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Colloquia: Pontecorvo100

Bruno Pontecorvo and solar neutrinos

A. B. McDonald
Queen's University - Kingston, Ontario, Canada

Summary. — Bruno Pontecorvo had a very substantial impact on measurements of solar neutrinos, proposing a technique in 1948 that led to measurements by Davis and proposing that neutrinos could oscillate, a process that has been found to influence observed fluxes substantially. The past history and future prospects of solar neutrino measurements are reviewed, including a discussion of the contributions by Pontecorvo.

1. – Introduction

It is a pleasure and an honour to speak at this 100$^{\text{th}}$ Birthday celebration for Bruno Pontecorvo, particularly on the subject of solar neutrinos, a topic in which he made such significant contributions. It is amazing to note [1] that back in 1946, in an unpublished technical note at the Atomic Energy Division of the National Research Council of Canada at Chalk River laboratories, Bruno Pontecorvo proposed that chlorine could be used to detect neutrinos from reactors or from the sun. Of course at that time, the distinction between neutrinos and anti-neutrinos was not known but a subsequent negative measurement in the 1950s by Ray Davis with chlorine-based detectors at a reactor helped to determine that reactors actually emit anti-neutrinos that do not interact with chlorine. Measurements by Davis starting in 1967 of neutrinos from the sun with chlorine-based detectors won him the Nobel Prize in 2002, confirming the prescient nature of the proposal by Pontecorvo.

The seminal contributions of Pontecorvo to the physics of neutrinos: suggesting the possibility of oscillations in his 1958 paper [1] and following this in 1967 in his paper with Gribov [1] by suggesting that solar neutrinos could undergo oscillation, set the stage for subsequent observations of solar neutrino oscillations as I will discuss below. I also have personal reasons to enjoy speaking about this remarkable scientist as there have been several other connections between him, Chalk River and the Sudbury Neutrino Observatory (SNO) collaboration of which I have been the Director for many years. I personally worked at the Atomic Energy of Canada Chalk River Nuclear Laboratories during the 1970s and noted that Bruno Pontecorvo is recognized as the first tennis champion there in 1948. His tennis prowess has been remarked upon by others and was certainly evident at that time. He also provided one of the first stringent limits on neutrino mass using tritium in a high resolution proportional counter. His work at Chalk River involved early stages of development of the CANDU style nuclear reactor using heavy water as a moderator. As a result of the success of that style of reactor, Canada developed large reserves of heavy water from which the SNO project was able to borrow 1000 tonnes for 10 years for its measurement program. Pontecorvo wrote strongly encouraging letters supporting the SNO project during the 1980s and I was pleased to observe his interest in a model of the SNO detector when we visited the Canadian pavilion at EXPO 1992 in Seville during the excursion day of the Granada NEUTRINO 1992 conference.

It is also interesting to note that we were able to use other technology for the SNO project that he had pioneered in the early 1940s. When he first moved to the US, he worked for a mining company and developed the technique of oil prospecting using neutron activation techniques. As part of our calibration program for the SNO experiment, we purchased a neutron generator used in such well logging to produce short-lived ^{16}N and ^{8}Li radioactivity that was transported to the center of the detector for calibration. It is clear that we have benefited from his experimental and theoretical ideas greatly in the field of neutrino physics and for the SNO project in particular.

2. – Solar neutrino measurements to data

The field of research in solar neutrinos has been a very active one [1] starting with the pioneering theoretical work of John Bahcall and experimental work of Ray Davis in the 1960s. From the first reported experimental results, there was a discrepancy between the measurements and the predictions of theory.

Results from a succession of sophisticated experiments performed in underground locations through the 1980s and 1990s continued to show lower fluxes than predicted by factors of 2 or 3. These experiments, which were all sensitive either exclusively or primarily to the electron neutrinos produced in the sun, included the Davis experiment using Chlorine to observe predominantly fluxes from the ^{8}B and ^{7}Be sources in the sun, the SAGE, GALLEX and GNO experiments [2] that used large masses of Ga to look for transformation to Ge by inverse beta decay induced by pp source neutrinos and the Kamiokande and SuperKamiokande experiments [3] that detected ^{8}B source neutrinos via Cerenkov light from the elastic scattering from electrons in large volumes of H_2O.

Given the differences between measurements and solar model predictions, it was difficult to distinguish clearly between a scenario where there was some problem with the solar models giving lower electron neutrino fluxes and one where electron neutrinos were oscillating into other active or sterile types which were either undetectable by inverse beta decay or observed with a lower sensitivity via the electron scattering reaction. The theory for oscillation of massive neutrinos was developed in great detail during this period and many other possible oscillation effects were also considered, including oscillations combined with effects of finite magnetic moments and sterile neutrinos. The basic theory, building on the work of Pontecorvo and that of Maki, Nakagawa and Sakata [4] proposed that the three active flavor eigenstates are linear combinations of mass eigenstates that change as the neutrinos propagate in vacuum. When one of the flavor states is measured after propagation, the probability of observation would have an oscillatory pattern. This process is dependent on three mixing angles labeled θ_{12}, θ_{23}, θ_{13} and the squares of two mass differences Δm^2_{21} and Δm^2_{23}. This theory has come to be known as the PMNS theory.

An important further theoretical calculation for solar neutrinos was published in 1986 by Mikheyev and Smirnov, building on the work of Wolfenstein [5]and referred to as the MSW effect. The MSW calculations indicated that for certain values of the mixing parameters, interactions of electron neutrinos with the electron density in the sun or earth could perturb the oscillation probabilities significantly and produce an energy dependence in the oscillation probability. If this process is observed it can be used to determine the sign of the mass differences and thereby the hierarchy of the masses.

The Sudbury Neutrino Observatory (SNO) experiment was developed to provide a way to distinguish between the two possible scenarios and determine clearly if neutrino oscillations were occurring for solar neutrinos. Using 1000 tones of heavy water, SNO primarily observed a Charged Current (CC) reaction on deuterium sensitive only to electron neutrinos and a Neutral Current (NC) reaction on deuterium equally sensitive to all active neutrino types. The elastic scattering (ES) reaction on electrons is sensitive to all flavors as well, but with reduced sensitivity to ν_μ and ν_τ. The NC reaction was observed through the detection of the neutron in the final state of the reaction using three different techniques for separate phases of the experiment. Results from the first phase of SNO [6] showed with 5.3 σ significance that about 2/3 of the electron neutrinos from ^{8}B decay in the sun changed to other active types before reaching the earth. A previous comparison of the SNO results for the CC reaction with the ES reaction measured by the SuperKamiokande experiment showed a 3.3 σ effect [7].

This gave a clear indication that some electron neutrinos are changing to other active type before reaching the earth and that the total flux of active neutrinos measured by the NC reaction was in reasonable agreement with the predictions of the solar models for ^{8}B neutrinos. This provided motivation to perform a global fit using the PMNS and MSW theories to all of the solar neutrino measurements, using the solar models to predict initial fluxes. The result was a very good fit to the observed measurements, with parameters involving the MSW effect in the sun which converts ^{8}B electron neutrinos in transit through the solar core almost completely to the mass 2 eigenstate where they stay during further propagation to the detector on earth. On the other hand, neutrinos with energies below 0.5 MeV, such as the pp neutrinos, essentially are unaffected by matter-enhancement via the MSW effect.

Figure 1 from reference [8] shows the predicted energy dependence of the electron neutrino survival probability as a function of neutrino energy as well as a summary of measurements of solar electron neutrino survival relative to solar model fluxes as measured by the gallium experiments for pp neutrinos, Borexino for ^{7}Be, pep and CNO neutrinos and the combination of SuperKamiokande and SNO for the energy dependence of ^{8}B neutrinos. As can be seen, the energy dependence as measured is in reasonable agreement with the MSW effect combined with the oscillation of three active neutrino types. One major objective of future solar neutrino measurements is the improvement in accuracy of all of the experimental results as will be described below. The physics objective is a more accurate comparison with the MSW prediction to seek any discrepancy that might indicate new physical effects such as non-standard interactions, sterile neutrinos or even the possibility of mass-varying neutrinos.

A further objective of solar neutrino measurements experiments is tests of solar models. The results for global analyses of all solar neutrino experiments is consistent with but more precise than predictions using two different metal abundances. We have reached the stage where the experimental results are able to provide guidance to solar models as we will discuss further below for future experiments.

The SuperKamiokande and Borexino experiments have made a number of accurate

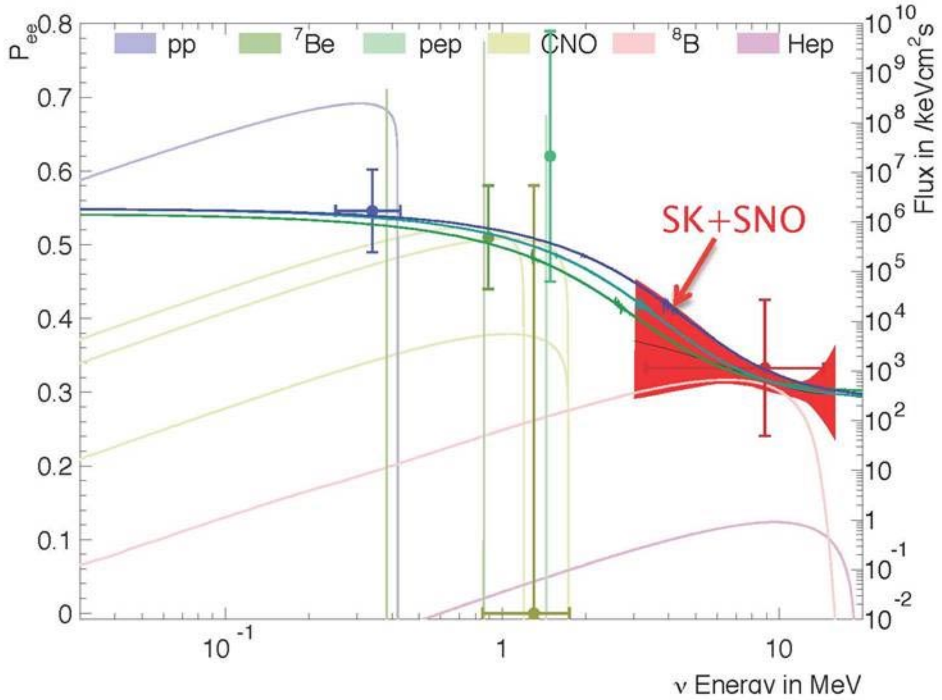

Fig. 1. – Predicted energy spectrum for the electron neutrino flux from the sun, together with measurements to date as described in the text.

measurements of solar neutrinos. These experiments detect the elastic scattering reaction (ES) on electrons in respectively light water and liquid scintillator. These experiments are continuing their operation, as is the SAGE experiment with about 50 tons of gallium observing inverse beta decay in the Baksan observatory in Russia. The SuperKamiokande experiment, with about 50,000 tons of light water, has provided very accurate measurements over more than 15 years and recently has provided a finite value for the day/night asymmetry in the detected ^{8}B neutrino flux due to regeneration in the earth. This measurement [8] $A = -4.2 \pm 1.2 \pm 0.8 \times 10^{-2}$ exceeds zero by about 2.7 standard deviations and is in agreement with the expected value predicted by MSW fits to all other solar neutrino data.

The Borexino experiment [9] has made measurements of the ^{7}Be, ^{8}B and pep fluxes and provided a limit on the CNO fluxes as illustrated in figure 1. These results are expected to become even more accurate with further running with reduced backgrounds using new purification techniques.

3. – Future solar neutrino experiments

Future experiments are aiming at more precise measurements across the energy spectrum as a test of the MSW prediction and a search for new physics. In addition, it may be possible to resolve present uncertainties on solar models by making accurate measurements of several fluxes, such as CNO and ^{8}B that have a different dependence on parameters such as the metal abundances.

The former SNO detector is being converted to SNO+ by replacing the former heavy water in the central volume with a liquid scintillator [10]. This will provide up to 100 times more light output and make possible measurements of lower energy solar neutrinos with good sensitivity. The 2 km depth of the SNO+ detector is equivalent to 6000 meters of water equivalent and this will almost completely remove a significant source of background observed in the Borexino and Kamland measurements, ^{11}C produced by residual muon fluxes. This will enable more sensitive measurements of pep and CNO neutrinos, providing that the inherent radioactive backgrounds can be controlled as substantially as has been done for Borexino. Large scale purification systems similar to those in use at Borexino are being installed.

Because the scintillator is lighter than the surrounding water, it was necessary to install a set of ropes to hold down the central acrylic vessel. This has now been done and the detector is being slowly filled with light water. It is expected that scintillator will be installed in 2014 and a short period of operation will occur to assess the radioactive backgrounds and accumulate a small amount of data on solar neutrinos. Following this operation, about 0.3% by weight of an organic Te compound will be dissolved in the scintillator and operation will proceed to study neutrino-less double beta decay for ^{130}Te. Further measurements for solar neutrinos are planned following the Te measurements. The principal solar neutrino objectives for the SNO+ experiment will be improved measurements of the pep and CNO fluxes and measurements of the ^{8}B neutrino flux to below 2 MeV.

The KamLAND detector with about 1000 kg of liquid scintillator is presently concentrating on the measurement of neutrino-less double beta decay with a central balloon in which ^{136}Xe has been dissolved (KamLAND-Zen [11]). Solar neutrino measurements have been postponed until after the present measurements are completed.

Several detectors have been proposed for the detection of pp neutrinos in real time using liquid noble gases. These liquids provide substantial light output, are very pure and can be constructed in sizes large enough for significant data rates (masses well in excess of 10 tons). Since 2010, the XMASS detector has been in operation to study neutrino-less double beta decay with 835 kg of liquid Xe. In future, a 20 ton detector is being considered for solar neutrino measurements [12]. The self-shielding of Xe is an attractive feature of liquid Xe detectors. The CLEAN detector [13] has been proposed to use about 50 tonnes of liquid Ne for the detection of pp neutrinos in real time. Such a detector would take advantage of the high purity of liquid Ne. A smaller scale prototype, Mini-CLEAN is being built with a few hundred kg of liquid Ar or Ne at SNOLAB.

The LENS experiment [14] is designed to detect solar neutrinos via the charged current electron neutrino capture on ^{115}In. The principal challenge for pp neutrino detection in LENS is the background originating from ^{115}In beta decay which is at a rate of 2.5 MHz compared to an expected pp neutrino rate of 400 per year. In order to reduce background in a 10 ton LENS to an acceptable level, the detector must be highly segmented (cellular). The detector design is being tested in the microLENS experiment, currently being constructed.

The MOON collaboration [15] plans to use the inverse beta reaction on ^{100}Mo, with a threshold of 168 keV to study pp and ^{7}Be solar neutrinos. Small prototype detectors with high granularity are being tested with the objective of eventually producing a full scale detector on the order of three tons. The IPNOS collaboration is also pursuing the study of solar neutrinos using InP detectors and is working on prototype detectors.

Very large scale projects using water or liquid argon aimed principally at other physics objectives such as long baseline neutrino oscillations could be capable of observing ^{8}B solar neutrinos with very high rates. Examples under planning are HyperK, MEMPHYS, LBNE and GLACIER. The LENA project with about 50 kton of liquid scintillator could provide measurements of ^{8}B, ^{7}Be, pep, and CNO neutrinos assuming strong control on radioactivity in the detector. The rates would be hundreds to thousands per day.

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