Experimental Test of Baryon Conservation: A New Limit on Neutron-Antineutron Oscillations in Oxygen

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This paper reports the result of a search for baryon-number–nonconserving neutron-antineutron transitions in oxygen using a 300-ton water Cherenkov detector located in the Homestake gold mine at a depth of 4200 meters of water equivalent. The 90%-confidence-level upper limit for the neutron partial lifetime for this process is found to be 1.4×10^{30} yr. According to a recent calculation of neutron-antineutron oscillations in oxygen, this result corresponds to a lower limit on the free-neutron oscillation time of 2×10^{7} sec.

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The possibility of violation of the law of baryon-number conservation is now a matter of considerable interest due to the prediction of such violations[1] by most gauge-theoretical models unifying the strong and electroweak interactions.[2] The standard SU(5) grand unified model predicts the $\Delta B=1$ nucleon-decay process, but forbids $\Delta B=2$ processes such as $n\to\bar{n}$. Other approaches to unification, however, permit certain $\Delta B=2$ baryon-number–nonconserving processes. Glashow,[3] for example, has proposed an extended SU(5) model with an effective six-fermion coupling that would permit the conversion of three quarks to three antiquarks, thereby allowing processes such as neutron-antineutron conversion. Mohapatra and Marshak[4] have developed quite a different gauge model with spontaneously broken local $B-L$ symmetry in which large amplitudes for $\Delta B=2$ processes exist. Before the advent of the modern gauge theories, the possible existence of neutron-antineutron oscillations had been discussed from a phenomenological viewpoint by Kuzmin.[5]

In general, a $\Delta B=2$ selection rule for baryon-number–nonconserving processes implies the existence of dimension-nine operators, compared to the dimension-six operators which would be appropriate to baryon-number nonconversation obeying a $\Delta(B-L)=0$ selection rule.[6] The effective Lagrangian resulting from $\Delta B=2$ baryon-number nonconservation would therefore involve three additional inverse powers of M, the mass scale for the invariance violation. This additional strong suppression would make such violations experimentally unobservable unless M were in the range 10^5 to 10^6 GeV, many orders of magnitude smaller than the range $M_X=10^{14-15}$ GeV appropriate to $\Delta(B-L)=0$ operators. Observation of $\Delta B=2$ processes thus would be indicative of the existence of new thresholds in the "desert" between M_W and M_X. Unfortunately, current models are unable to provide a crisp prediction of the masses associated with these thresholds. Improved limits on $n-\bar{n}$ oscillations, such as presented here, can therefore provide only rather modest constraints on such models.

We present here the results of a search with a deep underground 300-ton water Cherenkov detector for neutron-antineutron transitions in oxygen. Data from this detector concerning a search for nucleon decay have been reported previously.[7] In the present work we search for a Cherenkov pulse produced by antineutron annihilation secondaries followed several microseconds later by the smaller pulse which would be produced by the $\pi\to\mu\to e$ decay sequence resulting from decay of one of the positive pions produced by the same annihilation event.

The general features of the detector have been described elsewhere[7-9] and will be only briefly reviewed here. The fiducial mass for the present experiment was 150 tons of water containing 4×10^{31} neutrons. The detector consisted of fully segmented 4-m^3 modules each viewed by four photomultiplier tubes. With the electronic thresholds set at the single-photoelectron level, a trigger requirement of three phototubes firing within a 100-ns coincidence gate was used, yielding a detection threshold of about 12 MeV for electrons, adequate for the efficient detection of muon-decay electrons (mean energy 38 MeV).

The principal experimentally measured quantities for each event are the number and configuration of modules triggered, the visible energy deposited in each module, the presence or absence of anticoincidence signals, the absolute time of occurrence of the event, and the relative delays between prompt and subsequent pulses. From the topology of the prompt and delayed modules firing within a given event, it was possible to determine the direction of motion of the particle responsible for the delayed pulse.

The results presented here were obtained during two runs whose live time totaled 407 d. A total of 235 multiple-module muon decays were observed in 188 separate events. As explained in Ref. 7, the number of observed muon decays (which we attribute to the remnant cosmic-ray muon flux) allows determination of the effective exposure time of the apparatus in a self-normalizing manner. Our total exposure, corrected for all muon decay detection inefficiencies, is thus 6.5×10^{31} nucleon years, or 2.9×10^{31} neutron years (since neutrons comprise $\frac{8}{18}$ of the detector).

In Fig. 1 we present a scatter plot of the number of modules firing during the prompt pulse versus the total visible energy for the 42 muon decays which were unaccompanied by an anticoincidence signal and which were produced by upward- or sideward-moving particles. Our Monte Carlo calculations indicate that 59% of multimodule annihilation events yielding one or more muon decays would be characterized by a module number of 2 and would have visible energy less than 1500 MeV. The corresponding region in Fig. 1 contains five events, which are therefore candidates for $n\to\bar{n}$ transitions.

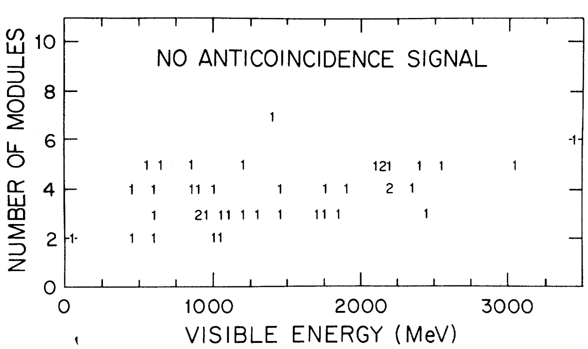

FIG. 1. Scatter plot of the number of 4-m^3 Cherenkov modules firing during the prompt pulse vs the total visible energy for the 42 muon decays which were unaccompanied by an anticoincidence signal and which were produced by upward- or sideward-moving particles.

To estimate the background, we examine Fig. 2, a similar scatter plot for the forty muon decays which were accompanied by anticoincidence signals and which therefore cannot be examples of the $n\to\bar{n}$ process. In this plot there are seven events in the appropriate energy window. Since the overall anticoincidence efficiency is about 50%, the unvetoed and vetoed backgrounds should be approximately equal. We therefore estimate the background as seven events, thereby yielding a net signal of $5-7=-2\pm3.5$ events. There is no positive net signal. We calculate 3.8 events to be the 90%-confidence-level (C.L.) upper limit on the observed number of neutron-antineutron transitions.

We thus obtain for the neutron partial lifetime for these transitions

$$T_{n-\bar{n}} > \frac{(2.9\times10^{31}\text{ neutron yr})\times\epsilon}{3.8\text{ events (90\%-C.L. upper limit)}}$$
$$=7.6\times10^{30}\epsilon\text{ yr},$$

where ϵ is the efficiency with which a neutron-antineutron transition event would yield an observable signal in our detector (i.e., a signal surviving all cuts).

To determine ϵ, we have performed a Monte Carlo calculation, taking the results of a measurement of 750-MeV antineutron annihilation in a heavy liquid bubble chamber[10] for input data. The π^+, π^-, and π^0 multiplicities are 1.6, 1.2, and 1.8, respectively, while the mean pion kinetic energies are 322 MeV, with a most probable value near 100 MeV. The Monte Carlo program used here is similar to the one used in Ref. 7. The result of this calculation is that 18% of the annihilation events would yield a two-module pulse pair surviving our energy and geometry cuts.

Our result for the mean lifetime of a bound

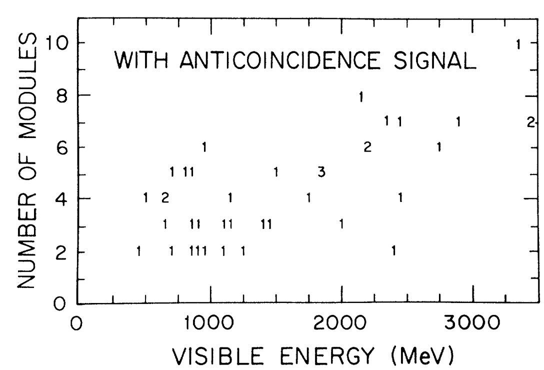

FIG. 2. Scatter plot for the 40 muon decays which were accompanied by anticoincidence signals.

neutron for the transition to an antineutron is therefore

$$T_{n-\bar{n}} > 1.4\times10^{30} \text{ yr (upper limit at 90\% C.L.).}$$

The relation between $T_{n-\bar{n}}$ for bound neutrons and the free-neutron oscillation time $\tau_{n-\bar{n}}$ has been calculated by a number of authors,[11-16] with varying approximations regarding the nuclear physics aspects of this problem. A recent study by Dover, Gal, and Richard[17] used a careful shell-model treatment of these nuclear effects and should therefore provide a more reliable result than previous calculations. They found that

$$\tau_{n-\bar{n}} = 1.5\times10^{7}\left[\frac{T_{n-\bar{n}}}{10^{30}\text{ yr}}\right]^{1/2} \text{ sec.}$$

Using this equation, our limit for $T_{n-\bar{n}}$ corresponds to a free-neutron lifetime greater than 2×10^{7} sec, or an off-diagonal mass-matrix element δm less than 4×10^{-23} eV.

The only existing measurement of $\tau_{n-\bar{n}}$ for free neutrons with which our result can be compared is the preliminary Grenoble result $\tau_{n-\bar{n}} > 10^5$ sec.[18]

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