Beta-strength, decay heat and anti-neutrino energy spectra from total absorption spectroscopy

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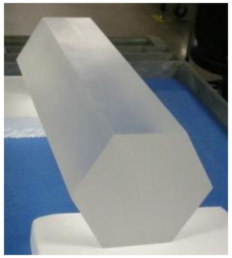
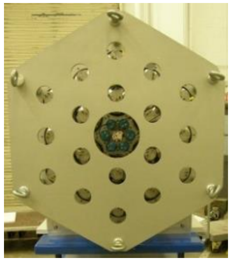
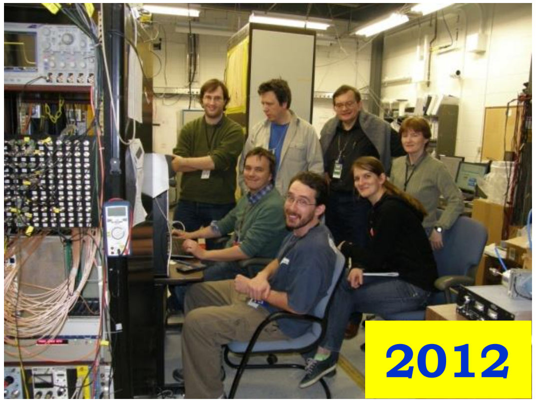
M.Karny, ***R.Grzywacz***, ***C.J. Gross, B.C. Rasco, E.Zganjar, J.J ohnson***,
K.C. Goetz, *K.Miernik, D. Miller, M. Madurga, S. Paulauskas, S.Padgett,*
D. Stracener, C. Jost, R. Goans, L. Cartegni, M. Al-Shudifat, E. Spejewski,

ARRA $$$ (Oct. 2009)







2012

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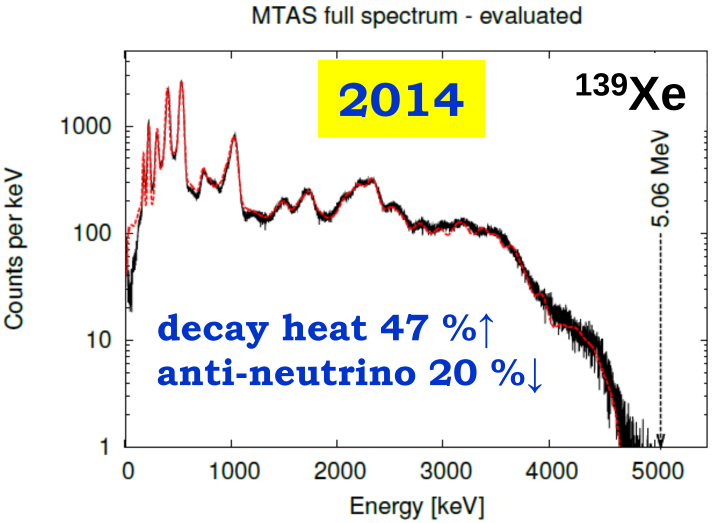

decay heat 47 %↑
anti-neutrino 20 %↓

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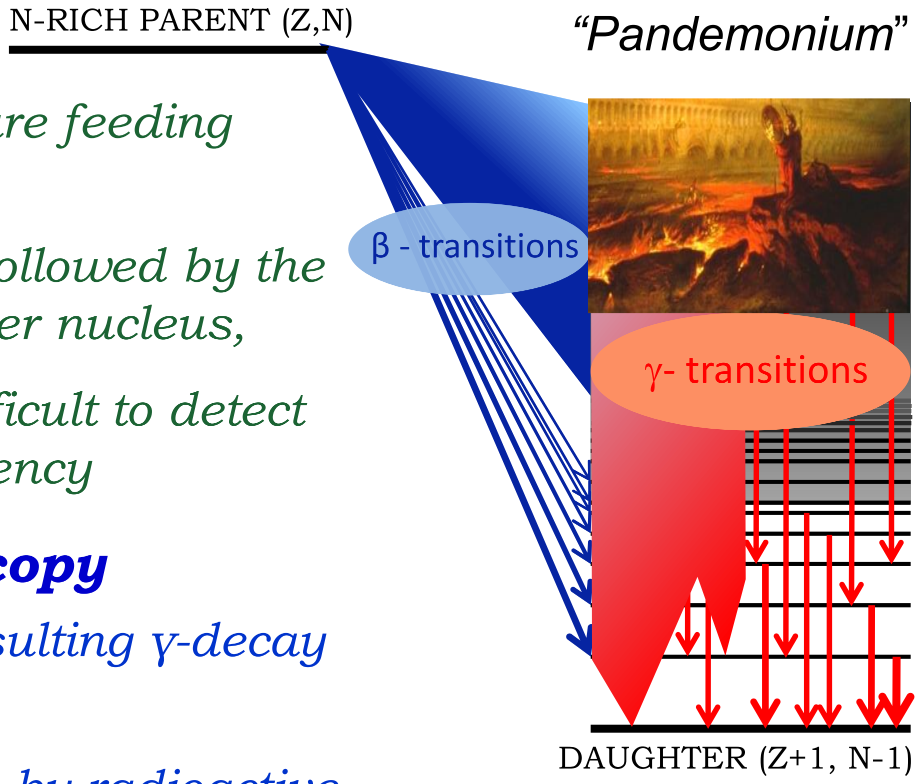
Complex β-decays

∗ β-transitions (mostly Gamow-Teller) are feeding highly excited states,

∗ these many, weak β-transitions are followed by the cascades of γ-transitions in the daughter nucleus,

∗ these weak γ-transitions are very difficult to detect with radiation detectors with low efficiency



The true picture of the neutron-rich parent nucleus (Z,N), with many weak β-transitions and following low intensity γ-transitions.

Total absorption γ-spectroscopy

∗ to determine ***true β-feeding*** *and resulting γ-decay patterns (nuclear structure),*

∗ to determine ***"decay heat"*** *released by radioactive nuclei produced during a nuclear fuel cycle*

∗ to determine ***anti-neutrino spectrum*** *associated with β-decay of fission products,* $Y \rightarrow X^* + e^- + \bar{\nu}$

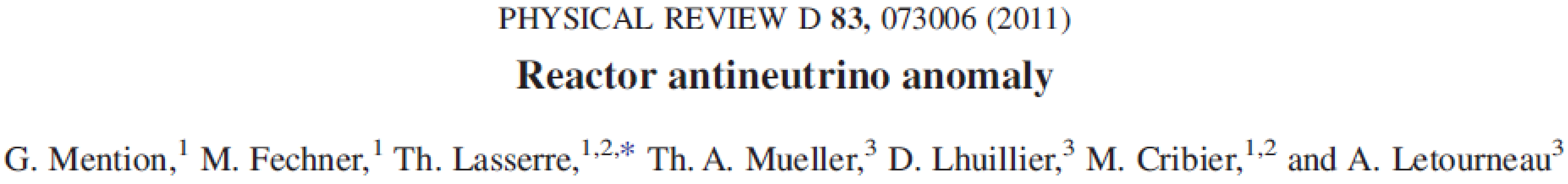
J. Hardy et al., Physics Letters 71 B, 307, 1977

A. Algora et al., PRL 105, 202501, 2010

K. P. Rykaczewski, Viewpoint in Physics 3, 94, 2010

K. P. Rykaczewski, 2013 McGraw-Hill Yearbook of Science and Technology, p.92

Reactor antineutrino anomaly



PHYSICAL REVIEW D 83, 073006 (2011)

Reactor antineutrino anomaly

G. Mention,[1] M. Fechner,[1] Th. Lasserre,[1,2,*] Th. A. Mueller,[3] D. Lhuillier,[3] M. Cribier,[1,2] and A. Letourneau[3]

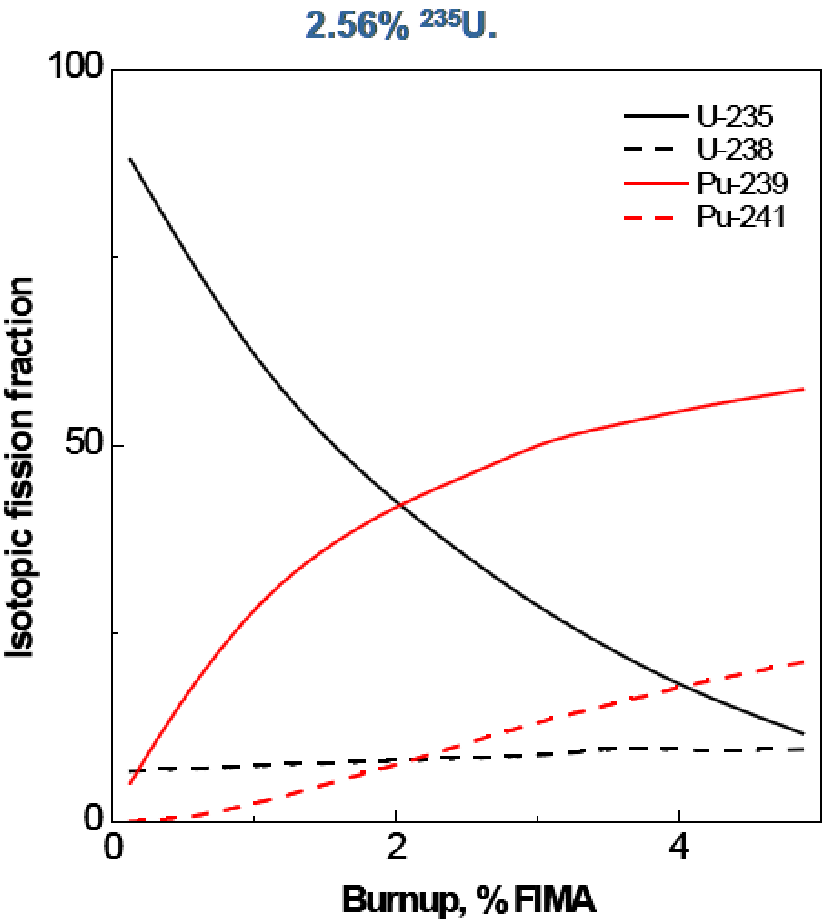
Deficit of detected anti-neutrinos vs expected counting rate at the level of 0.943(23) obtained after re-evaluation of 1980's integral β-energy spectra nicknamed "Schreckenbach data" for n + ^{235}U, ^{239,241}Pu reactions

More general – the differences between the expected and measured ***$\bar{\nu}$-spectrum***

Antineutrino energy spectra

Two basic pieces of information are needed to evaluate the energy spectrum of anti-neutrinos next to nuclear reactor:

1. Nuclear fuel content in a function of time (burn-up phase)
2. Knowledge of β-spectra (anti-ν spectra) in fission products



from Ian Gauld, 2014
Nuclear Reactor Science (ORNL)

Ian Gauld is a keeper of
Oak Ridge Isotope Generator code
(ORIGEN) code, which is
a part of SCALE package

β-spectra in fission products

Two methods:

1.“*Ab initio*” (or summation calculations)

→ use decay data base ENSDF and add up all beta-decays of fission products generating anti-neutrinos (fission yields are needed for reactor inventory nuclei)

2. Use integral experimental data on β-decays

→ “Schreckenbach data” from 1980’s (cumulative β-spectra for n+ ^{235}U, ^{239}Pu, ^{241}Pu)

e.g., K. Schreckenbach, G. Colvin, W. Gelletly, F. Von Feilitzsch, Phys. Lett. B 160, 325 (1985)

and recent n+ ^{238}U cumulative β-spectra: Haag,.., Schreckenbach, PRL 112,122501, 2014

(and A. Hayes et al., PRL 112, 202501 (2014) for discussion of GT/FF in β-spectra de-convolution)

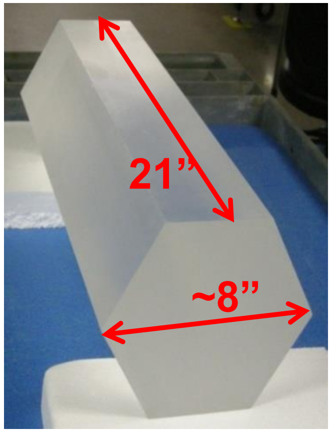
Our approach:

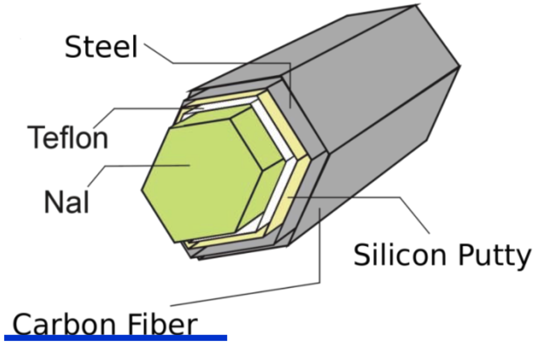
→ use MTAS verified/improved (true) β-decay data for summation calculations

First step – let’s check the effect of our MTAS results on fission products
with respect to the number of interacting anti-neutrinos

***M**odular **T**otal **A**bsorption **S**pectrometer (**MTAS**)*

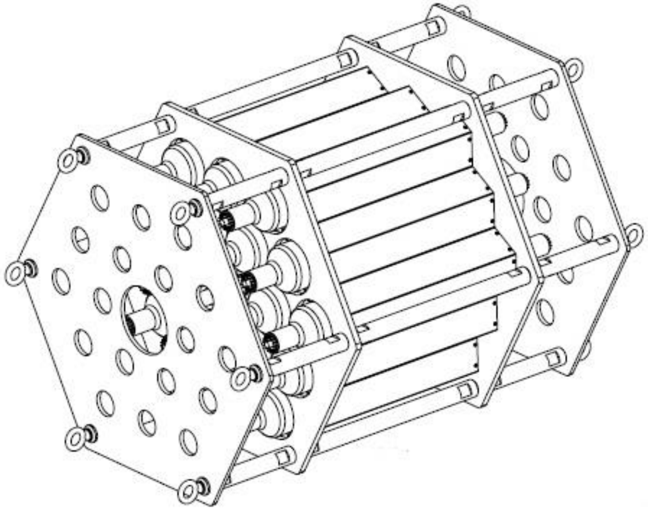
- ***19 NaI(Tl)** hexagonal shape blocks, each **21" long** and **8" maximum diameter (SGC, Hiram, OH)***





R&D for carbon fiber housing development

- *the weight of a single detector is **~120 pounds**, the total weight of the detector array is **~2 200 pounds***



January 2011

- *MTAS is mounted at the adjustable cart to facilitate measurements at different beam line height (47" – 53")*

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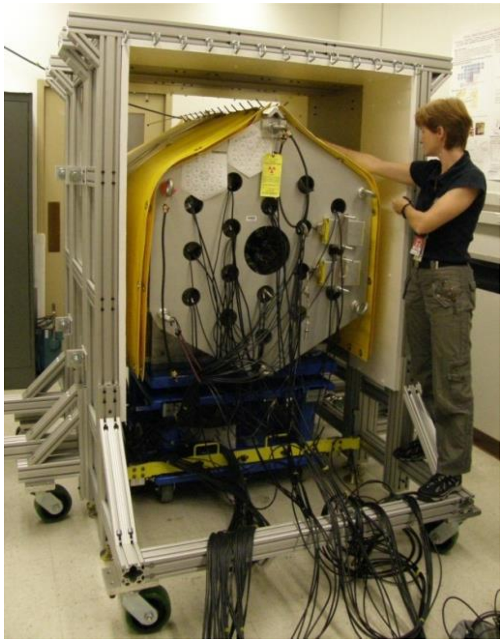
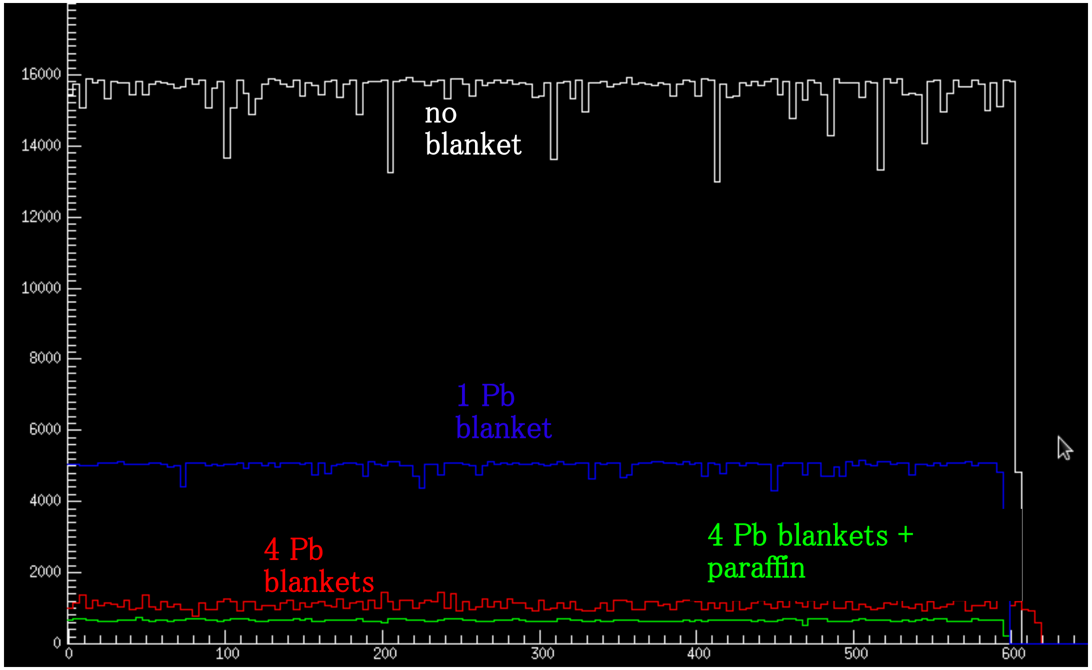
MTAS shielding (background reduction)

*The weight of (mostly Pb) shielding for this setup is **~12 000 pounds***
(with about 1" layer of solid lead and ~0.75" lead in lead wool blankets)



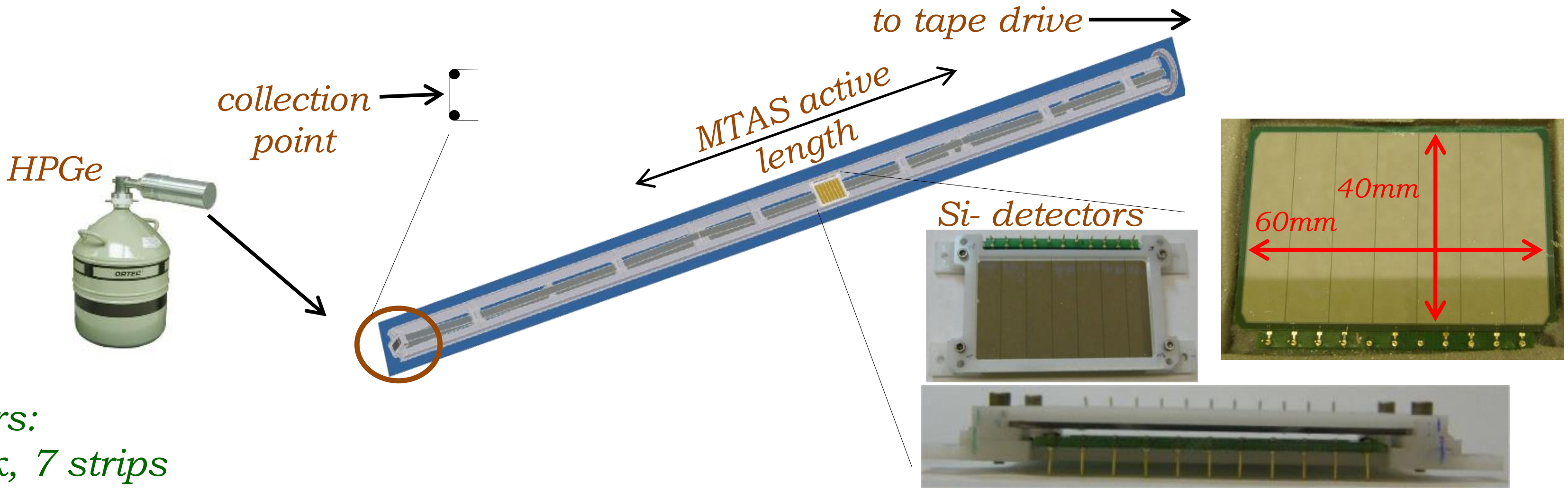


Rate for MTAS (most exposed single module)
- *without shielding **~16000 Hz** (test stand near a lab with some activated materials)*
- *with four Pb blankets and paraffin **~600 Hz***
- ***with "Pb house", Pb blankets and paraffin shielding ~160 Hz***

(now two SWX-227A layers instead of paraffin bricks)

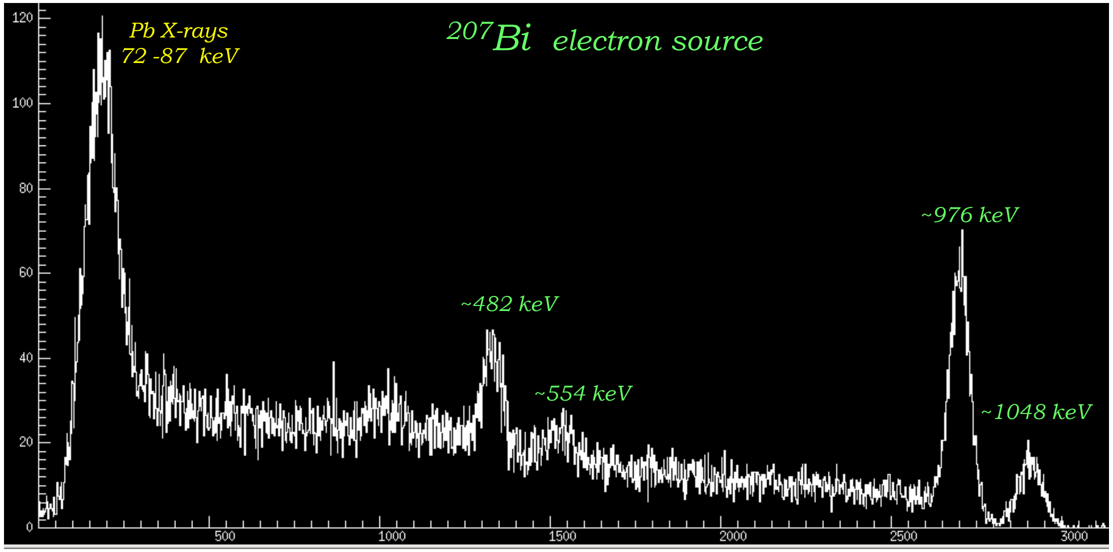
AUXILIARY DETECTORS and MOVING TAPE DRIVE

∗ *HPGe detector for sample composition monitoring,*



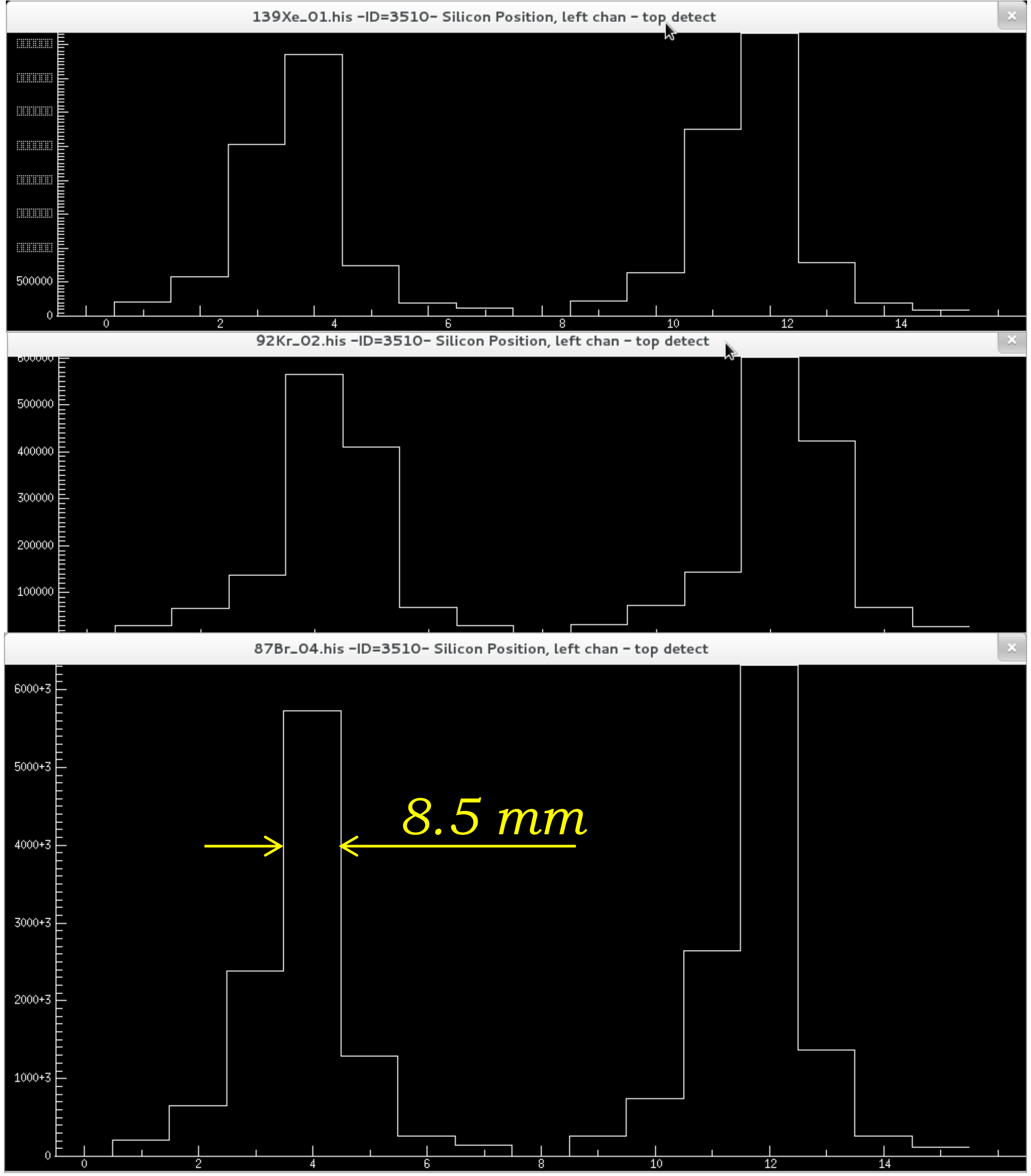
∗ *Si-detectors:*

- *1 mm thick, 7 strips*
- *surrounding the tape-collected sample (tape by Ed Zganjar, LSU)*
- *the solid angle covered by two Si-detectors - around 95% of 4π*
- *the low energy threshold for electrons < 50 keV*
- *the energy resolution for 976 keV electrons - 2.5 % (~25 keV)*



Beta energy loss spectra measured with segmented Si-detectors help to center radioactive samples in the middle of MTAS

top SSD *bottom SSD*



MTAS γ-efficiency verified using calibrated ^{137}Cs, ^{54}Mn and ^{65}Zn single γ-line sources

Simulations for:

— *"empty" MTAS*

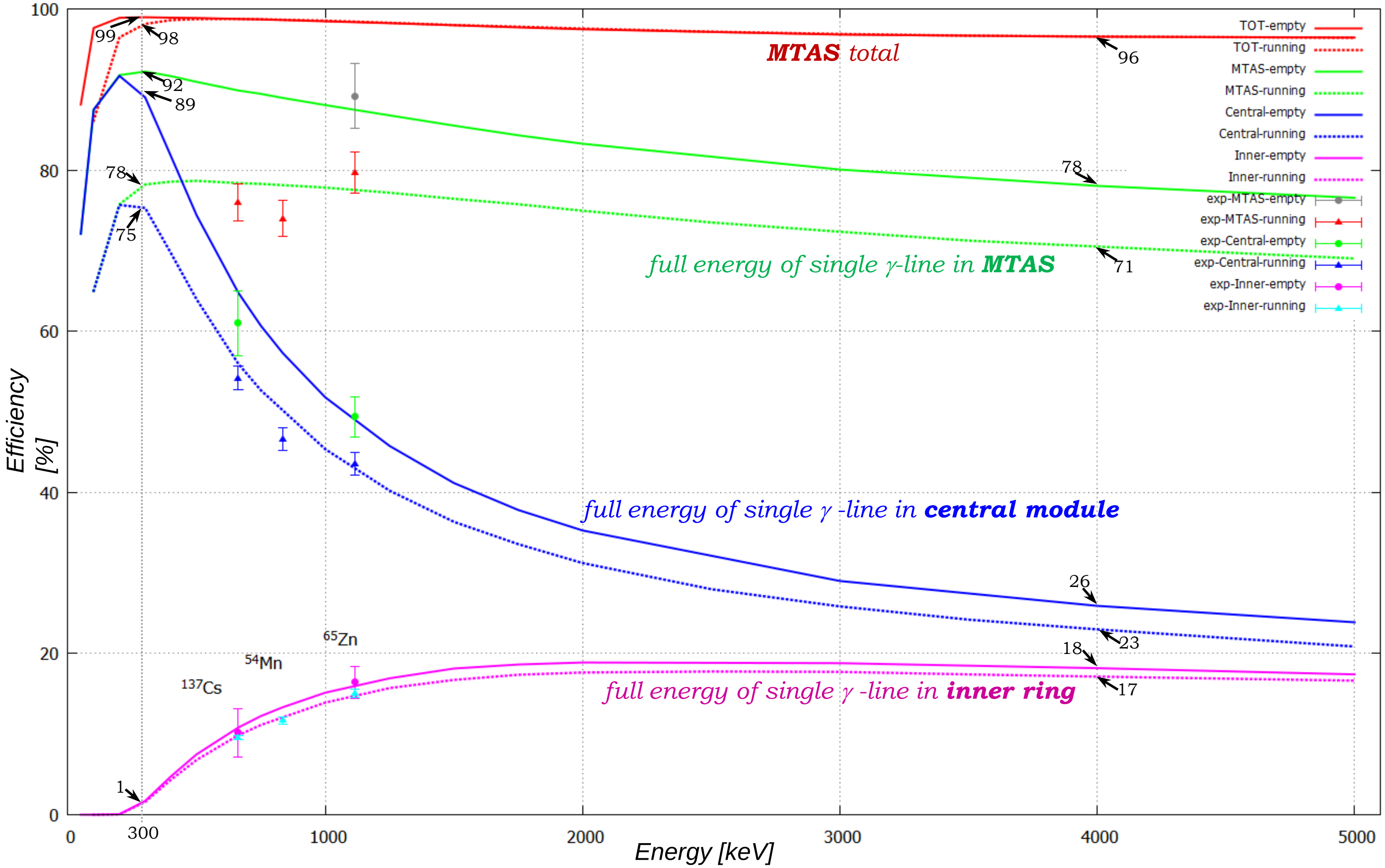
…… *"running" MTAS with beam pipe, Si-detectors and tape drive inside*

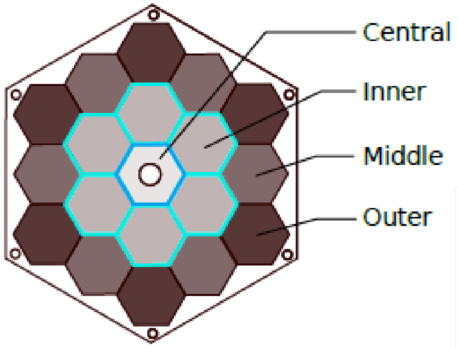
Experimental points:

^{137}Cs 662 keV

^{54}Mn 835 keV

^{65}Zn 1116 keV





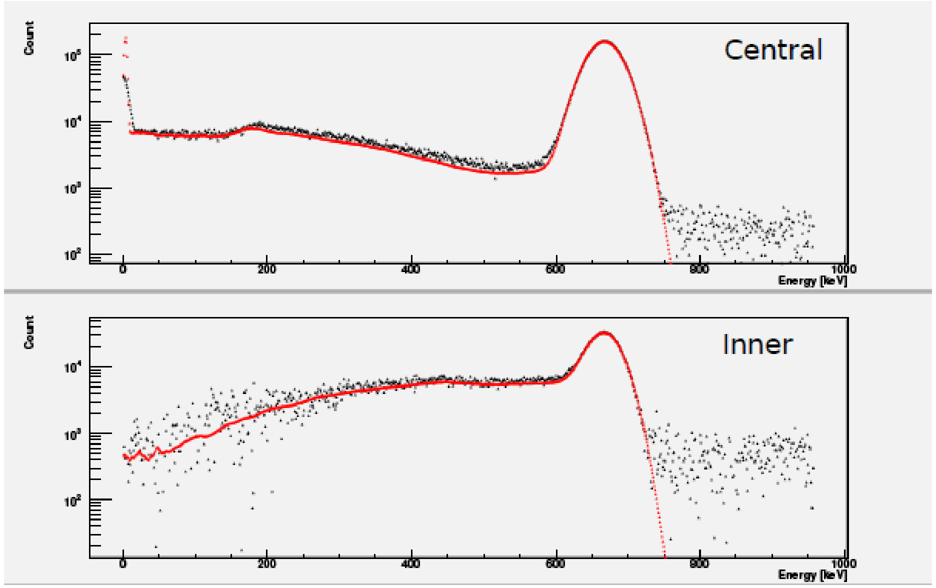
"simulations team"

A. Fijałkowska, B.C. Rasco, M. Karny

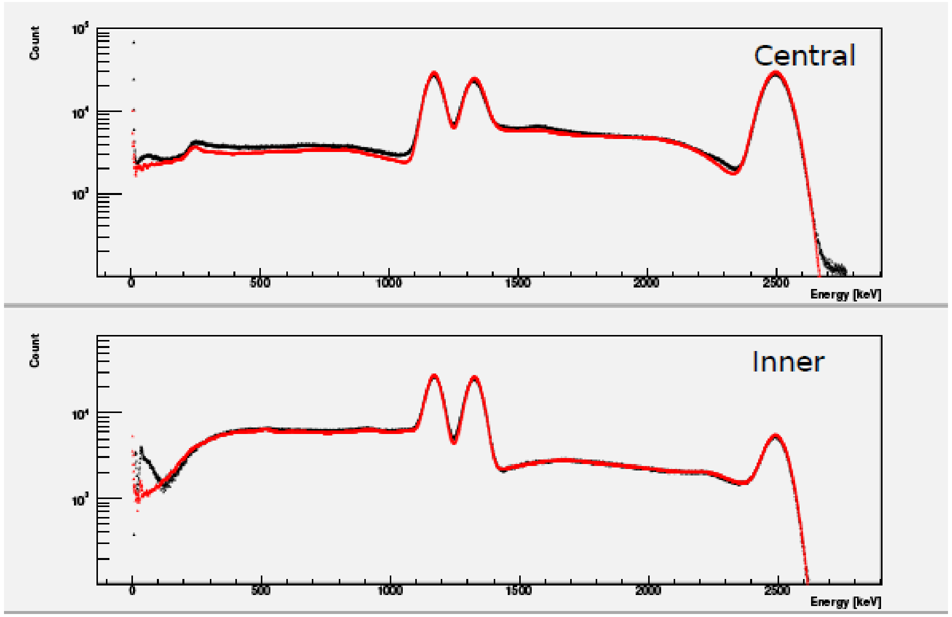
Oak Ridge National Laboratory

Measurements vs response function simulations

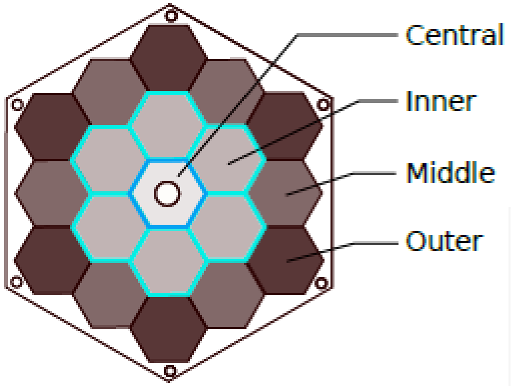
^{137}Cs



^{60}Co



black points – exp
red line - simulations



Aleksandra Fijałkowska
Charlie Rasco
Marek Karny

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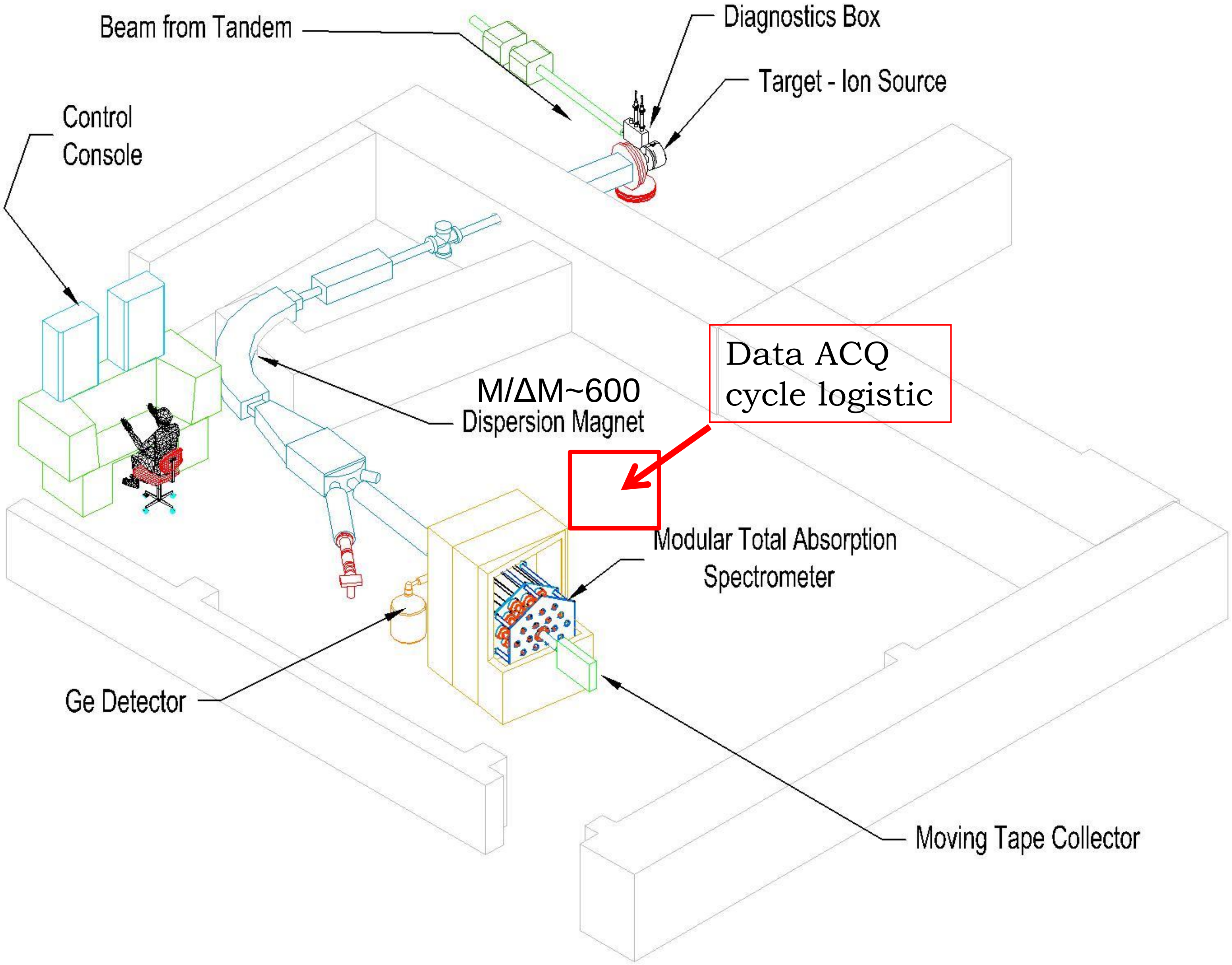
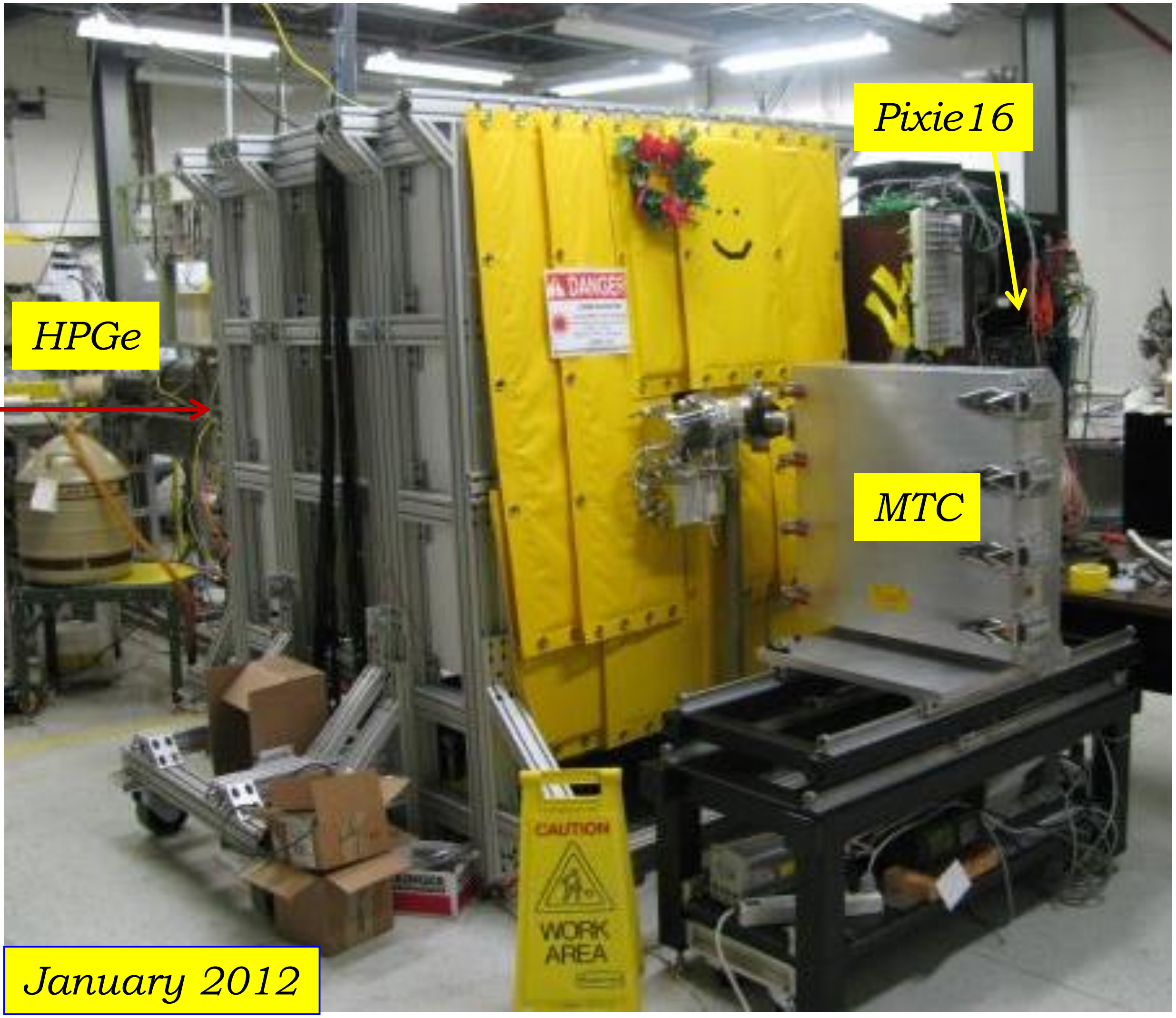


Data ACQ cycle logistic

MTAS on-line to the HRIBF mass separator OLTF (On-line Test Facility = ISOL, $m/\Delta m \sim 600$)

Ge detector for monitoring collection point



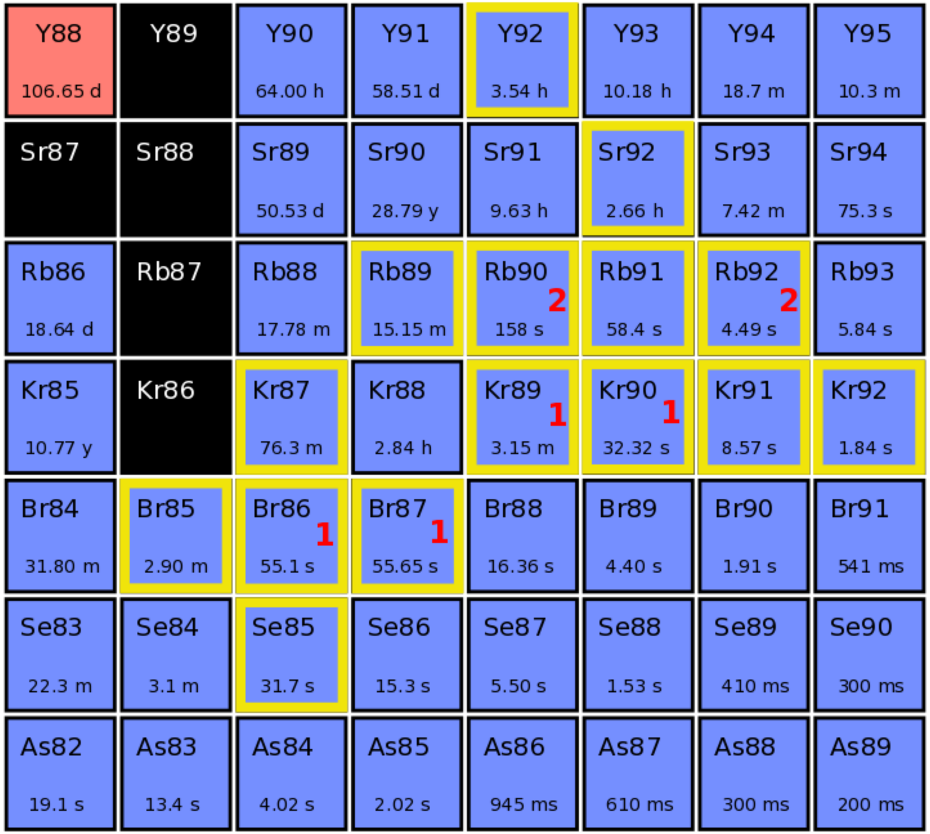
Data acquisition based on digital pulse processing and using XIA Pixie16 modules (100 MHz)

MTAS at the HRIBF, January 2012
studies at mass A ~ 90 and 140 regions with OLTF and Tandem

The decays of fission products produced at the HRIBF on-line mass separator (OLTF) using Tandem beam and studied with new Modular Total Absorption Spectrometer (MTAS) are marked by yellow and red squares.

The label“1” indicates the highest priority for decay heat measurement established by the Nuclear Energy Agency evaluation in 2007.

La 137 60 ky	La 138 0.09	La 139 99.91	La 140 1.68 d	La 141 3.92 h	La 142 92.6 m	La 143 14.3 m
Ba 136 7.85	Ba 137 11.23	Ba 138 71.7	Ba 139 83.06 m	Ba 140 12.75 d	Ba 141 18.27 m	Ba 142 10.7 m
Cs 135 2.3 My	Cs 136 13.16 d	Cs 137 30.17 y	Cs 138 32.2 m	Cs 139 9.27 m	Cs 140 63.7 s	Cs 141 24.94 s
Xe 134 10.44	Xe 135 9.10 h	Xe 136 8.87	Xe 137 1 3.83 m	Xe 138 14.08 m	Xe 139 1 39.68 s	Xe 140 13.6 s
I 133 20.8 h	I 134 52 m	I 135 6.61 h	I 136 84 s	I 137 1 24.2 s	I 138 6.4 s	I 139 2.29 s
Te 132 3.2 d	Te 133 12.5 m	Te 134 41.8 m	Te 135 18.6 s	Te 136 17.5 s	Te 137 2.49 s	Te 138 1.4 s



Y88 106.65 d	Y89	Y90 64.00 h	Y91 58.51 d	Y92 3.54 h	Y93 10.18 h	Y94 18.7 m	Y95 10.3 m
Sr87	Sr88	Sr89 50.53 d	Sr90 28.79 y	Sr91 9.63 h	Sr92 2.66 h	Sr93 7.42 m	Sr94 75.3 s
Rb86 18.64 d	Rb87	Rb88 17.78 m	Rb89 15.15 m	Rb90 2 158 s	Rb91 58.4 s	Rb92 2 4.49 s	Rb93 5.84 s
Kr85 10.77 y	Kr86	Kr87 76.3 m	Kr88 2.84 h	Kr89 1 3.15 m	Kr90 1 32.32 s	Kr91 8.57 s	Kr92 1.84 s
Br84 31.80 m	Br85 2.90 m	Br86 1 55.1 s	Br87 1 55.65 s	Br88 16.36 s	Br89 4.40 s	Br90 1.91 s	Br91 541 ms
Se83 22.3 m	Se84 3.1 m	Se85 31.7 s	Se86 15.3 s	Se87 5.50 s	Se88 1.53 s	Se89 410 ms	Se90 300 ms
As82 19.1 s	As83 13.4 s	As84 4.02 s	As85 2.02 s	As86 945 ms	As87 610 ms	As88 300 ms	As89 200 ms

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International Evaluation Co-operation

Volume 25

ASSESSMENT OF FISSION PRODUCT DECAY DATA FOR DECAY HEAT CALCULATIONS

A report by the Working Party
on International Evaluation Co-operation
of the NEA Nuclear Science Committee

Co-ordinator
T. Yoshida
Musashi Institute of Technology
JAPAN

Monitor
A.L. Nichols
International Atomic Energy Agency
AUSTRIA

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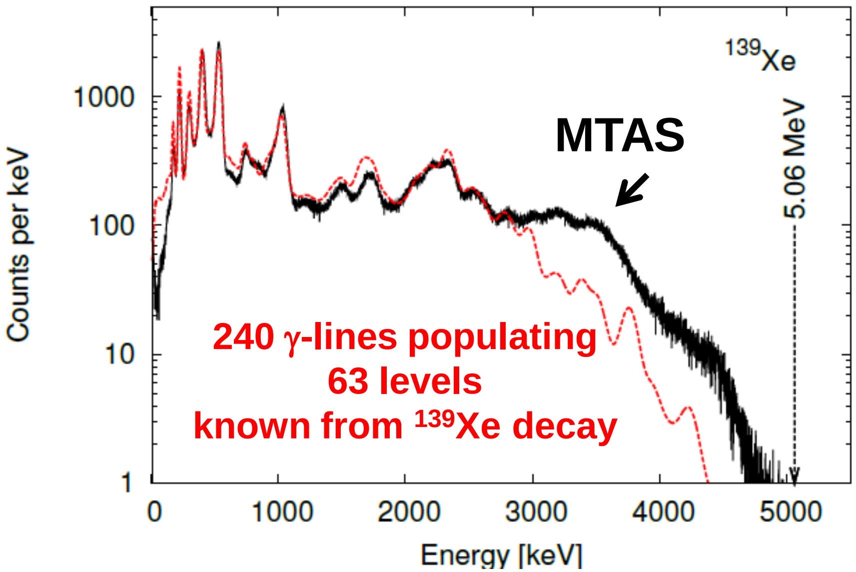
NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Priority "1" $^{139}Xe \rightarrow ^{139}Cs$ decay ($T_{1/2}$= 39.7 s)

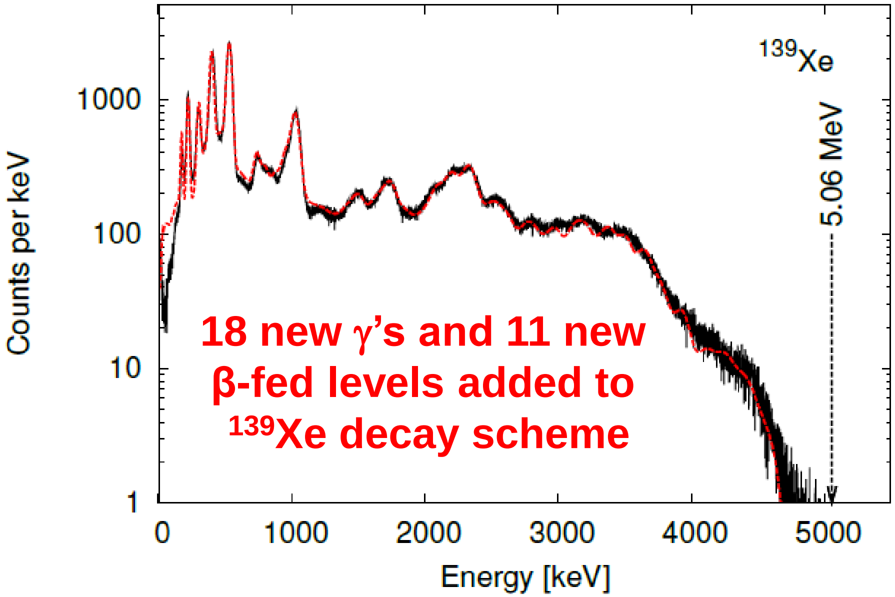
cumulative yield of ^{139}Xe in n_{th} + ^{235}U fission is about 5%

MTAS full spectrum ENSDF decay scheme



240 γ-lines populating
63 levels
known from ^{139}Xe decay

MTAS full spectrum - evaluated



18 new γ's and 11 new
β-fed levels added to
^{139}Xe decay scheme

MTAS result:

average **gamma** energy release per ^{139}Xe decay increased from 935 keV to 1370 keV

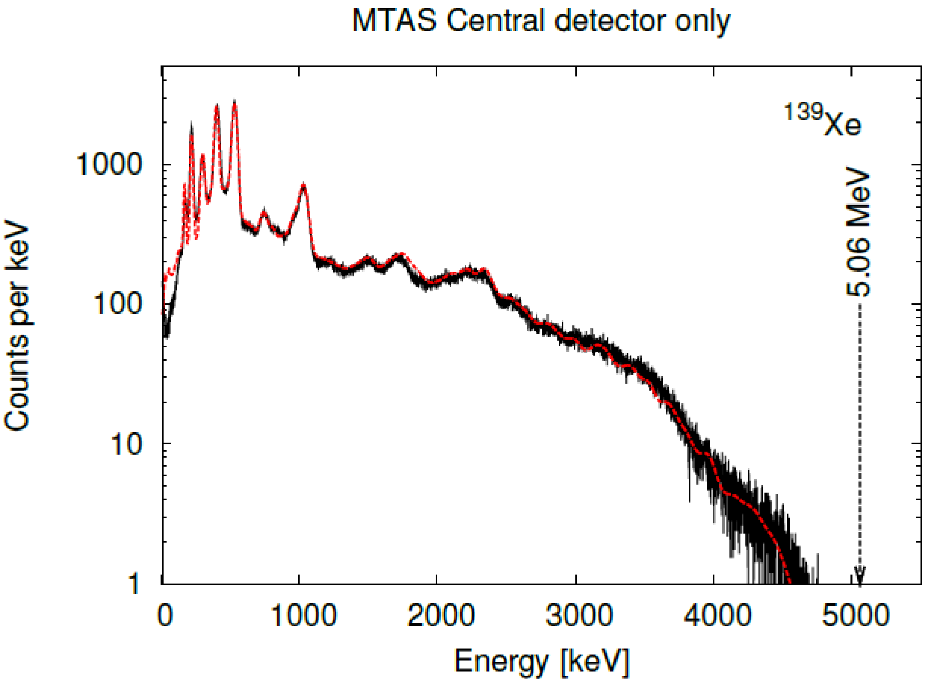
46.5 % increase

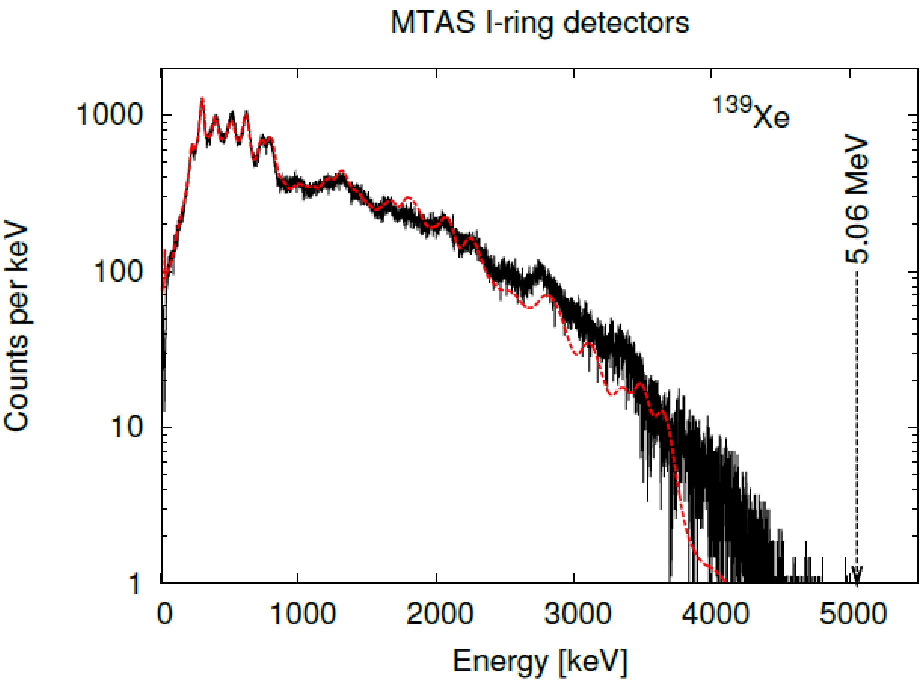
average **beta** energy release per ^{139}Xe decay decreased from1774 keV to 1573 keV

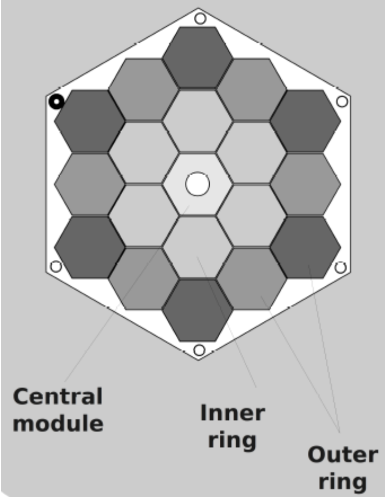
13% decrease

Aleksandra Fijałkowska *et al.*, Nuclear Data Sheets 120, 26 (2014)

Measured and **modified** ^{139}Xe decay in central and inner rings of MTAS



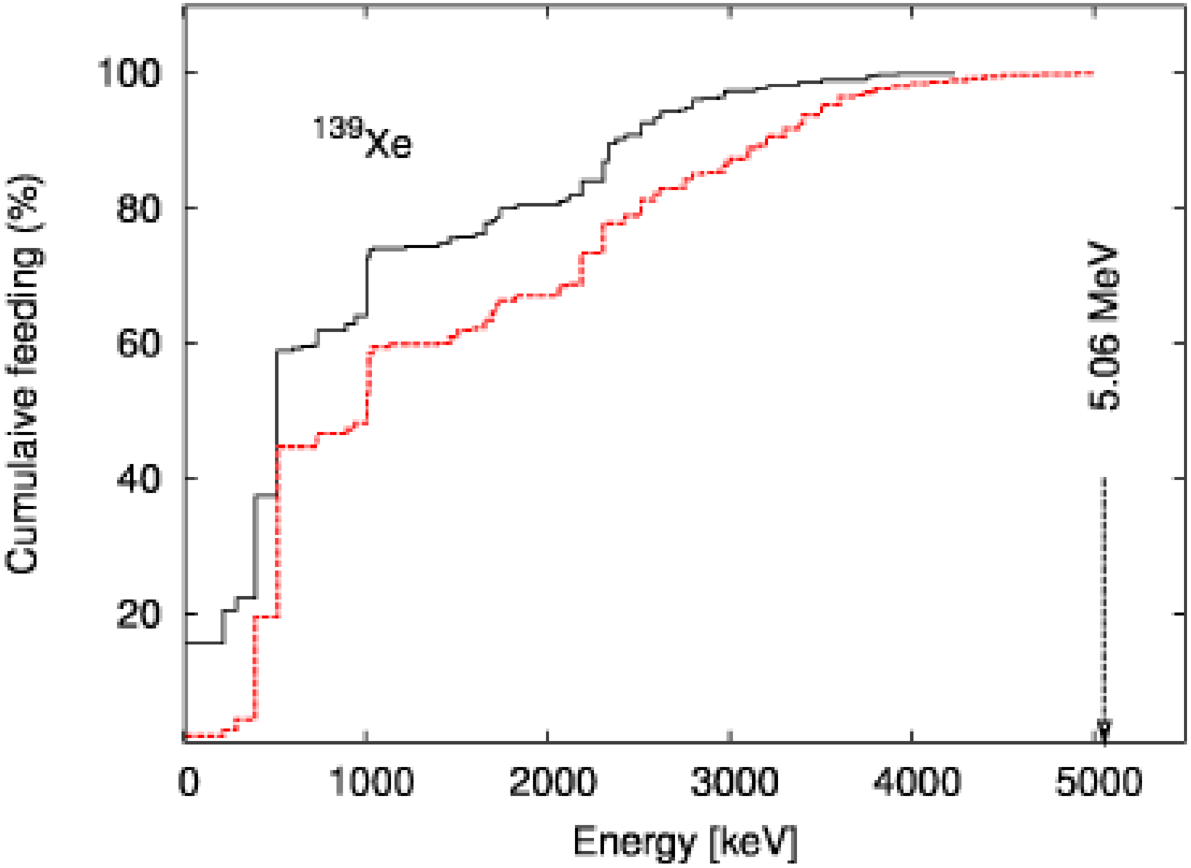




Modular construction of MTAS helps to validate results !

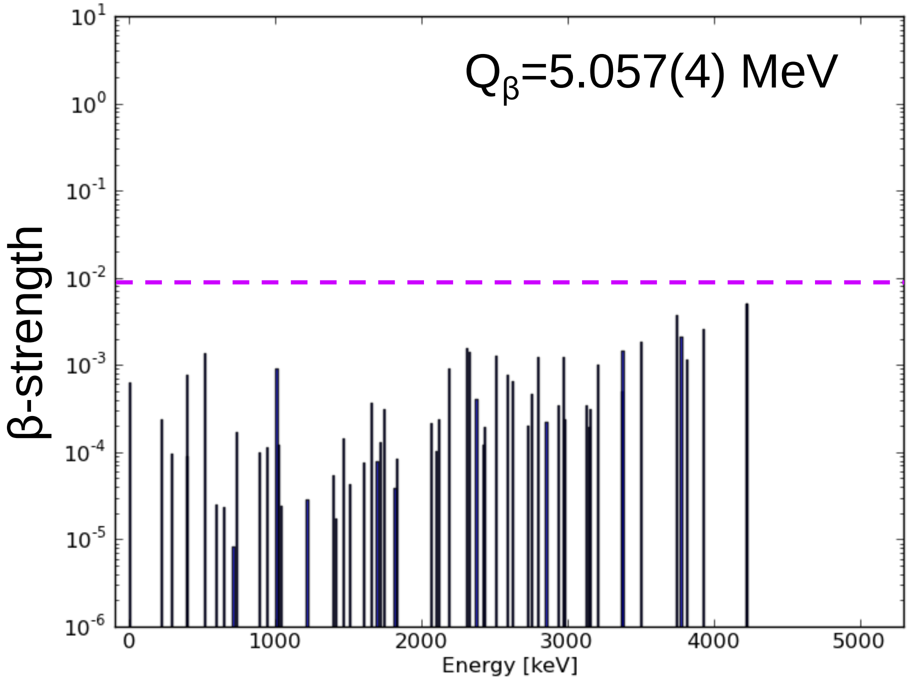
see also Rasco et al., ARIS 2014 proceedings

Cumulative β-feeding in ^{139}Xe decay, ENSDF vs MTAS



β-strength in ^{139}Xe decay

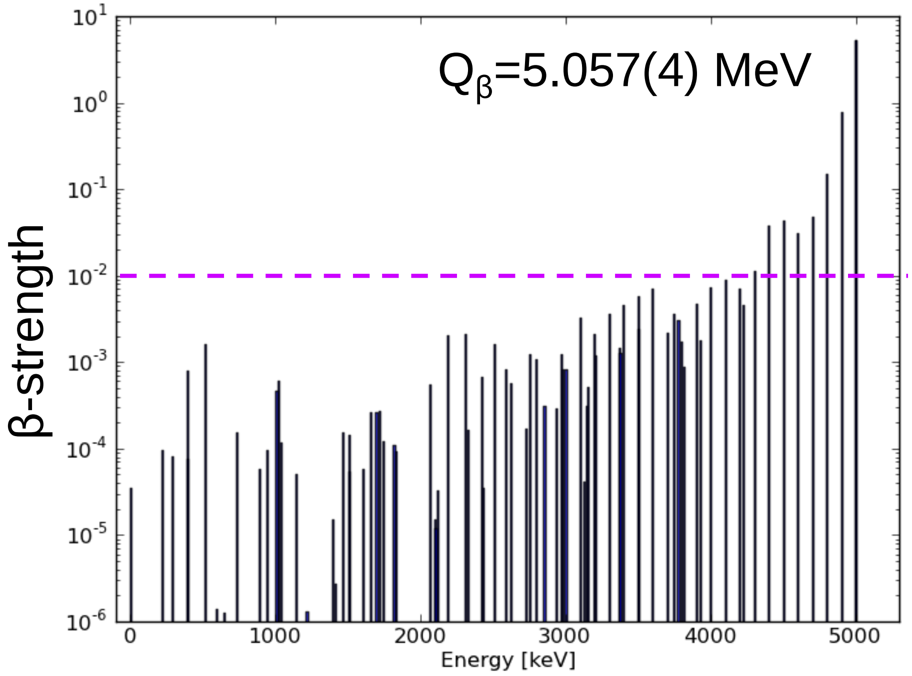
ENSDF



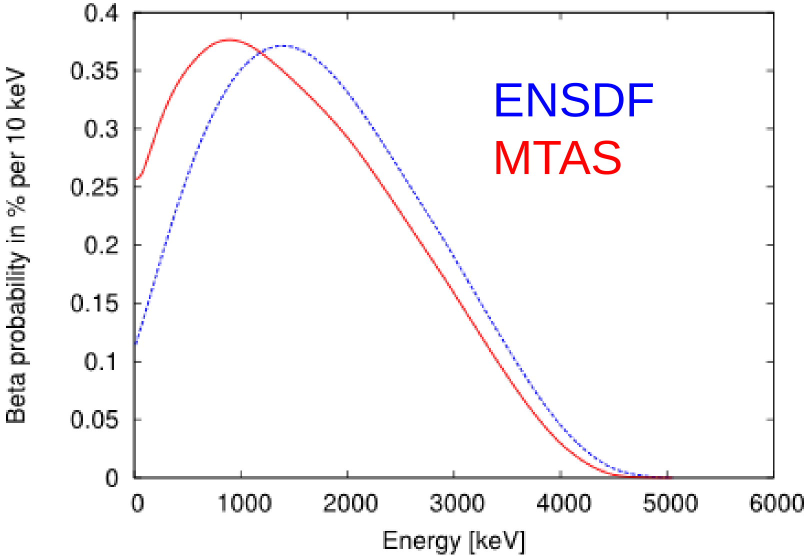
β-strength in ^{139}Xe decay

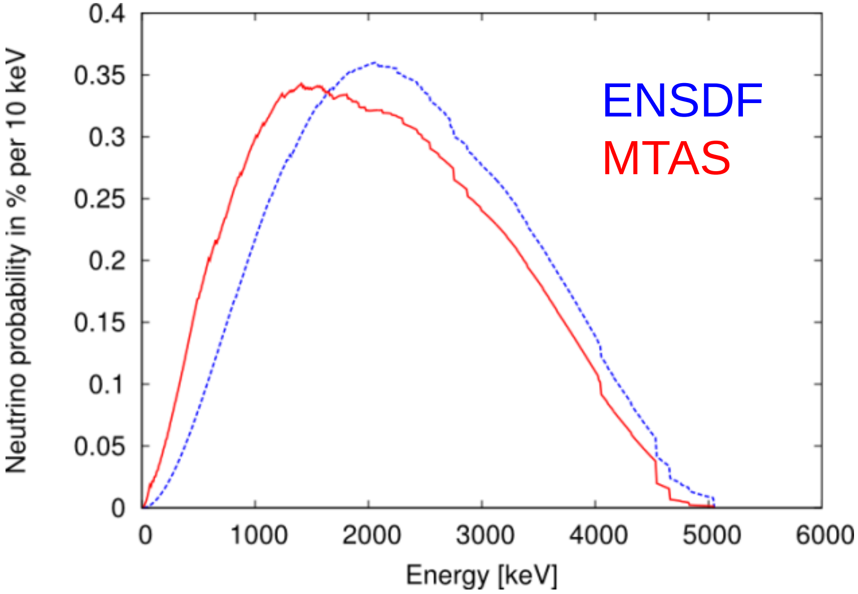
MTAS

A. Fijałkowska 2014



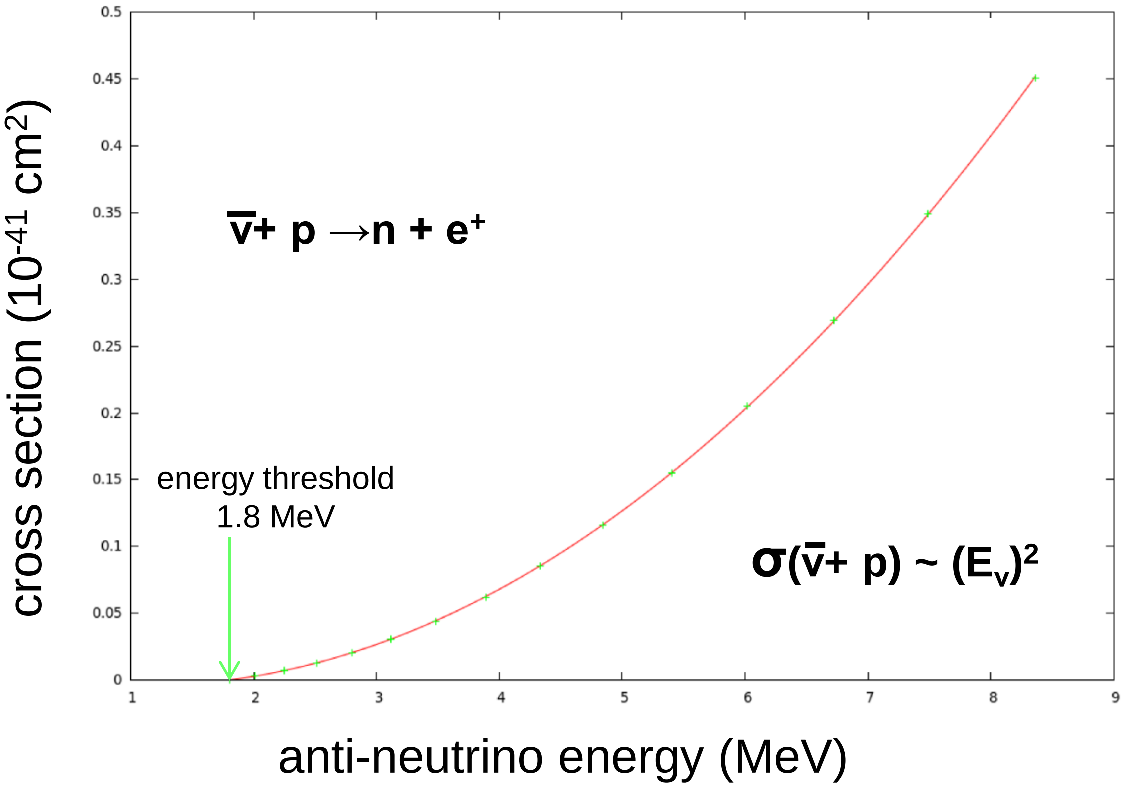
Electron and anti-neutrino energy spectra in ^{139}Xe decay


Energy spectrum of electrons


Energy spectrum of anti-neutrinos

In ^{139}Xe decay, the average anti-neutrino energy is shifted down from 2348 keV (ENSDF) to 2114 keV (MTAS), i.e., by 234 keV

Anti-neutrino interactions with protons



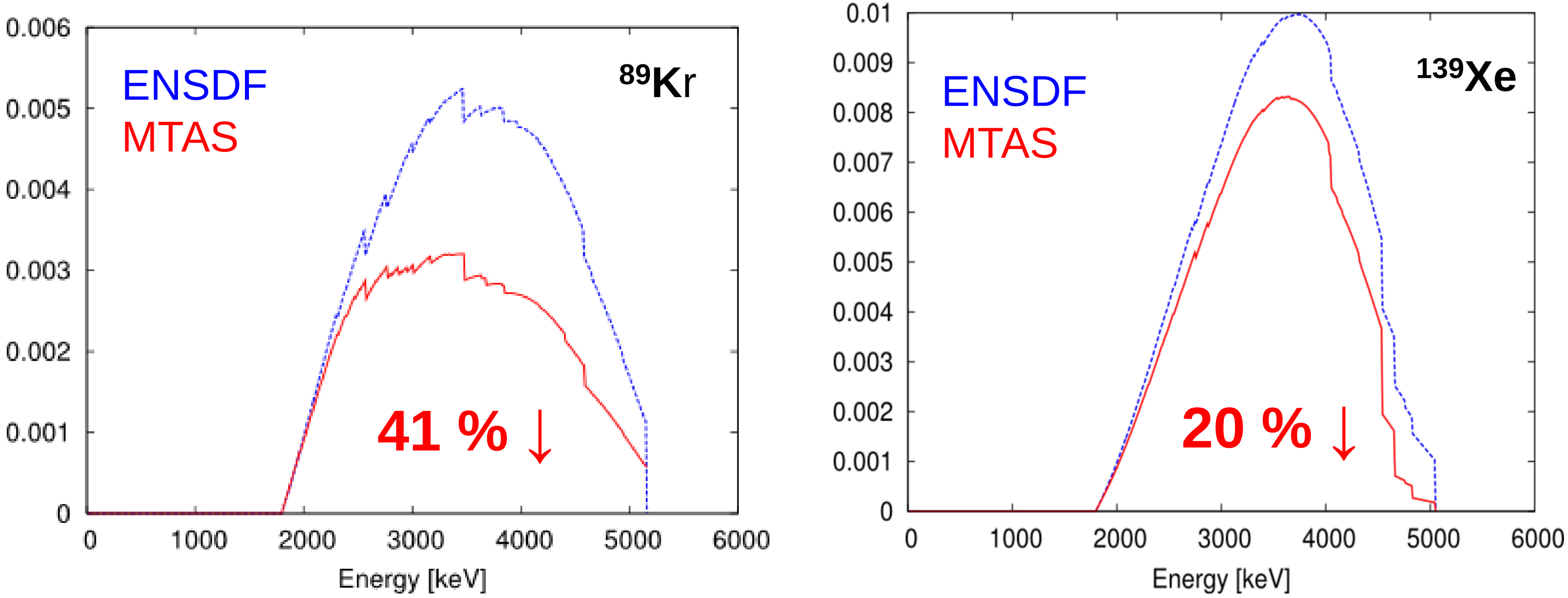
A. Strumia and F. Vissani, PL B 564, 42, 2003

High energy anti-neutrinos
have higher cross section
for the interactions with protons,
i.e.,
have higher probability to be
removed from $\bar{\nu}$ beam.

For anti-neutrinos with energies
below 1.8 MeV energy threshold:
no interactions on protons.

Interacting anti-neutrinos emitted in ^{89}Kr and ^{139}Xe decay

Number of interactions of ^{89}Kr and ^{139}Xe anti-neutrinos per 10 keV energy bin (in % x 10^{-43} cm^2 units).



reactor antineutrino anomaly 94.3(23) % ⟶ ~ 6 % missing

MTAS results for ^{89}Kr and ^{139}Xe decays account for **2.9 of the *“missing 6%”*** difference in the reactor anti-neutrino anomaly for **a fresh nuclear fuel load**, and for **1.8** and **1.5 out of the missing 6%** for the burn-up phases corresponding to **2% FIMA and 3% FIMA**, respectively, if applied to the anti-neutrino anomaly as calculated from all data contained in ENSDF.

Summary

Modular Total Absorption Spectrometer *with its auxiliary Si strip detectors, HPGe detector, shielding structure and tape collector system was constructed, characterized and applied to the decay studies of* ***over twenty*** *fission products, seven of highest NEA priority, at the HRIBF at Oak Ridge.*

MTAS *is the* ***largest and the most efficient*** *Total Absorption Spectrometer ever built (factor 7 in volume). Its* ***modular construction*** *helps to verify the analysis of complex decay patterns (now similar construction - DTAS from Valencia).*

Test decay chain ^{142}**Ba->**^{142}**La->**^{142}**Ce**, *where earlier measured high resolution and total absorption data were used to generate the β-strength distribution, demonstrated a* ***reasonable agreement between MTAS experimental spectra and simulated MTAS response****.*

Deduced true beta-strength patterns offer the guidance and verification for the theoretical calculations of beta-decay process in neutron-rich nuclei *(to be done, mostly deformed nuclei).*

Summary (results)

New data on decays of abundant ^{235,238}U fission products, like ^{89}Kr and ^{139}Xe, demonstrated an increase in average γ-energy emitted per decay (decay heat) by 28 % and 47 %, respectively.

New beta-decay schemes based on MTAS data, with an increased beta feeding to the high energy states (hence lower beta transition energies) affect also anti-neutrino spectra. Lower energies of anti-neutrino largely reduce the number of interactions with protons (matter).

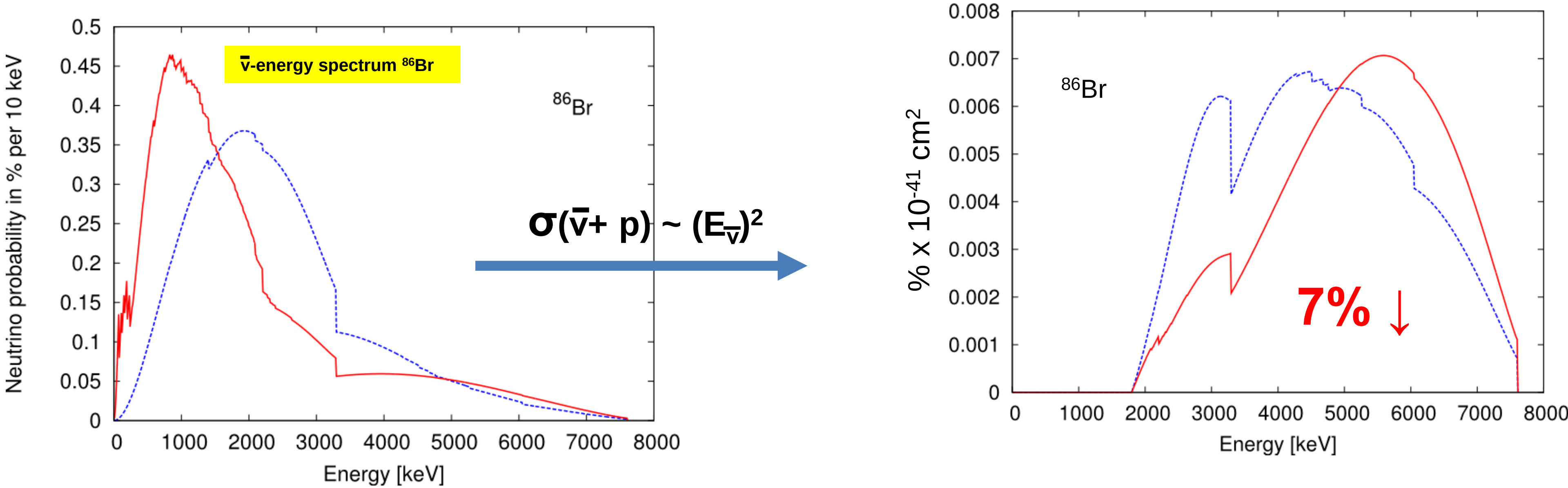
^{89}Kr – 41% and ^{139}Xe - 20%

These two decays alone reduce the number of reactor anti-neutrinos interacting with protons by about 1.5 % (up to 3 %)

Single detector experiments detecting anti-neutrinos next to the power reactors should take into account the correct(ed) anti-neutrino energy spectra, when deducing the magnitude of "reactor anti-neutrino anomaly"

Anti-neutrino interactions with protons deduced from MTAS measurements for ^{86}Br

MTAS vs **ENDSF**



$\sigma(\bar{\nu} + p) \sim (E_{\bar{\nu}})^2$

In average, in ^{86}Br decay we have about **7% less** of anti-neutrino interactions with protons.

It is NOT a typical case, since the beta feeding to high energy levels (low end-point energies) was partially compensated by the increased feeding to the ground state.

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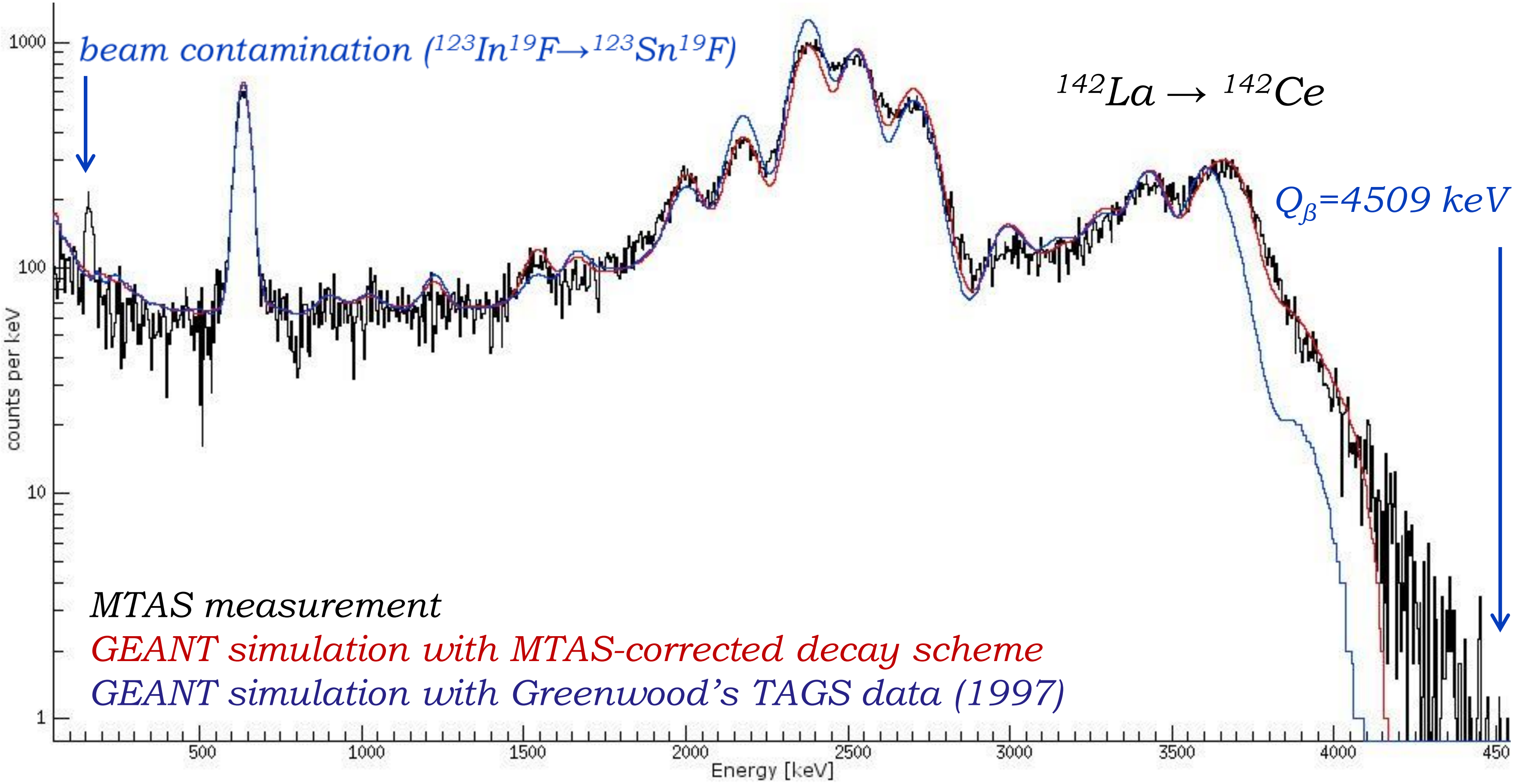
Total β-gated MTAS spectrum for ^{142}La decay

Earlier measurements for ^{142}La decay included total absorption spectroscopy
[see Greenwood et al. NIM A390 (1997)]



TAGS based simulations are close to MTAS data

Marzena Wolinska-Cichocka et al., Nuclear Data Sheets 120, 22 (2014)

Maybe it is not the end …

New proposal submitted to DOE Nuclear Data Program is asking for a funding of two-weeks of ORNL Tandem operation for the OLTF-MTAS

Parent	Half-life	Ion rate at 50 nA (pps)	MTAS Q_β (Q_β-Emax level) [MeV]	^{238}U yield [%]	Shifts required
136I^{gs,m}	83s/47s	6.8E5	6.9 **(0.3/2.8)**	1.3	1
138I	6.2 s	1.3E4	7.8 **(2.5)**	**3.1**	1
139I	2.3 s	1.5E3	6.8 **(5.1)**	2.1	2
140I	0.86 s	1.0E2	8.7 **(6.9)**	0.9	3
140Xe	14 s	1.0E2	4.1 **(1.5)**	**4.9**	3

MTAS “discovery window”: Qβ - Emax_level

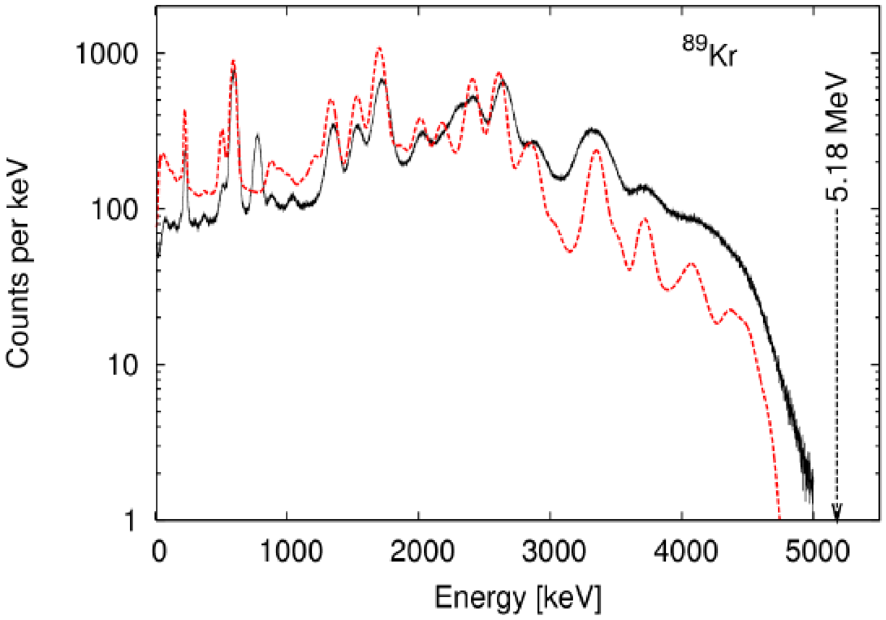
new beginning (of experiments at the Tandem)

Parent	**Half-life**	**Ion rate at 50 nA (pps)**	**MTAS Q_β (Q_β-Emax level) [MeV]**	**^{238}U yield [%]**	**Shifts required**
85Br	2.9 m	5.7E5	2.9 (0.8)	0.74	1
88Br **88Kr**	16 s 2.8 h	1.3E5	9.0 (2.0) 2.92 (0.15)	1.5 2.0	1 1
89Br	4.4 s	1.5E4	8.3 (**3.5**)	1.9	2
90Br	1.9 s	2.8E3	10.4 (**4.6**)	1.4	2
91Br	0.54 s	1.8E2	9.8 (**5.4**)	0.8	3

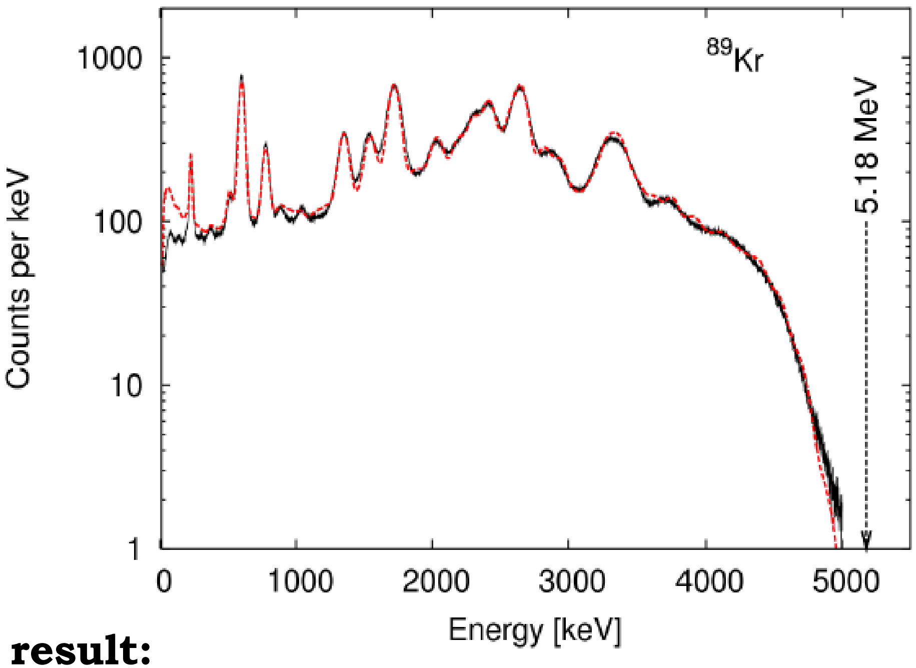
priority “1” ^{89}Kr →^{89}Rb decay

Cumulative yield of ^{89}Kr in n_{th} + ^{235}U fission is about 4.5%.
(# 13 in direct yield, of 3.4%)
There are 57 β-fed levels in ^{89}Rb daughter followed by 288 γ’s listed in ENSDF !

MTAS vs ENSDF



MTAS vs modified decay scheme



MTAS result:

average **gamma** energy release per ^{89}Kr decay increased from 1801 keV to 2304 keV

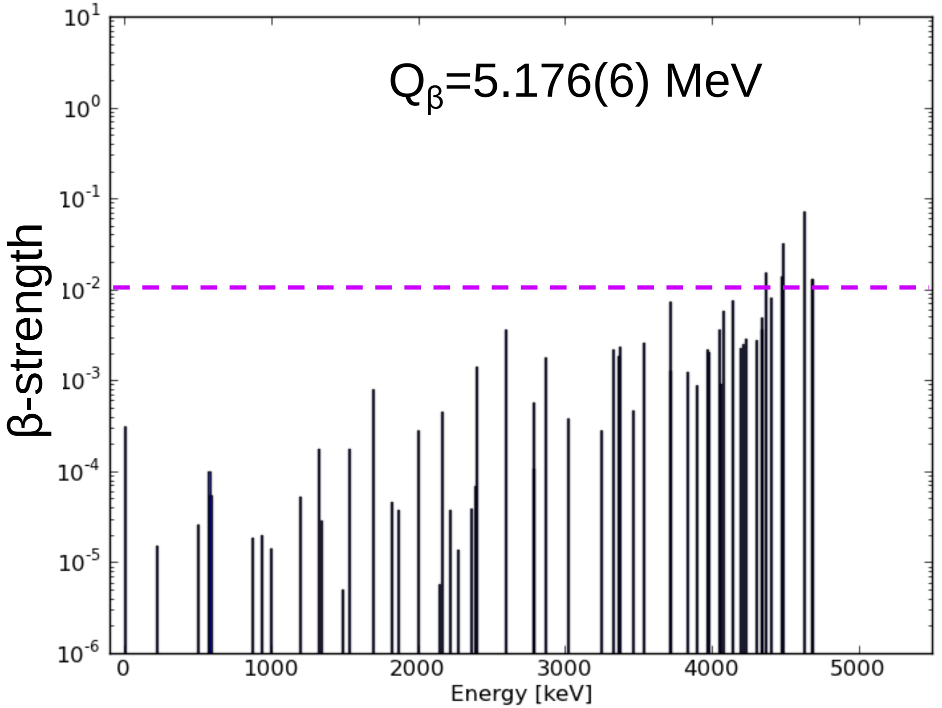
28 % increase

the average energy of **beta** particles per 89Kr decay decreased from 1462 keV to 1222 keV

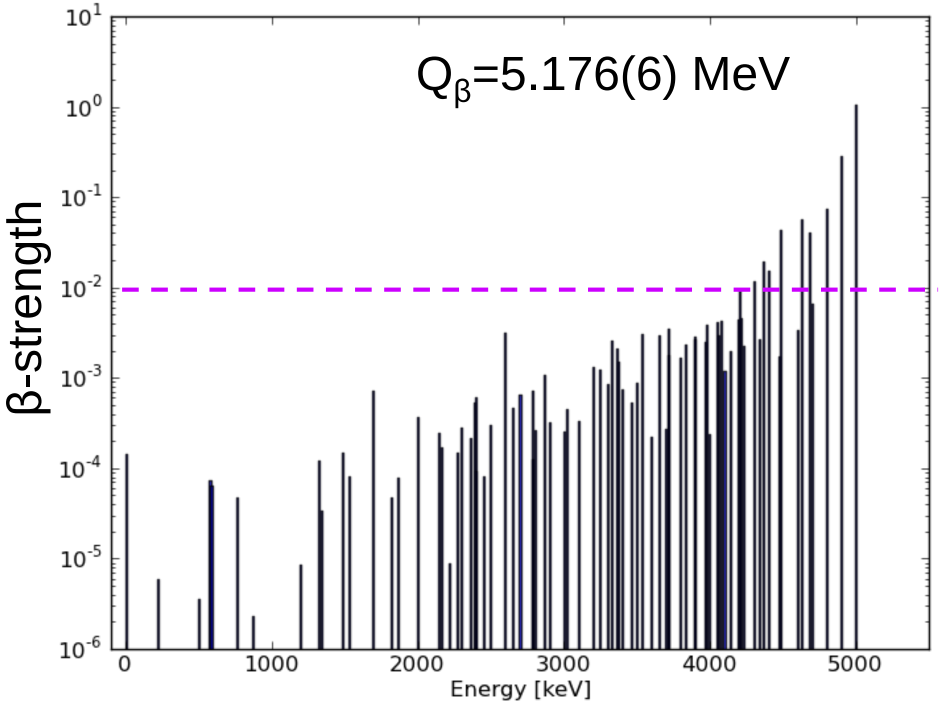
20% decrease

Marek Karny *et al.*, in presentation at ND 2013
Aleksandra Fijałkowska *et al.*, Nuclear Data Sheets 120, 26 (2014)

β-strength in ^{89}Kr decay
ENSDF



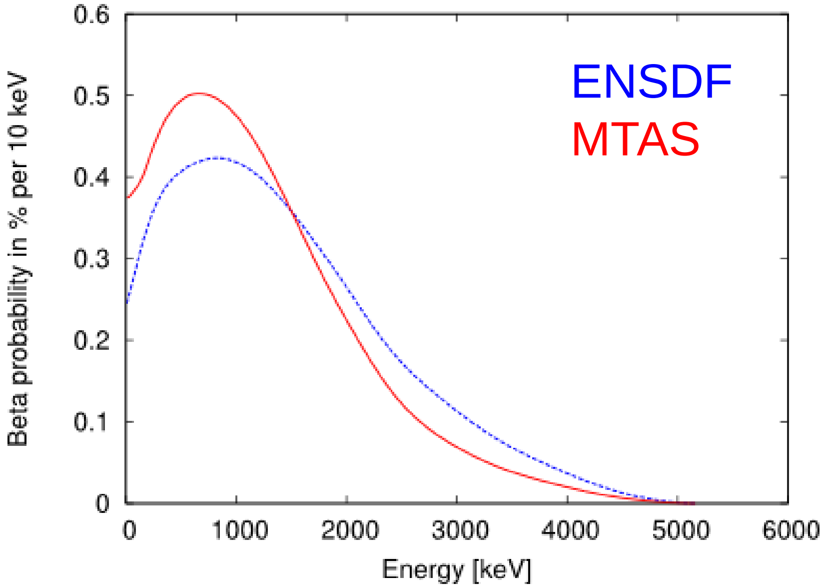
β-strength in ^{89}Kr decay
MTAS
A. Fijałkowska 2014



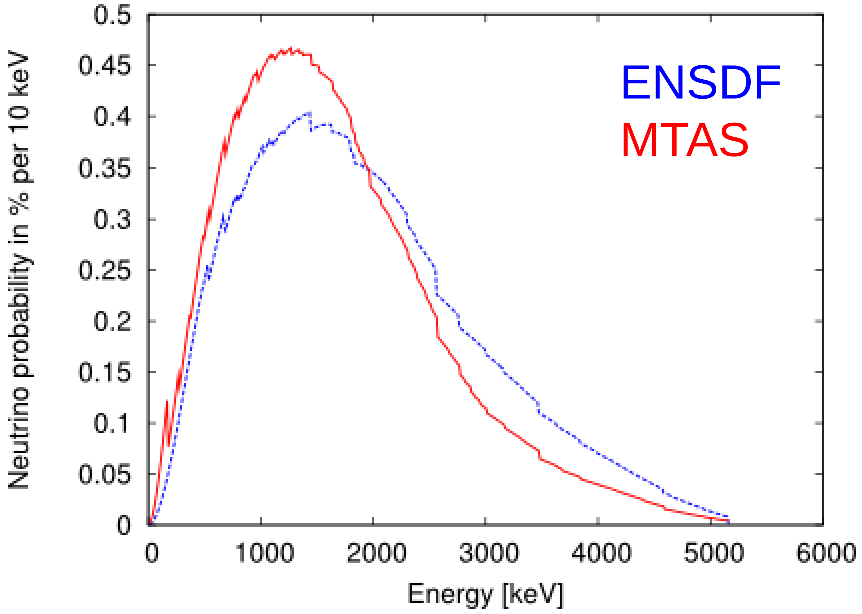
Oak Ridge National Laboratory

Electron and anti-neutrino spectra in ^{89}Kr decay

Energy spectrum of electrons

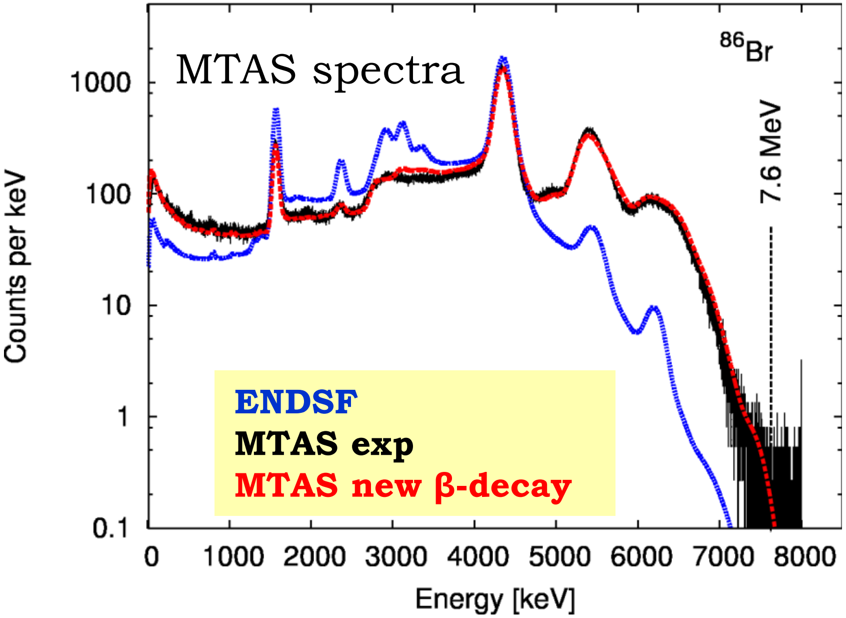


Energy spectrum of anti-neutrinos

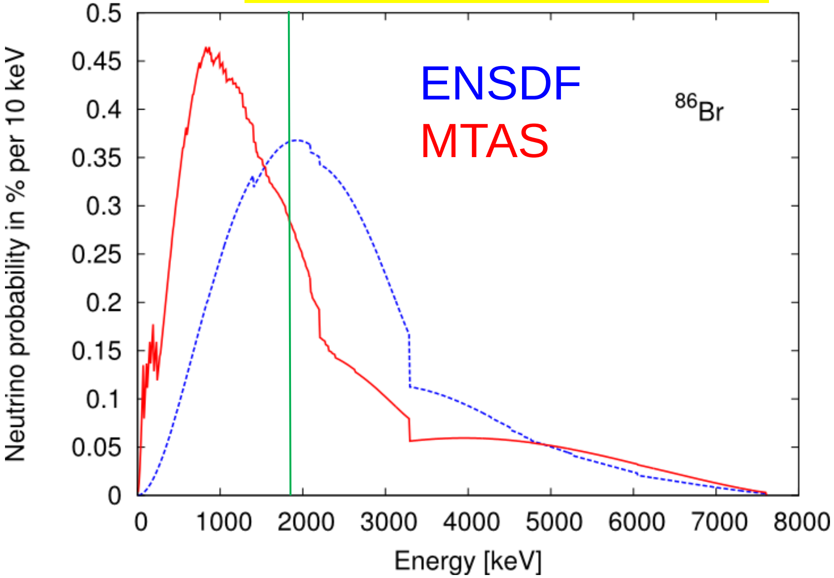


In ^{89}Kr decay, the average anti-neutrino energy is shifted from 1914 keV (ENSDF) to 1650 keV (MTAS), i.e., by 264 keV

Anti-neutrino energy spectrum deduced from MTAS measurements



$\bar{\nu}$-spectrum from ^{86}Br

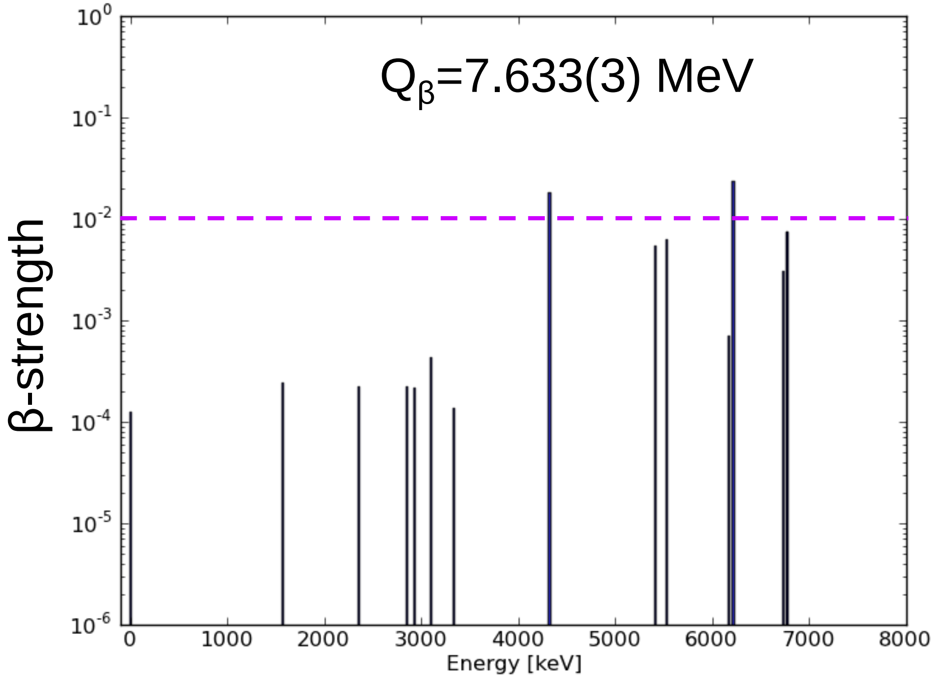


A. Fijałkowska et al., Acta Phys. Pol. B 45, 545, 2014

MTAS-corrected β-decay scheme of ^{86}Br **(+14 %** in decay heat) points to a larger fraction of low energy anti-neutrinos than can be expected from ENDSF.

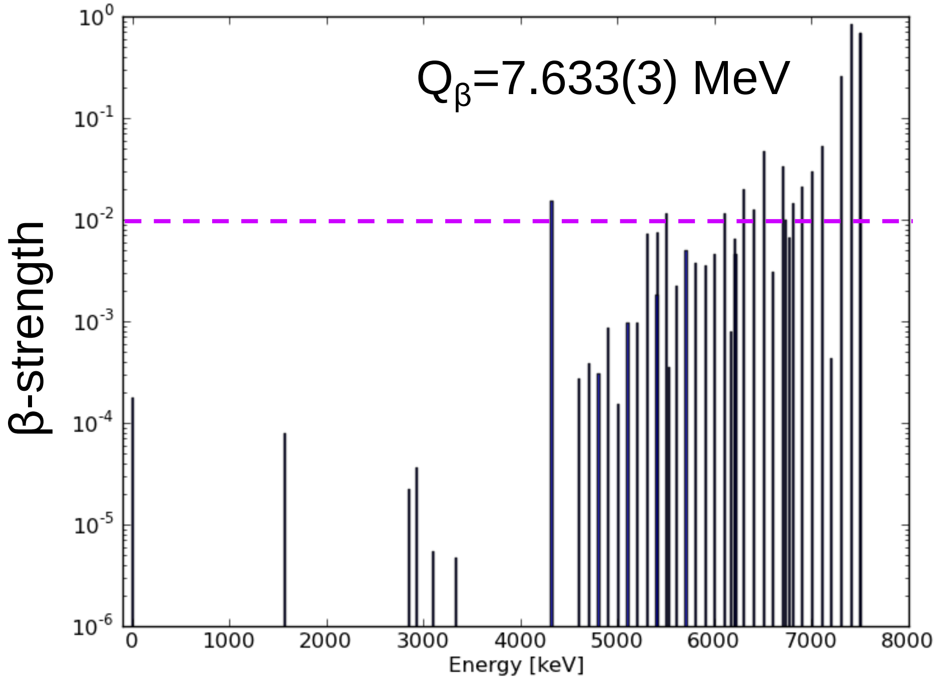
Note that the energy threshold for the $\bar{\nu} + p \rightarrow n + e^+$ reaction is **1.8 MeV**, exactly at the energy region where the change occurred.

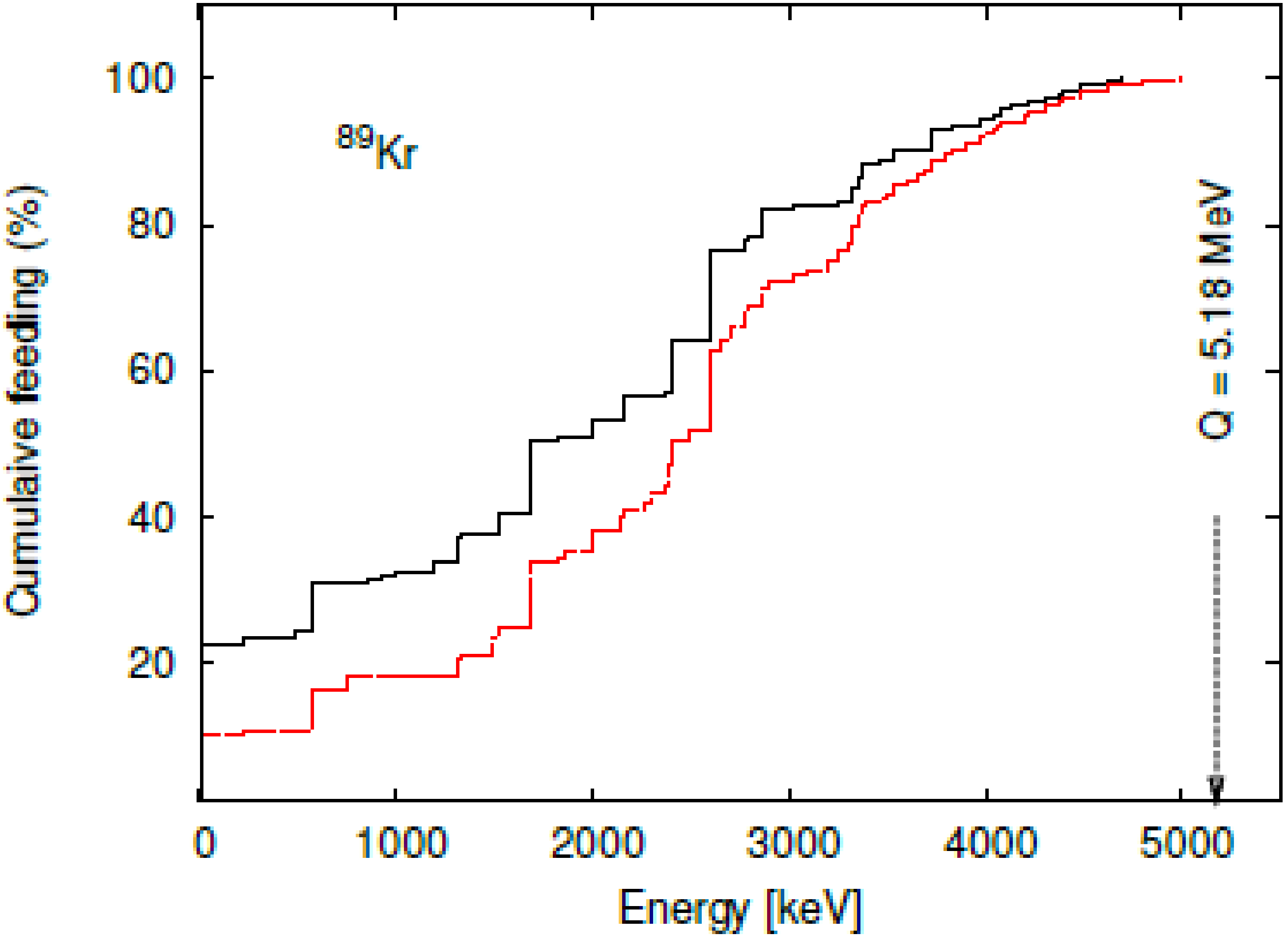
β-strength in ^{86}Br decay
ENSDF



β-strength in ^{86}Br decay
MTAS

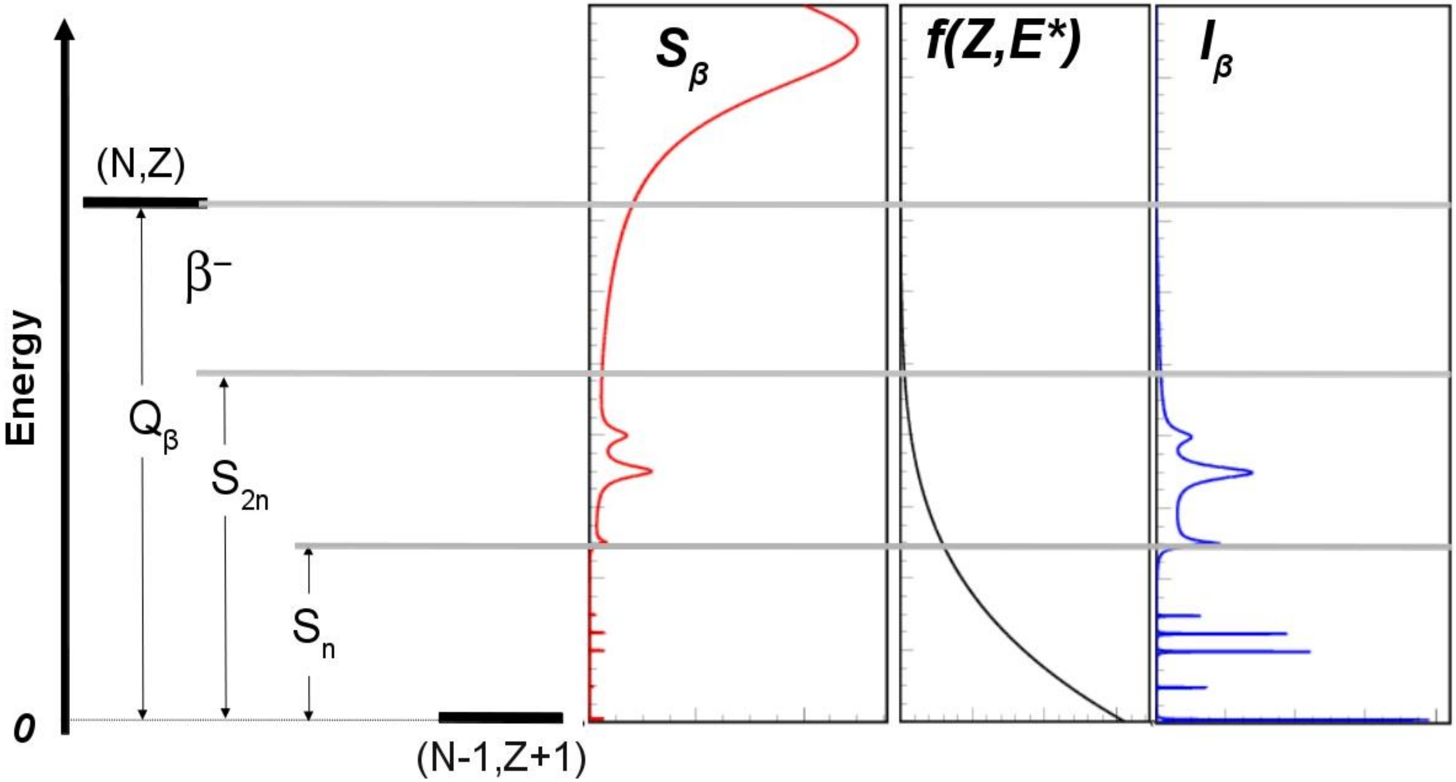
A. Fijałkowska 2014





^{89}Kr
Cumulaive feeding (%)
Energy [keV]
Q = 5.18 MeV
0
20
40
60
80
100
0
1000
2000
3000
4000
5000

Beta decay of very neutron-rich nuclei is indeed interesting and complex



neutron detection
3Hen, VANDLE ….

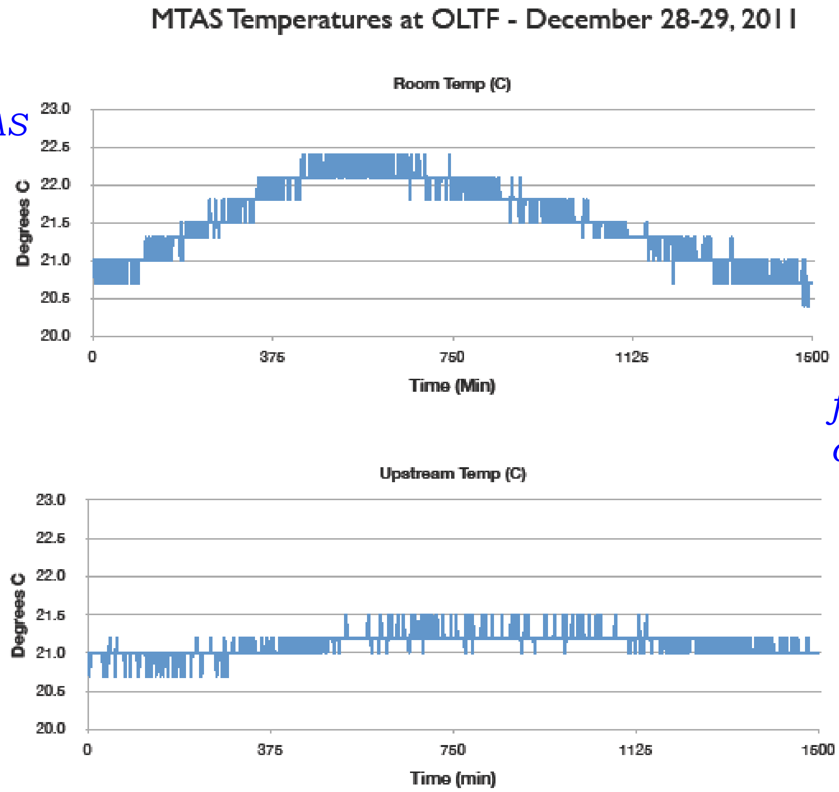
βγ
and
MTAS

Part of beta-strength “under S_n“ is easier (not easy) to study and compare to models
(it is *easier* to investigate, if you have right tools like **MTAS** array)

MTAS amplitude stability

Temperature sensor outside MTAS
(room temperature)

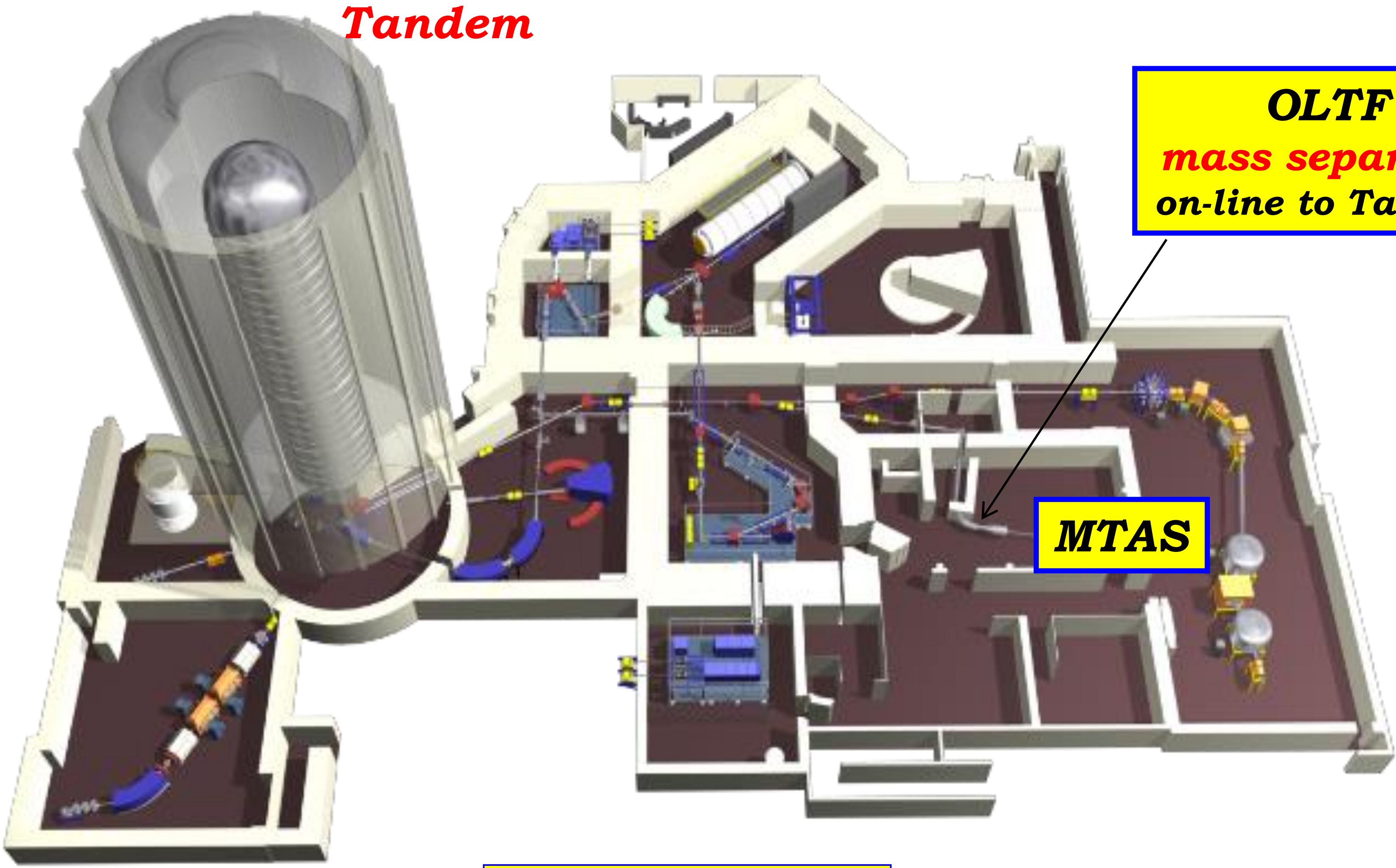
Temperature inside MTAS
(under shielding)


MTAS Temperatures at OLTF - December 28-29, 2011

four temperature sensors
outside and inside MTAS
(C.J. Gross)

Amplitude stability is not a problem when room temperature is stable
(gain matching/testing with 1115 keV γ-line from ^{65}Zn)
Work on an active amplification control in progress: K.C. Goetz, R. Grzywacz (UTK)
(laser light pulser split over reference detector and MTAS modules)

Holifield Radioactive Ion Beam Facility at Oak Ridge



Tandem

OLTF
mass separator
on-line to Tandem

MTAS

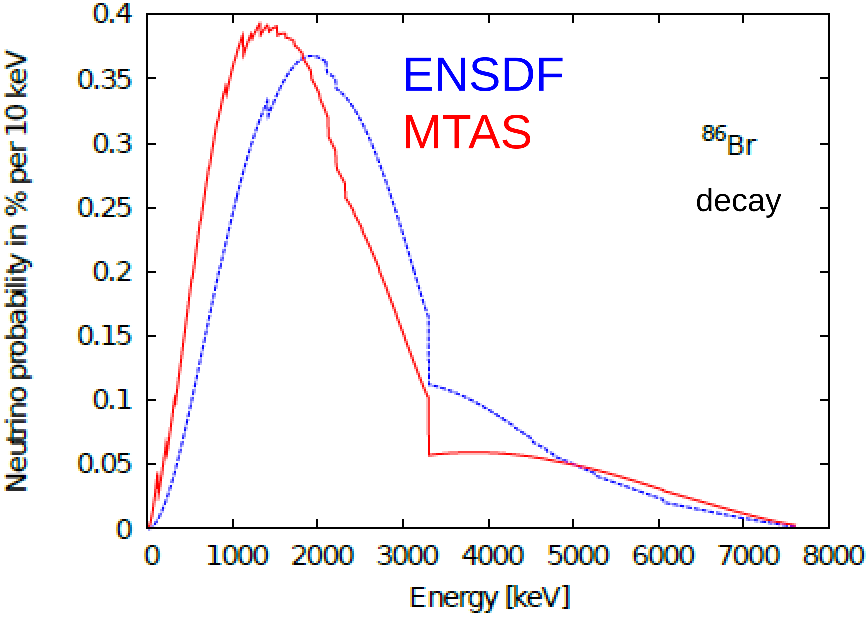
January 2012

Oak Ridge National Laboratory

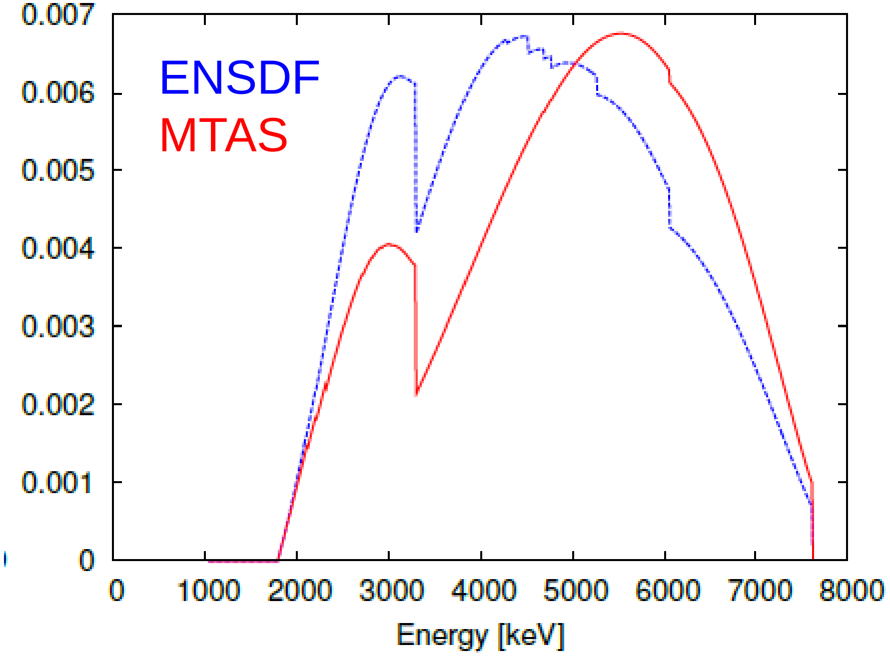
Anti-neutrino energy spectra from beta-decay of fission products

$${}_{Z}X_{N} \xrightarrow{\beta^-} {}_{Z+1}Y_{N-1} + e^- + \bar{\nu}$$

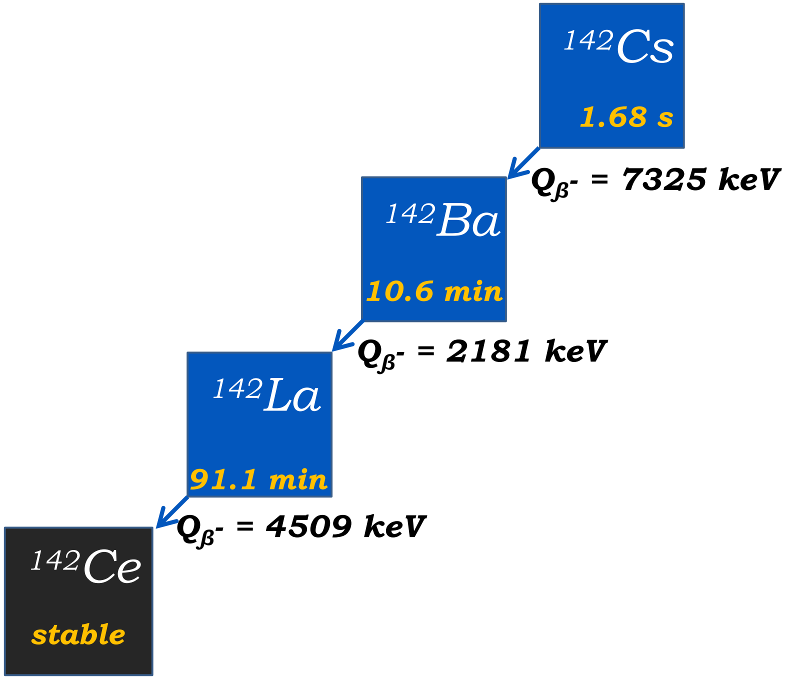
e^- energy spectrum



$\bar{\nu}$ energy spectrum



A=142 test measurement



^{142}Cs
1.68 s

Q_{β^-} = 7325 keV

^{142}Ba
10.6 min

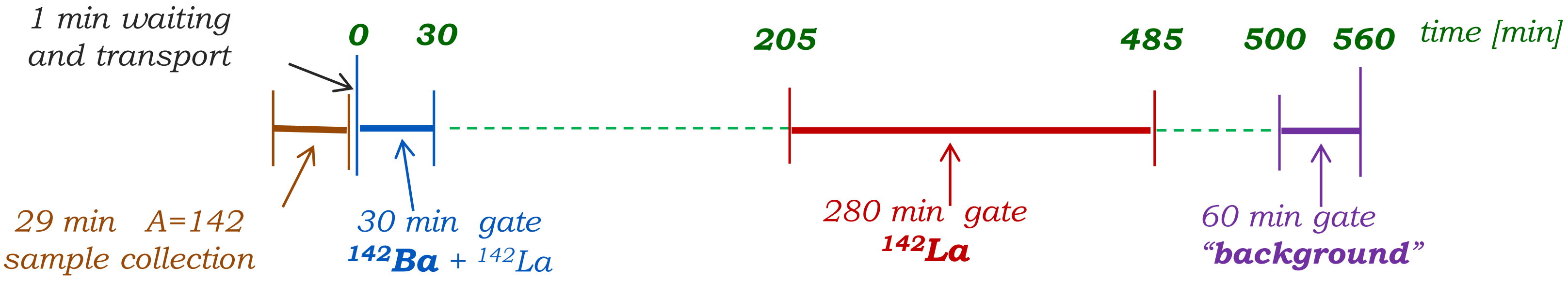
Q_{β^-} = 2181 keV

^{142}La
91.1 min

Q_{β^-} = 4509 keV

^{142}Ce
stable

Time scale of A=142 experiment and analysis time gates



1 min waiting and transport

0 30 205 485 500 560 time [min]

29 min A=142 sample collection

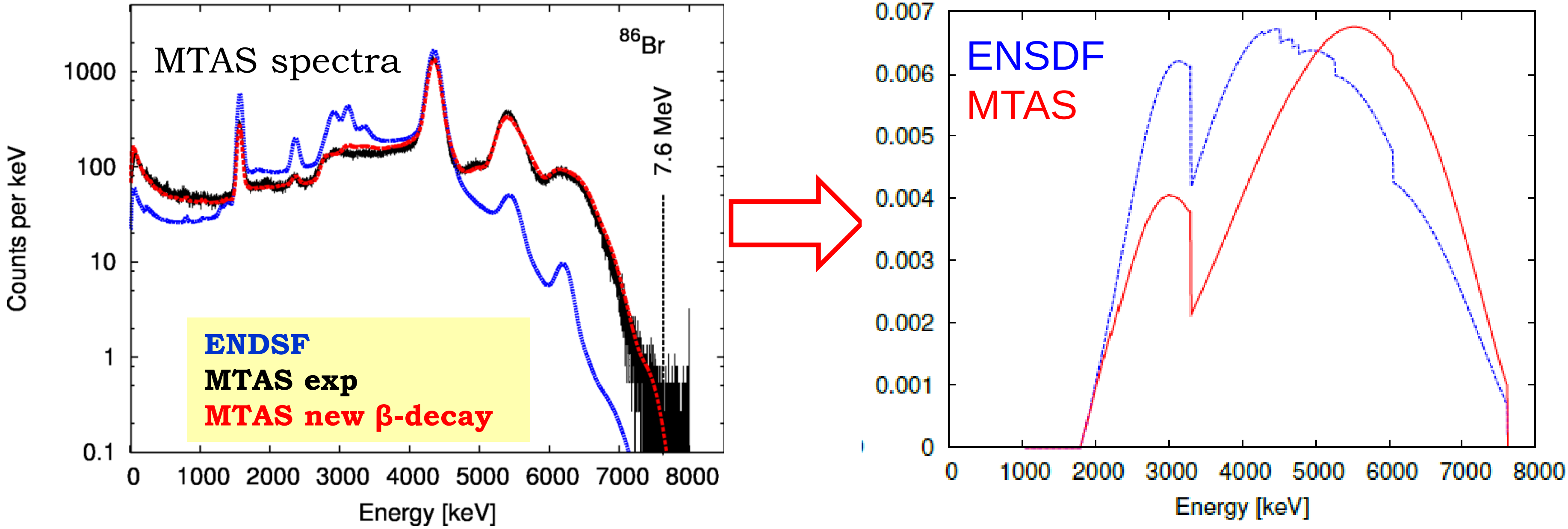
30 min gate
^{142}**Ba** + ^{142}La

280 min gate
^{142}**La**

60 min gate
"**background**"

Anti-neutrino energy spectrum deduced from MTAS measurements

Interacting $\bar{\nu}$ from ^{86}Br

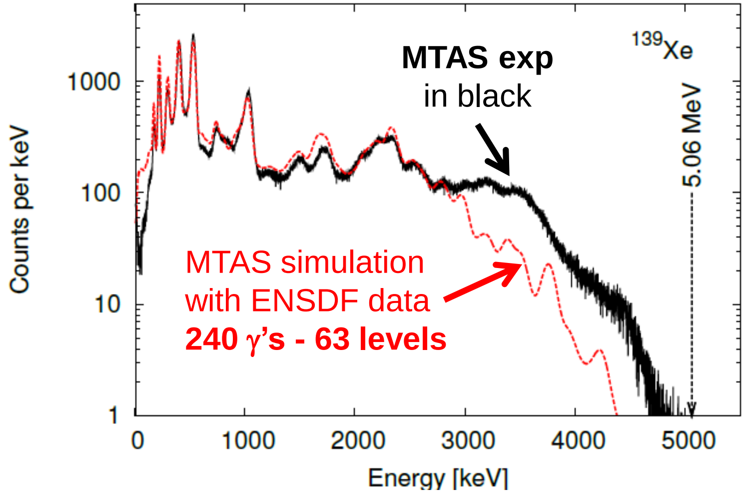


A. Fijałkowska et al., Acta Phys. Pol. B 45, 545, 2014

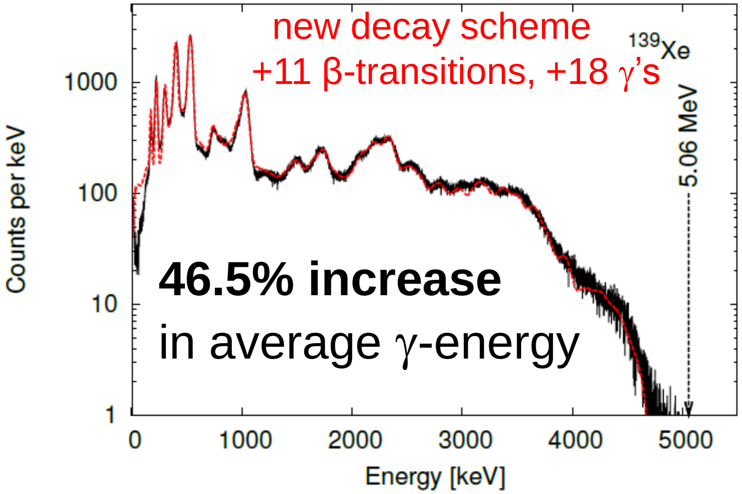
MTAS-corrected β-decay scheme of ^{86}Br **(+14 %** in decay heat) points to a larger fraction of low energy anti-neutrinos than can be expected from ENDSF.
Note that the energy threshold for the $\bar{\nu} + p \rightarrow n + e^{+}$ reaction is 1.8 MeV, exactly at the energy region where the change occurred.

Anti-neutrino interactions with protons deduced from MTAS measurements for ^{139}Xe decay

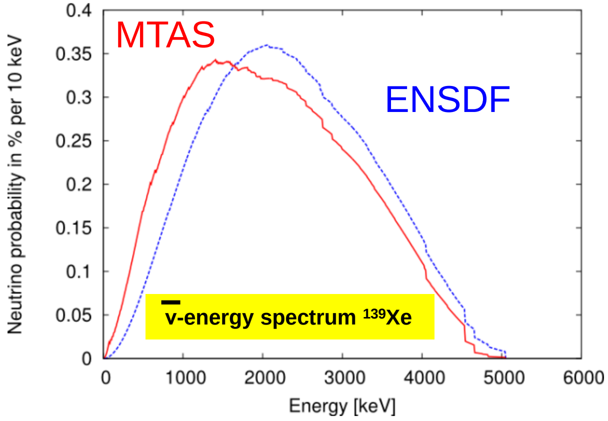
^{139}Xe makes 3.3% of n_{th}+^{238}U direct fission products and 4.3% for n_{th}+ ^{235}U


MTAS exp in black

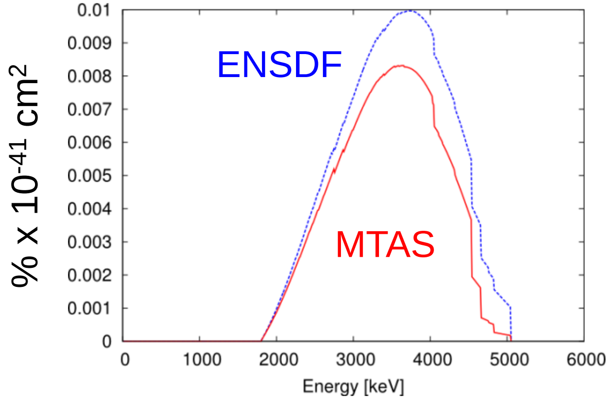
MTAS simulation with ENSDF data
240 γ's - 63 levels


new decay scheme
+11 β-transitions, +18 γ's

46.5% increase
in average γ-energy

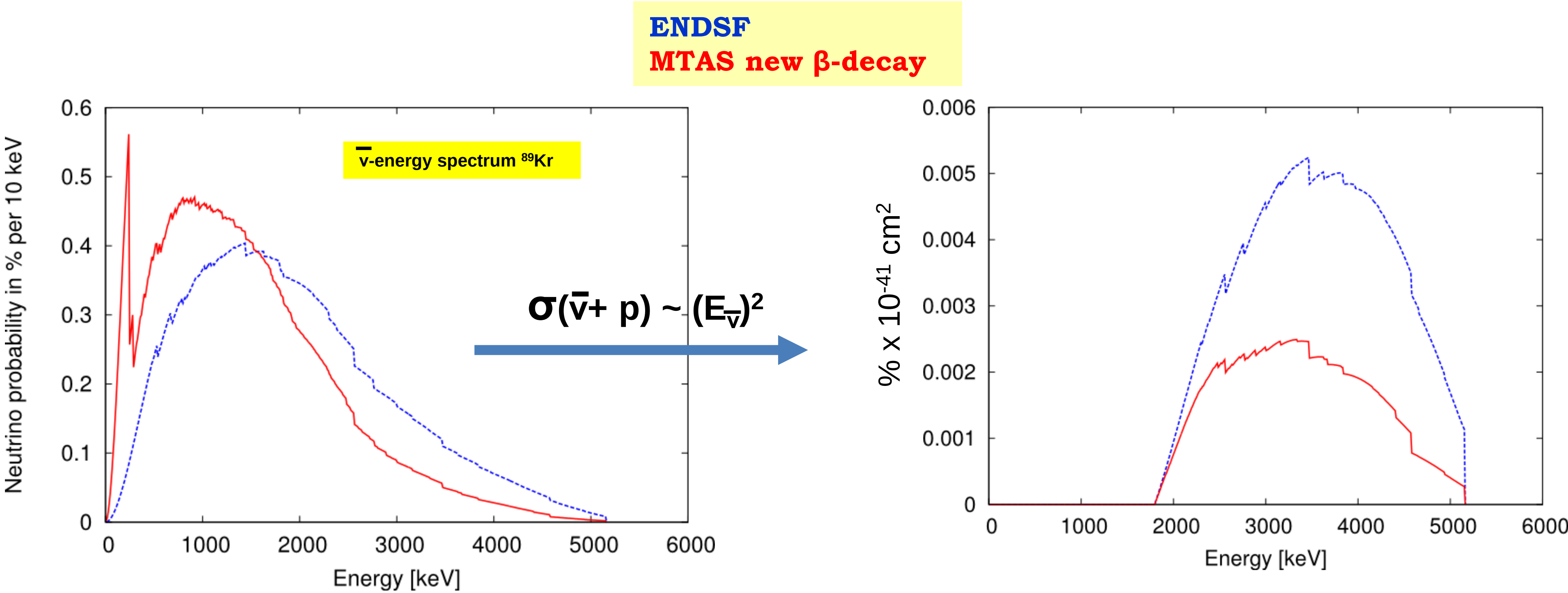

$\bar{\nu}$-energy spectrum ^{139}Xe

$\sigma(\bar{\nu} + p) \sim (E_{\bar{\nu}})^2$



MTAS: number of ^{139}Xe anti-neutrino interactions with protons reduced by 21%

In ^{89}Kr decay, this effect is as large as 41 % !

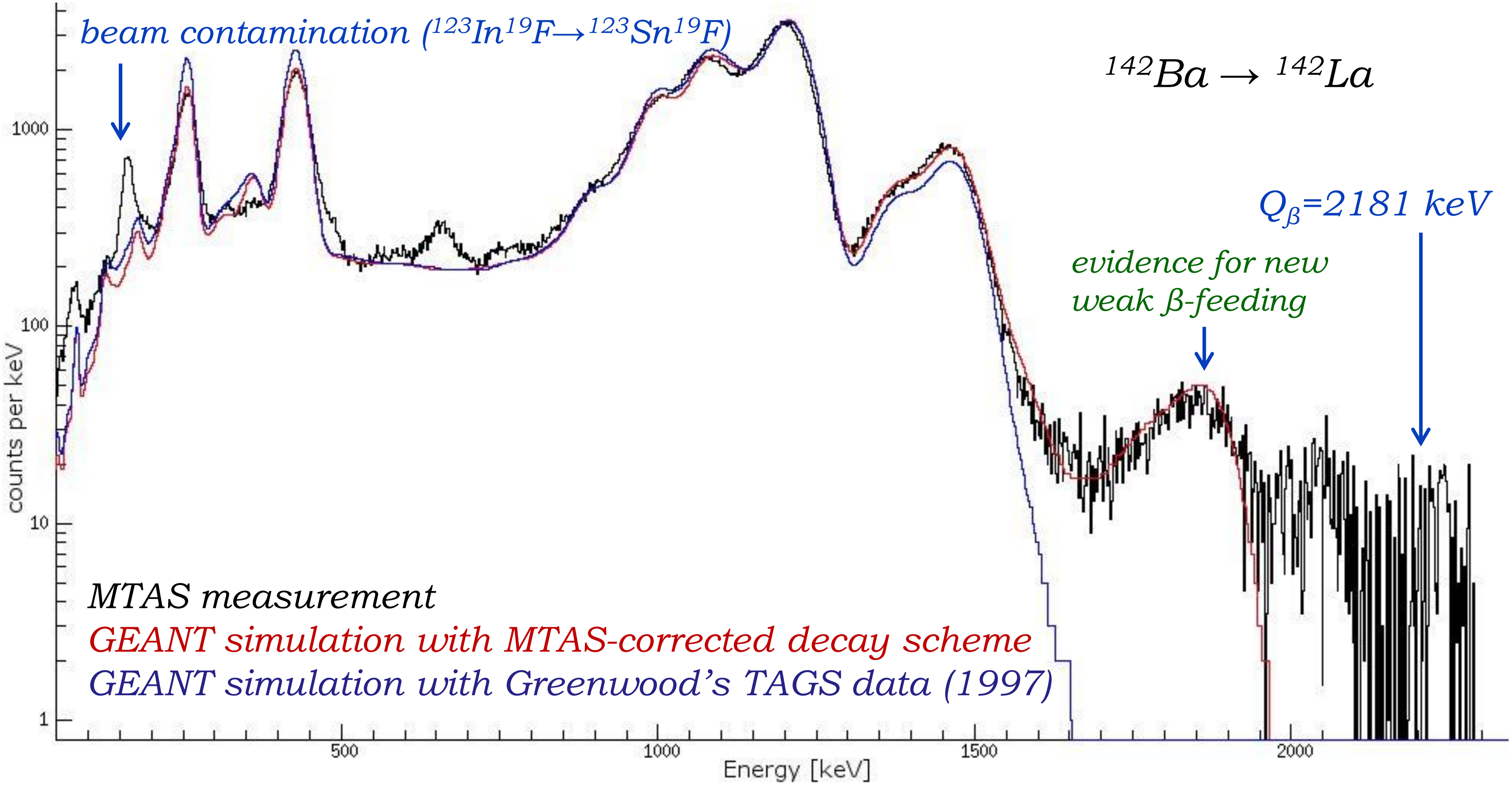


$\sigma(\bar{\nu} + p) \sim (E_{\bar{\nu}})^2$

Impact on the reactor anti-neutrino measurements with a single detector !

Total β-gated MTAS spectrum for ^{142}Ba decay

(^{142}La contribution subtracted)



beam contamination (^{123}In^{19}F→^{123}Sn^{19}F)

^{142}Ba → ^{142}La

Q_β=2181 keV

evidence for new weak β-feeding

MTAS measurement
GEANT simulation with MTAS-corrected decay scheme
GEANT simulation with Greenwood's TAGS data (1997)

Earlier measurements for ^{142}Ba decay:
- *high resolution Ge detectors data [see ENSDF / NDS 112, 8 (2011)]*
- *total absorption spectroscopy [see Greenwood et al. NIM A390 (1997)]*

high resolution data are similar to TAGS data
MTAS data agree with previously adopted β-decay pattern

Marzena Wolinska-Cichocka et al., Nuclear Data Sheets 120, 22 (2014)

Sterile anti-neutrinos rule ! (see DNP APS-JPS, Oct. 2014)

T. Maruyama → dark matter candidate

Warren et al (Notre Dame) → enhancing of SN explosion energy

Maricic – 10 MCi activities ^{51}Cr (Q_{EC}=0.75 MeV) as a source of mono-energetic neutrinos
10^4 Ci ^{144}Ce-^{144}Pr 3 MeV β^- endpoint (see PRL107, 2011).

Padgett (former UT, now LLNL), Orrell (PNNL) – better cumulative β-spectra

Mumm (NIST), Classen (LLNL) → great prospects of PROSPECT (at HFIR)

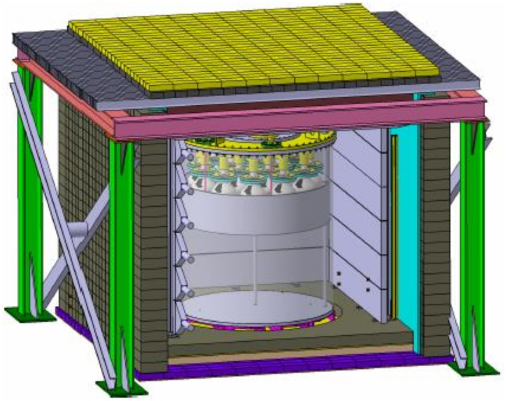
Lasserre (Saclay) → Nucifer detector 7m from Osiris reactor (Saclay)

Learned, Vogelar - NuLAT 3D anti-neutrino detection at 1500 MW Navy Reactor ..

Warnings:
No new cosmological concordance with massive sterile neutrino, PRL113,041301, 2014
Daya Bay data interpretation does not require an extra neutrino, PRL 113,141802, 2014

Efforts by the Neutrino Community

Numerous Very Short Baseline Experiments ranging from operating to planning stages

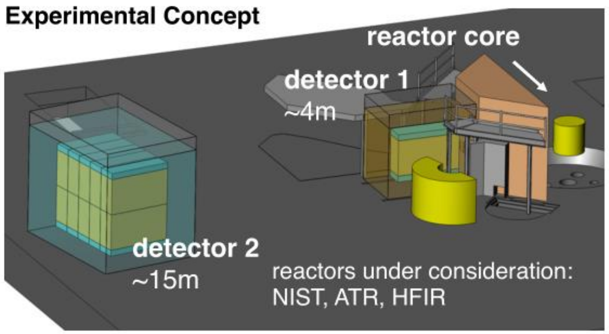


Nucifer, France

Operational, D=7m

Neutrino-4, Russia

Nearly Operational, D=6-13m



PROSPECT, USA

Coming soon at HFIR ?

CORMORAD – Italy, PANDA – Japan, SOLiD - France

from Libby Mc Cutchan (Nuclear Data BNL)
Caribu decay spectroscopy workshop, May 2014.