with the neutrinos, which change as they travel from the core of the Sun to the Earth."

How did the SNO scientists — a collaboration of 113 scientists from 11 universities and laboratories in Canada, the United States and the United Kingdom — solve the solar neutrino mystery? Over 2,000 metres below the Earth's surface, within an active copper and nickel mine, the SNO collaboration built a laboratory[4] the size of a ten-storey building. Here, their underground detector is shielded from cosmic rays and radioactive contamination from dust — the laboratory is so clean it contains less than a teaspoon of dust. SNO scientists built a spherical detector, 12 metres in diameter, which contains 1,000 tonnes of heavy water (D_2O) and is itself immersed in a 30-metre cavity filled with normal water (H_2O). Neutrinos from the Sun are occasionally detected by the heavy water (about five per day), producing light that is measured by 10,000 photomultipliers.

In the initial results reported by SNO, only electron neutrinos were detected (by a specific reaction in the heavy water). A Japanese–American experiment, known as Super-Kamiokande[5], can detect all three types of neutrinos, but is mostly sensitive to electron neutrinos. But Super-Kamiokande, which uses pure H_2O in an underground detector in northern Japan, does not distinguish between electron-type and other solar neutrinos.

If only electron neutrinos travel from the Sun to the Earth, then SNO and Super-Kamiokande would measure the same number of neutrinos. If some solar neutrinos are muon or tau neutrinos, then Super-Kamiokande would measure a larger number. Indeed, the Super-Kamiokande number exceeds the SNO number with a probability of 99.96% (3.3 standard deviations), conservatively calculated. This is a smoking gun.

The Sun emits neutrinos over a wide range of energies, but SNO and Super-Kamiokande are sensitive to a specific energy range. Using data from both measurements, SNO scientists calculated the total number of these solar neutrinos that reach the Earth. The measured number agrees well (within 0.3 standard deviations) with the prediction of the standard solar model[6].

What does all this mean? In 1969 two Russian scientists first proposed[7] that neutrino oscillations cause the observed discrepancy between the predicted and measured numbers of solar neutrinos. In 1998, experiments at the Super-Kamiokande detector[8] provided the first evidence of neutrino oscillations by studying neutrinos produced when cosmic rays interact with the Earth's atmosphere. SNO has now confirmed that solar neutrinos undergo oscillation.

The Sun only produces electron neutrinos, but some muon or tau neutrinos reach us from the Sun. Therefore, solar neutrinos must oscillate from one type to another. This phenomenon, which requires that neutrinos have non-zero mass, is not predicted by the simplest version of the textbook theory of weak particle interactions (called electroweak theory). The standard theory of weak interactions must be modified slightly, which is important but not unexpected. Most importantly, the specific way neutrinos oscillate, which must be determined by future experiments, may help select the correct generalization of existing physical theories.

Neutrinos contribute to the mass density of the Universe. Combining results on neutrino masses from SNO, Super-Kamiokande and nuclear physics experiments, SNO scientists conclude that electron, muon and tau neutrinos contribute between 0.1% and 18% of the critical mass density of the Universe. The most plausible value is 0.1%. A neutrino mass density of 0.1% is probably too small to affect significantly the geometry or fate of the Universe, but it is about one-quarter of the mass density of all the stars we observe. So even though there is an enormous number of neutrinos in the Universe, the small amount of mass they contribute is not going to solve the problem of the Universe's missing 'dark matter'.

Arguably, the most spectacular result from SNO is that the total number of solar neutrinos measured by the observatory and Super-Kamiokande is bang on that predicted by the standard solar model. In appropriate units, the predicted value is 5.05 ± 0.2 and the measured value inferred by comparing the results of SNO and Super-Kamiokande is 5.44 ± 1.0. This is a triumph for the theory of stellar evolution. The predicted number of neutrinos depends on the 25th power of the central temperature of the Sun. Getting the neutrinos correct to 20% implies we can calculate the Sun's central temperature (15.7 million kelvin) to better than 1%. As stellar evolution theory is widely used to interpret observations of stars and galaxies, this agreement is a cause for rejoicing among astronomers.

Physicists are happy because they have an interesting phenomenon to study; astronomers are happy because their solar theory has been proven correct. But the work has only just begun. Scientists have so far made detailed measurements of only 0.005% of the neutrinos astronomers believe are emitted by the Sun. The remaining neutrinos are at lower energies and so are more difficult to detect. Until these lower-energy neutrinos are observed and compared with theory, we cannot be sure we really understand the intricacies of the mystery of the missing neutrinos. In the meantime, SNO and Super-Kamiokande have crucial additional measurements to make. It is a great time to be involved in neutrino research. ■

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NATURE

100 YEARS AGO

Catalase is the name given to a new enzyme of general occurrence described by Dr. Oscar Loew in Report (No. 68) of the U.S. Department of Agriculture (Division of Vegetable Physiology and Pathology) with special reference to the tobacco plant. This enzyme possesses the power of producing catalytic decomposition of hydrogen peroxide, a decomposition which, according to the author's experiments, is probably not produced by any other known enzyme. The enzyme appears to exist in an insoluble and in a soluble form, which are designated α- and β- catalase respectively… Experiments on the nature of catalase indicate that it is an oxidising enzyme, the most characteristic reaction studied in this direction being its rapid oxidation of hydroquinone to quinone. Numerous tests have established the general occurrence of catalase in the vegetable kingdom. No living plant or vegetable organ tested was found free from it, some plants containing more of the soluble, others more of the insoluble, form. In the animal kingdom it also appears to be widely distributed.

From *Nature* 4 July 1901.

50 YEARS AGO

A situation provoking speculation has been found during the course of a preliminary investigation of one-shear (1½-year old) rams offered for sale at the Feilding Stud Ram Fair… Data used in these analyses were derived from the catalogues of the 1948, 1949 and 1950 sales and the 1948 Flock Book of the New Zealand Romney Marsh Breed Society. Of the 612 rams offered for sale in the three years, 52.6 per cent were sired either by lambs or by one-shear rams. The offspring of the one-shear rams brought the highest average price and had a lower rejection-rate than any other age… However, Goot has shown that one-shear sires comprise only 27.8 per cent of the sires available for use in those flocks static in numbers and consisting of 400 or more ewes. Selection of rams for the Stud Fair and for single-entry in the Flock Book is almost solely on phenotype and certainly without reference to age of the parents, nor does this latter point interest buyers. Because of this, it would be expected that the sires of rams chosen for single-entry and for sale would be represented in the same proportion as they are used in the flocks… Further analyses are planned to throw more light on these rather perplexing problems.

From *Nature* 7 July 1951.