The present status of neutrino oscillation searches with reactors and accelerators is reviewed. An outlook, especially on future long baseline neutrino oscillation projects, is given.

1 Introduction

For several reasons, massive neutrinos are important in modern particle physics. The theoretical extensions in form of grand unified theories of the very successful standard model may be checked by their prediction of neutrino masses. Moreover massive neutrinos would open up a variety of new phenomena which could be investigated by experiments. Also many astrophysical and cosmological implications would emerge from it. For example, neutrino oscillations are the preferred particle physics solution of the solar neutrino problem. Neutrinos in the mass region of a few eV serve as good candidates for hot dark matter. Experimental evidence for effects due to neutrino masses are seen in solar neutrinos, atmospheric neutrinos and the LSND experiment (see sec. 5.1).

On the theoretical side, two groups of models for neutrino masses emerged over the past years to explain the present observations of neutrino experiments. The first one is the "classical" quadratic see-saw-mechanism, resulting in a strong scaling behaviour of the neutrino masses like

$$m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} \propto m_u^2 : m_c^2 : m_t^2$$

(1)

where $m_u$, $m_c$ and $m_t$ are the corresponding quark masses. Recently another type of see-saw-mechanism has been coming up resulting in more or less almost degenerated neutrinos. At present, on the experimental side, the direct limits for neutrino masses are [1]:

- $m_{\nu_e} < 15$ eV  SN 1987a
- $m_{\nu_\mu} < 170$ keV  $\pi$-decay
- $m_{\nu_\tau} < 18.2$ MeV  $\tau$-decay

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1 to appear in Proc. 4th Int. Solar Neutrino Conference, Heidelberg, April 1997
The current results for $m_{\nu_e}$ taken from tritium beta decay experiments are more stringent and give a limit of 3.5 eV but face the problem of negative $m^2$-values. Another bound valid only for Majorana neutrinos results from double beta decay and is given by

$$\langle m_{\nu_e} \rangle = |\sum_i U^2_{ei} m_i | < 0.5 \text{eV}$$ (2)

It should also be mentioned that the recently started E872 experiment at Fermilab will make it possible for the first time to directly proof the existence of $\nu_{\tau}$ via weak charged current reactions. From the above mentioned experimental bounds on the neutrino masses it becomes obvious, that a direct kinematic test of $m_{\nu_\mu}$ and $m_{\nu_\tau}$ and perhaps $m_{\nu_e}$ in the eV or even sub-eV-region is impossible, the only possibility to explore this region is via neutrino oscillations.

## 2 Neutrino oscillations

Similar to the quark sector, the mass eigenstates need not to be the same as the flavour eigenstates for neutrinos as well offering the possibility of oscillations. In the simplified case of two flavours the mixing can be described by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$ (3)

While $\sin^2 2\theta$ describes the amplitude of the oscillation, $\Delta m^2 = m_2^2 - m_1^2$ determines the oscillation length, characterising a full cycle of oscillation between two flavours. In practical units the oscillation length $L$ is given by

$$L = \frac{4\pi E\hbar}{\Delta m^2 c^3} = 2.48\left(\frac{E}{\text{MeV}}\right)\left(\frac{eV^2}{\Delta m^2}\right) \text{m}$$ (4)

As can be seen, oscillations do not allow an absolute mass measurement. Furthermore to allow oscillations, the neutrinos must not be exactly degenerated. Solar neutrinos are in a unique position to explore the small $\Delta m^2$ - region because of their relative low energy and the large distance of the sun. From first principles there is no preferred region in the $\Delta m^2 - \sin^2 2\theta$ parameter space and therefore the whole has to be investigated experimentally.

## 3 Reactor experiments

On earth two artificial neutrino sources exist in form of nuclear power reactors and accelerators.

### 3.1 Principles

Reactors are a source of MeV $\bar{\nu}_e$ due to the fission of nuclear fuel. The main isotopes involved are $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$. The neutrino rate per fission has been measured for all
isotopes except $^{238}$U and is in good agreement with theoretical calculations. Experiments typically try to measure the positron spectrum which can be deduced from the $\bar{\nu}_e$ spectrum and either compare it directly to the theoretical predictions or measure it at several distances from the reactor and search for spectral changes. Both types of experiments were done in the past. The detection reaction is

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

with an energy threshold of 1.804 MeV. Reactor experiments are disappearance experiments looking for $\bar{\nu}_e \rightarrow \bar{\nu}_X$.

### 3.2 Status

The detection reaction is always the same, resulting in different strategies for the detection of the positron and the neutron. Normally coincidence techniques are used between the annihilation photons and the neutrons which diffuse and thermalise within $10-100 \mu s$. The main background are cosmic ray muons producing neutrons in the surrounding of the detector. Several reactor experiments have been done in the past (see Tab.1). All these experiments had a fiducial mass of less than 0.5 t and the distance to the reactor was never more than 250 m.
| reactor                      | thermal power [MW] | distance [m] |
|-----------------------------|--------------------|--------------|
| ILL-Grenoble (F)            | 57                 | 8.75         |
| Bugey (F)                   | 2800               | 13.6, 18.3   |
| Rovno (USSR)                | 1400               | 18.0, 25.0   |
| Savannah River (USA)        | 2300               | 18.5, 23.8   |
| Gösgen (CH)                 | 2800               | 37.9, 45.9, 64.7 |
| Krasnojarsk (Russia)        | ?                  | 57.0, 57.6, 231.4 |
| Bugey III (F)               | 2800               | 15.0, 40.0, 95.0 |

Tab.1: List of done reactor experiments. Given are the thermal power of the reactors and the distance of the experiments with respect to the reactor.

The achievements of the most stringent reactor experiments are shown as an exclusion plot in Fig. 1.

Figure 2: Principal design of the CHOOZ reactor experiment in France. Two 4.2 GW reactors in a distance of 1030 m are used to produce an antineutrino flux at the experiment of about $10^{10} \text{cm}^{-2}\text{s}^{-1}$.

4 Future

Two new reactor experiments are coming up and will be in operation in 1997. The first one is the CHOOZ-experiment in France [6] (Fig. 2). This detector has some advantages with respect to previous experiments. First of all the detector is located underground with a shielding of 300
mwe, reducing the background due to cosmics by a factor of 300. Moreover, the detector is about 1030 m away from the reactor (more than a factor 4 in comparison to previous experiments) enlarging the sensitivity to smaller $\Delta m^2$. In addition the main target has about 4.8 t and is therefore much larger than those used before. The main target consists of a specially developed Gd-loaded scintillator. This inner detector is surrounded by an additional detector containing 17 t of scintillator without Gd and 90 t of scintillator as an outer veto. The signal in the inner detector will be the detection of the annihilation photons in coincidence with n-capture on Gd, the latter producing gammas with a total sum of up to 8 MeV. The light from the inner region is detected by 160 photomultipliers. Calibration runs were done in September and October 1996. The measured background is lower than the expected 2.5 counts per day (cpd) so the expected signal of 31 cpd should be clearly visible. The two 4.2 GW reactors will be on full power in July 1997, but data taking has already started.

The second experiment is the Palo Verde (former San Onofre) experiment [7] near Phoenix, AZ (USA). It will consist of 12 t liquid scintillator also loaded with Gd. The scintillator is filled in 66 modules arranged in an $11 \times 6$ array (Fig. 3). As a signal serves the coincidence of three modules. The experiment will be located under a shielding of 46 mwe in a distance of about 750 (820) m to the reactors. The experiment will be online by late summer 1997 with an expected signal of 51 cpd.

Both experiments should recognize a clear signal in case the atmospheric neutrino problem is due to $\nu_e - \nu_\mu$ oscillations.
As a project for the very future plans for a 1000 t detector (Perry) are also discussed. A further large scale reactor experiment using the former Kamioka detector in a distance of 160 km to a reactor is approved by the Japanese Government.

5 Accelerators

The second source of terrestrial neutrinos are high energy accelerators. Accelerators typically produce neutrino beams by shooting a proton beam on a fixed target. The produced secondary pions and kaons decay and create a neutrino beam dominantly consisting of $\nu_\mu$. The detection mechanism is via charged weak currents

$$\nu_i N \rightarrow i + X \quad i = e, \mu, \tau$$

where $N$ is a nucleon and $X$ the hadronic final state. Depending on the intended goal, the search for oscillations therefore requires a detector which is capable of detecting electrons, muons and $\tau$-leptons in the final state. Accelerator experiments are typical appearance experiments working in the channels $\nu_\mu - \nu_X$ and $\nu_e - \nu_X$.

Figure 4: Neutrino spectrum resulting from pion and muon decays. Beside a monoenergetic line at 29.8 MeV we can expect a continuous spectrum up to 55.8 MeV. The contamination of the beam with $\bar{\nu}_e$ is normally very small.
5.1 Accelerators at medium energy

At present there are two experiments running with neutrinos at medium energies \( (E_{\nu} \approx 30 - 50 \text{ MeV}) \) namely KARMEN and LSND. Both experiments use 800 MeV proton beams on a beam dump to produce pions. The expected neutrino spectrum from pion and \( \mu \)-decay is shown in Fig. 4. The beam contamination of \( \bar{\nu}_e \) is in the order of \( 10^{-4} \).

The KARMEN experiment at the neutron spallation source ISIS at Rutherford Appleton Laboratory is using 56 t of a segmented liquid scintillator. The main advantage of this experiment is the known time structure of the two proton pulses hitting the beam dump (two pulses of 100 ns with a separation of 330 ns and a repetition rate of 50 Hz). Because of the pulsed beam positrons are expected within 0.5-10.5 \( \mu s \) after beam on target. The signature for detection is a delayed coincidence of a positron in the 10 - 50 MeV region together with \( \gamma \)-emission from either \( p(n,\gamma)D \) or \( \text{Gd}(n,\gamma)\text{Gd} \) reactions. The first results in 2.2 MeV photons while the latter allow gammas up to 8 MeV. The limits reached so far are shown in Fig. 5. To improve the sensitivity for neutrino oscillation searches by reducing the neutron background a new veto shield against atmospheric muons was constructed which has been in operation since Feb. 1997 and is surrounding the whole detector. The region which can be excluded in 2-3 years of running in the upgraded version is also shown in Fig. 5.

The LSND experiment at LAMPF is a 167 t mineral oil based liquid scintillation detector using scintillation light and Cerenkov light for detection. It consists of an approximately cylin-
drical tank 8.3 m long and 5.7 m in diameter. The experiment is about 30 m away from a copper beam stop under an angle of 12° with respect to the proton beam. For the oscillation search in the channel $\bar{\nu}_\mu - \bar{\nu}_e$ a signature of a positron within the energy range $36 < E_e < 60$ MeV together with a time and spatial correlated 2.2 MeV photon from $p(n, \gamma)D$ is required. The analysis [10] ends up in evidence for oscillations in the region shown in Fig. 5. Recently LSND published their $\nu_e - \nu_\mu$ analysis for pion decays in flight [11] which is in agreement with the former evidence from pion decay at rest. Also LSND continues with data acquisition.

An increase in sensitivity in the $\nu_\mu - \nu_e$ oscillation channel can be reached in the future if there is a possibility for neutrino physics at the European Spallation Source (ESS) which is in the planning phase or the National Spallation Neutron Source (NSNS) at Oak Ridge which might have a 1 GeV proton beam in 2004. The Fermilab 8 GeV proton booster offers the chance for a neutrino experiment (BooNE) as well which could start data taking in 2001.

5.2 Accelerators at high energy

High energy accelerators provide neutrino beams with an average energy in the GeV region. With respect to high energy experiments at present especially CHORUS and NOMAD at CERN will provide new limits. They are running at the CERN wide band neutrino beam with an average energy of around 25 GeV, produced by 450 GeV protons accelerated in the SPS and then hitting a beryllium beam dump. Both experiments are 823 m (CHORUS) and 835 m (NOMAD) away from the beam dump and designed to improve the existing limits on $\nu_\mu - \nu_\tau$ oscillations by an order of magnitude. The beam contamination of prompt $\nu_\tau$ from $D_s^\pm$-decays is of the order $10^{-6}$. Both experiments differ in their detection technique. While CHORUS relies on seeing the track of the $\tau$-lepton and the associated decay vertex with the associated kink because of the decay, NOMAD relies on kinematical criteria.

The CHORUS experiment [12] (Fig. 6) uses emulsions with a total mass of 800 kg segmented into 4 stacks, 8 sectors each as a main target. To determine the vertex within the emulsion as accurate as possible systems of thin emulsion sheets and scintillating fibre trackers are used. Behind the tracking devices follows a hexagonal air core magnet for momentum determination of hadronic tracks, an electromagnetic lead-scintillating fibre calorimeter with an energy resolution of $13 \%/ \sqrt{E}$ for electrons as well as a muon spectrometer. A $\tau$-lepton created in the emulsion by a charged current reaction is producing a track of a few hundred $\mu$m. Focussing on the muonic and hadronic decay modes of the $\tau$ a signature like the one shown in Fig. 7 is expected. The kink of the decay and the displacement of the muon from the primary vertex should be clearly visible. After the running period the emulsions are scanned with automatic microscopes coupled to CCDs. The experiment has been taking data since 1994 and will continue until the end of 1997. The present limit provided by CHORUS for the $\nu_\mu - \nu_\tau$ channel for large $\Delta m^2$ is [13]

$$\sin^2 2\theta < 8 \times 10^{-3} \quad (90\% CL)$$  (7)
The final goal is to reach a sensitivity down to $\sin^2 2\theta \approx 2 \times 10^{-4}$ for large $\Delta m^2$.

The NOMAD experiment\cite{14} (Fig. 8) on the other hand relies on the kinematics. It has as a main active target 45 drift chambers corresponding to a total mass of 2.7 tons followed by transition radiation and preshower detectors for $e/\pi$ separation. After an electromagnetic calorimeter with an energy resolution of $\Delta E/E = 3.22\% / \sqrt{E} \oplus 1.04\%$ and a hadronic calorimeter five muon chambers follow. Because most of the devices are located within a magnetic field of 0.4 T a precise momentum determination due to the curvature of tracks is possible. The $\tau$-lepton cannot be seen directly, the signature is determined by the decay kinematics (Fig. 10). The main background for the $\tau$-search are regular charged current reactions. In normal $\nu_\mu$ charged current events the muon balances the hadronic final state in transverse momentum $p_T$ with respect to the neutrino beam. Hence the value for missing transverse momentum is small. The angle $\Phi_{lh}$ between the outgoing lepton and the hadronic final state is close to 180° while the angle $\Phi_{mh}$ between the missing momentum and the hadronic final state is more or less equally distributed. In case of a $\tau$ - decay there is significant missing $p_T$ because of the escaping $\nu_\tau$ as well as a concentration of $\Phi_{mh}$ to larger angles because of the kinematics. In the $\nu_\mu - \nu_\tau$ channel for large $\Delta m^2$ NOMAD gives a preliminary limit of \cite{15}

$$\sin^2 2\theta < 4 \times 10^{-3} \quad (90\% CL)$$

(8)

slightly better than the limit of E531. Having a good electron identification NOMAD also offers the possibility to search for oscillations in the $\nu_\mu - \nu_e$ channel. A preliminary limit (Fig. 9) on
Figure 7: Schematical view of the detection principle of CHORUS. In this case the muon from the decay $\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$ is visible as a kink after a short $\tau$-track.

$\nu_\mu - \nu_e$ is available as $[15]$ (for large $\Delta m^2$)

$$\sin^22\theta < 2 \times 10^{-3} \quad (90\%CL)$$ (9)

This and a recently published CCFR result $[16]$ seem to rule out the large $\Delta m^2$ region of the LSND evidence. NOMAD will continue data taking at least until end of 1997 as well.
Figure 8: Side view of the NOMAD detector at CERN.

Figure 9: Preliminary NOMAD exclusion plot for $\nu_e - \nu_\mu$ oscillation in comparison with LSND results. The high $\Delta m^2$ region is excluded.
Background
\(\nu_{e,\mu} - \text{CC}\)

\[\Phi_{lh}\]

\[\Phi_{mh}\]

Signal
\(\nu_\tau - \text{CC}\)

\[p_T\]

\[\Phi_{lh}\]

\[\Phi_{mh}\]

Jet

Jet

Figure 10: Definition of the kinematic variables within the NOMAD-experiment. For typical charged current events the angle \(\Phi_{lh}\) is close to 180 degrees (upper left). In \(\tau\) - decays also the angle \(\Phi_{mh}\) concentrates towards larger values (upper right). Double angle plots for Monte Carlo distribution for \(\nu_\mu\) charged current events (lower left) and \(\nu_\tau\) signal events (lower right). By cutting in both angles it is possible to reduce the overwhelming charged current background to an acceptable level.
6 Future accelerator experiments

Possible future ideas split into two groups depending on the physical goal. One group is focussing on improving the existing bounds by another order of magnitude with respect to CHORUS and NOMAD. This effort is motivated by the classical see-saw-mechanism which offers a $\nu_{\tau}$ in the eV-region as a good candidate for hot dark matter by assuming that the solar neutrino problem can be solved by $\nu_e - \nu_\mu$ oscillations. The other group plans to increase the source - detector distance to probe smaller $\Delta m^2$ and to be directly comparable to atmospheric scales.

6.1 Short and medium baseline experiments

Several ideas exist for a next generation of short baseline experiments. At CERN the follow up could be a detector combining features of NOMAD and CHORUS. The idea is to use 2.4 tons of emulsion within the NOMAD magnet in form of 6 target modules. Each module contains an emulsion target consisting of 72 emulsion plates, as well as a set of large silicon microstrip detector planes and a set of honeycomb tracker planes. To verify the feasibility of large silicon detector planes maintaining excellent spatial resolution over larger areas NOMAD included a prototype (STAR) in the 1997 data taking. For the future experiment, options to extract a neutrino beam at lower energy of the proton beam (350 GeV) at the CERN SPS to reduce the prompt $\nu_{\tau}$ background are discussed as well. At Fermilab the COSMOS (E803) experiment is proposed to improve the sensitivity in the $\nu_{\mu} - \nu_{\tau}$ channel by one order of magnitude with respect to CHORUS and NOMAD by using the new Main Injector. It will produce a proton beam of 120 GeV resulting in an average neutrino energy of $< E_\nu > \approx 12$ GeV. The main target consists of two parts each containing 4 quadrants of emulsions. Each quadrant (90 cm wide, 70 cm high and 4.9 cm thick) will contain 45 emulsion sheets summing up to a total mass of 865 kg. The vertex finding is done with fibre trackers. The complete tracking system is followed by a lead-glass electromagnetic calorimeter and a muon spectrometer consisting of 6 steel slabs each followed by proportional tubes. The distance to the beam dump will be 960 m. This experiment could start data taking at the beginning of the next century. Both experiments propose a sensitivity in the $\nu_{\mu} - \nu_{\tau}$ channel of around $2 \times 10^{-5}$ for large $\Delta m^2$ ($\Delta m^2 > 100 eV^2$). Also a proposal for a medium baseline search exists. The CERN neutrino beam used by CHORUS and NOMAD is coming up to the surface again in a distance of about 17 km away from the beam dump. An installation of an ICARUS-type detector (liquid Ar TPC) or a 27 kton water-RICH, see below, could be installed here.

6.2 Long baseline experiments

Several accelerators and underground laboratories around the world offer the possibilities to perform long baseline experiments. This is of special importance to probe directly the region of atmospheric neutrinos.
6.2.1 KEK - Superkamiokande

The first of these experiments will be the KEK-E362 experiment\[20\] in Japan sending a neutrino beam from KEK to Superkamiokande. The distance is 235 km. A 1 kt front detector, about 1 km away from the beam dump will serve as a reference and measure the neutrino spectrum. The neutrino beam with an average energy of 1 GeV is produced by a 12 GeV proton beam dump. The detection method within Superkamiokande will be identical to that of their atmospheric neutrino detection. The beamline should be finished by the end of 1998 so the experiment will start data taking in 1999. An upgrade of KEK is planned to a 50 GeV proton beam, which could start producing data around 2004.

6.2.2 Fermilab - Soudan

A big neutrino program is also associated with the new Main Injector at Fermilab. The long baseline project will send a neutrino beam to the Soudan mine about 735 km away from Fermilab. Here the MINOS experiment\[21\] will be installed. It also consists of a front detector located at Fermilab just upstream of COSMOS and a far detector at Soudan. The far detector will be made of 10 kt magnetized Fe toroids in 600 layers with 4 cm thickness interrupted by about 32000 m$^2$ active detector planes in form of streamer tubes with x and y readout to get the necessary tracking informations. The project could start at the beginning of next century.

6.2.3 CERN - Gran Sasso

A further program considered in Europe are long baseline experiments using a neutrino beam from CERN down to Gran Sasso Laboratory. The distance is 732 km. Several experiments have been proposed for the oscillation search. The first proposal is the ICARUS experiment\[22\] which will be installed in Gran Sasso anyway for the search of proton decay and solar neutrinos. This liquid Ar TPC can also be used for long baseline searches. A prototyp of 600 t is approved for installation. A second proposal, the NOE experiment\[23\], plans to build a giant lead-scintillating fibre detector with a total mass of 4 kt. It will consist of 4 modules each 8m × 7.9 m × 7.3 m followed by a module for muon identification. A third proposal is the building of a 27 kt water-RICH detector\[24\], which could be installed either inside or outside the Gran Sasso tunnel. The readout is done by 3600 HPDs with a diameter of 250 mm and having single photon sensitivity. By using the RICH technique more complex event topologies like in standard water detectors can be investigated. Finally there exists a proposal for a 1kt iron-emulsion sandwich detector\[25\] which could be installed either at the Fermilab-Soudan or the CERN-Gran Sasso project. It could consist of 2240 modules arranged in 140 planes each containing 4 × 4 modules. The thickness of the iron and emulsion planes is about 1 mm.
7 Summary and Conclusion

Massive neutrinos offer a wide range of new phenomena in neutrino physics especially that of neutrino oscillations. Evidence for such oscillations comes from solar neutrinos, atmospheric neutrinos and the LSND experiment. The allowed regions in the $\Delta m^2$ - $\sin^2 2\theta$ parameter space are schematically shown in Fig. 11. Different scenarios which could be deduced from the observed evidence as well as the preferred hot dark matter candidate and the observability in short baseline experiment and long baseline experiment are summarized in Tab. 2.

Figure 11: Schematic presentation of parameter regions to explain the solar (dark), atmospheric (grey) and LSND (white) results with neutrino oscillations.

Figure 12: Proposed exclusion regions from future reactor and accelerator experiments for the $\nu_e$ - $\nu_\mu$ channel (left) and the $\nu_\mu$ - $\nu_\tau$ channel (right).
Apart from that, terrestrial neutrino experiments in form of nuclear reactors and high energy accelerators also exclude large parts of the parameter space because of non-observation of oscillation effects. Because the region of the MSW-solution for solar neutrinos are out of range for terrestrial experiments, present and to a large extend future oscillation experiments focus on the atmospheric region and a proof of the LSND results (Fig.12).

| solar          | no dramatic new results |
|----------------|-------------------------|
| atmos.        | C                       | C                       | NC                       | NC                       |
| LSND          | C                       | NC                      | C                        | NC                       |
| $|\Delta m_{12}^2|$ | $\approx 1$           | $\approx 10^{-5}$       | $\approx 1$              | $\approx 10^{-5}$         |
| $|\Delta m_{23}^2|$ | $\approx 10^{-2}$     | $\approx 10^{-2}$       | $\approx 1$              | ?                        |
| $|\Delta m_{13}^2|$ | $\approx 1$           | $\approx 10^{-2}$       | $\approx 10^{-5}$        | ?                        |
| Short B.L.    | $\nu_e - \nu_\tau$    | NO                      | YES                      | YES                      |
| Long B.L.     | $\nu_\mu - \nu_\tau$  | YES                     | NO                       | YES                      |
| HDM           | $\nu_{\mu,\tau}$      | $\nu_{e,\mu,\tau}$    | $\nu_\mu$                | $\nu_\tau(\nu_{e,\mu})$ |

Tab. 2: Comparison of different scenarios for the very near future depending on the confirmation (C) or non-confirmation (NC) of the atmospheric neutrino data and LSND results (partly compiled by L. diLella). Also shown is the resulting observability in short and long-baseline experiments. Neutrinos in the eV-range acting as hot dark matter are shown in the last row. Only the last column allows the classical see-saw mechanism. The first column normally cannot be explained in the framework of three neutrinos. Note that because of unitarity the following relation is valid: $\Delta m_{12}^2 + \Delta m_{23}^2 = \Delta m_{13}^2$.

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