THE LENS PROJECT: A REAL-TIME MEASUREMENT OF THE LOW ENERGY SOLAR NEUTRINO SPECTRUM

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ABSTRACT

The LENS project aims at measuring the solar neutrino spectrum at low energy with a real time signature of ν_e interactions. A detector containing several tens of tons of Gd or Yb used as a neutrino target should give several hundred events per year. Studies are underway to decide which is the best detection technique (liquid scintillator, crystals) and estimate the backgrounds.

1. Motivations

It is a well-known fact that all experiments measuring the solar neutrino flux find a deficit of 50% or higher [1)]. Purely astrophysical explanations are ruled out, since data are inconsistent with any combination of pp, Be and B fluxes [2)]. Furthermore, the so-called standard solar model has been dramatically confirmed and constrained by recent data on helioseismology [4)]. The most probable explanation for the observed deficit is therefore neutrino oscillations, for which there exists several possible scenarios describing the present data [2,3)]:

- The just-so scenario, corresponding to oscillations in vacuum with maximal mixing and oscillation lengths around 1 astronomical unit
- three so-called MSW solutions, where ν_e's experience an adiabatic transition towards an heavy mass eigenstate, driven by the decreasing electron density inside the sun. Two solutions with Δm^2 around 10^{-5} eV^2 differ by the mixing angle in vacuum, either small (SMA) or large (LMA), while a third solution exists for high mixing angle and a lower Δm^2 around 10^{-7} eV^2 (LOW).

These solutions are shown in the usual $\sin^2 2\theta - \Delta m^2$ plot on figures 1 and 2.

These solutions have very different predictions on the solar ν spectral distorsion, as can be seen on figure 3:

- MSW at small angle (SMA) keeps the pp flux unaffected, while the Be line disappears and the B spectrum is stongly distorted.
- MSW at large angle (LMA) shows a much smoother dependance on energy, each component being roughly divided by 2 or 3. It predicts variations between day and night on the high energy part of the spectrum due to a partial regeneration of ν_e's in the Earth.

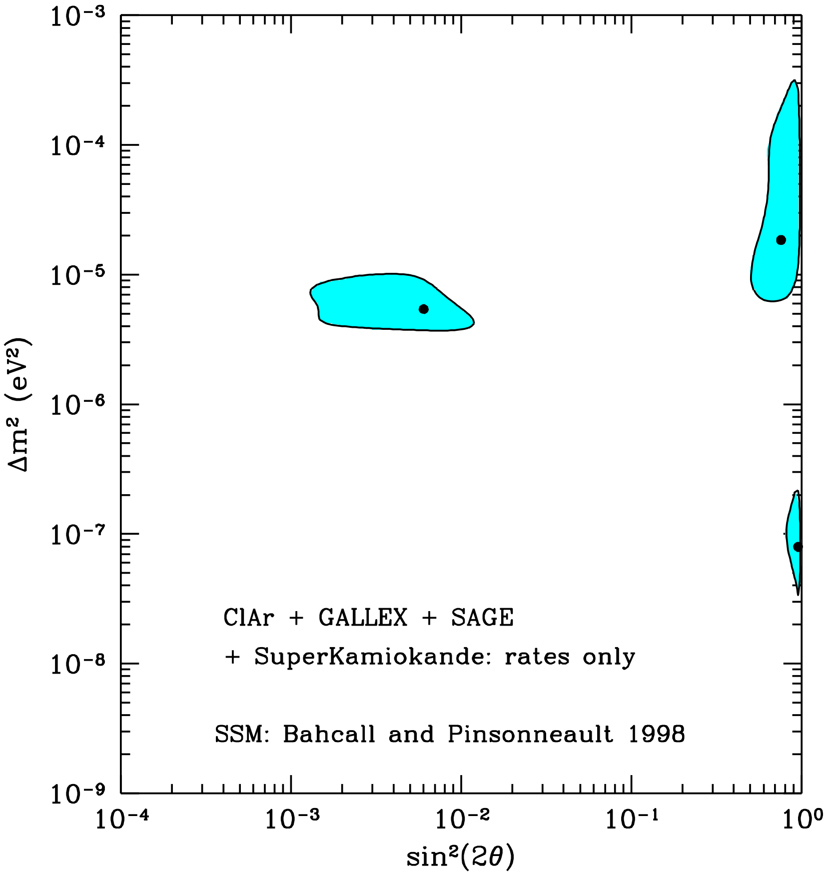

Figure 1: The 3 MSW solutions (SMA upper left, LMA upper right, and LOW) explaining the rates observed by Homestake, Gallex/SAGE and SuperKamioka (from [3]).

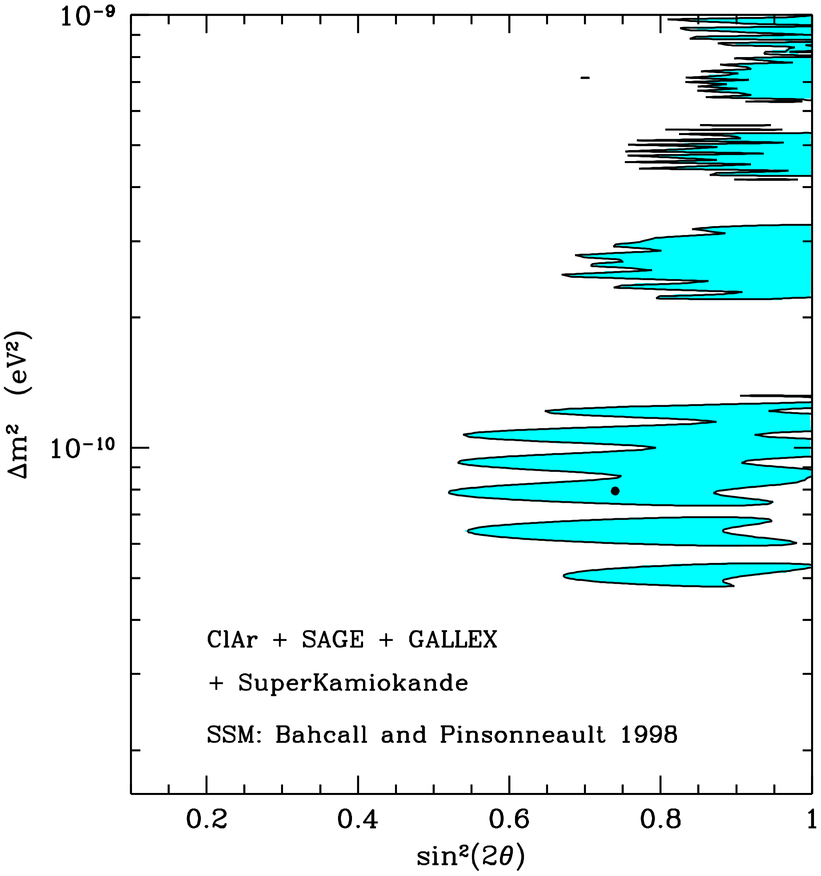

Figure 2: The just-so vacuum oscillation explaining the rates observed by Homestake, Gallex/SAGE and SuperKamioka (from [3]).

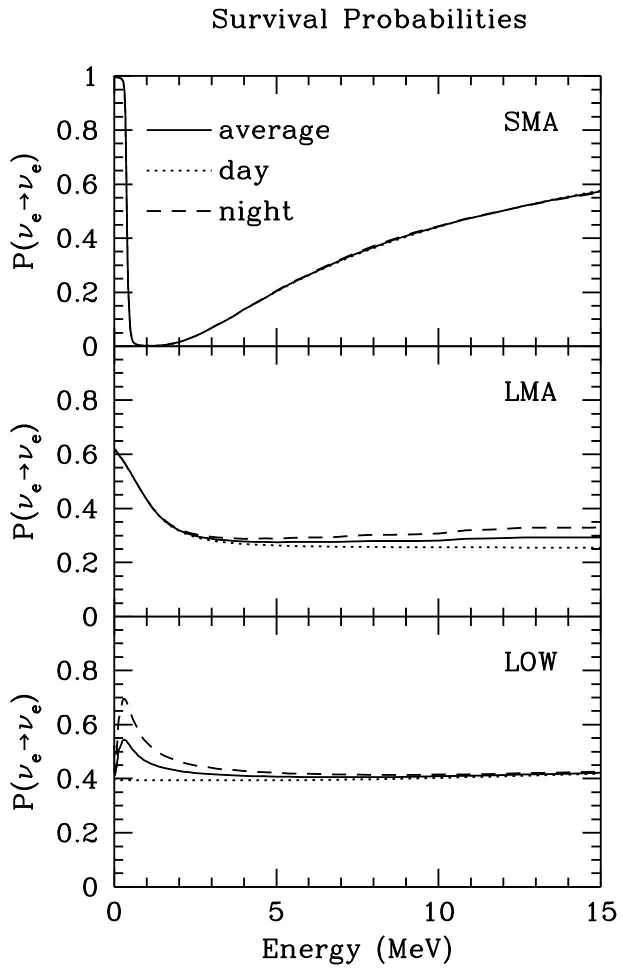

Figure 3: The survival probability of ν_e neutrinos as a function of energy for the 3 MSW solutions (from [3]).

- MSW at lower mass (LOW) shows roughly the same energy dependance as LMA, but it predicts strong day-night effects at low energy.
- The just-so oscillation pattern is that of vacuum oscillations, more visible on the pp spectrum, and we expect seasonal variations on all components due to the excentricity of the Earth orbit around the sun.

The presently planned experiments (SuperK, SNO, Borexino) should help in choosing between these solutions by either studying the B spectrum and day-night effects above 5 MeV (SNO, SuperK) or measuring the Be line intensity (Borexino).

But it is clear from figure 3 that a *measurement* of the neutrino spectrum below 1 MeV, clearly distinguishing the pp and Be components, is absolutely needed: it would be complementary to the 3 above-mentionned experiments and bring unvaluable constraints to exclude/confirm either one of the possible scenarios.

2. The detection principle

The idea, proposed by R.Raghavan [5], consists in using as a target for solar ν_e detection by charged current interactions a nucleus:

- having a sufficiently low threshold to detect pp neutrinos, and deduce the ν energy from that of the produced electron
- giving a final nucleus in an isomeric excited state, so that desexcitation γ lines give a specific signature of the reaction by means of delayed coïncidences, thus allowing for a strong rejection of possible backgrounds.

Three such nuclei have been identified, and their reaction schemes are shown on figures 4 and 5:

- the $^{160}Gd(0^+)$ has a threshold of 244 keV, and the ^{160}Tb is created in 1^+ states giving rise to 2 delayed γ's: the first at 75 keV with an 8 ns lifetime, the second at 64 keV with an 86 ns lifetime. Depending on whether the 8ns delay for the first γ is detectable or not, we either have an identification with a triple coïncidence or only a double coïncidence but with a 75 keV "boost" on the electron energy.
- the ^{176}Yb has a threshold of 301 keV, and the ^{176}Lu is created in 1^+ states giving rise to a delayed γ with an energy of 72 keV and a lifetime of 50 ns.
- the ^{82}Se has a threshold of 173 keV, and the ^{82}Br is created in 1^+ states giving rise to a delayed γ with an energy of 29 keV and a lifetime of 10 ns.

The cross-sections for the ν reaction on ^{160}Gd or ^{176}Yb can be deduced from (p,n) or (^3He,^3H) cross-sections on the same isotopes [6]. These measurements indicate that

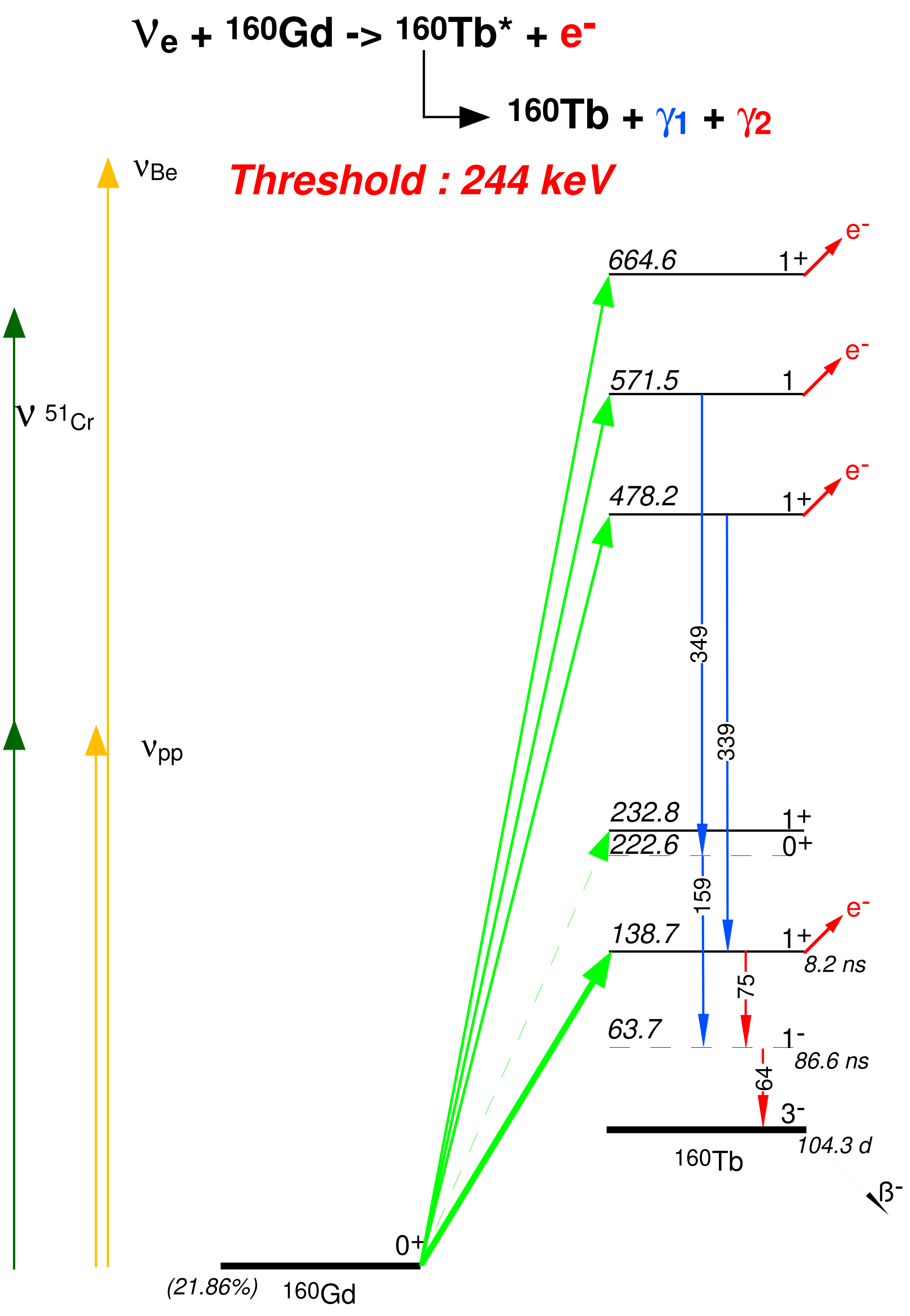

Figure 4: The reaction scheme of electron neutrinos on ^{160}Gd, showing the 2 delayed gammas of 75 and 64 keV, with lifetimes of 8.2 and 86.6 ns

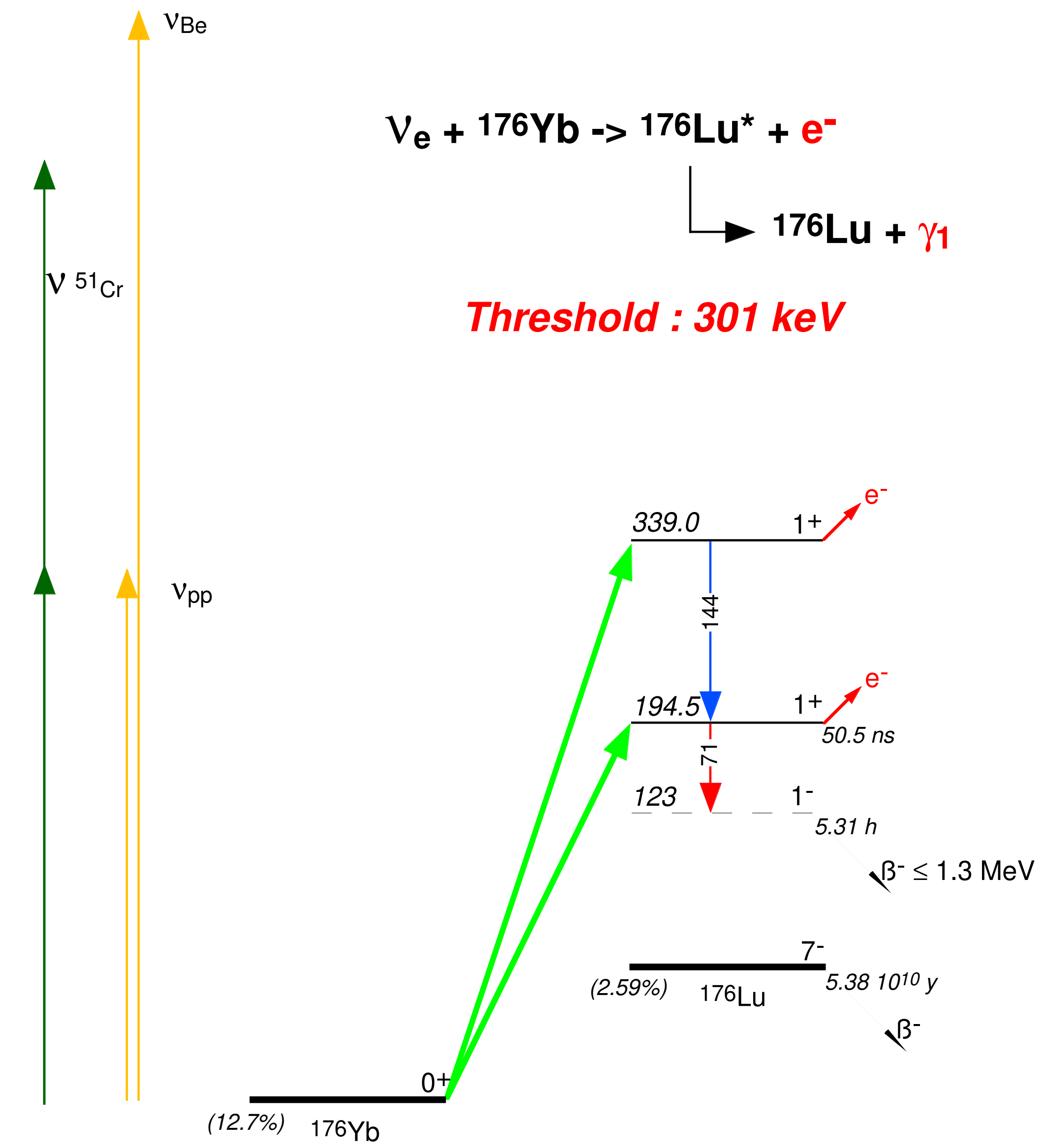

Figure 5: The reaction scheme of electron neutrinos on ^{176}Yb, showing a delayed gamma of 71 keV, with a lifetime of 50.5 ns

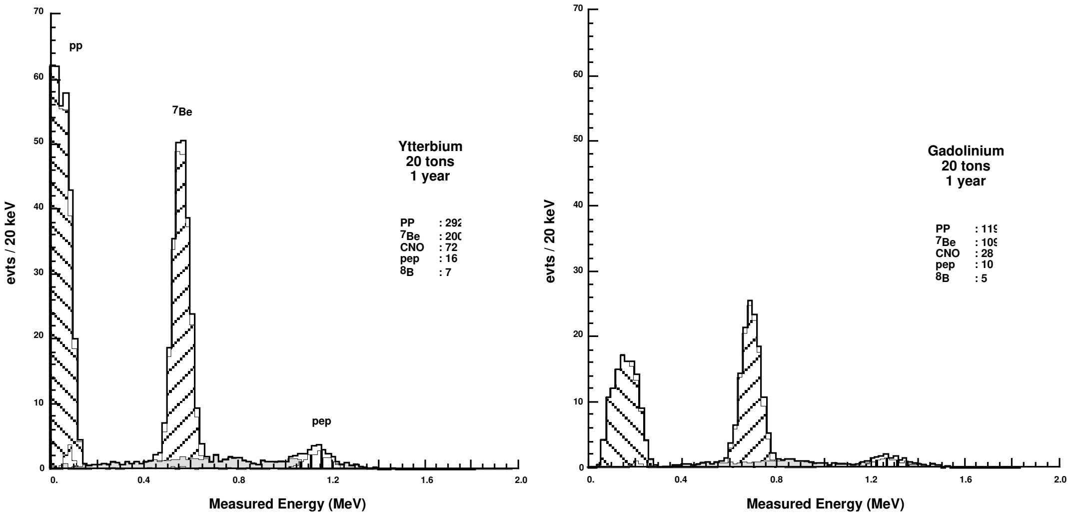

Figure 6: Measured energies of electrons produced by charge currents of solar electron neutrinos after one year of data taking. Left: 20 tons of natural Ytterbium. Right: 20 tons of natural Gadolinium (notice the 75 keV boost in energy). The resolution corresponds to a light yield of 400 photoelectrons/MeV

in order to detect 1 solar neutrino per day, one needs a target mass of roughly 10 tons of natural Yb or 20 tons of natural Gd. Typical spectra, as obtained after one year of data taking, are shown on figure 6.

However, the predictions of the ν_e capture cross-sections from these measurements are just orders of magnitude, and it will be mandatory to calibrate our detector with an artificial ^{51}Cr neutrino source of several Megacuries. Such a source emits 2 neutrino lines at 426 and 751 keV, thus perfectly matching the pp and Be solar neutrinos.

Let us emphasize that LENS will measure only the electronic neutrinos, so that it will be complementary to Borexino, which is sensitive to other flavours (which can interact with electrons). A comparison of LENS and Borexino results for the ^{7}Be line will thus give an indication on the flavor composition of the interacting neutrinos.

3. The possible implementations

Two main possibilities are presently being studied:

- the first one uses a liquid scintillator heavily doped (up to 10% in mass) with Gd or Yb
- the second uses crystals with a high Gd content, such as GSO [7]. (Yb is known to give poor scintillation)

In both cases, the main parameters for a good detection of the signal are:

- the light yield, as we need to detect 50 keV with reasonable precision
- the scintillation speed, in order to identify pulses separated by tens of ns.

A third possibility, based on gaseous detectors, could offer potential advantages, such as a high speed and a very precise timing, but its implementation has not yet been really studied (one could think of depositing Gd or Yb on the electrodes, or use gaseous compounds of ^{82}Se).

4. The backgrounds

Backgrounds can be classified in different categories:

- Correlated backgrounds, where coïncidences mimicking the signal are produced by decay cascades of some undesirable isotopes; 3 categories of isotopes have to be considered, depending on their lifetime:
  - Very long-lived isotopes (mainly from U and Th chains), present at some level as impurities in the materials
  - Cosmogenic isotopes produced at sea-level with lifetimes bigger than several months
  - Isotopes produced by muon showers when the detector lies in its underground location
- Accidental backgrounds, due to fortuitious coïncidences (in time and in position) between single pulses. The single rate will be proportional to the contamination of the detector in α, β, γ emitters (long-lived or produced by cosmics at sea-level) plus the part of the radiations (γ's, neutrons) produced outside the detector which penetrate it and induce signals, and the coincidence rate will be inversely proportional to the spatial granularity of the detector.

Some backgrounds are common to all implementations, some will be specific to the target isotope (Gd or Yb) or to the technique used (liquid or crystal). All the presently identified backgrounds are reviewed hereafter.

4.1. Correlated background: long-lived isotopes

The main source of background is the ^{231}Th, a daughter of ^{235}U whose β decay is followed by an 84 keV γ with 63 ns lifetime, thus mimicking the neutrino signal. A purity level as high as 10^{-15} g/g in crystals and 10^{-16} g/g in liquids is requested to keep this background to a sufficiently low level. Such a level has been achieved by the Borexino collaboration for unloaded liquids, and chemists think they can achieve the required purity on Gd or Yb compounds entering the liquid. For GSO crystals, we also need a high purification of the powder, and we expect further purification due to Uranium ion segregation during the growth of the crystal.

The contamination in Lutetium (specific to Ytterbium) has to be kept very low, since ^{176}Lu, present in natural Lu at a level of 2.6 percent, has a lifetime of 5.4 10^{10} years and gives β decays followed by an 88 keV γ with a delay of 2 ns. A contamination of Yb by Lu as low as 10^{-7} g/g can be achieved, but this implies 1.6 10^{9} such decays per year in 10 tons of Yb. A cut on the coincidence time at 37 ns would reduce the backgound by a factor 10^{8}, but reduce the signal efficiency by half. Better purification against Lutetium is therefore highly desirable.

4.2. Correlated background: cosmogenic isotopes

Among cosmogenic isotopes, we have identified ^{151}Gd and ^{153}Gd as potentially dangerous, since they have respectively 177 and 346 day lifetimes and decay both by electron capture with delayed gammas. The main source of background is a 103 keV γ, delayed by 5.5 ns, which is emitted in a substantial fraction of ^{153}Gd decays. A rough estimate leads to 2 10^{6} such decays per year in 20 tons of Gd. A cut on the coincidence time at 60 ns could reduce this number to 30 per year, the price being a loss in signal efficiency by a factor 2.

4.3. Correlated background: muon-induced isotopes

Some preliminary measurements have been performed in a muon beam at CERN where samples of Ytterbium and Gadolinium have been exposed to the beam behind 2.4 meters of concrete, and the induced isotopes measured using a HPGe counter. So far, the only identified isotope whose production in an underground laboratory could lead to a dangerous background is ^{159}Eu (produced from Gd), which has a 26 mn lifetime and whose β decay is accompanied by a 68 keV γ delayed by 38 ns. Present estimates indicate that the count rate at Gran Sasso could reach half the neutrino signal, but these measurements have to be repeated more carefully and will be in the near future.

4.4. Accidental background

The accidental rate strongly depends on the granularity of the neutrino detector. We anticipate a spatial resolution of 10^{-4} compared to the full detector volume, easily achievable with crystals, and obtained by spatial segmentation and longitudinal localization for liquid scintillators.

The uranium concentration, as demanded by ^{232}Th , will not induce any sizeable accidental background. The same is true for Lutetium for concentrations smaller than 10^{-7}.

For liquids, we rely on the Borexino results obtained with their counting test facility (CTF) [8] to achieve a sufficiently low level on Radon, Potassium and ^{14}C.

For GSO crystals, ^{32}Si seems to be sufficiently low (3 Bq/ton observed in silicon diodes [9]) not to be a problem.

Potassium from photomultipliers could be a concern, unless they are carefully chosen and/or put at some distance from the active part of the detector.

The main problem is ^{152}Gd, present in natural Gd at the level of 0.2 percent; this isotope gives α decays at a rate of 1.6 Hz/kg. The emitted alpha has an energy of 2.1 MeV, but the observed energy will be smaller, due to quenching. We have measured an electron-equivalent energy of 390 keV in GSO crystals, that is just inbetween pp and ^{7}Be neutrinos, and 130 keV in a Gd-loaded liquid scintillator doped with ^{147}Sm (which emits 2.2 MeV α's). This kills any possibility to perform the experiment with Gd-loaded scintillators, unless one decides to restrict the measurement to the Be line.

For crystals, the situation is more favorable, but one has to prove that single pulses at a rate exceeding 10^9 times the expected signal coincidence rate for pp neutrinos will not fake double pulses (because of Poisson fluctuations in light emission times) with a probability bigger than 10^{-9}. Figure 7 shows the observed energy spectrum with an hypothetic 10^9 rejection on single pulses. Monte-Carlo simulations are certainly not reliable enough to assess such a rejection power, which has still to be measured with real pulses and optimal algorithms.

5. Present status of R & D

5.1. Liquid scintillators

Extensive studies on the loading of pseudocumene liquid scintillators with organometallic compounds and complexes of Yb and Gd have been performed at Bell Labs [5] and are still underway. Russian groups at INR and IPC (Moscow) are preparing samples of Yb loaded pseudocumene scintillators (8% loading). They have expertise on the production of these compounds at an industrial scale, and are confident that Uranium levels as low as 10^{-15} g/g and Lutetium levels below 10^{-7} g/g can be achieved. A french manufacturer, Rhodia, has already prepared samples of Gd-loaded scintillators (8% and 11% loading) with slightly different techniques. Italian physicists from LVD have also provided us with toluene based Gd-loaded liquid scintillators (10% loading).

Several measurements have been performed concerning the light yield and the transparency of these liquids. The light yield measured with a Cs source shows a 50% loss compared to unloaded pseudocumene. Rhodia and LVD liquids have been measured in a small cell (20 cm long) at Saclay and presently give 100 photoelectrons per MeV on backward Compton electrons. The main concern for all the liquids is

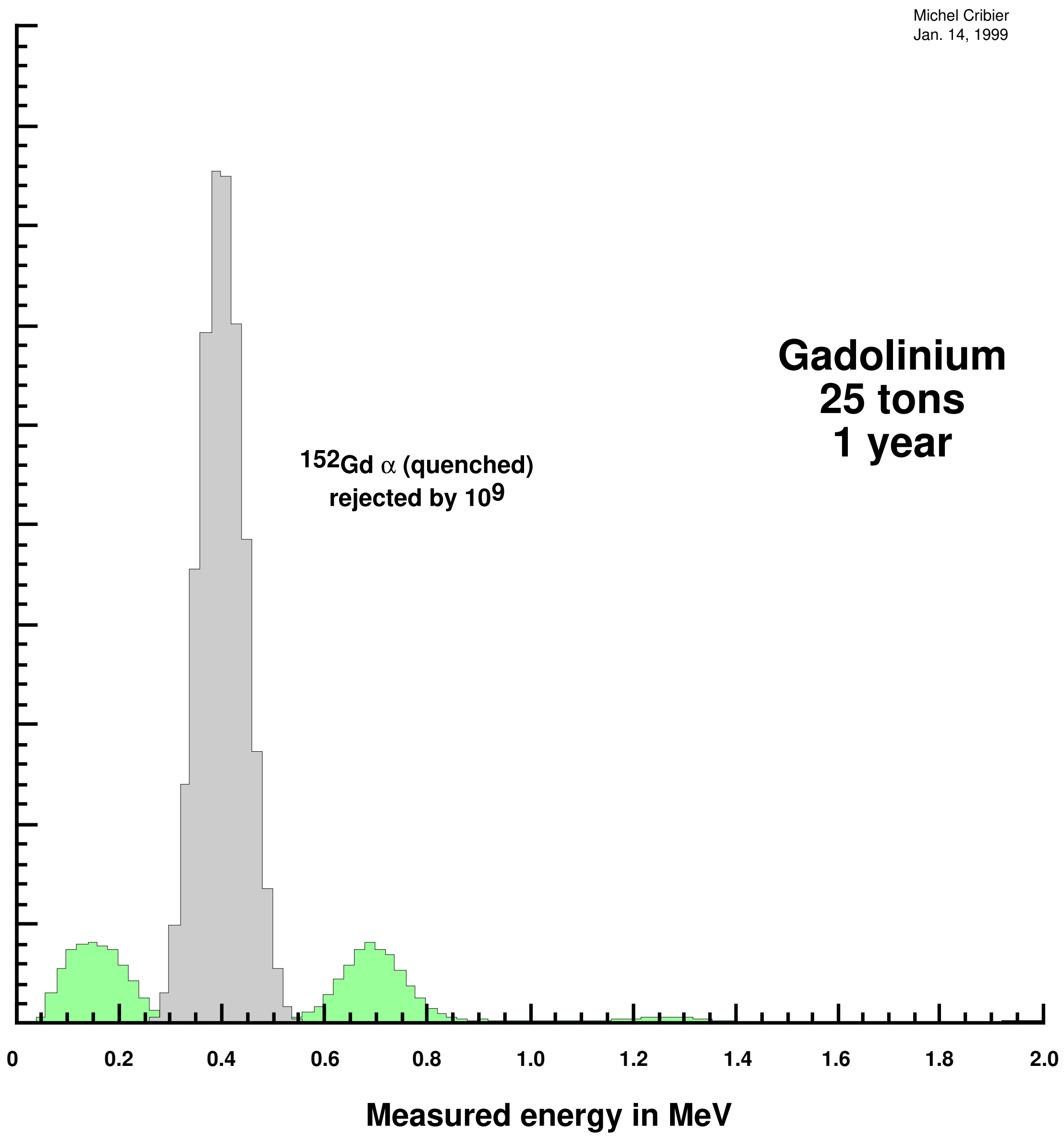

Figure 7: The observed spectrum of solar neutrinos together with ^{152}Gd alphas reduced by a factor 10^9, in a detector made with GSO crystals containing 25 tons of natural Gd. The resolution corresponds to a pessimistic light yield of 200 photoelectrons/MeV

their transparency, with transmission lengths ranging from around 30 cm at 420 nm to 80 cm at 500 nm, but improvements are expected with higher purity ingredients. Further measurements with longer cells (80 cm) are foreseen in Saclay.

5.2. Crystals

Large size GSO [Gd_2SiO_5] crystals have been grown by several laboratories [10]. Hitachi Chemical Co. is now producing them at a semi-industrial scale. These crystals have a density of 6.7 g/cm^3, and contain 75 % of Gd in mass. The doping with Cerium gives a fast scintillation with a lifetime around 30 ns, while retaining a high light yield of about 9000 photons/MeV. A 2 x 2 x 20 cm^3 Hitachi crystal is under study at ISN-Grenoble since last october. A number of relevant properties have been measured, including energy resolution, pulse timing properties and longitudinal response. The ^{152}Gd alpha has been observed at 390 keV. A minimum value of 450 photoelectrons/MeV has been deduced from the energy resolution at the center of the crystal. Efficiency and discrimination figures of the neutrino signature are presently studied, partly based on the ^{231}Th coïncidence mimicking the neutrino signature. The ^{232}Th contamination has been measured at 2 10^{-10} using the ^{212}Bi-Po β-α cascade, limits have been put on other contaminants using a low-background Germanium detector (^{238}U has been seen at the level of 10^{-8}). Globally, the presently observed single rate implies an accidental coincidence rate about 2 orders of magnitude larger than the neutrino signal. However, no special care was taken on the radiopurity of the materials used in the manufacture of this crystal, and large improvements are realistic since single rates up to 40 times lower have already been obtained with GSO crystals [11].

5.3. Neutrino cross-sections

Analysis of data on charge exchange reactions on Yb and Gd is continuing at IUCF Indiana and at RCNP Osaka in connection with Bell Labs, with a view to understanding the nuclear physics impact on the reliability of the results. New experiments are being planned, including measurements with ^{82}Se.

5.4. The chromium source

Based on the 36 kg of enriched chromium produced for GALLEX and available, it seems possible to produce in Russia an artificial source of 8 Megacuries by neutron irradiation in a nuclear reactor. Such a source would give 61 events at 426 keV and 1525 at 751 keV in a liquid scintillation detector loaded with 10 tons of Yb, together with a solar neutrino expected yield (for no oscillations) of 25 pp events and 57 ^{7}Be events. The manufacturing of such a source will most probably be a common task for several experiments (LENS, Borexino,GNO) and efforts are already coordinated at the european level with our russian colleagues.

6. Outlook

Although the LENS project is only one year old, many labs worldwide have already joined the collaboration and bring a wide spectrum of expertise and/or industrial connections. The collaboration will welcome other groups that could widen the range of critical expertise.

The crystal solution shows sufficiently high light yields to ensure a satisfactory energy resolution, but suffers from the many backgrounds sources associated to Gd.

For liquids, the emphasis is now put on Yb loaded scintillators, but improvements have to be made on transparency and light yield before reaching an acceptable solution.

In conclusion, much more work is evidently needed to assess the feasibility of the LENS project; our collaboration is actively pursuing its efforts and hopes to converge towards a proposal within one or two years.

7. The LENS collaboration

The LENS project is a common effort from several laboratories worldwide:

France
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