Studies of βn-emitters with BRIKEN
“ORNL proposal”

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Workshop on beta-delayed neutron emission experiments at RIBF

RIKEN, Wako

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Selection of βn- emitters to be studied with BRIKEN

- Important physics case: **β**1n and **β**2n competition, r-process path

(exotic nuclei like β2n emitters are all of interest for r-process calculations, R. Surman, Gordon Conf 2013)

- Realistic measurement:

total ion count ~ 1000 of wanted fragment vs **total rate** up to ~ 200 pps.

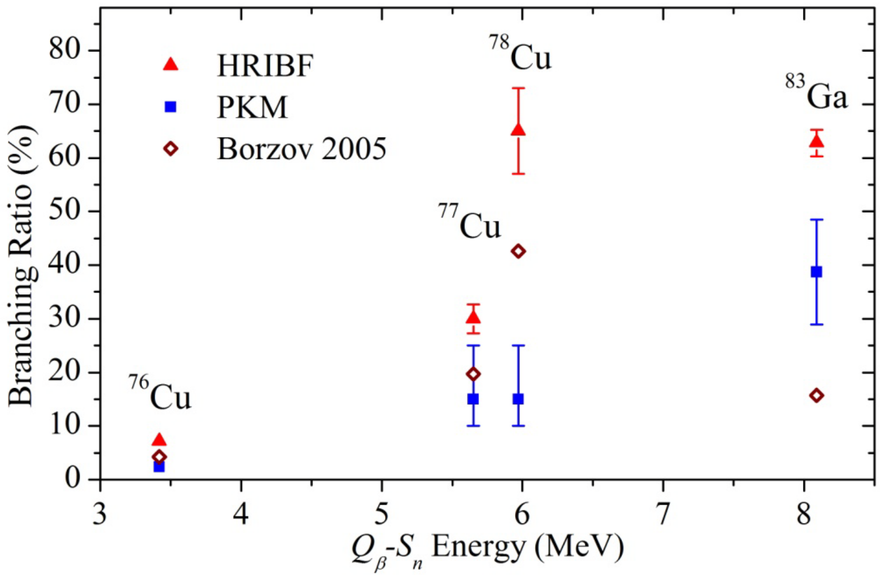
maximum of 100 hours counting with 10 pnA 345 MeV/u ^{238}U beam

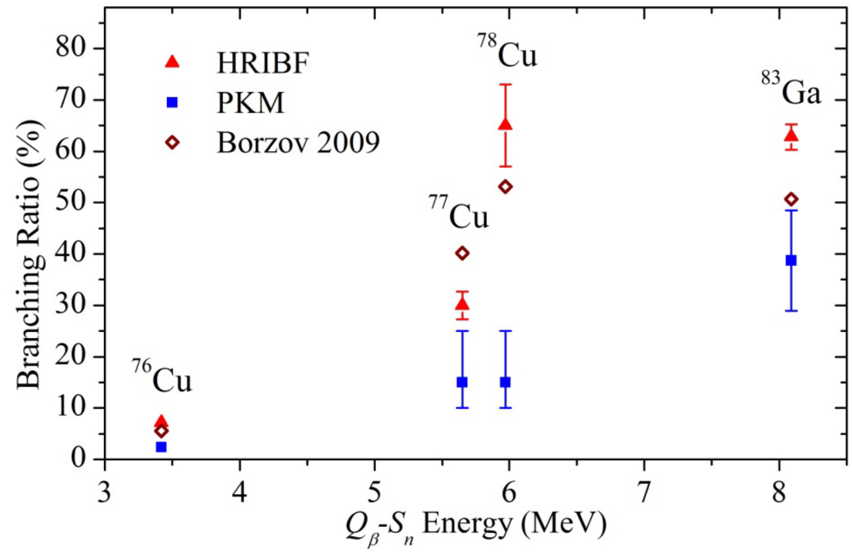
BRIKEN with ~ 80% neutron-efficiency will have 2n efficiency ~ 16 times higher than hybrid 3Hen

12 beta-n-n events identified β2n decay channel for about 13 000 ions of ^{86}Ga collected at Oak Ridge

- **Bonus info**: measurable rate and possibly β0n/βn of **even more exotic** isotone (e.g., ^{83}Zn vs ^{82}Cu), for potential future n-γ counting

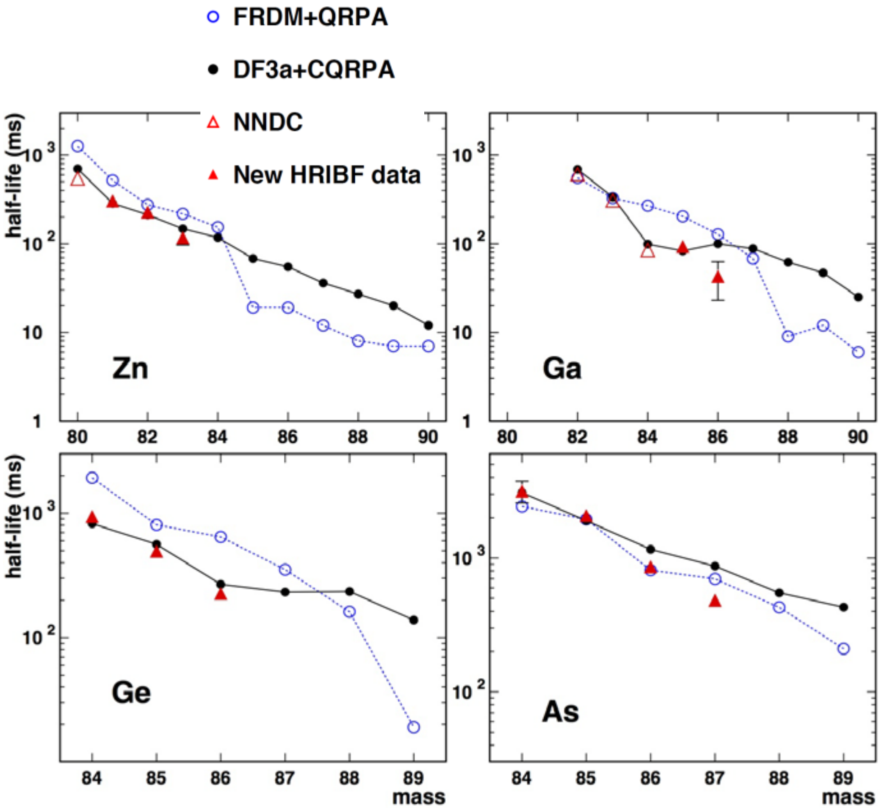
Experiments guiding theoretical calculations of β-decay properties

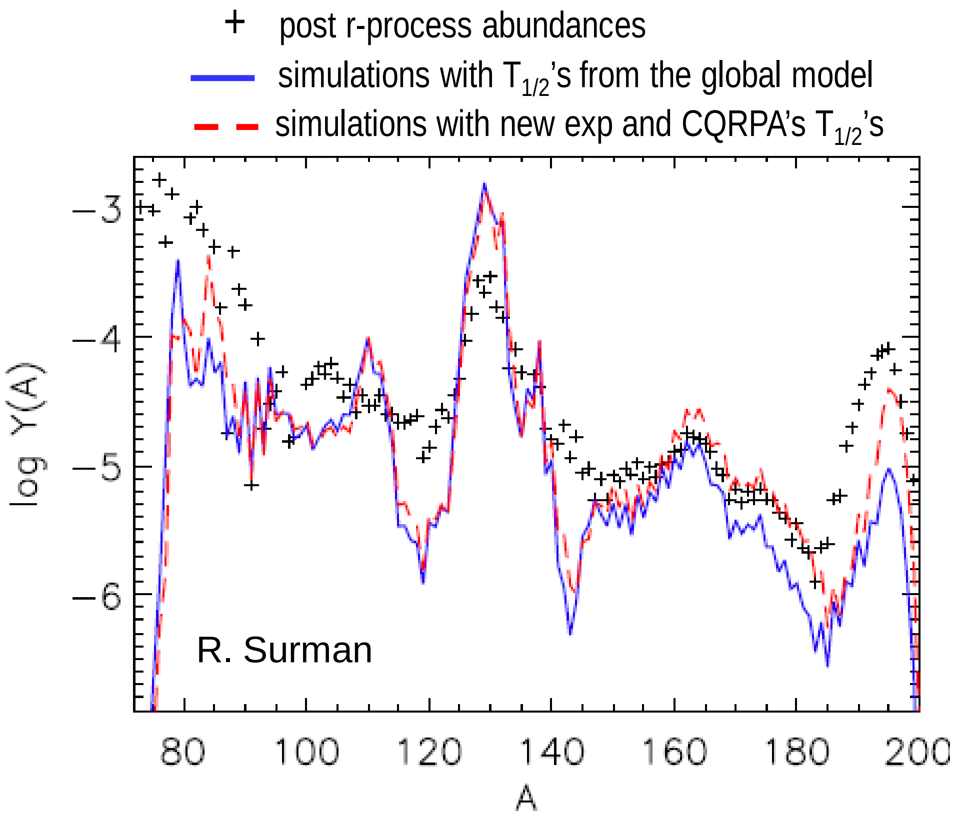




Beta Decay Properties for n-rich nuclei

Madurga et al., Phys. Rev. Lett. 109, 112501, 2012 , Mazzocchi et al., Phys. Rev. C 87, 034315, 2013, Miernik et al., 2013





- Experimental beta half-lives are shorter than FRDM+QRPA predictions used in r-process simulations.

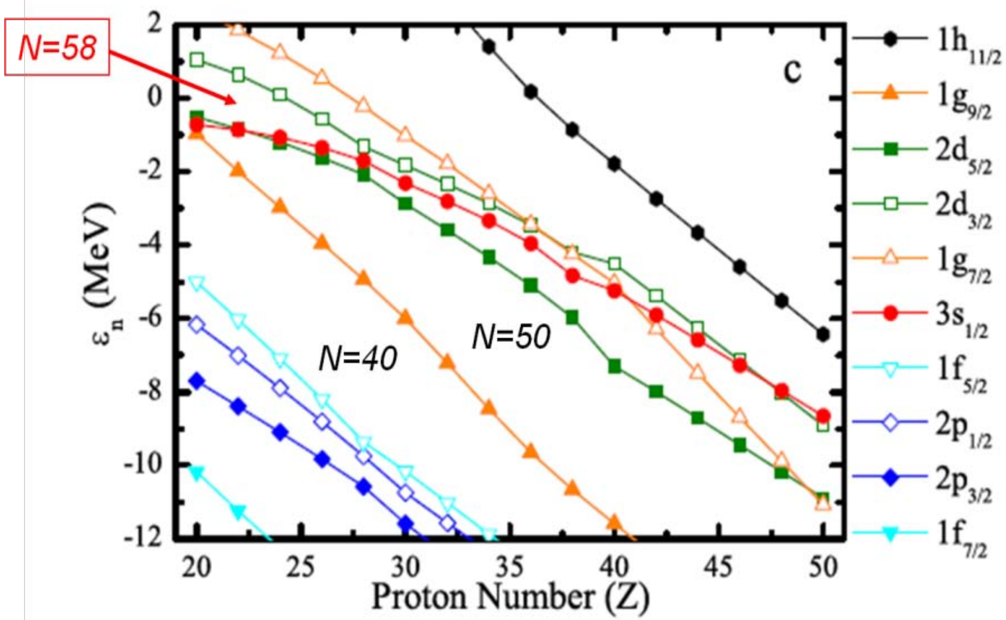
- DF3a+CQRPA are mostly in good agreement with experiment but start to depart from experiment away from ^{78}Ni.

r-process sensitivity study

- β-decays near ^{78}Ni influence abundances of A > 140 nuclei
- better agreement with data.

Extension of HRIBF βn-studies to β1n-β2n emitters produced at RIKEN

- The **best production rates** of very exotic neutron-rich nuclei at RIKEN.
- Counting of identified implanted ions helps to determine **absolute branching ratios** (ranging-out and fragmentation).
- BRIKEN high efficiency/granularity allows to study **β1n and β2n competition (branching ratios).**
- Hybrid BRIKEN allows for **ion-beta-neutron-gamma** counting.



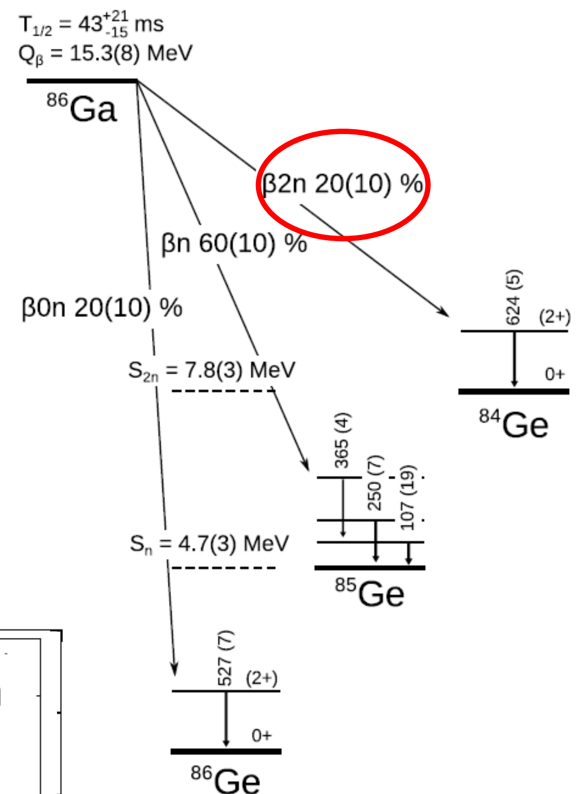
N=58, N=56 or no sub-shell closure beyond N=50 ?

J. Dobaczewski in Winger et al., PR C81, 2010

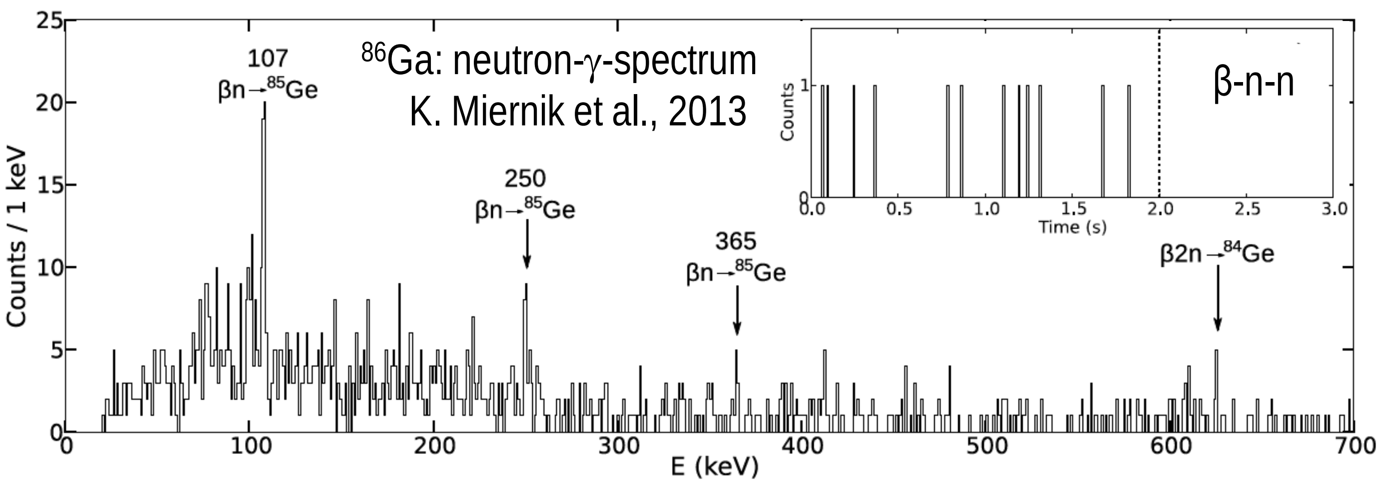
R. Grzywacz in Padgett et al, PR C 82, 2010

Competition of β1n and β2n emission in ^{86}Ga decay

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



- Data on only two β2n emitters are published for 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%
  - HRIBF exp : β1n : β2n → **60% : 20%**
- Large **β2n** 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

- (some of) the **βn-emitters N≥50 studied at the HRIBF (Oak Ridge), including β2n** emitter ^{86}Ga

		N=50		52		54		56		58		60		62
Se							3% / 0%	1% / 0%	4% / 0%	3% / 0%	10% / 0%	4% / 0%	26% / 3%	42% / 1%
As				12% / 0%	20% / 0% •	37% / 0% •	32% / 2%	76% / 1%	28% / 3%	89% / 3%	45% / 39%	82% / 12%	32% / 44%	68% / 19%
Ge				10% / 0%	11% / 0% •	24% / 0% •	31% / 5%	49% / 0%	10% / 1%	74% / 3%	43% / 19%			
Ga		5% / 0% •	9% / 0% •	59% / 0% •	27% / 15% •	61% / 10% •	21% / 44% •	69% / 13%	35% / 41%	70% / 19%	20% / 45%	39% / 16%		
Zn		6% / 0% •	13% / 0% •	45% / 0% •	29% / 21% •	49% / 13%	28% / 9%	64% / 5%	46% / 27%					
Cu	11% / 0% •	25% / 0% •	44% / 13%	62% / 21%	29% / 57%	46% / 31%	13% / 64%	24% / 43%						
Ni Z=28	25% / 0%	39% / 0%	62% / 5%	64% / 14%	20% / 57%	37% / 22%								
Co	26% / 6%	69% / 7%	41% / 25%	67% / 16%	1% / 73%									

P. Moeller's predictions 2012 for **β1n** vs **β2n**

http://t2.lanl.gov/nis/molleretal/publications/tpnff.dat

^{135}In setting: Setting parameters and rates

Calculations from Naoki Fukuda, Toshi Kubo, Naohito Inabe and Robert Grzywacz for lighter nuclei

LISE++ file: *238U_135In_Be3mm_F1deg5mm_F5deg5mm.lpp*

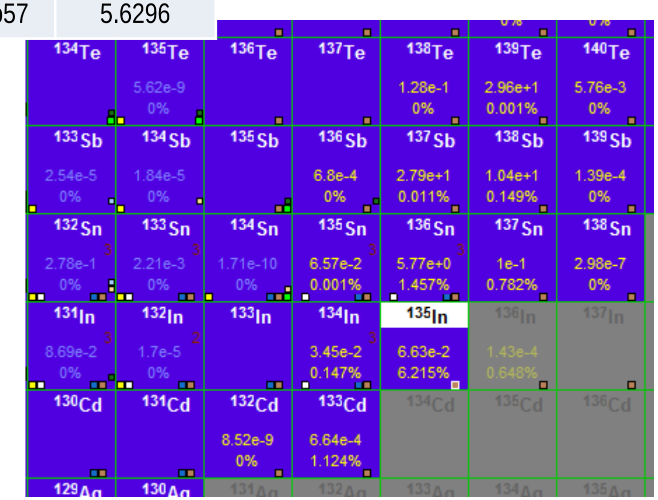
Primary beam: $^{238}U^{86+}$, 345 MeV/u, 10 pnA

	Thickness(wedge angle)
Target	Be 3 mm
F1 deg.	Al 5 mm(-5.7 mrad), d/R = 0.300
F5 deg.	Al 5 mm(4.3 mrad), d/R = 0.435

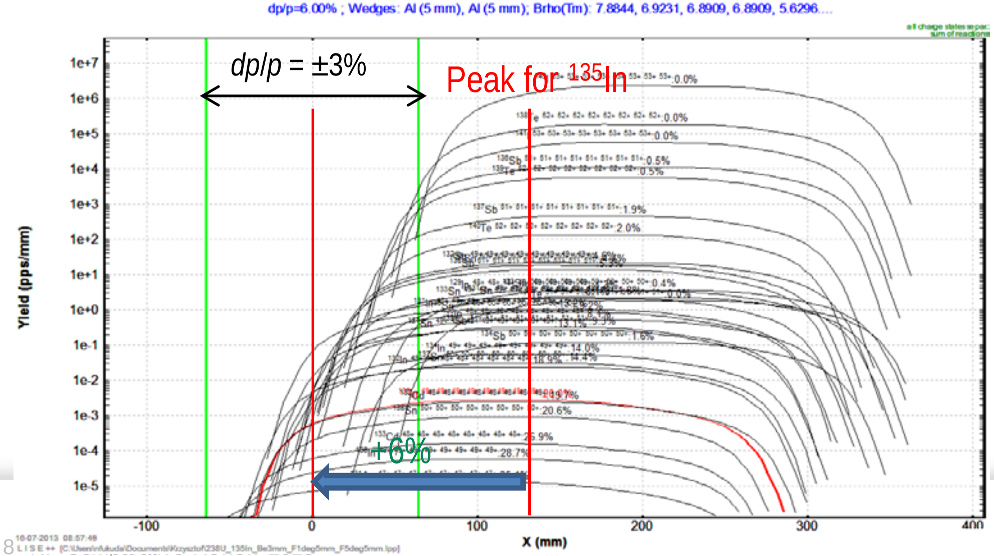
Focus	L (mm)	R (mm)
Exit B.D.	80	125
F1	64.2	64.2
F2	3	3
F5	120	120
F7	3	3

	Brho (Tm)
Brho01	7.8844
Brho12	6.9231
Brho35	6.8909
Brho57	5.6296

E(^{137}In) = 181 MeV/u after F7



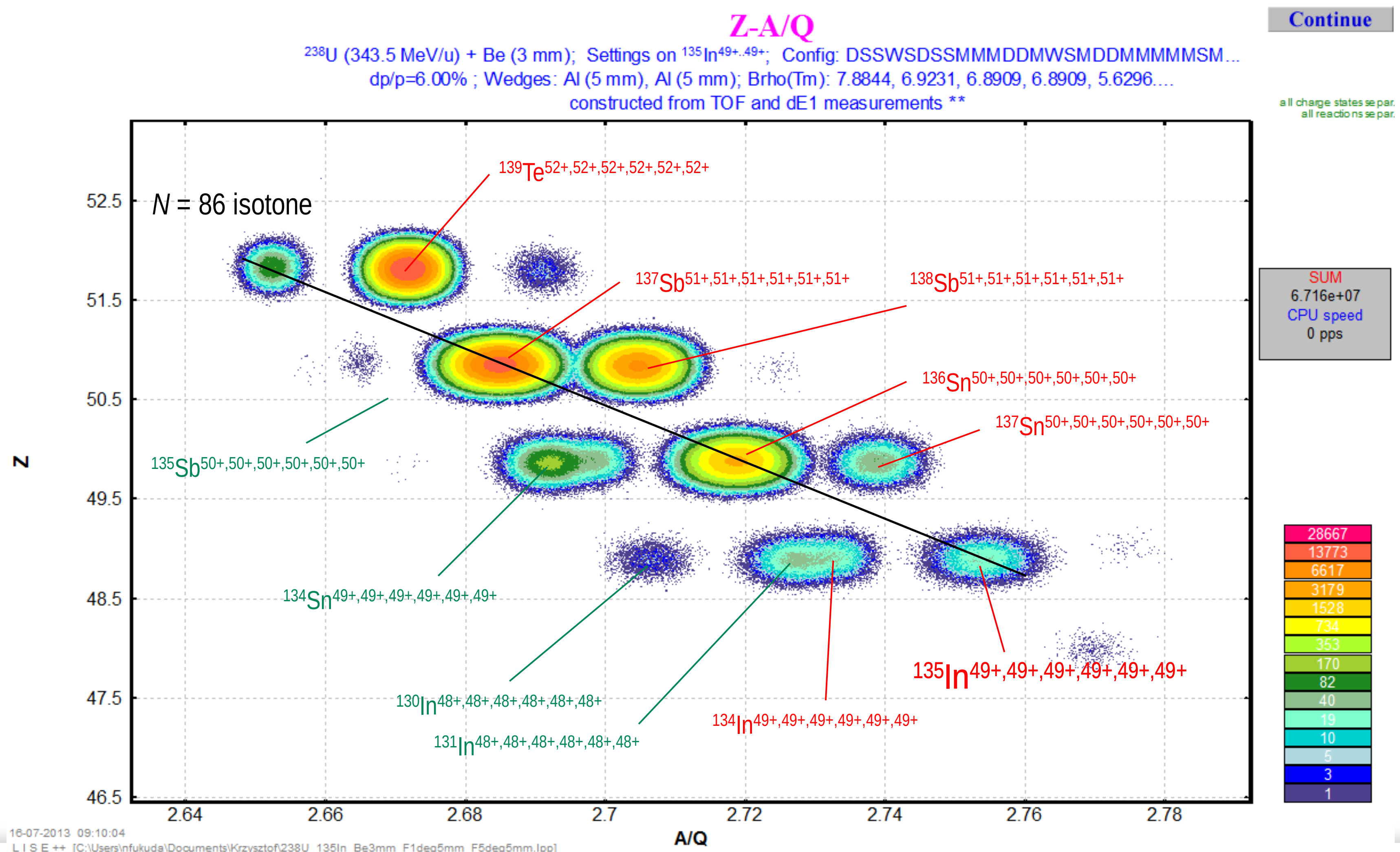
F1x (*Bρ* distribution)



	Rate (pps/10 pnA)
^{135}In rate	6.63×10^{-2}
Total rate at F3	1.6×10^{4}
Total rate at F7	75

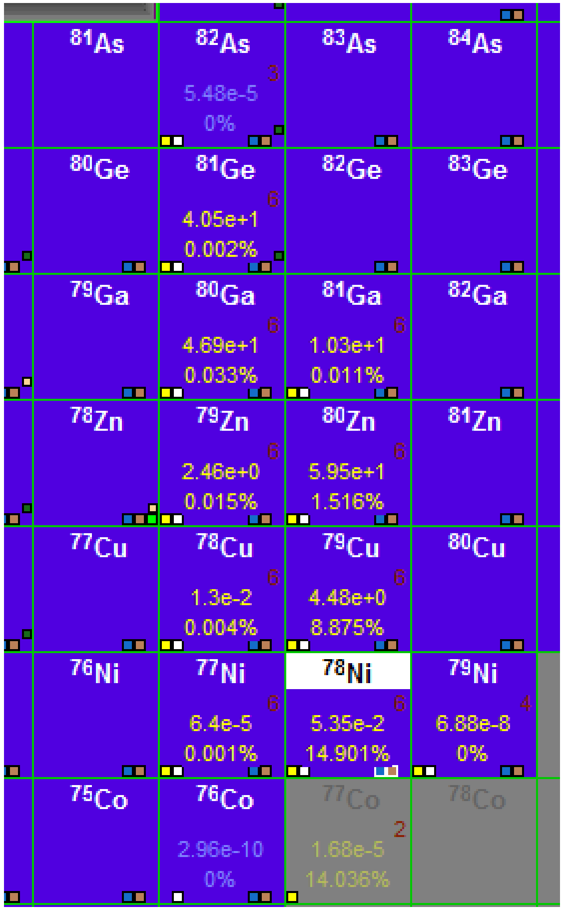
100 hours accumulation: ^{135}In 2.4×10^{4} counts

^{135}In setting: *Z* vs *A*/*Q* plot
/from Naoki Fukuda – Toshi Kubo/



β1n emitter ^{78}Ni, $T_{1/2}$~110 ms, P_n ~39% (P. Moeller)

- ^{78}Ni - the only doubly-magic nucleus on the r-process path and one of the anchor points for nuclear structure
- ^{79}Cu - also N=50 waiting point, $T_{1/2}$ = 290 (20) ms from HRIBF, verification of P_n data, exp β1n ~ 72% - 55%



^{78}Ni setting:

total ion count ^{78}Ni – 19 000 vs total rate of ~ 180 pps,

total ion count ^{79}Cu – 1.6 * 10^5

total ion count ^{80}Zn – 2 * 10^7

total ion count ^{81}Ga – 3.7 * 10^6

consistent study of four N=50 emitters

an example of 10 hours experiment, not 100 hours one

LISE++/BigRIPS calculations by
Naoki Fukuda, Naohito Inabe, Toshi Kubo
and by R. Grzywacz

β1n - β2n emitter ^{81}Cu and β1n ^{82}Zn, $T_{1/2}$=228(10) ms,

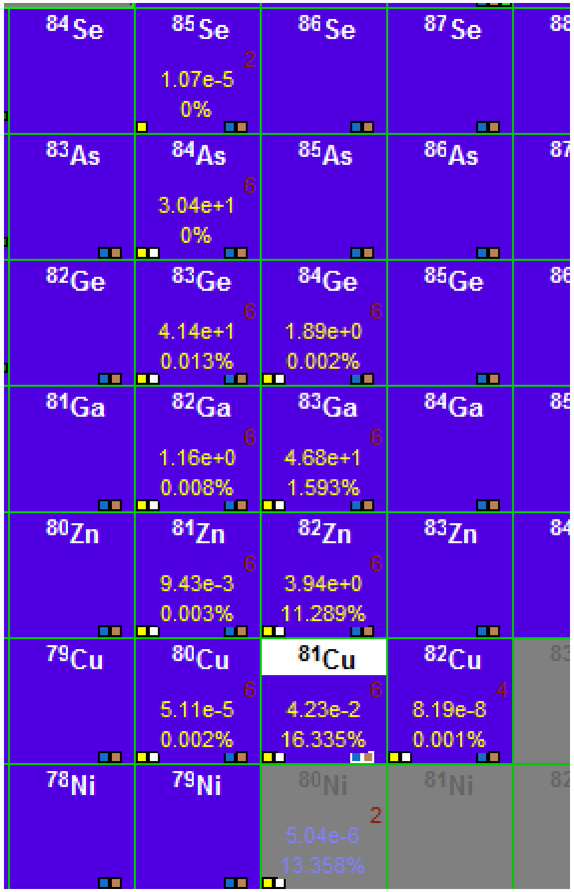
- β1n and β2n competition 62% : 21 % (^{81}Cu) and 45% β1n predicted for ^{82}Zn, both **on r-process** path
- ^{81}Cu important for potential **future n-γ** counting with hybrid BRIKEN

^{81}Cu setting:

total ion count ^{82}Zn – 1.4 * 10^6 vs total rate of ~ 130 pps,

total ion count ^{81}Cu – 1500

both results achievable within 100 hours counting



LISE++/BigRIPS calculations by
Naoki Fukuda, Naohito Inabe, Toshi Kubo
and by R. Grzywacz

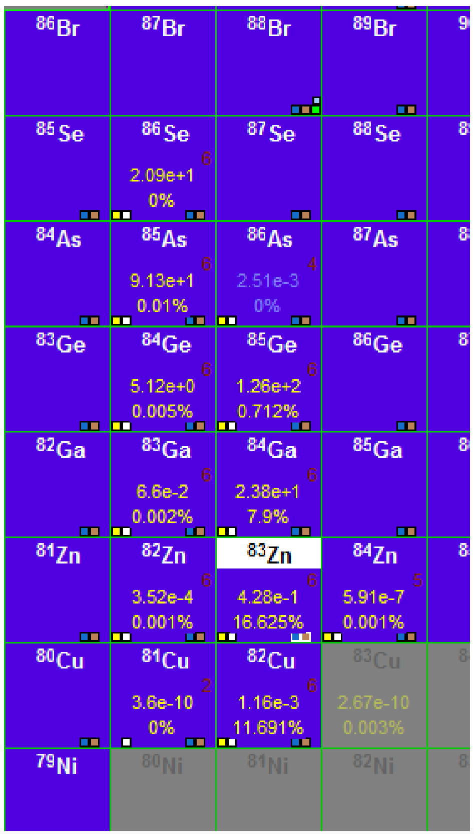
β1n- β2n emitters ^{83}Zn, $T_{1/2}$=117(20) ms, and ^{82}Cu

- β1n and β2n competition 29% : 21 % (^{83}Zn) and 29%: 57% (^{82}Cu), both **on r-process** path
- ^{82}Cu also important for potential **future n-γ** counting with hybrid BRIKEN

^{83}Zn setting:

total ion count ^{83}Zn – 154 000 vs total rate of ~ 250 pps,

total ion count ^{82}Cu – 400

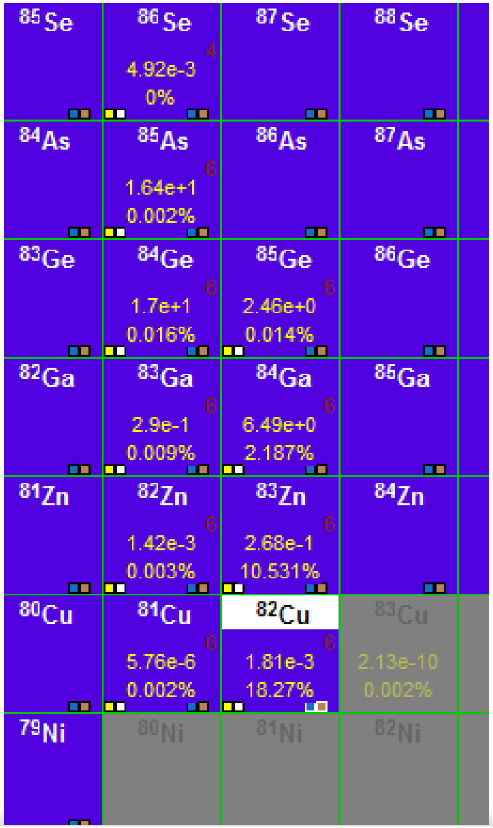


^{82}Cu setting:

total ion count ^{83}Zn – 96 000 vs total rate of ~ 50 pps,

total ion count ^{82}Cu – 650

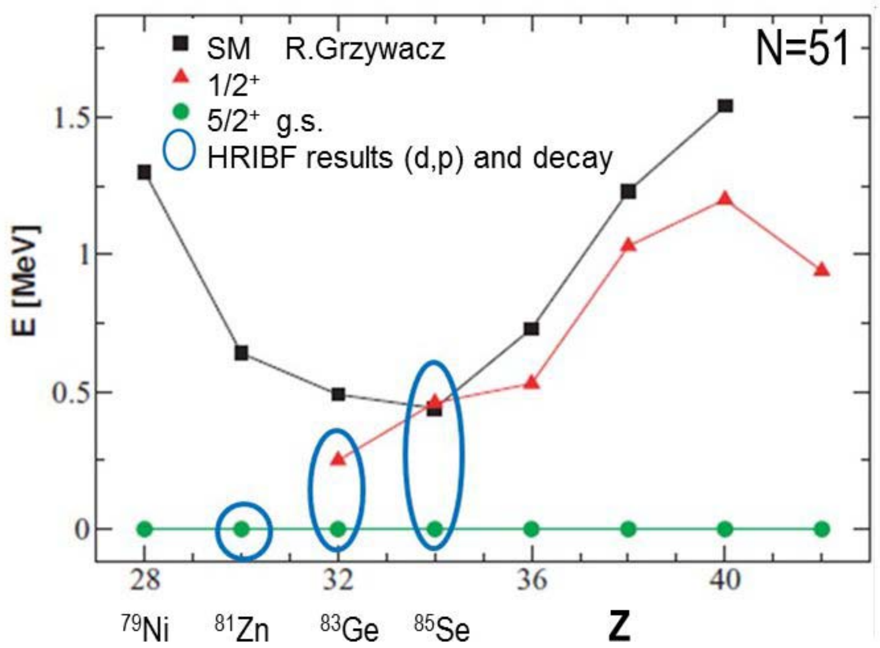
LISE++/BigRIPS calculations by
Naoki Fukuda, Naohito Inabe, Toshi Kubo
and by R. Grzywacz

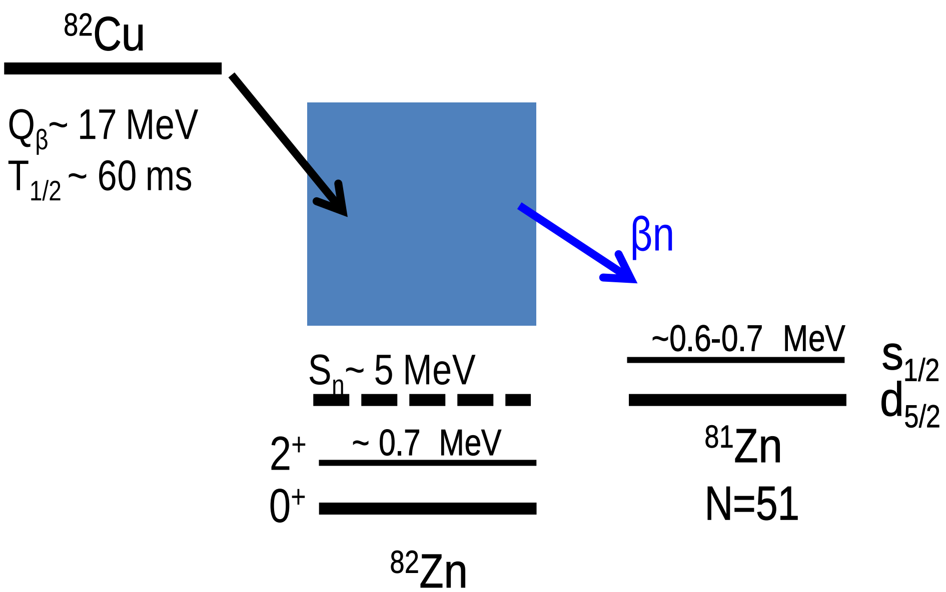


Evolution of neutron single-particle states for N > 50

search for a potential sub-shell closure $\nu 2d_{5/2}$ - $\nu 3s_{1/2}$

Padgett et al., Phys. Rev C **82**, 064314, 2010





- Energy gap at N=56 or at N=58 or no gap beyond ^{78}Ni ?
- Single particle energy of $3s_{1/2}$ vs $2d_{5/2}$ in N=51 ^{79}Ni ?

- **Answer → ^{81,82}Cu β-n-γ exp at RIKEN and ^{79,80}Co β-n-γ exp at FRIB**

β1n - β2n emitter ^{84}Zn and β1n ^{85}Ga, $T_{1/2}$=93(7) ms,

- β1n and β2n competition 49% : 13 % in ^{84}Zn

  and predicted as 61% : 10 % for ^{85}Ga, but β2n was not observed at Oak Ridge in three experiments, βnγ data compatible with β0n : β1n ~ 25:75
- verification of ^{86}Ge β1n measured recently at Oak Ridge as ~ 45(15)%, Moeller gives β1n as 24%

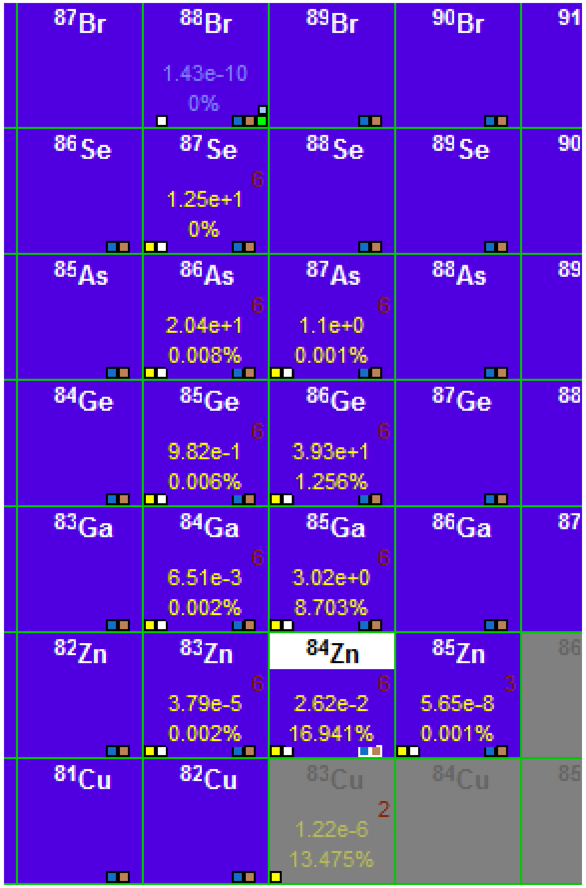
^{84}Zn setting:

total ion count ^{84}Zn – 9400 vs total rate of ~ 80 pps,

total ion count ^{85}Ga – 1.1*10^{6}

total ion count ^{86}Ge ~ 14*10^{6}

an example of 10 hours experiment, not 100 hours one



LISE++/BigRIPS calculations by
Naoki Fukuda, Naohito Inabe, Toshi Kubo
and by R. Grzywacz

Potential Z=34 and N=56 or N=58 sub-shell closures and βnγ decays of ^{91,92}As to ^{90,92}Se* isotopes.

- with increasing Z above Z=28, proton $f_{5/2}$ orbital is getting filled for neutron-rich nuclei N > 50 , up to Z=34
- depending on the relative energies of neutron $2d_{5/2}$ and $3s_{1/2}$ orbitals above N=50, an energy gap can be created at N=56 or at N=58
- an onset of substantial deformation can change this simplified picture, the experimental verification like the structure of Z=34 Se isotopes is needed. The most n-rich and (partially) published As→Se β-decay is ^{87}As βγ/ βnγ-decay (Mazzocchi et al, 2013). Likely, new EURICA data will contribute here.
- The final experiments on n-rich As isotopes are for hybrid BRIKEN βnγ

^{91}As **βn**-decay to 2+ level in N=56 ^{90}Se

total ion count ^{91}As (β1n/2n~ 28%/2%) ~ 1.3*10^{5} vs total rate of ~ 70 pps

(~ 10 hours experiment)

^{92}As **β**-decay to 2+ level in N=58 ^{92}Se

total ion count ^{92}As (β1n/2n~ 89%/3%) ~ 3.6*10^{4} vs total rate of ~ 10 pps

(~ 100 hours exp)

LISE++/BigRIPS calculations by
Naohito Inabe - Toshi Kubo

multi-neutron emitters beyond ^{132}Sn: $^{134\text{-}137}$In

(βn-emission driven by ^{132}Sn double shell closure and respective large Q_β values)

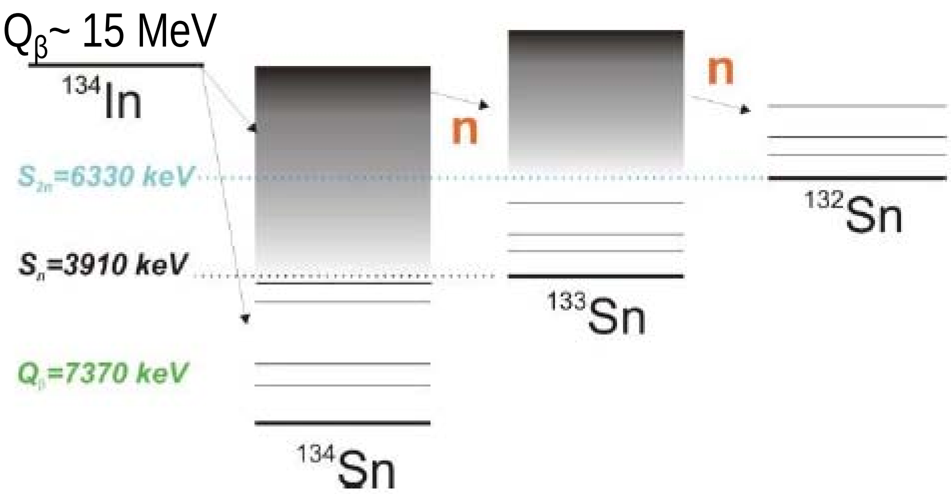
		82		84		86		88		90		92
Te				2% / 0%	5% / 0%	2% / 0%	27% / 0%	10% / 0%	36% / 1%	12% / 0%	18% / 1%	
				32% / 0%	34% / 6%	56% / 1%	37% / 30%	77% / 10%	11% / 67%	93% / 3%	40% / 51%	
Sn				58% / 0%	52% / 5%	64% / 1%	49% / 23%	83% / 4%	49% / 32%	88% / 4%	34% / 7%	
	1% / 0%	4% / 0%	11% / 0%	93% / 0%	6% / 87%	24% / 64%	4% / 77%	15% / 67%				
Cd		3% / 0%	40% / 0%	64% / 0%	21% / 50%	31% / 43%						
	7% / 0%	10% / 0%	64% / 3%	85% / 11%	3% / 88%	8% / 69%						
Pd	8% / 0%	7% / 0%	76% / 2%	76% / 10%	10% / 73%	15% / 30%						
	23% / 0%	26% / 0%	62% / 11%	71% / 24%	2% / 69%							

P. Moeller's predictions 2012 for **β1n** vs **β2n**

β1n - β2n emitters ^{134}In and ^{133}Cd

- β1n and β2n competition 6% : 87 % (^{134}In) and 50% : 21% (^{133}Cd)

conflicting reports on P_n values for ^{134}In, see e.g., Abriola, Singh, Dillmann, "βn-emission evaluation" 2011.

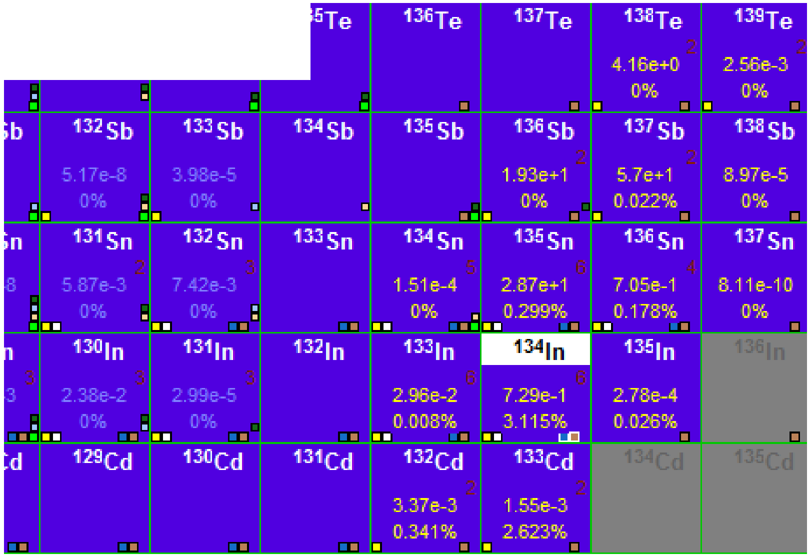


^{134}In setting:

total ion count ^{134}In – 2.6 * 10^5 vs total rate of ~ 120 pps,

total ion count ^{133}Cd ~ 500 vs total rate of ~ 120 pps

10 hours exp for ^{134}In, and 100 hours for ^{133}Cd



LISE++/BigRIPS calculations by
Naoki Fukuda - Toshi Kubo

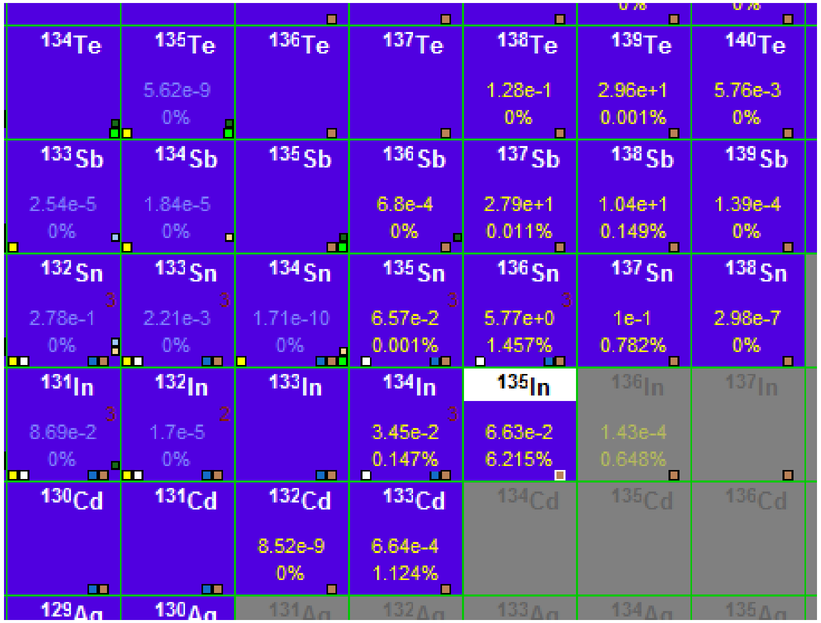
β1n - β2n – β3n emitter ^{135}In (Q_β ~ 14.1 MeV)

- $Q_{\beta 1n}$ = 11.9 MeV, $Q_{\beta 2n}$ = 7.9 MeV and $Q_{\beta 3n}$ = 5.5 MeV, β3n ending in doubly-magic ^{132}Sn
- competition of **β1n : β2n : β3n** is about 24% : 64 % : 7% according to P. Moeller

^{135}In setting:

total ion count ^{134}In – 2.4 * 10^4 vs total rate of ~ 80 pps

50 hours exp for ^{135}In should reveal
the presence of multi-neutron emission



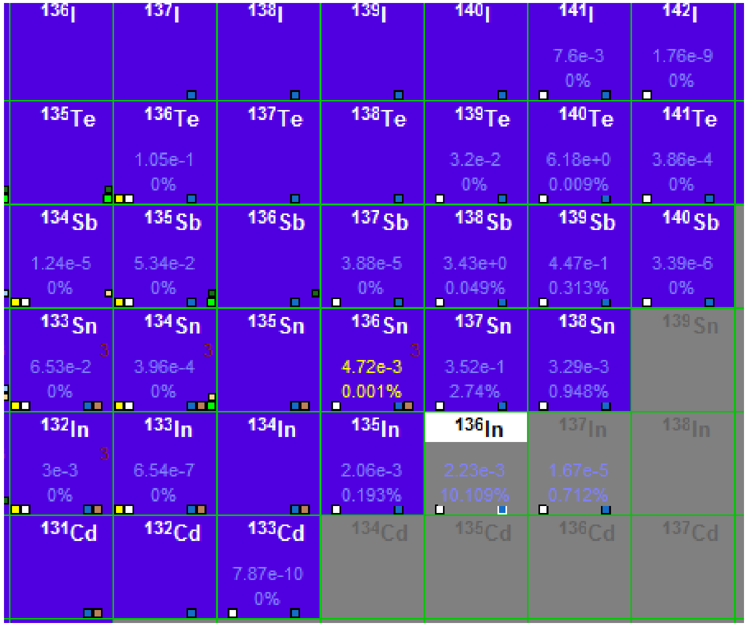
LISE++/BigRIPS calculations by
Naoki Fukuda - Toshi Kubo

β1n - β2n - β3n - (β4n) emitter ^{136}In (Q_β ~ 15 MeV)

- $Q_{\beta 1n}$ = 11.7 MeV, $Q_{\beta 2n}$ = 9.4 MeV, $Q_{\beta 3n}$ = 5.5 MeV ($Q_{\beta 4n}$ = 3.1 MeV thanks to ^{132}Sn)
- competition of **β1n** : **β2n** : β3n is about 7% : 4 % : 77% according to P. Moeller

^{136}In setting:

total ion count ^{134}In ~ 800 counts vs total rate of ~ 10 pps,



100 hours exp for ^{136}In has a chance
to reveal the presence of 1n, 2n and 3n (4n ?) emission
(after further ^{238}U beam intensity increase at RIKEN)

LISE++/BigRIPS calculations by
Naoki Fukuda -Toshi Kubo

Summary of proposed '1st and 2nd day' BRIKEN exps

ion setting	physics (in addition to r-process input)	counting time (10 hours or 100 hours)
^{78}Ni	the only doubly-magic βn-emitter βn-values other N=50 ^{79}Cu, ^{80}Zn, ^{81}Ga	10 h
^{81}Cu	^{81}Cu β1n/2n, ^{82}Zn β1n	^{82}Zn-10 h, ^{81}Cu – 100 h
^{82}Cu	^{82}Cu, ^{83}Zn β1n/2n, future βnγ	^{83}Zn-10 h, ^{82}Cu – 100 h
^{84}Zn	^{84}Zn, ^{85}Ga β1n/2n, ^{86}Ge β1n	10 h
^{91}As	β1n for future βnγ (2^+ in N=56 ^{90}Se,$ns_{1/2}$-$nd_{5/2}$)	10 hours
^{92}As	β0n/ β1n for future βnγ (2^+ in N=58 ^{92}Se, $ns_{1/2}$-$nd_{5/2}$)	100 hours
^{134}In	^{134}In – flag example of β2n-emitter (1n/2n?)	^{134}In - 10 h
	^{133}Cd β1n/2n, future βnγ	^{133}Cd - 100 h
^{135}In	^{135}In – β1n/2n/3n	50 h
^{136}In	^{136}In – β1n/2n/3n/4n	> 100 hours