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Charge non-conservation restrictions from the nuclear levels excitation of ^{129}Xe induced by the electron's decay on the atomic shell

P. Belli [a], R. Bernabei [a], C.J. Dai [b], G. Ignesti [c], A. Incicchitti [c], F. Montecchia [a], O.A. Ponkratenko [d], D. Prosperi [c], V.I. Tretyak [d], Yu.G. Zdesenko [d]

[a] Dip. di Fisica, Universita' di Roma ''Tor Vergata'' and INFN, sez. Roma2, I-00133 Rome, Italy
[b] IHEP, Chinese Academy, P.O. Box 918 / 3, Beijing 100039, China
[c] Dip. di Fisica, Universita' di Roma ''La Sapienza'' and INFN, sez. Roma, I-00185 Rome, Italy
[d] Institute for Nuclear Research, 252680 Kiev, Ukraine

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Abstract

Life time limits on the charge non-conserving (CNC) electron capture with nuclear levels excitation of ^{129}Xe are established for the first time by analysing a statistics of 823.1 kg · day collected by the $\simeq 6.5$ kg liquid Xenon DAMA scintillator at the Gran Sasso National Laboratory of INFN. These limits are in the range $\tau > (1\text{–}4) \cdot 10^{24}$ y at 90% C.L. for the different excited levels of ^{129}Xe. The presently most stringent restrictions on the relative strengths of charge non-conserving (CNC) processes are derived: $\varepsilon_W^2 < 2.2 \cdot 10^{-26}$ and $\varepsilon_\gamma^2 < 1.3 \cdot 10^{-42}$ at 90% C.L.

1. Introduction and theoretical consideration

The electric charge conservation (CC) is a fundamental law of QED; nevertheless, the possibility that CC may be broken in future unified gauge theories and the relative implications have been discussed in literature intensively [1–5]. Moreover, experimental tests of this basic feature of nature are continuing since 1959 [6]. Several experiments, allowing to test charge conservation for electrons and nucleons separately, have been performed (see [5,7] and references therein). The highest life time limit established for the electron's ''disappearance'' from the atomic shell is: $\tau_e > 2.4 \cdot 10^{24}$ y at 90% C.L. [7]. For the particular decay mode $e^- \to \nu_e + \gamma$ the best obtained limit is even higher: $\tau_e > 2.1 \cdot 10^{25}$ y at 90% C.L. [8] [1]. Among the experiments [10–15] aiming to study charge non-conserving (CNC) processes involving nucleons the highest τ limit has been set for the

[1] However, the result for $e^- \to \nu_e + \gamma$ may be affected by the catastrophic emission of longitudinal bremsstrahlung photons with tiny energies, thus the decay of an electron will not be accompanied by the 255.5 keV γ rays [5]. On the contrary, the filling of the shell after the electron disappearance would occur before the emission of soft photons and will not be affected by them (see [8]). Therefore the disappearance τ limit is considered more ''safe'' and model independent [9].

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CNC beta decay $^{71}Ga \rightarrow {}^{71}Ge$ ($\tau > 3.5 \cdot 10^{26}$ y at 68% C.L. [15]).

Holjevic et al. [16] have proposed and realized another approach for the CNC quest; it searches for processes in which an electron disappears from the atomic shell and the nucleus is left in an excited state. Such processes are analogous to the usual electron capture but do not change the nucleus' charge:

$$(A,Z) + e^- \rightarrow (A,Z)^* + \nu_e. \quad (1)$$

Possible mechanisms of this kind have been examined in Refs. [16,17], where their advantages for the CNC quest have been pointed out. First, the CNC nuclear excitation includes both the weak boson and photon mediating processes. Secondly, while the electron decay is concerned with the CNC process at the lepton sector, the nuclear excitation (as the nuclear beta decay) is concerned with both the lepton and quark sectors [17].

The CNC electron capture (1) can feed the excited states of the nucleus with energies E_{exc} up to $m_e c^2 - E_B$ (E_B is the binding energy of the electron in the considered atomic shell). It is supposed that CNC excitation feeds preferably the lowest levels with difference in spin between ground and excited state $\Delta J = 0,1$ and that K electrons most probably are involved in the process being the closest to the nucleus. In the de-excitation the nucleus returns to the ground state emitting γ quanta and conversion electrons which could be observed using a proper detector. If the electron capture takes place in the detector itself, the observed energies will be shifted to the value $E_{exc} + E_B$ due to absorption of X-rays and Auger electrons emitted in the relaxation of the atomic shell.

The first experimental investigation [16] for such a kind of processes was performed by using a NaI(Tl) scintillator ($\simeq 7500$ cm^3 volume) looking for the possible nuclear level excitations of ^{127}I; the corresponding γ rays were searched for in the measured energy spectrum, obtaining for the CNC electron capture process $\tau \gtrsim 2 \cdot 10^{21}$ y at 90% C.L. [16]. This result was later improved ($\tau \gtrsim 6 \cdot 10^{22}$ y at 68% C.L.) by the Osaka group using a 0.18 m^3 total volume NaI(Tl) array at the Kamioka underground laboratory [17]. More recently, the DAMA collaboration has established new τ limits on the CNC electron capture of ^{127}I and ^{23}Na in the range of (1.5–2.4) $\cdot 10^{23}$ y at 90% C.L. by exploiting the $\simeq 100$ kg NaI(Tl) DAMA set up features [18].

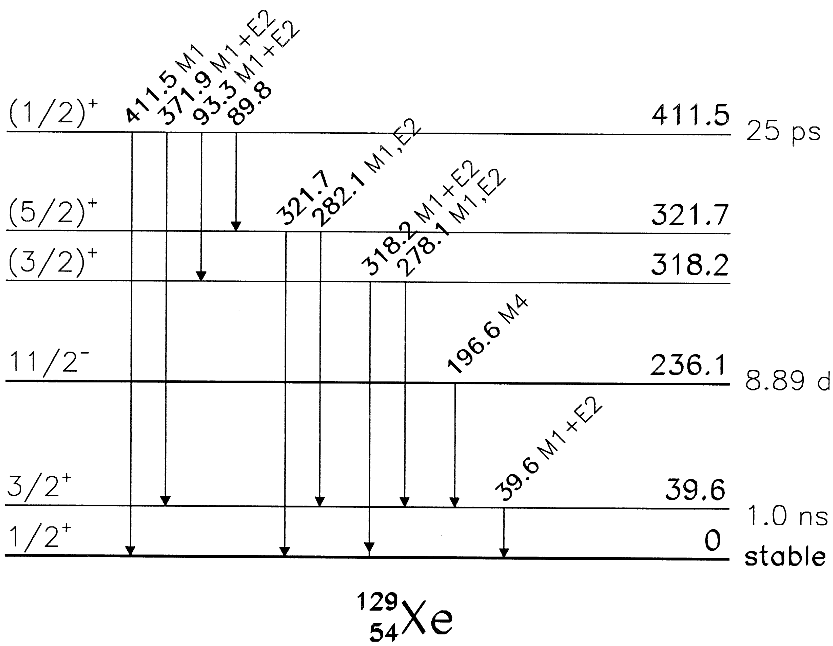

Fig. 1. Low energy part of the level scheme of ^{129}Xe [23].

In this paper the first investigation of the CNC electron capture involving nuclear levels excitation of ^{129}Xe is presented. It has been realized by using the 6.5 kg DAMA liquid Xenon (LXe) scintillator (filled with Kr-free Xenon enriched in ^{129}Xe at 99.5%). In the last years by means of this LXe set up several results in the particle Dark Matter searches have been achieved [19–21]. Besides, it was also applied to study the electron stability, obtaining $\tau_e > 1.5 \cdot 10^{23}$ y for the electron disappearance and $\tau_e > 2 \cdot 10^{25}$ y for the $e^- \to \nu_e + \gamma$ decay mode (both at 68% C.L.) [22]. In accordance with the level scheme shown in Fig. 1 five levels of ^{129}Xe could be excited due to the process (1) searched for ($E_{\rm exc} = 39.6$; 236.1;318.2;321.7 and 411.5 keV) [23]. The first one is the most interesting due to the difference in spin $\Delta J = 1$ between ground $(1/2^+)$ and excited level $(3/2^+)$ and to the very low energy (39.6 keV) which is favorable to derive restrictions on the CNC parameters of the theory from the experimental τ limits.

Following Bahcall [24] a suitable parameter to describe CNC in the lepton sector is the relative strength of the CNC process to the corresponding allowed CC one; this choice is based on the assumption that the weak interactions include a small CNC part which has the usual form except for a neutrino replacing the electron in the lepton current [24]. For the particular case of the CNC electron capture with nuclear levels excitation a similar approach was exploited in [16,17] and developed further in [18]. Here we recall briefly the main results of the calculation connecting $\tau^{\rm CNC}$ with the above quoted parameter [18] which will be used in the present work.

Let us consider two CNC processes whose diagrams are presented in Fig. 2a (CC is violated in the hadron sector) and Fig. 2b (CC is violated in the

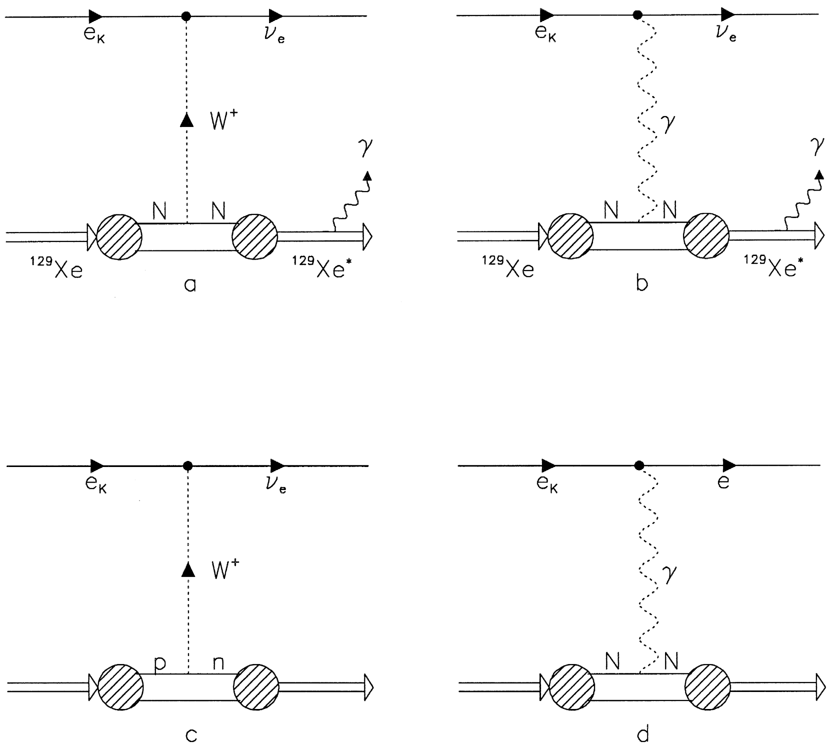

Fig. 2. Diagrams of CNC processes: (a) charge conservation violated in the hadron sector; (b) CC violated in the lepton sector. Analogous CC processes are shown for electron capture (c) and internal electron conversion (d). Amplitudes (a) and (b) are proportional to $G_W^{\rm CNC} = \varepsilon_W \times G_F$ and $G_\gamma^{\rm CNC} = \varepsilon_\gamma \times \alpha$, respectively ($G_F$ and α are the Fermi and the fine structure constants).

lepton sector). The analogous CC processes are shown in Fig. 2c (electron capture) and Fig. 2d (internal electron conversion). The transition probability for the CNC process through weak boson exchange (Fig. 2a) can be written in the form:

$$\lambda_W^{CNC}\left(e_K + {}^{129}\mathrm{Xe} \to \nu_e + {}^{129}\mathrm{Xe}^*\right) = \varepsilon_W^2 \lambda^{CC}(\mathrm{EC}), \tag{2}$$

where $\varepsilon_W^2 = (G_W^{CNC}/G^{CC})^2$ ($G^{CC} = G_F$ is the usual Fermi coupling constant). Moreover, $\lambda^{CC}(\mathrm{EC})$ can be formally treated as a probability of a standard K electron capture process. Using the well known expression for $\lambda^{CC}(\mathrm{EC})$ [25] and applying additional factor $1/2$ to obtain the probability for a single K electron, we obtain:

$$\lambda_W^{CNC} = \varepsilon_W^2 \cdot \frac{1}{2} \cdot \left(\frac{G_F}{\hbar^3 c^3}\right)^2 \left(\frac{C_A}{C_V}\right)^2 \frac{\left(m_e c^2\right)^3}{(2\pi)^2 \hbar} \times \left(m_e c^2 - E_B^K - E_{\mathrm{exc}}\right)^2 \cdot g_K^2 \cdot \sigma_{i\to f}^2, \tag{3}$$

where $G_F/\hbar^3 c^3 = 1.166 \cdot 10^{-11}$ MeV^{-2}, $C_A/C_V = -1.23$, m_e is the electron mass, E_B^K is the binding energy of the electron in the K atomic shell ($E_B^K =$ 34.6 keV for Xe), g_K^2 is the squared radial wave function of K electrons inside the nucleus, and $\sigma_{i\to f}^2$ is the appropriated squared matrix element for transition from the initial ground $1/2^+$ state of ^{129}Xe (i) to final excited level of the nucleus (f). For the values of g_K^2 we can use the calculations of Ref. [26] which take into account screening effect, corrections for finite nuclear size, etc.: $g_K^2 = 0.57$ for ^{129}Xe.

Matrix elements $\sigma_{i\to f}^2$ are related to matrix elements $\sigma_{f\to i}^2$ for the inverse process of decay of the excited nuclear levels to ground state by the expression:

$$\sigma_{i\to f}^2 = \frac{2J_f + 1}{2J_i + 1} \sigma_{f\to i}^2, \tag{4}$$

where J_i (J_f) is the initial (final) spin of the nucleus. Moreover, $\sigma_{f\to i}^2$ can be obtained from the experimental life times of the excited levels τ_{exc}. The probability of γ decay for an M1 transition is [27]:

$$\lambda_{\gamma,f\to i}(\mathrm{M1}) = \frac{4}{3}\left(\frac{e\hbar}{2m_p c}\right)^2 |\mu_p - \tfrac{1}{2}|^2 \times \frac{1}{\hbar}\left(\frac{E_\gamma}{\hbar c}\right)^3 \sigma_{f\to i}^2, \tag{5}$$

where $e\hbar/2m_p c$ is the nuclear magneton and $\mu_p = 2.793$ is the proton magnetic moment. Taking into account the contribution of E2 admixture in the M1 radiative decay as well as the emission of conversion electrons, it is immediate to relate $\lambda_{\gamma,f\to i}(\mathrm{M1})$ to the total decay probability $\lambda_{\mathrm{exc}} = \tau_{\mathrm{exc}}^{-1}$:

$$\lambda_{\gamma,f\to i}(\mathrm{M1}) = \tau_{\mathrm{exc}}^{-1} \cdot \frac{I_{\gamma,f\to i}}{\sum_n I_{\gamma,f\to n}(1+\alpha_{f\to n})} \cdot p_{\gamma,f\to i}(\mathrm{M1}), \tag{6}$$

where $I_{\gamma,f\to n}$ is the experimental relative photon intensity of $f\to n$ transition, $p_{\gamma,f\to i}(\mathrm{M1})$ is the contribution of M1 multipolarity to the $f\to i$ radiative transition, $\alpha_{f\to n}$ is the full electron conversion coefficient for the given transition and sum is over all possible transitions from the excited level of the nucleus. The values of $I_{\gamma,f\to i}$, $p_{\gamma,f\to i}(\mathrm{M1})$ and $\alpha_{f\to n}$ are given in [23] or in corresponding issues of Nuclear Data Sheets. Using formulae (3)–(6) together yields (energies in MeV):

$$\varepsilon_W^2 = 4.18 \cdot 10^{16} \cdot \frac{\tau_{\mathrm{exc}}}{\tau^{CNC}} \cdot \frac{1}{g_K^2} \cdot \frac{2J_i + 1}{2J_f + 1} \cdot \frac{E_\gamma^3}{\left(m_e c^2 - E_B^K - E_{\mathrm{exc}}\right)^2} \cdot \frac{\sum_n I_{\gamma,f\to n}(1+\alpha_{f\to n})}{p_{\gamma,f\to i}(\mathrm{M1}) \cdot I_{\gamma,f\to i}}. \tag{7}$$

It is obvious from Eq. (7) that, due to dependence $\varepsilon_W^2 \sim E_\gamma^3$ the lowest levels are preferable to derive the most stringent limits on ε_W^2. From (7) one can find numerically for the $3/2^+$ level (39.6 keV) of ^{129}Xe:

$$\varepsilon_W^2 = 2.4 \cdot 10^{-2}/\tau^{CNC}, \tag{8}$$

where τ^{CNC} is in years. Analogous expressions for other excited levels of ^{129}Xe can be calculated from Eq. (7) similarly; however, the most stringent limits on ε_W^2 are obtained from the 39.6 keV level.

Let us consider now the CNC nuclear excitation process of ^{129}Xe through photon exchange (Fig. 2b). The analogous CC one (Fig. 2d) is the standard internal electron conversion process (IC). Taking into account, as before, corrections for different spins of the nucleus in the f and i states and the fact that the phase space factor for the CNC process is proportional to p_ν^2, while for the CC process it is proportional to p_e^2, it yields:

$$\lambda_\gamma^{CNC}\left(e_K + {}^{129}\mathrm{Xe} \to \nu_e + {}^{129}\mathrm{Xe}^*\right) = \varepsilon_\gamma^2 \cdot \frac{2J_f+1}{2J_i+1} \cdot \left(\frac{p_\nu}{p_e}\right)^2 \cdot \lambda_K^{CC}(\mathrm{IC}), \quad (9)$$

where $\varepsilon_\gamma^2 = (G_\gamma^{CNC}/\alpha)^2$, $\lambda_K^{CC}(\mathrm{IC})$ is the probability of IC from the K atomic shell, $(p_\nu c)^2 = (m_e c^2 - E_B^K - E_{exc})^2$ and $(p_e c)^2 = (m_e c^2 - E_B^K + E_{exc})^2 - (m_e c^2)^2$.

Further, the probability of internal conversion for a single K electron is related to the total decay probability $\lambda_{exc} = \tau_{exc}^{-1}$ by the expression:

$$\lambda_K^{CC}(\mathrm{IC}) = \tfrac{1}{2} \cdot \tau_{exc}^{-1} \cdot \alpha_{f\to i}^K \cdot I_{\gamma,f\to i} \Big/ \left[\sum_n I_{\gamma,f\to n}\left(1+\alpha_{f\to n}\right)\right], \quad (10)$$

where $\alpha_{f\to n}^K$ is the K conversion coefficient for the $f \to n$ transition, and $\alpha_{f\to n}$ is the full conversion coefficient. In case of E2 admixtures in the radiative decay, instead of $\alpha_{f\to n}^K$ we should use the part of coefficient connected with the M1 transition $\alpha_{f\to n}^{K(M1)}$. In absence of the experimental data on $\alpha_{f\to n}^{K(M1)}$, the theoretical tables [28] or graphs for their values [23] can be used.

Using formulae (9), (10) we obtain:

$$\varepsilon_\gamma^2 = \frac{\tau_{exc}}{\tau^{CNC}} \cdot \frac{2J_i+1}{2J_f+1} \cdot \frac{\left(m_e c^2 - E_B^K + E_{exc}\right)^2 - \left(m_e c^2\right)^2}{\left(m_e c^2 - E_B^K - E_{exc}\right)^2} \cdot \frac{2\sum_n I_{\gamma,f\to n}\left(1+\alpha_{f\to n}\right)}{\alpha_{f\to i}^{K(M1)} \cdot I_{\gamma,f\to i}}. \quad (11)$$

From (11) one can see that the lowest limits on ε_γ^2 could be obtained for levels with $E_{exc} \approx E_B^K$. Numerically it is found for the $3/2^+$ level (39.6 keV) of ^{129}Xe:

$$\varepsilon_\gamma^2 = 1.4 \cdot 10^{-18}/\tau^{CNC}, \quad (12)$$

where τ^{CNC} is in years. The relations (8) and (12) will be used to derive restrictions on ε_W^2 and ε_γ^2 from the experimental limit for the first excited level of ^{129}Xe.

2. Measurements, data analysis and discussion of the results

The description of the DAMA set up with $\simeq$ 6.5 kg (i.e. $\simeq$ 2 l) of liquid xenon scintillator and its performances have been published elsewhere [20,22]. Here we recall the main features of this apparatus. The used gas is Kr-free xenon enriched in ^{129}Xe at 99.5% by ISOTEC company. It was measured [22] that U/Th contamination of ^{129}Xe does not exceed $\approx$ 2 ppt at 90% C.L. The vessel for the LXe is made by the OFHC and low activity copper ($\leq$ 100 μBq/kg for U/Th and $\leq$ 310 μBq/kg for potassium). The scintillation light collection has been assured by three EMI photomultipliers (PMT) with MgF_2 windows working in coincidence. The quantum efficiency of the PMT's photocathodes is ranging between 18 and 32%. The PMT-s collect light through three windows (3'' in diameter) made of special cultured crystal quartz (total transmission of the LXe scintillation light $\approx$ 80%, including the reflection losses). A low activity copper shield inside the thermo-insulation vacuum cell surrounds the PMT-s; then, 2 cm of steel (insulation vessel thickness), 5 − 10 cm of low activity copper, 15 cm of low activity lead, $\approx$ 1 mm of cadmium and $\approx$ 10 cm of polyethylene are used as outer hard shielding. The environmental Radon nearby the detector is removed by continuous flushing of a high purity Nitrogen gas from bottles stored underground since a long time. An external envelop – made of Supronyl – offers an additional Radon protection.

Each PMT is connected with a low noise preamplifier, whose outputs are fed to the data acquisition system. For every event the following information are recorded: amplitudes of each single PMT pulse; amplitude and shape of the sum pulse (recorded with the help of a Lecroy transient digitizer). The energy dependence of the detector resolution was measured [22] with ^{109}Cd source (peaks at 22 and 88 keV) and can be expressed in the energy region of interest as following:

$$\sigma/E = 0.056 + 1.19/\sqrt{E[\mathrm{keV}]}\,. \quad (13)$$

The idea of the present work is to search for γ rays from the possible de-excitation processes in ^{129}Xe which could follow the CNC electron captures

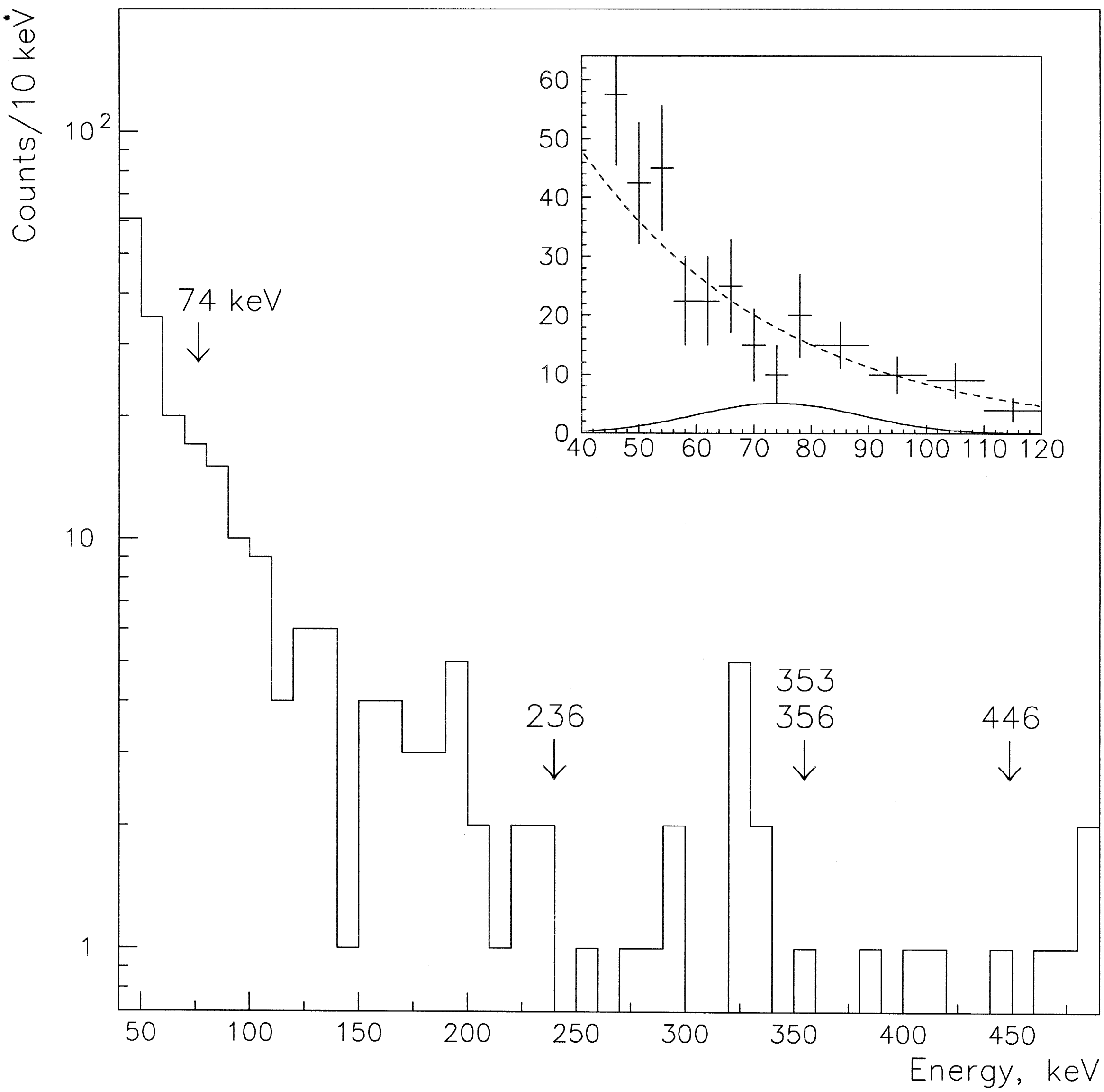

Fig. 3. Energy spectrum measured by the LXe scintillator in the energy region 40–500 keV with total statistics of 823.1 kg · day. In the insert the low energy part is shown in linear scale together with the fitting curve and excluded peak ($\tau = 1.1 \cdot 10^{24}$ y) for the first excited level of ^{129}Xe.

(1). The energy distribution measured by the DAMA LXe set-up (and already considered for Dark Matter search by investigating the WIMP-^{129}Xe inelastic scattering in Ref. [20]) is analysed here for this purpose. As it was already mentioned five levels could be excited due to the process (1) in ^{129}Xe (Fig. 1). Taking into account the binding energy of the Xe K atomic shell ($E_B^K = 34.6$ keV), the energies of the possible γ peaks in the background spectra should be: 74.2; 236.1 [2]; 352.8, 356.3 and 446.1 keV. The experimental spectrum of the LXe scintillator in the energy region 40–500 keV with total statistics of

[2] Because the second excited level is long-lived ($t_{1/2} = 8.89$ d) the energy of peak searched for is equal to $E_{exc} = 236.1$ keV.

Table 1
Experimental life time limits on the CNC electron capture involving nuclear levels excitation of ^{129}Xe

E_{exc}	Efficiency η	Excluded area S, 90 (68)% C.L.	τ limits, year 90 (68)% C.L.
39.6 keV	0.99	18.5 (10.4)	$1.1(2.0)\cdot 10^{24}$
236.1 keV	0.97	5.5 (3.2)	$3.7(6.4)\cdot 10^{24}$
318.2 keV	0.65	6.1 (3.5)	$2.2(3.9)\cdot 10^{24}$
321.7 keV	0.67	5.6 (3.2)	$2.5(4.4)\cdot 10^{24}$
411.5 keV	0.50	4.6 (2.5)	$2.3(4.2)\cdot 10^{24}$

823.1 kg · day is shown in Fig. 3, where the absence of these peaks is evident. Thus limits can be set for the probabilities of CNC nuclear excitations of ^{129}Xe nuclei. To estimate the life time limits τ, we use the standard formula: $\tau = (\eta \cdot N \cdot t)/S$, where η is the detection efficiency, N is the number of electrons on the K shell of Xe atoms, t is the measuring time, and S is the number of signal events, which can be excluded at a given confidence level on the base of the experimental data. To calculate the efficiency values η, de-excitation processes in ^{129}Xe nuclei inside the LXe scintillator and the response function of the detector were simulated with the help of GEANT3.21 package [29]. The code DECAY4 [30] was used for description of the event's kinematics. Calculated efficiencies η are given in Table 1 and their values are varied from 0.99 for $E_{exc} = 39.6$ keV to 0.50 for $E_{exc} = 411.5$ keV. The S values were determined in two ways. Firstly, by using the so called ''one σ approach'', in which the excluded number of signal events is estimated simply as square root of the number of background counts in a suitably chosen energy window ΔE. Notwithstanding its simplicity this method gives the right scale of the sensitivity of the experiment. For instance, in the measured spectrum within the energy interval 45–103 keV (it contains 95% of expected 74.2 keV peak area) there are 129 counts; thus, the square root estimate gives $S < 11.4$ events. Using this value S, total number of K electrons in the LXe detector ($N = 6.0 \cdot 10^{25}$), measuring time and calculated efficiency, we obtain the life time limits $\tau > 1.7 \cdot 10^{24}$ y (68% C.L.) for the 74.2 keV peak. The results for other peaks are within $\tau > (3–7) \cdot 10^{24}$ y at 68% C.L. Further, S values were determined by using the standard least square procedure, where the experimental energy distribution in the neighborhood of the peak searched for was fitted by the sum of contributions due to the background (exponential behaviour for the first peak and a straight line for the others) and to the signals peak being sought. As the last one the response function of the detector was simulated by a gaussian with the proper width (13). For example, the obtained area for the first peak (74.2 keV) is -11 ± 15 counts (χ^2/d.o.f. value is 1.3), thus giving no evidence for the signal. Then, the number of signal events, which can be excluded at 90 (68)% C.L. were calculated [9] as 18.5 (10.4). It gives the life time limit $\tau > 1.1(2.0) \cdot 10^{24}$ y at 90 (68)% C.L. for the first ($E_{exc} = 39.6$ keV) excited level of ^{129}Xe. The excluded number of signal events for other levels obtained by a similar procedure and the corresponding τ limits are shown in Table 1. For illustration the fitting curve and excluded peak for the first excited level is depicted in the insert of Fig. 3.

The present limits, established for the CNC nuclear excitation of ^{129}Xe for the first time, are higher than the best result obtained for the CNC nuclear excitation of ^{127}I ($\tau > 2.4 \cdot 10^{23}$ y at 90% C.L.) [18]. The corresponding restrictions on the CNC parameters ε^2 derived for the ^{127}I are: $\varepsilon_W^2 < 9.6 \cdot 10^{-26}$ and $\varepsilon_\gamma^2 < 1.2 \cdot 10^{-40}$ (both at 90% C.L.) [18]. By substituting into Eqs. (8) and (12) our experimental limit for the first excited level of ^{129}Xe one obtains $\varepsilon_W^2 < 2.2 \cdot 10^{-26}$ and $\varepsilon_\gamma^2 < 1.3 \cdot 10^{-42}$ (both at 90% C.L.), which are more severe than values [3] of [18].

[3] The ε_γ^2 restriction could be also derived from the τ limit of the electron decay $e^- \to \nu_e + \gamma$. However due to the known problem of the catastrophic emission of longitudinal bremsstrahlung photons affecting this particular decay mode (see [5] and footnote 1) such a restriction seems to be less ''safe'' than those obtained from the experiments on the CNC nuclear excitation, CNC beta decay and electron disappearance.

Finally, we recall the stringent restriction on ε_W^2 derived in Ref. [18] from the best τ limit measured in Ref. [7] for the electron disappearance channel: $e^- \to \nu_e + \bar{\nu}_e + \nu_e$; it results: $\varepsilon_{e3\nu}^2 < 11(6.2) \cdot 10^{-27}$ at 90(68)% C.L.

3. Conclusion

In conclusion the present experimental limit on the CNC electron capture through the first excited state of ^{129}Xe ($3/2^+$; $E_{\rm exc} = 39.6$ keV) gives the most stringent restrictions on the relative strengths of both weak boson and photon mediating CNC processes. These are $\varepsilon_W^2 < 2.2 \cdot 10^{-26}$ and $\varepsilon_\gamma^2 < 1.3 \cdot 10^{-42}$ (both at 90% C.L.), which are bounds substantially more severe than those obtained from the CNC excitation study of ^{127}I. Together with the bound $\varepsilon_{e3\nu}^2 < 11(6.2) \cdot 10^{-27}$ at 90(68)% C.L. derived in Ref. [18], these restrictions cover a relevant area of possible CNC parameters ε^2 available for a quest at present.

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