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New limits on di-nucleons decay into invisible channels

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Data of the radiochemical experiment (E.L. Fireman, 1978) with 1.7 t of $KC_2H_3O_2$, accumulated deep underground during $\simeq$1 yr, were reanalyzed to set limits on di-nucleons (nn and np) decays into invisible channels (disappearance, decay into neutrinos, etc.). The obtained lifetime bounds $\tau_{np} > 2.1 \cdot 10^{25}$ yr and $\tau_{nn} > 4.2 \cdot 10^{25}$ yr (at 90% C.L.) are better (or competitive) than those established in the recent experiments.

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More than three decades searches for the proton decay, which is predicted by the Grand Unified Theories, continue to be one of the most important and intriguing subjects in quest of the effects beyond the Standard Model of elementary particles [1]. Up to now, only lifetime limits were established for such processes, being on the level of $\tau > 10^{30} - 10^{33}$ yr for the nucleons decay into particles, which can strongly or electromagnetically interact with the nuclei contained in the detector's sensitive volume [2]. Recently, the interest increased to nucleon decays into so called "invisible" channels (which are complementary to conventional ones [2]) when nucleon or pair of nucleons decay into some weakly interacting particles (for example, neutrinos) or disappear. The last possibility is related with theories describing our world as four-dimensional brane embedded into higher-dimensional structure [3 – 5]. According to [5], disappearance of particles into extra dimensions is a generic property of matter. Searches for disappeared energy and/or momentum in particles' collision are planned with accelerators at high energies [6]. An experiment to search for disappearance of orthopositronium is discussed in [7]. Perspectives to search for invisible decays of neutrons and di-neutrons in ^{12}C with the 1000 t KamLAND detector are examined in [8], and sensitivities of future 1000 t lead perchlorate detector for n disappearance in ^{35} Cl and ^{208}Pb are considered in [9].

As for the to-date status, the most stringent limits for nucleons and di-nucleons decay into invisible channels have been known from the experiments performed during few last years (all bounds are given with 90% C.L.):

(1) $\tau_p > 3.5 \cdot 10^{28}$ yr – from number of free neutrons which could be created in result of p disappearance in deuterium nuclei ($d = pn$), which are contained in 1000 t of D_2O of the SNO apparatus [10];

(2) $\tau_p > 3.9 \cdot 10^{29}$ yr and $\tau_n > 3.9 \cdot 10^{29}$ yr – from number of γ quanta with $E_\gamma = 6 - 7$ MeV which will be emitted in deexcitation of ^{15}O or ^{15}N after n or p disappearance in ^{16}O nucleus in 1000 t of the SNO heavy water [11];

(3) $\tau_{pp} > 5.0 \cdot 10^{25}$ yr and $\tau_{nn} > 4.9 \cdot 10^{25}$ yr – from the search for decay of radioactive nuclei (^{10}C, ^{11}Be and ^{14}O) created after pp and nn disappearance in ^{12}C, ^{13}C and ^{16}O nuclei in liquid scintillator (4.2 t of $C_{16}H_{18}$) and water shield (1000 t) of the BOREXINO Counting Test Facility [12];

(4) $\tau_{np} > 3.2 \cdot 10^{23}$ yr – from the search for decay of ^{134}I created in result of np disappearance in ^{136}Xe [13].

In order to improve the τ_{np} limit, we reanalyze here the data of the old radiochemical experiment [14] where the daughter nuclide ^{37}Ar was searched for as a possible product of the p or n disappearance in ^{39}K. The target, 1710 kg of potassium acetate $KC_2H_3O_2$ which contains $9.7 \cdot 10^{27}$ atoms of ^{39}K, was exposed deep underground (the Homestake mine, 4400 m w.e.) during more than 1 year. The production rate of ^{37}Ar, extracted from the target and detected due to its radioactive decay $^{37}\text{Ar} \to {}^{37}\text{Cl}$ ($T_{1/2} = 35$ d), for the last 3.5 months period was measured as 0.3±0.6 atom/day. On this basis authors have accepted the limit on production rate of ^{37}Ar as one atom/day and have calculated the restrictions on the p and n lifetimes [14, 15]. For example, after the p decay in $^{39}_{19}$K, the nucleus $^{38}_{18}$Ar will be created, as a rule being in an excited state (unless the disappeared p was on the outermost shell). The authors estimated that in 22.2% of cases additional neutron will be emitted from $^{38}_{18}$Ar in deexcitation process giving rise to $^{37}_{18}$Ar nucleus [14, 15]. Similarly, after the n disappearance in initial $^{39}_{19}$K, produced $^{38}_{19}$K emits p with 20.4% probability, which will also result in the $^{37}_{18}$Ar nucleus. From these values, accounting for 19 protons and 20 neutrons in the $^{39}_{19}$ K, the limits $\tau_p = \tau_n = 1.1 \cdot 10^{26}$ yr were set [14, 15].

However, the same data can be used to calculate the τ_{np} limit, just noticing that simultaneous disappearance

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of the np pair in $^{39}_{19}$K also will produce the $^{37}_{18}$Ar nucleus. The corresponding limit on lifetime can be derived by using the formula:

$$\lim\tau = N_{nucl} \times N^{\text{eff}}_{obj} \times t/\lim S, \quad (1)$$

where N_{nucl} is the number of ^{39}K nuclei; N^{eff}_{obj} is the "effective" number of objects (here np pairs) whose disappearance in the parent nucleus will result in creation of the daughter nuclide; t is the time of measurements; and $\lim S$ is the number of effect's events which can be excluded at a given confidence level on the basis of the experimental data.

According to the Feldman-Cousins procedure [2, 16], the measured value of ^{37}K production rate $S/t = 0.3 \pm 0.6$ atom/day results in the limit $\lim S/t = 1.28$ atom/day at 90% C.L. Conservatively supposing only *one* np pair (for 1 unpaired proton in the $^{39}_{19}$K nucleus; disappearance of the outermost proton and neutron on nucleons shell in parent nucleus will produce daughter in a non-excited state) and using the eq. (1) with $N_{nucl} = 9.7 \cdot 10^{27}$, we obtain the following np lifetime limit:

$$\lim\tau_{np} = 2.1 \cdot 10^{25}\,\text{yr at 90\% C.L.}$$

In addition, the τ_{nn} bound can be also determined: disappearance of the nn pair from $^{39}_{19}$K nucleus will give $^{37}_{19}$K which quickly decays again to $^{37}_{18}$Ar with $T_{1/2} = 1.2$ s [17] [2] . The number of objects, N^{eff}_{obj}, can be calculated in the following way [12, 18, 19]. After disappearance of neutrons with binding energies $E^b_{n1}(A,Z)$ and $E^b_{n2}(A,Z)$ in (A,Z) nucleus, the excitation energy of the $(A-2,Z)$ daughter, E_{exc}, can be approximated as $E_{exc} = E^b_{n1}(A,Z) + E^b_{n2}(A,Z) - 2S_n(A,Z)$, where $S_n(A,Z)$ is the binding energy of the least bound neutron in the (A,Z) nucleus. In the process of deexcitation of the $(A-2,Z)$ daughter only γ quanta can be emitted when the value of E_{exc} is lower than the binding energy of the least bound nucleon in the $(A-2,Z)$ nucleus: $E_{exc} < S_N(A-2,Z)$, where $S_N(A-2,Z) = \min\{S_n(A-2,Z),\ S_p(A-2,Z)\}$[3]. Under this condition we receive the restriction on the values of the neutrons binding energies: $E^b_{n1}(A,Z) + E^b_{n2}(A,Z) < 2S_n(A,Z) + S_N(A-2,Z)$.

Values of the separation energies S_n and S_p were taken from [20]. Single-particle energies $E^b_n(A,Z)$ for neutrons in the $^{39}_{19}$K nucleus were calculated with the WSBETA code [21] using the Blomqvist-Wahlborn parameterization of the Woods-Saxon potential [22]. Calculated value of the neutron separation energy $S^{\text{calc}}_n = 13.08$ MeV is in good agreement with the experimental value $S^{\text{exp}}_n = 13.07$ MeV [20]. We conservatively suppose that contributions to the effective number of objects, N^{eff}_{obj}, give only paired neutrons (i.e. neutrons with equal values of all quantum numbers, except for the magnetic quantum number), and neglect contributions from other neutrons. Taking into account that the binding energies of such particles are equal, the appropriate equation is as follows: $2E^b_n(A,Z) < 2S_n(A,Z) + S_N(A-2,Z)$. This condition gives only 2 nn pairs whose disappearance from $^{39}_{19}$K will produce relatively low-excited daughter $^{37}_{19}$K, which emit only γ quanta (hence, can not be transformed to nucleus with $A < 37$ in result of ejection of additional nucleons). Substituting the values $N_{\text{nucl}} = 9.7 \times 10^{27}$, $N^{\text{eff}}_{obj} = 2$ and $\lim S/t = 1.28$ 1/day in eq. (1) one gets

$$\lim\tau_{nn} = 4.2 \cdot 10^{25}\ \text{yr at 90\% C.L.}$$

In conclusion, reanalysis of the data of the radiochemical experiment of Fireman [14] allows us to establish the limits: $\tau_{nn} > 4.2 \cdot 10^{25}$ yr and $\tau_{np} > 2.1 \cdot 10^{25}$ yr at 90% C.L. The τ_{nn} value is near the same as that given recently by the BOREXINO Collaboration ($\tau_{nn} > 4.9 \cdot 10^{25}$ yr [12]), while the obtained value for τ_{np} is two orders of magnitude higher than that set in [13] and is the most restrictive up-to-date limit for the np decays into invisible channels.

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[2] Unfortunately, disappearance of the pp-pair results in creation of stable nucleus $^{37}_{17}$Cl, and, thus, cannot be investigated in this approach.

[3] Higher excitations of daughter nucleus will result in deexcitation process with emission of mostly n, p, etc., instead of γ quanta, and give not the $(A-2, Z)$ nucleus but isotopes with lower A and Z values.

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