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SEARCH FOR PROTON DECAY AS A
TEST OF BARYON CONSERVATION

MASTER

by

FREDERICK WILLIAM DIX

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for the Degree of Doctor of Philosophy

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Abstract

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A large volume heavy water Cerenkov detector enclosed in a liquid scintillator anticoincidence shield was used to search for proton decay. The 550 gallons of D_2O used were obtained on loan from the Savannah River Plant of the Atomic Energy Commission. The experimental site was located 1950 feet underground to reduce cosmic ray and other background. A lower limit on the proton lifetime of 3.1×10^{23} years was established, independent of the mode of decay. The results were also interpreted to set an upper limit on the B^8 solar neutrino flux of $9.5 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$.

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1. INTRODUCTION

The stability of the proton against decay has often been used as a sensitive test of the law of baryon conservation, which states that in any physical process, the number of baryons minus the number of antibaryons is a constant. This law, first proposed by Stuckelberg and later extended by Wigner,^{1,2} has been found to hold true in direct reactions, but experiments which search for decay of protons offer a more sensitive test, since the proton cannot decay into known particles without violating the law of baryon conservation.

An investigation of possible decay products reveals, however, that proton decay to known particles cannot occur without also violating at least one other conservation law such as energy, momentum, angular momentum, charge, or lepton number. Previous experiments have assumed one or another of these conservation laws to be violated, and have searched for the decay products (π^+ , e^+ , etc.) that would occur under this assumption. The present work, however, has been designed to be sensitive to proton decay irrespective of whatever other conservation law is violated.

2. "RESIDUAL NEUTRON" METHOD OF DETECTING PROTON DECAY

The method makes use of the fact that the deuteron is a loosely bound proton and neutron. If the proton decays, then irrespective of the mode of proton decay, the neutron remains behind, and can be detected.

Since the binding energy is small compared to the rest mass of the proton (or the available kinetic energy any known decay particles would receive), it is reasonable to assume that the interaction of proton and neutron has no effect on the decay rate of the proton.

Since the decay of the proton into lighter strongly-interacting particles such as π 's or K's is ruled out (within the half-life determined by this experiment) by other experiments,^{3,4} final states resulting from proton decay are most unlikely to interact with the resulting neutron to give it sufficient kinetic energy to escape the tank without being thermalized (~ 100 Mev). Such neutron energies are further ruled out by the fact that the deuterium present in the organic scintillators used in the experiments referred to above (.015% of the hydrogen present) would produce knock-on protons secondary to these presumed high energy neutrons, which would have been detected.

If proton decay occurs, a large volume of heavy water can then be thought of as a neutron source whose activity is

equal to the proton decay rate associated with the deuterons. Since the volume used in this work (550 gallons) produces little reabsorption of neutrons ($\sim 5\%$), and is also an excellent moderator of neutrons, any proton decay associated with the deuterons in this volume gives rise to a flux of thermal neutrons at the surface. In this experiment the D_2O is enclosed in a steel tank of $1/4$ " wall thickness. The neutrons are captured by the iron nuclei, emitting gamma rays totaling 7.3 Mev.⁵ These gamma rays can then interact in the D_2O , producing Compton electrons whose energy is greater than the Cerenkov threshold. The Cerenkov radiation is then detected by a large array of photomultiplier tubes. Thus the tank of D_2O serves as source, moderator, converter, and detector of proton decay.

3. DESCRIPTION OF EQUIPMENT

Detector

The detector proper (Fig. 1) consists of a cylindrical steel tank four feet in diameter and seven feet high filled to a depth of approximately 5' 10" with D_2O . The D_2O was furnished on loan from the Savannah River Plant of the Atomic Energy Commission, and was composed of 99.7 to 99.8% D_2O , .2 to .3% H_2O . The interior walls were painted with Nuclear Enterprise epoxy based paint NE-561 to provide high reflectivity and prevent corrosion of the tank walls. Fifty-five 5" photomultiplier tubes were mounted on a plate covering the top of the tank so that the tube faces were in optical contact with the liquid. This "inner tank" was enclosed in an outer anticoincidence tank, one foot larger in radius and height than the inner tank. The space between the tanks was filled with mineral oil-based liquid scintillator, and formed a one foot thick anticoincidence shield against cosmic rays and gamma rays. This tank was viewed by thirty-seven 5" photomultiplier tubes spaced around the sides and bottom of the tank. These tubes were enclosed in cylindrical ports welded onto the outside of the tank, and silicone grease was used to optically couple the tube faces to 1/4" thick plexiglass windows mounted in the tank wall.

A third cylindrical tank, six feet in diameter and one foot high was placed on top of the other two to complete the 4π

anticoincidence shield, and was viewed by nine 5" photomultiplier tubes. This tank could be easily removed for access to the inner tank and its associated electronics. A vertical 1/4" pipe welded to a hole in the bottom of the tank and extending up through the lid allowed various radioactive sources to be lowered into the inner tank for calibration and efficiency measurements, and a larger curved pipe was used to route signal and power supply cables into the inner tank.

Electronics

A block diagram of the electronics is shown in Fig. 2. The fifty-five photomultipliers in the inner tank were divided into three banks (A, B, and C) of 18, 19, and 18 tubes, respectively. At each tube socket was a resistor chain (Fig. 3) to supply voltage to each dynode, and a variable resistor used to adjust the overall voltage to the tube. The high voltage leads from all tubes in each bank were tied in parallel and supplied from a high voltage distribution network which effectively decoupled the three banks. The signal outputs from the tubes in each bank were connected in parallel with shielded cable and fed to one of three charge sensitive preamplifiers located on top of the inner tank. The three signals were then amplified by double differentiating amplifiers.⁶

The tubes in the outer tank were all supplied by a common high voltage line from a separate high voltage supply, each

tube having a voltage dropping resistor for adjusting its gain. The outputs were all connected in parallel and fed to a preamplifier and amplifier.

The three inner tank signals were sent to integral discriminators using zero-crossover for timing (Ortec Model 420), and the outer tank signal used a simple leading-edge integral discriminator (Ortec Model 421). A three channel coincidence - one channel anticoincidence circuit (Ortec Model 414A) was then used to determine when an interesting event had occurred. The output of this circuit triggered a camera control circuit. (Fig. 4)

The four signals were routed through delay lines and then displayed on a dual beam oscilloscope (Tektronix Model RM565) using dual trace amplifiers for the vertical deflection of each beam. A fast trace ($2 \mu\text{sec/cm}$) on one beam displayed the three inner tank pulses separately on the upper trace and the outer tank pulse on the lower trace. A much slower sweep speed (2 ms/cm) was used on the other beam, and the outer tank pulse and the sum of the three inner tank pulses were displayed on the two traces. Acoustic delay lines were used to position the pulses in the center of the display, and to allow pulses up to 6 msec prior to an event to be recorded. Since muons interacting in the inner tank to produce neutrons could cause background events several milliseconds after the passage of the muon, this slow sweep allowed the muon pulse to be displayed, and thus rejected as a possible

proton decay event.

The oscilloscope display was recorded by a modified Beattie-Coleman Varitron D camera using a shutterless lens. A databox showing the time, date, and run number was simultaneously recorded. The camera control unit governed the triggering of the oscilloscope display and advanced the film.

The apparatus was located in a plywood shack approximately 1900 feet underground in the Morton Salt Company, Fairport mine. The intensity of low energy gamma rays was reduced by a factor of ~ 40 , and cosmic rays were down by ~ 4000 from the intensities at the surface. The shack was covered with $1/4$ " mesh hardware cloth to reduce the pickup of electrical noise, and electrical power to the electronics was supplied from a Sola constant voltage transformer. As this power line entered the shack it passed through an isolation transformer and an r.f. filter. A separate unregulated power line was used to supply power to the lights and a 25,000 BTU air conditioner.

4. CALIBRATION AND OPERATION OF EQUIPMENT

The energy calibration of the inner tank was derived from the Cerenkov light produced by cosmic ray muons passing vertically through the tank. Since the great majority of cosmic ray muons 1900 feet underground are near-vertical, the spectrum of pulse heights accumulated on a pulse height analyzer showed a characteristic spectral shape called the "through-peak" (Fig. 5). After accumulating a spectrum, a precision pulse generator was used to determine the input voltage to the preamplifier which corresponded to the pulse height associated with the vertical muons. This measurement determined the relationship between pulser voltage and path length.

Since the intensity of muons underground was low (approximately one every two minutes passing through the tank), several days were needed to calibrate all three banks of tubes. Consequently, a secondary calibration source was used for routine calibration of the inner tank. This consisted of a small amount of Ce^{144} and Pilot B plastic scintillator sealed in an aluminum tube with a small glass window. When the "through-peak" calibration of a bank was completed, the pulser voltage corresponding to a 10 Mev energy deposit in the tank was fed into the preamplifier, and the discriminator on that channel adjusted so that it was just barely triggered by these pulses. This pulser voltage was calculated by taking the pulser voltage of the through-peak and dividing it by the ratio between the light output expected from a minimum ioniz-

ing particle passing vertically through the tank and the light output expected from a 10 Mev electron in water. The Ce^{144} source was then lowered into the center of the tank through an access hole and the integral rate above 10 Mev measured. This source was then used later to calibrate the detector by adjusting the amplifier gains to produce the same rates (adjusted for the 285 day half-life of Ce^{144} above discriminator level. This source was also used to set the delays on the three inner tank discriminators to insure maximum coincidence efficiency, and was used as an overall check of the operation of the electronics. A check of inner tank calibration and coincidence efficiency was made at the beginning and end of each 100 foot roll of film used for recording data.

To be recorded, an event had to satisfy the following requirements: (1) the discriminator on each of the three inner tank channels must be triggered, corresponding to an energy deposit of 5 Mev or more, (2) all three discriminators must be triggered within a 0.1 μsec span, (3) there must be no pulse present from the outer tank on the order of 1 Mev or greater. The purpose of these requirements was to eliminate events caused by either cosmic rays or tube noise. The low light output from Cerenkov radiation induced by 7 Mev gamma rays meant that pulses from these events had to be detected in a background from tube noise on the order of 1000 counts/sec. Separation of the inner tank tubes into three banks and requiring coincidence of all three banks meant that only an accidental coincidence of three tube

noise pulses above the 5 Mev level could produce a false trigger of the apparatus. Measurement of the tube noise rates verified that the events due to tube noise were only a small percentage of all events recorded.

Two sequences of runs were made, each approximately one week in length. In the first sequence the inner tank was filled with D_2O , and these runs measured the rate due to proton decay plus background due to neutrons (other than from proton decay), high energy gamma rays, etc. The second sequence measured the background rate by replacing the D_2O with H_2O . Since the apparatus should have the same response to radiation (except for neutrons) with H_2O as D_2O , the difference between the rates from the two sequences of runs is a measure of the neutron associated activity of the D_2O .

The H_2O used, which was distilled tap water, appeared slightly blue compared to the D_2O , which appeared perfectly clear to the eye. Preliminary measurements when the H_2O was first used indicated that, due to increased light absorption, signal levels were decreased to the point that accidental events from tube noise were unacceptably high. The H_2O was replaced with another batch, this from a different supplier. No improvement in signal level was found. In order to compensate for the loss of light, a false bottom of 1/16" aluminum was installed 1.4 feet from the bottom of the inner tank. This increased the ratio of photocathode area to wall area by 23%, which brought signal levels back to acceptable

levels and insured that an event of a given energy in the H_2O would produce the same number of photons (and photoelectrons) at the tubes as in the D_2O .

5. NEUTRON EFFICIENCY

A calibrated⁷ Pu-Be neutron source ($729(1 \pm .047)$ neutron/sec.) was used to determine the efficiency of the apparatus for detecting the neutrons associated with proton decay. The energy spectrum of neutrons emitted by this source extended up to 10 Mev, but, as with the proton decay neutrons, these are thermalized in a few inches. The average distance from neutron creation to thermalization may be approximated by the mean free path to first collision; in the case of D_2O and 10 Mev neutrons, this is ~ 3 inches. The same coincidence requirements were used as for the data runs, but instead of recording pulse heights on film the three inner tank pulses were electronically added and analyzed on a 100 channel pulse height analyzer gated by the coincidence pulse. An additional run was made in which the neutron events were recorded on film in order to check that the spectral shape as recorded on the analyzer corresponded to the shape as determined from the film. Efficiency measurements were made at five locations along the axis of the tank, at 0, 1, 2, 3, and 4 feet from the bottom.

The Pu-Be source is also a source of 4.4 Mev gammas (from an excited state of carbon in the Be (α , n) reaction) which, because of the poor resolution of the inner tank, can simulate neutron events. Consequently, the neutron efficiency measurements were repeated with H_2O in the tank. Since the H_2O absorbs the

neutrons, producing 2.23 Mev gammas, the events seen in H_2O are essentially due to the 4.8 Mev gamma background, and were subtracted point by point from the D_2O data. The gamma contamination in the D_2O neutron efficiency measurements was $\sim 20\%$ (Fig. 6).

The efficiency for neutrons produced near the tank wall was considerably lower (.7%) than the others (1.0% - 1.2%), as might be expected since these neutrons are not as likely to be moderated when they reach the tank wall and are more likely to be captured in the liquid scintillator of the outer tank, producing gamma rays too low in energy to be detected. The integrated efficiency of the tank was determined to be 0.9% (Appendix A).

6. ANALYSIS AND INTERPRETATION OF RESULTS

Proton Lifetime

The H_2O and D_2O data film were visually scanned in a Recordak film reader. Each run consisted of 10 to 15 calibration frames followed by the data frames, and then 10 to 15 more calibration frames at the end of the run. Pulse heights (in cm.) from the calibration frames were recorded in tabular form and also templates were made indicating the position of the calibration pulses on the fast and slow traces so as to show the location of expected anti-coincidence pulses from the outer tank. For the data frames, the pulse heights of the three inner tank pulses were recorded plus the pulse height in the outer tank (if any). Further, the existence of any large energy deposit in the outer or inner tank up to 6 msec prior to the event (indicating the passage of a muon through either tank) was noted.

In the D_2O and H_2O runs, two types of events were rejected in the process of reading the film: "overload" events and "noise" events. The first consisted of frames which in all respects were acceptable but whose inner tank pulses overloaded the amplifiers. Since overload started at pulse levels corresponding to ~ 30 Mev none of these events were consistent with proton decay events. "Noise" events included events with many closely spaced or overlapping pulses from the inner tank, and examination of the

slow traces showed that in many cases these events were associated with a series of pulses in both the inner and outer tank lasting several milliseconds. Again, the magnitude of the inner tank pulses were so large as to be inconsistent with proton decay events. Possible sources of these two types of events are: first, very large tube noise pulses, causing inductive pickup in the unshielded sections of the signal yoke of the inner tank; and second, noise radiated by the electric motors or welding equipment located in other parts of the mine. These rejected events occurred with about the same frequency ($\sim 20\%$ of all events) in both the D_2O and H_2O runs, and no detailed investigation was made of their cause. Typical examples of these events are shown in Fig. 7, and the distribution of types of events is shown in Table 1.

Pulse heights from the acceptable frames and other information were punched on cards, and the data from each run was read into an IBM 1800 computer. Pulse heights were converted to energy coordinates and stored in magnetic tape by a preliminary analysis program, details of which are given in Appendix B. A second analysis program used the data stored on the tape to produce spectra of the data subject to various restrictions on pulse heights.

An investigation of the effects of changing the acceptance level on the three individual banks revealed that raising the acceptance level to 6 Mev decreased the efficiency by 40% but eliminated 70% of the D_2O events. Consequently this higher level was required on all acceptable events in the analysis.

The effect on neutron detection efficiency of increasing the acceptance level was calculated from the roll of film data taken with the neutron source in the tank. Information was available on the pulse heights in each bank, and using the PLOTT program described in Appendix B, histograms were made showing the sum spectra with and without the higher discriminator. The reduction in efficiency was given by the percentage decrease of events in the 5 - 10 Mev range. Although this reduction (46%) was measured at only one point in the tank, this figure was used as the overall reduction in efficiency for the entire tank for two reasons: (1) the shapes of the sum spectra from various neutron source positions are essentially the same, which indicates that the effects of changing discriminator levels should be essentially the same, (2) although the source is in the center of the tank, the neutrons are converted to gammas at the tank walls, and the isotropic diffusion of neutrons to the walls means a representative sampling of many points of origin of the gammas distributed throughout the tank.

The sum spectra of the D_2O and H_2O runs are shown in Fig. 8, and the total rates in the 6 - 10 Mev region of interest are shown in Table 2. To be subtracted from the D_2O rates, the H_2O rates must be scaled up to account for the smaller effective volume of the H_2O . For gammas of 7 Mev, the tank diameter is on the order of 3 mean free paths, thus the tank volume absorbs nearly all gamma radiation incident upon it. For isotropic background, then, the count rate is proportional to the surface area of the

tank. Since the D_2O surface area is 23% greater than the surface area of the effective volume of the H_2O , the H_2O rates must be increased by this percentage to be subtracted from the D_2O rates.

From Table 2, the residual rate in the D_2O due to neutron events is $(+1.3 \pm 2.0 \text{ day}^{-1})$, where the error quoted is the standard deviation associated with the counting statistics. As an upper limit on the rate we may use the value such that the integral of the likelihood function up to that value is .9, giving:

$$R_{\text{obs}} < 4.1 \text{ day}^{-1}$$

The lower limit on the half-life can then be calculated from

$$T_{1/2} = \frac{.69N}{dN/dt}$$

where dN/dt is the upper limit on the decay rate and N is the number of neutrons (1.37×10^{29}), or

$$T_{1/2} = \frac{.69 \epsilon N}{R_{\text{obs}}}$$

where ϵ is the average efficiency for detecting proton decay events. Evaluating this expression using the R_{obs} given above yields

$$T_{1/2} > 3.1 \times 10^{23} \text{ years (90\% confidence level)}.$$

Sources of Background

Gamma and beta rays from naturally occurring radioisotopes and fission products appear to be ruled out as sources of the observed background for two reasons: first, the highest energies available from these isotopes (~ 3 Mev) is well below the energies observed; and second, the non-linear response of the Cerenkov process in the water to low energy betas or Compton electrons from gammas. This means that low energy electrons produce fewer photons in proportion to their energy than high energy electrons. This second effect discriminates very heavily against "pile-up", the simulation of a high energy event by the accidental coincidence of two or more low energy events. Two other possible sources of background with sufficient energy to produce the observed events are cosmic rays (muons) and neutrons. Of these, the muons which pass through the tank ($\sim 700 \text{ day}^{-1}$) are eliminated by the anticoincidence requirement, although muon interactions near the tank might yield high energy gammas to penetrate the anticoincidence shield and produce background events in the 6 - 10 Mev region. Neutrons are produced by the spontaneous fission of thorium and uranium in the walls of the tunnel. From the percentage of rock in the tunnel walls ($\sim 4\%$) and the neutron flux quoted⁸ as representative of that in a rock mine ($10^{-5} \text{ cm}^{-2} \text{ sec}^{-1}$), we may

estimate a neutron flux at the outer tank of $\sim 4 \times 10^{-6} \text{ cm}^{-2} \text{ sec.}^{-1}$. These neutrons can be captured in the 1/4" thick steel walls of the outer tank in much the same manner as the proton decay-associated neutrons would be captured in the walls of the inner tank. If the attenuation of the gamma rays by the scintillator ($\sim 10^{-1}$) and the efficiency of the inner tank for detecting the gammas ($\sim 10^{-1}$) is taken into account, the expected rate from these background neutrons is on the order of 10/day, the same order of magnitude as the observed rates in the D_2O and H_2O . It should be pointed out that this background mechanism is the same for both D_2O and H_2O systems, since only the gammas reach the inner tank and the gamma efficiencies for the D_2O and H_2O systems are the same, with two exceptions. One is the effective volume difference mentioned above. The other is caused by the 1.4 foot thick layer of water underneath the false bottom in the H_2O runs. This water may absorb some of the gamma rays which would otherwise be detected by the H_2O , and lead to an underestimation of the background rate. The attenuation of background gamma rays by this water, assuming that the background is isotropic, is at most 5% of the total H_2O rate; and, within statistics, the $\text{D}_2\text{O} - \text{H}_2\text{O}$ difference is zero whether or not this correction is made. Evidence for the sensitivity of the inner tank to externally produced neutrons was discovered early in the experiment when a high background rate was found to be associated with a neutron source ($\sim 700 \text{ neutron/sec.}$) stored in a cave in the

tunnel ~ 20 feet from the tank. In spite of the distance from the tank and ~ 1 foot of shielding by the salt, a background rate of several hundred events per day was found to be associated with this source. The background of $\sim 10/\text{day}$ is also consistent with the background measurements of East⁹ in this same location. His scintillator tank of roughly the same surface area as our inner tank had a background rate in the 6 - 10 Mev range of $\sim 10^{-2} \text{ sec.}^{-1}$. If this rate is attributed to gamma rays incident on the tank, then allowing for the attenuation of these by the scintillator of our outer tank ($\sim 10^{-1}$) and the reduced efficiency of our inner tank for detecting gammas in this energy range ($\sim 10^{-1}$), the expected rate from our apparatus is again $\sim 10/\text{day}$.

Solar Neutrinos

The nuclear fusion process, generally thought of as being the source of the sun's energy, may be represented by the general reaction:

believed to occur in the sun's central core.

Detailed knowledge of the fusion process presently comes from solar models adjusted to fit known surface conditions such as solar mass, radius, luminosity, and observed atomic abundances,

etc. Neutrinos produced in the core reach the solar surface with negligible attenuation, and detection of these neutrinos at the earth would confirm the existence of the fusion process, and knowledge of the energies of these neutrinos would provide information on the specific steps in the fusion cycle. Recently, calculations of expected neutrino fluxes have been made, and on the basis of cross section calculations for specific neutrino detection processes, several experiments have been undertaken to search for these neutrinos.

The neutrinos of greatest interest here come from B^8 decay

in the p-p cycle, because of their high energy (14.1 Mev end point). The flux of these neutrinos has been calculated¹⁰ to be $2.1 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$. These will interact with the deuterons via the reaction:

producing an electron in the 6 - 10 Mev energy range whose Cerenkov radiation can be detected in our tank. Kelly and Uberall¹¹ have calculated the cross section and electron spectrum for reac-

tion (7), and obtain an integrated product of flux and cross section of $2.3 \times 10^{-35} \text{ sec}^{-1}$ (per deuteron). Since neutrino-induced events would be observed in the D_2O and none would be seen in the H_2O , the upper limit on our background subtracted rate from 6 - 10 Mev of 4.1 day^{-1} may be interpreted as an upper limit on the neutrino reaction rate. Taking into account the neutrino detection efficiency of 30% (Appendix C), and the number of deuterons in the tank, we obtain an upper limit for the integrated flux-cross section product of

$$\int \sigma(\nu_e + \text{H}^2) \phi(\text{B}^8) d\nu < 1.15 \times 10^{-33} \text{ sec}^{-1} \text{ (90\% confidence level)} \quad (8)$$

per deuteron. From the cross section¹² for the reaction averaged over the B^8 neutrino spectrum of

$$\bar{\sigma}_{\text{B}^8} = 1.2 \times 10^{-42} \text{ cm}^2 \quad (9)$$

the upper limit on the B^8 neutrino flux is:

$$\phi(\text{B}^8) < 9.5 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1} \text{ (90\% confidence level)} \quad (10)$$

Davis et al.¹³ have looked for solar neutrinos using the $\text{Cl}^{37} (\nu, e^-) \text{A}^{37}$ reaction and have set an upper limit for the flux-cross section product of $3 \times 10^{-36} \text{ sec}^{-1}$ per Cl^{37} atom. The

upper limit on the B^8 neutrino flux is given by these authors as $2 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$. Reines and Kropp¹⁴ have been able to set a limit on the B^8 flux by looking for elastic scattering of the B^8 neutrinos by electrons. The upper limit on the B^8 neutrino flux, which is obtained using the predicted elastic scattering cross sections from conserved vector current theory, is $5 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$. The results of these experiments are shown in Table 3.

Conclusions

No evidence is found for the existence of proton decay, and a lower limit (90% confidence) on the half life is found to be 3.1×10^{23} years, independent of the mode of the decay. An upper limit is also set on the B^8 solar neutrino flux of $9.5 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1}$. The bulk of the events detected are consistent with being caused by fission neutrons from the mine walls.

APPENDIX A. NEUTRON DETECTION EFFICIENCY

For the purposes of calculating the average neutron detection efficiency, the tank is divided into five sections, each corresponding to one of the five neutron source locations in the detection efficiency measurements (Fig. 9). The region within six inches of the tank wall should be considered a special case since neutrons originating in this volume are not necessarily thermalized when they reach the iron. The use of the Pu-Be source, which emits higher energy neutrons than might be expected from proton decay, allows for this possible decrease in efficiency; and the measured efficiency for detecting neutrons from the source (.7%) at the bottom of the tank may be considered a conservative estimate of the detection efficiency for proton decay events in this region.

The rest of the tank volume is divided into horizontal layers corresponding to the other four source locations; and essentially all neutrons from these regions, whether from the source or from proton decay, are thermalized by the time they reach the tank wall. The average efficiency is determined by multiplying the percentage of total volume in each of these regions by the measured efficiency for that region and then summing the products, as shown in Table 4.

APPENDIX B. DATA ANALYSIS PROGRAMS

WDATA Program

Processing of the data from the D_2O , H_2O , and neutron efficiency runs was done on an IBM 1800 computer using Fortran coding. The program used for preliminary analysis and storage of data (WDATA) read in information from punched cards, converted pulse height coordinates to energy coordinates, and stored this information on magnetic tape. The first data card read contained parameters necessary for the data conversion, such as pulser voltages corresponding to the "Pilot source" calibration, pulser voltages used in the film calibration, and run number. Following this came the cards containing the pulse heights from the calibration frames from the beginning and end of each run. In the first column of each card was punched a code number indicating the type of information on the card as follows:

- 1 - Pulser calibration for A bank
- 2 - Pulser calibration for B bank
- 3 - Pulser calibration for C bank
- 4 - End of pulser calibration frames
- 5 - Pulser calibration for all three banks

Upon encountering a card with a "4" in column 1, the computer averaged the pulse heights of the calibration frames and calculated the conversion factors used to convert pulse height coordi-

nates in the following data frames to energy coordinates.

The magnetic tape was then positioned to the end of all previous runs written on tape. All information on tape was in the form of equal-length blocks consisting of an integer run number followed by an 8 x 100 real array containing the data from 100 frames of film. At the end of the last run on tape was a dummy block having a run number 10000, which was used in the tape positioning routines.

Data cards containing the pulse height information from the data frames were then read and stored in an 8 x 100 array. The pulse heights were converted to energy coordinates and the array together with the run number was then stored on tape. Blocks were converted and stored in this fashion until a card with a 1 in column 38 was encountered signifying the end of data cards for that run. The remainder of the block being analyzed at that point was filled with zeros and then written on tape followed by the dummy block with run number 10000. The tape was then rewound, spaced forward to the beginning of the run just written, and the first 20 frames were printed as a check on the operation of the program.

PLOTT Program

This program was used to print histograms of selected runs stored on the tape, and allowed various conditions to be imposed on those events which were to be included in the histogram.

Several numbers were typed in on the keyboard at the start of the program, including:

1. Logical unit number of the tape drive used.
2. Energy scale of the histogram output (lower and upper limits).
3. Run numbers (up to 16 runs).
4. Energy acceptance level for each bank.

The first block was then read in from the magnetic tape and its run number checked to see if it was included in the list of runs to be analyzed. If not, then the following blocks were read until a run number was encountered that was included in the list. Each event was then checked to see if it satisfied the energy acceptance level criterion. If any of three individual bank energies fell below the acceptance level, the event was ignored. If not, then the histogram subroutine was entered, which could accumulate three separate histograms of individual bank energies, or a single histogram of the sum energy.

After the block was analyzed, the program continued reading through the tape in the same manner until run number 10000 was encountered, at which point the histogram(s) were printed out. Control was returned to the beginning of the program, and a different set of runs could be analyzed with different acceptance levels. The program was terminated by typing in "0" for the first run number.

APPENDIX C. DETECTION EFFICIENCY FOR ELECTRONS

FROM B^8 SOLAR NEUTRINOS

Failure to detect all electrons from solar neutrino reactions arises from two causes, both related to the final 6 Mev acceptance level imposed on all three inner tank channels for an acceptable event. First, the sum energy of the event must be greater than 6 Mev, but this alone does not insure that the event will be recorded. The poor resolution of the inner tank results in considerable variation in pulse heights from bank to bank, so that an event whose sum energy is above 6 Mev may include one or two individual channel pulses which are less than 6 Mev. This variation in pulse heights is mainly due to the small number of photoelectrons produced at the tube photocathodes (~ 80 total photoelectrons for a 10 Mev event), and the statistical fluctuations in the way these photoelectrons are distributed among the three banks. If N photoelectrons are produced each with equal probability ($1/3$) of being in any one of the three banks, and the acceptance level corresponds to K photoelectrons in each bank, then what is the probability of all three banks having at least K photoelectrons? This is calculated by adding the number of ways N photoelectrons can be distributed to satisfy the acceptance criterion and dividing by the total number of possible distributions. This is given by:

$$P(N,K) = \frac{\sum_{J=K}^{N-2K} \frac{N(N-1)(N-2)\cdots(N-J+1)}{J!} \sum_{L=K}^{N-J-K} \frac{(N-J)(N-J-1)(N-J-2)\cdots(N-J-L+1)}{L!}}{3^N}$$

This function must be multiplied by the electron spectrum from neutrino interactions¹¹ where the electron energy is expressed in photoelectrons. The average number of photoelectrons per Mev of electron energy depends on the reflectivity of the tank walls and the photon absorption in the water, and reasonable values of these parameters yield an average response of eight photoelectrons per Mev. Because of the uncertainty in these parameters, however, the neutrino detection efficiency calculations were done for values of 5 and 10 photoelectrons per Mev. The efficiencies obtained were 30% and 36% respectively for events whose sum energy was between 6 and 10 Mev, and which satisfied the acceptance requirement. The lower value of 30% was used in the neutrino flux calculations as a conservative estimate of the detection efficiency.

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Run No.	Total frames	Unreadable	Overload	Noise	Analyzed	Time	Adjusted time
08177	67	11	0	0	56	1355 min.	1133min.
08187	347	7	14	88	238	5457	5347
10137	110	5	8	0	97	3344	3192
10187	37	9	0	1	27	1202	910
Total D ₂ O	561	32	22	89	418	11358	10582
06108	85	0	3	13	69	1199	1199
06118	86	2	3	21	60	1336	1305
06148	86	0	2	4	80	1699	1699
06178	226	1	43	10	172	5798	5772
Total H ₂ O	483	3	51	48	381	10032	9975

Table 1 -- Classification of data frames. "Adjusted time" shown is given by multiplying "total time" by the fraction of total frames that are readable.

Run Numbers	Type	Time	6 - 10 Mev Events	Rates scaled to full D ₂ O volume and run time
08177 08187 10137 10187	D ₂ O	10582 min.	102 ± 10 ($13.9 \pm 1.4 \text{ day}^{-1}$)	$13.9 \pm 1.4 \text{ day}^{-1}$
06108 06118 06148 06178	H ₂ O	9975 min.	71 ± 8.5 ($10.2 \pm 1.2 \text{ day}^{-1}$)	$12.6 \pm 1.5 \text{ day}^{-1}$
Net rate (D ₂ O - H ₂ O): $+ 1.3 \pm 2.0 \text{ day}^{-1}$				

Table 2 -- D₂O and H₂O rates between 6 and 10 Mev.

Experiment	Reaction	$\int \phi \sigma$	ϕ (B^8)
Davis et al.	$\nu + Cl^{37} \rightarrow e^- + A^{37}$	$<3 \times 10^{-36} \text{ sec}^{-1}$	$<2 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$
			$<5 \times 10^8$
This work	$\nu + D \rightarrow e^- + 2p$	$<1.2 \times 10^{-33}$	<9.5

Table 3 -- Results of solar neutrino experiments.

Region	Volume	% of total volume	Efficiency	Product of columns 3 and 4
I	36.5 ft ³	54.5 %	.007	.00382
II	7.07	10.55	.0109	.00115
III	7.07	10.55	.0114	.00120
IV	7.07	10.55	.0122	.00129
V	9.44	14.1	.0105	.00148
Average efficiency:				.00894

Table 4 -- Neutron detection efficiency calculations.

The roman numerals refer to the regions indicated
in Fig. 9.

Fig. 1 -- Inner Cerenkov tank with outer anticoincidence shield.

Fig. 2 -- Block diagram of electronics.

Fig. 3 -- Photomultiplier voltage divider.

Fig. 4 -- Camera control circuit.

Fig. 5 -- Cosmic ray spectrum of the inner tank. Points plotted are the sum of three adjacent channels, and the "edge" corresponding to a vertical muon is shown by the arrow above channel 58.

Fig. 6 -- Sum spectra of neutron source in D₂O and H₂O with source three feet from bottom of tank

a

b

c

d

Fig. 7 -- Examples of data frames: a) pulser calibration, b) acceptable event, c) overload pulses from inner tank, d) noise event.

Fig. 8 -- Sum spectra of the D₂O and H₂O runs. Acceptance levels on the three individual banks is 6 Mev.

x - Source positions

Fig. 9 -- Neutron source locations for neutron detection efficiency measurements.