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TESTS OF NEW PHYSICS IN RARE PROCESSES AND COSMIC RAYS

New Limit on the Proton Lifetime from Neutrino Experiments with Heavy Water*

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Abstract—Experimental data on the number of neutrons born in the heavy water targets of large neutrino detectors are used to set the limit on the proton lifetime independently of the decay mode through the reaction $d \to n + ?$ The best up-to-date limit $\tau_p > 4 \times 10^{23}$ yr with 95% C.L. is derived from measurements with the D_2O target (mass of 267 kg) installed near the Bugey reactor. This value can be improved by six orders of magnitude with future data accumulated with the SNO detector containing 1000 t of D_2O. *© 2003 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

While the baryon (B) and lepton (L) numbers are absolutely conserved in the Standard Model (SM), many extensions of the SM consider conservation of B and L as an approximate law due to absence of any underlying symmetry principle. Incorporation of B- and L-violating interactions in modern gauge theories leads to decay of protons and neutrons bound in nuclei. The processes with $\Delta B = 1$ or 2, $\Delta(B - L) = 0$ or 2 have been discussed [1], while the disappearance of nucleons (or decay into "nothing") has been addressed in connection with the possible existence of extra dimensions [2].

The nucleon instability has been searched for in many underground experiments [3]. About 90 decay modes were investigated, and no evidence for the N (N is p or n) decay was found. For the modes in which N decays to particles strongly or electromagnetically interacting with the detector, the lifetime limits obtained are in the range of 10^{30}–10^{33} yr [4], while, for decays to only weakly interacting products (neutrinos), the bounds are up to ten orders of magnitude lower [4, 5]. However, because it is not known a priori which mode of proton decay is preferable, the limits on the p decay independent of the channel are important. The following approaches were used to establish such limits:

(i) Supposing that the parent nucleus will be destroyed in p decay, the bound $\tau(p \to ?) > 1.2 \times 10^{23}$ yr was determined on the basis of the limit for the branching ratio of ^{232}Th spontaneous fission [6].[1)]

(ii) The limit $\tau(p \to ?) > 3 \times 10^{23}$ yr was obtained by searching for neutrons born in liquid scintillator, enriched in deuterium, as a result of p decay in the d nucleus ($d \to n + ?$) [7].[2)]

(iii) The limit $\tau(p \to 3\nu) > 7.4 \times 10^{24}$ yr was set on the basis of geochemical measurements with Te ore by looking for a possible daughter nuclide ($^{130}\text{Te} \to \cdots \to {}^{129}\text{Xe}$) [8],[3)] while the bound $\tau(p \to 3\nu) > 1.1 \times 10^{26}$ yr was achieved in radiochemical measurements with 1710 kg of potassium acetate $KC_2H_3O_2$ placed deep underground ($^{39}\text{K} \to \cdots \to {}^{37}\text{Ar}$) [9]. These limits are usually quoted as "independent of the channel"; however, it is evident that they are valid only for p decay into invisible channels or disappearance, in which the parent nucleus is not fully destroyed (like ^{232}Th in [6]). At the same time, the bound on p decay from deuterium disintegration requires a less stringent hypothesis on the stability of the daughter nuclear system and, hence, it is less model dependent.

The value based on d disintegration [7] can be improved by using data from modern neutrino experiments with heavy water, well shielded against

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[1)] We recalculated the value quoted in [6] $\tau(N \to ?) > 3 \times 10^{23}$ yr (given for 232 particles: 142 neutrons and 90 protons) for 90 protons that should be taken into consideration here.

[2)] Because [7] is not a source easily accessible and because in [4], where this limit is quoted, there is no indication of confidence level, we assume that it corresponds to 68% C.L.

[3)] The value $\tau(N \to 3\nu) > 1.6 \times 10^{25}$ yr quoted in [8] as given for 52 particles (28 neutrons and 24 protons) was recalculated for 24 protons.

cosmic rays and natural radioactivity [10]. With this aim, we analyze the measurements of [11] with the 267-kg D_2O target and show that the limit $\tau(p \to ?)$ can be highly improved with the SNO large-volume detector [12] containing 1000 t of D_2O.

2. REACTOR EXPERIMENTS WITH HEAVY WATER

The experiment [11] aimed to measure the cross sections for d disintegration by reactor $\overline{\nu}_e$ through reactions $\overline{\nu}_e + d \to \overline{\nu}_e + n + p$ and $\overline{\nu}_e + d \to e^+ + n + n$. The detector was located at a depth of 25 m w.e., 18.5 m away from the center of the Reactor 5 core at the Bugey site. The cylindrical tank with 267 kg of 99.85% pure D_2O was surrounded by layers of Pb (10 cm) and Cd (1 mm) to absorb thermal n from external surroundings. The tank and the Pb–Cd shield were inserted in a large liquid-scintillator detector that served as an inner cosmic-ray veto. The subsequent layer of Pb (10 cm) aimed to reduce the flux of external γ quanta with energies $E_\gamma > 2.23$ MeV, which can photodisintegrate deuterons and create background events. However, this shielding itself was a significant source of neutrons in the target detector created due to interaction of cosmic rays with Pb. To suppress this background, an additional layer of cosmic-ray veto detectors was installed outside the Pb shielding; this reduced the n background in the target by a factor of nearly 6. Neutrons were detected by ^{3}He proportional counters installed in the tank with D_2O.

The decay or disappearance of p bound in a d nucleus, which consists only of p and n, will result in appearance of a free neutron: $d \to n + \ ?$. Thus, the p-lifetime limit can be estimated on the basis of the neutron rate detected in the D_2O volume when the reactor is switched off. To calculate $\lim \tau(p \to ?)$, we use the formula $\lim \tau(p \to ?) = \varepsilon N_d t / \lim S$, where ε is the efficiency for the neutron detection, N_d is the number of deuterons ($N_d = 1.605 \times 10^{28}$), t is the time of measurement, and $\lim S$ is the number of p decays that can be excluded with a given confidence level on the basis of the neutron background measured in the experiment. The mean efficiency for a single n born isotropically throughout the D_2O volume was determined as $\varepsilon = 0.29 \pm 0.01$ [11]. The one-neutron rate with the reactor off, corrected for the software efficiency, is 57.00 ± 1.53 counts/d. For very rough estimation of the p lifetime, we can attribute all neutron events to proton decays and obtain the $\lim S/t$ value of 59.5 counts/d at 95% C.L. Substituting this value into the formula, we get the limit $\tau(p \to ?) > 2.1 \times 10^{23}$ yr with 95% C.L.[4] The τ limit derived in this way is very conservative because the dominant part of the observed n rate has origins other than p decay [15]. The main sources of neutrons are (i) interaction of cosmic μ with the detector, shield, and surrounding materials; (ii) photodisintegration of d by γ quanta with $E_\gamma > 2.23$ MeV originating from the radioactive contamination of the detector materials and shield and from the environment; and (iii) residual n background at the reactor site. The Bugey setups [11, 16] were located at only 25–40 m w.e. overburden and at distance of 15–18 m from the reactor core. Thus, the dominant part of the n background in [11, 16] is associated with the reactor site and μ flux. As was proved by a detailed simulation and careful analysis of the n background in the reactor-off periods of the experiment [16], $(67 \pm 3)\%$ of the n rate is attributed to the known origin. Thus, we can make a conservative estimate that at least 50% of one-neutron events measured in [11] are caused by sources (i)–(iii). Taking the remaining part of the one-neutron rate as the excluded number of p decays ($\lim S/t =$ 30 counts/d), we obtain $\tau(p \to ?) > 4 \times 10^{23}$ yr with 95% C.L., which is higher than the previous limit [7].

3. EXPECTED IMPROVEMENTS WITH THE SNO DETECTOR

The Sudbury Neutrino Observatory (SNO) is a large Cherenkov detector constructed with an emphasis on the study of Solar neutrinos [12]. The detector, containing 1000 t of 99.917% pure heavy water, is located in a nickel mine at the depth of 2039 m (about 6000 m w.e.); this reduces the μ flux to 70 muons per day in the detector area. About 7000 t of ultrapure light water shield the central D_2O detector from natural radioactivity from the surroundings. All components of the detector are made of selected materials with low radioactive contamination.

Solar neutrinos will be detected through the following reactions with electrons and deuterons: $\nu_i + e^- \to \nu_i + e^-$ $(i = e, \mu, \tau)$, $\nu_e + d \to e^- + p + p$, and $\nu_i + d \to \nu_i + n + p$. About 9600 PMTs are used to observe the Cherenkov light produced in the D_2O volume by high-energy products. Neutrons released in d disintegration will be detected by n capture on deuterons in pure D_2O, or by capture on ^{35}Cl by dissolving MgCl salt in heavy water, or by capture

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[4] The similar limit $\tau(p \to ?) > 1.9 \times 10^{23}$ yr with 95% C.L. can be derived from another neutrino deuteron experiment at the Krasnoyarsk (Russia) nuclear reactor [13]. A more modest result can be obtained from the data of the Rovno experiment [14]: $\tau(p \to ?) > 2.3 \times 10^{22}$ yr with 95% C.L.

on ^{3}He using proportional counters. The expected number of neutrons from all sources in the D_2O volume is calculated as $\approx 5 \times 10^3$ during a 1-yr period of exposition, with the main contribution from the Solar neutrinos. The efficiency for n detection is 83% for n capture on ^{35}Cl [12].

With these unique features of the SNO detector (superlow background, large amount of D_2O, and high sensitivity to neutrons), the limit on the p decay independent of the channel can be highly improved. Again, for rough estimation of the p lifetime, we can conservatively attribute all neutrons in the D_2O volume to p decays and take it as the excluded value of $\lim S$. Substituting $\varepsilon = 0.83$, measuring time $t =$ 1 yr, number of deuterons $N_d = 6 \times 10^{31}$, and $\lim S =$ 5×10^3 counts into the formula for τ, we obtain $\tau(p \to ?) > 1 \times 10^{28}$ yr, which is about five orders of magnitude higher than the present-day limit.

However, this value can be improved further by considering the n events originating from Solar neutrinos and high-energy γ quanta. The number of n born in the D_2O volume due to disintegration $\nu_i + d \to \nu_i + n + p$ can be estimated independently by using information on the number of Solar ν interactions with the detector volume through the reaction $\nu_i + e^- \to \nu_i + e^-$. Neutrons created by γ quanta can also be calculated if the levels of pollution of the detector components and external γ flux are measured. In this case, the excluded number of n due to possible p decay will be restricted only by statistical uncertainties of the measured n background, which gives $\lim S = 2\sqrt{5000}$ with 95% C.L. The corresponding bound on the p lifetime is $\tau(p \to ?) > 4 \times 10^{29}$ yr with 95% C.L. This value is close to the limits established for the particular modes of nucleon decays to charged or strongly interacting particles and would be of great importance for many extensions of modern gauge theories.

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