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DETECTOR LENS AS A NEW TOOL FOR SOLAR NEUTRINO SPECTROSCOPY

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LENS detector is a low-threshold, electron-flavor specific detector for real time measurement of the solar neutrino spectrum at low energies. It is expected that 20 tons of Yb used as a neutrino target should give several hundred events per year. The basic method for implementation of the LENS detector is scintillator technique, namely a liquid scintillator doped (up to 10 % in mass) with natural Yb.

Детектор LENS предназначен для детектирования с низким энергетическим порогом в реальном времени спектра солнечных нейтрино низких энергий. Ожидается, что использование в качестве мишени 20 т Yb позволит зарегистрировать несколько сотен событий в год. В основе метода регистрации LENS используется жидкий сцинтиллятор с добавкой (до 10 % по массе) природного Yb.

INTRODUCTION

Four pioneering experiments: Chlorine [1], SuperKamiokande [2], GALLEX [3] and SAGE [4], have observed neutrino fluxes with substantially lower intensity than that predicted by Standard Solar Model (SSM). These predictions have recently been confirmed by helioseismology [5] to a high precision, a fact disfavours astrophysical solutions proposed to explain the discrepancies between the theory and measurements. This discrepancy constitutes the so-called «Solar Neutrino Problem» which is the one of the most intriguing problems of modern physics and astrophysics. Most physicists consider the solution of this problem to lie in new physics, namely, physics of flavor oscillation of massive neutrino, that is a possibility of great importance for all of the modern physics. The flavor oscillation models are based on either vacuum oscillations («just-so» mechanism) or matter conversion (MSW effect) with distinct sets of neutrino parameters.

These scenarios have very different predictions on the solar neutrino spectral distorsion (see Fig. 1 [6]): MSW at small angle (SMA (*a*)) keeps the *pp* flux intact, while the ^{7}Be flux is completely converted; MSW at large angle (LMA (*b*)) predicts variations between day and night on high energy part of the spectrum due to a partional regeneration of neutrinos in the Earth, the *pp* and ^{7}Be flux being decreased by a factor of 2 or 3, respectively. MSW at low mass value (LOW (*c*)) predicts strong day-night effects at low energy. The «just-so» mechanism will cause seasonal variations on all components due to the excentricity of the Earth orbit around the sun.

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Thus the scenarios for flavor conversion will most likely be discriminated through measurement of solar neutrino flux including temporal variations, at all energies and for all neutrino spicies. The robust predictions of the SSM are for the *pp*, *pep* and ^{7}Be fluxes, the *pp* flux being most strongly constrained by the solar luminosity. In this context, it is no surprise that real-time detection of the complete ν_e spectrum from the sun and source-specific fluxes is of crucial importance for solving the solar neutrino problem. Only the integral signal rates above a threshold from the low-threshold Ga detectors are available till now, but not the fluxes from specific solar neutrino sources. So far, there exist several proposals to mesure the *pp* flux in real time: HERON [7], GENIUS [8], HELLAZ [9], MOON [10], and LENS [11]. First three experiments are based on neutrino-electron scattering, which is caused both by the neutral and charged weak currents, thus the signal is determined by the flavor composion of the incident neutrino. The scientific aim of MOON and LENS is the direct observation of the specific ν_e fluxes from *pp*, ^{7}Be and CNO reactions. In this paper, we discuss the LENS (Low Energy Neutrino Spectroscopy) project.

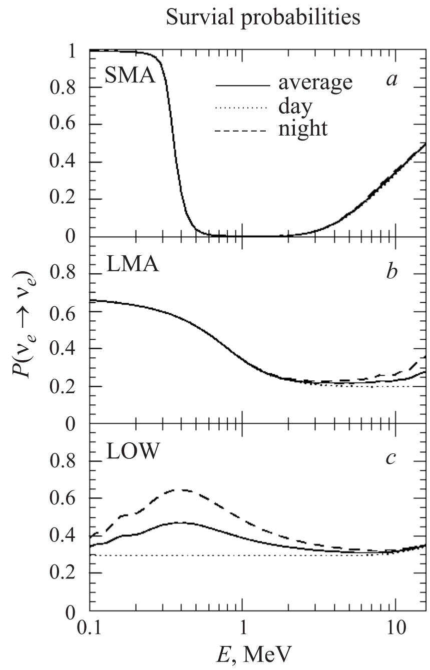

Fig. 1. Predictions on the solar neutrino spectral distorsion [6]

1. THE DETECTION PRINCIPLE AND RESPONSE TO NEUTRINO CONVERSION SCENARIOS

Detector LENS [11] is based on using the Yb target for the solar neutrino capture (see Fig. 2). Neutrino capture by ^{176}Yb nucleous results in 194.5 and 339 keV excited isomer states of ^{176}Lu which decay to the 123 keV long-lived isomer state of ^{176}Lu with a time delay of 50 ns (the so-called «tagged» event). These neutrino events have a highly specific signature: two events produced at the same point in the detector with an average delay time, namely, a prompt electron with energy $E_\nu - Q$ and a 72 keV γ ray. Such a signature gives the possibility of discriminating the neutrino signal against background by a factor of 10^6. The neutrino threshold $Q = 301$ keV implies a sensitivity to the complete spectrum of low energy solar neutrino, indentifying the *pp* and ^{7}Be fluxes.

The basic input data for designing LENS are the cross sections of the GT transitions in ^{176}Yb for which the weak matrix elements B(GT) must be determined for each of the 1^+ states excited by neutrino capture. These values have been measured by charge exchange nuclear reactions (p, n) and (^{3}He, ^{3}H) on ^{176}Yb with projectile energy of 120–150 MeV/nucleon at the cyclotron facility at Indiana (IUCF) and Osaka (RCNP) Universities in 1997–1999 [12]. The good agreement of the B(GT) values obtained in the two reactions provides a confidence that the neutrino cross sections are reliable (B(GT) = 0.20 and 0.11 for 195 and 339 keV excited states of ^{176}Lu, respectively).

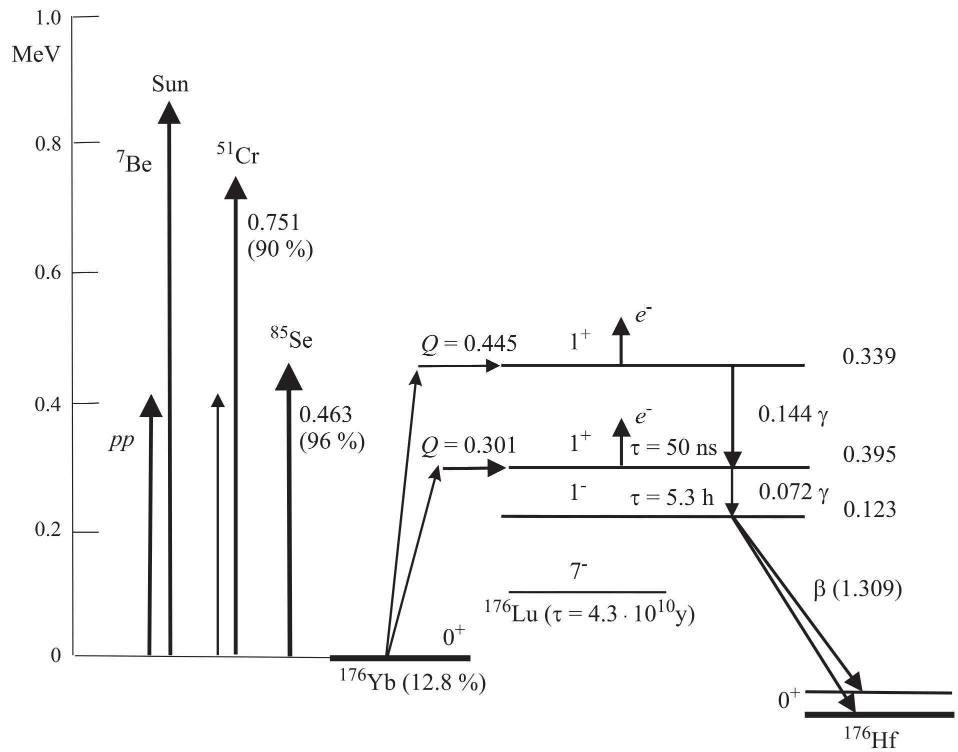

Fig. 2. Yb–Lu levels and tags structure (energy values are in MeV). The left: neutrino lines from the Sun and ^{51}Cr and ^{75}Se sources

Figure 3 [13] shows the response of the LENS detector to the various scenarios for flavor conversion mentioned above. Direct proof of conversion is visible in the large changes produced on the *pp* neutrino peak in all of these scenarios (SMA (*a*), LMA (*b*), LOW (*c*) and «just-so» mechanism). The SMA scenario keeps the *pp* flux nearly unaffected, while the ^{7}Be neutrino peak completly disappears. This zero result for charge weak current signal can be compared in direct contrast to the nonzero electron-scattering signal in BOREXINO produced by the converted μ/τ neutrinos via the neutral weak current. Thus, LENS detector would be complementary to the BOREXINO and bring most direct demonstration of flavor conversion of the ^{7}Be neutrino line.

2. IMPLEMENTATION

As envisaged from the beginning, the basic method for implementation of the LENS detector is scintillator technique. The main technology for the Yb-loaded scintillator, presently being studied, is a liquid scintillator (LS) doped (up to 10 % in mass) with natural Yb. Two possibilities of detector design (segmentation detector and whole volume detector) are being discussed now.

Another possibility which now is under investigation is a plastic scintillator doped with Yb.

The main parameters for a good detection of the signal with LS are:

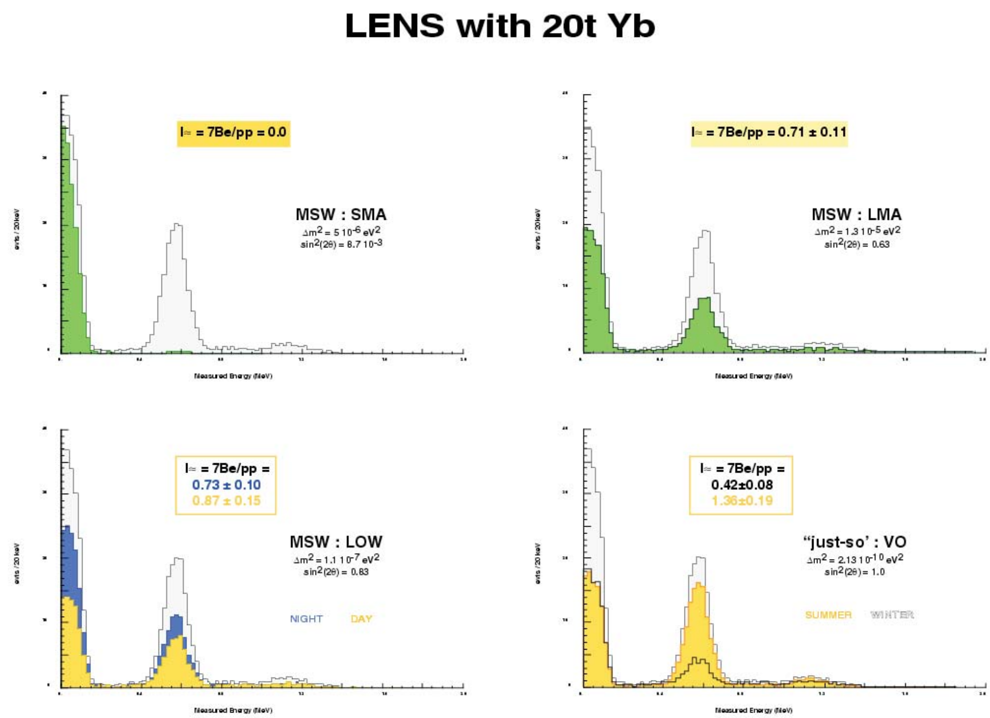

Fig. 3. Response of Yb detector to neutrino conversion scenarios [13]

- the light output of the Yb-loaded scintillator should be no less than 50 % of that of unloaded scintillator, as one need detect 50 keV with reasonable precision;
- light transmission length is several meters;
- fast pulse timing, in order to identify pulses separated by tens of ns;
- long-term stability over periods of several years.

3. THE BACKGROUND

The neutrino signature in LENS is a delayed coincidence between two pulses occuring at the same point in the detector. Thus, backgrounds can be classified in three different categories:

Self-Correlation (SC) of Single Pulses. Since both prompt electron and γ-tag events are detected in the same module, the time profile of scintillation photon emission from single event can contain a statistical (Poisson) fluctuation with a time structure of a real pulse, mimicking the delayed occurrence of γ-tag event. These SC-events rate increases with energy, so a small transient mimicking of 72 keV event is more probable for a large initial pulse (e.g., in the ^{7}Be and pep energy window) but relatively rare with low enegy events (in the pp energy gate). This effect depends crucially upon a signal quality (yield of photoelectrons/MeV) and scintillation pulse time (percentage of slow component in the given time window and fall time of a signal). The main defence against SC is a minimum delay cut (MDC) in the ν_e tag at the cost of signal efficiency. For example, at MDC of 12 ns on the ^{7}Be/pep signal candidates could eliminate the SC background at the cost of $\sim 20\,\%$ of the signal [13].

Accidental Background. Random coincidence between two uncorrelated single pulses are responsible for this type of backgrounds. The rate will depend upon the contamination of the detector in α, β and γ emitters plus the part of the environment radiations (γ rays, neutrons) able to reach the detector, and the coincidence rate will be inversely propotional to the spatial granularity of the detector. The rate will be $R = N_1 N_2 \Lambda \tau$, where N_1, N_2 are the signals rates in the energy windows in the whole detector; Λ ($\sim 10^{-4}$) is the fractional volume of the module and τ (~ 100 ns) is the time gate. For these typical values the tolerant level of U/Th concentration is 0.1 ppb and $^{\rm nat}$K/$^{\rm nat}$Lu is 0.1 ppm.

Correlated Background. Two sources of correlated background in LENS detector are coincident cascades from two specific impurities, ^{235}U and ^{176}Lu in the Yb material.

Lu contains 2.6 % long-lived ^{176}Lu which emits the $\beta\gamma$ cascade: ($\beta+\gamma$: 508–1100 keV) – ($\tau = 2$ ns) – (γ: 88 keV), a profile similar to the neutrino tag. The ^{176}Lu decay is relevant despite the short lifetime of 2 ns because its specific activity is high. Since the Lu events occur mostly at ≥ 500 keV, they do not affect the pp signal (≤ 120 keV). At 0.1 ppm Lu in Yb (considered industrially feasible), the Lu false-events reduce to $\sim$ 4/y if the MDC $=$ 40 ns, entailing a signal loss of $\sim 55\,\%$ (worst case solution). There is the possibility of producing Yb with purity ≤ 1 ppb of $^{\rm nat}$Lu with displacement ion exchange complexing chromatography. Laboratory tests have been done [14]; proper equipment and industrial scale technology exists in Russia.

^{235}U isotope (natural abundance 0.7 %) emits a delayed $\beta\gamma$ cascade: ^{235}U $\longrightarrow$ ^{231}Pa((β: 0–300 keV) – ($\tau = 60$ ns) – (γ: 84 keV)) that closely mimics the Yb pp signal tag at 0–120 keV. The Be and pep signals are not affected. A purity level as high as 10^{-16} g/g is requested to keep this background to a sufficiently low level. The purity at level 10^{-12} g/g can be achievable in Yb materials because the rare-earth industry uses standard extractants which are several orders of magnitudes more efficient for actinidies than the rare-earths. Then isotope dilution technique with U carrier depleted in ^{235}U (10^{-7} g/g) should be applied [15].

4. CALIBRATION WITH NEUTRINO SOURCE(S)

The interpretation of such an experiment has one major problem: the neutrino cross section for the transition of ^{176}Yb to the excited states of ^{176}Lu is deduced from the cross sections of (p,n) or (^{3}He, ^{3}H) scattering reactions with accuracy about $20\,\%$ [12]. Thus we plan to measure with high accuracy the specific neutrino cross sections to the two states in Yb–Lu using two MCi-scale radioactive sources based on ^{51}Cr and ^{75}Se.

The ^{51}Cr decays by electron capture with a Q-value of 751 keV and $T_{1/2} = 27.7$ days to the ground state of ^{51}V and to its first excited state, which de-excites to the ground state with the emission of a 320 keV γ ray. The neutrino spectrum consists of four monoenergetic lines 746 keV (81 %), 751 keV (9 %), 426 keV (9 %) and 431 keV (1 %) ([16, 17]). The high energy neutrino lines (90 % yield) will populate both the Yb transitions.

The ^{75}Se [18] decays by electron capture with Q-value of 865 keV to the excited states of ^{75}As, which de-excite to the ground state and emit several neutrino lines, basic of them are 451.08 keV (84.97 %) and 461.42 keV (10.93 %). The half-life for ^{75}Se is 119.79 days, this allows one to make the calibration experiment quite uninhibitedly. The basic neutrino lines (96 % yield) are sensitive only to the lower level of ^{176}Lu.

Thus these principal neutrino lines are of two sources that individually probe the two of states of ^{176}Lu. With this calibration strategy, the neutrino response of LENS can be characterized completely.

The nuclear reactors and the technology for producing the sources are available in Russia [19–21]. The LENS Coll. plans to reuse the ^{50}Cr material of GALLEX to make the ^{51}Cr source and produce a new isotopically enriched target of ^{74}Se for ^{75}Se source. The kg-scale ^{82}Se material for $\beta\beta$ study (NEMO Coll. [22]) have been produced in Russia with gaseous centrifugation of volatile SeF_6. The technical developments for neutrino sources production are being coordinated at two suitable reactors L-2 (nickname LUDMILA) [19, 20] and SM-3 [21] by a French-Germany-Russian team from LENS.

5. LIQUID SCINTILLATOR TECHNOLOGY

The main problem in the preparation of the Yb loaded scintillator is to find out the Yb complex organic compound, highly soluble in aromatic solvent. Generally, the preparation of the Yb loaded scintillator is grounded on a liquid-liquid extraction process (LLE). The LLE is well established technological process, which proved its large application for a preparation of highly concentrated and stable rare-earth complexes soluble in organic solvents. Many types of rare-earth compounds and organic extractants have already been investigated [11, 23–25]. It was found that as extractants of the most interest are neutral phosphorusorganics (P=O): phosphates, phosphonates and phosphine oxides, and carboxylic acids (C=O).

Carboxylic acids directly produce organometallic compounds which are dissolved in organic diluent. A technique for incorporating a macroconcentration Yb ($\sim$ 15 wt. %) in a scintillation liquid by using one type of the carboxylic acid (2-ethylhexanoate acid) was demonstrated by R.Raghavan [11].

However, the rare-earth carboxylates are not very stable. The (C=O)-compound degradation caused by a hydrolyses leads to a formation of a precipitate. So, extensive basic chemical research of the carboxylic acids is continuing.

The main advantage of phosporusorganics as extractants is that the pH-range of complex formation with the rare-earths is not overlapping with the hydrolyses pH-range [23]. Furthermore the chemical bonds that hold Yb ion to organic ligand increases in the order phosphate $<$ phosphonates $<$ phosphinates $<$ phosphine oxides more than 100 times.

Thus, the production of Yb liquid scintillator formulation consists of the following components:

- inorganic forms: Yb metal, $YbCl_3$, and $Yb(NO_3)_3$;
- organic extractants: carboxylic acids, phosphates (TBP — tributylphosphate, TEP — triethylphosphate), phosphonates (DBBP — dibutylbutylphosphonate, MDBP — methyldibutylphosphonate), phosphine oxides (TiAPO — triisoamilphosphine oxide);

- aromatic solvents: single-ring aromatics PC (pseudocumene), and double-ring aromatics 1-MN (α-methylnaphtalene), etc;
- fluor dopants and waveshifters: BPO, PPO, POPOP, bis-MSB.

The major results emerging in the Yb loaded liquid scintillator research can be summarized as follows:

- loading: typically $\sim 8\,\%$ for (P=O) compounds and $\sim 12\,\%$ for (C=O) compounds;
- the light output value: $\sim 40\,\%$ for nitrates in double-ring (1-MN, DiPN) aromatics; $\sim 40\,\%$ and $\sim 60\,\%$ for chlorides with (P=O) in single-ring and double-ring aromatics, correspondingly; $\sim 50\,\%$ for $12\,\%$ Yb loading with 2-ethylhexanoates (C=O) in double-ring aromatics;
- transparency: transparency of most LS components is good ($\sim$ several meters), but except aromatic solvent — 1-MN, (P=O) extractants — TiAPO, DBBP and LS based on these reagents ($\sim 50-120$ cm);
- long term stability: all nitrate compounds are stable ≥ 1 y, chlorides are stable with phosphonates and phosphinoxides; Yb organometallic compounds (with C=O) are not stable and still under intensive investigation.

It is important to note that the preparation of Yb loaded LS is also compatible with industrial scale of production and purification technology of rare-earths which is based on LLE process using the same (P=O)-compounds.

6. CENTRAL LABORATORY FOR LENS (CELL)

CELL is created to transfer and implement the LS technologies developed in local laboratories and produce test programs of interest to the prototype program using the facilities of Laboratori Nazionali del Gran Sasso (LNGS) such as its underground γ-ray counting set-ups for quality control of radiopurity of materials, the well-instrumented chemical laboratory facility, and others. The starting phase of CELL is influenced by the impact of the acknowledged chemical and nuclear expertise of Russian groups and can be enhanced by opportunities for research work in the facilities of LNGS.

Scientific goals of CELL are:

- quantity control of each component and final scintillator mixure;
- development of ultraclean liquid handling system for distributing scintillator to measurement modules;
- production of final Yb loaded LS.

Objectives of CELL are:

- development of infrastructure and expertise of personall to carry out the LENS program;
- production of ton-scale scintillator protopype for optimization of design;
- making measurement with prototype.

7. RUSSIA IN LENS

Several institutions from Russian Academy of Science and Ministry of Atomic Energy are participating in LENS. Their potential contributions to the project can be outlined as a list of the following items:

- production of high activity neutrino sources (^{51}Cr and ^{75}Se) for LENS calibration procedure;
- production and purification at «kg»-scale of high enriched in ^{50}Cr/^{74}Se material as a target for ^{51}Cr and ^{75}Se source production;
- production of high enriched ^{238}U (depleted in ^{235}U at 0.1 ppm) at tenths (hundred) grams for isotope dilute purification procedure;
- production of 20 tons of high purity Yb (Lu free at ~ 1 ppb level);
- production of high purity extractans: TBP, TiAPO, DBBP, etc., at ~ 100 t scale.

The high flux nuclear reactors, high productivity gaseous centrifuges, industrial chemical equipments for Yb production and purification are available in Russia [26]. The main question here is how to finance these enterprises in the framework of LENS project.

CONCLUSION

LENS is ν_e-flavor, real time detector for measurement of low energy solar neutrino flux, specifying the *pp* and ^{7}Be neutrinos individually. It will complement future low energy neutrino experiments (BOREXINO, HELLAZ, HERON, GENIUS), all of which are scattering experiments (whose signal depends on the flavor mixure of the incident neutrinos).

The main goal now is to develop the optimum formulation of Yb-loaded LS and build up the prototype of ~ 1 m^3 volume to study the backgrounds and detector performance. After positive answer the questions we hope to converge towards a proposal of LENS project.

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