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New experimental limits for the electron stability

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Abstract

A set of two natural abundance Ge detectors of 1.1 kg each, located in the Homestake mine, and one small, 0.253 kg, Ge detector operating in the Canfranc railway tunnel in Spain, have been used to obtain bounds on the stability of the electron against the decay modes $e^- \to \gamma\nu_e$ and $e^- \to \nu_e\nu_e\bar{\nu}_e$. The bounds on the mean lifes are $\tau(\gamma\nu_e) > 3.7(2.1) \times 10^{25}$ yr, 68%(90%) CL and $\tau(\nu_e\nu_e\bar{\nu}_e) > 4.3(2.6) \times 10^{23}$ yr, 68%(90%) CL, which are at present the most stringent laboratory limits for these decays.

1. Introduction

In the context of gauge field theories, the invariance of the Lagrangian, $\mathscr{L}$, under a given gauge transformation corresponds to the conservation of some specific type of "charge". In some grand unified theories, for example, terms appear in $\mathscr{L}$ which break the global gauge-invariance associated with barionic charge (baryon number) leading to proton decay at some level [1,2]. In the electroweak sector, the local gauge-invariance of the Lagrangian corresponding to the equations of quantum electrodynamics, dictates strict electric charge conservation and a massless photon. Accordingly, in the context of this class of theories, we do not expect electrons to decay, because there is no lighter charged lepton, and the decay into photons and/or neutrinos requires the violation of charge conservation. Nevertheless, to neglect searches for the unexpected is tantamount to assuming a priori that our current understanding of particle physics is complete and correct. It is of paramount importance to test each conservation law to the best of our experimental ability.

A number of detailed theoretical discussions of electric charge conservation in the context of renormalizable gauge field theories have appeared in the literature [3–6]. An essential point is that the local gauge invariance of the Lagrangian of quantum electrodynamics (QED) stems from the massless gauge bosons and guarantees via Noether's theorem that the corresponding charge is exactly conserved. In fact, a finite photon mass alone would not destroy

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exact charge conservation; this would also require terms in the Lagrangian that destroy global as well as local gauge invariance [2]. Recently, however, there have been some reasonably cogent theoretical arguments against the use of X-ray and γ-ray data to search for the decay of the electron [7–10]. These arguments, however, require certain fundamental assumptions in the interpretation of infinite amplitudes rendering the conclusions model dependent. See the theoretical considerations of Ref. [11].

Experimental tests of charge conservation via the search for spontaneous X-rays or 255 keV γ-rays from the decay modes $e^- \to \nu_e \nu_e \bar{\nu}_e$ and $e^- \to \gamma \nu_e$, respectively, have a long history well covered in the literature [12–18]. In both types of searches, an ultralow background detector is needed. The lower the achieved background the more stringent the limit obtained for the lifetime of the above processes. The experimental limits for the electron decay stand presently at $\tau(\nu_e \nu_e \bar{\nu}_e) > 2.7\ (1.7) \times 10^{23}$ yr [19] and $\tau(\nu_e \gamma) > 2.35\ (1.19) \times 10^{25}$ yr [20], expressed at 68% (90%) CL.

This paper reports new limits on the mean life of the electron by using the data of the background spectra obtained with two sets of germanium detectors: A pair of twin Ge detectors of about 1.1 kg each, operating 1438 meters underground in the Homestake Laboratory (4000 m.w.e.), South Dakota, USA, and one small 0.253 kg Ge detector located in the Canfranc Laboratory, Aragonese Pyrenees, Spain, located 260 m underground (675 m.w.e.). The results are by-products of ongoing investigations on the double beta decay of ^{76}Ge and on the search for particle dark matter in the galactic halo.

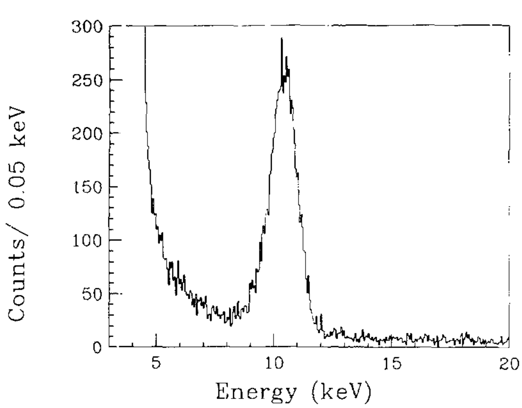

Fig. 1. The low energy region of the spectrum of the TWIN detectors after 1.92 kg yr of total effective exposure.

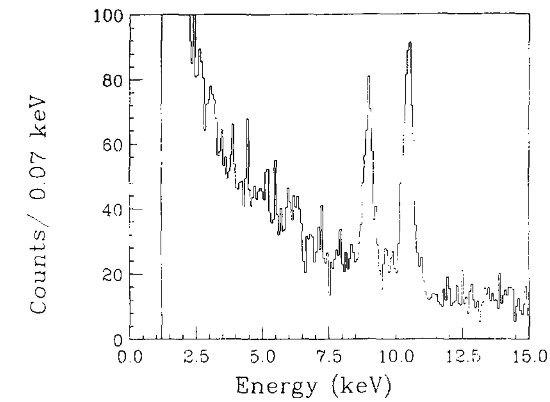

Fig. 2. Background spectrum of the TWIN detectors around the 255 keV region after 1.92 kg yr.

2. Experimental procedure

The TWIN detectors consist in a set of two ~ 1.1 kg natural abundance germanium crystals mounted in specially constructed dipstick-type cryostats electroformed from a copper sulphate solution. They operated in the Homestake gold mine in a shielding configuration of 40 cm of lead bricks for a total effective exposure of 1.92 kg yr. Details of the experimental set-up are given in Ref. [21]. Fig. 1, which corresponds to the low energy data accumulated during these 1.92 kg yr, shows the X-ray lines of copper and zinc cosmogenically induced on the detectors. Unlike the COSME detector described below, the poor instrumental resolution of the detectors does not allow to resolve these peaks. Fig. 2 shows the 255 keV energy region recorded with these detectors.

The COSME detector is a p-type coaxial hyperpure natural germanium crystal, of an active volume of 44 cm^3 and a mass of 253 g (including the dead layer) which has a long term resolution of 0.43 keV FWHM at 10.37 keV and an energy threshold of 1.6 keV. The detector is also mounted in a dipstick-type electroformed copper cryostat. The detector is placed within a shielding of 10 cm of 2000-year-old (roman) lead – inner layer – plus 20 cm of low activity lead (about 70 years old). A sheet of cadmium and

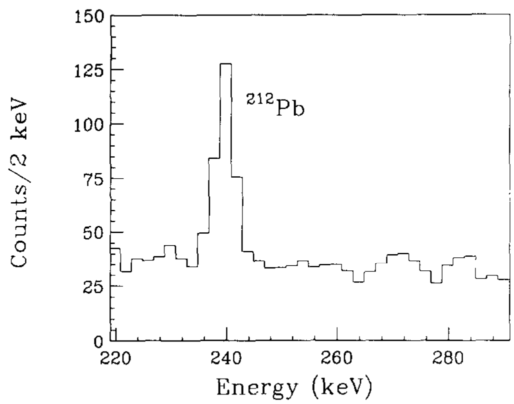

Fig. 3. The low energy region of the filtered spectrum obtained with the COSME detector after 130.7 kg d of effective exposure.

20 cm of paraffin and borated polyethylene complete the shielding. Details of the experimental set up and parameters are given in Ref. [22].

To improve the background and performances of the COSME detector a method of filtering the microphonic noise [23] based on the simultaneous use of two different shaping times in the processing of the signal – combined with a conventional time filtering process [19] to eliminate events not distributed evenly in time – has been developed.

The filtered spectrum shown in Fig. 3 corresponds to an exposure of $Mt = 130.7$ kg · d of COSME in the vicinity of the 11.1 keV region. Some peaks which clearly appear in the spectra, are the Cu X-ray (at 8.98 keV) and Ga X-ray (at 10.37 keV), cosmogenically induced in the detector. Both X-rays peaks are clearly resolved and, obviously, not affected by the filtering procedures previously mentioned.

3. Experimental results

Due to the features (energy threshold, energy resolutions and backgrounds) of each Ge detector we will use the data from TWIN to set lifetime limits for the decay mode $e^- \to \nu_e \gamma$, whereas COSME will be employed to obtain the lifetime bound in the $e^- \to \nu_e \nu_e \bar{\nu}_e$ decay search. The lower energy part of the spectrum is clearly resolved in COSME which features also a fairly low energy threshold. The TWIN, on the contrary, show a better background, in particular in the 255 keV energy region.

In the case of the search for the $e^- \to \nu_e \gamma$ decay channel, the lower limit of the mean life can be expressed as $\tau(\nu_e \gamma) > \sum \varepsilon_i N_i t / A$ where N_i stands for the number of electrons in the various components of the experimental device (Ge crystal, Cu cryostat, Pb shielding,...) and ε_i represents the corresponding absolute peak detection efficiencies for the 255 keV γ-ray. The quantity A is the maximum number of counts under the 255 keV peak (peak area) which could be attributed to the electron decay. Its value is obtained by means of standard statistical procedures [24]. The detector efficiencies were estimated through the EGS Monte Carlo simulation. The above expression, however, does not take into account the effect of the Doppler broadening on the decay of electrons in the different atomic shells [17]. Because of the average kinetic energy of the electrons in their orbital motion, the energy resolution of the detector is broadened from its nominal instrumental value. This effect is important for K- and L-shell electrons and should be also considered for M-shell electron decay. For instance, the decay of Cu K-shell (L-shell) electrons give a large Doppler width of ~ 80 keV (27 keV) FWHM, causing their contribution to the 255 keV peak to be minimal.

The Doppler-broadened line shape has been calculated by assuming that the electrons have a temperature corresponding to the expectation value of the kinetic energy in a given energy level, which according to the virial theorem is $\langle E_{\rm kin} \rangle = -\frac{1}{2} \langle E_{\rm pot} \rangle$ for the Coulomb potential. The Doppler line shape is given as

$$I(E) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-(E - E_0)^2 / 2\sigma^2 \right],$$

where

$$\sigma = \sqrt{\frac{KT}{mc^2}}\, E_0 = \sqrt{\frac{E_{\rm B}}{mc^2}}\, E_0,$$

with K the Boltzman constant, T the absolute electron temperature, m the electron mass, and E_0 the γ-ray energy from the decay of the electron in a given level. $E_{\rm B}$ is the absolute value of the electron binding energy:

$$E_0 = \frac{mc^2 - E_{\rm B}}{2}.$$

As there are various different subshells involved for the Ge, Cu and Pb electrons which may decay, a sum of different gaussian lines contributes to the line shape:

$$\sum_{i=1}^{29} \frac{1}{\sqrt{2\pi}\,\sigma_i} \exp\left[-(E-E_{0i})^2/2\sigma_i^2\right] \varepsilon_{Cu} N_{at}(Cu)$$
$$+ \sum_{i=1}^{32} \frac{1}{\sqrt{2\pi}\,\sigma_i} \exp\left[-(E-E_{0i})^2/2\sigma_i^2\right]$$
$$\times \varepsilon_{Ge} N_{at}(Ge)$$
$$+ \sum_{i=1}^{82} \frac{1}{\sqrt{2\pi}\,\sigma_i} \exp\left[-(E-E_{0i})^2/2\sigma_i^2\right]$$
$$\times \varepsilon_{Pb} N_{at}(Pb).$$

The number of atoms are $N_{at}(Ge) = 8.78 \times 10^{24}$ (for each Twin detector), $N_{at}(Cu) = 8.5 \times 10^{24}$ and $N_{at}(Pb) = 8.13 \times 10^{25}$. The absolute peak detection efficiencies for 255 keV gamma rays are $\varepsilon_{Ge} = 0.66$, $\varepsilon_{Cu} = 0.04$ and $\varepsilon_{Pb} = 2.9 \times 10^{-3}$ for electron's emission in Ge (dead zone included), in the Cu cryostat and in the Pb shielding, respectively. In this analysis the contribution from Pb atoms residing deeper than 0.61 cm into the internal cavity surrounding the detectors has been neglected, due to the total screening of a 255.5 keV gamma originating beyond that layer. The X-rays following K-electron decays in germanium and copper have been considered in a simplified model in which only a photon of the total K-shell binding energy is emitted. The K-electron decays in lead does not contribute to the 255 keV peak due to the fact that in this case the signal is expected far from this energy and is largely broadened by the Doppler effect. For X-rays of other shells complete absorption in the place of production has been assumed. The detector resolution at 255 keV, $\Gamma_{FWHM} = 3.9$ keV, rises up to 11.2 keV after Doppler-broadening is included. In this experiment, the background is $B(\sim 255 \text{ keV}) = 8.8$ c keV^{-1} kg^{-1} yr^{-1} (see Fig. 2). A maximum likelihood analysis of the region 220–280 keV gives a maximum number of counts under the 255.5 keV Doppler broadened peak of 10.6 (19.0) at 68% (90%) confidence level. This in turn leads to a mean life lower limit of

$$\tau(\nu_e \gamma) > 3.7\ (2.1) \times 10^{25} \text{ yr } (68\%\ (90\%)\ \text{CL}),$$

which improves the best previously published limits [20].

Another more general method to test the electron stability is to search for the "invisible" decays $e^- \to \nu_e \nu_e \bar{\nu}_e$. The decay of a K-shell electron will leave a hole and the consequent X-ray cascade will result in a peak of 11.1 keV (binding energy of an 1s electron in Ge). These X-rays are difficult to measure, even with low background detectors. The current limits stand at levels two orders of magnitude less stringent than the bounds obtained through the less general, specific channel $e^- \to \nu_e \gamma$. As stressed above the good energy resolution of COSME allows us to resolve the 11.1 keV peak from the other X-ray peaks in that region (Cu X-ray at 8.98 keV, Zn X-ray at 9.66 keV and Ga X-ray peaks at 10.37 keV). Furthermore, the fairly good background of COSME in that region (5–15 keV) allows us to extract, in conclusion, better mean life lower limits than those reported up to now.

The data obtained with the COSME detector refer to an effective running time of $t = 13404$ h. The background in the 11.1 keV energy region is $B(\sim 11.1 \text{ keV}) = 1.6$ c keV^{-1} kg^{-1} d^{-1}. The mass of the germanium crystal is of 253 g, i.e., $N_{at}(Ge) = 2.10 \times 10^{24}$ atoms. We obtain the mean life lower limit by using the expression $\tau(\nu_e \nu_e \bar{\nu}_e) > N_1 \varepsilon_1 t/A$. Here $N_1 = 2 \times 2.1 \times 10^{24}$ is the number of K-electrons in Ge quoted above, $t = 13404$ h is the running time and the peak efficiency for the 11.1 keV X-rays emitted anywhere in the germanium crystal (dead layer included) is $\varepsilon_1 = 0.93$. The upper limit to the number of counts under the 11.1 keV peak, A, is determined by fitting four gaussians and a second order polynomial to the experimental spectrum in the region 5–15 keV. The gaussian centroids are fixed at the values $E_a = 11.1$ keV, $E_b = 10.37$ keV, $E_c = 9.66$ keV, $E_d = 8.98$ keV, and their widths at $\sigma_a = 0.20$ keV, $\sigma_b = 0.19$ keV, $\sigma_c = 0.18$ keV, $\sigma_d = 0.17$ keV. This fit yields the areas $A_a = 2 \pm 13$, $A_b = 491 \pm 27$, $A_c = 43 \pm 16$, $A_d = 321 \pm 24$, and therefore a maximum number of 11.1 keV X-rays $A = 13.8$ (22.7) at 68% (90%) CL. The corresponding electron lifetime lower limit so obtained is

$$\tau(\nu_e \nu_e \bar{\nu}_e) > 4.3\ (2.6) \times 10^{23} \text{ yr } (68\%\ (90\%)\ \text{CL}).$$

This value represents an improvement of a factor 1.5 over the previous best value obtained with Ge detectors [19], and of a factor 3.5 with respect to the best limit from K-electron decay in NaI detectors [25].

Acknowledgements

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