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U.S. DEPARTMENT OF ENERGY

Current Decay Experiments

Libby McCutchan

National Nuclear Data Center

WoNDRAM – June 20th, 2021

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Experimental Campaigns

Funded through Nuclear Data Interagency Working Group Lab Call

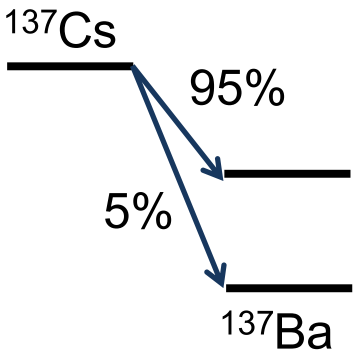
- Improving the Nuclear Data on Fission Product Decays at CARIBU
    LLNL-ANL – 4 year project funded from FY2018
- Novel approach for Improving Nuclear Data for Antineutrino Spectra Predictions
    ANL - 4 year project funded from FY2018
- Beta-strength function, reactor decay heat and anti-neutrino properties from total absorption spectroscopy of fission fragments
    ORNL, 4 year project funded from FY2019

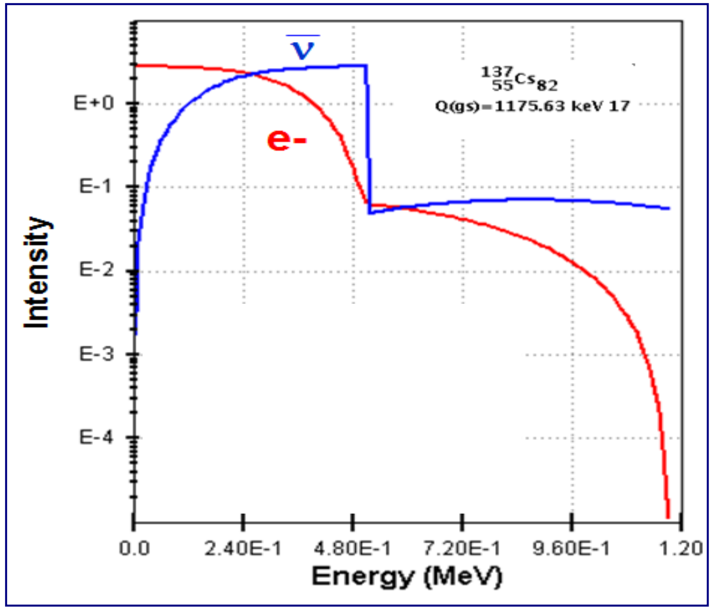
Any decay data on fission fragments helps !

- TAGS : Valencia/Jyvaskyla and MSU/SUN
- Discrete Spectroscopy
- Beta Shape Measurements

Required decay data: Beta intensities

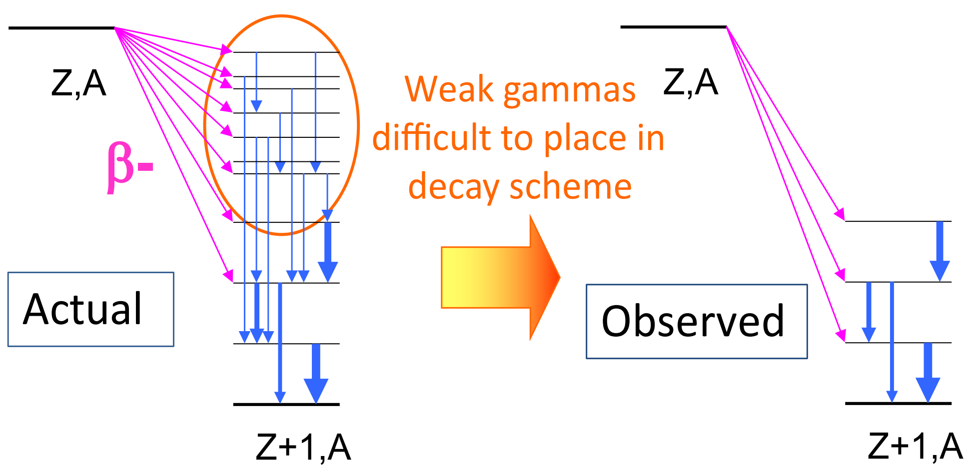
One major ingredient is beta feeding intensities

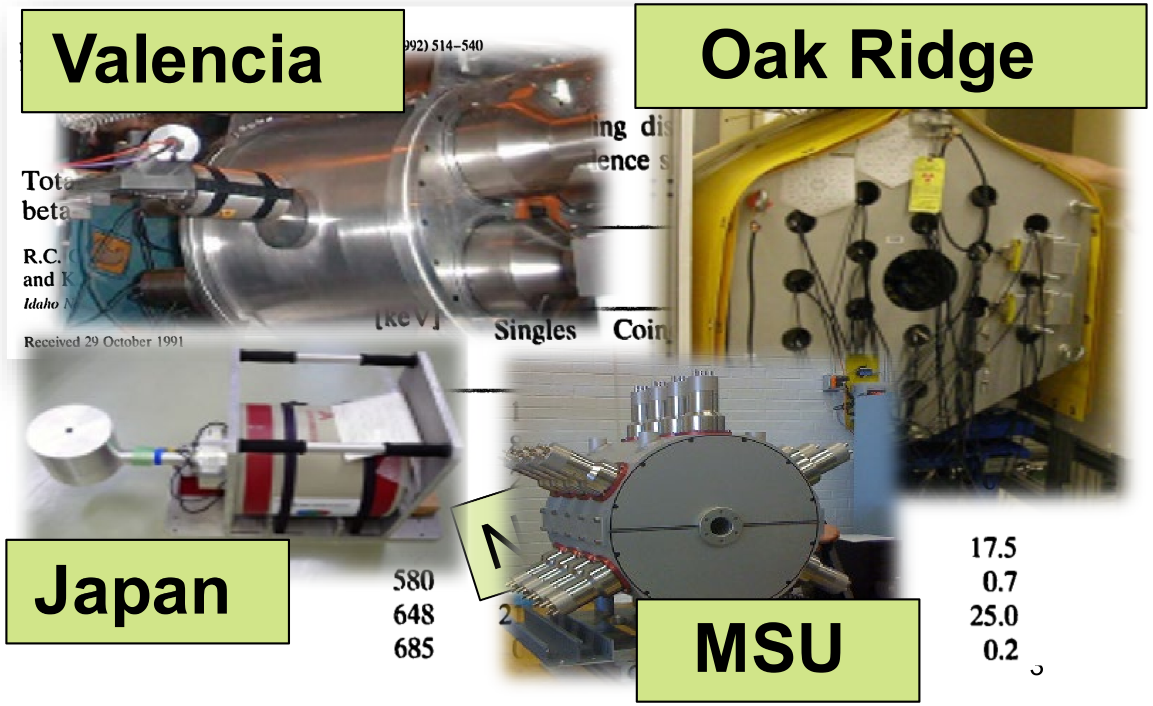




$$S(E)=N\,W\,(W^2-1)^{1/2}(W-W_0)^2\,F(Z,W)\,C(Z,W)(1+\delta)$$

The problem for high Q values : Pandemonium





Required decay data : shape factor

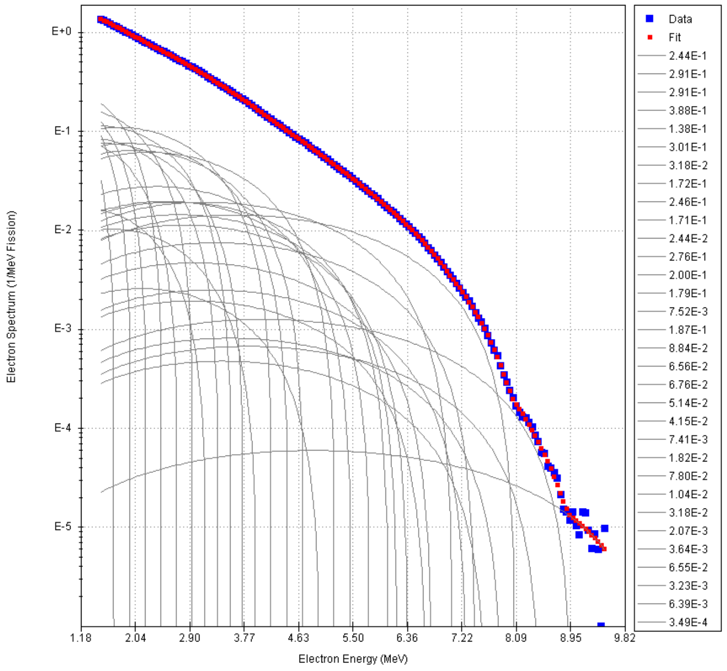
$$I(E)=N\,W\,(W^2-1)^{1/2}(W-W_0)^2\,F(Z,W)\,C(Z,W)\,\delta_{screen}\delta_{WM}\delta_{rad}$$

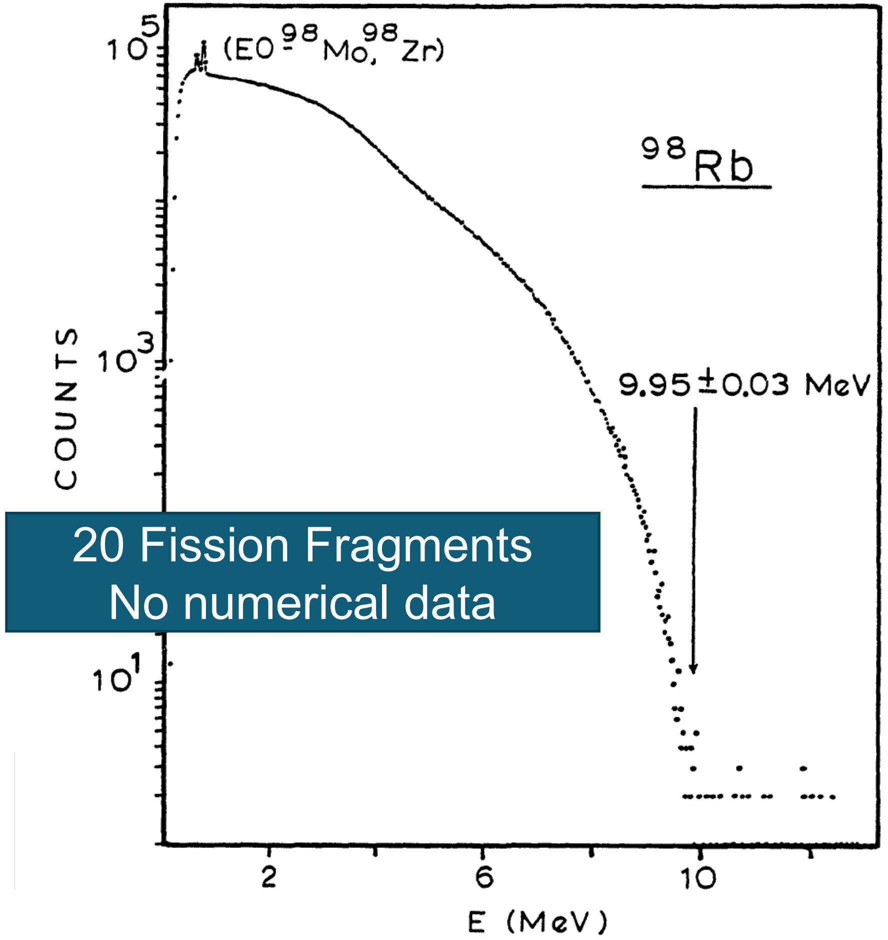
$$C_{exp}=1+a_1W+a_2W^2+a_3W^3+b_1/W$$

Shape factor : remaining correction accounting for nuclear structure
C= 1 for allowed transitions – adopted in most calculations

Important in both

- Summation
- Conversion

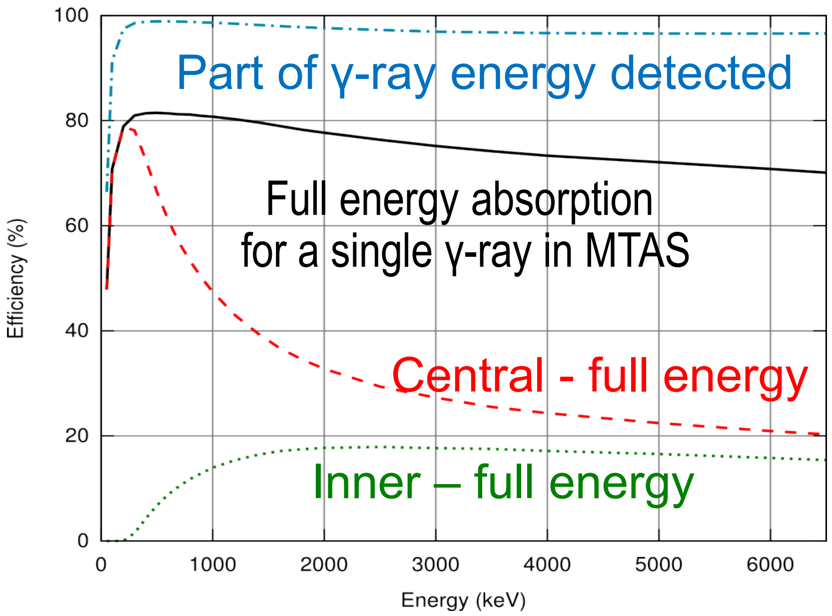




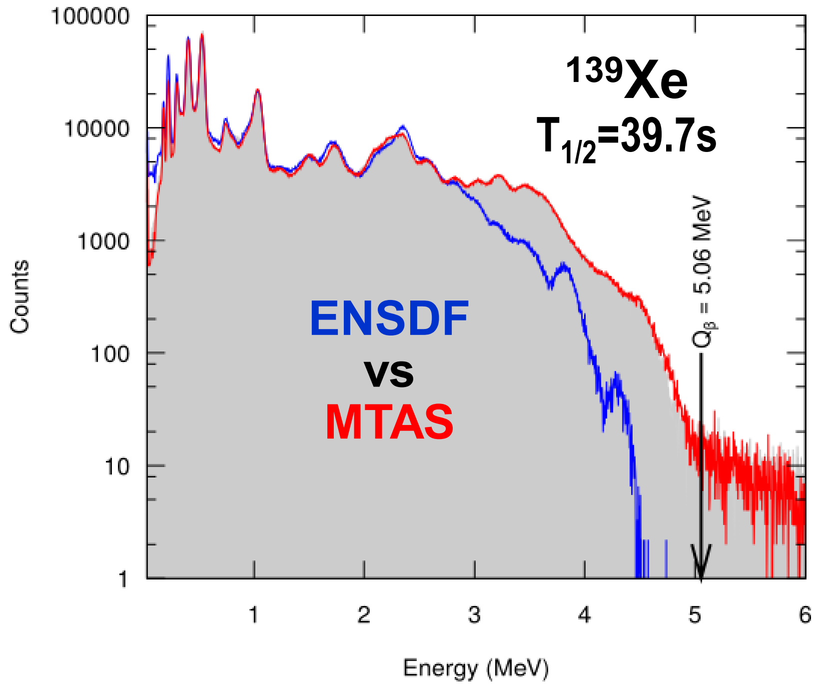
20 Fission Fragments
No numerical data

MTAS measurements

Studies with ORNL's **Modular Total Absorption Spectrometer (MTAS)**
at the ORNL's HRIBF and at the ANL's CARIBU facilities



Impressive efficiency, plotted here up to 6 MeV
total 99%-98%, single γ-line 80%-70%



ENSDF: 240 γ's, 63 levels

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Krzysztof Piotr Rykaczewski and Bertis Charlie Rasco
Physics Division ORNL

Slide courtesy of K. Rykaczewski

MTAS measurements : light mass fission peak

Nb 89 2.03 h	Nb 90 14.60 h	Nb 91 680 y	Nb 92 34.7 My	Nb 93 100.	Nb 94 20.3 ky	Nb 95 34.991 d	Nb 96 23.35 h	Nb 97 72.1 m	Nb 98 1 2.86 s	Nb 99 15.0 s	Nb 100 1.5 s	Nb 101 7.1 s	Nb 102 1.3 s
Zr 88 83.4 d	Zr 89 78.41 h	Zr 90 51.45	Zr 91 11.22	Zr 92 17.15	Zr 93 1.53 My	Zr 94 17.38	Zr 95 64.032 d	Zr 96 2.80	Zr 97 16.90 h	Zr 98 30.7 s	Zr 99 2.1 s	Zr 100 7.1 s	Zr 101 2.3 s
Y 87 79.8 h	Y 88 106.65 d	Y 89 100	Y 90 64.00 h	Y 91 58.51 d	Y 92 3.54 h	Y 93 10.18 h	Y 94 18.7 m	Y 95 10.3 m	Y 96 2 ν 5.34 s	Y 97 ν 3.75 s	Y 98 ν 548 ms	Y 99 1.470 s	Y 100 735 ms
Sr 86 9.86	Sr 87 7.00	Sr 88 82.58	Sr 89 50.53 d	Sr 90 28.79 y	Sr 91 9.63 h	Sr 92 2.66 h	Sr 93 7.423 m	Sr 94 75.3 s	Sr 95 ν 23.90 s	Sr 96 1.07 s	Sr 97 2 429 ms	Sr 98 653 ms	Sr 99 269 ms
Rb 85 72.17	Rb 86 18.642 d	Rb 87 27.83	Rb 88 17.78 m	Rb 89 15.15 m	Rb 90 2 ν 2.6 m	Rb 91 58.4 s	Rb 92 2 ν 4.492 s	Rb 93 ν 5.84 s	Rb 94 ν 2.702 s	Rb 95 ν 377.5 ms	Rb 96 203 ms	Rb 97 169.9 ms	Rb 98 114 ms
Kr 84 57.00	Kr 85 10.776 y	Kr 86 17.30	Kr 87 76.3 m	Kr 88 2.84 h	Kr 89 1 3.18 m	Kr 90 1 32.32 s	Kr 91 ν 8.57 s	Kr 92 1.840 s	Kr 93 1.286 s	Kr 94 210 ms	Kr 95 114 ms		
Br 83 2.40 h	Br 84 31.80 m	Br 85 2.90 m	Br 86 1 ν 55.1 s	Br 87 1 55.65 s	Br 88 1 ν 16.36 s	Br 89 ν 4.40 s	Br 90 1.910 s	Br 91 0.64 s	Br 92 343 ms	Br 93 102 ms	Br 94 70 ms		
Se 82 8.73	Se 83 22.3 m	Se 84 3.1 m	Se 85 33 s	Se 86 14.1 s	Se 87 5.8 s	Se 88 1.53 s	Se 89 410 ms	Se 90 >300 ns	Se 91 270 ms	Se 92 100 ms	Se 93 50 ms	20 ms	

1 : 6 priority 1 for decay heat
2: 4 priority 2 for decay heat
v: 13 priority for antineutrinos

39 decays measured between 2012 and 2016

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Slide courtesy of K. Rykaczewski

MTAS measurements : heavy mass fission peak

1 : 7 priority 1 for decay heat
2: 4 priority 2 for decay heat
v: 8 priority for antineutrinos

38 decays measured between 2012 and 2016

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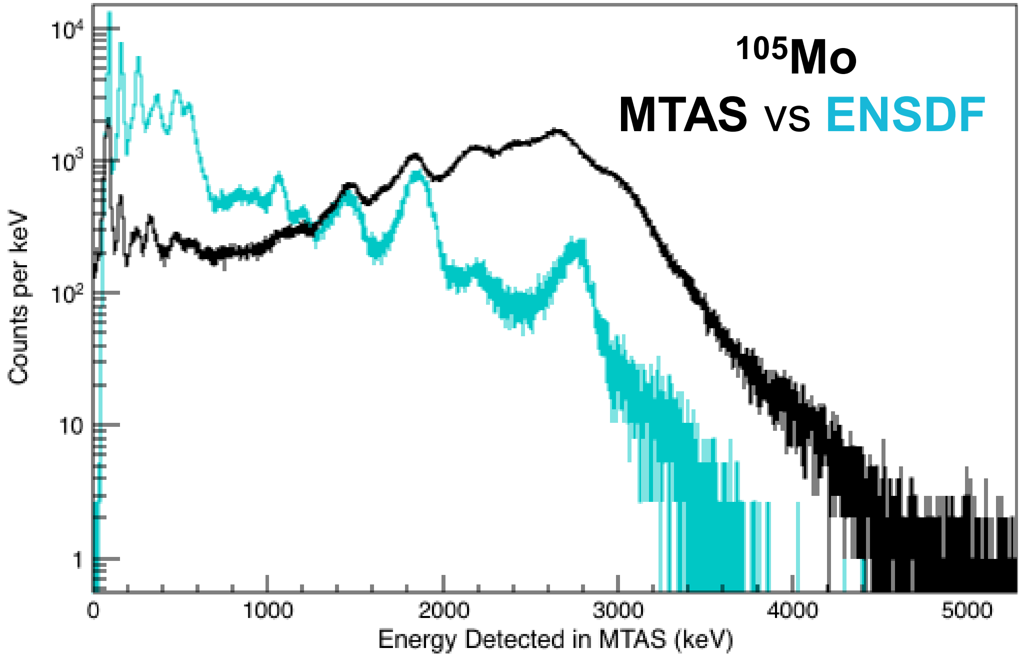
Slide courtesy of K. Rykaczewski

MTAS current campaign at CARIBU at ANL



Decays of 14 isotopes marked by black ovals were studied during the experiments with MTAS at CARIBU.

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Slide courtesy of K. Rykaczewski

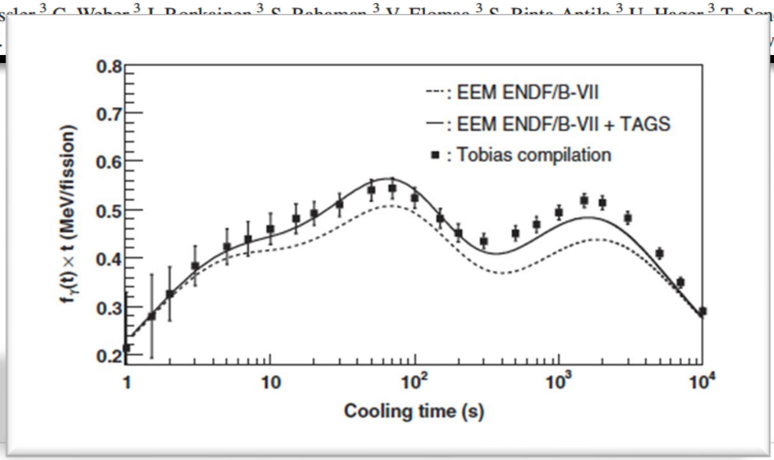
And more TAGS measurements

Valencia/Jyvaskyla collaboration

PRL 105, 202501 (2010) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 12 NOVEMBER 2010

Reactor Decay Heat in ^{239}Pu: Solving the γ Discrepancy in the 4–3000-s Cooling Period

A. Algora,[1,2,*] D. Jordan,[1] J. L. Taín,[1] B. Rubio,[1] J. Agramunt,[1] A. B. Perez-Cerdan,[1] F. Molina,[1] L. Caballero,[1]
E. Nácher,[1] A. Krasznahorkay,[2] M. D. Hunyadi,[2] J. Gulyás,[2] A. Vitéz,[2] M. Csatlós,[2] L. Csige,[2] J. Äysto,[3] H. Penttilä,[3]
I. D. Moore,[3] T. Eronen,[3] A. Jokinen,[3] A. Nieminen,[3] J. Hakala,[3] P. Karvonen,[3] A. Kankainen,[3] A. Saastamoinen,[3]
J. Rissanen,[3] T. Kessler,[3] ... T. Sonoda,[3]
K. Burkard,[4] W. ...



PHYSICAL REVIEW LETTERS 122, 042502 (2019)

Large Impact of the Decay of Niobium Isomers on the Reactor $\bar{\nu}_e$ Summation Calculations

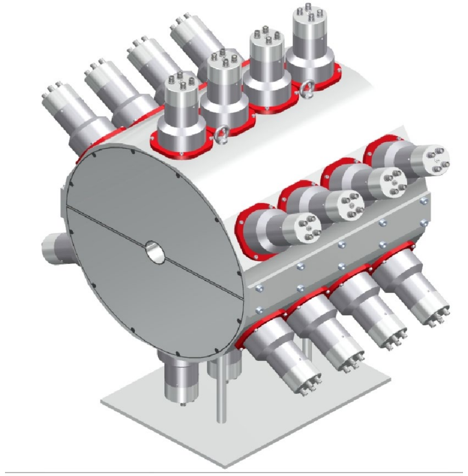
V. Guadilla,[1,*] A. Algora,[1,2,†] J. L. Tain,[1] M. Estienne,[3] M. Fallot,[3] A. A. Sonzogni,[4] J. Agramunt,[1] J. Äystö,[5] J. A. Briz,[3]
A. Cucoanes,[3] T. Eronen,[5] ...
A. Kankaine...
I. Moore...

PHYSICAL REVIEW C 102, 064304 (2020)

Determination of β-decay ground state feeding of nuclei of importance for reactor applications

V. Guadilla,* J. L. Tain, A. Algora,† J. Agramunt, D. Jordan, M. Monserrate, A. Montaner-Pizá,
S. E. A. Orrigo, B. Rubio, and E. Valencia
Instituto de Física Corpuscular, CSIC-Universidad de Valencia, E-46071 Valencia, Spain

MSU/FRIB – SUN detector



https://groups.nscl.msu.edu/SuN/SuN_info.php

PHYSICAL REVIEW C 103, 025810 (2021)

Total absorption spectroscopy of the β decay of ^{101,102}Zr and ^{109}Tc

A. C. Dombos,[1,2,3,*] A. Spyrou,[1,2,3] F. Naqvi,[1,3] S. J. Quinn,[1,2,3] S. N. Liddick,[1,4,3] A. Algora,[5,6] T. Baumann,[1]
J. Brett,[7] B. P. Crider,[1,8] P. A. DeYoung,[7] T. Ginter,[1] J. Gombas,[7] S. Lyons,[1,3,†] T. Marketin,[9] P. Möller,[10,‡]

PHYSICAL REVIEW C 103, 035803 (2021)

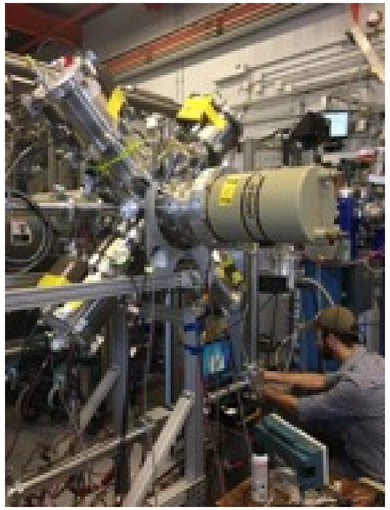
β-decay feeding intensity distributions for ^{103,104m}Nb

J. Gombas,[1,2,*] P. A. DeYoung,[1,†] A. Spyrou,[2,3,4,‡] A. C. Dombos,[2,3,4] A. Algora,[5,6] T. Baumann,[3] B. Crider,[3]
J. Engel,[7] T. Ginter,[3] E. Kwan,[3] S. N. Liddick,[3,4,8] S. Lyons,[3,4,§] F. Naqvi,[3,4] E. M. Ney,[7] J. Pereira,[3,4] C. Prokop,[3,8]

Nuclear Data on Fission Product Decays at CARIBU

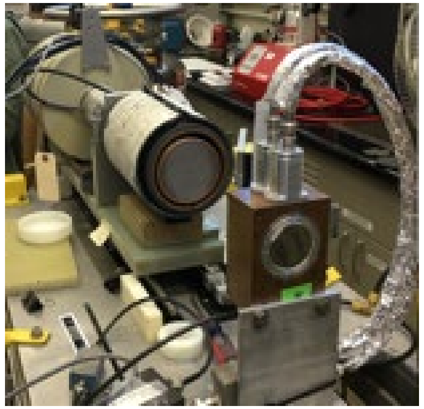
- Fission product selection by compact CARIBU isobar separator
- **CARIBU delivers mass-separated beams of any fission product with $t_{1/2}$ > 25 ms**

LLNL-ANL teams performs various decay experiments:



Beta-particle energy distribution

^{92}Rb beta energy spectrum - neutrino anomaly



Beta-delayed γ-ray branching ratios

Nuclear data for fission yields – impacts nuclear forensics

Fission-product isomer-to-ground state ratios

Understanding of fission dynamics and angular momentum

Kay Kolos

Nick Scielzo

Argonne NATIONAL LABORATORY

Guy Savard

Filip Kondev

A&M

University of California Irvine

Berkeley UNIVERSITY OF CALIFORNIA

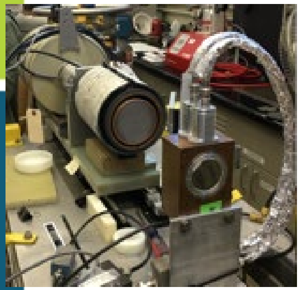
Brookhaven National Laboratory

LLNL-PRES-816784

Slide courtesy of K. Kolos

Fission product decays

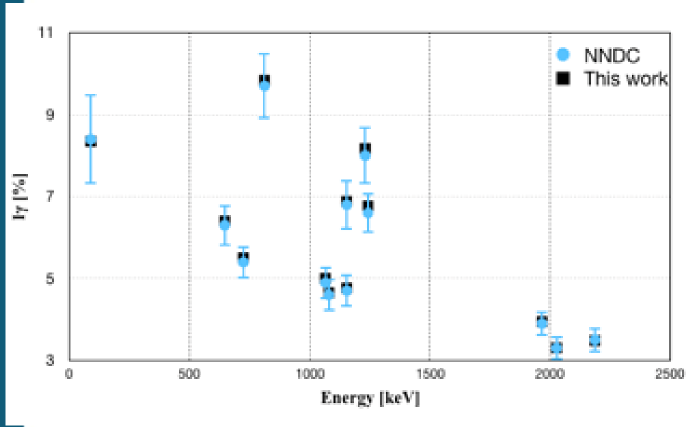
Isomer-to-g.s. measurement on $^{102,102m}Nb$



Precision branching ratio measurements

Radiopure sample harvested at CARIBU

- Ions deposited on thin carbon foil
- Precision gamma-ray measurements at TAMU



→ Comparison of current (NNDC) evaluated data with our results for γ-ray branching ratios

- Isotopes measured so far: ^{95}Zr, ^{147}Nd, ^{144}Ce and ^{156}Eu

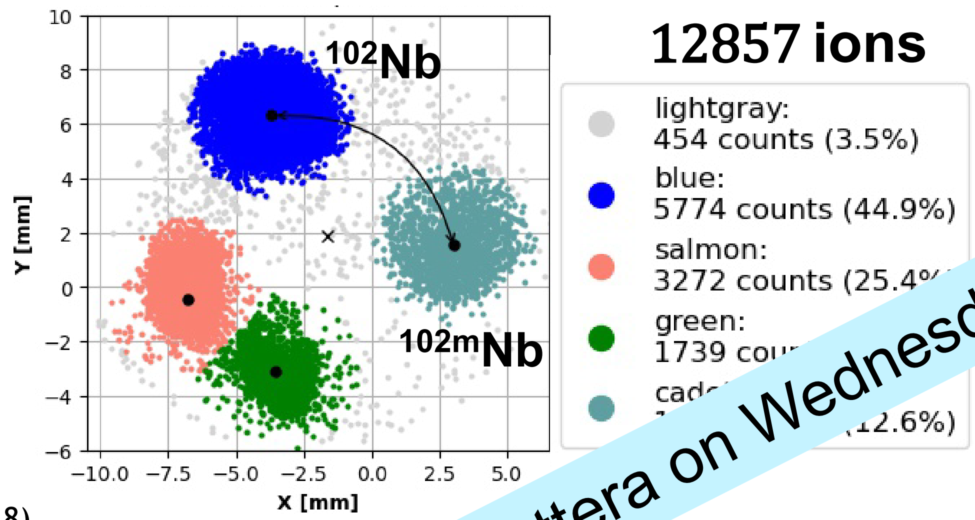
Figures: Most recent results for ^{156}Eu

K. Siegl, K. Kolos, N. D. Scielzo et al. "Beta-decay half-lives of $^{134,134m}Sb$ and their isomeric yield ratio produced by the spontaneous fission of ^{252}Cf" PRC 98, 054307 (2018)

K. Kolos, A. M. Hennessy, N. D. Scielzo et al. "New approach to precisely measure γ-ray intensities for long-lived fission products, with results for the decay of ^{95}Zr" NIM A 1000 165240 (2020)

Demonstrated resolution of >10^7 allowing isomers to be separated

- Ions are trapped
- Excited to a particular radius in trap
- Allowed to rotate freely in trap along circle
- Ejected after a period of time to measure location



Talk by A. Mattera on Wednesday

- 1st isotope of ... campaign
- Due to ... chnical issues at CARIBU, we had to pause
- Preli... ry number : ground : isomer ~ 3.1 (5)
- **More measurements to come!**

Slide courtesy of K. Kolos

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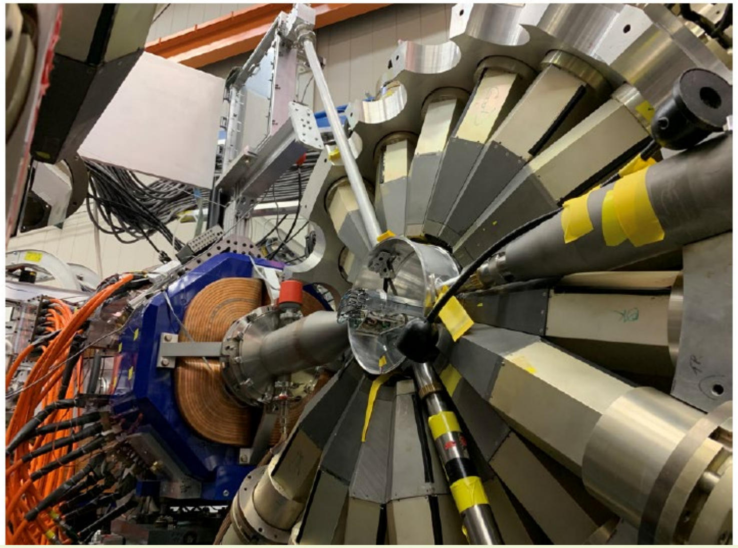
LLNL-PRES-816784

Decay Spectroscopy with Gammasphere

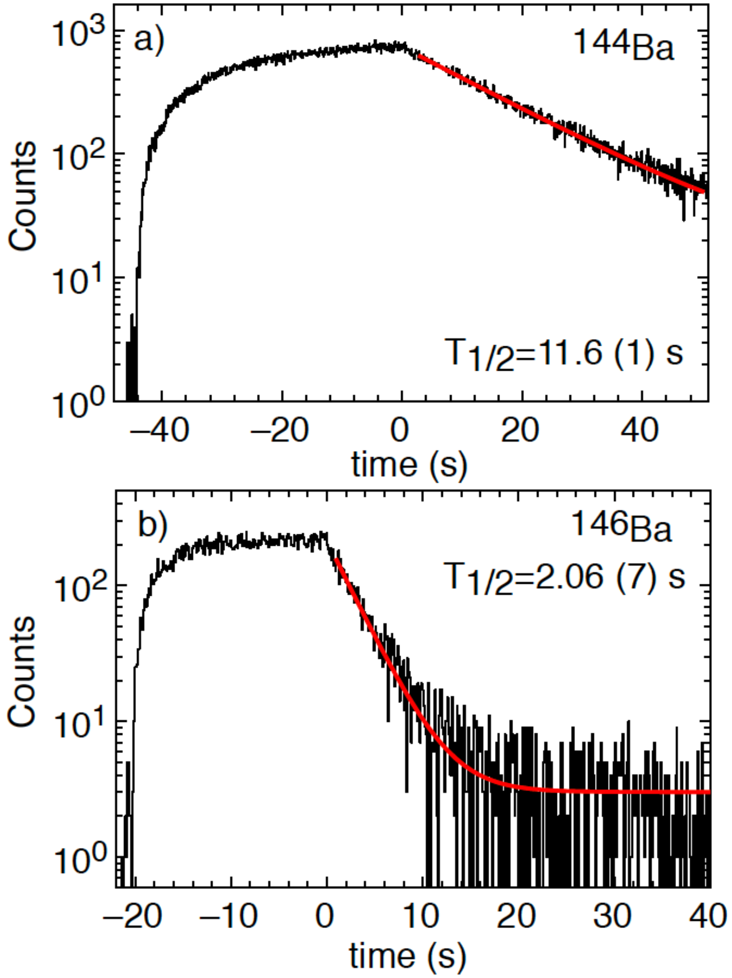
Funded under : Novel approach for Improving Nuclear Data for Antineutrino Spectra Predictions

Two experimental campaigns

- ^{144}La, ^{146g,m}La, ^{144}Ba, ^{146}Ce
- ^{102g,m}Nb, ^{104g,m}Nb, ^{102}Zr, ^{104}Zr, ^{102}Mo, ^{104}Mo



Gammasphere for Beta Decay
New moving tape system + 6 plastic scintillators



F.G. Kondev *et al.*, EPJ Web of Conferences **223**, 01028 (2019)

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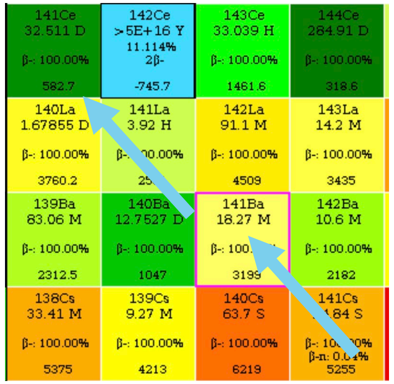
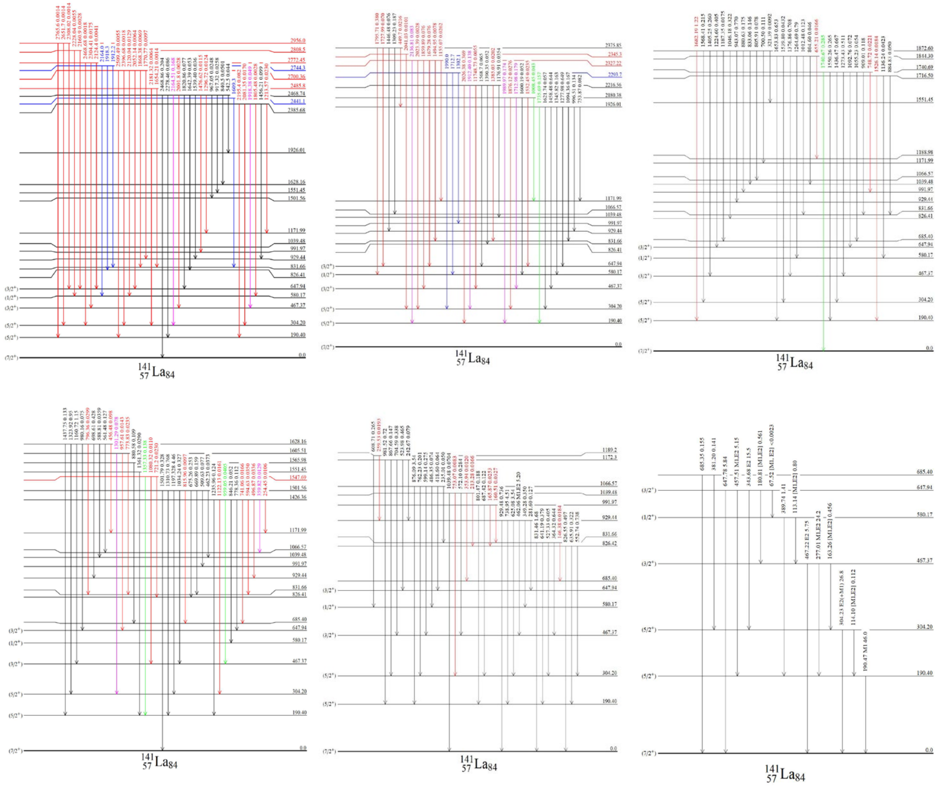
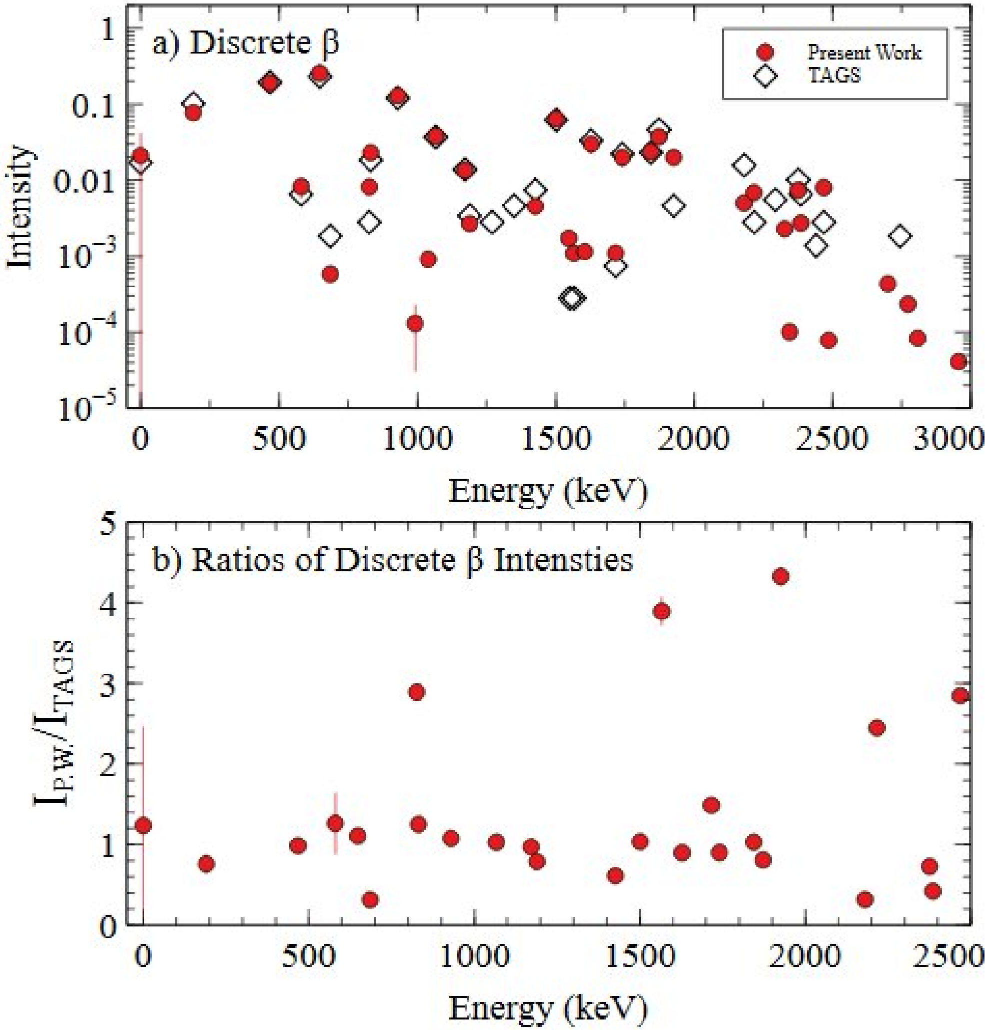
Gammasphere vs. TAGS

Where does Pandemonium take over?



^{141}Ba:
3.2 MeV Q value
High fission yield
Discrete measurement: 1980’s
Greenwood TAGS : 1990’s

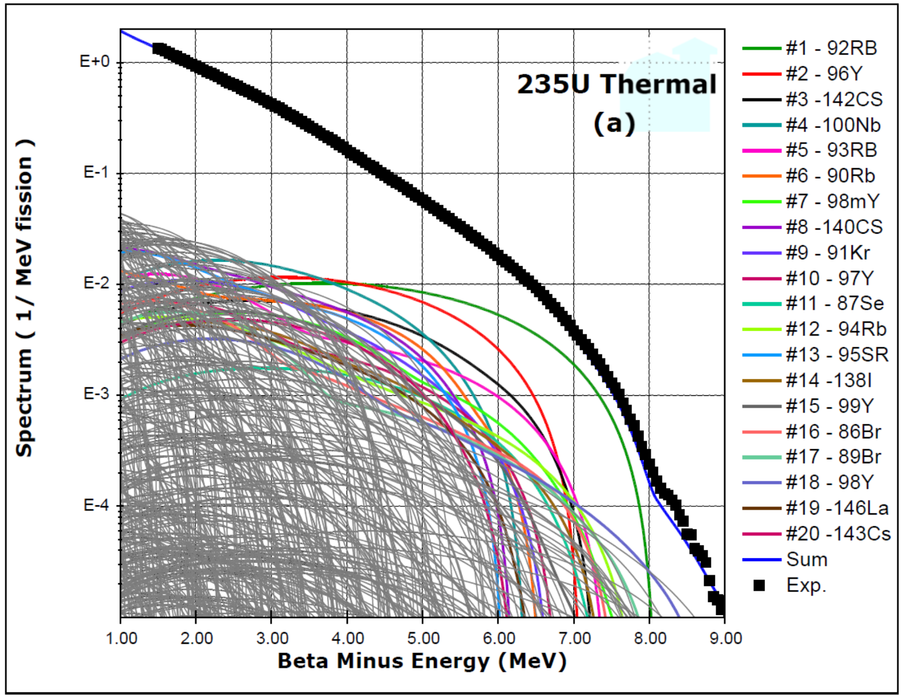




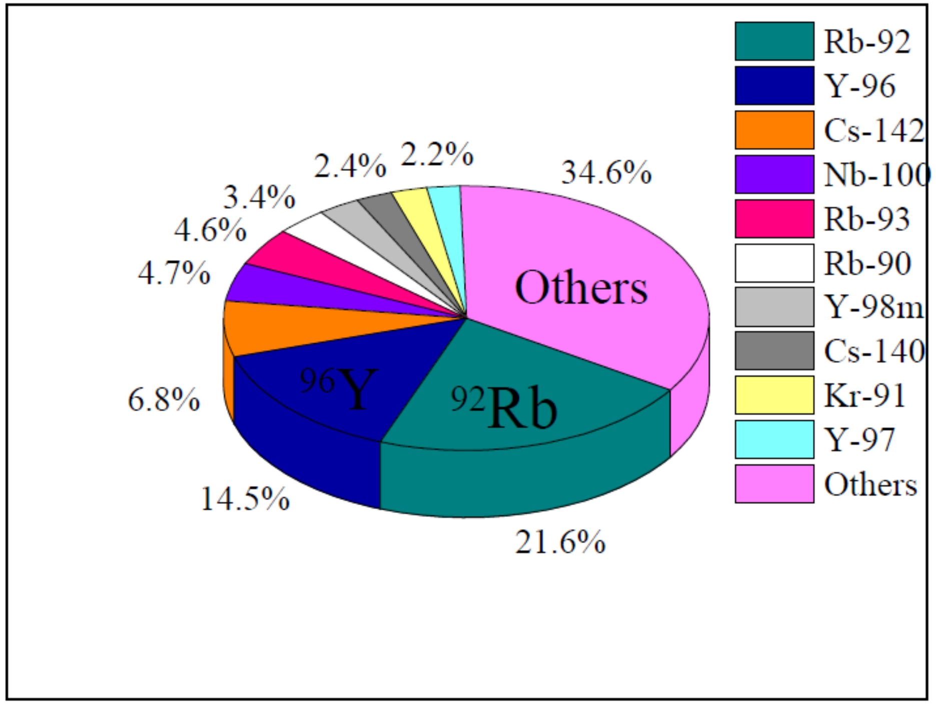
Excellent agreement with TAGS for strong transitions

Javier Rufino
NNDC SULI student going to Notre Dame PhD

All the pieces are coming together



A.A. Sonzogni et al., Phys. Rev. C 91, 011301(R) (2015).



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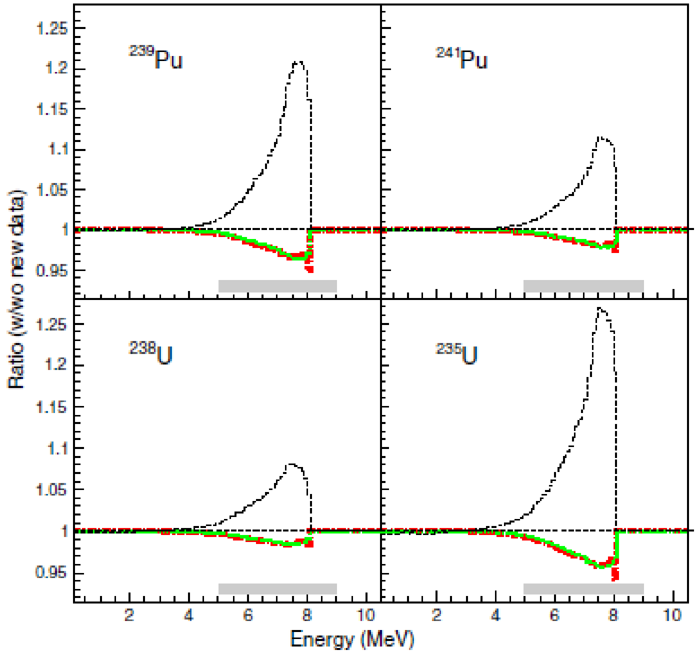
TAGS measurements

PRL 115, 102503 (2015) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2015

Total Absorption Spectroscopy Study of ^{92}Rb Decay: A Major Contributor to Reactor Antineutrino Spectrum Shape

A.-A. Zakari-Issoufou,[1] M. Fallot,[1] A. Porta,[1,*] A. Algora,[2,3] J. L. Tain,[2] E. Valencia,[2] S. Rice,[4] V. M Bui,[1] S. Cormon,[1] M. Estienne,[1] J. Agramunt,[2] J. Äystö,[5] M. Bowry,[4] J. A. Briz,[1] R. Caballero-Folch,[6] D. Cano-Ott,[7] A. Cucoanes,[1] V.-V. Elomaa,[8] T. Eronen,[8] E. Estévez,[2] G. F. Farrelly,[4] A. R. Garcia,[7] W. Gelletly,[2,4] M. B. Gomez-Hornillos,[6] V. Gorlychev,[6] J. Hakala,[8] A. Jokinen,[8] M. D. Jordan,[2] A. Kankainen,[8] P. Karvonen,[8] V. S. Kolhinen,[8] F. G. Kondev,[9] T. Martinez,[7] E. Mendoza,[7] F. Molina,[2,†] I. Moore,[8] A. B. Perez-Cerdán,[2] Zs. Podolyák,[4] H. Penttilä,[8] P. H. Regan,[4,10] M. Reponen,[8,‡] J. Rissanen,[8] B. Rubio,[2] T. Shiba,[1] A. A. Sonzogni,[11] C. Weber,[8,§] and IGISOL collaboration[8]

G.S. Branch 87.2 (25)%

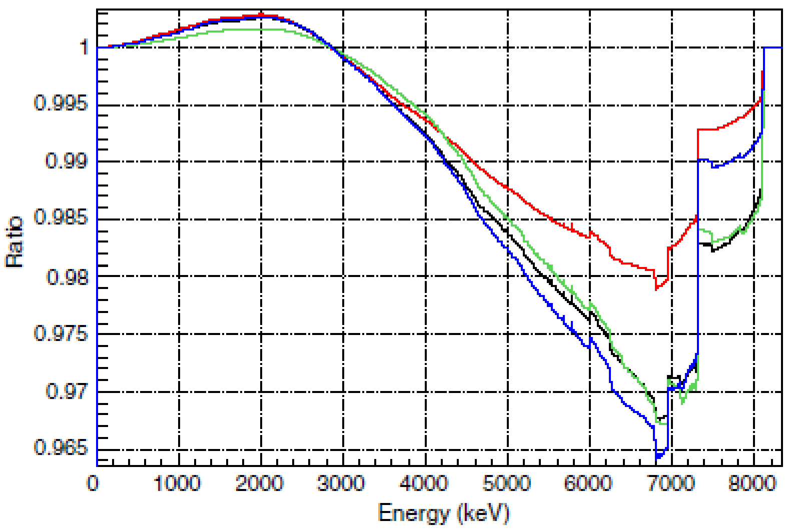


PRL 117, 092501 (2016) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2016

Decays of the Three Top Contributors to the Reactor $\bar{\nu}_e$ High-Energy Spectrum, ^{92}Rb, ^{96gs}Y, and ^{142}Cs, Studied with Total Absorption Spectroscopy

B. C. Rasco,[1,2,3,4,*] M. Wolińska-Cichocka,[5,2,1] A. Fijałkowska,[6,3] K. P. Rykaczewski,[2] M. Karny,[6,2,1] R. K. Grzywacz,[3,2,1] K. C. Goetz,[7,3] C. J. Gross,[2] D. W. Stracener,[2] E. F. Zganjar,[4] J. C. Batchelder,[8,1] J. C. Blackmon,[4] N. T. Brewer,[1,2,3] S. Go,[3] B. Heffron,[3,2] T. King,[3] J. T. Matta,[2] K. Miernik,[6,1] C. D. Nesaraja,[2] S. V. Paulauskas,[3] M. M. Rajabali,[9] E. H. Wang,[10] J. A. Winger,[11] Y. Xiao,[3] and C. J. Zachary[10]

G.S. Branch 91 (3) %



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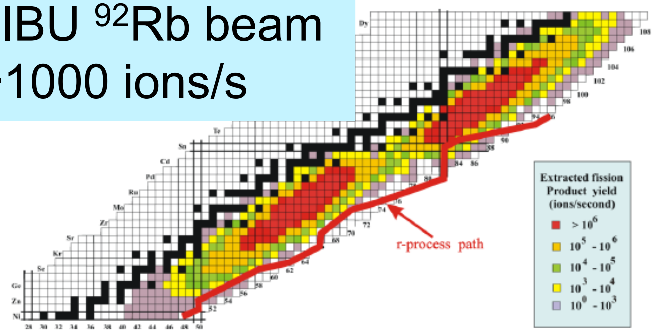
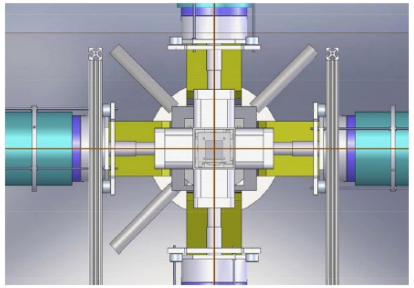
Discrete Spectroscopy

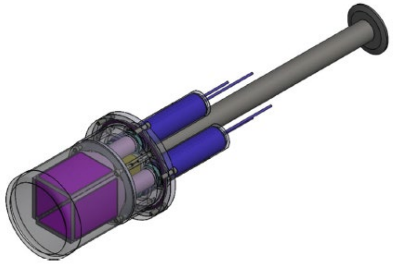
CARIBU ^{92}Rb beam
~1000 ions/s



X- Array+ SATURN – ^{92}Rb

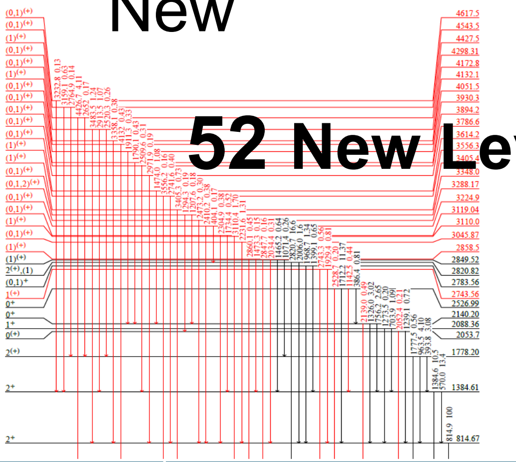


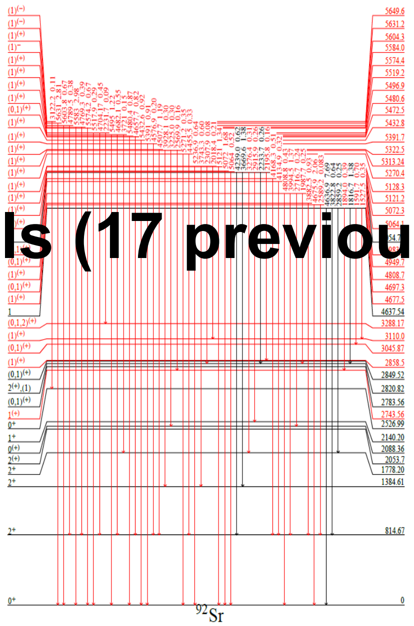
5 HPGe Clover Detectors

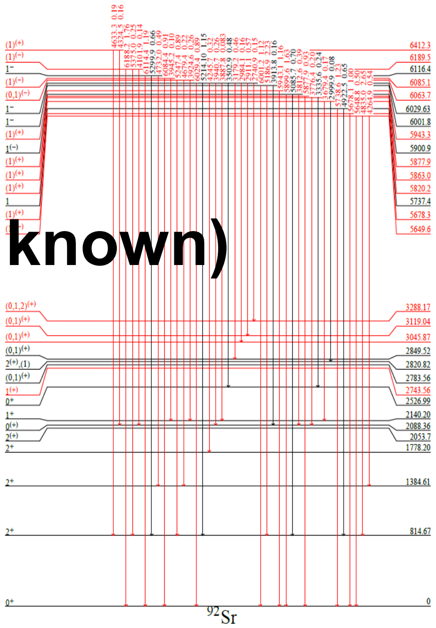


Large plastic scintillator

Confirmed
New

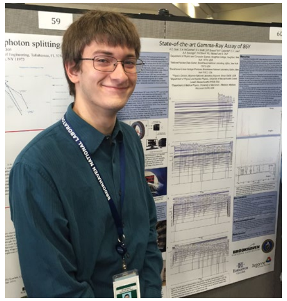






52 New Levels (17 previously known)

	Measurement Type	G.S. Beta feeding
Zakari-Issoufou et al,	TAGS	87.2(25)%
Rasco et al.,	TAGS	91(3)%
Present Work	Beta-HPGe	91(2)%



August Gula
NNDC SULI student now
Notre Dame PhD

Beta spectra for short-lived fission products

Isotopes that emit many high energy νs contribute the most to the signal:

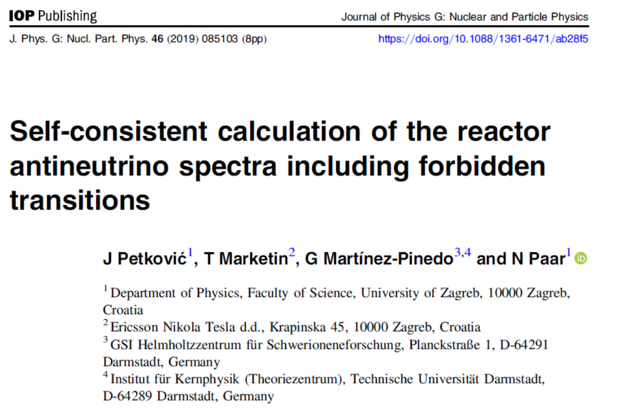
- Large (cumulative) fission yields
- Large Q values
- Large BRs to low-lying states

→ **short-lived isotopes at the mass peak such as ^{92}Rb, ^{96}Y, ^{142}Cs, etc.**

Most of the important transitions are first forbidden… but reactor calculations assume a nearly allowed shape

Recent calculations indicate different first-forbidden operators lead to large distortions from allowed shape

We are making precision investigations of the spectral shape!


IOP Publishing
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J. Phys. G: Nucl. Part. Phys. 46 (2019) 085103 (8pp)
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Self-consistent calculation of the reactor antineutrino spectra including forbidden transitions

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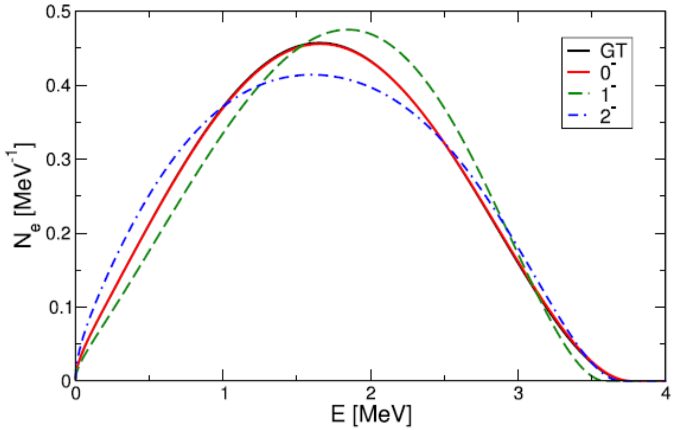
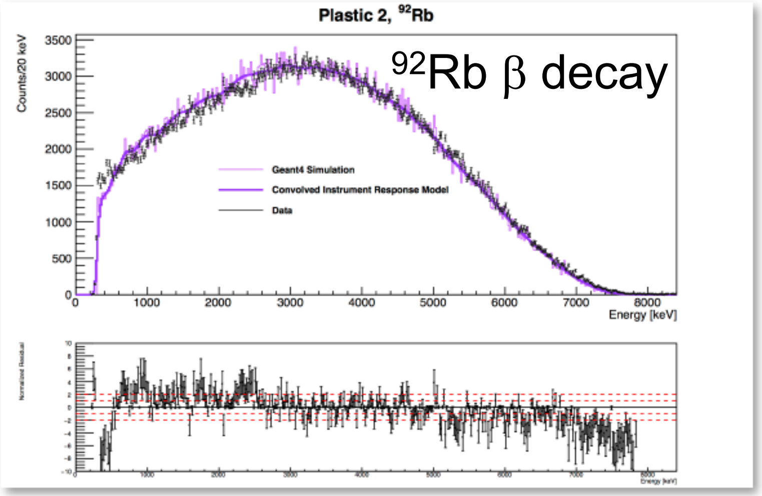
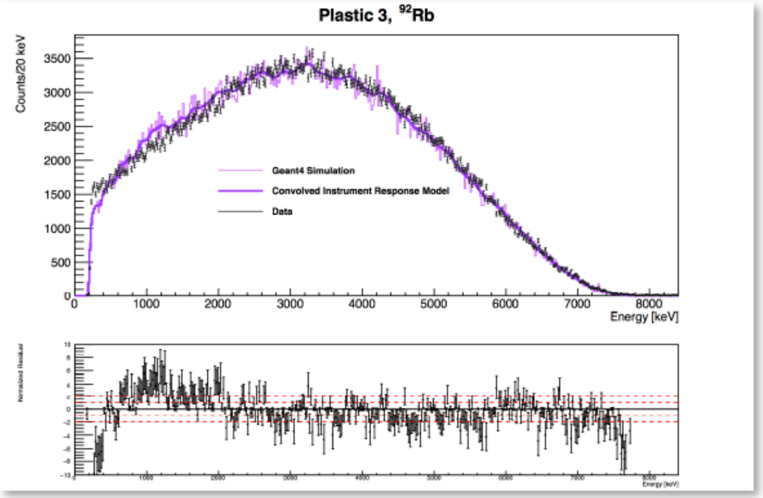


See also: L. Hayen et al., PRC 100, 054323 (

We started with ^{92}Rb – highest-impact decay





Preliminary results indicate 0^- → 0^+ transition has allowed shape

Slide courtesy of K. Kolos

Nuclear Structure repurposed

PHYSICAL REVIEW C **101**, 044311 (2020)

Editors' Suggestion

Shape evolution of neutron-rich ^{106,108,110}Mo isotopes in the triaxial degree of freedom

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PHYSICAL REVIEW C **103**, 024323 (2021)

Ground-state and decay properties of neutron-rich ^{106}Nb

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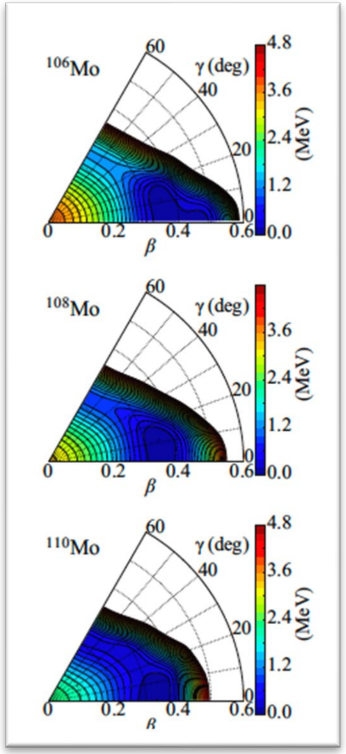

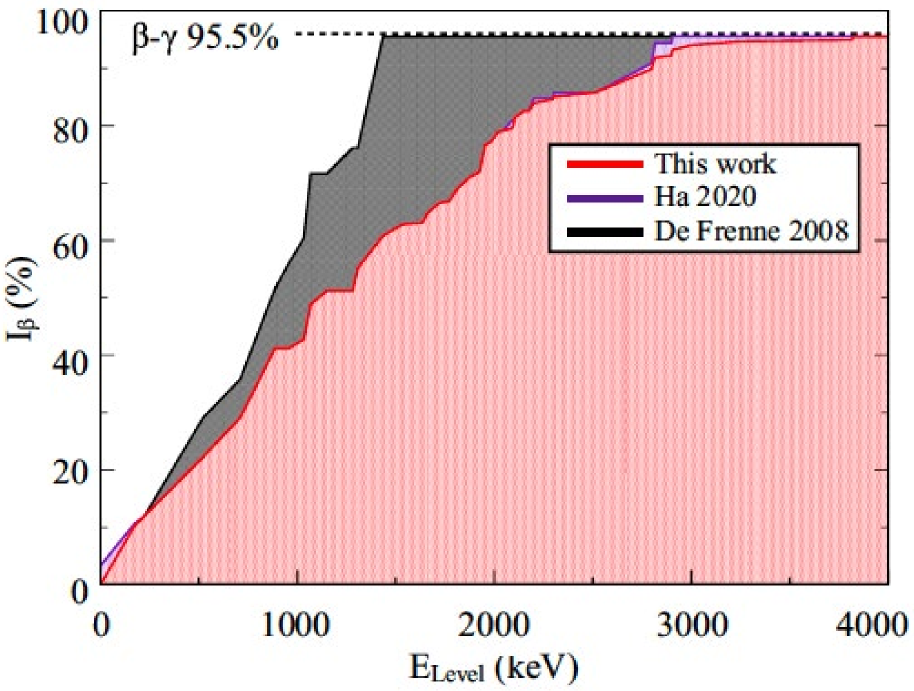

High Priority List for Reactor Antineutrinos

P. Dimitriou, A.L. Nichols, IAEA report INDC(NDS)-0676, IAEA (Austria, Vienna, 2015)

Kr-91 ☀	Sr-97 ☀	Nb-98 ☀	I-138 ☀
Rb-88 ☀	Y-94 ☀	Nb-100 ☾	Xe-139 ☀
Rb-90 ☀ ☾	Y-95 ☀	Nb-101	Xe-141
Rb-92 ☀ ☾	Y-96 ☀ ☾	Nb-102 ☾ ◯	Cs-139 ☀
Rb-93 ☀ ☾	Y-97/97m ☀	Nb-104m ⚡ ☾ ◯	Cs-140 ☀ ☾
Rb-94 ☀ ☾	Y-98m ☀ ☾	Te-135 ☀	Cs-141 ☀
Sr-95 ☀	Y-99	I-136/136m ☀	Cs-142 ☀ ☾
Sr-96 ☀	Zr-101 ⚡	I-137 ☀ ☾	La-146 ☀ ◯

☀ ORNL -MTAS

☾ Valencia/Jyvaskyla TAGS

⚡ MSU - SUN

◯ ANL - Gammasphere

Summary and Conclusions

- 100’s of experiments on data decay relevant to reactor antineutrinos have been performed in the last 10 years.

- For beta intensities – we are approaching multiple measurements from multiple groups for nearly all “high-priority” isotopes.

- Next, hopefully, will come similar campaigns of beta shape measurements.

- And even more data from future RIB facilities – fully documented so can be utilized for reactor antineutrino calculations