What Do We Learn from Neutrinos?

J. Steinberger

Each type of particle, by definition, is special. The special property of neutrinos is that they are penetrating. This has made their discovery and the understanding of their properties elusive, but it has also made them a useful tool in the study of particles and their interactions. In astrophysics, on account of this property, neutrinos provide an important means for energy transfer and permit insight into the interior of stars hidden to other radiation. The special conditions in space permit, in turn, the study of neutrino properties not possible in the laboratory.

The written history of the neutrino begins with Wolfgang Pauli's (Fig. 1) letter of 1930 to his "Liebe Radioaktive Damen und Herren" (Fig. 2). He timidly suggests a new particle to solve two outstanding problems—the apparent violation of energy conservation in β decay and the "wrong" statistics of certain nuclei, for example nitrogen-14—but he does not dare to publish it until 3 years later (*1*). In the meantime, the name he proposed for it (neutron) was taken by the discovery by Chadwick of the neutral partner of the proton, the discovery that also solved the statistics problem. At the time, the nuclear energy levels were so uncertain that Pauli could only restrict the mass of his proposed neutral particle to less than 0.01 proton masses. The present upper limit is lower by the factor 10^8, about 10 eV, on the basis of measurements on the tritium β spectrum near its end point. For all we know today, the neutrino mass may very well be zero.

In 1934 Fermi proposed a theory of β decay (*2*), which incorporated the neutrino and was remarkably simple, successful, and long-lived. With the Fermi theory, the neutrino became a particle like the others. As muon capture and decay became understood in the late 1940s, the Fermi theory became the universal theory of weak interactions. It was superseded in the early 1970s by the beautiful electroweak gauge theory that unified the weak and electromagnetic interactions, but it still survives as a useful approximation.

The direct detection of neutrinos was not possible at the time because of the very small interaction rates, as correctly predicted by the Fermi theory. Neutrinos are the only particles with only weak interaction. No experiment to detect them could be imagined until the advent of the atomic age. The first observation of a neutrino-induced process, the inverse β decay reaction $\nu + p \rightarrow n + e^+$, had to wait until 1956 (*3*) for the development of the hydrogen bomb and the Savannah River tritium-producing reactors, which could generate a sufficiently large flux of neutrinos. The target was a water tank with some cadmium salt dissolved in it. The reaction was identified on the basis of the signal from the gamma rays emitted in the capture by the cadmium of the slowed down neutron, these gamma rays in delayed coincidence with the gamma rays resulting from the annihilation of the positron with an electron.

The author is in the PPE Division, CERN, CH-1211 Geneva 23, Switzerland.

The postwar years witnessed the discovery of whole new and unsuspected worlds of particles. The discoveries were at first in cosmic ray experiments, with nuclear emulsion detectors and cloud chambers, but the field was quickly taken over by accelerator experiments. The available energies increased dramatically with time, always opening new vistas. With the construction, in the end of the 1950s, both at Brookhaven National Laboratory and at CERN, of proton accelerators in the range of 30 GeV, it became possible to contemplate the production of high-energy neutrino beams of sufficient intensity to perform experiments (*4*). The accelerator energy is doubly important for neutrino beam experimentation: the cross sections increase linearly with energy, and the beams are more collimated and therefore more intense at higher energy. Neutrino experiments opened entirely new possibilities in the study of particle properties and the weak interaction (*5*).

The first high-energy neutrino experiment was performed at Brookhaven in 1962 (*6*). The hadrons produced on a target inside the alternating gradient synchrotron (AGS) accelerator were allowed to enter a 17-m-long decay region (Fig. 3). The dominant source of neutrinos is the decay of the pion to a muon and a neutrino, and to a somewhat smaller extent, but with higher neutrino energy, the decay of the kaon to the same final state. The decay region was followed by a thick iron shield and a 10-ton detector consisting of 2.5-cm-thick aluminum plates separated by spark gaps. The target doubles as particle detector, a feature of almost all subsequent neutrino experiments, which is necessitated by the smallness of the neutrino cross sections. The sparks are photographed; energetic particles traverse several plates and can be recognized as tracks.

After some months of running, a few dozen events were obtained, and it could be demonstrated that these are due to neutrinos. One of these is reproduced in Fig. 4. The most striking feature of the events was that the large majority contained a muon, recognized on the basis of its large penetration in the aluminum. The muon track can be seen clearly in Fig. 4; the other sparks are caused by hadronic debris. No events containing a high-energy electron could be identified. This demonstrated that the neutrinos produced in pion and kaon decay, in association with muons, are not the same as the neutrinos originating in β decay, in association with electrons. The latter would necessarily produce electrons in their interaction with matter (*7*). So, already the first neutrino experiment observed a fundamental, important result. This pairing of neutrinos with charged leptons into families is one of the basic features of the electroweak theory.

High-energy neutrino experiments have been pursued actively since that time until the present. Probably the most important result was the discovery in 1973 of a new weak interaction, the "neutral current." In the late 1960s and early 1970s the electroweak theory took form. The theory represented an enormous step forward in our formal understanding of particles. It unified two of the three particle interactions and

Fig. 1. Wolfgang Pauli.

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen.

As the bearer of these lines, to whom I ask you to lend most graciously your ears, will explain in greater detail, I have hit, in view of the "false" statistics of the N and Li-6 nuclei and of the continuous β–spectrum, upon a desperate expedient for saving the "Wechselsatz" of statistics and energy conversation. This is the possibility that electrically neutral particles, which I shall call neutrons, might exist in the nucleus, having spin 1/2 and obeying the exclusion principle. In addition they differ from light quanta in that they do not travel at the speed of light. The mass of the neutron should be of the same order of magnitude as that of the electron and in any event no greater than 0.01 of the proton mass. The continuous β–spectrum would then be comprehensible on the assumption that on β–decay a neutron is emitted with the electron in such a way that the sum of the neutron and the electron energy is constant.

Furthermore the question arises which forces act on the neutron. For reasons of wave mechanics (the bearer of these lines knows more about this) the likeliest model for the neutron seems to me to be, that the neutron at rest is a magnetic dipole with a certain moment μ. Experiments apparently demand that the ionising effect of such a neutron is no greater than that of a γ–ray, in which case μ should be no greater than e (10^{-13} cm).

For the moment I would not venture to publish anything on this notion and should like first of all to turn trustingly to you, dear Radioactives, with the question concerning the prospects for experimental verification of the existence of such a neutron if it were to have the same or perhaps a 10 times greater penetrating power as a γ–ray.

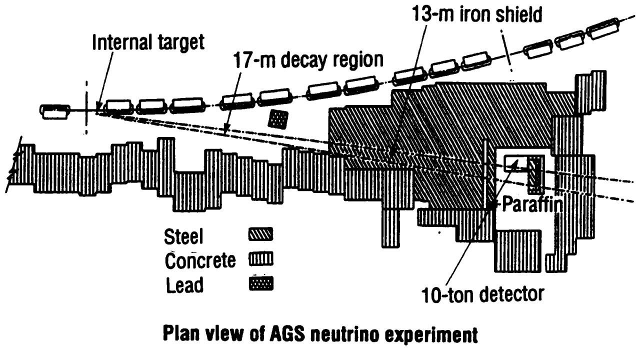
I admit that my expedient may seem rather improbable from the first, because if neutrons existed they would have been discovered long since. Nevertheless, nothing ventured nothing gained, and the seriousness of the situation with the continuous β–spectrum is illustrated by a statement by my esteemed predecessor in office, Mr. Debye, who recently told me in Brussels: "Oh, it's better to ignore that completely, just like the new taxes". We should therefore be seriously discussing every path to salvation. So, dear Radioactives, consider and judge. Unfortunately I cannot come to Tübingen in person since my presence here is essential as a result of a ball held on the night of 6th to 7th December in Zürich.

With kind regards to all of you and Mr. Back, I remain,
your humble servant,

(signed) W. Pauli

Fig. 2. An English translation of Pauli's original letter in German suggesting the neutrino to the Tübingen congress. The term "Wechselsatz" refers to Fermi statistics and half-numbered spin for nuclei with an odd total number of particles and to Bose statistics and integer spin for nuclei with an even number of particles. [Courtesy of the CERN translation service, as revised by M. Schmelling, R. Wanke, and B. Wolf]

Fig. 3. Arrangement of the first accelerator neutrino experiment, which found the separate identity of the muon neutrino.



offered, for the first time, the possibility of calculating weak interaction processes in higher order perturbation theory, something not possible in the Fermi theory.

It was not immediately clear that the new theory was correct. All known manifestations of the weak interaction, almost all of them particle decays, could already be quantitatively understood in terms of the old Fermi theory. The new theory agreed with the old on these processes, but it also predicted two entirely new phenomena: the "neutral current" and the existence of the vector bosons, particles of a vastly greater mass than had been seen before. The first of these predictions to be verified was the "neutral current." This discovery established the new theory beyond any doubt. The vector bosons were discovered 10 years later, also at CERN. Until the "Gargamelle" experiment, all observed neutrino interactions, as best one knew, involved the emission of a charged lepton, a muon or electron, in the final state: one can think of it as the conversion of the neutrino into the other lepton member of its "family." The "neutral current" permits the scattering of the neutrino, with its reappearance in the final state.

Gargamelle was a large bubble chamber constructed at the Paris Ecole Polytechnique and exposed in a neutrino beam at CERN (Fig. 5). It was 4 m long and 2 m in

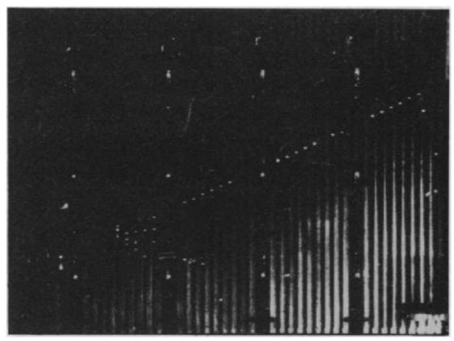


Fig. 4. One of the hadron decay events. The upper track is the muon; the lower sparks are attributable to the hadronic debris.

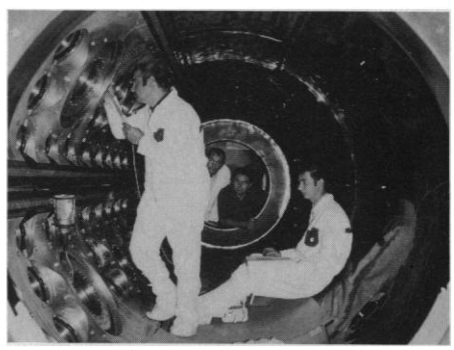


Fig. 5. Inside the Gargamelle bubble chamber.

diameter, inside a large magnet producing 2 T, and filled with a heavy liquid, freon. "Muonless" events were searched for and several hundred were found, both in neutrino and in antineutrino beams. Such an event is shown in Fig. 6. Both of the outgoing particles are identified: one is a kaon and the other is a lambda hyperon; there is no muon. The nonhadronic nature of the beam particle was demonstrated by the distribution in depth along the chamber. The distribution is consistent with being independent of depth, as expected for neutrinos. Neutrons, on the other hand, would be attenuated with an exponential constant roughly equal to one-quarter of the total depth of the chamber.

The ratio of rates relative to the more numerous "charged current" events gave a first measure of the weak mixing angle, an important free constant in the theory. The ratio of antineutrino to neutrino neutral current cross sections was predicted by the theory. The measured result, in agreement with the theoretical prediction, constituted additional, quantitative confirmation of the theory.

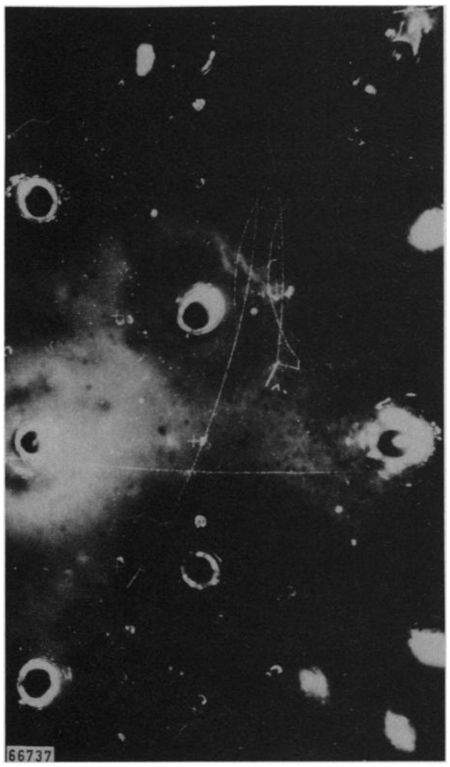


Fig. 6. One of the original Gargamelle neutral current events. The neutrinos are coming from the top. At the interaction point a neutral particle and a single charged track are produced. The charged particle identifies itself as a positive kaon by its decay, after scattering in the chamber. The V, which points to the production vertex, is a lambda particle, decaying to a proton and a negative pi meson. There is no muon.

In the years 1969 to 1972 the inelastic scattering of high-energy electrons on protons and deuterons (neutrons) at the Stanford Linear Accelerator Center (SLAC) revealed a point-like constituency of the nucleon. This was a capital discovery: nucleons were no longer elementary. Subsequently, neutrinos proved to be excellent projectiles for complementary studies on the nature of the structure of the nucleon. On account of the weakness of their interaction, neutrinos penetrate the nucleon, and the nature of their interaction with the quarks, the primary candidates for the elementary constituency of nuclear matter, was already predicted by the electroweak theory.

Experiments were carried out with a new generation of massive, electronic neutrino detectors at the new 400-GeV proton synchrotron at CERN. A photograph of the 1000-ton apparatus built by the CERN, Dortmund, Heidelberg, and Saclay (CDHS) collaboration is shown in Fig. 7. On account of the more massive detector, the higher beam energy, and the more sophisticated beam optics, millions of events were now obtained in comparison with the handful of the first neutrino experiment, and each event contained more detailed and precise information on the scattering than had been possible before. A typical event is shown in Fig. 8. The results, in conjunction with the SLAC electron scattering results, demonstrated the quark nature (quarks had been postulated as particles of spin 1/2 and of 1/3 integral electric charge, interacting strongly with each other) of the nuclear constituency.

An additional important result of these neutrino studies was their contribution to the experimental confirmation of the now universally accepted theory of the strong quark forces, the theory of quantum chromodynamics (QCD). This theory predicted small, calculable deviations from the simple point-like scattering that was expected in the "naïve" quark model and that results in cross sections independent of the momentum transfer called "scaling." Scaling was the basic element of the SLAC discovery, but it is only approximately true. The neutrino experiments (8, 9) confirmed the scaling violations predicted by QCD and so gave important experimental support to the QCD theory.

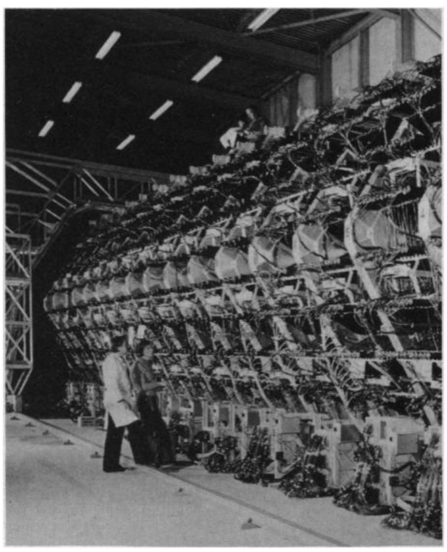


Fig. 7. The CDHS 1200-ton electronic neutrino detector at CERN.

Neutrinos continue to be an important tool in the study of nucleon structure and the properties of the weak interaction. Recently neutrinos played an indirect but important role in establishing the number of fermion families that constitute matter. In the standard model—the sum of the electroweak and the QCD theories—"families" consist of four elementary particles: a charged lepton and its associated neutrino plus a pair of quarks of electric charges 2/3 and $-1/3$, respectively. Two of these families are known entirely; in the third family the "top" quark is still missing, presumably because its mass is too large to have been produced in sufficient quantity for detection so far. The general belief is that it will soon be found. The standard model does not predict how many families there should be. With the possible exception of the neutrinos, whose masses are smaller than could so far be measured, the masses of the members of succeeding families increase rapidly, by a

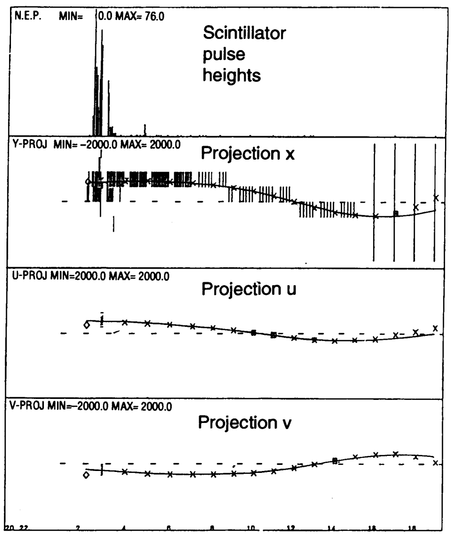


Fig. 8. A typical charged current event in the CDHS detector. The neutrino turns into a muon, which is the long track, seen in three projections, that penetrates several meters of iron. Its energy is measured on the basis of its curvature in the magnetized iron. The accompanying hadronic particles are dissipated in the first meter of iron, and their energy is measured by means of scintillation counters sandwiched between the 5-cm-thick iron plates.

factor of the order of 100 from one family to the next. If additional families existed, they might be out of the reach of present accelerators because of the large possible masses of their members. But based only on the assumption that the masses of the neutrino members of possible higher mass families would also be small, recent experiments at the large electron-positron (LEP) collider have been able to demonstrate that there are three families of matter and no more.

The LEP result uses the measurement of the resonance line shape of the Z particle. The Z, the particle with the highest mass yet discovered, about 100 times heavier than the proton, decays into many different final states. Each of these consists of a fermion-antifermion pair. A typical Z decay, here into a quark-antiquark pair, is shown in Fig. 9. All fermion species contribute, with probabilities predicted in the

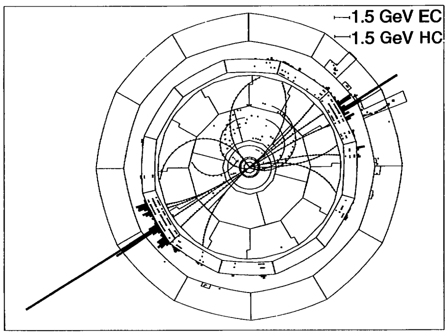


Fig. 9. Decay of a Z into a quark-antiquark pair as seen in the ALEPH detector at LEP. The quark and antiquark materialize as jets, which are typically composed of a dozen or so hadrons. The momenta of the charged particles are measured by the stiffness (inverse curvature) of their tracks. The neutral particles are measured by means of the "calorimeters" that surround the track chambers.

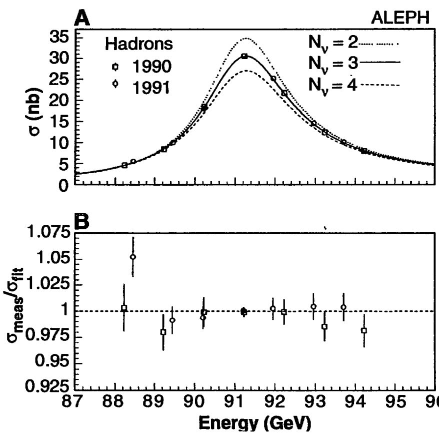


Fig. 10. LEP result for the Z resonance, in good agreement with three families of neutrinos and in disagreement with fewer or more families. **(A)** Experimental data points and theoretical predictions for different numbers of neutrinos. **(B)** Residuals from fit.

standard model. The width of the resonance curve, therefore, is the sum of the contributions from all fermions accessible on energetic grounds, that is, whose mass is less than one-half the Z mass. The neutrino member of a higher mass family would contribute, provided only that its mass is less than one-half the very heavy Z mass. The resonance curve has been very accurately measured at the LEP collider (*10*) (Fig. 10). The width is known now with a precision of 0.4% and is precisely the width expected for the three known families of matter. The neutrino of a possible fourth family is excluded with a precision of one-twentieth of the expected contribution of such a neutrino to the width.

Let us turn now to what we have learned about stars by studying neutrino radiation and, in turn, to what we might learn about neutrinos from those that arrive on our Earth from far away. I will touch on three topics: neutrinos from the sun, neutrinos from supernovas, and neutrinos during the big bang.

We see the sun dominantly by means of the visual spectrum. This thermal energy takes about 10^6 years and 10^{30} collisions from the time of its creation to get out of the sun and is modified in the process so that it cannot tell us much about the conditions that created it. Neutrinos, however, typically traverse the sun without collision. Although the solar neutrino flux on Earth is far from negligible: $\sim 10^{11}$ solar neutrinos arrive here per square centimeter per second, with an energy flux as large as several percent of the sun's thermal energy, because the neutrino interaction cross section is so small, their detection has been a big challenge.

The first experiment to detect solar neutrinos, and the only one until just a few years ago, dates to 1970 (*11*). It is still running. Neutrinos are detected by the inverse β-decay interaction on chlorine: $^{37}Cl + \nu \rightarrow {}^{37}Ar + e^-$. The reaction is observed by means of the argon β decay, which has a lifetime of 35 days. The chlorine is in the form of 400 m^3 (133 tons) of perchloretylene, 1500 m underground, to get away from background produced by cosmic radiation, in the Homestake gold mine in the United States. About one of the 10^{30} chlorine atoms per day is expected to be converted to argon by the solar neutrino radiation. Every couple of months the radioactive argon is flushed out by means of a small amount of nonradioactive argon isotope and counted. The results, which have taken much patience to accumulate, have been consistently below the expectations of models of nuclear energy production in the sun. They now stand at 0.4 ± 0.06 atoms per day, about one-third of the rate predicted by detailed models of solar nuclear energy production.

In the last several years, this depletion has been confirmed by an experiment that uses a radically different method of detection (*12*). The basic reaction is the elastic scattering of the neutrinos on electrons, with the observation of the recoil electron. The detector is a large tank of water, about 20 m on each side, which is viewed by an array of photomultipliers. These measure the energy and direction of the little recoil electron on the basis of emitted Cerenkov light. Again, the detector is shielded from cosmic rays in a deep mine, the Kamiokande mine in Japan. The results, which are very clear, correspond to 0.46 ± 0.05 times the expectations of the solar models.

The deviation from the expectations of the standard solar model of the combined results of the two solar neutrino experiments, by a factor of the order of 1/3 to 1/2, that is, the "solar neutrino puzzle," is of great interest because the process of nuclear energy production in the sun is believed to be adequately understood. To keep the experimental result in perspective, it should

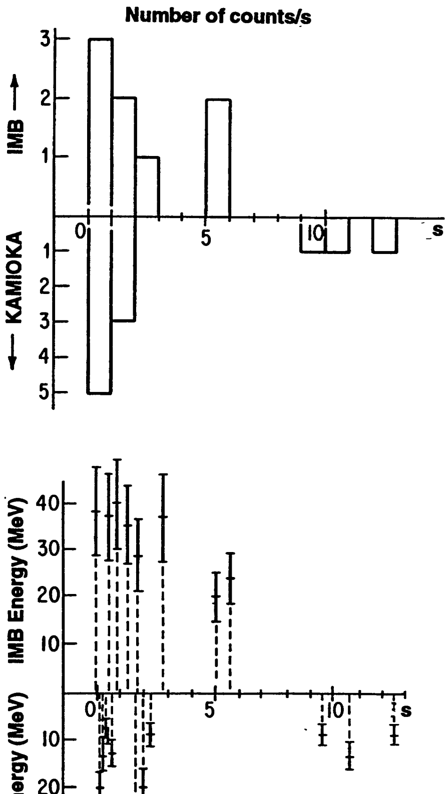


Fig. 11. Time distributions for the neutrino events observed in the Kamiokande and IMB underground water Cerenkov detectors and attributed to the supernova SN1987A. For the neutrinos, it was all finished in 10 s. **(A)** Count rate versus time. **(B)** Energy of events versus time.

be kept in mind that on the one hand the experiments are difficult and on the other hand both experiments are sensitive only to the relatively rare high-energy component of the expected solar neutrino flux, essentially only to the decay of ^8B, because the neutrino energy threshold is 0.814 MeV for the chlorine reaction and about 7.5 MeV for the Kamiokande detector. The experiments are insensitive to the lower energy neutrinos from the reaction $p + p \rightarrow d + \nu + e^+$, which accounts for the large bulk of solar neutrinos. There is a larger theoretical uncertainty for this high-energy tail of the solar neutrino spectrum than for the pp component.

For this reason two new experiments are now under way, using the gallium reaction $^{71}Ga + \nu \rightarrow {}^{71}Ge + e^-$, which is sensitive to the pp reaction neutrinos: an American-Russian collaboration at Baksan in the Caucasus as well as a European collaboration in the Grand Sasso tunnel in Italy. Following an initial very low result (*13*) of the Baksan experiment, at a level of 15 ± 15% of the expectations of the solar model, the Grand Sasso experiment (*14*) gave a clear signal at 63 ± 17%, not so different from solar model expectation. This is now confirmed also by the Baksan experiment (*15*).

These solar neutrino experiments, at signal levels of the order of one radioactive atom per day in a sea of 10^{30} normal atoms, are difficult. We are therefore not absolutely sure that the discrepancies are significant. The observation of solar neutrinos in roughly the right numbers can instead be considered a beautiful confirmation of our basic understanding of how energy is produced in the sun.

However, if the discrepancies were confirmed, it would be a demonstration of new physics in the properties of neutrinos. Pontecorvo was the first to note (*16*) the possibility of neutrino flavor oscillation, Wolfenstein pointed out (*17*) that neutrino oscillations would be markedly affected by matter, and Mikheyev and Smirnov used this mechanism to provide a possible explanation of the "solar neutrino puzzle" (*18*). For neutrino masses of much less than 1 eV, it is expected that in dense matter, the electron neutrino, by virtue of its charged current scattering on electrons, will have a higher effective mass than the muon neutrino, even if its "free" mass is slightly lower. An electron neutrino born in the center of the sun would then, if there is adequate mixing between the flavors, leave the sun as a muon neutrino, impotent to perform inverse β decay. If both the present experiments as well as the standard solar model calculations are correct, then the parameter space of neutrino mass differences and mixing angles is very tightly limited to mass differences in the range of a few thousandths of an electron volt and a substantial mixing angle. The end of this story is not yet told, but it is a nice example of the symbiotic relationship between particle physics and astronomy.

Another interesting example of this relationship was the detection of neutrinos from the supernova SN1987A. Neutrinos are the dominant (99%) mechanism by which supernovas are expected to dissipate the energy released in the gravitational collapse of its core into a neutron star. Prior to the event of 1987, it was calculated that in a typical supernova more than 10^{53} ergs should be radiated in the form of neutrinos. These are thermal neutrinos with typical energies of the order of 10 MeV. On 23 March 1987 at 07:35 U.T., 11 and 8 events, respectively, of such low-energy neutrino events were registered in the Kamiokande (*19*) and Irvine-Michigan-Brookhaven (*20*) large underground water Cerenkov detectors. The time distribution of the burst, of the order of 10-s duration (Fig. 11), was in line with the expectations of the supernova collapse models, as were the energy distribution and the overall rate. The observation was useful in establishing a new level of confidence in the present understanding of the theory of supernovas.

The observations were serendipitous in the sense that these detectors were built to study an entirely different process, the possibility of the decay of the nucleon. They also provided new information on the properties of neutrinos because the time coherence of the events, despite the energy differences of the individual neutrinos, permits an upper limit of 25 eV on the electron neutrino mass. Other neutrino properties that follow from the observation were a lower bound of 1.6×10^5 years on the electron neutrino lifetime based on the time of flight from the supernova as well as an upper bound on its electric charge of 10^{-17} electron charges and an upper bound on its magnetic moment 10^{-11} times smaller than the electron magnetic moment, both based on the passage of the neutrinos through the matter of the supernova.

The energy density of neutrinos as well as the energy transfer by neutrinos played an important role in the dynamics of the early universe. The competition between the expansion rate (or the cooling time) and the neutron decay time is determinant in the formation of the primordial helium after the temperature has decreased to about 1 MeV and the weak interaction has frozen out of thermal equilibrium. From the measured cosmic abundances of deuterium, helium, and lithium-7 relative to hydrogen, it has been deduced that there should have been of the order of three families of neutrinos, in agreement with the particle physics result. If one of the families would have a neutrino of the order of 10 to 20 eV, the remnants of these neutrinos from the big bang would be possible candidates for the "dark matter" that is known to dominate the universe.

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21. This article is adapted from a lecture given at the Universitat Autònoma de Barcelona, Barcelona, Spain, on 8 May 1992.