Digital beta-delayed neutron array 3Hen at ORNL

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Workshop on beta-delayed neutron emission experiments at RIBF

RIKEN, Wako

30th July 2013

Motivation for our decay studies of neutron-rich nuclei (including beta-delayed neutron emitters)

- Decay rates are important for understanding the origin of atoms and nuclei
  - **β half-lives** and **β-delayed (multi) neutron emission** during rapid neutron capture process

- Decay spectroscopy tracks the evolution of nuclear matter at the limits
  - single-particle states and onset of collectivity near doubly-magic ^{78}Ni and ^{132}Sn studied using, e.g., **neutron-gated gamma counting**

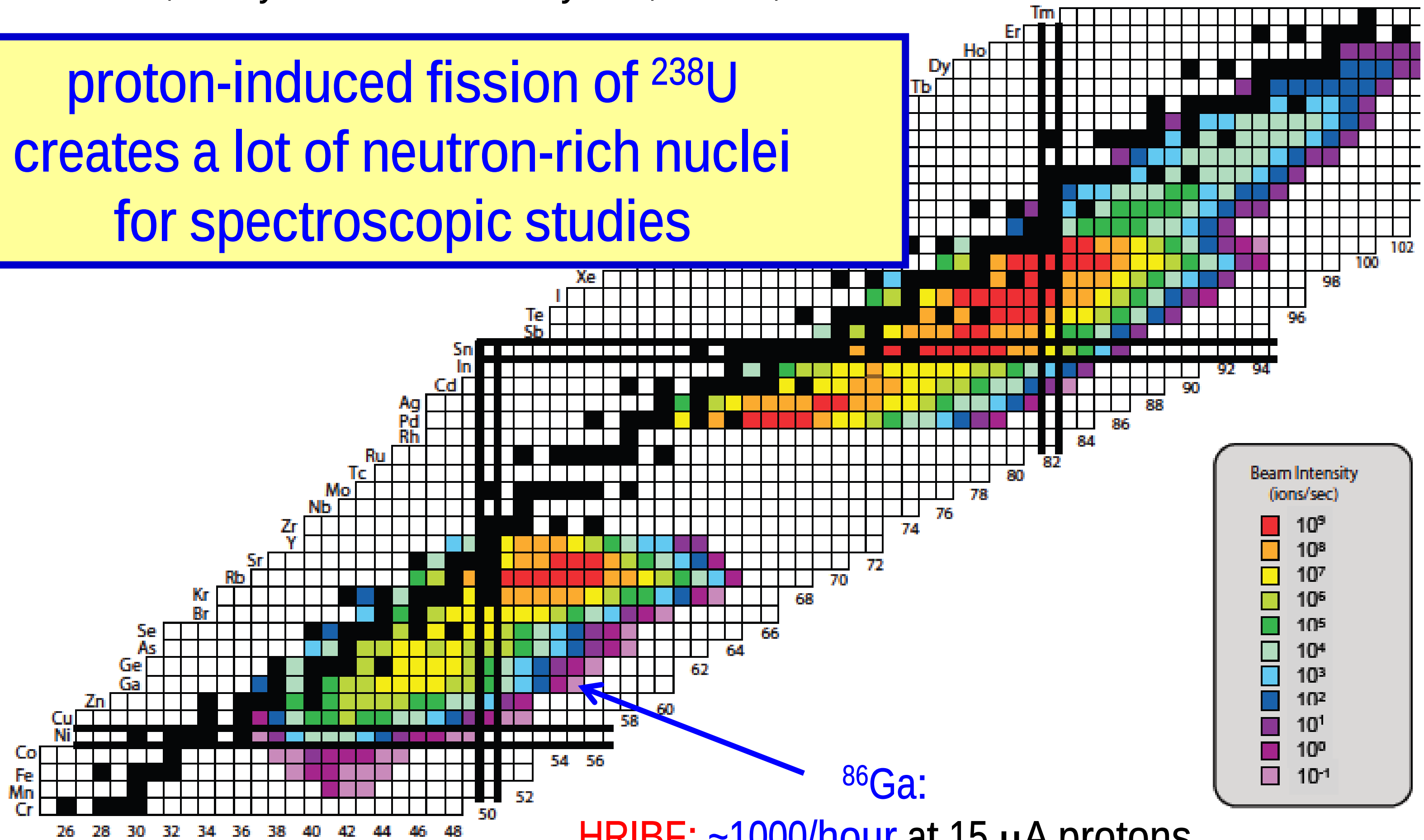
- Decay spectroscopy results impact our society
  - **decay heat** and **beta-delayed neutrons** released during nuclear fuel cycle

Decay spectroscopy is sensitive to the most exotic isotopes produced at very low rates, so often provides crucial last data before extrapolation into the unknown.

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



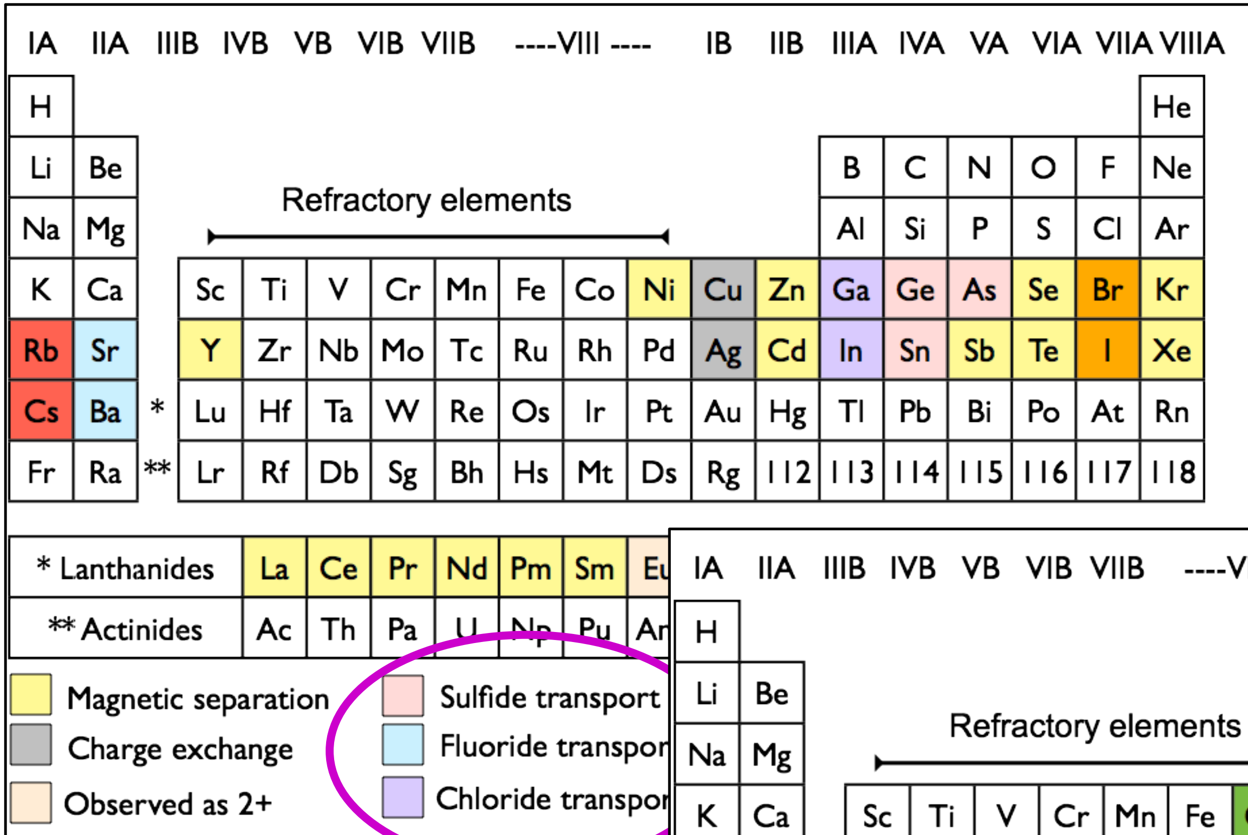
^{86}Ga:

HRIBF: ~1000/hour at 15 μA protons

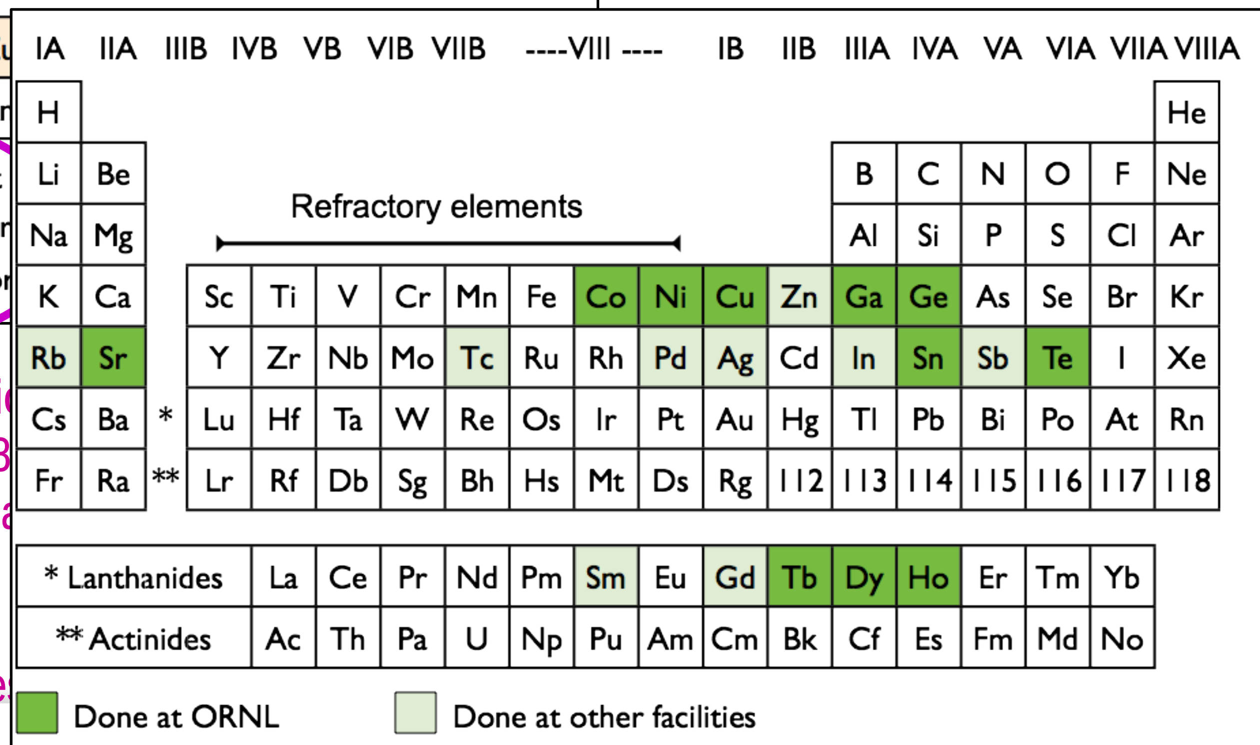
pure beam at the HRIBF !

RIKEN:10/hour at 0.2 pnA ^{238}U, Ohnishi et al., JPSJ 2010

A variety of beam purification methods



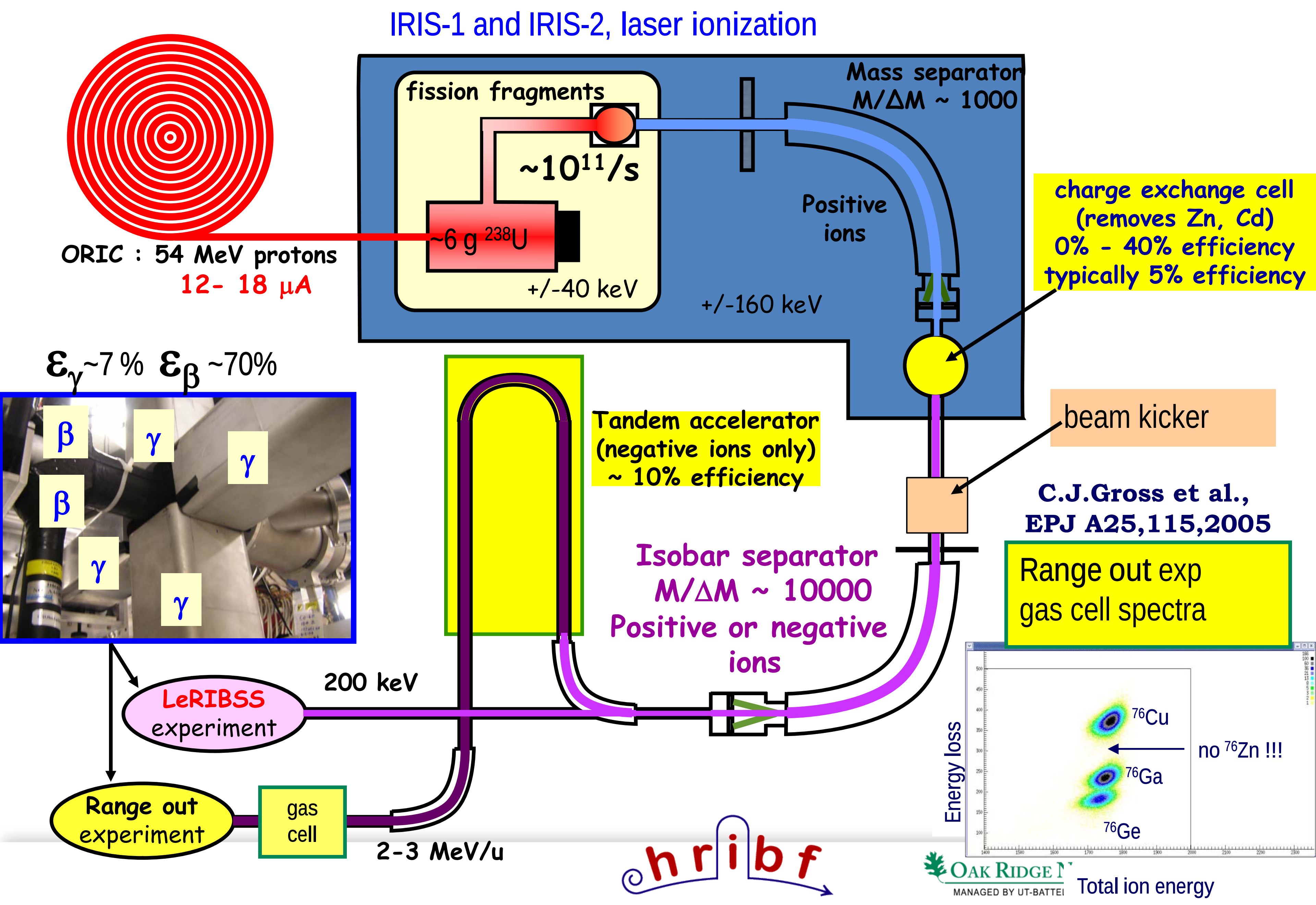
selective
laser ionization



two-stage magnetic separati
from molecular beams (like A=118
to pure "nominal mass A" bea
(like A=86)

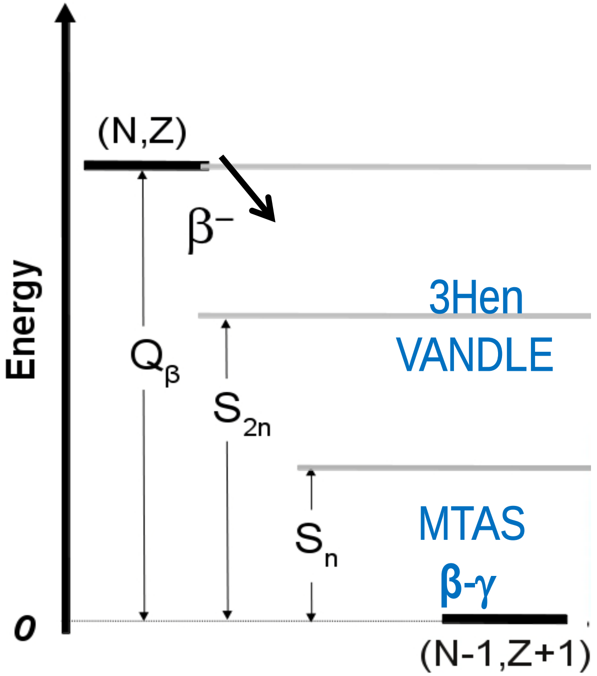
example: new $^{84-86}$Ge,$^{84-87}$As re

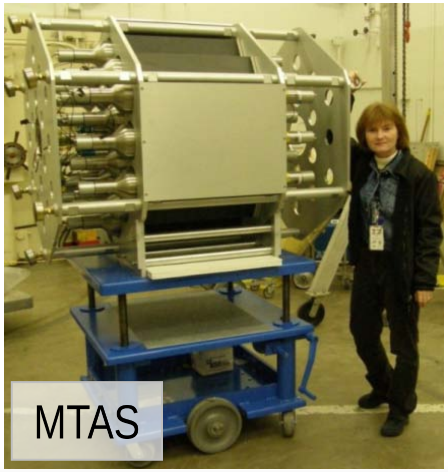
Decay studies of fission products at the HRIBF

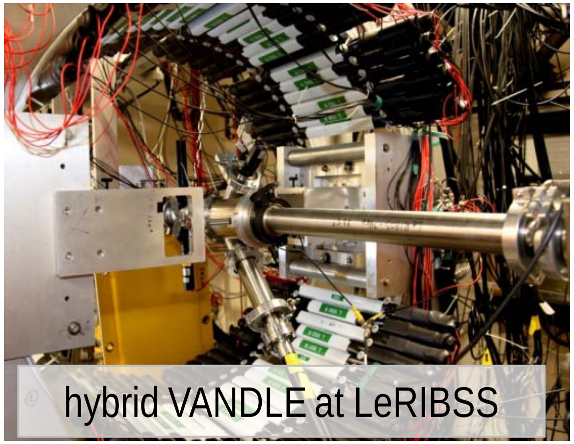


Development of Detectors for Studies of β-strength function in neutron-rich nuclei

- High efficiency detectors for complete spectroscopy of beta-decays in full decay energy window
- Modular designs allow hybrid β-γ-neutron configurations at Low–energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS)
- Important contributions from LSU and UTK collaborators
- Decays of about 70 neutron-rich nuclei were studied in 2010-2013 using **β-γ**, 3Hen, VANDLE and MTAS

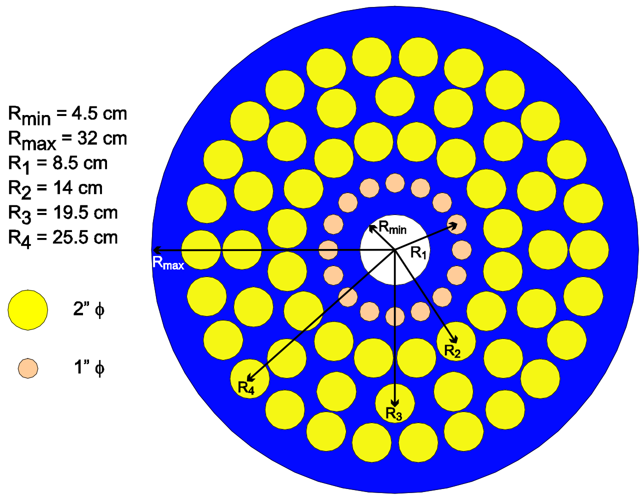



MTAS


hybrid VANDLE at LeRIBSS

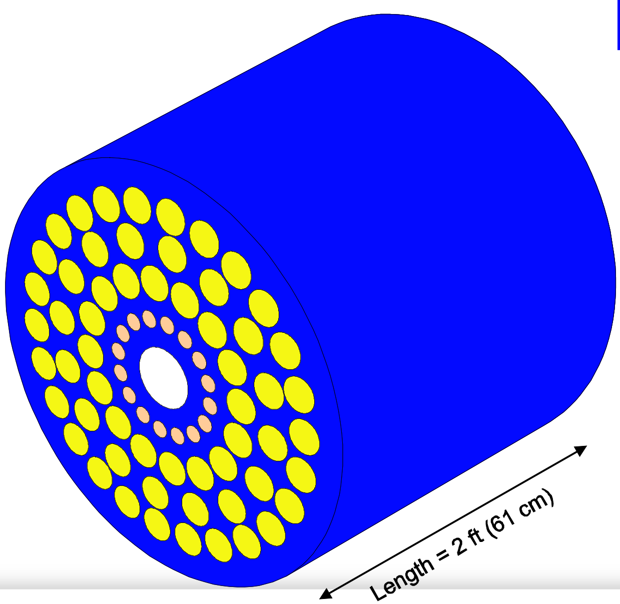

hybrid 3Hen at LeRIBSS

Digital beta-delayed neutron detector ^{3}Hen



art by Carl Gross

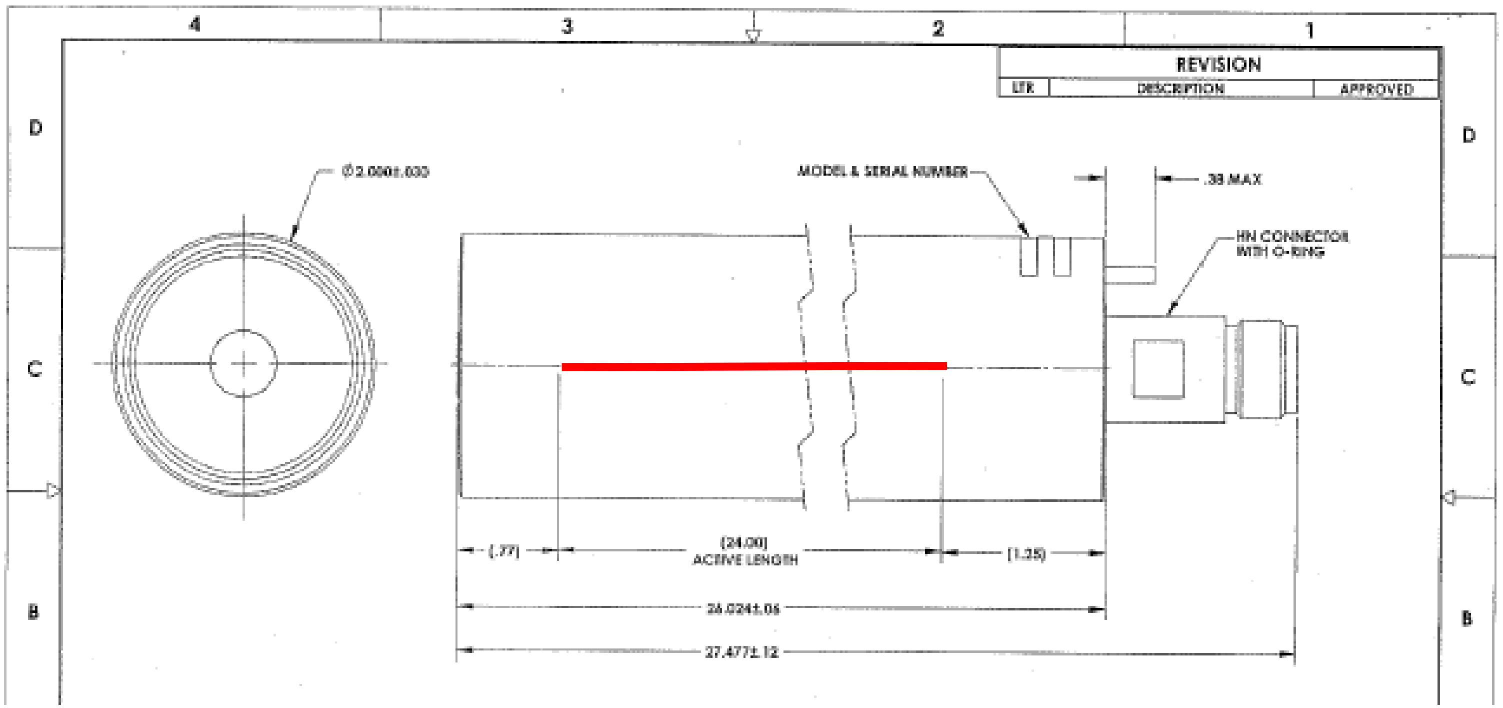
seventy four neutron detecting ^{3}He tubes
in a High-Density Polyethylen (HDPE) moderator structure
(purchase order for next five 2", 10 atm tubes submitted)



90 mm diameter thru-hole
(to accommodate β-trigger detectors)
~ 1" of HDPE before reaching the first ring of 3He tubes

3He, 10 atm, 2” diameter tube from GE Reuter Stokes

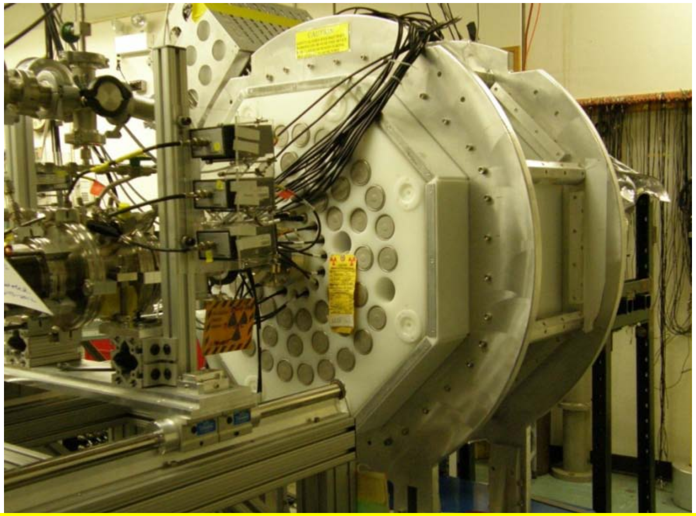
note the dimensions (drawing not too scale) and active length position !



27.5” total solid length plus cable connector

3Hen detector for βn decay studies

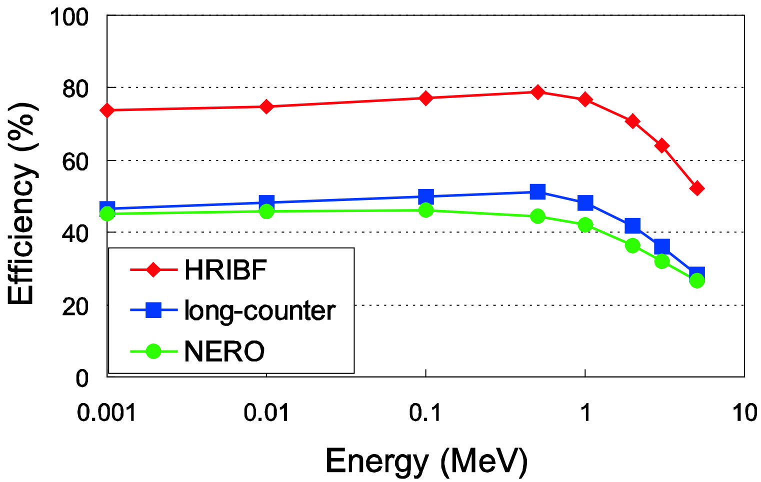
3Hen array after "ranging-out" of post-accelerated radioactive ions



~ 800 liters of ^{3}He in 10 atm tubes
1" HDPE+1 mm Cd n-shields around 3Hen

efficiency simulations done using MCNP (R. Lilly) and GEANT4 (S. Liddick) - good agreement reached.

HRIBF, Long-counter, and NERO Neutron Efficiency

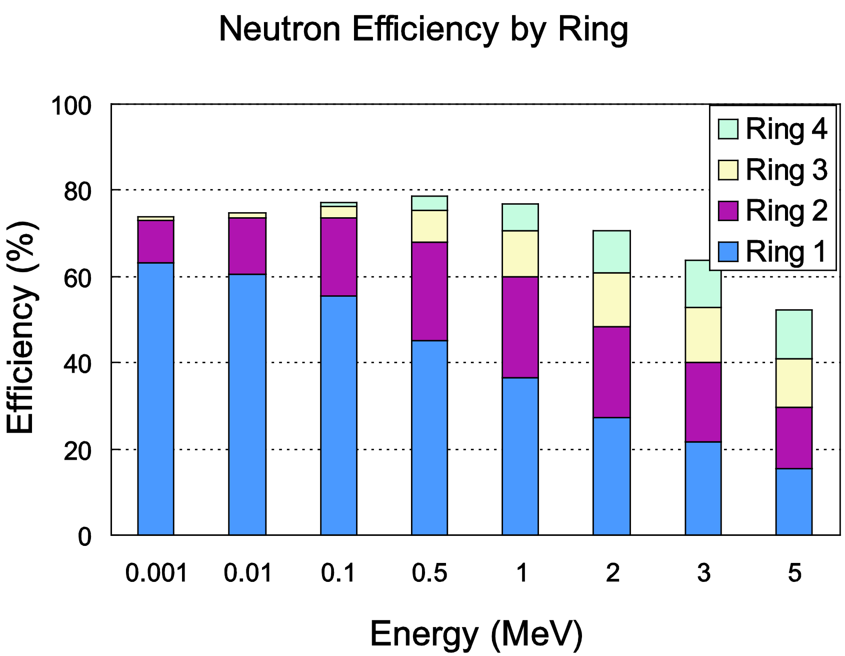


calculated ε_n nearly 80% around 800 keV and over 50% at 5 MeV

seven MESYTEC 16-channel preamps with one HV distributed channel each,
remotely controlled MPOD-ISEG HV supply (several positive HV cards available)
all signals collected using Pixie16 100 MHz or 250 MHz digital electronics

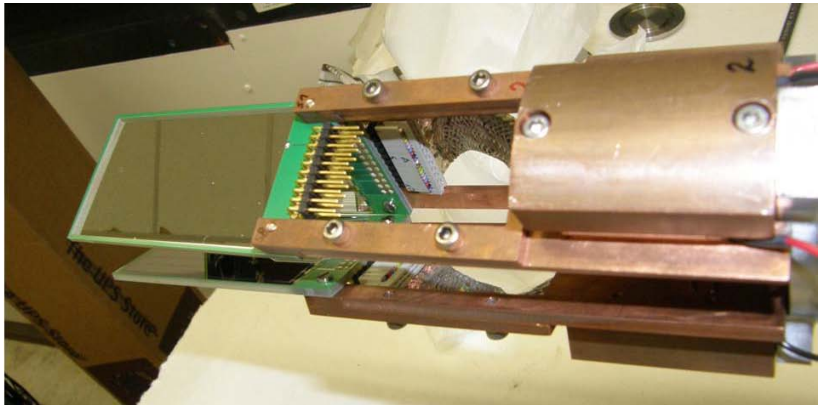
More about ^{3}Hen Detector

ORNL, UTK, LSU, Mississippi, NSCL, UNIRIB



GEANT4 simulations: Sean Liddick
MCNP: R. Lilly (ORNL)

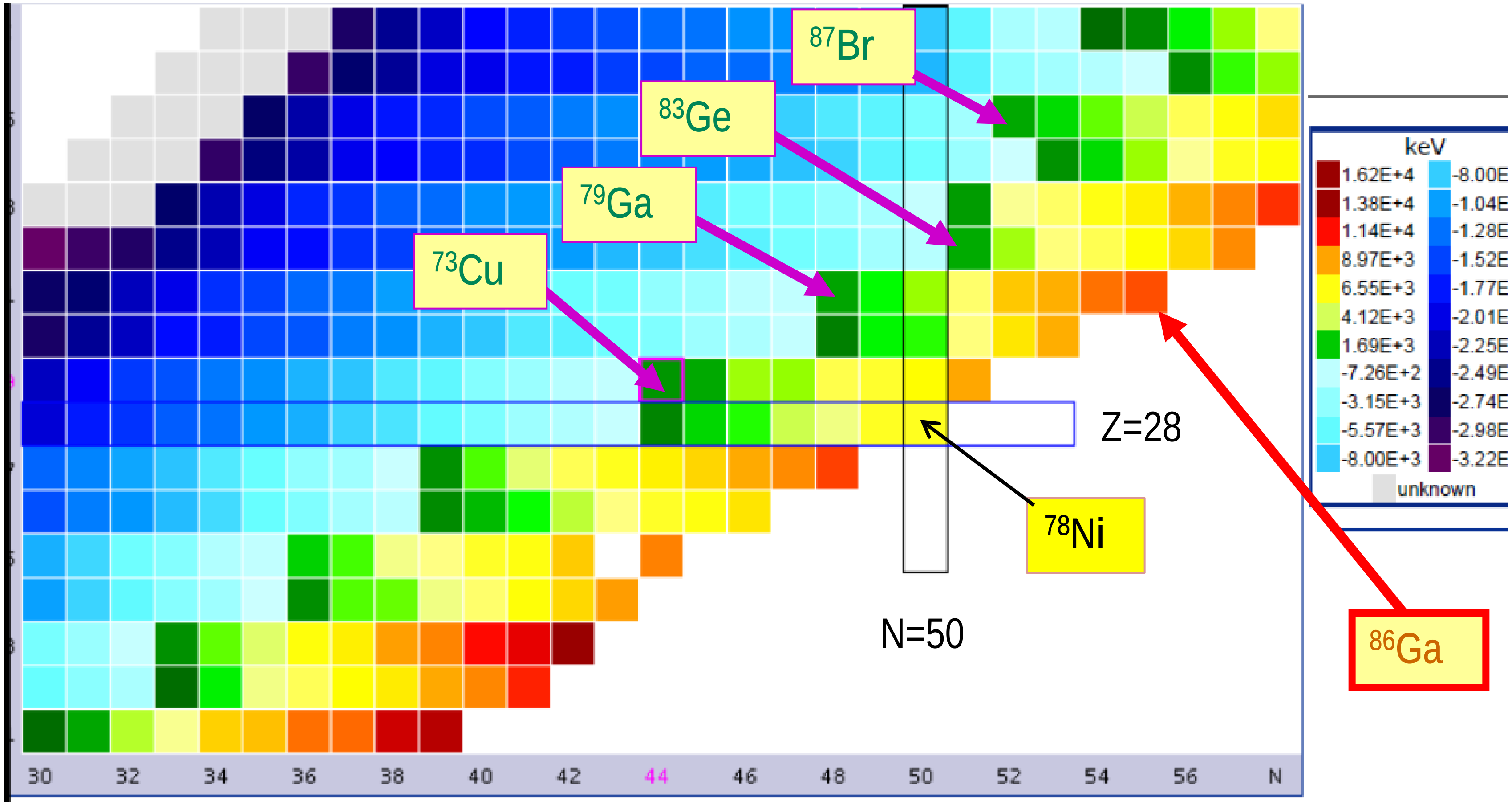
Si-triangle inside 3Hen – beta energy-loss trigger
three 1-mm thick 8-strips SSDs, ~ 80 mm long
~ 20 keV fwhm for 400-1000 keV electron energy range
~ 35 keV energy threshold, ~ 70 % efficiency



beta detectors surrounding
the activity collected on movable tape

discovery experiments (HRIBF, NSCL, TRIUMF, RIKEN, FRIB)
and applied studies (HRIBF, TRIUMF)

from NNDC :
energy window (Q_β - S_n) for β-delayed neutron emission precursors



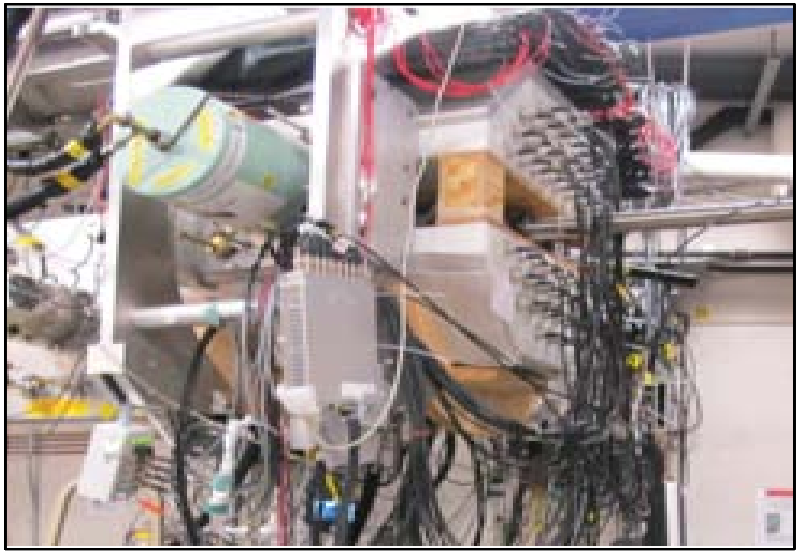
blue color – βn emission not possible

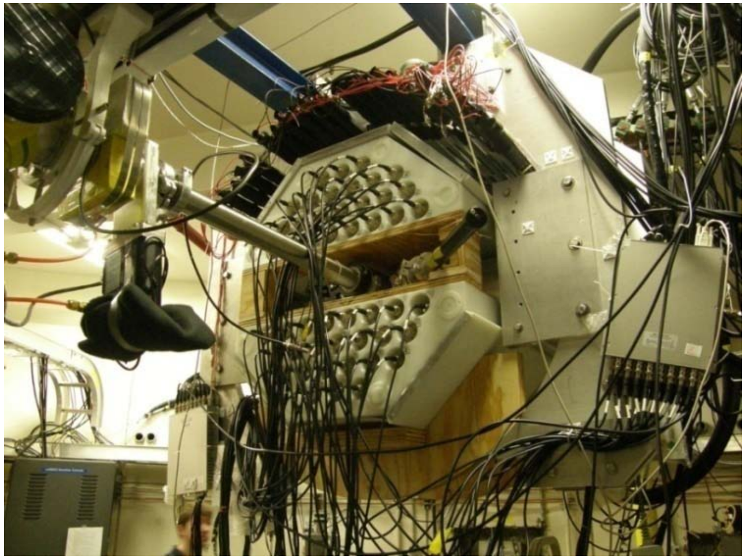
green color – 3Hen $I_{\beta n}$ measurements of low energy βn's

red-brown colors – beta-delayed 2n emission (low energy?)

hybrid 3Hen array for β-n-γ decay studies at LeRIBSS

(200 keV isobar-separated beams from laser ion source)





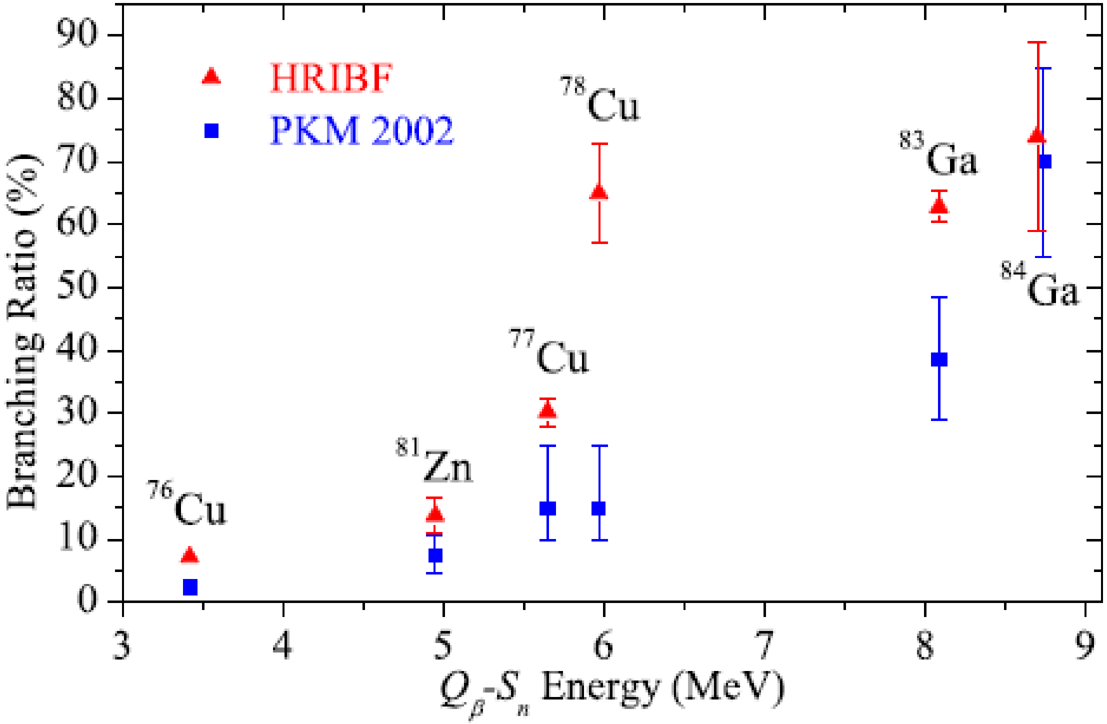
forty-eight 2” tubes with
about 600 liters of ^{3}He at 10 atm
two 1 mm plastic beta counters
and **two** 4” by 4” clovers
around 2” thin-wall beam pipe

ε_n ~ 20-30%
ε_γ(80 keV) ~ 22 %
ε_γ(1 MeV) ~ 5 %

Beta-delayed neutron emission:
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)

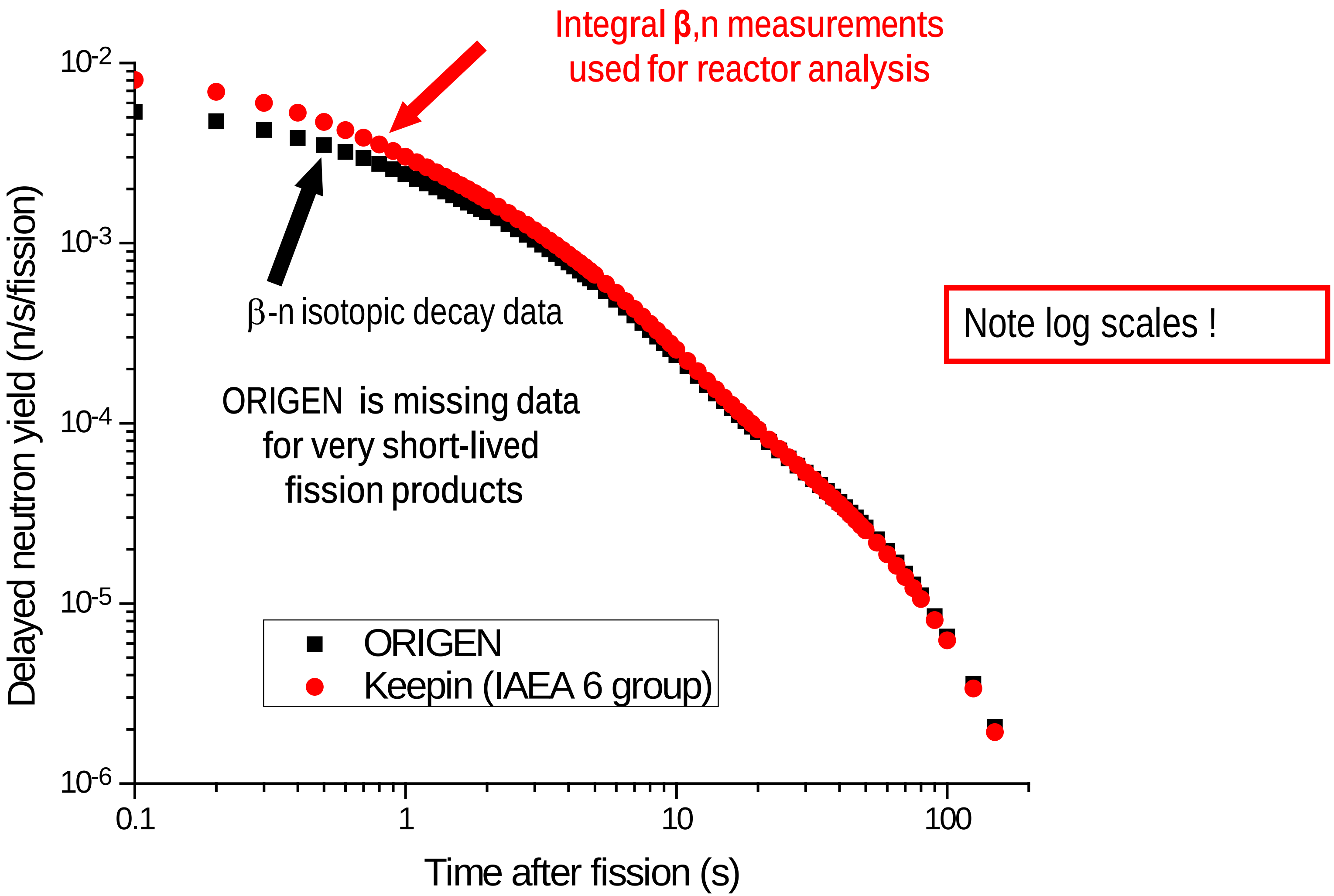


all βn-precursors given in this plot have $T_{1/2} < 1$ s

J. Winger et al., PRL 102, 142501 (2009); PR C 80, 054304 (2009); PR C81, 044303 (2010), PR C82, 064314 (2010), PR C83, 014322 (2011)

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

Delayed Neutron Yield following ^{235}U fission



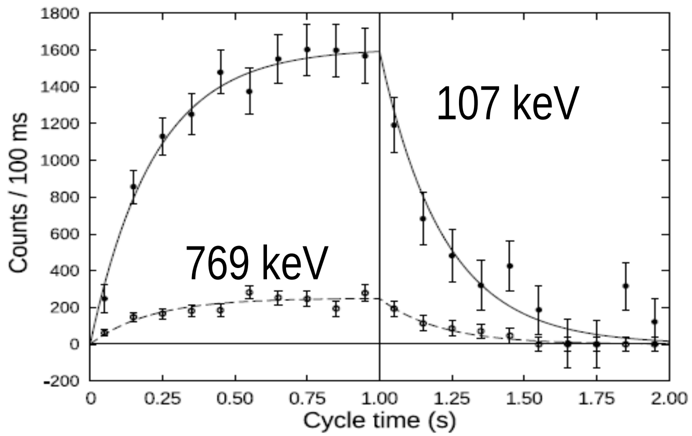
from Ian C. Gauld, ORNL Reactor Science Group (2010)

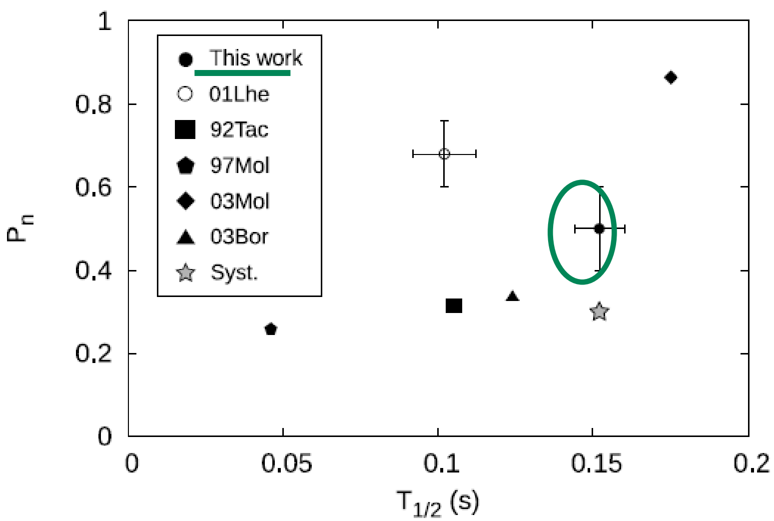
Example of corrected β-decay data: ^{93}Br decay

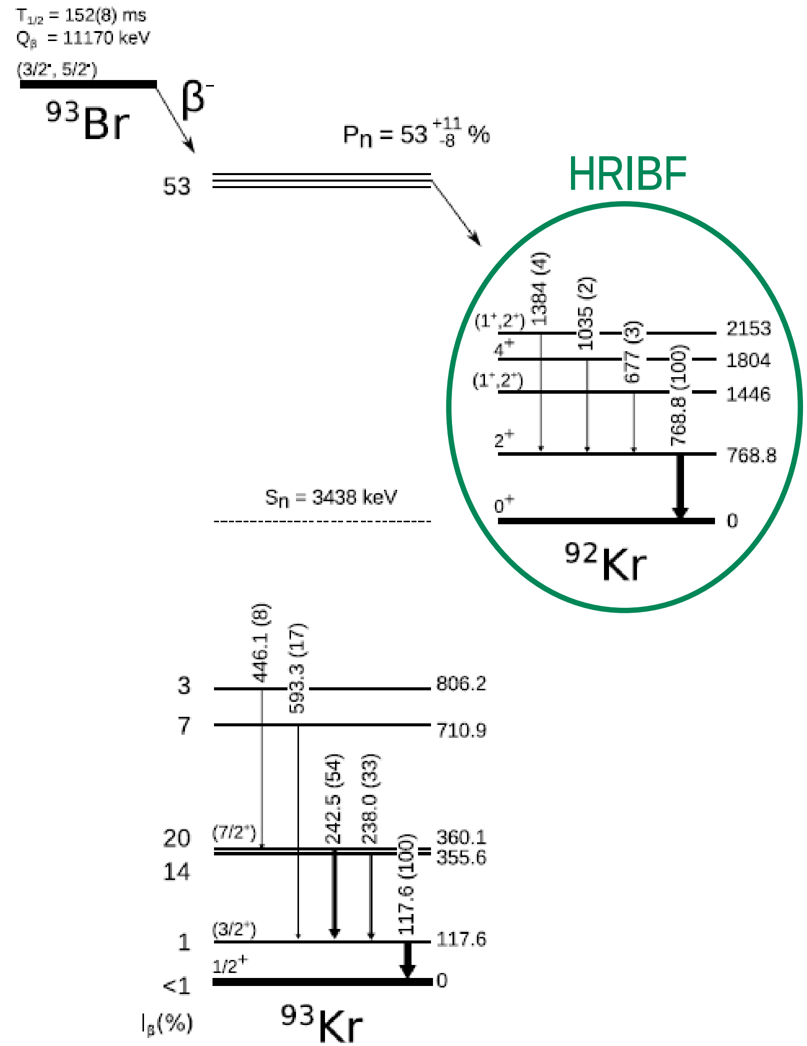
K. Miernik et al, PR C88, 014309, 2013

Previous two papers on ^{93}Br decay listed a half-life of 102(10) ms without giving an experimental evidence, and Pn branching ratios of 10(5) % and 68(7)% based on the same data. Only β0n-γ data were presented.

$T_{1/2}(^{93}Br)$ = 152(8) ms

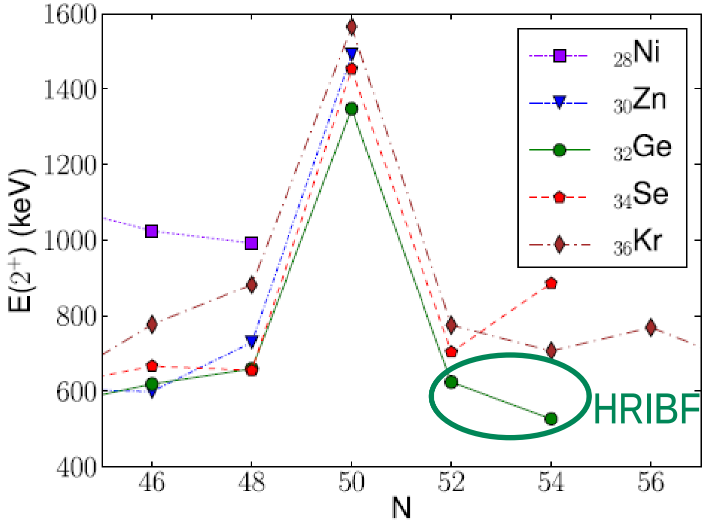




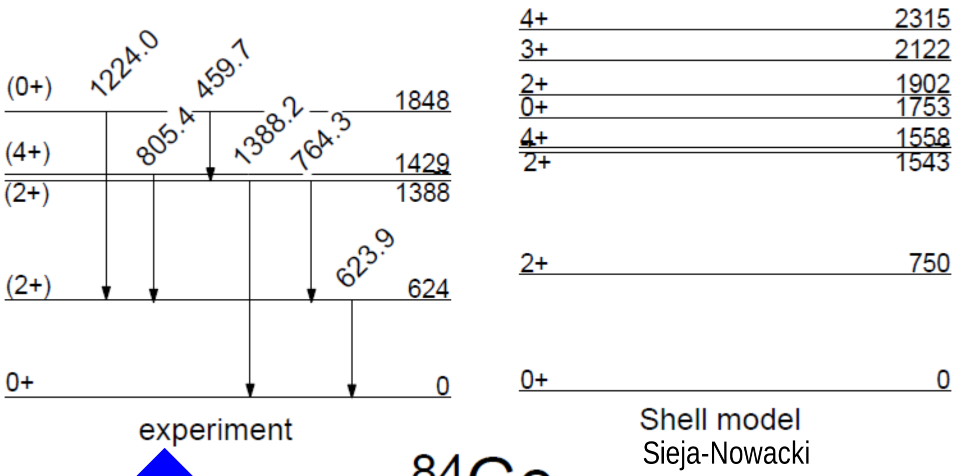


Structure of Even-Even Nuclei beyond ^{78}Ni

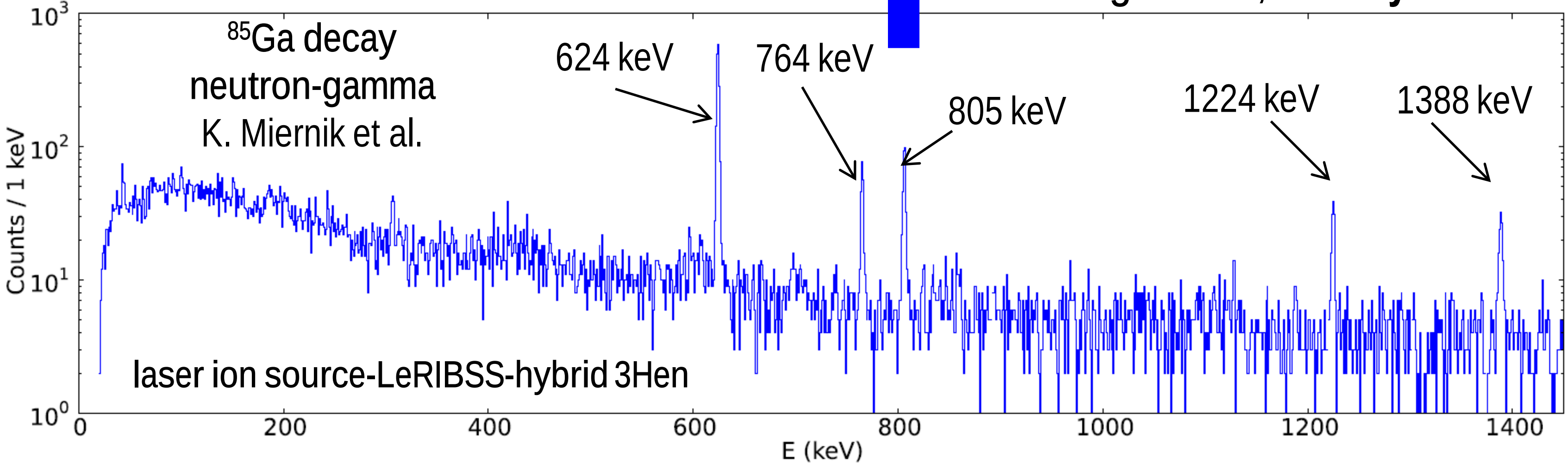
- Intriguing increase of 2^+ state energy in N=54 ^{88}Se
- 2^+ states in N=52 ^{84}Ge and in N=54 ^{86}Ge identified with more collective energy pattern



Decay pattern and shell model aided assignment of excited states



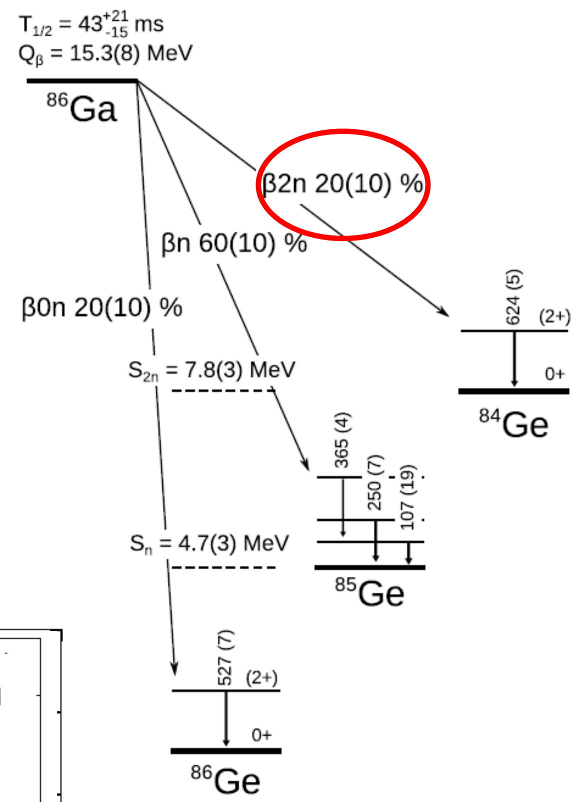
A. Korgul et al., → **Phys. Rev. C**

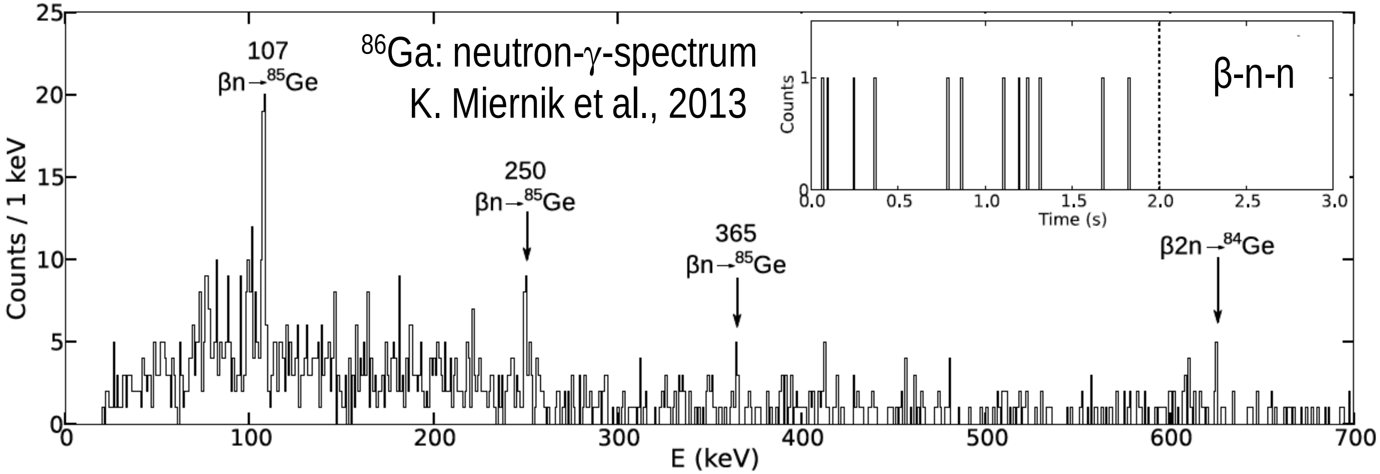


Beta-Delayed 1n and 2n Emission in ^{86}Ga Decay

β1n ~ 60 %, β2n ~ 20%, Miernik et al., submitted to PRL

- Only two β2n emitters are known in the region of heavy nuclei ^{98}Rb (β2n ~ 0.06%) and ^{100}Rb (β2n ~ 0.16%)
- ^{86}Ga, N/Z~1.77, is 15 neutrons away from last stable Ga isotope
  FRDM-QRPA : β1n : β2n → 21% : 44%,
  DF3a+CQRPA : β1n : β2n → 20% : 12%
- Large **β**2n branching ratios indeed occur in exotic nuclei like ^{86}Ga
  but modeling should account for 1n – 2n competition!





100 μs time gate was used for n-γ correlations

β1n-β2n → **IAEA Coordinated Research Project on β**n-emission, 2013 - 2017

Conclusions

- hybrid 3Hen with its auxiliary detectors and digital data acquisition was tested on-line and produced nice results on exotic nuclei north-east of ^{78}Ni

- β-delayed multi-neutron emission (^{86}Ga) and fine structure in βn-emission affect the energy spectrum of emitted neutrons in environments like r-process and nuclear fuel.

  Interesting test ground for β-decay theories, a proper account for β1n – β2n competition needed

- Data on the level structure of N > 50 nuclei show the evolution of single-particle states and collectivity (2^+ energies in N=52 and N=54 Ge call for a revision of N=54 ^{88}Se data)..