Long-term solar neutrino flux and geological 205Pb assay

Henning Walter1, Amthauer Georg2, Aničić Ivan3, Boev Štabož4, Bosch Fritz5, Brüchle Willy5, Cvetković Vladica6, Faestermann Thomas1, Niedermann Samuel1, Pavčević K. Miodrag, Pejović Vladan, Uesaka Tomohiro, Weiss Achim9

1Technische Universität München, Physik Department E12, James Franck Straße, D-85748 Munich, Germany
2Institute of Physics, Zemun, Pregrevica 118, 1100 Belgrade, Serbia
3Gesellschaft für Schwerionenforschung (GSI), Planckstr. 1, D-64291 Darmstadt, Germany
4Geoforschungszentrum Potsdam, Telegrafenberg, Haus B, D-14473 Potsdam, Germany
5Max-Planck Institute für Astrophysik, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany
6University of Salzburg, Division of Materials Science and Physics, Hellbrunnerstr. 34 A-5020 Salzburg, Austria
7University of Split, Faculty of Mining and Geological, Gooz Delces 49, 52000 Split, HR
8Einstein Nordamerica Center for Accelerator Based Science 2.1 Herrnauge, Maki, Sakaishi 551-0190, Japan
9Presenter

Submitted Neutrino 2014, 2 – 7. June, Boston, USA

Motivation and Goals of LOREX

The central goal of the LOREX LoRAnDite E xrperiment (1) is the determination of the long-time average (over ~ 4 MY) of the solar neutrino flux Φ, with the neutrino-capture reaction:

\[ ^{205}\text{Pb} + e^- \rightarrow ^{205}\text{Pb} + \nu_e \quad [1] \]

As was pointed out originally (2), the thallium-bearing mineral lorandite, TlAsS₂, from the mine of Alilchar, Macedonia. The average flux Φ over the exposure time (age of lorandite since its mineralization) follows from the common activation equation, where η is the solar neutrino capture cross section and t is the decay constant of 205Pb:

\[ \Phi = N_0 (1 - e^{-t\eta}) \]  

where N₀ is the number of 205Pb atoms in lorandite. The calculation of the 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 Eν ≳ 50 keV for (solar) neutrinos.

The central problem of LOREX is the quantitative determination of 205Pb 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 205Pb 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 205Pb: The ratio 205Pb/205Tl provides only the product of solar neutrino flux and neutrino capture probability into the different nuclear states of 205Pb. However, the capture of neutrinos should populate predominantly the first excited state at Eν = 2.3 keV. Hence, to get the neutrino flux itself, one has to determine the capture probability into this low-lying state of 205Pb.

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

1. Background reactions and erosion rate

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

1. The 205Tl(p,n)205Pb reaction: contribution of fast muons
2. The 205Tl(pp)205Pb reaction: contribution of stopped muons
3. The 205Pb(p,n)205Tl and 205Pb(2n,3n)205Tl reactions
4. The 205Pb mobilized from the environment of the lorandite mineral

Fig. 2 shows present estimates of different contributions to the production of 205Pb in lorandite on the basis of the measurements of TlAsS₂ (4) and the method developed by Heisinger and Nolet (3) as a function of the paleo-depth dp of the deposit.

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

The difficult measurement of the decay probability of the bare 205Tl nucleus to the first excited state of 205Pb, 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.

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

The final steps of LOREX will be the prospection and separation of lorandite from the Alilchar 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 205Pb/205Tl ratio.

After the last step of chemical separation, a lead matrix will be obtained, where the 205Pb fraction is expected to range from 10⁻³ to 5 x 10⁻¹. Supposing the value of 146 SNU for the solar neutrino capture rate, the geological age since the Tl-mineralization as a = 4.3 x 10⁶ yr, the decay probability λ for the electron-capture decay of 205Pb back to 205Tl as λ = 4.68 x 10⁻⁹ yr⁻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 205Pb atoms the value of:

\[ \text{227} \text{atoms of } ^{205}\text{Pb in lorandite} \quad [3] \]

Chemical separation of Pb from Tl in the lorandite sample is expected to produce a ration of 205Pb/205Tl of about 10¹⁴. The key challenges are therefore Pb isotope separation of the order of 10¹⁴ and 205Pb/205Tl isobar separation of 10¹⁲. 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 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-rings at the RIKEN Nishina Center, where upstream identification signals of ions (and 205Pb candidates) are forwarded to a kicker at the entrance of the mass-ring projection on the central orbit, and thus reduce 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 isobars and isotopes in the 10⁻⁴ range; however, searches for a strong recycling E1 optical transition have only been 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%.