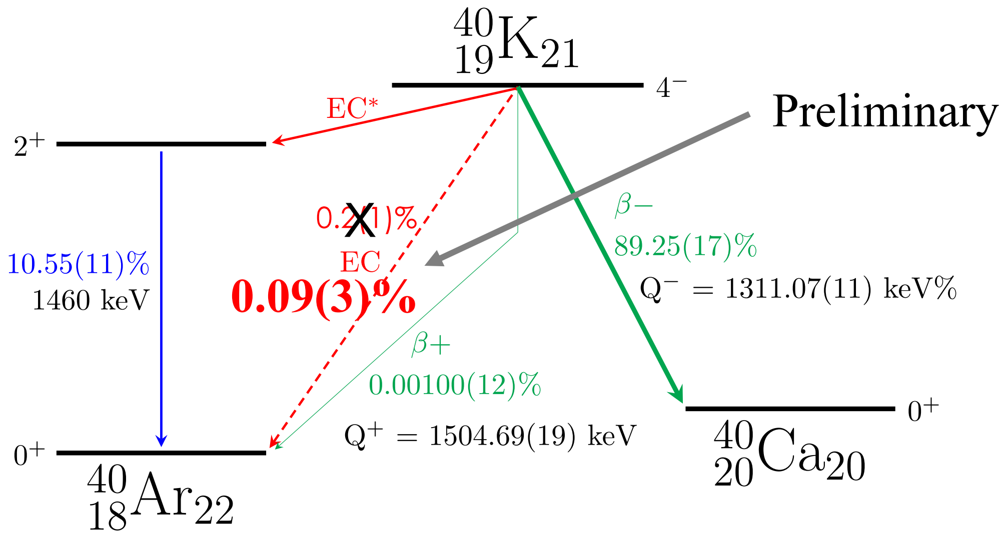


Ground-State and first-excited state β-feeding intensities biggest changes.
Detected ^{142}La Antineutrinos reduced by 5%.
Change comes mainly from reduced ground-state to ground-state feeding when compared with ENSDF value.
With its 4.5-5.9% Cummulative Fission yield this is impactful.

M. Wolińska-Cichocka, *et al.*, Submitted to PRC (2023)

MTAS - ORNL





Electron Capture directly to the ^{40}Ar ground state has never been experimentally measured!

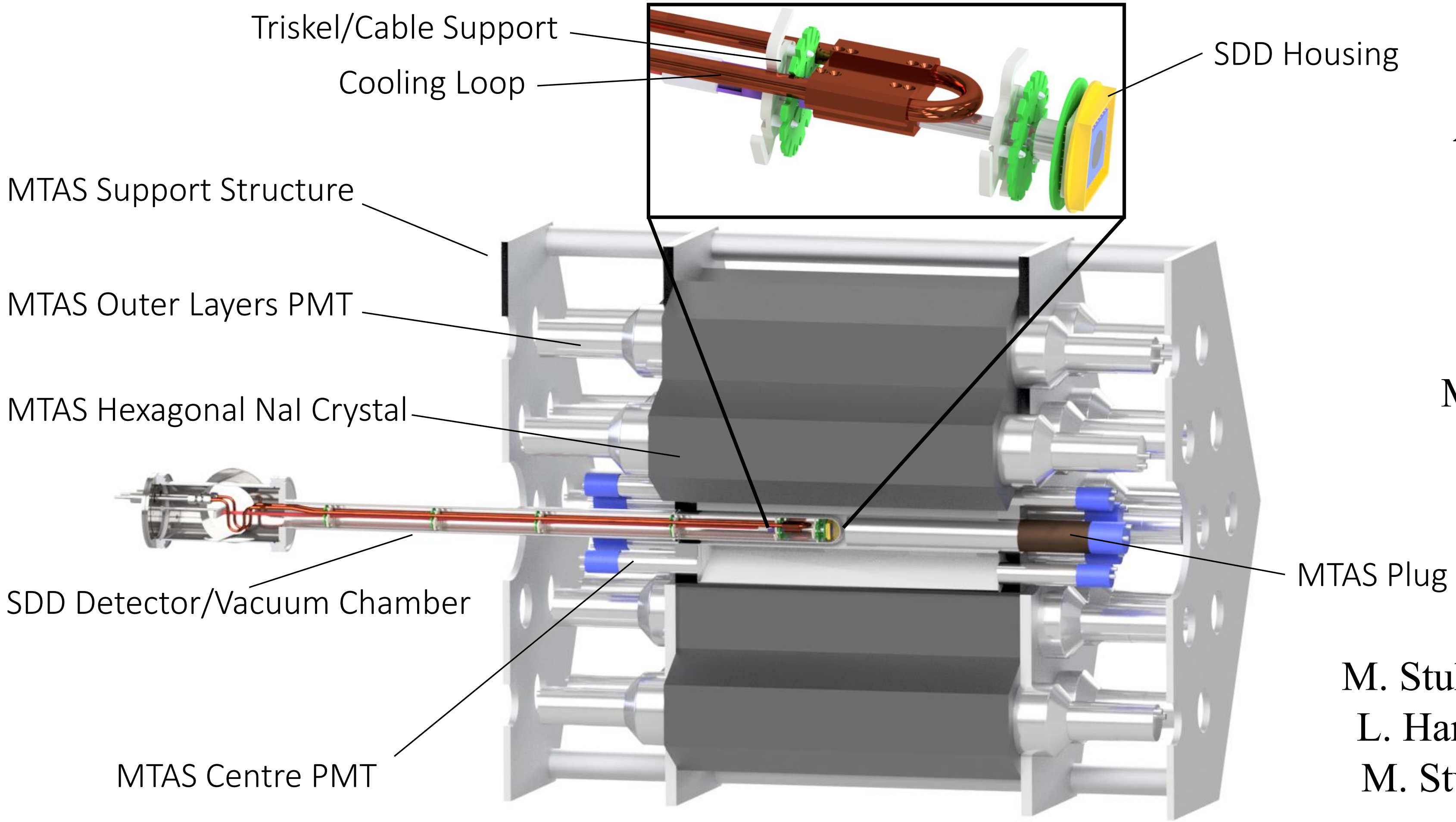
Ground-State Electron Capture in ENSDF as 0.2(1)% but predictions range from 0.0-0.8%

This Feeding Impacts:
1) Neutrinoless double β-decay predictions
2) Background for exotic physics experiments
3) Solar-System and Geochronology Precision

The KDK Collaboration

M. Stukel, *et al.*, NIM **A 1012**, 165593 (2021)
L. Hariasz, *et al.*, arXiV:2211.10343, (2022)
M. Stukel, *et al.*, arXiV:2211.10319, (2022)

KDK - MTAS + X-Ray Detector



0.45mm Thick Silicon Drift Dectector (SDD)

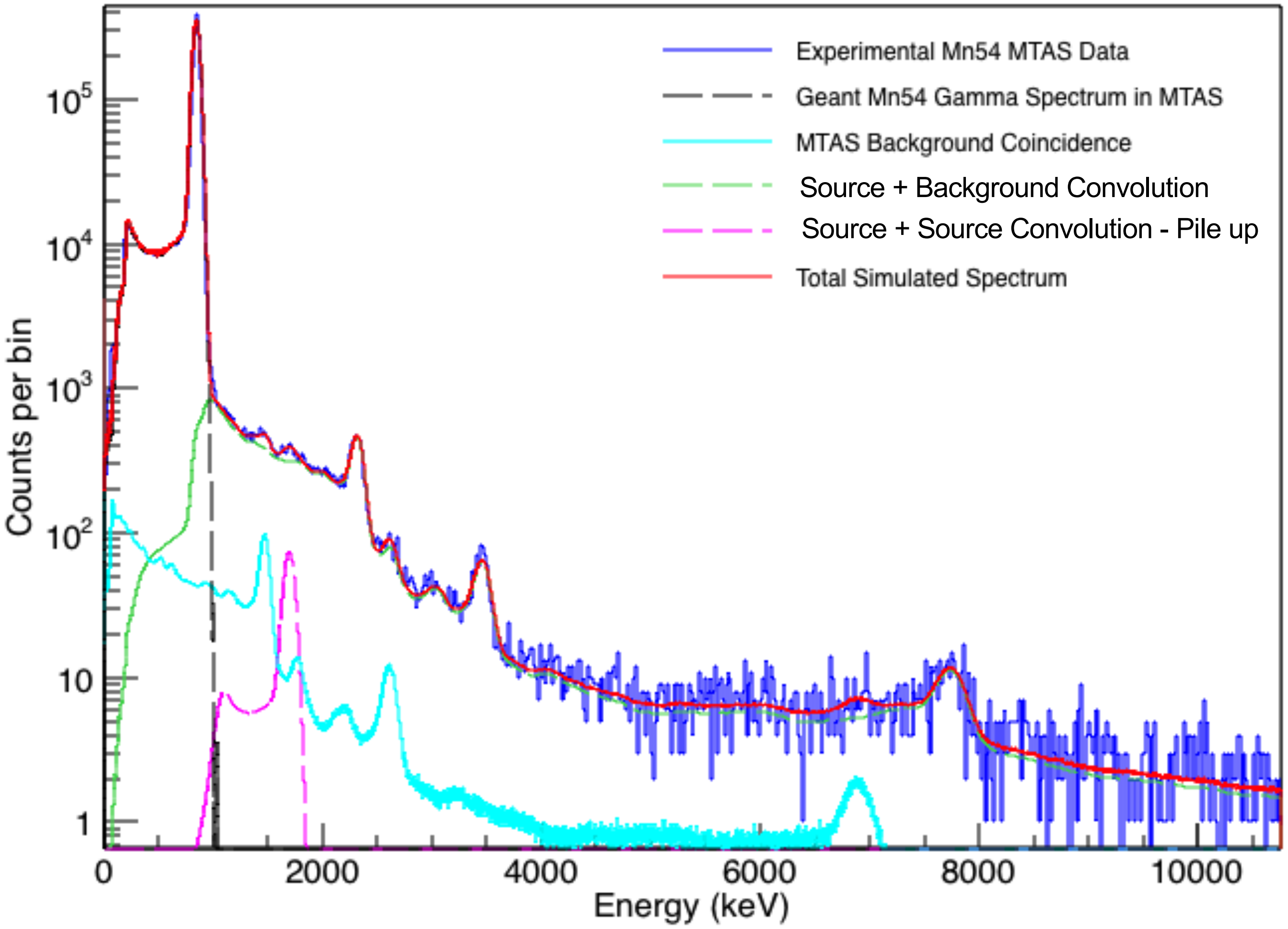
Source, created at ORNL, is 11µm thick 16.5% enriched ^{40}K allowing 3 keV x rays to escape source.

Source is about 3 B.E activity.

MTAS tags ~98% of 1460 keV γ rays.

M. Stukel, *et al.*, NIM **A 1012**, 165593 (2021)
L. Hariasz, *et al.*, arXiV:2211.10343, (2022)
M. Stukel, *et al.*, arXiV:2211.10319, (2022)

KDK - MTAS + X-Ray Detector



Simple Single γ Decay
with SDD X Ray Trigger:
^{54}Mn

A single 835 keV γ ray with 5.4 and 5.9 keV X Rays (+Auger Electrons)

A 4 μs coincidence window and our background rate of ~2500 counts per second has about a 1% background coindence rate

M. Stukel, *et al.*, NIM **A 1012**, 165593 (2021)
L. Hariasz, *et al.*, arXiV:2211.10343, (2022)
M. Stukel, *et al.*, arXiV:2211.10319, (2022)

Thank You for Your Attention

Total Absorption Physics Impacts

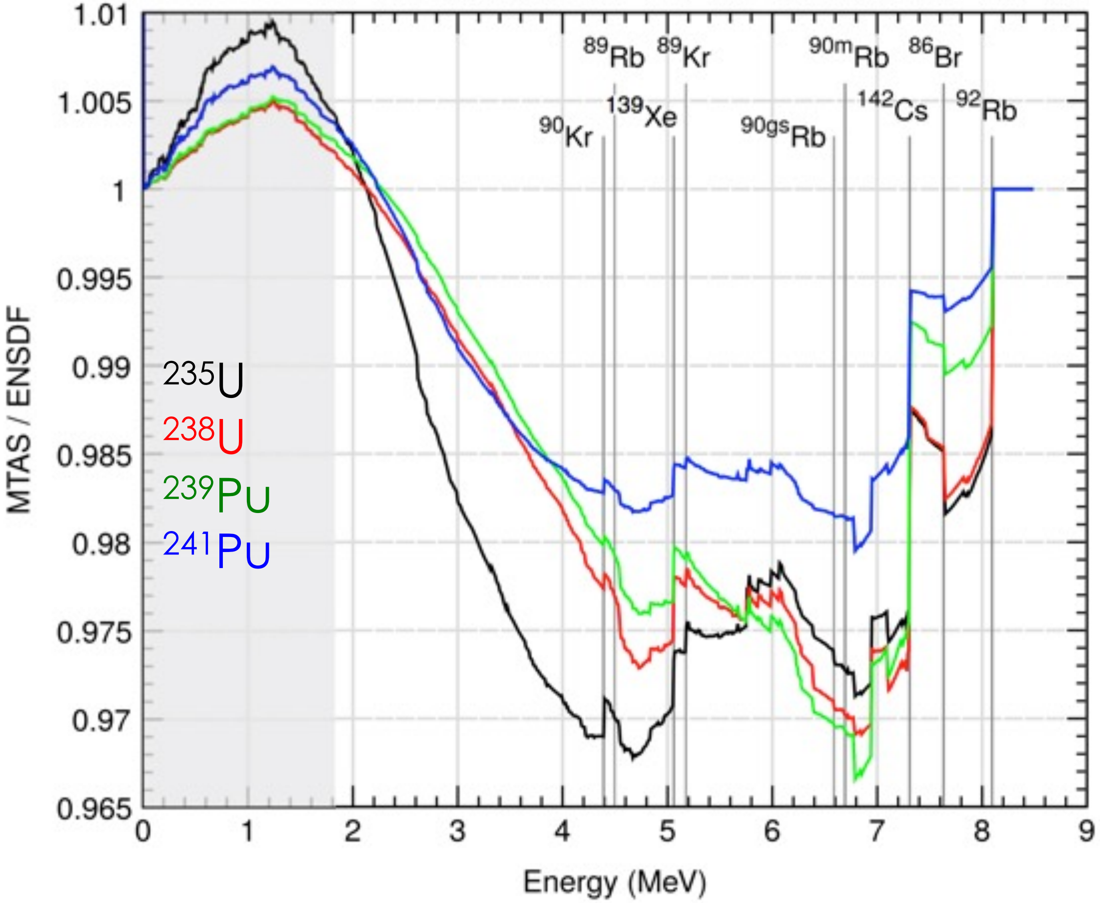
Reactor Physics

The Reactor Antineutrino Anomaly (RAA) is the over prediction of antineutrinos emitted from a reactor

Due to the Pandemonium Effect, low efficiency experiments *systematically* underestimate β-decay energy emitted as g rays while overestimating energy emitted as electrons and antineutrinos.

For the Pandemonium effect, this is a one way correction.

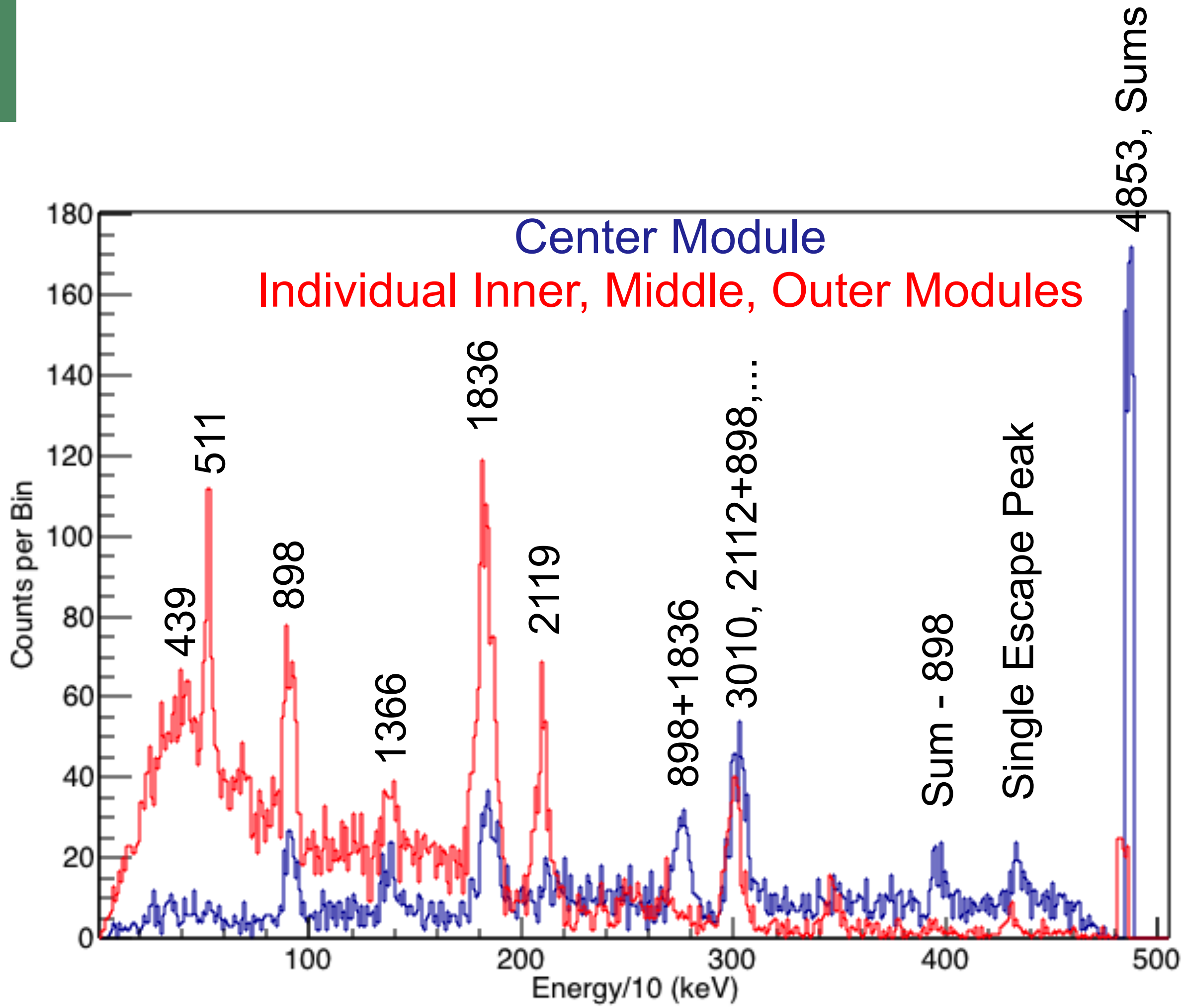
Unity means no change



A. Fijałkowska, *et al.*, PRL **119**, 052503 (2017)

Also See
P. Huber, PRC 84, 024617, 2011
G. Mention, *et al.*, PRD 83, 073006, 2011
A.A. Sonzogni, *et al.*, PRC 98, 014323 (2018)

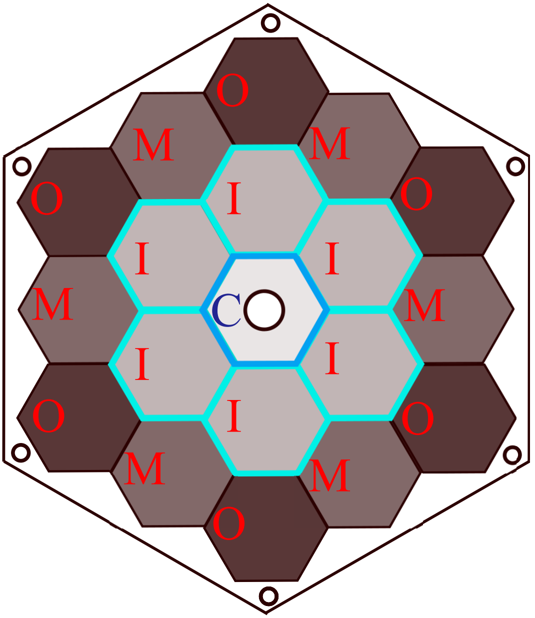
MTAS – Modular Total Absorption Spectrometer



Multiple γ rays: ^{88}Rb 2D Decay Path Information

Gating on total energy between 4830-4880 keV and looking at the individual modules gives individual γ content of level. Precise energies from HPGe measurements.

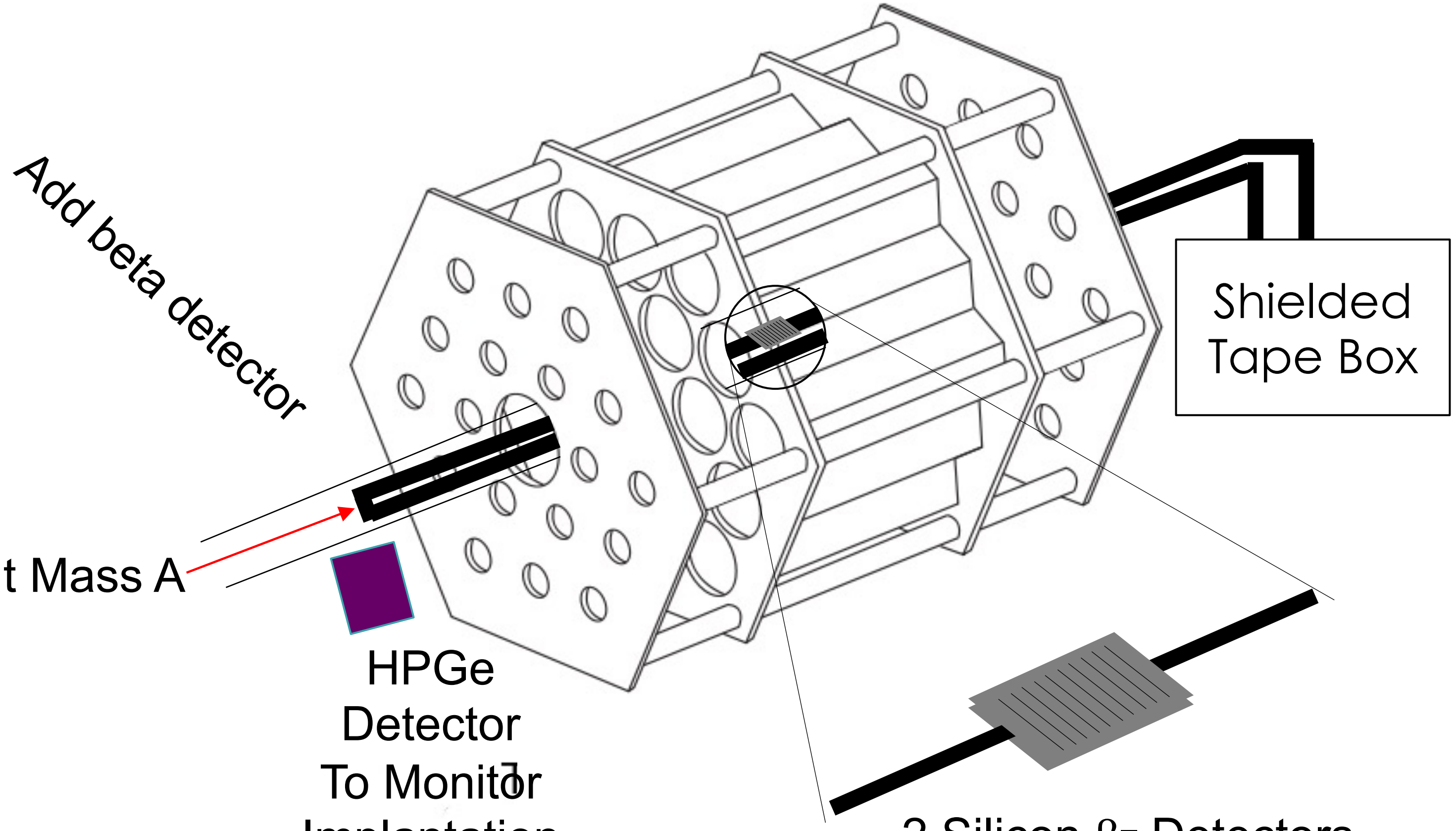
Sharing between modules gives individual γ-ray information.



Analysis being performed by P. Shuai of JINPA/ORNL based on technique first presented in B.C. Rasco, *et al.*, Phys. Rev. C **95**, 054328 (2017)

MTAS - ANL

Focus on Decay Heat and Antineutrino Predictions



Add beta detector

Implant Mass A

HPGe
Detector
To Monitor
Implantation

Shielded
Tape Box

2 Silicon β⁻ Detectors
(~96% solid angle
coverage)
in the center of MTAS

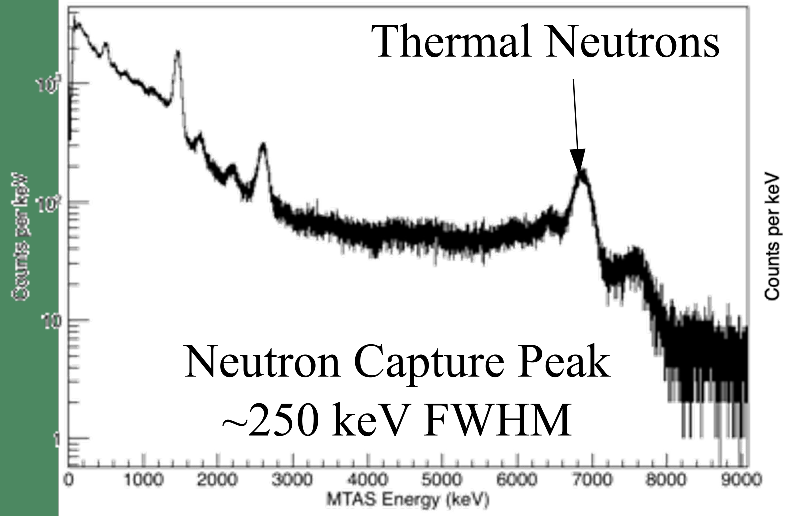
Total β-Feeding:
Ground-State Feeding

Excited Level Feeding
Decay Via:
γ rays
Conversion Electrons (no γ rays)
β-delayed neutrons

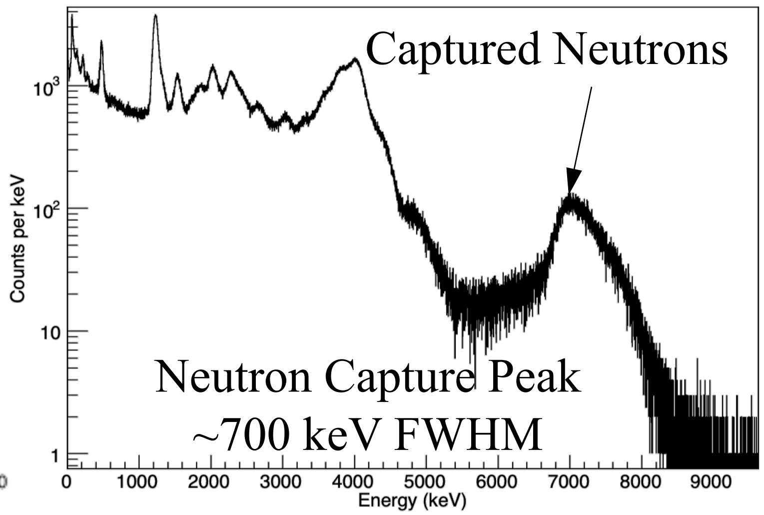
B.C. Rasco, *et al.*, Phys. Rev. Lett. **117**, 092501 (2016)
A. Fijałkowska, *et al.*, PRL **119**, 052503 (2017)
B.C. Rasco, et al., PRC (2017)
P. Shuai, et al., PRC (2022)
B.C. Rasco, et al., PRC (2022)
M. Wolińska-Cichocka submitted to PRC (2023)

Total Absorption Physics Impacts - Neutrons

MTAS Background Spectrum

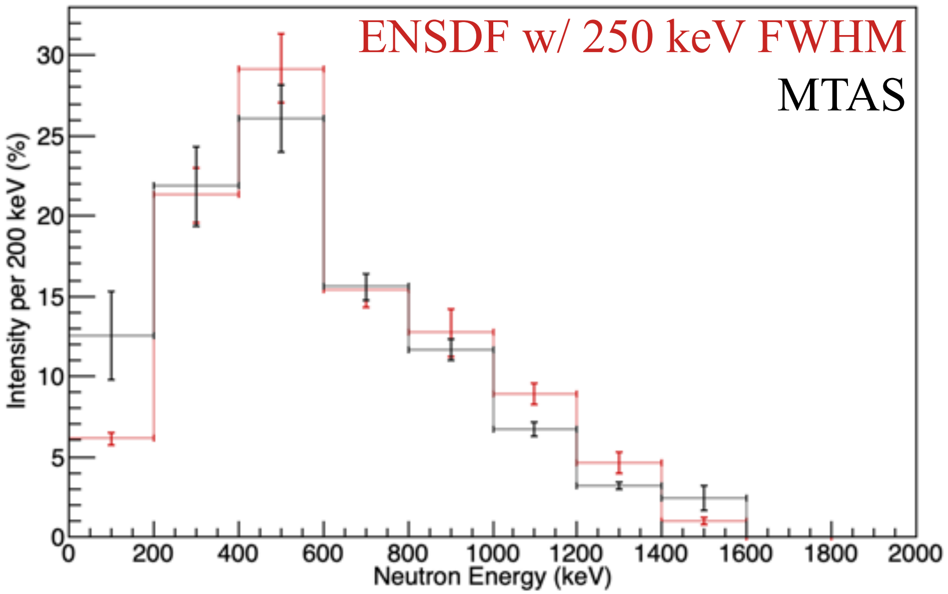


MTAS ^{137}I Spectrum



B.C. Rasco, *et al.*, Phys. Rev. C **95**, 054328 (2017)

Extracted ^{137}I Neutron Energy Spectrum



^{137}I β-Delayed Neutron Probability

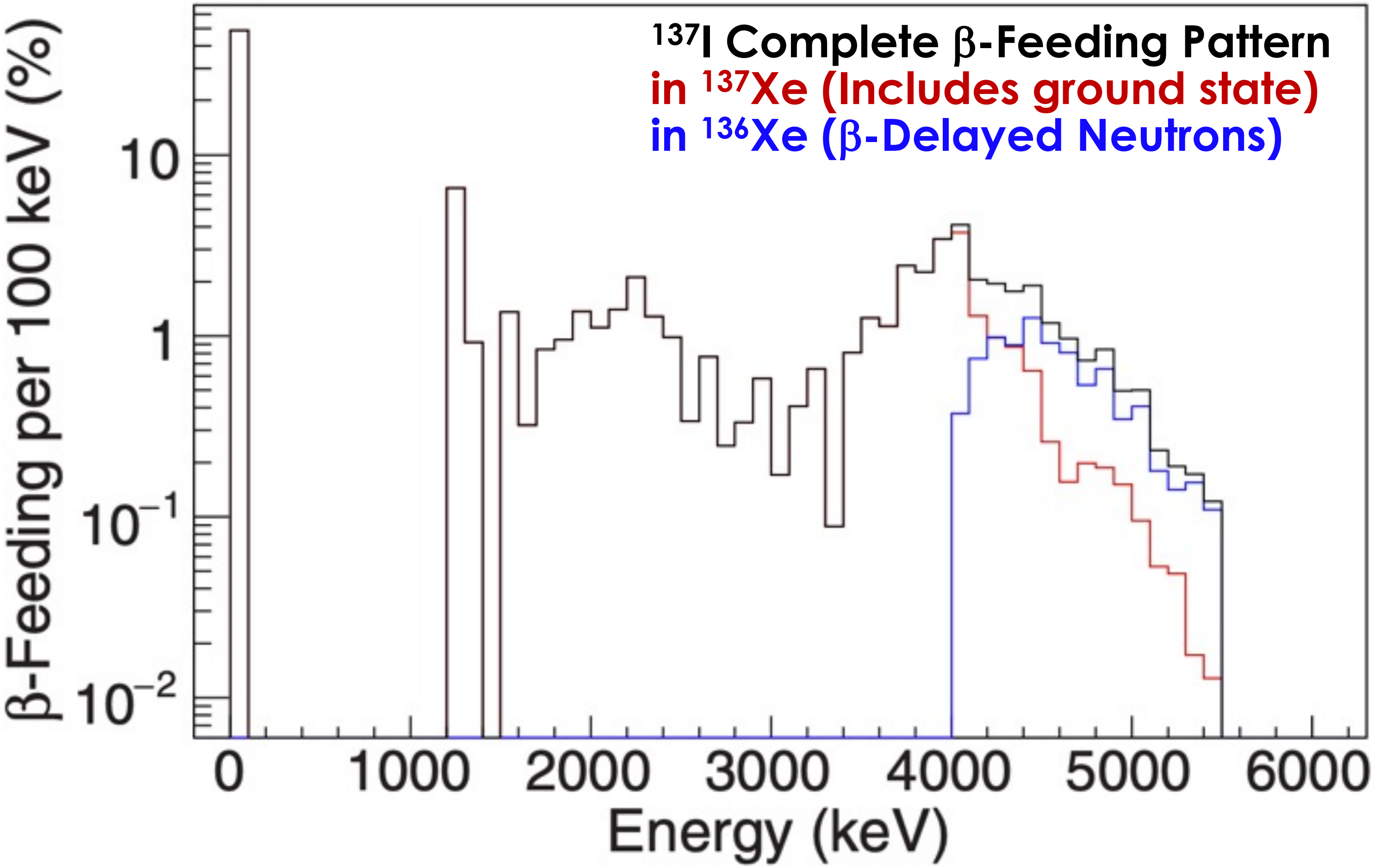
MTAS
P_n=7.9(5)%

ENSDF
P_n = 7.66(14)%

Complete Beta-Feeding Intensities

Beta-Delayed Neutron Branching Intensities
Beta-Delayed Neutron Energy Spectra

Total Absorption Physics Impacts

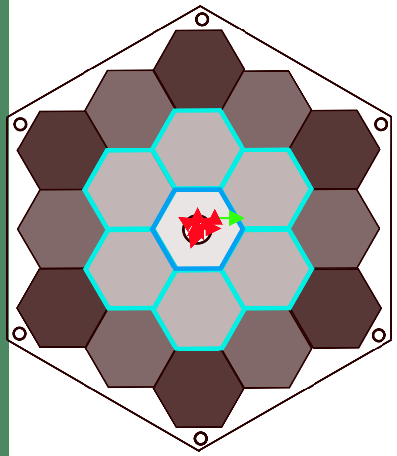


B.C. Rasco, *et al.*, Phys. Rev. C **95**, 054328 (2017)

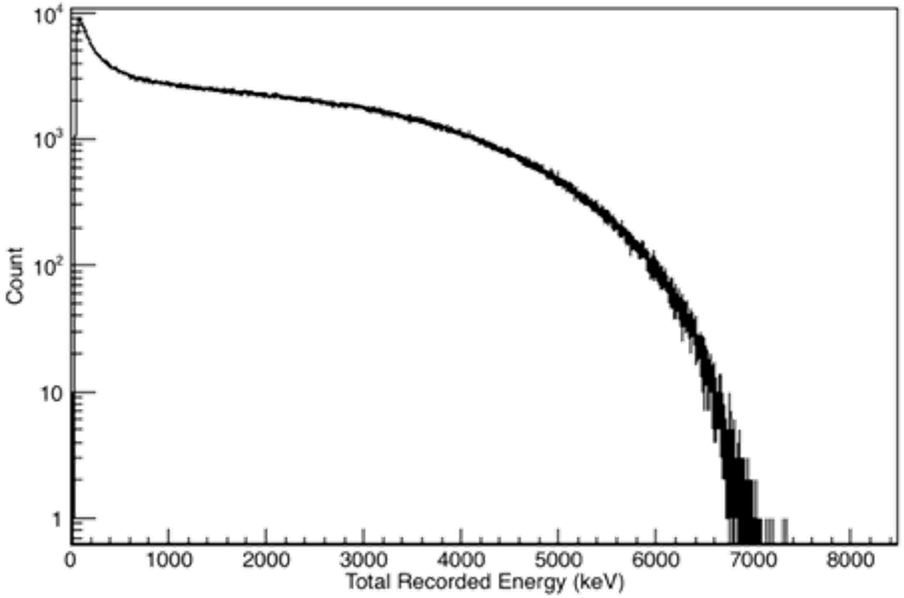
Complete Beta-Feeding Intensities
Beta-Decay Ground-State Feeding Intensities
Beta-Delayed Neutron Branching Intensities
Beta-Delayed Neutron Energy Spectra
Improved Nuclear Data
Endpoint Energies

MTAS – Ground-State Feeding

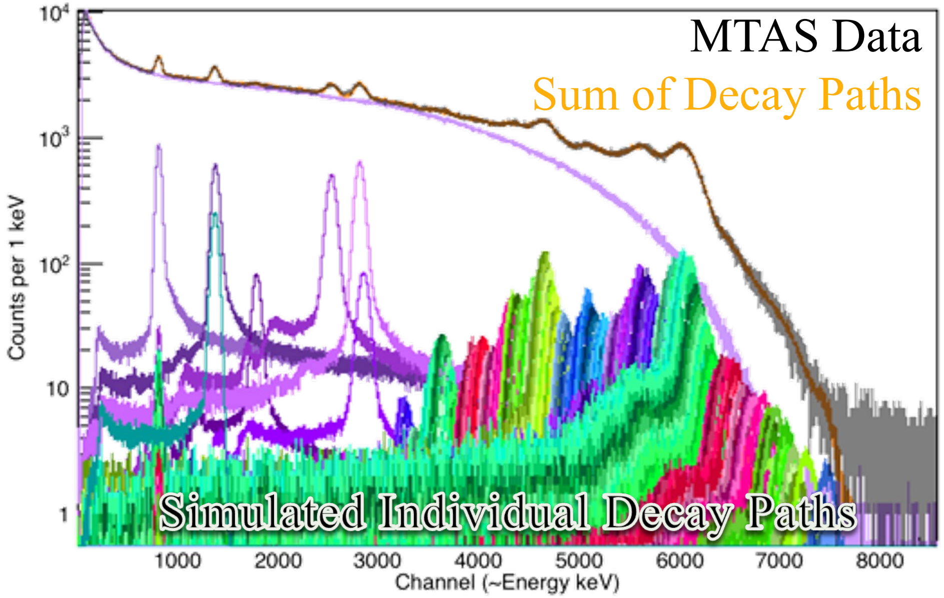
βs in MTAS



Simulated Total MTAS response to βs from ^{92}Rb ground state to ^{92}Sr ground state decay (Q_β = 8095 keV)



^{92}Rb: Q_β= 8095(6) keV $T_{1/2}$= 4.48(3) s



B.C. Rasco, et al., PRL **117**, 092501 (2016)

MTAS ground-state feeding = 91(3)%

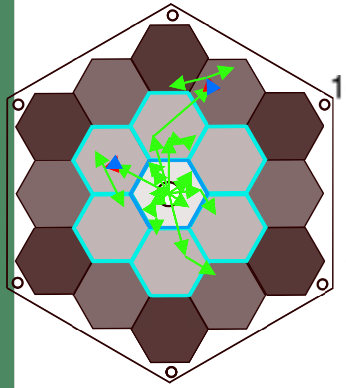
Valencia TAS ground-state feeding = 87.5(2.5)%

ENSDF ground-state feeding = 95.2(7)% (Uncertainty way too small!)

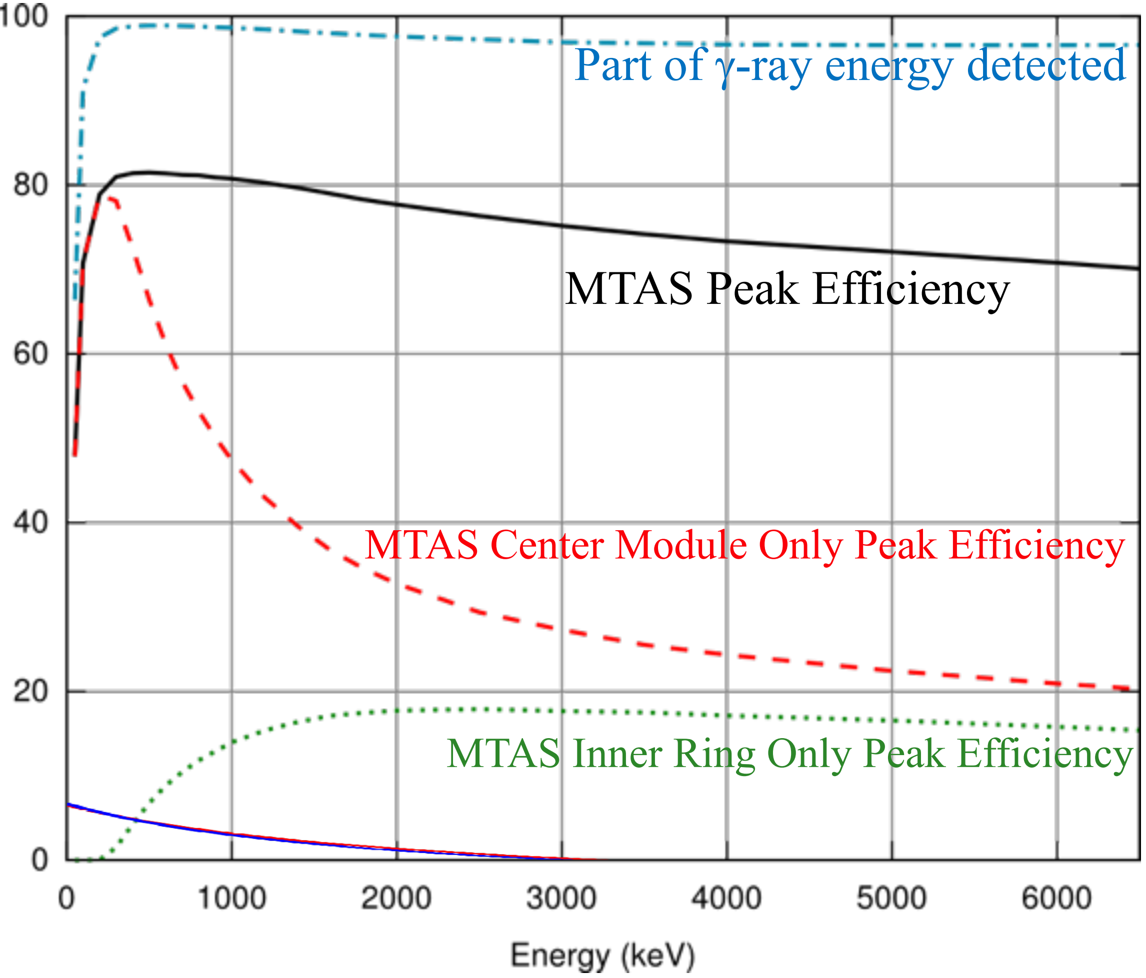
MTAS has measured up to 53 MeV electrons

MTAS – Modular Total Absorption Spectrometer

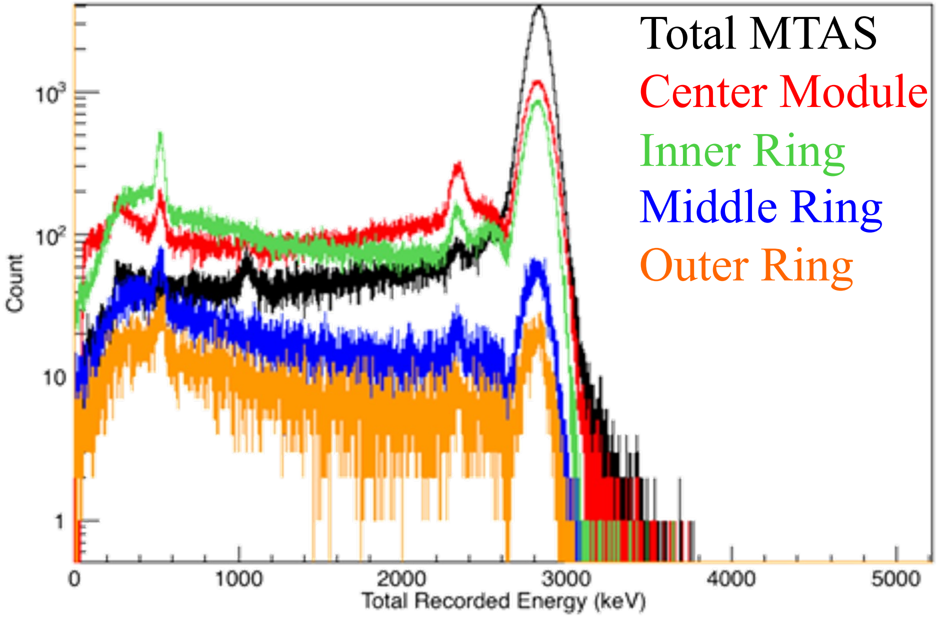
γs in MTAS



Single γ-ray efficiency of various MTAS regions and comparison with a high-efficiency HPGe Array.



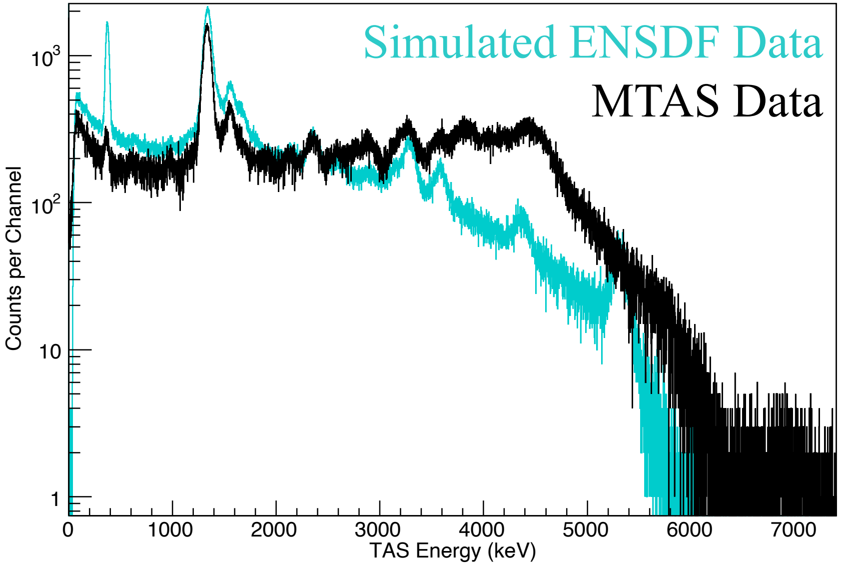
Karny, *et al.*, NIM A, 836, 83-90 (2016)



Simulated MTAS response to a 2850 keV γ-ray including β spectrum for ^{137}Xe

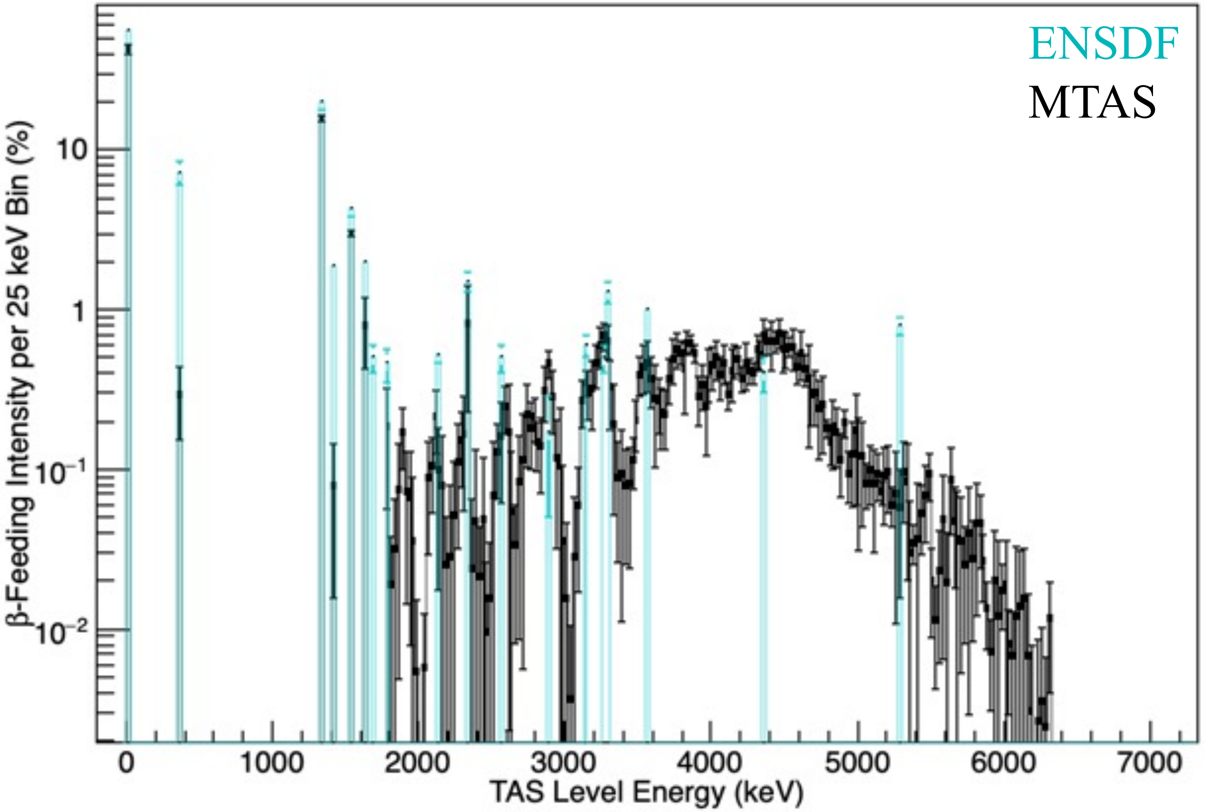
Includes nonlinear light production in NaI crystals.
Rasco, *et al.*, NIM A, 788, 137-145 (2015)

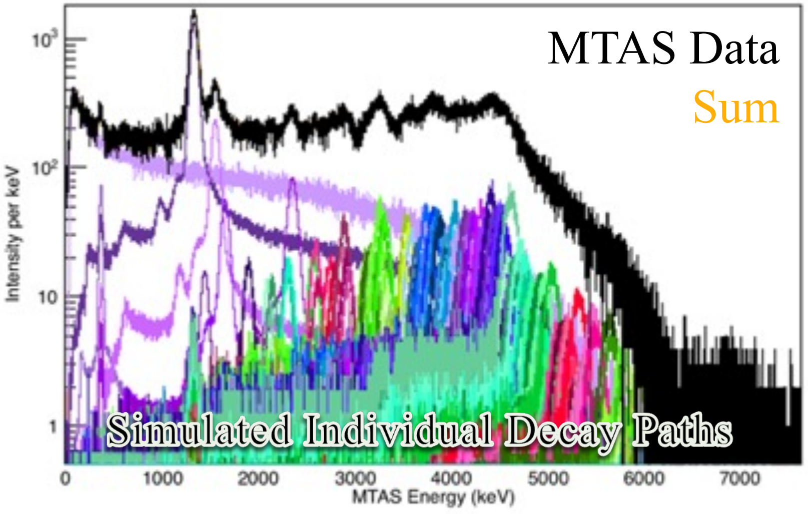
MTAS – ^{142}Cs



Q_β= 7325 (9) keV $T_{1/2}$= 1.684(14) s

Big Changes in β-Feeding Intensity



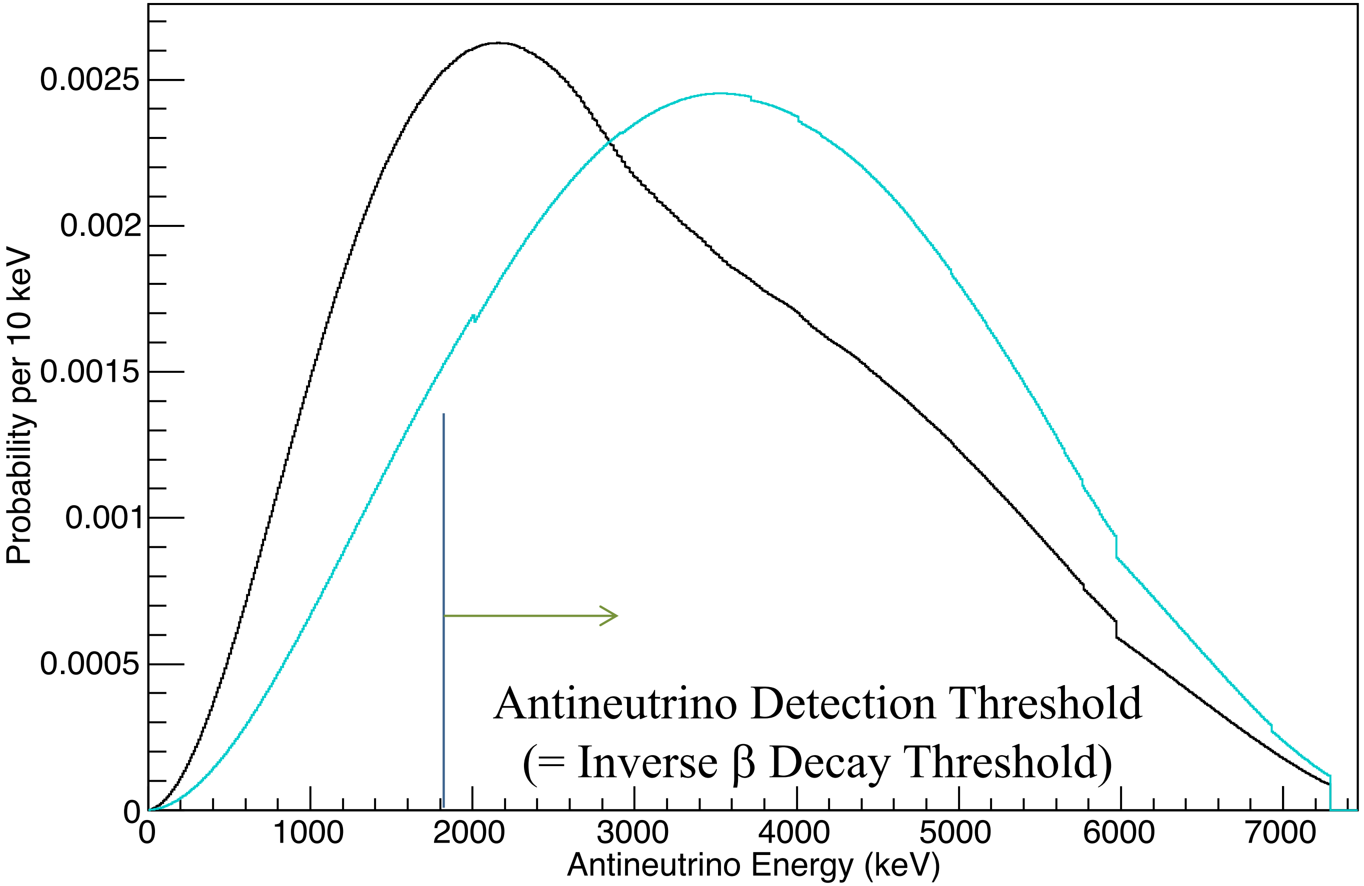


B.C. Rasco, et al., PRL **117**, 092501 (2016)

MTAS – Modular Total Absorption Spectrometer

Antineutrino spectrum for ^{142}Cs MTAS assuming allowed β decay spectrum.

ENSDF antineutrino spectrum for ^{142}Cs (treated as allowed)



Antineutrino Detection Threshold
(= Inverse β Decay Threshold)

B.C. Rasco, *et al.*, PRL **117**, 092501 (2016)

Fraction Change from ENSDF Below 1.8 MeV
(i.e. Not Detectable in antineutrino experiment):
0.11 to 0.23(3)

Fraction Change from ENSDF Above 5 MeV:
0.20 to 0.14(1)

MTAS – Modular Total Absorption Spectrometer

Antineutrino spectrum for ^{98}Nb MTAS assuming allowed β decay spectrum.

ENSDF antineutrino spectrum for ^{98}Nb (treated as allowed)