Geochemical Determination of the Solar pp-Neutrino Flux with LOREX: A Progress Report

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Abstract. LOREX (LORandite EXperiment) is a geochemical experiment addressing the solar (pp) neutrino flux for the period of 4.3 Ma from the reaction $^{205}Tl + \nu_e \rightarrow {}^{205}Pb + e^-$ with an unprecedentedly low threshold (52 keV) for solar pp-neutrino capture. A decisive step for this purpose is getting the precise, background-corrected ratio of $^{205}Pb/^{205}Tl$ in lorandite (TlAsS2). This report presents the status of major challenges being addressed, in particular the determination of the paleo-depth of lorandite, including the eroded layer over 4.3 Ma, as well as the choice of appropriate techniques for extraction, separation and quantitative determination of the ultra-low ^{205}Pb concentration in the extracted lorandite samples.

1. Introduction

The goal of LOREX [1] is the determination of the long-time average (over ~ 4 MY) of the solar pp-neutrino flux Φ_ν via the neutrino-capture reaction [2]:

$$^{205}Tl + \nu_e\ (\geq 52\ keV) \rightarrow {}^{205}Pb^* + e^- \quad (1)$$

with the unprecedentedly low threshold of $E_{\nu e} \geq 52$ keV for solar neutrino capture, and the precise, background-corrected determination of transmuted ^{205}Pb atoms in the thallium-bearing mineral lorandite

(TlAsS2) at the mine of Allchar. This geochemical experiment was proposed originally by Freedman [2]. The average neutrino flux Φ_ν over the exposure time *a* (age of lorandite since its mineralization) follows from the common activation equation:

$$\Phi_\nu = N^{-1} (T - B) (\sigma\varepsilon)^{-1} \lambda [1 - \exp(-\lambda a)]^{-1} \quad (2)$$

with *N*, the total number of ^{205}Tl atoms, *T*, the total number of ^{205}Pb atoms, *B*, the background-induced number of ^{205}Pb atoms [mainly from ^{205}Tl (μp, n) ^{205}Pb], *σ,* the neutrino capture cross section, *ε*, the overall detection efficiency, $\lambda = 4.00 \cdot 10^{-8}$/y the decay constant of ^{205}Pb, and $a = 4.3 \cdot 10^6$ y, the age of lorandite. This renders finally the *mean solar pp-neutrino flux, i.e. the mean luminosity of the sun during the last 4.3 million years, the geological age a of lorandite.*

The central problem of LOREX *is the quantitative determination of ^{205}Pb atoms in lorandite*. For this purpose three problems must be reliably addressed and solved:

1. Background, erosion and paleo-depth: The background of ^{205}Pb atoms produced by cosmic radiation and by natural radioactivity must be determined quantitatively. In this context, the knowledge of the *erosion rate* of the overburden rock during the existence of lorandite is of utmost importance.
2. Extraction, separation and detection of ^{205}Pb trace concentration: How can the expected ultra-low abundance of ^{205}Pb be reliably measured?
3. Solar pp-neutrino capture probability transmuting ^{205}Tl into ^{205}Pb

2. Recent advances in the research on the LOREX project

2.1 Background, erosion rate and paleo-depth

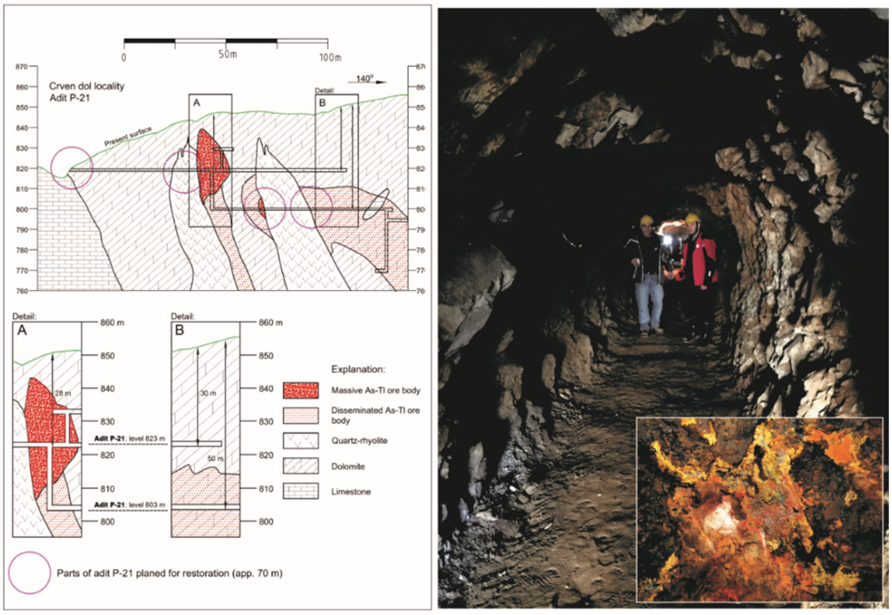
About 10 tons of lorandite have been extracted from ore body Crven Dol (Figures 1a, 1b and 1c). The separation of lorandite has been performed by crushing, hand-picking and cleaning of lorandite crystals, obtaining finally about 1 kg of 98 % pure lorandite grains that were controlled and quality-checked by means of SEM-EDX and ICP-MS methods.

The erosion rate has been determined by counting in situ radioactive atoms, yielding as minimal (from ^{3}He and ^{21}Ne) and maximal (from ^{26}Al and ^{36}Cl) erosion rates $E_{min} = 75\ m/(10^6\ y)$ and $E_{max} = 387\ m/(10^6\ y)$. From these data minimal and maximal paleo-depths of lorandite in Crven Dol were extracted: $d_{min} = 1390$ *mwe* (meter-water-equivalent), $d_{max} = 2330$ *mwe*, for an age $a = 4.3 \cdot 10^6$ y.

With the paleo-depth known, the amount of cosmic-ray (mainly muons) induced ^{205}Pb atoms could be calculated as function of the depth of the lorandite location (see Table 1). For the natural radioactivity the following values (in ppm) were figured out: U = 0.102(10), Th = 0.096(75) Bi = 0.008(2), Hg = 231(92). Finally, for the total lead concentration in lorandite a value 1.5(5) has been found.

2.2 Extraction, separation and detection of ultra-low amounts of ^{205}Pb in lorandite

Decisive steps of LOREX already started with the prospection and separation of lorandite from the Allchar mine (Figure 1), the extraction of thallium and lead (the mean concentration of lead in lorandite amounts to 1.5 ppm) and the quantitative determination of the ratio ^{205}Pb / ^{205}Tl sc. ^{205}Pb / Pb.



Figures 1a, 1b and 1c:1a Geological cross-section of ore body Crven Dol, 1b photograph of corridor in the ore body Crven Dol and 1c lorandite mineralization.

Table 1: Total contribution to N (^{205}Pb) from cosmic rays and from fast muons (μ) [3].

Depth of location (m)	Erosion rate (m/10^6 y)	Paleo-depth (mwe)	N(^{205}Pb) Fast muons 10^4 (1 kg lorandite)	N(^{205}Pb) Total 10^4 (1 kg lorandite)	N(^{205}Pb)$_\nu$ %	N(^{205}Pb)$_\mu$ %
28	75*	1390	8.1	10.3	21	79
28	387**	2330	1.7	3.9	56	44

**) Min erosion rate (^{3}He, ^{21}Ne)   **) Max erosion rate (^{26}Al, ^{36}Cl)*

After the last step of chemical separation, a lead matrix will be obtained, where the ^{205}Pb/Pb ratio is expected to range from 10^{-14} to 5 10^{-13}. Supposing a value of *146 SNU* for the solar neutrino capture rate (this number is based on the presently best *theoretical* value), the geological age *a* since the Tl-mineralization as $a = 4.3\ \ 10^6\ y$, the decay probability λ for the electron-capture decay of ^{205}Pb back to ^{205}Tl as $\lambda = 4.00\ \ 10^{-8}\ y^{-1}$ and a molar mass M of lorandite as M = 343 g / Mol, one gets for the expected time-integrated *number of solar pp-neutrino induced ^{205}Pb atoms* the value of 22(7) atoms of ^{205}Pb/g lorandite.

Identification of the ^{205}Pb nuclei in the lead sample extracted from the lorandite mineral requires from 10^{-10} to 10^{-11} overall detection sensitivity for ^{205}Pb/Pb and comparable suppression of the ^{205}Tl isobar [5]. This is proposed by full stripping of ^{205}Pb at high energy (345MeV/u) at the RIKEN-RIBF ion-beam facility. ^{205}Tl isobar separation is in principle already largely achieved by chemical Pb-Tl separation by the overall sample preparation. Samples with a higher concentration (^{205}Tl/natPb = 1%) are necessary for a guide-beam and initial accelerator tuning. A sample with a considerably lower level of about 10^{-8} is needed for control of the beam analysis system with ^{205}Tl ions, in the presence ultimately of a lighter guide beam, to limit the in-beam production of ^{205}Pb by the ^{205}Tl (p,n)^{205}Pb reaction in the energy-loss and ion-stripping steps in the accelerator and the subsequent BigRIPS/Mass-Ring. In this case, the whole approach then involves 4 steps: i) Establishing beam tuning and control for a trace beam with an 1% ^{205}Tl sample; ii) using the guide beam to confirm ^{205}Tl beam control, for the 1% and a ~10^{-10} Tl sample; iii) extension to a calibration sample with known ^{205}Pb concentration at the 10^{-13} level; iv) measurement of the ^{205}Pb neutrino sample. Test experiments to verify the various aspects of the proposed approach at the RIBF are under development.

2.3 Solar pp-neutrino capture probability into the 2.3 keV state of ^{205}Pb

The ratio ^{205}Pb/^{205}Tl provides *only the product* of solar neutrino flux and neutrino capture probability into the different nuclear states of ^{205}Pb. The capture of neutrinos should populate predominantly the first excited state at E* = 2.3 keV [4]. Its probability can be determined from the *bound-state β decay probability (β_b)* according to $^{205}Tl^{81+} \longrightarrow {}^{205}Pb^{*81+}$ (E* = 2.3 keV) + e^-_b + ν_{bar}, since this decay shares the same nuclear transition matrix element with the neutrino capture (cf. Figure 2)
The proposal for the measurement at the Experimental Storage Ring of GSI of the β_b decay of bare $^{205}Tl_{81+}$ to $^{205}Pb^{*81+}$′has been already approved by the international Program Advisory Committee. However, due to a long break of the GSI accelerators in course of the construction of the new FAIR facility, this experiment cannot be addressed before the year 2018.

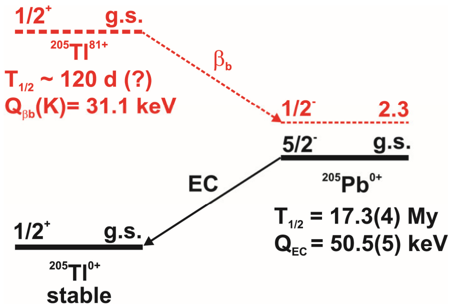


Figure 2: Decay schemes of neutral $^{205}Pb^0$ and of bare $^{205}Tl^{81+}$ via bound-state β decay (β_b)

3. Present status of LOREX and conclusions

Taking into account the present-day state-of-the-art of all the techniques needed to solve the main challenges of LOREX, and acknowledging the achievements of hard working during the last years concerning the determination of the erosion rate and of the background, as well as the development of a probably feasible scenario for the detection of the ultra-low ^{205}Pb concentration, we conclude that it seems realistic to expect the first result for the solar pp-neutrino flux averaged over the last 4.3 million years in the foreseeable future.

However, this assessment supposes that the β_b experiment –irrevocable for the precise knowledge of the solar pp-neutrino capture probability- could be (successfully) performed. The final number for the background-corrected amount of solar neutrino-induced ^{205}Pb atoms will have probably still a large error margin in the order of 30% (68% CL) or even more. We expect, however, that this accuracy could be improved with time, and that it might finally reach a level below 30%.

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