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New limit on the proton life-time independent on channel from the neutrino experiments with heavy water

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Experimental data on the number of neutrons born in the heavy water targets of the large neutrino detectors are used to set the limit on the proton life-time independently on decay mode through the reaction $d \to n+?$. The best up-to-date limit $\tau_p > 4\times10^{23}$ yr with 95% C.L. is derived from the measurements with D_2O target (mass 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.

1. INRTRODUCTION

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 approximate law due to absence of any underlying symmetry principle behind it. Incorporation of B and L violating interactions in modern gauge theories lead to decay of protons and neutrons bounded in nuclei. The processes with ΔB=1 or 2, $\Delta(B\text{–}L)$=0 or 2 have been discussed [1], while the disappearance of nucleons (or decay into "nothing") has been addressed in connection with possible existence of extra dimensions [2].

The nucleon instability has been searched for in many underground experiments [3], however no evidence for the N decay has been found. For the modes in which N decays to particles strongly or electromagnetically interacting with detector, the obtained life-time limits 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 10 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 on channel are important. The following approaches were used to establish such limits:

(1) Supposing that parent nucleus will be destroyed in result of p decay, the bound $\tau(p \to ?)>1.3\times10^{23}$ yr was determined on the basis of the limit for the branching ratio of ^{232}Th spontaneous fission [6] (the value quoted in [6] $\tau(N \to ?) > 3 \times 10^{23}$ yr was given for 232 nucleons: 142 neutrons and 90 protons).

(2) The limit $\tau(p \to ?)>3\times10^{23}$ yr was obtained by searching for neutrons born in liquid scintillator, enriched in deuterium, in result of p decay in d nucleus ($d \to n+?$) [7].

(3) The limit $\tau(p \to 3\nu)>7.4\times10^{24}$ yr was set on the basis of geochemical measurements with Te ore by looking for possible daughter nuclide (^{130}Te $\to$ ....$\to$ ^{129}Xe) [8], while the bound $\tau(p \to 3\nu)>1.1\times10^{26}$ yr was achieved in radiochemical measurements with 1710 kg of potassium acetate $KC_2H_3O_2$ placed deep underground (^{39}K $\to$ ....$\to$ ^{37}Ar) [9]. These limits usually are quoted as "independent on channel", however it is evident that they are valid only for the 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, bound on the p decay from the deuterium disintegration requires the less stringent hypothesis on the stability of daughter nuclear system and, hence, it is less model dependent.

The value based on the d disintegration [7] can be improved by using the data from the modern neutrino experiments with heavy water, well shielded against cosmic rays and natural radioactivity [10]. With this aim we analyze the measurements of ref. [11] with the 267 kg D_2O target

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and show that obtained 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] was aimed to measure the cross sections for the d disintegration by reactor $\bar{\nu}_e$ through reactions $\bar{\nu}_e + d \to \bar{\nu}_e + n + p$ and $\bar{\nu}_e + d \to e^+ + n + n$. The detector was located on the depth of 25 mwe at 18.5 m distance 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 Pb-Cd shield were inserted in large liquid scintillator detector which served as cosmic ray veto. Subsequent layer of Pb (10 cm) was aimed to reduce the flux of external γ quanta with energies E_γ>2.23 MeV which can photodisintegrate the 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 near 6. Neutrons were detected by ^{3}He proportional counters installed in the tank with D_2O.

The decay or disappearance of p bounded in d nucleus, which consists only of p and n, will result in the appearance of free neutron: $d \to n + ?$. Thus the p life-time 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 the $\lim \tau(p \to ?)$, we use the formula $\lim \tau(p \to ?) = \varepsilon \times N_d \times t / \lim S$, where ε is the efficiency for the neutron's detection, N_d is 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 which can be excluded with a given confidence level on the basis of the n background measured in the experiment. Mean efficiency for single n born isotropically throughout the D_2O volume was determined as ε=0.29±0.01 [11]. One-neutron rate with the reactor down, corrected for software efficiency, is 57.00±1.53 cpd. For very rough estimate of the p life-time we can attribute all n events to p decays and obtain the $\lim S$ value as 59.5 cpd at 95% C.L. Substituting this value in the formula, we get the limit $\tau(p \to ?) > 2.1 \times 10^{23}$ yr with 95% C.L.[1] This value is very conservative because the dominant part of observed n rate has other origins rather than p decay. The main sources of neutrons are [15]: (i) interaction of cosmic μ with the detector, shield and surrounding materials; (ii) photodisintegration of d by γ's with E_γ>2.23 MeV from the radioactive contamination of the detector materials and shield, and from environment; (iii) residual n background at the reactor site. The Bugey set-ups [11,16] were located only 25–40 mwe overburden and at 15–18 m distance from the reactor core. Thus, the dominant part of n background is associated with the reactor site and μ flux. As it was proved by the detail simulation and careful analysis of n background in reactor-off periods of the experiment [16], the 67±3% of n rate are attributed to known origins. Thus we can make conservative estimation that at least 50% of one-neutron events measured in [11] are caused by the sources (i)–(iii). Accepting the remaining part of one-neutron rate as the excluded number of p decays ($\lim S$ = 30 cpd) we obtain $\tau(p \to ?) > 4 \times 10^{23}$ yr with 95% C.L., which is higher than 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 mine on the depth of 2039 m (near 6000 mwe); this reduces the μ flux to 70 muons per day in the detector area. Near 7000 t of ultra-pure light water shield the central D_2O detector from natural radioactivity from the sur-

[1] The similar limit $\tau(p \to ?) > 1.9 \times 10^{23}$ yr with 95% C.L. can be derived from other neutrino deuteron experiment at Krasnoyarsk (Russia) nuclear reactor [13]. 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.

roundings. All components of the detector are made of selected materials with low radioactivity contamination.

Solar neutrinos are 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 $\nu_i+d \to \nu_i+n+p$. Near 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 the heavy water, or by capture on ^{3}He using proportional counters. Expected number of neutrons from all sources in the D_2O volume is calculated as $\approx 5\times10^3$ during 1 yr period of exposition, with main contribution from the Solar ν's. Efficiency for n detection is 83% for n capture on ^{35}Cl [12].

Using super-low background, large amount of D_2O and high sensitivity of the SNO detector, the limit on the p decay independent on channel can be highly improved. Again, we can conservatively attribute all neutrons in the D_2O volume to p decays and accept it as the excluded value of $\lim S$. Substituting in the formula for τ the values of ε=0.83, measuring time t=1 yr, number of deuterons $N_d=6\times10^{31}$ and $\lim S = 5\times10^3$ counts, we receive $\tau(p \to ?) > 1\times10^{28}$ yr, which is about five orders of magnitude higher than present-day limit.

However this value can be improved further by accounting the n events originating from Solar ν's and high energy γ quanta. Number of n born in the D_2O volume due to disintegration $\nu_i+d \to \nu_i+n+p$ can be estimated independently using the number of Solar ν interactions with the detector through reaction $\nu_i+e^- \to \nu_i+e^-$. Neutrons created by γ quanta can be also 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 rate, that gives $\lim S = 2\sqrt{5000}$ with 95% C.L. Corresponding bound on the p life-time is $\tau(p \to ?) > 4\times10^{29}$ yr. This value is close to the limits established for the particular modes of the nucleon decays to charged or strongly interacting particles and would be of a great importance for many extensions of the modern gauge theories.

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