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New experimental limits for electron decay and charge conservation

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New experimental limits for the decay $e^- \to \gamma + \nu_e$ are reported. The lower limit for the half-life of this decay mode is $T^e_{1/2} > 1.63 \times 10^{25}$ yr (68% CL). The data were collected for 3199 h by using one of the enriched germanium detectors of the Heidelberg–Moscow $\beta\beta$ Collaboration. This detector has an active volume of 591 cm^3. This value is up to now the most stringent laboratory limit for this decay mode. Also charge nonconservation in nuclei is shortly discussed in the Ga–Ge system using the data of gallium solar neutrino experiments.

1. Introduction

The standard model of elementary particle physics is in excellent agreement with all experimental results obtained with accelerators. Looking for physics beyond the standard model the search for rare events and tests of the fundamental laws of physics seem to be promising. One of the possible tests is that of charge conservation.

The application of local gauge invariance in field theory implies the conservation of the corresponding charge. The U(1) gauge invariance of the QED requires the conservation of the electric charge. This is in contrast to a violation of baryon number B, because there is no known underlying symmetry. In B-violating GUT's therefore proton decay like $p \to e^+ + \pi^0$ is possible, but electric charge is still conserved. Nonconservation of the electric charge will only be possible if the lagrangian of QED contains terms which destroy global as well as local gauge invariance. Thus the investigation of electron decay is a step towards non-standard physics, which would require a new description of our present understanding of nature. For a description of charge nonconservation in nuclei see ref. [1].

There are mainly two possible ways of observing the e^--decay in Ge-semiconductor detectors: (i) the search for the 255 keV γ ray coming from the decay $e^- \to \gamma + \nu_e$, and (ii) looking for the decay $e^- \to \nu_e + \nu_e + \bar{\nu}_e$. The decay mode (ii) creates K-shell X rays which are, even with a very low-background detector, difficult to measure. Thus we search for the decay mode $e^- \to \gamma + \nu_e$; this investigation is handled as a byproduct of the ongoing Heidelberg–Moscow $\beta\beta$ experiment which will be described below. The present limits for the electron decay are $T_{1/2} > 1.0 \times 10^{25}$ yr for the decay mode (i) [2] and $T_{1/2} > 1.9 \times 10^{23}$ yr for the decay mode (ii) [3].

2. Experimental setup

The observation of the rare electron decay will only be possible if a detector with ultralow background is used; otherwise the expected weak signal of the 255 keV γ-line of the decay would be lost in the underground radiation. The enriched germanium detectors of the Heidelberg–Moscow $\beta\beta$ Collab. which are used to search for neutrinoless $\beta\beta$ decay are very well

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suitable to look also for the electron decay. Therefore the data of one of these detectors with a mass of 2.88 kg of 86% enriched ^{76}Ge are analysed.

The detector is operated in the Gran Sasso Underground Laboratory where the shielding of the surrounding rock corresponds to 3500 m.w.e. This reduces the cosmic muon flux by six orders of magnitude and excludes the influence of the cosmic hadrons. To reduce the radioactivity coming from the rock the detector is mounted in a passive inner shielding of 10 cm ultra-low background lead, followed by 20 cm of boliden lead. The whole equipment is placed in a box of iron purged with nitrogen to keep away the gaseous parts of the primordial radioactivity in the air. These techniques reduce the background in the vicinity of the expected γ-line of the electron decay by more than about four orders of magnitude. All parts of the crystal holder are made out of electrolytic copper and are specially selected.

The measured spectrum is mainly dominated by cosmic-ray-generated isotopes in the copper, i.e. ^{54}Mn, ^{57,58,60}Co and ^{65}Zn. Besides these lines also the internal lines (arising from activities inside the germanium crystal) can be detected (because they are shifted by the accompanied X-ray energy). Finally a remaining part of the primordial radioactivity and man-made isotopes (i.e. ^{40}K, ^{137}Cs and the radon components of the ^{232}Th/^{238}U chains) can be found. The activities of these lines are in the order of μBq/kg; the detection of these lines shows the excellent sensitivity of the installed detector. For additional information about the used detectors and their shieldings see ref. [4].

3. Data analysis and results

Data were collected for 3199 h using the experimental setup discussed above. The resulting spectrum is shown in fig. 1. The background count rate in the region of 255 keV is 25.8 counts/keV kg yr. To obtain the lower limit for the half-life $T^e_{1/2}$ of the electron decay we can write the expression for $T^e_{1/2}$ as

$$T^e_{1/2} \geq \ln 2 \frac{t}{N_{\text{excl}}} \left(P_{\text{Cu}} N_{\text{Cu}} + P_{\text{Ge}} N_{\text{Ge}}\right) , \qquad (1)$$

where $N_{\text{Ge,Cu}}$ are the numbers of electrons in the Ge detector and the copper of the cryostat, respectively, $P_{\text{Ge,Cu}}$ are the detection efficiencies for the 255 keV γ ray, and t is the measuring time. The numbers of electrons are $N_{\text{Cu}} = 1.13 \times 10^{27}$ and $N_{\text{Ge}} = 5.04 \times 10^{26}$. Here no K- and L-shell electrons are used for both Ge and Cu because of the reasons discussed below. The efficiencies are calculated with the use of the GEANT3 Monte Carlo program [5]. They are $P_{\text{Cu}} = 4.62\%$ and $P_{\text{Ge}} = 55.7\%$, respectively.

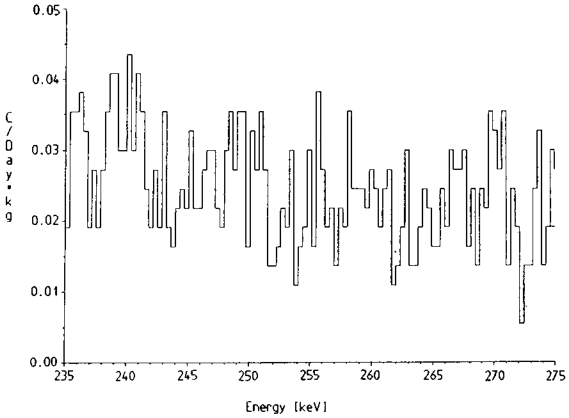

Fig. 1. Background spectrum of the enriched germanium detector in the vicinity of 255 keV after 368 kg d of measuring time.

The quantity N_{excl} is the maximum number of electron decay events which can be excluded at the peak position. For the calculation we use the algorithm given by the Particle Data Group [6]. To obtain the value of N_{excl} one has to take into account the Doppler broadening, as first mentioned by ref. [7]: due to the (average) kinetic energy of the electrons moving in their atomic shells the resolution will be larger than the pure detector resolution. This effect is not negligible: the K- and L-shell electrons are almost completely lost from the analysis (FWHM ~85 keV and ~30 keV, respectively), and also for the remaining M-shell electrons one has to take into account the Doppler broadening.

The Doppler broadening is calculated under the assumption that the virial theorem, $\langle E_{\text{kin}} \rangle = -\frac{1}{2} \langle E_{\text{pot}} \rangle$, is fulfilled. The expectation value of the kinetic energy in a given energy level therefore corresponds to an electron temperature. Thus the Doppler line shape is given by

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

with $\sigma = E_0\sqrt{kT/m_e c^2}$, where k is Boltzmann's constant, T is the absolute electron temperatures, m_e is the electron mass, and E_0 is the γ ray energy from the electron decay (in a given level). This can be expressed in terms of the absolute binding energy E_B of the electron,

$$\sigma = 4.47\times10^{-2}E_0\sqrt{E_B(\mathrm{keV})}\ . \tag{3}$$

Actually there exist several shells in both the Ge and Cu atoms. Thus the complete Doppler broadening of the FWHM is the sum of the seven shells of both Ge and Cu, so that in the end fourteen different gaussian lines contribute to the line shape. This can be expressed as

$$I(E) = \sum_i \frac{n_i}{\sqrt{\pi}\,\sigma_i}\exp\left(-\frac{(E-E_{0,i})^2}{2\sigma_i^2}\right) \tag{4}$$

with

$$\sigma_i = 4.47\times10^{-2}E_{0,i}\sqrt{E_{B,i}(\mathrm{keV})}\ ,$$

where n_i is the fraction of electrons, $E_{0,i}$ is the corresponding γ ray energy from the electron decay, and $E_{B,i}$ is the binding energy in the ith shell; the index i runs over the M1 shell to the M4/5 shell of both Cu and Ge. The overall FWHM rises from 2.5 keV (resolution of the detector) up to 7.6 keV if the Doppler broadening is taken into account. This is shown in fig. 2. With the corrected FWHM one gets the following values for N_{excl}: $N_{\mathrm{excl}} < 5.15$ counts (68.3% CL), < 10.19 counts (90% CL) and < 29.08 counts (99.9% CL), respectively. With these values the resulting limits for the half-life $T^e_{1/2}$ are $T^e_{1/2} > 1.63\times10^{25}$ yr (68.3% CL), $> 8.26\times10^{24}$ yr (90% CL), $> 2.89\times10^{24}$ yr (99.9% CL), respectively. The value of the half-life is about one and a half times better than the up to now best value for the decay $e^- \to \gamma + \nu_e$ quoted in ref. [2].

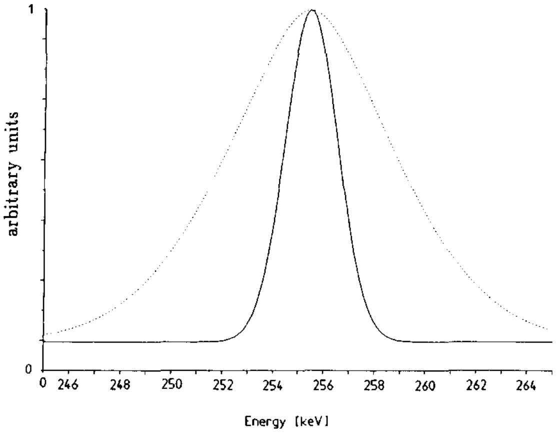

Fig. 2. The expected line shape at 255 keV; solid curve: detector resolution, dotted curve: after including both the Doppler broadening due to electron motion and the binding energy shift.

How can this limit be seen in the context of astrophysics? From astronomical observation it is also possible to calculate lower limits for the electron decay. A rough estimate can be found if we assume that (i) the proton is stable (the half-life for the proton decay is $T^p_{1.2} > 5\times10^{32}$ yr for the decay mode $p \to e^+e^+e^-$ [8] and therefore much higher than the experimental value of $T^e_{1/2}$), (ii) all astronomical objects are made out of hydrogen, and (iii) there is no non-baryonic dark matter. We start with the radioactive decay law

$$1-\exp(-\lambda t) \approx \lambda t = \frac{N_Q}{N_0}\ , \tag{5}$$

where $N_Q = N_Q(t)$ is the number of electrons at time t, N_0 is the number of electrons at $t=0$, i.e. the time of the formation of the universe. With the approximations (i)–(iii) given above we can set $N_0 = N_B$ (N_B is the number of baryons). Furthermore we can replace the relation for the produced excess charge, N_Q/N_B, by the relation of charge to baryon density n_Q/n_B; thus we find

$$\lambda t = \frac{n_Q}{n_B}\ . \tag{6}$$

To get the limit for contracting an interstellar hydrogen [9] gives $n_Q/n_B < 10^{-18}$. Because the sun exists for about 4.5×10^9 yr this leads to ($\lambda = \ln 2/T^e_{1/2}$) $T^e_{1/2} > 3.6\times10^{27}$ yr. A better estimate for the half-life of the electron is calculated if we use upper limits for the anisotropy of the cosmic radiation [9]; Orito and Yoshimura [9] found the limit to $n_Q/n_B < 6\times10^{-28}$. Together with an estimated age of our galaxy of about 15×10^9 yr this leads to $T^e_{1/2} > 1.6\times10^{39}$ yr. This is far beyond the limits determined in laboratories, but the disadvantage of the astronomical limits (especially the second limit) is the dependence on some unknown parameters (stability of the proton, neglecting the dark matter problem, charge excess due to other origins). Therefore the laboratory limit remains important because it is not dependent on any model. On the other hand it should be mentioned that there are strong theoretical arguments against the search for the decay mode $e^- \rightarrow \gamma + \nu_e$ [10–12]: the calculation of ref. [10] showed that the electron decays in a way called catastrophic bremsstrahlung: instead of the decay $e^- \rightarrow \gamma + \mu_e$ it is expected that the decay channel is $e^- \rightarrow \nu_e + N_\gamma \gamma$ with $N_\gamma \approx 10^{14-21}$. These γ rays are in the far infrared and therefore not observable. With the use of the upper limit of the mass of the photon, $m_\gamma < 6 \times 10^{-16}$ eV [13], these calculations give a lower limit $T^e_{1/2} > e^{10^{20}}$ yr.

Another possibility is too look for a nucleus decaying through charge-nonconservation [1]. One of the possible systems to study these decay modes is the ^{71}Ga–^{71}Ge system. The ^{71}Ga nucleus is heavier than ^{71}Ge, but the mass difference is less than the electron mass, so normal β decay is not allowed. This offers charge-nonconserving decay modes like

$$^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + X$$

$$X = \gamma,\ \bar{\nu}\nu,\ \text{pseudoscalar particles} \dots .$$

The present published half life limit for these modes in the ^{71}Ga–^{71}Ge system is $T_{1/2} > 2.3 \times 10^{23}$ yr (90% CL) [14]. Fortunately, due to the mentioned mass difference, this reaction can also be used to build a low threshold detector for solar neutrinos first proposed by Kuz'min [15] via the reaction

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^- .$$

Because of the long standing solar neutrino problem two of such gallium detectors were built and have started measurement recently: the GALLEX and the SAGE experiment, respectively. Here we will concentrate on the GALLEX experiment. For an ad hoc estimate without experimental results see ref. [16]. The GALLEX experiment [17] is using 30.3 t of Ga in form of about 110 t $GaCl_3$ solution; the experiment is located in the Gran Sasso Underground Laboratory (Italy). The natural abundance of ^{71}Ga is about 39.9%, so that the source strength in GALLEX is 1.03×10^{29} atoms. In the following evaluation we will make the most conservative assumption that all ^{71}Ge is produced by the charge nonconserving processes instead of solar neutrinos or other reactions like $^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$. The GALLEX Collaboration gives a value of 83 ± 19 (stat.) ± 8 (sys.) SNU (1 SNU = 1 capture per 10^{36} target atoms per second) [18]. The SNU numbers can be converted in a production rate of ^{71}Ge atoms per day. The GALLEX rate corresponds to about 0.9 ^{71}Ge atoms per day. The half life can be calculated according to (assuming an exponential decay law and $t \ll T_{1/2}$)

$$T_{1/2} = \ln 2 \, \frac{N_{\mathrm{Ga}}}{N_{\mathrm{Ge}}} \, t .$$

The measuring time of GALLEX corresponds to 295 days. With the conservative assumption that all 83 SNU's are produced in charge nonconservation processes instead of solar neutrinos we obtain a half-life limit of $T_{1/2} > 2.4 \times 10^{26}$ yr for GALLEX. Using the 2σ upper limit the half life limit changes to $T_{1/2} > 1.71 \times 10^{26}$ yr. This is about three orders of magnitude better than the previously reported value of $T_{1/2} > 2.3 \times 10^{23}$ yr and one order of magnitude better than the half-life limit for the electron decay of $e^- \rightarrow \gamma + \nu_e$.

4. Conclusion and outlook

We report a new lower limit for the electron decay mode $e^- \rightarrow \gamma + \nu_e$. The half-life for this decay after 3199 h of measuring time of $T_{1/2} > 1.63 \times 10^{25}$ yr (68% CL). In the future it will be possible to operate with 10 kg of enriched germanium; this will make it possible to increase the limit for $T_{1/2}$ by at least one order of magnitude.

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References

[1] H. Ejiri et al., Phys. Rev. C 44 (1991) 502; Phys. Lett. B 282 (1992) 281.

[2] F.T. Avignone et al., Phys. Rev. D 34 (1986) 97.
[3] D. Reusser et al., Phys. Lett. B 255 (1991) 143.
[4] Heidelberg–Moscow-experiment, A. Balysh et al., Phys. Lett. B 283 (1992) 32.
[5] A. Müller, Ph.D. Thesis (Heidelberg, 1992).
[6] Particle Data Group, J.J. Hernández et al., Review of particle properties, Phys. Lett. B 239 (1990) III.36.
[7] E. Bellotti et al., Phys. Lett. B 124 (1983) 435.
[8] Particle Data Group, J.J. Hernández et al., Review of particle properties, Phys. Lett. B 239 (1990) VIII.1.
[9] S. Orito and M. Yoshimura, Phys. Rev. Lett. 54 (1985) 2457.
[10] L.B. Okun and Ya.B. Zel'dovich, Phys. Lett. B 78 (1978) 597.
[11] M.B. Voloshin and L.B. Okun, Pis'ma Zh. Eksp. Teor. Fiz. 28 (1978) 156.
[12] A.D. Dolgov and Ya.B. Zel'dovich, Rev. Mod. Phys. 53 (1981) 1.
[13] L. Davis, A.S. Goldhaber and M.M. Nieto, Phys. Rev. Lett. 35 (1975) 1042.
[14] I.R. Barabanov et al., JETP Lett. 32 (1980) 359.
[15] V.A. Kuzmin, Sov. Phys. JETP 22 (1966) 1050.
[16] O.V. Bychuk and V.N. Gavrin, Pis'ma Zh. Eksp. Teor. Fiz. 48 (1988) 116;
J.N. Bahcall, Neutrino astrophysics (Cambridge U.P., Cambridge, 1989).
[17] T. Kirsten and GALLEX Collab., in: Proc. Inside the Sun, IAU Colloq. (Versailles), eds. G. Berthomieu and M. Cribier (Reidel, Dordrecht, 1990) p. 187.
[18] GALLEX Collab., P. Anselmann et al., Phys. Lett. B 285 (1992) 376, 390.