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High Noon for Solar Neutrinos

by John Bahcall

Fewer neutrinos reach the Earth than particle physicists predict. Are their theories wrong or do we know less than we thought about the Sun?

In attempting to understand how the Sun shines, physicists and astronomers have been unexpectedly confronted with a mystery: the case of the missing neutrinos. These exotic particles, produced in the Sun, have been observed in an experiment that has been running for a quarter of a century at the bottom of a gold mine. But fewer neutrinos have been detected than standard theories predict. There are two possible reasons for this. Astronomers could be wrong about the way the Sun works. Or physicists may need to rethink their theories of how weakly interacting particles behave. The discrepancy has generated a flood of theoretical proposals and several new experiments to test these ideas. The latest, which many hoped would provide the definitive answer, has added yet another twist to the tale.

Physicists and astronomers believe that the Sun shines because of the conversion of hydrogen nuclei (protons) to helium nuclei (alpha particles) in the solar core (see Figure 1a). In the process, positive electrons (positrons) and neutrinos (v) are also produced along with about 25 million electronvolts (MeV) of thermal energy for every four protons burned; one electronvolt is the energy an electron acquires by passing through a potential of one volt. About 600 tonnes of hydrogen are converted to helium every second in the Sun's central regions, providing the energy that we know as sunlight and making life on Earth possible.

The standard model of how the Sun works is constructed with the aid of a computer from the most accurate data concerning solar nuclear reactions, the most precise available physical description of the solar interior, and the general equations that are thought to govern the evolution of stars. Since we know more about the Sun than about any other star and since the Sun is believed to be in an easy-to-calculate, stable middle-aged state, a precise test of the standard solar model provides a unique and critical test of how stars produce energy and evolve.

Neutrinos are elementary particles that travel at essentially the speed of light. As well as being produced in the Sun they are produced on Earth in nuclear reactions that involve natural radioactivity, in nuclear fission reactors, and in high-energy physics accelerators. Unlike the traditional messengers of astronomy, light particles weakly with matter. This weak interaction enables them to escape directly from the centre of the Sun and to provide astronomers with otherwise inaccessible information about the centre of our nearest star.

The Sun acts as a natural particle accelerator, producing a beam of neutrinos that can be used to probe the so-called electroweak interactions that act between subatomic particles. The theory of electroweak interactions offers a single, extraordinarily precise description of all the known electric, magnetic and weak interactions among elementary particles. There are three types of neutrino: electron-type, muon-type and tau-type. According to the standard model of electroweak interactions, neutrinos have no mass, travel at essentially the speed of light, and never change from one type to another. Solar neutrino experiments test the standard formulation of electroweak theory on energy scales or timescales that cannot be achieved with traditional laboratory experiments. Neutrinos from the Sun offer a glimpse of what is happening deep inside a star and so allow us to test in detail theories of how the stars shine as a result of nuclear reactions, and how they evolve.

Deep physics

Because neutrinos interact only weakly with matter, large detectors, typically made up of hundreds or thousands of tonnes of material, are needed to capture them. These detectors must be placed far underground in sheltered places like mines and specially built deep laboratories. Otherwise, the rare occasions when astronomical neutrinos trigger something observable in the detectors would be confused with the more numerous background interactions caused by high-energy, strongly interacting particles known as cosmic rays that come to us from various parts of the Galaxy.

For two decades, beginning in 1967, the only operating solar neutrino experiment was carried out by the chemist Raymond Davis, now at the University of Pennsylvania. Davis uses an under ground tank in the Homestake gold mine in South Dakota, containing more than 600 tonnes of a dry-cleaning fluid called perchloroethylene. A quarter of the chlorine atoms that occur naturally in this fluid are the isotope chlorine-37, rather than the more common chlorine-35. A chlorine-37 atom conveniently and efficiently captures neutrinos to become a radioactive argon-37 atom. Davis detected only about one-quarter of the solar neutrinos predicted by theoretical calculations. This disparity between theory and observation is known as the solar neutrino problem.

Prompted by this puzzle, Japanese researchers, together with physicists from the University of Pennsylvania developed a second experiment in 1987 in an underground laboratory in the Japanese Alps. This experiment, currently led by Yoji Totsuka of the University of Tokyo, detects the scattering of incoming solar neutrinos by electrons in 680 tonnes of ultra-pure water. The scattered electrons are observed with the aid of large photosensitive detectors that collect the characteristic light emitted by fast-moving electrons. The direction in which this light is emitted shows that the neutrinos come from the Sun.

The water experiment, called Kamiokande II, has confirmed the discrepancy between theory and observation. The energy threshold for detecting neutrinos in the Japanese experiment—that is, the lower limit of neutrino energies it can detectis much higher than for the chlorine experiment and the discrepancy with theory is less. The degree of disagreement with standard calculations appears to depend upon the energy of the solar neutrinos.

Most of the neutrinos that the chlorine and water experiments were designed to detect come from a rare reaction in which beryllium-7, an unstable isotope, captures a proton to form radioactive boron-8. The rate of this reaction is very slow. In order to get dose enough to fuse, the proton and the beryllium nuclei must overcome a large energy barrier due to the repulsion of their electric charges. This reaction is calculated to occur only once in every 5000 times that four hydrogen nuclei are burned as in Figure 1a. Despite this, the predicted number of neutrinos detected in the chlorine and the water experiments is dominated by the rare reaction because it produces high-energy neutrinos to which the detectors are much more sensitive.

Physicists and astronomers believe that most solar neutrinos are produced in the fundamental initial reaction in the solar energy-generating process of Figure 1a, the so-called proton-proton (p-p) reaction (Figure 1b). In this reaction, a proton (p) decays to a neutron in the vicinity of another proton forming a heavy hydrogen nucleus called deuterium (hydrogen-2), and emitting a positron and a neutrino. The neutrinos that this reaction produces have energies of less than 0.4 MeV, too low to be detected by the chlorine and the water experiments. Astrophysicists can calculate to within 2 per cent the number of pep neutrinos that should be produced per unit of time according to the standard solar model.

Sun on the spot

In a crucial test of both the standard solar model and the physics of how neutrinos behave, the low-energy pep neutrinos are currently being observed in two experiments with large gallium detectors in underground observatories: one in Russia, where 60 tonnes of gallium metal are used, the other in Italy where the detector contains 30 tonnes of gallium in the form of a gallium chloride solution.

The isotope gallium-37 is converted into germanium-71 when gallium absorbs a neutrino. The germanium isotope is radioactive and can be extracted chemically and counted in a manner similar to the way argon-37 is extracted and counted in the chlorine experiment. American scientists are participating in the Russian experiment, which is called SAGE (for Soviet American Gallium Experiment) and is being carried out in the Baksan Laboratory which was specially excavated underneath the Andyrchi mountain massif in the North Caucasus region. The European experiment, called Gallex, involves scientists from Germany, France, Italy, Israel, and the US and is taking place in the Gran Sasso Underground Laboratory in Italy. In June 1990, at a scientific meeting at CERN in Geneva, Tom Bowles of Los Alamos National Laboratory, who leads the American team, and Vladimir Gavrin of the University of Moscow, who leads the Russians, created a sensation by announcing that the preliminary results of the SAGE experiment indicated that most of the basic pep neutrinos (see Figure 1b) were missing. If these results were correct, the consequences would be revolutionary: new physics would be needed to explain why so few pep neutrinos were being detected.

Two months ago, many of the same scientists assembled in Granada, Spain to hear from Till Kirsten of the Max Planck Institute for Nuclear Physics in Heidelberg the first results from the Gallex collaboration (see New Scientist, Science, 11 July). For several months prior to this meeting, conflicting rumours pulsed through the scientific community. Both astronomers and physicists were looking to the results of the Gallex experiments, in combination with those already announced from the SAGE experiment, to provide unequivocal answers to basic questions. Is our conventional understanding of how the Sun shines incorrect? Or do we need new physics beyond the textbook theory of electroweak interactions?

When the Gallex results were announced on 1 June, the long-awaited answer was a resounding "maybe". The results identify neither the astronomers nor the physicists as clear culprits in the solar neutrino problem. The measured rate of 83 ± 21 solar neutrino units (an SNU is a convenient unit for measuring the rate at which solar neutrinos are detected) is significantly different from the rate of 132 ± 7 SNU calculated with the standard solar model. But it is not far enough off, considering the large experimental uncertainties, to demand new physics rather than new astronomy. The Gallex experiment has not solved the solar neutrino problem, but it has made a major advance by observing the fundamental, low-energy pep neutrinos for the first time.

At the same meeting, the SAGE researchers presented other interesting results. These indicate that more neutrinos are being detected in their experiment than was originally suggested. It seems likely that the SAGE and Gallex experiments will eventually yield similar answers once they have been running for a few more years and uncertainties with the equipment and statistics have been reduced.

Missing neutrinos

The core of the solar neutrino problem remains the low counting rate observed in Davis's chlorine experiment. His result is especially difficult to explain when combined with the more moderate deficit of high-energy neutrinos detected by the Japanese Kamiokande II pure water experiment. Both these experiments are sensitive primarily to the same rare neutrinos from radioactive boron. Hans Bethe of Cornell University and I have argued that the only way to reconcile the published results of these two experiments is to infer that the physicists' standard electroweak model does not correctly predict the behaviour of the electron-type neutrino.

So far, four solar neutrino experiments have measured the rates at which neutrinos of different energies arrive at Earth and all four have found rates outside the range predicted on the basis of the combined standard solar and standard electroweak models. But some scientists have expressed reservations about whether we really need new physics.

When will we know the final answer? Not until 1994, or perhaps even 1996. By 1994, the two gallium experiments should yield results of higher statistical accuracy, which may yet point us towards a solution to the solar neutrino problem. If not, by 1996 two powerful new experiments will be operating with large counting rates and high statistical accuracy. One of these, called the Super-Kamiokande experiment, is being constructed in Japan. It is a much improved, much larger version of the Kamiokande II pure water experiment. The second new experiment, the Sudbury Neutrino Observatory (SNO), is being built in an INCO nickel mine near Sudbury in Ontario. The SNO experiment will capture neutrinos with a thousand tonnes of precious heavy water (D_2O), in which deuterium replaces ordinary hydrogen.

Both of these new experiments will detect neutrinos using photosensitive detectors, similar to those developed for the Kamiokande II experiment, which collect light emitted by the fast-moving electrons produced by the neutrino interactions. Most importantly, they will also use electronic means to measure the energies of individual neutrinos and so determine the energy spectrum of neutrinos that reach us—that is, the relative numbers of neutrinos with different energies.

This energy spectrum is a crucial test: errors in astrophysical theory can only change the total numbers of neutrinos from a given nuclear reaction; they do not affect the neutrino energy spectrum. On the other hand, some attractive theoretical explanations contradict the standard electroweak model and imply that the neutrino energy spectrum can be changed. The new measurements of the neutrino energy spectrum should tell us whether it is correct to infer deviations from the standard model of particle physics on the basis of the chlorine and Kamiokande II experiments. It also appears likely that an Italian-American collaboration called Borexino will be able to make a crucial diagnostic test by observing neutrinos of a specific and relatively low energy produced by beryllium nuclei in the Sun.

While they wait for these experiments physicists and astrophysicists are guided by an aesthetic sense. There is a beautiful theory, developed between 1978 and 1986, that resolves the solar neutrino problem by contradicting the standard assumption that neutrinos have no mass. Named the MSW effect after the three scientists who devised it—Stanislav P. Mikheyev and Alexei Yu. Smirnov of Moscow University and Lincoln Wolfenstein of the Carnegie Institute of Technology in Pittsburgh—it describes how neutrinos can lose their sense of identity when interacting with the large number of electrons in the Sun. Solar fusion reactions produce electron-type neutrinos which can be detected relatively easily by existing experiments. According to the MSW theory, as they interact with the many electrons in the Sun these electron-type neutrinos are converted into another type of neutrino, either a "muon-type" or a "tau-type", that is much more difficult to detect. If the MSW theory is correct, the long-sought solar neutrinos are not really missing—merely hard to observe.

Testing aesthetics

By comparing the rate of two different reactions called "charge current" and "neutral current" reactions in their heavy water experiment, the SNO researchers will be able to test directly the MSW prediction. The charge current reaction records only electron-type neutrinos; the neutral current reaction registers neutrinos of all types. If the standard electroweak theory is correct, and neutrinos do not change their type, the flux of electron-type neutrinos measured with the charge current reaction and with the neutral current reaction will be the same because standard theory predicts that the Sun produces only electron-type neutrinos.

One formulation of the MSW theory that agrees with the Gallex,the chlorine and the Kamiokande II experimental results implies that the electron-type neutrino is physically slightly mixed with a neutrino of a different type that has a tiny mass of about 0.003 eV This mass is more than a thousand times smaller than existing terrestrial experiments can measure. Solar neutrino experiments are sensitive to such tiny values of the mass because the neutrino beam in the centre of the Sun encounters enormous amounts of solar matter in travelling from the centre of the Sun to the underground detectors on Earth.

With our level of understanding of the Sun, calculations of neutrino emission from the solar interior can be done with relatively high precision. For the past quarter of a century, many astronomers have therefore taken the position: "We understand the Sun, so if there is a problem, it must be in the physics of the neutrino." Until relatively recently, many physicists adopted

a similar attitude towards astronomy, suggesting that the solar neutrino problem proves that astrophysicists don't know what they are talking about. Solar neutrino research to date hinges on the question of who is right.

The first quarter-century of solar neutrino astronomy produced a scientific mystery, the missing solar neutrinos. In the next few years experimenters expect to solve this mystery, or at least to identify the principal culprit and to point us towards either a more complete theory of stellar energy generation or a better theory of neutrino propagation. If we are lucky, they might do both.

In any event, astronomers and astrophysicists are likely to be pleased by the present situation. When the first detailed calculation of solar neutrino fluxes was carried out in 1962, a few outspoken physicists doubted whether astrophysicists could calculate the results of solar evolution with sufficient accuracy to make a solar neutrino experiment meaningful. Now the situation is different: physicists are debating whether the estimated 15 per cent theoretical uncertainty (approximately one standard deviation) in the higher-energy, boron-8 solar neutrino flux is sufficiently conservative. Since this rare neutrino reaction is estimated to occur only once in every 5000 times the Sun burns four hydrogen nuclei to form a helium nucleus—that is, the energy production is right to one part in 5000—any astronomical uncertainties are small and the basic correctness of the solar calculations is no longer being questioned. Solar neutrino experiments have confirmed with impressive accuracy the fundamental idea that stars shine by nuclear fusion reactions among light elements. Astronomers and astrophysicists have plenty to be pleased about.

John N. Bahcall is a professor of Natural Sciences at the Institute for Advanced Study in Princeton, New Jersey. Further reading: *Neutrino Astrophysics* by John N. Bahcall Cambridge University Press, 1989.

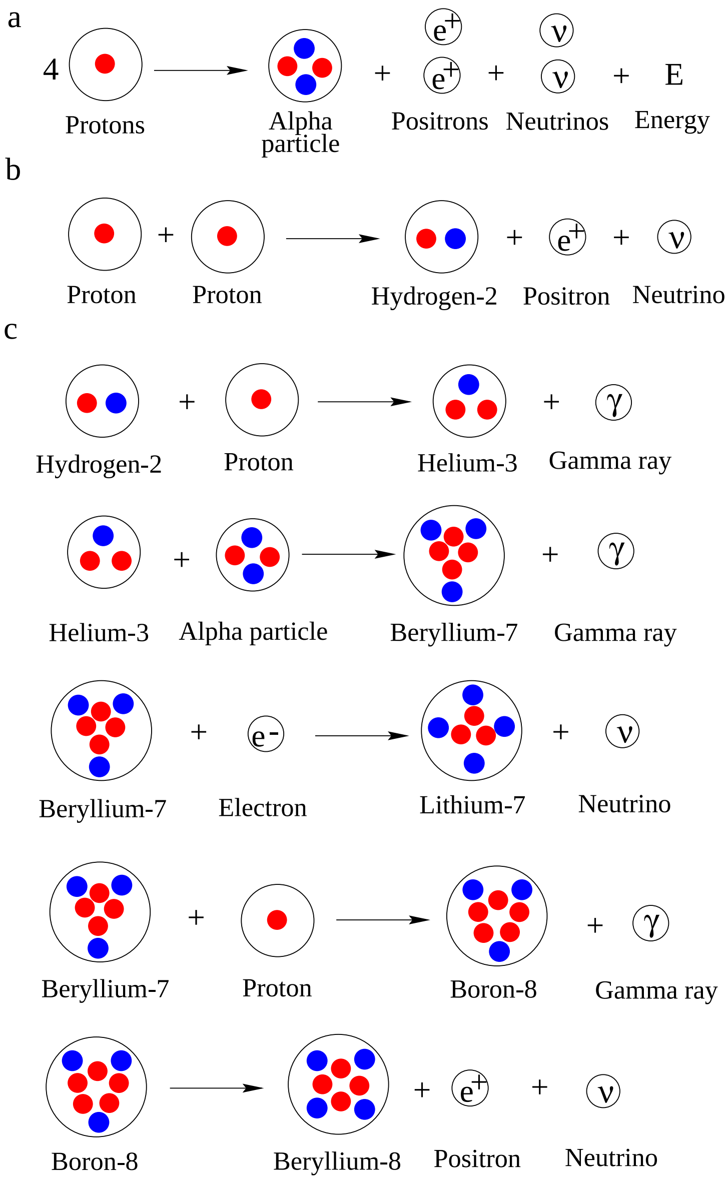

Figure 1: (a) The process that is thought to generate the Sun's energy, the conversion of hydrogen nuclei (protons) to helium nuclei (alpha particles), also produces neutrinos. Most of these solar neutrinos come from a fundamental initial reaction between two protons, called the p-p reaction (b). The p-p reaction is also the start of a chain of reactions that produce other, rarer neutrinos of higher energies (c).

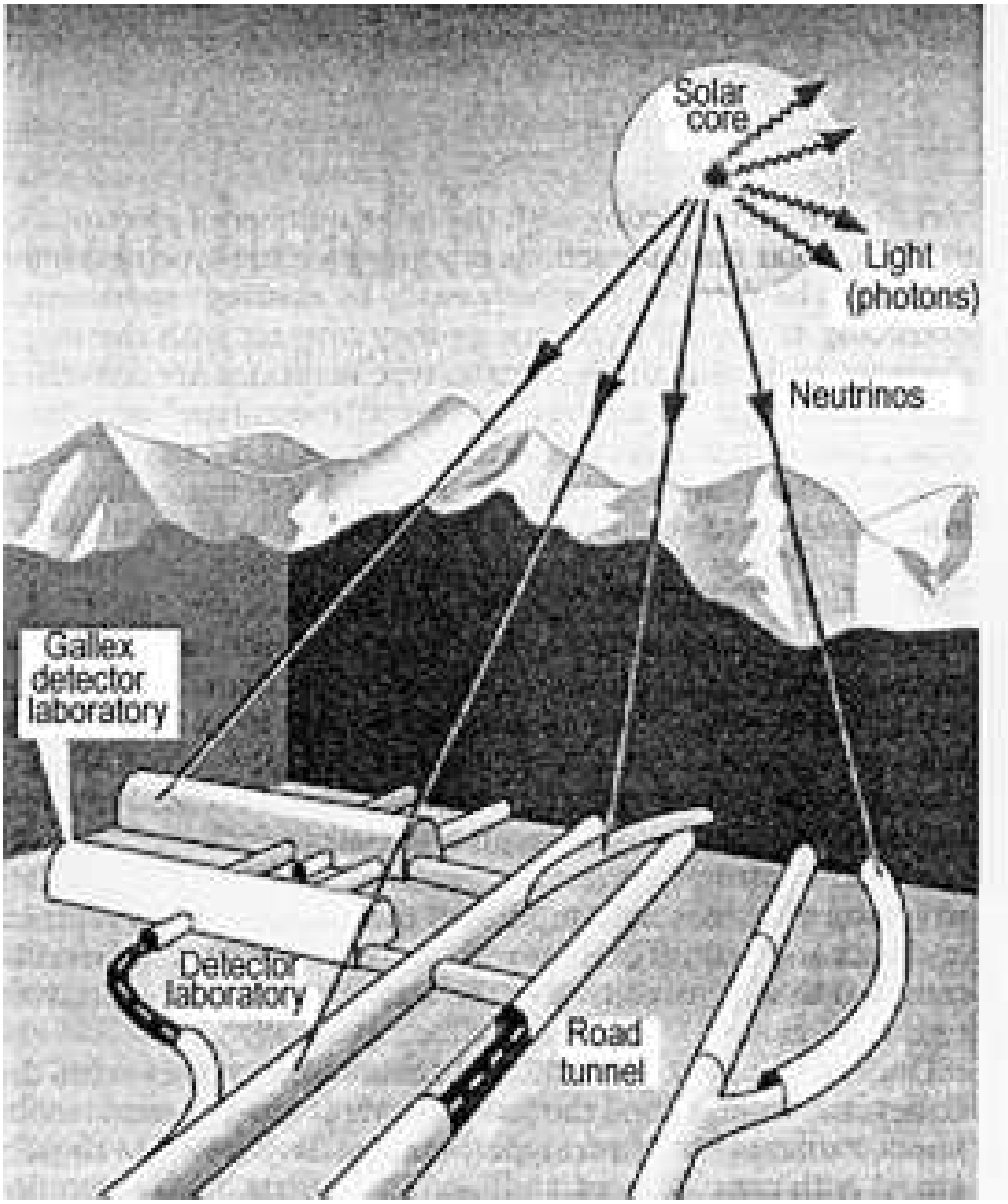

Figure 2: Researchers hoped that the Gallex experiment in the Gran Sasso Tunnel in Italy would go a long way towards solving the solar neutrino problem.

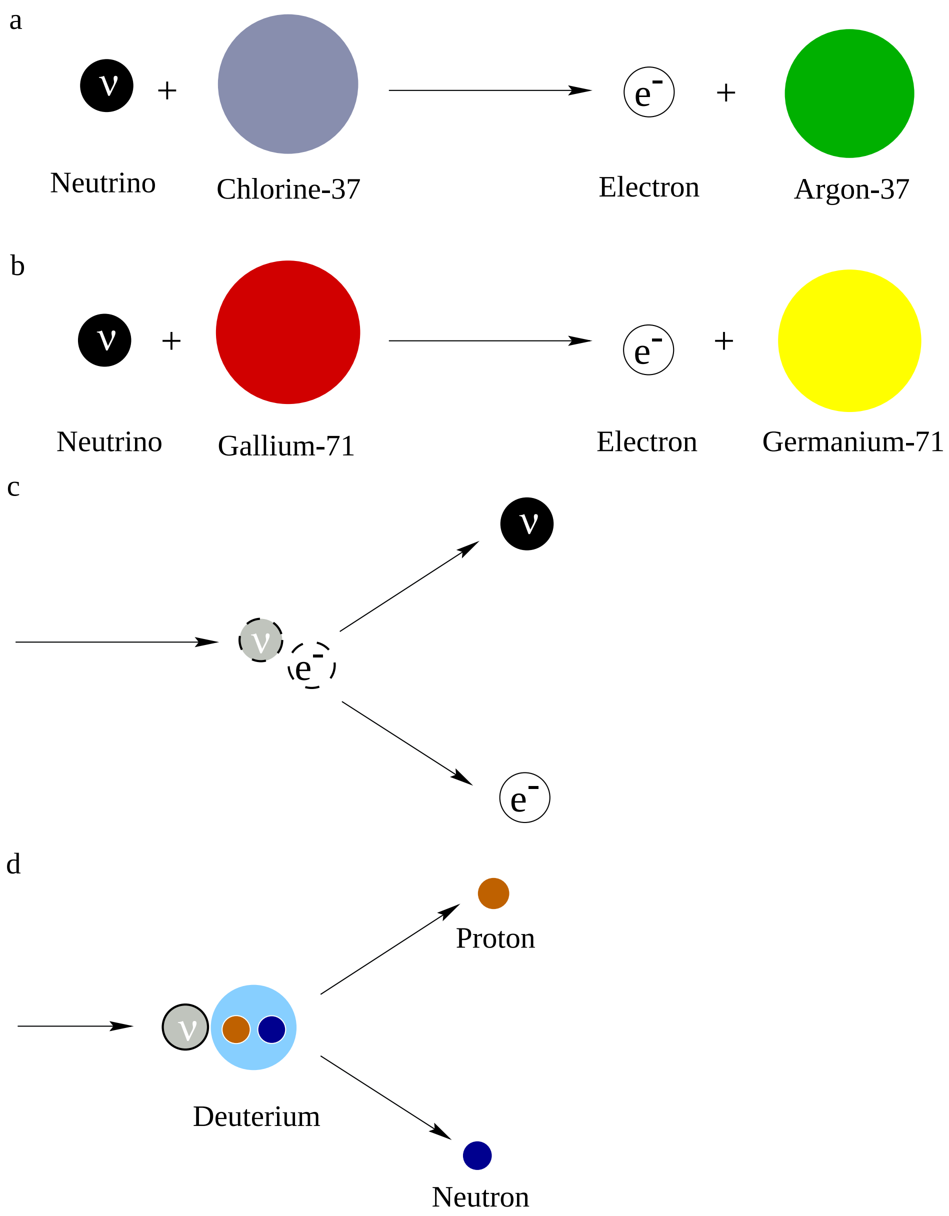

Figure 3: Four ways to trap solar neutrinos. (a) The longest-running experiment in Homestake mine, South Dakota; (b) the SAGE and Gallex experiments; (c) Kamiokande II, based on electron scattering and (d) the "neutral current" reaction at the Sudbury Neutrino Observatory.