Measurement of multiple neutron emitters

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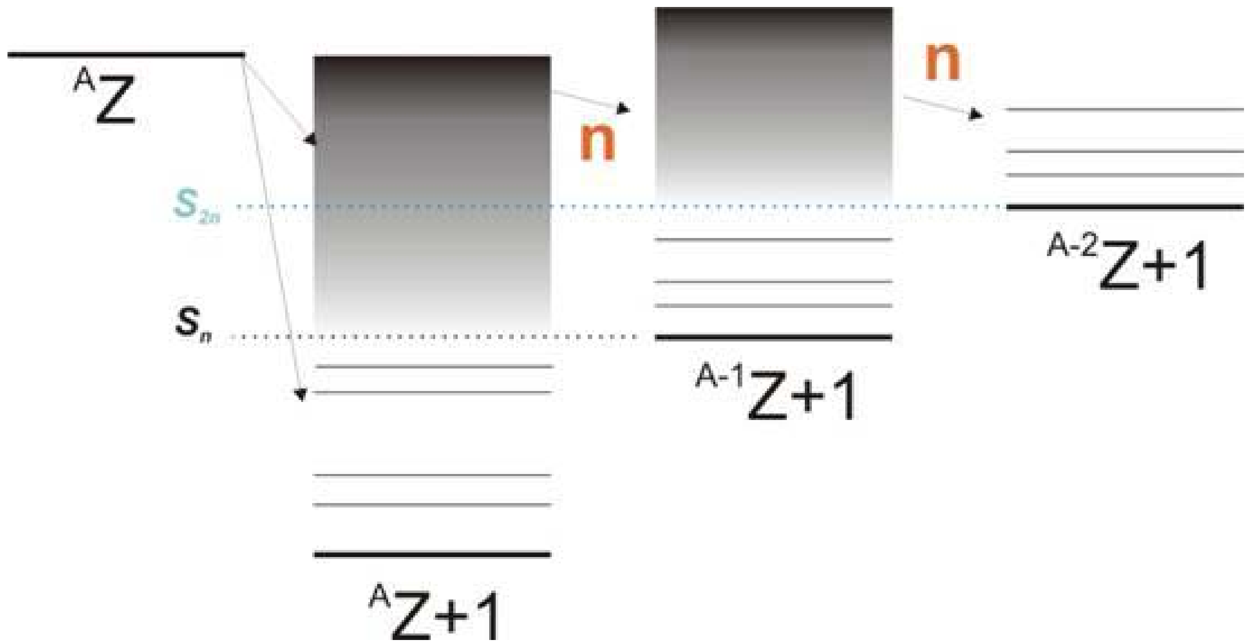
HELMHOLTZ ASSOCIATION

β-delayed neutron emission

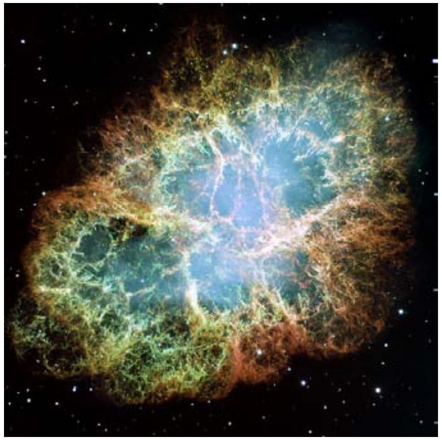
$S_{2n} < Q_\beta$



- Discovered in 1939 by Roberts et al.
- "Delayed": emission with β-decay half-life of the precursor ^{A}Z
- $t_{1/2} \approx$ few ms– 55.65 s (^{87}Br)

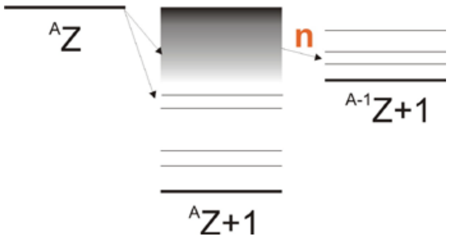
R.B. Roberts, R.C. Meyer, P. Wang, Phys. Rev. **55**, 510 (1939).

Why multiple βn?



Astrophysics (rapid neutron capture (r) process)

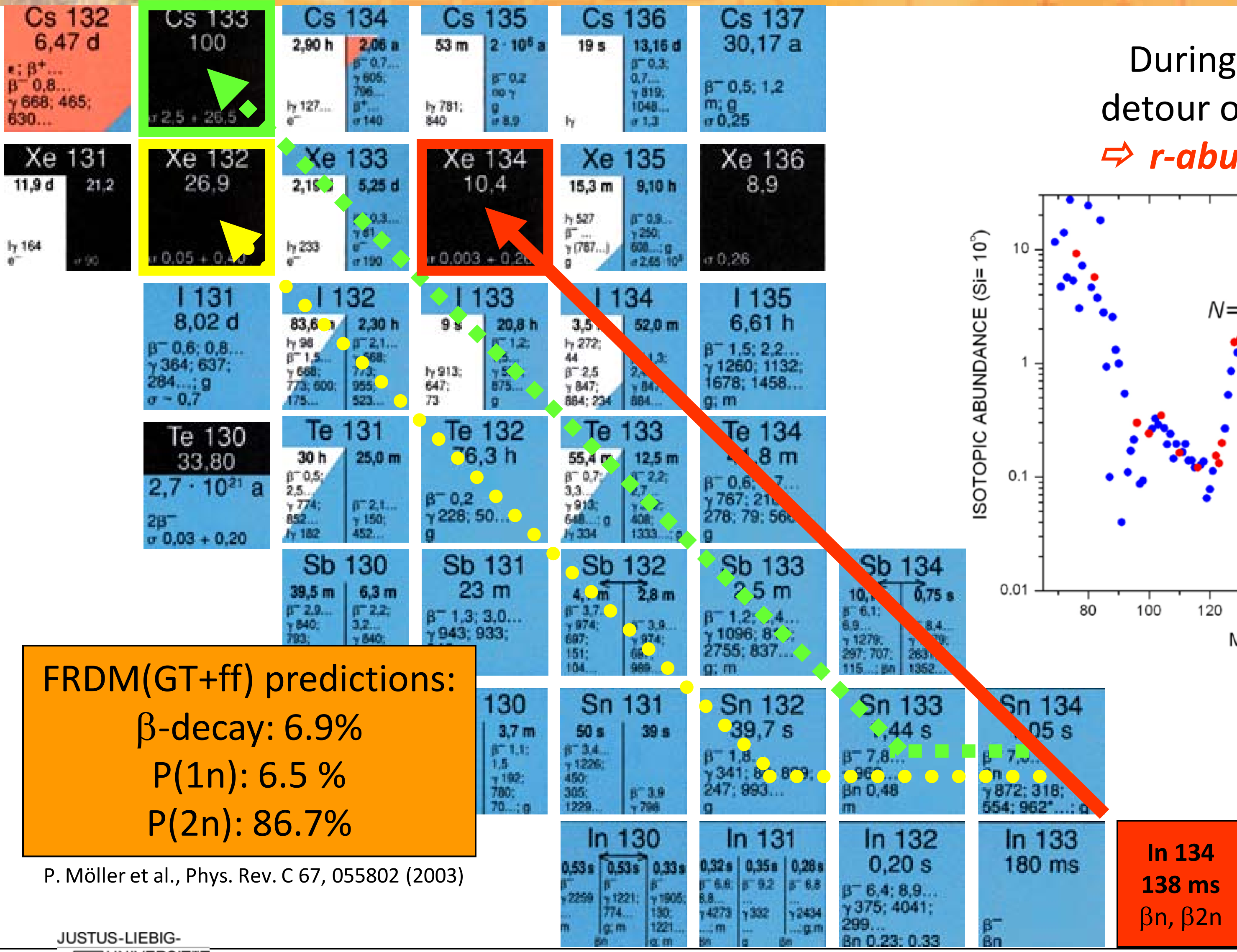
- Detour of β-decay chains
- Re-capture of neutrons in late-stage evolution
- Influence on solar r-abundance curve



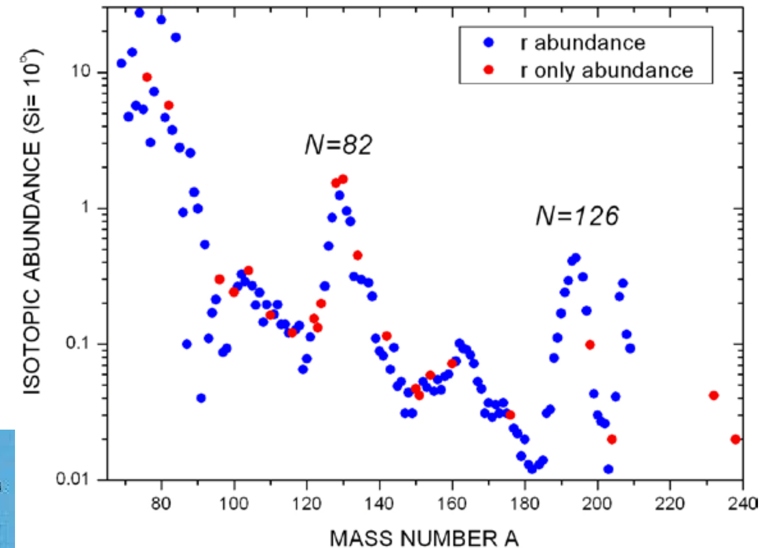
Nuclear structure

- Dominant decay process for very n-rich nuclei
- β-strength above S_n
- Competition with other β-delayed emission processes

Astrophysical influence



During „Freeze-out“:
detour of β-decay chains
⇨ r-abundance changes



FRDM(GT+ff) predictions:
β-decay: 6.9%
P(1n): 6.5 %
P(2n): 86.7%

P. Möller et al., Phys. Rev. C 67, 055802 (2003)

β-delayed 1-neutron emitters

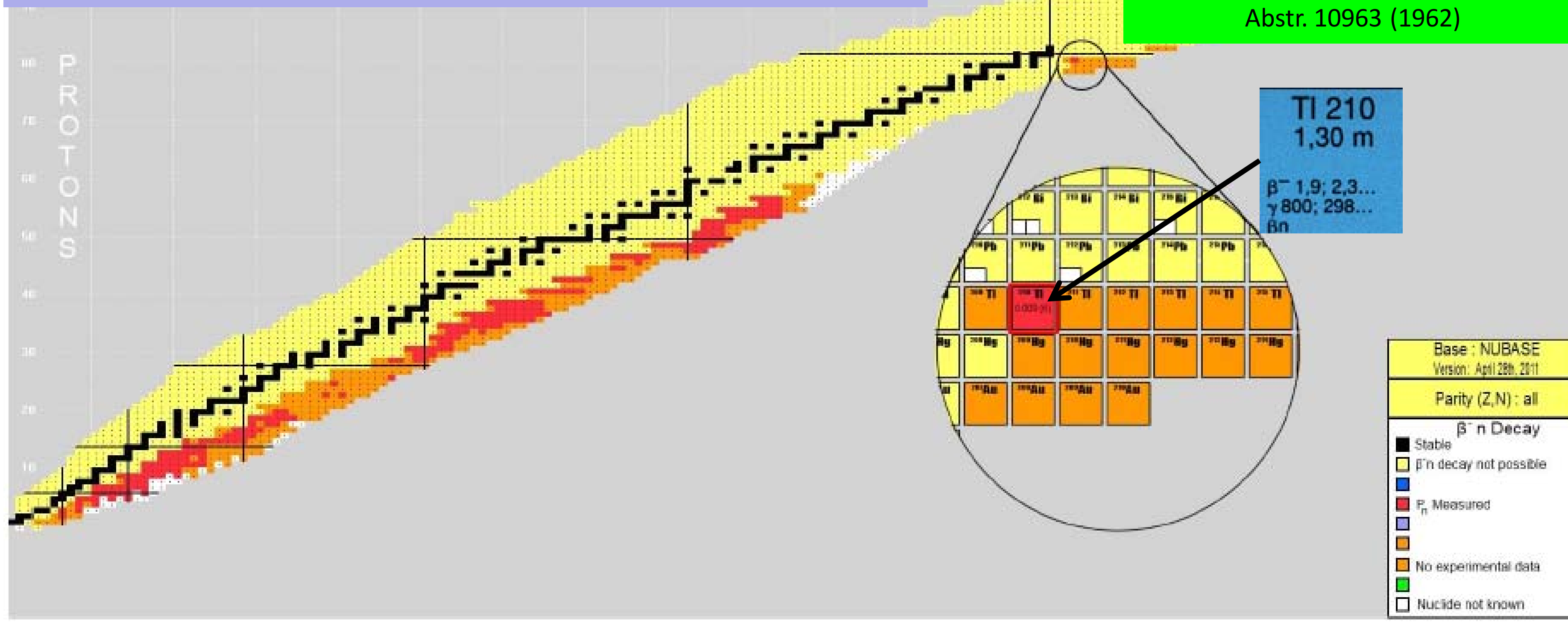
- 606 energetically possible cases (AME2012)
- ^{8}He- ^{150}La: 227 datasets available, ≈75 in non-fission region (A<70)

Only 1 measurement for A>150:

P_n= 0.007 (+0.007 -0.004) %

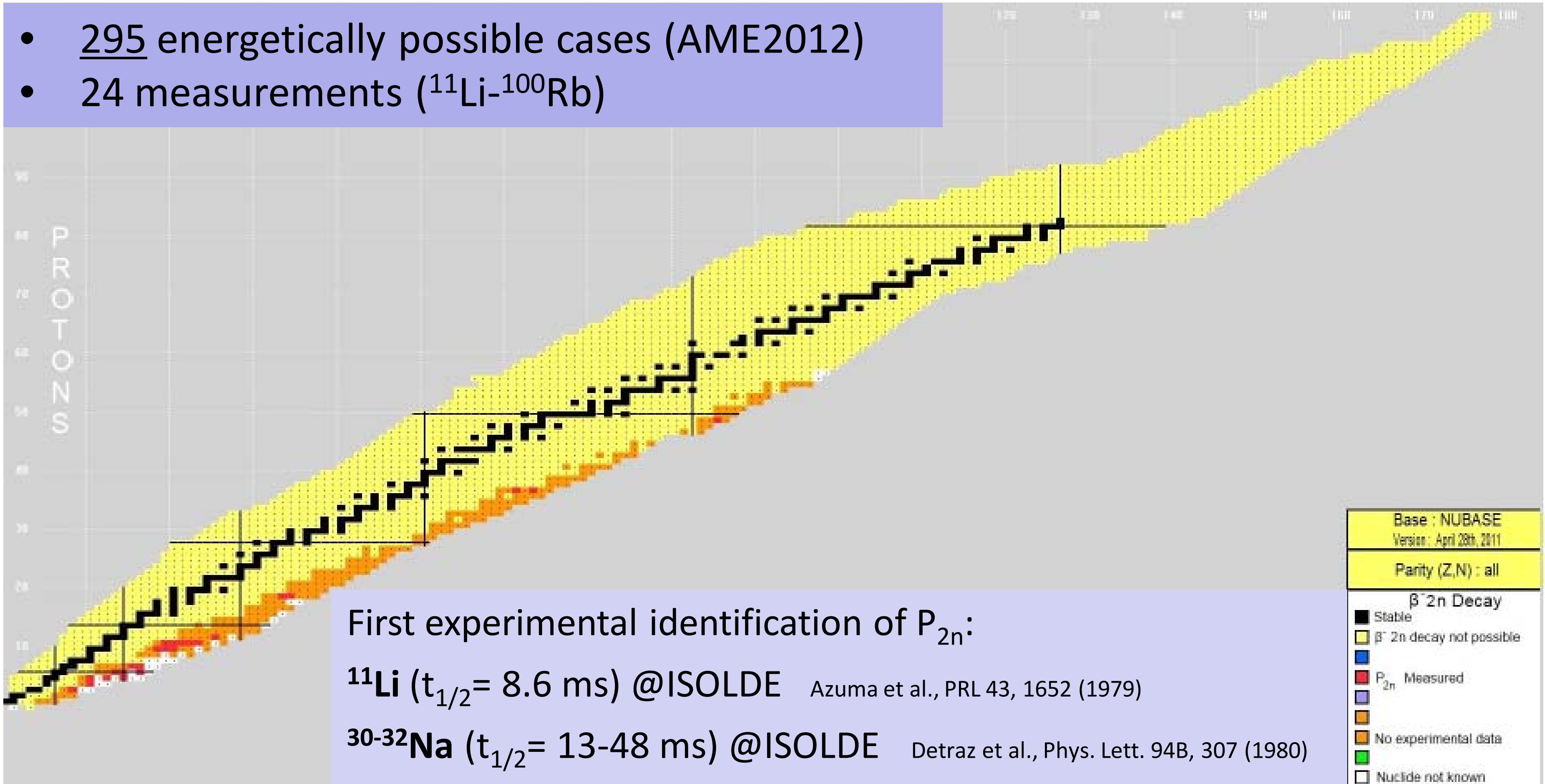
Validation missing

G. Stetter, Nucl. Sci. Abstr. 16, 1409, Abstr. 10963 (1962)



β-delayed 2-neutron emitters

- 295 energetically possible cases (AME2012)
- 24 measurements (^{11}Li-^{100}Rb)



First experimental identification of P_{2n}:

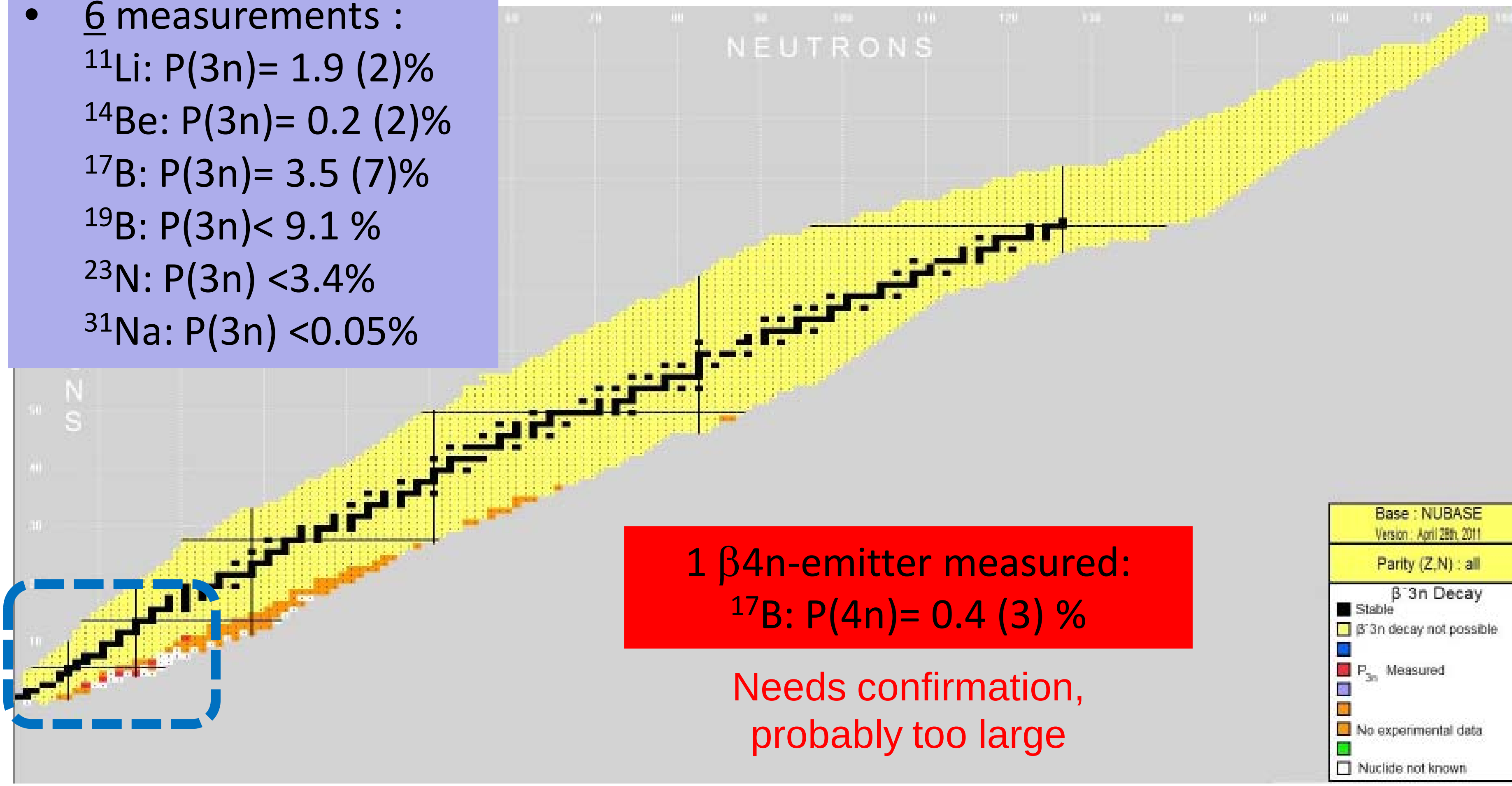
^{11}Li ($t_{1/2}$= 8.6 ms) @ISOLDE Azuma et al., PRL 43, 1652 (1979)

$^{30\text{-}32}$Na ($t_{1/2}$= 13-48 ms) @ISOLDE Detraz et al., Phys. Lett. 94B, 307 (1980)

^{98}Rb ($t_{1/2}$= 114 ms) @TRISTAN Reeder et al., PRL 47, 483 (1981)

β-delayed 3-/4-neutron emitters

- 104 possible cases
- 6 measurements :
  ^{11}Li: P(3n)= 1.9 (2)%
  ^{14}Be: P(3n)= 0.2 (2)%
  ^{17}B: P(3n)= 3.5 (7)%
  ^{19}B: P(3n)< 9.1 %
  ^{23}N: P(3n) <3.4%
  ^{31}Na: P(3n) <0.05%

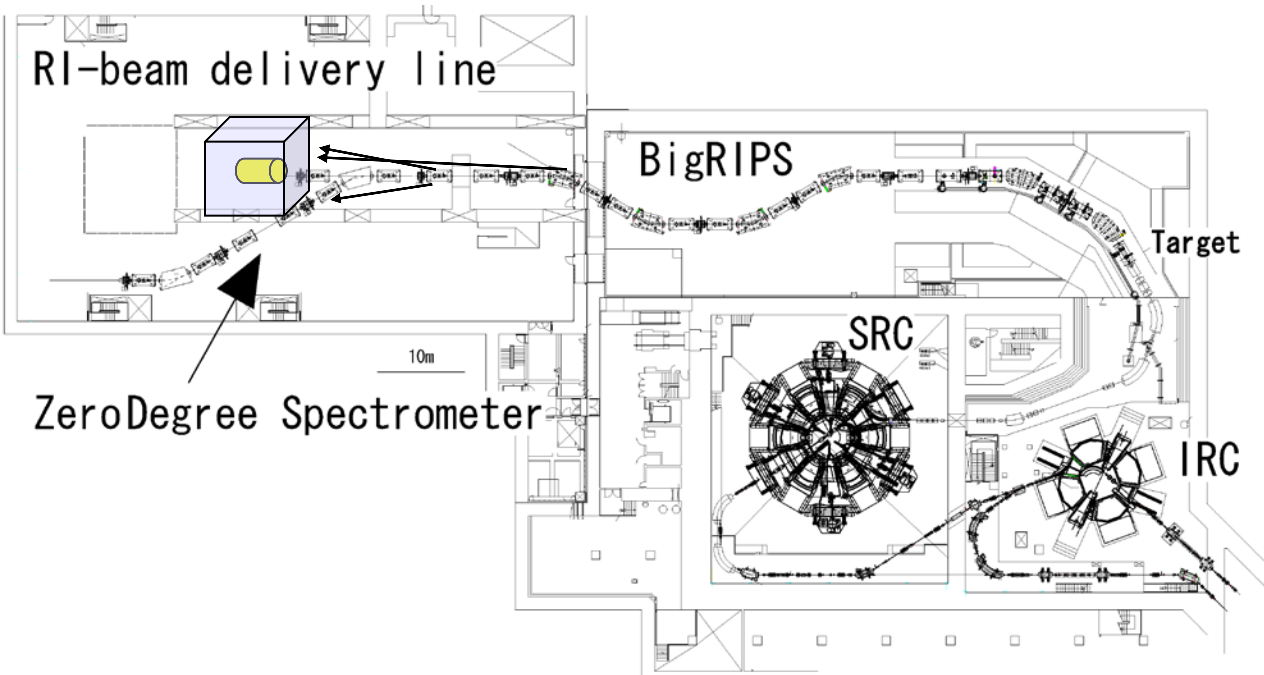


1 β4n-emitter measured:
^{17}B: P(4n)= 0.4 (3) %

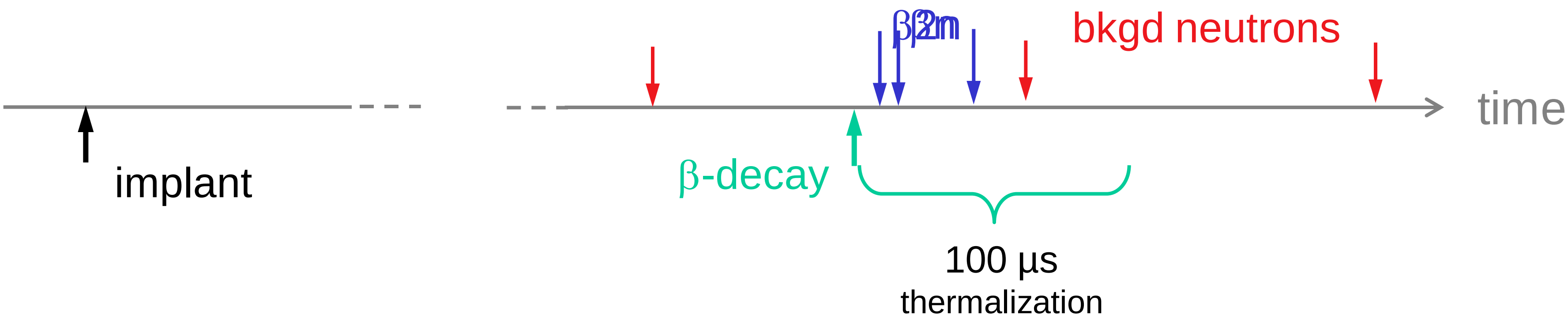
Needs confirmation,
probably too large

Set up + conditions needed

- RIB facility: deliver (many) pps exotic species decaying xβn
- Segmented detector: implant and β-decay detection (ε_β=50%)
- High-efficiency surrounding neutron detector (ε_{neu}=50%) + flexible DAQ
  - Method: β-n coincidence, independent of ε_β
- Low neutron (beam-induced?) background (1n/s)



Sensitivity: influence of background



- β-decay identified -> expect neutrons in the next 100µs

$$Signal(\beta xn) = prod \cdot \varepsilon_{\beta} \cdot P(xn) \cdot \varepsilon_{neu}{}^{x}$$

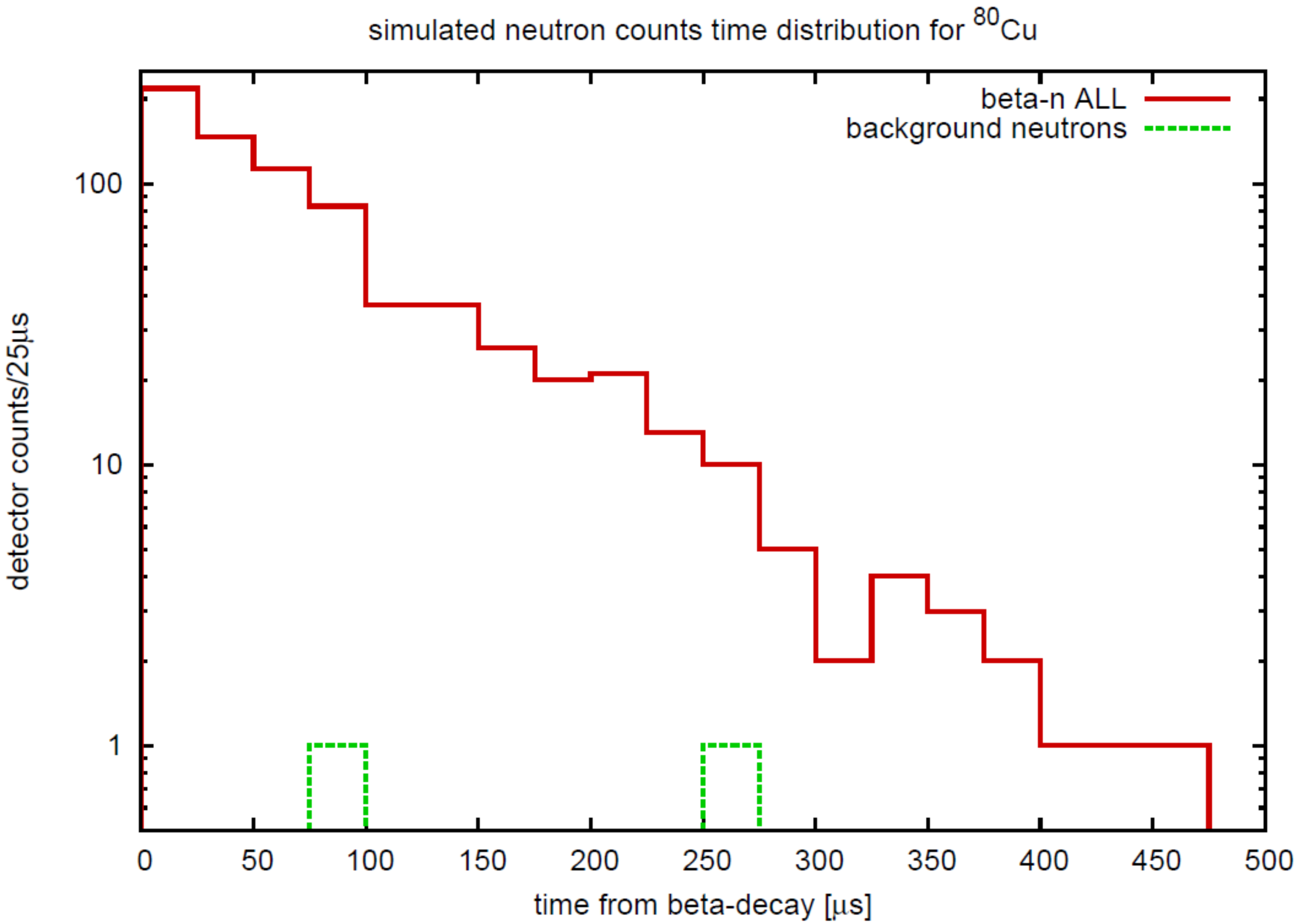
- Background n randomly appears in the moderation time window
  - 1n/s -> 0.0001 probability to fall in the 0.1ms window
  - Rate bkgd n / day = prob * # decay/day

$$Noise = 0.0001 \cdot rate_{neu,bkgd} \cdot prod \cdot \varepsilon_{\beta}$$

- Sensitivity (S/N>10) with assumed conditions: P(1n)>0.2%, P(2n)>0.4%, P(3n)>0.8%

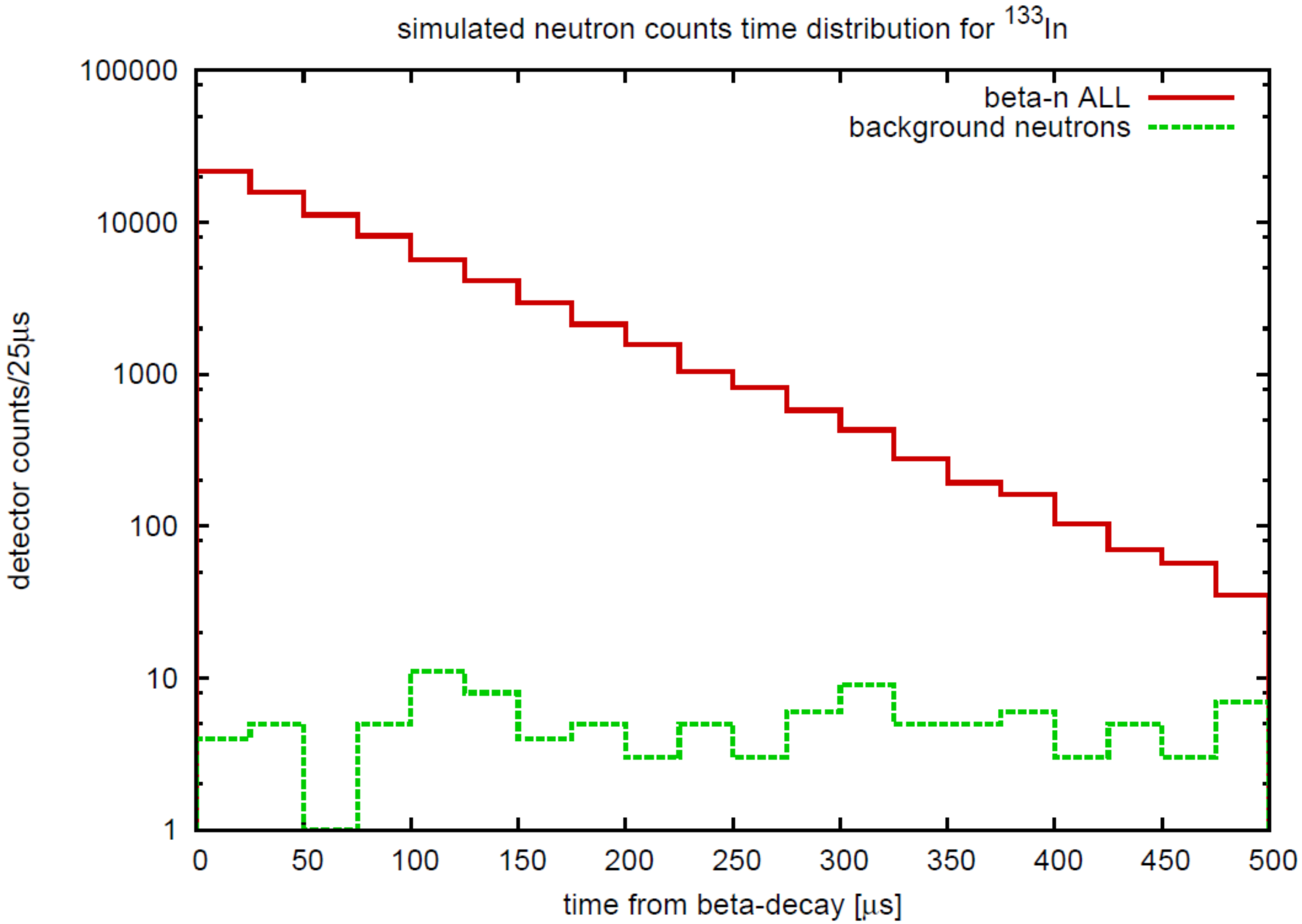
Simulated time distribution of neutron bkgd+β2n: the ^{80}Cu (nice) case

- Production rate 0.05 pps, P(1n)=43.9% , P(2n)=12.6%, 1-day, bkgd 1n/s

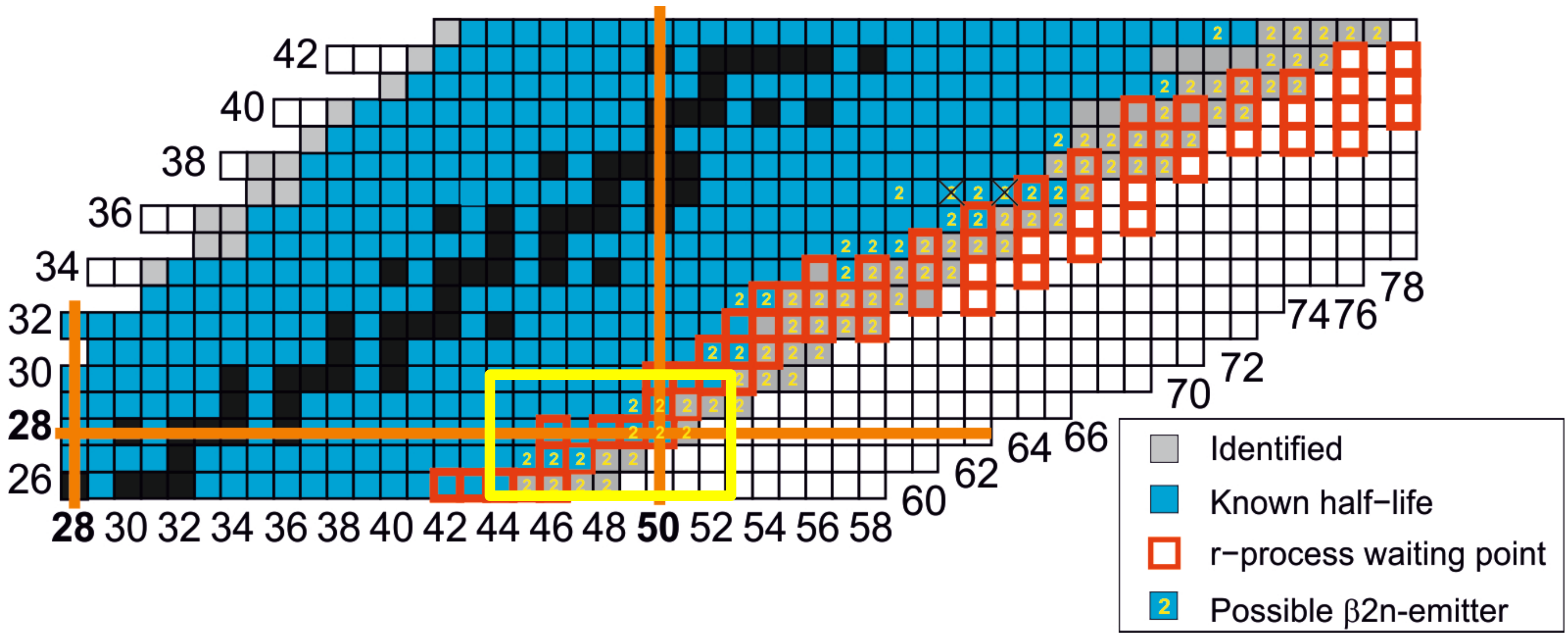


Simulated time distribution of neutron bkgd+β2n: the ^{133}In (ugly) case

- Production rate 50pps, P(1n)=85% , P(2n)=0.21%, 2 hours, bkgd 1n/s



Around ^{78}Ni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28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58
60
62
64
66
70
72
74
76
78
Identified
Known half−life
r−process waiting point
Possible β2n-emitter

Rate estimations

ε(beta)~50 %
ε(neutron)~50 %

$\varepsilon(\beta n)$~25 %
$\varepsilon(\beta nn)$~12.5 %

$\mathrm{Rate}_{neu,bkgd}$
1n/s

	Z	cts/s/pnA	10 pnA pps	part/day	t1/2 (ms)	P(n) (%)	P(2n) (%)	N(bn) per day	N(bnn) per day	N(bkgd) per day
76Co	27	5.00E-04	5.00E-03	432.0		26.4	5.64	28.5	3.05	0.02
77Co	**27**	**5.00E-05**	**5.00E-04**	**43.2**		**69.4**	**6.8**	**7.50**	**0.37**	**0.002**
78Ni	**28**	**1.00E-03**	**1.00E-02**	**864.0**	**110**	**39.2**	**0**	**85**		
79Ni	28	1.00E-04	1.00E-03	86.4		62.1	4.75	13.4	0.51	0.004
79Cu	**29**	**5.00E-02**	**5.00E-01**	**43200.0**	**257**	**72**	**0**	**7776**		
80Cu	29	5.00E-03	5.00E-02	4320.0	170	43.9	12.6	474	68.0	0.2
81Cu	29	5.00E-04	5.00E-03	432.0		62	21	67	11.3	0.02

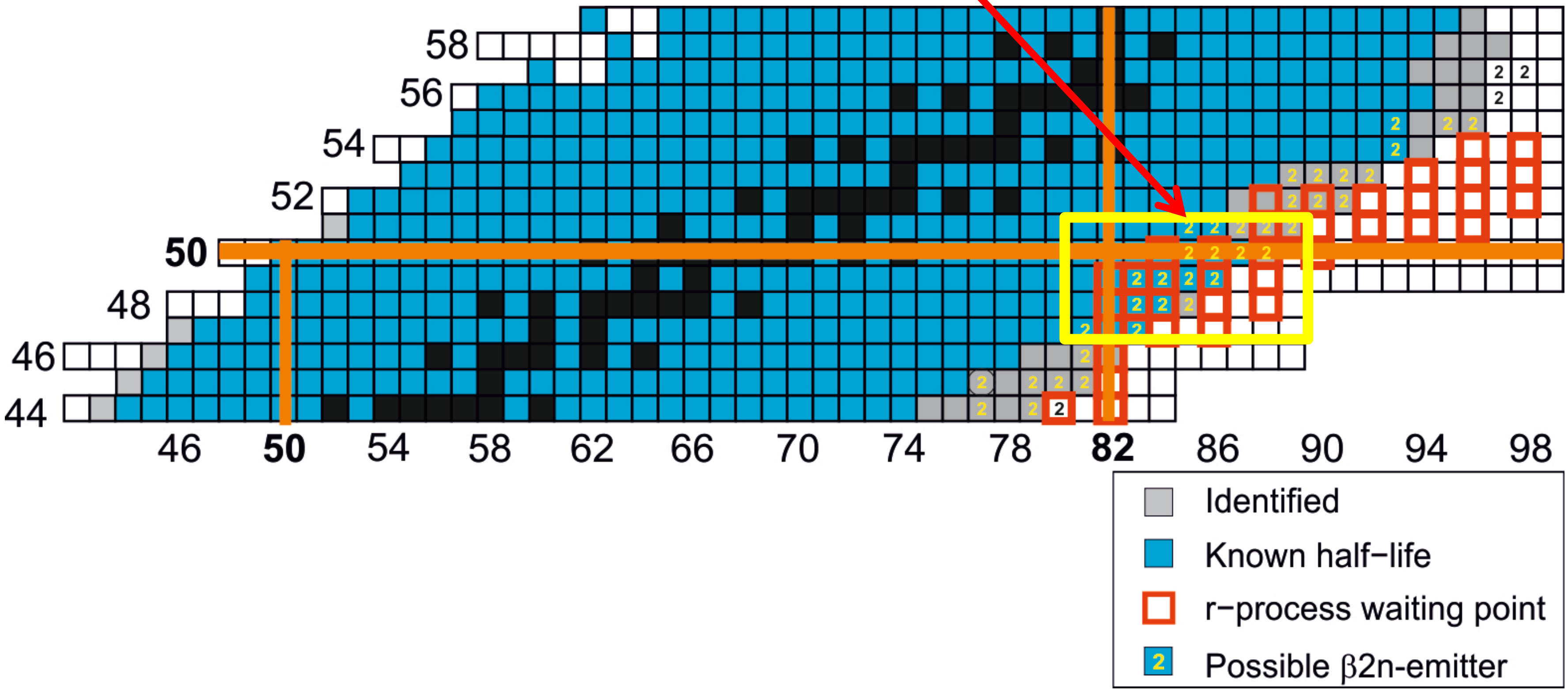
Ohnishi 2010

orange: measured

Möller 2003

Around ^{132}Sn

^{136}Sb: accepted JYFL proposal



Rate estimations

ε(beta)~50 %
ε(neutron)~50 %

$\varepsilon(\beta n)$~25 %
$\varepsilon(\beta nn)$~12.5 %
$\varepsilon(\beta nnn)$~6.3 %

If ε_{neu}= 75%
$\varepsilon(\beta nnn)$~21 %

$Rate_{neu,bkgd}$
1n/s

	Z	est. cts/s/pnA	10 pnA pps	part/day	t1/2 (ms)	P(n) (%)	P(2n) (%)	P(3n) (%)	N(bn) per day	N(bnn) per day	N(bnnn) per day	N(bkgd) per day
134Sn	50	5.00E+02	5.00E+03	4.32E+08	1050	17%			1.8E+07			2.2E+04
135Sn	50	1.00E+01	1.00E+02	8.64E+06	530	21%	5.5%		4.5E+05	5.9E+04		4.3E+02
132In	49	5.00E+01	5.00E+02	4.32E+07	200	6.30%	0.01%		6.8E+05	5.4E+02		2.2E+03
133In	49	5.00E+00	5.00E+01	4.32E+06	180	85.00%	0.21%		9.2E+05	1.1E+03		2.2E+02
134In	49	1.00E+00	1.00E+01	8.64E+05	138	65.00%	86.67%		1.4E+05	9.4E+04		4.3E+01
135In	49		1.30E-03	1.12E+02	92	23.50%	64.26%	7.39%	6.60	9.02	0.52	0.006
130Cd	48	1.00E+00	1.00E+01	8.64E+05	162	3.50%			7.6E+03			43.2
131Cd	48	1.00E-01	1.00E+00	8.64E+04	68	3.50%			7.6E+02			4.3
132Cd	48	1.00E-02	1.00E-01	8.64E+03	97	60.00%	0.23%		1.3E+03	2.48		0.43
133Cd	48	1.00E-03	1.00E-02	8.64E+02	185	21.10%	50.30%		45.6	54.3		0.04

Ohnishi 2010

orange: measured

Möller 2003

yellow: signal ≈ bkgd n

red: signal < bkgd n

Conclusion

- Idea: measure β-delayed multiple neutron emission of nuclei around the first and second peak for r process (and to guide the theory)
- β2n measurements possible with reasonable beam time required (days)
- Neutron background critical for sensitivity (investigate also in other regions + shield with enriched-boron rubber?)

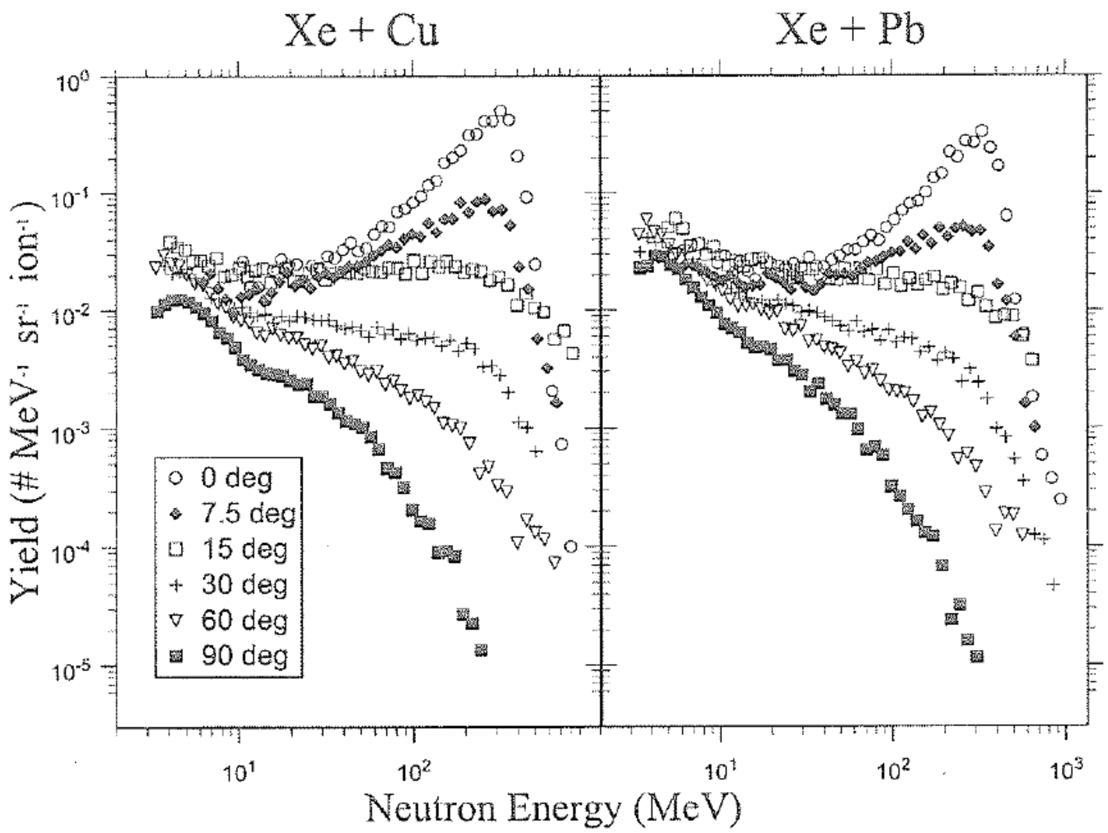
OUTLOOK

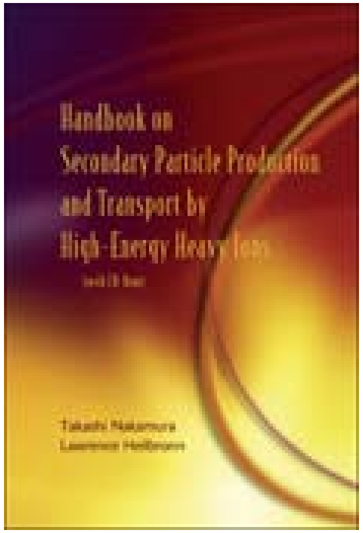
- Investigate the solution of neutron detector "with Clovers" for gamma-n correlation

EXTRA SLIDES

Appendix: beam induced n background

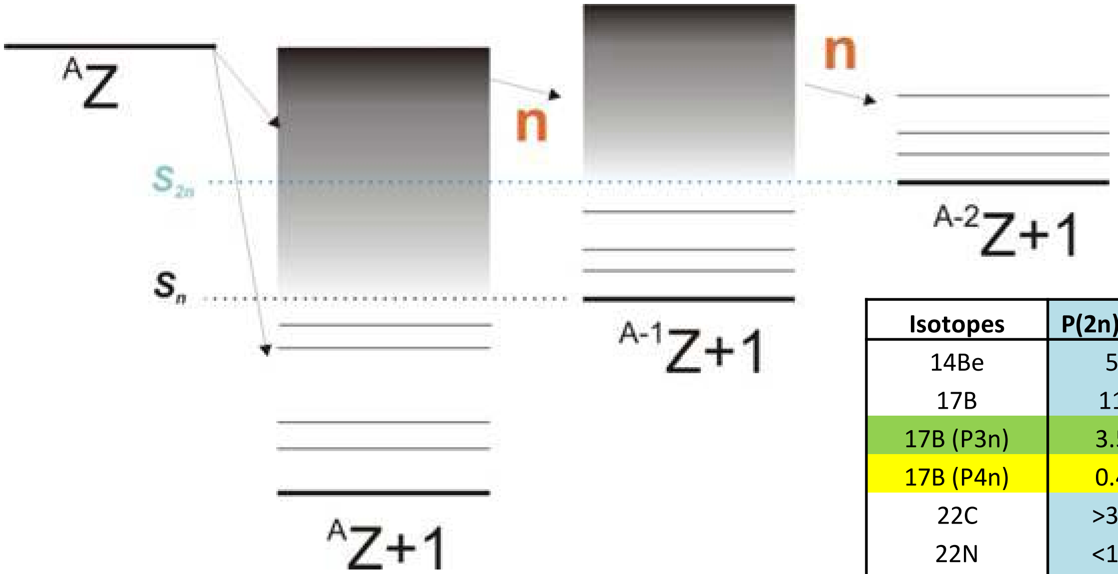
Handbook On Secondary Particle Production And Transport By High-Energy Heavy Ions





- A=150 ions on Iron: more than 100 fast neutrons per ion

β-delayed two neutron emission



$S_{2n} < Q_{\beta}$

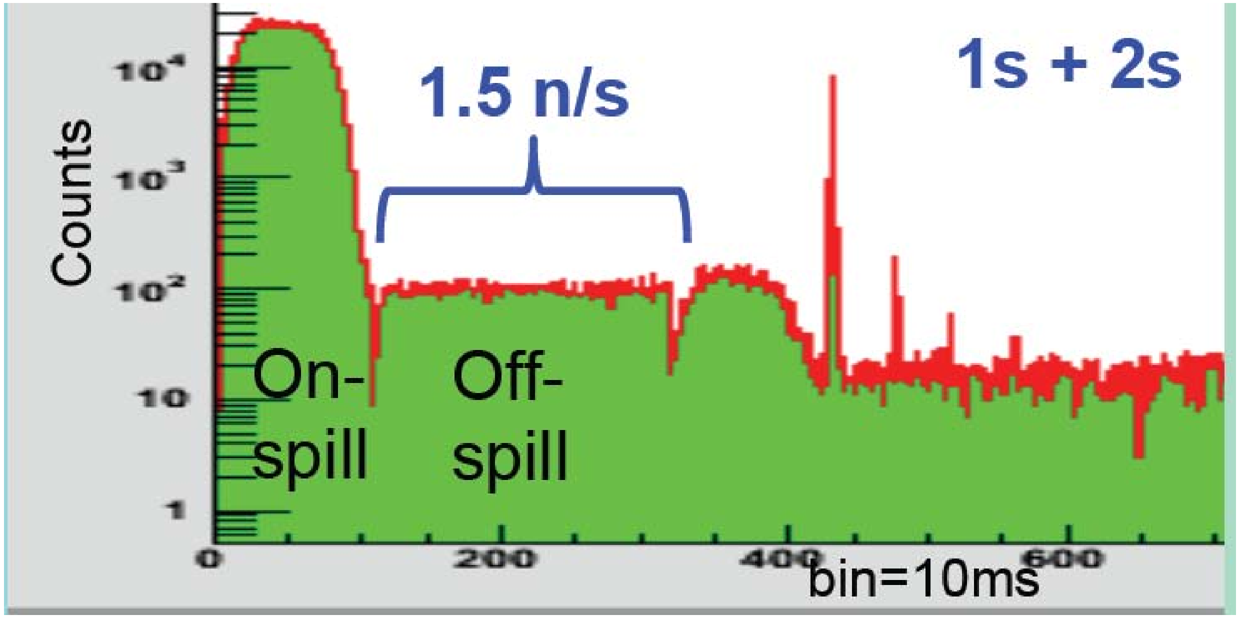
Isotopes	P(2n) (%)	Err (%)	Möller (%)
14Be	5	2	-
17B	11	7	-
17B (P3n)	3.5	0.7	-
17B (P4n)	0.4	0.3	-
22C	>37		-
22N	<13		-
28Ne	3.6	0.5	0.01
29Ne	4	1	1.89
30Ne	8.9	2.3	3.46
30Na	1.15	0.25	0.38
31Na	0.87	0.24	1.3
31Na (P3n)	<0.05		-
32Na	8	2	9.24
33Na	13	3	4.44
34Na	50		21.8
52K	21		4.9
53K	17		2.8
98Rb	0.051	0.007	0.2
100Rb	0.16	0.08	0.92

- 18 β2n-emitter known
- New AME2012:

$$\left.\begin{array}{l} Q_{\beta} > S_{2n} \\ Q(\beta 2n) > 500\ \text{keV} \end{array}\right\}\ \text{305 cases}$$

- 3 β3n-emitter: ^{11}Li, ^{14}Be, ^{17}B
- 1 β4n emitter: ^{17}B

Beam-induced neutron background GSI



Courtesy of J. L. Tain