Measuring Radioactive Decay Without Detecting the Light Decay Particle(s)

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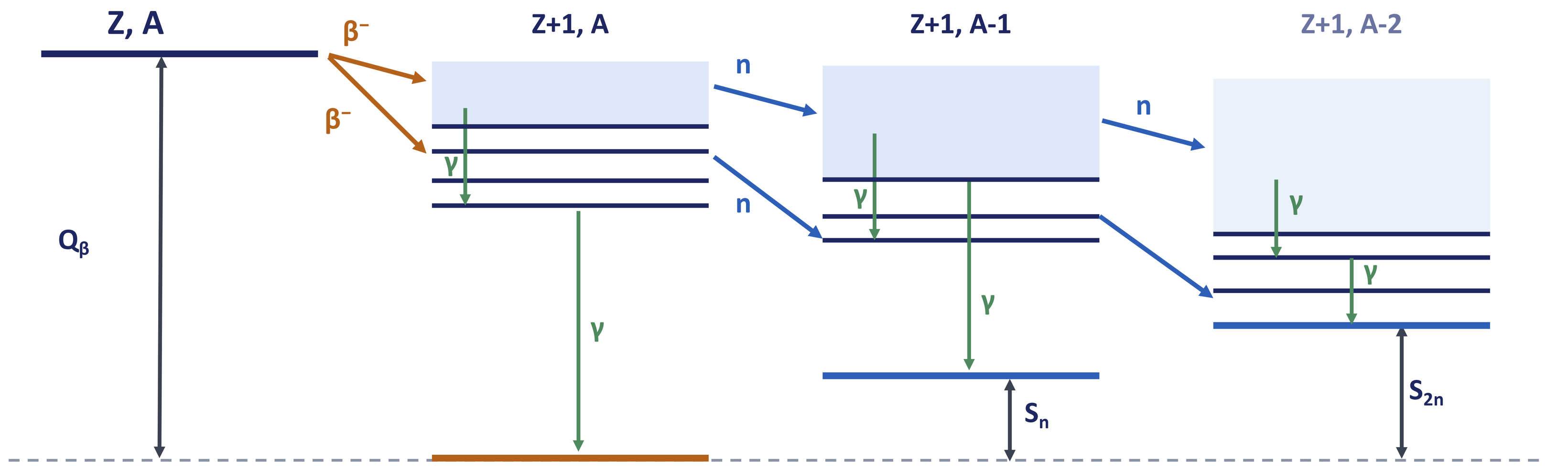
1 What is β-delayed neutron emission?

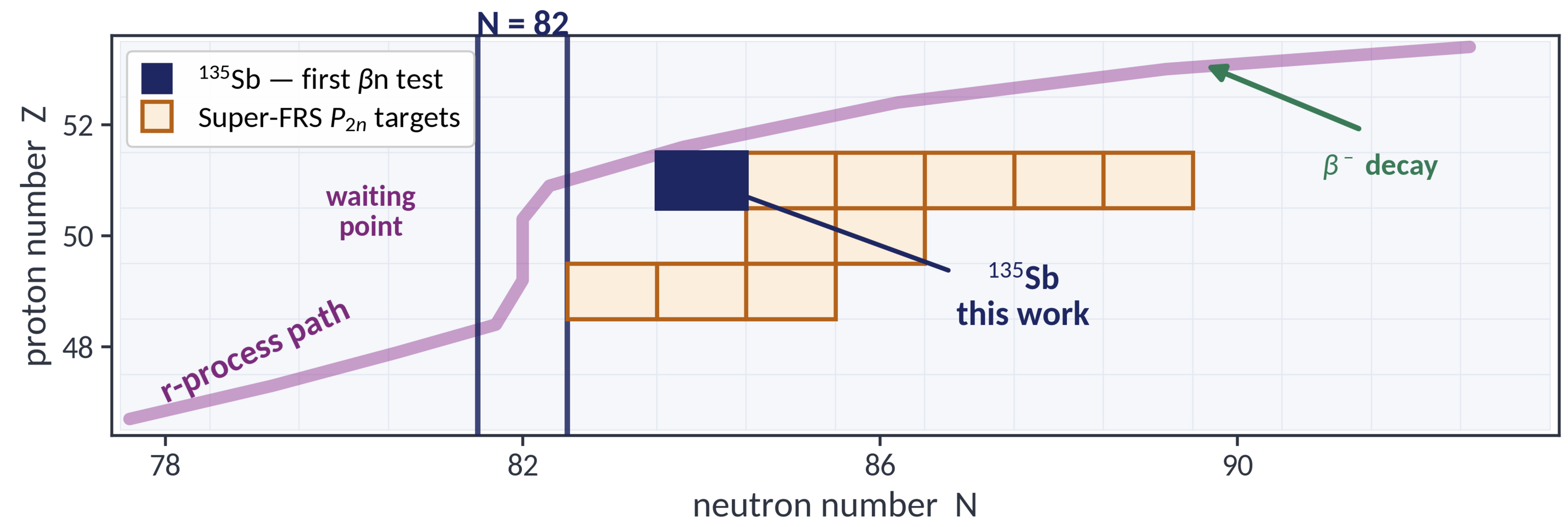
- β^- decay of a very neutron-rich nucleus populates excited states of the daughter. If the excitation exceeds the neutron separation energy (possible when $Q_\beta > S_{xn}$), a neutron can be emitted instead of a γ ray.
- **P_{xn}** — the probability for x neutron emissions following a β decay — rises towards the neutron drip line, where Q_β grows and S_{xn} shrinks.



β decay populates states above S_n; the daughter then de-excites by neutron or γ emission.

2 Why does P_{xn} matter for the r-process?

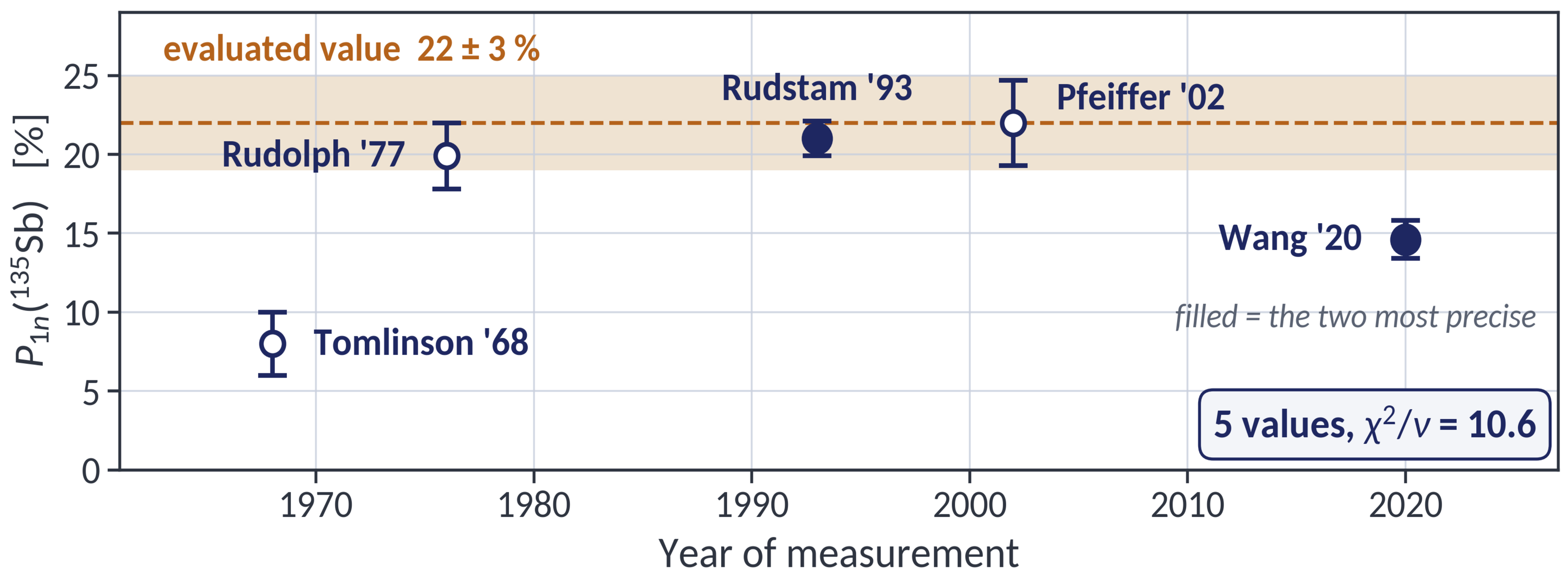
- Roughly half of all nuclei heavier than iron are built by the r-process. After freeze-out the material β-decays back towards stability, and every delayed neutron shifts that chain by one mass unit.
- P_{xn} therefore sets where the chains land and how many neutrons are released for late recapture, shaping the abundance pattern around the A ≈ 130 peak — exactly the Sn–Sb–Te region measured here.



Schematic r-process path through the N = 82 region, with the nuclei this method targets.

3 The problem: neutrons are hard to count

- P_{1n} is known for only ~49% of eligible fission products, P_{2n} for ~8% [4].
- Detection efficiency for x coincident neutrons scales as ε_n^x and depends on the neutron energy itself.
- The five published $P_{1n}(^{135}Sb)$ values (most recent)[5] are mutually inconsistent: $\chi^2/\nu = 10.6$ for ν = 4 ($p \approx 10^{-8}$) — systematic, not statistical.



All published $P_{1n}(^{135}Sb)$ values, 1968–2020, against the evaluated value.

4 The idea: count daughters, not neutrons

The parents are stopped in helium gas and held for a storage time t_s. β decay leaves the daughter at mass A; β-delayed neutron emission leaves it at A−1. The neutron is never detected — it signs its presence by the missing mass unit. For ^{135}Sb only x = 0 and 1 are open; over the 2 s storage ^{134}Te is stable while ^{135}Te loses ~4%, an exactly calculable correction.

$$P_{xn} = D_x(t_s) \,/\, \Sigma_i D_i(t_s)$$

where $D_x(t_s)$ is the number of daughters counted after storage time t_s following emission of x neutrons; the sum runs over all open channels (x = 0, 1, 2, …).

- Both daughters are isotopes of the **same element** (^{135}Te and ^{134}Te here), so stopping, extraction and detection efficiencies cancel in the ratio.
- One daughter is just as easy to count for one, two or three emitted neutrons — no ε_n^x penalty. Masses, $Q_{\beta xn}$ and half-lives come from the same data.

5 The instrument: FRS Ion Catcher at GSI

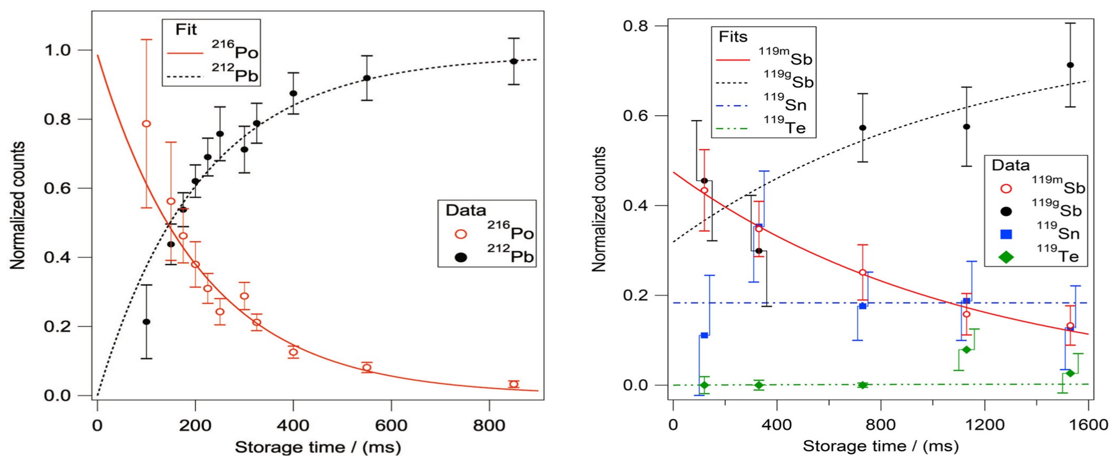
- **FRS** (Fragment Separator) — in-flight production and separation of fission products
- **CSC** (Cryogenic Stopping Cell) — stops and thermalises the ions in helium gas [2]
- **RFQ** (Radio-Frequency Quadrupole) beamline — transport, cooling and mass filtering
- **MR-TOF-MS** — identifies and counts every species; resolving power up to 10^6 [3]

Storage in the CSC: the parents are held in the cell for a time t_s and decay in place; parents and daughters are then released together for mass analysis.

Schematic of the FRS Ion Catcher beam line.

6 Method already validated on published data

- **α decay:** ^{216}Po → ^{212}Pb: parent decay and daughter in-growth followed against storage time, returning the known half-life [1].
- **Isomeric transition:** all open channels of ^{119m2}Sb tested at once; first direct proof that it decays 100% by internal transition [1].

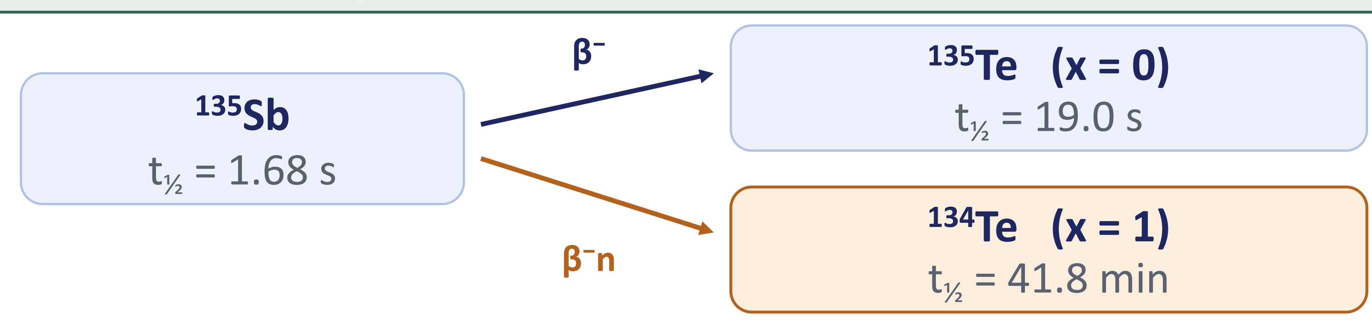


Measured decay-and-growth curves, Miskun et al. (2019) [1].

7 First βn test: ^{135}Sb

- ^{135}Sb ($t_{1/2}$ = 1.68 s): $\beta^- \rightarrow {}^{135}$Te (x = 0); $\beta^-n \rightarrow {}^{134}$Te (x = 1) — both daughters are isotopes of tellurium.
- Within FAIR Phase-0 experiment G-22-00027: ^{135}Sb produced by ^{238}U in-flight fission and stopped in the CSC.

Established in this run: storage in the CSC commissioned and synchronised with the beam spill; the internal ^{252}Cf background shown to be independent of storage time, so it cancels in the storage-on/off comparison; ^{135}Sb identified and counted. P_{1n} extraction in progress, collaboration review pending.



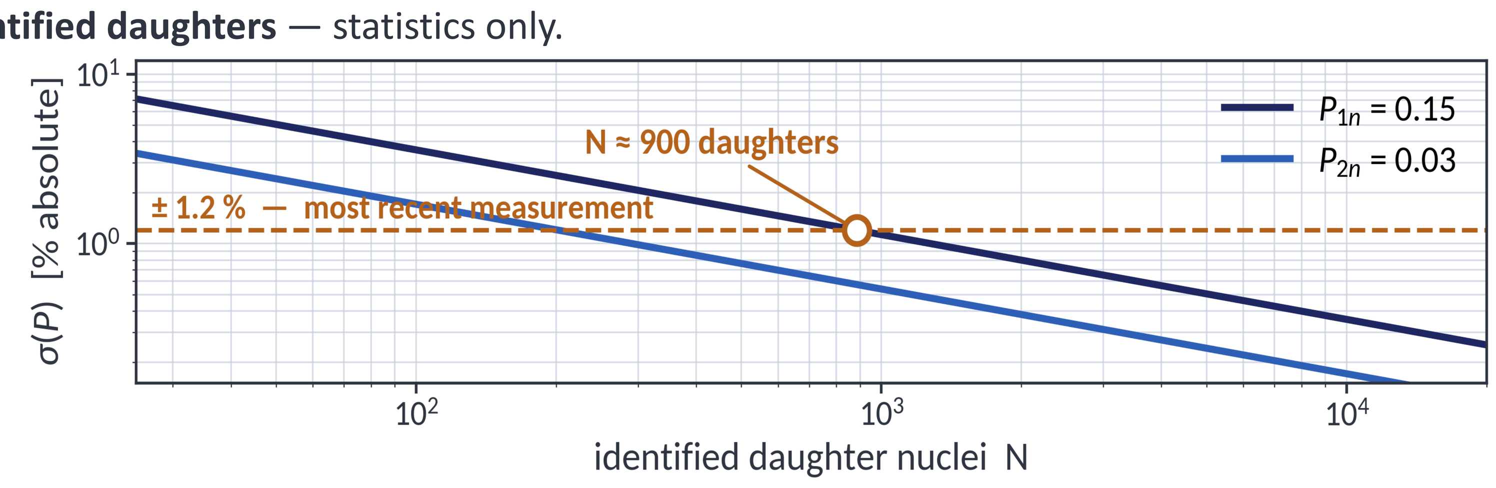
The two decay branches of ^{135}Sb, separated by one mass unit.

8 Stress-testing the ratio: systematics

- **Mass-dependent extraction across ΔA = 1:** same element, one mass unit apart — stopping, extraction and transport efficiencies are common-mode and divide out.
- **Isobaric and molecular contamination at A = 134, 135:** ^{134}Xe, ^{134}I and ^{134}Te are resolved at the $R \approx 6\times10^5$ achieved in this run, but their tails overlap; a simultaneous multi-peak fit is mandatory. Hydrides are resolved too: $^{134}TeH^+$ sits 2.7 mmu from ^{135}Te — 12 FWHM at this resolving power — and is fitted out.
- **In-beam ^{134}Sb:** it β-decays to the signal isotope ^{134}Te, but it is resolved in the same spectrum, so its contribution is subtracted using its known half-life.
- **Direct FRS production of Te and source background:** quantified in the no-storage reference run and by the storage-time independence of the ^{252}Cf source.

9 What the method can deliver

Precision is binomial: $\sigma(P) = \sqrt{P(1-P)/N}$. Matching the most recent measurement needs **N ≈ 900 identified daughters** — statistics only.



Statistical reach of the daughter-counting ratio.

- At the Super-FRS Ion Catcher (FAIR Early Science) the rates are more than 1000× those of this first test, putting P_{2n} of $^{132–134}$In, ^{135,136}Sn and $^{136–140}$Sb, several for the first time, within reach.

Takeaway: a β-delayed neutron measurement that never detects a neutron. The storage-and-count sequence is already validated on published α and isomeric-transition data and has now been run end to end on a β^-n case. Because the observable is a ratio of two daughter masses of the same element, it is free of neutron-detection efficiency and it does not degrade for two or three neutrons, which is where the database is emptiest.

References & acknowledgements

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Based on experiment G-22-00027, performed at the FRS at GSI Helmholtzzentrum für Schwerionenforschung (Darmstadt, Germany) in the context of FAIR Phase-0.

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