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Bound-state β^- decay of $^{205}Tl^{81+}$ clarifies ^{205}Pb dating in the early Solar System

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^{205}Pb is a crucial Short-Lived Radionuclide (SLR, nuclei with $t_{1/2}$ = 1 – 100 My) that can constrain formation times and active nucleosynthesis in the Early Solar System (ESS). Production of ^{205}Pb in Asymptotic Giant Branch (AGB) stars depends on the bound-state β-decay of ^{205}Tl [1]. The half-life for fully stripped $^{205}Tl^{81+}$ was measured at GSI Darmstadt in the Experimental Storage Ring (ESR) to be 291^{+33}_{-27} days. The corresponding isolation time for the ESS was consistent for the first time.

Bound state β^- decay of ^{205}Tl

- Bound-state β^- decay (β_b decay) occurs in highly charged ions and can change the stability of a nucleus.
- The β-electron is created directly in a bound atomic orbital of the daughter nucleus instead of being emitted into the continuum in normal β decay (Fig 1).

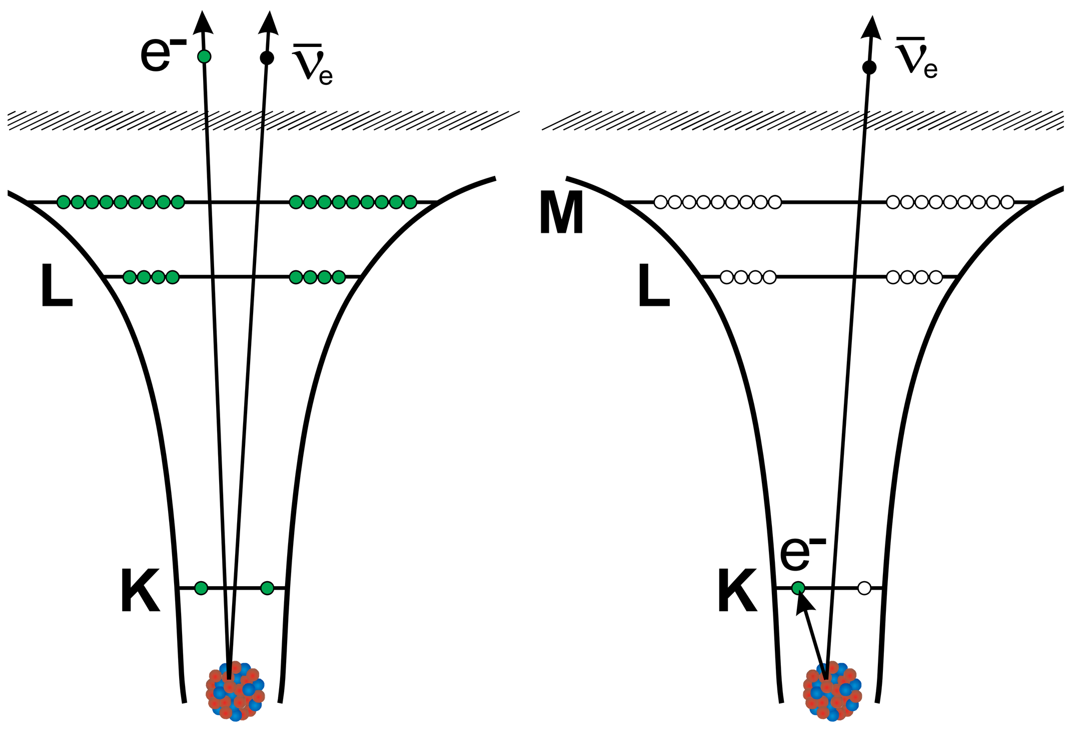

Fig 1: normal (left) vs bound-state β-decay (right)

- Terrestrially, $^{205}Tl^{0+}$ is stable and ^{205}Pb decays via electron capture with $t_{1/2}$ = 17.3 My.
- When ^{205}Tl is fully stripped to the 80/81+ charge state, β_b decay is possible.
- The binding energy of the K-shell is saved, making the Q-value positive.

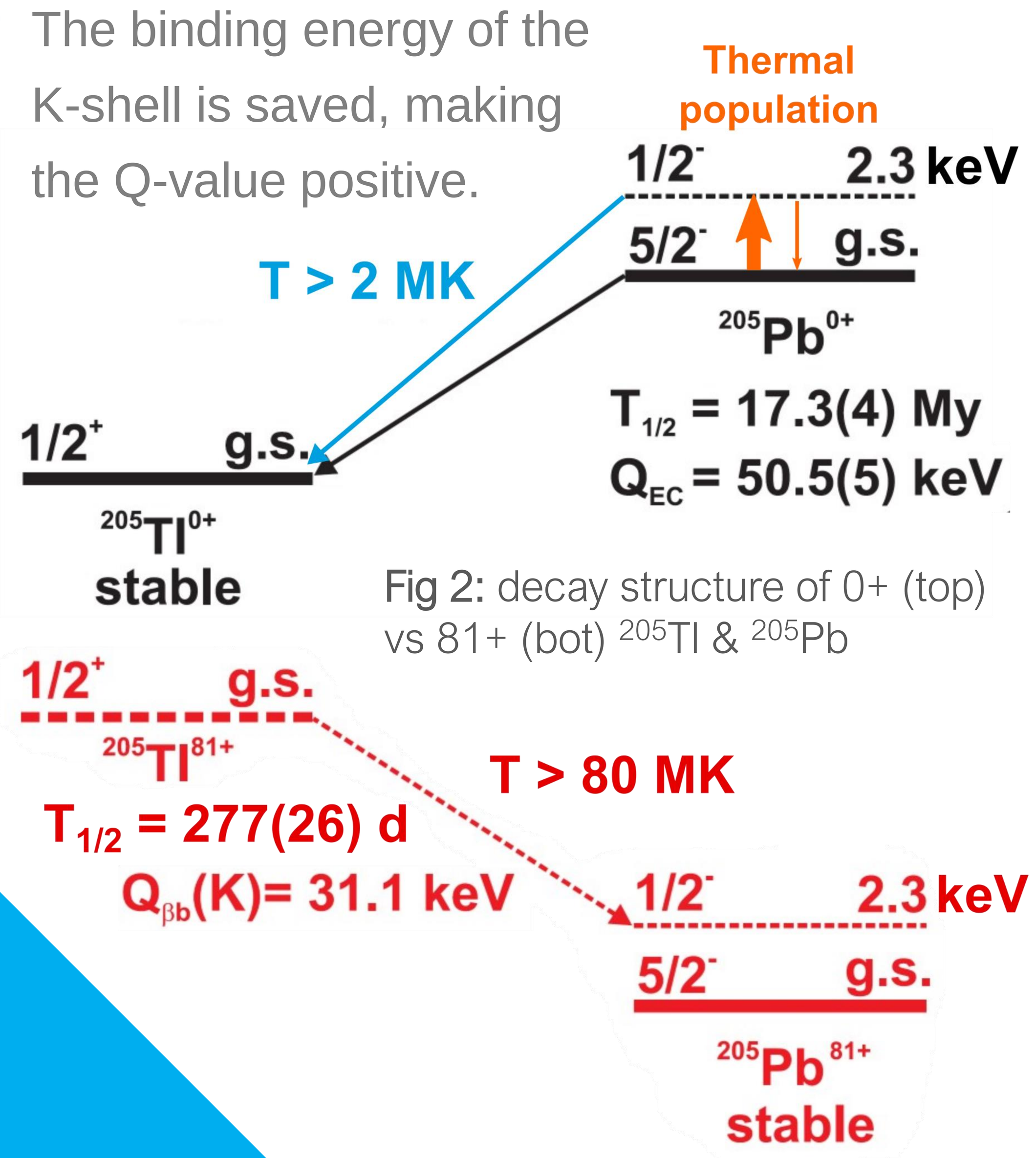

Fig 2: decay structure of 0+ (top) vs 81+ (bot) ^{205}Tl & ^{205}Pb

$^{205}Tl^{81+}$ Decay Experiment

- $^{205}Tl^{81+}$ ions were created via fragmentation of ^{206}Pb primary beam, then stacked in ESR.
- Ions were stored in the ESR for 0 – 10 hours allowing the $^{205}Tl^{81+}$ ions to decay to $^{205}Pb^{81+}$.
- Ions were monitored with Schottky detectors that non-destructively track the ion intensity.
- Longer storage times produced more ^{205}Pb daughter ions. Linear fit gives the half-life of $\mathbf{291^{+33}_{-27}}$ **days** or a **log-**$\boldsymbol{ft} = \mathbf{5.91(5)}$ (Fig 3).

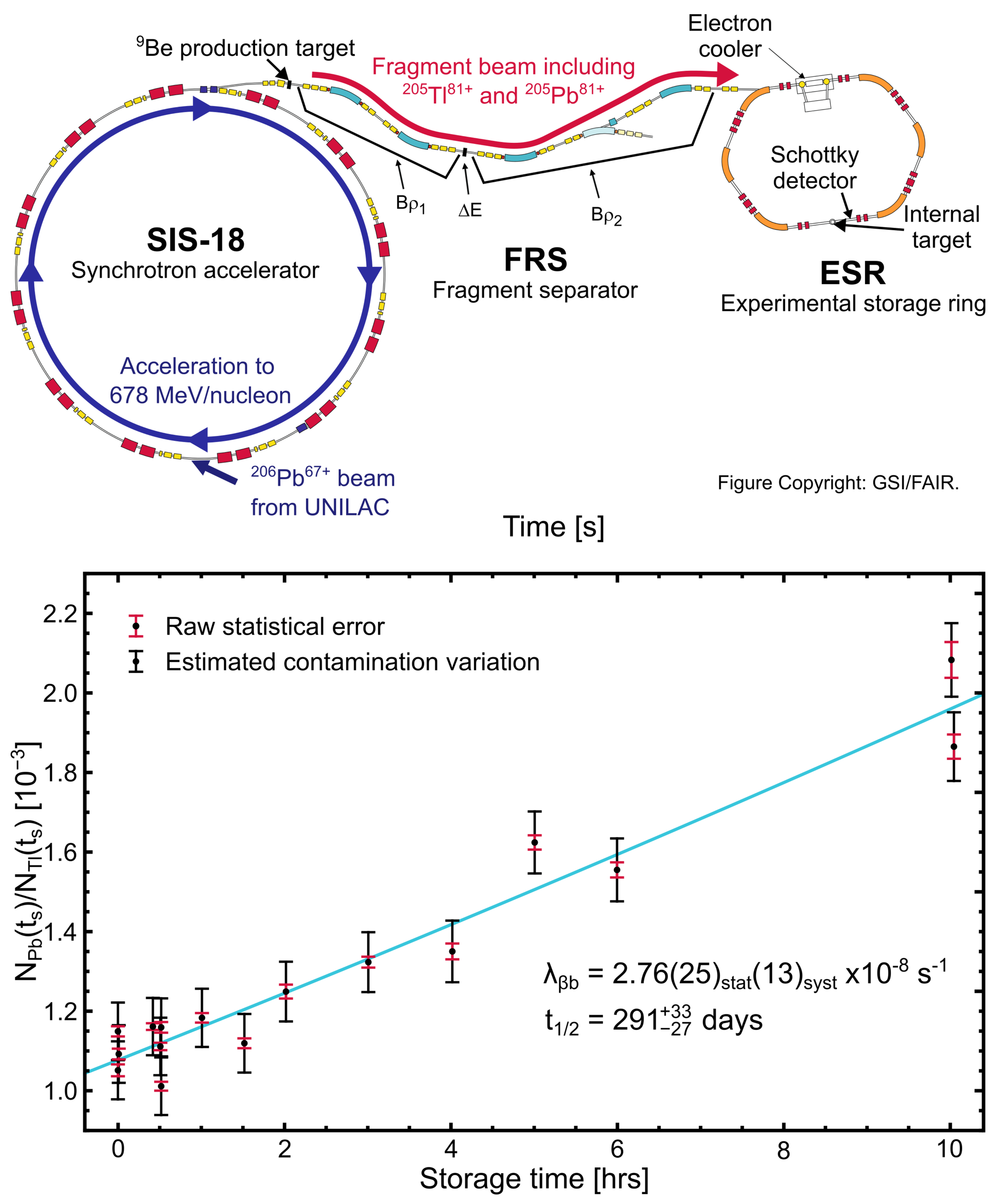

Fig 3: bound-state β-decay experimental setup and fit

Theory estimates log-ft values of 5.3 [3], 5.4 [4], 5.7 [5] and 5.1 [6] due to no knowledge of the nuclear matrix element of the decay. Our measured value is larger than any estimate.

^{205}Pb in the Early Solar System

- Meteorites preserve isotopic ratios from the ESS when they formed.
- SLRs are used to constrain the isolation time of the solar system from its parent nebula [2].
- ^{205}Pb is the only SLR produced exclusively by the s-process (Fig 4).

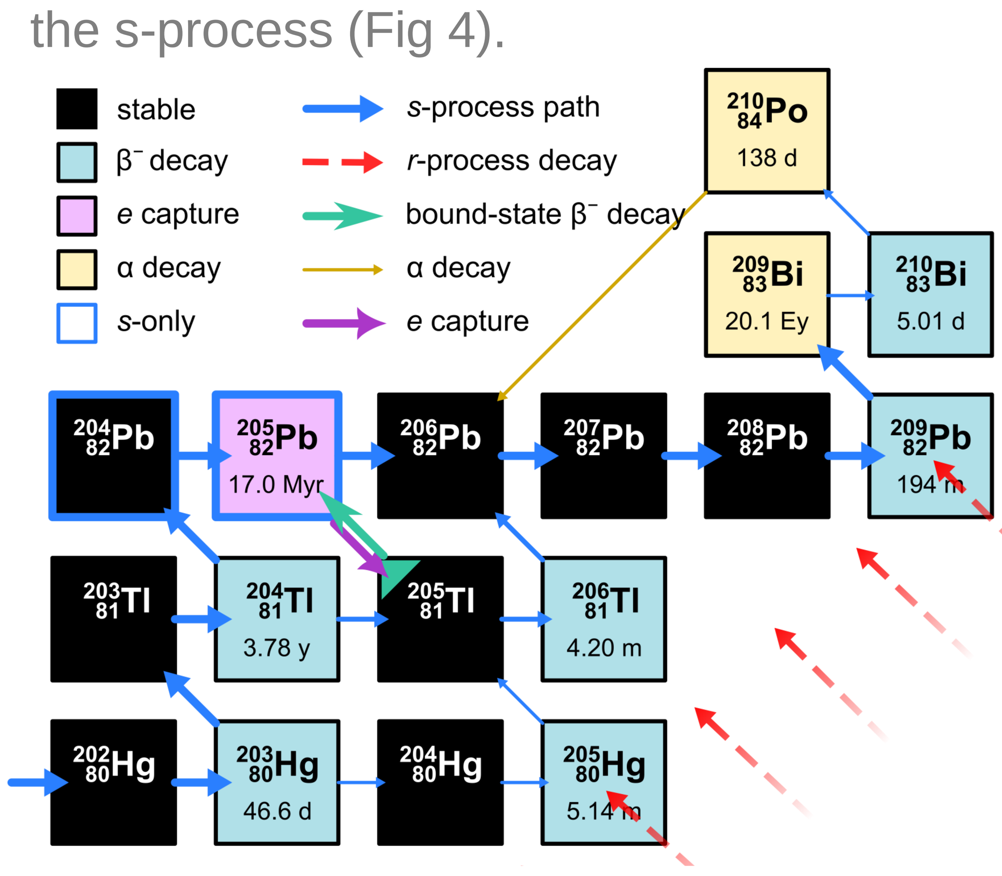

Fig 4: ^{205}Pb and the s-process termination point

^{205}Pb in Thermally-Pulsing Asymptotic Giant Branch stars

In AGB stars where ^{205}Pb is produced, there are two important *s*-process sites:

1) **^{13}C pocket – T ~ 90 MK.** All ^{205}Pb that is produced in the ^{13}C pocket decays due to thermal population of 2.3 keV excited state.
2) **He shell flash – T ~ 250 MK.** At such high temperatures, ^{205}Tl is stripped bare and decays via bound-state β-decay to ^{205}Pb. However, ^{205}Pb must survive until the third-dredge up for it to be mixed into envelope.

See **poster by T. Neff** for calculation of the astrophysical weak decay rates.

Using new experimental weak rates, we:

- Ran Monash, FUNS, and NuGrid models of AGB stars to calculate ^{205}Pb yields.
- Used AGB yields to determine steady-state abundance of ^{205}Pb in the Interstellar Medium.
- Compared $^{205}Pb/^{204}Pb$ ratio in ISM vs the ESS meteorite ratio to calculate the isolation/ collapse time of the solar gas parcel from its parent molecular cloud.
- Probability distributions for the isolation time form 3 s-process SLRs are shown in Fig 5.
- Our results produce consistent and positive isolation values for the first time, suggesting ^{205}Pb could be used as an ESS chronometer.

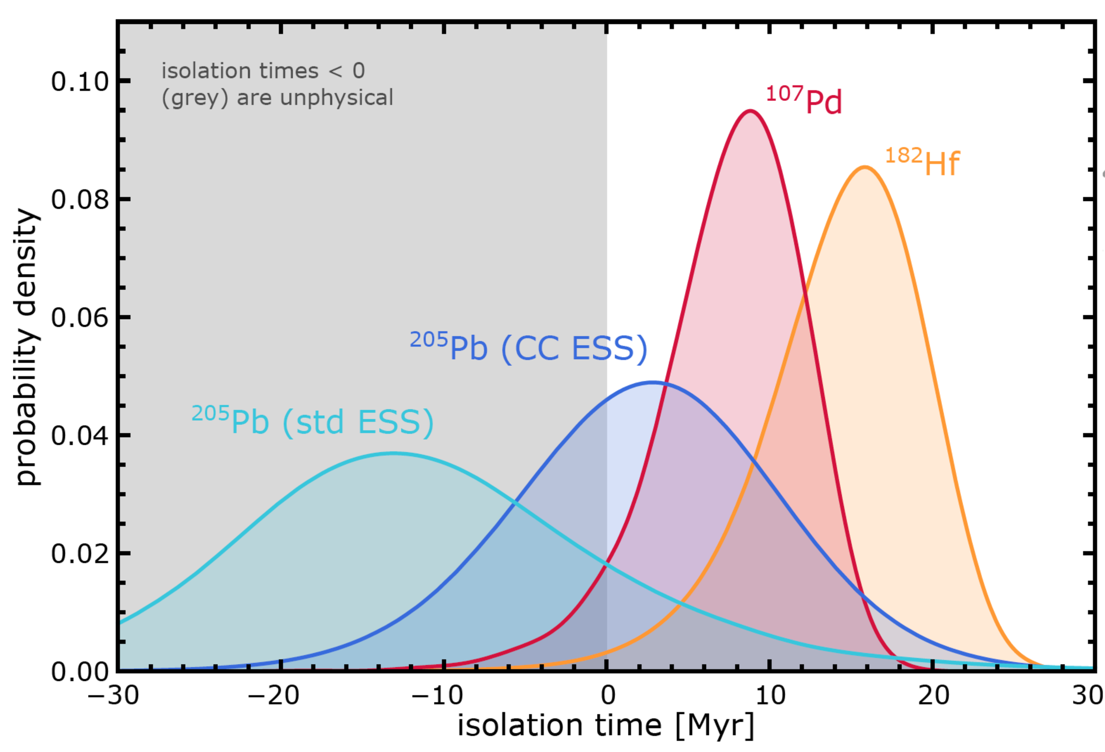

Fig 5: calculated isolation time for *s*-process SLRs. Distributions include stochastic ISM enrichment and meteorite uncertainties. Standard vs Carbonaceous Chondrites are two possible meteorite values [7,8].

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