Ray Davis: The Scientist and the Man

John Bahcall
Institute for Advanced Study
Olden Lane, Princeton, NJ 08540

Ray Davis discovered solar neutrinos. Without Ray, I believe this discovery would not have been made in the 20$^{\text{th}}$ century. You can get some feeling for how hard solar neutrino experiments are from the fact that it took more than twenty years after Ray began his experiment before a second experiment (Kamiokande) was started.

In the early days of the subject, Ray was the only experimentalist willing to risk a significant fraction of his research career in an effort to try to detect solar neutrinos. Solar neutrinos was not a fashionable research topic in the early 1960's. In fact, all the people working steadily on solar neutrinos (theorists and experimentalists) could (and often did) fit comfortably into the front seat of Ray's car.

A few words about Ray himself. Ray was born on October 14, 1914. He will be 81 next month. He married Anna Tomre in 1948, 47 years ago. They have five children, and nine grandchildren, in all of whom they delight and take great pride. Ray's Ph.D. is in Physical Chemistry from Yale in 1942. He was a member of the Chemistry Department at Brookhaven National Laboratory from 1948 to 1985, and is now emeritus. Since 1985, he has been Research Professor of Astronomy at the University of Pennsylvania. Despite his claims to be a chemist, most of Ray's research papers are published in the *Physical Review* or the *Physical Review Letters*.

Ray is best known for his work using chlorine as a detector of neutrinos, as first suggested by Bruno Pontecorvo. In 1955, he published in *Phys. Rev.* the results of his search for antineutrinos from a reactor. He showed that reactor anti-neutrinos are not absorbed by chlorine, $\bar{\nu}_e + {}^{37}\mathrm{Cl} \not\Rightarrow e^- + {}^{37}\mathrm{Ar}$, which was the first experimental evidence that an antineutrino is different from a neutrino. In 1964, we published back-to-back papers in *Phys. Rev. Lett.* arguing that the expected rate of capture of solar neutrinos in a chlorine detector was large enough to be detected in a practical experiment. In 1968, the first results of the chlorine experiment were published; the observed rate was less than the theoretical prediction. The situation has not changed much, as far as the chlorine experiment is concerned, in the subsequent two-and-a-half decades.

For the first 20 years, Ray's experiment was the sole basis for the claim that solar neutrinos had been discovered. It was also the sole basis for the solar neutrino problem, the discrepancy between Ray's experiment (continually refined) and the theoretical expectations (continually refined). In the past five years, three beautiful experiments, Kamiokande, GALLEX and SAGE, have confirmed the discovery of solar neutrinos and provided further evidence for a discrepancy between theory and observation.

Ray is widely admired as a great scientist. He also had at least one great political triumph, a fact which – until today – was known only to Ray and myself. In order to tell you about his political success, I have to tell you a bit about our joint efforts.

Our collaboration began in 1961, when Ray wrote to me (at Willy Fowler's suggestion) to ask if I could calculate a precise rate for the reaction $e^- + {}^7\mathrm{Be} \rightarrow \nu_e + {}^7\mathrm{Li}$ in the sun. I did and, in 1962, I moved to CalTech, in part to carry out the first detailed solar model calculation of neutrino fluxes (with stellar model experts, Iben and Sears). Both Ray and I were enormously disappointed that the calculated rate was too low by an order of magnitude to be detected in what Ray believed he could achieve in a practical chlorine experiment. The situation changed in 1963, with the realization that the superallowed transition from the ground-state of ^{37}Cl to the isotopic analogue state at about 5 MeV in ^{37}Ar increased the predicted capture rate by about a factor of 20. This led to our 1963 joint conference paper and our pair of *Phys. Rev. Lett.* papers arguing that a chlorine solar neutrino experiment was practical. It also led to Ray's greatest political achievement.

Ray invented a way to sell the experiment to Maurice Goldhaber – then director of Brookhaven National Laboratory (and therefore Ray's boss). Maurice's attitude toward astrophysics was said to be: "No astrophysicist can calculate anything with sufficient precision to be of any interest to any particle physicist." Ray proposed, and I reluctantly agreed, that in our crucial meeting with Goldhaber requesting Brookhaven support for the chlorine experiment we would not discuss the astrophysical motivation. As Ray suggested, we discussed at the meeting only the nuclear physics of the much-increased predicted capture rate via the isotopic analogue state and the experimental tests of this idea (which I had also worked out) that were possible at Brookhaven. Both Maurice and his wife are distinguished nuclear physicists and Maurice (an insightful theorist and a talented experimentalist) loved, according to Ray, to talk about any new idea in physics. As Ray had hoped, Maurice was much interested in the nuclear physics ideas and tests and, perhaps incidentally, also approved the solar neutrino experiment.

Because of the many tests of the chlorine experiment that Ray performed and because of Ray's character and personality, other scientists came to believe that it was worthwhile to invest years trying to observe solar neutrinos.

Before each extraction, Ray added a known amount of carrier (non-radioactive) argon and showed that he got the correct amount of carrier argon out of his tank at the end of each run. He placed a small neutron source near the center of the tank and showed that this produced the expected number of ^{37}Ar atoms. At Willy Fowler's suggestion, Ray introduced 500 ^{37}Ar atoms into his detector, stirred them up, and showed that he extracted the expected number of argon atoms. He also performed an overall test of the experiment using ^{36}Cl, which beta-decays to ^{36}Ar in a way that mimics well what occurs in neutrino absorption.

Ray's character and personal approach to the experiment were as important in gaining credibility for the experiment as the actual tests he performed. Over the past 30 years, Ray and I have appeared together more than 100 times in formal discussions (like today's) of solar neutrinos, and many more times informally. I have never seen Ray loose his patience or get angry in answering questions about his experiment. He has answered each question with friendly directness, with complete openness, and – whenever possible – with empirical tests. He invited everyone who was interested to come to Brookhaven, or to the Homestake mine, to see him perform the experiment and to discuss techniques. Many distinguished physicists did come and Ray explained every detail to them.

Ray loves science. He wants to see good experiments done and he wants to understand the results. He is not interested in personal credit.

Let me give just a few illustrative examples. Ray made the ^{7}Be target for Parker's famous ^{7}Be(p, γ)^{8}B experiment and he provided low background prototype ^{71}Ge counters for the SAGE experiment. The chemical techniques used in both the GALLEX and the SAGE experiments were originally developed, in collaboration with some colleagues (especially Cleveland, Dostrovsky, Lande, and Rowley), in Ray's laboratory and were made available to any interested scientist. Many of the senior people in this room had their early lessons in low counting rate experiments and in background suppression under Ray's tutelage. Ray is generous and helpful to other scientists in their work.

Before I summarize these remarks, I want to show you two pictures taken in 1966 when Ray's tank was first being installed. Here is the first picture, Figure 1. Notice the look on Ray's face. Can you figure out what was bothering him? Anyone care to guess? No. Well, I had just explained to Ray (jokingly) that I had found an error of a factor of 4π in my theoretical calculation.

Figure 1. Ray Davis (circa 1966) with a quizzical look.

Figure 2. Ray Davis (also circa 1966) with a young assistant.

The second figure shows, from the same period, Ray explaining some of the features of the tank to a young assistant. (I hope that despite the ravages of time, you can recognize both people in Figure 2.)

Ray's principal scientific achievement is the observation of solar neutrinos. The nuclear reactions that produce the neutrinos also cause the sun to shine. Thus Ray has shown experimentally that nuclear fusion among light elements is responsible for energy generation in the sun. This closes experimentally the scientific debate on the age of the earth and the energy generation of the sun that originated with Helmoltz and Darwin in the middle of the 19$^{\text{th}}$ century. His experiment also created the first solar neutrino problem, the discrepancy between his measured rate and the standard model predictions. Together with the other three great pioneering experiments (Kamiokande, GALLEX and SAGE), the chlorine experiment shows that we can take advantage of the Solar Neutrino Opportunity – the possibility of using solar neutrino beams to do unique particle physics experiments.

Equally important, in my view, Ray has shown that it is possible to be a great scientist and also a great man. He is kind, modest, friendly, open, enthusiastic, and generous. As the chair of this session (Till Kirsten) remarked to me last night, Ray treats everyone with respect and generosity, independent of whether the person to whom he is talking is a student novice or a senior professor, a friendly miner or an unfriendly scientist. I hope you will join me in expressing professional admiration for Ray's work and personal affection for him as a wonderful individual.