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Neutrino Physics at the Dawn of the Twenty-First Century

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Neutrino Physics in recent decades has undergone a rapid growth and has evolved into a discipline of relevance for various research fields, ranging from geophysics to cosmology. On the other hand, however, the knowledge that we have about the neutrino itself, i.e., its very nature and intrinsic properties, is still rather fragmentary. This article summarizes the present status of pure and applied neutrino physics, emphasizing on pointing out the links to neighboring disciplines.

Introduction

At the end of the twentieth century neutrinos have taken over a “title role” in modern science, being equally important for and providing a link between cosmology, nuclear physics, particle physics, and astrophysics. Not surprisingly therefore neutrinos are not only at the heart of specialists’ research in these fields but have for some years attracted considerable and steadily increasing interest from scientists of other areas as well and even from the broad public.

The twentieth century saw the “birth” of the neutrino, followed by a flourishing period in which neutrino beams contributed substantially to the establishment of what we nowadays refer to as the “standard model of particle physics”, i.e., our understanding of the fundamental constituents of matter and their interactions. In the 1980s and 1990s efforts have concentrated on measuring intrinsic neutrino properties such as mass, magnetic moment, charge conjugation, and flavor state mixing property, and lifetime, culminating in 1998 in the claim of the Japanese Superkamiokande collaboration of having discovered neutrino mass in their measurements of neutrinos produced in the earth’s atmosphere from the interaction of primary cosmic radiation (Fukuda et al. 1998; Kajita et al. 1998). In recent decades the enormous interdisciplinary importance of neutrinos for astrophysical processes, such as star burning and supernova explosions, for the formation of structure in our universe, and for its future development has become increasingly evident (Raffelt 1996). The turn of the millennium is a good point at which to review where we stand in neutrino physics, what we know, and what we still do not know about neutrinos and to consider the direction in which future developments are likely to lead.

A Short Historical Tour: What We Know About Neutrinos

The neutrino was initially nothing more than a purely hypothetical speculation. In 1930 Pauli postulated a new uncharged and very weakly interacting particle

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We dedicate this contribution to our teacher Prof. Rudolf L. Mößbauer on the occasion of his 70th birthday.

as a “desperate revenue” to save the laws of angular momentum conservation and of energy conservation in nuclear beta decay (Pauli 1985, for translation see Winter 1991). However, it took more than 25 years to establish the neutrino experimentally: In 1956–1957 Cowan and Reines reported the first direct detection of neutrinos in an experiment at the Savannah River reactor. After their finding had been confirmed in other measurements, in around 1960 the neutrino was unanimously considered “real”.

The type of neutrino detected by Cowan and Reines is the so-called electron antineutrino, the antiparticle of the electron neutrino. As we know today, it is not the only neutrino type (or “flavor”): Similar to their “partners”, the electrically charged leptons electron, muon, and tauon, three families of neutrinos exist. In 1962 Schwartz and coworkers communicated a new success; they had discovered muon neutrinos at a high-energy particle accelerator – the second neutrino flavor was proven to exist (Danby et al. 1962). It is interesting to note that the third type of neutrino, the tau neutrino, has not yet been detected in a direct experiment, at though for various reasons noone seriously doubts that it exists.

In 1990 precision measurements of the decay width of the Z° vector boson at the European Particle Physics Laboratory CERN in Geneva, Switzerland, showed that the number of neutrino flavors is $N_\nu = 2.994 \pm 0.012$ (Caso et al. 1998), a result which is valid for neutrinos with mass $m_\nu \lesssim 45\,\mathrm{GeV}$ and standard coupling properties to the Z°. Similar if somewhat weaker constraints are derived from astrophysical considerations on the abundance of light elements produced in primordial nucleosynthesis shortly after the “big bang” and from observations of neutrinos from the 1987 supernova SN 1987A.

In addition to the number of neutrino flavors, to date we know only some few of the intrinsic properties of these particles. From the neutrality of atoms one can conclude that neutrinos are indeed neutral particles, as initially suggested by Pauli: the experimental limit for an electric charge of the neutrino is $Q(\nu) < (10^{-21} - 10^{-23})\,e$. Measurements of the neutrino mean charge radius, from which information on the spatial extension can be deduced, classify the neutrino as pointlike. There does not exist to date any experimental indication that neutrinos are composed of smaller constituents, i.e., neutrinos seem to be elementary particles in a strict sense. Neutrinos are fermions; their spin quantum number is $s = 1/2$. Since 1958 when Goldhaber and coworkers, in one of the most elegant experiments in physics history, measured the helicity of neutrinos, we further know that they are left-handed particles. As particle and antiparticle always have opposite helicity, antineutrinos thus are right-handed.

Physics with Neutrinos: Neutrinos as Experimental Tools

Considering the time between postulation and experimental confirmation of the neutrino, it took only an astonishingly short period for the new particle to become a standard tool in high energy physics and later also in astrophysics. The reason is that neutrinos carry no electric charge and are subject only to the “weak interaction” (and, of course, also to gravity, which, however, in practice plays a role only for macroscopic objects), thus making them unique both for scattering experiments and for investigating dense astrophysical objects, which are highly opaque for any other kind of radiation.

Neutrinos as Tools for Investigating Nucleon Structure

Neutrinos have been used very successfully to reveal the inner structure of the nucleon. The energy dependence of the cross section in neutrino nucleon scattering shows that nucleons, i.e., protons and neutrons, are not elementary (as previously believed), but rather are composed of pointlike constituents, so-called quarks. Experimentally this was confirmed by bombarding a proton target with high energy ν_μ, in which the production of charged muons and of hadrons was observed. Although this process appears very complicated, the cross section turned out to be proportional simply to the neutrino energy, exactly what one would expect if the reaction is described by elastic scattering of neutrinos on quarks: the proton was shown to exhibit a substructure.

Comparing the results of scattering experiments with neutrinos and electrons as projectiles provides information on the electric charge of the quarks inside a nucleon. Electrons and neutrinos “see” the quarks. However, neutrinos as neutral particles are “blind” to the electric charge of quarks, whereas the amplitude of electron-quark scattering is proportional to the quark charge. Quarks have been found to carry an electric charge in units of $1/3\,e$. In addition, the number of valence quarks, which can be regarded as the “physical” particles, is theoretically predicted to be 3, in good agreement with the experimental value of 2.8 ± 0.5. (The proton consists of two up-quarks with charge +2/3 and one down-quark with charge -1/3. Their sum gives the electric charge +1 for the proton.) Neutrino-nucleon scattering also yields information about the average antiquark density in the nucleon; this is as much as approx 10% of the quark density.

Neutrinos as Tools for Establishing the Standard Model of Particle Physics

A widely used detection principle for neutrinos is based on observation of the charged leptonic partner in reactions such as $\nu_e + n \rightarrow e^- + p$. Since these interactions are associated with a charge transfer in the leptonic and hadronic currents, they are called "charged current reactions". Theory describes them by an exchange of a charged vector boson $W^\pm$ between the neutrino and its reaction partner. These intermediate bosons $W^\pm$ were discovered in 1983 at CERN by investigating W^+ production in proton anti-proton collisions and observing the subsequent decay: $W^+ \rightarrow e^+ + \nu_e$. The idea of describing interactions of elementary particles as an exchange of intermediate bosons has been applied very successfully in quantum electrodynamics, where the photon acts as exchange particle. As the intrinsic coupling strengths of the massive $W^\pm$ and massless photons to elementary particles were found to be comparable, the question arose of whether electrodynamics and weak interaction have common roots, whether both fundamental forces can be unified. If this were the case, there should exist an additional intermediate boson Z° which is neutral, as with the photon, but has a mass comparable to the $W^\pm$, i.e., resembling a "heavy brother" of the photon.

The existence of Z° was postulated by Weinberg et al. in 1967 when they proposed a theory to unify electromagnetism and weak interaction. Neutrino reactions via the exchange of Z°, so-called "neutral current reactions", were first observed in 1973 in the "Gargamelle" bubble chamber at CERN. Clear evidence for the existence of neutral currents was obtained in reactions of the type $\nu_\mu + N \rightarrow \nu_\mu + X$, where N and X are hadronic states. In 1983 the production of Z° particles and the subsequent decay $Z^\circ \rightarrow e^+e^-$, $\mu^+\mu^-$ was observed at the CERN collider. Z° mass was measured to be $91.2\,\mathrm{GeV}/c^2$, a value close to the $W^\pm$ mass of $80.4\,\mathrm{GeV}/c^2$. These discoveries were milestones for the successful approach of unifying electromagnetic and weak interactions and helped to guide the direction into which modern particle theory has since evolved.

Neutrinos as Tools for Investigating the Sun

In addition to the prominent role that neutrinos play in high energy physics, these particles have become increasingly important tools in modern astrophysics. The most important astrophysical object for terrestrial life is of course our sun. In terms of astrophysics, however, the sun is not at all exceptional. It is an ordinary main sequence star, radiating energy released by hydrogen-to-helium fusion, and about 4.55×10^9 years old, which means that it will continue shining for another 5×10^9 years. At this point we may ask a number of fundamental questions: How do we know that hydrogen fusion is indeed the source of the sun's energy? How can we know what is happening deep inside the sun? What approaches do we have to experimentally verify our theoretical models of stellar structure, internal dynamics and evolution?

From the observation of solar luminosity it is well known that the sun releases an average of power of $P_{\mathrm{sol}} = 3.8 \times 10^{26}\,\mathrm{W} = 2.4 \times 10^{45}\,\mathrm{eV/s}$ by means

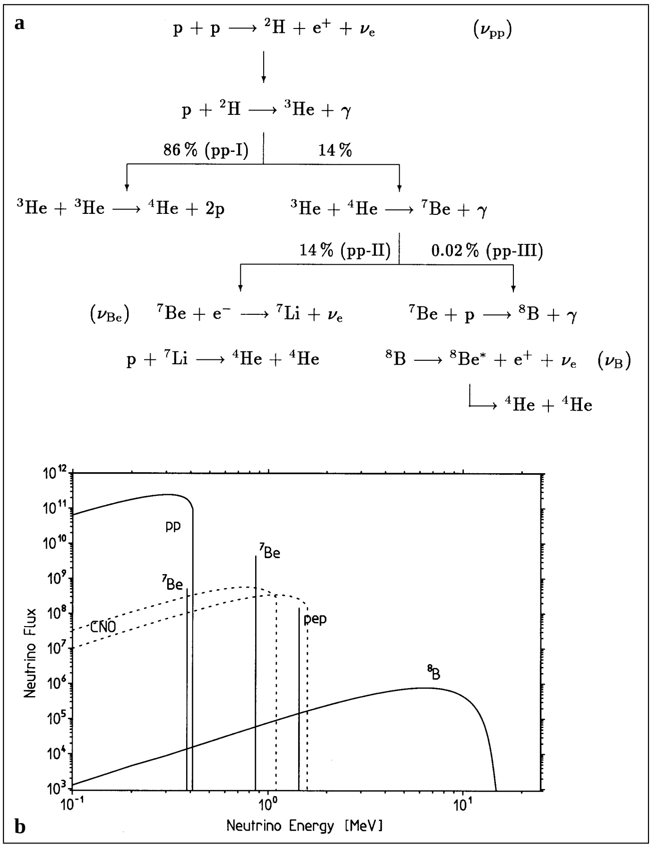

Fig. 1. a) The pp cycle is the dominant energy generation mechanism in the sun. It is subdivided into four chains, the pp I-chain being by far the most frequent cycle termination (86% pp I, 14% pp II, <0.1% pp III, $\lesssim 10^{-3}$ % pp IV). The ppIV reaction $^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + \nu + e^+$, giving rise to the continuous spectrum of so-called hep-neutrinos is omitted. b) The neutrino spectrum resulting from the solar fusion reactions. *Solid lines* neutrinos from the pp cycle; *dotted lines* the CNO cycle, which, however, plays only a minor role for the sun. Fluxes are given in units of $\mathrm{MeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for continuous spectra and $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for lines

of electromagnetic radiation into space. This immense power is believed to be generated by the fusion of protons to helium via the net reaction $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ deep inside the solar core, which occurs not in one step but in a series of fusion reactions. The most important of these for the sun are depicted in Fig. 1. As the sun is highly opaque for electromagnetic radiation, it takes about 10^5 years for photons to "diffuse" from their generation in the solar core outwards to the sun's surface. On their way they are continuously absorbed, reemitted and scattered, resulting in essentially a black-body radiation characteristics. This means that any information on the generation process is lost. For the neutrinos generated in the fusion processes, however, the situation is fundamentally different. Due to their weak interaction the sun is essentially transparent for them (To illustrate: one would need a massive wall several light-years thick to attenuate a beam of neutrinos with energy typical for the sun or nuclear reactors to 50%.). Hence, 8.3 min after their creation solar neutrinos reach the earth, still carrying information on their generation, i.e., energy and time. Neutrinos thus are unique tools for examining the processes taking place in the solar core. This possibility was the initial motivation for proposing a solar neutrino experiment, a fact which often is seldom realized, with the emphasis in solar neutrino research having evolved to investigating intrinsic neutrino properties by means of neutrino oscillations.

As early as 1967 Davis and coworkers detected neutrinos from the sun, however, only ones with rather high energy, which cannot be produced in the main branch of the pp cycle. In 1992 the situation changed dramatically. For the first time ever the pp neutrinos were clearly observed from the initial fusion reaction $2p \rightarrow {}^2H + e^+ + \nu_e$, which contributes more than 90% to the integral solar neutrino flux, using a radiochemical detector with gallium as target nuclide (Gallex Collaborators 1992, 1999). This breakthrough provided the ultimate proof that pp fusion is indeed the source of solar energy. Since then solar neutrino spectroscopy together with helioseismology has evolved into a standard tool in stellar model calculations, which try theoretically to describe the composition and structure, internal dynamics, and evolution of main sequence stars. The helioseismological technique, which investigates vibration modes of the solar plasma sphere in this respect is complementary to solar neutrino measurements as it allows the gathering of information on the solar density profile, from the surface inwards to about 5% of the radius. The goal in solar neutrino physics for the next, say, 10 years is to examine with high precision the entire solar neutrino spectrum depicted in Fig. 1 to improve our understanding of the detailed physics of stars and, particularly, to elucidate some of the still unknown intrinsic properties of neutrinos. In this context it is essential to note that the measured solar ν_e flux is substantially below the theoretically predicted level, and that the extent of difference is energy dependent. As described below, this can be interpreted as a manifestation of the exciting phenomenon of neutrino oscillations.

Neutrinos as Tools for Understanding Supernova Explosions

The collapse of stars with weight exceeding roughly eight solar masses is inevitable once the thermal fusion processes in the center of the object come to an end. Within a fraction of a second the core collapses, and its gravitational binding energy ($E_b \approx 3 \times 10^{46}$ J) is radiated essentially in the form of neutrinos. The only direct observation of neutrinos from such an event was made on 23 February 1987, when a blue supergiant exploded in the Large Magellanic Cloud, the famous supernova SN 1987A. Just before the collapse the stellar core consists mainly of iron-group elements. Fusion ceases because these are already the most tightly bound nuclei and no further nuclear burning can be ignited. At the "Chandrasekar limit" of about 1.5 solar masses the electrons become relativistic, are captured via the reaction $e^- + p \rightarrow n + \nu_e$, and a neutron star forms. This process is maintained by photo-dissociation of iron, which reduces the thermal pressure of the object. The ν_e emitted during neutronization escape freely. However, at a certain density of the core not even neutrinos are able to stream freely out of the inner regions but are trapped. The collapse then occurs adiabatically, the temperature reaches typical values of several MeV on the energy scale, and all flavors of neutrinos are generated. Since the virtually free fall of outer parts of the former star is supersonic, a shock wave forms which is reflected on the inner core of supranuclear density. In spallation reactions the shock then destroys heavy nuclei, and the trapped neutrinos can finally escape from the inner regions. They carry information about the inner part (a typical size is 10–20 km) of a supernova.

The water Cherenkov detectors IMB (United States) and Kamiokande (Japan) detected neutrinos via the light emitted by secondary charged particles created in neutrino reactions. The Baksan Scintillator Telescope (BST) in the Caucasian Mountains measured the scintillation light produced by these charged particles. In the case of SN 1987A the most relevant reaction was the inverse beta decay, $\bar{\nu}_e + p \rightarrow e^+ + n$, the protons of the water or the scintillator acting as target for the supernova neutrinos. At 7:35 UT on 23 February 1987, Kamiokande, IMB, and BST registered bursts of 11, 8, and 5 events, respectively, within a period of some 10s, clearly separated from background signals. The average $\overline{\nu}_e$ energy was 9 MeV, and the inferred total $\overline{\nu}_e$ energy emitted by SN 1987A was 0.84×10^{46} J, which corresponds to the total binding energy of the neutron star of 5.0×10^{46} J, assuming exact equipartition of the energy among the three neutrino flavors and their antiparticles. It was possible to deduce further information about SN 1987A, such as the luminosity decay time scale and the radius of the source. All these values agree reasonably with that one would expect for a supernova core collapse.

Although the general picture of neutrino emission from a core collapse was confirmed experimentally by the observation of SN 1987A, the sparse data did not allow distinguishing between various models for the details of the supernova mechanism. Therefore it would be desirable to observe a supernova signal with higher statistical significance. Neutrinos from future supernova explosions could be detected in a number of large underground experiments. The Superkamiokande detector in Japan has been operational since April 1996. Its fiducial mass for supernova neutrino detection is 32,000 tons which is larger than that of Kamiokande by a factor of approx. 15. Thus one may be able to observe a neutrino signal from a supernova at a distance of about 200 kpc, which includes the entire Milky Way and, in addition, the Large and the Small Magellanic Clouds.

As the rate at which supernovae occur is rather uncertain, it is not implausible to hope for a supernova in our galaxy within a decade. Assuming a distance of 10 kpc (which is the distance from the sun to the center of the Milky Way), one expects at Superkamiokande about 4000 signals from the inverse beta reaction. This is enough to determine a statistically significant energy and time spectrum of the neutrino burst which would provide detailed information about the processes occurring during a stellar core collapse.

A proposed dedicated detector, sensitive principally to the ν_μ and the ν_τ components of a supernova, is OMNIS (Smith 1998). Here neutrino detection is based on neutral current nuclear excitation, leading to neutron emission. These neutrons are captured in Gd- or Li-loaded scintillator modules. As target for ν-interaction natural rock, Fe, and Pb are considered. The latter two provide higher neutron production rates, and with Pb also a charged current excitation mode. Hence differences in the counting rate between rock, Fe and Pb can be used to infer mixing between $\nu_{\mu,\tau}$ and ν_e. The expected event number for a supernova explosion in the galactic center is approx. 2000 for $\nu_{\mu,\tau}$ and approx. 300 for ν_e, assuming a target mass of 16,000 tons in total and using an active scintillator volume of about 200 m^3. Neutrino mass would alter the time profile of the neutrino burst arriving at earth. This allows direct time-of-flight measurement of the mass of at least one neutrino type. Therefore OMNIS would not only give complementary information to the $\overline{\nu}_e$ signal of, for example, Superkamiokande but could also provide direct observation of a cosmologically significant neutrino mass in the range 10–100 eV, for which neutrinos would form the dominant component of the mass of the universe.

Neutrinos as Tools in High-Energy Astronomy

In contrast to neutrinos from thermal fusion in stars or from supernova collapses there exist several astrophysical objects which emit neutrinos with very high energies, i.e., $E_\nu > 50$ GeV. Being electrically neutral, neutrinos are not deflected in the galactic and intergalactic magnetic fields and hence provide information on the direction of their source. Such high energetic neutrinos have not yet been detected experimentally. However, as the accompanying photons have been measured in air shower experiments, it is widely assumed that they must exist.

High energetic neutrinos are created in the decays of charged pions and kaons which are produced in collisions of high energetic protons or photons with nuclei, for example:

$$\mathrm{p} + \mathrm{p}(\gamma) \rightarrow \pi^\circ + \pi^\pm + \mathrm{K}^\pm + \text{ further particles;}$$
$$\pi^\pm \rightarrow \mu + \nu \quad \text{and} \quad \mu \rightarrow \mathrm{e} + \nu + \overline{\nu}$$

In pp reactions very high energy (VHE) neutrinos can be emitted with $E_\nu > 50$ GeV, whereas in pγ reactions so-called ultra high energy (UHE) neutrinos are produced, with $E_\nu > 10^6$ GeV (Berezinsky 1992). Despite continuous experimental and theoretical endeavors the origin of the highest energy cosmic radiation remains largely unclear. High-energy neutrino astronomy offers a promising direction in which to proceed toward settling this unsolved problem. Possibilities for the way in which cosmic acceleration of protons functions can be tested using VHE and UHE neutrinos as probes. Possible astrophysical accelerators are:

- Young supernova remnants: Protons inside an expanding supernova nebula could be accelerated due to a fast rotation of the strong magnetic field of a pulsar or a black hole in the center, or in the collision of two shockwaves.

- Binary systems: In a binary system (e.g., Cygnus X-3, Hercules X-1) matter of a large accompanying star such as a red giant can flow to a compact object, for example, a neutron star or a black hole. This matter forms a rotating accretion disk which acts as a dynamo in the strong magnetic field of the compact object. This creates a strong electric field which accelerates charged particles. Target for neutrino production is the matter of the accompanying star.
- Active galactic nuclei: The strongest and most distant sources of radiation in our universe are active galactic nuclei (AGNs). These reach luminosities equal to the strength of approx. 10^{14} suns, or about 100 big galaxies, but their dimensions do not differ from those of a normal galaxy. It is thought that AGNs are young active galaxies with a superheavy black hole in the center. From a thick accretion disk matter flows to the black hole. During this process the matter is accelerated and transforms into a hot and dense plasma. Some of the plasma may fall into the black hole, and the rest can be deflected by strong magnetic fields in two oppositely directed jets. Extremely high proton energies are presumably reached in both processes. In reactions with matter either inside the disk or in the cosmos high-energy neutrinos are generated.

In addition to acceleration processes, the decay or annihilation of heavy, hitherto unknown particles can also create high-energetic neutrinos. Among the most prominent candidates for such particles are so-called weakly interacting massive particles (WIMPs), which may provide a substantial part of the dark matter in the universe. WIMPs accumulated in the core of stars via gravitational capture following energy loss in scattering processes annihilate and produce VHE neutrinos.

To detect VHE neutrinos the charged current reaction, $\nu_\mu + \mathrm{N} \rightarrow \mu + \mathrm{X}$ can be utilized, where N is a nucleus in the target material of the detector, and the charged muon is observed. To avoid the large background from atmospheric muons these detectors are located deep underground. Detection of UHE neutrinos is dominated by the process of $\overline{\nu}_\mathrm{e} + \mathrm{e}^- \rightarrow \mathrm{W}^- \rightarrow \mathrm{hadrons}$, because at $E_\nu = 6.3 \times 10^6$ GeV in the laboratory frame this reaction is resonantly enhanced. The reason for the enhancement is that in the center of the mass system this energy corresponds to the mass of the W boson. Since atmospheric neutrinos, with their much higher flux, constitute a serious background problem for the detection of VHE neutrinos, in this energy range only neutrinos from point sources can be detected. UHE neutrinos, in contrast, have sufficiently high energy to render background from atmospheric neutrinos negligible. In this case one can hope to identify even diffuse fluxes of UHE neutrinos. Such diffuse ν fluxes can be created, for instance, when high-energy protons from AGNs collide with photons of the cosmic microwave background radiation, which abundantly exist in the universe as remnants of the "big bang".

Very large Cherenkov detectors, so-called neutrino telescopes, are under construction. To detect VHE and UHE neutrinos with reasonable statistical significance the effective areas of such telescopes must be in the order of $1\,\mathrm{km}^2$. Such telescopes can be constructed as underwater detectors in the ocean, or in the Antarctis where the clear ice acts as target medium. Among the projects currently under construction are Antares in the Mediterranean Sea and Amanda at the South Pole. Both of these telescopes detect neutrinos via upgoing muons which are produced in neutrino-nucleon reactions below the detectors. The experiments are complementary in that Antares searches for cosmic neutrinos from the Southern Hemisphere, while Amanda detects point sources in the opposite direction. Amanda is already collecting data, and both projects are expected to reach full-scale installation in 2001.

Two alternative methods for UHE neutrino telescopes are the detection of coherent radio-Cherenkov radiation and the measurement of acoustic waves. Both types of radiation are produced in neutrino-induced electromagnetic showers, which are created in neutrino reactions with π° production. The π° decays into two photons which subsequently initiate an electromagnetic shower by electron-positron pair production and annihilation. In the microwave region (100 MHz–1 GHz) the Cherenkov radiation is coherent, and the signal thus is amplified significantly. It is thought that UHE neutrinos produce showers in the Antarctic ice which are large enough to create radio signals exceeding the background noise. Since the damping of radio signals in ice is weak, very large detector volumes can be realized. The particles of the shower lose their energy mainly in ionizing processes which locally heat the medium, causing density changes that are transported through the medium as acoustic waves. These waves can be detected by devices sensitive to pressure changes, for example, by piezo-sensors.

Neutrinos as Tools for Tracing back to the Big Bang

According to current cosmological theory, the universe was created about 2×10^{10} years ago in the so-called big bang and has continued to expand and evolve since then. This model is supported by essentially three observations.

- Characteristic light emission lines from distant objects appear red-shifted with respect to the original wavelength. This phenomenon, similar to the well-known analogon in acoustics, shows that the universe is expanding.
- The global abundances of the light elements ^{2}H, ^{3}He, ^{4}He, and ^{7}Li are found to be that which is expected from calculations of primordial nucleosynthesis, which took place about 3 min after the "big bang".
- In 1957 Penzias and Wilson discovered cosmic microwave background radiation. This electromagnetic radiation, theoretically predicted as a remnant of the big bang, is filling almost isotropically the entire universe, exhibiting a perfect Planck black body spectrum of $T_\gamma = 2.7\,\mathrm{K}$.

Big-bang theory, however, makes an additional prediction. There should be another kind of background "radiation", exhibiting a similar spectroscopic characteristic as background photons: relic neutrinos. The characteristic temperature of the neutrino Planck spectrum, T_ν, is related to T_γ via the relation $T_\nu = (4/11)^{1/3}\, T_\gamma$, i.e., $T_\nu = 1.9\,\mathrm{K}$ only, corresponding to $E_\nu = 0.2\,\mathrm{meV}$. Thus, relic neutrinos are even lower in energy than cosmic microwave background photons! The average neutrino density in the universe is expected to be as much as $100\,\mathrm{cm}^{-3}$ per flavor, i.e., about 300 relic neutrinos per cubic centimeter for the three known families.

Detecting these background neutrinos presumably would constitute the ultimate proof for the validity of the big bang theory as the description of the physics in the first seconds after creation of our cosmos. However, noone has yet been able to propose any experimentally viable method for detecting neutrinos of such low energy.

Neutrinos as Tools in Geophysics

The weak interaction of neutrinos also makes them potentially interesting in geophysics. Electron antineutrinos $\bar{\nu}_e$ are created in nuclear beta decays, the continuous spectrum they exhibit being to some extent characteristic for the decaying isotope. It is well known that the earth is not in thermal equilibrium but radiates substantially more energy than it absorbs from the sun. In fact, with a power of about 16 TW a substantial part of this excess energy is produced by natural radioactivity, i.e., by beta decay of uranium, thorium and other long-lived natural radioisotopes present in the crust and mantle of the earth. According to model descriptions of the earth, about 50% of the total uranium and thorium are dispersed in the mantle (approx. 2900 km thick), while the rest is concentrated essentially in an approx. 35-km-thick crust under the continents. The oceanic crust, in contrast, is much thinner and, in addition, has a substantially smaller thorium and uranium abundance. Measuring the spectra of antineutrinos emitted in beta decays of uranium and thorium can provide information on the composition of the earth's interior and its thermal history. Within the next 5 years two new neutrino detectors, Borexino in Italy and Kamland in Japan, originally built for observating solar and reactor neutrinos, will be recording data on geophysical neutrinos (Raghavan et al. 1998). Comparing their results will be of exceptional interest, as Borexino will see mainly neutrinos from the thick continental crust, whereas Kamland is situated on the edge of the much older oceanic crust.

Physics of Neutrinos: Unraveling Intrinsic Neutrino Properties

Do Neutrinos Have a Mass?

No, they are by definition massless particles. This is the unambiguous answer that the standard model of electroweak interactions gives to our question. On the other hand, however, setting $m_\nu = 0$, as in the standard model, is entirely arbitrary. In fact, we do not know of any deeper symmetry principle which prohibits neutrino mass. This is a qualitatively different situation to that of the photon, for example, which is required to be exactly massless in order not to violate the underlying gauge symmetry. Moreover, there is broad consensus that the electroweak standard model because of its various shortcomings cannot be the ultimate answer but, in contrast, is expected to prove as a low-energy, effective description embedded in a more complete theory. Interestingly, essentially all of the modern theories which attempt to unify the present electroweak standard model with the other known interactions predict neutrinos with mass. On the other hand, however, they are not able to predict explicit values for m_ν, leaving it to experiments to specify them. Thus, searching for neutrino masses is well motivated and constitutes a key experimental test for the validity of "beyond standard model" theories. Of course, determining the values of m_ν is of paramount importance for astrophysics and cosmology, due to the enormous implications that massive neutrinos have there.

What experimental approaches do we then have for detecting possible manifestations of $m_\nu > 0$? First, let us remember the process that led Pauli to his neutrino hypothesis: nuclear beta decay. This can be understood as a transformation of a neutron into a proton, an electron, and an electron anti-neutrino, according to $\mathrm{n} \to \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$. (More fundamentally, it is a d-quark which transforms into an u-quark, an e^- and a $\bar{\nu}_\mathrm{e}$.) Obviously, the phase space available for the electron close to its maximal possible energy, i.e., just below the Q value of the respective beta decay, depends on the mass of the neutrino: electron, proton, and neutrino must share the energy release. The maximal kinetic energy of the electron is thus: $E_\mathrm{kin}^\mathrm{max} = Q - m_\nu c^2$. In addition, the shape of the electron spectrum in the region just below $E_\mathrm{kin}^\mathrm{max}$ is also influenced by m_ν. One could therefore precisely measure the spectral shape of the electrons emitted from beta decay close to the endpoint. Two groups, one at Mainz, Germany, the other at Troitzk, Russia, are applying this kinematic technique. Although they have achieved astonishing sensitivity, no indication of neutrino mass has yet bee found. Instead, the groups report upper limits for the mass of the electron anti-neutrino, $m_\nu c^2 < 5\,\mathrm{eV}$ (95% C.I.; Mainz) and $m_\nu c^2 < 2.7\,\mathrm{eV}$ (95% C.I.; Troitzk). Assuming CPT invariance, these limits also apply to the electron neutrino. Improved and enlarged spectrometers should allow exploration of the sub-eV region within the next years (Lobashev 1998).

In addition to the electron neutrino, experiments have also tried to detect nonvanishing masses of muon and tauon neutrinos by kinematic methods. However, also in this case no indication for neutrino masses has been found, the present limits being $m_\nu < 170\,\mathrm{keV}$ (90% C.I.) for the muon and $m_\nu < 18.2\,\mathrm{MeV}$ (95% C.I.) for the tauon neutrino (Caso et al. 1998). Although these limits are much weaker than the constraint for ν_e, it hardly seems feasible to improve them substantially with present experimental techniques.

Thus a constraint derived from cosmological arguments will remain of importance. Within about a factor of 2, the mass of all light, stable (or at least quasi-stable, compared to the age of the universe) neutrino types must fulfill $\sum_i m_\nu^{(i)} c^2 < 50\,\mathrm{eV}$ (presumably $i = \mathrm{e}, \mu, \tau$ only), in order not to overclose the universe.

Do Neutrinos Oscillate?

A quantum-mechanical interference effect called neutrino oscillations is much more sensitive towards small neutrino masses than direct kinematic experiments. However, in addition to neutrino masses, it requires that the neutrino states coupling to the $W^\pm$ gauge bosons, the so-called neutrino flavor eigenstates ν_α ($\alpha = e, \mu, \tau$), do not coincide with the states of definite mass, the mass eigenstates ν_i ($i = 1, 2, 3$). In contrast, the relationship between mass and flavor states is given by the expression $\nu_\alpha = \sum_i U_{\alpha i} \nu_i$ with U being an unitary matrix. This mixing phenomenon – by analogy, well known and experimentally established for quarks – makes transitions between various neutrino flavors possible, i.e., there is a nonvanishing probability P that a neutrino which was created, say, as a ν_μ is detected as an electron neutrino ν_e at some distance x. In the simple case of relativistic neutrinos and dominant mixing between two flavors only, the mixing matrix U can be parameterized as:

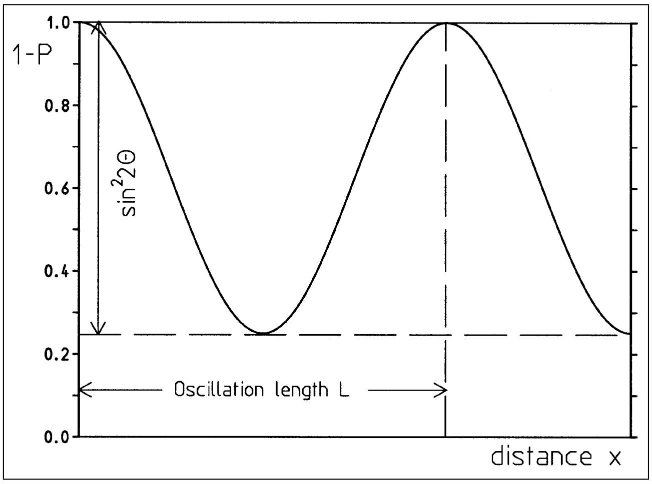

Fig. 2. Neutrino oscillations. Survival probability $1 - P$ for a muon neutrino created at $x = 0$ to still be a muon neutrino at $x > 0$ for the simple case of two-flavor oscillations. P depends on distance x, neutrino energy E_ν, neutrino mass difference Δm^2, and mixing strength $\sin\theta$. In this example $\sin^2 2\theta = 0.75$. L depicts the so-called oscillation length where the initial flavor content is restored again for the first time. The oscillation phenomenon offers an experimental access even to tiny neutrino masses

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{1}$$

and the oscillation probability is:

$$P = \frac{1}{2} \sin^2 2\theta \; (1 - \cos(2\pi x/L)) \tag{2}$$

where x is the distance between neutrino source and detector:

$$\begin{aligned} L &= 4\pi E_\nu / \Delta m^2 \\ &\approx 2.47\,(E/\mathrm{MeV})/(c^4\,\Delta m^2/\mathrm{eV}^2)\ [\mathrm{meters}] \end{aligned} \tag{3}$$

is the characteristic oscillation length, E_ν the neutrino energy, and $\Delta m^2 = |m_2^2 - m_1^2|$ the mass-squared difference of the involved neutrino mass eigenstates. The oscillation length L is the distance at which the original flavor content is fully restored again for the first time, as indicated in Fig. 2.

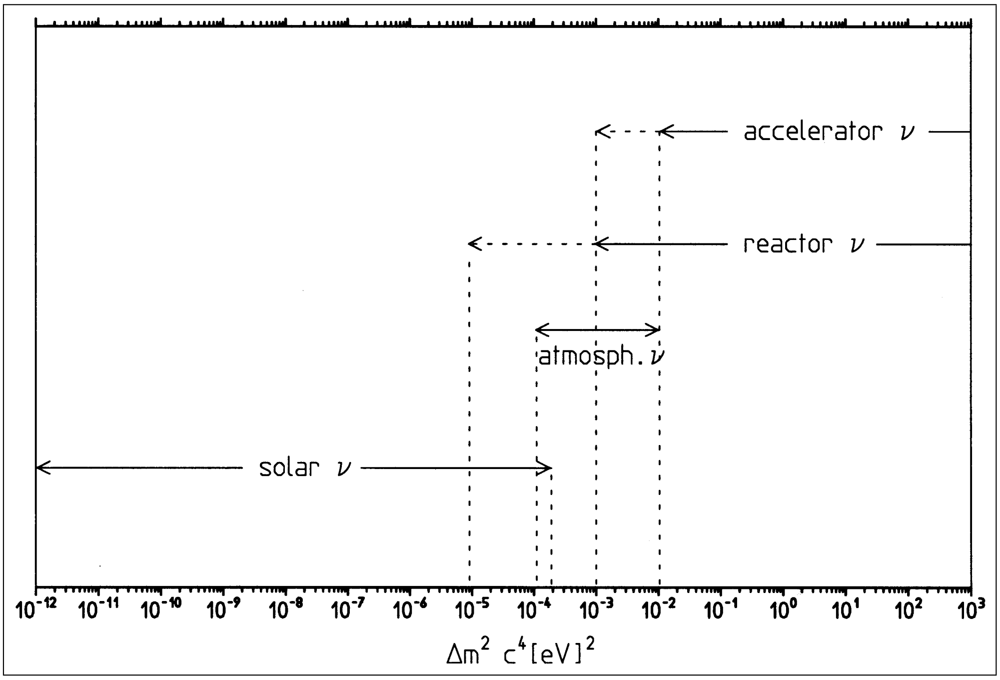

Fig. 3. Ranges of sensitivity for probing Δm^2 for different neutrino sources. In general, according to Eq. 3, the lower E_ν and the larger the distance between source and detector, the lower the Δm^2-range which can be investigated. For nuclear reactors and accelerator neutrinos several experiments exhibiting extremely long "baselines" of some 100 km are being planned. *Dotted lines* their ranges of sensitivity

Neutrino oscillations can be made intuitively plausible by considering the fact that neutrinos are created in weak processes as eigenstates ν_α of the "flavor basis". The appropriate frame governing neutrino propagation in space-time, however, is the "mass basis" defined by ν_i, where the mixing matrix U describes how to transform the initial ν_α into the new basis states ν_i. As neutrinos ν_i of the same energy (but different masses m_i) travel at different speeds, the state $|\nu(x,t)\rangle$ is no rigid time-constant ν_i superposition. This leads to a periodic variation of the flavor content of our neutrino beam – oscillations $\nu_\alpha \to \nu_\beta$ occur. Experimentally, neutrino oscillations are *the* key to search for tiny neutrino masses in the sub-eV region. (Strictly speaking, neutrino oscillations are sensitive to mass differences between two mass eigenstates, not to the masses themselves. However, if the masses are non degenerate, i.e., $m_i \ll m_j$ holds, in a good approximation $\Delta m_{ij}^2 \simeq m_j^2$. Such a strict mass hierarchy for neutrinos seems natural, as it is also realized for all other known elementary constituents of matter, i.e., quarks and charged leptons.)

As neutrinos from different sources are characterized by different energies, for example, typically 1–100 GeV for accelerator and atmospheric neutrinos, 100 keV to several MeV for reactor and solar neutrinos, and different source–detector distances, ranging from some 10 m at nuclear reactors to 1.49×10^8 km for the sun, according to Eq. 3, a wide Δm^2 range down to $\Delta m^2 \lesssim 10^{-12}\,\mathrm{eV}^2/c^4$ can be investigated. Figure 3 illustrates typical sensitivity ranges.

Oscillations are being sought in a number of experiments, exploiting various neutrino sources: nuclear reactors ($\overline{\nu}_\mathrm{e}$), particle accelerators ($\overline{\nu}_\mu$, ν_μ), neutrinos produced in the upper atmosphere of the earth ($\overline{\nu}_\mu$, ν_μ, $\overline{\nu}_\mathrm{e}$, ν_e), and solar neutrinos from stellar fusion (ν_e). Several of these measurements provide evidence that neutrinos do indeed oscillate. For about 30 years all solar neutrino experiments, exploiting different detection mechanisms and different spectral sensitivity, have consistently reported a substantial electron-neutrino deficit compared to the predictions of stellar model calculations. In addition, the spectrum of recoil electrons from $\nu - e^-$ scattering being measured in the Superkamiokande detector seems to be inconsistent with that expected for massless neutrinos. An extensive discussion of the solar neutrino puzzle has been presented by Altmann and von Feilitzsch (1997), and therefore we mention only some key issues here. Within the past few years the increasingly accurate results of the five running experiments, Homestake-^{37}Cl, Sage, Gallex, and Kamiokande/Superkamiokande have shown the failure of "classical" attempts to explain the observed energy-dependent ν_e deficit, for example, by applying ad hoc modifications to solar models. The only reasonable explanation for these observations is that solar

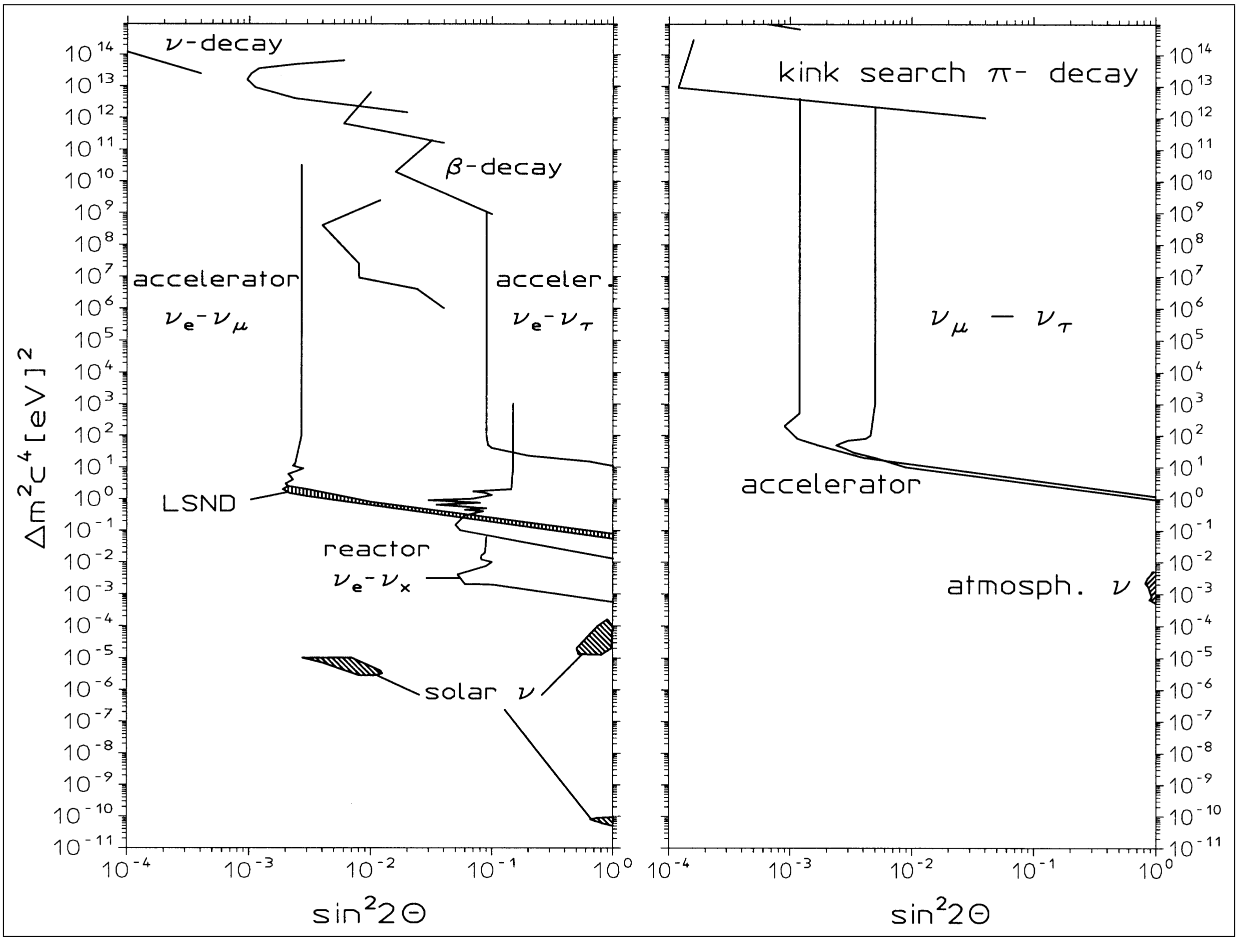

Fig. 4. Experimental status of neutrino oscillation and decay searches. The region in the $\Delta m^2 - \sin^2 2\theta$-plane right to the curves is excluded by the respective experiments. *Hatched areas*, in contrast, indicate neutrino parameters which can explain evidences for neutrino masses from solar and atmospheric neutrinos and from a terrestrial accelerator experiment

electron neutrinos have oscillated into some other species on their way from generation in the solar interior to the terrestrial detectors. The neutrino parameter combinations which can explain the experimental results are marked in Fig. 4. In passing, we note that within the next decade several new dedicated experiments (SNO, Borexino, GNO; Suzuki and Totsuka, 1999) will yield statistical data which, together with existing results, might allow even the singling out one of the three regions of Fig. 4.

Another indication for oscillations comes from atmospheric neutrino measurements. In 1998 the Japanese Superkamiokande collaborators (Fukuda et al. 1998; Kajita et al. 1998) claimed strong evidence that muon neutrinos produced in $\pi^{\pm}$ and $\mu^{\pm}$ decays in the earth's atmosphere oscillate into some other species, most probably ν_τ. This breakthrough observation raised enormous public interest and filled headlines in major newspapers all over the world. Grouping their data according to neutrino energy E_ν and travel distance x, the Superkamiokande collaborators observed a clear dependence on x/E_ν, as expected from Eq. 2 in the case of oscillations. Figure 5a,b shows these data. Superkamiokande observes a suppression of the ν_μ flux for large values of x/E_ν, which corresponds essentially to neutrinos having traversed earth. For ν_e, in contrast, the expected flux is detected, basically independently of x/E_ν. As oscillations $\nu_\mu \to \nu_e$ in the relevant parameter range are excluded by reactor experiments (see Fig. 4), the favored explanation is $\nu_\mu \to \nu_\tau$ oscillations. Accelerator experiments exhibiting an extremely long baseline of about 700 km between source and detector are being planned to verify this interpretation.

Less compelling as the evidence from solar and atmospheric neutrino measurements is an indication for massive neutrinos from the American LSND accelerator oscillation search (White et al. 1998), as it is partially contradicted by other, although less sensitive, experiments. However, several more years wil

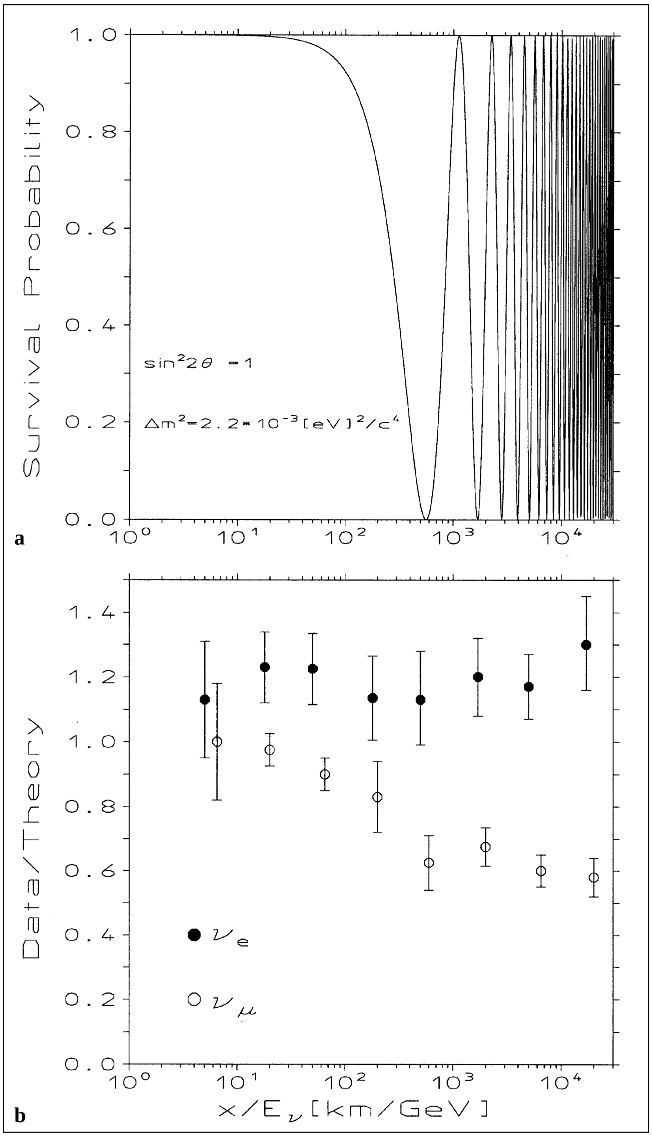

Fig. 5a,b. Results from the Superkamiokande atmospheric neutrino measurements. b) Experimental results show at large values of x/E_ν a significant suppression of the observed number of ν_μ with respect to the theoretical expectation, indicating neutrino oscillations. The best-fit parameters are $\Delta m^2 = 2.2 \times 10^{-3}\,\mathrm{eV}^2/c^4$ and $\sin^2 2\theta = 1$. a) The corresponding survival probability $1 - P$ for ν_μ of energy E_ν produced in the earth's atmosphere traveling the distance x between generation and the detector. At high values of x/E_ν the limited resolution of the detector causes a wash-out of the oscillation pattern in the experimental data

be needed before one can decide whether the LSND indication of massive neutrinos will be confirmed or falsified by a more advanced set-up presently being constructed at the United States Fermilab accelerator. In any case, however, with the compelling and consistent evidence from several solar and atmospheric neutrino experiments we are in the position to state that neutrinos do oscillate, and thus have mass and exhibit flavor mixing.

Are Neutrinos Stable?

If neutrinos oscillate, i.e., if they have mass and flavor mixing is found among leptons, neutrino decay is an inevitable consequence. In this case, only the lightest neutrino mass eigenstate is stable; all the others must decay. Their mean lifetime, however, could be very long, even longer than the age of the universe, $\simeq 10^{10}$ years, depending on their mass and the mixing strength. Possible decay modes of massive neutrinos are $\nu_j \to \nu_i + \gamma$, $\nu_j \to \nu_i + 2\gamma$, and, if $m_j c^2 > 1.022\,\mathrm{MeV}$ also the electron-positron decay $\nu_j \to \nu_i + e^+ + e^-$. All these modes have been searched for experimentally with accelerators and nuclear reactors, and for neutrinos emitted from the supernova SN 1987A. However, no indication of any of them has been found. In contrast, experiments have led to stringent limits to possible neutrino mass-mixing combinations which outperform that from neutrino oscillation searches for high masses. Figure 4 presents the most stringent limits.

Is the Neutrino Its Own Antiparticle?

In contrast to electrically charged particles, for a neutral particle such as the neutrino there is no apriori reason for it to be inherently different from the corresponding antiparticle. Such particles which are their own antiparticles, are called Majorana-particles. (The opposite, i.e., particles in which the antiparticle is different, are called Dirac particles.) Therefore it may well be that the neutrino ν and its antineutrino $\bar{\nu}$ are identical particles – we simply do not know to date. A special radioactive process called "neutrinoless double beta decay" might help to solve this question. Double beta decay transitions ($\beta\beta$) to next-to-neighboring nuclei as second-order processes are experimentally observable for a number of nuclei with even neutron and proton numbers. Among the most prominent examples are ^{76}Ge, ^{100}Mo, ^{130}Te, and ^{136}Xe.

With the emission of two neutrinos $\beta\beta$ decay is a standard process, which has been readily observed for several elements. By far more appealing for neutrino physics, cosmology, and astrophysics, however, is neutrinoless double beta decay. This can occur only if neutrinos have mass and are of Majorana nature. Unfortunately, the correponding experiments are neither easy to perform nor particularly sensitive to small neutrino masses. The most advanced experiment searching for neutrinoless $\beta\beta$ decay is the Heidelberg-Moscow installation, using large germanium detectors made of material enriched in the $\beta\beta$ isotope ^{76}Ge (86% vs. 7.8% in natural Ge). However, the experiment has found no indication of neutrinoless double beta decay and reports a limit of $T_{1/2}^{\beta\beta0\nu} > 5.7 \times 10^{25}$ years (90% C.I.) for this decay channel [12]. A quantitative conversion of the half-life limit to a constraint on an "effective" Majorana neutrino mass suffers from a substantial theoretical uncertainty, as it involves nuclear matrix elements which are only poorly known. The Heidelberg-Moscow Collaborators (1999), using matrix elements calculated by themselves, reports a limit of $\langle m_\nu \rangle \, c^2 < 0.2$ eV. We indicate with brackets here that this limit does not apply to one of the intrinsic neutrino masses m_j but rather is valid for a linear combination $\langle m_\nu \rangle = \sum_{j=1}^{3} \eta_j |U_{j\mathrm{e}}|^2 m_j$, where η_j are so-called Majorana CP phases which can take on values $\eta = \pm 1$, and $U_{j\mathrm{e}}$ are elements of the lepton flavor mixing matrix. In any case, of course, the $\langle m_\nu \rangle$ limit is valid only if the neutrino is a Majorana particle. Proposals have been made to substantially enlarge the mass of double-beta source material and to improve background, in order to access $\beta\beta0\nu-$half-lifes of $T_{1/2}^{\beta\beta0\nu} \approx 10^{27}$ years, in the hope of finding a positive signal in the newly explored region.

Do Neutrinos Interact Magnetically?

Neutrinos, if massive and not Majorana but Dirac particles, exhibit magnetic moments μ_ν^{mag}. Hence they would interact with magnetic fields which can induce a spin flip and thus a helicity inversion. In the easiest theoretical framework, a minimally enlarged standard model, the magnetic moment of a Dirac neutrino of mass m_ν is expected to be $\mu_\nu^{\mathrm{mag}} = 3.2 \times 10^{-19} \mu_B m_\nu c^2/\mathrm{eV}$, where $\mu_B = 1.9 \times 10^{-11}$ e cm is the Bohr magneton. Experiments have not found conclusive indications for $\mu_\nu^{\mathrm{mag}} \neq 0$. The most restrictive direct measurements, in contrast, have put limits of $\mu_\nu^{\mathrm{mag}}(\nu_\tau) < 3.3 \times 10^{-6} \, \mu_B$ (90% C.I.) $\mu_\nu^{\mathrm{mag}}(\nu_\mu) < 7.4 \times 10^{-10} \, \mu_B$ (90% C.I.), and $\mu_\nu^{\mathrm{mag}}(\bar{\nu}_e) < 1.8 \times 10^{-10} \, \mu_B$ (90% C.I.) [5]. It is straightforward to see that these constraints still are orders of magnitude weaker than that obtained from inserting the kinematic neutrino mass limits discussed above into the formula. However, it should be mentioned that, firstly, theories have been proposed which allow for much higher values of μ_ν^{mag} than the minimally enlarged standard model, and, secondly, more stringent yet quite model-dependent bounds can be derived from astrophysical arguments involving, for example, supernova SN 1987A, cooling of He-burning stars, the observed luminosities of red giant stars, and primordial nucleosynthesis [17].

Neutrino Physics in the Twenty-first Century: An Outlook

Neutrinos most probably do have mass, and lepton mixing does occur. This is the conclusion that we can draw from the results observed in experiments detecting solar and atmospheric neutrinos, constituting one of the most fundamental and far-reaching discoveries in physics at the end of the twentieth century. What will be next? First, although we know now that neutrinos have mass, we do not yet have definite knowledge of what their masses are, nor do we know the elements of the complete lepton mixing matrix. Scrutinizing these parameters will most likely constitute the bread-and-butter neutrino physics of the next century – similar to nuclear spectroscopy in the 1960s and precision tests of standard model parameters in the 1980s and 1990s for nuclear and particle physics. Once we have definite knowledge of the neutrino mass values, we will also know whether neutrinos contribute substantially to the dark matter in the universe, the nature of which is still largely unknown.

High-energy neutrino astrophysics will no doubt experience a flourishing period, neutrinos being unique tools for discovering and tracking extragalactic high-energy point sources. AGNs, hot supernova remnants – there are many fascinating discoveries waiting to be made. The field of high energy neutrino astronomy is only starting to grow to maturity. Early in the twenty-first century several large-scale neutrino detectors will be operative which have the capability to detect with high statistical significance supernovae exploding in our own Milky Way or in neighboring galaxies.

Probably the most demanding challenge, however, is the long-standing quest for relic cosmic background neutrinos, remnants from the big bang which should be filling our entire universe. Their detection constitutes an extremely hard but undoubtedly a worthwhile mission for future generations. We hope that they will be successful one day – perhaps already in the twenty-first century, as Stodolsky (1998) speculated.

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