21st June 2023

Beta decay studies in the HISPEC/DESPEC FAIR Phase-0 campaign at GSI

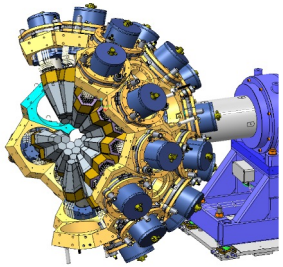
Marta Polettini

University and INFN Padova

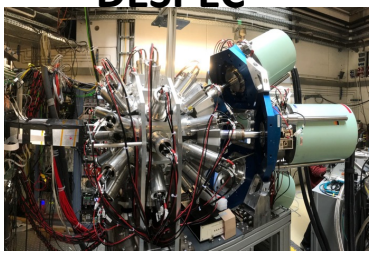
HISPEC-DESPEC at GSI-FAIR

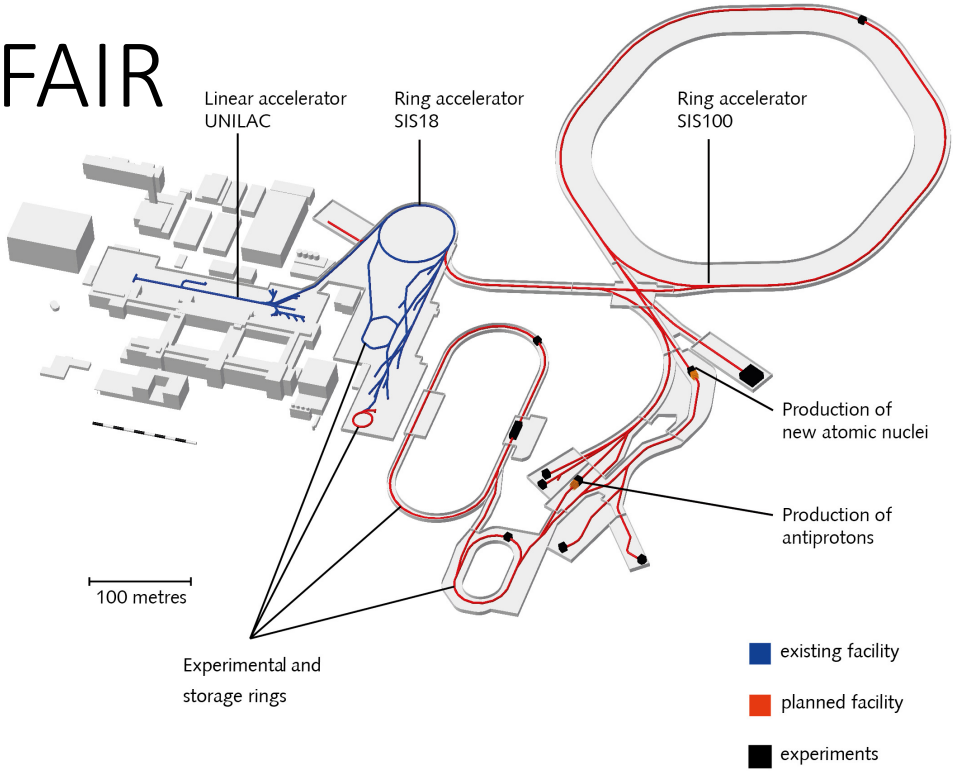
Spectroscopic studies both **in-beam** (HISPEC) and with **stopped ions** (DESPEC).

AGATA



DESPEC





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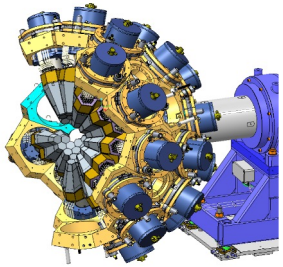

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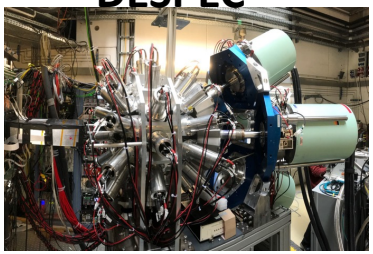
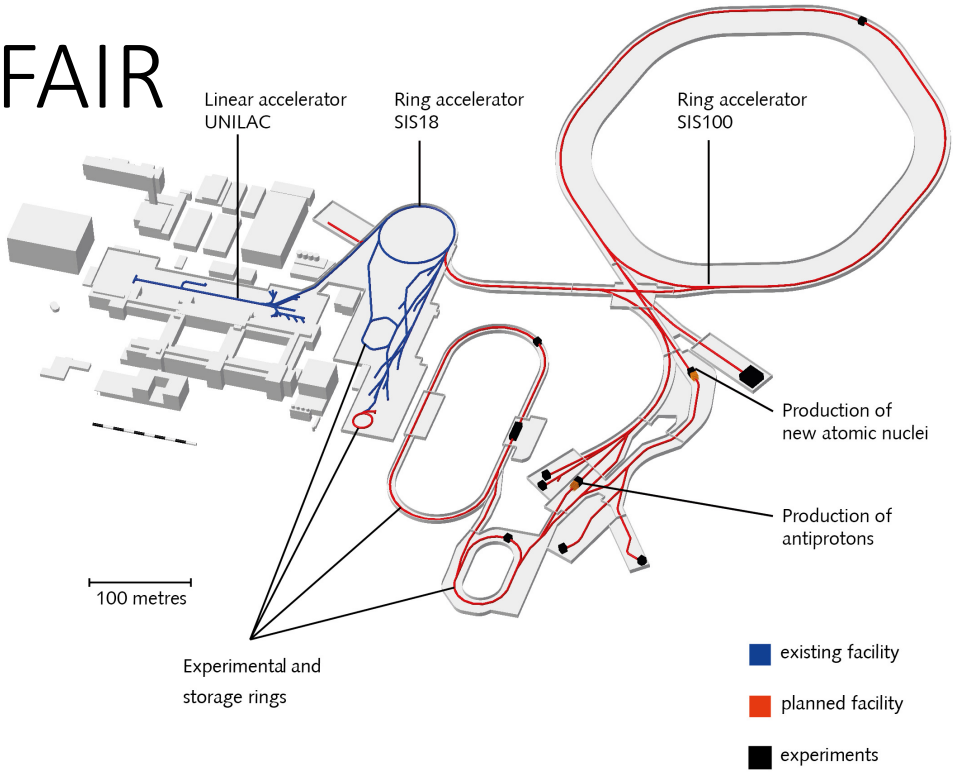


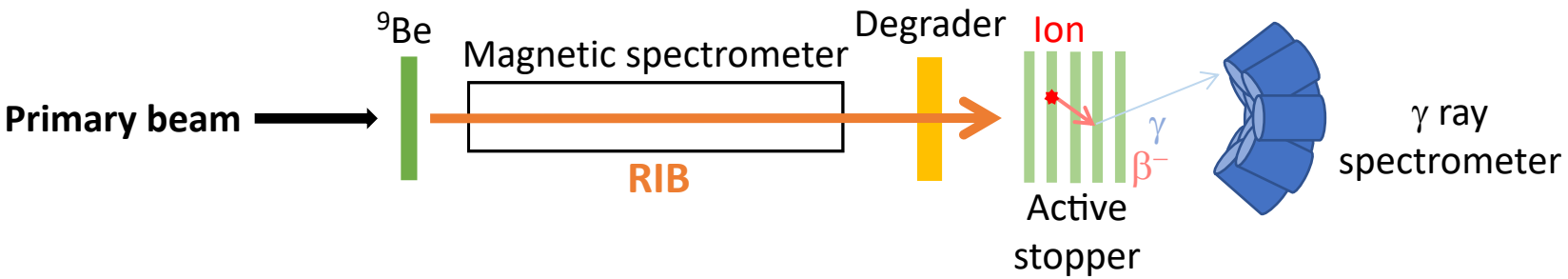


Strength of HISPEC/DESPEC:
Use combination of unique detectors for complete spectroscopy of exotic nuclei with yields as low as **one ion per hour** (~nb)

Key goals exploiting unique GSI-FAIR beams:

- Approach the r-process path along N=126: **nucleosynthesis of heavy nuclei**
- Evolution of the shell structure and exotic nuclear shapes in **uncharted nuclear territory**

The FRS+DESPEC setup



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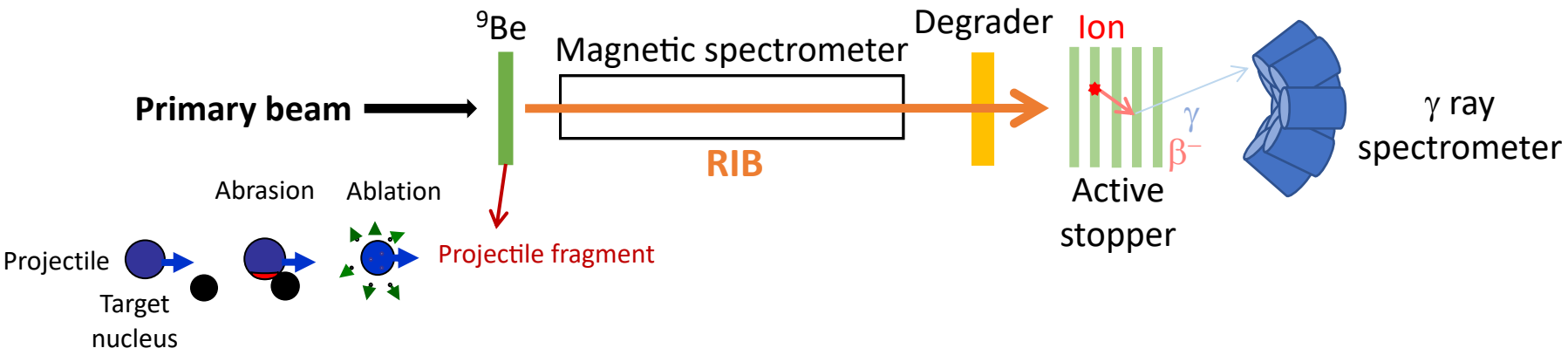

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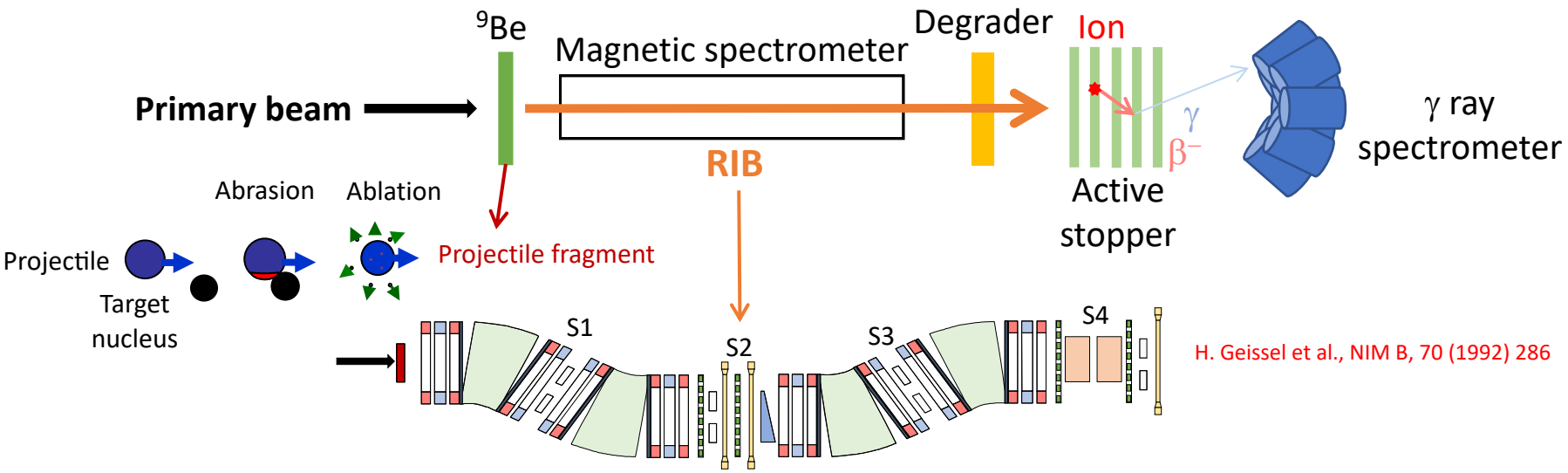

H. Geissel et al., NIM B, 70 (1992) 286

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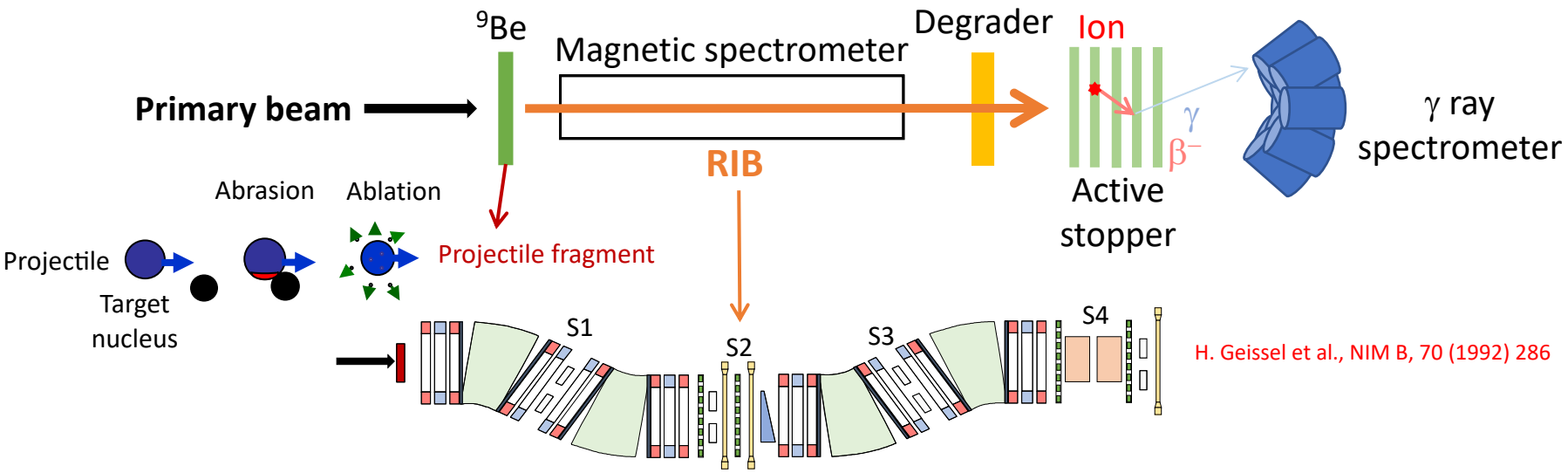
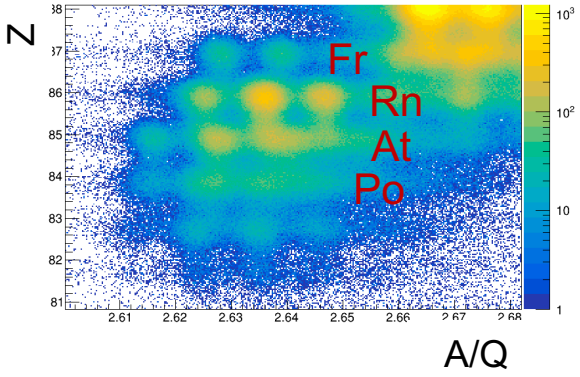
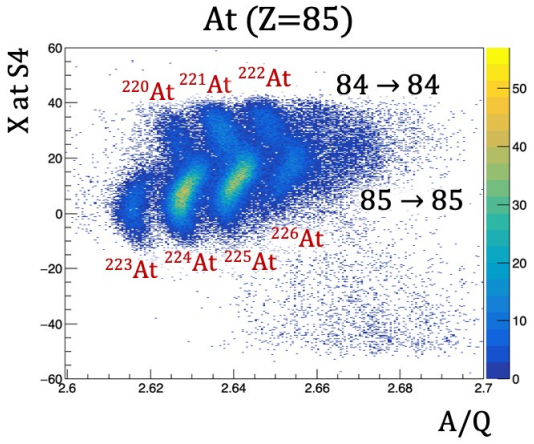


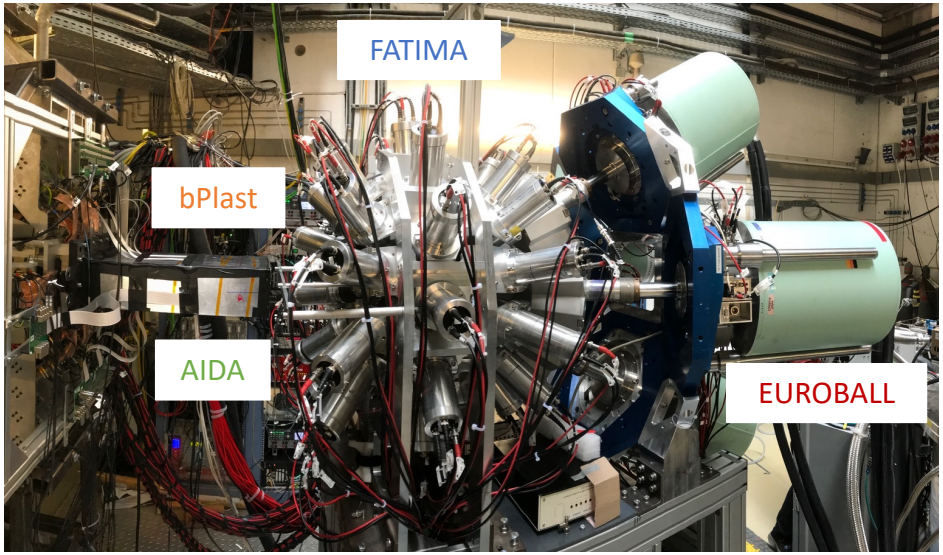
Selection and identification: $B\rho - \Delta E - B\rho$ & $ToF - B\rho - \Delta E$

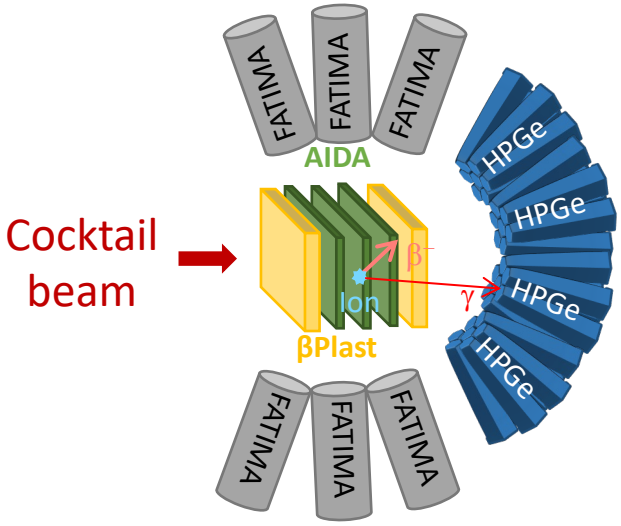




The DESPEC station

A. K. Mistry et al., NIM A 1033 (2022) 166662





- **AIDA:** 8x8 cm^2 DSSSD tiles, 16384 pixels
- **bPlast:** BC-400 plastic detector
- **Euroball:** four 7-fold HPGe clusters
- **FATIMA:** 36 $LaBr_3(Ce)$ detectors

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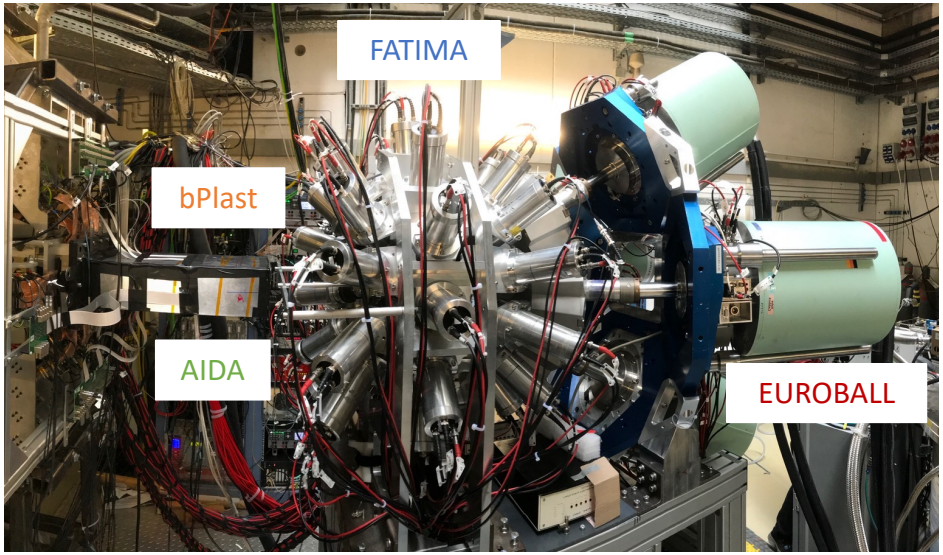

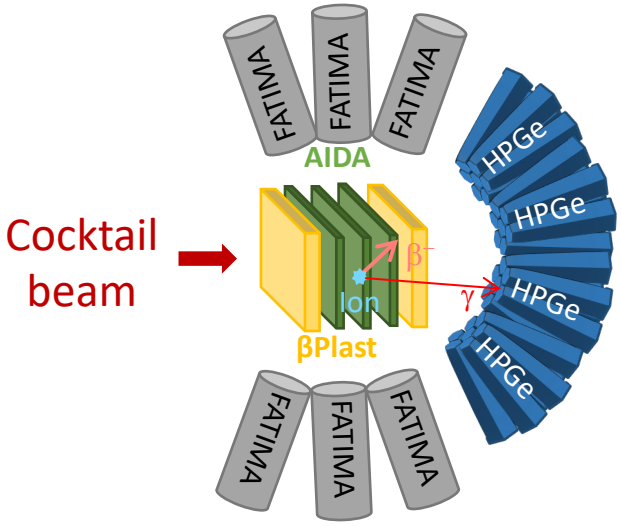

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Ion → β decay → γ rays

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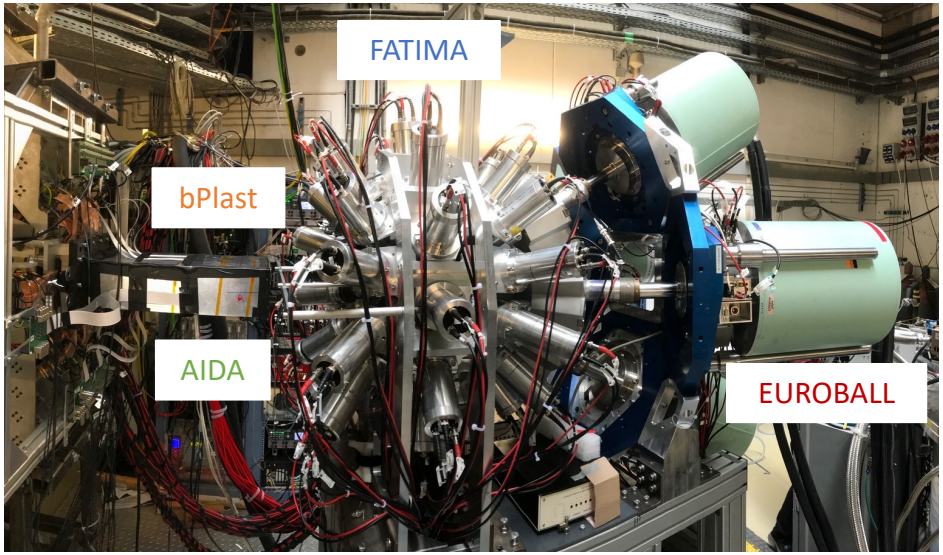

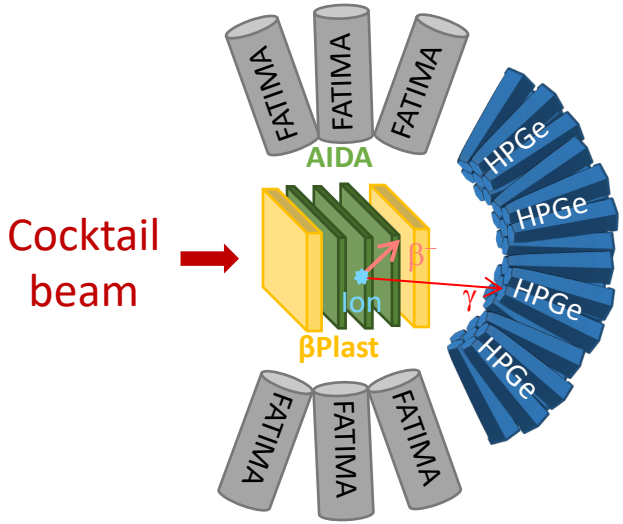

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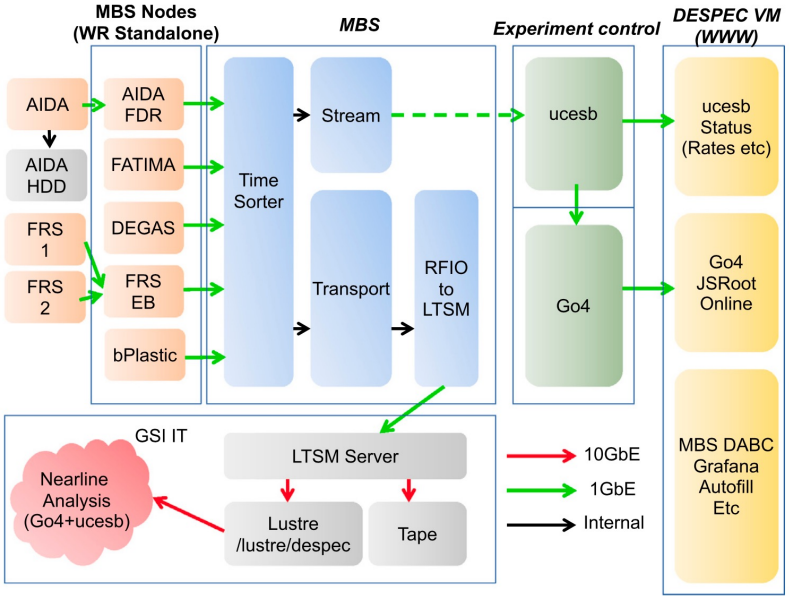
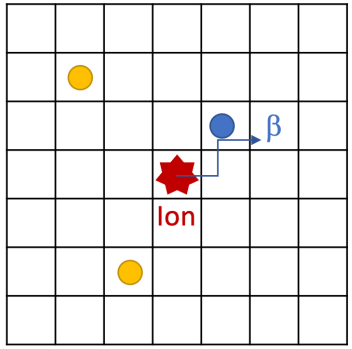
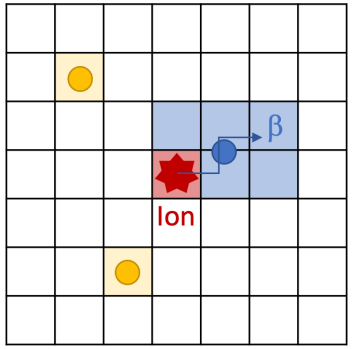


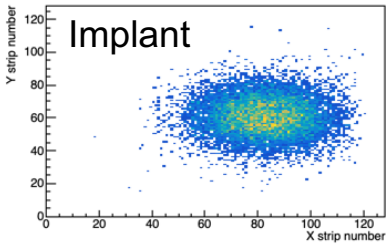
Ion–β–γ correlations

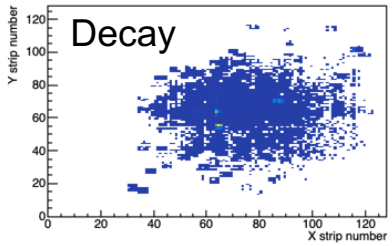




Ion–β correlations:

- Position condition → ion and β cluster overlap
- Time condition → $dT(Ion - \beta) < 5\tau_\beta$





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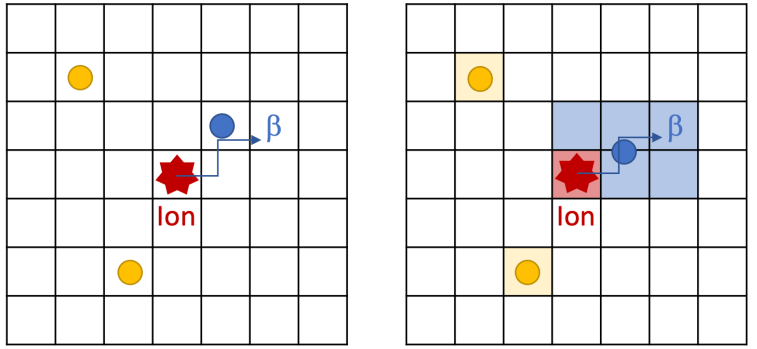

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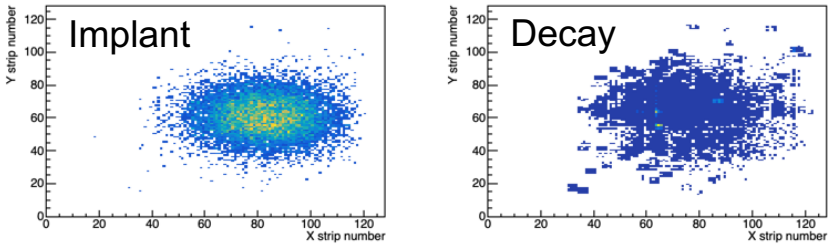
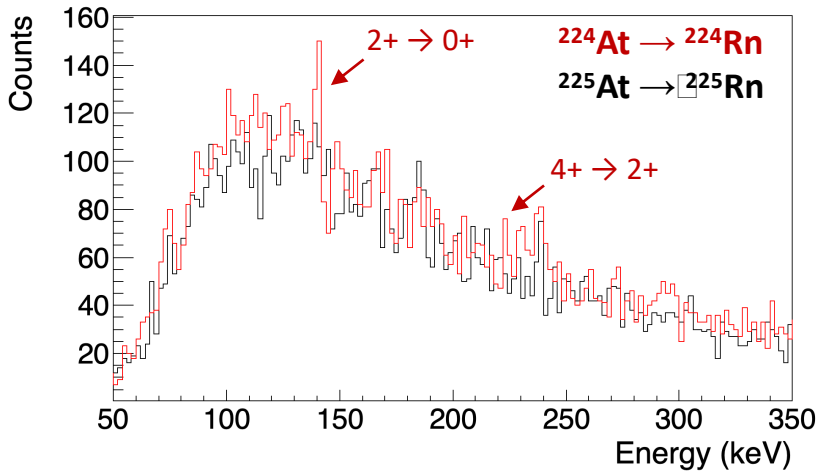
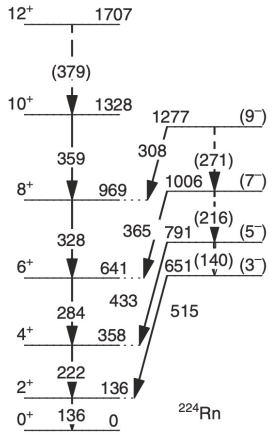


β–γ correlations:

- Prompt coincidence: $\Delta T(\gamma-\beta) < 100\ ns$

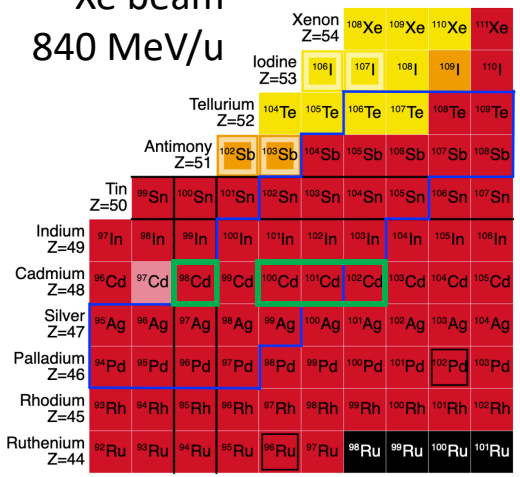




P. A. Butler et al., Nat. Commun. 10 (2019) 2473

INFN experiments in FAIR Phase-0 campaign

^{124}Xe beam
840 MeV/u



^{100}Sn region

- $N = Z = 50$ doubly magic
- Core-breaking effects

A~ 225 Po-Fr region

- Input to *r*-process models
- Octupole deformation expected

^{238}U beam
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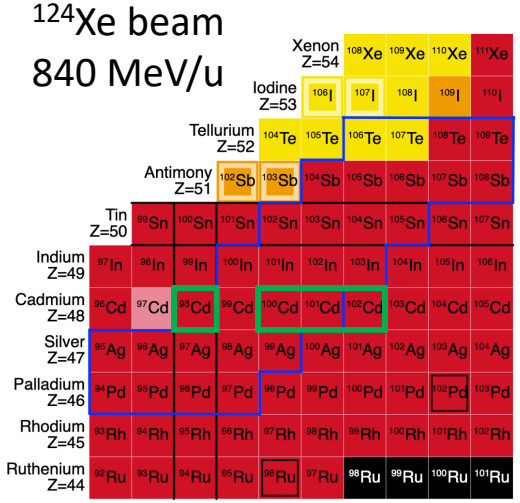

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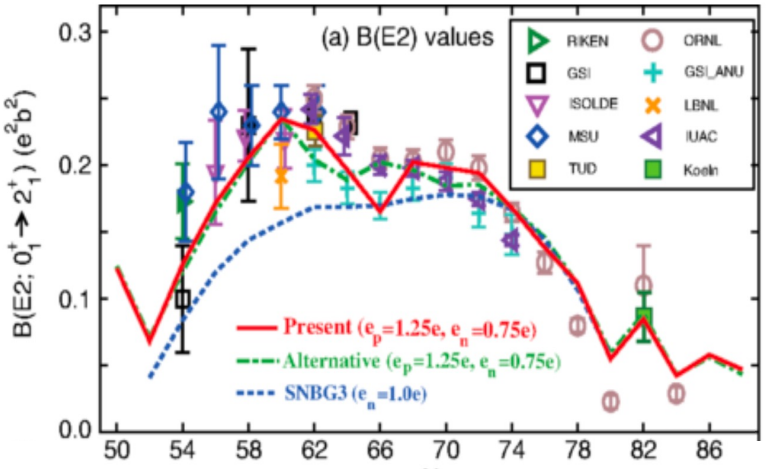
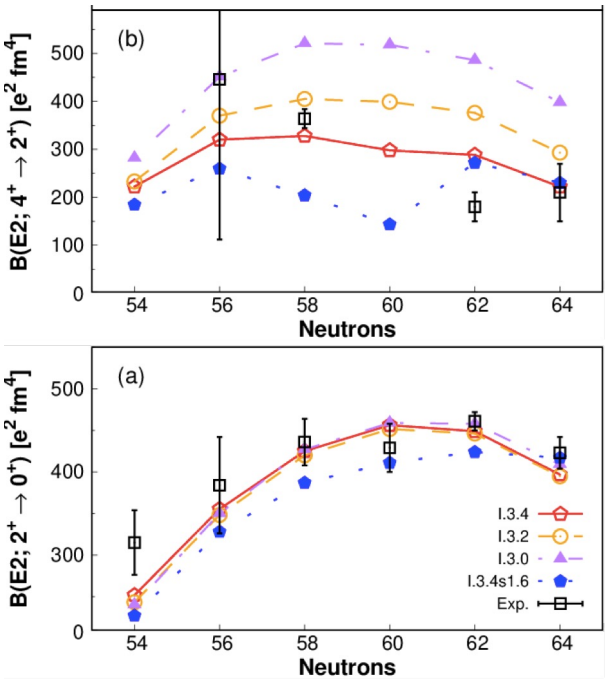
The ^{100}Sn region

The ^{100}Sn region is subject of a multitude of experimental and theoretical studies to assess:

- the robustness of its **double shell closure**
- the evolution of **single-particle energies**
- the role of **proton-neutron pairing**



T. Togashi et al., Phys. Rev. Lett. 121 (2018) 062501



A. P. Zuker et al., Phys. Rev. C 103, 024322 (2021)
M. Siciliano et al., Phys. Lett. B 806, 135474 (2020)

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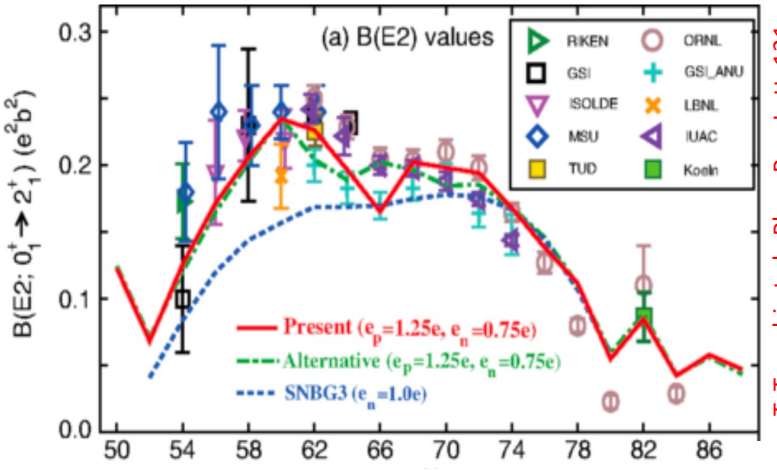

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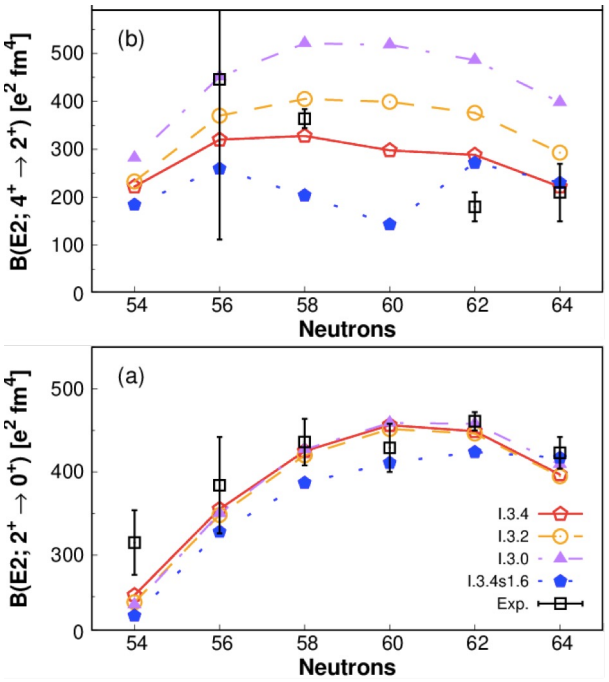
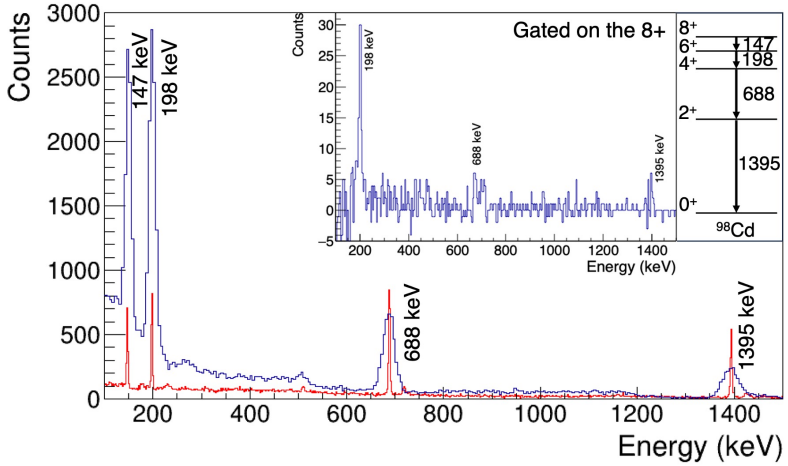


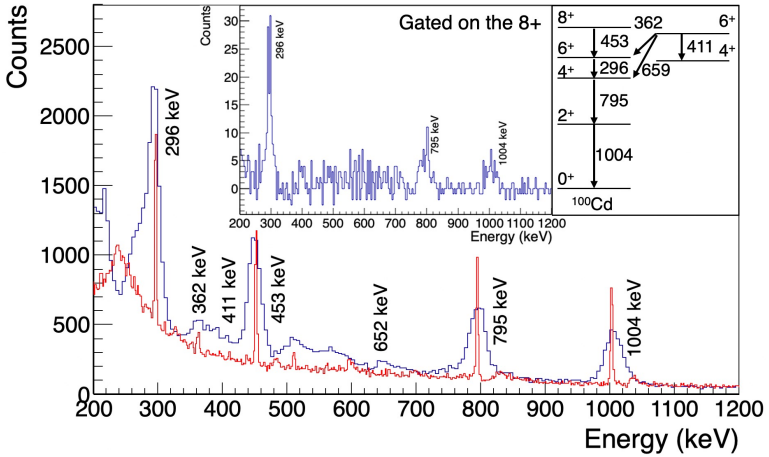
$_{48}$Cd isotopic chain → two proton holes in $g_{9/2}$ orbits

- B(E2) measurements of levels below seniority isomers
- Beta decay spectroscopy studies

A. P. Zuker et al., Phys. Rev. C 103, 024322 (2021)
M. Siciliano et al., Phys. Lett. B 806, 135474 (2020)

^{98,100}Cd levels' lifetimes





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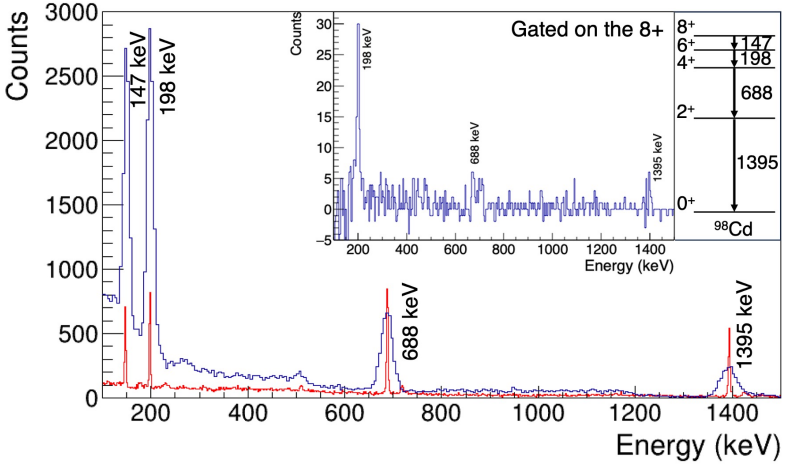
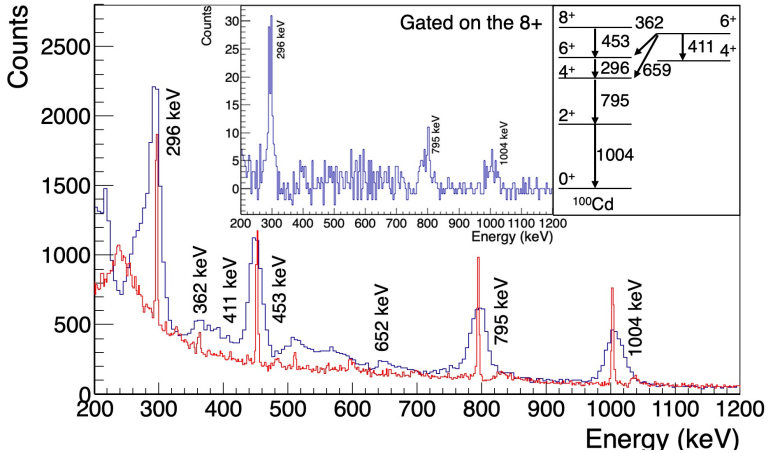
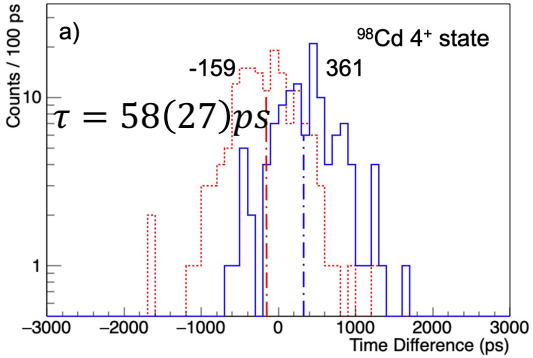
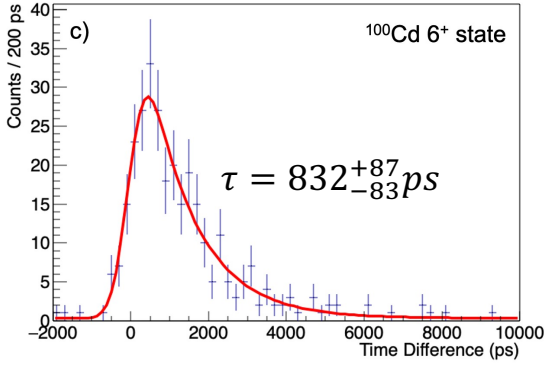
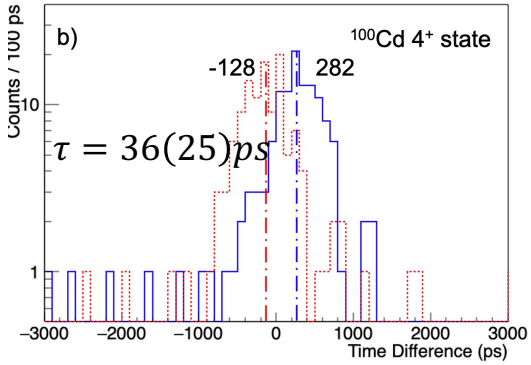




- The **lifetimes of low-lying excited states** below the 8$^+$ seniority isomer were directly measured in ^{98,100}Cd
- **B(E2) values** extracted using measured levels' lifetimes
- **Comparison with shell model calculations** being investigated



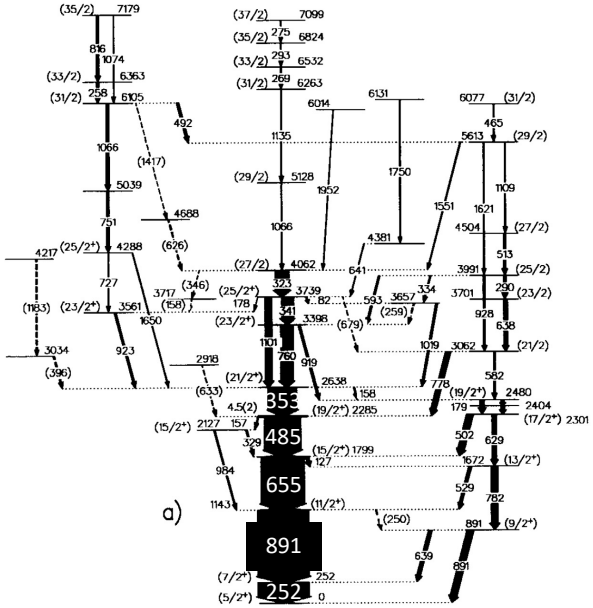




Calculations performed by:
A. Gargano, G. De Gregorio - INFN Napoli
F. Nowacki - Uni Strasbourg

^{101}Cd: first measurement of I_β and log*ft*

Fusion-evaporation reaction



M. Palacz et al., Nucl. Phys. A 608 (1996) 227–242

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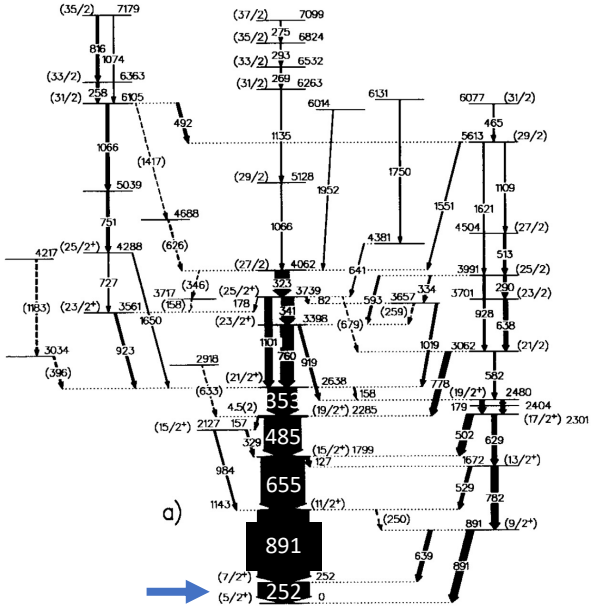

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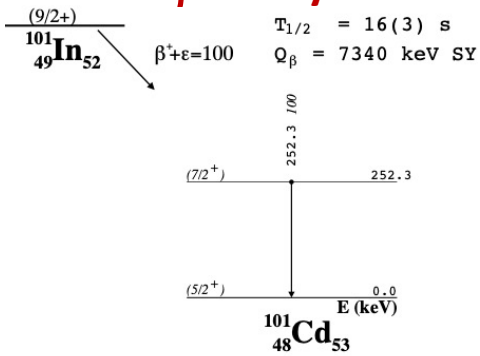
β decay



M. Huyse et al., Z. Phys. A 330 (1988) 121–122

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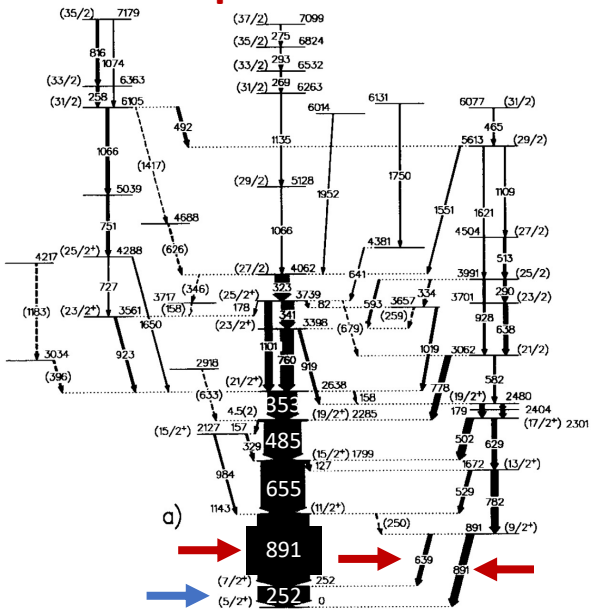

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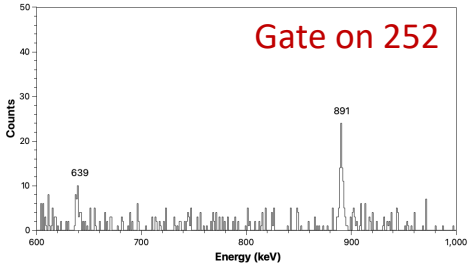
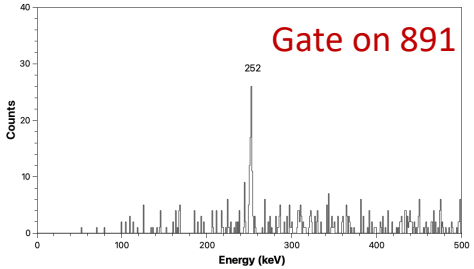
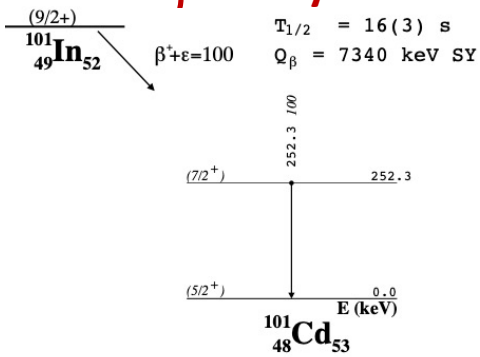




β decay



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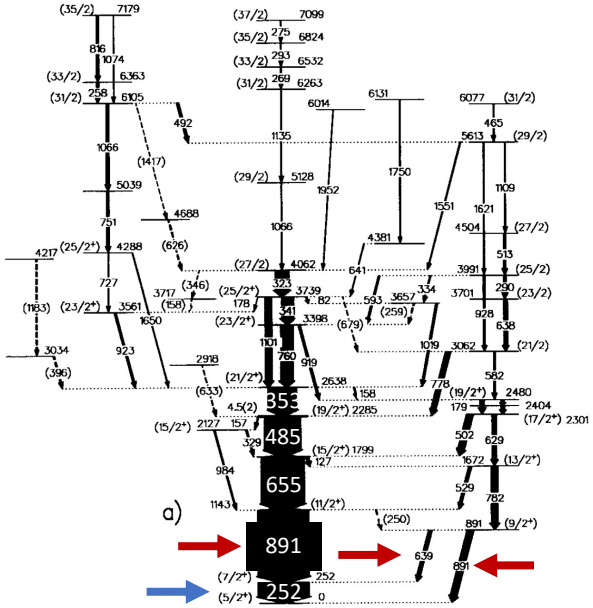
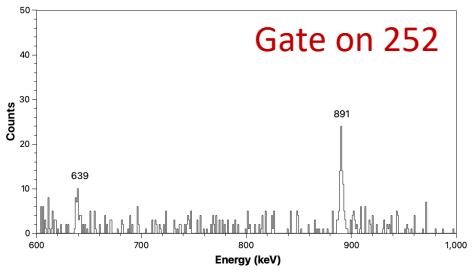
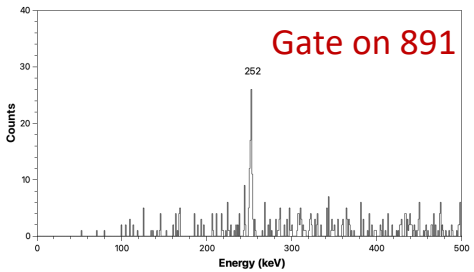
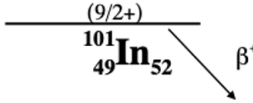


M. Palacz et al., Nucl. Phys. A 608 (1996) 227–242



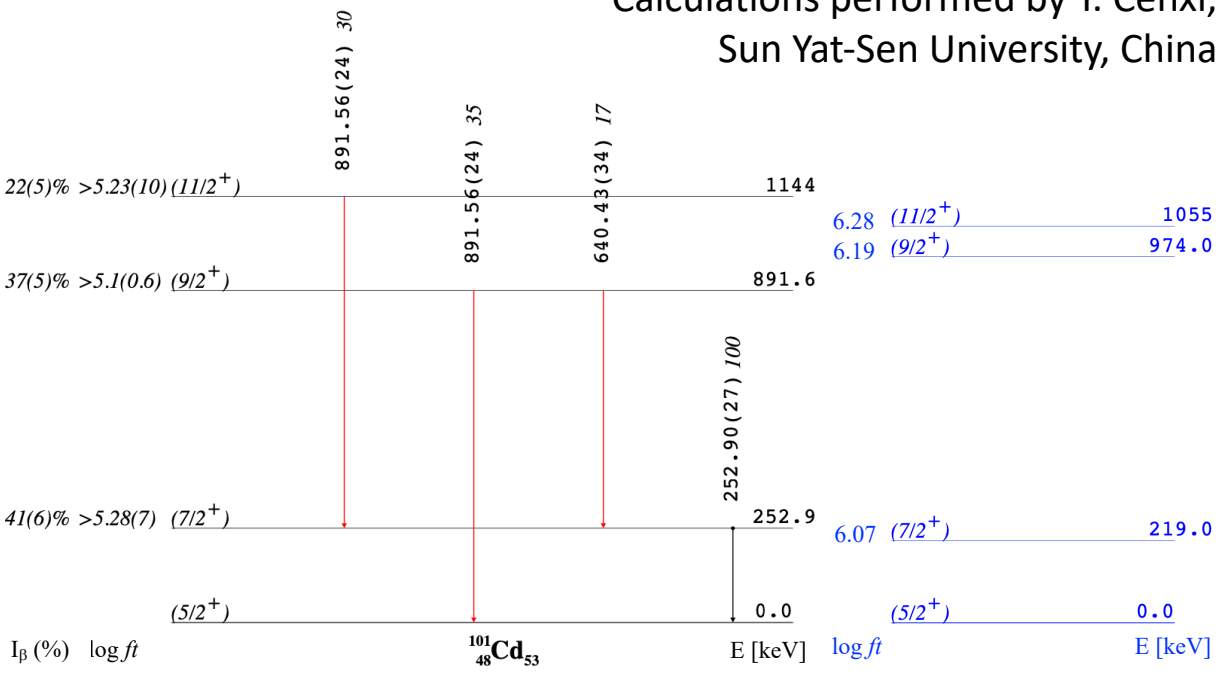




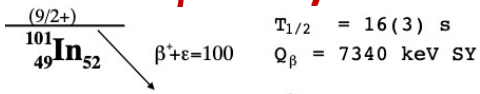
$T_{1/2}$ = 15.1(0.3) s

Q_β = 7291(5) keV

Calculations performed by Y. Cenxi, Sun Yat-Sen University, China

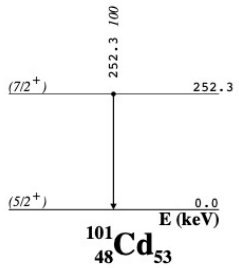


β decay



$T_{1/2}$ = 16(3) s

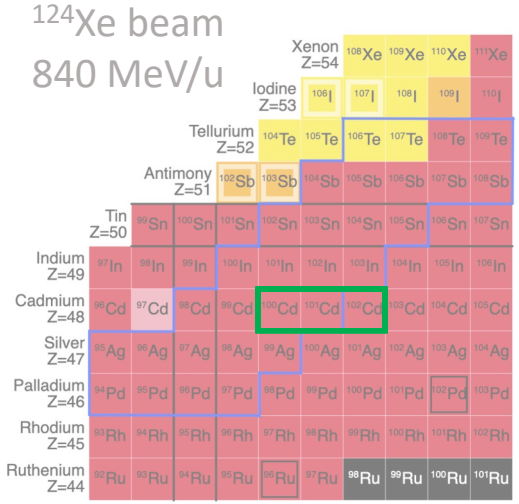
Q_β = 7340 keV SY



M. Huyse et al., Z. Phys. A 330 (1988) 121–122

INFN experiments in HISPEC-DESPEC in 2021

^{124}Xe beam
840 MeV/u



^{100}Sn region

- $N = Z = 50$ doubly magic
- Core-breaking effects

A~ 225 Po-Fr region

- Input to *r*-process models
- Octupole deformation expected

^{238}U beam
1 GeV/u

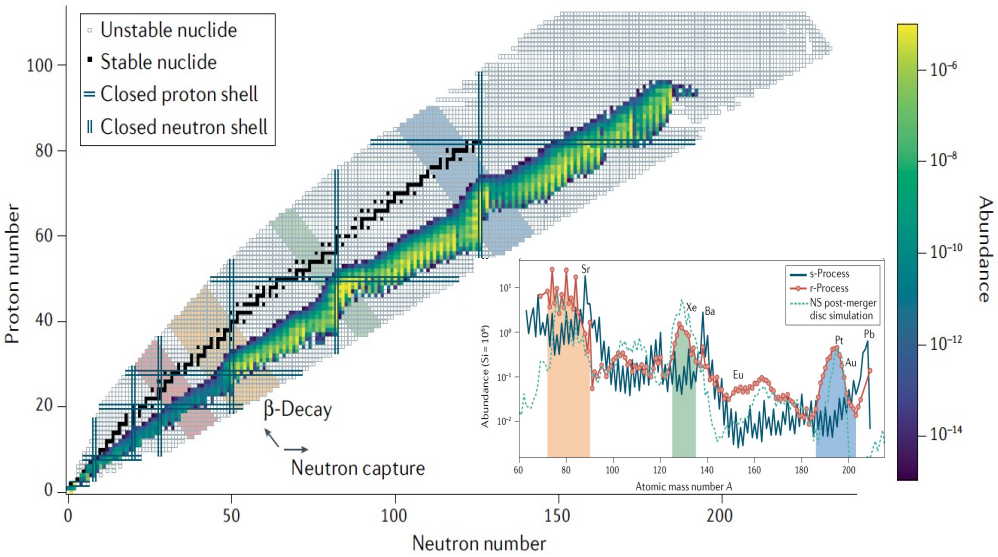
The A~225 region

Octupole deformation around A~225

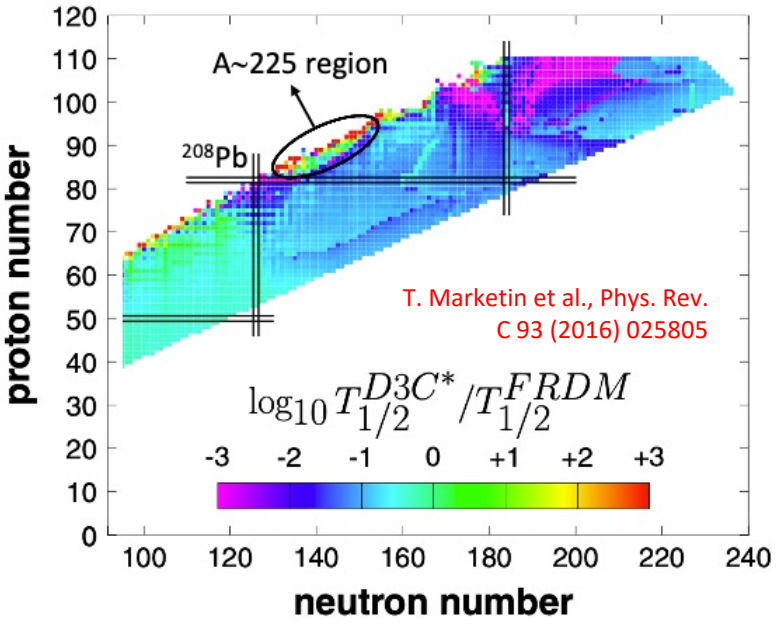
- Locate low-lying 1^- and 3^- states
- Measure reduced transition strengths

Test of nuclear models for *r* process

- Measurement of ground state β–decay half-lives
- Determination of possible competing α branches



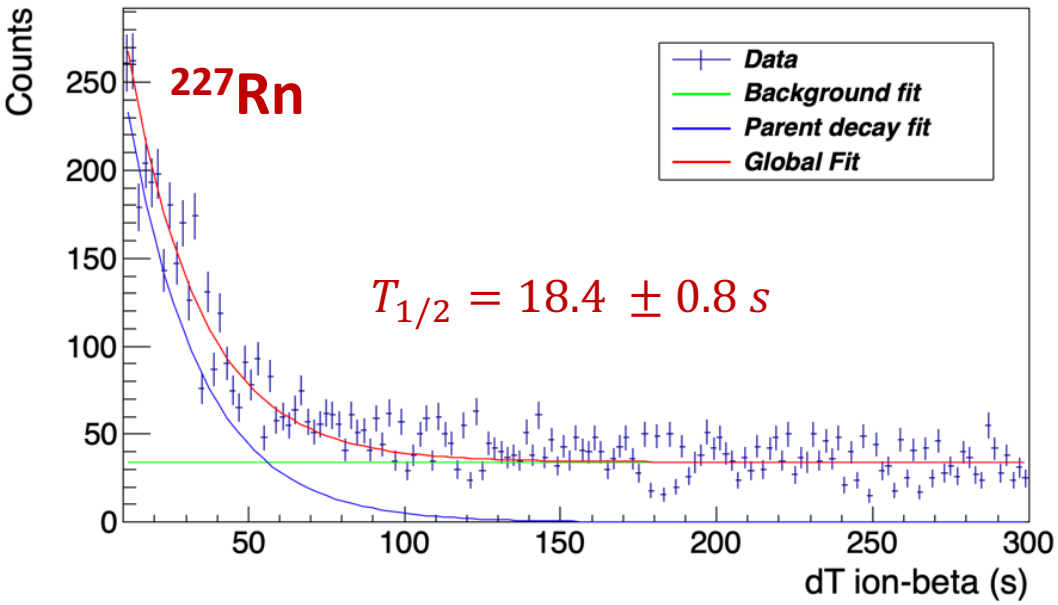
D. M. Siegel, Nat Rev Phys 4, 306–318 (2022)

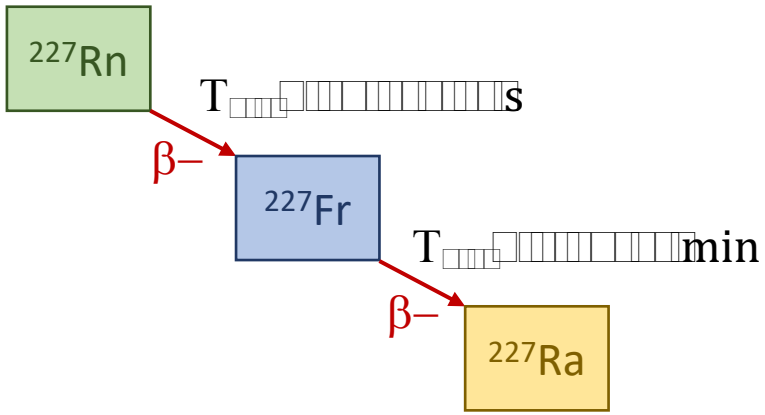


The *r* process:

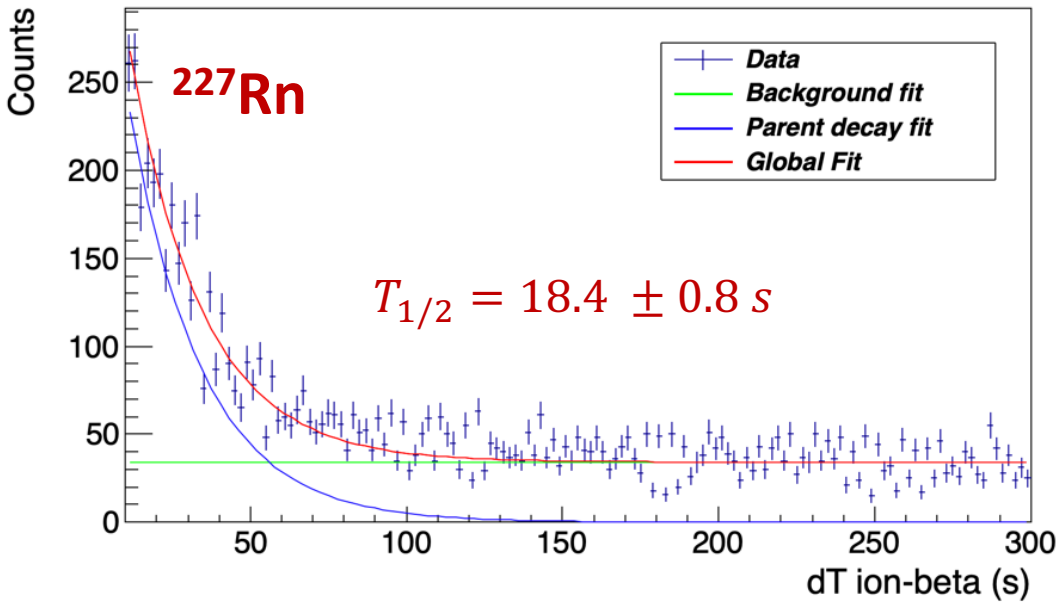
- Neutron capture at a very short time scale as compared to β decay
- One of the main synthesis mode of elements up to A~200
- Three abundance peaks at A~80,130,195 (N = 50,82,126 shell closures)

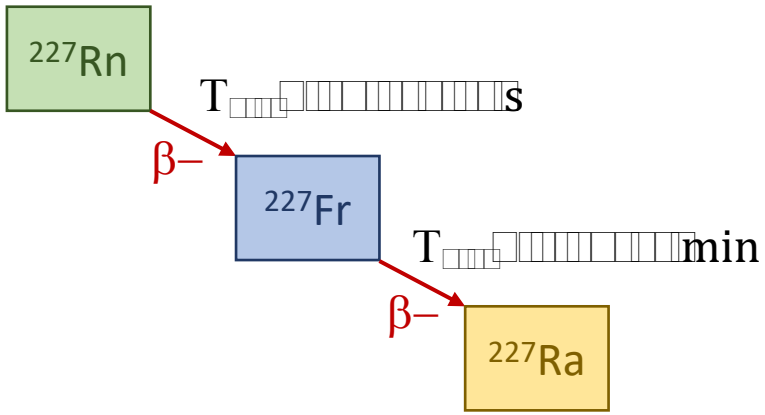
New β–decay half-lives in At and Po isotopes





New β–decay half-lives in At and Po isotopes

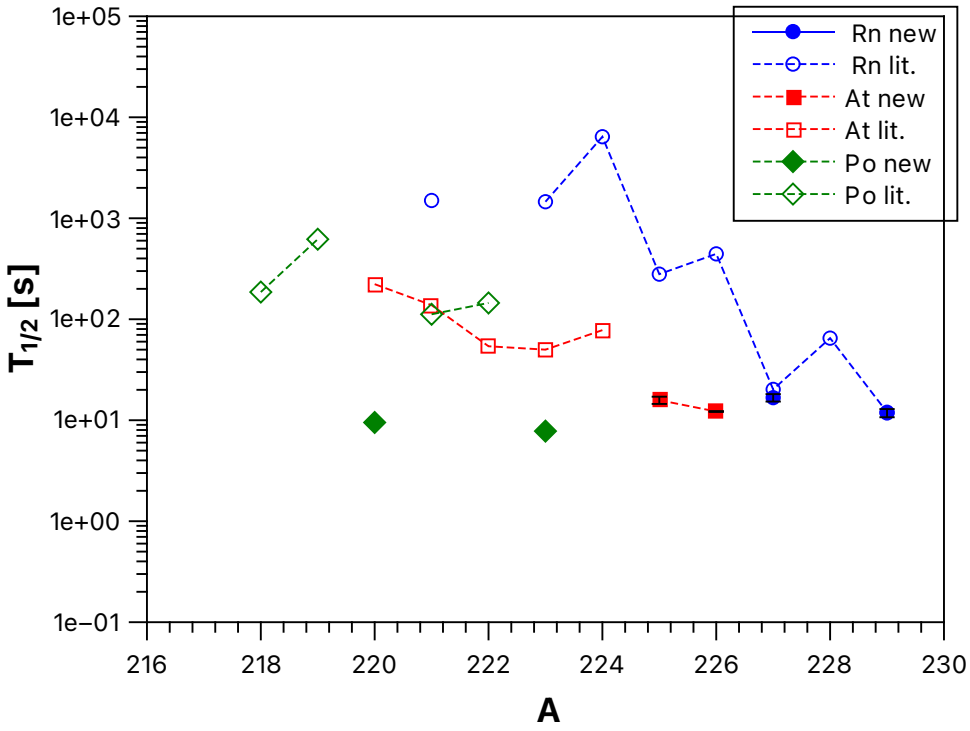




Ion	Q_{value} [MeV]	Experimental values [s] Present work	Literature
^{227}Rn→^{227}Fr	1.32	16.7 ± 1.4	[1]20.2 ± 0.4 (14)
^{229}Rn→^{229}Fr	1.87	11.8 ± 1.1	[2]$12^{+1.2}_{-1.3}$ (15)
^{225}At→^{225}Rn	2.71	15.8 ± 1.3	-
^{226}At→^{226}Rn	1.22	12.2 ± 1.7	-
^{220}Po→^{220}At	0.88	9 ± 2	-
^{223}Po→^{223}At	3.65	7.8 ± 0.7	-

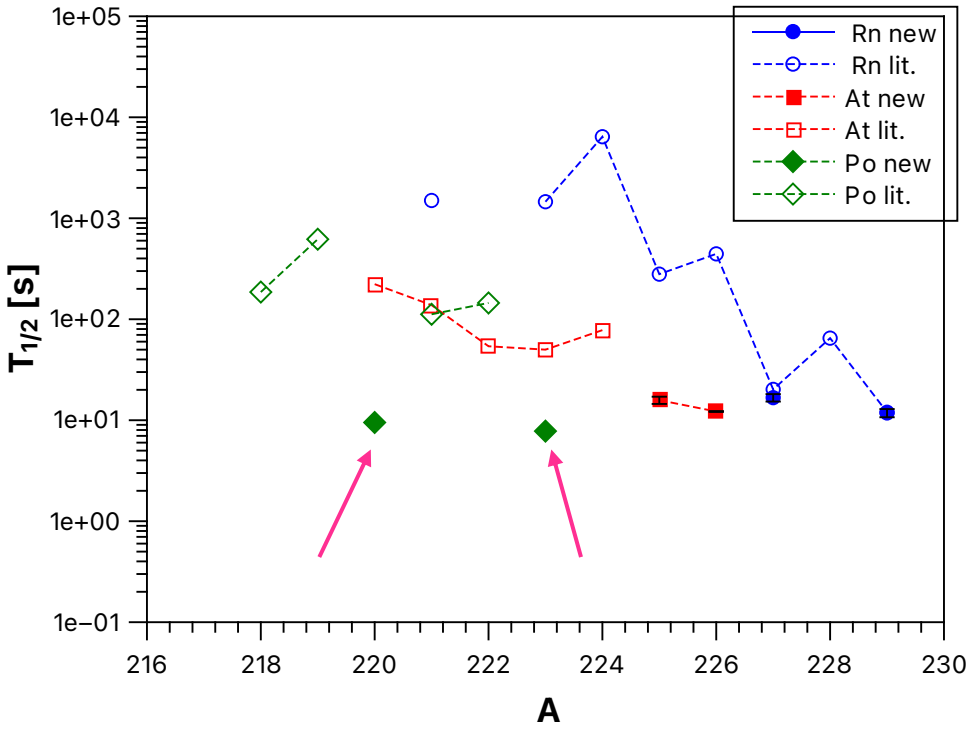
[1]W. Kurcewicz et al., *Nucl. Phys. A* 621.4 (1997) 827–852
[2]D. Neidherr et al., *Phys. Rev. Lett.* 102 (2009) 112501

Results and comparison with literature data



- Remeasured values agree with existing data
- Rn and At new data points follow general trend
- Pronounced odd-even staggering in Rn chain

Results and comparison with literature data



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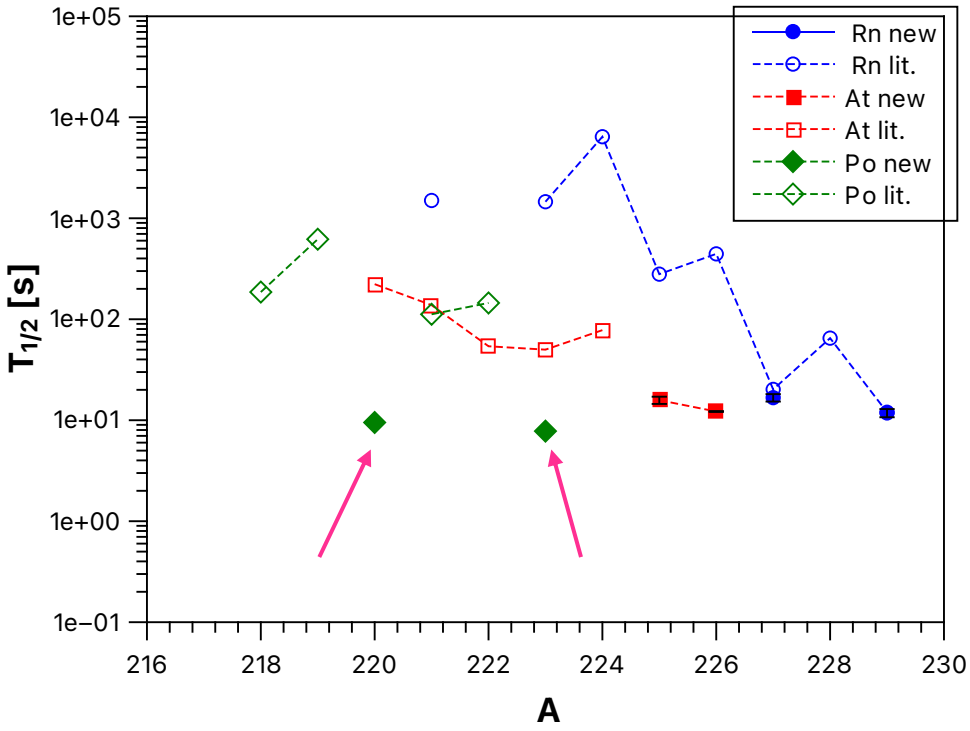
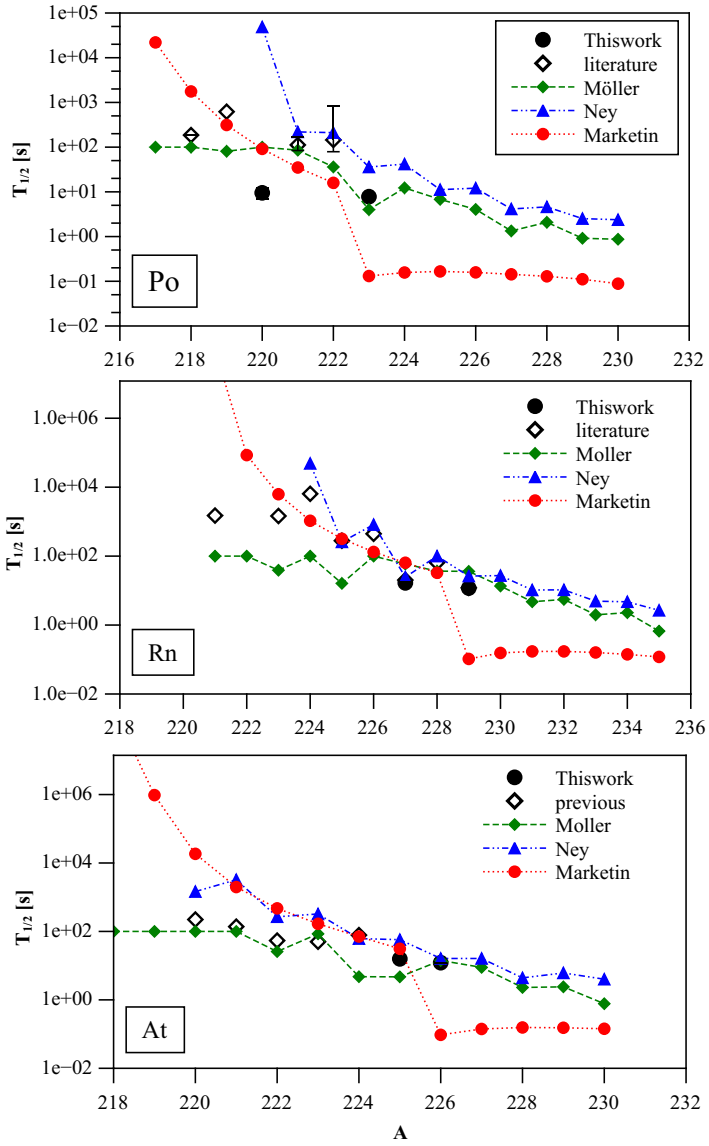




- Remeasured values agree with existing data
- Rn and At new data points follow general trend
- Pronounced odd-even staggering in Rn chain

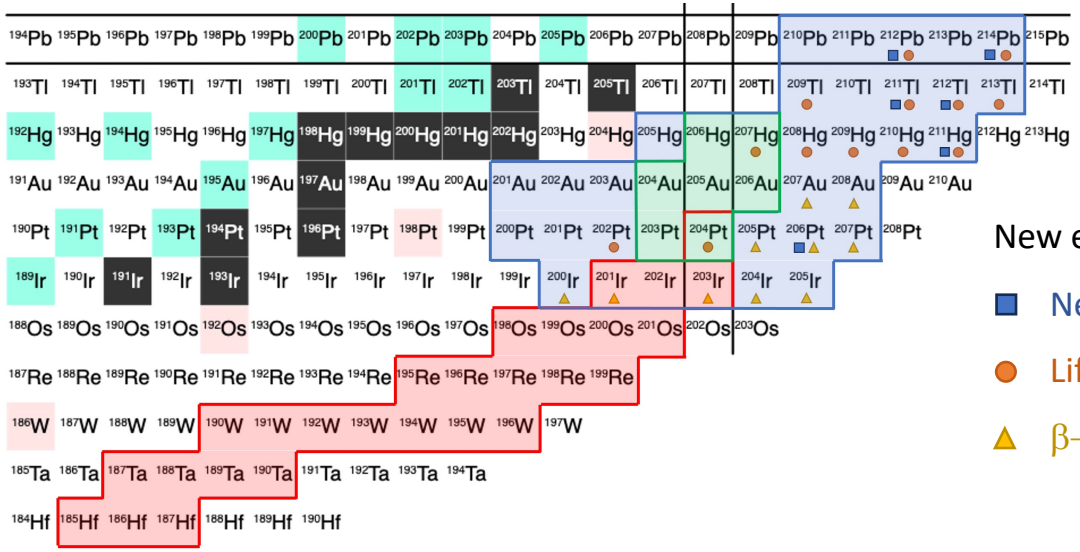
New experiment at GSI in June 2024

Spokepersons: M. Polettini, A. I. Morales

Main goals:

⇒ Obtain nuclear properties used as inputs into r-process network calculations

⇒ Provide new data to test nuclear models towards the N=126 waiting point



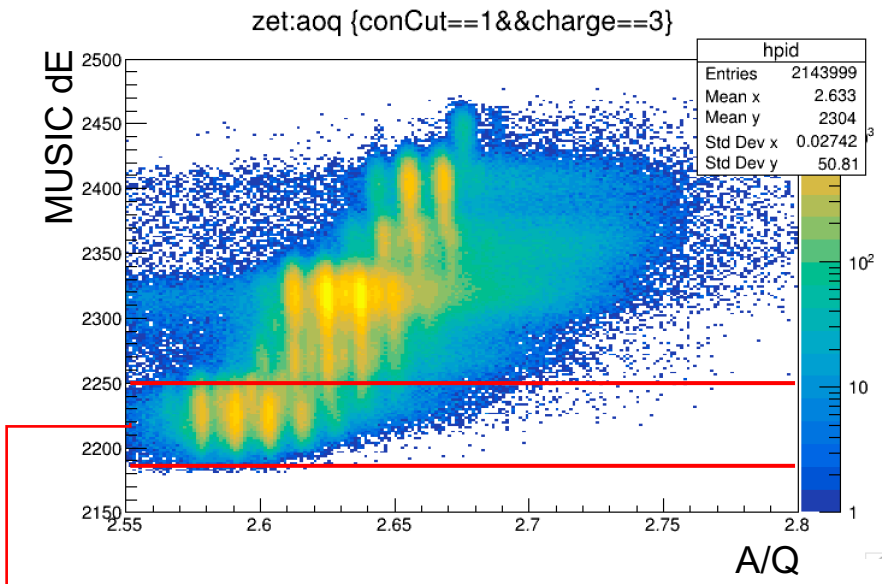
New experimental measurements on:

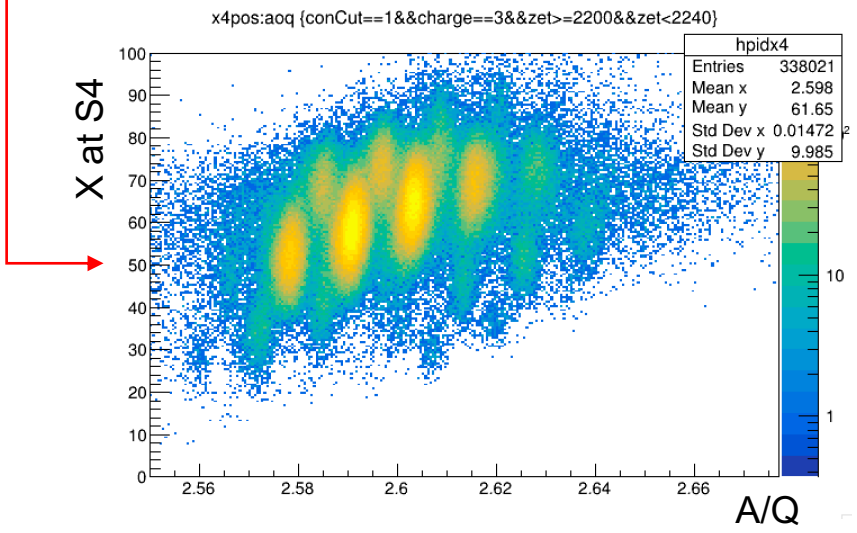
- New isomeric states
- Lifetime of low-lying states
- β–decay half-lives and spectroscopy

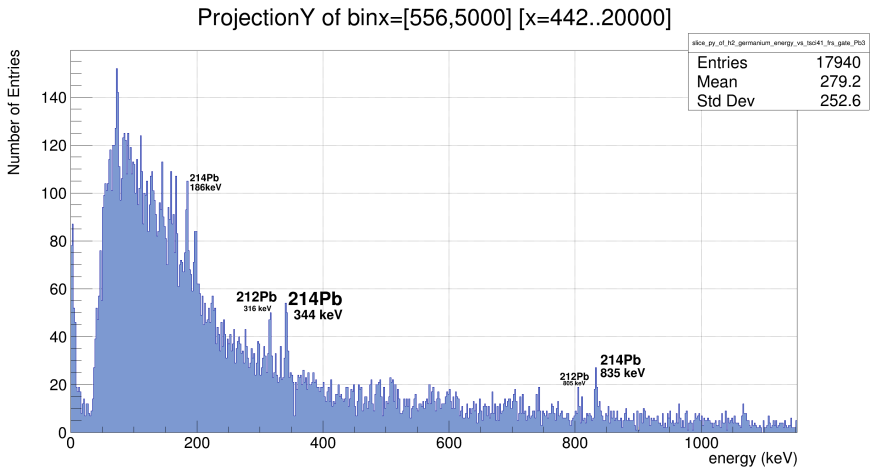
Focus on the Pt isotopic chain:

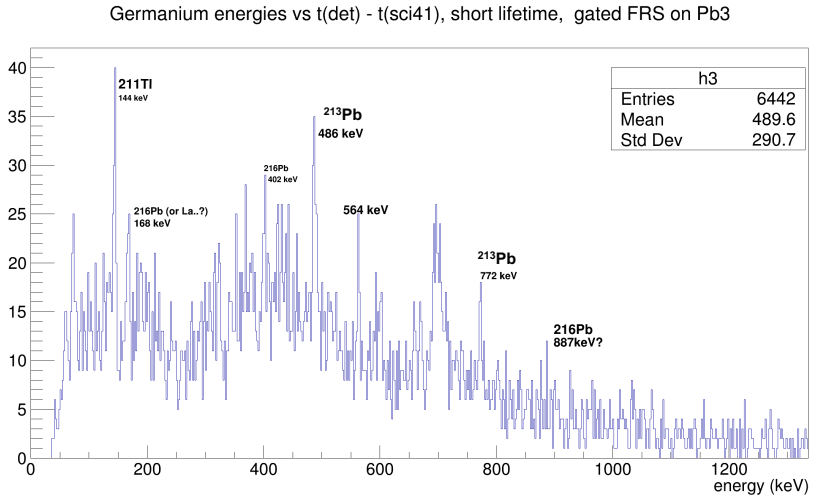
- Trace the evolution of **decay schemes** between N=122 and N=129
- Search for a **seniority isomer** in ^{206}Pt
- New **β-decay half-lives** measurements in ^{205,206,207}Pt and ^{207,208}Au

New experiment: online results









Conclusions

β decay studies in the A∼225 Po-Fr n-rich region and ^{100}Sn p-rich region. The experiments were performed at GSI in April 2021 using the FRS+DESPEC setup.

Obtained results:

- Study of low-lying states in ^{100,101,102}Cd via β−delayed spectroscopy and lifetime measurements in ^{98,100}Cd
- New β-decay half-lives measured in ^{220,223}Po, ^{225,226}At, good agreement with previous measurements for ^{227,229}Rn

Outlook:

- Two scientific papers and letters in preparation
- New experiment in N=126 region run in June 2024

The DESPEC collaboration for the S496 experiment

G. Zhang[a,b], M. Polettini[a,b], D. Mengoni[a,b], G. Benzoni[c], Z. Huang[a,b], M. Gorska[d], A. Blazhev[e], L. M. Fraile[f], A. Gargano[g], G. de Gregorio[g], F. Nowacki[h], H. M. Albers[d], A. Algora[i], S. Alhomaidhi[j], C. Appleton[k], T. Arıcı[d], M. Armstrong[e], A. Astier[l], A. Banerjee[d], D. Bazzacco[a,b], S. Bottoni[c], P. Boutachkov[d], A.Bracco[c], A. Bruce[m], D. Brugnara[a,b], F.Camera[c], B. Cederwall[n], M. Cicerchia[o], A. Corsi[p], M. L. Cortes[o], F.C.L. Crespi[c], T. Davidson[k], G. de Angelis[o], T. Dickel[d], A. Esmaylzadeh[e], F. Galtarossa[a,b], E. R. Gamba[c], J. Gerl[d], A. Goasduff[o], A. Gottardo[o], A. Gozzelino[o], T. Grahn[q], J. Ha[a,b], E. Haettner[d], O. Hall[k], L. Harkness-Brennan[r], H. Heggen[d], N. Hubbard[j], A. Illana[q], P.R. John[j], J. Jolie[e], I. Kojouharov[d], N. Kurz[d], M. Labiche[s], S. M. Lenzi[a,b], S. Leoni[c], R. Lozeva[l], G. Mantovani[o], T. Marchi[o], H. Mayr[j], M. Mazzocco[a,b], R. Menegazzo[a,b], B. Million[c], A. K. Mistry[j], E. Nacher[i], D. R. Napoli[o], R. Page[r], G. Pasqualato[a,b], J. Pellumaj[o], C. M. Petrache[l], R.M. Perez Vidal[o], N. Pietralla[j], Zs. Podolyák[t], A. Raggio[a,b], F. Recchia[a,b], P. H. Regan[t], J. M. Regis[e], P. Reiter[e], B. Rubio[i], M. Rudigier[j], P. Ruotsalainen[q], E. Sahin[j], H. Schaffner[d], Ch. Scheidenberger[d], L. Sexton[k], A. Sharma[d], M. Siciliano[u], J. Simpson[s], F. Soramel[a,b], T. Stetz[j], J. J. Valiente-Dobon[o], J.Vesic[v], V. Werner[j], O.Wieland[c], P. Woods[k], A. Yaneva[d], I. Zanon[o], K. K. Zheng[l], R. Zidarovaj

[a]Universita degli Studi di Padova, Padova, 35131, Italy
[b]INFN Sezione di Padova, Padova, 35131, Italy
[c]INFN Sezione di Milano, Milano, 20133, Italy
[d]GSI Helmholtzzentrum fur Schwerionenforschung, Darmstadt, 64291, Germany
[e]Institut fur Kernphysik, Universitat zu Koln, Cologne, 50937, Germany
[f]Grupo de Fisica Nuclear and IPARCOS, Universidad Complutense de Madrid, Madrid, E-28040, Spain
[g]Instituto Nazionale di Fisica Nucleare, Napoli, I-80126, Italy
[h]Universite de Strasbourg, IPHC, Strasbourg, 67037, France
[i]Instituto de Fisica Corpuscular, CSIC-Universidad de Valencia, Valencia, E-46071, Spain
[j]Institut fur Kernphysik, Technische Universitat Darmstadt, Darmstadt, 64289, Germany
[k]School of Physics and Astronomy, University of Edinburgh, Edinburgh, H9 3FD, UK
[l]University Paris-Saclay, IJCLab, CNRS/IN2P3, Orsay, F-91405, France
[m]School of Computing Engineering and Mathematics, University of Brighton, Brighton, BN2 4AT, UK
[n]Department of Physics, KTH Royal Institute of Technology, Stockholm, SE-10691, Sweden
[o]INFN Laboratori Nazionali di Legnaro, Legnaro, 35020, Italy
[p]CEA-Saclay, IRFU/Service de Physique Nucleaire, Gif-sur-Yvette, 91191, France
[q]University of Jyvaskyla, Jyvaskyla, 40014, Finland
[r]Department of Physics, Oliver Ladge Laboratory, University of Liverpool, Liverpool, L69 7ZE, UK
[s]STFC Daresbury Laboratory, Daresbury, WA4 4AD, UK
[t]Department of Physics, University of Surrey, Surrey, GU2 7XH, UK
[u]Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[v]Jozef Stefan Institute, Ljubljana, 1000, Slovenia

The DESPEC collaboration for the S460 experiment

M. Polettini[(1)(*)], G. Benzoni[(1)], J. Pellumaj[(2)(3)], J. J. Valiente-Dobón[(3)], G. Zhang[(4)], D. Mengoni[(4)], R. M. Perez Vidal[(3)], Z. Huang[(4)], D. Genna[(1)], A. Bracco[(1)], G. Aggez[(5)], U. Ahmed[(6)], Ö. Aktas[(7)], M. Al Aqueel[(8)], B. Alayed[(9)(10)], H. M. Albers[(11)], A. Algora[(12)], S. Alhomaidhi[(11)(6)], C. Appleton[(13)], T. Arici[(5)], M. Armstrong[(14)], K. Arnswald[(14)], M. Balogh[(3)], A. Banerjee[(11)], J. Benito García[(15)], A. Blazhev[(14)], S. Bottoni[(1)],P. Boutachkov[(11)], A. Bruce(16), C. Bruno[(13)], F. Camera[(1)],B. Cederwall[(7)], M. M. R. Chishti[(17)], M. L. Cortés[(6)], D. M. Cox[(18)], F. C. L. Crespi[(1)], B. Das[(7)], T. Davinson[(13)], G. De Angelis[(3)], T. Dickel[(11)], M. Doncel[(19)], R. Donthi[(20)], A. Ertoprak[(3)], R. Escudeiro[(4)], A. Esmaylzadeh[(14)], L. M. Fraile[(15)], L. Gaffney[(9)], E. R. Gamba[(1)], J. Gerl[(11)], M. Górska[(11)], A. Gottardo[(3)], J. Ha[(4)], E. Haettner[(11)], O. Hall[(13)], H. Heggen[(11)], Y. Hrabar[(18)], N. Hubbard[(11)(6)],S. Jazrawi[(17)(21)], P. R. John[(6)], J. Jolie[(14)], C. Jones(16), D. Joss[(9)],D. Judson[(9)], D. Kahl[(22)], V. Karayonchev[(14)], E. Kazantseva[(11)],R. Kern[(6)], L. Knafla[(14)], I. Kojouharov[(11)], A. Korgul[(23)], W. Korten[(24)], P. Koseoglou[(6)], G. Kosir[(25)], D. Kostyleva[(11)], T. Kurtukian-Nieto[(26)], N. Kurz[(11)], N. Kuzminchuk[(11)], M. Labiche[(27)], S. Lenzi[(4)], S. Leoni[(1)], M. Llanos Expósito[(15)], R. Lozeva[(28)], T. J. Mertzimekis[(29)], M. Mikolajczuk[(23)], B. Million[(1)], A. K. Mistry[(11)(6)], A. Morales[(12)], I. Mukha[(11)], J. R. Murias[(15)], D. Napoli[(4)], B. S. Nara Singh[(30)], D. O'Donnell[(30)], S. E. A. Orrigo[(12)], R. Page[(9)], S. Pelonis[(29)],J. Petrovic[(7)], N. Pietralla[(6)], S. Pietri[(11)], S. Pigliapoco[(4)], Zs. Podolyak[(17)], C. Porzio[(1)], B. Quintana Arnes[(31)], F. Recchia[(4)],P. H. Regan[(17)(21)], J.-M. Régis[(14)], P. Reiter[(14)], K. Rezynkina[(4)], P. Roy[(32)(11)], M. Rudigier[(6)], P. Ruotsalainen[(33)], E. Sahin[(11)(6)],L. G. Sarmiento[(18)], M.-M. Satrazani[(9)], H. Schaffner[(11)], C. Scheidenberger[(11)], L. Sexton[(13)], A. Sharma[(34)], J. Smallcombe[(9)], P.-A. Söderström[(22)], A. Sood[(7)], P. Vasileiou[(29)], J. Vesic[(25)],J. Vilhena[(35)], L. Waring[(9)], H. Weick[(11)], V. Werner[(6)],J. Wiederhold[(6)], O. Wieland[(1)], K. Wimmer[(11)], H. J. Wollersheim[(11)], P. Woods[(13)], A. Yaneva[(14)], I. Zanon[(2)(3)], J. Zhao[(11)],R. Zidarova[(6)], S. Ziliani[(1)], G. Zimba[(33)] and A. Zyriliou[(29)]

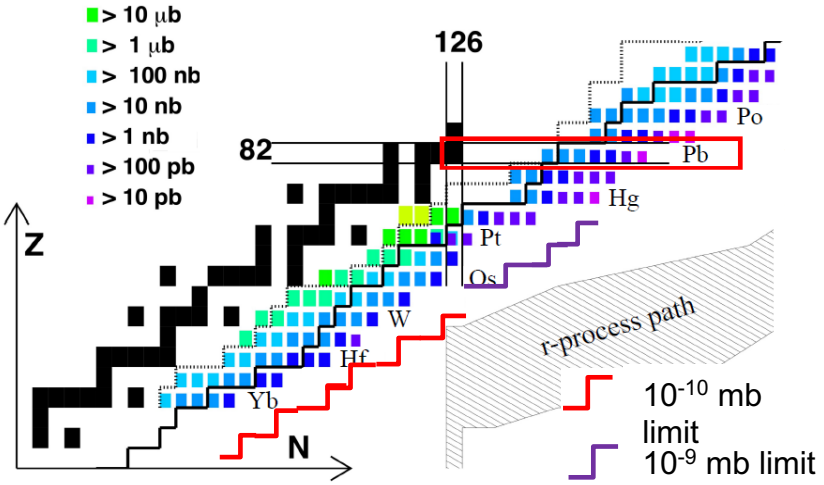
[(1)] Dipartimento di Fisica, Università degli Studi di Milano and INFN Milano - Milan, Italy, [(2)] Dipartimento di Fisica e Scienze della Terra, Università di Ferrara - Ferrara, Italy , [(3)] INFN, Laboratori Nazionali di Legnaro - Legnaro, Italy, [(4)] Dipartimento di Fisica e Astronomia, Università di Padova and INFN Padova - Padua, Italy , [(5)] Istanbul University, Graduate School of Sciences, Department of Physics - Istanbul, Turkey, [(6)] Institut für Kernphysik, Technische Universität Darmstadt - Darmstadt, Germany, [(7)] KTH Royal Institute of Technology - Stockholm, Sweden, [(8)] Imam Mohammad Ibn Saud Islamic University - Riyadh, Saudi Arabia, [(9)] Department of Physics, Oliver Lodge Laboratory, University of Liverpool - Liverpool, UK, [(10)] Ar Rass College of Sciences and Arts, Qassim University - Quassim, Saudi Arabia, [(11)] GSI Helmholtzzentrum für Schwerionenforschung GmbH - Darmstadt, Germany, [(12)] Instituto de Fisica Corpuscular, CSIC-Universidad de Valencia - Valencia, Spain, [(13)] University of Edinburgh, School of Physics and Astronomy - Edinburgh, UK, [(14)] Institut für Kernphysik der Universit¨at zu Köln - Köln, Germany, [(15)] Grupo de Física Nuclear and IPARCOS, Universidad Complutense de Madrid - Madrid, Spain, [(16)] School of Computing Engineering and Mathematics, University of Brighton Brighton, UK, [(17)] Department of Physics, University of Surrey - Guildford, UK, [(18)] Department of Physics, Lund University - Lund, Sweden, [(19)] Department of Physics, University of Stockholm - Stockholm, Sweden, [(20)] Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Mumbai, India, [(21)] National Physical Laboratory - Teddington, UK, [(22)] ELI-NP Center for Extreme Light Infrastructure, Nuclear Physics - Magurele, Romania, [(23)] Department of Physics, University of Warsaw - Warsaw, Poland, [(24)] Irfu, CEA, Université Paris-Saclay - Paris-Saclay, France, [(25)] Jozef Stefan Institute - Ljubljana, Slovenia, [(26)] CENBG, Universit´e de Bordeaux, CNRS/IN2P3 - Bordeaux, France, [(27)] STFC, Daresbury Laboratory - Daresbury, UK, [(28)] Université Paris-Saclay, IJCLab, CNRS/IN2P3 - Paris-Saclay, France, [(29)] National and Kapodistrian University of Athens - Athens, Greece, [(30)] School of Computing, Engineering and Physical Sciences, University of West Scotland, Glasgow, UK, [(31)] Laboratorio de Radiaciones Ionizantes, Universidad de Salamanca - Salamanca, Spain, [(32)] Variable Energy Cyclotron Centre - 1/AF Bidhan Nagar, Kolkata, India, [(33)] University of Jyväskylä - Jyväskylä, Finland, [(34)] Department of Physics, Indian Institute of Technology Ropar - Ropar, India, [(35)] LPMCN, Université de Lyon - Lyon, France

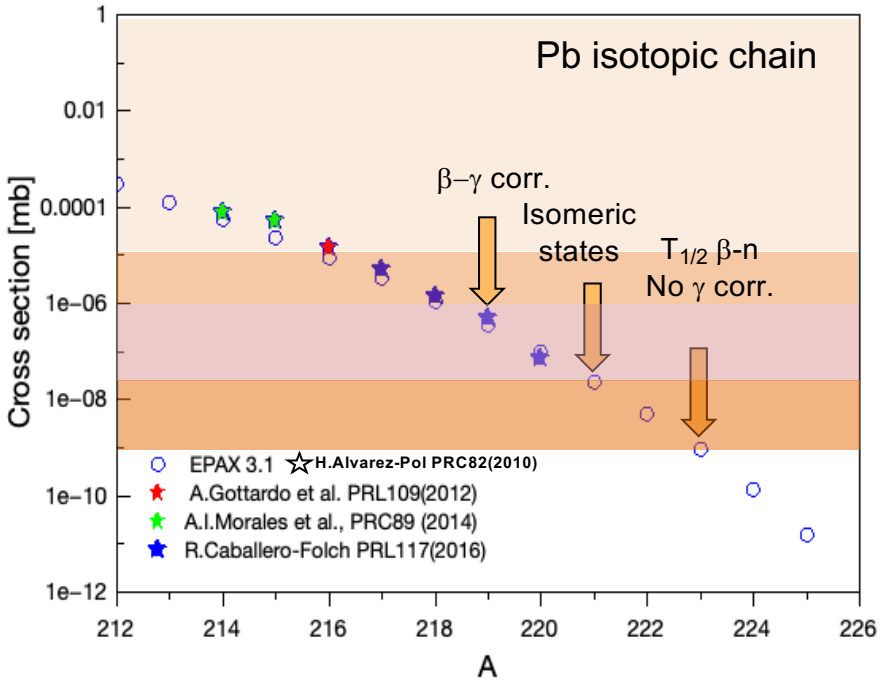
Thank you for your attention!

A quest towards the *r*-process waiting point

Answering to fundamental questions:

- **Exact location** of r-process path for heavy elements
- Role of **first-forbidden β–decay**
- Role of **delayed-neutron emission**
- **Fission recycling**





2009 RISING campaign ε_γ = 16.2%

2022 DESPEC @ Phase-0 ε_γ = 21.2%

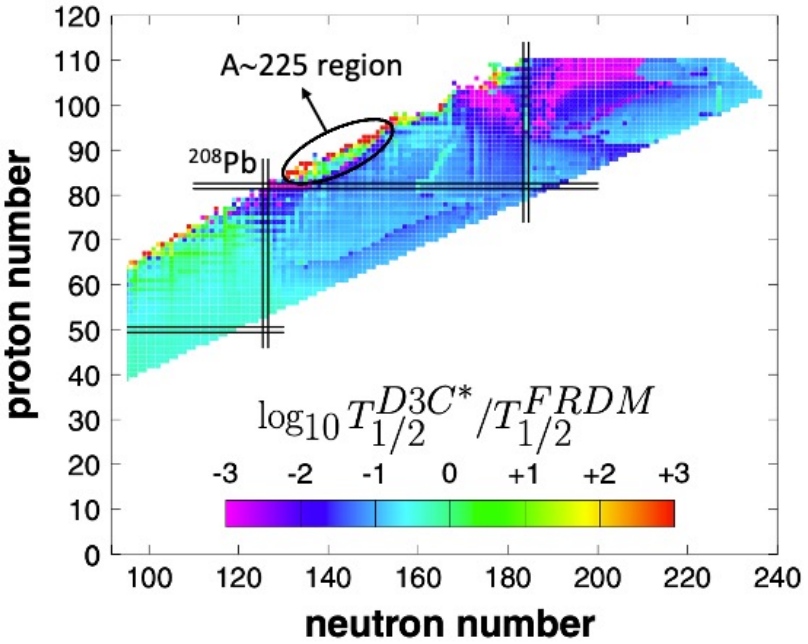
Early Science

First Science

- Increasing primary beam intensity
- Improved γ efficiency
- Faster DAQ
- Improved FRS transmission

Nuclear physics inputs

- Key quantities in nucleosynthesis calculations:
  - nuclear masses → S_n , Q_β
  - decay rates → beta and alpha lifetimes τ_α, τ_β
  - β-delayed neutron emission → P_n
  - neutron capture rates → $\sigma(n,\gamma), \sigma(\gamma,n)$
  - fission probabilities

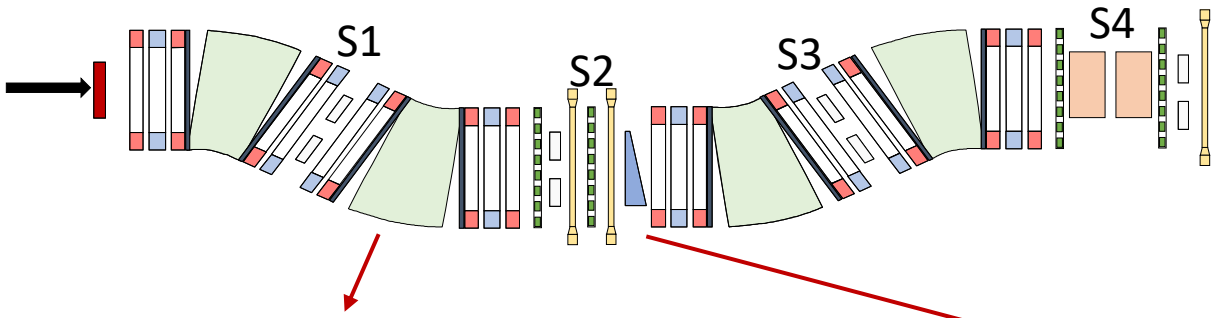


T. Marketin et al., Phys. Rev. C 93 (2016) 025805

Theoretical models show deviations in heavy n-rich nuclei

→ **Need for β–decay half-lives measurements in the $N > 126$ region**

The FRS magnetic spectrometer



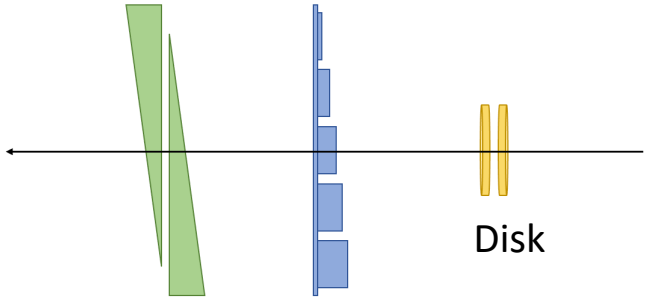
Selection and transport:
$\boldsymbol{B\rho - \Delta E - B\rho}$

Identification:
$\boldsymbol{ToF - B\rho - \Delta E}$

Dipole magnets

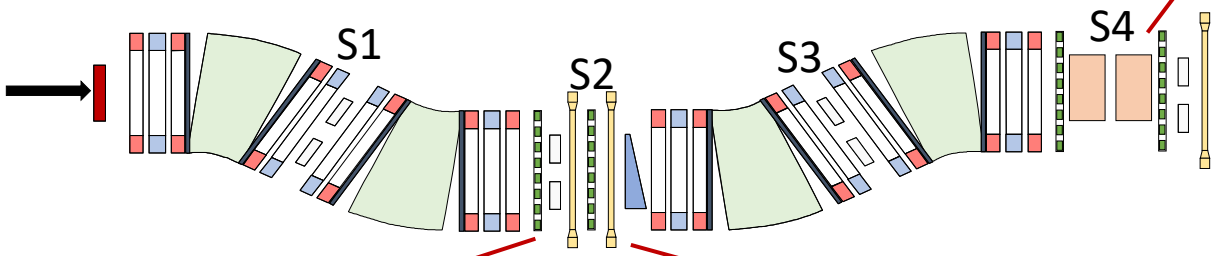
$$B\rho \propto \frac{A}{Q}\,\beta\gamma$$

Degrader

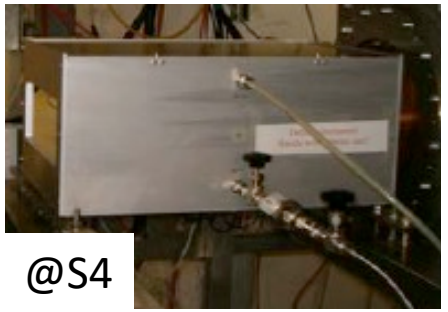


$\Delta E \rightarrow$ transmission mode

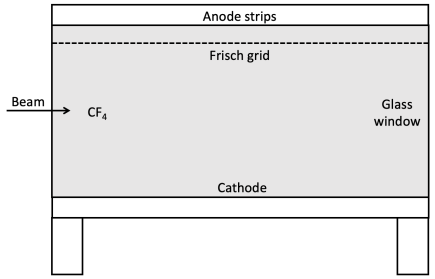
Ion identification



Multi Sampling Ionisation Chambers (MUSIC)

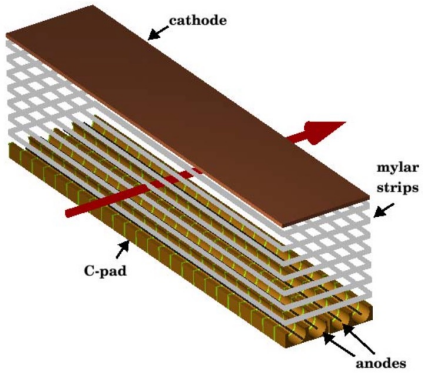


@S4



Time Projection Chamber (TPC)

@S2,S4



Plastic scintillators

@S2,S4

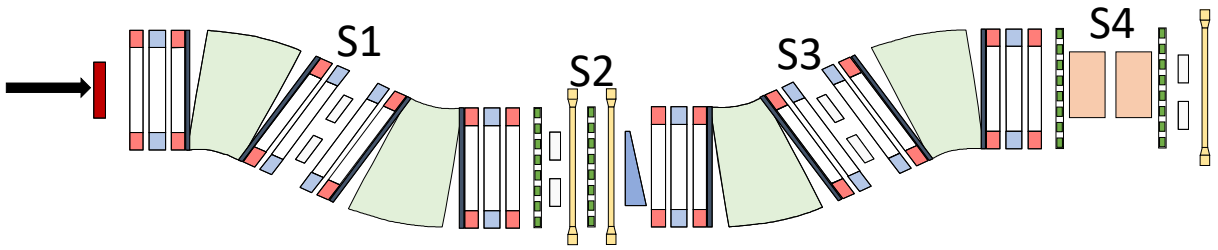
A/Q

$$\frac{A}{Q} = \frac{B\rho}{\beta\gamma}$$

Z

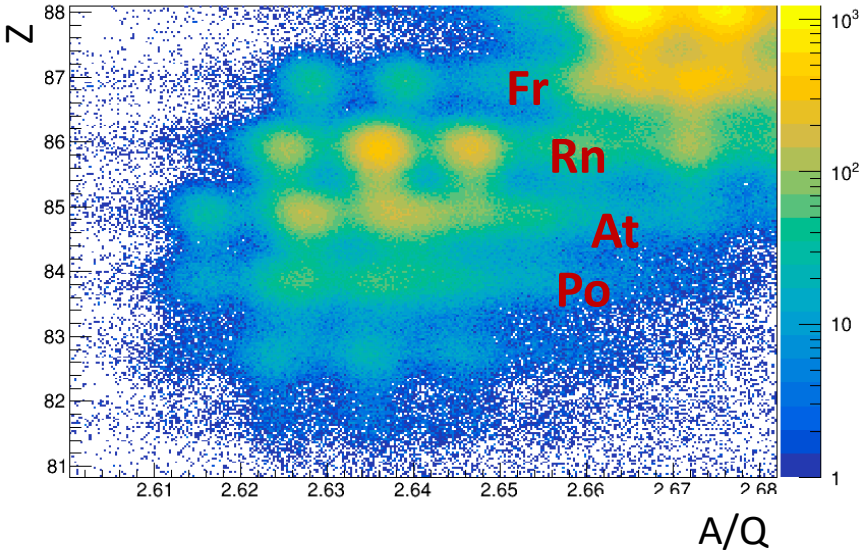
$$\Delta E \propto Z^2 f(\beta)$$

Ion identification

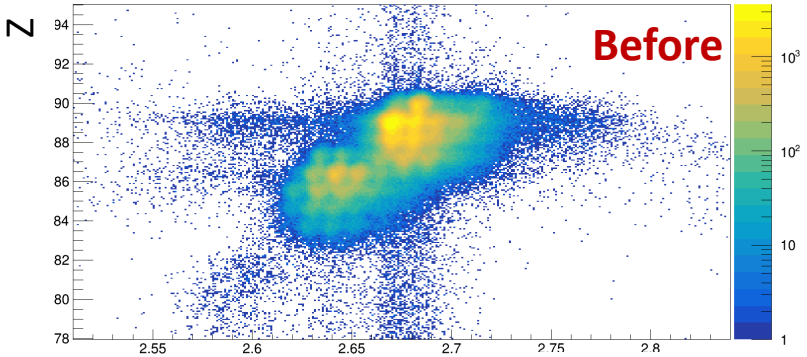


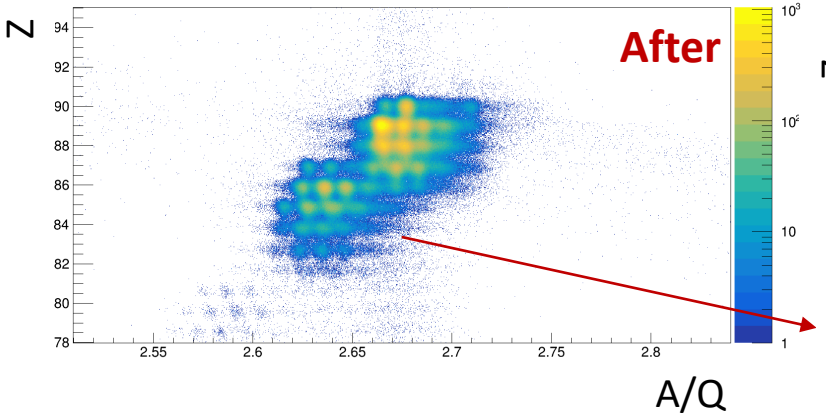
ID plot produced via the measurement of:

- The ratio of **mass number over ionic charge** A/Q
- The **atomic number Z** or the **X position** in the focal planes



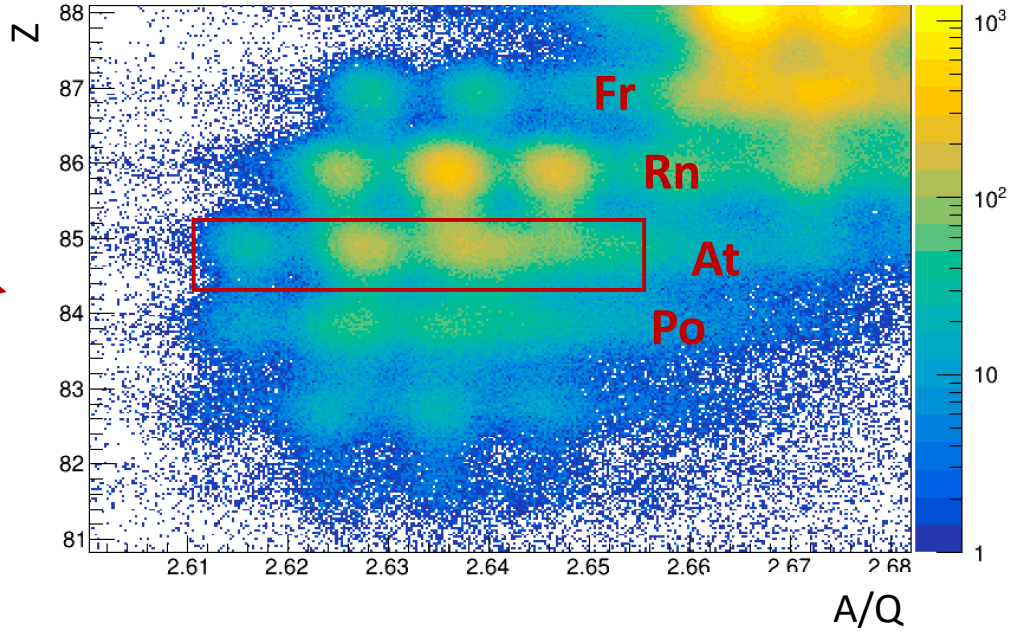
Identification plot





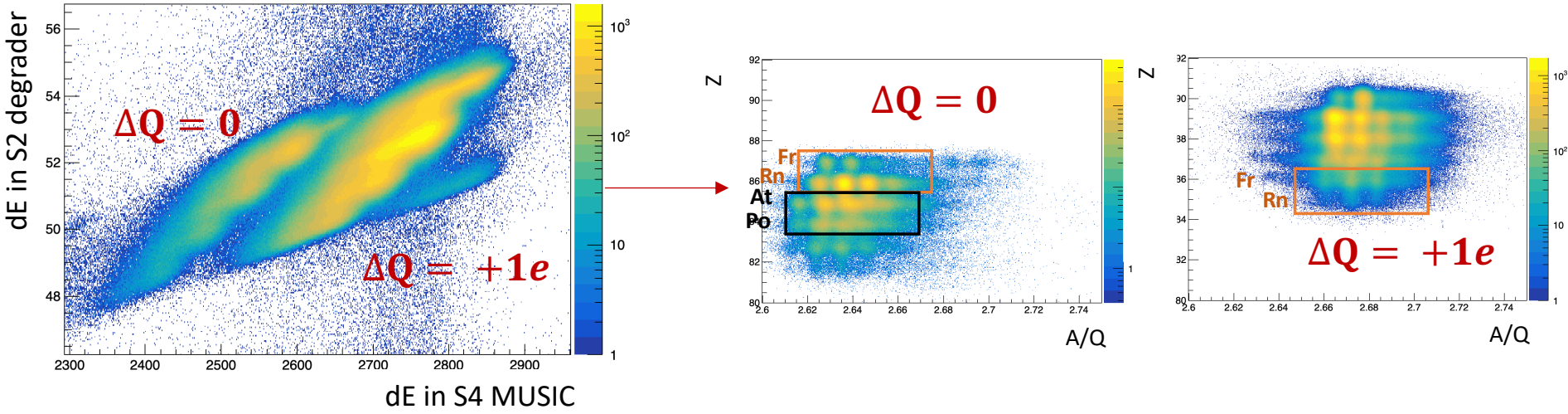
A/Q resolution improvement: ~30%

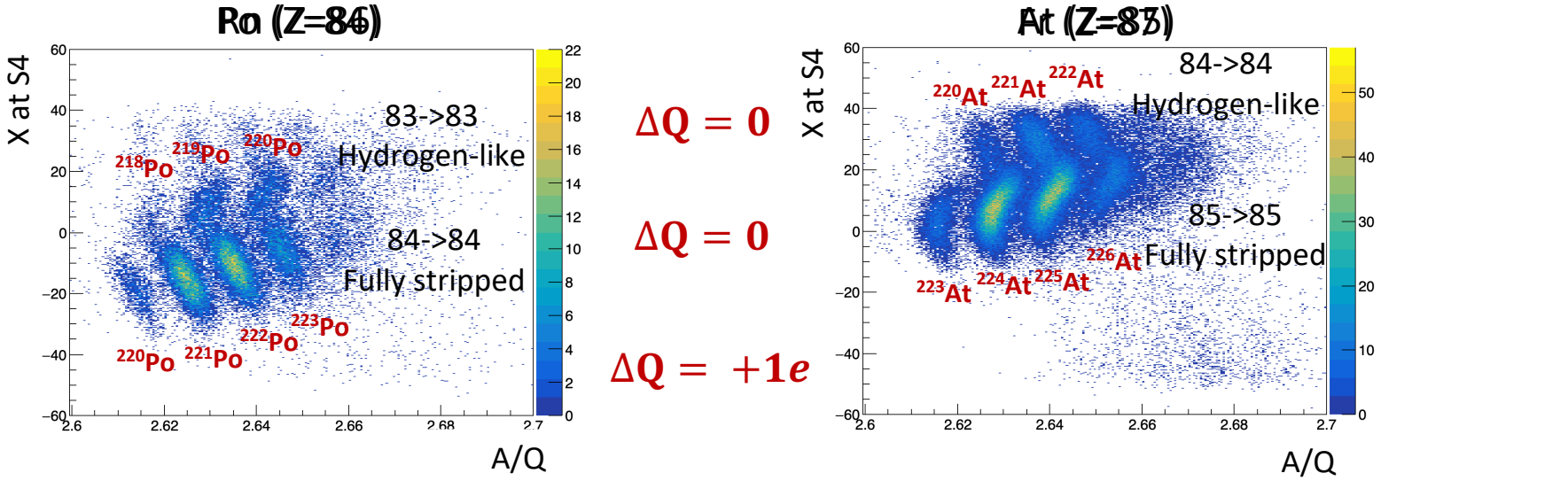
- ✓ ToF and MUSIC calibration
- ✓ Position calibration
- ✓ Gain drift correction
- ✓ Angle correction at S2 and S4



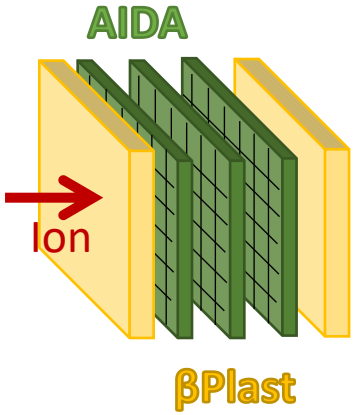
Davide Genna, BSc thesis

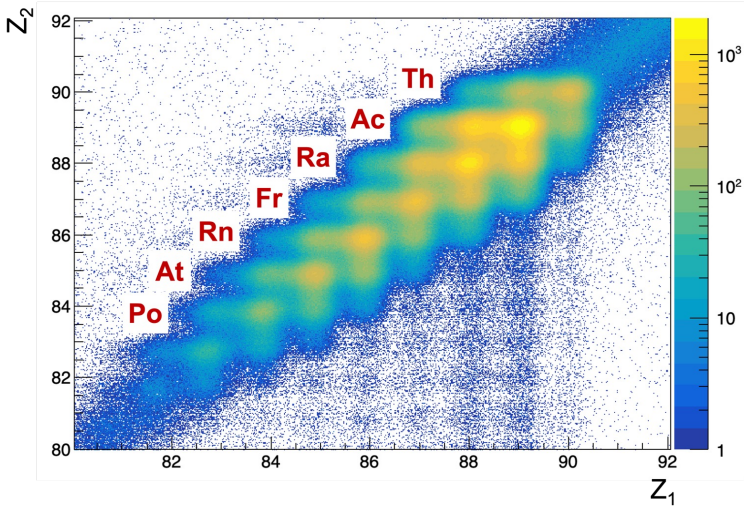
FRS analysis: study of charge states

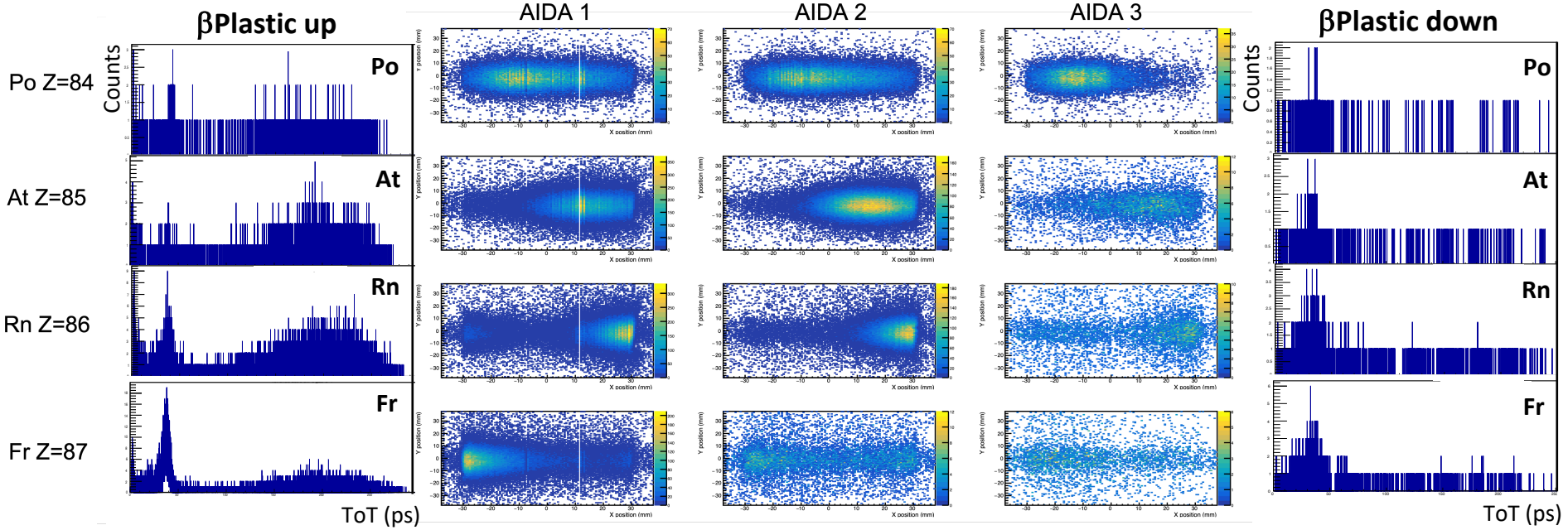




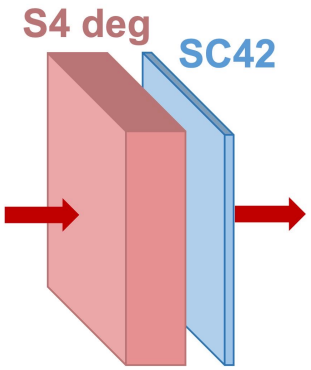
Implantation profile

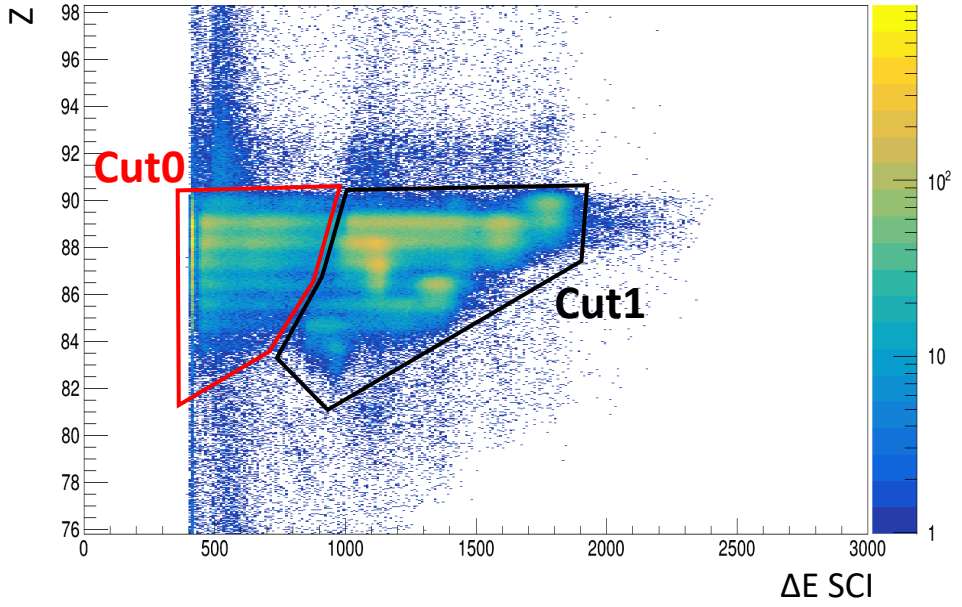




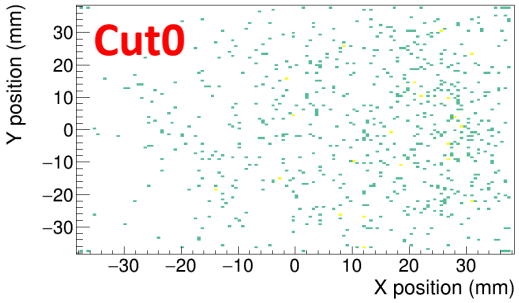


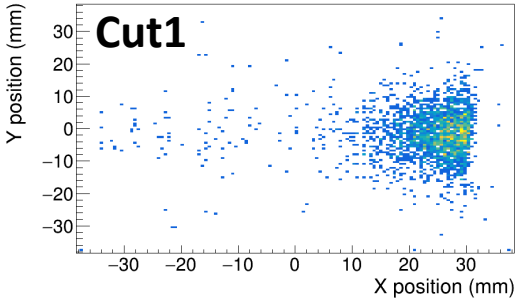
Secondary reactions in S4 degrader





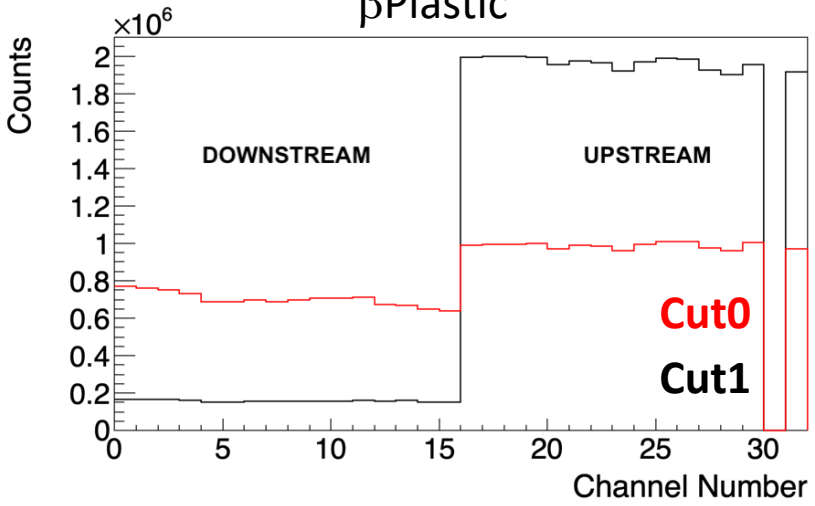
AIDA





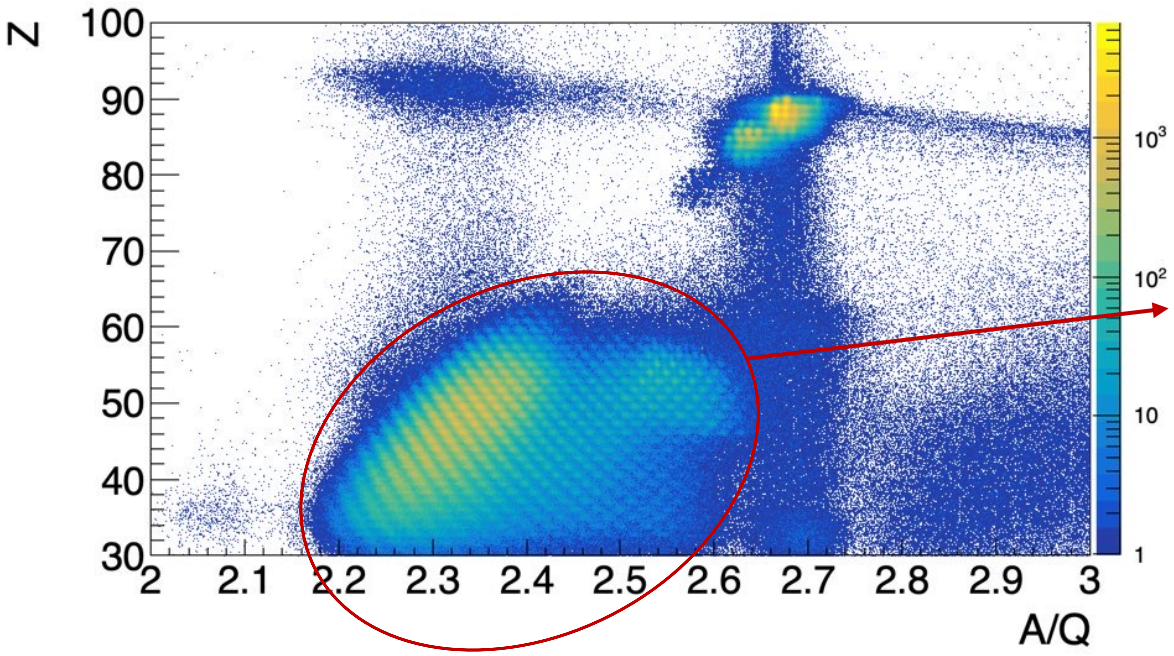
Rn
Z=86

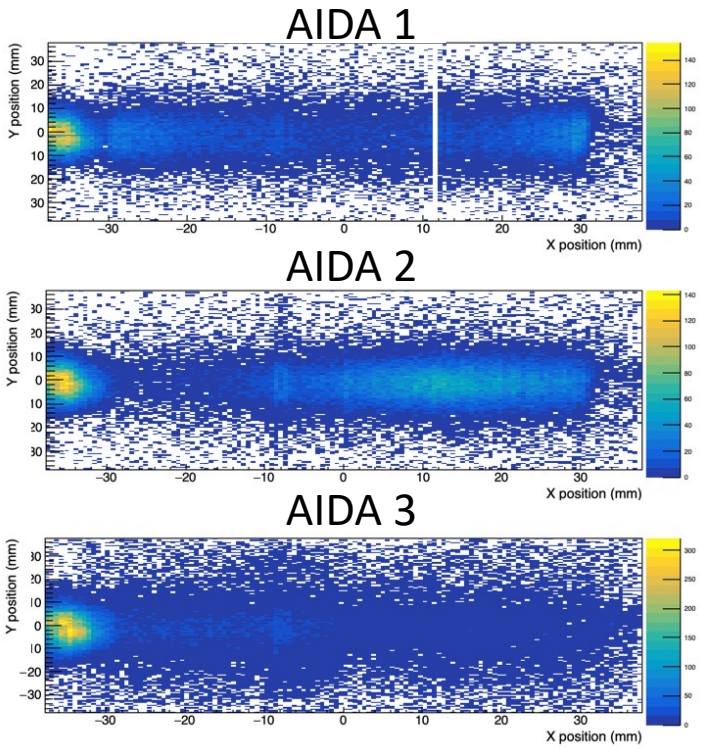
βPlastic



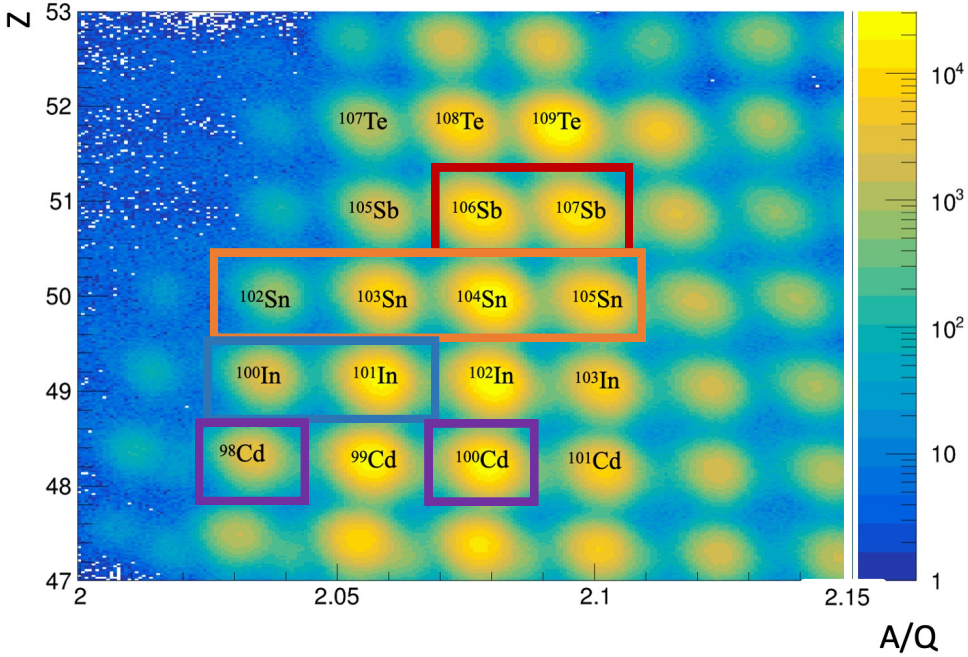
Fission fragments contribution

- Implantation rate: $\sim 10^3$ pps per detector
- Fission fragments contribution: $\sim 90\%$





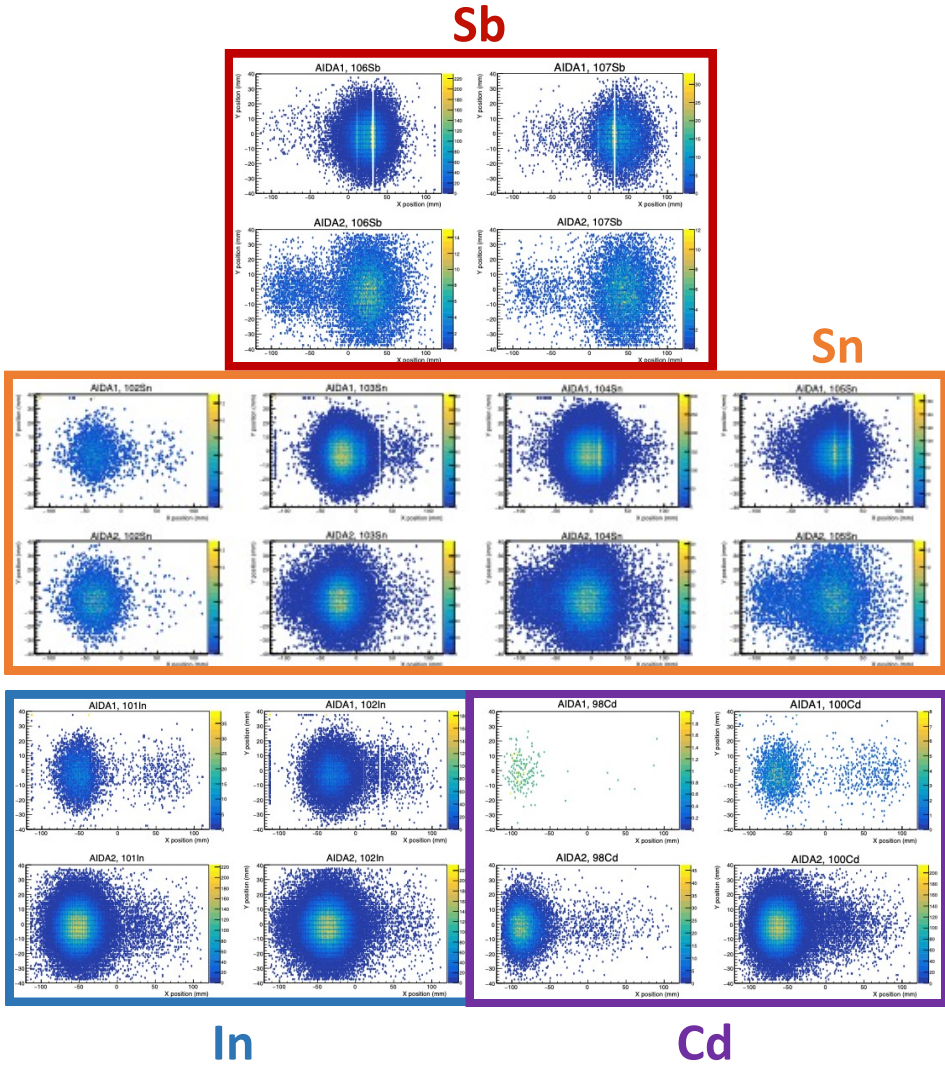
ID plot for Dataset2



Not-fully achromatic mode

↓

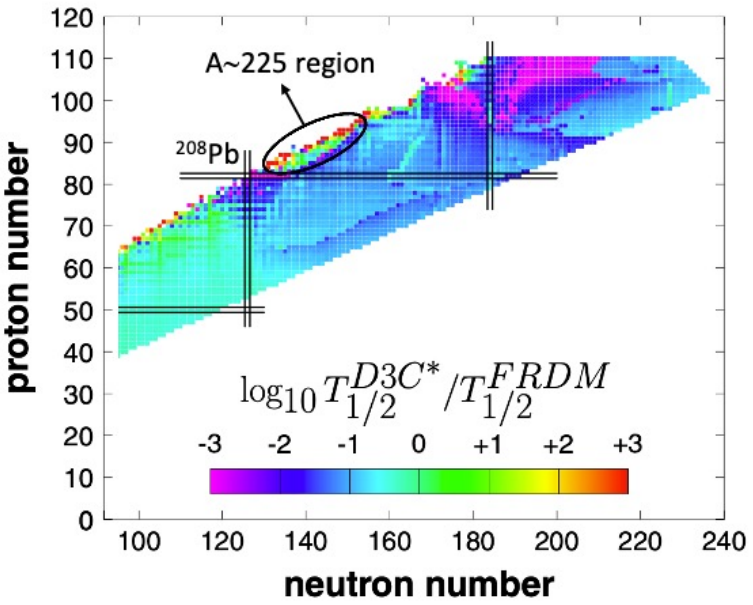
High overlap in implantation



Available theoretical models

Global models providing full β-decay tables for n-rich isotopes:

- P. Möller et al. (2019)
  - ground state masses based on FRDM,
  - β-decay half-lives determined from QRPA
- T. Marketin et al. (2016)
  - self consistent, microscopic description based on RHB
  - *even* ground states computed for odd-A and odd-odd nuclei
- E. M. Ney et al. (2020)
  - microscopic description based on a global Skyrme density functional
  - Equal filling approximation applied to describe odd-A and odd-odd nuclei



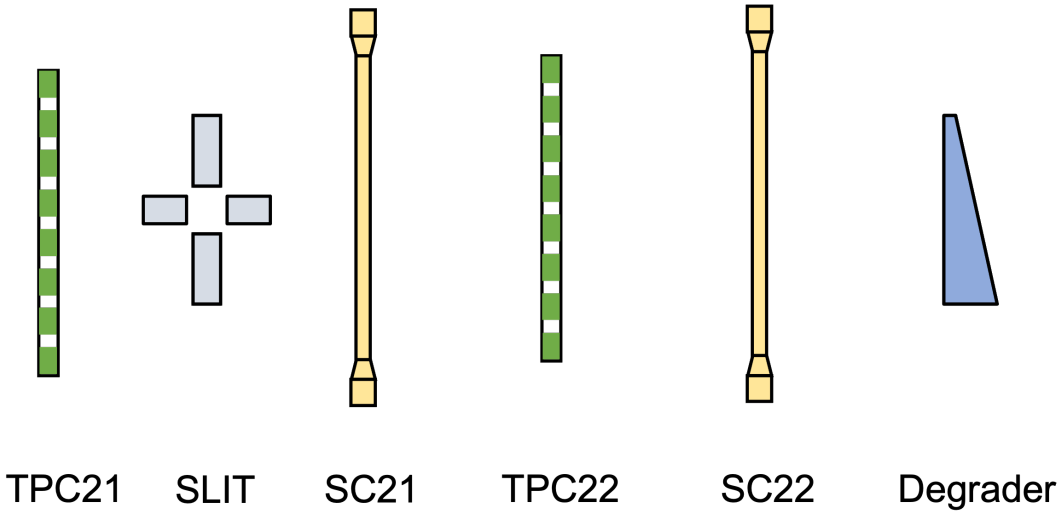
T. Marketin et al., Phys. Rev. C 93 (2016) 025805

Small error in *Q-value*

→ large effect on the $T_{1/2}$

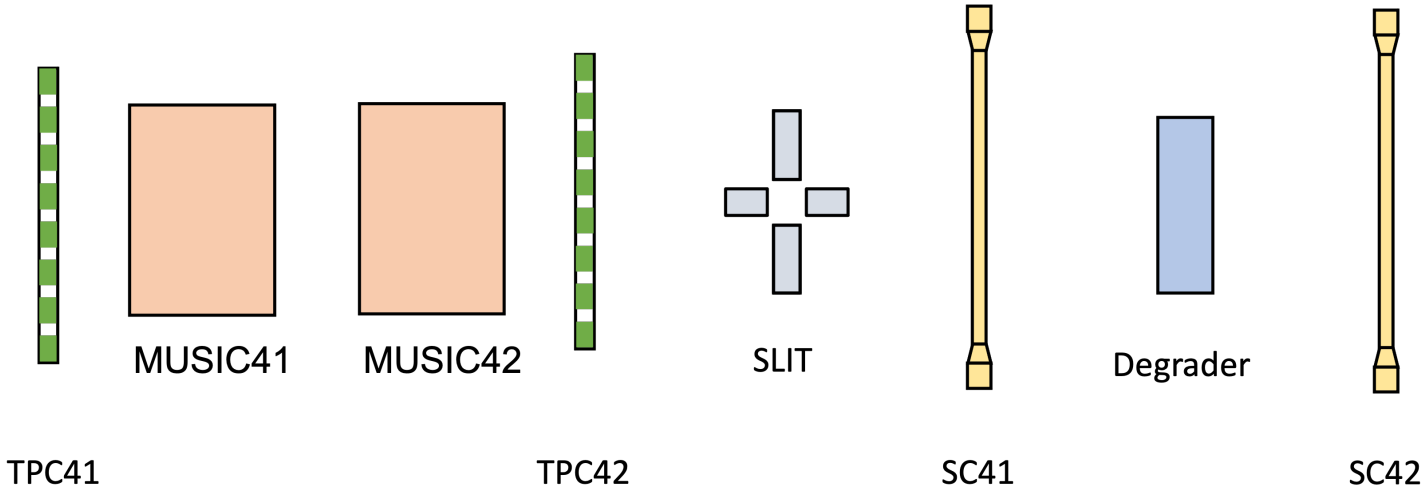
$$T_{1/2} \propto \frac{1}{S_\beta (Q_\beta - E^*)^5}$$

The S2 detectors



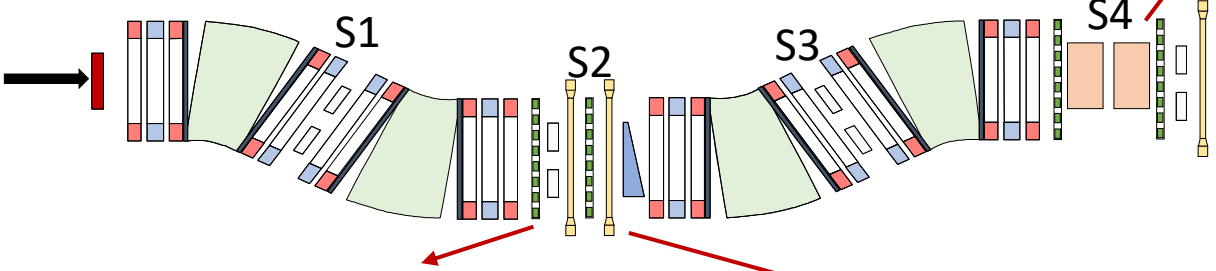
- 2 TPC detectors for position measurements
- 2 scintillators for TOF determination
- XY slits
- Degrader wedge

The S4 detectors

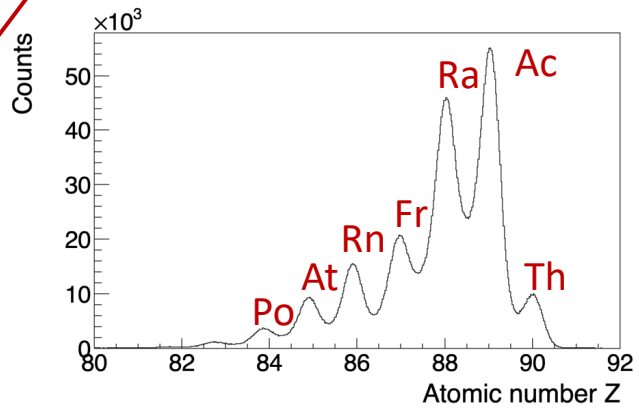


- 2 TPC detectors for position measurements
- 2 MUSIC detector for Z measurements
- XY slits
- 2 scintillators for TOF determination
- Degrader

Detectors along FRS

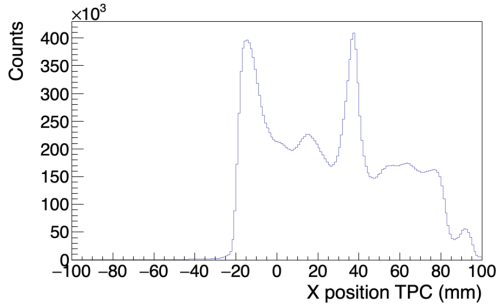


Multi Sampling Ionisation Chambers (MUSIC)

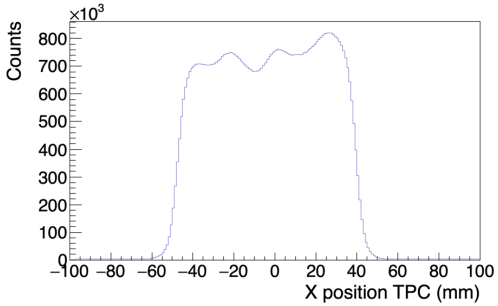


Time Projection Chamber (TPC)

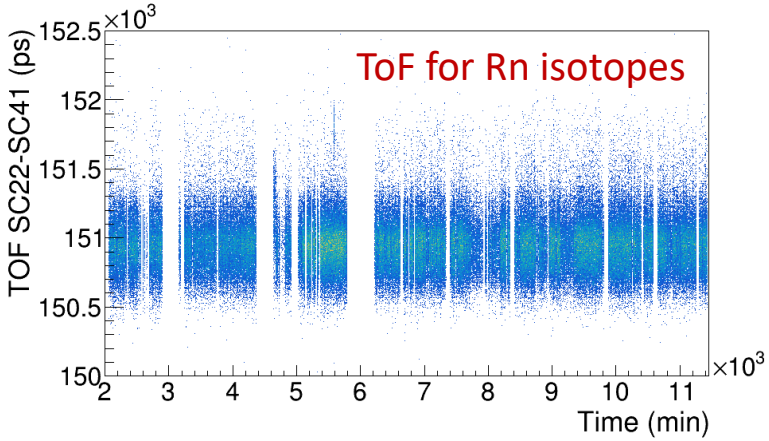
S2



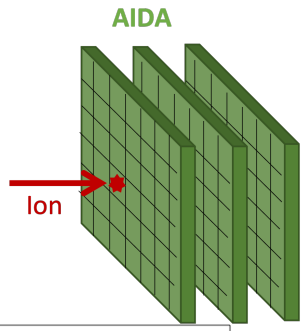
S4

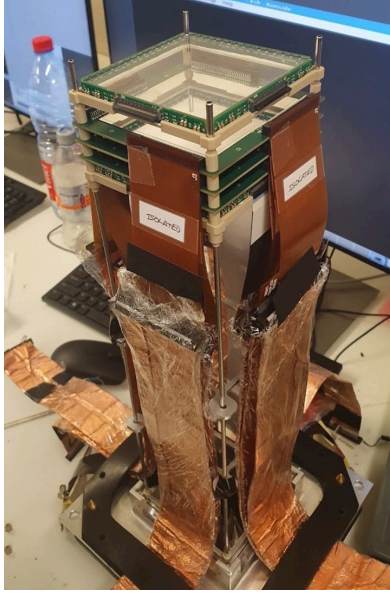


Plastic scintillators

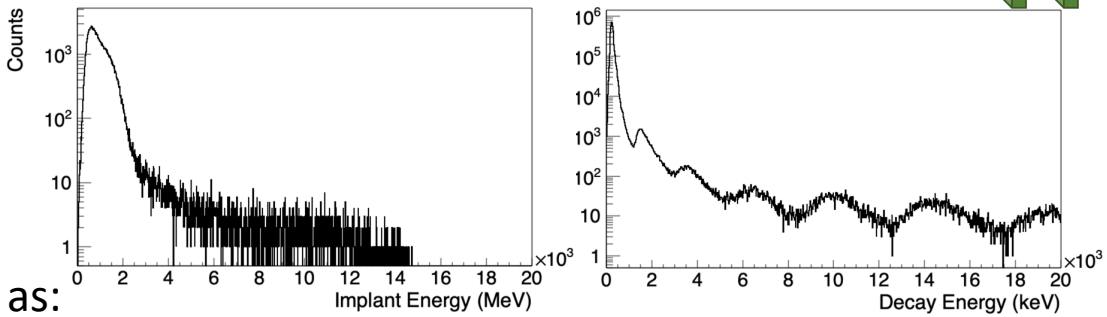


The AIDA detector



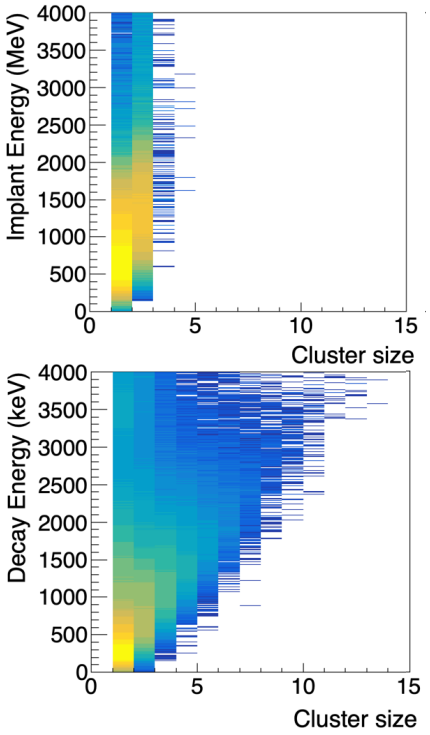


DSSD tiles: 8 cm x 8 cm, 1 mm thick, 0.056 mm pitch

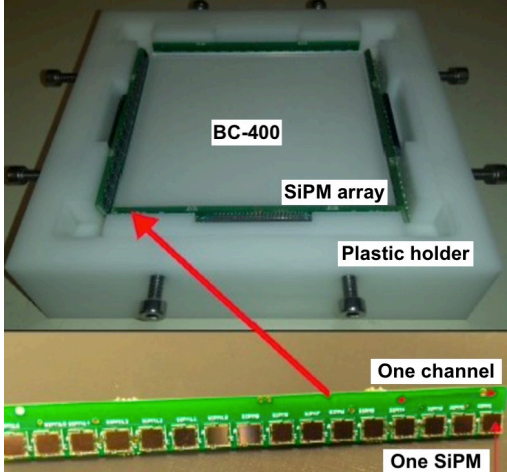


Data organised as:

- Event number
- DSSD layer number,
- Strip X,Y
- Position X,Y in mm
- Energy (MeV for implants, keV for decays)
- Energy X,Y
- Cluster size X,Y
- Time (10 ns precision for implants, 2 µs for decays)
- Time X,Y
- Fast time (10 ns precision for implants and decays)
- Stopped (if the implant is stopped in the DSSD)

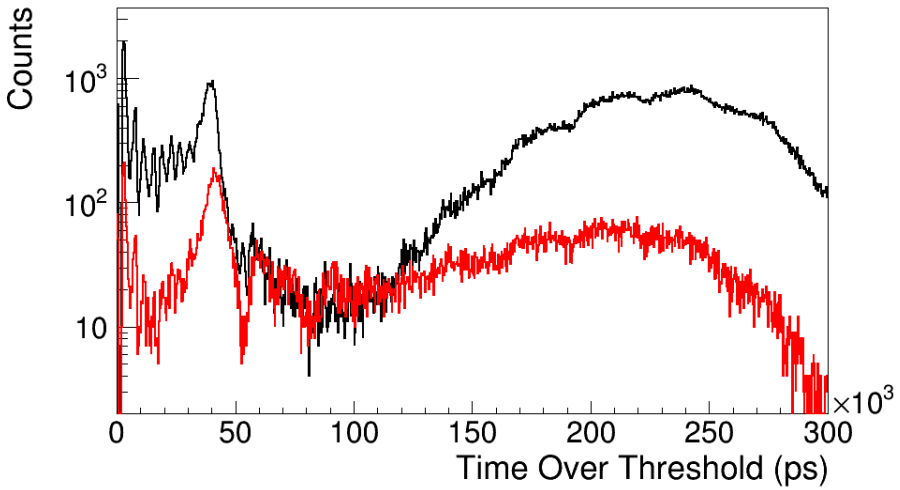


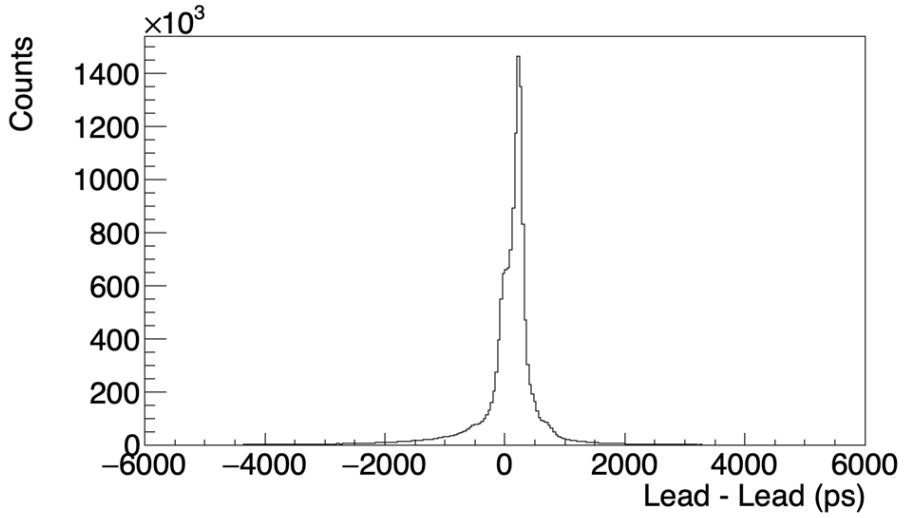
The βPlastic detector



Two 3mm thick plastic scintillator coupled to SiPMs

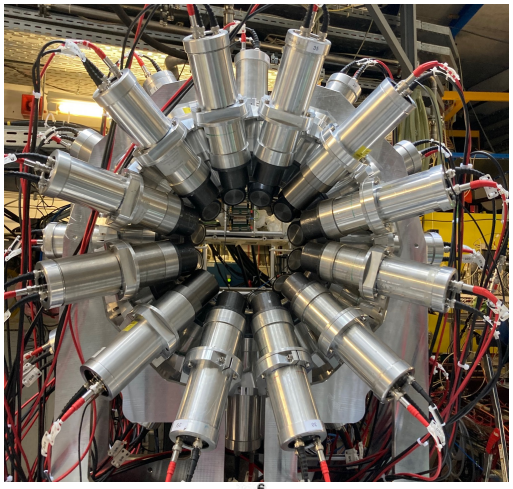
- Energy info conveyed by a time over threshold spectrum
- Timing measurements as time difference between two channels

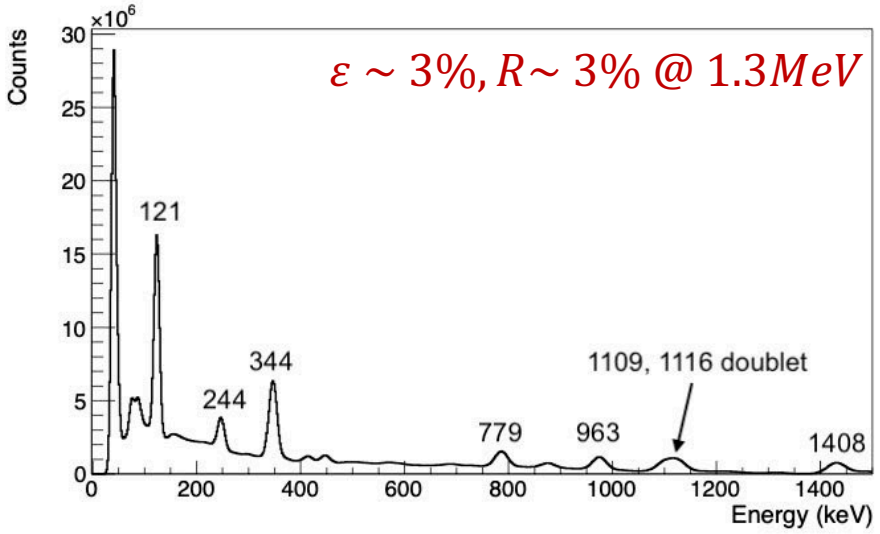


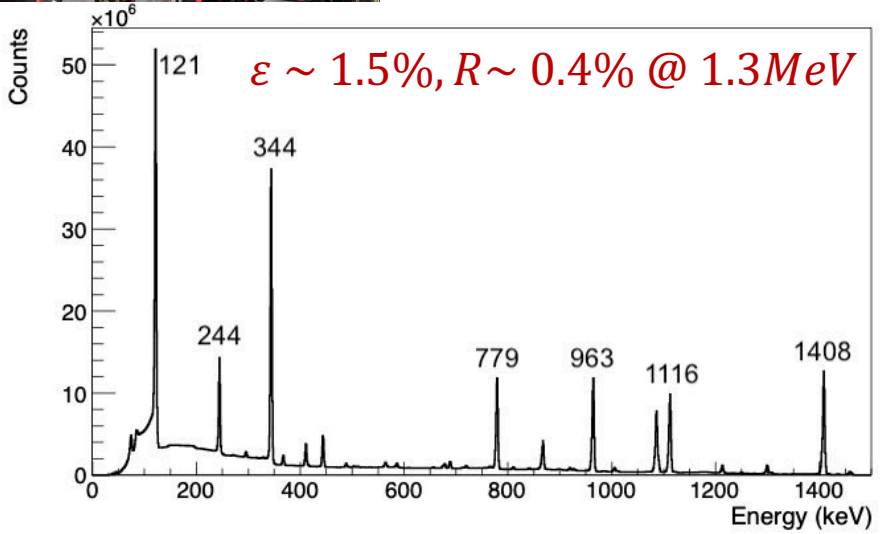


The γ detector array

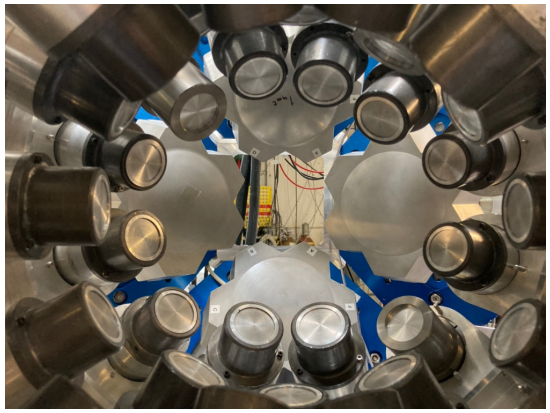
FATIMA - 36 $LaBr_3(Ce)$ detectors



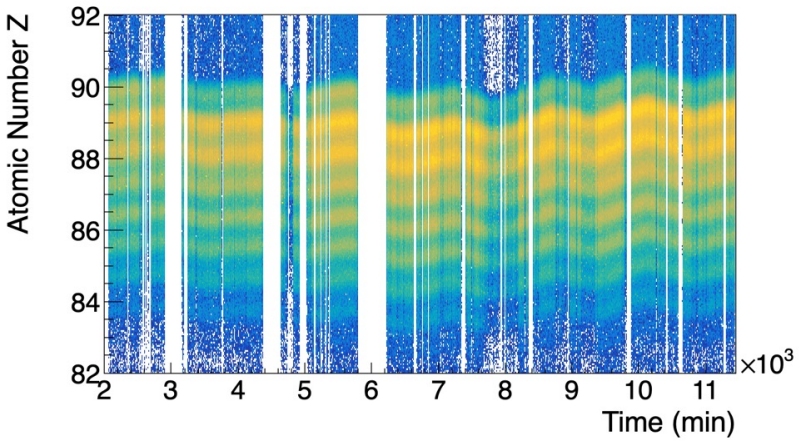


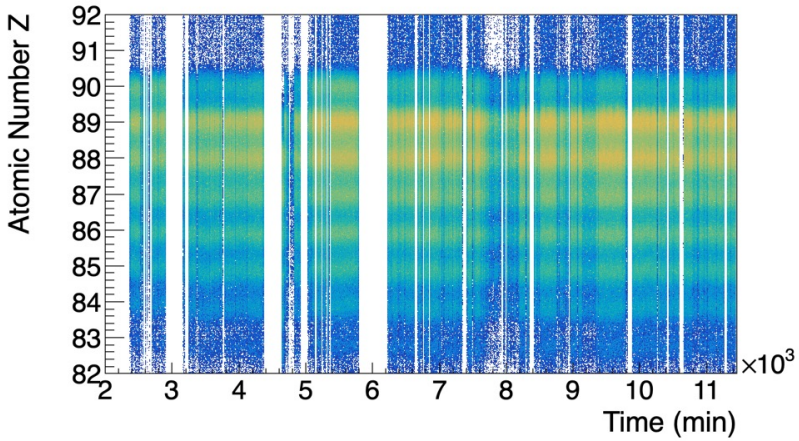


HPGe - 4 EUROBALL 7-fold clusters



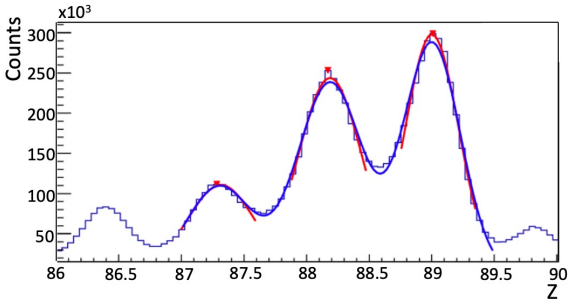
MUSIC: calibration and gain-matching

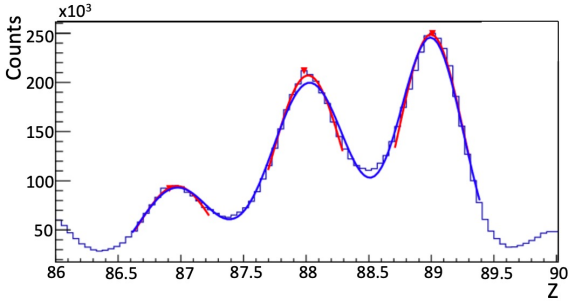




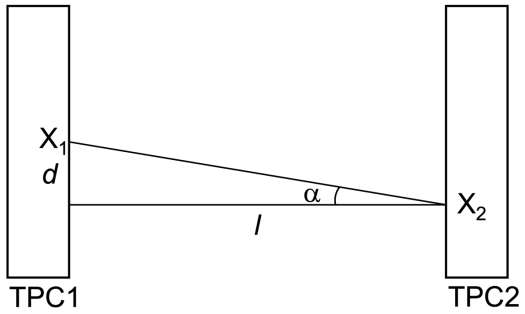
Two methods:

- Offset calculated between the strongest Z peak and the correspondent Z=89
- Linear calibration considering Z=87,88,89

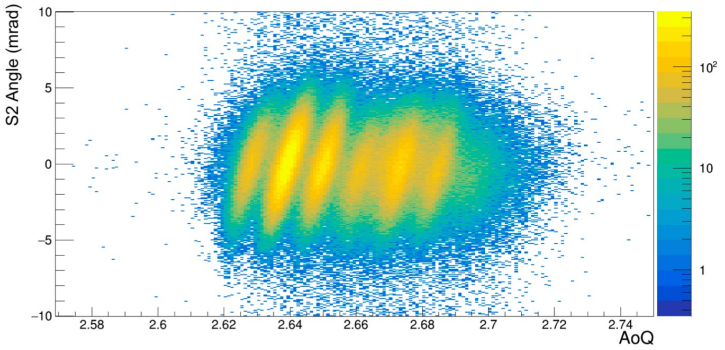


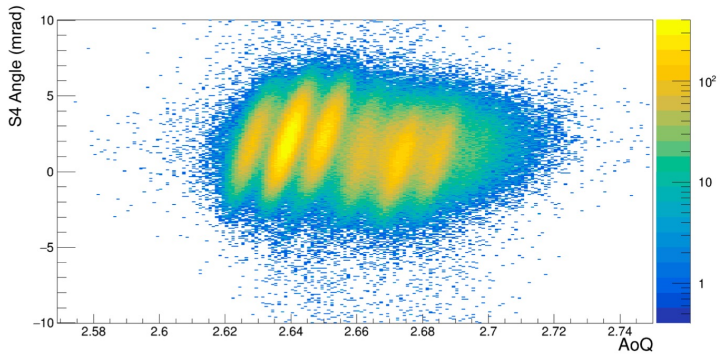


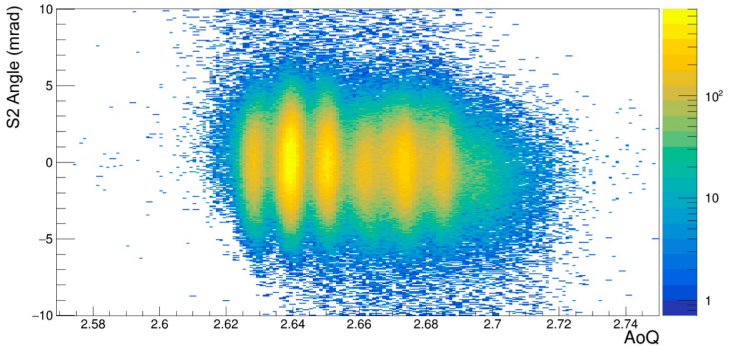
Angle correction

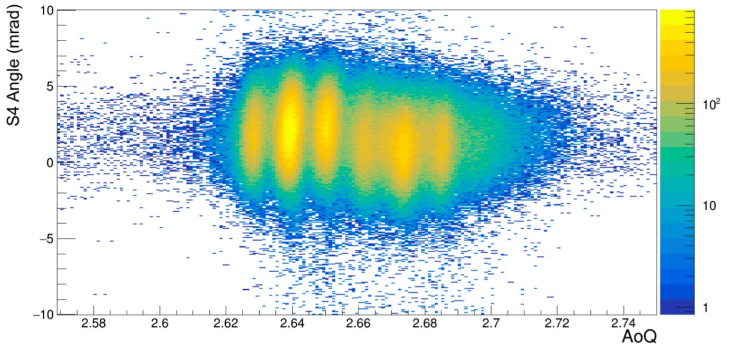


- The ions' trajectory is defined by their Bρ, which has a dependence on A/Q
- Aberrations of beam optics → angular dispersion of ~10mrad

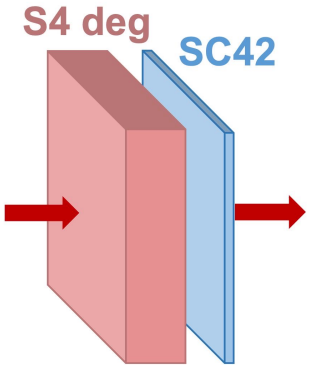








S4 degrader thickness calibration

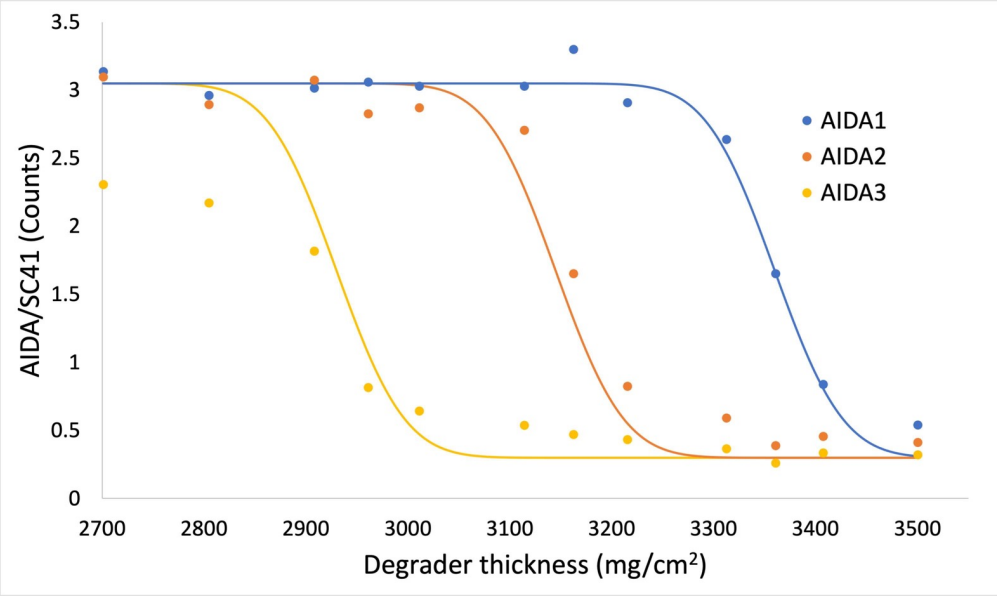


Procedure:

- low intensity primary beam and varying the degrader thickness
- rate ratio between AIDA layers and SC41

Calculated degrader offset:

~ 165 mg/cm^2.



Specific setup for S496

Triple AIDA and bPlast

- 24×8 cm^2
- 384×128 strips (49152 pixels)