5 August 1999

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 460 (1999) 236–241

New experimental limit on the electron stability and non-paulian transitions in Iodine atoms

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

[a] *Dip. di Fisica, Università 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, Università di Roma ''La Sapienza'' and INFN, sez. Roma, I-00185 Rome, Italy*
[d] *Institute for Nuclear Research, 252650 Kiev, Ukraine*

Received 21 April 1999
Editor: K. Winter

Abstract

A new limit on the mean life of the electron in the ''disappearance'' approach has been established: $\tau_e > 4.2(2.4) \cdot 10^{24}$ yr at 68% (90%) C.L., by using the $\simeq 100$ kg DAMA NaI(Tl) set-up at the Gran Sasso National Laboratory of INFN.

1. Introduction

The stability of the electron implies the conservation of the electric charge, since it is the lightest electrically charged particle. In the framework of the standard quantum electrodynamics, the charge conservation is a direct consequence (Weinberg theorem [1]) of massless photons, which are imposed by the fundamental underlying principle of gauge invariance. Nevertheless, the possibility that the electric charge conservation may be broken in unified gauge theories and the related implications have been intensively discussed in literature [2–6]. Although no self consistent theory describing non-conservation of electric charge has been yet constructed (see for details reviews [6] and refs. therein), many efforts have been devoted to test this fundamental feature of the nature in direct experiments [7–17] since the early search by Feinberg and Goldhaber in 1959 [7].

The idea of the pioneering experiment [7] was to use a NaI(Tl) scintillator to look for the X-ray and Auger electrons cascade, which would follow the decay of a K electron in a Iodine atom (energy release is 33.2 keV). This approach – named ''disappearance'' approach – is sensitive to all the decay modes giving decay particles which escape the detector without depositing energy (for example: $e^- \rightarrow \nu_e \bar{\nu}_e \nu_e$). Another approach, sensitive to the $e^- \rightarrow \nu_e \gamma$ decay mode, searches for 255.5 keV gamma quantum; in this case electron decays in the surrounding materials will contribute as well as the ones inside the detector. All the results available in literature – for both types of experiments – are summarized in Table 1. The best limit on the mean life of the

0370-2693/99/$ - see front matter © 1999 Published by Elsevier Science B.V. All rights reserved.
PII: S0370-2693(99)00783-2

Table 1
Experimental limit on the electron life time at 68% (90%) C.L.

Detector (volume)	limit on $\tau_e(e^- \to \nu_e \bar{\nu}_e \nu_e)$ yr	limit on $\tau_e(e^- \to \nu_e \gamma)$ yr	year [Ref.]
NaI(Tl) (1287 cm^3)	$1.0 \cdot 10^{18}$	$1.0 \cdot 10^{19}$	1959 [7]
NaI(Tl) (348 cm^3)	$2.0 \cdot 10^{21}$	$4.0 \cdot 10^{22}$	1965 [8]
Ge(Li) (66 cm^3)	$5.3 \cdot 10^{21}$	–	1975 [9]
NaI(Tl) (1539 cm^3)	$2.0 \cdot 10^{22}$	$3.5 \cdot 10^{23}$	1979 [10]
Ge(Li) (130 cm^3)	$2.0 \cdot 10^{22}$	$3.0 \cdot 10^{23}$	1983 [11]
Hp–Ge (135 cm^3)	–	$1.5\ (1.1) \cdot 10^{25}$	1986 [12]
Hp–Ge ($3 \cdot 140$ cm^3)	$2.7(1.7) \cdot 10^{23}$	–	1991 [13]
NaI(Tl) ($17 \cdot 10570$ cm^3)	$1.2 \cdot 10^{23}$	–	1992 [14]
Hp–Ge (591 cm^3)	–	$2.4(1.2) \cdot 10^{25}$	1993 [15]
Hp–Ge ($48 + 2 \cdot 209$ cm^3)	$4.3(2.6) \cdot 10^{23}$	$3.7(2.1) \cdot 10^{25}$	1995 [16]
LXe (2000 cm^3)	$1.5 \cdot 10^{23}$	$2.0(1.0) \cdot 10^{25}$	1996 [17]
NaI(Tl) ($9 \cdot 2643$ cm^3)	$4.2\ (2.4) \cdot 10^{24}$	–	1999 – this work

electron in the ‘‘disappearance’’ channels previously available was: $\tau_e > 4.3(2.6) \cdot 10^{23}$ yr at 68% (90%) C.L. [16]. It should be noted that the baryon number conservation has been tested more exactly: proton mean life limit independent on decay mode $\tau_p > 1.6 \cdot 10^{25}$ yr and in various proton decay channels $\tau_p/B_i \gtrsim 10^{32}$ yr (B_i is the branching ratio) [18].

The best life time limit obtained for the $e^- \to \nu_e \gamma$ decay mode is higher than that for the ‘‘disappearance’’ modes; it results: $\tau_e(e^- \to \nu_e \gamma) > 3.7(2.1) \cdot 10^{25}$ yr [16]. However, as it has been already mentioned, currently there is no self-consistent and non-contradictory description of possible small violation of the charge conservation. Moreover, the detailed analysis of Ref. [6] shows that its spontaneous violation is impossible. The remaining possibility is an explicit violation, which however would lead to the catastrophic emission of huge amount (10^{14}–10^{21}) of longitudinal bremsstrahlung photons with tiny energies, which are unobservable. As a consequence, 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. Notwithstanding, recently it was argued that the filling of the shell after the electron disappearance will occur before the emission of soft photons and cannot be affected by this last process (see [16] and refs. therein). Considering this argument, we can conclude that the ‘‘disappearance’’ life time limit of the electron is the more ‘‘safe’’ and model independent. The last is proved by Particle Data Group publication [18].

Anyhow, we would like to remind that for fundamental questions – like the one we are discussing about – any ‘‘a priori’’ argument based on pure esthetic or other principles could give wrong results (as it was demonstrated, for instance, with parity conservation) and on some level we could face unexpected things. ‘‘If something in fundamental physics can be tested, then it absolutely must be tested’’ [6].

This paper describes the new improved limit on electron stability which was obtained as a ‘‘by-product’’ result of the DAMA data taking [19,20], mainly dedicated to the particle Dark Matter direct search [21,22,19,20,23].

2. Detectors and measurement procedure

The detailed description of the highly radiopure $\simeq 100$ kg NaI(Tl) set-up and its performances are discussed in Ref. [23]. Results of the DAMA Dark Matter studies and by-product results have been also previously published [21,22,19,20,24]. Here we briefly recall only the main features of this apparatus [19,20]. The detector system consists of nine 9.70 kg NaI(Tl) crystal scintillators enclosed in radiopure Cu housings; they are part of the $\simeq 100$ kg highly radiopure DAMA NaI(Tl) set-up operating at the Gran Sasso National Laboratory of INFN [21,22,19,20,23,24]. 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 considered software energy threshold [21,19,20]. The detectors are enclosed in a low radioactive copper box inside a low radioactive shield made of 10 cm Cu and 15 cm Pb; the Pb is surrounded by 1.5 mm Cd foils and about 10 cm of polyethylene/paraffin. A high purity (HP) Nitrogen atmosphere is maintained inside the Cu box by a continuous flux of HP Nitrogen gas from bottles stored underground since time; the Cu box is in slight overpressure with respect to the external environment. The whole shield is wrapped in Supronyl and maintained also in HP Nitrogen atmosphere. The installation is subjected to air conditioning to avoid any significative influence of the temperature on the light yield of the crystals, on the PMT's spectral sensitivity and gain and on the stability of the electronics; it allows to keep constant the energy scale, the energy resolution and the energy threshold of the detectors, as verified also by the continuous monitoring of the stability parameters and by the routine energy scale calibrations [19,20,23,24].

The usually considered 2 keV software energy threshold [19,20,23,24] is well supported by the energy calibrations performed with external low energy γ sources (such as ^{55}Fe, ^{109}Cd, ^{241}Am) and with Compton electrons as well as by the relatively large number of available photoelectrons/keV (5.5–7.5). The typical energy resolution is $\sigma/E = 7.5\%$ at 59.5 keV.

A pulse shape analysis is considered to reject the residual noise by exploiting the different time structure of the PMT noise (fast pulses with decay time of order of tens ns) and scintillation signals (decay time of order of hundreds ns); see Ref. [20,23] for details. For this purpose, the pulse shape information are recorded over 3250 ns by a Lecroy transient digitizer. Software cuts are applied to the production data to reject the noise and to the ^{241}Am data (in the same energy region) to evaluate the corresponding software cut efficiencies [20,23]. These values have been properly taken into account to obtain the energy distribution analysed in the following.

The knowledge of the energy scale is assured by periodical calibrations with ^{241}Am source and by monitoring the position and resolution of the ^{210}Pb peak, which is present at level of few cpd/kg in the energy distributions measured by our detectors. This peak is mainly due to a surface contamination by environmental Radon occurred during the first period of the crystals storage deep underground. In particular, using the DAMA/NaI-2 data, it has been shown in Ref. [20] that the distribution of the calibration factor from the ^{210}Pb peak – for all the nine detectors in the whole running period and before applying any correction – shows a gaussian behaviour with $\sigma = 1.2$ % [20,23]. Therefore, considering that the calibration factor used in the data analysis is continuously monitored and corrected by the results both of the ^{241}Am routine calibrations and of the ^{210}Pb peak, this will introduce only an additional overall relative energy spread $\lesssim 10^{-4}$ at 2 keV up to $\lesssim 10^{-3}$ at 20 keV [24] to the energy resolution.

In conclusion, owing to all the 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 the present work is to use the distinguished features of the DAMA set-up to look for signals from X-ray and Auger electron cascade, which would follow the decay not only of a K (energy released 33.2 keV) but also of a L electron (energy release of about 5 keV) in a Iodine atom of the NaI(Tl).

Each Iodine atom contains 8 electrons on L-shell (two electrons on L1-, two on L2-, and four on L3-subshell), while only 2 are available on K-shell. Thus, the possibility to investigate the energy region corresponding to L-shell electron decays will increase the source strength by a factor 4 with respect to the standard procedure searching for K-electron decay.

The study of the L-shell electron decay is possible here owing to the low energy threshold and the low counting rate of the DAMA set-up.

In particular, in the following we will consider only L-shell electron decay, because the K-shell will contribute to the overall sensitivity on τ_e only at

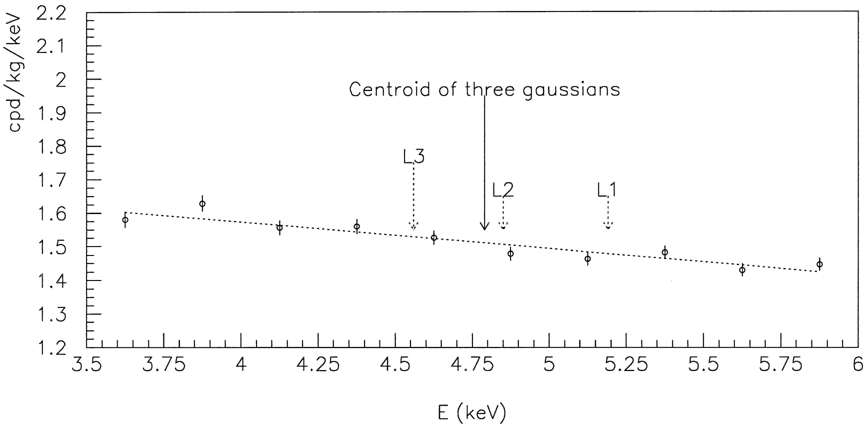

Fig. 1. Cumulative experimental energy distribution (already corrected for the needed efficiencies) in the region of interest for the process searched for; the statistics is 19511 kg · day. The dotted line represents the result of a fit given by the sum of a linear function (simplified background model 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).

$\simeq$ 1%, when – as in our case – the counting rates in two energy intervals are similar [1].

The statistics considered in the present analysis is 19511 kg · day (DAMA/NaI-1&2 running periods) [19,20]. The 2–20 keV energy distributions of each detector can be found in Ref. [19,20]. Since the behaviours of these distributions in the energy region of interest here are not very different, the cumulative energy distribution (Fig. 1) can be used for the electron life time estimate.

The possible decay of L-electrons in Iodine atoms inside the NaI(Tl) detectors 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 [25]) 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 in Fig. 1. Thus, the experimental distribution can be used to determine the limit on the electron life time. For this purpose we can use the known formula: $\tau = (\epsilon \cdot N \cdot t)/S$, where ϵ is the detection efficiency, N is the number of electrons on L-shell of Iodine atoms, t is the measuring time and S is the number of events due to the effect searched for and excluded at the given C.L.

The cascade of low energy X-rays and Auger electrons with the same energy of about 5 keV will be absorbed in a large NaI(Tl) crystal giving an efficiency $\epsilon = 1$. Nine 9.70 kg detectors include 3.51 $\cdot 10^{26}$ NaI molecules, that correspond to 2.81 $\cdot 10^{27}$ electrons on L-shell of Iodine atoms. Thus, the total $N \cdot t$ is equal to $1.72 \cdot 10^{27}$ electrons · year. As the simplest estimate of the excluded number of events S we can accept the standard statistical deviation of the total number of events in the 3.5–6.0 keV energy region. 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% (ϵ_{window}) of the total area. The value $S = (\delta \cdot w)/\epsilon_{\text{window}} = 482(793)$ 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). The obtained result gives the following limit on the electron ''disappearance'' life time: $\tau_e(e^- \to \nu_e \bar{\nu}_e \nu_e) > 3.6(2.2) \cdot 10^{24}$ yr with 68% (90%) C.L.

Then, with the aim to make the estimation of S more accurate, we used the following procedure. The

[1] In fact, the overall sensitivity on τ_e can be written as: $\tau_{\text{lim},L+K} \simeq \sqrt{\tau^2_{\text{lim},L} + \tau^2_{\text{lim},K}} = \tau_{\text{lim},L} \cdot \sqrt{1 + 0.024 \cdot \frac{R_L}{R_K}}$, being: (i) $\tau_{\text{lim},L(K)}$ proportional to $\frac{N_{L(K)}}{\sqrt{R_{L(K)} \cdot \sigma_{L(K)}}}$, with $N_{L(K)}$, $R_{L(K)}$ and $\sigma_{L(K)}$ the number of electrons of the L(K)-shell, the counting rate and the energy resolution in the L(K) region, respectively; (ii) $N_L / N_K = 4$; (iii) $\frac{\sigma_L}{\sigma_K} \simeq \sqrt{\frac{\langle E_L \rangle}{E_K}} = 0.38$.

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 resolutions scaled here according to: $\sigma/E \propto \frac{1}{\sqrt{E}}$. Moreover, the amplitudes of the gaussians have 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 1.2. Using these values the upper limit on the events number S was calculated according to 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: $S < 413(715)$ and $\tau_e(e^- \to \nu_e \bar{\nu}_e \nu_e) > 4.2(2.4) \cdot 10^{24}$ yr at 68% (90%) C.L.

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

The searches for ‘‘disappearance’’ of electrons on the atomic shells are related with the experimental quest for the violation of another fundamental principle: the Pauli exclusion principle (PEP). The transition of electrons to fully filled L-shell – process usually forbidden by PEP – will result in an energy release equal to the binding energy of the electron on L-shell. From an experimental point of view, both processes are undistinguishable in NaI(Tl) detector; thus the established limit on τ_e could be regarded also as a limit on the probability of the PEP violation. It should be noted, however, that according to theoretical arguments (see [6] and refs. therein) – at least in the framework of standard quantum mechanics – transitions to a filled shell are forbidden regardless of whether the PEP is violated or not, since they would change the commutation symmetry of the wave function of a given set of particles.

As mentioned in the introduction, the electric charge conservation is related with the mass of photon, m_γ. The relation between τ_e and m_γ was established, for example in the framework of the SU(5) model [27] as following: $\tau_e \simeq 10^{-25}(m_Z/m_\gamma)^2$ yr, where $m_Z = 91.2$ GeV is the mass of the Z boson. Using this relation and our value $\tau_e > 4.2 \cdot 10^{24}$ yr, we can receive $m_\gamma < 1.4 \cdot 10^{-14}$ eV. It can be compared with the best laboratory limit $m_\gamma < 2 \cdot 10^{-16}$ eV which was found in the recent experiment with thoroidal Cavendish balance [28].

4. Conclusions

Using the interesting features of the $\simeq 100$ kg NaI(Tl) DAMA set-up, the electron stability has been studied by looking for the signal from X-ray and Auger electron cascade which would follow the ‘‘disappearance’’ decay of L- electrons in Iodine atoms inside the NaI(Tl) detectors (energy released of about 5 keV).

With the total statistics of 19511 kg · day the limit on the electron ‘‘disappearance’’ life time was established to be: $\tau_e(e^- \to \nu_e \bar{\nu}_e \nu_e) > 4.2(2.4) \cdot 10^{24}$ yr with 68% (90%) C.L. This limit on τ_e could be regarded also as the limit for possible transitions of electrons in Iodine atoms to filled L-shell, which are usually forbidden by the Pauli exclusion principle.

The obtained result is one order of magnitude higher than the best limit previously achieved in Ref. [16] by considering the K-shell electrons in Ge detectors.

Acknowledgements

We wish to thank: Prof. C. Bacci, Prof. L.K. Ding, Dr. W. Di Nicolantonio for their contribution to the Collaboration efforts, and the students: R. Cerulli and M. Amato who are preparing their theses in the activities of the DAMA Collaboration. It is also a pleasure to thank Mr. A. Bussolotti and Mr. A. Mattei for technical help and the LNGS staff for support.

References

[1] S. Weinberg, Phys. Rev. B135 (1964) 1049.
[2] L.B. Okun, Ya.B. Zeldovich, Phys. Lett. B 78 (1978) 597.
[3] M.B. Voloshin, L.B. Okun, JETP Lett. 32 (1978) 145.
[4] R.N. Mohapatra, Phys. Rev. Lett. 59 (1987) 1510.
[5] L.B. Okun, Lepton and Quarks, North-Holland, Amsterdam, 1982, p. 181.
[6] L.B. Okun, Sov. Phys. Usp. 32 (1989) 543; Comments Nucl. Part. Phys. 19 (1989) 99; Phys. Rev. D45 (1992), VI 10.
[7] G. Feinberg, M. Goldhaber, Proc. Nat. Acad. Sc., USA 45 (1959) 1301.
[8] M.K. Moe, F. Reines, Phys. Rev. B 140 (1965) 992.
[9] R.I. Steinberg, K. Kwiatkowski, W. Maenhaut, N.S. Wall, Phys. Rev. D 12 (1975) 2582.
[10] E.L. Koval'chuk, A.A. Pomansky, A.A. Smol'nikov, JETP Lett. 29 (1979) 145.
[11] E. Bellotti, M. Corti, E. Fiorini, Phys. Lett. B 142 (1983) 435.
[12] F.T. Avignone III, R.L. Brodzinski, W.K. Hensley, Phys. Rev. D34 (1986) 97.
[13] D. Reusser, Phys. Lett. B 255 (1991) 143.
[14] H. Ejiri, H. Kinoshita, H. Sano, H. Ohsumi, Phys. Lett. B 282 (1992) 281.
[15] A. Balysh, M. Beck, S. Belyaev, Phys. Lett. B 298 (1993) 278.
[16] Y. Aharonov, F.T. Avignone III, R.L. Brodzinski et al., Phys. Lett. B 353 (1995) 168; Phys. Rev. D52 (1995) 3785.
[17] P. Belli, R. Bernabei, W. Di Nicolantonio, Astrop. Phys. 5 (1996) 217.
[18] Particle Data Group: Review of Particle Physics, Eur. Phys. J. C3 (1998) 1.
[19] R. Bernabei, Phys. Lett. B 424 (1998) 195.
[20] R. Bernabei, Phys. Lett. B 450 (1999) 448.
[21] R. Bernabei, Phys. Lett. B 389 (1996) 757.
[22] R. Bernabei, Phys. Lett. B 408 (1997) 439.
[23] R. Bernabei et al., pre-print ROM2F/98/27 to appear on Il Nuovo Cim. A.
[24] R. Bernabei et al., pre-print ROM2F/99/06 to appear on the Proc. of the Int. Conf. 3K-Cosmology, Rome, Oct. 98.
[25] R.B. Firestone, Table of isotopes, V.S. Shirley (Ed.), 8th ed., John Wiley and Sons, N.Y., 1996.
[26] G.J. Feldman, R.D. Cousins, Phys. Rev. D57 (1998) 3873.
[27] J.C. Huang, J. Phys. G. 13 (1987) 273.
[28] R. Lakes, Phys. Rev. Lett. 80 (1998) 1826.