After some forty years' research work, the solar neutrino puzzle - the consistent deficit found in Earth-based detectors - has been solved. Understanding of the nuclear fusion reactions, on which the Sun and other stars depend for their energy, is sufficiently mature to allow precise predictions to be made, regarding the emission source for these particles. It has now been ascertained that the shortfall in observed neutrinos is due to an astonishing property of neutrinos: these fickle particles transform on their way to us!

Solar neutrinos:
a puzzle finally solved

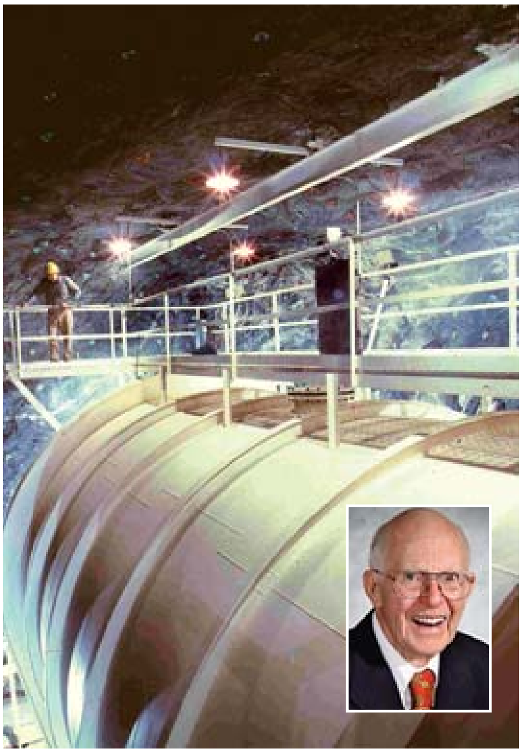

SNO

A view of the target of the Sudbury Neutrino Observatory (SNO), during construction, comprising 1,000 tonnes of heavy water, contained in an acrylic-plastic vessel. This volume is monitored by 9,600 detectors, borne on the metal structure.

For a long time, scientists wondered about the mechanisms capable of yielding the tremendous power ($3.86 \cdot 10^{26}$ **watts**) the Sun has been radiating for billions of years. The answer, built up from 1938 on, shows it is essentially the **fusion** of four **hydrogen nuclei** (**protons**) into one **helium** nucleus (two protons and two **neutrons**) which makes the Sun, and the stars like it, shine (see *The nuclear Sun*). Every fusion of this type releases some 27 **MeV** ($4.4 \cdot 10^{-12}$ joule), but also two **neutrinos**. We must thus be getting, on Earth, 65 billion such neutrinos per second per square centimeter.

For forty years now, experimentalists have been engaged in detection of neutrinos from the Sun. It was the chlorine experiment, designed by a US chemist, Raymond Davis Jr., which first achieved this. In a paper published on 28 May 1968, Davis showed that the neutrino flux recorded by his detector only amounted to 30% of predictions from solar models. The issue stood in abeyance until 1988, when a second detector, known as Kamiokande, in Japan, constructed thanks to the impetus provided by Masatoshi Koshiba, confirmed that deficit, further verifying that the neutrinos did indeed originate in the Sun.

At the end of the 1980s, two collaborative projects, Sage and Gallex, set up experiments using gallium, in which low-energy neutrinos (over 233 keV) could transmute



Courtesy Brookhaven National Laboratory

The tank used for the historic experiment set up by Raymond Davis (inset), the key component in the neutrino-detection experiment carried out, from the 1960s on, in the Homestake mine (South Dakota).

gallium into germanium. In 1992, European collaboration Gallex reported the first observation of neutrinos produced in the **primordial** fusion reaction between two protons inside the Sun's **core** - the reaction responsible for the energy generated by our star. The team stressed, however, that the neutrino flux measured was smaller, by a full third, than what astrophysicists were predicting. The Sage experiment soon confirmed a similar shortfall.

Two avenues of investigation were then open: to reexamine our ideas as to the way stars function, or to adduce new phenomena in neutrino physics and revisit the **standard model** of elementary particles (see Box C, ***Elementary particles and fundamental interactions***). As advances in **helioseismology** corroborated the solar models, suspicion grew with respect to neutrinos. Finally, in 2001, the SNO (Sudbury Neutrino Observatory) experiment showed these suspicions had been justified: neutrinos produced in the Sun's center, in the numbers expected, change their nature before they reach the Earth.

It is this investigation we shall revisit here, in the light of our knowledge of energy- and neutrino-producing reactions in the Sun. Analysis of the experiments will allow the nature of the deficit to be best grasped, and set constraints on possible explanations.

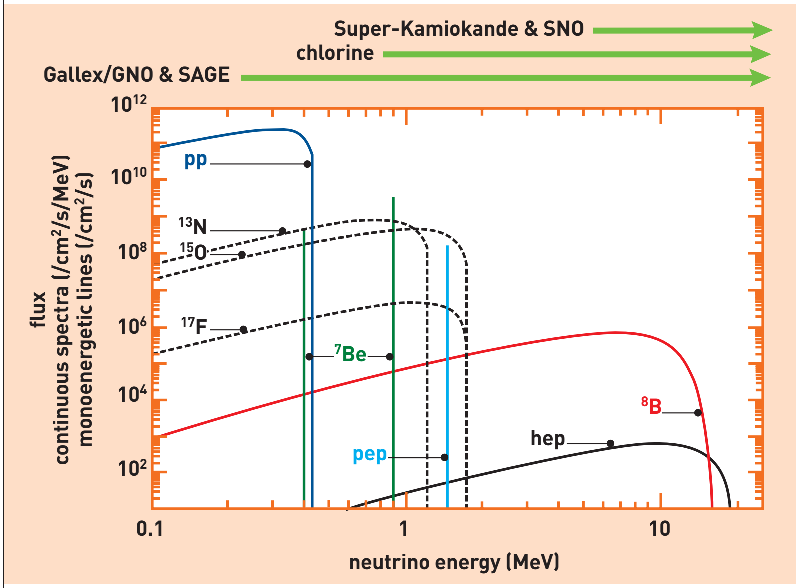


Figure 1.
Energy spectrum of solar neutrinos. The overall flux of solar neutrinos reaching the Earth stands at 65 billion per square centimeter per second. This is predominantly made up of ν_{pp} (60 billion), boron neutrinos only accounting for 6 million. The latter's higher energy makes detection easier. Sensitivity ranges for the various experiments are shown at the top of the diagram.

Neutrinos at the Sun's core

The Sun is a "run-of-the-mill" star, of the kind there are billions of around the Universe. This huge ball of **ionized** gas (essentially hydrogen and helium) is in a state of equilibrium between gravitational collapse, under its own mass, and thermal pressure; central temperature (over 15 million degrees) is high enough to enable nuclear reactions to occur, by overcoming **electrostatic** repulsion between positively-charged particles (**Coulomb barrier**).

A chain of reactions effects fusion between protons, resulting in a helium nucleus (see *The nuclear Sun*, Box 1). The fusion of two protons into one **deuterium**, D or ^{2}H, nucleus (comprising one proton and one neutron), with the release of one **positron** and one neutrino, plays a central role: $p + p \rightarrow {}^2H + e^+ + \nu_e$. This reaction is a **weak interaction**, the relative rarity of which accounts for the Sun's longevity: 92% of solar neutrinos (so-called "primordial" neutrinos, ν_{pp}) are generated by this reaction, with an energy, however, not exceeding 0.420 MeV. The deuterium thus formed is quickly burnt, yielding one helium 3. In 85% of occurrences, two helium 3 undergo fusion, resulting in one helium 4 by release of two protons. In 15% of cases, one helium 3 fuses with one helium 4, yielding one beryllium 7. The beryllium 7 deexcites into **lithium** by way of an electron capture, (1) releasing one monoenergetic neutrino (ν_{Be}). However, very rarely, the beryllium 7 may also capture a proton, transforming into one boron 8, which **decays**, or disintegrates, while releasing a neutrino (ν_B) with a spectrum ranging up to 15 MeV (see Figure 1).

One difference should be emphasized, between the way the Sun functions and the fusion facilities developed by humans on Earth (see Chapter II): the applications, be they civil or military, make use of the fusion between deuterium and **tritium** nuclei, this being a **strong interaction** process, involving no direct release of neutrinos.

Curious neutrinos

For particle physicists, neutrinos are indeed elementary, just as **electrons** or **quarks**. They form part of the twelve building blocks of matter (see Box C). While our knowledge of neutrinos has greatly advanced of

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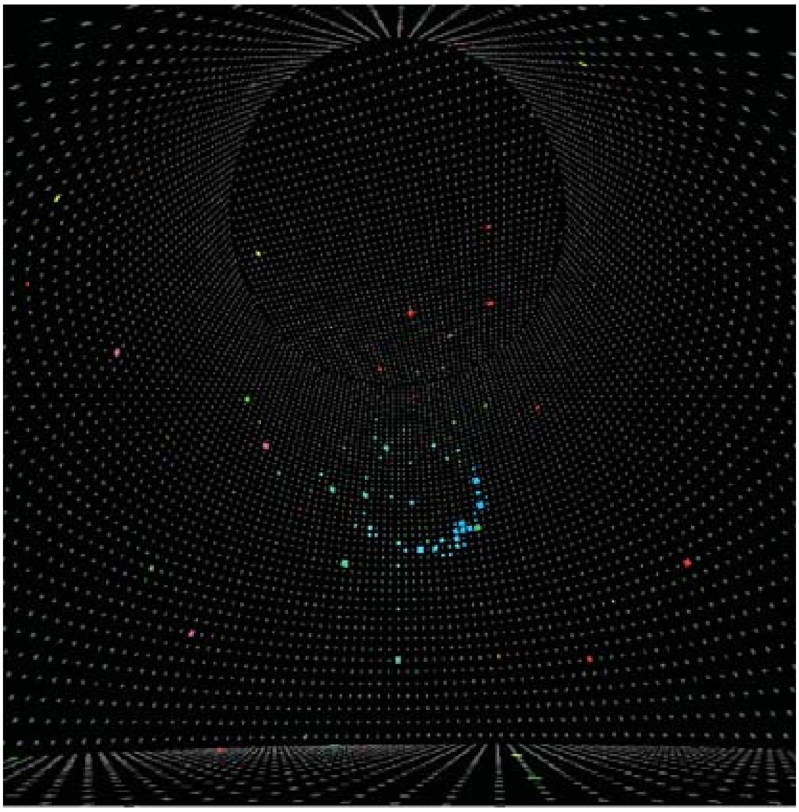
(1) Electron capture: capture of an electron, from the innermost shells of an atom, by a proton which transforms into a neutron, while releasing a neutrino.

late, their properties remain curious. Although physicists now know they have mass, their masses are so low it has not so far proved possible to measure them. One thing is certain: the mass of the heaviest neutrino is two million times smaller than the mass of the lightest particle, the electron. Having no electrical charge, neutrinos interact with matter only through weak interaction, in other words with a very low probability. Of 100,000 billion neutrinos going through the Earth, less than one is stopped. Neutrinos can thus escape quite freely from the Sun's core, by contrast to what happens with **photons**, and, eight minutes after being generated in a fusion reaction, pass through the Earth "inadvertently," so to speak.

Though exceedingly hard to trap, neutrinos play a very major part in the Universe. Vast quantities of them were created in the first few instants of the initial explosion, some 14 billion years ago. Every cubic centimeter in space contains slightly over 300 neutrinos, ten billion times the numbers of **nucleons**. Their mass, while it is too low to account for the missing mass in the Universe, is large enough for neutrinos to "weigh" as much as all of the stars that shine in it!

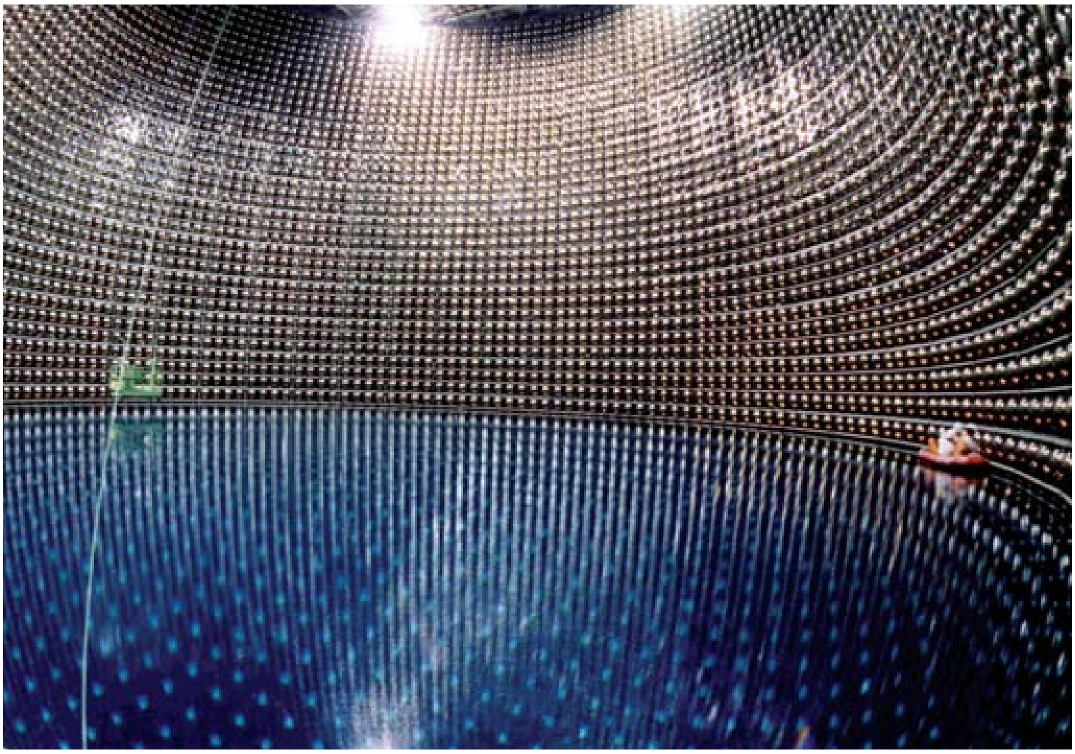
The hunt for solar neutrinos

When Raymond Davis set up, in 1968, the first experiment to detect solar neutrinos, he used an inverse b reaction, whereby a neutrino transmutes chlorine into argon: $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$. Five or six times a year, the argon 37 generated in the experiment would be purged by means of a flow of helium. This **radioactive isotope** decays with a **period** of 50 days, emitting a characteristic radiation. The probability for this reaction is very low, and it can only occur if the neutrino has an energy greater than 814 keV. Placing 615 tonnes of tetrachloroethylene (C_2Cl_4) at the bottom of the Homestake gold mine, in South Dakota (USA), Davis expected to detect one interaction a day. He detected one every three days only. This discrepancy between theory and observation is at the root of the solar neutrino puzzle.

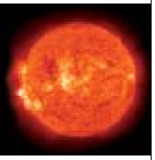

Kamioka Observatory/Tomasz Barszczak

View of an event recorded in 1998 by the Super-Kamiokande detector (having an energy of the order of 12.5 MeV). The color scale is a function of time.

The Japanese Kamiokande experiment, and the succeeding Super-Kamiokande experiment, confirmed, from 1988 on, that shortfall. In this case, the target

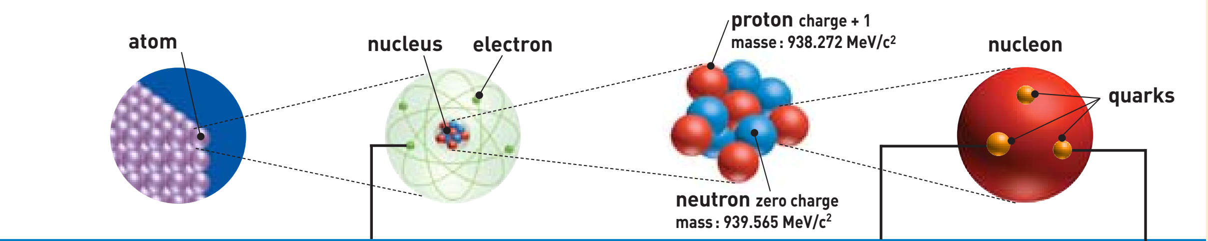

Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

The Super-Kamiokande detector.



C Elementary particles and fundamental interactions

Neutrinos are the stealthiest particles in the standard model of particle physics, the theoretical framework describing all known elementary particles and the fundamental interactions they mediate (see Table).
The basic constituents of matter, fermions, are partitioned into two main categories: leptons, which do not respond to strong interaction, and quarks, which are subject to all of the interactions. The six quarks form three pairs (up/down, charmed/strange, beauty/top). In the lepton category, the charged leptons (electron e^-, muon μ, tau τ) are involved in the electromagnetic interaction and the weak interaction, while neutral leptons (electron neutrino ν_e, muon neutrino $\nu\mu$, tau neutrino ν_τ) are only subject to weak interaction. In the standard model, neutrinos have zero mass, however experiments have shown they do have some mass, though very small, the exact value of which is as yet unknown. Involvement



		leptons able to move freely		**quarks** held captive in larger particles, they are not observed separately	
Fermions Common matter is made up of particles from this group.	first family	**electron** Responsible for electricity and chemical reactions. Charge: – 1. mass: 0.511 MeV/c²	**electron neutrino** Has no electric charge, and interacts very seldom with the ambient medium.	**down** Electric charge: – 1/3. The proton holds one, the neutron two. mass: 5 – 8,5 MeV/c²	**up** Electric charge: + 2/3. The proton holds two, the neutron one. mass: 1,5 – 4,5 MeV/c²
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	second family	**muon** A more massive companion to the electron. mass: 105,658 MeV/c²	**muon neutrino** Properties similar to those of the electron neutrino.	**strange** A heavier companion to "up." mass: 80 – 155 MeV/c²	**charmed** A heavier companion to "down." mass: 1 000 – 1 400 MeV/c²
	third family	**tau** Heavier still. mass: 1 777 MeV/c²	**tau neutrino** Properties similar to those of the electron neutrino.	**beauty** Heavier still. mass: 4 000 – 4 500 MeV/c²	**top** Heaviest in the family (observed in 1985): 180 times the proton mass. mass: 174 300 ± 5 100 MeV/c²
Vector Bosons Fundamental particles carrying out transmission of all natural forces.		**photon** Elementary grain of light, vector for the electromagnetic force.	**gluon** Bearer of the strong force between quarks.	**W±, Z⁰** W⁺ W⁻ Z⁰ Bearers of the weak force, responsible for some forms of radioactive decay.	
Higgs Boson?		Responsible for "electroweak symmetry breaking."			

Tableau.
Constituants élémentaires.

C (next)

of the various elementary constituents in the fundamental interactions is governed by their quantum numbers, or interaction charges (electric charge, color charge (1)...). To every constituent of matter is associated its **antiparticle**, a particle having the same mass and opposite charges. The **gravitational force**, which is not included in the standard model, acts on all fermions in proportion to their mass.

The table of elementary constituents of matter manifests another classification – independently from their involvement in fundamental interactions – into three generations, or families. From one family to the next, charged quarks and leptons having the same charges only differ by their mass. The electron, up quark and down quark, which all belong to the first family, are the lightest massive particles. They are stable particles, and the constituents of common matter. For instance, the **proton** is made up of two up quarks and one down quark; the **neutron**, of two down quarks and one up quark. Particles in the other two families are unstable, and rapidly decay into stable first-generation particles. This is why all the stable matter in the Universe is made up from constituents from the first family.

According to quantum mechanics, for an interaction to take place, at least one elementary particle, a **boson**, must be emitted, absorbed or exchanged. The **photon** is the vector for the electromagnetic interaction, the **W$^+$**, **W$^-$** and **Z^0** mediate the weak interaction, and **gluons** act as messengers for the strong interaction.

Quarks and charged leptons exchange photons, but conserve their electric charge after the exchange, the photon having no electric charge. Since the photon's mass is zero, the electromagnetic interaction's range is infinite. Having no electric charge, neutrinos are the only elementary fermions that are not subject to electromagnetic interaction.

In the electroweak theory (a unification of the weak and electromagnetic interactions), the weak interaction has two aspects: charged-current weak interaction, for which the interaction vectors are the W$^+$ and W$^-$; and neutral-current weak interaction, for which the mediator is Z^0. These two forms of weak interaction are active between all elementary fermions (quarks, charged leptons and neutrinos). The mass of these bosons being very large (80,000 MeV/c^2 for W$^\pm$, 91,180 MeV/c^2 for Z^0), the range of the weak interaction is tiny – of the order of 10^{-18} m. Since W$^\pm$ bosons have a nonzero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (flavor). Conversely, since the Z^0 boson has no electric charge, fermions exchanging one undergo no change in nature. In effect, neutral-current weak interaction is somewhat akin to exchanging a photon. As a general rule, if two fermions are able to exchange a photon, they can also exchange a Z^0. On the other hand, a neutrino has the ability to exchange a Z^0 with another particle, though not a photon.

Only those quarks that have a color charge exchange gluons, these in turn being bearers of a color charge. Thus, when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.

The graviton, the vector for gravitational interaction, has not so far been observed.

Theory predicts that another fundamental interaction mechanism exists, responsible for the mass of elementary particles, for which the messenger is the Higgs boson, which remains as yet undiscovered. This boson makes it possible to assign a mass to elementary fermions of zero mass that interact with it.

fundamental interaction	**messenger**	**actions**
gravitational	graviton?	responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic	photon	responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak	W$^+$, W$^-$, Z^0	the root cause of **thermonuclear fusion** inside the Sun, ensuring its longevity. β$^-$ and β$^+$ radioactivity, and reactions involving neutrinos are weak interactions
strong	gluons	ensures the cohesion of the atomic nucleus

Table.
Fundamental interaction and elementary constituents.

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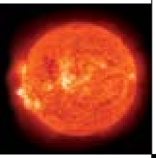
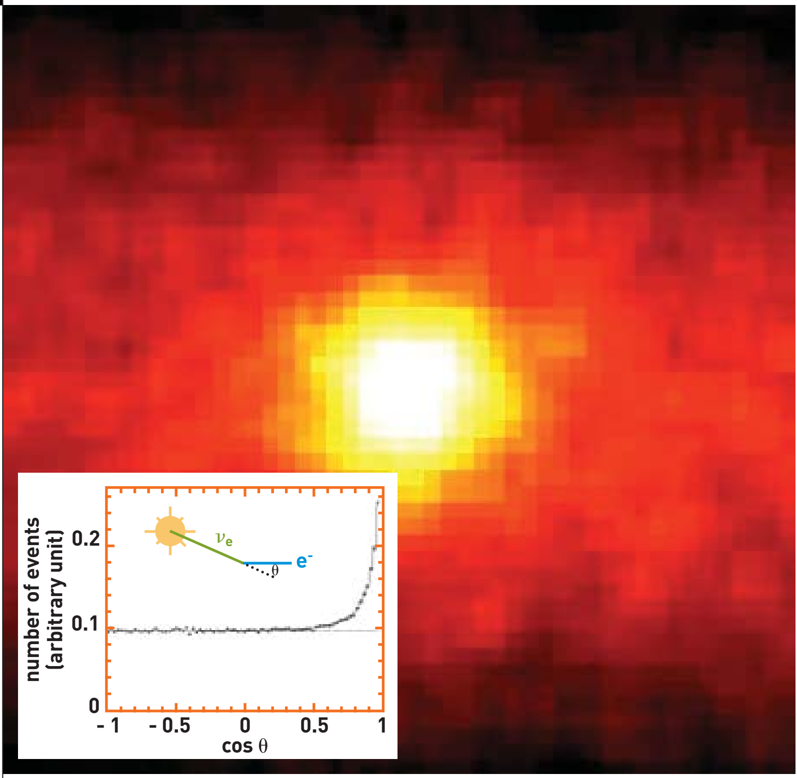
(1) Color charge: a quantum number that determines whether a particle is involved in strong interaction. The color charge can take on three values: "red," "green," or "blue" – such colors bearing no relation to visible colors. Every quark bears one of the three color charges, every antiquark one of the three anticolor charges. Gluons bear double color–anticolor charges (eight possible combinations).





Kamioka Observatory

Figure 2.
The neutrino Sun, and the Super-Kamiokande finding.
Interaction with a neutrino yields a recoil electron, retaining some memory of the initial direction. The signal from solar neutrinos thus stands out over and above an **isotropic** background noise in the histogram, being separated by angle θ (angle between electron path and Sun-Earth direction at the instant of interaction). Solar models, however, predict a signal, in the direction of the Sun (cos θ = 1), stronger than that measured, after 5.4 years' operation. Taking an "exposure time" of 1,496 days, it is now possible to reproduce such a "neutrography" of the Sun, even though fineness of detail is still anything but outstanding.

consisted in 2,100 tonnes of extremely pure water. That same detector captured, on 23 February 1987, a dozen neutrinos emitted in the Large Magellanic Cloud by **supernova** SN 1987a. Interactions of the ν_e with the water's electrons impart a certain momentum to the latter. The electrons thus set in motion radiate **Cerenkov light**, observed by an array of **photomultipliers** (2) set all around the tank. The direction taken by the electron yields information on that of the incoming neutrino, providing evidence that the neutrinos observed did indeed originate in the Sun (see Figure 2). Unfortunately, only neutrinos of over 4-6 MeV generate enough light to be detected in this manner. The findings corroborated, qualitatively at any rate, those arrived at by Davis: the neutrino flux observed was about one half of the predictions from the standard model of the Sun.

These two very neat experiments did labor under one small shortcoming: the neutrinos observed essentially came from the nuclear reactions involving, in the Sun, beryllium and boron (see *The nuclear Sun*, Box 1). They did not detect the primordial solar neutrinos, whose energy was too low to show up in their detectors. Herein indeed lay the solar neutrino puzzle, however it could be this only concerned neutrinos generated at the end of the chain of nuclear reactions, not "primordial" neutrinos. Now, it was widely known that prediction of the flux of such energetic neutrinos is particularly tricky.

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(2) Photomultiplier: a device, used in particular in nuclear physics, industry and medical imaging, having the property of converting light into an electrical signal, comprising a photoemissive cathode associated to electron multipliers.

Behind the scenes with Gallex

1

GNO

Chemical extraction of germanium 71 from the gallium-chloride target solution, prior to conversion of the germanium chloride into germanium hydride, during the Gallex experiment.

In the Gallex experiment, gallium is in the form of a chloride solution, mixed with a large quantity of hydrochloric acid, contained in a cylindrical, 8-m by 4-m, tank. The germanium produced is also in the form of a chloride, this having the property of being highly volatile in the presence of hydrochloric acid. Every two or three weeks, the experimenters pass through the tank several thousand cubic meters of nitrogen, bubbles of which will entrain the germanium-chloride molecules, ready to escape as they are. A trap, in the form of a simple column containing small circular glass strands, is positioned at the tank outlet, to retain the chloride; pure water is circulated through this, from top to bottom, while the nitrogen, with its precious germanium charge, circulates from bottom to top. The pure water captures the germanium chloride, allowing the nitrogen to escape.

The second step consists in converting the germanium chloride into germanium hydride (GeH_4). This gas is then put into a small *proportional* counter, where the **decay** of germanium through electron capture leaves a highly characteristic electrical signal. Each counter is left for several months inside its lead shield, itself placed inside a Faraday cage, where parasitic radiation is kept to a minimum. Veritable hand-cut, hand-crafted gems, these small counters are subjected to ruthless selection, only the best-performing being retained, inducing least parasitic noise.

In order to settle the issue, new experiments were then set up.

Gallex, a "primordial" experiment

To detect "primordial" neutrinos, the most numerous, though the least energetic, scientists found just one sensitive element, gallium. Two experiments using this were put together in the late 1980s, Gallex and Sage. A Russian-American collaboration, Sage was set up in an underground laboratory in the Caucasus. Gallex brought together physicists from Europe (Germany, France and Italy), the United States and Israel. Its target consisted in 30 tonnes of gallium. When solar neutrinos interact with this element, they transform one of its isotopes, gallium 71, into a germanium isotope having the same atomic number: $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$. The neutrinos' energy need only be greater than 233 keV for the reaction to be possible. This threshold, much lower than their 420-keV energy, meant a large part of the ν_{pp} became detectable. A radioactive isotope, germanium 71 decays with a period of 11.4 days.

After exposing the gallium to solar neutrinos for several weeks, the germanium atoms produced first had to be recovered, then their decay observed (see Box 1). Given the gallium mass involved, and theory, researchers expected solar neutrinos to yield just over one germanium atom a day.

The experiment was put underground in the Gran Sasso laboratory (Italy), set mid-way along the motorway tunnel crossing the Apennine Mountains, thus shielding the experiment from **cosmic rays** (mainly **muons**), capable of producing the very same germanium atoms.

From the first day of its operation in 1991, the Gallex experiment, known nowadays as GNO (Gallium Neutrino Observatory), recorded solar neutrino interaction. Drawing up the balance of short-lived germanium-71 atoms found, the outcome only amounted to 54 ± 6% of the neutrinos predicted by computations. The Sage experiment, operating on a very similar principle with 56 tonnes of metallic gallium, came up with the same finding.

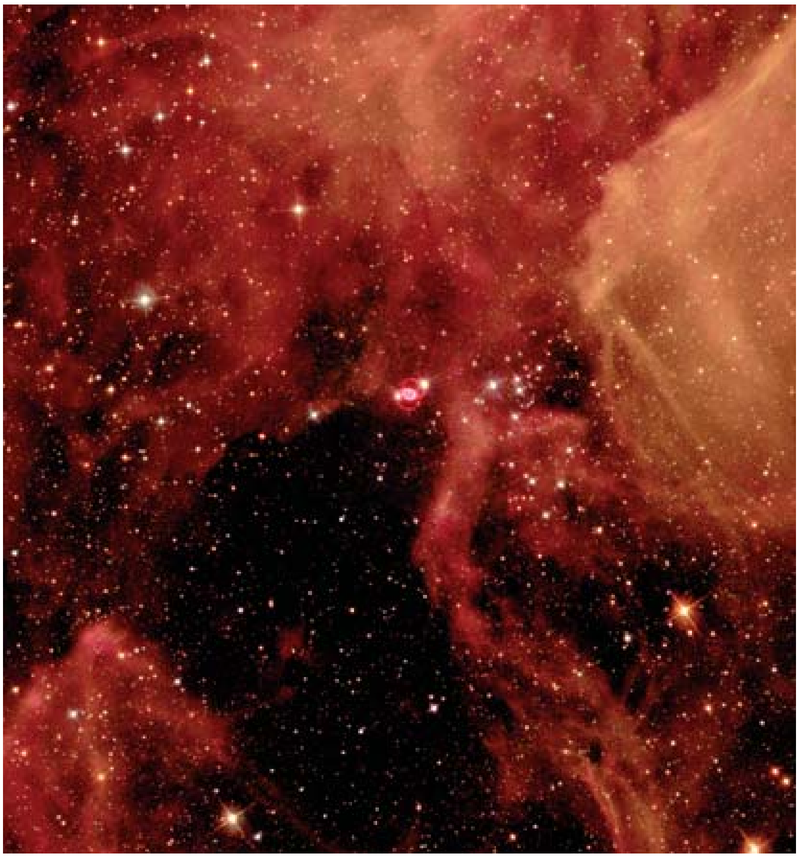
While the principle remained quite simple, extracting homeopathic doses of a few atoms from a tank holding several tonnes of fluid (10^{30} atoms) represented a real feat. At the time, there were some grounds for skepticism, as regards this finding. It was thus essential for the experimenters to "validate" it. Gallex was the first solar-neutrino experiment to achieve this, in the summer of 1994. All that was required, for this purpose, was to expose the detector to an artificial neutrino source whose flux was precisely known - a small "artificial Sun."

An artificial neutrino Sun

The Sun is not easily mimicked... even if one is content with emulating its neutrino light (accounting for less than 1% of the Sun's total emitted power). Researchers, however, do have one advantage: they have the option of bringing their surrogate Sun as close as they wish to the detector. One disadvantage also, however: they have no way of switching off the Sun, while they carry out their measurement. The signal from the replica must be much stronger than that from the original. The source's activity, expressed in **becquerels** (disintegrations per second), has to be a few tens of million-billions per second, i.e. several petabecquerels (PBq) strong. Such an activity would be fearsome, were it not neutrinos that are involved, the most inoffensive particles around. To fabricate such a source, a chromium isotope, chromium 51, was selected. As it decays, this emits virtually only neutrinos with an energy, at 750 keV, close enough to that of neutrinos from the Sun. Chromium 51 was obtained by irradiating chromium with neutrons, this being carried out in the core of the Siloé reactor, in Grenoble (France).

The source would then be introduced into the well set into the center of the Gallex tank, irradiating the gallium target with ten times more neutrinos. After three and a half months, its power, inexorably waning with a 40-day period, would only be equal to that of the Sun, as received on Earth. The source would thus have generated several hundred germanium-71 atoms. 11 germanium-extraction and counting operations would then be carried out, in identical fashion to what was done for solar neutrinos.

Drawing up the balance of atoms observed, referred to the numbers expected (considering the source's activity), agreement was impressive: the ratio was 0.97, with a 10% error. The artificial Sun had met its designers' expectations: the Gallex finding was validated, meaning the solar-neutrino deficit, while indeed real, may not be attributed to some deficiency in the experiment. There remained to adduce an interpretation for this.



NASA/The Hubble Heritage Team (STScI/AURA)

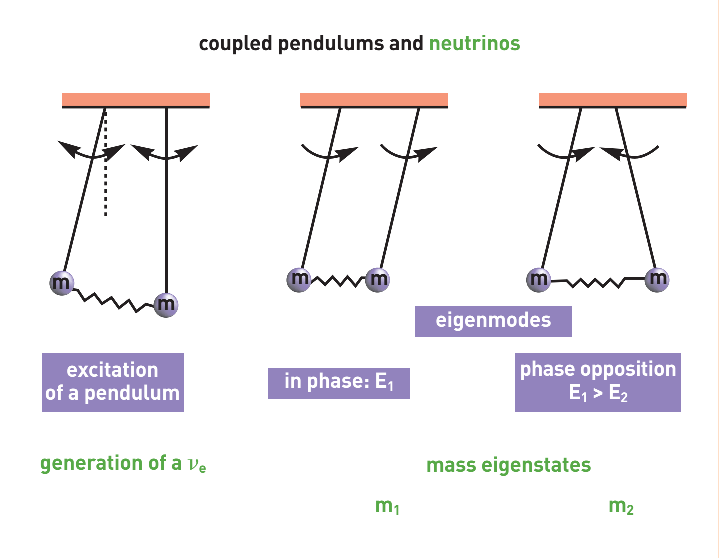
SN 1987A, in the Large Magellanic Cloud, as seen by the Hubble Space Telescope. The Kamiokande detector caught, on 23 February 1987, a dozen neutrinos from this supernova's emissions.

Coupled pendulums and the MSW effect

2

The MSW effect (from the names of physicists S. P. Mikheyev and A. Y. Smirnov, both from Moscow, and L. Wolfenstein, from Pittsburgh) is hardly easily grasped, as is the case with any quantum phenomenon. A macroscopic mechanical phenomenon may be used, however, to illustrate - however imperfectly - this mechanism, of an oscillation perturbed by matter, as brilliantly propounded by US physicist Steven Weinberg: coupled pendulums.

Two pendulums are connected by a spring (assumed to be non-material). In the classical experiment, excitation of the sole right-hand pendulum will propagate to the one on the left; the first pendulum slows down, and even stops oscillating, then starts moving again even as the second pendulum's amplitude decreases, and so on. One sees energy being transferred from one pendulum to the other: it oscillates. Such a system has two "eigenstates," one for which the oscillations of both pendulums are in phase (E_1), and the mode where there is phase opposition (E_2).



Neutrinos propagating in a vacuum are likewise best described in terms of their eigenstates, designated ν_1 and ν_2, these each having a well-defined mass (energy), m_1 and m_2. The MSW effect occurs when neutrino propagation takes place in dense matter, having a density varying along the propagation path. This can alter quite strongly the oscillation observed in a vacuum.

In our analogy, the pendulums are now subjected to coupling that may be varied. Very strong coupling entails that setting one pendulum in motion instantly induces motion in the other, i.e. excitation is according to mode E_1 (in phase). This is the condition prevailing in the Sun's center, where the electron neutrinos are generated.

The stiffness of the spring now decreases; according the rate of change, the state of the pendulums will not be the same. The rate at which spring stiffness wanes and pendulum period should be close, for the analogue of the MSW effect to be as effective as possible in the coupled pendulums. One finally gets a spring so weak that it no longer fulfils its coupling role, allowing each pendulum to oscillate as if it were free, while retaining however the memory of the oscillation mode imposed by their earlier common state. Such uncoupled oscillations are the analogue of neutrino propagation in a vacuum.

Solar neutrinos generated in the Sun's center, where density stands at 150 g/cm^3, pass through layers of matter having densities that decrease almost exponentially $[\rho(R) = \rho_0 \cdot e^{-R/L}]$, before continuing their journey in vacuum till they reach the Earth. If the oscillation length from one neutrino species to another, which is solely dependent on $E_\nu/(m_1^2-m_2^2)$, is close to the distance L characterizing density diminution, the MSW effect practically transforms a ν_e into a ν_2 as it exits the Sun.

When neutrinos are counted in Earth-based detectors, only that fraction of the ν_e which is held in eigenstate ν_2 is picked up.

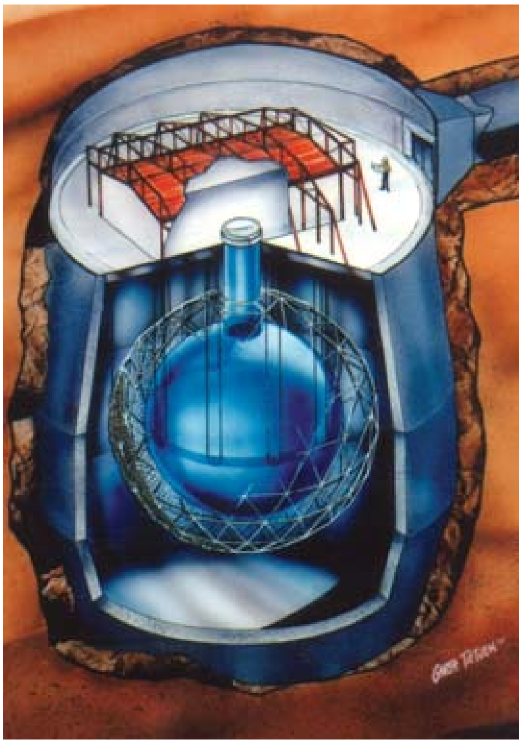
The new puzzle

The primordial fusion reaction between two protons is intimately bound up with the Sun's energy generation and luminosity. It initiates all the other nuclear reactions. When interpreting the makeup of the signal observed by Gallex, consideration must first be given to these "primordial" neutrinos, as a principle of economy, owing to the fundamental character of the pp reaction. In this respect, Gallex may legitimately be claimed to have been the first to detect "primordial" neutrinos from the Sun. It is indeed fusion of two protons into one deuterium that enables stars to function. As regards the Sun's luminosity, this reaction already accounts for a large component in the Gallex signal.

The chlorine, Kamiokande, Gallex and Sage experiments had all found a large shortfall in solar neutrinos. At the same time, developments in helioseismology showed that astrophysicists were getting right their understanding of the Sun. It appeared the solution of the puzzle would have to be sought for in something else than the way the Sun functions. Hence, researchers went on to address the properties of neutrinos.

Neutrino oscillations and the MSW effect

Of the twelve basic building blocks of which matter is made up, three are neutrinos: the electron neutrino ν_e, the muon neutrino ν_μ, the tau neutrino ν_τ (see Box C). Inside the Sun, only electron neutrinos are generated. Now, solar-neutrino detectors, at the time, were only sensitive to that one species of neutrino. If the ne made inside the Sun transform into their ν_μ or ν_τ cousins, then the detectors would show fewer neutrinos than expected.


SNO

Artist's impression of the Sudbury Neutrino Observatory detector.

Now, if neutrinos have mass, theory predicts they will have the possibility of "oscillating" over time, i.e. a neutrino starting off as ν_e may, after travelling a certain distance, mutate into nm or nt. Terming this an oscillation is warranted by the fact that the ν_μ and ν_τ will, in turn, be able to transform back into ν_e. The probability for the phenomenon depends on a number of the neutrinos' characteristics, in particular their energy, and mass. In 1986, this theoretical possibility was bolstered by discovery of the MSW effect (see Box 2). This effect takes into account the neutrinos' travel within solar matter itself, where a number of phenomena may occur, amplifying this oscillation. This was a highly plausible solution for the solar-neutrino problem, accounting at the same time for the various and different deficits observed. For the experiments were sensitive to neutrinos of diverse energies, these being subject in varying fashion to the oscillation phenomena. What experiment would be liable to provide incontrovertible evidence that the neutrino oscillation mechanism does indeed operate inside the Sun? The MSW effect entails three consequences that are specific, and spectacular: the presence of other neutrino species, originating in the Sun (the MSW effect transforms some ν_e into ν_μ or ν_τ, which none of the nuclear reactions inside the Sun can yield); a possible distortion of the boron-neutrino energy spectrum; and the day-night effect, whereby, paradoxically, the Sun is "brighter" in terms of ν_e (electron neutrinos) by night than by day.

Detection of flavors by the SNO experiment

It was then becoming increasingly apparent that some of the solar neutrinos do indeed take on the guise of other members of the family, thus becoming undetectable. The oscillation mechanism thought up by the theorists did make sense. There remained to make it manifest. An experiment was set up in Canada, to test the hypothesis.

The Sudbury Neutrino Observatory (SNO) was constructed more than two kilometers below ground, in a nickel mine near Sudbury (Ontario). Inside a 22-meter diameter, 34-meter tall cavity, the detector consisted in 1,000 tonnes of heavy water,(3) contained in an acrylic-plastic vessel surrounded by ultra-pure common water. In this volume, no fewer than 9,600 detectors picked up the small jets of light caused by neutrinos being stopped, or scattered.

Using heavy water as it did, the experiment was able to measure the number of electron neutrinos generated in the Sun's core reaching the Earth, as had the previous experiments, however it also had the capability to evaluate independently the overall number of neutrinos (see Figure 3). This exceptional functionality enabled determination of the issue, whether neutrinos generated in the Sun's core do mutate as they travel to the Earth.

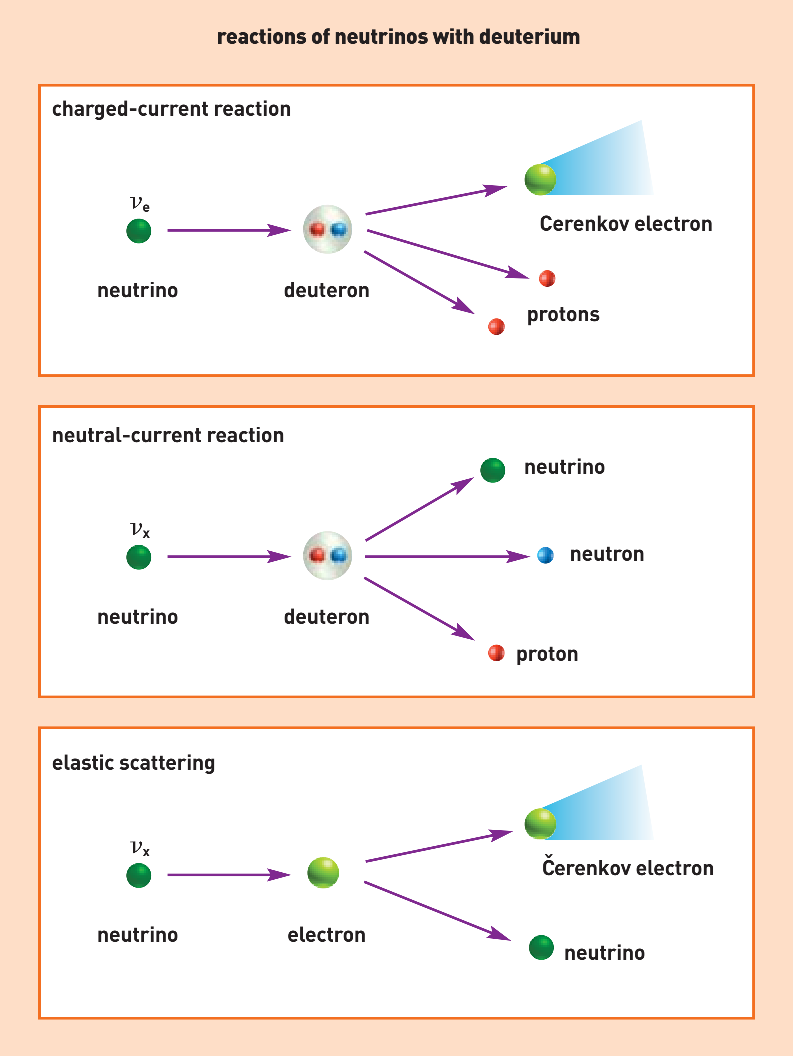


Figure 3.
The reactions used at the Sudbury Neutrino Observatory (SNO). The first one yields the energy spectrum for electron neutrinos only; the second one allows measurement of the overall flux of solar neutrinos from boron-8 decay; the third one, sensitive to all three neutrino types, though mainly to electron neutrinos, shows strong directional sensitivity.
Note: neutrino and electron size is considerably exaggerated, relative to the size of protons, neutrons and deuterons (deuterium-atom nuclei).

In May 2001, SNO confirmed, once again, the deficit in electron neutrinos observed. Further, thanks to specific reactions with the deuterium atoms in the target, it was able to detect all three neutrino **flavors**, by way of a so-called "**neutral current**" reaction. The findings were impressive: the three flavors of neutrinos were detected, originating in the Sun, in accordance with expectations if oscillation is the case. They established, incontrovertibly, that solar electron neutrinos do spontaneously transform into muon and tau neutrinos, even as they journey from Sun to Earth.

The end of the puzzle

In September 2003, the same experiment refined its measurement of the overall neutron flux from the Sun. Addition of highly purified common salt (NaCl) to the heavy water enhanced its sensitivity to the other neutrino species. The finding, astounding in its precision, was that the flux of all flavors of neutrinos reaching the Earth matches, to within less than 15%, that predicted from solar models, for boron neutrinos.

Once that experiment came through, there was no solar-neutrino puzzle left. Those missing in one spe-

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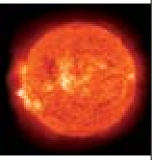
(3) Heavy water: water having its hydrogen (^{1}H) substituted with the isotope **deuterium** (^{2}H).



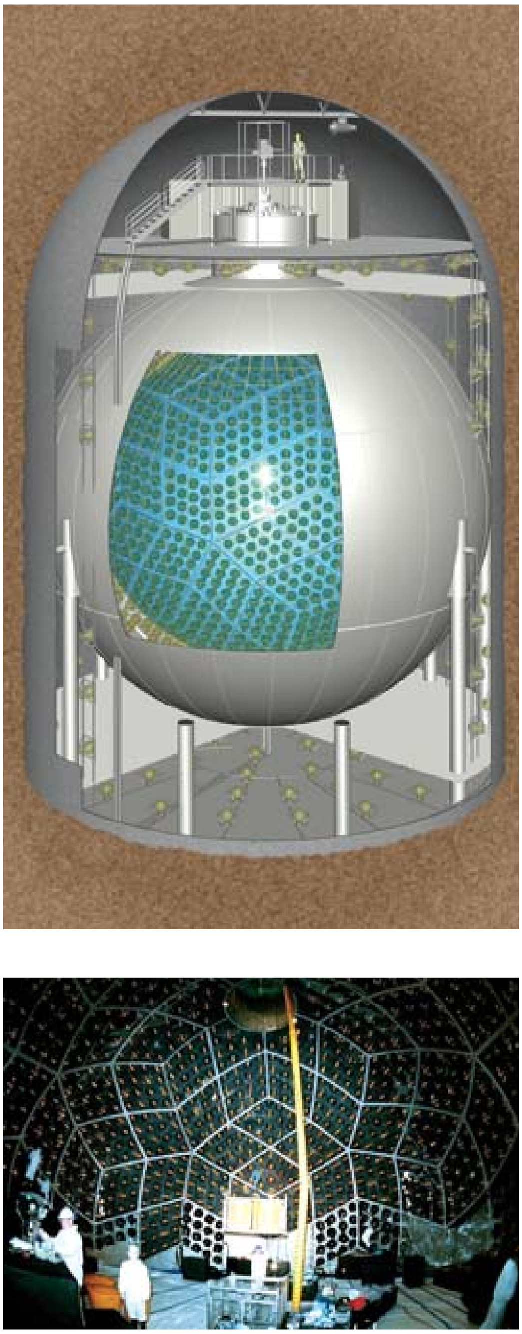
cies are indeed to be found in the others, and overall numbers of neutrinos, taking all species together, show very good agreement with predictions for the solar machinery, made over thirty years earlier. A few ambiguities remained to be sorted out, however, regarding neutrino masses.

Confirmation from the KamLAND experiment

One final finding, again from Japan, would resolve these last remaining ambiguities. The KamLAND experiment is an underground detector consisting in about a thousand tonnes of **liquid scintillator**. (4) It does not count solar neutrinos (for the time being, at any rate), rather it counts **antineutrinos** emitted by Japanese nuclear reactors, sited at a mean distance of 180 km from it. In December 2002, for the finding from the initial 142 days' counting, there could be but two possibilities: either a reading of 85 detections, for massless, non-oscillating neutrinos, or considerably fewer for neutrinos having a slight mass, and thus having the ability to mutate from one species into another, as observed in the solar-neutrino experiments. The experiment came up with a count of 52 interactions, an outcome matching one of the possible oscillation solutions, very stringently narrowing down the range for the neutrinos' mass parameters.

Hans Mehlin/The Nobel Foundation

The King of Sweden awards the 2002 Nobel Prize for Physics to Raymond Davis. Fellow prizewinners Masatoshi Koshiba and Riccardo Giacconi can be seen in the front row of spectators, at left.



KamLAND/Stanford University

A model (top) of the entire detector complex for the KamLAND experiment.
Bottom: a view inside the detector, as the photomultiplier tubes were being installed.

Why such lightness?

By way of a happy ending to this great story, it was with shared delight that, in October 2002, the small solar-neutrino community heard that the Nobel Prize for Physics had been awarded to Raymond Davis and Masatoshi Koshiba, the two pioneers in this investigation, thus crowning nigh on forty years' research work. Thus, coming out of these incredibly subtle experiments, carried out on every continent, as the outcome of theoretical calculations drawing on knowledge from all branches of physics, thanks to fruitful collaborations and healthy rivalry between scientists speaking a variety of languages, but urged on by a common goal, an impressive tally may be set out:

- neutrinos generated in reactions in the Sun's core are indeed observed on Earth. This is direct evidence that understanding by physicists is correct, as to how the nuclear fusion of hydrogen can constitute the energy source in the Sun, as in **main-sequence** stars similar to it;
- solar models do account for, and reproduce, all observations of the Sun, be it of the various acoustic oscillation modes measured on the surface, or of the more energetic - but the more marginal, in terms of energy production - neutrinos. The temperature at the Sun's center is now known to within better than 0.5%!
- one certainty has been gained: neutrinos do oscillate, transforming from one species into another; which can only happen if these particles have mass, contrary to what had been assumed earlier.

This, however, brings up a new mystery in turn: why are neutrinos so light, compared to the other nine fundamental particles of matter? What theoretical mechanism can be adduced to assign such a mass to them? What window is such minuteness for the neutrinos' mass easing open for us?

> **Michel Cribier**
Physical Sciences Division
CEA Saclay Center

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(4) Liquid scintillator: an organic liquid containing aromatic benzene nuclei that are excited by electrically-charged particles passing through the liquid. The nuclei then emit photons, making the particle's path visible, in numbers yielding information as to the particle's energy.

A Spotlight on the Sun

The largest object in the solar system, the Sun accounts for some 99.8% of its total mass. Initially consisting in over 70% hydrogen and more than 25% helium, the Sun is a huge rotating gas ball.

The Sun's internal structure comprises four distinct regions (see Figure). The core, where the prevailing temperature and density conditions are extreme, is host to numerous nuclear reactions, turning hydrogen into helium. The energy released will end up as visible light at the surface.

In the radiative region, extending from the core to a distance equal to 0.71 of the solar radius, energy is transported to the Sun's surface through photon-matter interaction (radiative transport). Photons are absorbed and re-emitted millions of times in countless collisions with the atoms they encounter, which are highly ionized. It takes over one million years for photons to reach the tachocline, which is a thin transition layer, between the radiative and convective regions, that plays an essential part in the solar magnetic field.

In the convective region, owing to the lower temperature, the environment, consisting in partly-ionized atoms and neutral atoms, is more opaque. The photons' progression becomes arduous. Moreover, local density varies by a factor of one million between base and surface. Such steep temperature and density gradients cause convective motions that are observable on the surface, such as the granules (with a life span is of the order of a few minutes), or the supergranules, with sizes of the order of 1,000 km and 35,000 km respectively.

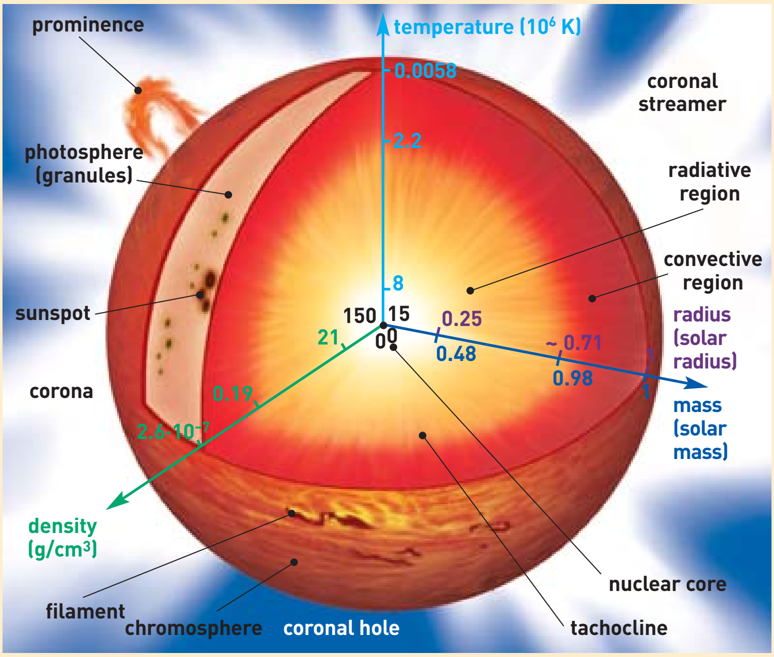

Figure.

The solar atmosphere comprises four regions (see Figure). The surface, or photosphere, only some 400 km deep and with a temperature close to 5,800 K, thus presents a granulated aspect, featuring more or less dark areas. Darker areas, known as sunspots, occurring singly or in clusters, are at a temperature of 3,800 K. They appear to be black, owing to the difference of temperature with adjoining areas. They are subject to an 11-year cycle, and are associated to regions where the magnetic field is much more intense (several thousand gauss) than for the Sun as a whole (1 gauss). These sunspots may reach a diameter of 50,000 km. They can last from a few days to several months. Lighter, hotter areas, known as faculae, which may occur in isolation, but are as a rule located around clusters of sunspots, may also be observed.

Beyond the photosphere, extending for thousands of kilometers, is the chromosphere, where density goes on falling off rapidly, while temperature reaches 20,000 K. In this region are to be found plages, bright regions characteristic of the strong magnetic fields occurring with sunspots, prominences, or filaments (when seen against the Sun's disk), magnetic structures that are denser and cooler (10,000 K) than the surrounding medium, and spicules, small, short-lived (5-10 minutes) jets of matter shooting out towards the corona, at velocities of up to 20 km/s.

Between the chromosphere and corona lies the transition region, a thin, irregular layer where temperature rises abruptly.

The corona, where gas is rarefied, reaches out for millions of kilometers, and is characterized by a temperature of over 1,500,000 K, and low density. It features numerous magnetic structures, or structures associated with magnetic structures, such as coronal loops, coronal holes, bright points... In this constantly-changing region, the prominences, or filaments, appear as huge plumes of hot gases, originating in the chromosphere.

Solar activity is not constant. Repeatedly, and with intensities that are cyclical, violent eruptions occur in the active regions. These are sudden releases of high-energy particles into the interplanetary environment. Such coronal mass ejections (CMEs) may on occasion attain a height of 100,000 km, for a length of 200,000 km. According to the direction in which they are ejected, the high-energy particles thus released may interact with the Earth's atmosphere.

The Sun also expels a constant flow of charged particles, mainly protons and electrons, forming a plasma, the so-called solar wind. This propagates right out of the solar system, with a velocity of some 450 km/s. The Sun thus depletes itself by about one hundred thousand-billionth of its mass every year.

B Tell-tale spectra

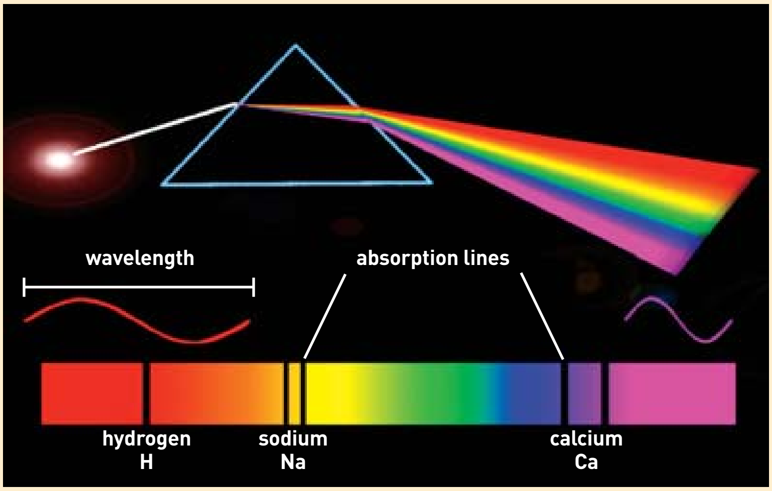

Figure a.

The various categories of radiation are distributed across the electromagnetic spectrum according to their wavelength, from the shorter, more energetic wavelengths (gamma radiation) to the longer ones (radio waves) through visible light. The spectrum of the latter domain, for instance, may be obtained by passing light through a prism, which decomposes it into its various components, from red to purple (see Figure a). A rainbow likewise exhibits a spectrum of the visible light emanating from the Sun, through refraction in, and reflection on, water droplets.

The same principle is applied for the whole range of electromagnetic radiation, through the use of spectrographs, which analyze the spectral energy distribution of such radiation, and spectrometers, which record each component of the spectra by means of photoelectric sensors and measure radiation intensity, plotted against wavelength.

In astrophysics, spectroscopy consists in the remote investigation of bodies from the radiation emitted by them, or the alterations induced in that radiation as it encounters other bodies in its path. Spectra exhibit, between wide, continuous bands (each of which is termed a spectral continuum), discrete lines, each corresponding to a specific wavelength and, ultimately, to an energy level of an atom or molecule in the body observed. These spectral lines are of two types, emission lines and absorption lines.

Bright emission lines correspond to radiation directly emitted by a body heated to a very high temperature. An emission spectrum thus allows detection of the presence of certain atoms or molecules in the emitting body.

Dark absorption lines also correspond to a specific wavelength, this being due, however, to the process whereby a radiation's intensity decreases as it goes through a material medium, to which it transfers all or part of its energy. Thus, the composition of a hot, radiating source such as the Sun may be analyzed from the absorption by its atmosphere of part of the electromagnetic radiation emitted (absorption spectrum).

Matters do not end there: analysis of spectral shift allows the relative motion of the emitting body to be estimated, thanks to the Doppler effect, (1) on the selfsame principle whereby the sound of an approaching vehicle gets higher-pitched, and lower-pitched for a receding vehicle. The apparent change in frequency (higher even as wavelength is shorter) is thus proportional to the relative velocity of observer and source. For a light source, this effect implies that lines in that source's spectrum will be shifted towards blue (blueshift), i.e. to shorter wavelengths, if it is approaching, or towards red (redshift), corresponding to longer wavelengths, if it is receding (see Figure b).

The Doppler effect is used in astrophysics, particularly to establish the radial velocity of stars or galaxies, for their perspective motion causes a shift in the lines emitted, relative to their nominal positions, or compared to the same lines emitted by a terrestrial source.

Finally, the splitting of spectral lines induced by a magnetic field (*Zeeman effect*) is used to measure the intensity of the magnetic fields associated to astronomical objects, the Sun in particular.

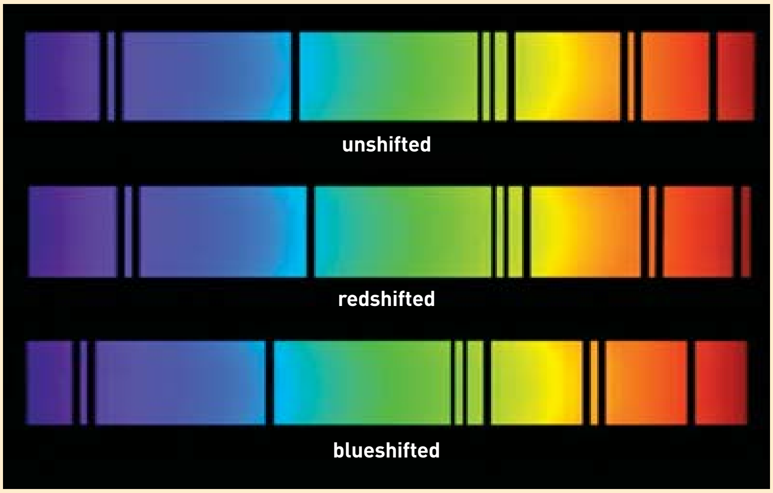

Figure b.

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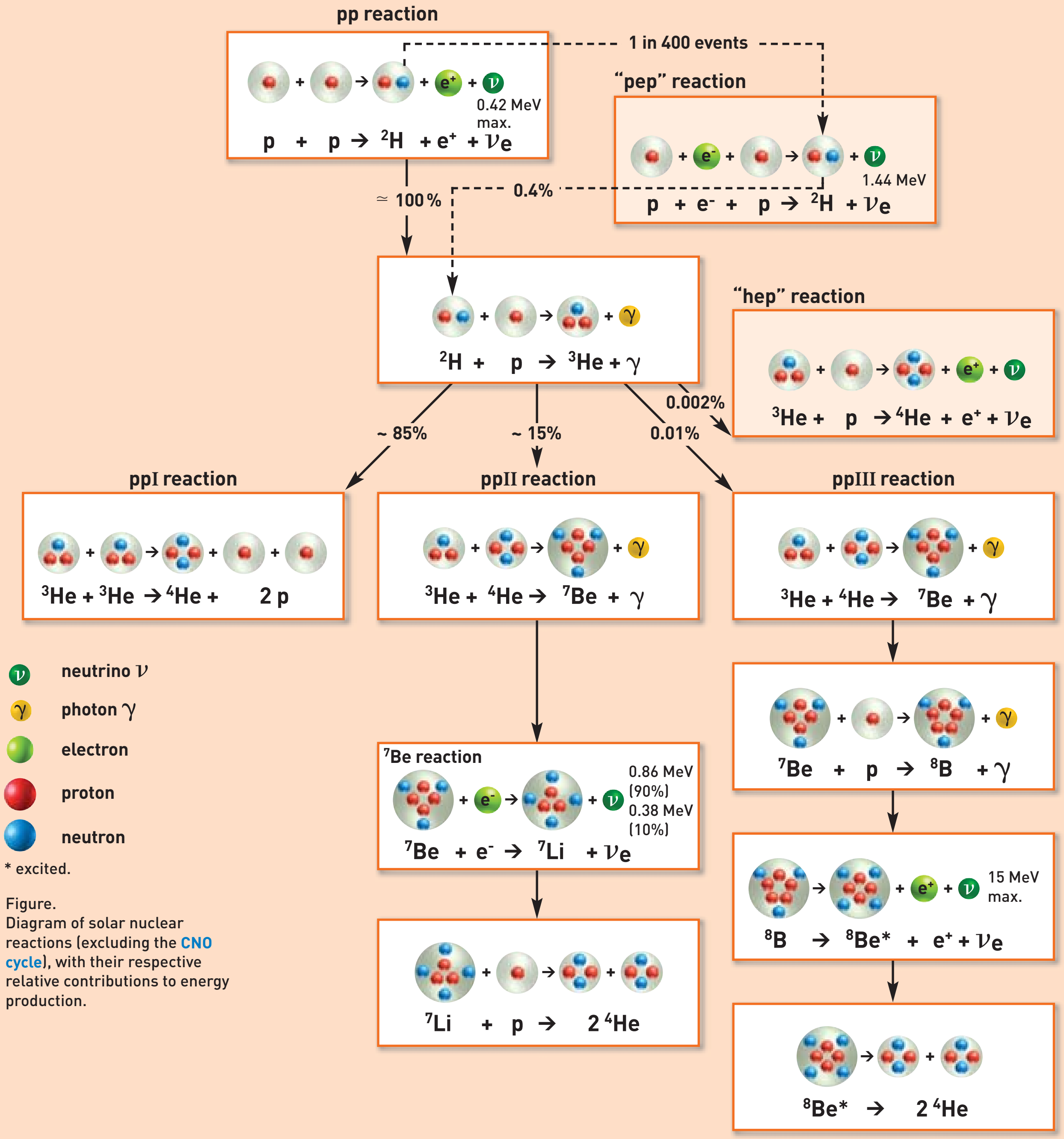
(1) Or, more accurately, Doppler-Fizeau effect. Discovered by Austrian physicist Christian Doppler for sound waves, the effect was extended to optics by French physicist Hippolyte Fizeau.

Solar nuclear reactions



pp reaction

$p + p \rightarrow {}^2H + e^+ + \nu_e$

0.42 MeV max.

1 in 400 events

“pep” reaction

$p + e^- + p \rightarrow {}^2H + \nu_e$

1.44 MeV

≃ 100 %

0.4%

$^2H + p \rightarrow {}^3He + \gamma$

“hep” reaction

$^3He + p \rightarrow {}^4He + e^+ + \nu_e$

0.002%

~ 85%

~ 15%

0.01%

ppI reaction

$^3He + {}^3He \rightarrow {}^4He + 2\,p$

ppII reaction

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

ppIII reaction

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

15 MeV max.

$^8Be^* \rightarrow 2\,{}^4He$

^{7}Be reaction

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

0.86 MeV (90%)
0.38 MeV (10%)

$^7Li + p \rightarrow 2\,{}^4He$

neutrino ν
photon γ
electron
proton
neutron

* excited.

Figure.
Diagram of solar nuclear reactions (excluding the CNO cycle), with their respective relative contributions to energy production.

$$4\,p + 2e^- \rightarrow {}^4He + 2\,\nu_e + 27\ \text{MeV}^{(1)}$$

The nuclear reactions start off with the fusion of two protons, and end in production of helium 4, one chain being by way of helium 3, the other by way of beryllium 7, this being followed, according to the reaction, by production of further light elements (lithium 7, or beryllium 8 by way of boron 8). These proton–proton reaction chains are known as ppI, ppII, and ppIII (see Figure).

In the initial basic reaction, one of the two protons transforms into a neutron through weak interaction. Conjunction of the two particles gives birth to a variety of hydrogen, deuterium (D, or ^{2}H), whose nucleus thus comprises one proton and one neutron; at the same time, one anti-electron, or positron, and one low-energy (electron) neutrino are released.

The deuterium nucleus captures a proton, yielding a helium 3 nucleus and a gamma photon. Two helium 3 nuclei react to produce one helium 4 nucleus, releasing two protons, thus available to initiate a new chain. In some 85% of instances, such is the end of the **ppI chain**. This chain is prolific in neutrinos: some 65 billion of these pass through every square centimeter of our skin in any second. However, these low-energy neutrinos are hard to detect. It took all the sensitivity of the Gallex detector and similar devices to record them (see *Solar neutrinos: a puzzle finally solved*).

In the 15% of remaining instances, one helium 3 undergoes fusion with one helium 4, yielding one beryllium 7 and one gamma photon. Then, either the beryllium 7 transforms into lithium 7 by capturing an electron, this lithium 7 in turn capturing one proton to yield two helium 4 nuclei directly (**ppII**); or, by capturing one proton, the beryllium 7 yields the same outcome indirectly, by way of boron 8, this disintegrating, with the release of a high-energy neutrino, into beryllium 8, which instantly breaks up into helium 4 (**ppIII**).

The **ppIII** chain thus ends with the disintegration of boron 8 into beryllium 8, this yielding high-energy neutrinos, greatly prized by solar-neutrino hunters.

Reaction rates inside the solar plasma must be corrected for the screening effect of free electrons (see *Static and dynamic views of the solar interior*).

The energy generated in the guise of gamma rays goes to keeping the solar furnace hot, thus precluding it from collapsing, and to making it shine. This energy, in the guise of photons, filters through to the surface. It is scattered, absorbed, re-emitted by ions and electrons. The neutrinos alone pass right through the Sun, in a straight line, this taking some two seconds.

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(1) This is an averaged value for energy.