



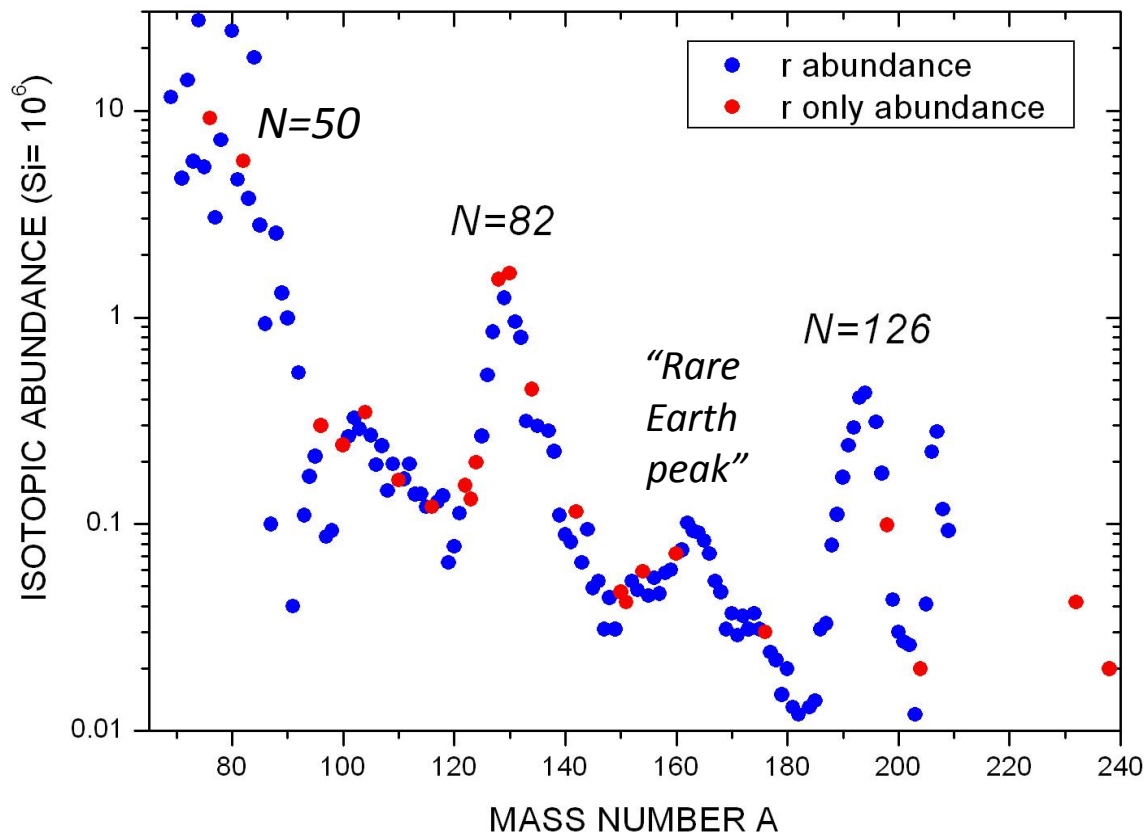
Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

From the lab to the cosmos: Measuring neutron-rich isotopes at TRIUMF (and Jyväskylä) and RIKEN

Iris Dillmann
Associate Scientist (TRIUMF)
Adjunct Professor (University of Victoria)

June 28, 2017

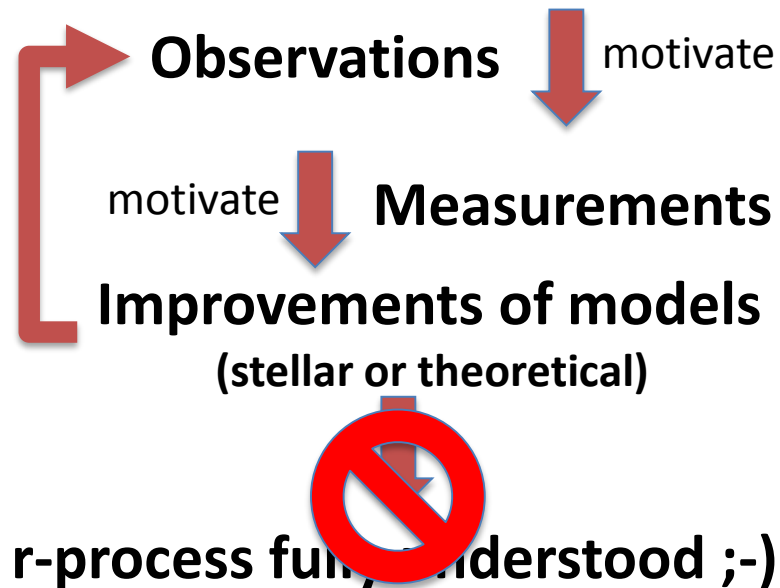
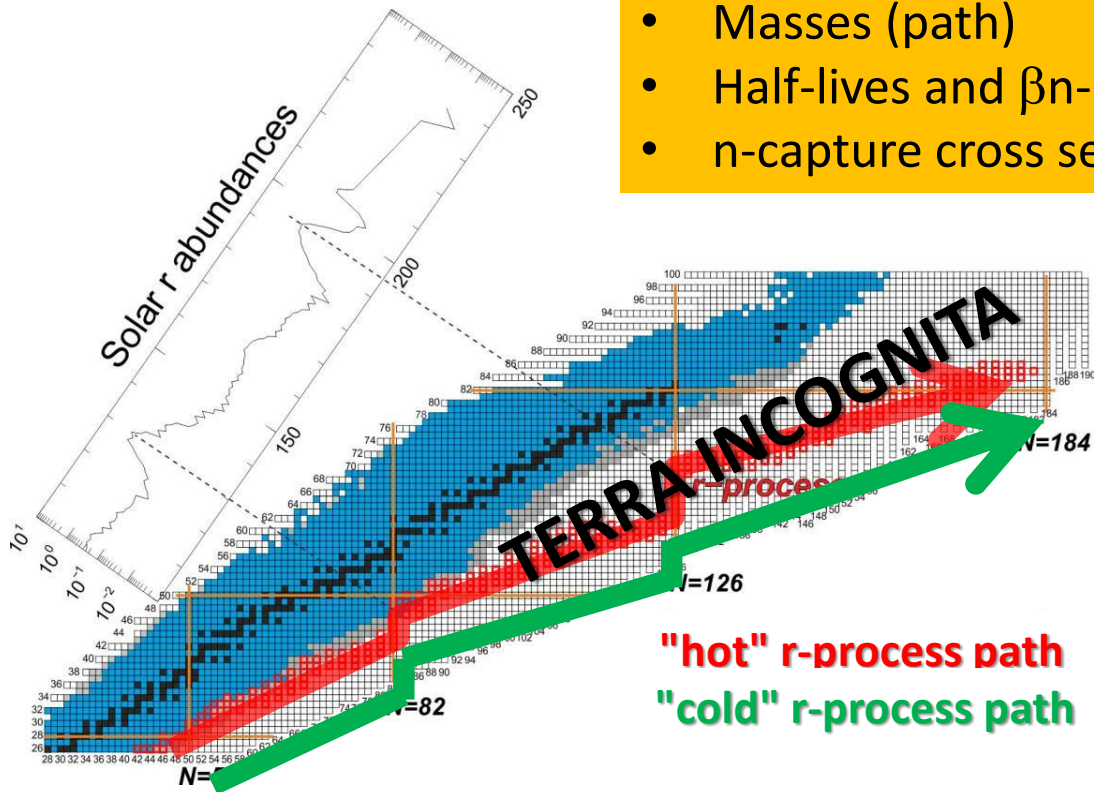




Connection between
nuclear structure
far off stability and
"observed" abundances !

Most important nuclear physics inputs:

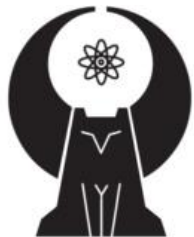
- Masses (path)
- Half-lives and β n-branching ratios (peak shape)
- n-capture cross sections (peak shape)



1. γ -Spectroscopy of neutron-rich isotopes
 - ⇒ half-lives, (nuclear structure)
2. Measurement of β -delayed neutron emitters
 - ⇒ half-lives, β -delayed neutron branching ratios
3. Measurement of i-process key reactions
 - ⇒ (n,γ) reaction rates

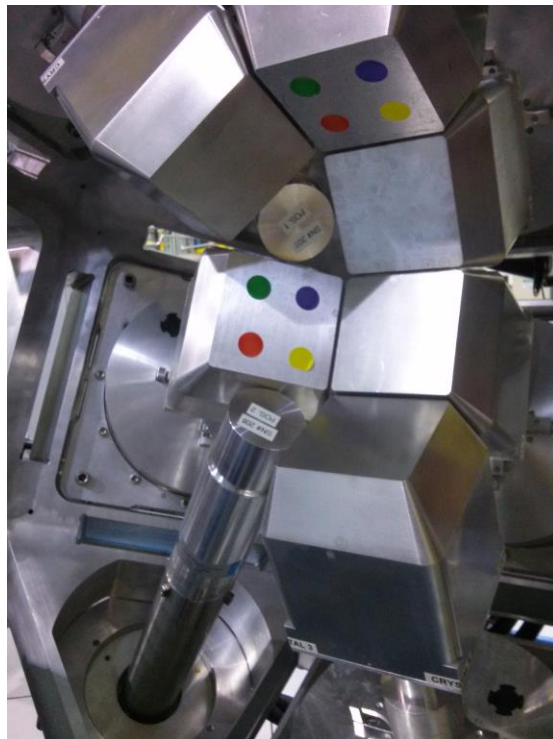
γ -Spectroscopy of neutron-rich isotopes at TRIUMF





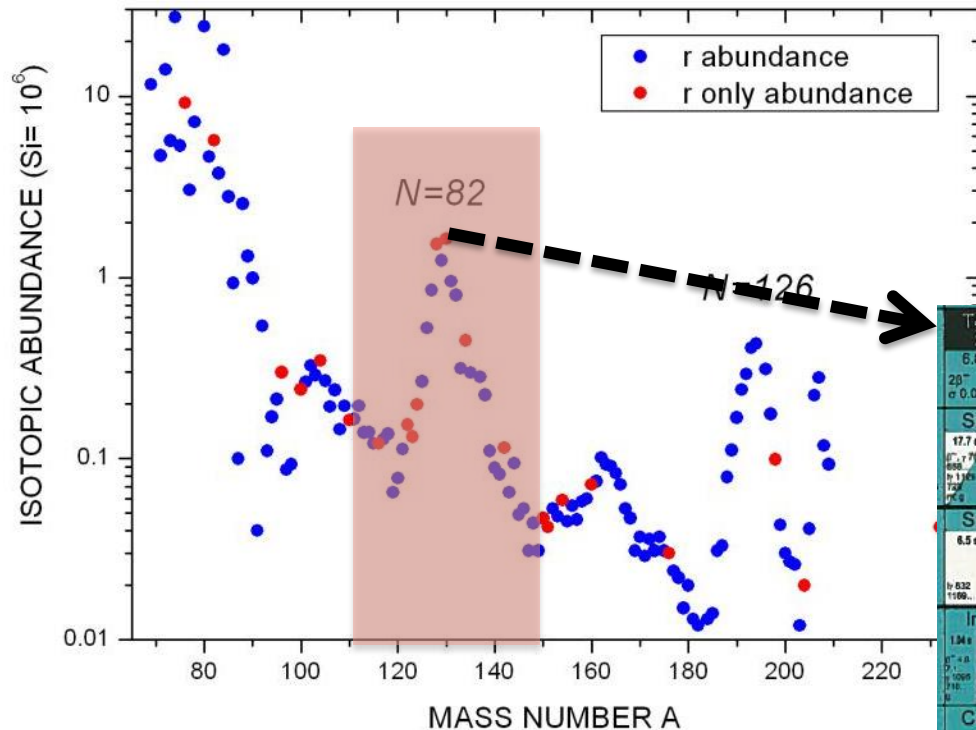
GRIFFIN

Gamma-**R**ay
Infrastructure **F**or
Fundamental
Investigations
of **N**uclei



- High efficiency γ -ray spectrometer
- 16 HPGe Clovers
- Coupled with ancillary detectors: plastic scintillators, conversion electron spectrometer, LaBr_3 fast timing array, neutron detectors,...

In operation since fall 2014



Solar r-abundance at A=130:
Stable ^{130}Te from decay of
N=82 ^{130}Cd and neighbors

N=82

Te 130 34 108 6.8·10 ⁸ a 20 ⁺ α 0.01 + 0.19	Te 131 34 109 33.25 h 2.8 β ⁻ 0.9 γ 175 g	Te 132 34 110 76.3 h β ⁻ 2.1 γ 228, 50... g	Te 133 34 111 55.4 m 12.5 m β ⁻ 0.7 γ 312, 409 1333. g	Te 134 34 112 41.8 m β ⁻ 0.6, 0.7... γ 787, 210, 278 79, 556... g	Te 135 34 113 18.6 s β ⁻ 6.0... γ 804, 267, 870 1133... g	Te 136 34 114 17.5 s β ⁻ 2.8, 4... γ 2076, 334, 679 2696, 3205... g	Te 137 34 115 2.5 s β ⁻ 6.3, 6.8... γ 243, 554 489... g	Te 138 34 116 1.4 s β ⁻
Sb 129 51 79 17.7 m β ⁻ 0.8 γ 790 g	Sb 130 51 80 4.40 h 6.3 m β ⁻ 2.9 γ 840, 793 531, 162... g	Sb 131 51 81 23 m β ⁻ 1.3, 3.0... γ 943, 933 842... g	Sb 132 51 82 4.1 m 2.8 m β ⁻ 3.7 γ 974, 897 151, 191... g	Sb 133 51 83 2.34 m β ⁻ 1.2, 2.9... γ 1098, 818 2755, 837... g	Sb 134 51 84 10.1 s 0.75 s β ⁻ 8.1... γ 1278 267, 707 2831 1352... g	Sb 135 51 85 1.7 s β ⁻ 8.1... γ 145, 1.04... 1360... g	Sb 136 51 86 923 ms β ⁻	Sb 137 51 87 450 ms β ⁻
Sn 128 50 78 6.5 s β ⁻ 0.7 γ 832 1109... g	Sn 129 50 79 59.1 m 2.2 m β ⁻ 2.9 γ 1191 432, 70 567, 981... g	Sn 130 50 80 2.2 m β ⁻ 3.3 γ 843 g	Sn 131 50 81 1.3 m 3.7 m β ⁻ 4 γ 143, 889 84, 311... g	Sn 132 50 82 39 s 39 s β ⁻ 3.4 γ 220 450, 208 1226... g	Sn 133 50 83 1.46 s β ⁻ 8.1... γ 982... m	Sn 134 50 84 1.05 s β ⁻ 7.0... γ 872, 318, 554 982... g	Sn 135 50 85 530 ms β ⁻ 282, 925, 733 1207... g	Sn 136 50 86 250 ms β ⁻
In 127 49 77 1.94 s β ⁻ 4.8, 5.2... γ 280, 426... g	In 128 49 78 0.22 s 0.34 s β ⁻ 5.9 γ 1235, 375 524, 1067... g	In 129 49 79 0.87 s 1.23 s 0.81 s β ⁻ 5.9 γ 248, 857... g	In 130 49 80 0.27 s β ⁻	In 131 49 81 1.90 s β ⁻	In 132 49 82 0.20 s β ⁻ 6.4, 8.9... γ 375, 4041 299... g	In 133 49 83 160 ms 165 ms β ⁻ 662, 854 1561... g	In 134 49 84 140 ms β ⁻ 1561, 854... g	In 135 49 85 92 ms β ⁻
Cd 126 48 76 0.51 s β ⁻ 4.8, 5.2... γ 280, 426... g	Cd 127 48 77 0.37 s β ⁻ 5.5... γ 1235, 375 524, 1067... g	Cd 128 48 78 0.30 s β ⁻ 5.9 γ 248, 857... g	Cd 129 48 79 0.27 s β ⁻	Cd 130 48 80 162 ms β ⁻ 6.2, 8.3... γ 1959, 451 1171, 950... g	Cd 131 48 81 88 ms β ⁻	Cd 132 48 82 97 ms β ⁻	Cd 133 48 83 57 ms β ⁻	7.79 6.87
Ag 125 47 75 166 ms β ⁻	Ag 126 47 76 95 ms β ⁻ 652, 815 402... g	Ag 127 47 77 79 ms β ⁻	Ag 128 47 78 58 ms β ⁻ 645, 784... g	Ag 129 47 79 -160 ms 44 ms β ⁻	Ag 130 47 80 -50 ms β ⁻ 857 βn?	2.878 3.724	4.296 5.274	6.60 6.99

PHYSICAL REVIEW C 93, 062801(R) (2016)

Half-lives of neutron-rich $^{128-130}\text{Cd}$

R. Dunlop,^{1,*} V. Bildstein,¹ I. Dillmann,^{2,3,†} A. Jungclauss,⁴ C. E. Svensson,¹ C. Andreoiu,⁵ G. C. Ball,² N. Bernier,^{2,6} H. Bidaman,¹ P. Boubel,¹ C. Burbadge,¹ R. Caballero-Folch,² M. R. Dunlop,¹ L. J. Evitts,^{2,7} F. Garcia,⁵ A. B. Garnsworthy,² P. E. Garrett,¹ G. Hackman,² S. Hallam,^{2,7} J. Henderson,² S. Ilyushkin,⁸ D. Kisliuk,¹ R. Krücken,^{2,6} J. Lassen,^{2,9} R. Li,² E. MacConnachie,² A. D. MacLean,¹ E. McGee,¹ M. Moukaddam,² B. Olaizola,¹ E. Padilla-Rodal,¹⁰ J. Park,^{2,6} O. Paetkau,² C. M. Petrache,¹¹ J. L. Pore,⁵ A. J. Radich,¹ P. Ruotsalainen,² J. Smallcombe,² J. K. Smith,² S. L. Tabor,¹² A. Teigelhöfer,^{2,9} J. Turko,¹ and T. Zidar¹

^{130}Cd half-life:

ISOLDE (1986): $t_{1/2} = 195(35)$ ms

K.-L. Kratz, et al., Z. Phys. A 325, 489 (1986).

ISOLDE (2001): $t_{1/2} = 162(7)$ ms

M. Hannawald et al., NP A688, 578 (2001).

EURICA (2015): $t_{1/2} = 127(2)$ ms

G. Lorusso et al., PRL 114, 192501 (2015).

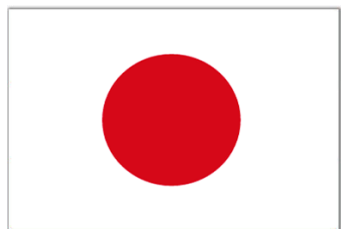
GRIFFIN (2016): $t_{1/2} = 126(4)$ ms

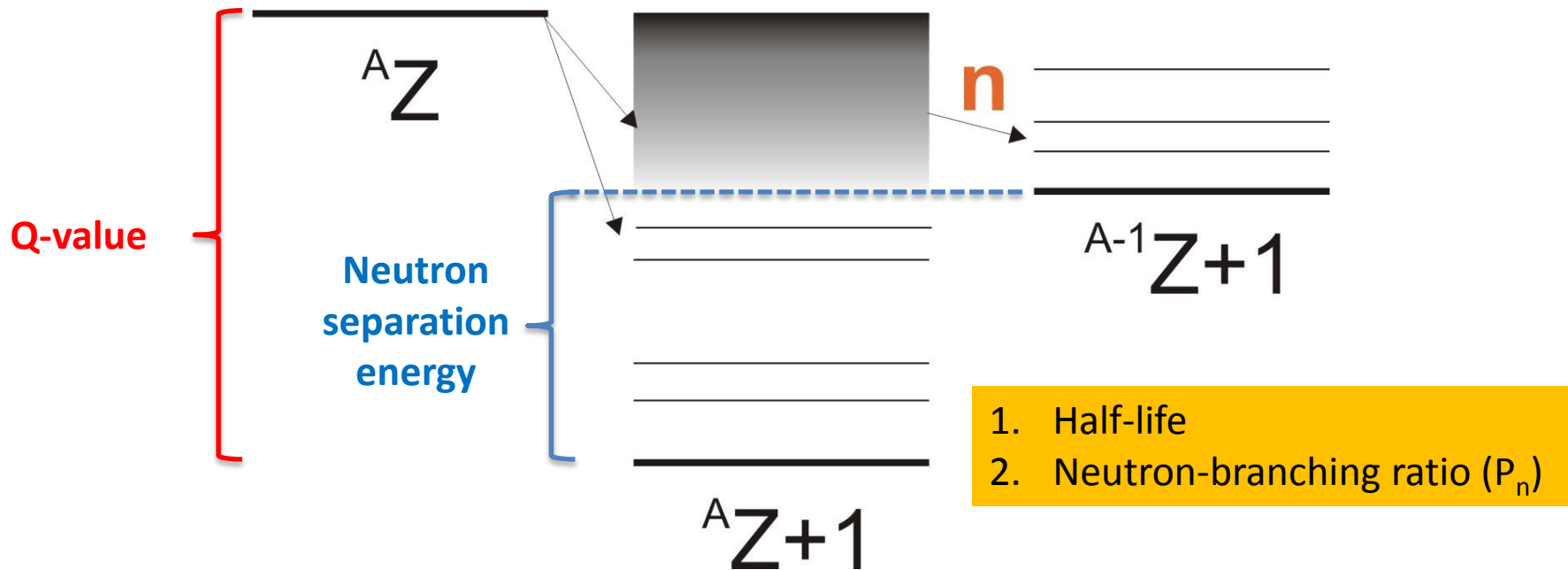
R. Dunlop et al., Phys. Rev. C93 (2016)



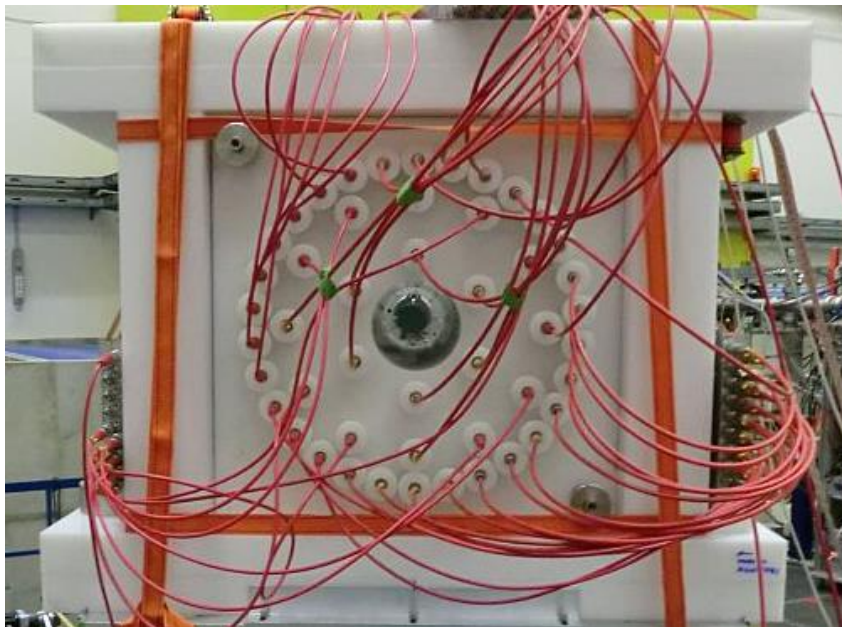
*Previous ^{130}Cd half-life was used to **adjust Gamow-Teller quenching factor** for lighter $N=82$ isotopes: New predictions will yield **shorter half-lives** for ^{128}Pd , ^{127}Rh , ^{126}Ru ...*

Measurement of β -delayed neutron emitters





Dominant decay mechanism for very neutron-rich isotopes



High-pressure ^3He long counters
in polyethylene moderator:
 $^3\text{He} + n \rightarrow ^3\text{H} + p + 765 \text{ keV}$



Universidad Politecnica de Cataluna,
Barcelona



IFIC Valencia



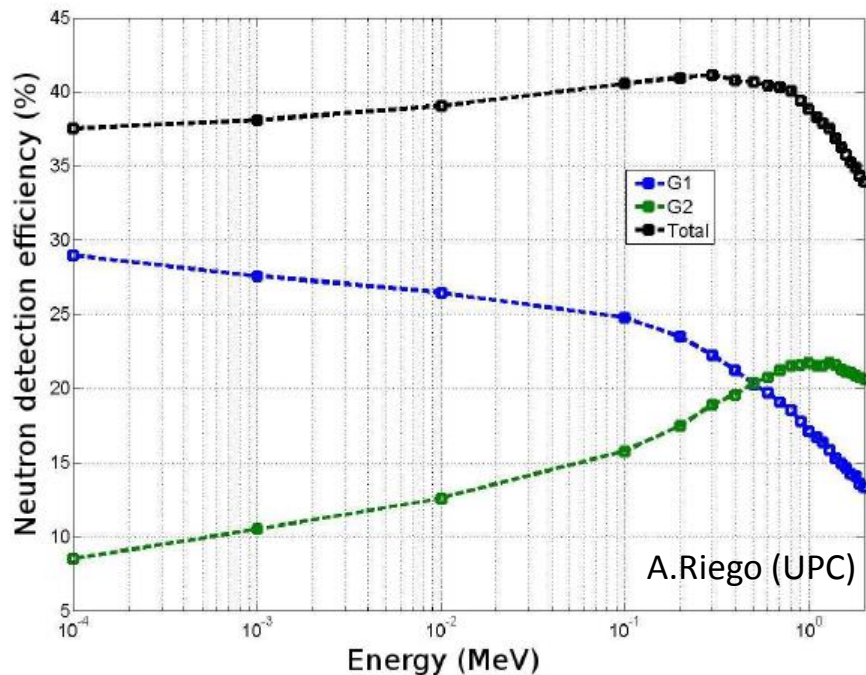
CIEMAT Madrid



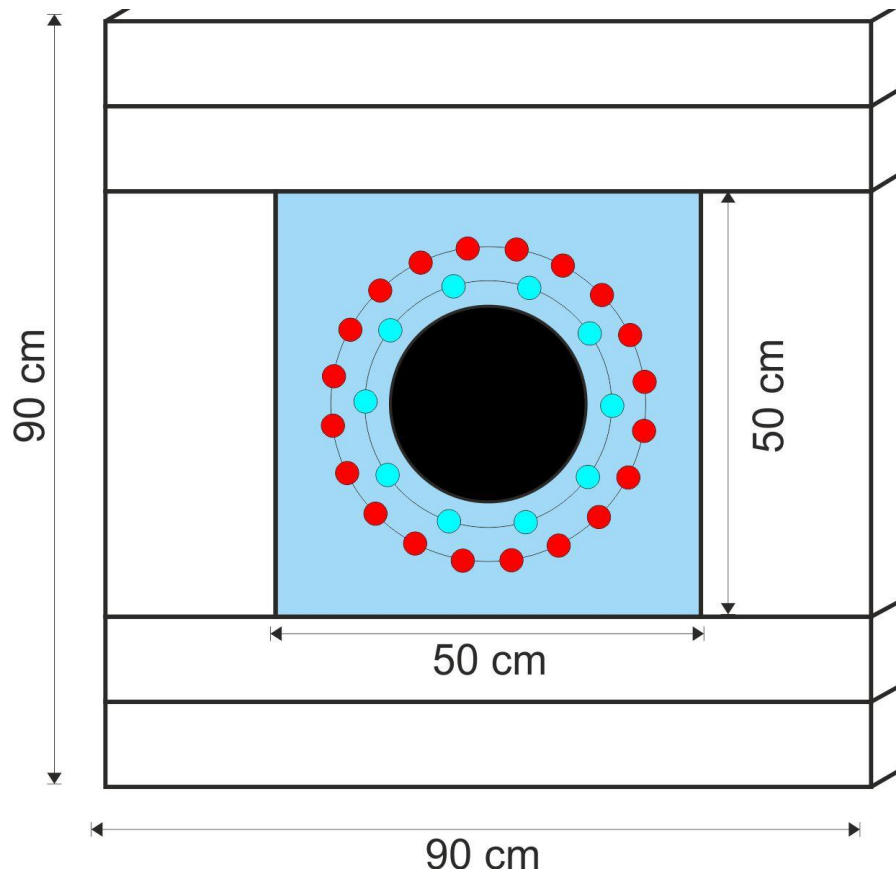
GSI Helmholtz Center Darmstadt



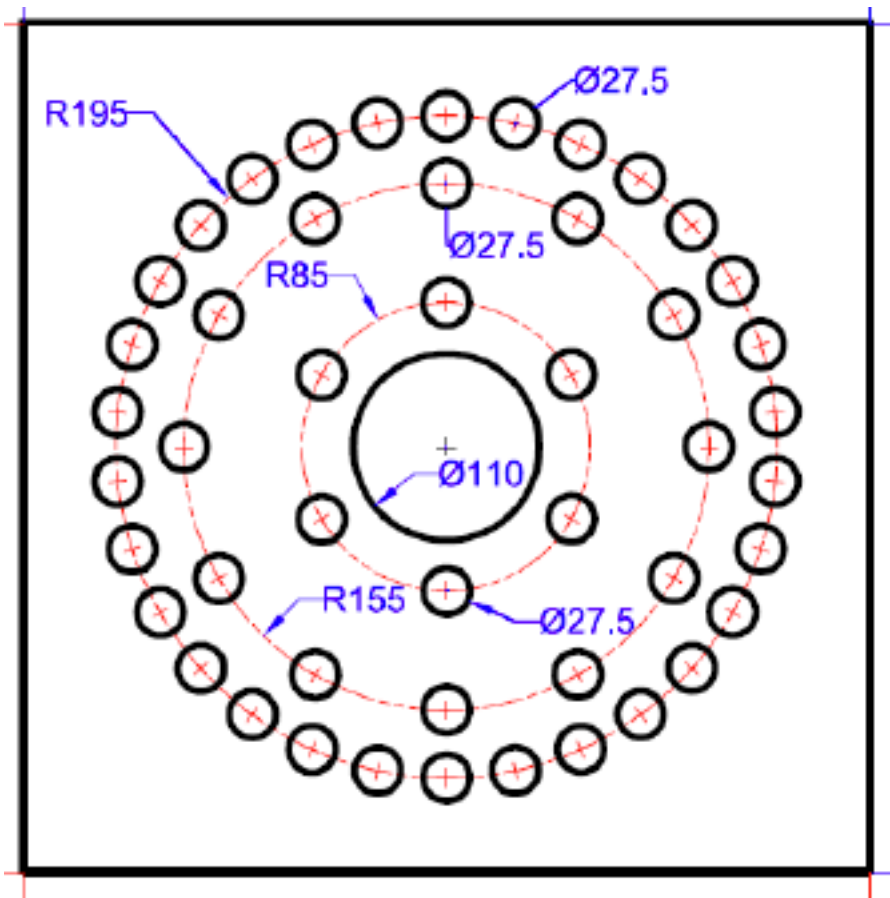
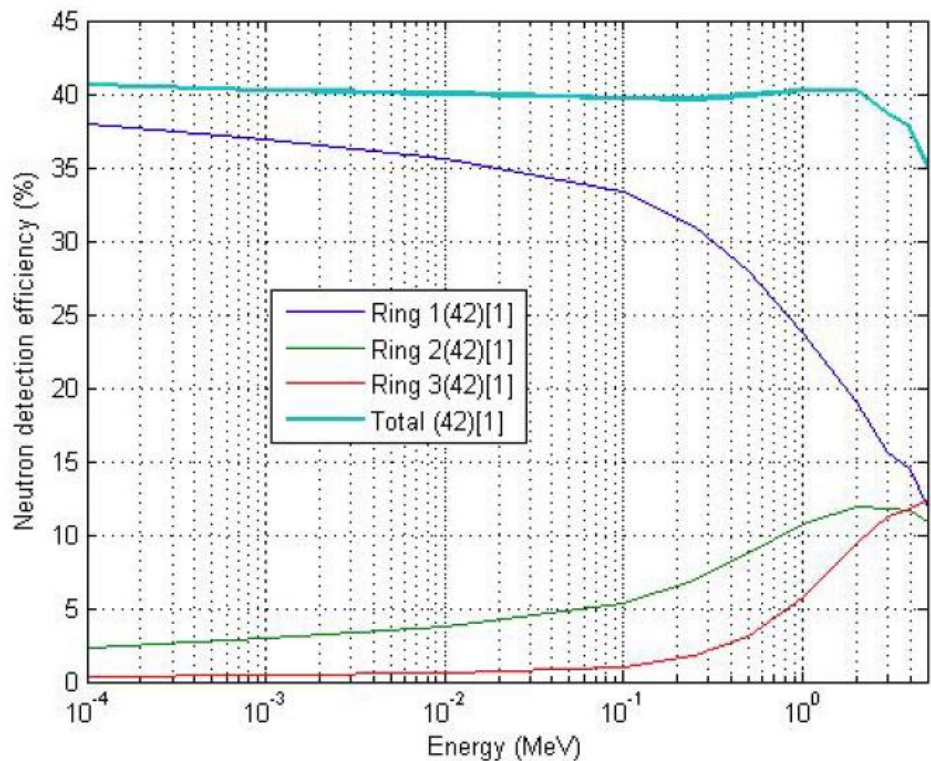
Setup with implantation detector in center



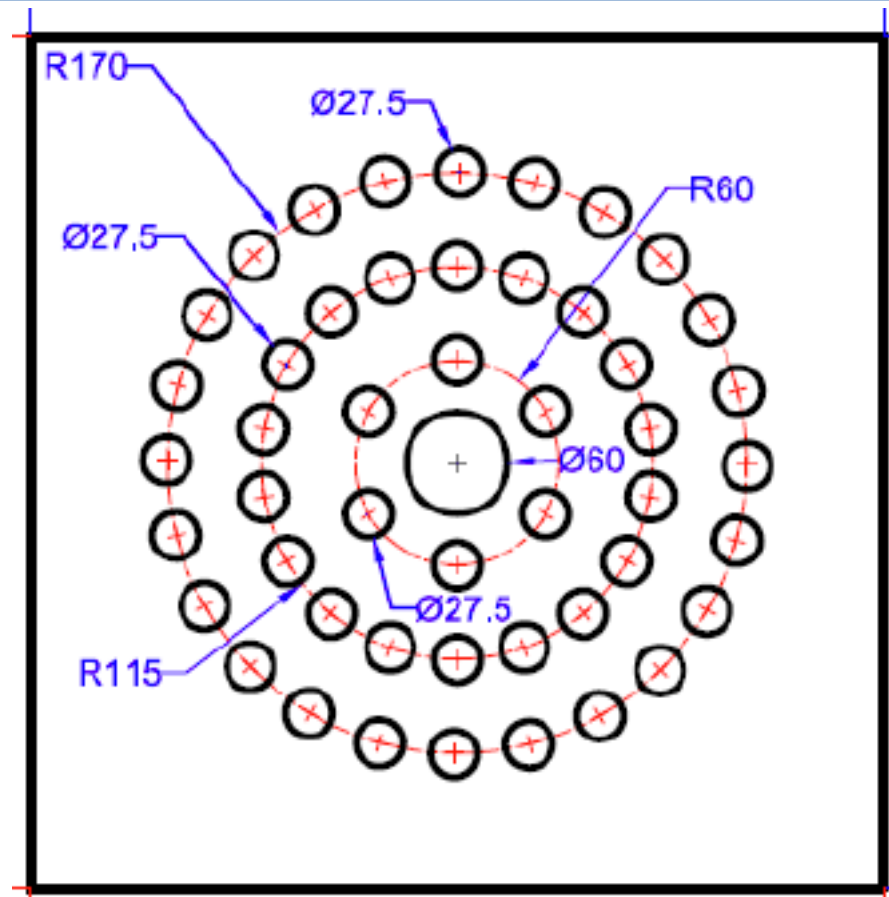
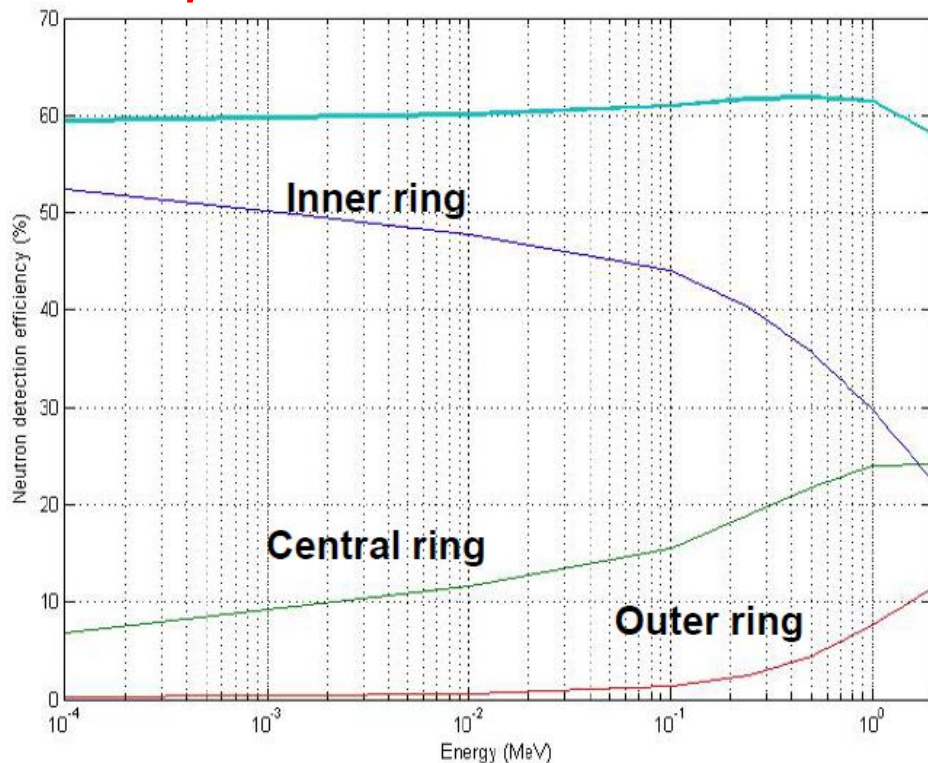
Efficiency for BELEN version with 30 ³He counters

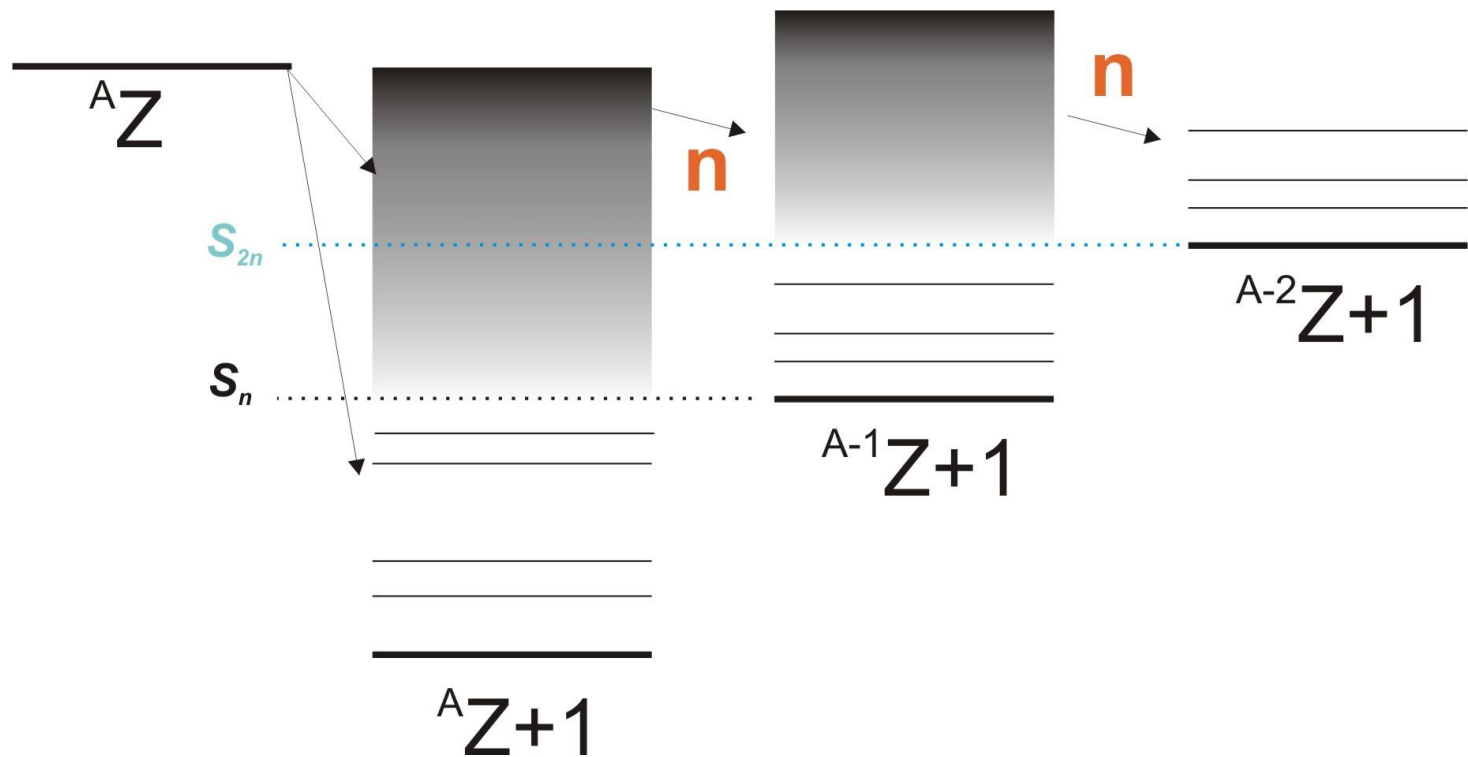


⇒ Hybrid setup with space for one HPGe

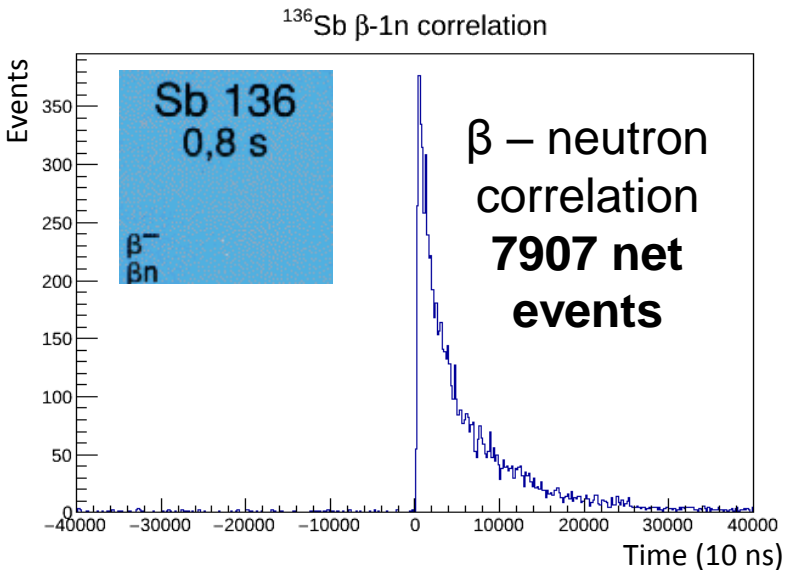


Up to 60% detection efficiency
⇒ β -delayed 2-neutron emitters



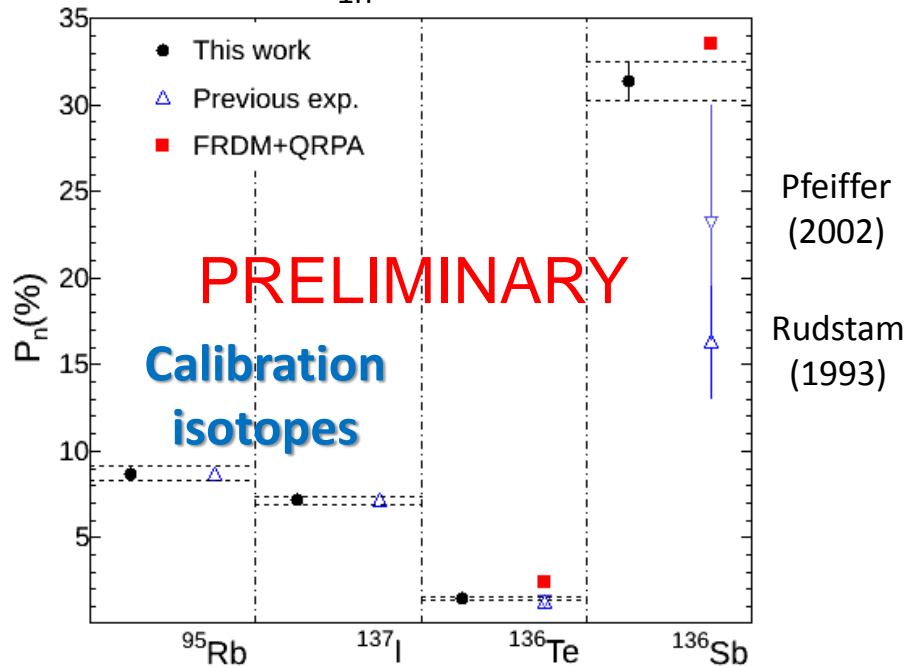


^{136}Sb $\beta 1n$ correlation (6 days of beamtime)



Roger Caballero et al.,
presented at Zakopane (2016) and Nuclear Data
Conf. (Bruges 2016); in prep. for PRC (2017)

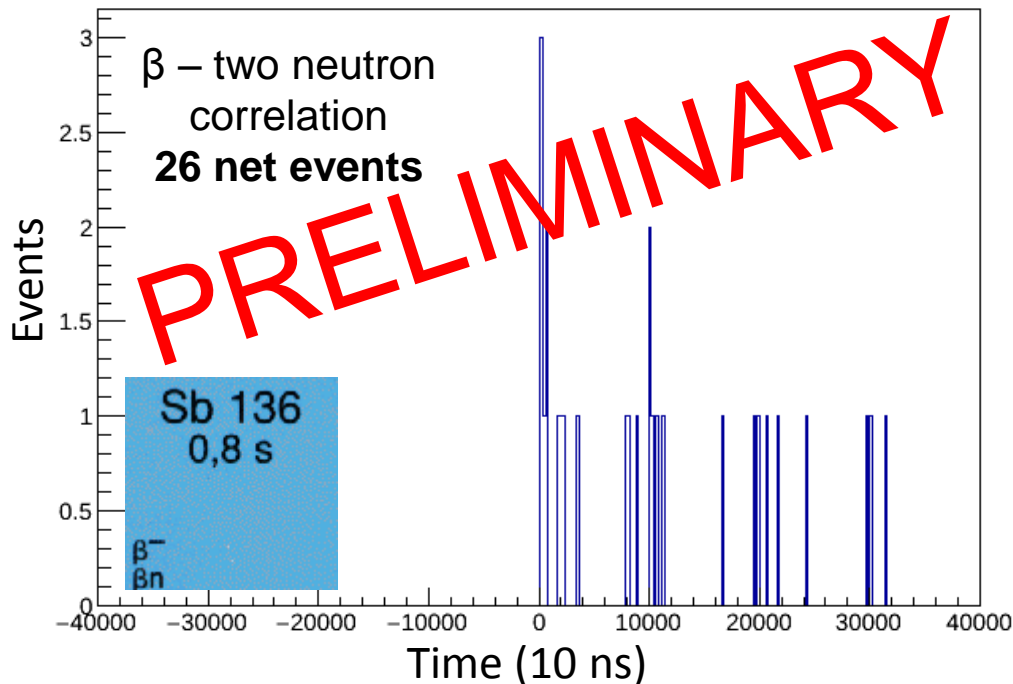
P_{1n} results



^{136}Sb : Higher P_{1n} than
previously measured

After 6 days of beamtime, **26** $\beta 2n$ -events confirmed!

n-n correlation (β conditioned)



Preliminary result:

$$P_{2n} \approx 0.1-0.2\%$$

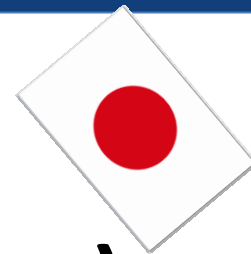
(Theoretical predictions: $P_{2n} = 6.2\%$)

Moeller et al. 2003

*Roger Caballero et al.,
presented at Zakopane (2016) and Nuclear Data
Conf. (Bruges 2016); in prep. for PRC (2017)*



The BRIKEN project (2016-...)



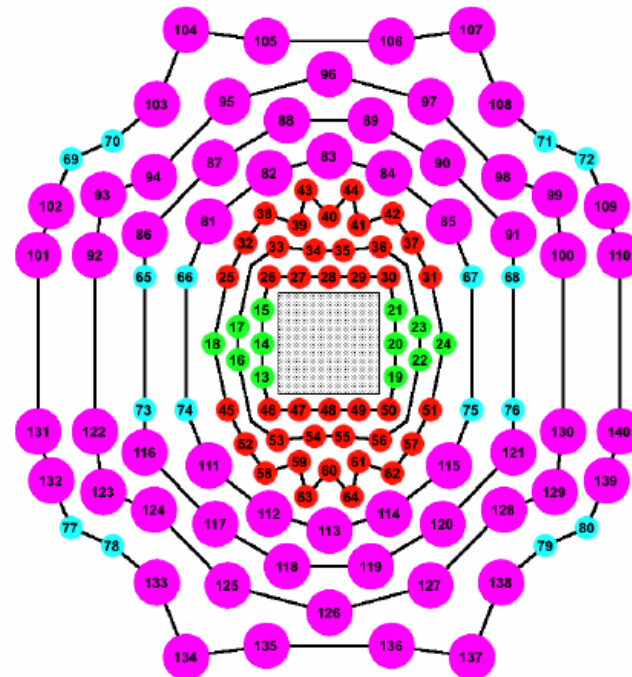
“Beta-delayed neutron measurements at RIKEN for nuclear structure, astrophysics, and applications”



Conceptual design of a hybrid neutron-gamma detector for study of β -delayed neutrons at the RIB facility of RIKEN

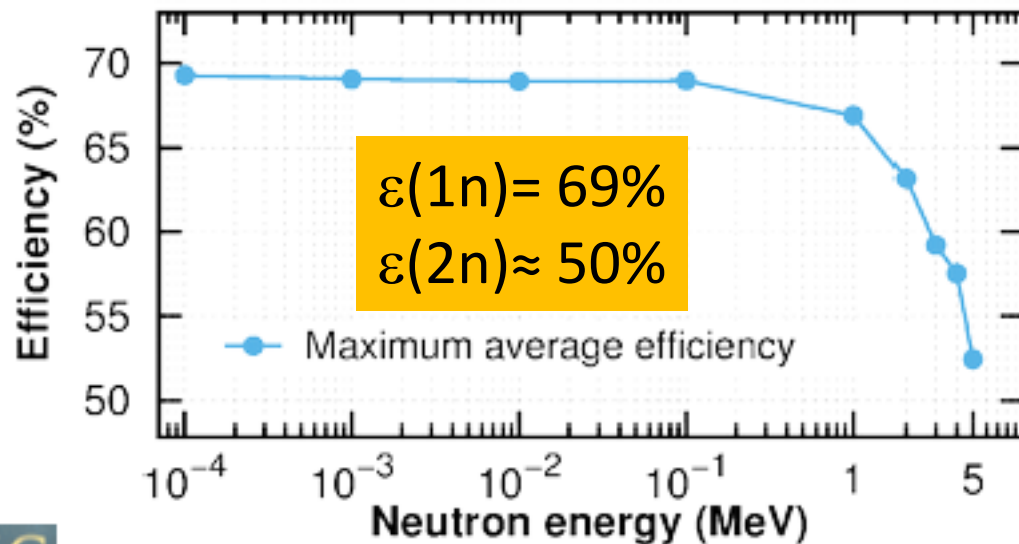
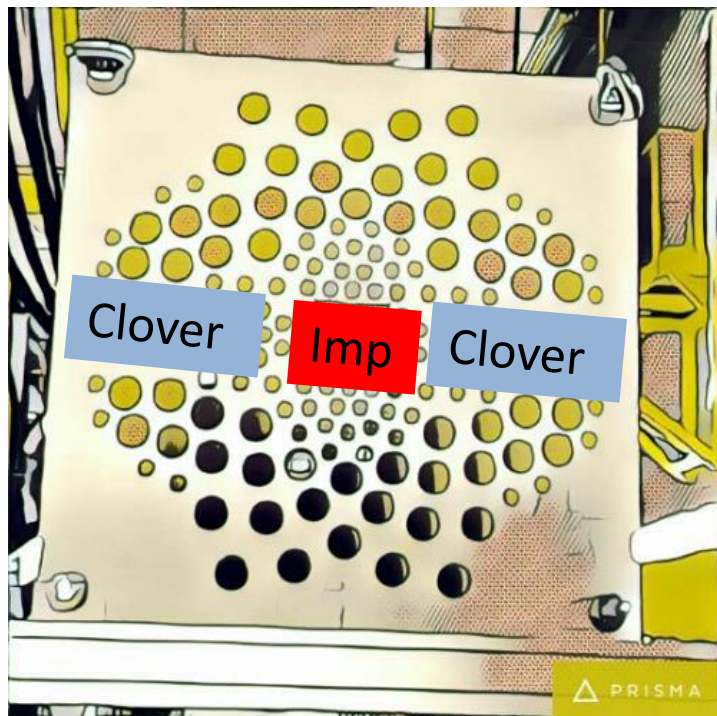
The BRIKEN collaboration

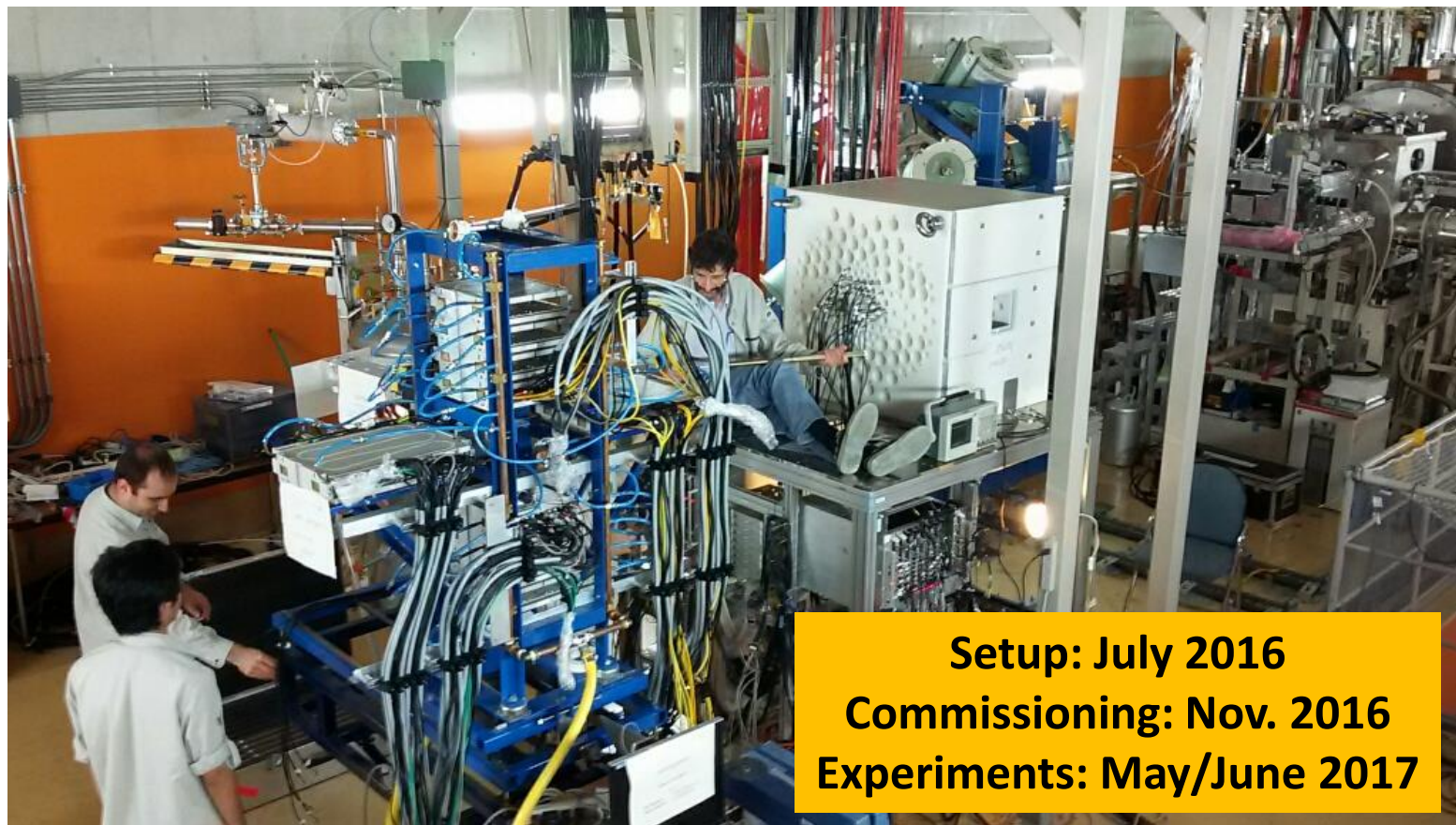
A. Tarifeño-Saldivia,^{a,b,1} J.L. Tain,^b C. Domingo-Pardo,^b F. Calviño,^a G. Cortés,^a V.H. Phong,^c A. Riego,^a J. Agramunt,^b A. Algora,^{b,p} N. Brewer,^{d,f} R. Caballero-Folch,^g P.J. Coleman-Smith,^k T. Davinson,^h I. Dillmann,^g A. Estradé,^{h,n,o} C.J. Griffin,^h R. Grzywacz,^e L.J. Harkness-Brennan,^j G.G. Kiss,^{c,p} M. Kogimtzis,^k M. Labiche,^k I.H. Lazarus,^k G. Lorusso,^{s,i} K. Matsui,^c K. Miernik,^r F. Montes,^{m,n} A.I. Morales,^b S. Nishimura,^c R.D. Page,^j Z.S. Podolyák,ⁱ V.F.E. Pucknell,^k B.C. Rasco,^{d,f} P. Regan,ⁱ B. Rubio,^b K.P. Rykaczewski,^d Y. Salto,^{c,g} H. Sakurai,^c J. Simpson,^k E. Sokol,^t R. Surman,^q A. Svirikhin,^t S.L. Thomas,^l A. Tolosa^b and P. Woods^h



A. Tarifeño et al., *J. Instrum.*12, P04006 (2017)

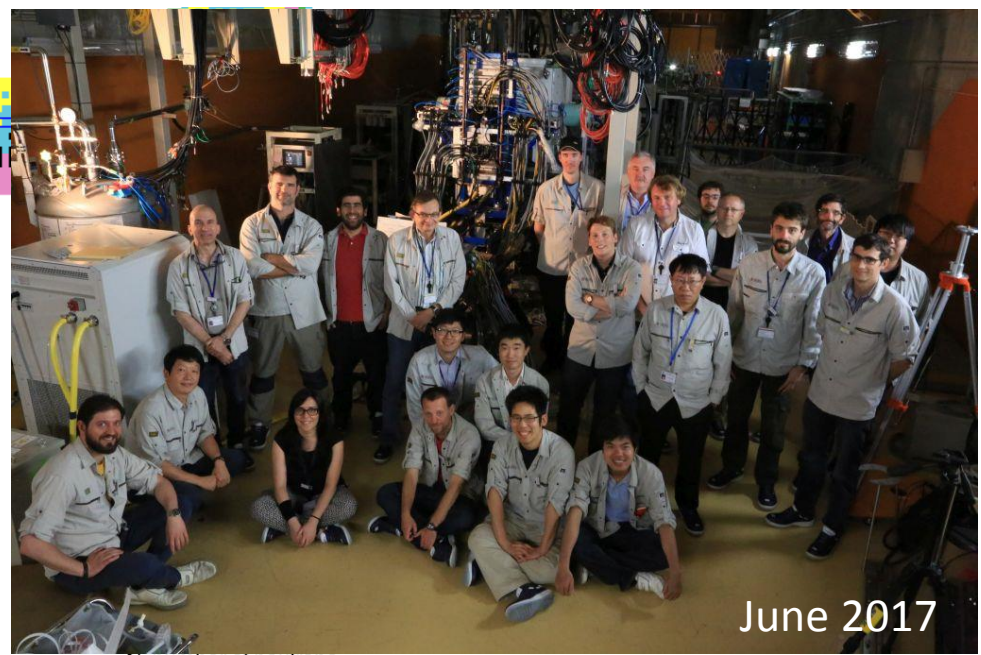
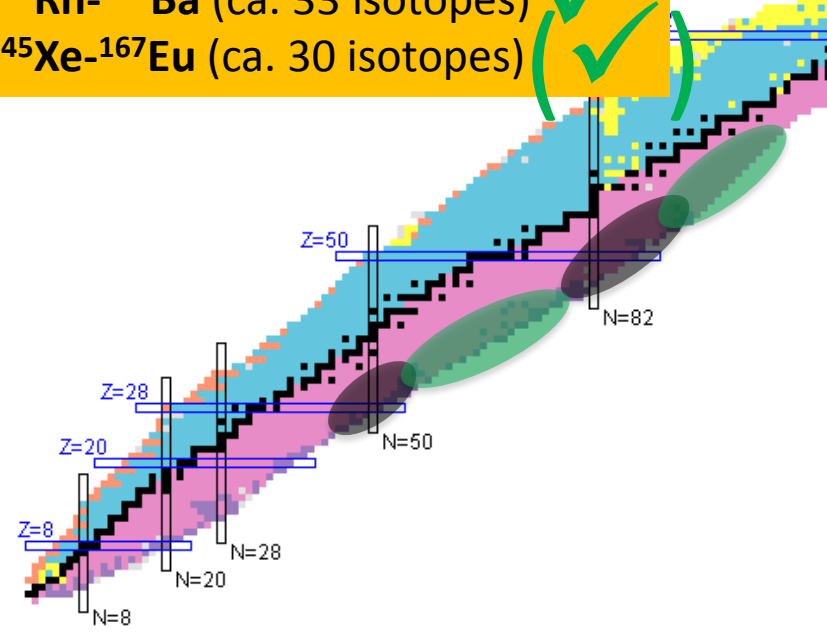
- 148 ^3He counters from Japan, Russia, Spain, USA
- 2 HPGe clovers (ORNL)
- Implantation detector AIDA (Edinburg, Daresbury, Liverpool)






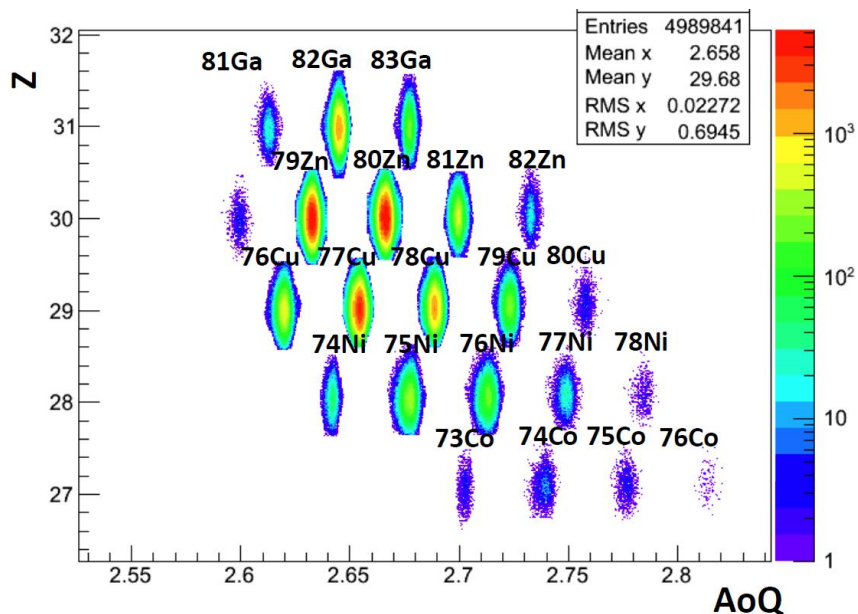
^{76}Co - ^{92}Se (ca. 30 isotopes) ✓
 ^{93}Se - ^{121}Tc : 90 new P_{1n} , 20 new P_{2n} ,
 23 new half-lives
 ^{121}Rh - ^{152}Ba (ca. 33 isotopes) ✓
 ^{145}Xe - ^{167}Eu (ca. 30 isotopes) ✓

Largest global investigation of βn -emitters so far



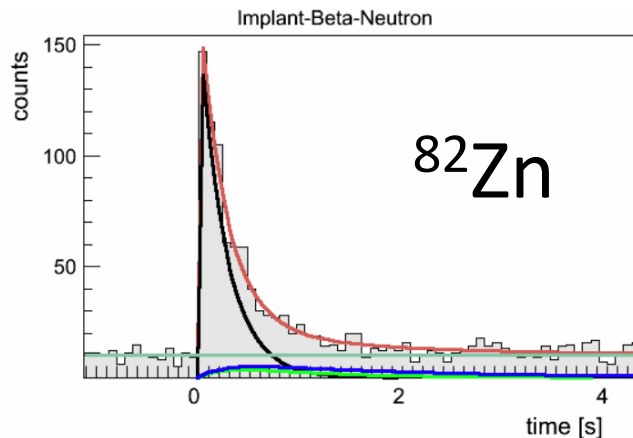
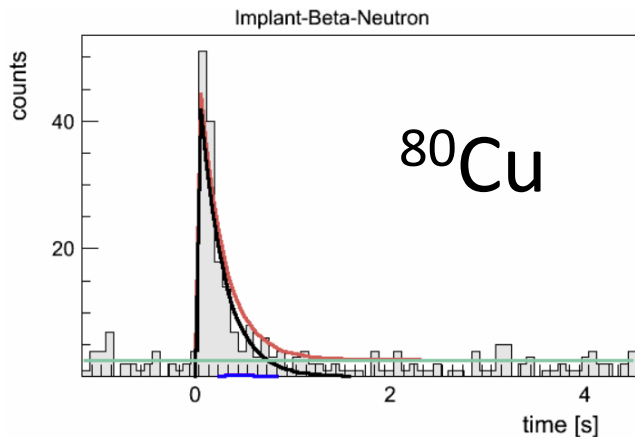
June 2017

N, number of neutrons


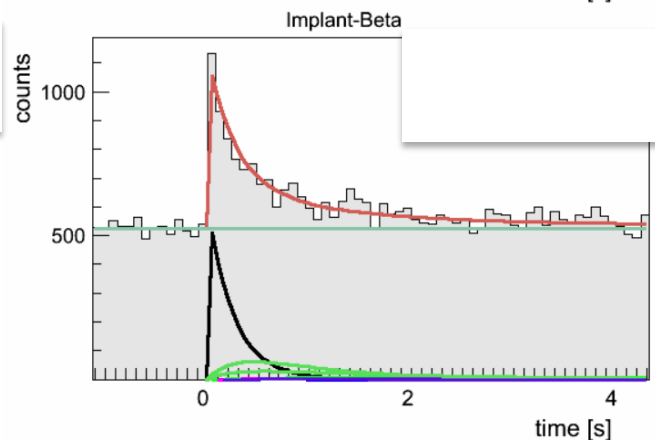
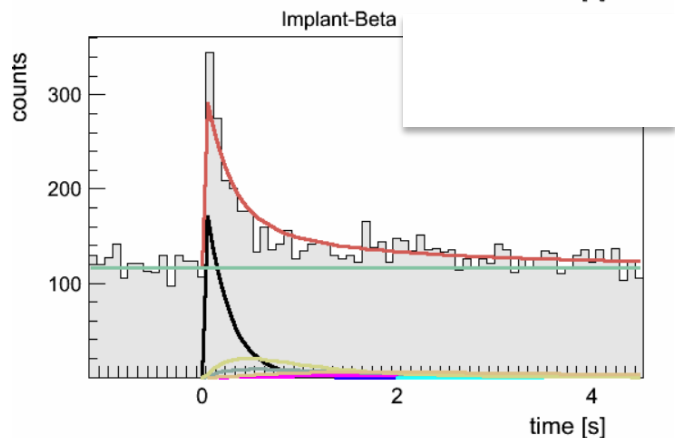


AoQ

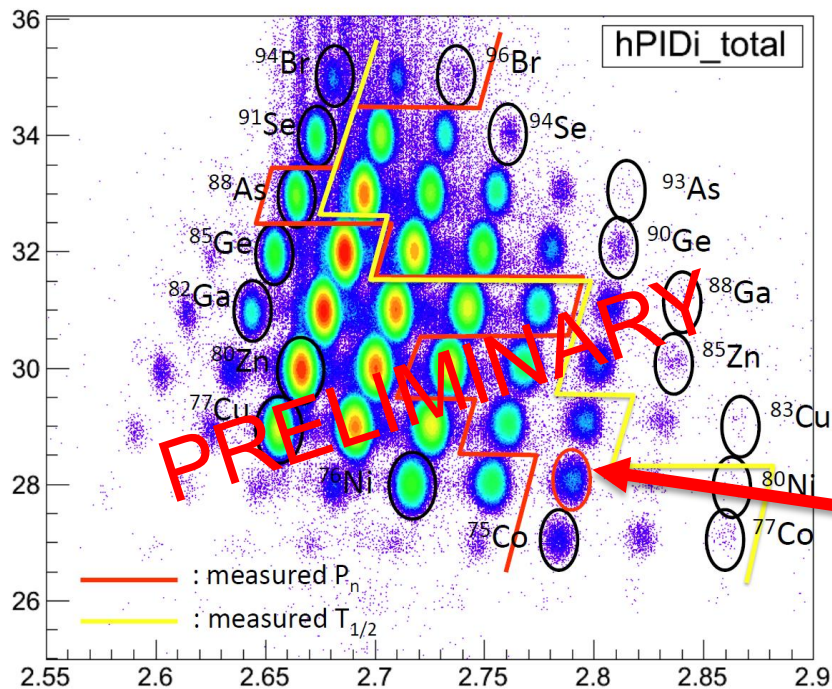




11h of data



19 P_{1n} measured
5 for the first time

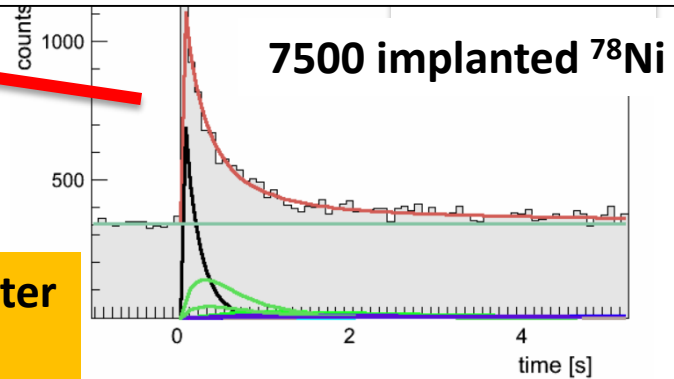


Iris Dillmann
 @Spacegirl1978

78Ni stats: @NSCL (Hosmer PRL 2005): 11 events in 104h. BRIKEN @RIBF 2017: >100 implants PER HOUR... 3 orders of magnitude in 12 years 🙄👉

Retweet 1 Likes 2

8:04 PM - 29 May 2017

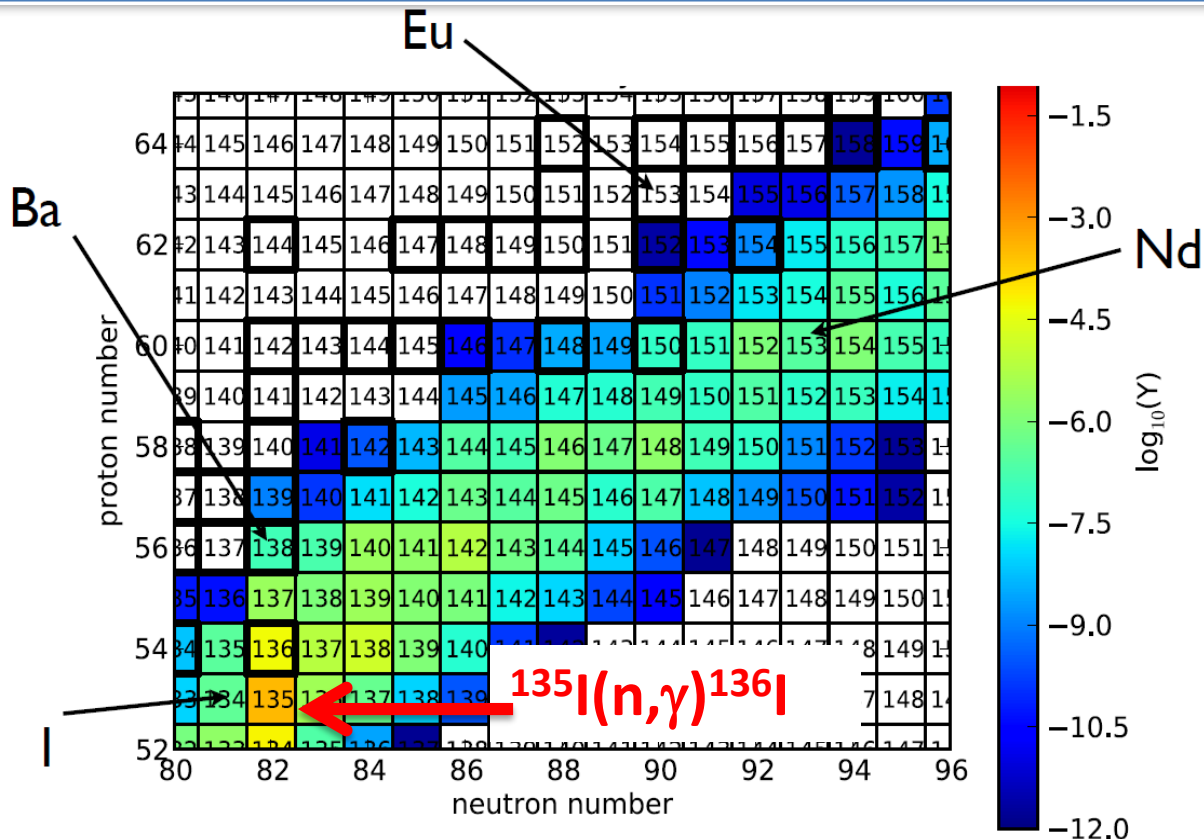


(Spokespersons: Tain, Rykaczewski, Grzywacz, Dillmann)

**≈ 29 new P_{1n}/P_{2n} emitter
 ≈ 20 new $t_{1/2}$ (tbc)**

Measurement of i-process key reactions





Neutron densities **up to 10^{15} cm^{-3}** : „**intermediate neutron capture process**“
(Cowan and Rose, 1977)

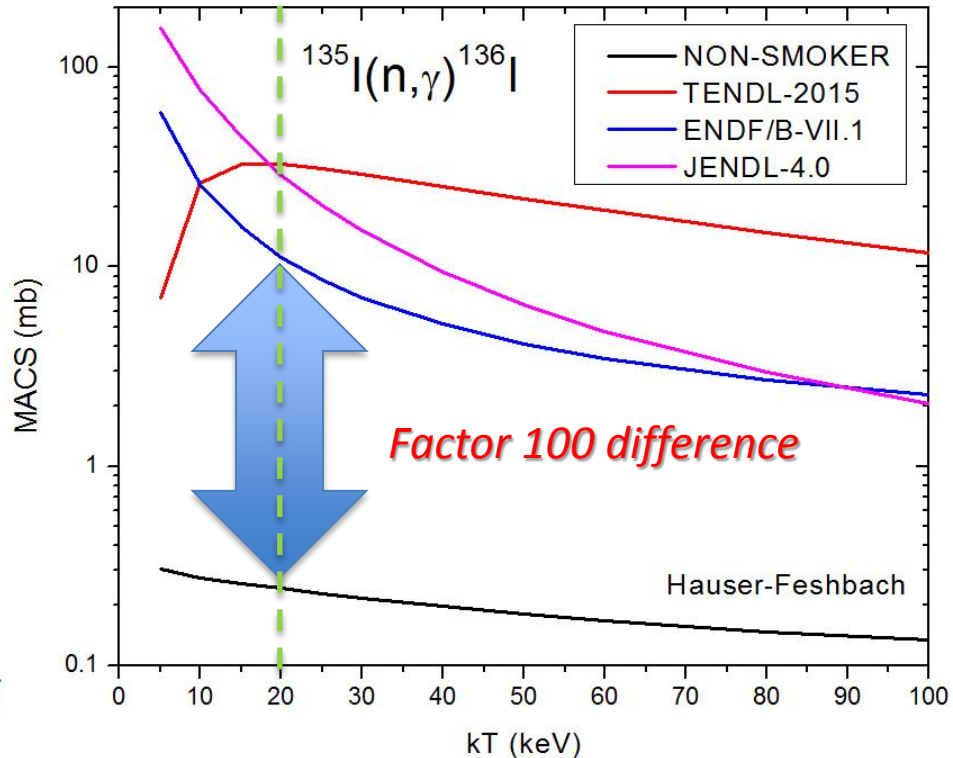
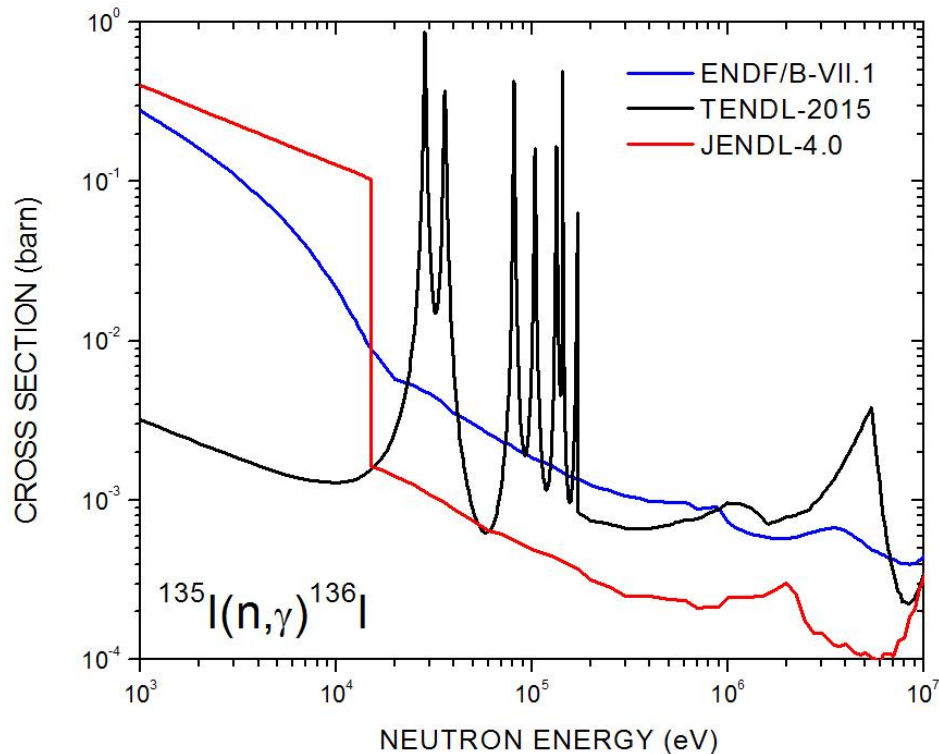
Needs neutron capture data **outside valley of stability**

"i process" calculations (F. Herwig et al., UVic)

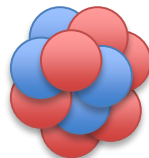
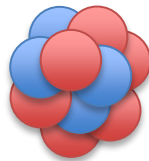
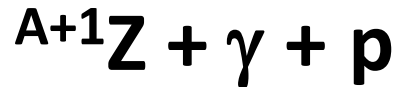
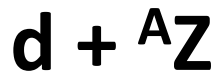
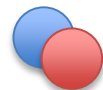
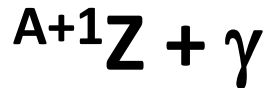
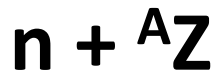
La 135 19.4 h c, β^+ ... γ 481, (875 588...) g	La 136 9.9 m c β^+ 1.9... γ 819, (761 1323...) g	La 137 6·10 ⁴ a c no γ	La 138 0.08881 1.05·10 ¹¹ a c β^+ 0.3 γ 439, 789 57	La 139 99.91119 c β^- ✓	La 140 40.272 h β^- 1.4, 2.2... γ 1598, 487 816, 329... σ 2.7	La 141 3.93 h β^- 2.4... γ 1355...
Ba 134 2.417 c β^- ✓	Ba 135 28.7 h 6.592 c β^- ✓	Ba 136 7.854 c β^- ✓	Ba 137 2.55 m 11.737 c β^- ✓	Ba 138 71.698 c β^- ✓	Ba 139 83.08 m β^- 2.4... γ 186, (1421...) σ 5	Ba 140 12.75 d β^- 1.0... γ 537, 30, 163 305... σ 1.6
Cs 133 100 c β^- ✓	Cs 134 2.90 h 2.06 a β^- 0.7 γ 905 790... c β^- ✓	Cs 135 53 m 2·10 ⁴ a c β^- ✓	Cs 136 19 s 13.16 d c β^- ✓	Cs 137 30.08 a β^- 0.5, 1.2... γ (284) m, g σ 0.20 + 0.07	Cs 138 2.90 m 32.2 m β^- 0.3 γ 819 1438 453 463, 192... 1010...	Cs 139 9.3 m β^- 4.2... γ 1283, 827 1421...
Xe 132 26.9086 c β^- ✓	Xe 133 2.198 d 5.2475 d c β^- ✓	Xe 134 10.4357 c β^- ✓	Xe 135 15.3 m 9.18 h c β^- ✓	Xe 136 8.8573 c β^- ✓	Xe 137 3.83 m β^- 4.1... γ 456, (849...)	Xe 138 14.1 m β^- 0.8, 2.8... γ 258, 434 1768, 2016... g
I 131 8.0228 d β^- 0.6, 0.8... γ 364, 637 284... g σ -0.7	I 132 83.8 m 2.30 h c β^- ✓	I 133 9 a 20.83 h c β^- ✓	I 134 3.5 m 82.0 h c β^- ✓	I 135 6.61 h β^- 1.5, 2.2... γ 1280, 1132 1678, 1458... g, m	I 136 84 s c β^- ✓	I 137 24.2 s β^- 5.0... γ 1218, 801... β n 0.37, 0.48...
Te 130 34.08 6.8·10 ¹⁰ a 2 β^- ✓	Te 131 33.25 h 25.0 m c β^- ✓	Te 132 76.3 h c β^- ✓	Te 133 55.4 m 12.5 m c β^- ✓	Te 134 41.8 m c β^- ✓	Te 135 18.6 s β^- 6.0... γ 604, 287, 870 1133...	Te 136 17.5 s β^- 2.5, 4.8... γ 2078, 334, 579 2660, 3235... β n 0.43...
Sb 129 17.7 m 4.40 h c β^- ✓	Sb 130 38.5 m 6.3 m c β^- ✓	Sb 131 23 m β^- 1.3, 3.0... γ 843, 933 842...	Sb 132 4.1 m 2.8 m c β^- ✓	Sb 133 2.34 m β^- 1.2, 2.9... γ 1086, 818 2755, 837... g, m	Sb 134 10.1 s 0.75 s c β^- ✓	Sb 135 1.7 s β^- 8.1... β n 1.45, 1.04... γ 1127, 1279* 1360...

... but far away for direct measurements.

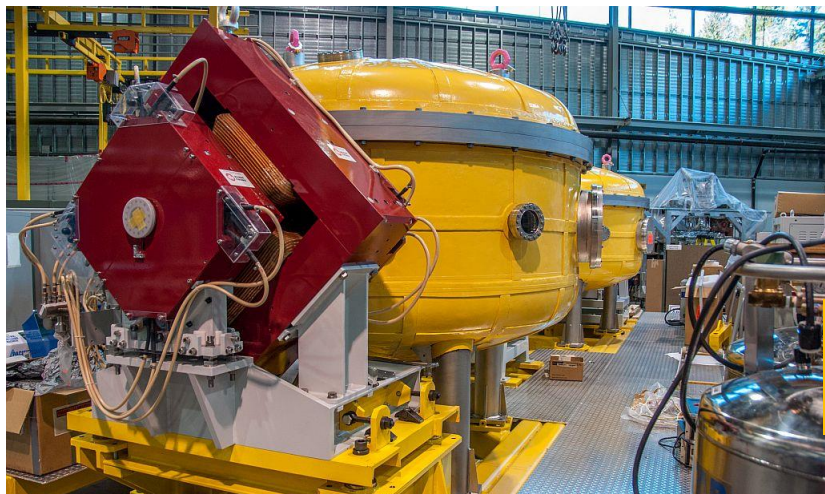
- Needed: (n,γ) cross section at $kT \approx 20$ keV (He burning)
- Why not using Hauser-Feshbach calculations?
 \Rightarrow low level density at $N=82$ shell closure, not applicable at low temperatures (e.g. up to $kT=25$ keV for NON-SMOKER)



Solution: (d,p) with radioactive beams to constrain (n,γ) cross section



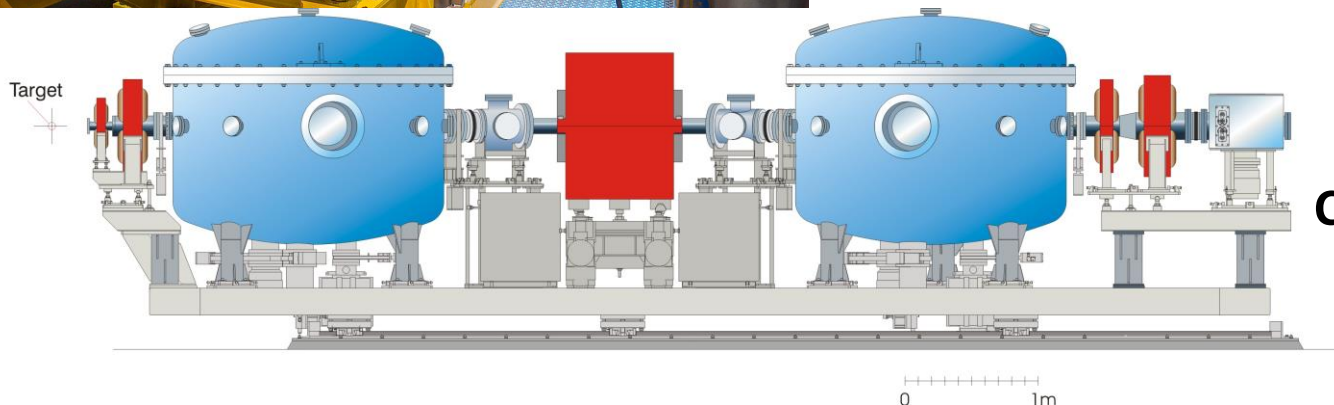
Surrogate method: deduce spectroscopic strength which is needed for direct and radiative (n, γ) capture measurements



ElectroMagnetic Mass Analyser

Recoil mass spectrometer designed with $M/\Delta M > 300$ to separate recoils from beam

Proposal to be submitted in 2017 (with Barry Davids)
Experiment can be performed from late 2018 on



Commissioned in 2016

- Experimentalists need to know which isotopes/ physical properties they should measure
 - ⇒ Observational constraints
 - ⇒ Sensitivity studies
- r-process nucleosynthesis :
 - ⇒ Isotopes around $N=50, 82, 126$ shell closure (spherical nuclei)
 - ⇒ Isotopes/isobars around $A \approx 100$ and 165 (deformed nuclei)
 - ⇒ any other isotopes?
- i process nucleosynthesis:
 - ⇒ bottle neck at ^{135}I ($N=82$)
 - ⇒ Need measurements where statistical model not applicable due to low level density



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Thank you!
Merci!

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