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Experimental limit on the charge non-conserving β decay of ^{73}Ge

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Abstract

Data collected during 637 days in the Baksan Neutrino Observatory with 1 kg high purity Ge semiconductor detector have been analyzed to search for charge non-conserving β decay of ^{73}Ge. It is the first real-time experiment, in which one of the best up-to-date life time limits has been established for this process as: τ_{CNC} ($^{73}\text{Ge} \to {}^{73}\text{As}) > 2.6 \times 10^{23}$ yr at 90% C.L. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The investigation of the possibility that electric charge conservation (CC) can be broken in certain classes of unified theories has a long history and was discussed intensively in the literature (see [1–6] and reviews [7,8]). It is well known that invariance of the QED Lagrangian under U(1) local gauge transformations requires massless photons and exact CC in accordance with the Weinberg theorem [9]. Thus, to provide charge non-conservation (CNC) phenomena, photons cannot be exactly massless, which in turn requires either no gauge invariance at all, or broken gauge symmetry. Unfortunately, both these assumptions are rather artificial. Indeed, cancellation of gauge invariance principle in some models, where small explicit mass of photon is introduced "by hand", looks quite unmotivated theoretically. On the other hand, Higgs mechanism of spontaneous breaking of a U(1) gauge symmetry calls for existence of a charged scalar field, whose tiny vacuum expectation value should be also introduced "by hand", and whose charge should not exceed 10^{-3} of the electron charge to avoid noticeable contribution to the Lamb shift, etc. [8,10]. Moreover, the detailed analysis performed in Refs. [1,2,7,8] shows that "*emission and absorption of such almost-massless charged bosons would drastically change the whole of electrodynamics, so their existence in our world is definitely ruled out*" [8]. The remaining possibility of an explicit gauge symmetry break-

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ing would lead to the catastrophic emission of huge amount (10^{14}–10^{21}) of longitudinal bremsstrahlung photons with tiny energies, which are unobservable [1, 2,8]. Hence, one can conclude that no self-consistent theory describing non-conservation of electric charge has been constructed yet.

Notwithstanding these theoretical problems, the experimental efforts to test the underlying principle of charge conservation are continuing since 1959 [11]. The standard approach (the pioneer work [11]) is to look for the X ray and Auger electron cascades, which would follow the electron decay on an atomic shell of any atom inside the sensitive volume of a suitable detector. This so-called "disappearance" approach is appropriate to study all electron decay modes, in which product particles escape the detector without depositing energy; an example is the $e^- \to \nu_e \bar{\nu}_e \nu_e$ mode. The highest bound on the mean life of the electron's "disappearance" is: $\tau_e > 2.4 \times 10^{24}$ yr at 90% C.L. [12]. Another method, sensitive only to the electron decay into a neutrino and photon, $e^- \to \nu_e \gamma$, is to search for γ rays of ≈ 255.5 keV following the decay of electron. To date the best limit for the decay channel $e^- \to \nu_e \gamma$ is even higher: $\tau_e > 2.0 \times 10^{26}$ yr at 90% C.L. [13]. However, because of the mentioned problem of the catastrophic emission of longitudinal bremsstrahlung photons, the decay of an electron may not be accompanied by a γ line with energy 255.5 keV [8]. At the same time, it was argued that the filling of the atomic shell after the electron disappearance will occur before the emission of soft photons and cannot be affected by this process (see for details [14]). In that sense the "disappearance" limit is more "safe" and model independent.[1] An additional approach consists in a search for the disappearance of electrons on atomic shells, involving excitation of low-energy nuclear levels: the highest bound is $\tau_e > 3.7 \times 10^{24}$ yr at 90% C.L. [18].

Besides mentioned methods, the electric charge conservation can be also tested for nucleons by looking for the CNC β decay, as it was first pointed out in [11]. However, such processes were investigated less extensively as compared to those for the electron's decays. In particular, the CNC β decay was studied with three nuclei: ^{87}Rb $\to$ $^{87\mathrm{m}}$Sr [19–21], ^{113}Cd $\to$ $^{113\mathrm{m}}$In [22] and ^{71}Ga $\to$ ^{71}Ge [23,24]. It is necessary to emphasize that in all these experiments the chemical extraction of the daughter element with subsequent search for its radioactive decay has been used.

In this Letter the results of the search for the CNC β decay of ^{73}Ge in the direct real-time experiment are presented for the first time. They were obtained by re-analyzing the data (≈ 1.7 yr kg statistics) initially collected with the low-background high purity (HP) Ge semiconductor detector for the Dark Matter particles quest [25].

2. Experimental approach

If single neutron in parent nucleus (A, Z) undergoes CNC β decay

$$n \to p + \text{neutrals}, \tag{1}$$

in which massless uncharged particles (f.e., ν_e or γ) are emitted instead of an electron, the additional 511 keV of energy release (as compared with that of charge conserving β decay $n \to p + e^- + \bar{\nu}_e$) would become available. The latter could make it energetically possible the decay of parent nucleus (A, Z) to ground state or to excited levels of daughter $(A, Z+1)$, otherwise forbidden. For the first time the CNC β decay was searched for with ^{87}Rb [19], and idea of this study is illustrated by Fig. 1, where ^{87}Rb–^{87}Sr level scheme [26] is depicted. Usually the ^{87}Rb undergoes β decay to ground state of ^{87}Sr ($T_{1/2} = 4.8 \times 10^{10}$ yr, $Q_\beta = 273$ keV), thus decay to the $^{87\mathrm{m}}$Sr isomeric state ($T_{1/2} = 2.8$ h, $E = 388$ keV) is not energetically allowed. However, if decay (1)

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[1] Nowadays, the quest for the electron "disappearance" has became more actual due to development of theories with more than three spatial dimensions. Recently the emphasis in these theories [15] has shifted toward "brane world" picture, in which ordinary matter is trapped to a three-dimensional brane embedded in the multi-dimensional space (see review [16]). In such a scenario extra dimensions may be large, and even infinite. One of prediction of this "brane world" picture is that massive fermions, in particular electrons, may escape our world into extra dimensions [10,16, 17]. Hence, observation of the electron "disappearance" would be a signature of infinite extra dimensions. Unfortunately, at current stage of theory quantitative calculation of the probability of such an electron escape is too premature [16], however the simplest estimate made in Ref. [10] gives $\tau_e \approx 10^{27}$ yr, which is not so far from the present level of sensitivity of the experiments.

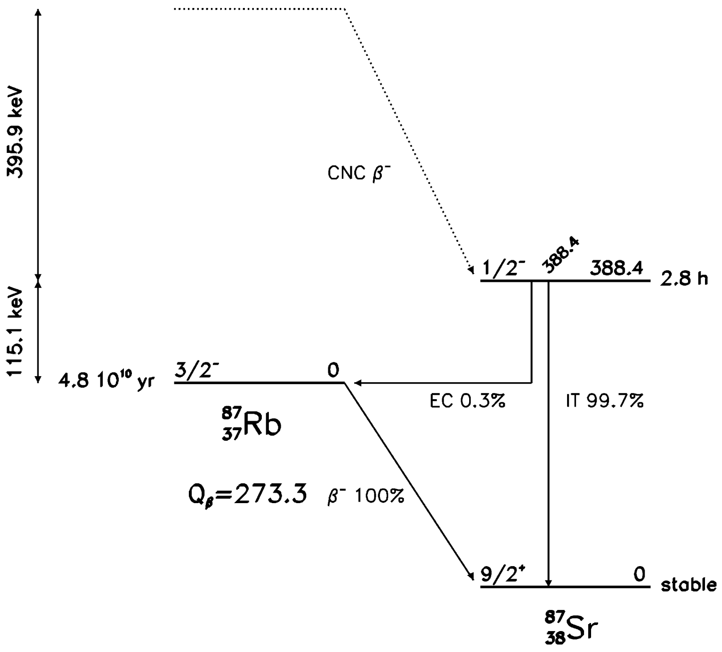

Fig. 1. Level scheme of the ^{87}Rb–^{87}Sr. Energies of excited levels are given in keV [26].

Table 1
Experimental life time limits on the charge non-conserving β decay

CNC β decay	Target, weight	Used technique, detector	Limit τ_{CNC}, yr (at 90% C.L.)[a]	Year, reference
$^{87}\mathrm{Rb} \to {}^{87\mathrm{m}}\mathrm{Sr}$	RbF, 30 g	Chemical separation, NaI(Tl) detector	$> 1.8 \times 10^{16}$	1960 [19]
$^{87}\mathrm{Rb} \to {}^{87\mathrm{m}}\mathrm{Sr}$	$\mathrm{Rb_2CO_3}$, 400 g	CS[b], Ge(Li)	$> 1.9 \times 10^{18}$	1979 [20]
$^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}$	Ga, 300 kg	CS, prop. counter	$> 2.3 \times 10^{23}$	1980 [23]
$^{87}\mathrm{Rb} \to {}^{87\mathrm{m}}\mathrm{Sr}$	$\mathrm{Rb_2CO_3}$, 800 g	CS, Si(Li)	$> 7.5 \times 10^{19}$	1983 [21]
$^{113}\mathrm{Cd} \to {}^{113\mathrm{m}}\mathrm{In}$	$\mathrm{CdCl_2}$, 1.5 kg	CS, Si(Li) + NaI(Tl)	$> 1.4 \times 10^{18}$	1983 [22]
$^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}$	$\mathrm{GaCl_3}$–HCl, 101 t + Ga, 57 t	CS, prop. counter	$> 3.5 \times 10^{26}$	1996 [24]
$^{73}\mathrm{Ge} \to {}^{73}\mathrm{As}$	Ge, 952 g	Real-time measur., HP Ge	$> 2.6 \times 10^{23}$	This work

[a] Limits [19] and [24] are given at 68% C.L.
[b] CS means chemical separation.

occurs in ^{87}Rb nucleus, the $^{87\mathrm{m}}$Sr isomeric state can be populated due to the additional 511 keV energy release. In the experiment [19] the Sr fraction, which could be created in the used RbF sample with mass of 30 g, was separated chemically. Then, Sr extract was measured with the help of NaI(Tl) detector aiming to observe the $^{87\mathrm{m}}$Sr decay, which would indicate the existence of the CNC β decay of ^{87}Rb. However, only the life time limit $\tau > 1.8 \times 10^{16}$ yr was established for this process [19]. Hereafter, this bound was advanced up to $\tau > 7.5 \times 10^{19}$ yr at 90% C.L. [21]. Besides, two other nuclides were investigated: $^{113}\mathrm{Cd} \to {}^{113\mathrm{m}}\mathrm{In}$ ($\tau > 1.4 \times 10^{18}$ yr at 90% C.L.) [22] and $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}$ (the best limit is $\tau > 3.5 \times 10^{26}$ yr at 68% C.L. [24]).[2] Summary of the results is given in Table 1. As it is seen from this table, in all previous experiments the exploited technique includes chemical separation of the daughter $(A, Z + 1)$ element and subsequent search for its radioactive decay with the help of appropriate detector.

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[2] This bound was obtained on the basis of results of the SAGE and GALLEX solar neutrino experiments, in which Ga targets with total mass of ≈ 100 t were used.

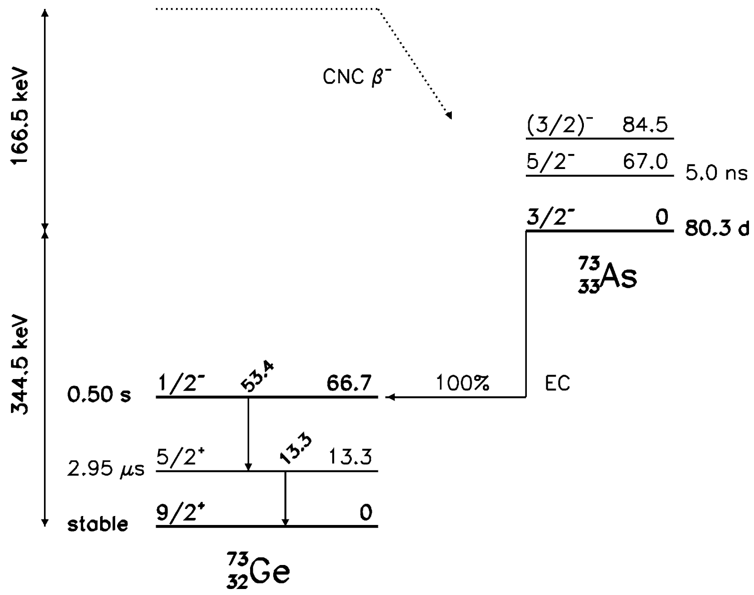

Fig. 2. Scheme of the CNC β decay of ^{73}Ge.

The procedure of chemical separation allows one to decrease mass of the sample by many orders of magnitude, and consequently, to reduce the background of the detector substantially. At the same time, the procedure of chemical separation is very laborious and restricts the number of nuclides, which can be used in such experiments. Another disadvantage of this method is the losses (sizable in some cases) of effect's events due to decay of $(A, Z+1)$ nuclei during the period of their accumulation and chemical separation. Besides, there are processes which will also result in the production of $(A, Z+1)$ nuclei (or their daughters) from the (A, Z) parent. These are: (i) (p, n) reaction caused by proton flux near the Earth's surface (or deep underground, where protons are born in the interactions of cosmic muons with matter); (ii) $(\alpha, p3n)$ reaction due to α particles from natural U and Th radioactive chains; (iii) capture of solar neutrinos $(A, Z) + \nu_e \to (A, Z+1) + e^-$. Two-neutrino 2β decay $(A, Z) \to (A, Z+2) + 2e^- + 2\bar{\nu}_e$ can mimic the CNC β decay too. Indeed, if the $(A, Z+1)$ nucleus, created in the CNC β decay, is unstable and transforms further to $(A, Z+2)$ nucleus through usual β decay, both CNC β decay and $2\nu 2\beta$ decay will give the same $(A, Z+2)$ product. Thus one cannot decide from geochemical and radiochemical experiments, aiming to search for $(A, Z+2)$ nuclei in (A, Z) target, which process is responsible for the appearance of $(A, Z+2)$ daughters. The contributions from these processes must be also taken into account when evaluating the limits on the probability of the CNC β decay from experimental data.

Almost all these drawbacks can be overcame in other class of experiments, in which a parent isotope is embedded in the detector itself (so called "active source = detector" technique), and in which decay events can be processed in a real-time without any losses and with efficiency close to unit. In such an approach the large masses up to several tons (using, f.e., the future 2β decay, dark matter, and solar neutrinos detectors) can be exploited and much wider list of candidate nuclei is available. However, because absence of the chemical separation, the background of the large mass detector would be also huge, thus to suppress it strongly, only particular candidate nuclei (A, Z) with very distinguished features of the daughter's decay (f.e., with a peculiar time structure of the decay) could be appropriate.

One good candidate for the CNC β decay study is ^{73}Ge. Its natural abundance is $\delta = 7.73\%$ [27], hence, high purity Ge semiconductor detectors with the excellent energy resolution can be used. The ^{73}Ge–^{73}As level scheme is shown in Fig. 2. The ground state and two first excited levels of ^{73}As can be populated in the CNC β decay. Then ^{73}As nucleus transforms back to ^{73}Ge through an electron capture, where the excited level of ^{73}Ge with the energy of 66.7 keV is populated with 100% probability [26]. The two excited levels of ^{73}Ge, 66.7 and 13.3 keV, through which a deexcitation process goes, have half-lives of 0.50 s and 2.95 µs, respectively. Due to these circumstances, the time evolution of a signal from ^{73}As electron capture has very unique features: (1) the event with the energy of 11.1 keV, corresponding to the deexcitation process in ^{73}Ge atomic shell after the capture of K electron in ^{73}As, which can be used as a trigger; (2) the cascade of two pulses: (a) the first one with the energy release of 53.4 keV delayed up to a few seconds after the trigger (it corresponds to deexcitation of the 66.7 keV level with emission of conversion electron or γ quantum); (b) the second one with the energy of 13.3 keV and with an additional delay of a few µs (corresponding to the deexcitation of the 13.3 keV level). Such a time structure of the ^{73}As decay signal (in addition to the exactly known energies of each component) allows one to suppress background of the detector practically to a zero level.

3. Measurements and data analysis

The description of the experimental setup with HP Ge detector and its performance have been published elsewhere [25], thus only the main features of this apparatus are summarized here. Measurements were performed in the Low Background Underground Laboratory of the BNO INR at a depth of 660 m of water equivalent. The setup was placed in a low background chamber, which was made of consequent layers of low radioactive concrete (50 cm), dunite (50 cm) and steel (0.8 cm) [28].

The HP Ge detector with sensitive mass of 952 g and with natural isotopic composition of Ge was used. It contains 74 g of ^{73}Ge or 6.07×10^{23} of ^{73}Ge nuclei. The passive shield of the detector consists of high purity copper (12 cm), lead (21 cm) and borated polyethylene (8 cm). Because air in the low background chamber can be contaminated by radon, the setup was isolated against air penetration and a high purity nitrogen gas was continuously flushed inside the shield. The passive shield was surrounded by 5 modules of liquid scintillators (with 10–15 cm thickness) used as veto counters.

The data acquisition permits to record complete information for each signal of the Ge detector, including: (i) its amplitude (energy) from ADC with precision 0.05 keV per channel; (ii) its digitized pulse shape from digital oscilloscope CompuScope 220 (sampling rate 20 MHz, precision 256 points) in the time interval 3–12 µs; (iii) arrival time of Ge event with precision of 1 ms from computer clock; (iv) time interval between last veto signal from active shield and Ge pulse with precision of 0.25 ms. The energy scale and resolution of the detector were determined in the calibration measurements with different sources (^{60}Co, ^{137}Cs, ^{207}Bi and ^{241}Am). For instance, the energy resolution of the detector for 59.5 keV line of ^{241}Am was equal to FWHM $= 0.76$ keV, while the energy threshold was about 2 keV.

As it was shown in our previous papers [25] the initial background spectrum of the detector below 80 keV has three relatively intensive peaks at ≈ 6, ≈ 9 and ≈ 10.4 keV from the decays of cosmogenically produced ^{54}Mn, ^{65}Zn, and ^{68}Ge, respectively. The entire background spectrum in the region from 20 keV to 80 keV is actually flat with an average count rate of 36 counts $\mathrm{yr}^{-1}\,\mathrm{keV}^{-1}\,\mathrm{kg}^{-1}$ [25].

The data accumulated during 15 288 h live time were processed in the following way. The events with the energy 66.7 ± 0.7 keV ($\pm 2\sigma$ region around the energy of ^{73}Ge deexcitation that includes 95.5% of expected events) were chosen as a trigger. Afterwards, the preceding signals within the time interval of 0–3 s and in the energy range 2.5–35.0 keV were searched for.[3] Five such events were found with the following energies: 2.5 keV (time interval between this event and signal of 66.7 keV is $\Delta t = 0.32$ s), 2.6 keV ($\Delta t = 0.92$ s), 4.4 keV ($\Delta t = 0.83$ s), 8.7 keV ($\Delta t = 0.07$ s), and 11.1 keV ($\Delta t = 1.43$ s). It yields an average count rate of 2.9 counts yr^{-1} in the 2.5–35.0 keV energy interval of preceding pulses. The same analysis was also performed for triggers, whose energy windows (of the same width ± 0.7 keV) were centered at 55 and

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[3] Because limited dynamical range of the digital oscilloscope it was not possible to investigate the time sub-structure of the 66.7 keV signal within the time range of a few µs. Thus, in the current analysis we were not able to use all unique time-amplitude features of the expected signal.

75 keV, i.e., one below, the other above the 66.7 keV. In these cases no preceding pulses were found.

The observed events can be explained by the neutrons[4] inelastic scattering on ^{73}Ge nuclei with excitation of the 66.7 keV level of ^{73}Ge. This assumption was proved in the quest for WIMPs (Weakly Interacting Massive Particles) inelastic scattering on ^{73}Ge nuclei with excitation of the 13.3 keV level of ^{73}Ge accomplished with the help of our apparatus [25]. With this aim double events (second pulses with the energy 13.3 ± 0.5 keV) in the time interval 3–15 µs were searched for and 32 such events were found. All of them were in coincidence with the active shielding, i.e., they were due to the cosmic ray neutron background [25].

However, one observed event with the energy 11.1 keV could be considered as candidate for ^{73}As electron capture. Most probably this event is decay of remaining ^{73}As, produced by cosmic rays in Ge crystal during period when detector was on the Earth surface. It could be also caused by background reactions (p,n), $(\alpha, p3n)$ or (ν_e, e^-), or can be imitated because of ignorance of the time substructure of the 66.7 keV signal. Hence, only a limit on the life time for the CNC β decay of ^{73}Ge can be established on the basis of our experimental data. For this purpose the known formula was used

$$\lim \tau = \frac{\varepsilon N t}{\lim S}, \qquad (2)$$

where ε is the efficiency of the event's detection (in which all cuts are taken into account); N is the number of ^{73}Ge nuclei ($N = 6.07 \times 10^{23}$); t is the time of measurements ($t = 15\,288$ h); and $\lim S$ is the number of effect's events which can be excluded with a given confidence level. The overall efficiency $\varepsilon = 0.85$ is a product of several terms: $\varepsilon = \varepsilon_K \varepsilon_{\Delta E} \varepsilon_{\Delta t} \varepsilon_{11.1} \varepsilon_{53.4} \varepsilon_{13.3}$, where $\varepsilon_K = 0.88$ is the probability of the electron capture in ^{73}As from K atomic shell, $\varepsilon_{\Delta E} = 0.955$ is the part of events inside $\pm 2\sigma$ region around energy of 66.7 keV, $\varepsilon_{\Delta t} = 0.984$ is the part of events in the time interval of 3 s corresponding to the half-life $T_{1/2} = 0.50$ s of the 66.7 keV level. Efficiencies to detect the peaks of full absorption with energies of 11.1 keV, 13.3 keV and 53.4 keV are equal $\varepsilon_{11.1} = \varepsilon_{13.3} = 1$, $\varepsilon_{53.4} = 0.99$, in particular because of high coefficients of internal conversion $(e/\gamma)_{13.3} = 325$ and $(e/\gamma)_{53.4} = 9$ [26].

The $\lim S$ value was determined by using the Feldman–Cousins procedure [29], which is recommended by the Particle Data Group [30]. The expected background was estimated first as follows. With four counts observed in the 2.5–35.0 keV energy region (beside event at 11.1 keV) and with the energy resolution of FWHM = 0.7 keV at 11.1 keV, it is anticipated about 0.15 counts in $\pm 2\sigma$ interval around 11.1 keV. In accordance with [29] one detected event, while 0.15 counts are expected as background, gives limit on the effect searched for as $\lim S < 4.2$ counts at 90% C.L. In fact, it is a very conservative bound because observed event was most likely caused by background origins listed above. Forasmuch it is not possible—at least for the moment—to calculate quantitatively the contributions of these origins, we can simply suppose that measured event belongs to background and accept one count in the $\pm 2\sigma$ energy interval around 11.1 keV as expected background. In this case the excluded number of events due to the CNC β decay of ^{73}Ge will be $\lim S < 3.4$ counts at 90% C.L. [29].

By substituting the last value into the formula (2) we get the life time limit

$$\tau_{\mathrm{CNC}}\big({}^{73}\mathrm{Ge} \to {}^{73}\mathrm{As}\big) > 2.6 \times 10^{23}\ \mathrm{yr} \quad \text{at 90\% C.L.}$$

It is one of the most stringent bounds on the CNC β decay processes established up to now (see Table 1). At the same time, it is the first result obtained by using the real-time detector ("active source = detector" technique).

4. Discussion and conclusions

As it was mentioned in the Introduction, currently there is no self-consistent theory, which can describe the possible small violation of the charge conservation (and which can allow one to derive restrictions on the CNC theoretical parameters on the basis of the obtained experimental life time limits on the CNC processes). Nevertheless, suitable CNC parameter is the relative strength of the CNC process to the corresponding charge conserving process. It can be introduced, f.e., according to Bachcall [31], by assum-

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[4] Because set up is located at relatively low depth (660 m of water equivalent) neutrons are created due to interaction of cosmic muons with the detector, passive shield and surrounding materials.

ing that the weak interactions include a small CNC part having the usual form, but with a neutrino replacing the electron in the lepton current. In the particular case of the CNC β decay this parameter, ε^2, may be expressed as the ratio of the probabilities of the elementary neutron decay through CNC channel $n \to p + \nu_e + \bar{\nu}_e$ to the ordinary one $n \to p + e^- + \bar{\nu}_e$ [31]

$$\varepsilon^2 = \frac{\Gamma(n \to p + \nu_e + \bar{\nu}_e)}{\Gamma(n \to p + e^- + \bar{\nu}_e)} = \frac{\tau(n)}{\tau_{\mathrm{CNC}}(A,Z)} \left[\left(\frac{W(n)}{W(A,Z)} \right)^5 \frac{ft_{1/2}(A,Z)}{ft_{1/2}(n)} \right]. \quad (3)$$

Here $\tau(n)$ is the mean life of free neutron (886.7 s [30]); $\tau_{\mathrm{CNC}}(A,Z)$ is the mean life of the CNC beta decay of the (A,Z) nuclide; $W(n)$ is the n–p mass difference (1.293 MeV [30]); $W(A,Z)$ is the *nuclear* mass difference between (A,Z) and $(A,Z+1)$ nuclei (in our case the difference between ground states of ^{73}Ge and ^{73}As is 166.5 keV [26]); $ft_{1/2}(n)$ is the comparative half-life of the neutron (using the value of $f = 1.692$ [32] and $\tau(n) = 886.7$ s [30], we get $ft_{1/2}(n) = 1040$ s). The comparative half-life $ft_{1/2}(A,Z)$ can be calculated from $ft_{1/2}(A,Z+1)$ with correction for the statistical factor, which takes into account the difference in spin between initial and final nuclear states: $ft_{1/2}(A,Z) = ft_{1/2}(A,Z+1)[2J(A,Z)+1]/[2J(A,Z+1)+1]$. However, the $ft_{1/2}(A,Z+1)$ value for transition from ground state of ^{73}As to ground state of ^{73}Ge is unknown (electron capture with 100% probability goes to excited 66.7 keV level of ^{73}Ge), and for estimation of the ε^2 limit we will use the recommended value for the threefold forbidden non-unique β processes: $\log ft_{1/2} = 18.2$ [33]. By substituting these numbers and our experimental bound in (3), we receive the limit: $\varepsilon^2 < 1.1 \times 10^{-8}$ at 90% C.L. This result is poor in comparison with previous limits (see, f.e., [24]). Nevertheless, it should be noted that bounds on parameter ε^2 are related only with the CNC admixture in the weak interactions, in which neutrino replaces an electron, while a τ_{CNC} limit is of more wide significance because it is valid for any CNC channel with emission of other massless uncharged particles: γ quantum, majoron(s), etc.

The obtained in this work bound can be improved at least by one order of magnitude in the future dark matter experiments with Ge detectors enriched in ^{73}Ge [25,34], or can be even advanced further in the large scale projects on 2β decay quest of ^{76}Ge with the help of HP Ge detectors with total mass in the range of 0.5–1 tons (GEM [35], GENIUS [36] and MAJORANA [37]). The limits on the CNC β decay of isotopes other than ^{73}Ge can be also obtained, as by-products, in the high sensitivity 2β decay experiments: NEMO [38] (for ^{100}Mo), CAMEO [39] (for ^{113}Cd and ^{116}Cd), CUORE [40] (for ^{125}Te and ^{130}Te), XMASS [41], EXO [42] (for ^{131}Xe and ^{136}Xe), and others.

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