Long-tem solar neutrino flux and geological ^{205}Pb assay

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Motivation and Goals of LOREX

The central goal of the LOREX *LOR*andite *EX*periment (1) is the determination of the long-time average (over ~ 4 MY) of the solar neutrino flux Φ_ν with the neutrino-capture reaction [2]:

$$^{205}\mathrm{Tl} + \nu_e \rightarrow {}^{205}\mathrm{Pb} + e^- \quad \ldots [1]$$

As was pointed out originally (2), the thallium-bearing mineral lorandite, $TlAsS_2$, from the mine of Allchar, Macedonia. The average flux Φ over the exposure time (age of lorandite since its mineralization) follows from the common activation equation, where σ is the solar neutrino capture cross section and λ the decay constant of ^{205}Pb:

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

T – total number of ^{205}Pb atoms **B** – background number of ^{205}Pb atoms [^{205}Tl (μp,n) ^{205}Pb] **λ – decay constant of** ^{205}Pb **ε – overal detection efficiency σ – neutrino capture cross section.**

This renders the mean solar neutrino flux, i.e. *the mean luminosity of the sun during the* geological age of lorandite of *4.3 million years*.

Reaction [1] exploits the *by far* ***lowest threshold of*** $E_{\nu e} \geq 50$ ***keV*** for (solar) neutrinos.

The central problem of LOREX *is the quantitative determination of* ^{205}*Pb* atoms in lorandite. Before entering the final phase of the experiment, four problems must be reliably addressed:

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. 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. However, the capture of neutrinos should populate predominantly the first excited state at E* = 2.3 keV. Hence, to get the neutrino flux itself, one has to determine the capture probability into this low-lying state of ^{205}Pb.

3. Extraction, separation and detection of ^{205}***Pb trace concentration:*** *How can the expected ultra-low abundance of* ^{205}*Pb be reliably measured.*

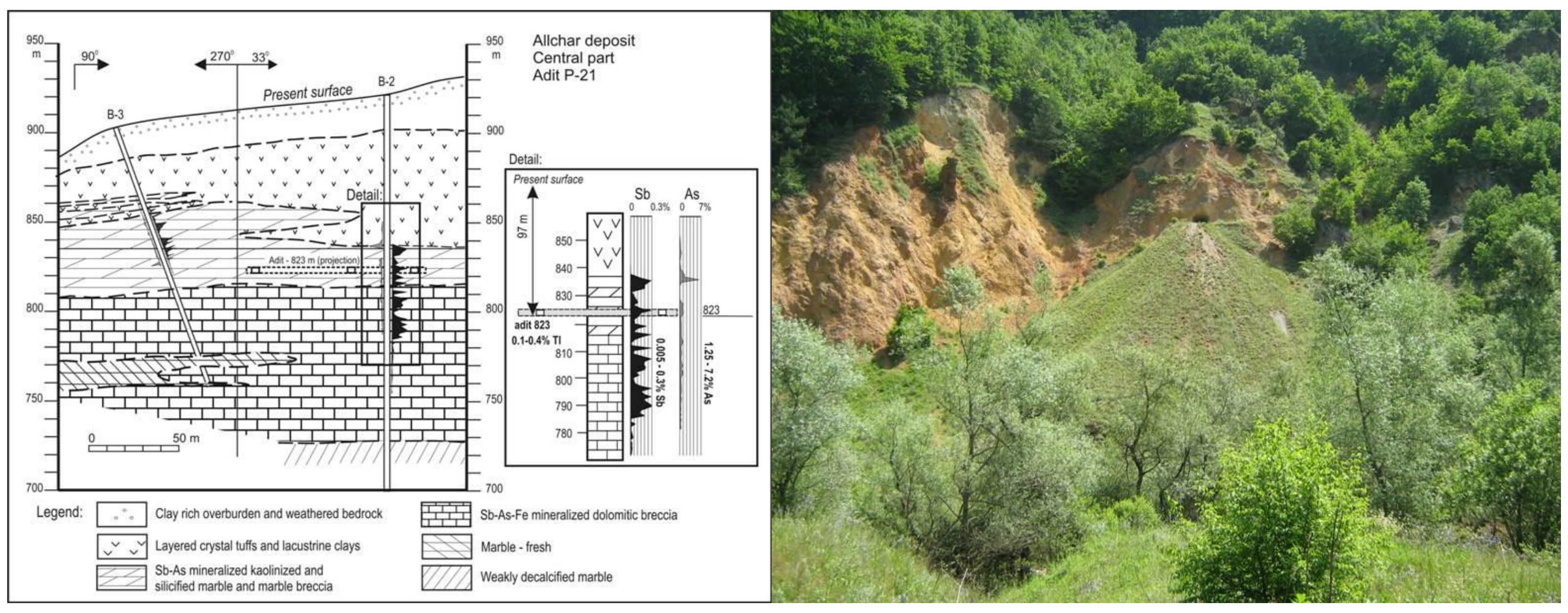

Fig. 1a and 1b: Geological cross-section and photograph of ore-body Crven Dol

1. Background reactions and erosion rate

In the case of LOREX more than 30 processes have been identified and analyzed which potentially contribute to the "background" of ^{205}Pb. After careful evaluation only four processes turned out which might have non-negligible contributions:

1. The ^{205}Tl(μp,n)^{205}Pb reaction: contribution of *fast* muons
2. The ^{205}Tl(μp,n)^{205}Pb reaction: contribution of *stopped* muons
3. The ^{204}Pb(n,γ)^{205}Pb and ^{206}Pb(n,2n)^{205}Pb reactions
4. The ^{205}Pb mobilized from the environment of the lorandite mineral

Fig. 2 shows present estimates of different contributions to the production of ^{205}Pb in lorandite on the basis of the measurements of ^{26}**Al** (4) and the method developed by Heisinger and Nolte (3) as a function of the paleo-depth d_p of the deposit.

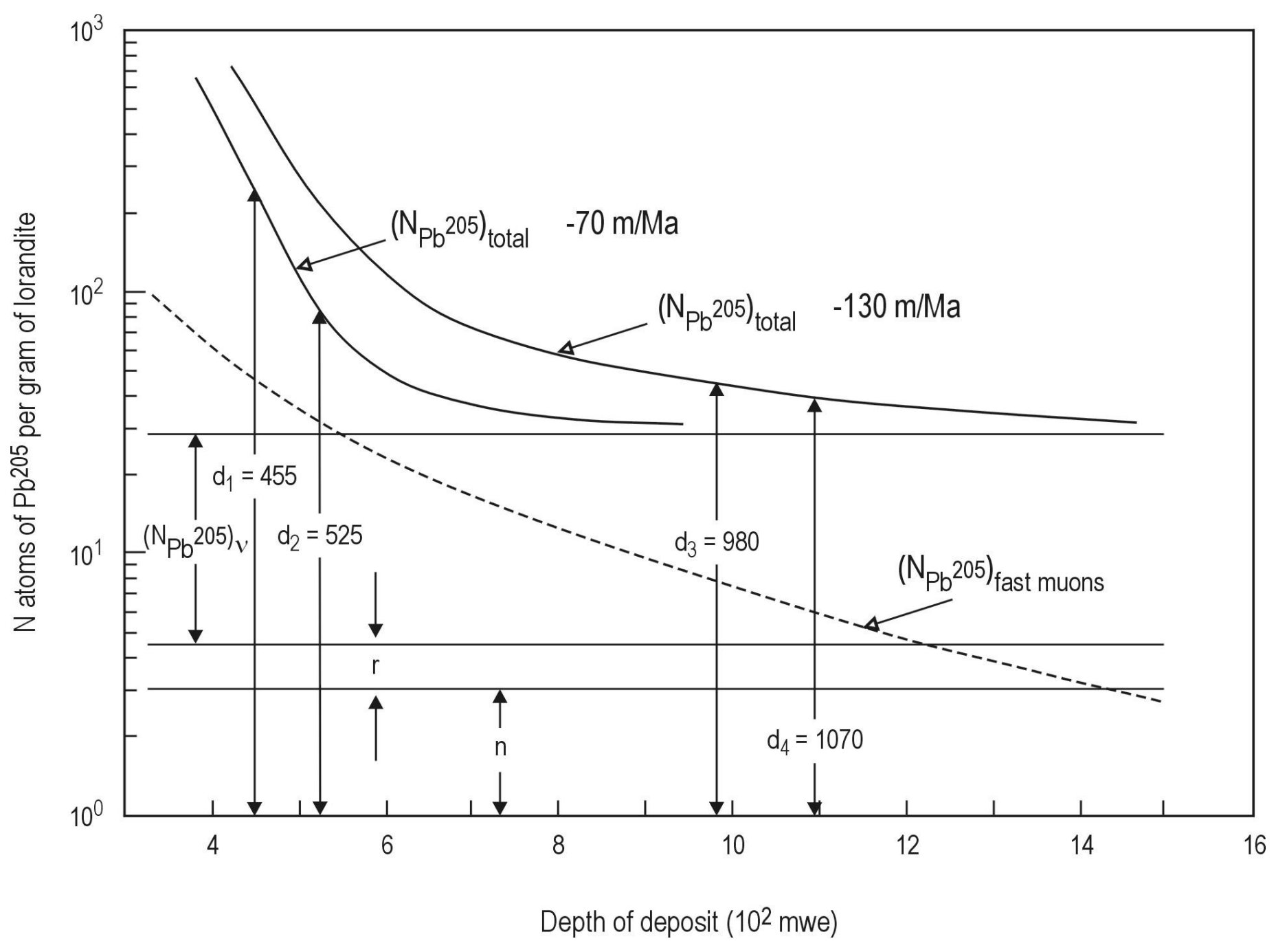

Fig.2: Estimate of the present amount of ^{205}Pb in lorandite due to solar neutrinos and to background reactions in the last $4.3 \cdot 10^6$ years as a function of the paleo-depth d_p of lorandite. The values are calculated by Pejovic 2008 according data of 0.55 μb sross-section for ^{205}Tl and the method of Heisinger and Nolte (3). **n**: contributions due to lead mobilized from the rock walls. **r**: contributions from natural radioactivity. **N(Pb^{205})** $_{\text{fast muons}}$: contribution due to reactions induced by fast cosmic muons. **N(Pb^{205})** $_\nu$: number of ^{205}Pb due to solar neutrino capture, for a capture rate of 146 SNU (1 SNU = 10^{-36} captures/ (target atoms · sec)), yielded after correcting the original 260 SNU for neutrino flavour-oscillations. **N(Pb^{205})** $_{\textbf{total}}$: the sum of the neutrino contribution and of all background contributions [4].

2. Determination of the neutrino capture probability into the 2.3 keV state of ^{205}Pb

The difficult measurement of the decay probability of the bare ^{205}**Tl** nucleus to the first excited state of ^{205}**Pb**, by the exotic process of **bound-state** beta decay, has been **approved at the Experimental Storage Ring of GSI.** This decay probability **provides the nuclear matrix element for the dominant pp-neutrino capture cross-section which would thus become known** with **sufficient accuracy.**

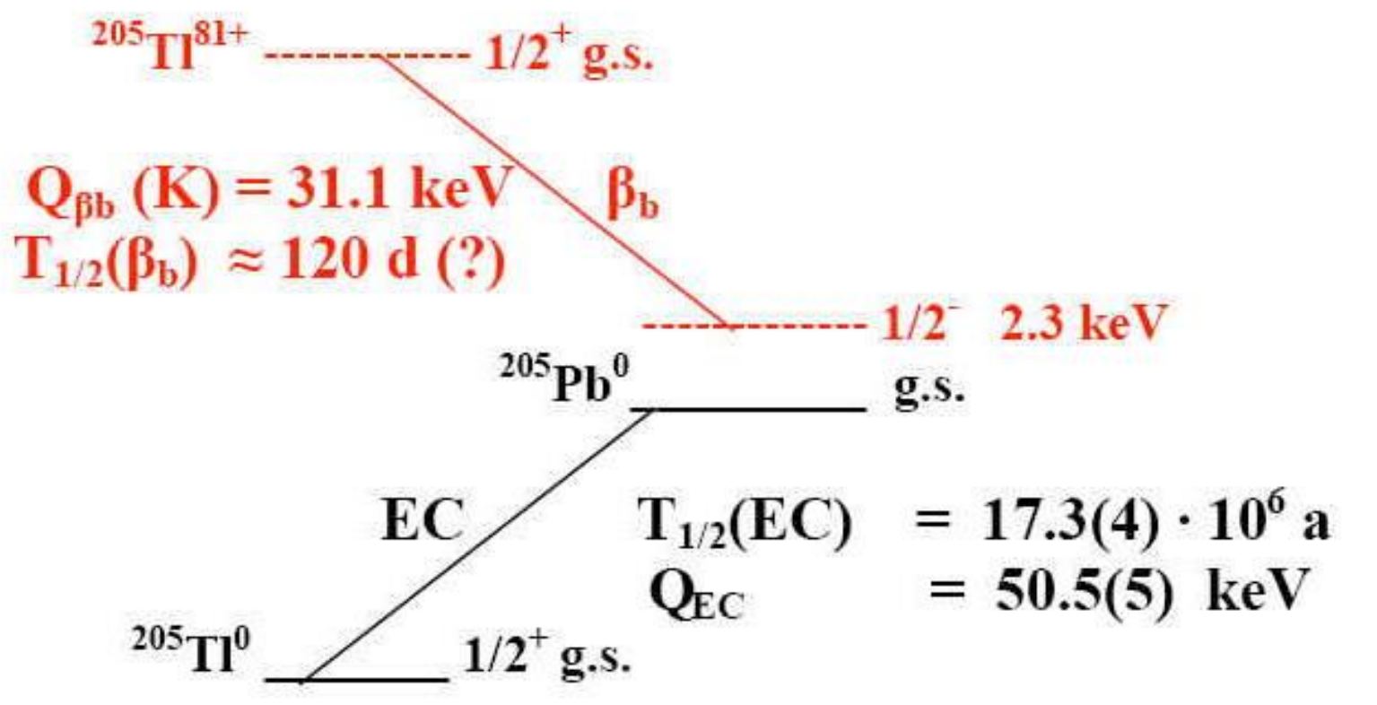

Fig.3: Decay scheme of neutral ^{205}Pb atoms (black) and of bare $^{205}Tl^{81+}$ ions (red). Whereas neutral ^{205}Pb atoms decay by unique first-forbidden orbital electron capture (EC) from the L and higher electron shells to stable neutral ^{205}Tl atoms with a half-life of 17.3 million years and a Q value of 50.5 keV, bare $^{205}Tl^{81+}$ (or H-like $^{205}Tl^{80+}$) ions can decay to almost 100% by β_b decay to the first excited state of $^{205}Pb^{81+}$ at E^*=2.3 keV, where the generated electron will be captured into the K shell (5).

3. Extraction and detection of ultra-low amounts of ^{205}Pb in lorandite

The final steps of LOREX will be the prospection and separation of lorandite from the Allchar mine (Fig. 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.
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 $5 \cdot 10^{-13}$. Supposing the value of *146 SNU* for the solar neutrino capture rate, the geological age *a* since the Tl-mineralization as $a = 4.3 \cdot 10^6\,y$, the decay probability λ for the electron-capture decay of ^{205}Pb back to ^{205}Tl as $\lambda = 4.68 \cdot 10^{-7}\,y^{-1}$ 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:

$$22(7) \text{ atoms of } {}^{205}\mathrm{Pb/g\ lorandite} \quad \ldots [3]$$

Chemical separation of Pb from Tl in the lorandite sample is expected to produce a ration of ^{205}Pb/^{205}Tl of about 10^{-13}. The key challenges are therefore Pb isotope separation of the order of 10^{-14} and ^{205}Pb/^{205}Tl isobar separation of 10^{-13}. The approaches being investigated include:
- Conventional accelerator mass spectrometry (AMS) which provides for the required isotope separation; isobar separation on the basis of characteristic energy loss measurements with particle detectors alone cannot achieve the required level. However, combining a gas-filled magnetic separator as a first stage, leading to partial spatial separation of the ion of interest and the interfering isobars, and an advanced energy-loss measurement based on a high-quality passive absorber and high-resolution time-of flight for the second stage, appears a possible option.
- Isobar separation in a high-energy storage ring by full stripping is the most attractive approach; except that it will most likely lead to reduced efficiency compared to the conventional AMS.
- Increased efficiency might be gained by using the novel ion-mass ring at the RIKEN Nishina Center, where upstream identification signals of ions (and ^{205}Pb candidates) are forwarded to a kicker at the entrance of the mass ring proving injection on the central orbit and thus little loss of intensity.
- Finally, we have looked into atom trap trace analysis (ATTA) as successfully developed and applied at Argonne National Laboratory for noble gas trace elements (Ar and Kr). Laser resonance spectroscopy allows sensitivity between isotopes and isobars in the 10^{-16} range; however, searches for a strong recycling E1 optical transition have only be found in the wavelength region outside that amenable for strong optical lasers. This will be further pursued.

Conclusion: Taking into account the present-day state-of-the-art of all the techniques needed to solve the four perennial problems of LOREX, we conclude that it is realistic to expect the first result for the solar pp neutrino flux averaged over the last 4.3 million years in the foreseeable future. This number will have most probably still an error margin in the order of 30% or even larger, at the 68%CL. We expect, however, that this accuracy could be improved with time, and that it might reach finally a level ≤ 30%.

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