Experimental beta-decay half-lives and beta-delayed neutron emission probabilities in medium-mass nuclei (A ~ 110)

β-delayed neutrons at RIKEN

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for the BRIKEN collaboration

RIKEN

RIKEN NiSHiNA CENTER

[RIBF ULIC mini-WS] Structure of neutron-rich matter revealed by beta decay | July 29th, 2024

Contents

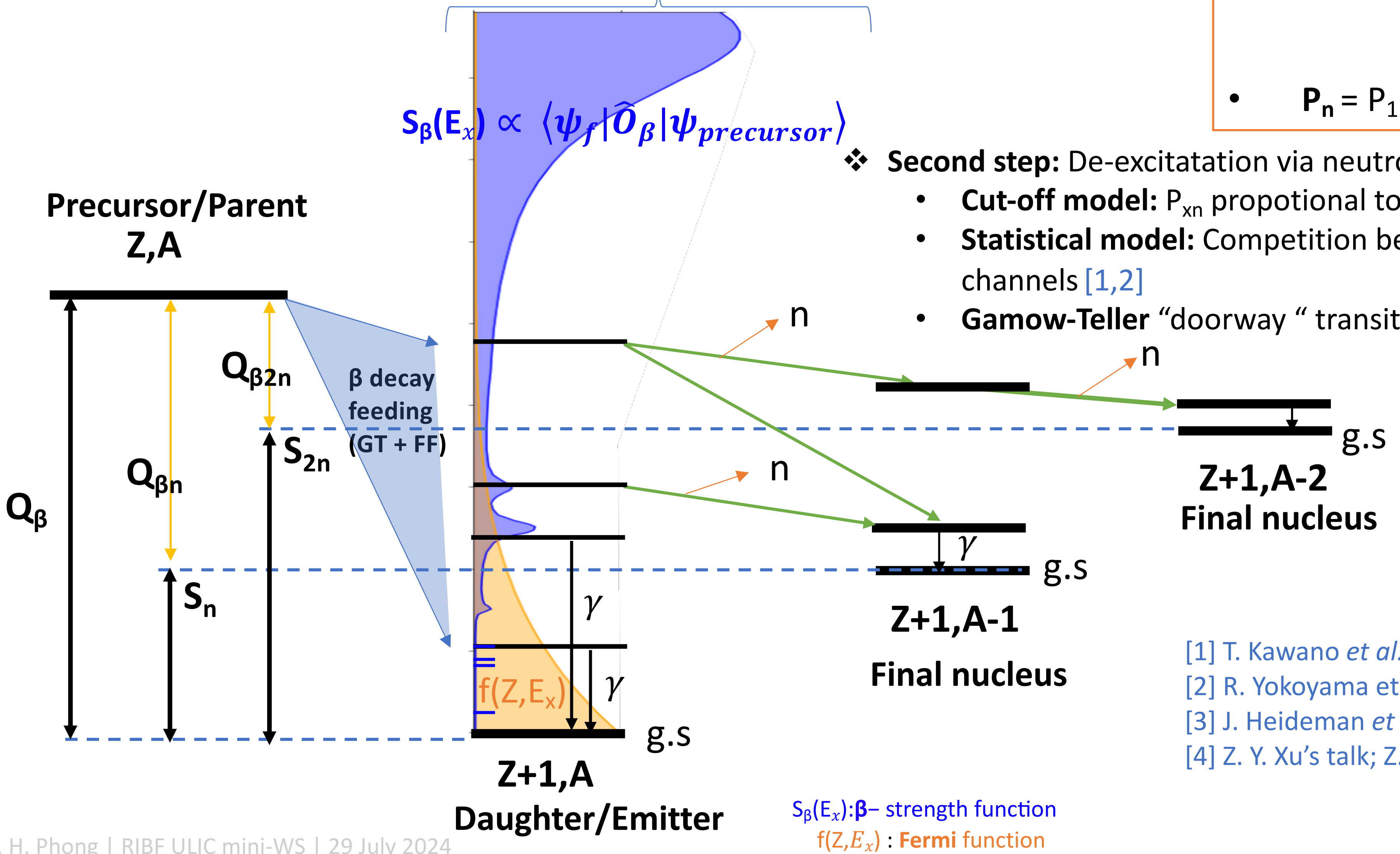
- Nuclear structure and astrophysical motivations
- Measuring $\mathbf{P_{xn}}$ with **BRIKEN**: experimental details.
- Results and discussion
- Future projects with new beta-decay station at RIBF
- Summary

Beta-delayed neutron emission (βn) probabilities - P_{xn} values

- **P_{xn} values** - Probabilities of **x** neutron emission per β-decay
  $$P_{xn} = N_{xn} / N_{decays}$$
- $P_n = P_{1n}+P_{2n}+P_{3n}+\ldots$

❖ **First step:** β-decay feeding to neutron-unbound states

❖ **Second step:** De-excitatation via neutron/gamma emission
- **Cut-off model:** P_{xn} propotional to the integral of β-intensity within $Q_{\beta xn}$
- **Statistical model:** Competition between, γ, 1n and 2n … emission channels [1,2]
- **Gamow-Teller** “doorway “ transitions [3,4]



[1] T. Kawano *et al.*, PRC **78**, 054601 (2008).
[2] R. Yokoyama et al. PRC **100**, 031302(R) (2019)
[3] J. Heideman *et al.*, PRC **108**, 024311 (2023).
[4] Z. Y. Xu’s talk; Z. Y. Xu *et al.*, PRL **133**, 042501 (2024)

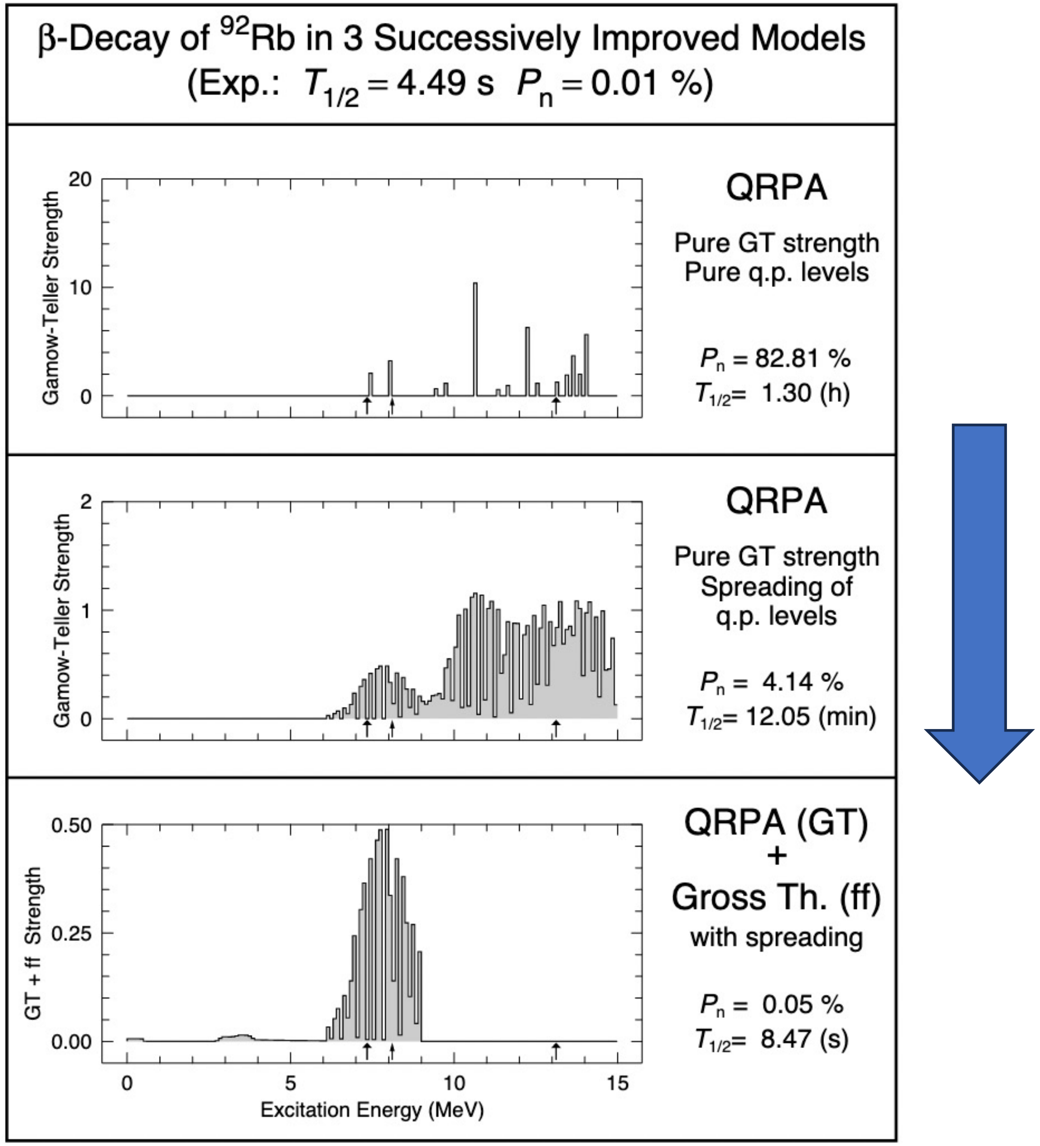
Sensitivity of P_{xn} values to nuclear structure information

- P_{xn} value measure the fraction of the β strength function above the neutron separation energy S_{xn}
  ➞ Sensitive to the low-lying states just above S_{xn}
- For very neutron-rich nuclei, P_{xn} values together with half-lives ($T_{1/2}$) provide first access to nuclear structure information

$$\frac{1}{T_{1/2}} \propto \int_{0}^{Q_\beta} S_\beta(E_x) f(Z,E_x)\, dE_x$$

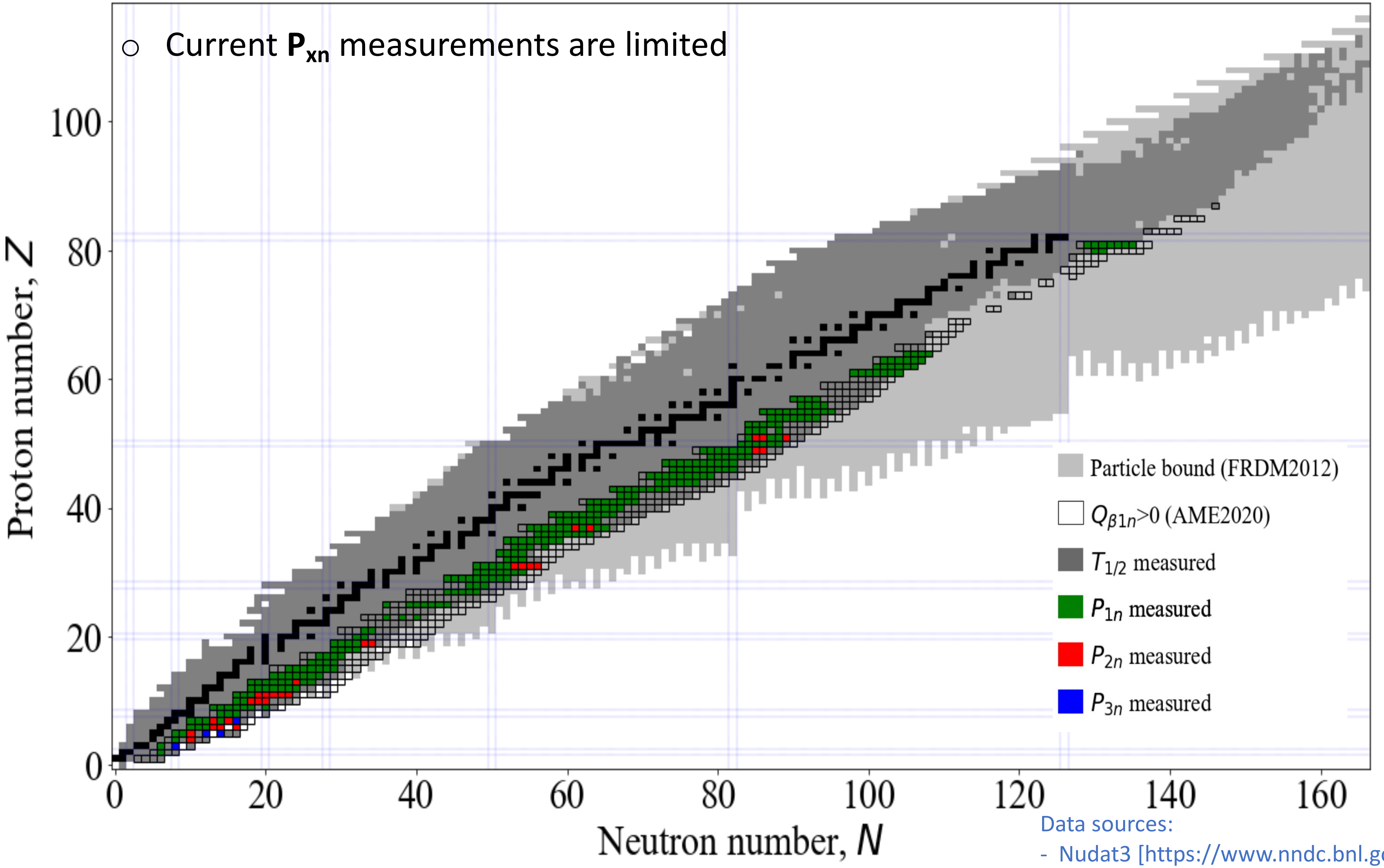
$$P_n \propto \frac{\int_{S_n}^{Q_\beta} S_\beta(E_x) f(Z,E_x) \frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma} dE_x}{\int_0^{Q_\beta} S_\beta(E_x) f(Z,E_x)\, dE_x}$$

- P_{xn} values provides important benchmarks to improve theoretical models
- First-fobbiden transitions, also with small matrix element could contribute to the β-intensity and thus affecting the predictions of P_{xn} value and $T_{1/2}$ due to phase space factor



P. Möller et. al., PRC ***67***, 055802 (2003).

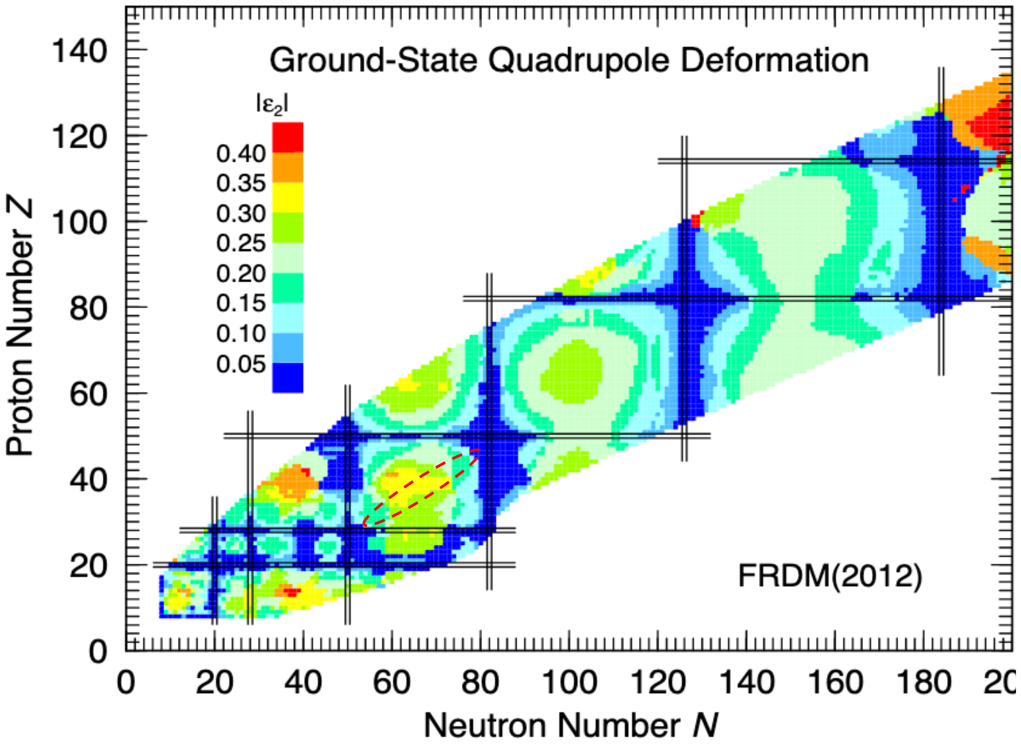
Beta-delayed neutron emission (βn) probabilities



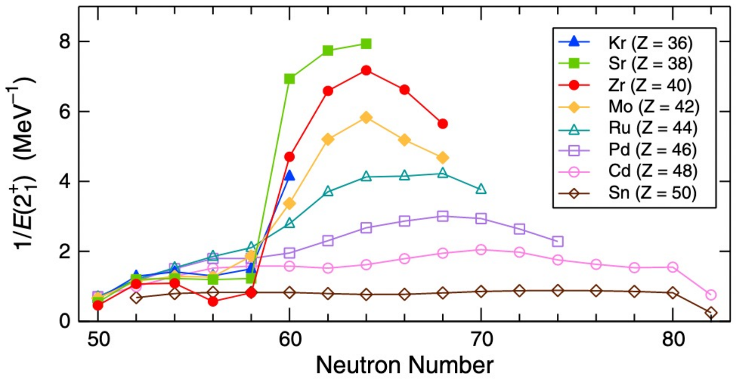
Data sources:
- Nudat3 [https://www.nndc.bnl.gov/nudat3]
- FRDM2012 [*P. Möller et. al., ADNDT* ***109–110****, 1 (2016)]*
- AME2020 [Meng Wang *et al.* 2021 *Chinese Phys. C* **45** 030003]

The mid-shell region around A~110

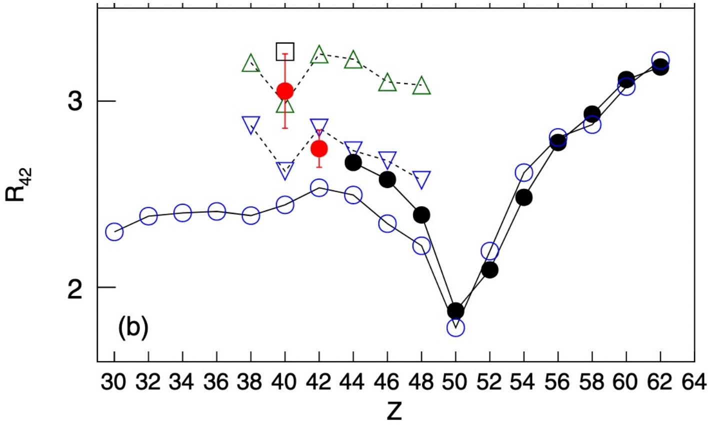
*P. Möller et al., ADNDT **109–110**, 1 (2016).*



- This talk: Experimental P_{1n} , P_{2n} and $T_{1/2}$ around the neutron-rich mid-shell region **50<N<82**



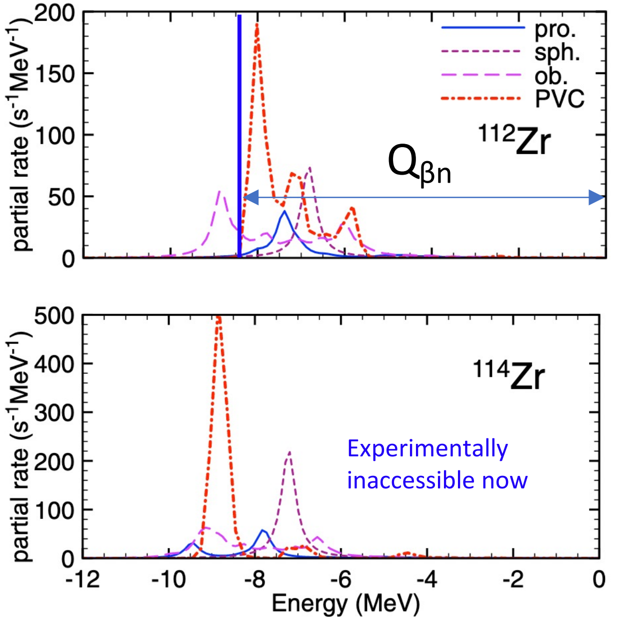
T. Sumikama et al., PRL 106, 202501 (2011)



N. Paul et al., PRL 118, 032501 (2017)

=> Well deformed region up to N=70 (^{110}Zr for Zr chain)

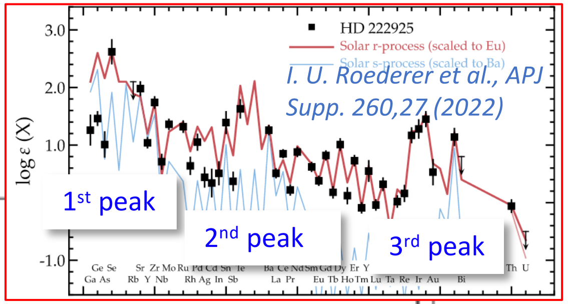
K. Yoshida et al., Phys. Rev. C 108. 034305 (2023)

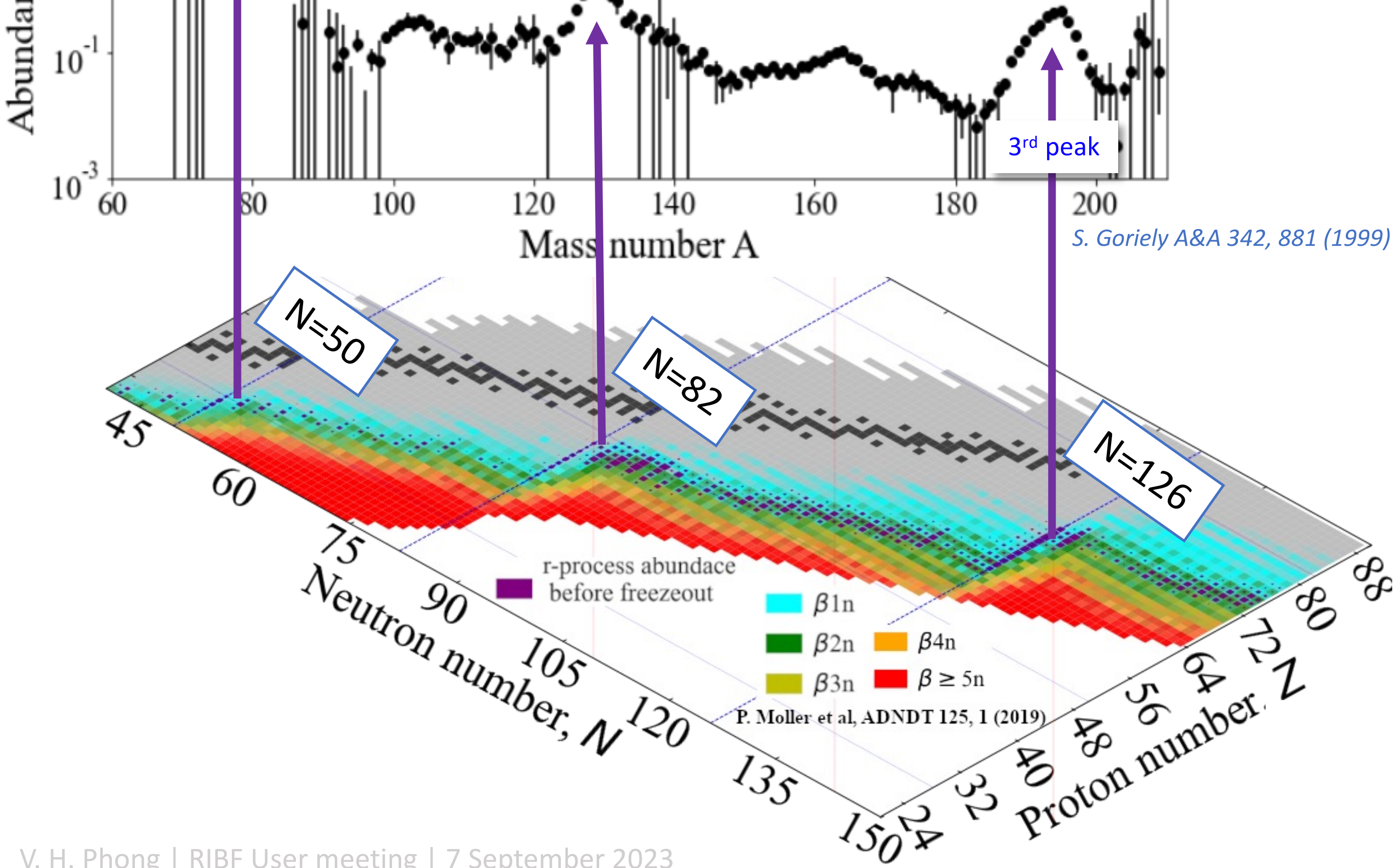


=> Deformation persist toward more neutron-rich region?

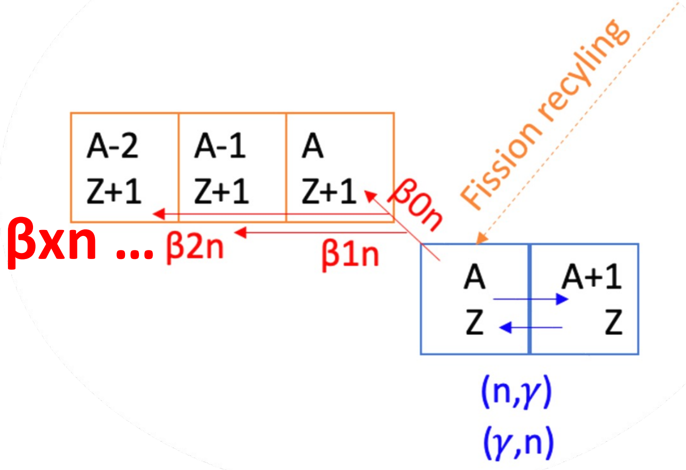
Beta-delayed neutrons of the r-process progenitor nuclei

r-process yields
(solar & metal poor stars)





Reaction rates for modern r-process dynamical reaction network calculations:



O Direct measurements of (n,γ) and fission rates are experimentally challenging

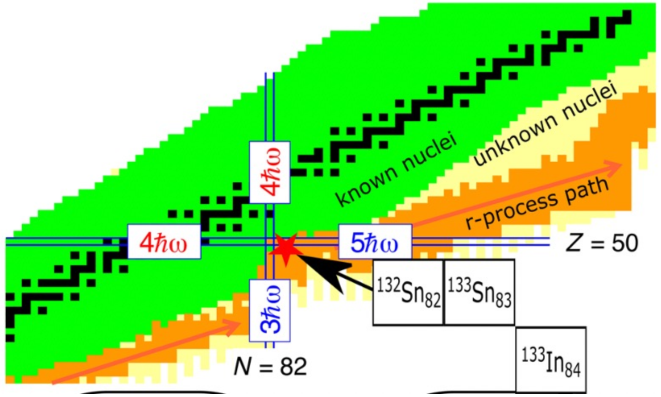
⭐ Experimental **βxn rates** are the **sole** direct inputs for the *r*-process calculations

$$\lambda_{(A,Z)\rightarrow(A-x,Z+1)+e^{-}+\bar{\nu}_e+xn} = \frac{ln(2)}{T_{1/2}} P_{xn}$$

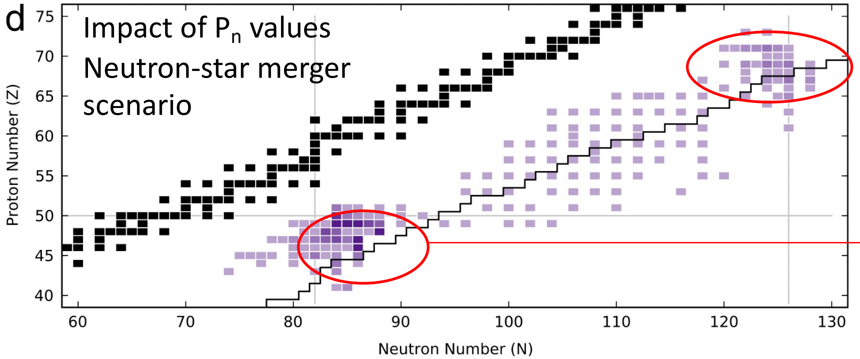
Experimental nuclear properties relevant to the *r*-process

❖ Complementary approach on the "experimental nuclear properties" for the *r*-process:

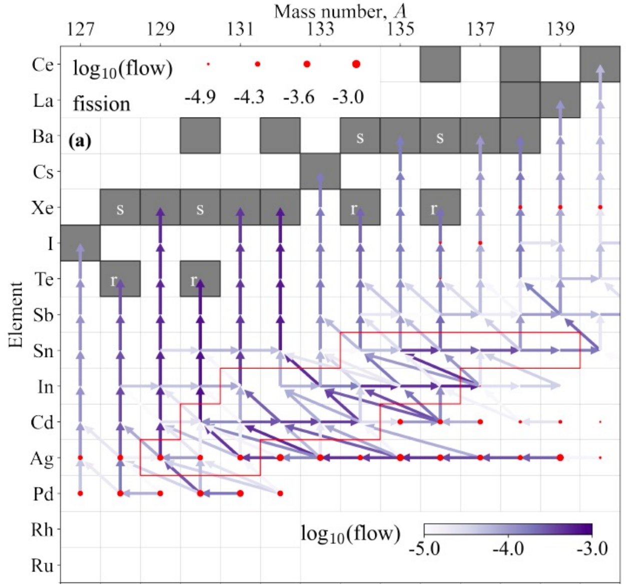
- Measurements of key-nuclei with most-significant direct impact:
  - On the "r-process path".
  - Near the neutron shell-closure or "waiting point" nuclei.
- Measurements of key-nuclei that benchmark theoretical models and improve them.
- Measuring properties of a large number of neutron-rich nuclei in **one** or a **series of experiments** => This talk: experimental P_{1n} , P_{2n} and $T_{1/2}$ around the neutron-rich mid-shell region **50<N<82.**



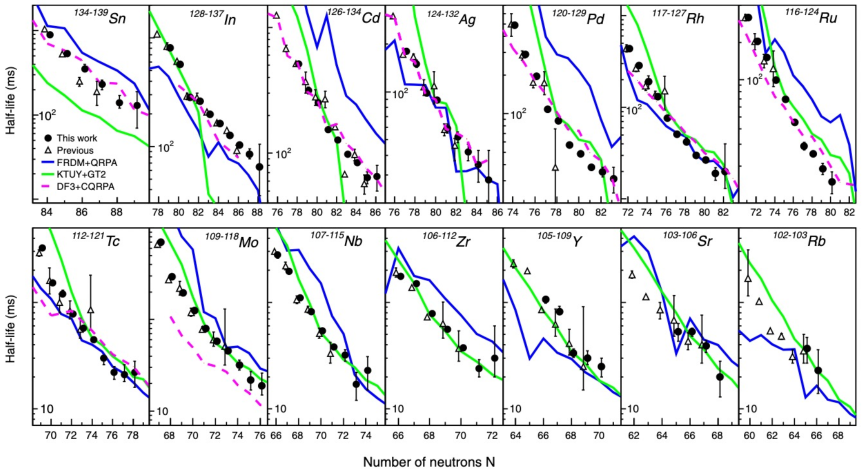
Z. Y. Xu et al., *In 133 : A Rosetta Stone for Decays of r -Process Nuclei*, Phys. Rev. Lett. **131**, 022501 (2023). (Xu-san talk tomorrow)



M. R. Mumpower et al., *The Impact of Individual Nuclear Properties on r-Process Nucleosynthesis*, Progress in Particle and Nuclear Physics **86**, 86 (2016).



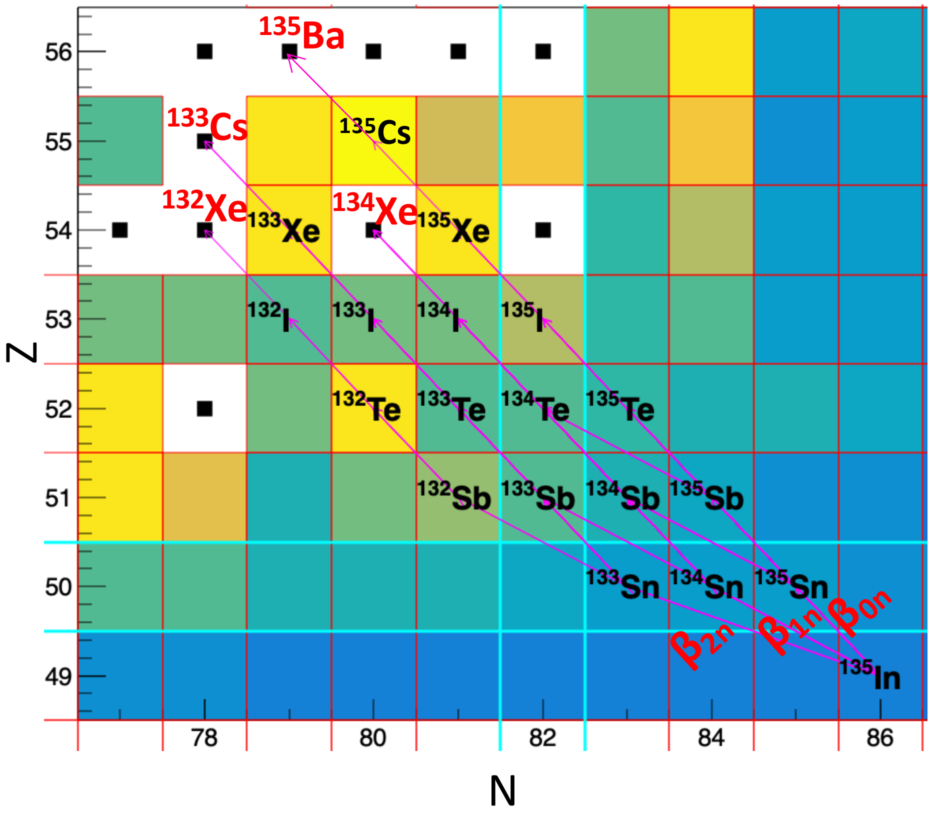
V. H. Phong et al., β-Delayed One and Two Neutron Emission Probabilities South-East of ^{132}Sn and the Odd-Even Systematics in r-Process Nuclide Abundances, Phys. Rev. Lett. 129, 172701 (2022)



G. Lorusso et al., β -Decay Half-Lives of 110 Neutron-Rich Nuclei across the N = 82 Shell Gap: Implications for the Mechanism and Universality of the Astrophysical r Process, Phys. Rev. Lett. 114, 192501 (2015).

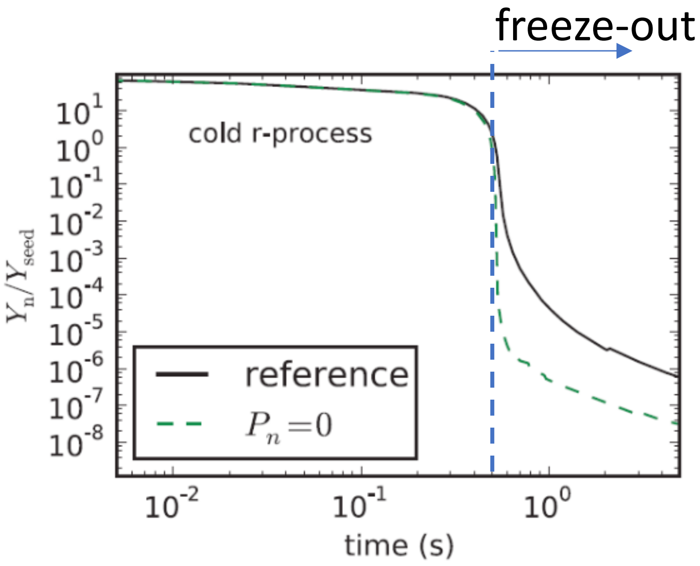
The r-process "freeze-out" and the role of P_{xn} values

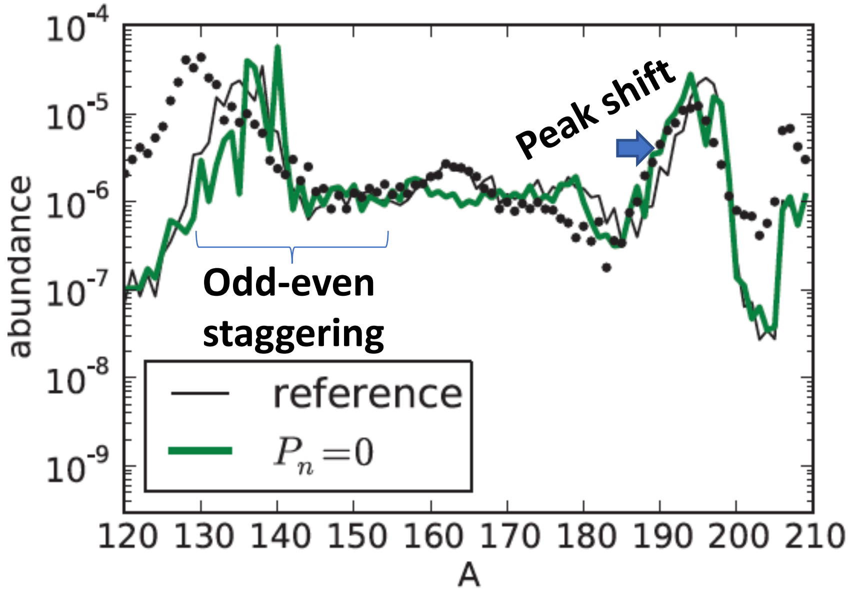
r-process "freeze-out"**:**
Free neutrons are depleted
↳ Neutron-to-seed ratio drop bellow unity
↳ Matters decay to stability



- **β-delayed x neutron branching ratios – emission probabilities (P_{xn})**
  - Altering the **β**-decay path to stability during freezeout

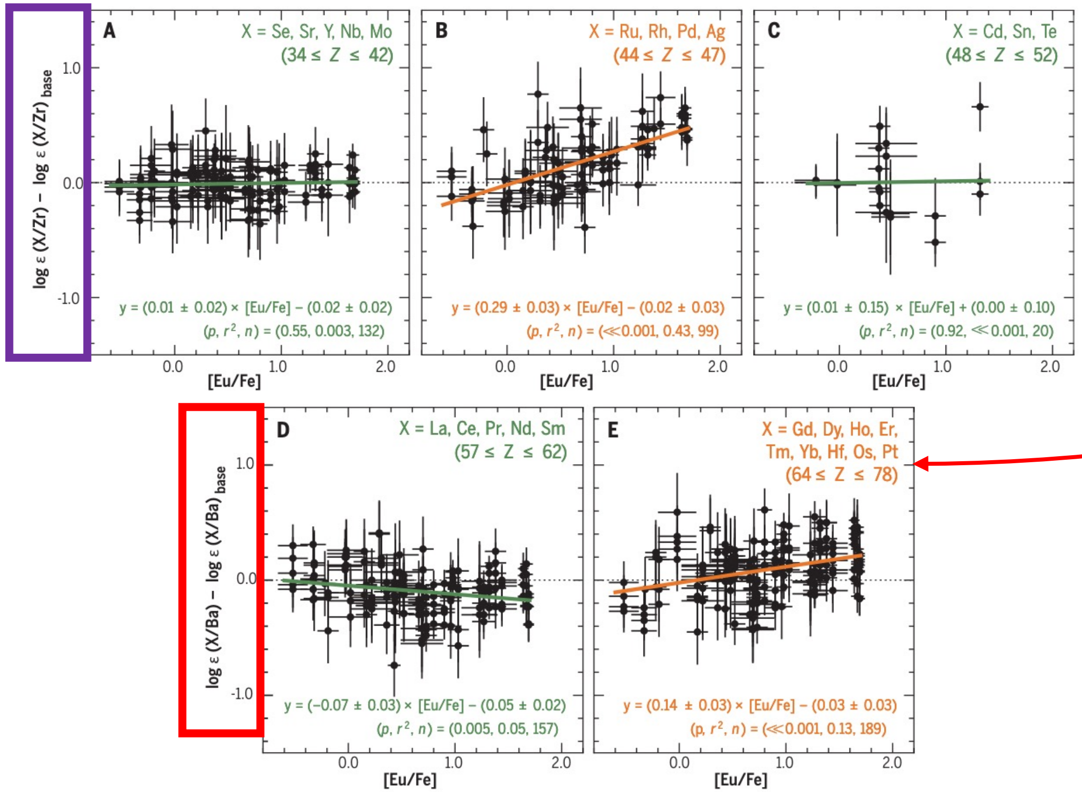
  => Modifying the odd-even staggering pattern
  - Additional source of neutrons for additional neutron-captures during freeze-out

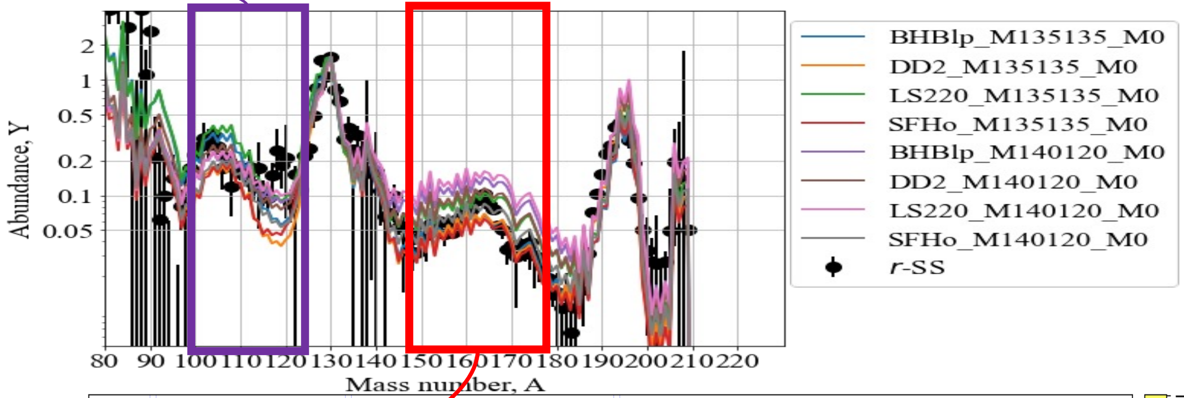


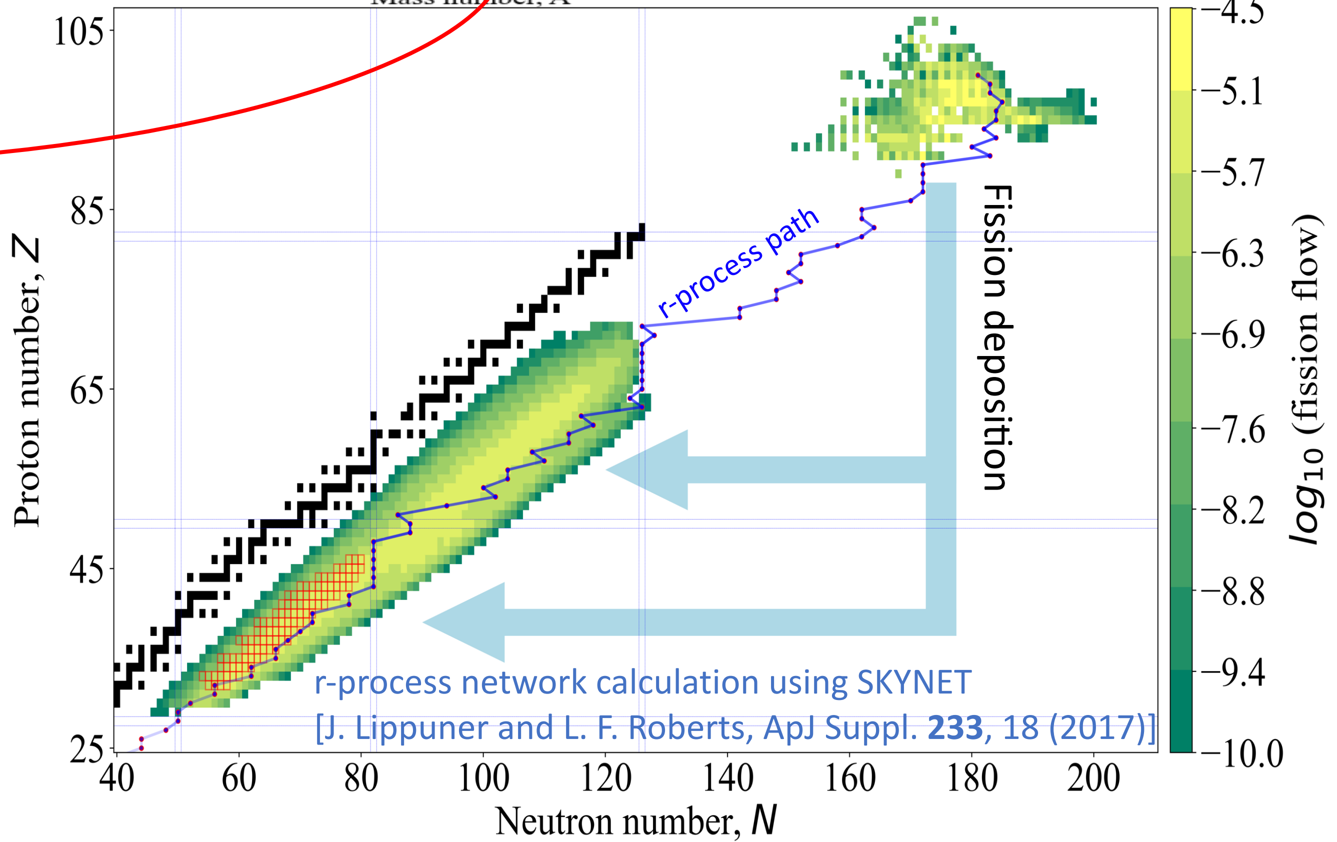


[A. Arcones and G. Martínez-Pinedo. 2011]

r-process progenitors right-wing of the second r-process peak







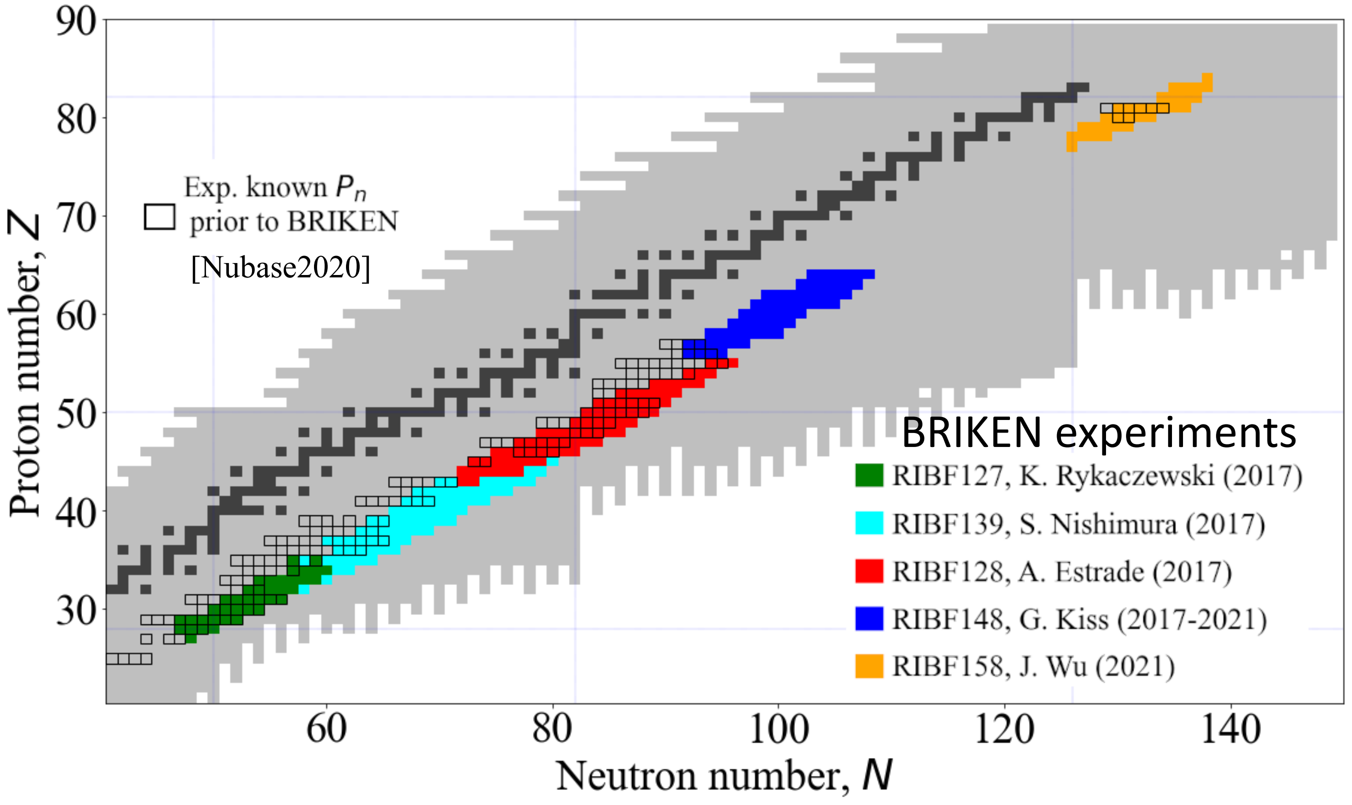
"Strength" of the r-process

I. U. Roederer et al., *Element Abundance Patterns in Stars Indicate Fission of Nuclei Heavier than Uranium*, Science **382**, 1177 (2023).

r-process network calculation using SKYNET
[J. Lippuner and L. F. Roberts, ApJ Suppl. **233**, 18 (2017)]

Experimental setup: the BRIKEN project

BRIKEN: **B**eta-delayed neutron measurements at **RIKEN**



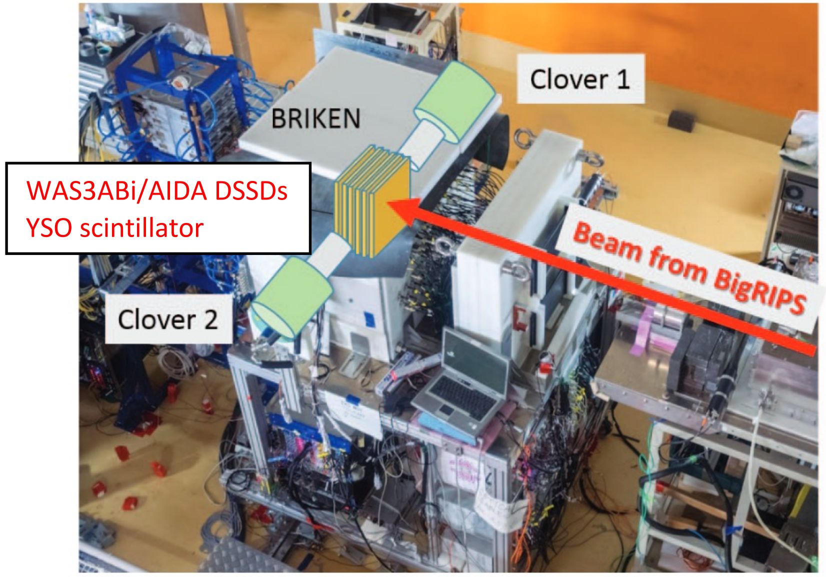
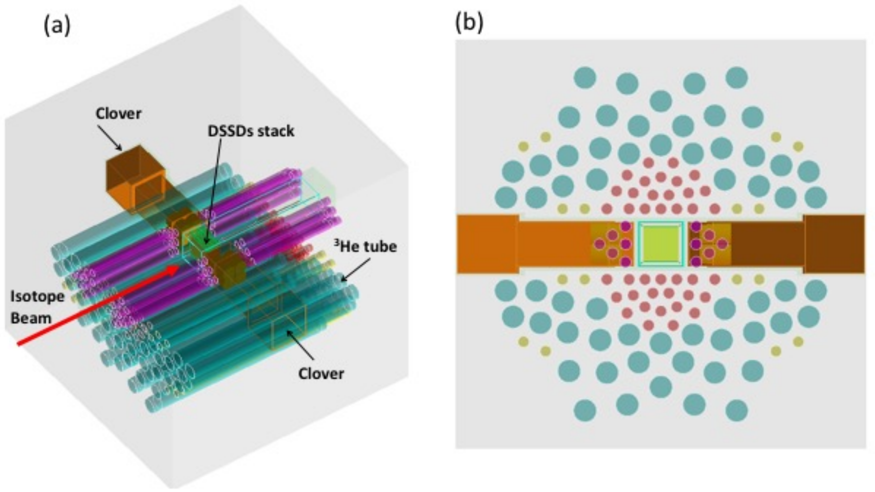


Figure 4. *BRIKEN hybrid setup with schematic positions of the AIDA detectors and the two HPGe clovers.*

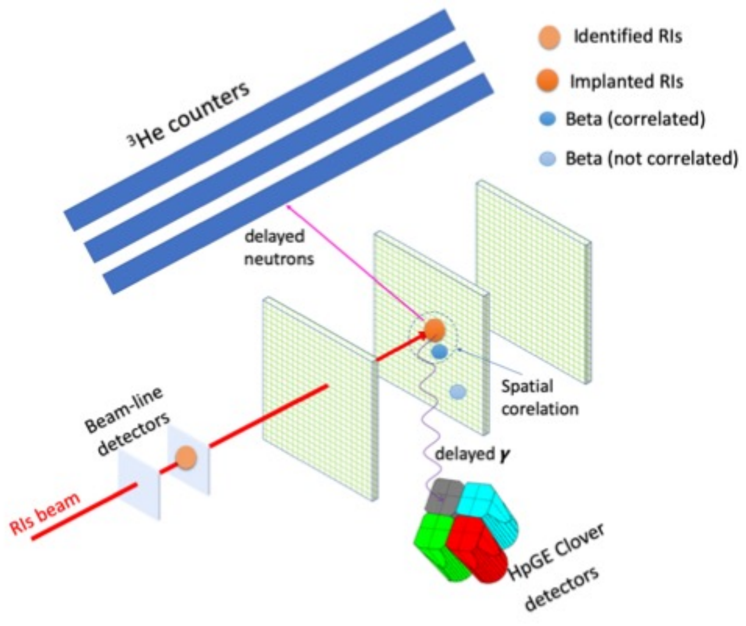
30 *Nuclear Physics News*, Vol. 28, No. 1, 2018

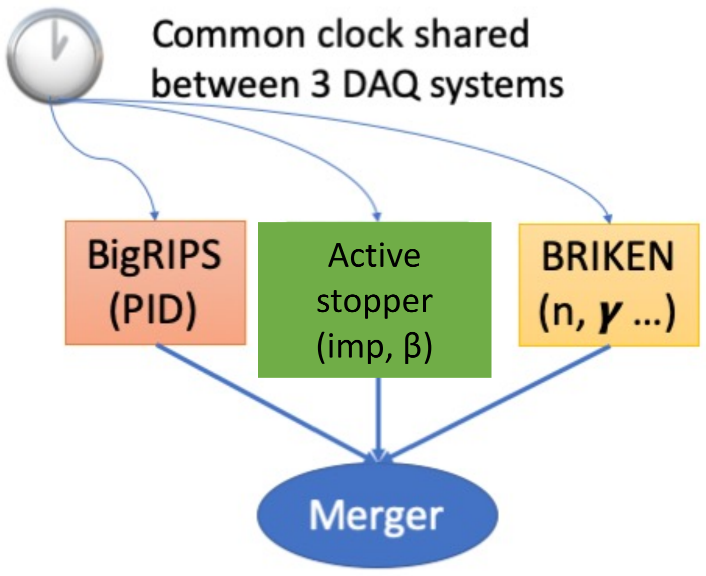


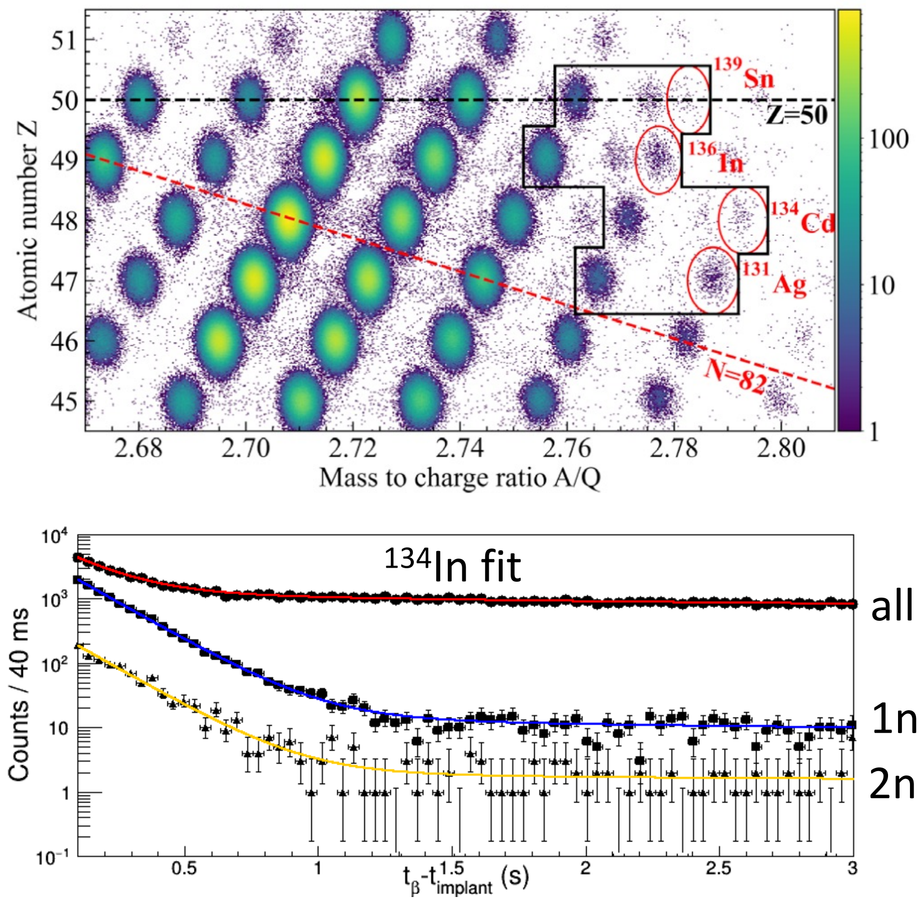
Total beam time: ~ 42 days

Physics papers: PRC x 3, PLB x1, PRL x 1, ApJ x 1 and counting…

Data analysis: data merging and fits to extract P_{1n}, P_{2n} and $T_{1/2}$







- Sorting the data produced from 3 independent DAQs
- Merging the data from 3 DAQs based on time-stamp
- Time and position correlation → β decay curves: $T_\beta - T_{implant}$ with/without neutron gates
- Unbinned MLH fits to Bateman functions that include corrections for random coincidences to extract $T_{1/2}$, P_{1n} and P_{2n}

(V. H. P. et al., **CIP** 28, 311 (2018), A. Tolosa-Delgado et al., **NIMA** 925, 133 (2019))

New BRIKEN data of neutron-rich mid-shell region 50<N<82

Upcoming BRIKEN data of neutron-rich mid-shell region $50<N<82$: Systematics trend vs mass number

- Half-lives ($T_{1/2}$) **mostly agreed** with literature values
- Some **noticable differences** with previous data for P_{1n} values, mainly coming from old ISOLDE data.
- Theoretical calculations widely used for *r*-process calculations **do not predict well** both $T_{1/2}$ and $P_{1,2n}$ values.

● This work
○ Literature

Upcoming BRIKEN data of neutron-rich mid-shell region 50<N<82:
Odd-even systematic vs mass number A

While we are still working on theoretical intepretation, some initial speculations can be made:

- **Odd-Z nuclei,** in general, have **higher** P_{1n} , P_{2n}values and more clear **odd-even staggering pattern**
- Odd-even staggering pattern is **inverted** for $\mathbf{P_{2n}}$ **w.r.t.** $\mathbf{P_{1n}}$
- P_{1n} **odd-even staggering** is a well-known phenomenon, attributed to pairing effects
- However, the **degree** of odd-even staggering is **quite different** with theoretical predictions

Odd-Z

preliminary

● This work
○ Literature

Even-Z

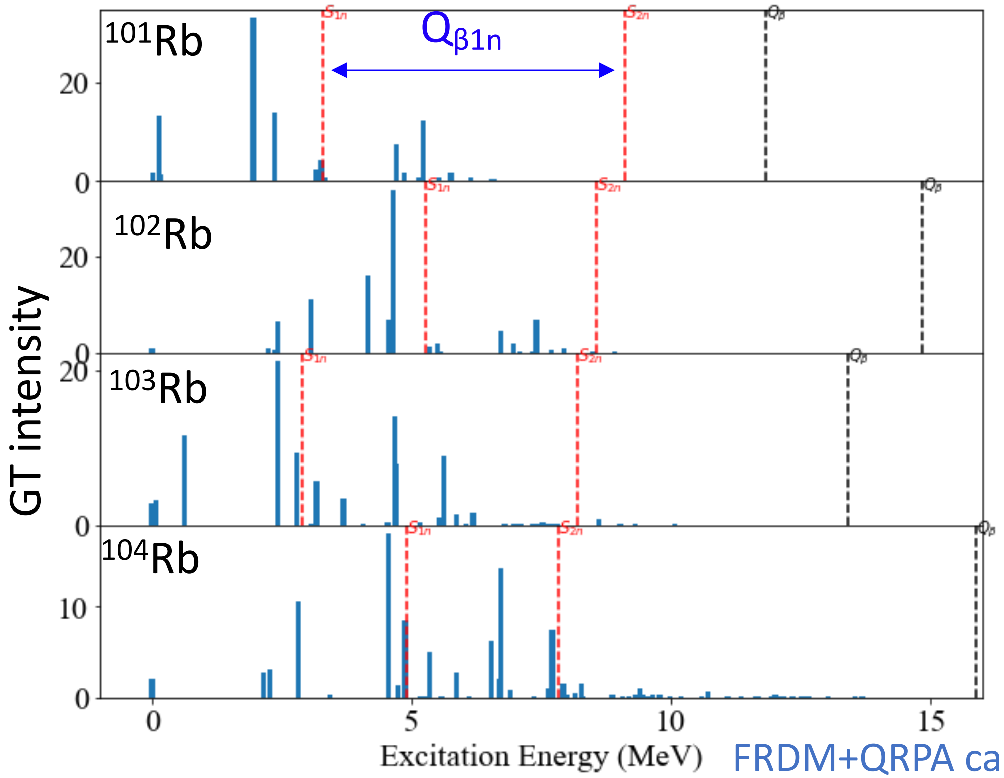
preliminary

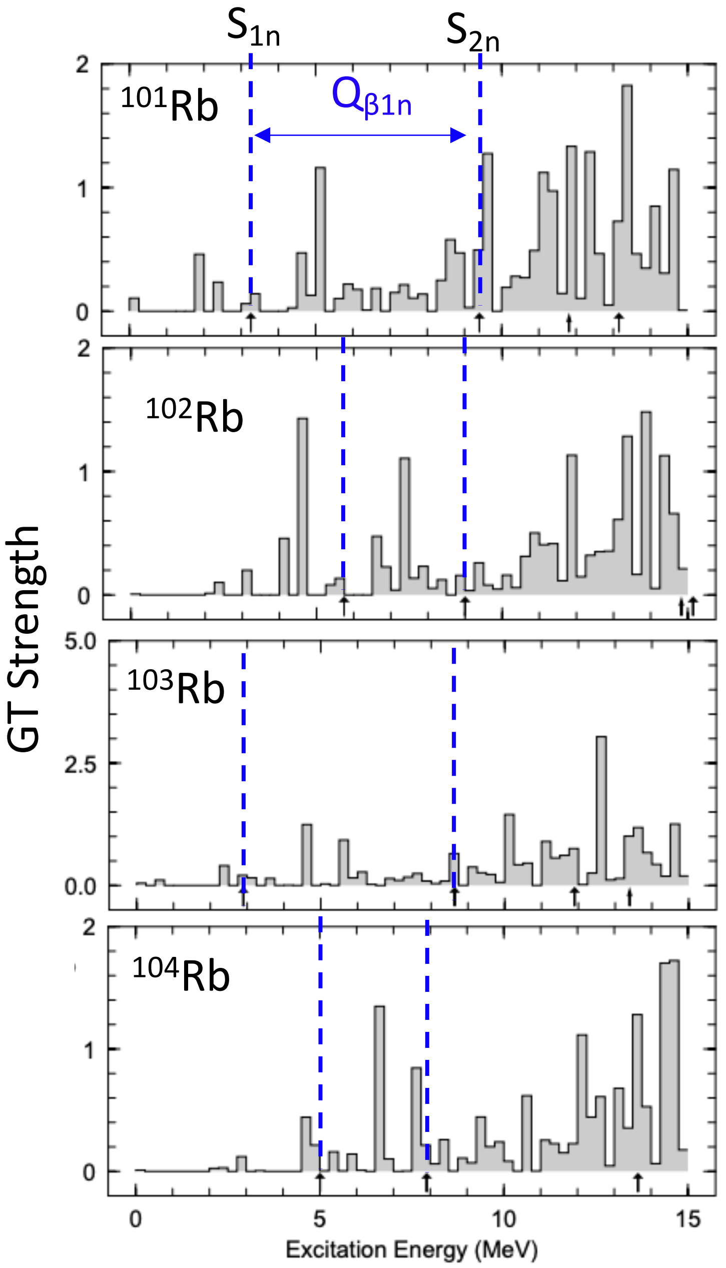
Solid line : FRDM+QRPA+HF [P. Möller et. al., ADNDT 109, 1 (2016)]
Dashed line: RHB+pnQRPA+HF [F. Minato et. al., PRC 104, 044321 (2021)]

Upcoming BRIKEN data of neutron-rich mid-shell region 50<N<82: Systematics trend

- The degree of odd-even staggering **does not only depend on** the change in the $Q_{\beta xn}$ window, but also:
  - Details of the β-strengh function
  - Competition between neutron/gamma emission channels

↳ More ellaborated theoretical models needed to accurately describe P_{xn} values
↳ Measurements of β-strengh functions above S_n are needed





FRDM+QRPA calculations[P. Möller, private communication]

(Preliminary) Impact of the new BRIKEN data on the r-process

- Reaction network calculations ultilizing the SkyNet code [1] and the HOKUSAI BigWaterfall2 computing system
- Mass-weighted trajectories from the output the 3D hydrodynamical simulations in Ref. [2]
- Update REACLIB V2.2 [3] with latest nuclear properties from NUBASE2020 [4] and FRDM2012 [5] and neutron-capture rates from TALYS calculation [6]
- Update with fission rate and fragment distribution from the latest FRLDM models and TALYS code [6-9]

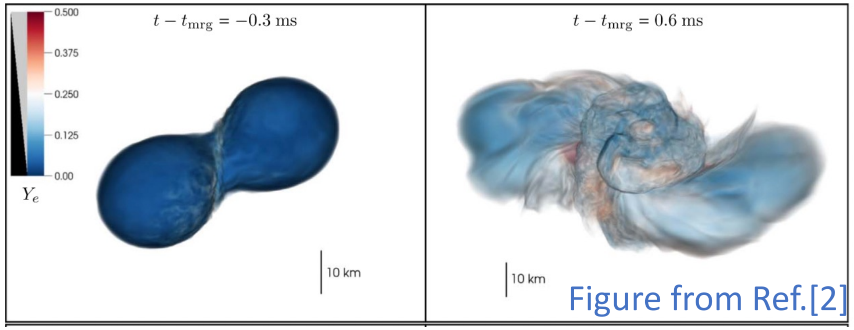
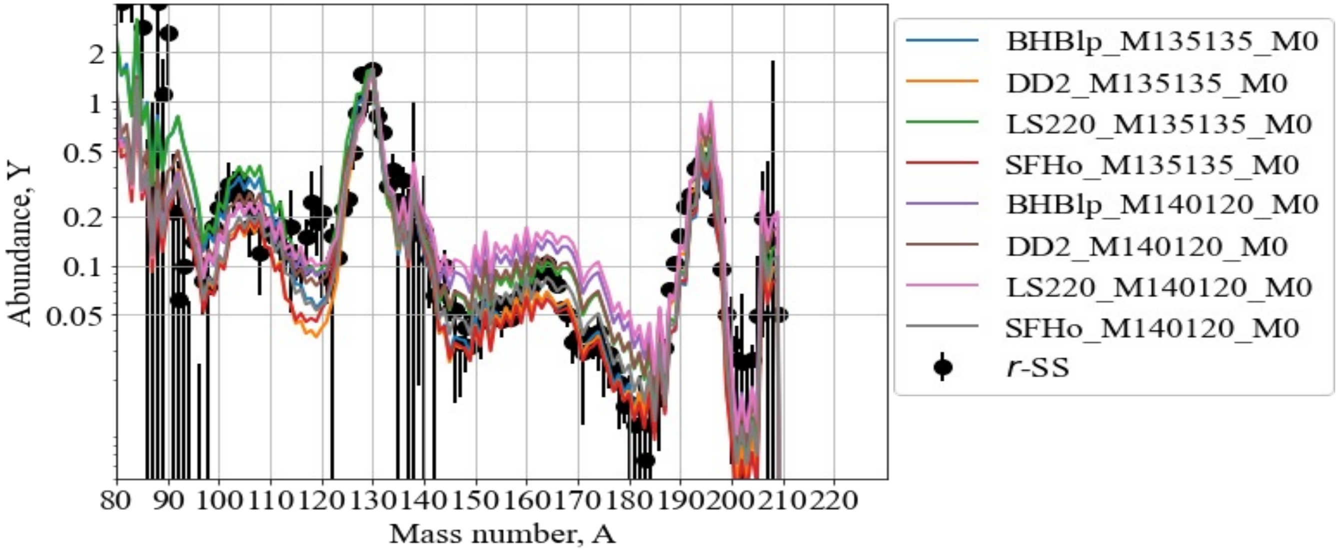


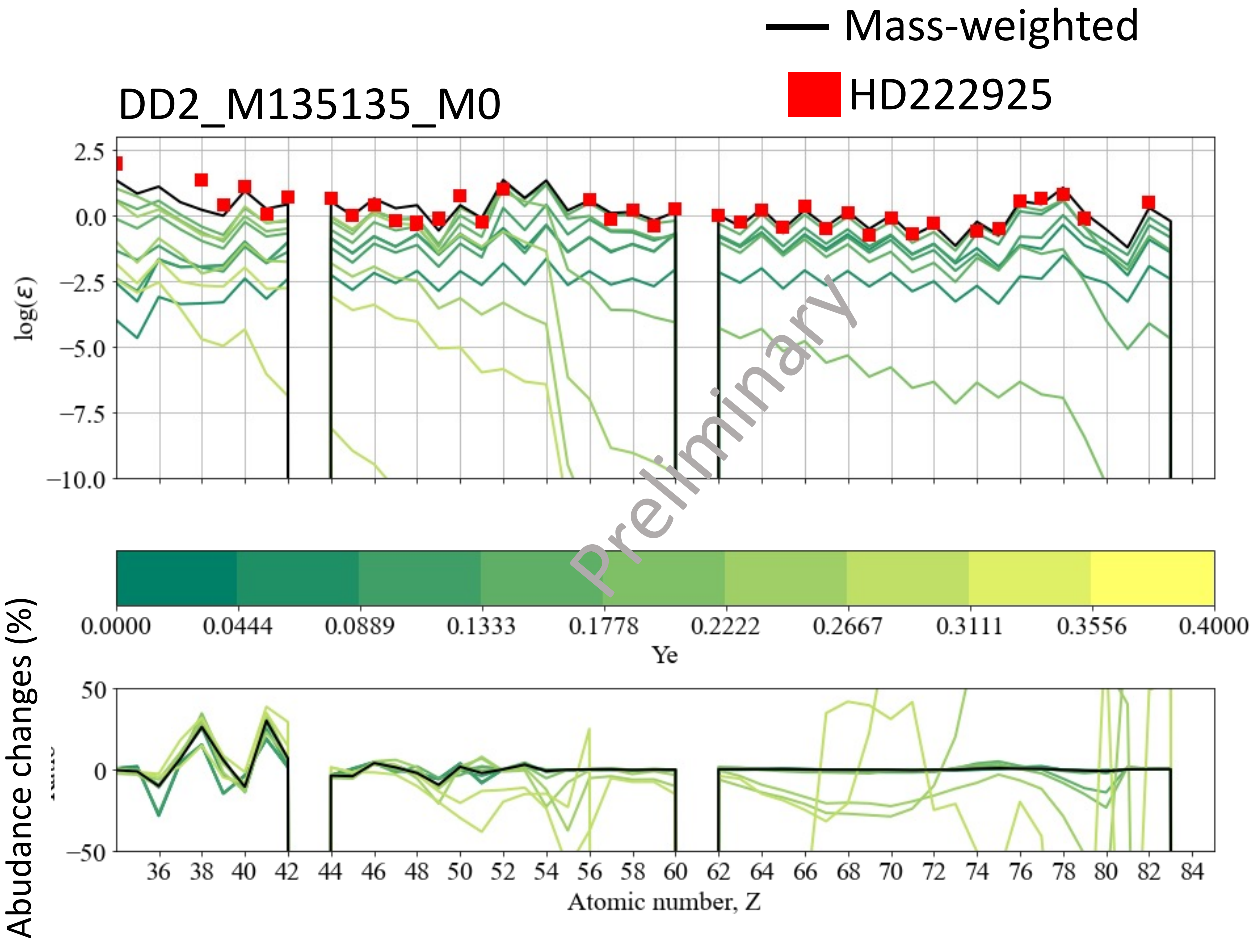
Figure from Ref.[2]

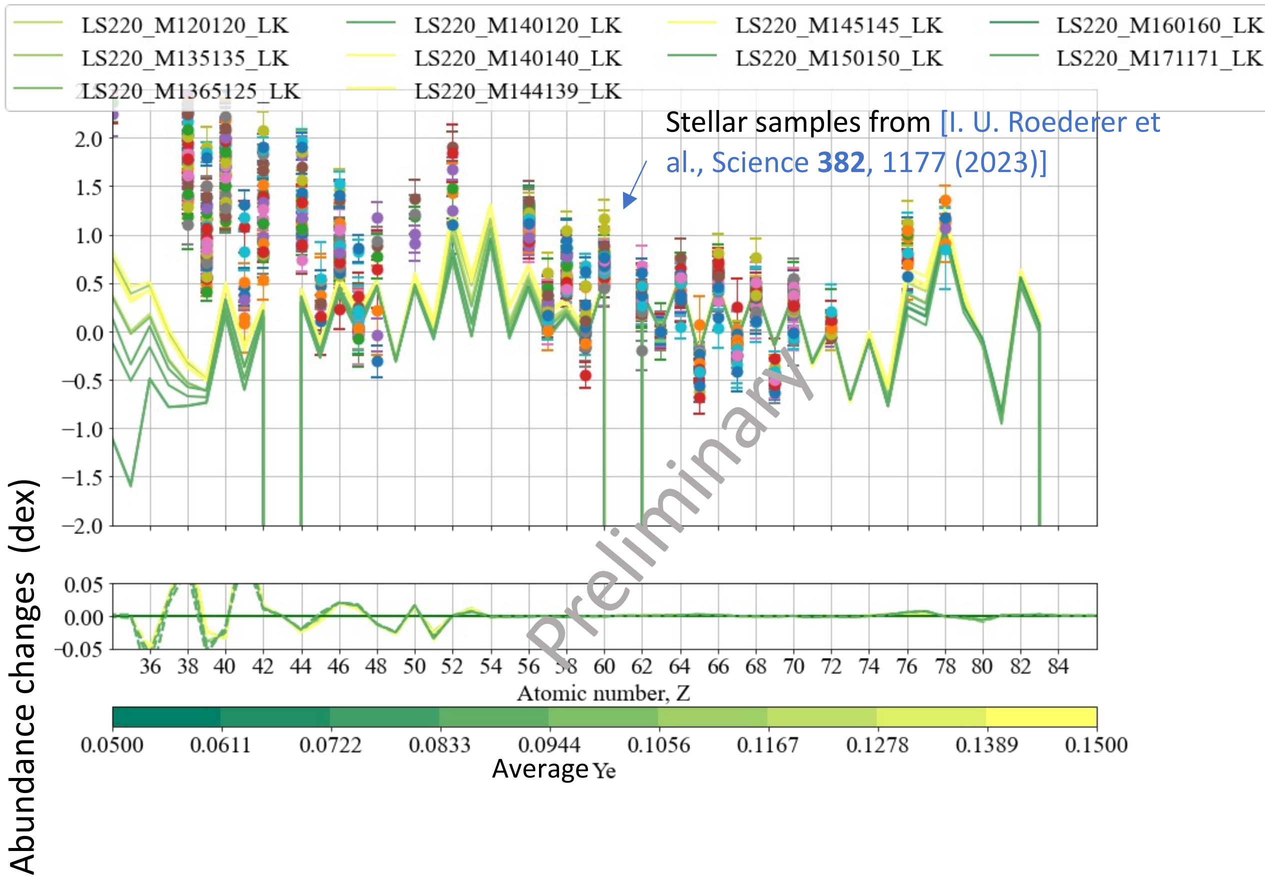


[1] J. Lippuner and L. F. Roberts, ApJ Suppl. 233, 18 (2017)
[2] D. Radice et al., ApJ 869, 130 (2018).
[3] R. H. Cyburt et al., ApJ Suppl. 189, 240 (2010).
[4] F. G. Kondev et al., Chinese Phys. C 45, 030001 (2021).
[5] P. Möller, A. J. Sierk, T. Ichikawa, and H. Sagawa, ADNDT 109–110, 1 (2016).
[6] A. J. Koning, S. Hilaire, and S. Goriely, EPJA, 59(6), 131 (2023)
[7] P. Möller, et. al. *Fission Barriers at the End of the Chart of the Nuclides*, Phys. Rev. C 91, 024310 (2015).
[8] M. R. Mumpower, T. Kawano, T. M. Sprouse, N. Vassh, E. M. Holmbeck, R. Surman, and P. Möller, β *-Delayed Fission in* r *-Process Nucleosynthesis*, ApJ **869**, 14 (2018).
[9] M. R. Mumpower, P. Jaffke, M. Verriere, and J. Randrup, *Primary Fission Fragment Mass Yields across the Chart of Nuclides*, Phys. Rev. C **101**, 054607 (2020).

(Preliminary) Impact of the new BRIKEN data ~A=110 on elemental abundance the r-process

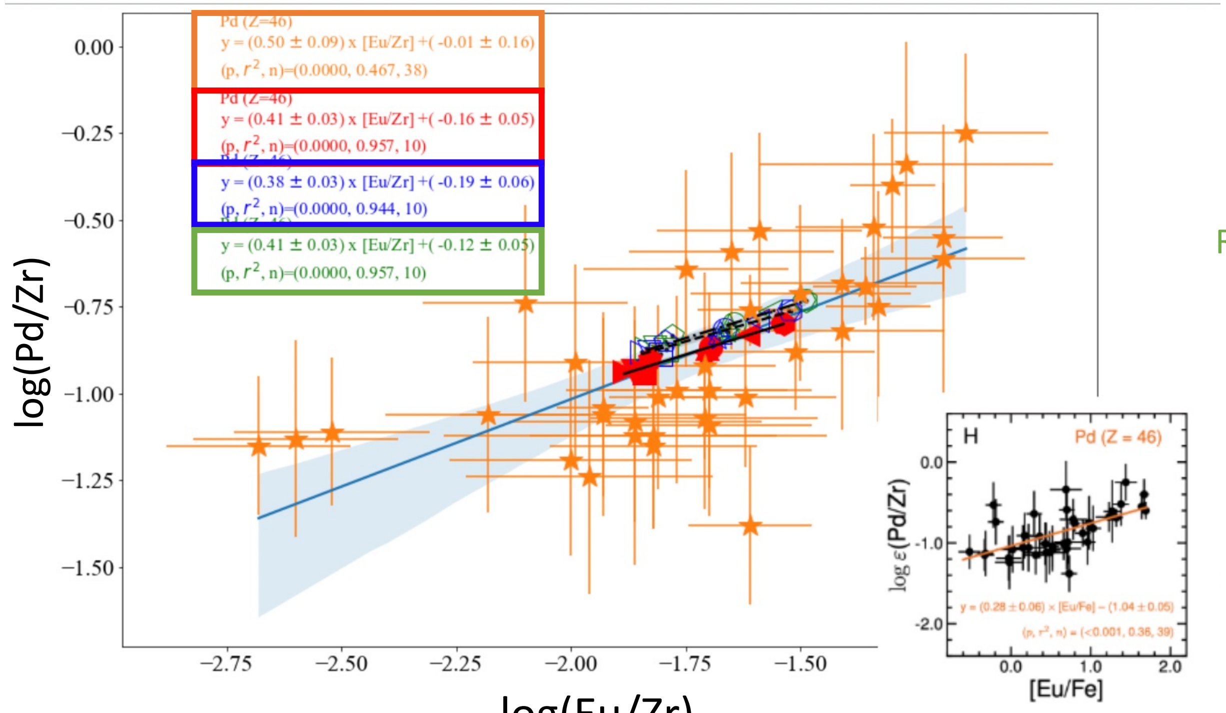
❖ Comparion with final abundances calculated with the reaction network with new BRIKEN data and the network without new BRIKEN data.

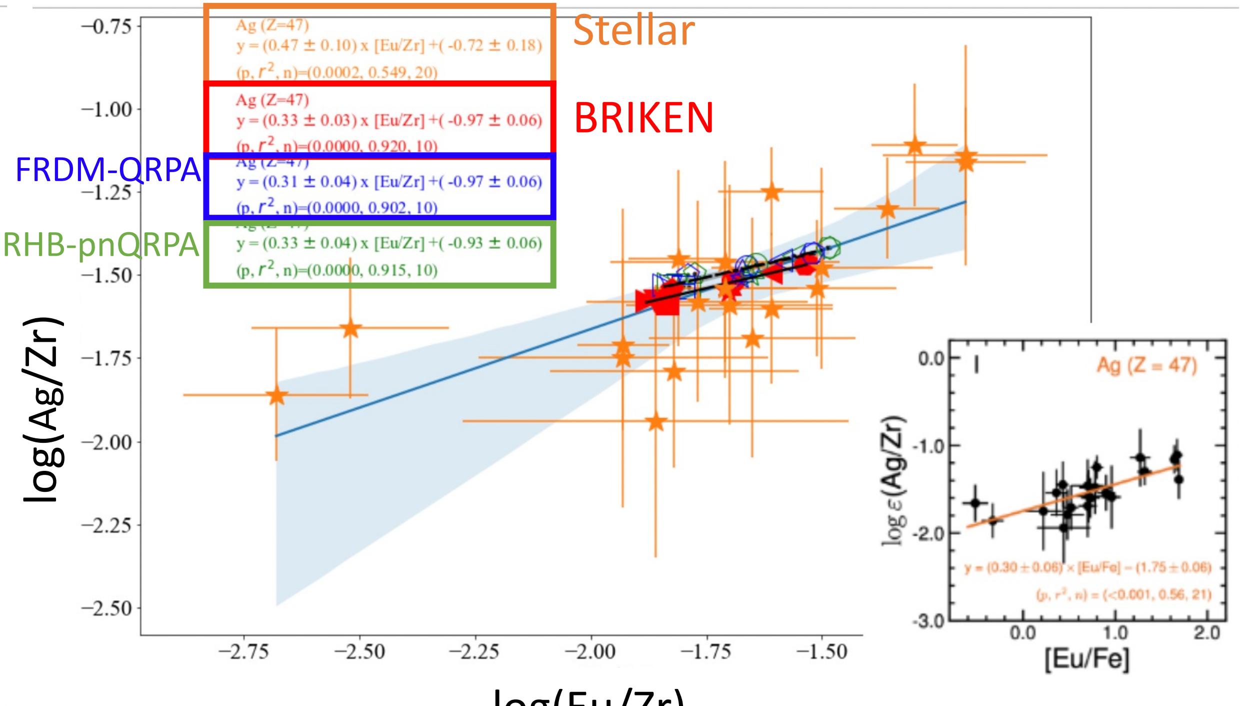




(Preliminary) Impact of the new BRIKEN data ~A=110 on elemental abundance the r-process on the correlation parameters

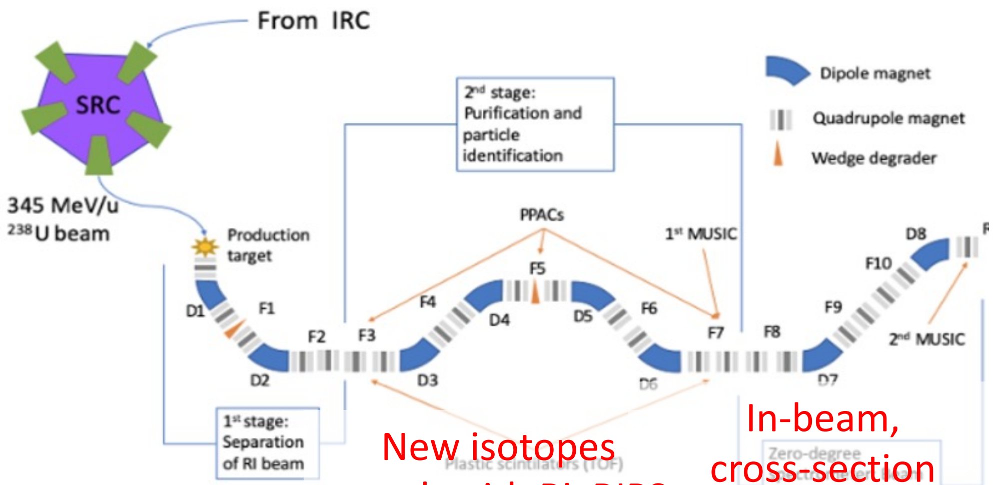
- Using stellar samples from [I. U. Roederer et al., Science **382**, 1177 (2023)] and plot the elemental ratio versus log(Eu/Zr) ratios





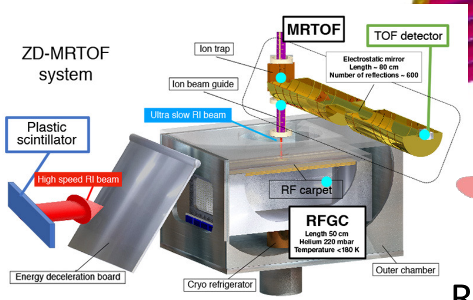
- Correlations analogous to that in [I. U. Roederer et al., Science **382**, 1177 (2023)] can be seen
- Direct comparison with simulation results reveal the impacts of the BRIKEN data on the correlation parameters

New β-decay station for Beta-delayed Neutrons Time-of-flight spectroscopy in tandem with the ZD-MRTOF mass measurement setup



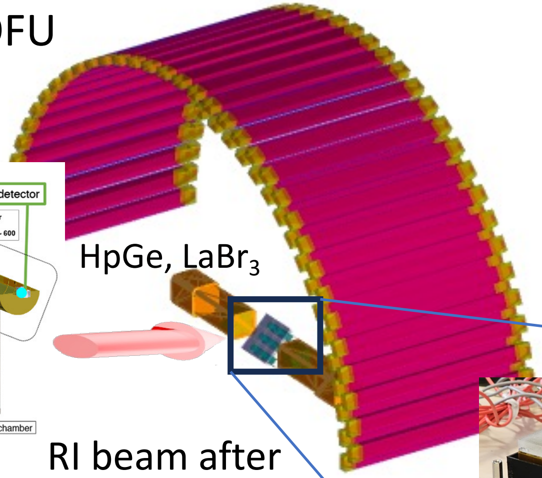
New isotopes search with BigRIPS

In-beam, cross-section measurements



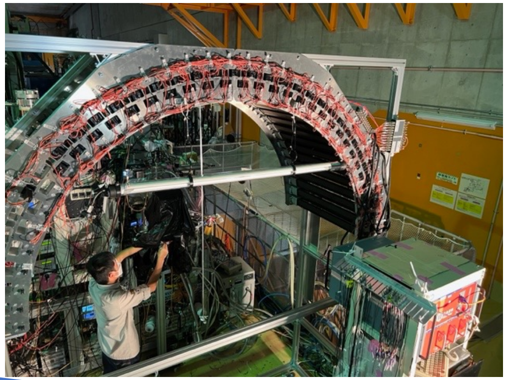
Gas-cell ZD-MRTOF Mass measurement

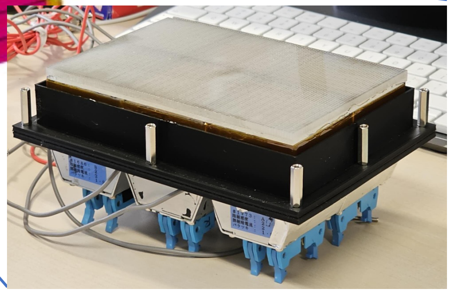
Neutron TOF detector TOFU



HpGe, $LaBr_3$

RI beam after Gas-cell



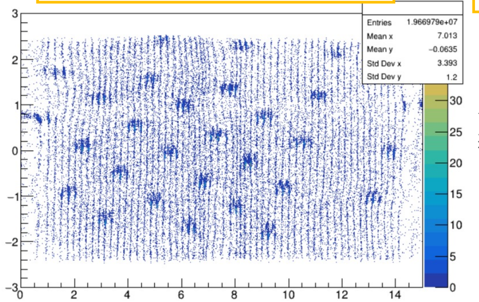


- ❖ **GARi** : **G**as-cell **A**ctive detector for **R**adio**i**sotope decay
  - Segmented plastic scintillator: EJ-228 (150×100×6 mm^3)
  - PSPMT: Hamamatsu H12700 (x6)
- ❖ **TOFU**: **T**ime **O**f **F**light detector array for **U**niversal purposes
  - 70 plastic scintillator bars at 100 cm, ~ 8% efficiency for 1 MeV neutron
- ❖ Several **HPGE clover and $LaBr_3$** detectors will be installed
- ❖ **Fully digital DAQ** (for beamline, MRTOF and β - decay station detectors)

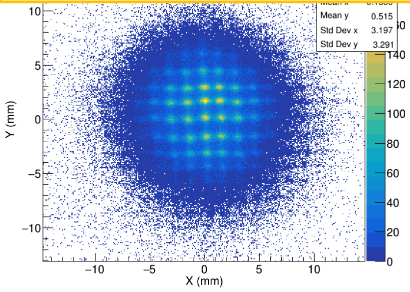
Position-sensitive Scintillator GARi

[See Z. Quanbo talks for more details]

(Masked) ion hit pattern

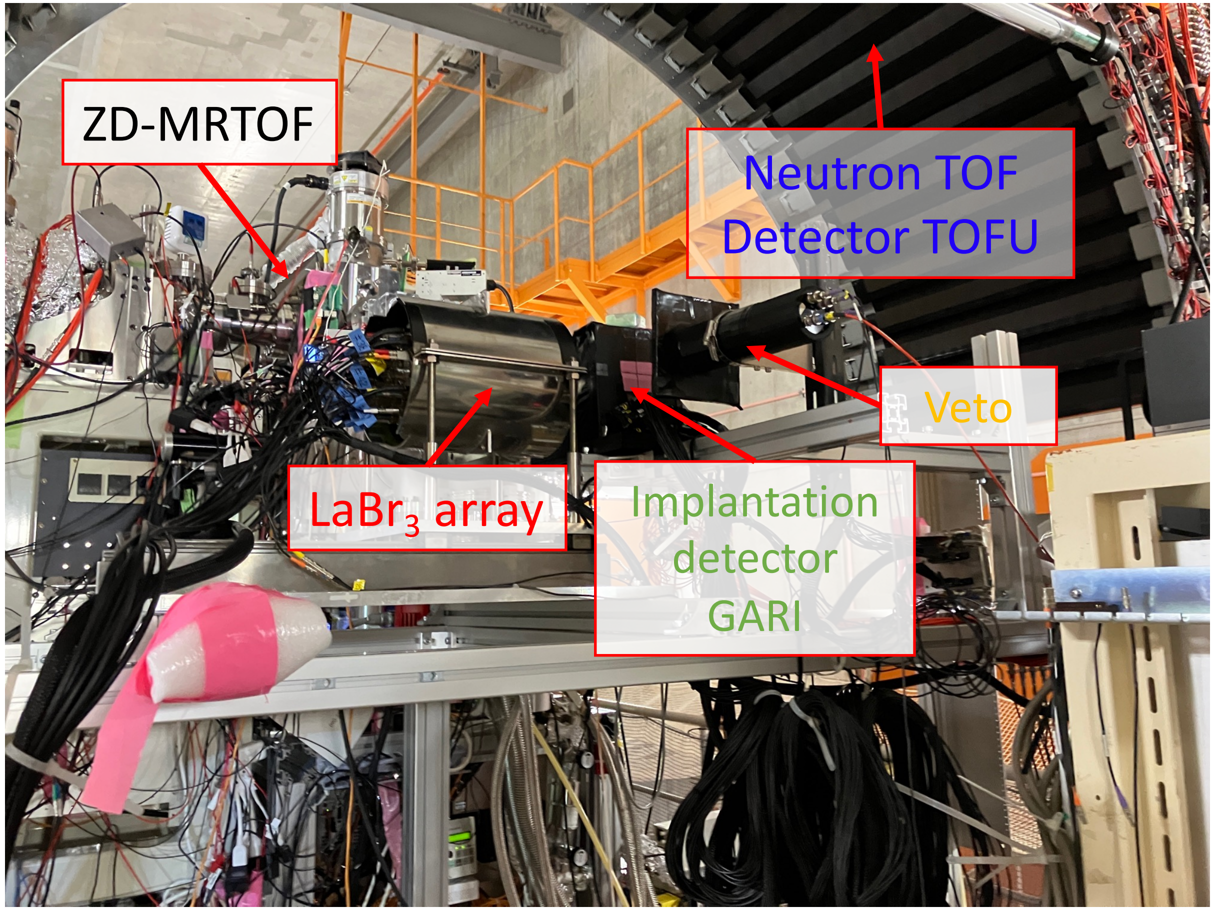


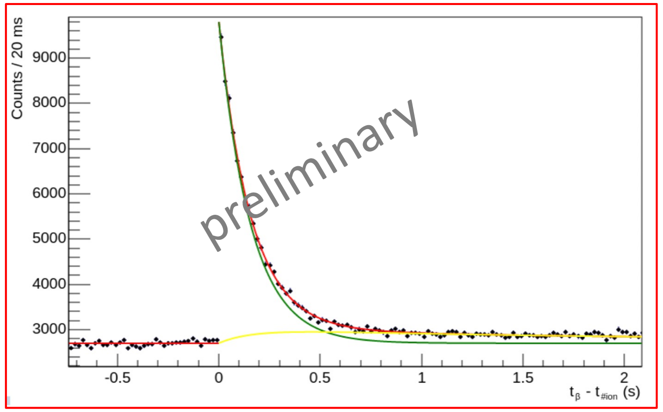
Beta hit pattern (^{90}Sr source)

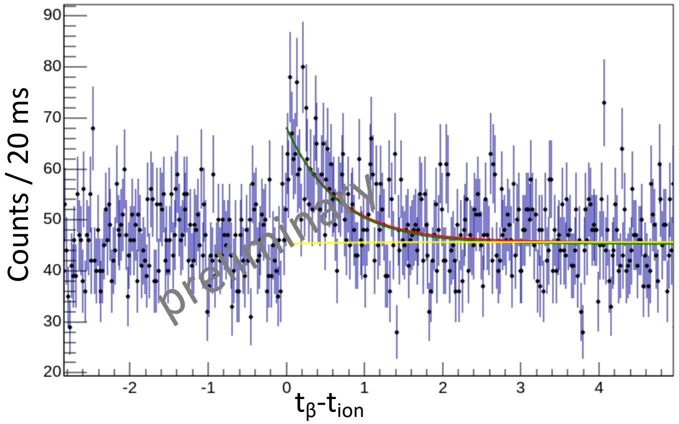


Preliminary results from a parasitic experiment and future experiment with new β-decay station

- ✓ Several test experiments in parasitic mode have been recently performed.
- ✓ In-beam/transmission cross-section, mass and β-decay spectroscopy using same beam => Efficient use of RI beam.







1. Nudat3
2. I. Cox et al., PRL **132**, 152503 (2024)
3. Z. Y. Xu *et al.*, PRL **133**, 042501 (2024)

Summary and perspectives

- ❖ $T_{1/2}$ and P_{xn} were studied for wide range of neutron-rich nuclei spanning mid-shell region $50<N<82$
- ❖ Odd-even staggering effects can be seen: Awaiting further investigations.
- ❖ The results provide benchmarks for development of theoretical β-decay models.
- ❖ Preliminary astrophysics impacts are presented
- ❖ New β-decay station in tandem with the mass measurement program at RIKEN RIBF

Thank you for your attention!

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β-Delayed One and Two Neutron Emission Probabilities South-East of ^{132}Sn and the Odd-Even Systematics in *r*-Process Nuclide Abundances

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