International Conference on Science and Technology for FAIR in Europe

Worms, Germany, October 13-17, 2014

β-decay half-lives and β-delayed neutron emission measurements for very exotic nuclei beyond N=126

Roger Caballero-Folch (DFEN/INTE –UPC)
Worms (Germany) 16 d’octubre de 2014

International Conference on Science and Technology for FAIR in Europe

Worms, Germany, October 13-17, 2014

S410 experiment collaboration:

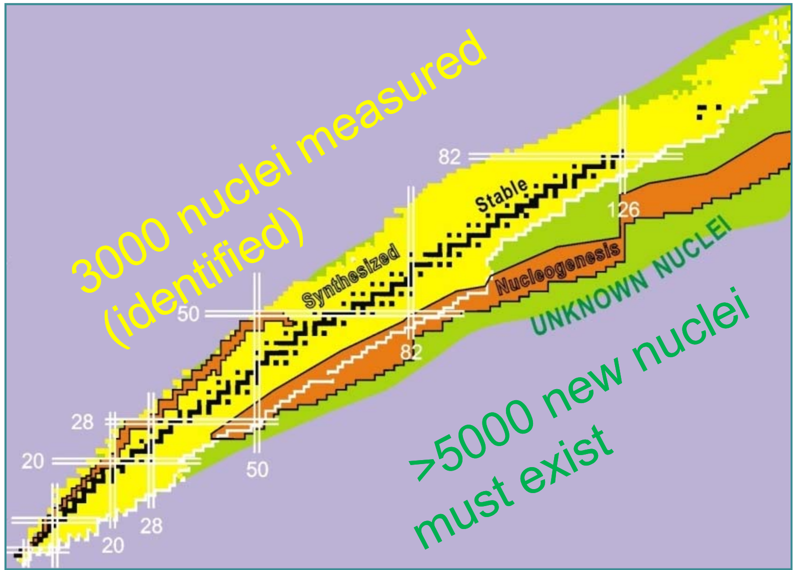
R. Caballero-Folch, C. Domingo-Pardo, G. Cortes, J.L. Taín, J. Agramunt, A. Algora, F. Ameil, Y. Ayyad, J. Benlliure, M. Bowry, F. Calviño, D. Cano-Ott, T. Davinson, I. Dillmann, A. Estrade, A. Evdokimov, T. Faestermann, F. Farinon, D. Galaviz, A. García-Ríos, H. Geissel, W. Gelletly, R. Gernhäuser, M.B. Gomez-Hornillos, C. Guerrero, M. Heil, C. Hinke, R. Knöbel, I. Kojouharov, J. Kurcewicz, N. Kurz, Y. Litvinov, L. Maier, J. Marganiec, M. Marta, T. Martnez, F. Montes, I. Mukha, D.R. Napoli, C. Nociforo, C. Paradela, S. Pietri, Zs. Podolyak, A. Prochazka, S. Rice, A. Riego, B. Rubio, H. Schaner, C. Scheidenberger, K. Smith, E. Sokol, K. Steiger, B. Sun, M. Takechi, D. Testov, H. Weick, E. Wilson, J.S. Wineld, R. Wood, P. Woods, and A. Yeremin.

Outline

- **Motivation**
- BELEN-20 and BELEN-48 detector
- BELEN-30 experiments at GSI (2011)
- BRIKEN collaboration

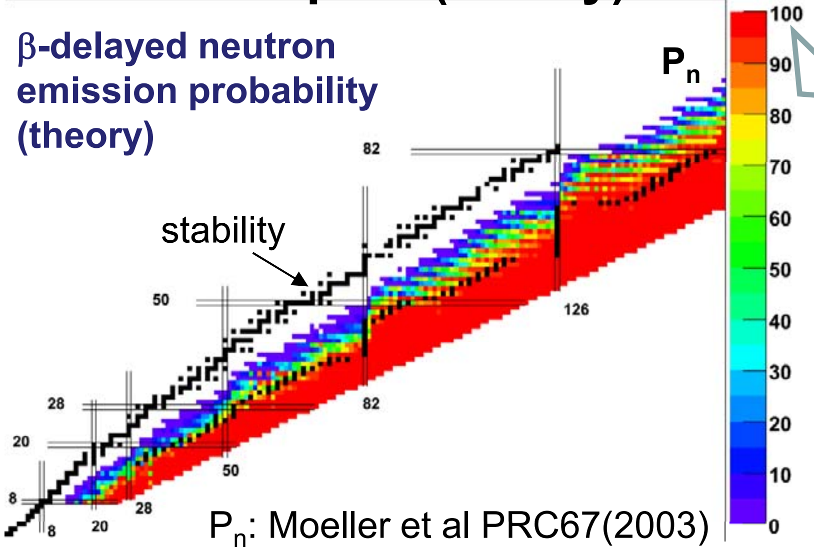
Motivation: interest of Pn measurements

About 3000 nuclei identified and known and of their properties whereas still more than 5000 new nuclei must exist.



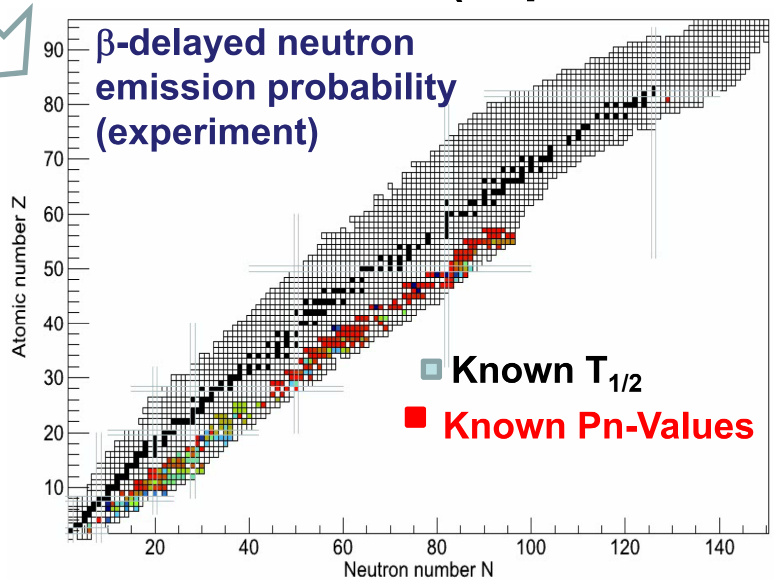
Almost all these new nuclei are expected to be neutron emitters, and hence, an understanding of this property and the involved technique becomes of pivotal impotance for NS and future studies.

What we expect (theory):



P_n: Moeller et al PRC67(2003)

What we know (experiments):

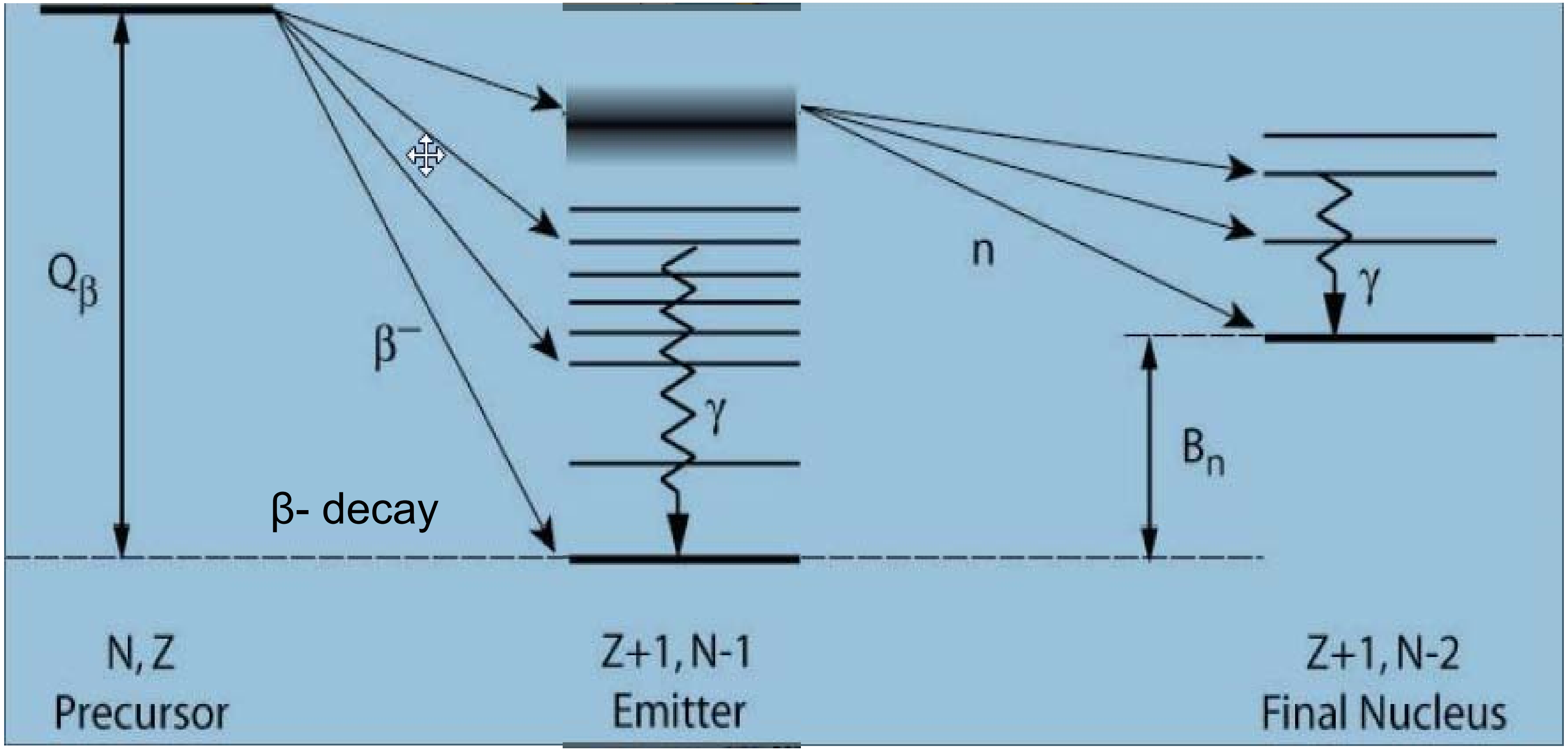


- Almost all new nuclei are expected to be n-emitters

- Only about 200 n-emitters are known

Slide from C. Domingo-Pardo, NUSTAR Week 2014

β delayed neutron emission



Motivation: interest of Pn measurements

1- Astrophysical interest in the *r*-process nucleosynthesis

Beta-delayed neutron emission modulates the element abundance curve in stellar nucleosynthesis:

- It enhances the neutron density of the environment after freeze-out (re-activation)
- It shifts the abundances towards lower masses (Pn: A → A-1, P2n: A → A-2, etc)

The experimental data from β-delayed neutron emission represents an important input to r-process model calculations..

2- Nuclear structure

Study different aspects of the decay of these nuclei. Provide information about their decay mechanism and structure.

3- Safety in nuclear reactors

Delayed neutron emission after fission is key to the safety and sustainability of the fission chain in the nuclear power reactor. New data is needed in the context of the nuclear fuel that will be used in the next generation of reactors.

Outline

- Motivation
- **BELEN-20 and BELEN-48 detector**
- BELEN-30 experiments at GSI (2011)
- BRIKEN collaboration

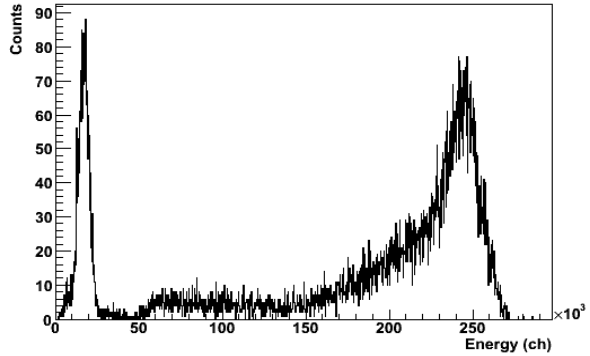
BELEN detector designs and experiments

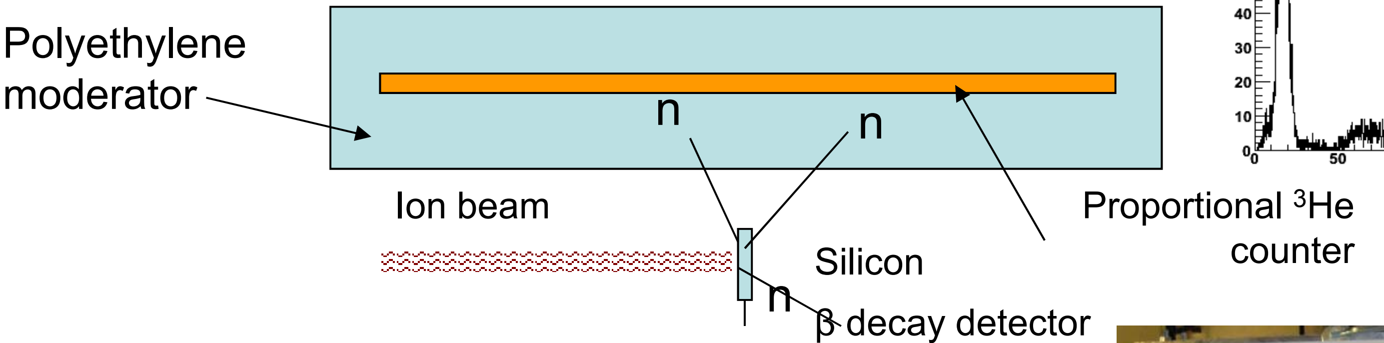
Beta Delayed Neutron detector - **BELEN**

Developed at the technical university UPC-Barcelona

✓ The detection of the neutron is based on the detection of products of the reaction of the neutron with 3He counters :

$$^{3}He + n \rightarrow {}^{3}H + {}^{1}H + 765\ keV$$





✓ Polyethylene matrix moderator

✓ Approx 700 kg weight

✓ Dimensions: 80cmx80cmx60cm

TDR approved!!!

BELEN detector designs and experiments

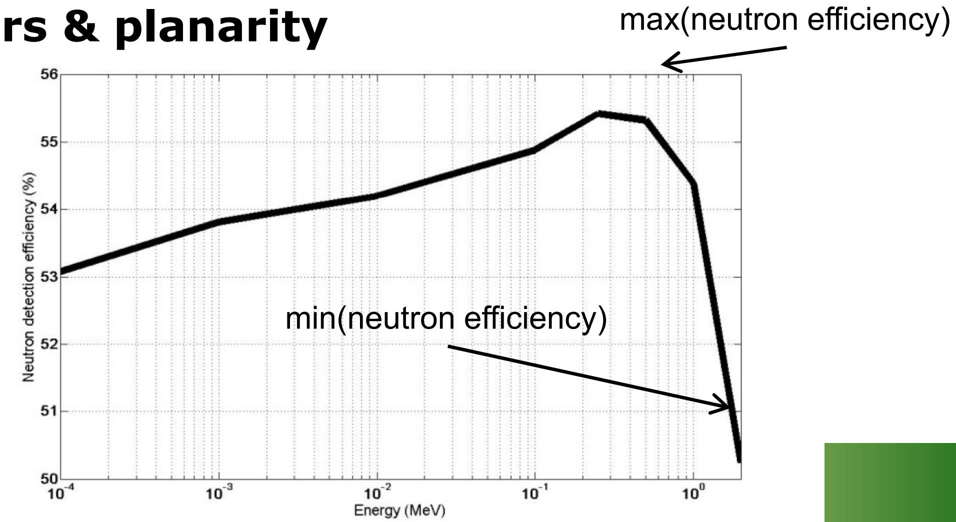
BELEN versions designed

Name	^{3}He counters	Pressure (atm)	Experiment	Efficiency up to 2 MeV	Efficiency up to 5 MeV	Central hole radius (cm)
BELEN-20	**20**	**20**	**JYFL-2009**	**30%**	**25%**	**5.5**
BELEN-20	**20**	**20**	**JYFL-2010**	**43%**	**38%**	**5.5**
BELEN-30	**20+10**	**20 & 10**	**GSI-2011**	**38%**	**33%**	**11.5 (SIMBA)**
BELEN-48	**40+8**	**8 & 10**	**PTB -2013** **JYFL-2014**	**39%** **-**	**40%** **60%**	**5.5** **3**
BELEN-48	**40+8 at least!**	**8 & 10**	**DESPEC**	**?**	**?**	**8 (AIDA)**

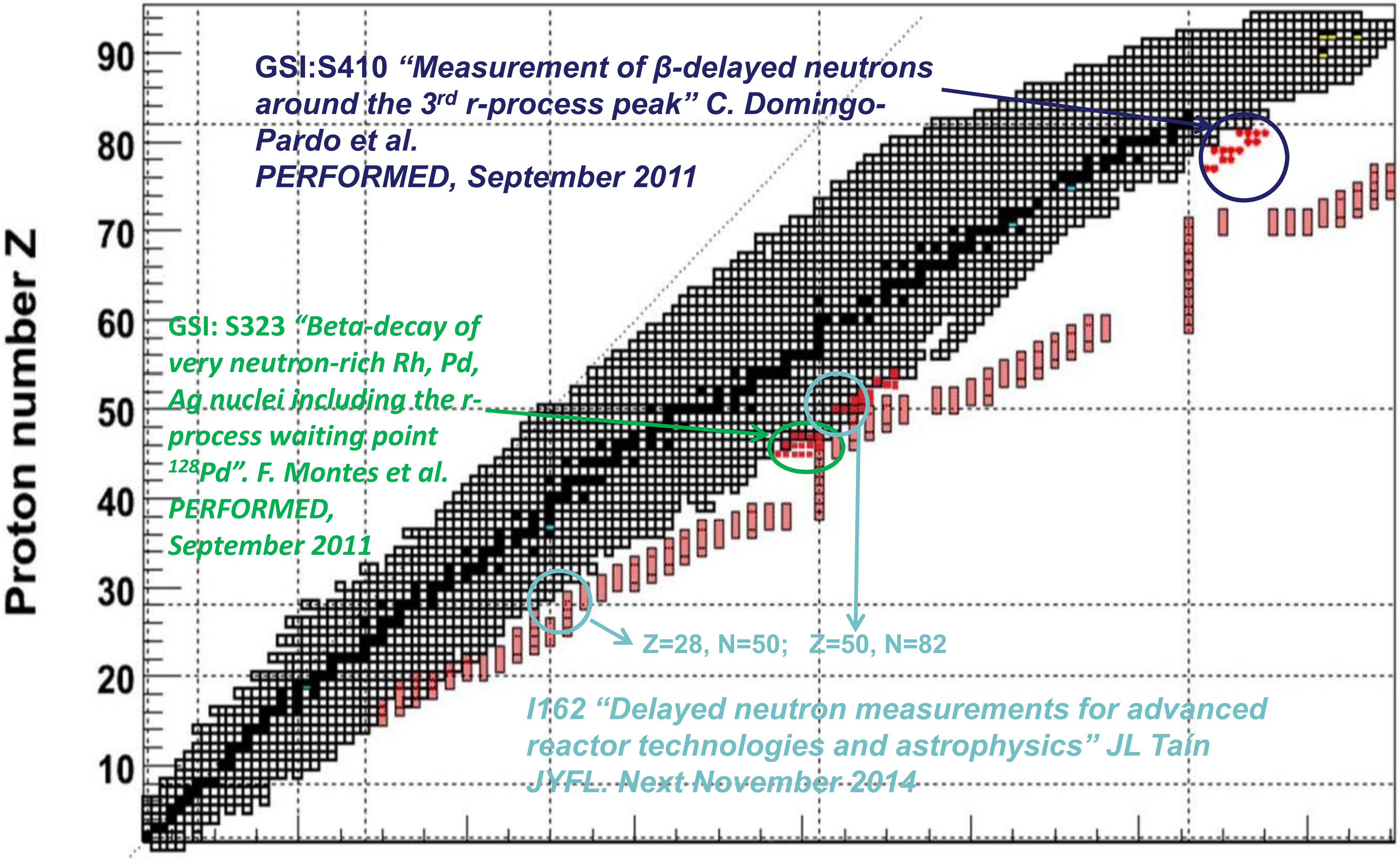
Observe: Central hole, num. counters & planarity

To define the efficiency flatness for a range of neutron energies

$$Ratio = \frac{\max(\text{neutron efficiency})}{\min(\text{neutron efficiency})}$$



Tests and experiments with BELEN detector



Tests and experiments with BELEN detector

BELEN-20 (20atm) for JYFL. Experiments at JYFLTRAP (Finland). Measurements of β delayed neutron emission of fission fragments (UPC, IFIC, CIEMAT):

Nov 2009: ^{95}Rb, ^{88}Br, ^{94}Rb, ^{138}I. (cal. and nucl. Structure)

Jun 2010 : ^{95}Rb, ^{88}Br, ^{85}As, ^{86}As, ^{85}Ge, ^{91}Br, ^{137}I.(decay heat and testing models)

Background measurements at GSI and Canfranc underground laboratory.

BELEN-30 (20 (20atm), 10 (10 atm)) for FRS-GSI. Two experiments at GSI with & SIMBA

September 2011, nuclei of astrophysical interest:

S323: ^{127}Pd, ^{126}Pd, ^{128}Ag

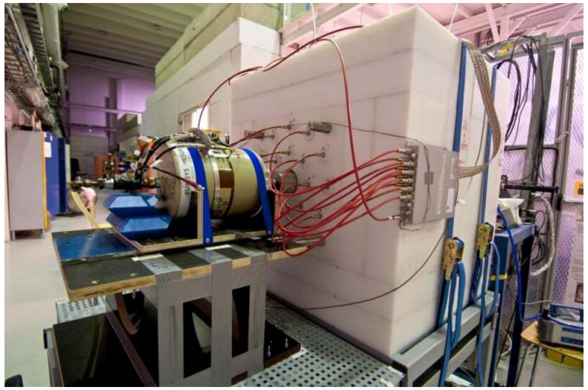
S410: ^{215}Tl, ^{211}Hg

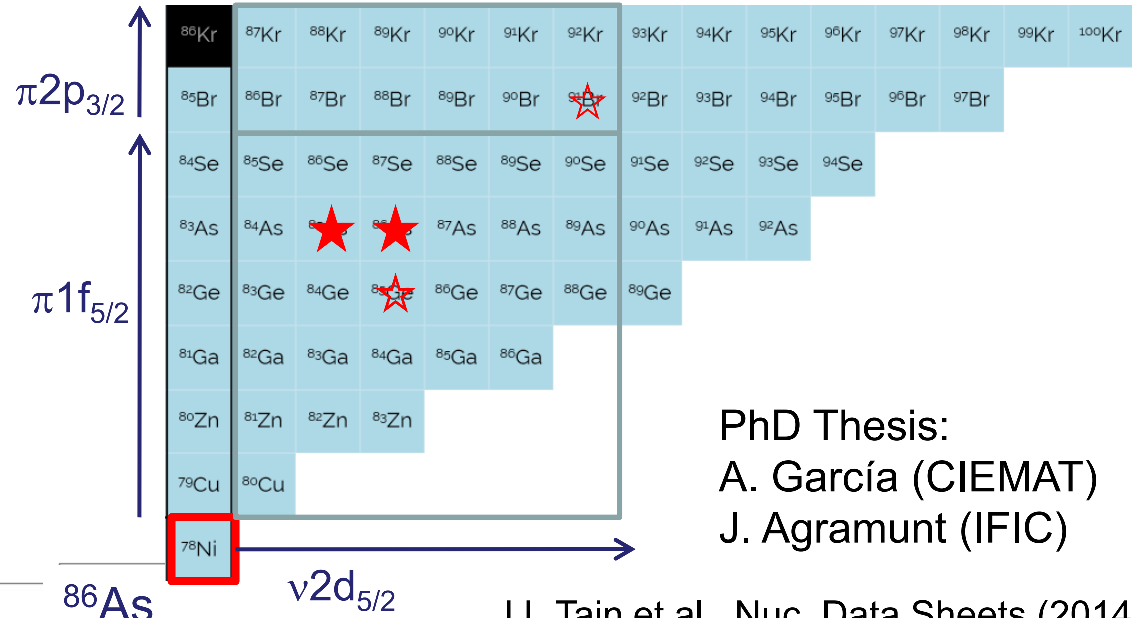
BELEN-48 (40 (8atm), 8 (10 atm)) PTB calibration (2013)

BELEN-48 (40 (8atm), 8 (10 atm)) JYFL experiment next month (Nov 2014)

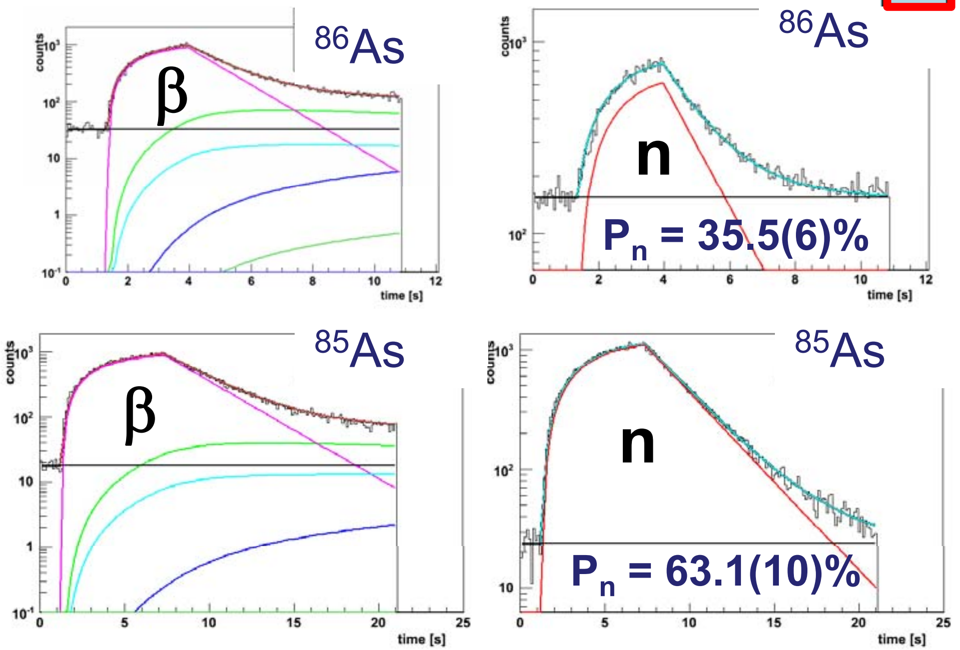
BELEN detector first results, experiments at JYFL

BELEN20 @ JYFL, 2009-2010

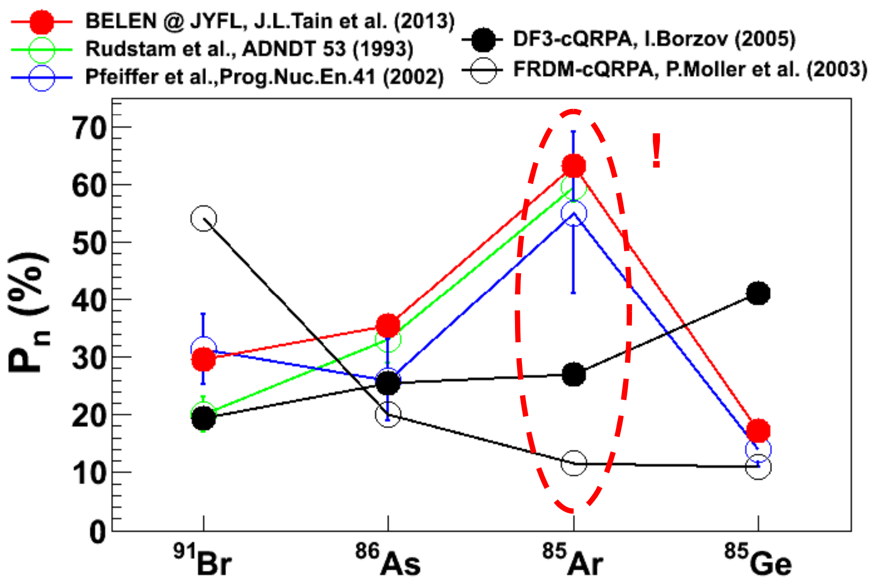




PhD Thesis:
A. García (CIEMAT)
J. Agramunt (IFIC)



J.L.Tain et al., Nuc. Data Sheets (2014)



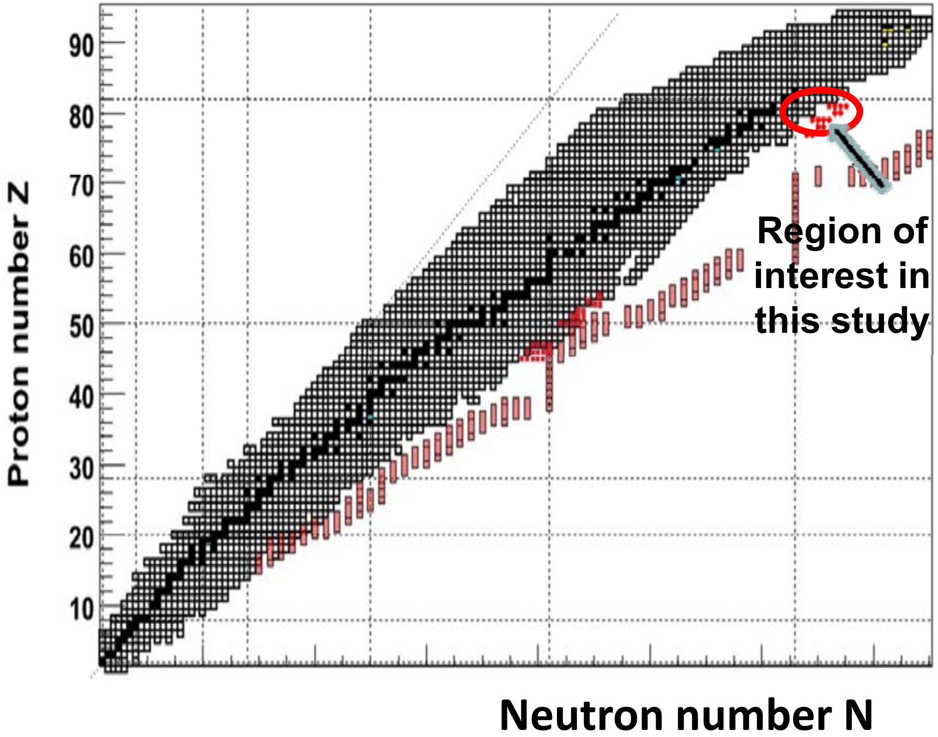
Slide from C. Domingo-Pardo, NUSTAR Week 2014

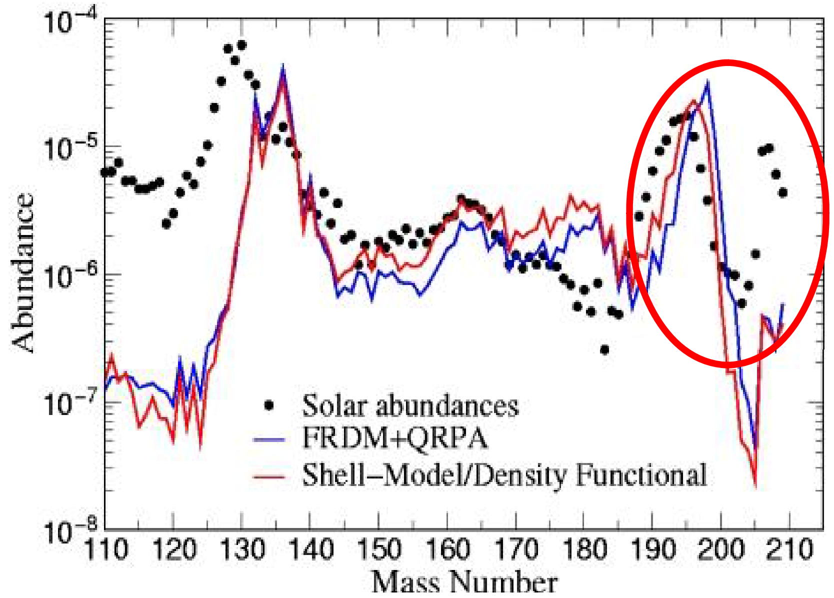
Outline

- Motivation
- BELEN-20 and BELEN-48 detector
- **BELEN-30 experiments at GSI (2011)**
- BRIKEN collaboration

S410: r-process nucleosynthesis interest

Goal: Experimental determination of half lives and neutron branchings of several exotic nuclei in the neutron rich region beyond N=126





The Astr. Jour., 579 (2002), H. Schatz et al.
Proc. CGS-13 (2009), G. Martinez-Pinedo

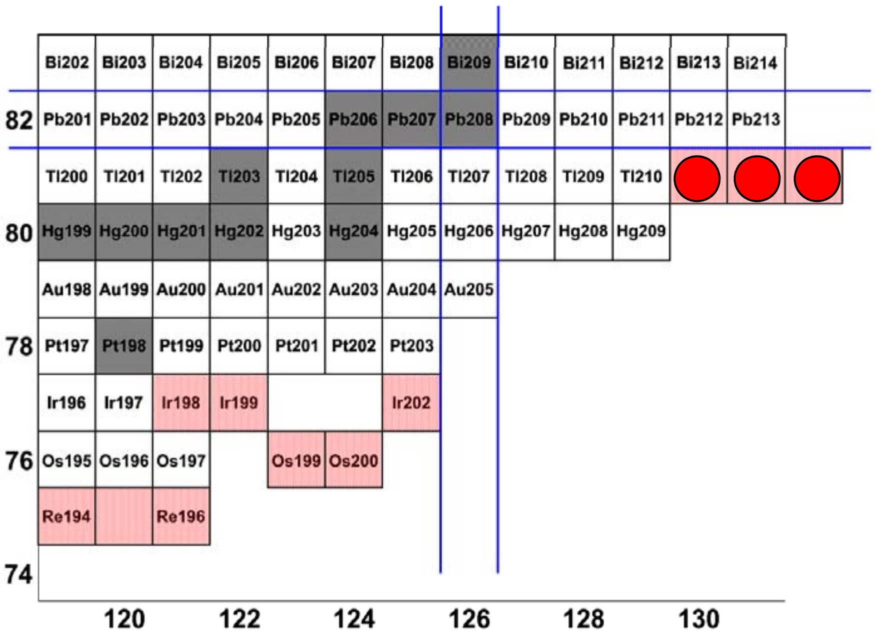
Understanding of A=195 peak in the r-process abundance pattern.

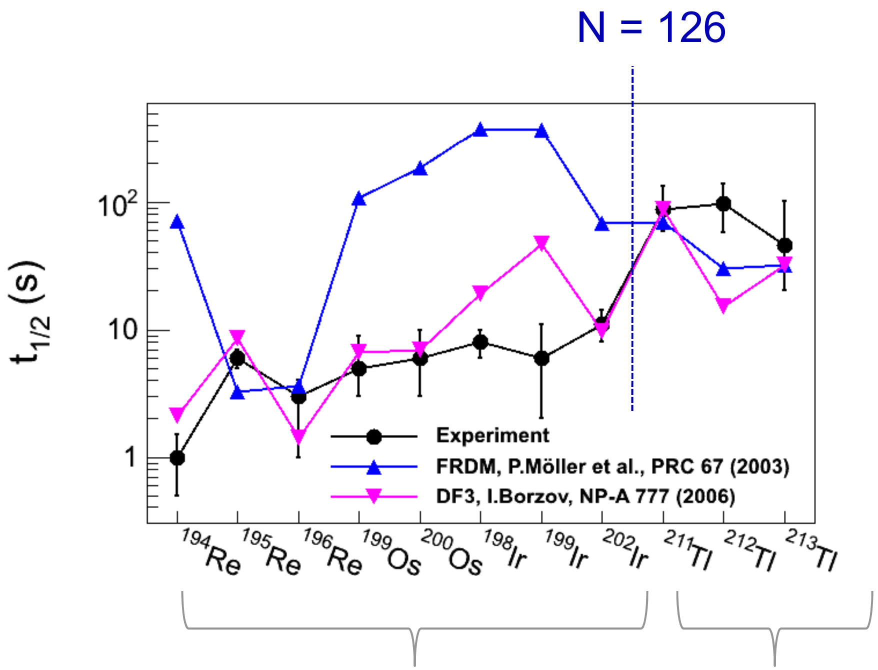
r-process calculations rely on theoretical predictions (QRPA & FRDM), with remarkable discrepancies and large uncertainties far of stability.

Nuclear data for the Pt-peak formation: state of the art

✓ N=126 is one of the regions most difficult to reproduce with *r-process* model calculations.

✓ Scarce experimental information available for β-decay half-lives, masses and β-delayed neutrons around N=126.





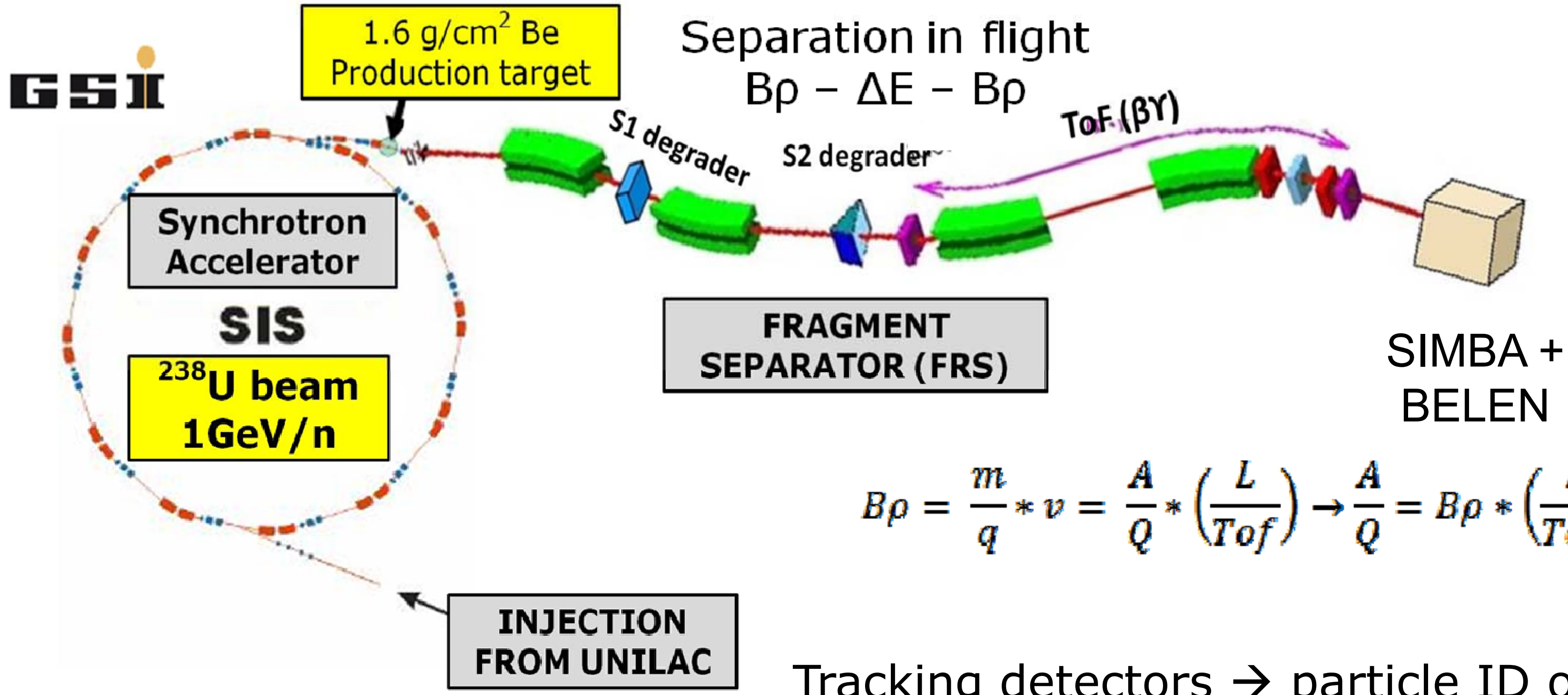
T. Kurtukian-Nieto et al., arXiv:0711.0101v1
J.Benlliure et al. NPA-V, 2012

G.Benzoni et al., Phys.Lett. B 715 (2012)

→ It seems that nuclear models tend to overestimate the b-decay half-live at N<126 and to underestimate it for N>126… but our results are according FRDM…

S323 & S410 experiments (2011). **BELEN at a fragmentation facility**

Large intensity (2x10^{9} ions/pulse) & high-energy (1 GeV/u) for ^{238}U beams

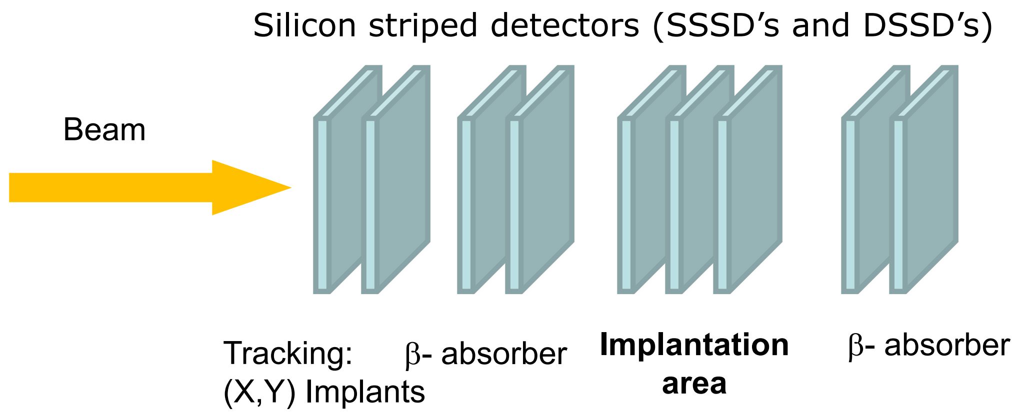


$$B\rho = \frac{m}{q} * v = \frac{A}{Q} * \left(\frac{L}{Tof}\right) \rightarrow \frac{A}{Q} = B\rho * \left(\frac{L}{Tof}\right)$$

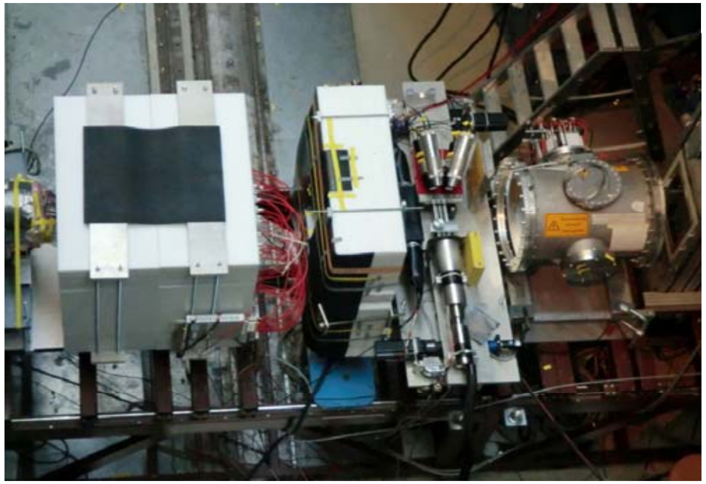
Tracking detectors → particle ID on an event-by-event basis.

The detection system is based on a stack of SSSD- and DSSD-detectors for measuring ion-implants and beta-decays (SIMBA). Implants-region was surrounded by the 4π neutron detector BELEN.

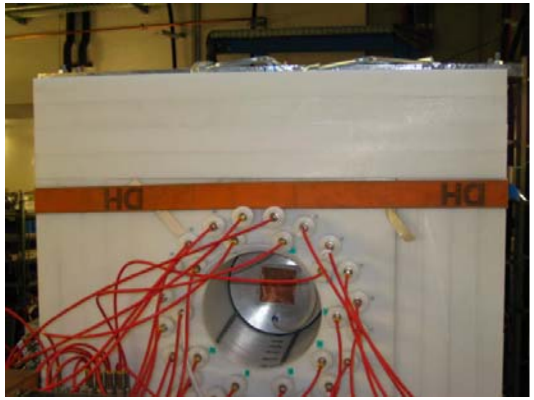
Implantation, β decay & neutron detection: SIMBA + BELEN



PhD thesis C. Hinke, TUM (2010)
Diploma thesis K. Steiger, TUM (2009)



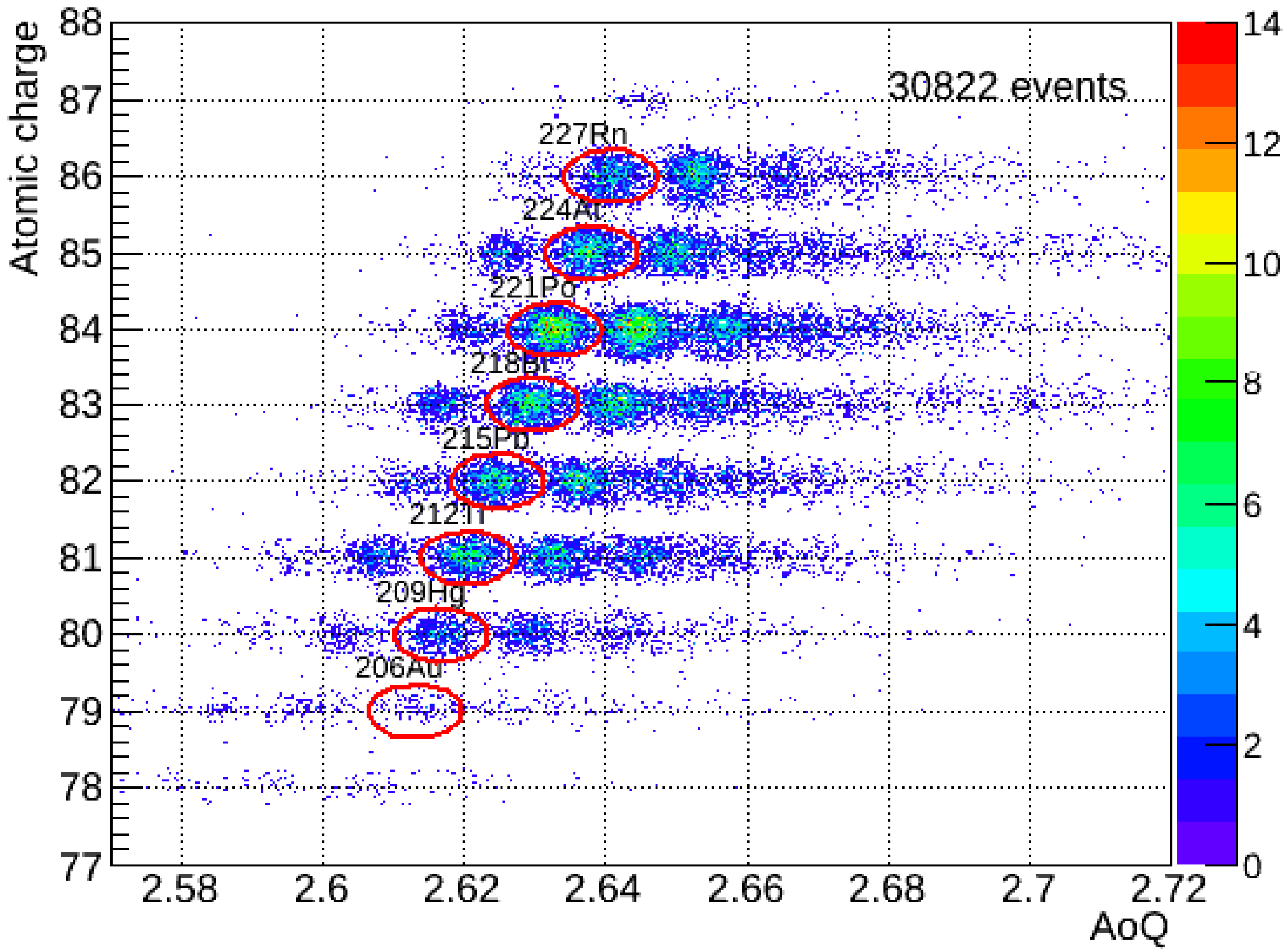
BELEN efficiency was about 40% (checked experimentally)



The Beta dELayEd Neutron (BELEN) detector, based in ^{3}He counters embedded in a polyethylene matrix, located around Silicon IMplantation Beta Absorber (SIMBA).

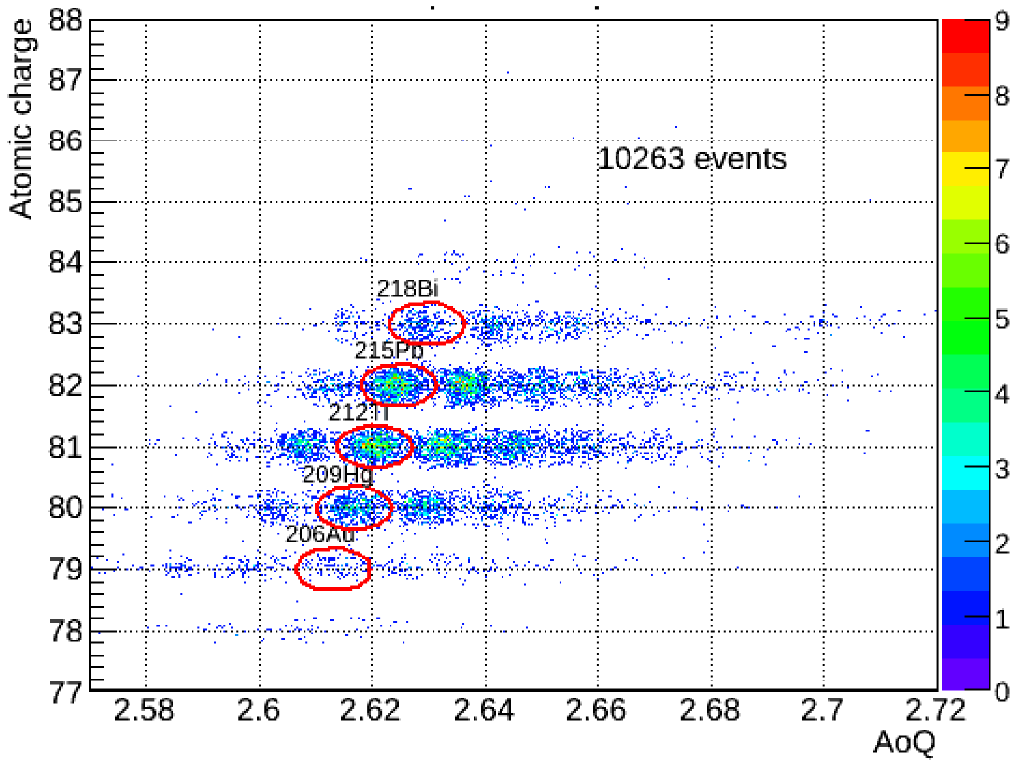
Isotopes of Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn and Fr identified

Isotopes beyond N=126 were identified

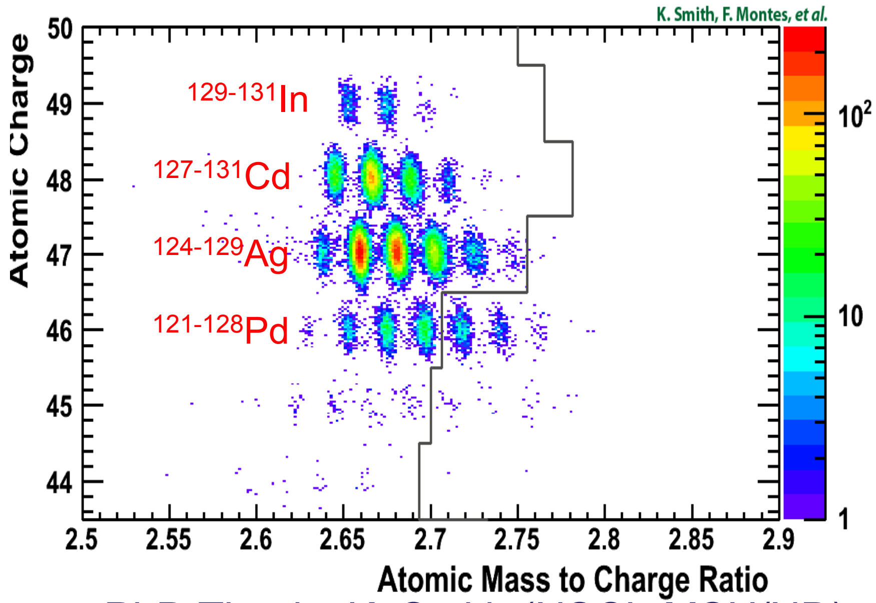


Isotopes of Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn and Fr identified

The implantation area was optimized for Hg and Tl region where good resolution has been obtained.



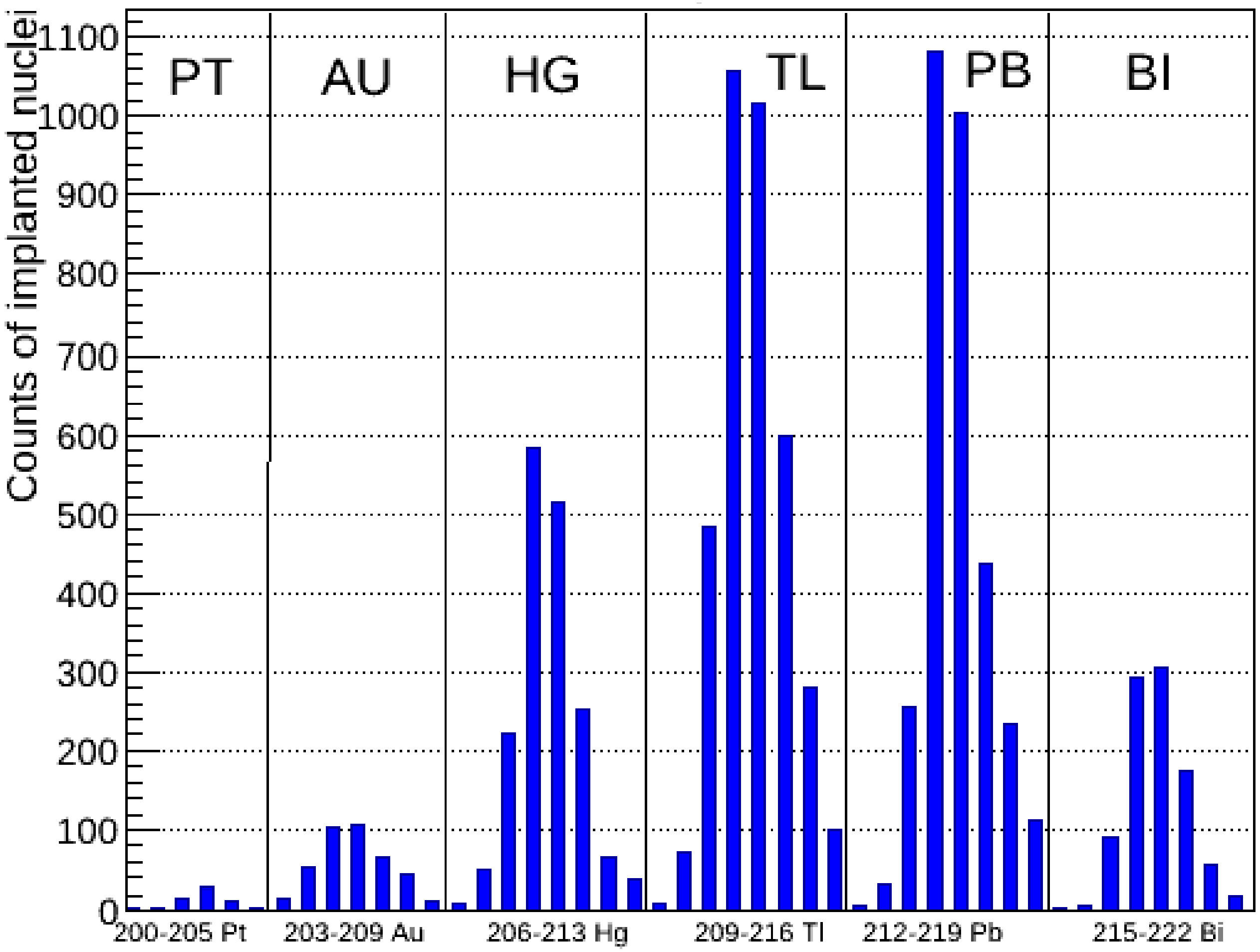
S323: Pn's around N=82



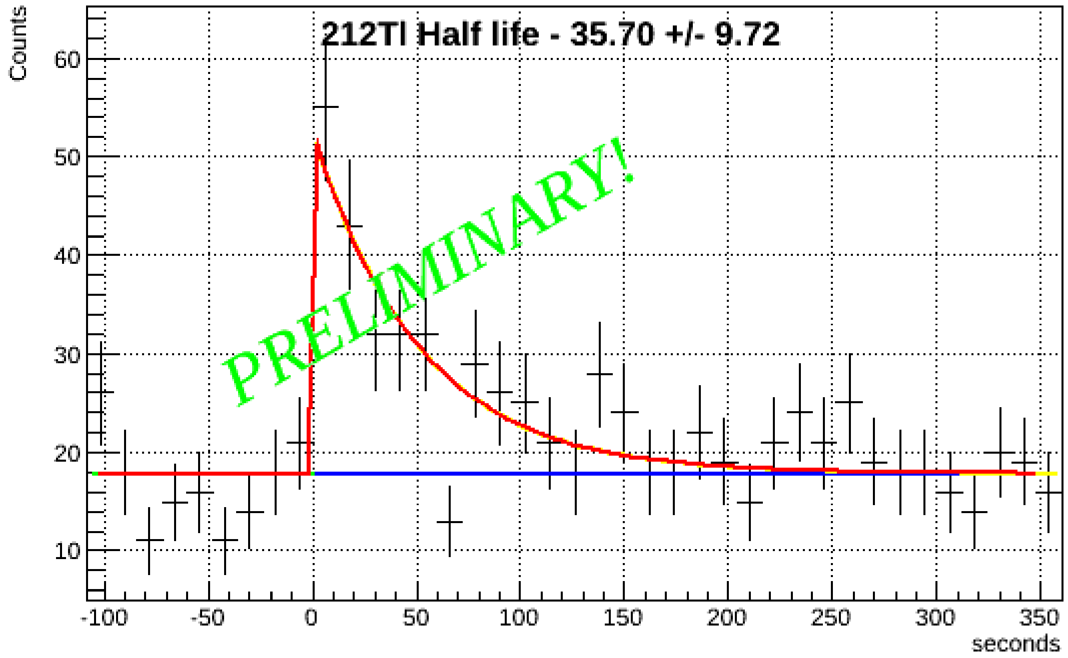
PhD Thesis: K. Smith (NSCL-MSU/ND)

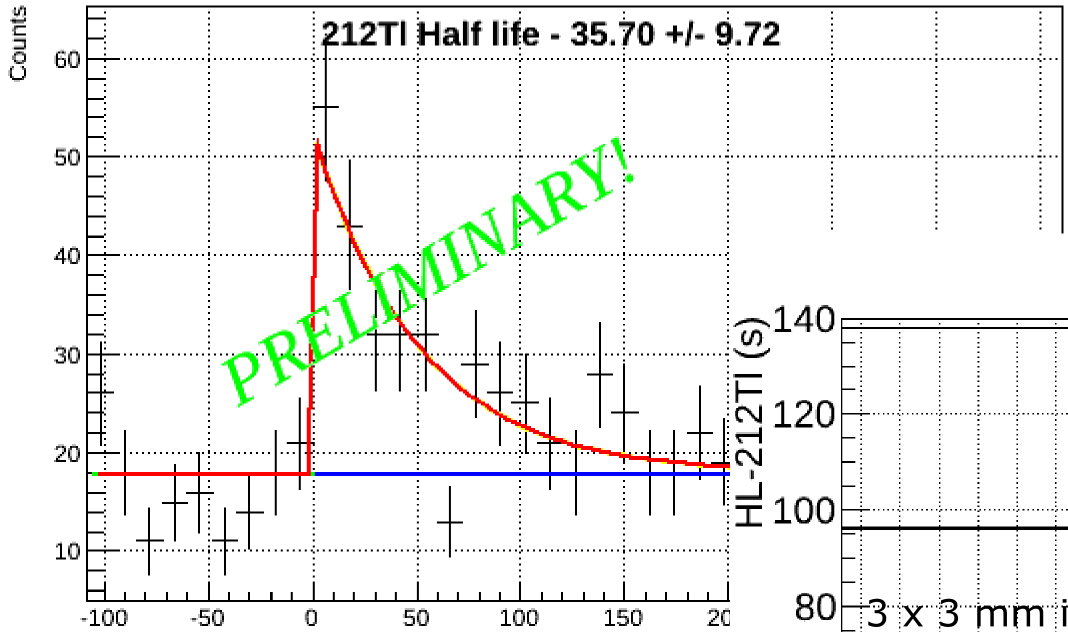
Isotopes $^{204-206}Au$, $^{208-211}Hg$, $^{211-215}Tl$, $^{215-218}Pb$ and $^{218-220}Bi$ implanted

Nuclei implants on the high segmented layers of SIMBA detector

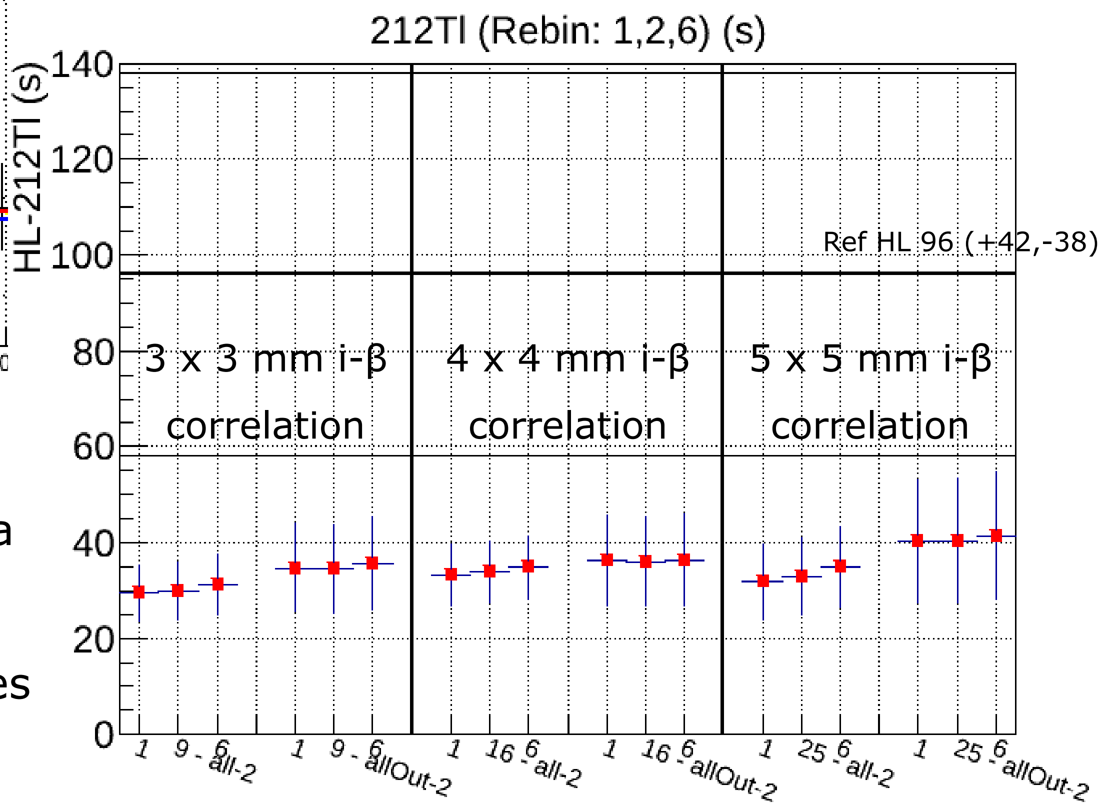


Thallium isotopes half-lives obtained





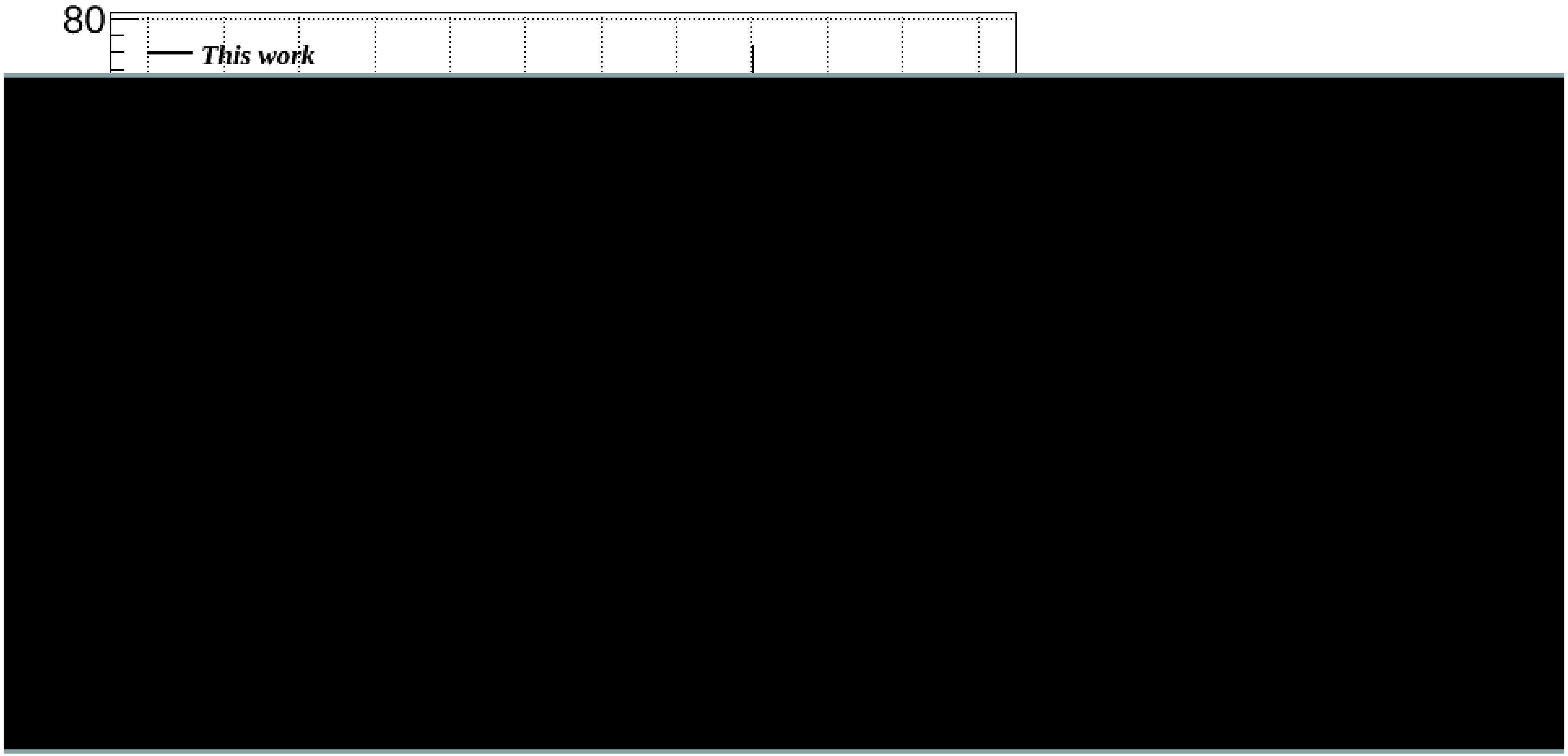
Consistent results obtained for all correlations



An accurate study for implant- beta correlations has been developed to obtain consistent values of half-lives

- SIMBA DSSD pixilation
- The beam constraints (IN/OUT spill)

Half-lives results for Au isotopes



A.I.Morales et al, PRL 113 (2014)
(review from recent studies USC group)

Other experimental data reported in www.nndc.bnl.gov

Half-lives results for Hg isotopes

[redacted]

Experimental data reported in www.nndc.bnl.gov

Half-lives results for Tl isotopes

[redacted]

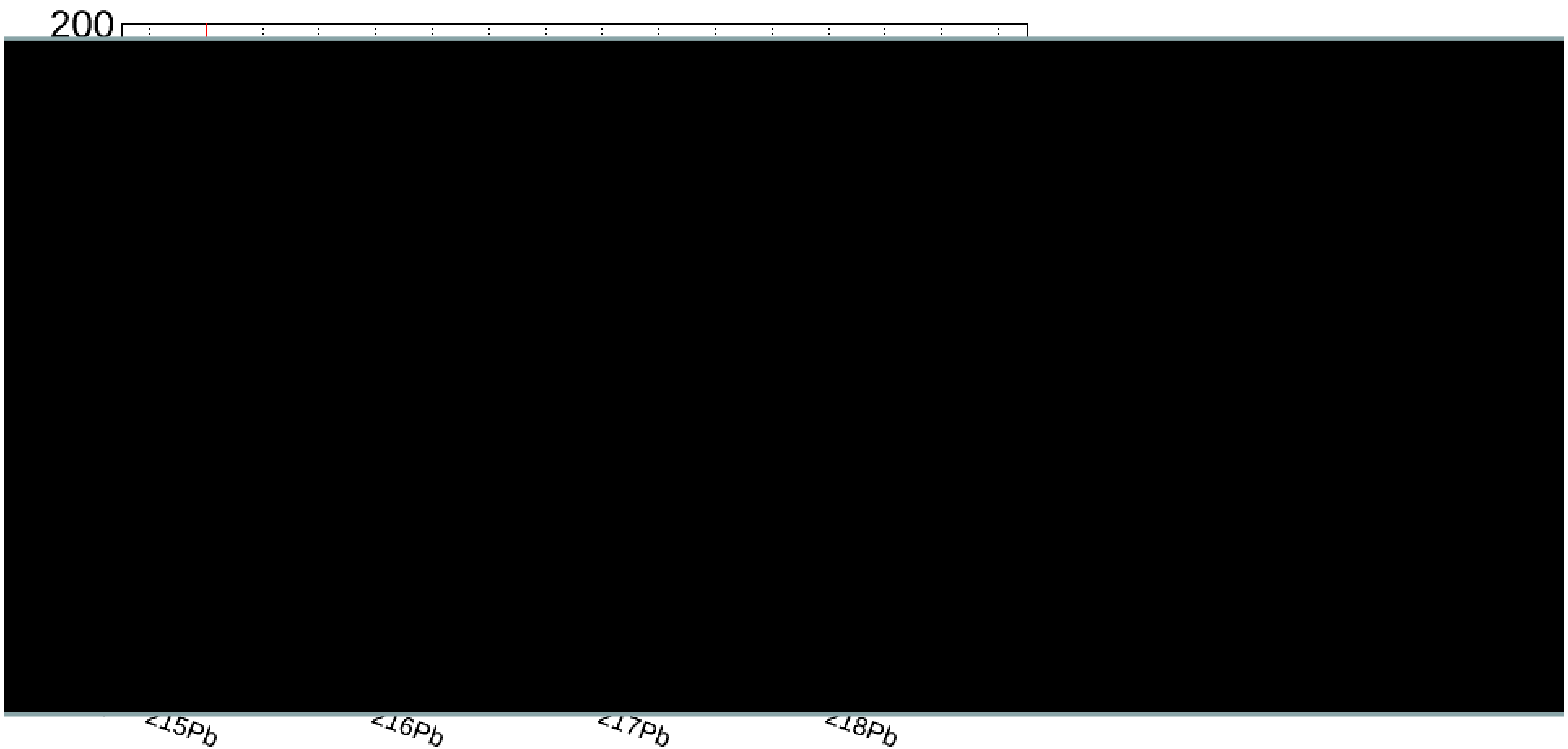
and 15 seconds

No previous exp. data

A.I.Morales et al, PRL 113 (2014)
(review from recent studies USC group)

Other experimental data reported in www.nndc.bnl.gov

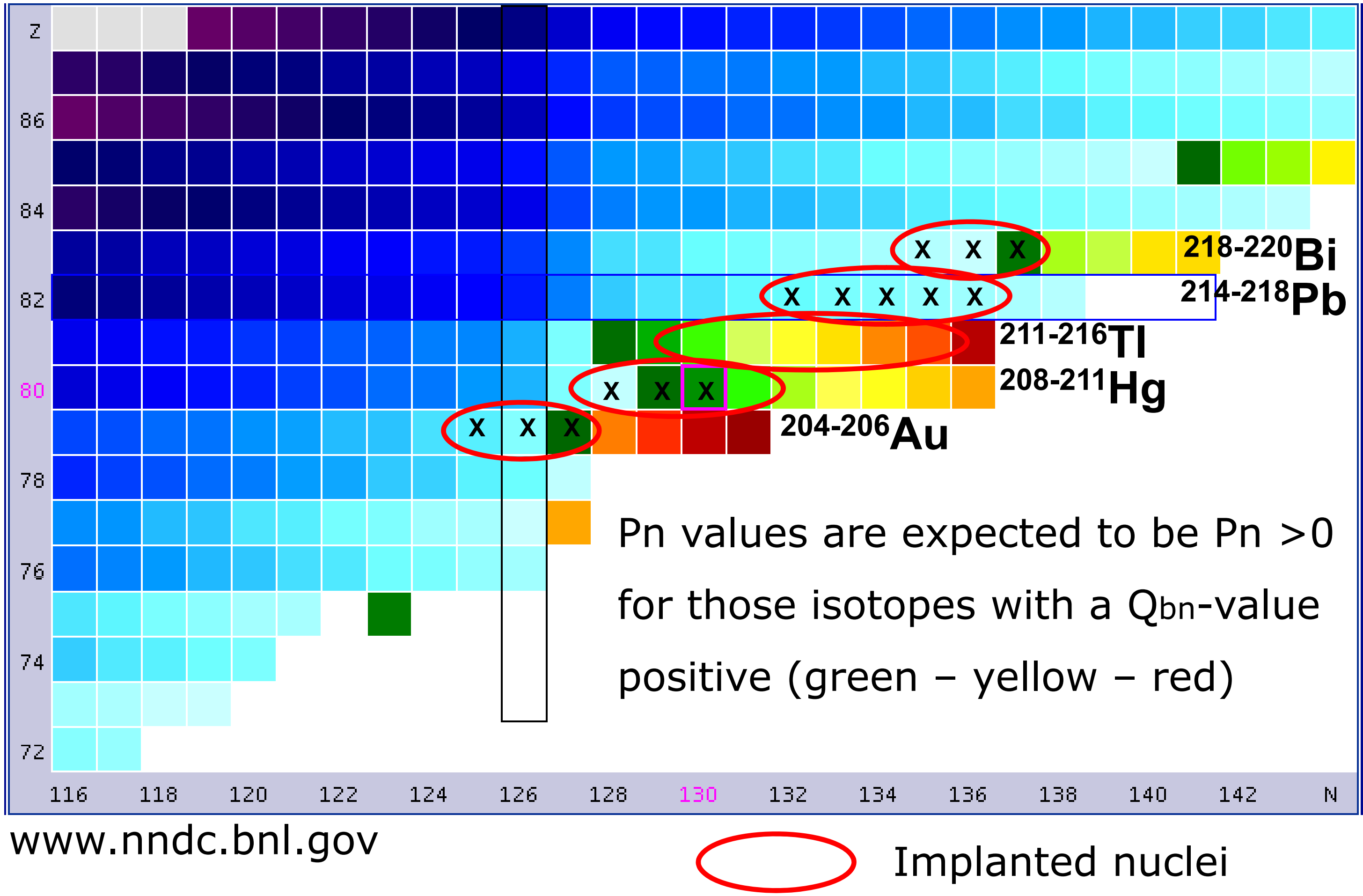
Half-lives results for Pb isotopes



A.I.Morales et al, PRL 113 (2014)
(review from recent studies USC group)

Other experimental data reported in www.nndc.bnl.gov

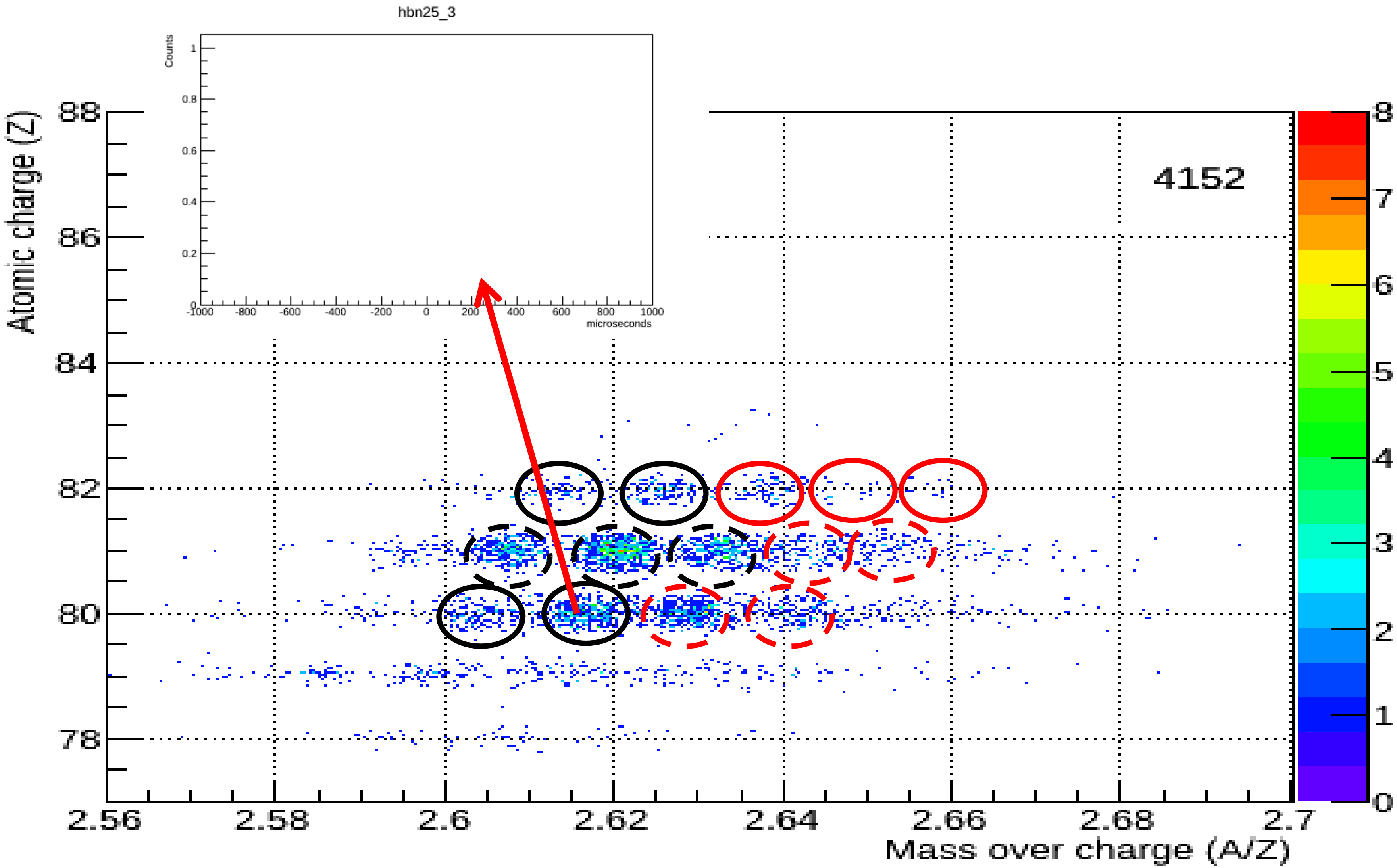
Nuclei with expected Pn values according to the Qbn measured



www.nndc.bnl.gov

PRELIMINARY implant – beta - neutron correlations

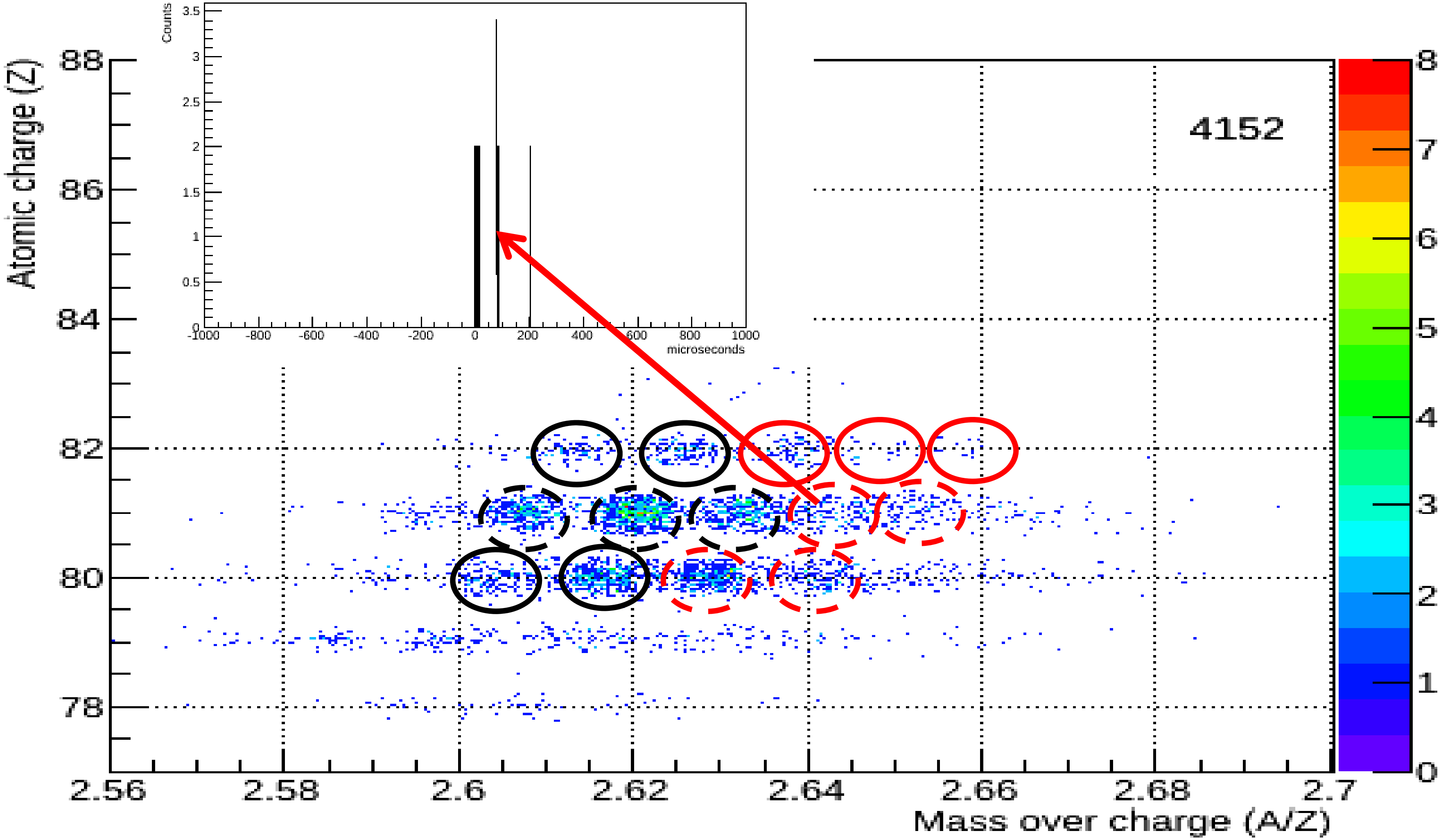
^{209}Hg No neutron emission expected and checked !



BELEN Efficiency ~40%

PRELIMINARY implant – beta - neutron correlations

[redacted]



BELEN Efficiency ~40%

S410 Experiment outlook

- Several species of neutron rich heavy nuclei have been produced and identified in the Au/Hg/Tl/Pb/Bi region, beyond the shell closure N=126.

- **half-lives** of 16 isotopes have been determined, via standard correlation methods, some of them for the first time.

-**β-delayed neutron emission (Pn)** probabilities have been obtained being the first experimental evidence of Pn beyond *N*=126 (Only G. Stetter, in 1962 reported a value for Tl-210). Results are consistent with Q_{bn}-values reported.

- Using this results as an input for the theoretical models can improve the understanding of the *r*-process nucleosynthesis beyond *N*=126 and the nuclear structure in the region.

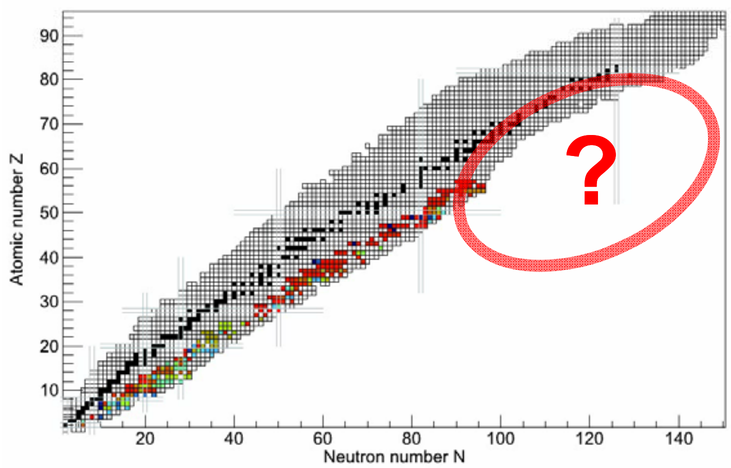
Outline

- Motivation – NUSTAR (DESPEC)
- BELEN-20 and BELEN-48 detector
- BELEN-30 experiments at GSI (2011)
- **BRIKEN collaboration**

New campaign for the measurement of b-delayed neutrons at RIKEN

BRIKEN campaign: Explore opportunities with the **BELEN** neutron detector at **RIKEN**

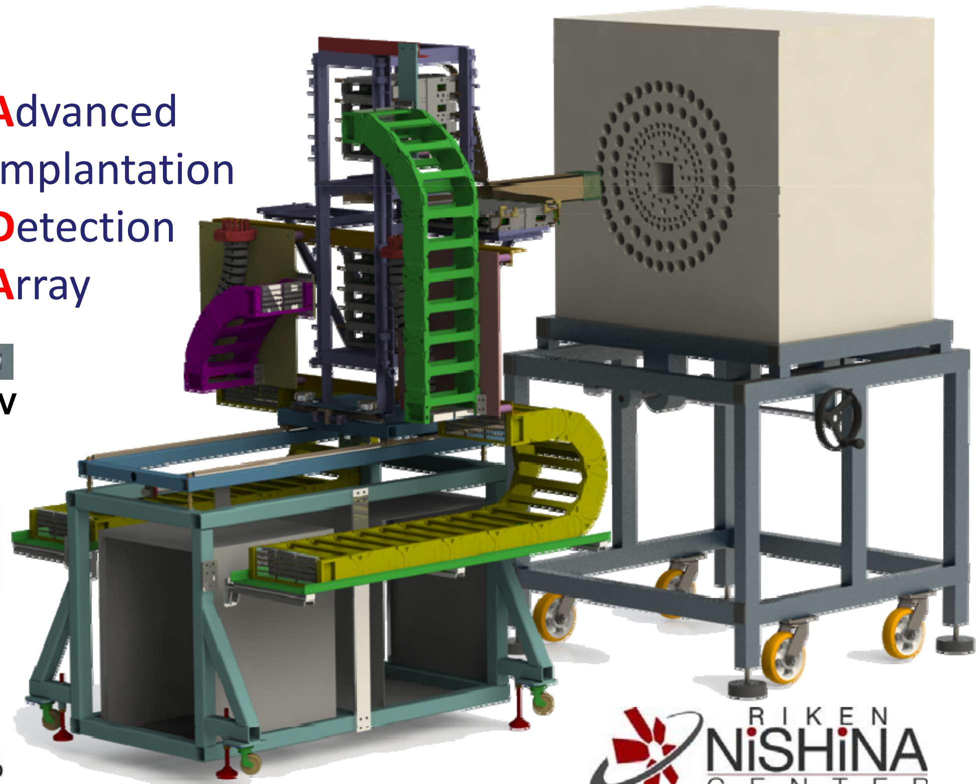
Improve the future plans, colaborations, detectors, test BELEN at larger RIB intensities

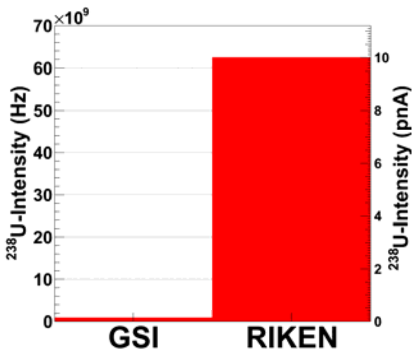


Large need of b-delayed neutron emission measurements!!!

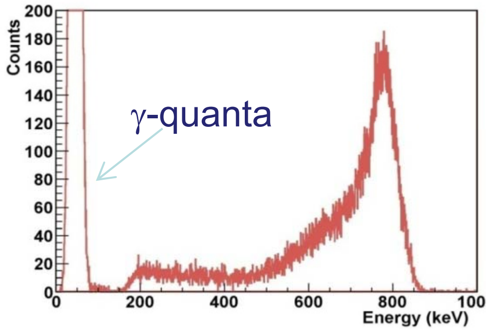
BRIKEN neutron detection set-up

Advanced **I**mplantation **D**etection **A**rray



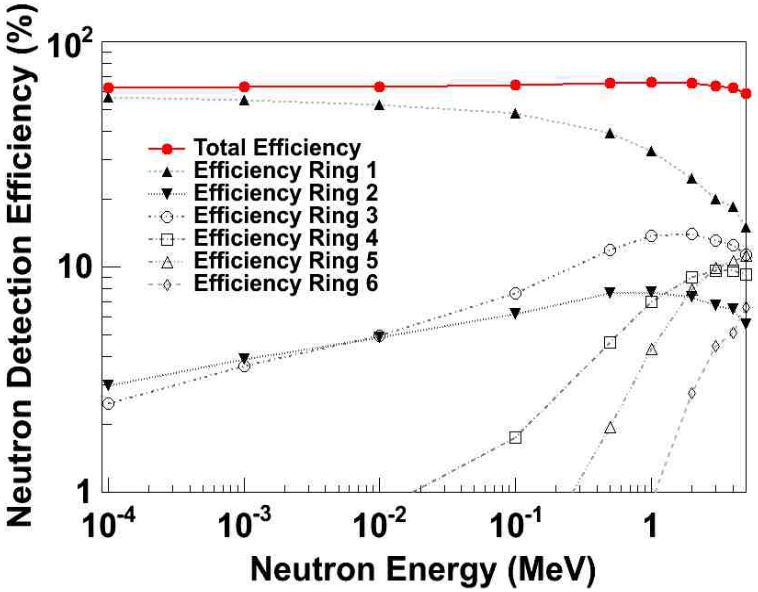


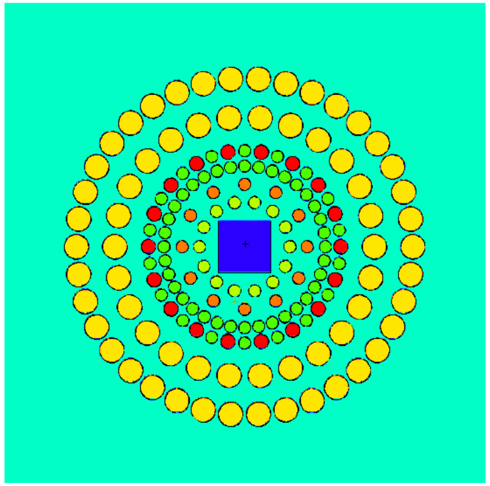
n + ^{3}He → ^{3}H + ^{1}H + 0.764 MeV
(abund.=0.00014%)

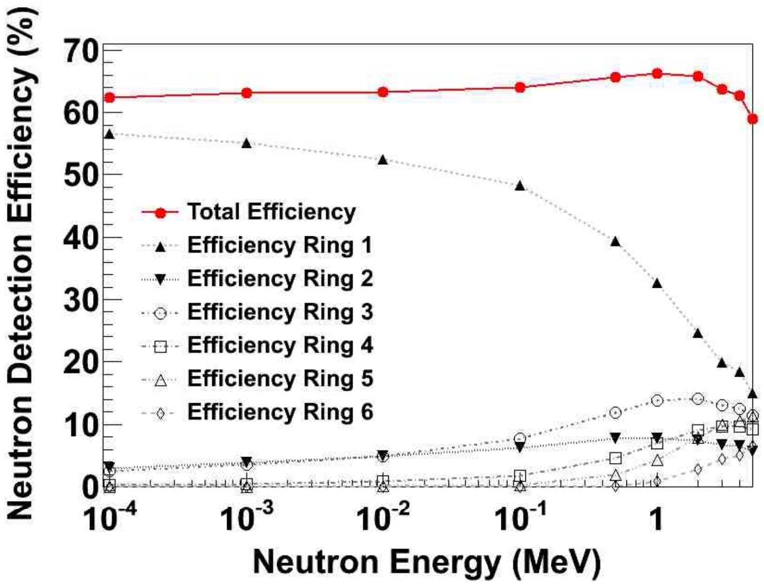


RIKEN NiSHiNA CENTER

GSI, TRIUMF, IFIC Institut de Física Corpuscular, UPC, JINR, NSCL, Oak Ridge National Laboratory, 東京大学, MTA Atomki, The University of Edinburgh, Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, University of Liverpool







174 ^{3}He tubes of 6 different types:

Ring	Radius (cm)	# ^{3}He Tubes	Pressure (atm)	Diameter (inch)	Institute
1	9.4	14	10	1	ORNL
2	13	12+12	5.13	1	RIKEN
3	16.8	10+26	10/8	1	GSI/UPC
4	20	18+18	5/8	1.18/1	JINR/UPC
5	27	26	10	2	ORNL
6	35	38	10	2	ORNL

- High average efficiency of > 60 %
- Flat efficiency 6% up to 4 MeV, 12% up to 5 MeV.

Slide from C. Domingo-Pardo, NUSTAR Week 2014

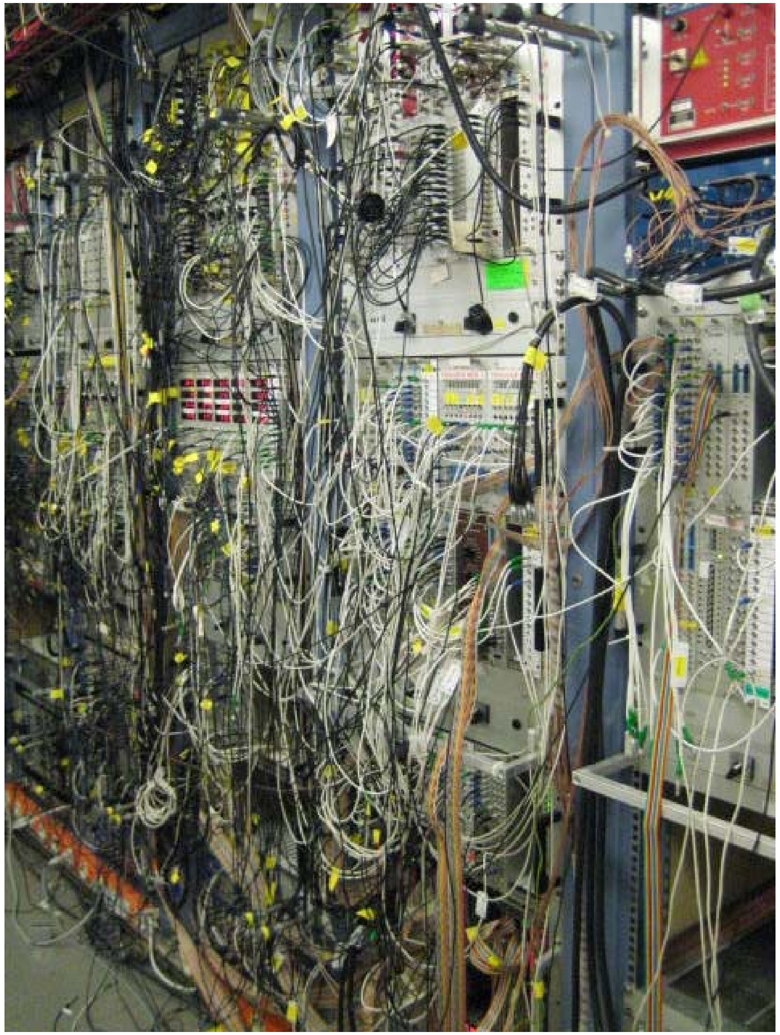
- BELEN detector has been used in several experiments with different silicon implantation detectors with successful results.

- New half-lives and Pn-values have been determined and confirmed since 2009.

- Specific acquisition system developed for BELEN has been integrated in the experimental facilities systems.

- BRIKEN campaign it’s an opportunity to test and check the detection system AIDA + BELEN in a fragmentation beam facility, which represents **to be ready on the day-one of FAIR**.

S410 experiment collaboration



Universitat Politècnica de Catalunya (UPC)

Institut de Física Corpuscular de València (IFIC)

Helmholtzzentrum für Schwerionenforschung GmbH (GSI)

NSCL, Michigan State University (MSU-USA)

CIEMAT (Madrid)

Universidade de Santigo de Compostela (USC)

Department of Physics, University of Surrey (UK)

CFNUL Universidade de Lisboa (Portugal)

School of Physics & Astronomy, U. Edinburgh (UK)

Department of Physics, University of Liverpool (UK)

STFC, Daresbury Laboratory (UK)

Laboratori Nazionali di Legnaro, INFN (Italy)

Flerov Laboratory, JINR, Dubna (Russia)

CENBG, Université Bordeaux (France)

et al.

Contact: roger.caballero@upc.edu

Work supported by the Spanish Ministry of Economy and Competitivity under contract

FPA 2011-28770-C03-03