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MEASUREMENT OF SOLAR PROTON-PROTON FUSION NEUTRINOS WITH A SOVIET-AMERICAN GALLIUM EXPERIMENT

Technical Progress Report DE-FG05-88ER40481

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Summary

A gallium solar neutrino detector is sensitive to low-energy proton-proton fusion neutrinos. A flux of 70 SNU is expected in a gallium detector from the p-p reaction independent of solar model calculations. If, however, neutrino oscillations in the solar interior are responsible for the suppressed ^{8}B flux measured by the Homestake ^{37}Cl experiment, then a comparison of the gallium and chlorine results may make possible a determination of the neutrino mass difference and mixing angle. A 60-ton gallium detector is currently being constructed in the Baksan laboratory in the Soviet Union, and should be taking data by the end of 1989.

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I. Introduction

The discrepancy between the solar neutrino capture rate predicted by standard solar model calculations and the ^{37}Ar rate measured by the chlorine experiment in the Homestake Gold mine has persisted now for eighteen years. Recent calculated values are in the range 6-8 SNU (1 solar neutrino unit = 10^{-36} captures/target atom/sec), while the measured $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ production rate is 2.1 ± 0.3 SNU (0.39 ± 0.05 captures/day) after subtracting a terrestrial background of 0.4 ± 0.2 SNU. It must be kept clearly in mind that the flux of the high-energy ^{8}B neutrinos (to which the chlorine experiment is most sensitive) is critically dependent on the temperature of the sun's core. In order to calculate the ^{37}Ar capture rate to within a factor of 3-4, the solar core temperature must be known to an accuracy of $\frac{\delta T}{T} \sim 10 - 20\%$. Numerous non-standard solar models have therefore been suggested, incorporating a variety of heavy element abundances, high magnetic fields, turbulent diffusion, continuous mixing, rapidly rotating or burned-out helium cores, convective mixing of hydrogen into the core, or new equations of state. All of these effects go in the direction of lowering the solar core temperature, and several of these non-standard solar models have predicted neutrino capture rates in good agreement with the experimental result.

In addition to solar model effects, it has also been suggested that our understanding of the relevant particle physics may be incomplete. Wolfenstein and Mikheyev and Smirnov (and legions of others) have pointed out that the different coupling of ν_e, ν_μ, and ν_τ to matter can cause an oscillation effect: if ν_e and $\nu_{\mu,\tau}$ are orthogonal linear combinations of the same mass eigenstates, then ν_e produced by ^{8}B decays in the sun's core can oscillate into ν_μ or ν_τ as they propagate outward through the sun's overlying layers.

The chlorine detector is insensitive to ν_μ and ν_τ, so that the ^{37}Ar rate is suppressed. Over the range of neutrino mass differences $\delta m^2 \sim 10^{-7} - 10^{-4}$ eV^2 and vacuum mixing angles $\sin 2\theta \sim 10^{-2} - 1$, the ^{37}Ar counting rate suppression can be just the required factor of 3-4. A neutrino magnetic moment $\sim 10^{-10} \mu B$ (which is surprisingly large but not ruled out by direct experiment) and neutrino decays (which must be tailored to explain the solar neutrino measurements yet not conflict with the observations of SN1987A) have also been invoked, as have weakly interacting massive particles and nuclei with extra quarks in the solar core.

The plethora of theoretical explanations makes exceedingly clear the need for experimental results capable of discriminating among models. In addition, the key assumption that neutrinos are produced as a result of proton-proton fusion in the sun must be checked directly. Solar neutrinos provide the only direct way of probing the sun's deep internal structure, and so far only radiochemical experiments can provide the low background and low threshold required to study the p-p flux. The essential radiochemical experiment required to measure the flux of low-energy p-p neutrinos in a solar model-independent way is the gallium experiment. A 60-ton gallium metal experiment is currently being constructed in the Baksan laboratory of the Soviet Institute of Nuclear Research by G. Zatsepin, V. Gavrin, and their colleagues at the INR in Moscow; B. Cleveland, T. Bowles, J. Wilkerson, D. Wark, S. Elliot, and H. O'Brien at the Los Alamos National Laboratory; R. Kouzes at Princeton University; R. Davis and K. Lande at the University of Pennsylvania; and M. Cherry at Louisiana State University.

Gallium, with a threshold of 0.23 MeV, is so far the only feasible target material capable of detecting the intense flux of p-p neutrinos below 0.42 MeV. Furthermore, of the total energy liberated by fusion in the sun's core, 94% is produced directly in the initial $p + p \rightarrow d + e^+ + \nu_e$ reaction. *On energetic grounds alone, therefore, under the assumptions that the sun is powered by nuclear fusion and that the rate of energy generation has remained constant over the 10^7 years required to transport energy from the solar core to the surface, the current observed energy output at the sun's surface corresponds to a neutrino flux of 6×10^{10} ν cm^{-2} sec^{-1} from the p-p reaction alone, independent of solar model calculations.* This corresponds to a counting rate in the gallium detector of 70 SNU. Observation of less than 70

SNU is direct evidence for new neutrino physics. Based on the standard solar model calculation of Bahcall and Ulrich, the total counting rate in gallium, including all reactions, is expected to be 132 SNU, corresponding to 2 counts/day in the 60 ton Soviet-US experiment.

II. Experimental Installation

The gallium-germanium neutrino telescope (GGNT) is situated in an underground laboratory specially built in the Baksan Valley of the Northern Caucasus, USSR. The laboratory is 60 m long, 10 m wide, and 12 m high. It is located 3.5 km from the entrance of a horizontal adit driven into the side of Mount Andyrchi, and has an overhead shielding of 4700 mwe.

The experiment exploits a radiochemical procedure. The Ga metal is kept molten (~30 C) in a chemical reactor throughout a 20-30 day exposure interval. At the beginning of the exposure, a known amount of non-radioactive Ge dissolved in Ga is introduced as a carrier. At the end of the exposure, a solution of H_2O, HCl, and H_2O_2 is added to the reactor so as to chemically extract the Ge carrier and any ^{71}Ge atoms that have been produced by neutrino capture. The mixture is stirred vigorously and the Ge migrates to the extraction solution. The process of extraction from the Ga requires only about 15 minutes, and the aqueous layer is then siphoned away from the liquid Ga. This solution is then concentrated by evaporation of much of the H_2O. Further concentration is accomplished by adding concentrated HCl, so as to form the volatile compound $GeCl_4$. Ar is then used to sweep the $GeCl_4$ into a small volume of H_2O. The $GeCl_4$ is extracted into CCl_4 and then back extracted into H_2O. From this final solution, the gas GeH_4 is synthesized.

The GeH_4 is mixed with Xe and counted in a low-background proportional counter with an internal volume of 0.5 - 1.0 cc. The number of ^{71}Ge atoms is determined by detecting the Auger electrons and/or x-rays in the K and L peaks of Ge (at 10.4 and 1.2 keV respectively) that are produced by ^{71}Ge decay. The counter is place in the well of a low-background NaI detector, which serves as an anticoincidence detector. The pulse amplitude and risetime for each counter, together with the NaI amplitude and time of each event, are all recorded.

The SSM predicts that 1.2 atoms of ^{71}Ge will be produced per day in 30 tons of Ga. After a one-month exposure, assuming an extraction efficiency of

90% and a counting efficiency of 60%, the combined initial counting rate in the K and L peaks will be about 0.5 events per day.

Measurements and calculations of the various known background processes imply that the total ^{71}Ge background rate from muons, radioactive impurities in the Ga, and fast neutrons is less than 1% of the SSM production rate.

III. Current Status

The experiment will be carried out in two stages. The first stage is to install the apparatus for operation with 30 tons of Ga. At the present time, this 30-ton experiment is fully operating and nearly all of the apparatus for a full-scale 60-ton experiment has been installed. As soon as the additional Ga has been adequately purified, the 60-ton experiment will begin.

The first 30 tons of Ga are housed in four reactors. The remaining 30 tons are stored underground, as well. The extraction efficiency is now approximately 75%; if the extracts from two successive extractions are combined, the yield is 90% or greater.

Two low-background counting systems, each with four channels, are now in operation. Four counting channels have a NaI crystal for background suppression. Each counter assembly is housed inside large passive shields made from low-activity copper, tungsten, and steel. It is anticipated that another 12 counting channels with waveform digitization will be operational this summer.

The total background rate of selected counters filled with 80% Xe/20% GeH_4 has been measured in the energy interval of 1 - 15 keV to be approximately 1.5 events per day. In the region of the ^{71}Ge K-peak energy, the background is 1 event per month with energy and risetime cuts (each with a 90% acceptance).

Each reactor has undergone more than 15 extractions to remove the germanium isotopes that were produced by cosmic-ray interactions while the Ga was on the surface. After the Ga was stored underground for 3 months, the initial activity of the Ge extracted from the 30 tons of Ga was 7700 events per day in the energy region of the Ge K-peak. The residual activity, with 90% energy and risetime selection, is now less than 1 count per day. With each extraction, the background continues to decrease. We are currently investigating the source of the remaining background.

I visited Baksan in December 1988 and again in June 1989. Progress during that time has been excellent. During the June visit, the US-supplied NaI shield and electronic counting system were made operational; we are now recording data from several proportional counters filled with samples from the April extraction. In addition, I delivered several new counters to Baksan; long-term tests are currently underway to measure the background rates of these counters.

Germanium extractions have been carried out in February, March, April and June. The next extraction is scheduled for July. Extraction efficiencies are typically in the range of 67 - 77% for a single sweep; two argon sweeps in succession therefore give total efficiencies of 89-95%. The system is currently operating with 30 tons of gallium in place, and plans are now being made to install the final 30 tons. The full 60-ton chemical extraction apparatus and reagent regeneration systems are due to be finished later this year.

There has been full and complete exchange of data, analysis algorithms, and information. On my last visit, I had extensive discussions with the Soviet chemists about the extraction data. We have received and analyzed raw data from the Soviet counting system, and will receive our next sample of data next month (this time - and for the first time - for samples being counted in both the US and the Soviet counting systems).

Status reports have been presented at WEIN 1989 (Montreal) and Inside the Sun (Versailles). A presentation is scheduled to be made at the next Intl. Cosmic Ray Conference in Adelaide in January. A copy of the Montreal paper is included as Report DOE/ER/40481-3.