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IMPROVED EXPERIMENTAL LIMIT ON THE ELECTRON STABILITY AND NON-PAULIAN TRANSITIONS IN I ATOM

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The background measurements have been performed in the Gran Sasso National Laboratory of INFN with the help of the large mass (≅100 kg) highly radiopure DAMA NaI(Tl) set up. Using statistics of 19511 kg · day, new limit on the mean life of the electron was established for "disappearance" channel: $\tau_e(e^- \to \nu_e\nu_e\nu_e) > 4.2\ (2.4) \cdot 10^{24}$ y at 68 %(90 %) C.L.

1. Introduction

Since electron is the lightest electrically charged particle, the stability of electron means the conservation of electric charge. In frame of standard quantum electrodynamics (QED) charge conservation is automatic consequence (Weinberg's theorem [1]) of massless photons, which are dictated in one's turn by the fundamental underlying principle of gauge invariance. Nevertheless, possibility that electric charge conservation may be broken in future unified gauge theories and implications of such a violation have been discussed in literature intensively [2 - 6]. In spite of the fact that no self-consistent theory describing electric charge non-conservation has been constructed yet (see for details reviews [6] and references therein), efforts to test and set the limits of this fundamental feature of nature in direct experiments are continuing [7 - 17] since the early search of G. Feinberg and M. Goldhaber in 1959 [7]. We should remember that pure esthetic arguments could give wrong results (as it was with parity conservation), and on some level we could face the unexpected things. "If something in fundamental physics *can* be tested, then it absolutely *must* be tested" [6].

The idea of pioneering experiment [7] was to use a NaI(Tl) crystal scintillator and to look for the X-ray and Auger-electron cascade which would follow the decay of K electron of one of the iodine atoms inside the crystal (energy released is 33.2 keV). This kind of study is sensitive to all electron's decay modes in which the decay particles escape from the detector without depositing energy, as an example: $e^- \to \nu_e\nu_e\nu_e$. Another approach, which is sensitive only to particular decay mode of electron into a neutrino and a gamma ($e^- \to \nu_e\gamma$), is to search for 255.5 keV gamma quantum following the decay of any electron inside the detector or from the surrounding. All results available at present from the literature are presented in Table for both types of experiments. The best limits on the mean lives of electron are: $\tau_e(e^- \to \nu_e\gamma) > 3.7(2.1) \cdot 10^{25}$ y and $\tau_e(e^- \to \nu_e\nu_e\nu_e) > 4.3(2.6) \cdot 10^{23}$ y at 68 % (90 %) C.L. [16]. It should be noted that the law of baryon number conservation is tested much more exactly: $\tau_p > \sim 10^{32}$ y (see [18] and references therein).

This paper describes the new limit on electron stability which was obtained as by-product result in the DAMA experiments devoted to the Dark Matter search [19 - 23].

2. Detectors and measurement procedure

The detail description of the ultra low background ≅100 kg NaI(Tl) set up and results of the DAMA Dark Matter studies have been previously published [19 - 23]. Here we will recall briefly the main features of the upgraded apparatus used in the last experiment [22]. The detector system consists of nine 9.70 kg NaI(Tl) crystal scintillators; they are part of the 115.5 kg highly radiopure DAMA NaI(Tl) set up operating in the Gran Sasso National Laboratory of INFN [19, 21, 23]. Each detector has two 10 cm long tetrasil-B light guides directly coupled to the opposite sides of the bare crystal. Two photomultipliers (PMT) EMI9265- B53/FL work in coincidence and collect light at single photoelectron threshold, while 2 keV is the software energy threshold [19, 21, 23]. The detectors are enclosed in a low radioactive copper box inside a low radioactive shield made of 10 cm copper and 15 cm lead; the lead is surrounded by 1.5 mm Cd foils and about 10 cm of polyethylene. A high purity (HP) Nitrogen atmosphere is maintained inside the copper box by a continuous flux of HP Nitrogen gas from bottles stored underground since time. The whole shield is wrapped in Supronyl and maintained also in the HP Nitrogen atmosphere. The installation is subjected to air conditioning (the maximum level of temperature variation is less than 0.2 °C) to avoid any influence of temperature on the light yield of the crystals, light collection, PMT's spectral sensitivity and amplification, stability of the electronics, which allow to keep constant energy scale, resolution and threshold of the detectors. The typical energy resolution (FWHM) is $\sigma/E = 7.5$ % at 59.5 keV. The 2 keV software energy threshold is well supported by the energy calibrations performed with low energy γ sources and Compton electrons and by the relatively large number of photoelectrons (about 5) per keV [19, 21, 23]. The pulse shape analysis (PSA) was applied to reject the residual noise above the energy threshold by exploiting the different time structure of the PMT noise (fast pulses with decay time of order of tens ns) and scintillation signal (decay time of order of hundreds ns), for which pulse shape information were recorded over 3250 ns by a Lecroy Transient Digitizer. The software cut efficiencies have been properly determined by applying PSA to the data collected with an ^{241}Am source. They ranged from about 30 or 40 % (depending on the crystal) at 2 keV and up to 100 % at 12 keV. These values have been properly taken into account to obtain the energy spectra discussed in the following. The knowledge of the energy scale was assured by periodical calibration with ^{241}Am and by monitoring the position and resolution of the ^{210}Pb peak (46.5 keV) which presented at level of few cpd/kg in the background distributions collected by our detectors. This peak is mainly due to a surface contamination by environmental Radon occurred

Experimental limits on the electron life time

Detector (volume)	Limit τ with 68%(90%) C.L., y		Year [Ref.]
	$e^- \to \nu_e\nu_e\nu_e$	$e^- \to \nu_e\gamma$	
NaI (1287 cm^3)	$1.0\cdot10^{18}$	$1.0\cdot10^{19}$	1959 [Fei59]
NaI (348 cm^3)	$2.0\cdot10^{21}$	$4.0\cdot10^{22}$	1965 [Moe65]
Ge(Li) (66 cm^3)	$5.3\cdot10^{21}$	-	1975 [Ste75]
NaI (1539 cm^3)	$2.0\cdot10^{22}$	$3.5\cdot10^{23}$	1979 [Kov79]
Ge(Li) (130 cm^3)	$2.0\cdot10^{22}$	$3.0\cdot10^{23}$	1983 [Bel83]
HP Ge (135 cm^3)	-	$1.5(1.1)\cdot10^{25}$	1986 [Avi86]
HP Ge (3×140 cm^3)	$2.7(1.7)\cdot10^{23}$	-	1991 [Reu91]
NaI (17×10570 cm^3)	$1.2\cdot10^{23}$	-	1992 [Eji92]
HP Ge (591 cm^3)	-	$2.4(1.2)\cdot10^{25}$	1993 [Bal93]
HP Ge (48 + 2×209 cm^3)	$4.3(2.6)\cdot10^{23}$	$3.7(2.1)\cdot10^{25}$	1995 [Aha95]
LXe (2000 cm^3)	$1.5\cdot10^{23}$	$2.0(1.0)\cdot10^{25}$	1996 [Bel96]
NaI (9×2643 cm^3)	$4.2(2.4)\cdot10^{24}$	-	1999 [this work]

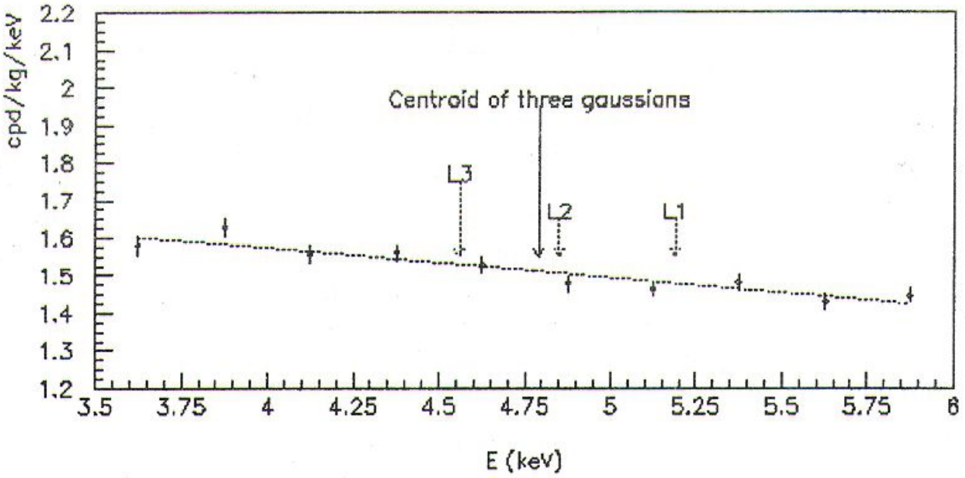
during the first period of the crystals storage deep underground. The standard deviation of this peak position estimated for all 9 detectors during the whole data taking period does not exceed 1.5 %.

In conclusion, owing to all above mentioned procedures, the energy scale, the energy resolution and the energy threshold of the detectors are well established.

3. Results and discussion

The idea of present work is to use the distinguished feature of the DAMA set up, namely the superlow energy threshold of 2 keV. It allows to look for the signal from X-ray and Auger-electron cascade which would follow decay of not only a K-electron of one of the iodine atoms inside the NaI(Tl) (released energy is 33.2 keV), but also the decay of any L-electrons (released energy of about 5 keV). Each iodine atom contains 8 electrons on L-shell (2 electrons on L1-, 2 on L2-, and 4 on L3-subshell), contrary to only 2 electrons on K-shell. Thus, using 2 keV energy threshold the source strength can be increased by factor 4 in comparison with the standard procedure searching for K-electron decay. Another important characteristic of the DAMA installation is the super-low background rate of the detectors in the energy region of interest - at the level of 1.5 count per day/kg · keV (cpd/kg · keV) - the last is also crucial for the sensitivity of the experiment.

The statistics considered in the present analysis is 19511 kg · day (DAMA/NaI-1 & 2 running periods). The parts of the background spectra in the energy region 2-20 keV, which were collected by each separate detector, can be found in ref. [19, 20]. Since mean values of the background rates (within 2-20 keV interval) were practically the same (~1.5 cpd/kg · keV), the cumulative energy distribution can be used for electron life time estimate. The corresponding part of total spectrum is shown in figure.



Cumulative experimental energy distribution (already corrected for the needed efficiencies) in the region of interest for the process searched for; the statistics is 19511 kg · day. The dotted line represents the result of a fit given by the sum of a linear function (simplified background model suitable for the present purposes) and of the sum of the three gaussians associated to the process searched for; this last contribution requires only one free parameter (see text).

The possible decay of L-electron of one of the iodine atoms inside the NaI(Tl) detector would be visible as a peak at the energy of about 5 keV (5.19 keV for L1-shell; 4.85 keV for L2-shell, and 4.56 keV for L3-shell [24]) with σ/E corresponding to the detector energy resolution for internal keV-range sources. The absence of such a peak in the collected data is evident from the figure. Thus experimental spectrum can be used to determine the upper limit of the electron life time. For this purpose we can use the known formula

$$\tau=\varepsilon N\cdot t/S,$$

where ε is efficiency of the signal detection, N is the number of electrons on L-shell of I atoms, t is time of the measurements, and S is the number of events of effect being searched excluded with a given confidence level.

The cascade of low energy X-rays and Auger-electrons with sum energy of near 5 keV will be fully absorbed in big NaI crystals giving $\varepsilon = 1$. Nine 9.70 kg detectors include $3.51\cdot10^{26}$ NaI molecules that corresponds to $2.81\cdot10^{27}$ electrons on L-shell of I. Thus the total $N\cdot t$ is equal to $1.72\cdot10^{27}$ electrons·years. Because the peak with energy ~5 keV is absent in Fig. 1 and the energy spectrum is very smooth, as an estimate of excluded number of events S we can accept the statistical deviation of full number of events in the energy region of 3.5 – 6.0 keV. The latter is a very sensitive interval which offers a practically symmetric window centered around the centroid of the 3 peaks and including 66.7 % ($\varepsilon_{\text{window}}$) of the total area. The value $S=(\delta w)/\varepsilon_{\text{window}} = 482(793)$ with 68 % (90 %) C.L. is found; there δ (0.0165 cpd/kg) is the standard deviation of the total rate in the 3.5 – 6.0 keV energy interval and w is the statistics (19511 kg · day). It gives the following limit for the electron "disappearance" life time: $\tau_e(e^- \rightarrow \nu_e\nu_e\nu_e) > 3.6(2.2)\cdot10^{24}$ y with 68 % (90 %) C.L.

Then, with the aim to make the S estimation more accurate, we used the following procedure. The experimental energy distribution in the energy interval 3.5 – 6.0 keV was fitted by the sum of two functions: the background and the effect being searched for. As simplified background model, suitable for the present purposes, the linear function has been assumed there. The effect has been represented by the sum of three gaussians, centered at 4.56, 4.85 and 5.19 keV respectively, and with energy resolution scaled here according to: $\sigma/E \sim 1/\sqrt{E}$. Moreover, the amplitudes of the gaussians has been normalized for two electrons on L1-, two electrons on L2-, and four electrons on L3-shell (requiring, therefore, only one free parameter for the effect amplitude). From the fit in this energy region the amplitude of the effect was found to be (–0.0029±0.0240) cpd/kg, giving no statistical evidence for it; the obtained χ^2/d.o.f. was equal to 1.2. Using these values the upper limit on the events number S was calculated in accordance with the Particle Data Group procedure [18, 26]. In fact, from the amplitude of the effect given by the fit, the lower limit 0.02118 (0.03663) cpd/kg at 68 % (90 %) C.L. can be estimated, giving: $S \leq 413(715)$ and

$$\tau_e(e^- \rightarrow \nu_e\nu_e\nu_e) \geq 4.2(2.4)\cdot10^{24} \text{ y with 68 \% (90 \%) C.L.}$$

The obtained result is one order of magnitude higher than the best limit previously established in the experiment [16] with HP Ge detectors where the "disappearance" of electrons on K-shell of Ge was searched for.

The searches for "disappearance" of electrons on the atomic shells are related with experimental searches for the violation of other fundamental principle: Pauli exclusion principle (PEP). The transition of electrons to fully filled L-shell, process which usually is forbidden by the PEP, will result in energy release equal to binding energy of electron on L-shell. From experimental point of view, both processes are indistinguishable in NaI detector. Thus established limit on τ_e could be regarded also as the limit on probability of the PEP violation. It should be noted however, that there are theoretical arguments [6] that, at least in the framework of standard quantum mechanics, transitions to a filled shell are forbidden regardless of whether the PEP is violated since they would change the commutation symmetry of the wave function of the given set of particles.

As we already mentioned in the Introduction, currently there is no self-consistent and non-contradictory description of possible small violation of the law of electric charge conservation. The consideration, detailed in [6], reveals that spontaneous violation of this law is impossible. Other possibility, which is explicit violation, would have led to the catastrophic emission of huge amount ($10^{14} - 10^{21}$) of longitudinal bremsstrahlung photons with tiny energies which are unobservable. In result, the decay of an electron will not be accompanied by a γ line with energy 255.5 keV, and no X-ray lines will be observed when an electron disappears on an atomic shell. However, recently it was argued that the filling of the shell after the electron disappearance will occur before the emission of soft photons and can not be affected by them (see [6] and references therein).

The electric charge conservation is related with mass of photon m_γ. Using the τ_e limit and the relation between τ_e and m_γ, for example, established [26] in the framework of SU(5) model,

$$\tau_e \approx 10^{-25} (m_Z/m_\gamma)^2 \text{ y},$$

where $m_Z = 91.2$ GeV is the mass of Z-boson, we can estimate the limit on the mass of γ quantum. With our value $\tau_e \geq 4.2 \cdot 10^{24}$ y we receive $m_\gamma \leq 1.4 \cdot 10^{-14}$ eV. It can be compared with the best laboratory limit $m_\gamma \leq 2 \cdot 10^{-16}$ eV which was found in the recent experiment with thoroidal Cavendish balance [27].

4. Conclusion

Using the unique features of the DAMA/NaI set-up with near 100 kg NaI detectors: low energy threshold (2 keV) and super low background rate in the low energy region (~1.5 cpd/kg·keV), the limit on the probability of "disappearance" of the electron on the L-shell of I atoms was established in the experiment with the total statistics of 19511 kg·day: $\tau_e(e^- \to \nu_e\nu_e\nu_e) \geq 4.2(2.4) \cdot 10^{24}$ y with 68 % (90 %) C.L. It is one order of magnitude higher than the best known up-to-date "disappearance" limit which was set for K-shell electrons in HP Ge detectors ($\tau_e^- \geq 4.3(2.6) \cdot 10^{23}$ y) [16]. The established limit on τ_e could be regarded also as the limit for possible transitions of electrons in I atomic shell to the filled L-shell which are usually forbidden by the Pauli exclusion principle.

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ПОКРАЩЕНА ЕКСПЕРИМЕНТАЛЬНА ГРАНИЦЯ НА СТАБІЛЬНІСТЬ ЕЛЕКТРОНА ТА ПЕРЕХОДИ З ПОРУШЕННЯМ ПРИНЦИПУ ПАУЛІ В АТОМАХ I

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Виміри фону було виконано у Національній лабораторії Гран Сассо за допомогою надчистих NaI(Tl) детекторів великої маси (≈100 кг) в установці DAMA. Використовуючи статистику у 19511 кг·днів, було встановлено нову границю на середній час життя електрона для каналу "зникнення": $\tau_e(e^- \to \nu_e \nu_e \nu_e) > 4.2(2.4) \cdot 10^{24}$ y при C.L.= 68 % (90 %).

УЛУЧШЕННЫЙ ЭКСПЕРИМЕНТАЛЬНЫЙ ПРЕДЕЛ НА СТАБИЛЬНОСТЬ ЭЛЕКТРОНА И ПЕРЕХОДЫ С НАРУШЕНИЕМ ПРИНЦИПА ПАУЛИ В АТОМАХ I

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Измерения фона были выполнены в Национальной лаборатории Гран Сассо с помощью сверхчистых NaI(Tl) детекторов большой массы (≈100 кг) в установке DAMA. Используя статистику в 19511 кг·дней, был установлен новый предел на среднее время жизни электрона для канала "исчезновение": $\tau_e(e^- \to \nu_e \nu_e \nu_e) > 4.2(2.4) \cdot 10^{24}$ y при C.L.= 68 % (90 %).