# Measuring the Bound-State Beta-decay Rate of Thallium-205

Guy Leckenby,[1,2] Iris Dillmann,[1,3] and Christopher Griffin[1]
[1]TRIUMF [2]University of British Columbia [3]University of Victoria
Contact: gleckenby@triumf.ca

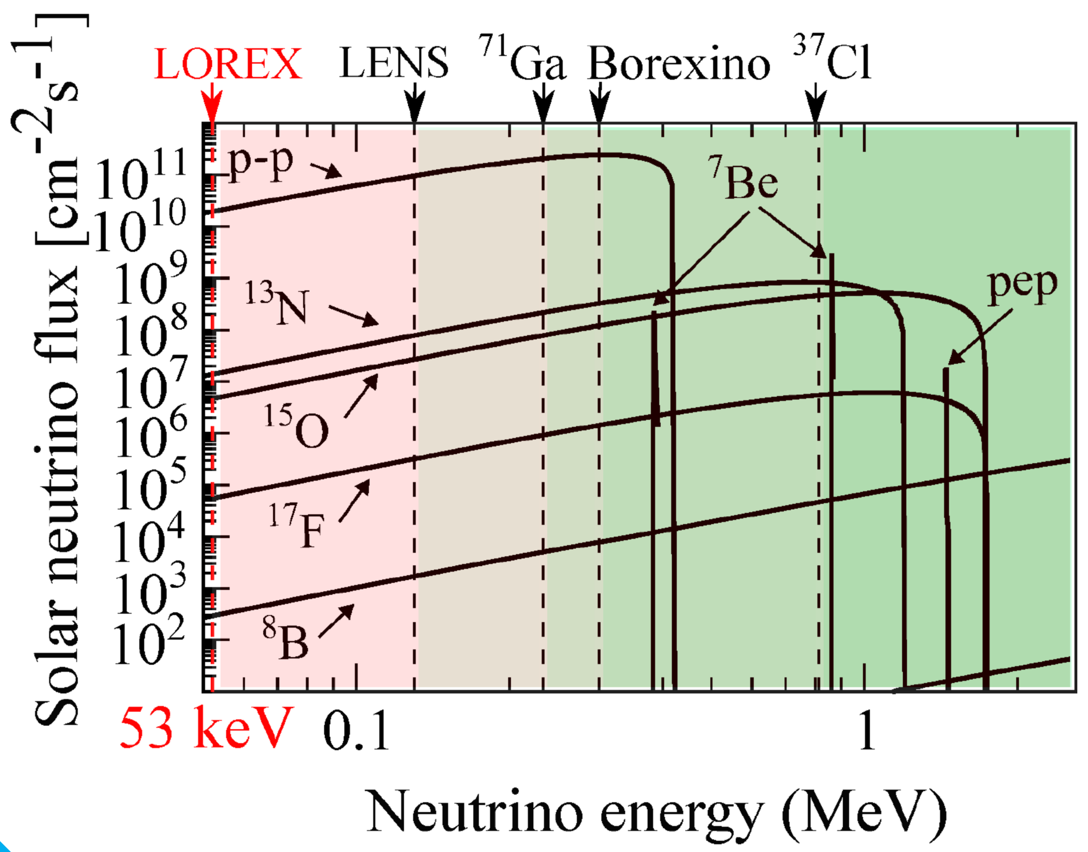
**Bound-state beta-decay** ($\beta_b^-$-decay) is an exotic decay mode where the ejected electron is emitted directly into an orbital of the daughter atom. It is a very interesting decay mode because it can **change the stability** of Highly Charged Ions (HCIs). This has revolutionised specific astrophysical applications. Two examples are highlighted next.

## LOREX Neutrino Flux

The $\beta_b^-$-decay of $^{205}Tl$ is crucial for a very exciting measurement of ultra-low-energy solar neutrinos via activation of the **thallium-bearing mineral lorandite**. The LOREX experiment measures $^{205}Pb$ accumulation to measure neutrino flux from neutrino capture:

$$^{205}Tl^{0+} + \nu_e(53\ keV) \rightarrow {}^{205}Pb^{0+,*} + e^-$$

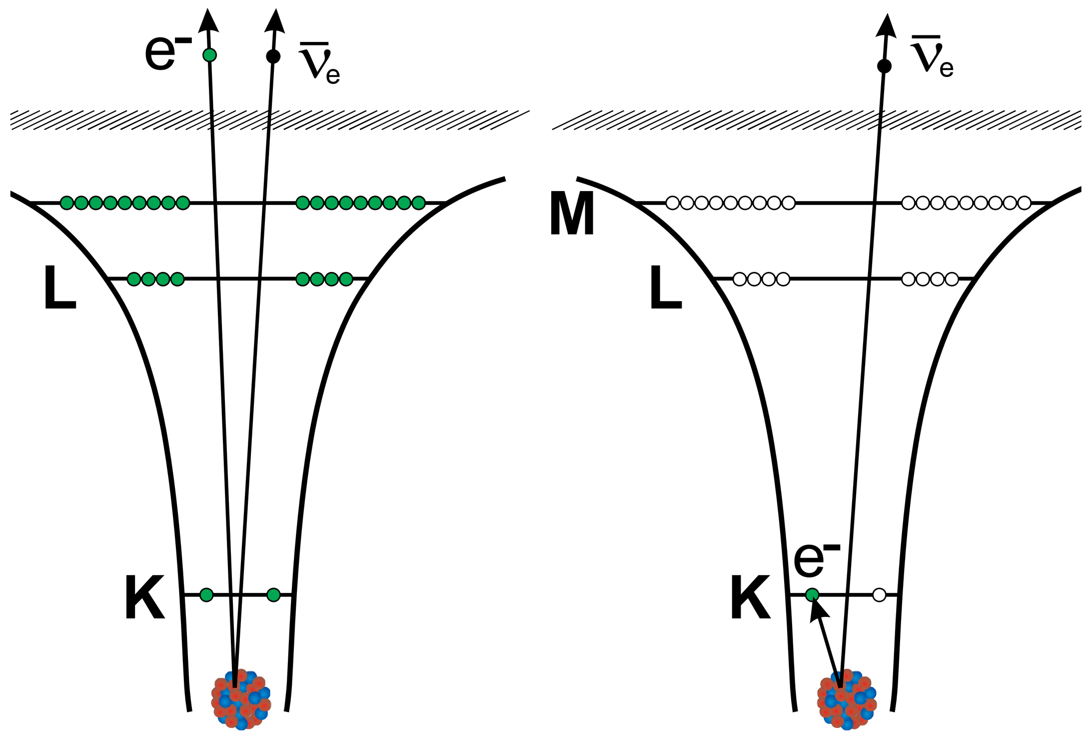
Because the neutrino capture reaction rate is unmeasurable, we need the **beta-decay nuclear matrix element** of $^{205}Tl$ for LOREX to succeed. Only the $\beta_b^-$-decay of $^{205}Tl$ can measure this because neutral $^{205}Tl$ is stable.




The low-energy solar neutrino spectrum, including energies probed by other neutrino activation experiments.
K.M. Subotic et al., AIP Conf. Proc. 455 (1998) 912
M.K. Pavicevic, Nucl. Inst. Meth. A 895 (2018) 62

## S-process Chronometer

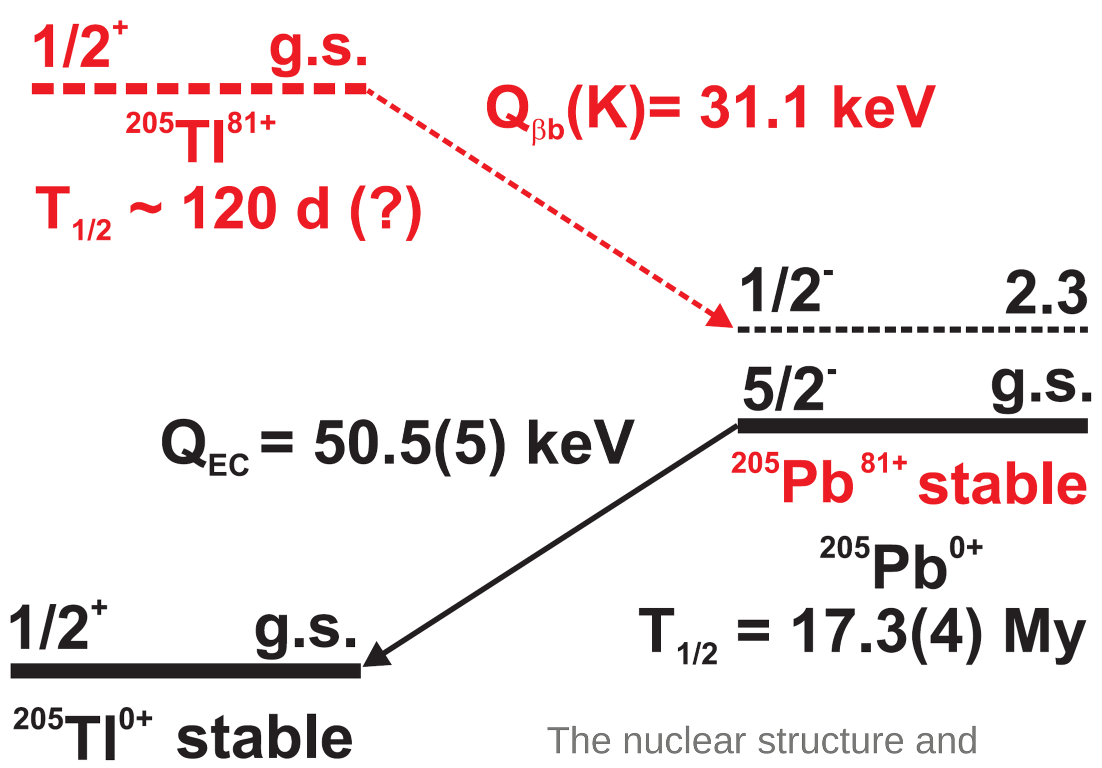
$^{205}Pb$ is an s-only isotope that is very valuable as a chronometer for early solar system formation, but we need to clarify the precise back-decay of $^{205}Tl$ in extreme environments.




Continuum beta-decay (left) ejects the electron vs bound-state beta-decay (right) where the electron is captured. $\beta_b^-$-decay is considered the time reverse of electron capture.

## Nuclear Structure of $^{205}Tl$

For bare ions, the Q-value of the beta-decay is increased by the K-shell binding energy causing some nuclei that are **stable in the neutral state to be radioactive in highly charged states**.




The nuclear structure and decay scheme of $^{205}Tl$ & $^{205}Pb$.

Image courtesy of Ragandeep Singh Sidhu (GSI).

## Storage Rings for Highly Charged Radioactive Ions

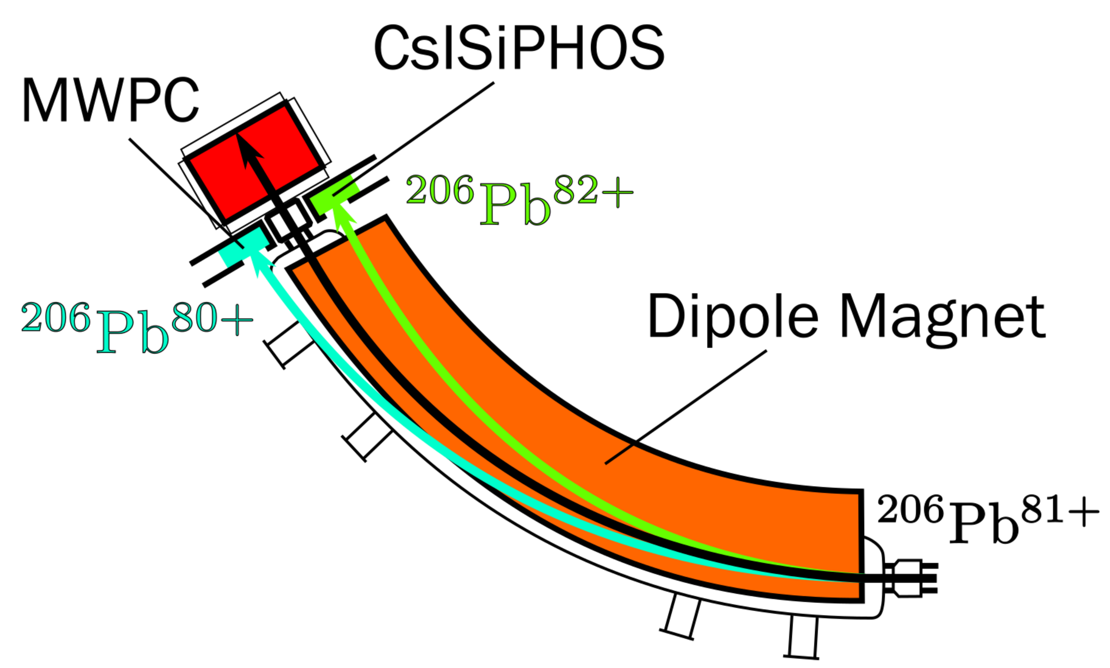
Highly Charged Ions (HCIs) will recombine upon contact with any matter. Storage rings are the only systems capable of **storing HCIs for hours** with ulta-high vacuum conditions. The Experimental Storage Ring (ESR) at GSI, Darmstadt is currently the only ring capable **of storing radioactive beams**. A $\beta_b^-$-decay measurement has two parts, the electron stripping correction and the storage + decay counting.

$$\frac{N_{Pb}(t_s)}{N_{Tl}(t_s)} = \frac{N^{+}_{Pb}(t_s)}{N_{Tl}(t_s)} \cdot \frac{\sigma_+ + \sigma_-}{\sigma_+} = \frac{\lambda_{\beta_b}}{\gamma} t_s \cdot \left[1 + \frac{1}{2}(\lambda^{cc}_{Pb} - \lambda^{cc}_{Tl}) t_s + \cdots\right]$$

### Part 1: Charge-Changing Cross Section Measurement

$\beta_b^-$-decay daughters have the same mass-charge ratio as parents; therefore, we cannot separate them in the storage ring. To count decay products, we need to **strip off the bound electron** with a gas target. Thus, we need to correct for daughters lost via electron capture. The charge-changing cross-section was measured with a hydrogen-like $^{206}Pb^{81+}$ beam.

- Electron **loss** products counted by CsISiPHOS detector on inner side of ring.
- Electron **capture** products counted by MWPC detector on outer side of ring.

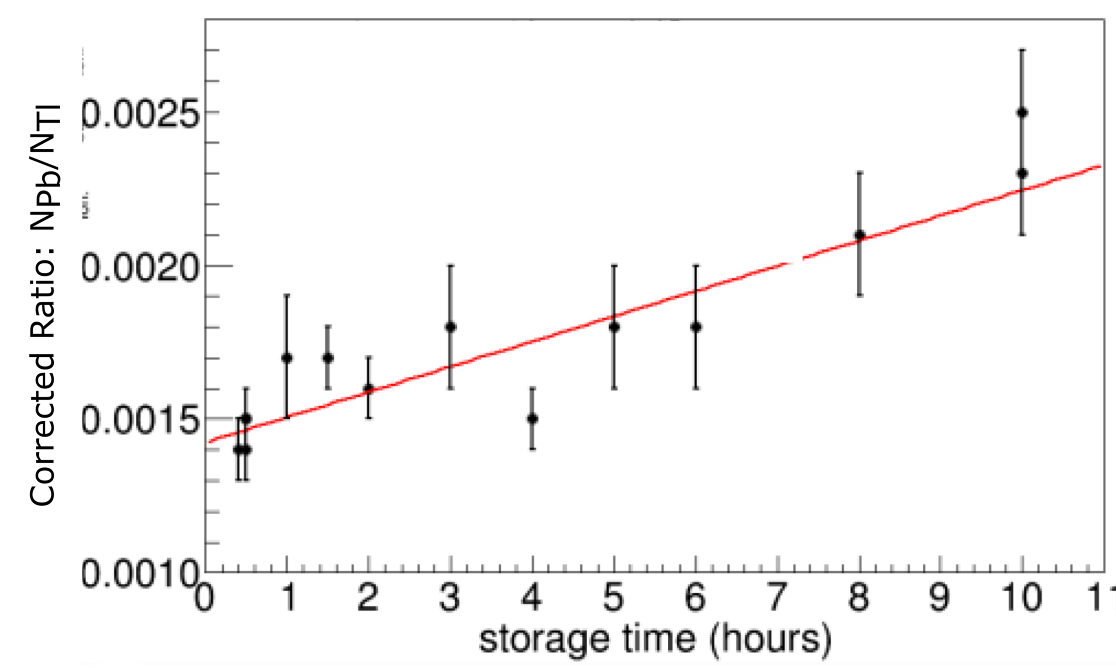



$^{206}Pb^{81+}$ beam impinged on Ar gas target causing electron capture and loss. These products are separated at the next dipole magnet for counting.

### Part 2: 205Tl Storage & Decay Ratio Counting

To measure the decay of $^{205}Tl$, over 100 injections from the FRagment Separator (FRS) are accumulated in the ESR. The $^{205}Tl$ beam **circulates for several storage periods**, between 0 – 10 hours. $^{205}Pb$ decay products are then stripped with an Ar gas target, and the intensity ratio of $^{205}Pb/^{205}Tl$ is measured.

Plotting this ratio (correcting for various losses in the ring) indicates accumulation of $^{205}Pb$ with storage time; directly attributable to $\beta_b^-$-decay. The slope gives us our desired reaction rate.




Final corrected ratio of decay products. Decay rate is extracted from the slope. Graph courtesy of Dr Rui Jiu Chen (GSI).

Discovery, accelerated