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The Solar Neutrino Problem Has Been Closed

The solar neutrino problem has been closed and the ability of neutrinos to change from one type, or "flavor," to another established directly for the first time by the efforts of the Sudbury Neutrino Observatory (SNO) collaboration. This finding gives physicists new confidence that they understand how energy is produced in the sun's core and that neutrinos are just as quirky as we thought.

The benevolent sunlight we receive on Earth has its origin in the sun's central fusion furnace, whence the light must fight its way outwards in a series of scatterings that takes, on average, hundreds of thousands of years. Solar neutrinos, setting out from the same place, flee unhindered, thus providing the most unadulterated proxy of activity at the core.

Measurements dating back to the 1960's of this neutrino flux were puzzling: only a fraction of the expected number arrived at detectors on Earth. Suspicion naturally fell on the experiments and on the standard solar model (SSM) used to calculate the flux.

Soon, however, the neutrinos themselves were implicated. If on their journey to Earth some of the neutrinos (basically solar reactions produce electron-neutrinos exclusively) had changed into muon- or tau-neutrinos, then terrestrial detectors designed only to spot electron neutrinos (e-nu's) would be cheated of their rightful numbers.

SNO scrutinizes a particular reaction in the sun: the decay of boron-8 into beryllium-8 plus a positron and an e-nu. SNO's gigantic apparatus consists of 1000 tons of heavy water (worth $300 million Canadian) held in an acrylic vessel surrounded by a galaxy of phototubes, the whole residing 2 km beneath the Earth's surface in an Ontario mine, the better to filter out distracting background interactions.

Last year SNO reported first results based on reactions in which a solar neutrino enters the detector and either (1) glances off an electron in one of the water molecules (this so-called elastic scattering (ES) is only poorly sensitive to muon and tau neutrinos) or (2) combines with the deuteron to create an electron and two protons, a reaction referred to as a "charged current" (CC) interaction since it is propagated by the charged W boson.

The SNO data, when supplemented with ES data from the Super Kamiokande experiment in Japan, provided preliminary evidence a year ago for the neutrino-oscillation solution for the solar neutrino problem.

Now the definitive result has been tendered by SNO scientists at this week's joint meeting of the American Physical Society (APS) and the American Astronomical Society (AAS) in Albuquerque.

The new findings update last year's CC and ES data and introduce, for the first time, evidence deriving from a reaction in which the incoming neutrino retains its identity but the deuteron (D) is sundered into a proton and neutron; this is why SNO went to such trouble and expense of using D_2O-for the weakly bound neutron inside each D.

This interaction, called a neutral-current (NC) reaction because the operative nuclear voltage spreads in the form of a neutral Z boson, is fully egalitarian when it comes to neutrino scattering; unlike last year's ES data, the NC reaction allows e-nu's, mu-nu's, and tau-nu's to scatter on an equal footing.

The upshot: all the nu's from the sun are directly accounted for. The missing nu-e flux shows up as an observable mu-nu and tau-nu flux. This conclusion is established with a statistical surety of 5.3 standard deviations, compared to the less robust 3.3 of a year ago. The measured e-nu flux (in units of one million per cm^2 per second) is 1.7 while that for the mu-nu and tau-nu combined is 3.4. (When one includes all the other types of neutrinos, the flux from the sun is billions/cm^2/sec.)

Even the issue of how the neutrino changes from one flavor to another can be addressed by viewing the day-night asymmetry of neutrino flux. When the whole of the earth is between the sun and the detector (night viewing) the oscillation process, which depends on a density of matter through which the nu proceeds, should be speeded up.

This type of measurement will also contribute to the eventual study of neutrino mass. An experiment like SNO can measure not mass but the square of the mass difference between nu species. Even if the nu mass is quite small (much lighter than the previously lightest known particle, the electron) it might still have played a large role in cosmology, where it might have been instrumental in shepherding galaxies; in supernovas, neutrinos might carry away as much as 99% of an exploding star's energy.

The SNO team has submitted its results to *Physical Review Letters*; preprints are available at the online preprint server: nucl-ex/0204008 and 0204009; see also the SNO website.

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