1. New technologies in neutrino physics

2. Introduction

Within the last two decades major progress was achieved in experimental neutrino physics. This was only possible due to the constant development of new technologies in this field. Today a very broad progress of technologies can be observed, making possible neutrino experiments at very low energies (i.e. in the sub-MeV regime) until extreme high energies. In this lecture I will try to describe two examples, how new technologies developped within the last years. Both are mainly dealing with low energy neutrinos (i.e. below ≈ 1 GeV), however we will see how this technology may also be expanded to search for proton decays. This contribution will begin with a brief description of neutrino oscillations and the experimental status quo, followed by a short discussion about open questions in neutrino physics. Then the new technology developped for the search of θ_{13} with the three reactor neutrino experiments will be presented, which started data taking in 2011. Finally I will discuss some aspects of a future project utilizing a very large, homogeneous liquid scintillator volume.

3. Phenomenology of Neutrino Oscillations

Three neutrino flavors exist in the energy regime below ~ 45 GeV. This we know from the Z^0-decay width and from the observation of charged current neutrino interactions, where the corresponding charged leptons (electron, muon, tau) appear in the end channel. Bruno Pontecorvo suggested neutrino- antineutrino oscillations as explanation of the observed deficit of solar neutrinos as seen by Davis in the Homestake experiment and in close analogy to $K^0-\bar{K}^0$-oscillations in the hadronic sector. Later he and others imposed neutrino flavor oscillations, a periodic transition in time of the probability to observe a distinct neutrino flavor. Precondition for neutrino oscillations are existing neutrino mass eigenstates which determine the propagation of neutrinos in vacuum. However neutrinos are created and detected in weak interactions. Flavor eigenstates ν_α ($\alpha = e, \mu, \tau$) therefore have no fixed mass, but they are rather linear superpositions of the mass eigenstates ν_i ($i = 1, 2, 3$):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

If no 4th, sterile neutrino exist the matrix $U_{\alpha i}$ is unitary and

$$\nu_i = U^\dagger_{\alpha i} \nu_\alpha.$$

Here, we define the assignment ν_α to ν_i in such a way, that the absolute values of the diagonal elements of the mixing matrix are maximal. Hence, no mass hierarchy in the sense $m_j > m_i$ for $j > i$ is assessed a priori.

The mixing matrix $U_{\alpha i}$ (sometimes called Pontecorvo-Maki-Nakagawa-Sato matrix) has 3 real free parameter, which can be interpreted as rotation angles and one imaginary phase δ, which can cause CP-violation in the leptonic sector. In case the neutrino is its own anti-particle (a so called Majorana particle) additional imaginary phases may occur. The matrix can be parameterized in the form

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

Here, $s_{ij} = \sin \Theta_{ij}$ and $c_{ij} = \cos \Theta_{ij}$ with the rotation angles Θ_{ij}. The evolution of the mass eigenstates $\nu_i(t) = \nu_i(0)exp(-i(E_i t - k_i x))$ will differ if E_i and k_i do not coincide and this will create interference effects leading to neutrino flavor oscillations. Here E_i and k_i are the energy and k-vector of the eigenstate ν_i, respectively. Therefore a neutrino with a determined flavor at $t = 0$ (e.g. in the solar fusion reaction $p + p \to d + e^+ + \nu_e$) will rotate into another flavor, if the differences in the mass eigenvalues of ν_i don't vanish and if the unitary matrix is not diagonal. In the simple case of two neutrino flavors the probability P to observe the same flavor at a distance L from the neutrino source is

$$P = 1 - \sin^2 2\Theta_{12} \cdot \sin^2(1.267 \frac{\Delta m_{12}^2}{eV^2} \frac{L/m}{E/MeV})$$

and the probability P to observe the other flavor is $P = 1 - P$. Here $\Delta m_{12}^2 =\mid m_2^2 - m_1^2 \mid$ is the quadratic mass splitting between the eigenvalues m_2 and m_1. The amplitude of these periodic functions is $\sin^2 2\Theta_{12}$ whereas the oscillation length is determined by the quotient $\Delta m_{12}^2 \cdot L/E$.

In the standard model of particle physics neutrinos have no mass. Only left-handed neutrino states exist and helicity is a good quantum number. Furthermore the standard model predicts lepton flavor number conservation. Therefore the observation of neutrino oscillation is a clear evidence for physics beyond the standard model.

Basically there are two types of experiments searching for neutrino oscillations, appearance and disappearance experiments. In the former one the appearance of neutrino interactions with a "strange" flavor is searched for. A typical example of this type are accelerator experiments, where the neutrino energies are high enough to produce all flavors in charged current weak processes. The advantage of appearance experiments is their high sensitivity for the oscillation amplitude. Typical examples of disappearance experiments are reactor and solar neutrino experiments. In both cases one is looking for a deficit in the neutrino flux and for a distortion in the energy spectrum. In disappearance experiments the neutrino energies are not sufficient to produce charged muons or tau-leptons. However, with such experiments one can be very sensitive on small values on the mass splitting Δm^2, especially at long baselines L.

4. Open questions in neutrino physics

Several important questions about intrinsic neutrino properties are still open. Here a list of them is given, which is albeit far from being complete:

- What is the absolute mass scale of neutrinos?
- Do we have normal or inverted mass hierarchy?
- What is the value of Θ_{13}?

– Are neutrinos Majorana or Dirac particles?
– Is there at least one CP-violating phase in the leptonic mixing matrix?
– Are there sterile neutrino states?

The absolute mass scale can be assessed experimentally by measuring beta spectra at the endpoint with great accuracy. An upper limit on $m_\nu = \sum m_i \cdot |U_{ei}|^2$ of 2.2eV has been achieved in the Mainz [16] as well as in the Troitsk experiment [17] at 95% cl. This limit sets the scale on all neutrino masses m_i, as the oscillation results reveal that the mass differences are much smaller. In KATRIN, an tritium experiment in the starting phase at Karlsruhe, Germany, the sensitivity of the existing mass limit of 2.2 eV should be improved by roughly one order of magnitude. An overview about the state of art of beta endpoint experiments and the potential of KATRIN can be found in [18].

Neutrinos are not massive enough to explain dark matter. However, they can have an important impact on structure formation in the universe on large scales. On the other hand astrophysical observations in conjunction with structure formation modeling can set limits on the sum of all neutrino species. Albeit model dependent these limits are interesting and in the range of about 1 eV (see e.g. [19]).

The question of mass hierarchy and Θ_{13} can be addressed by oscillation experiments which are sensitive to small mixing amplitudes. As $\Delta^2 m_{31}$ is known, the optimal baseline for experiments searching for Θ_{13} depends on the neutrino energy only: $L \approx (E/MeV) \cdot 0.5\,km$. For accelerator appearance experiments (E $\sim$ GeV) the appropriate distance between source and detector is in the order of a few hundred km, whereas reactor disappearance experiments operate at a range of 1 to 2 km. Both types of experiments started to taking data recently and they have in common the use of so called near detectors which should monitor the source and thereby minimize systematic uncertainties. The potential of reactor neutrino experiments searching for Θ_{13} are discussed in [20] and the corresponding information for future accelerator projects in e.g. [21], [22] and references therein.

Depending on the true value of Θ_{13} there is hope to discover CP-violation in future high energy experiments. One way to measure δ is to search for differences between neutrino and antineutrino oscillations. An alternative method is to look for distortions in the energy spectrum, which would not show up if δ vanishs. In order to realize such a project very powerful beams or even complete new concepts have to be accomplished. Recent information about the search for CP-violation can be found e.g. in [23], [24] and references therein.

The question whether the neutrino is a Dirac- or Majorana-type particle is investigated by searching for the neutrinoless double beta decay $A(Z) \rightarrow A(Z+2)+2e^-$. This ($\beta\beta0\nu$)-decay would violate total lepton number by $\Delta L = 2$ and can only occur when $\nu \equiv \bar{\nu}$. The decay amplitude is sensitive to the so-called effective neutrino mass $m_{ee} = |\sum U_{ei}^2 \cdot m_i|$, which is a coherent sum over all mass eigenstates.

As discussed before the values U_{ei}^2 may comprise complex phases, which could lead to partial cancellation of different terms in the sum and uncertainties in the nuclear matrix elements play an important role (see e.g. [25] or [26]). In addition other mechanism beyond the standard model, like right-handed weak charged currents, could contribute to the ($\beta\beta0\nu$)-decay. However, in any case the observation of it would be the proof, that at least one neutrino is a Majorana particle, as long as the corresponding physics is described in a gauge theory [27]. Hence, search for ($\beta\beta0\nu$)-decay is the key experiment to probe the nature of neutrinos.

Double beta decay is only observable in even-even nuclei, like ^{76}Ge. Often source and detector are equivalent. In Ge-semiconductor detectors the $(\beta\beta0\nu)$-decay would lead to a peak in the observed energy spectrum at the endpoint. Current limits on m_{ee} depend strongly on nuclear matrix elements and are in the range of ~ 1 eV. There is a claim of part of the Heidelberg-Moscow collaboration for a positive signal [28]. However, up to now it was not possible to confirm or to refuse this result.

Future experiments with substantial funding for construction, like CUORE, GERDA, in Europe and EXO-200, SNO+ in North-America aim to reach sensitivities below $m_{ee} \sim 0.1\ eV$. This would be an important step, as for an inverted mass hierarchy the expected value is between 0.01 eV and 0.1 eV, independent from CP-phase values. A recent overview about the experimental status and prospects in the search for $(\beta\beta0\nu)$-decay can be found in [29].

A further important aspects of neutrinos is their role as messengers from astrophysical objects. Solar neutrino physics and the detection of terrestrial neutrinos have been already mentioned and with a future large liquid scintillator detector (LENA, Low Energy Neutrino Astronomy in Europe, HANOHANO in USA) solar models as well as geophysical questions could be studied in more detail ([30], [33]). In addition subtle questions arising for neutrino oscillations can be addressed with LENA, like the observation of neutrino decoherence with reactor neutrinos [34]. However, there are further scientific cases seen in conjunction with low energy neutrino astronomy:

- First detection of the diffuse supernova neutrino background in our universe
- In case of a galactic supernova type II the study of a gravitational collapse via supernova neutrino detection
- Precision measurement of solar neutrinos - search for small flux fluctuations
- Precision measurement of geoneutrinos (separation U/Th contribution)
- Search for proton decay, which is predicted in grand unified theories
- Long baseline oscillation experiments with very high sensitivity on Θ_{13}, CP-violation, and mass hierarchy

In Europe three types of detectors with masses above $\sim 50\,kt$ are discussed: water Cherenkov (MEMPHIS), liquid argon (GLACIER), and liquid scintillator (LENA) ([35], [36], [37]). Currently an European design study (LAGUNA, Large Apparatus for Grand Unification and Neutrino Astrophysics) is investigating possible underground facilities for such large experiments [40]. Also in the US at DUSEL (Deep Underground Science and Engineering Laboratory) and Japan (Hyperkamiokande) very large water detectors are going to be planned.

5. Technology of reactor experiments searching for Θ_{13}

In 2011 three new reactor neutrino experiments started data taking with the aim to measure Θ_{13}: Double-Chooz (France), Rena (South-Korea), and Daya-Bay (China). All these projects identify the antineutrinos via the inverse beta decay reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. By measuring the total energy of the positron information about the neutrino energy can be gained. The neutron delivers a delayed signal which helps to separate this signal from background events.

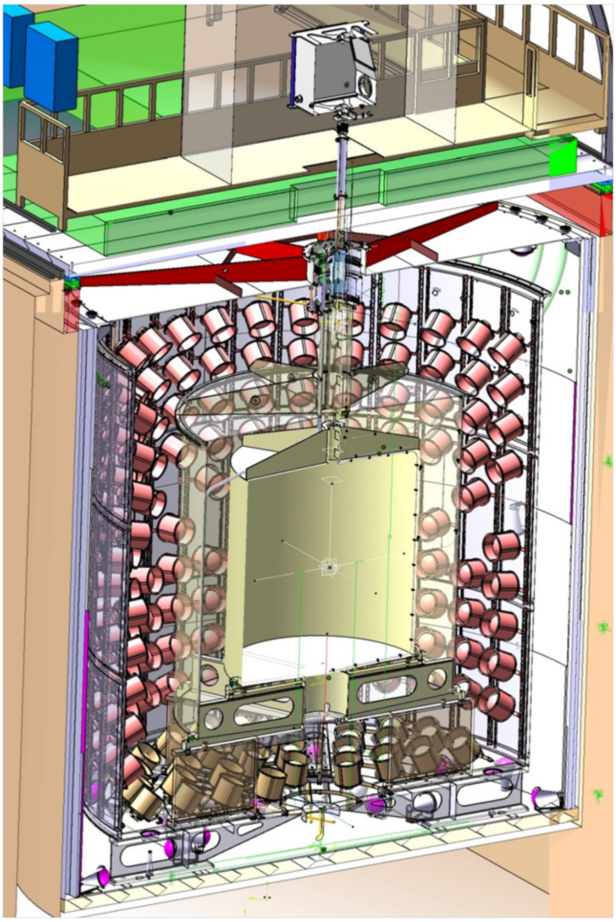

Fig. 1. Schematic view of the Double-Chooz neutrino detector. Explanation see text.

This is by far no new idea. Actually it is the same reaction which was used by Reines and Cowan for their first observation of neutrinos. However, very new is the precision which is aimed for in these new experiments. The aim of all three projects is to search for oscillations with amplitudes in the percent range. This can be principally achieved by comparing the measured rate with the expected one. Additionally the impact of oscillations on the energy spectrum can be studied. However, it is not possible to search for the appearance of a strange flavour, as the kinetic energies of neutrinos coming from beta decays from the fission products reach only ca. 10 MeV. Therefore the final sensitivity of these disappearance experiments depends directly on the absolute knowledge of the neutrino flux, the cross section, the number of target protons etc.. These systematic effects sum up quadratically and it is difficult to believe how deviations from the non-oscillated spectrum in the percent level could be observed. One way to minimize these systematics is the use of additional detectors close by the reactor stations. Indeed all three experiments are using this approach. With these near detectors the neutrino fluxes and their spectra can be monitored in time. A comparision with the far detector (of course taking into account the different distances to the reactor cores) can reveal oscillation effects. As

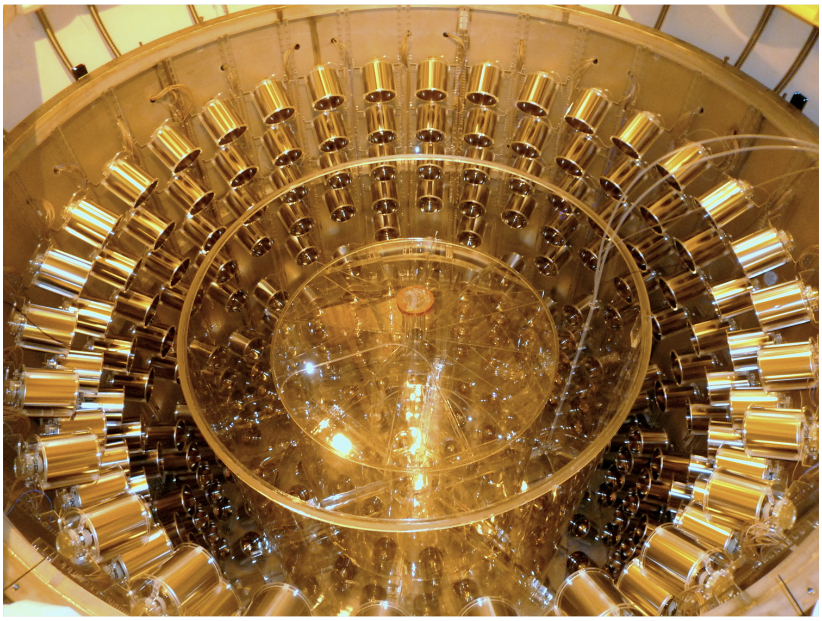

Fig. 2. Photo of the Double-Chooz far detector after installation of the acrylic vessels.

the near and far detectors are built in the same manner also such uncertainties like cross section of the inverse beta decay reaction will cancel.

However, the aim to be sensitive to a few percent is still compelling. This becomes clear regarding possible background contributions, which have to be identified. Generally there are two classes of possible background contributions. Accidental background occurs, when by chance two independent signals coincide within the time and energy windows used for the inverse beta decay. Correlated background is always connected with neutron signals which are not due to neutrino interactions. In order to discuss both background contributions the schematic detector set-up is shown in fig. 1 which shows the design of Double-Chooz, but is basically common to all three experiments. Fig. 2 shows the Double-Chooz detector after the installation of the acrylic vessels.

The target consists of an organic liquid scintillator, doped with Gadolinium. The liquid provides a high number of protons, acting as target for reactor neutrinos. Light emitted by the scintillator due to the kinetic energy of the positron plus the annihilation gamma rays is measured by photomultipliers. This prompt event is followed after $\approx 30\mu s$ by a gamma signal after the neutron is slowed down and finally captured by Gd-isotopes. Due to the very high cross sections for neutron capture this time delay is rather short which helps to reduce the accidental background event rate. The total amount of the gamma energy of this delayed event is about 8 MeV. Hence the accidental background rate is reduced further as this 8 MeV is far above the energy range of radioactive beta- and gamma-background events. The target region is surrounded by the so called gamma catcher. It is filled with a non-doped scintillator. As its name indicates it has the task to measure - together with the target - the total energy of the prompt and delayed events. This is especially important for neutrino events close to the target walls. Both active regions are surrounded by the buffer area. It is filled by a transparent, non scintillating

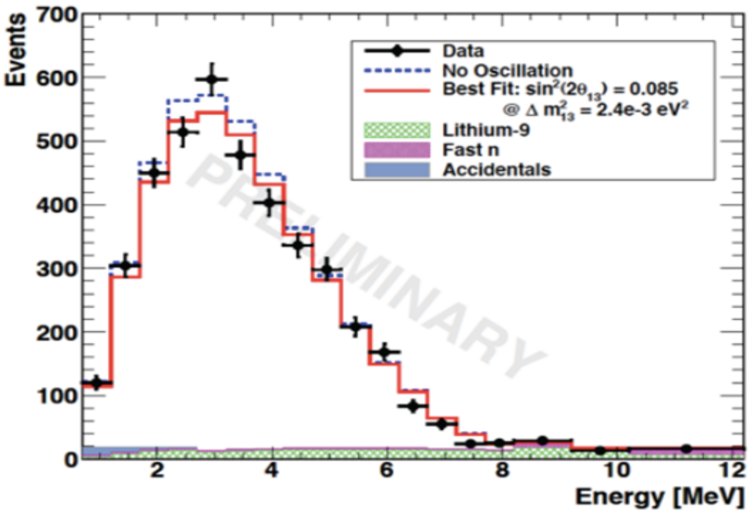

Fig. 3. Spectral distribution of reactor neutrino events in the Double-Chooz far detector. The dashed line shows expected spectrum for no-oscillation, the red curve is the best fit to the data. Coulored regions show accidental and correlated background contributions.

liquid and shields against external activity without triggering PM-tubes. Both, target as well as gamma catcher, are inside thin plexiglas vessels, whereas the buffer plus PM-tubes are inside a steel tank. This is embedded in a second, larger tank which acts as active muon veto. In case of Double-Chooz the veto liquid is again a scintillator, in case of Reno and Daya-Bay it is a water Cherenkov detector.

With this design the signal to background ratio can be optimized. External gammas are very well shielded by the veto as well as the buffer region. Screening and careful selection of materials used inside the buffer reduces the intrinsic gamma- and beta contamination. The remaining accidental rate can be measured in situ just by shifting the time window for the delayed event. This contribution will be subtracted statistically in the offline analysis. In case of Double-Chooz (far detector) the measured accidental rate is about 0.33 counts per day. This has to be compared by an average daily neutrino rate of about 40 counts. Correlated background is more critical, as its direct determination requires a complete reactor-off period which is not very probable, as all experiments are located at nuclear power plants with more than one reactor core. The best chances for a total reactor-off period has Double-Chooz as here only two cores are used as neutrino sources. Neutrons may be produced via (alpha,n)-reactions or cosmogenically. In order to reduce the contribution of the first one, the levels of scintillator contamination with nuclides of the U- and Th-chain should be kept low. For reactor experiments of this type the typical limits are in the order of 10^{-13} g/g. However, t may happen that this background is dominated by intrinsic ^{210}Po contamination fed by the decays of ^{210}Pb, which is often out of secular equilibrium. Cosmogenic background may arise due to beta-neutron cascading emitters like ^{9}Li and ^{8}He. These quite long-lived isotopes are produced in muonic spallation processesd on ^{12}C inside the organic scintillators. In addition high energy neutrons produced outside the veto may enter the inner active volume (without signal in the veto), scatter on protons to be finally captured. The combination of light due to the recoil protons and the delayed event is perfectly simulating a neutrino signal. However, both contributions can be studied as they provide signals in the energy region well above the prompt signal. As the energy spectra of the beta-neutron cascader are known, their contributions can be subtracted within the neutrino energy window statistically. The fast neutron contribution can be studied by searching for coincidences between neutrino candidates and the muon veto. In case of Double-Chooz it might be even possible to distinguish between neutron and other events in the veto as here a liquid scintillator is used. Strong background suppression can be achieved with these technologies. In case of Double-Chooz the estimated correlated background rate is ≈3 counts per day (far detector) and the signal to background ratio is about 40:3.

In November 2011 the Double-Chooz collaboration published its first result[46]. Only data from the far detector could be used as the near detector is still to be build up. Figure 3 shows the spectral distribution of neutrino events in the far detector.

An analysis based on the absolute counting and on the shape information yields as best fit $sin^2\Theta_{13} = 0.085 \pm 0.029 \pm 0.042$, with statistical and systematical uncertainties, respectively. This $\approx 1.7\sigma$ effect can be combined with the also positive signal from the long baseline T2K neutrino experiment[47] as shown in figure 4. The signifigance for a non-zero value for Θ_{13} is about 3 sigma for these two experiments. This result is even more pronounced, if the result of Minos[48] (not shown in this figure) is included. Both experiments are complementary: T2K restricts to small Θ_{13} values, Double-Chooz to large oscillation amplitudes. Also shown is a plot in the two-dimensional $\delta - sin^2(2\Theta_{13})$ plain. Again the restriction (shadowed area) of the allowed region due to the new Double-Chooz result is visible.

6. Large Scintillator Techniques

Liquid scintillator detectors (LSDs) are well known in experimental neutrino physics. The first detection of neutrinos by Reines and Cowan was performed with a liquid scintillator as target. Today this technology is used with big success in the underground detectors KamLAND (Japan) and Borexino (Italy). Search for neutrino oscillations by a non-vanishing mixing angle Θ_{13} with reactor neutrinos is going to be performed with Gd-loaded liquid scintillator detectors (Double-Chooz, Reno, Daya Bay) and soon the underground experiment SNO+ (Canada) will use a Nd-loaded scintillator. Up to now the main physical goals of these experiments were and are in the field of low energy neutrino physics. Besides reactor neutrinos, solar neutrinos (Borexino) as well as terrestrial neutrinos (KamLAND and Borexino) have been detected. Neutrino oscillations of reactor neutrinos have been found by KamLAND and the parameter space of the corresponding mass splitting is determined by this experiment mainly. The actual target mass of these successful experiments is in the range of about 1 kt. In this contribution the feasibility and the potential of future experiments with liquid scintillators of about 50 kt size will be discussed.

Such projects are currently under investigation in Europe (LAGUNA and LAGUNa-LBNO design studies) and in the US (Hanohano). As a generic name of these experiments I will use the acronym LENA, which stands for 'Low Energy Neutrino Astronomy' and is also used in the LAGUNA design studies. In LAGUNA and LAGUNA-LBNO feasibility studies also for very large water Cherenkov- and liquid argon detectors are performed.

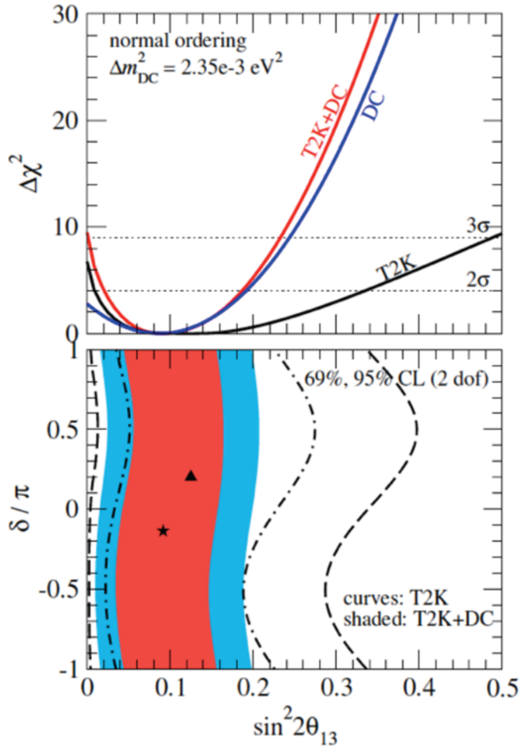

Fig. 4. Upper part: chi-squared distribution for a combined analysis of the T2K and Double-Chooz experiments. The probability for a non-zero Θ_{13} is at a 3 sigma level. Lower part: Contours at 69% and 95% cl in the two-dimensional cp- and oscillation amplitude plain.

In my lectures I was speaking about all three technologies. Due to time restrictions I will focus in this proceedings only on liquid scintillator technology. Recent reviews about the status of art of water Cherenkov and liquid argon detectors can be e.g. found at the homepage of the NNN11 workshop in Zurich 2011 (neutrino.ethz.ch/NNN11/).

6.1. *General experimental lay-out of LENA*

In order to perform successful solar neutrino and other low energy neutrino physics a minimal shielding of about 4000m.w.e. is necessary. Optical properties of liquid scintillators as well as geophysical constraints of deep underground excavation determine size and shape of the detector. Here a cylindrical tank with 30m diameter and 100m height is proposed. An active, inner volume with 13m diameter is filled with liquid scintillator, whereas the outer volume consists of a non-scintillating, but transparent buffer liquid. Solvents like LAB and PXE have been investigated in the past and were found to be very good candidates for LENA. As wavelength-shifters PPO/bis-MSB as well as PMP is considered. Absorption and scattering lengths of complete scintillating mixtures in the range of ca. 15-20m have been found [30]. A detailed description of fluorescence decay times relevant to LENA can be found in [38]. In order to obtain a yield of ca. 200 photoelectrons per MeV energy deposition in the centre of the detector an optical

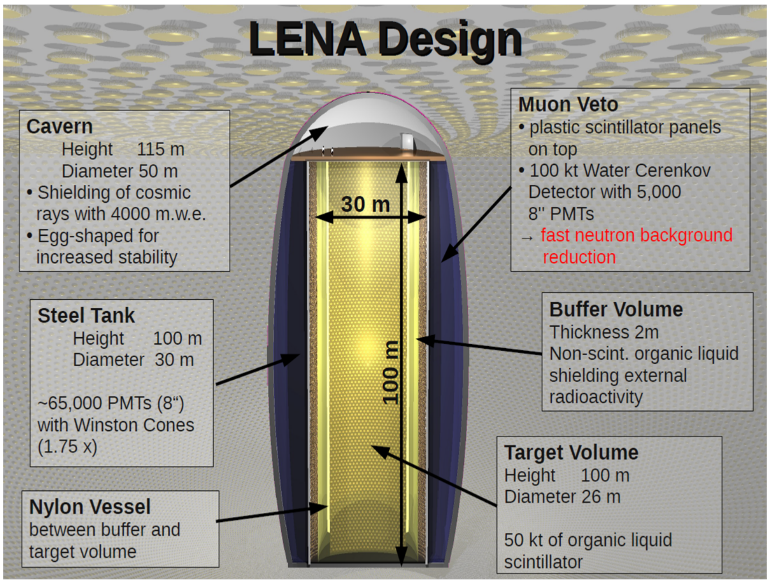

Fig. 5. Schematic view of the LENA detector with about 50 kton active liquid scintillator mass.

coverage of about 30% has to be achieved. To reach the physics goals quite demanding properties to photomultipliers is necessary. This encompasses high quantum efficiency, fast timing, a low time jitter, as well as a low afterpulse rate. Currently 8 inch to 12 inch tubes equipped with Winston cones are investigated. The total number of tubes required depends on the size of the tube and will be between 40000 to 60000. Special care on the purity in radioactivity inside the detector will be required. This is relevant for low energy neutrino physics and especially true for the liquid scintillator itself. Here the experiences gained in Borexino [39] may enter. Fig. 5 shows a schematic view of the detector lay-out of LENA.

6.2. *Low energy neutrino physics*

Low energy neutrino physics is typically a field of rare event search. Therefore it is evident, that larger detectors will benefit by a much better statistics. Interpretation of experimental results and tests of models very often will be only possible by better statistics. For instance, this is the case for the discussion of the implication of terrestrial neutrino results on geophysical models and more details of solar physics may be revealed by better statistics of neutrino experiments. In some cases the expected flux of neutrinos like those from the diffuse supernovae background (DSNB) is so low, that their detection will become only possible with future very large experiments. Main detection reactions at low neutrino energies are captures on free protons or on carbon nuclei present in organic liquid scintillators, but also scattering processes on protons and electrons contribute to the neutrino signal. A significant signature is common to all capture reactions, which allows to tag those events with high accuracy and to separate them from background signals. A prominent example is the inverse beta decay on free protons, where the delayed neutron capture is used to identify these neutrino reactions. In the following a brief

Channel	Rate
(1) $\bar{\nu}_e + p \to n + e^+$	7 500−13 800
(2) $\bar{\nu}_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^+$	150−610
(3) $\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N} + e^-$	200−690
(4) $\nu_e + {}^{13}\mathrm{C} \to {}^{13}\mathrm{N} + e^-$	∼10
(5) $\nu + {}^{12}\mathrm{C} \to {}^{12}\mathrm{C}^* + \nu$	680−2 070
(6) $\nu + e^- \to e^- + \nu$	680
(7) $\nu + p \to p + \nu$	1 500−5 700
(8) $\nu + {}^{13}\mathrm{C} \to {}^{13}\mathrm{C}^* + \nu$	∼10

Table 1
Overview of the detection channels for SN neutrinos available in LENA. The rates depend on the underlying SN model. Total event rates vary from 10 000 to 15 000 events for the standard SN scenario (8 $M_\odot$ progenitor in 10 kpc distance).

description of the main goals in low energy neutrino physics of LENA will be discussed.

Neutrinos from a galactic supernova: In case of a core-collapse SN within the Milky Way, a burst of neutrinos is expected to reach terrestrial detectors. The short neutronization signal of ν_e due to the conversion of protons to neutrons in the collapsing iron core is followed by an enormous signal of $\nu\bar{\nu}$ pairs of all flavors lasting for about 10 seconds. The latter are produced in the cooling phase of the developing proto-neutron star, radiating away about 99 % of the released gravitational energy.

While the dominant ν detection channel in present-day LSDs is the inverse beta decay (IBD), $\bar{\nu}_e + p \to n + e^+$, the target mass of LENA is large enough to exploit a variety of reaction channels for all flavors. In the standard SN scenario that describes the explosion of an 8 $\mathrm{M}_\odot$ progenitor star at 10 kpc distance, LENA will detect between 10 000 and 15 000 events. The numbers vary with the assumed SN neutrino spectra and with the occurrence of matter effects in the stellar envelope. An overview of the detection channels and their rates in LENA is given in Tab. 1.

More than half of the events are caused by the IBD (1) which allows a precision measurement of the $\bar{\nu}_e$ energy spectrum and the temporal evolution of the $\bar{\nu}_e$ flux. The energy resolution of a large-volume LSD offers the possibility to study the imprints of matter effects in the $\bar{\nu}_e$ spectrum that either result from the transit through the progenitor star envelope or the Earth. As the occurrence of these effects is closely linked to the size of the mixing angle θ_{13} and the neutrino mass hierarchy, SN ν detection in LENA is also sensitive to these up to now undetermined neutrino parameters. Further effects like the recently proposed collective oscillations might also be imprinted on the $\bar{\nu}_e$ spectrum.

The charged current (CC) reaction of ν_e on Carbon (3) will be mainly used to determine the ν_e flux. The event signature is hard to discern from the CC reaction of $\bar{\nu}_e$'s (2) on a event by event basis. However, statistical subtraction of the $\bar{\nu}_e$ flux which is determined very accurately by channel (1) can be used to isolate the ν_e signal at a 10 % level. The remaining uncertainty is mostly due to the uncertainties of the reaction cross sections.

While the channels (1-4) allow to discriminate ν_e and $\bar{\nu}_e$, channels (5-8) are accessible for all neutrinos independent of their flavors or anti-flavors. The neutral current (NC) reactions on Carbon (5+8) are flux measurements only and bear no spectral information. Both elastic electron scattering (6) and proton scattering (7) on the other hand provide

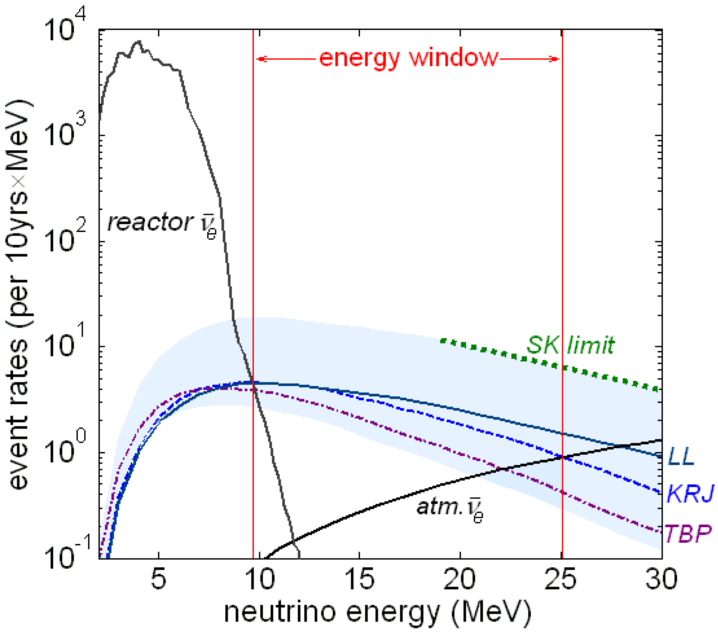

Fig. 6. Event rates of reactor, atmospheric and DSNB $\bar{\nu}_e$ (according to three different models) as expected for LENA in Pyhäsalmi after ten years of measurement. The shaded region represents the possible range of the DSNB rates depending on the normalization of the SN rate. The Super-Kamiokande limit is indicated.

spectral data for the combined flux of all flavors. Due to the strong dependence of the measured event rate on the mean neutrino energy, proton scattering is very sensitive to the temperature of the SN neutrinosphere. Models on gravitational star-collapses can be probed by comparing the measured NC-event rates with expectations, as these rates are independent from flavor oscillations.

Diffuse Supernova Neutrino Background: All SN explosions in the universe contribute to an – on cosmic scales – constant and isotropic flux of neutrinos, the Diffuse Supernova Neutrino Background (DSNB). The expected flux $\sim 10^2$ neutrinos per cm^{2}s is about eight orders of magnitude fainter than the terrestrial flux of solar neutrinos.

During proto-neutron star cooling, $\nu\bar{\nu}$ pairs of all flavors are generated. The most accessible for detection are $\bar{\nu}_e$, as the IBD reaction features the largest cross section at low energies. In addition the successive neutron capture on a proton yield a delayed 2.2 MeV gamma signal. This delayed coincidence can be used to reject background very efficiently. Present day LSDs lack the target mass necessary to detect the DSNB. LENA might be the first experiment capable of detecting these relic SN neutrinos. Depending on astrophysical models the expected rate may vary between 2 and 20 events per year for a 50 kton LENA detector [41].

Fig. 6 illustrates the detection window for DSNB events in LENA: While at energies below 10 MeV the $\bar{\nu}_e$ signal created by terrestrial nuclear power reactors is predominant, the $\bar{\nu}_e$ component of the atmospheric neutrino flux prevails above 25 MeV. Both reactor and atmospheric background fluxes depend on the detector location. Fig. 6 presents the situation in Pyhäsalmi.

Source	Neutrino Rate [d^{-1}]	
	BPS08(GS)	BPS08(AGS)
pp	24.92±0.15	25.21±0.13
pep	365±4	375±4
hep	0.16±0.02	0.17±0.03
^{7}Be	4984±297	4460±268
^{8}B	82±9	65±7
CNO	545±87	350±52

Table 2
Expected solar neutrino event rates induced by neutrino-electron scattering in LENA, assuming a detection threshold of 250 keV. Calculations are based on the high-metallicity BPS08(GS) and low-metallicity BPS08(AGS) models. The errors indicate the model uncertainties.

There are a number of cosmogenic backgrounds to be taken into account: The IBD coincidence signal can be mimicked by the βn-decay of cosmogenic ^{9}Li, fast neutrons produced either by muons in the rock and entering the detector unnoticed or by atmospheric neutrinos in NC reactions. Current MC calculations investigate the possibility to discard these backgrounds by pulse shape analysis.

Beyond the first discovery of the DSNB signal, event rates in LENA might be sufficient to cross-check the optical measurements of red-shift dependent SN rates up to red shifts of $\sim$2. Using the input of these astronomical measurements, it might be possible to put constraints on the mean energy of the original SN ν spectrum by deconvolving the red shift. Such a measurement represents the average of the ν spectra emitted by different types of SN, and might therefore complement the observations made from a single galactic SN ν burst.

Even more important would be a non-discovery of a DSNB signal. It would imply either new neutrino physics, or the failure of current astrophysical descriptions of supernovae explosions.

Solar Neutrinos: The experience with Borexino has shown that the radioactive contamination of a LSD can be reduced sufficiently to measure the solar ν spectrum down to energies of a few hundred keV [39]. The spectroscopic performance of LENA will probably be inferior to the one of Borexino as the expected photoelectron yield is lower. Nevertheless, the neutrino event rates in LENA will surpass the signal in Borexino by at least two orders of magnitude. In the following, a very conservative FV of 18 kt is chosen to ensure 7 m of shielding against external gamma-ray background. Table 2 lists the expected rates for the ν's emitted in the pp chain and the CNO cycle.

About 25 pp-ν-induced electron scattering events per day are expected above 250 keV. It is doubtful that this rate is sufficient to be distinguished from the overwhelming ^{14}C background intrinsic to the organic scintillator. About 5 000 ^{7}Be-ν events per day are expected: Presuming background levels and systematic uncertainties comparable to Borexino, the high statistics will allow a measurement of the ^{7}Be-ν flux with an accuracy unprecedented in neutrino physics. It might be particularly interesting to search for temporal variations in the signal: Currently on-going MC analyses indicate that LENA will be sensitive to rate modulations of a few $\times 10^{-3}$ in amplitude. In this way, fusion rate variations induced by helioseismic g-modes, ν flux modulations induced by spin flavor conversion as well as the day/night effect in terrestrial matter could be probed.

After three years of Borexino data taking it is evident that the detection of CNO and pep neutrinos decisively depends on the background level induced by β-decays of cosmogenic ^{11}C. The ^{11}C production rate is mainly a function of the rock overburden shielding the detector. If LENA will be operated at the intended depth of 4 000 mwe (meters water equivalent), the ratio of the CNO or pep-ν signals to the ^{11}C background rate will be 1:5, a factor 5 better than in Borexino. A high-statistics measurement of about 500 CNO-ν's per day will provide valuable information on solar metallicity, especially if the contributions from the individual fusion reactions can be distinguished. The measurement of the pep-ν flux can be used for a precision test of the ν_e survival probability in the MSW-LMA transition region. Calculations indicate that also the onset of the transition region could be tested utilizing low-energetic ^{8}B neutrinos.

Geo- and reactor neutrinos: Due to the low energy threshold, LSDs are sensitive to geoneutrinos via the IBD [31], as has also recently been demonstrated by Borexino [32]. The large target mass of LENA corresponds to roughly 1 000 events per year if the detector is located at Pyhäsalmi. The actual event rate is dependent on the detector location, as the geoneutrino flux depends on the crust thickness and composition near the detector site.

If the radiopurity levels of Borexino are reached in LENA, geoneutrino detection will suffer much less from internal α-induced background than the measurements performed by KamLAND [31]. In addition, for most of the sites investigated by LAGUNA the background from reactor neutrinos will be significantly lower. The abundances of ^{238}U and ^{232}Th and their natural decay chains can be determined in LENA by an analysis of the geoneutrino energy spectrum. In addition the hypothesis of a natural nuclear fission reactor in the Earth's center can be probed by LENA[33].

In spite of the high statistics, the directional information of the IBD events is not sufficient to distinguish the contributions of core, mantle, and crust to the total $\bar{\nu}_e$ flux: Ten years of exposure would be needed to positively identify a strong geoneutrino source of 20 TW at the Earth's core [33]. A more promising approach is the combination of geoneutrino rate measurements in several LSDs at different sites: The data of KamLAND, Borexino, SNO+, LENA, and HanoHano could be combined to determine the geoneutrino fluxes of crust and mantle.

For geoneutrino detection neutrinos from reactors are a severe background in the energy region below $\sim$ 3 MeV. On the other hand reactor neutrino spectroscopy allows a determination of the mass splitting Δ^2_{12} to an accuracy of about 1% [22].

6.3. *High Energy Neutrino Physics*

In this section the physics potential of LENA in particle physics is discussed. This encompasses search for proton decay as well as the use of LENA as detector of long baseline oscillation experiments with accelerator neutrinos.

Nucleon Decay Search: One of the most interesting questions in modern particle physics is the stability of the proton. The violation of Baryon number conservation is one of the three conditions for the observed matter-antimatter asymmetry in the universe. Grand Unified Theories usually prefer the proton decay into π^0 and e^+. This is also the channel water Čerenkov detectors (WCDs) are able to put the most stringent limits on [43]. The performance of LSDs for this decay channel heavily depends on their tracking capability at sub-GeV energies and is still to be investigated. Supersymmetry on the other hand favors the decay into K^+ and $\bar{\nu}$. Here, WCDs have a disadvantage: Both primary decay particles are invisible in the detector as the kaon is generated at a kinetic energy below the Čerenkov threshold, greatly reducing the detection efficiency.

Regarding the latter decay channel, LSDs offer a natural advantage as they are able to detect the kinetic energy deposited by the kaon [42]. The subsequent decay into $\pi^+\pi^0$ or $\mu^+\nu_\mu$ provides a very fast coincidence signal ($\tau_{K^+} \simeq 13\,\mathrm{ns}$) that can be used for background discrimination. The main background are atmospheric neutrinos in the energy regime of several 100 MeV. A rather simple pulse shape analysis can be exploited to reduce the atmospheric background to less than 1 count in 10 years, whereas the efficiency for detecting this specific proton decay branch is about 65%. This efficiency is about 10 times higher with respect to WCDs. If no signal were seen in 10 years, the proton-lifetime limit could be increased to $\tau_p \geq 4{\times}10^{34}$ yrs (at 90 % C.L.) for this decay mode [42]. This surpasses the present best limit set by the Super-Kamiokande experiment by about one order of magnitude [43].

Long baseline neutrino detection - track and flavor reconstruction: In recent studies the potential of track reconstruction for ν events in the GeV range has been investigated. This allows event reconstruction for quasi-elastic ν scattering on nucleons that dominates at energies of ~1 GeV or below. However, resonant single-pion production and deep-inelastic scattering prevail at higher energies. The presence of additional particles (mostly pions) considerably complicates the reconstruction of the interaction vertex. Nevertheless, the possibility to disentangle the superimposed light fronts has been tested in MC simulations [44]: A superposition of light patterns corresponding to MC standard events is fitted to the observed light patterns. For single-pion production, the energy of the incident neutrino can be reconstructed with an accuracy of only few per cent, including the information on the primary lepton flavor. Even for deep-inelastic interaction vertices featuring up to three pions, the lepton track and the overall event energy can be found. However, this method requires to record the signal shape of each individual PM. The signal of each PM has to be sampled by a Flash-ADC with ≤2 ns time resolution for at least 100 ns to achieve optimum results. These MC simulations applied a simplified model of light production and propagation, are limited to a horizontal plane, and do not include the reconstruction of certain particle types, e. g. π^0 and neutron events. However, these first results are very encouraging, and are presently followed up by more detailed simulations.

The expected performance of LENA at GeV energies [44] has been used to investigate the detector's aptitude for a next-generation neutrino beam. With LENA located in Pyhäsalmi, the distance to CERN would be 2288 km. For this beam baseline, the neutrino energy corresponding to the first oscillation maximum is 4.2 GeV. The assumed neutrino source is a wide-band beam featuring energies between 1 and 6 GeV and a peak energy slightly above 1.5 GeV. The projected beam power is 3.3×10^{20} POT per year or 1.5 MW, which is about twice the power of the T2K beam. The total running time is set to 10 years, using alternating ν_μ and $\bar{\nu}_\mu$ beams.

The energy resolution in LENA for CC ν events ranges from 3 to 8 % for energies between 1 and 5 GeV. Effects concerning the track reconstruction uncertainty, the influence of the Fermi motion and the ambiguities arising from the presence of hadronic particles, and a decrease in reconstruction efficiency above 3 GeV were taken into account. The far detector is considered to be on-axis with respect to the beam, trading a narrower ν spectrum for larger beam intensities. In this scenario, the systematic limitations on the experimental sensitivity to a ν_e appearance search arise from the intrinsic contamination of the beam with ν_e ($\sim$1 %), while NC π_0 production plays only a minor role. In the ν_μ disappearance search, the beam contamination with $\bar{\nu}_\mu$ as well as NC production of $\pi^\pm$ have to be considered.

The final sensitivity on oscillation parameters obviously depends on the exact values of the parameters, especially on the size of δ_{CP}. As a benchmark value, $\sin^2 2\theta_{13} > 5 \times 10^{-3}$ is required to reach a 3σ discovery potential for θ_{13} and δ_{CP}, and to be able to identify the mass hierarchy. More exact values can be estimated from [45]. Compared to the projected performance of T2K, this corresponds to an improvement of the sensitivity for θ_{13} by a factor ~ 4. In addition, the CERN-Pyhäsalmi baseline enables the search for δ_{CP} and neutrino mass hierarchy.

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