Decay studies with pure beams of ^{238}U fission products at the HRIBF

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powerful state-of-art ISOL facility offers unique and important research opportunities

even in the "RIKEN era" !

U.S. DEPARTMENT OF
ENERGY

OAK RIDGE NATIONAL LABORATORY
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among motivations of the HRIBF decay studies of fission products :

- ***understanding the evolution of nuclear structure***

-- single-particle levels around shell gaps

-- beta strength function related to the structure of parent and daughter states

- ***beta-decay data for the analysis of post r-process isotopic distributions and nuclear fuel cycle***

-- half-lives

-- properties of beta-delayed neutron emission

-- decay heat

-- antineutrino energy spectra (deduced from true β-transition probabilities)

-- low-energy states, isomers ...

HRIBF based decay studies of fission products substantially contributed to our understanding of neutron-rich nuclei

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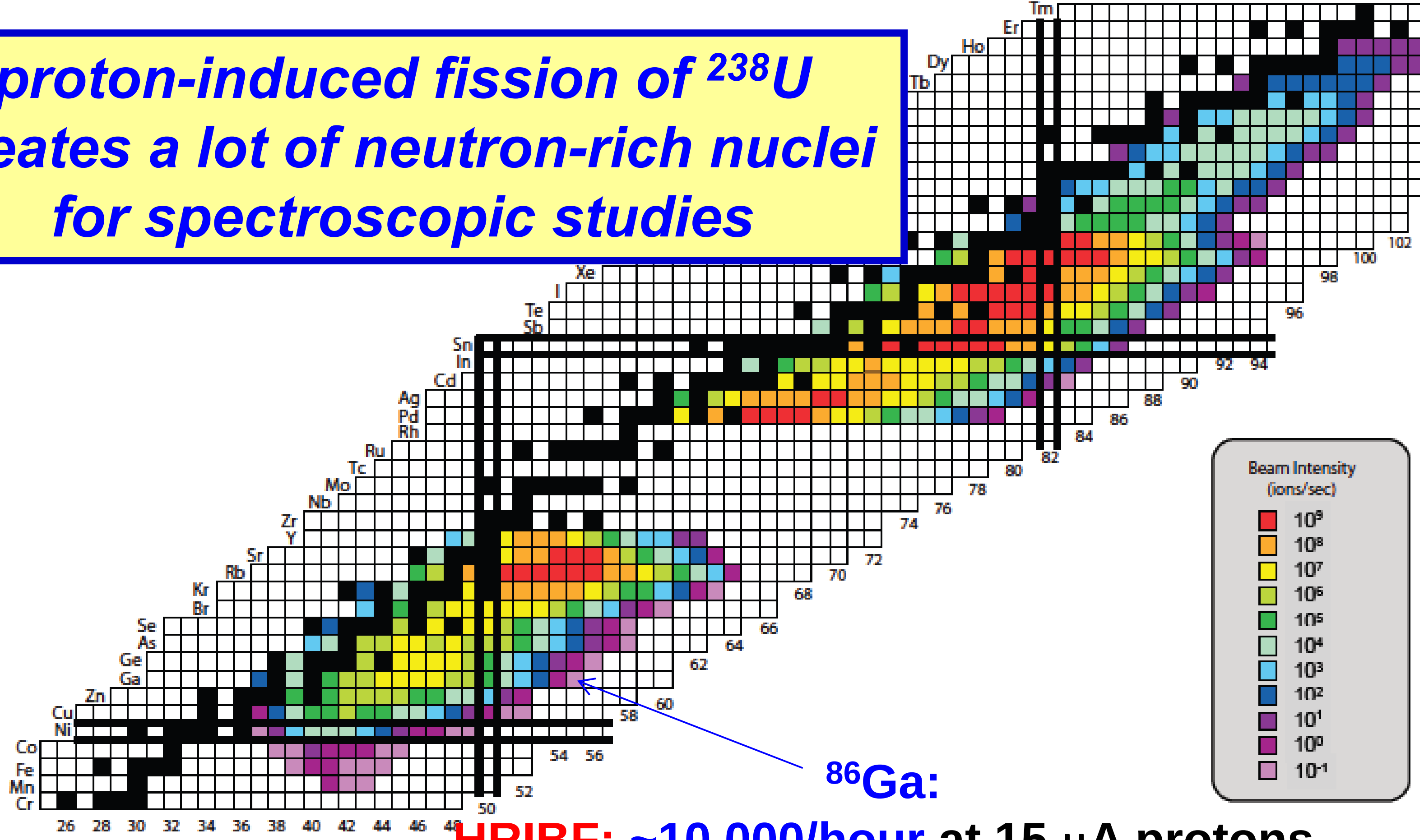
hribf = ***Holifield Radioactive Ion Beam Facility at Oak Ridge (1996 - 2012)***

J.R. Beene et al., J. Phys. G: Nucl. Part. Phys. 38, 024002, 2010

proton-induced fission of ^{238}U creates a lot of neutron-rich nuclei for spectroscopic studies



^{86}Ga:

HRIBF: ~10,000/hour at 15 μA protons

pure beam at the HRIBF !

RIKEN:10/hour at 0.2 pnA ^{238}U

(now ~ 10 pnA)

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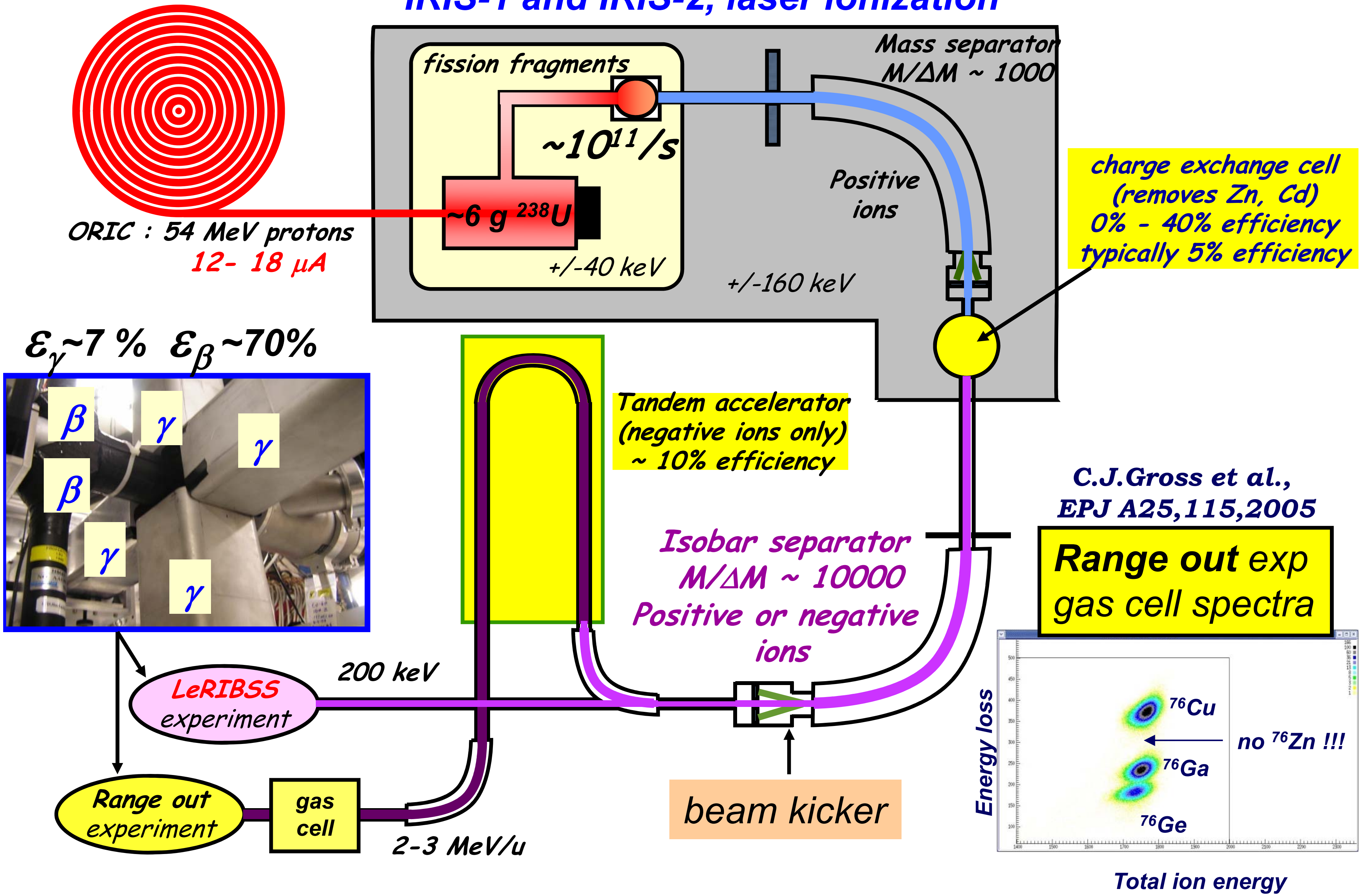
Decay studies of fission products at the hribf

IRIS-1 and IRIS-2, laser ionization



ORIC : 54 MeV protons
12- 18 μA

fission fragments

~10^{11}/s

~6 g ^{238}U

+/-40 keV

Mass separator
$M/\Delta M$ ~ 1000

Positive ions

+/-160 keV

charge exchange cell
(removes Zn, Cd)
0% - 40% efficiency
typically 5% efficiency

ε_γ~7 % ε_β~70%

Tandem accelerator
(negative ions only)
~ 10% efficiency

C.J.Gross et al.,
EPJ A25,115,2005

Isobar separator
$M/\Delta M$ ~ 10000
Positive or negative ions

Range out exp
gas cell spectra

200 keV

LeRIBSS experiment

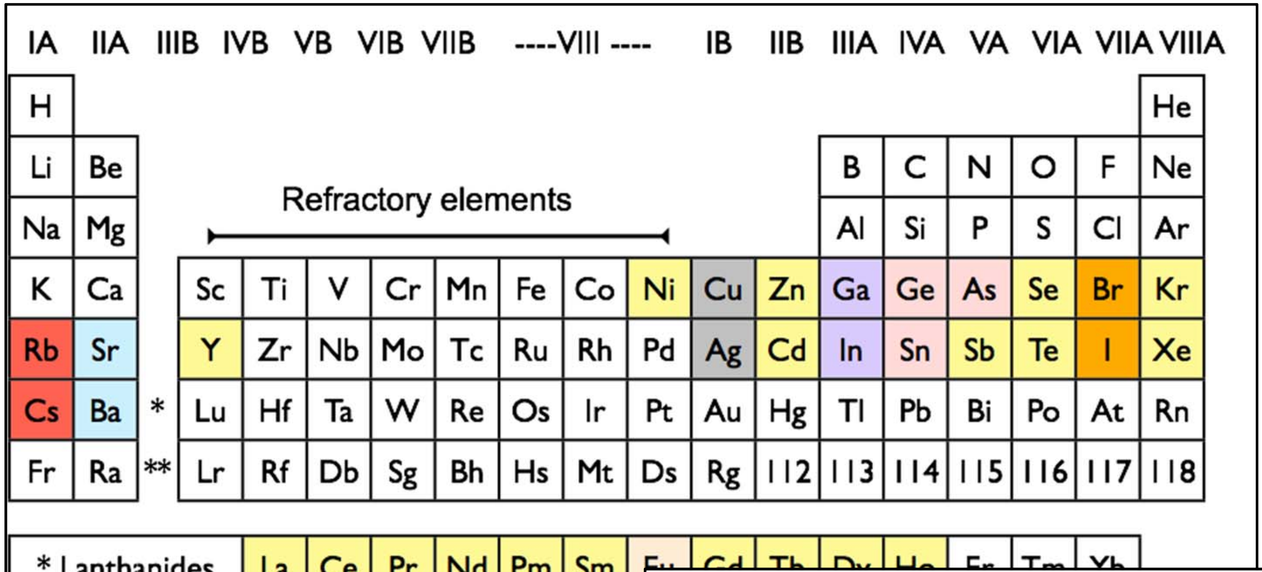
Range out experiment

gas cell

2-3 MeV/u

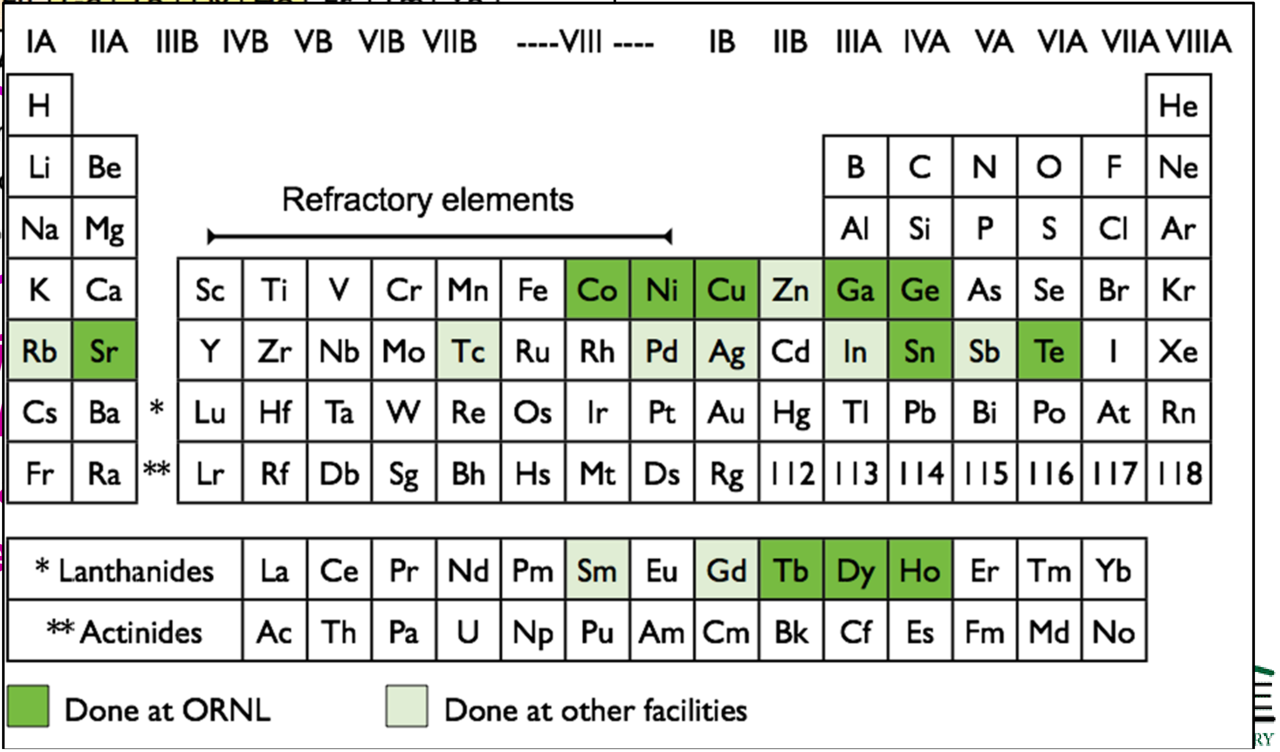
beam kicker

A variety of beam purification methods



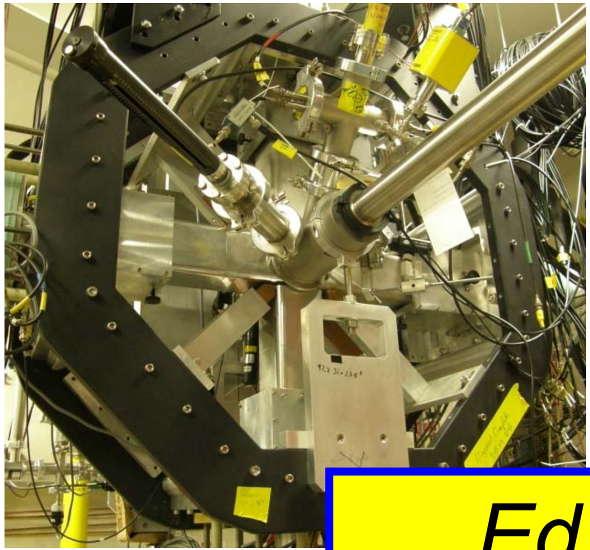
two-stage magneti
from molecular beams
to pure “nominal m
example: new $^{84-86}$Ge

selective
laser ionization

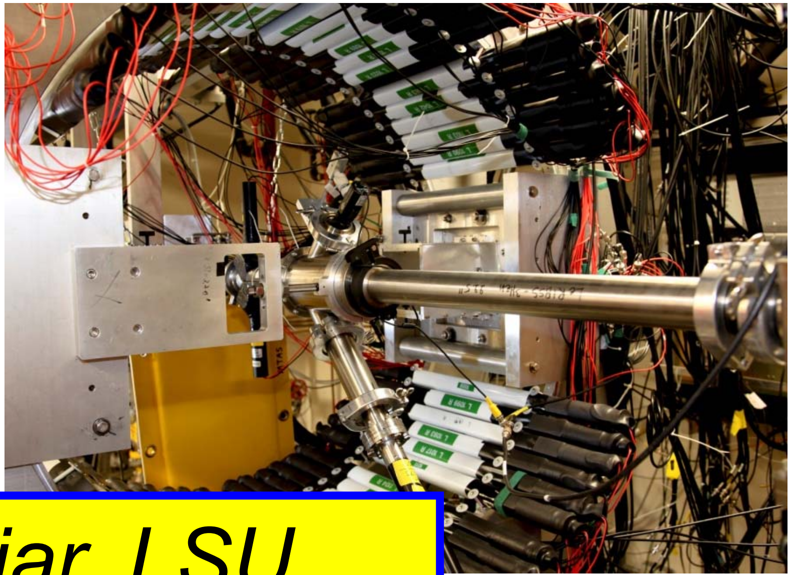


Detectors for beta decay studies

CARDS β-γ at LeRIBSS

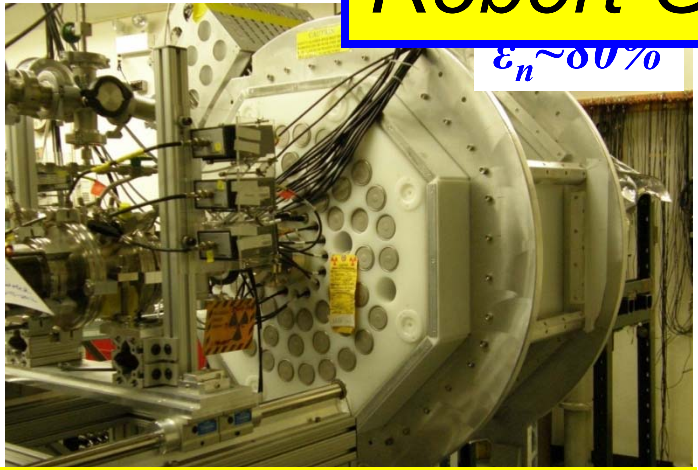


VANDLE n-TOF array at LeRIBSS



Ed Zganjar, LSU
Robert Grzywacz, UTK

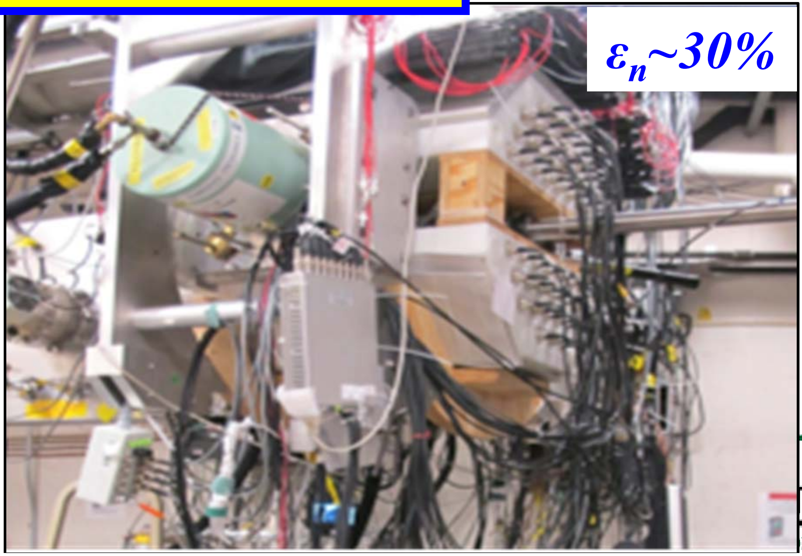
3Hen array after



ε_n~80%

850 liters of ^{3}He at 10 atm

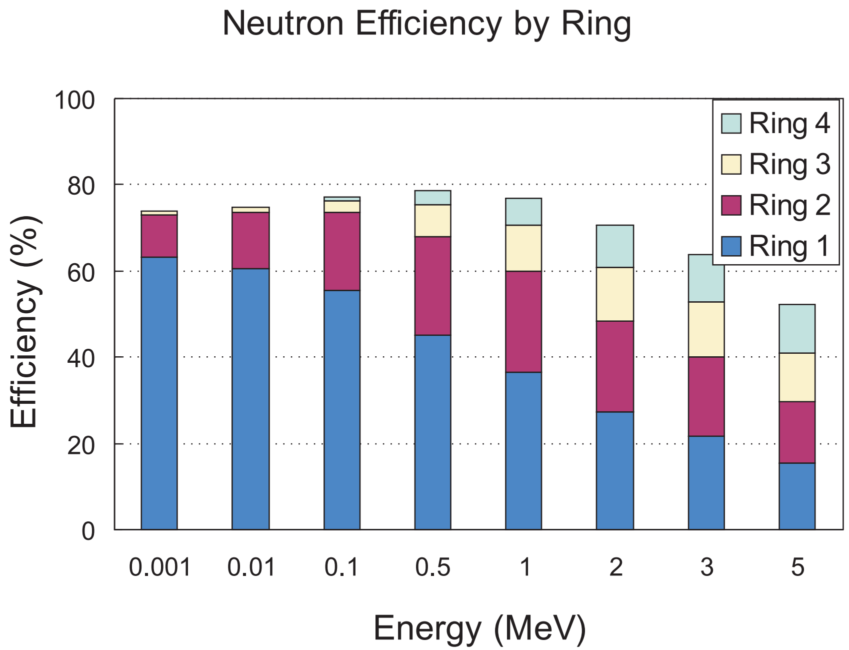
ray at LeRIBSS

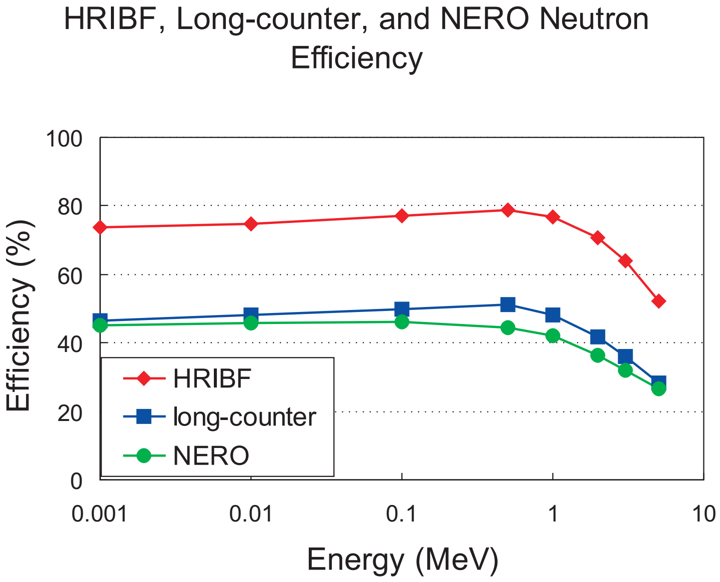


ε_n~30%

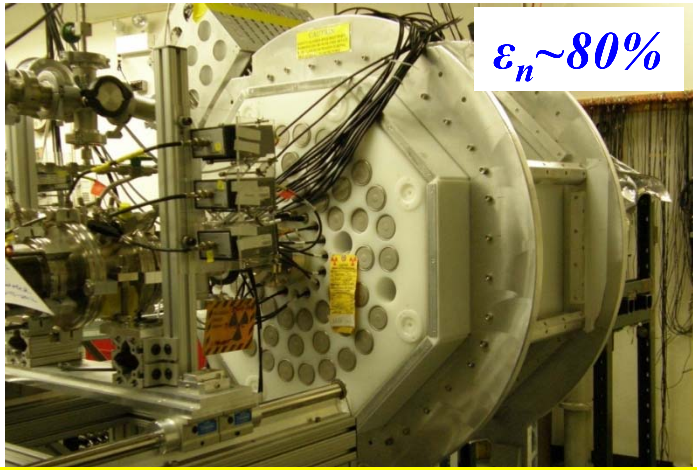
^{3}Hen Detector

nearly 80% efficient and segmented ^{3}Hen neutron counter





ORNL, UTK
LSU , Mississippi
UNIRIB



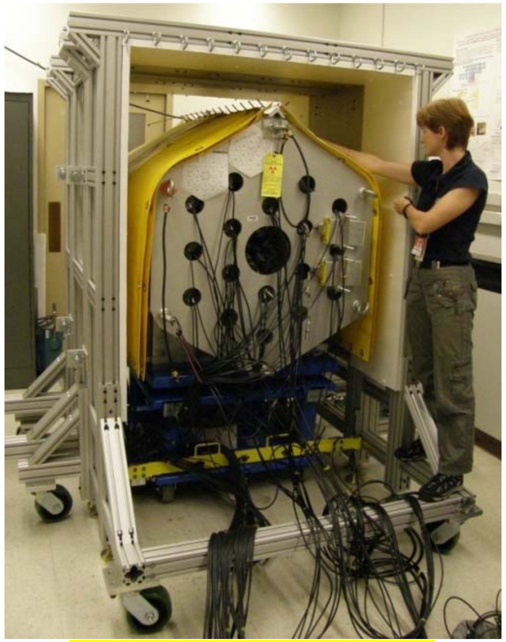
ε_n~80%

850 liters of ^{3}He at 10 atm

Detectors for beta decay studies

2200 pounds of NaI(Tl) - Modular Total Absorption Spectrometer (MTAS)
and its 12,000 pound shielding

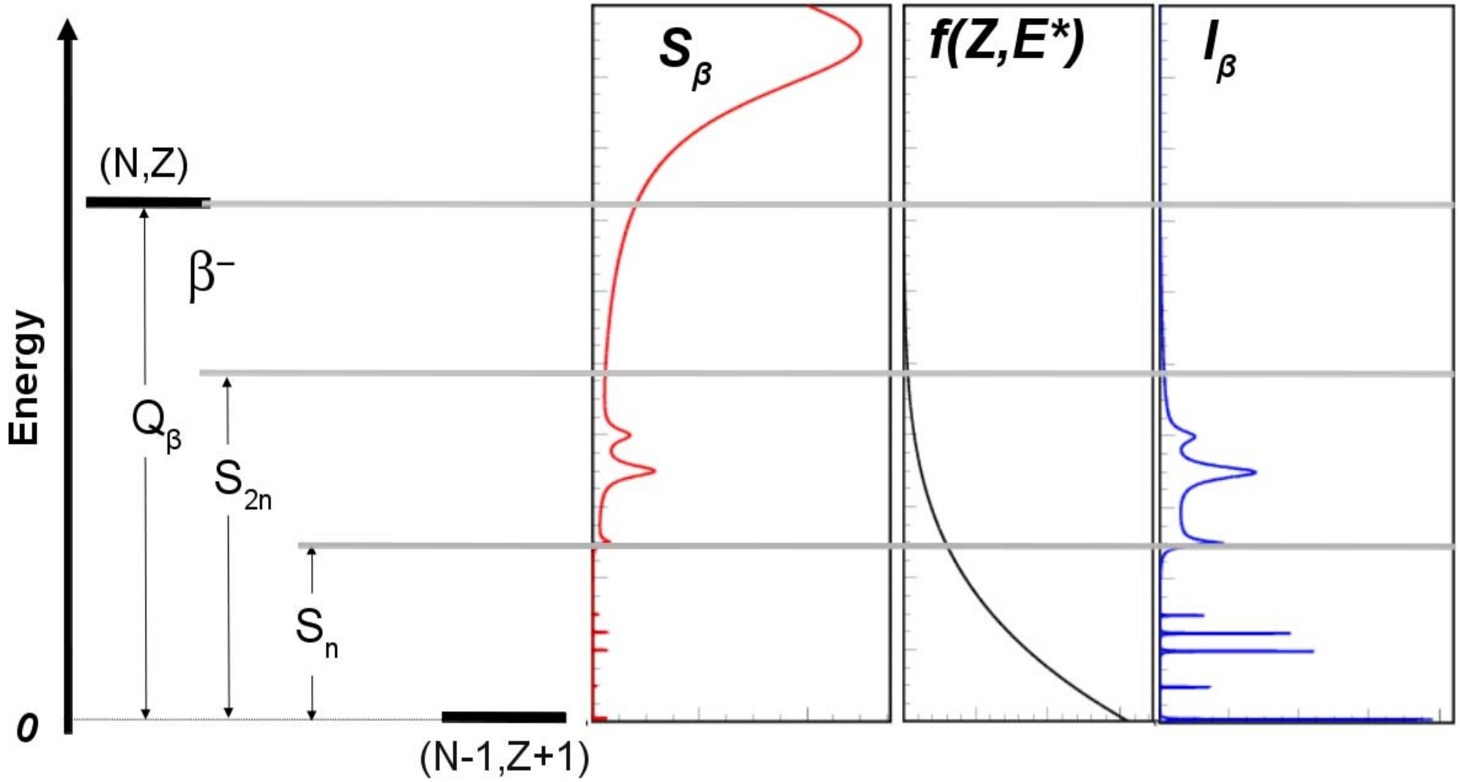
La 137 60 ky	La 138 0.09	La 139 99.91	La 140 1.68 d	La 141 3.92 h	La 142 92.6 m	La 143 14.3 m
Ba 136 7.85	Ba 137 11.23	Ba 138 71.7	Ba 139 83.06 m	Ba 140 12.75 d	Ba 141 18.27 m	Ba 142 10.7 m
Cs 135 2.3 My	Cs 136 13.16 d	Cs 137 30.17 y	Cs 138 32.2 m	Cs 139 9.27 m	Cs 140 63.7 s	Cs 141 24.94 s
Xe 134 10.44	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



Decays studied at HRIBF Tandem-OLTF-MTAS
are marked by yellow squares.
Labels “1” and “2” indicate the priority
for decay heat measurements established
by the Nuclear Energy Agency (NEA) in 2007

January 2012

Beta decay of very neutron-rich nuclei is very rich in interesting features



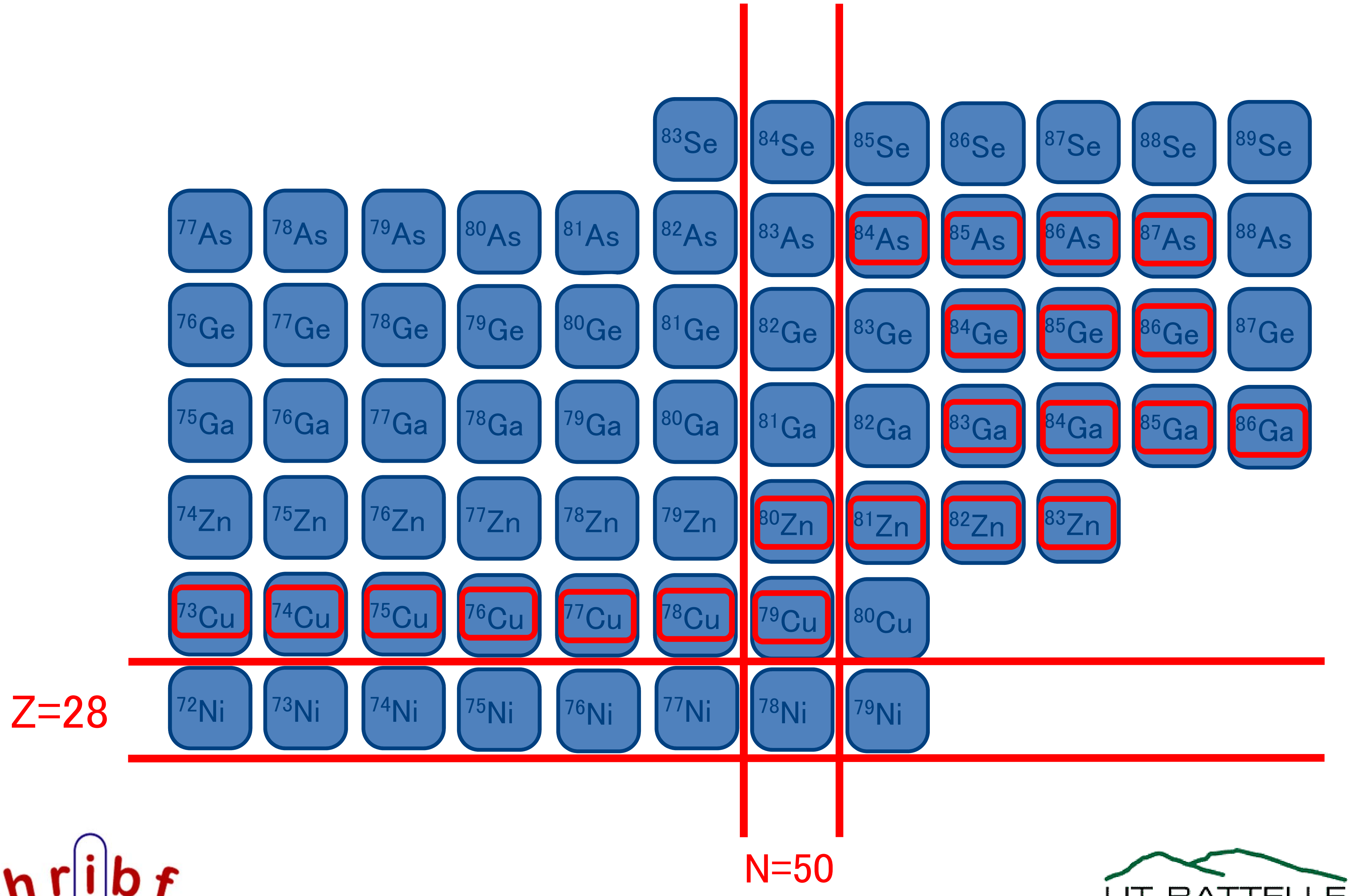
neutron detection

3Hen, VANDLE

$\beta\gamma$ ***and MTAS***

▢ ***22 parent radioactivities in ^{78}Ni region studied by means of βγ spectroscopy at the HRIBF***

^{78}Ni to ^{132}Sn region (~ 10), + MTAS (22), + VANDLE (29)

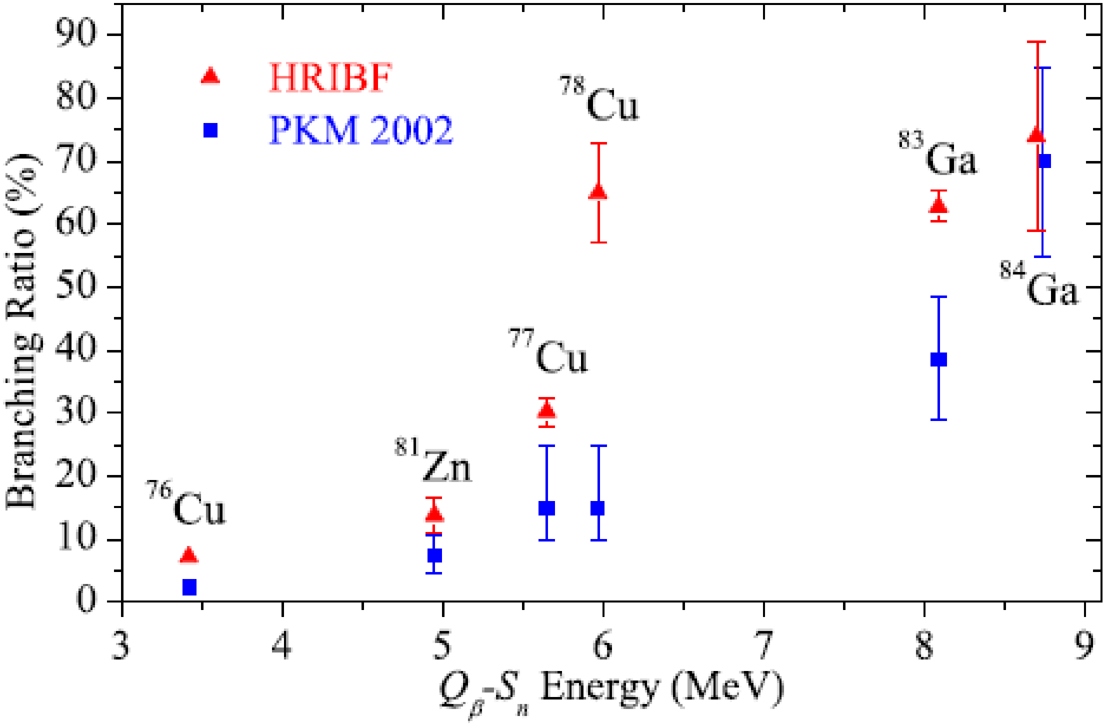


Beta-delayed neutron emission:

counting identified ions → absolute branching ratios

HRIBF results pointed to much higher β-delayed neutron branching ratios in comparison to earlier measurements and calculations

*see, e.g., **Pfeiffer, Kratz, Moeller (PKM 2002) Progress in Nucl. Energy, 41, 5 (2002)***

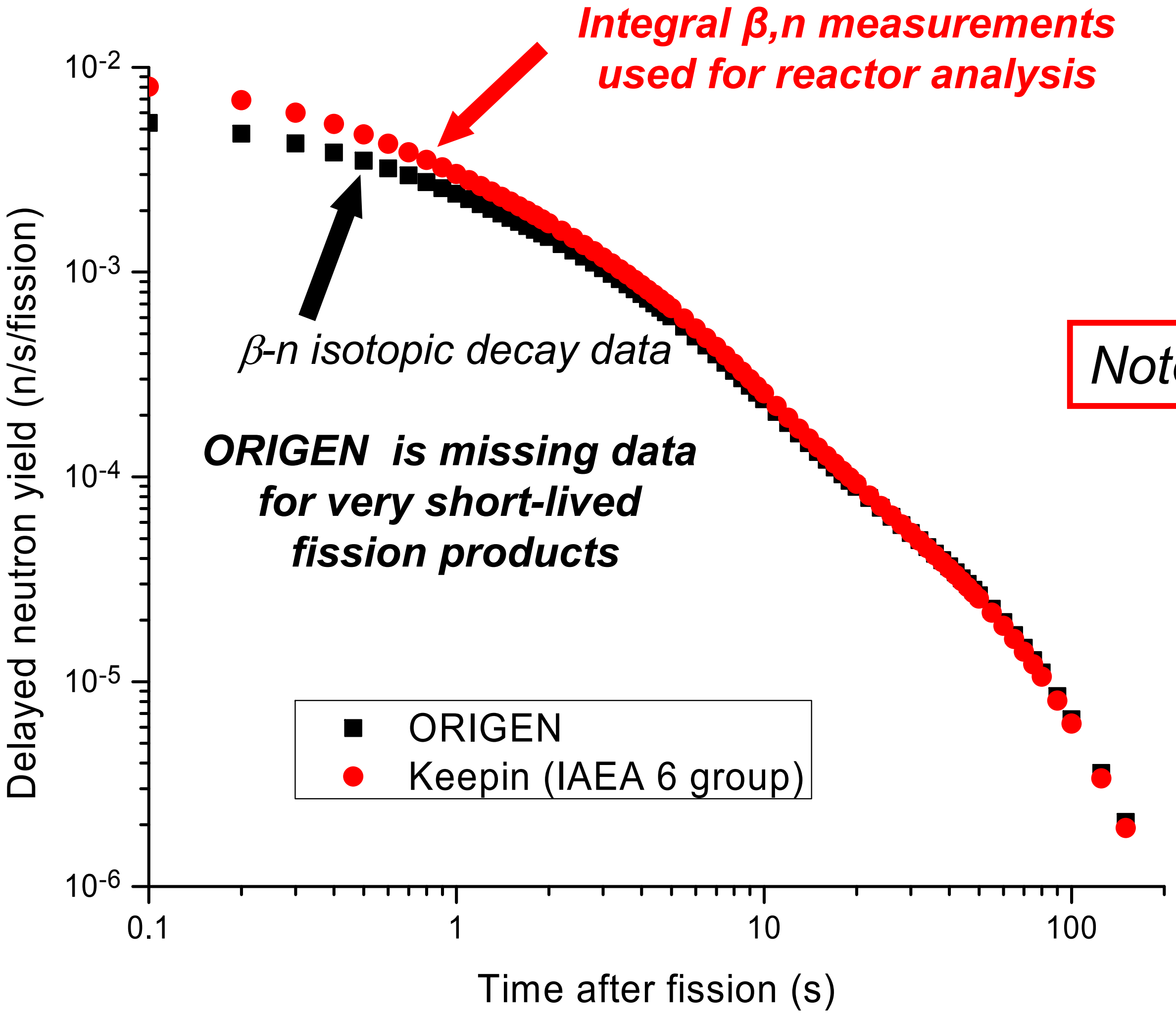


all βn-precursors given in this plot have $T_{1/2} < 1$ s

J. Winger et al., PRL 102, 142501 (2009) and *PRC **80**, 054304,2009; PRC **81**,044303,2010; PRC **82**, 064314 (2010); PRC **83**, 014322 (2011); PRC **86**, 024307,2012*

similar conclusions: P. Hosmer, H. Schatz et al., PR C82 , 025806, 2010

Delayed Neutron Yield following ^{235}U fission



Integral β,n measurements used for reactor analysis

β-n isotopic decay data

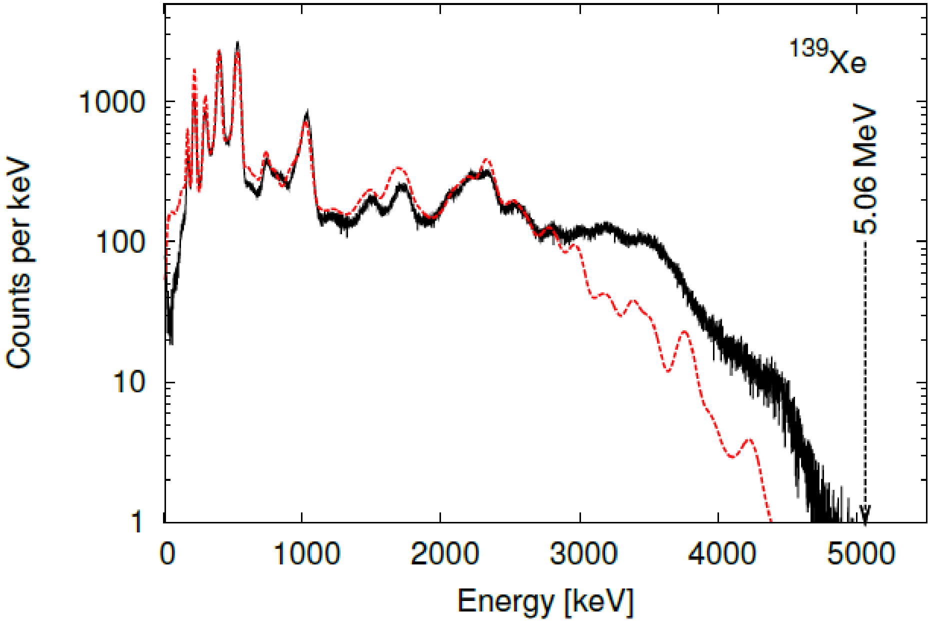
ORIGEN is missing data for very short-lived fission products

Note log scales !

from Ian C. Gauld, ORNL Reactor Science Group (2010)

Example of MTAS results – ^{139}Xe decay (A. Fijałkowska et al., ND2013)

(^{139}Xe ~5% cumulative fission yield for n_{th}+ ^{235}U)



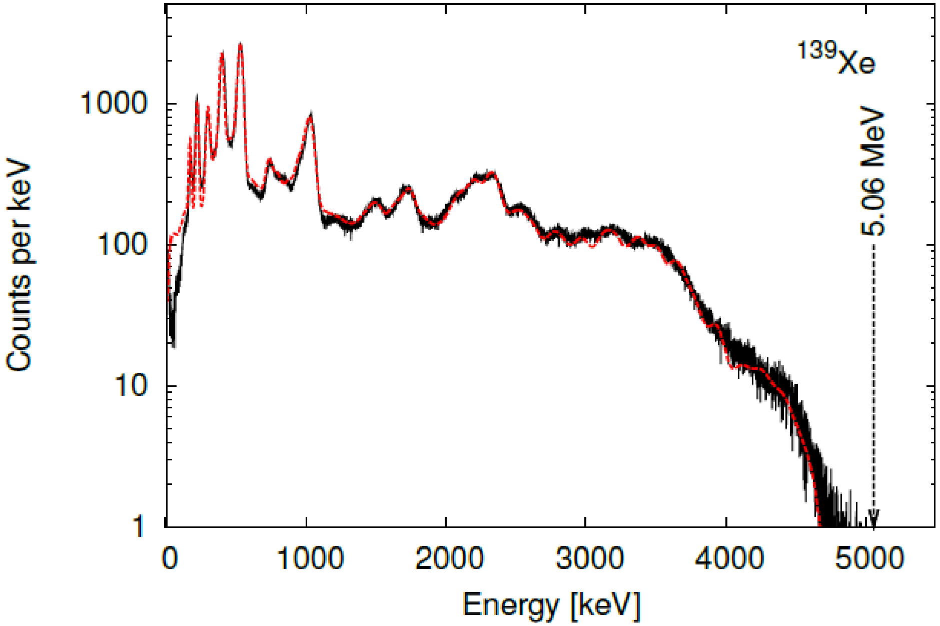
*MTAS data (**black**) compared to ENDSF-based simulations (red).*

Lack of β-feeding and following γ-energy release from highly excited states in a current data base !

MTAS-revised decay of ^{139}Xe

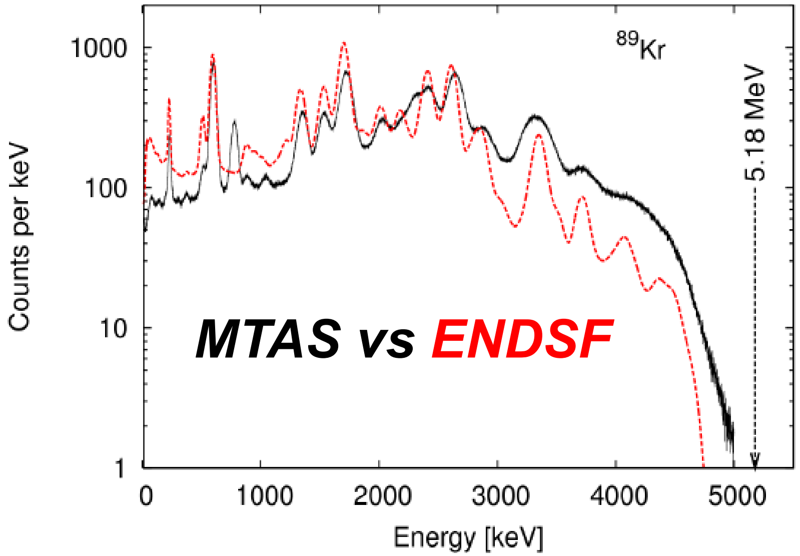
average γ-energy release increased

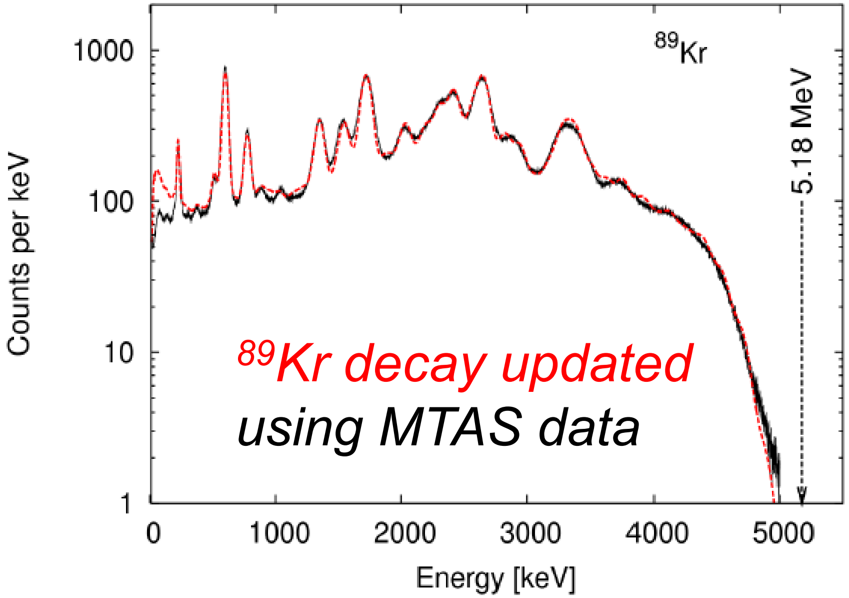
from 935 keV to 1146 keV (23%)



Examples of MTAS results (M. Karny et al., ND2013)

ENDSF decay scheme of 89Kr includes 57 levels and 288 γ-lines





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

average γ-energy release in ^{89}Kr β-decay increased from 1801 keV to 2467 keV

37% effect

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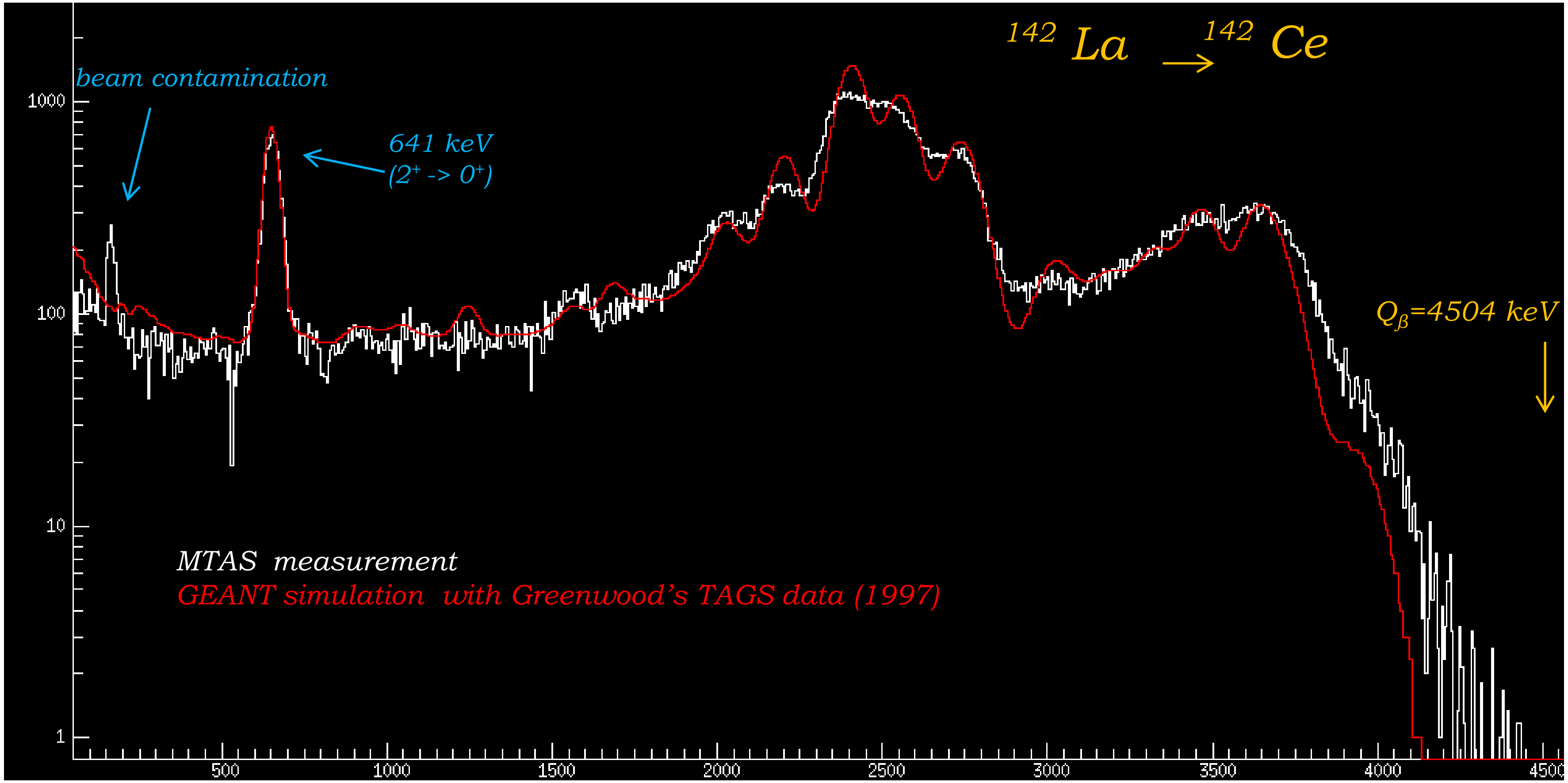
MTAS spectra fit reliable decay schemes
$^{142}La \rightarrow ^{142}Ce$, M. Wolinska-Cichocka et al., ND2013

Earlier measurement for ^{142}La decay was performed
with Total Absorption Gamma Spectrometer TAGS [see Greenwood et al. NIM A390 (1997)]



TAGS based simulations are close to MTAS data
(high-resolution data do not agree with TAGS and MTAS)

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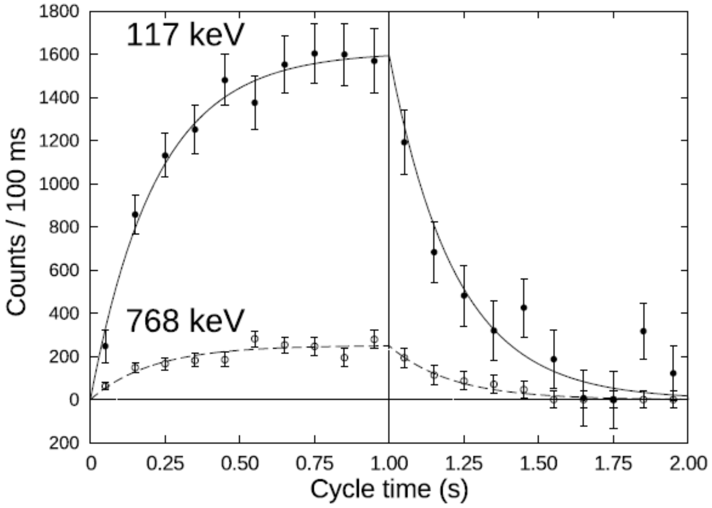
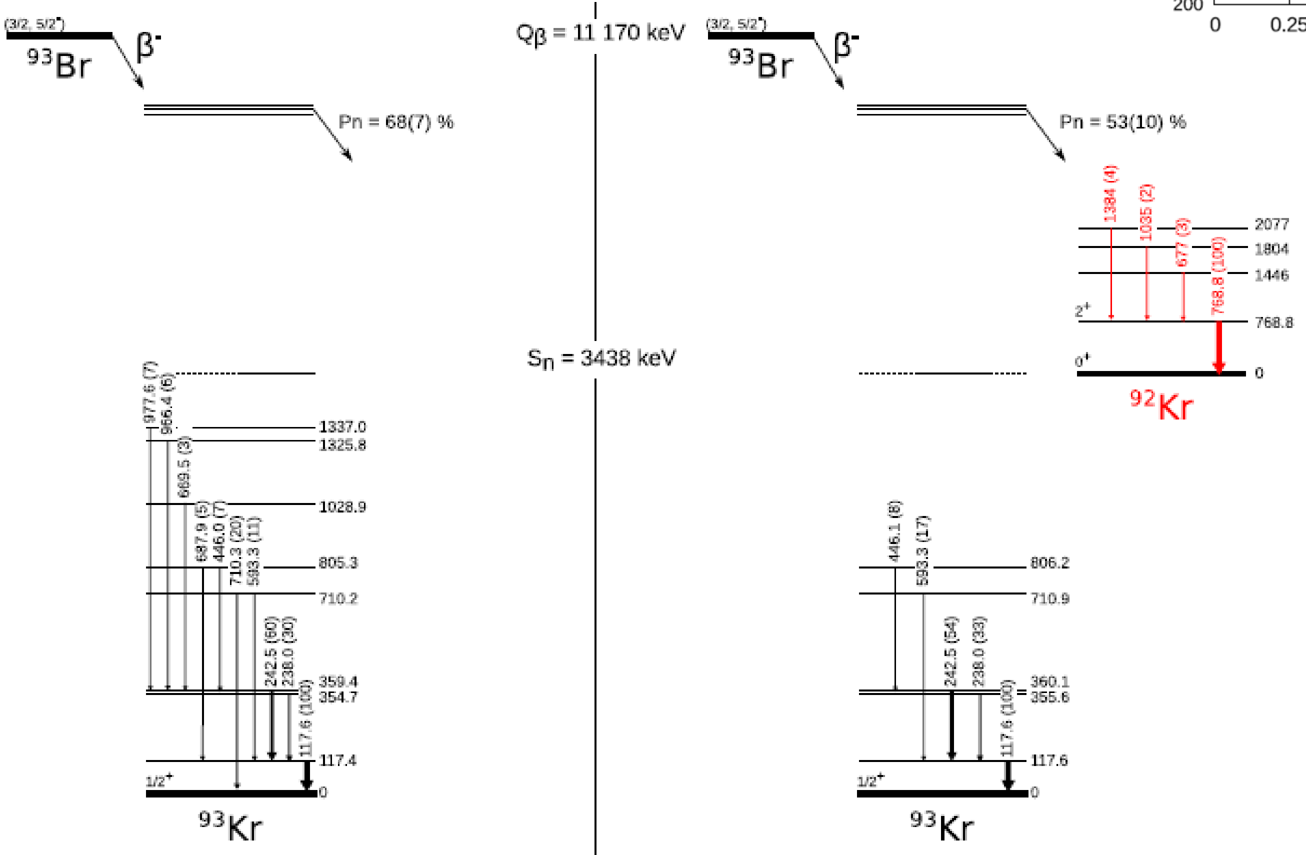
K. Miernik et al., ND 2013, March 2013

$\beta\gamma$- and $\beta n\gamma$- decay of ^{93}Br

$T_{1/2}$=102(10) ms ??
(no exp evidence presented)

$T_{1/2}$=152(8) ms





G. Lhersonneau et al. (2001)

This work

CASL

http://www.ornl.gov/sci/casl/

May 2010 : the Department of Energy creates the first nuclear energy innovation hub -- the ***Consortium for Advanced Simulation of Light Water Reactors (CASL)*** *-- headquartered at Oak Ridge.*

The first task will be to develop ***computer models that simulate*** *nuclear power plant operations, forming a "virtual reactor" for the predictive simulations of light water reactors. Other tasks include using* ***computer models*** *to reduce capital and operating costs per unit of energy, safely extending the lifetime of existing U.S. reactor and reducing nuclear waste volume generated by enabling higher fuel burn-ups.*

We should remember that even the very best simulations of nuclear fuel cycles require correct experimental input data.

"Conquering nuclear pandemonium"

KR's *Viewpoint* in Physics, 3, 94, 2010

(credit to A. Algora et al., PRL 105, 202501, 2010)

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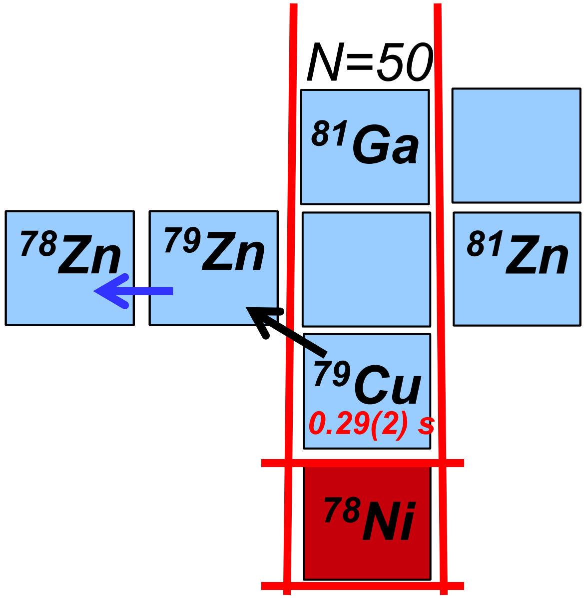
^{79}Cu decay (HRIBF LeRIBSS)



initial yields : **^{79}Zn ~ 10^5** *pps* *^{79}Cu$^+$ ~* **40** *pps*

after **charge exchange** *:* **^{79}Zn 0.0 pps** *^{79}Cu$^-$ ~* **2 pps**

pure beam of ^{79}Cu ions → single neutron-hole states in N=49 ^{79}Zn

half-life of ^{79}Cu

K.-L. Kratz 1991 : 188(25) ms (multi βn fit)

P. Hosmer 2010 : 257(+ 29,- 26) ms (ion-β)

D. Miller 2013: 290(20) ms (β-γ 730 keV)

D. Miller, R Grzywacz et al., to be published

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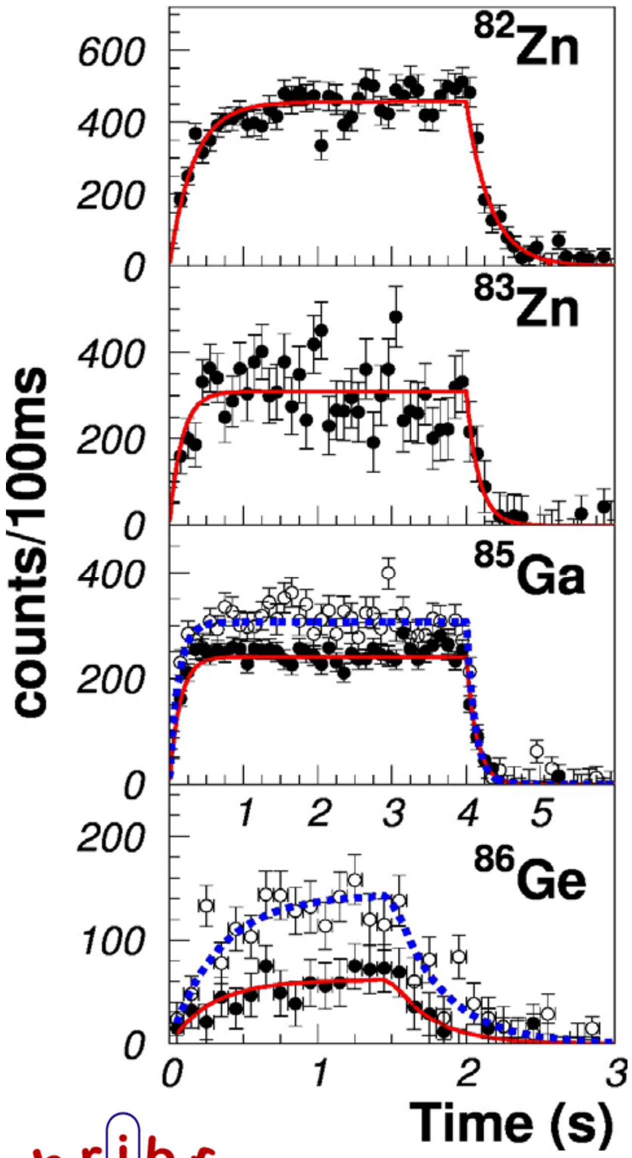
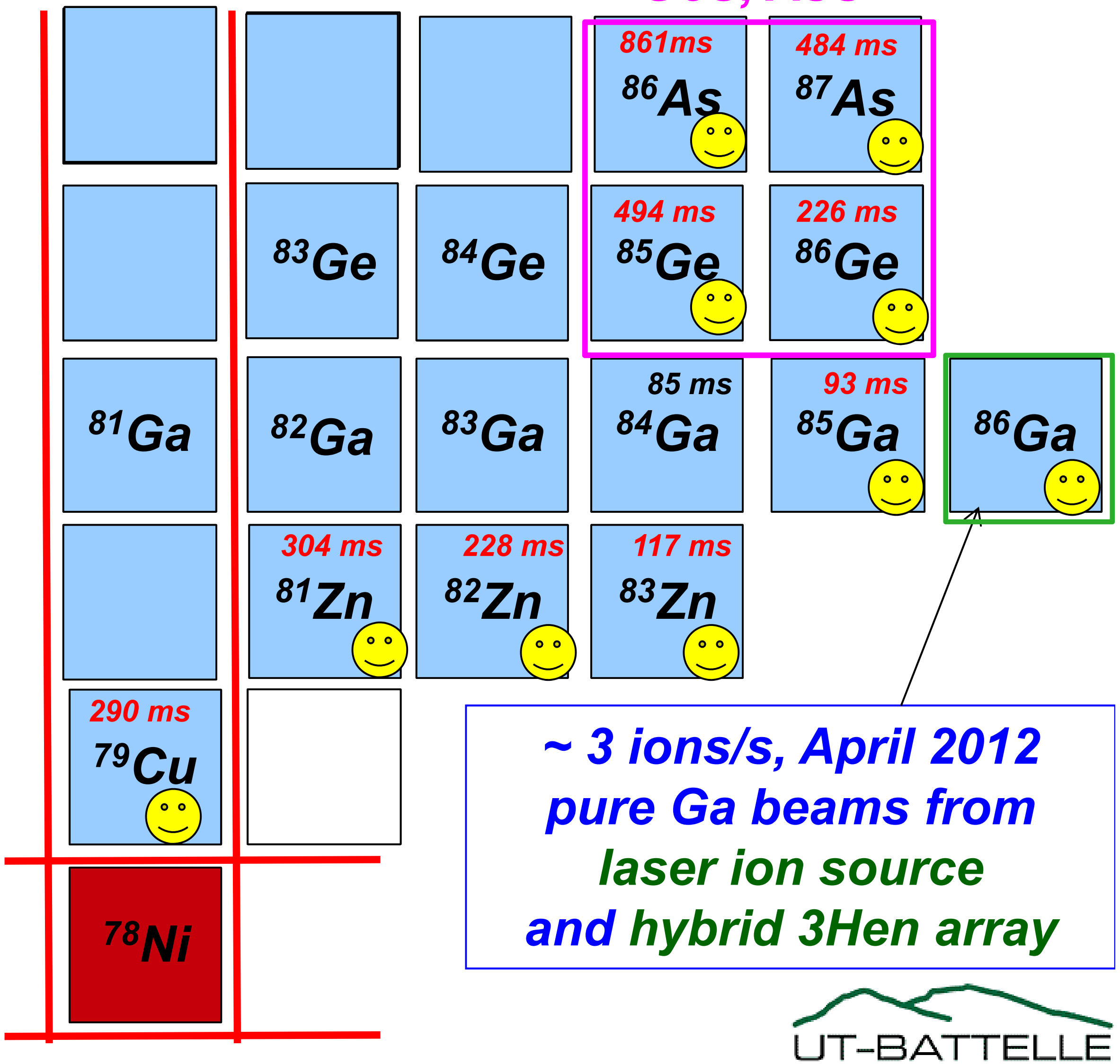
$\beta\gamma$ spectroscopy - new beta decays

Madurga et al., PRL 109, 2012 and *Mazzocchi et al., PRC 87, 2013*





molecular beams
GeS, AsS

861ms ^{86}As

484 ms ^{87}As

^{83}Ge

^{84}Ge

494 ms ^{85}Ge

226 ms ^{86}Ge

^{81}Ga

^{82}Ga

^{83}Ga

85 ms ^{84}Ga

93 ms ^{85}Ga

^{86}Ga

304 ms ^{81}Zn

228 ms ^{82}Zn

117 ms ^{83}Zn

290 ms ^{79}Cu

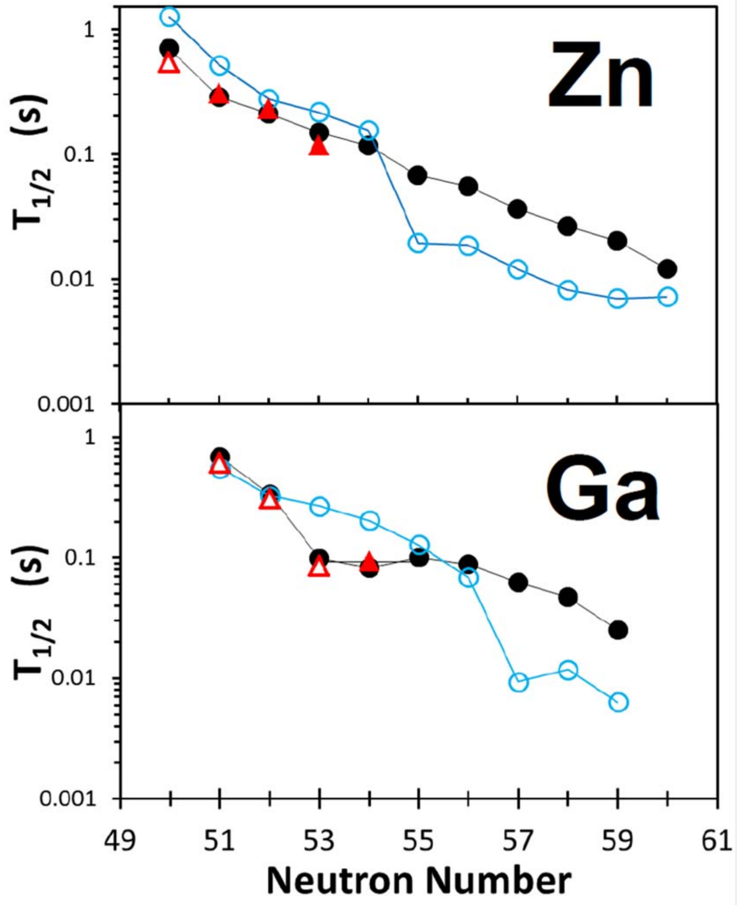
^{78}Ni

~ 3 ions/s, April 2012
pure Ga beams from
laser ion source
and hybrid 3Hen array

Exp half-lives → β-theory → r-process

(HRIBF measurements → I.Borzov's analysis → R.Surman's modeling)

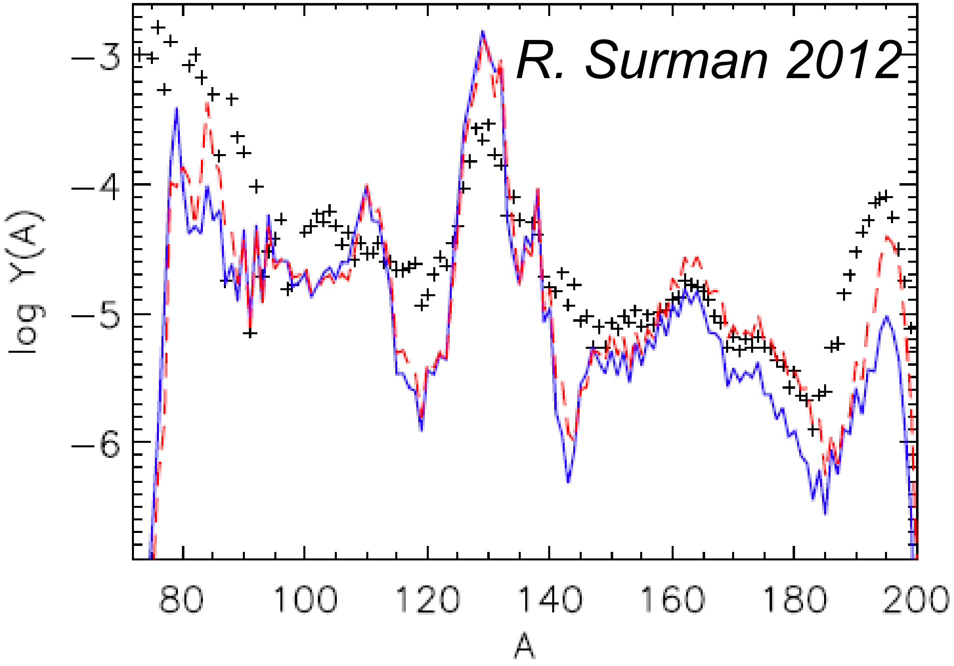
M. Madurga et al., Phys. Rev. Letters, 109, 112501, 2012



▲ *experiment*

○ *FRDM Moeller 2003*

● *DF3a+CQRPA Borzov 2011*



\+ *post r-process abundances*

— *simulations with Moeller'sT$_{1/2}$'s*

\- - *simulations with Borzov's T$_{1/2}$'s*

Beta-delayed multi-neutron emission

Decay of N=55 ^{86}Ga studied with “hybrid 3Hen” at LeRIBSS in April 2012. ***Pure*** *beams of ^{83,85,86}Ga isotopes were produced at the IRIS-2 RIB platform using* ***laser ion source*** *RILIS*

Y. Liu et al., Nucl. Instr. Meth. Phys. Res. B298, 5, 2013.

K. Miernik et al., 2013

pure beams: 100 pps of ^{85}Ga, ~ 1- 3 pps of ^{86}Ga

RIKEN now ~ 0.1 pps

Summary

Decay studies of fission products at the HRIBF created a lot of new and reliable data on fission products decays

1. High energy resolution measurements with pure beams
of known intensities (when post accelerated)
ranging-out technique and gamma-beta-conversion electron detectors
→ *basic "high energy resolution" decay scheme + βn-branching ratio*

*2. **Measurements with Modular Total Absorption Spectrometer MTAS***
MTAS energy spectra in segmented array
→ *beta strength within $\beta\gamma$-window (decay heat)*

*3. **Measurements involving 3Hen and VANDLE → β-delayed neutrons***
*βn-intensities and βn-energy spectra **/Robert Grzywacz/***
→ *beta strength above neutron separation energy*

Combining **high-res γ-data**, **3Hen, MTAS**, **VANDLE**

→ *determination of a full β-strength function and its consequences*
→ *comparison with theory and further development of modeling*

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2008-2012 LeRIBSS – OLTF HRIBF campaigns

ORNL : C.J. Gross, Y. Liu, T. Mendez, K. Miernik, KR , D. Shapira, D. Stracener
UT Knoxville : R. Grzywacz, K.C. Goetz, M. Madurga, D. Miller, S. Paulauskas, S. Padgett, L. Cartegni , A. Fijałkowska, M. Al-Shudifat and C.R. Bingham
ORAU/ORNL : C. Jost, M. Karny, M. Wolińska-Cichocka
Mississippi : J. A. Winger, S. Ilyushkin
Louisiana **:** Ed Zganjar, B.C. Rasco
UNIRIB : J.C. Batchelder , S. H. Liu
Vanderbilt : N. Brewer, J.H. Hamilton, J.K. Hwang, A. Ramayya, C. Goodin
Warszawa : A. Korgul , C. Mazzocchi
Kraków : W. Królas *IAEA:* I. Darby *NSCL-MSU:* S. Liddick

+ VANDLE collaboration (talk by R. Grzywacz)

theoretical analysis *:*

I.N. Borzov (*JIHIR/Dubna/Obninsk*), K. Sieja (*Strasbourg*), *R. Surman*(*NY-JINA)*
J. Dobaczewski (*Warszawa/Jyväskylä*), R. Grzywacz (UTK/ORNL)

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