NEUTRINO OSCILLATIONS AND DARK MATTER *

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Abstract
The significance of light massive neutrinos as hot dark matter is outlined. The power of neutrino oscillation experiments with respect to detect such neutrinos in the eV-region is discussed. Present hints for neutrino oscillations in solar, atmospheric and LSND data are reviewed as well as future experiments and their potential.

1 Introduction
Most astrophysical models which describe large-scale structure and the cosmic microwave background consistently end up with a mixture of hot dark matter and cold dark matter. The most obvious candidates for hot dark matter are stable neutrinos with masses in the eV-region. Their number density is given by

\[ n_{\nu_i} = \frac{3}{11} \left( \frac{g_{\nu_i}}{2} \right) \cdot n_{\gamma_0} \]  

resulting in a contribution to the mass density of (assuming \( g_{\nu_i} = 2 \))

\[ \rho_{\nu_i} = \sum m_{\nu_i} n_{\nu_i} \Rightarrow \sum m_{\nu_i} = 94\Omega_{\nu} h^2 eV \]  

If as suggested \( \Omega_{\nu} h^2 \) is about 0.2 - 0.3 any neutrino in the eV region contributes significantly.

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

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

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where \( m_u, m_c \) and \( m_t \) are the corresponding quark masses. Because of the large mass difference between the involved quarks only one neutrino can act as a dark matter candidate, for example \( \nu_\tau \). Recently another type of see-saw-mechanism was coming up resulting in more or less almost degenerated neutrinos \([1]\). This of course offers the chance that two or more neutrinos can act as hot dark matter. Indeed some astrophysical models favour scenarios with 2 neutrinos as hot dark matter \([2]\). The present direct limits for neutrino masses are \([3]\):

\[
\begin{align*}
\nu_e &< 15 \text{ eV} \\
\nu_\mu &< 170 \text{ keV} \\
\nu_\tau &< 18.2 \text{ MeV}
\end{align*}
\]

The actual results for \( m_{\nu_e} \) taken from tritium beta decay experiments are better 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 \([4]\)

\[
\langle m_{\nu_e} \rangle < 0.5 \text{ eV}
\]

What can be seen from the above is, that a direct kinematic test of \( m_{\nu_\mu} \) and \( m_{\nu_\tau} \) or even \( m_{\nu_e} \) in the eV or even sub-eV-region is impossible, the only possibility to explore this region is neutrino oscillations.

## 2 Neutrino oscillations

As in the quark sector also for neutrinos the mass eigenstates need not to be the same as the flavour eigenstates offering the possibility of oscillations. In the case of two flavours the mixing can be described by

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

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 is given by

\[
L_V = \frac{4\pi Eh}{\Delta m^2 c^3} = 2.48 \left( \frac{E}{MeV} \right) \left( \frac{eV^2}{\Delta m^2} \right) \text{ m}
\]

As can be seen oscillations do not allow an absolute mass measurement. Furthermore to allow oscillations, the neutrinos are not allowed to be exactly degenerated. Assuming the classical see-saw-mechanism and \( \nu_\tau \) as hot dark matter candidate the typical region to test is \( \Delta m^2 \) between 1-10^3eV^2. In contrast to this situation the almost degenerated scenario makes an investigation of the whole parameter space for possible oscillation signals necessary.
3 Present hints for neutrino oscillations

Besides many experiments which did not find any evidence for neutrino oscillations (see fig. 1) there are at present three fields of neutrino physics which at least show hints for neutrino oscillations. The first one is the long outstanding solar neutrino problem, now showing up in four different experiments, which have partly different energy thresholds. The present status is shown in Tab.1. Assigning the observed deficit to neutrino oscillations two solutions remain. First off all there exists the possibility of vacuum oscillations with $\Delta m^2 \approx 10^{-10}eV^2$ and large mixing angles ($\sin^2 2\theta \approx 1$) or, by considering neutrino oscillations in matter via the MSW-effect, the results are two regions around $\Delta m^2 \approx 10^{-5}eV^2$ with a large-angle solution ($\sin^2 2\theta \approx 1$) and a small angle solution ($\sin^2 2\theta \approx 10^{-2}$).

Another field where hints are seen is the one of atmospheric neutrinos. The production of pions and kaons in the atmosphere by cosmic ray primaries as well as their decays lead to predictions of observable fluxes of $\nu_\mu$ and $\nu_e$. Because of
absolute flux uncertainties people rely on the ratio $R$ defined as

$$R = \frac{\langle \mu/e \rangle_{\text{Data}}}{\langle \mu/e \rangle_{\text{MC}}}$$

(7)

| Experiment | Result       | Prediction BP | Prediction TC |
|------------|--------------|---------------|---------------|
| GALLEX [SNU]| $69.7 \pm 6.7^{+3.5}_{-3.5}$ | $131.5^{+7}_{-7}$ | $122.5 \pm 7$ |
| SAGE [SNU]  | $69 \pm 10^{+5}_{-5}$          | $131.5^{+7}_{-7}$ | $122.5 \pm 7$ |
| Cl [SNU]    | $2.56 \pm 0.16 \pm 0.14$       | $9.3^{+4.2}_{-1.6}$ | $6.4 \pm 1.4$ |
| Kamiokande  | $2.80 \pm 0.19 \pm 0.33$       | $42.4 \pm 5.8\% \cdot \Phi_t$ | $63.6\% \pm 8.9\% \cdot \Phi_t$ |

Tab. 1: Comparison of experimental solar neutrinos results with predictions of two solar model calculations (BP [6], TC [7]). The results for the gallium and chlorine-experiments are given in SNU ($1 \text{ SNU} = 10^{-36}$ captures per target atom per second), while the Kamiokande result is given as flux in units of $10^6 \text{cm}^{-2} \text{s}^{-1}$. The mentioned theoretical values correspond to the fraction of expected events. It should be mentioned that there are solar models which predict the right value for Kamiokande.

where $\mu$ expresses muon-like events and $e$ electron-like events. The present experimental values are (see also fig. 3):

Kamiokande: $R = 0.60 \pm 0.06 \pm 0.05$

IMB: $R = 0.56 \pm 0.04 \pm 0.04$

Soudan II: $R = 0.72 \pm 0.19^{+0.05}_{-0.07}$

MACRO: $R = 0.87 \pm 0.05 \pm 0.06$

Frejus: $R = 0.99 \pm 0.13 \pm 0.08$

NUSEX: $R = 0.99^{+0.35}_{-0.25}$

A detailed analysis shows that it is a deficit of muon neutrinos which is responsible for the lower $R$ value in the water Cerenkov detectors. The typical region to describe this deficit via neutrino oscillations is at $\Delta m^2 \approx 10^{-2} \text{eV}^2$ and $\sin^2 2\theta \approx 1$. A third hint comes from the LSND-experiment having excess events which can be explained by $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ - oscillations [8].

4 Future checks on solar neutrinos

To investigate the oscillation hypothesis for solar neutrinos several experiments are coming up. The first one is the Superkamiokande experiment running since 1. April 1996. Because of the 10-fold increase in fiducial volume, this detector will allow a high statistics measurement of the $^8\text{B}$-flux. Another experiment which will start data taking soon is a new radiochemical detector using in a first phase $100t^{127}\text{I}$ with a threshold energy of $E_{\text{Thr}} = 789 \text{keV}$. This experiment is installed in the Homestake-mine, close to the Cl-experiment. A big step forward in testing the oscillation hypothesis is the Sudbury Neutrino Observatory.
Figure 2: Comparison of $R$ as defined in eq.7 from different measurements on atmospheric neutrinos. While the water Cerenkov detectors see a deficit from the expected value of $R = 1$, most of the iron tracking calorimeters are more or less in agreement with the expectation.

(SNO) which is by using $\text{D}_2\text{O}$ able to measure flavour-blind (neutral current) and flavour-sensitive (charge current) via the reactions

$$\nu_e + d \rightarrow e^- + p + p \quad \text{and} \quad \nu + d \rightarrow \nu + p + n$$

It will be in operation in 1997. The present experimental situation of solar neutrinos results requires more or less the absence of $^7\text{Be}$ neutrinos. The BOREXINO-experiment at Gran Sasso is especially designed to measure these neutrinos [9]. A proposal for a real time pp-neutrino measurement is the HEL-LAZ experiment which could be online early next century.

A completely independent way to attack the solar neutrino problem is further investigation of the internal structure of the sun, especially with the help of helioseismology. Two new projects, the SOHO-satellite and the Global Oscillation Network Group (GONG) will give new insights to this and will help to define the temperature and density profile of the sun more accurate.

5 Future checks on atmospheric neutrinos

The main impact in the near future on atmospheric neutrinos will be Superkamiokande. It will allow a high statistics measurement of atmospheric neutrinos. The allowed parameter region can also be checked by upcoming reactor...
experiments and long baseline experiments with accelerators. Concerning re-
actor experiments these are the CHOOZ experiment in France, which started
data taking recently and the Palo Verde experiment in the US, having a first
module running by end of the year. Long baseline experiments at accelerators
will be discussed later.

6 Future checks on LSND

The allowed parameter range of LSND is already in some conflict with past or
ongoing experiments. A large part of their allowed range seems to be excluded
by the BNL E776, CCFR, KARMEN and Bugey experiments, leaving only a
little region in parameter space. The high $\Delta m^2$ region ($\Delta m^2 > 4eV^2$) can
also be adressed by NOMAD. The upgraded ongoing KARMEN experiment as
well as further data taking of LSND will clarify the situation. Also the above
mentioned reactor experiments may exclude some parts of the allowed parameter
region.

7 Future accelerator experiments

The next new results on neutrino oscillations from accelerators will come from
CHORUS [10] and NOMAD [10] at CERN. Both are designed to improve the
sensitivity for $\nu_\mu - \nu_\tau$ - oscillations by at least one order of magnitude in the
$\Delta m^2$-region for hot dark matter given by the quadratic see-saw-mechanism.
Proposals for a next generation neutrino detector at CERN exist, which should
be able to improve the sensitivity by another order of magnitude. At Fermilab
the proposed COSMOS-experiment (P803) will reach roughly the same sensi-
tivity. The wish to go down to smaller $\Delta m^2$ to check directly the region of
atmospheric neutrinos requires either to go to larger distances (long baseline
experiments) and/or lower energies. The first experiment to happen will be an
experiment shooting from KEK to Superkamiokande (KEK - E362). This ex-
periment has a baseline of 235 km and is expected to start data taking beginning
of 1999. An approved long baseline experiment is the MINOS-experiment using
the Fermilab neutrino beam to shoot to a detector in the Soudan mine, about
730 km away. Roughly the same distance would apply for proposed ideas for a
CERN - Gran Sasso long baseline experiment. Several proposals for detectors
exist like ICARUS [11], NOE [12] and a 27 kt Water-RICH [13].

8 Conclusions and outlook

Light neutrinos in the eV-region are still the best candidates for hot dark mat-
ter. While the classical see-saw-mechanism can be adjusted in a way that $\nu_\tau$ is
in the eV-range, the almost degenerated neutrinos scenarios allow all of them
as dark matter candidates. Possible hints for neutrino masses come out of solar and atmospheric neutrino data as well as the LSND experiment (fig.3). The main impact until the end of 1997 will come from Superkamiokande and further LSND measurements as well as other experiments checking their result. Tab.2 shows a comparison of different scenarios which can emerge out of these new measurements. Depending on the special scenario different mass hierarchies and models result and neutrinos of different flavour act as dark matter candidate. Note that if both LSND and the atmospheric neutrino problem are confirmed and the solar neutrino data are included, it is not possible to explain all data with the three standard model neutrinos. A possible solution could be additional sterile neutrinos. Only the scenario with both atmospheric and LSND not confirmed, leaves room for a $\nu_\tau$ as hot dark matter within the classical see-saw-mechanism. If LSND will be confirmed but not atmospheric neutrino problem, we even have an inverted mass hierarchy.

Figure 3: Schematic presentation of preferred parameter regions to explain the solar (dark), atmospheric (grey) and LSND (white) results with neutrino oscillations.
solar
no dramatic new results

|       | C    | C    | NC   | NC   |
|-------|------|------|------|------|
| atmos.| C    | C    | NC   | NC   |
| LSND  | C    | NC   | C    | NC   |
| $|\Delta m^2_{12}|$ | $\approx 1$ | $\approx 10^{-3}$ | $\approx 1$ | $\approx 10^{-5}$ |
| $|\Delta m^2_{23}|$ | $\approx 10^{-2}$ | $\approx 10^{-2}$ | $\approx 10^{-2}$ | $\approx 10^{-2}$ |
| $|\Delta m^2_{13}|$ | $\approx 1$ | $\approx 10^{-5}$ | $\approx 10^{-5}$ | $\approx 10^{-5}$ |

| 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 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. The neutrinos (eV-range) acting as hot dark matter are shown in the last row. Only the last column allows the classical see-saw mechanism.

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