1 Neutrinos

1.1 Introduction

It was a desperate attempt to rescue energy and angular momentum conservation in beta decay when Wolfgang Pauli postulated the existence of a new elusive particle, the neutrino. In 1930 Pauli expressed also his apprehension that this mysterious neutral particle may never get detected experimentally. Indeed it took 26 years until Reines and Cowan observed neutrinos for the first time directly [1]. They detected anti-neutrinos emitted in beta decays of fission products in a nuclear power reactor via the reaction $\bar{\nu_e} + p \rightarrow e^+ + n$. The measured cross section $\sigma = (1.1 \pm 0.3) 10^{-43} \, cm^2$ corresponds to the enormous absorption length of 29 light years in the detector material. This tiny cross section reflects that neutrinos solely exhibit the weak interaction with matter. After the discovery of parity violation in weak interactions the helicity of neutrinos was determined in a famous experiment by Goldhaber. The neutrino is purely left-handed, whereas its anti-particle is right-handed.

In the decay of charged pions $\pi^+ \rightarrow \mu^+ + \nu_\mu$ neutrinos of a different type are emitted. This was proven in a beam dump experiment at Brookhaven, USA, by Ledermann, Schwartz, and Steinberger in 1962 [2]. Neutrinos were generated via pion (and also kaon) decay and their interaction with matter was studied. Only charged muons were observed, no electrons. Hence, it is clear that ν_μ differ from ν_e. Neutrinos of the type ν_μ create μ^-, ν_e generate e^- in interactions with matter. Obviously neutrinos exist in more than one "flavor".

Today three ν-flavors are known. This was proven in an experiment at CERN, where the total width of the Z^0-resonance was measured. Besides the charged $W^\pm$-bosons the neutral Z^0 boson mediates weak interaction. It is responsible for neutral current weak processes. The more neutrino flavors exist the wider the Z^0-resonance must be. By comparing the experimentally determined value of the resonance width with the sum of all partial widths arising from the decay into known charged hadrons and leptons the data yield for the number of neutrino flavors $N_\nu = 3.00 \pm 0.06$. This value is valid for neutrino masses $m_\nu < 45 \, GeV$. If a forth neutrino flavor would exist within this mass range it must not couple to the Z^0 and to weak interaction in general. It would be a "sterile" neutrino.

The third neutrino flavor was directly detected in 2000 by the DONUT experiment at Fermilab, USA, where τ-decays of heavy charmed hadrons were studied [3]. This flavor is correlated to the charged τ-lepton.

In total we have three families in the leptonic sector:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

The charged leptons participate in electromagnetic and weak interactions.

The neutrinos are particles which exhibit only the weak interacting. One may assign a general lepton number ($L = 1$ for e^-, μ^-, τ^- and associated neutrinos, $L = -1$ for the anti-particles). In the standard model of particle physics the lepton number is conserved in all physical processes. Before the discovery of neutrino oscillations it was believed that also the individual lepton numbers L_e, L_μ, and L_τ should be conserved quantities.

1.2 Neutrino masses and neutrino oscillations

The question about the neutrino mass is of fundamental importance for particle and astrophysics. It can yield new insight into the mechanism of how particles achieve mass. Additionally neutrino masses may influence matter formation in the early universe. Connected with neutrino masses is the concept of neutrino mixing which finally leads to the phenomenon of neutrino oscillations.

Today the concept is based on the experimental fact that the three flavor eigenstates ν_e, ν_μ, and ν_τ are linear combinations of neutrino mass eigenstates ν_1, ν_2, and ν_3, which have mass values m_1, m_2, and m_3. The 3×3 complex, unitary matrix U linking flavor and mass eigenstates is called neutrino mixing matrix. If a neutrino is generated in a process it will be always in a definite flavor eigenstate. However, propagation in vacuum is determined by the mass of a particle. If the mass values m_i $(i = 1, 2, 3)$ are not equal, the mass eigenstates will propagate with different velocities. As a consequence the flavor content of the neutrino will change at increasing distances from the source. These changes can be described as oscillations. For the case of only two neutrino flavors the probability of a neutrino which started as ν_α $(\alpha = e, \mu, \tau)$ to be detected as ν_β $(\beta \neq \alpha)$ is

$$P_{\alpha\beta} = \sin^2(2\theta) \cdot \sin^2(1.27 \Delta m^2 L/E),$$

where θ is the mixing angle which describes the amplitude of the oscillations and Δm^2 is the squared mass difference $m_\alpha^2 - m_\beta^2$ (in eV^2), which together with the neutrino energy E (in MeV) determines the frequency of this phenomenon. The distance from the source is given by L (in m). One may define the oscillation length L_{osc} after which a full cycle is reached. In practical units one obtains $L_{osc}(m) = 2.48 \cdot E/\Delta m^2$.

Neutrino oscillations have been detected recently by studying atmospheric and solar neutrinos. In the Japanese SuperKamiokande water Cherenkov detector ν_e and ν_μ-neutrinos with energies around $1\,GeV$ were observed which are created by collisions of cosmic particles with nuclei in the upper atmosphere [4]. In a Cherenkov detector the direction of flight of a neutrino can be measured. It turned out that while the number of ν_μ's from the top ($L \sim 10\,to\,20\,km$) is as large as expected, the number of ν_μ's from the bottom ($L \sim 10^4\,km$) is significantly reduced! On the other hand, the electron neutrinos behave as expected. The data of SuperKamiokande are in excellent agreement with the hypothesis of neutrino oscillations $\nu_\mu \Leftrightarrow \nu_\tau$ with $1.5 \cdot 10^{-3} < \Delta m^2_{atm}/eV^2 < 3.4 \cdot 10^{-3}$ and a large mixing amplitude $\sin^2(2\theta) > 0.92$. The neutrino oscillation hypothesis has been confirmed, yet at lower statistical significance, by the atmospheric neutrino experiments MACRO at Gran Sasso, Italy, and SOUDAN2, USA. The possibility of $\nu_\mu \Leftrightarrow \nu_e$ oscillations is not sustained by the SuperKamiokande data and is completely ruled out by the results obtained in the reactor experiments CHOOZ (France) and Paolo Verde (USA).

A direct proof has been provided by the first long baseline accelerator experiment K2K [5]. Neutrinos with energies around 1 GeV are produced in the KEK accelerator facility and sent to the SuperKamiokande detector at a distance of 250 km. If the oscillation hypothesis is correct SuperKamiokande should detect muon neutrinos with a reduced probability $P_{\mu\mu} \sim 0.7$. After 5 years of measurements 108 ν_μ events have been detected, which is 71.5% of the value one expects in case of no oscillations. Hence, the oscillation hypothesis is confirmed and the K2K best fit value of $\Delta m^2 = 2.7 \cdot 10^{-3}\, eV^2$ is in excellent agreement with the allowed parameter range provided from the atmospheric neutrino experiments.

Solar neutrinos are described in this book in a separate chapter. Therefore only the main results of solar neutrino experiments are reported which are relevant for neutrino masses and mixing parameters. A number of experiments revealed that solar neutrinos, which are exclusively born in the ν_e-state change their flavor when going through the Sun. The final breakthrough was provided by the Canadian SNO experiment where the total neutrino flux (ν_e, ν_μ, and ν_τ) above $\sim 5\, MeV$ as well as the ν_e-flux alone were measured via two separate reactions in a heavy water Cherenkov detector [6]. Only one third of these solar neutrinos survive in the ν_e-state, the others change their flavor. This was the first direct proof of neutrino flavor changing and of the violation of the individual lepton number.

This result could be probed for anti-neutrinos by a reactor neutrino experiment. Former searches for $\bar{\nu}$-oscillations with reactors were performed at a distance not longer than $\sim 1\, km$, and no effect was seen. Since 2002 the Japanese KamLAND experiment [7] measures neutrinos from different remote reactors at an average distance of $\sim 180\, km$ with a $1\, kt$ liquid scintillator detector. After one year of measurement the ratio R of the observed rate with respect to the expected rate in case of no oscillation was found to be $R = 0.611 \pm 0.085\, (stat) \pm 0.041\, (syst)$. Today the confidence level for the disappearance of the reactor neutrinos is at 99.995%. In addition the shape of the neutrino spectrum agrees with the oscillation effect. From the spectral analysis alone the no-oscillation case is excluded at a confidence level of 99.9%. All oscillation parameters agree with those from solar data in an excellent way. A global analysis including the results from all solar experiments and KamLAND yields the result $\Delta m^2_{sol} = 8.2^{+0.6}_{-0.5} \cdot 10^{-5}\, eV^2$ and $\sin^2(2\theta_{sol}) = 0.82^{+0.04}_{-0.05}$. Obviously the mixing angle θ_{sol} is large but not maximal in this case. The mass splitting is significantly lower than that of atmospheric neutrinos. Today the general conviction is that solar data and the KamLAND experiment revealed $\nu_e \Leftrightarrow \nu_\mu$ oscillations with a mass splitting $m_2^2 - m_1^2 = \Delta m_{sol}^2$ and atmospheric experiments together with the K2K-measurement discovered $\nu_\mu \Leftrightarrow \nu_\tau$ oscillations with the larger mass splitting $m_3^2 - m_2^2 = \Delta m_{atm}^2$.

In the LSND accelerator experiment at Los Alamos, USA, also evidence for neutrino oscillations was claimed. However, the baseline in this experiment was rather short. Therefore, the mass splitting in this case must be significantly larger with respect to solar as well as atmospheric oscillations. As there are only 3 active neutrino flavors there is no room for explaining the LSND result with oscillations of active neutrinos. If the LSND result is correct a 4th flavor, a sterile neutrino, must exist. The LSND result is tested nowadays in the MiniBooNE experiment at Fermilab, USA.

1.3 Direct neutrino mass experiments

From the oscillation experiments we know that neutrinos are massive. However, oscillation experiments only tell us about mass differences. Thus we don't know the absolute mass values. The results from the oscillation experiments deliver a lower limit on the neutrino mass, but it could be that the mass values are degenerate and significantly larger than their differences. Upper limits come from direct neutrino mass searches.

The best limits are provided by investigating the endpoint of the beta spectrum of the decay $^3H \rightarrow ^3 He + \bar{\nu_e} + e^-$ as a non-zero neutrino mass reduces the maximal possible kinetic energy of the electrons. Two experiments TROITSK, Russia, and MAINZ, Germany, basically deliver the same upper limit of $2.2\,eV$ [8]. Both experiments use a large retarding magnetic solenoid with decelerating electrodes in order to filter electrons according to their kinetic energies. In the common future project KATRIN at Karlsruhe, Germany, the sensitivity is expected to be increased by one order of magnitude. Limits on neutrino masses are also derived by cosmological observations, as described in a separate chapter of this book. Although model dependent the reported limits are impressive and vary in the range between $0.7\,eV$ and $1.8\,eV$.

Besides the question concerning neutrino masses other neutrino properties are still unknown. One of the most important is the question whether the neutrino is its own anti-particle. In this case it would be a Majorana-particle and not a Dirac-particle. The state of a Dirac-particle, like the electron, is described with a four-component spinor. Two components account for the left- and right-handed state of the particle, the others for the anti-particle. However, only left-handed neutrinos and right-handed anti-neutrinos exist. Therefore a two-component spinor description is sufficient as Majorana pointed out already in the thirties of the last century. It is possible that the right-handed anti-neutrino is simply the chiral partner of the left-handed neutrino. This can be tested experimentally by investigating double-beta decays. Here a nucleus decays under the emission of two electrons and two right-handed neutrinos. If the neutrino is a Majorana-particle and has mass the neutrino can be a virtual particle connecting both vertices. Only in this case the "neutrinoless" double-beta decay $(A, Z) \rightarrow (A, Z+2) + 2e^-$ should occur. The probability for this lepton number violating process depends on the nuclear transition probability, on details of the neutrino mixing matrix including the neutrino mass values. Hence, in searches for this effect the Majorana-character as well as neutrino masses are investigated. Such experiments measure the energy spectrum of the two electrons emitted from double-beta instable nuclei. In case of the neutrinoless decay a sharp mono-energetic line should appear at the endpoint of the spectrum. The currently best limit on the lifetime for this effect is coming from the Heidelberg-Moscow experiment at the underground laboratory in Gran Sasso, Italy, which uses five Ge-detectors with a total mass of $10.9\,kg$, enriched in ^{76}Ge. The obtained limit of $T_{1/2} > 1.9 \cdot 10^{25}\,y$ corresponds to a mass limit $m_{\beta\beta} < 0.35\,eV$ [9]. Performing a new peak analysis of the spectrum a part of the collaboration has claimed evidence for a line at the endpoint, which is interpreted as originating from neutrinoless double-beta decay. However, the analysis has been criticized in various publications. Only future experiments can reveal this puzzle.

1.4 Prospects in neutrino physics

Still many neutrino properties are not known. Besides the absolute mass values there are important questions about the mass hierarchy, Majorana or Dirac character, magnetic ν-moments, and the existence of sterile neutrinos. In addition some parameter of the neutrino mixing matrix are still unknown. There exist three real mixing angles and at least one complex phase which can be responsible for CP-violating processes in the leptonic sector. Two of the mixing angles are known now. However, the third is still missing and there are different approaches to measure it via future reactor and accelerator experiments. Finally CP-violation might be revealed in the far future by long baseline experiments with very intensive neutrino beams. Besides the efforts to reveal ν-properties, neutrinos will be used as probes to understand so far unknown astrophysical sources. Large underground detectors will act as neutrino telescopes. Low energy neutrinos from galactic supernovae and even relict supernovae neutrinos might be detected. We will learn about details of gravitational collapses and star formation in the early universe. Geophysical problems like the origin of the Earth's power flux might get solved by detecting neutrinos from U- and Th-decay in the Earth's crust and mantle. High energy cosmic ray-neutrinos may tell us more about the sources, like active galactic nuclei, where they are emitted. The future of neutrino physics will be as fascinating as it was in the past.

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