New experimental limit on the stability of the electron

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A lower limit of 1.5×10^{25} yr (68% C.L.) is reported for the mean life of the electron decay via the branch $e^- \rightarrow \gamma + \nu_e$. This is significantly longer than the best previously reported limit. Data were collected for 8850 h with an ultralow-background 135-cm^3 Ge detector located 1438 m underground. The electrons of primary interest are in the germanium crystal and in 102 kg of copper surrounding the detector. A projection of the ultimate limit on the half-life for this decay mode which would be attainable using this technique, under the most optimistic circumstances, is about 3 orders of magnitude higher.

I. INTRODUCTION

The current experimental limit on the mean life of the proton to decay into a positron and neutral pion, $\tau_p(p\rightarrow\pi^0 e^+) > 2.5\times10^{32}$ yr, represents the most stringent test of a physical conservation law to date.[1] In the framework of the minimal SU(5) theory of Georgi and Glashow,[2] the baryon number is not exactly conserved. While the above experimental limit threatens minimal SU(5), there are alternate but similar grand unified theories[3] which can accommodate this result. Hence, the level of proton stability is of prime importance to the question of grand unification. The subject of conservation laws is always important in particle physics, and a comprehensive review of baryon and lepton conservation has been given by Primakoff and Rosen.[4]

Quite unlike the conservation of baryon number, the conservation of electric charge is theoretically predicted to be exactly obeyed in nature. A number of detailed theoretical discussions of charge conservation, in the context of renormalizable, gauge-invariant field theories, appear in the literature.[5–8] The essential point is that the Lagrangian of quantum electrodynamics (QED) enjoys local gauge invariance which depends on the gauge bosons being massless and guarantees, via Noether's theorem, that the corresponding charge is exactly conserved. In fact it can be shown[4] that a finite photon mass alone, particularly one consistent with experimental constraints, would not destroy exact charge conservation. To do this would require terms in the Lagrangian which destroy global as well as local gauge invariance. The search for the decay of the electron was first suggested by Feinberg and Goldhaber[9] as an experimental test of charge conservation.

In light of the above discussion, searches for the decays $p\rightarrow e^+ + \pi^0$ and $e^-\rightarrow\gamma+\nu_e$ are both important, but for very fundamentally different reasons. In the framework of the most attractive theory of grand unification, proton decay is expected at some level, whereas, in the framework of QED, exact charge conservation is predicted. Based on the current conventional wisdom, high priority will certainly not be given to the search for electron decay; however, it is always important to make significant improvements in the limits to which all conservation laws are tested and to give ultimate projections of the sensitivity of this type of experiment, particularly when this information can be extracted as a byproduct from ongoing experiments at no increase in cost. The purpose of this note is to report a new limit on the mean life of the electron for the decay mode $e^-\rightarrow\gamma+\nu_e$. The data are from background spectra of a well shielded ultralow-background 135-cm^3 intrinsic Ge detector. The detector and shield are located 1482 m underground in the Homestake gold mine in Lead, South Dakota. These data are the spinoff of an ultrasensitive search for two-neutrino and neutrinoless double-β ($\beta\beta$) decay of ^{76}Ge.

Charge conservation can be tested by searching for spontaneous K-shell x rays from the decay of the electron via the branch $e^-\rightarrow\nu_e+\nu_e+\bar{\nu}_e$, for example, or for the 255-keV γ ray from the decay $e^-\rightarrow\gamma+\nu_e$. We will refer to the mean lives corresponding to these branches as τ_x and τ_γ, respectively. The first search was made by der Mateosian and Goldhaber ($\tau_x > 10^{19}$ yr) quoted in Ref. 9. Later, limits were placed by Moe and Reines[10] ($\tau_x > 2\times10^{21}$ yr and $\tau_\gamma > 4\times10^{22}$ yr), by Steinberg, Kwiatowski, Maenhout, and Wall[11] ($\tau_x > 5.3\times10^{21}$ yr), and by Kovalchuk, Pomanski, and Smolnikov[12] ($\tau_x > 2\times10^{20}$ yr and $\tau_\gamma > 3.5\times10^{23}$ yr). Brief reviews of these results were given by Goldhaber[13] and by Reines and Sobel.[14] The first attempt to make these measurements using a Ge detector underground was reported by Bellotti *et al.*[15] ($\tau_x > 2\times10^{22}$ yr and $\tau_\gamma > 3\times10^{23}$ yr). It is difficult to compare this limit for τ_γ with those of earlier authors because Bellotti *et al.*[15] were the first to properly account for the Doppler shifts of the decay γ ray due to the average kinetic energy of orbital electron motion. In the case of the iodine K-shell electrons of Ref. 12, for example, the γ-ray line would have a full width at half maximum (FWHM) of 160 keV while for the L-shell electrons it would have a FWHM of 74 keV, when the Doppler broadening is combined with the 44-keV quoted instrumental resolution. The limit on τ_γ given in Ref. 12 was, however, the most stringent reported until the present work and shall be used for comparison neglecting, for the present, the Doppler broadening.

In 1974 Reines and Sobel[16] attempted to test the validity of the Pauli exclusion principle by placing limits on the appearance of spontaneous K-shell x rays from stable matter. In 1980, however, Amado and Primakoff[17] gave compelling arguments that the spontaneous appearance of K-shell x rays tests only charge conservation and not the validity of the exclusion principle. For this reason, from our point of view, a search for the decay $e^- \to \nu_e + \nu_e + \bar{\nu}_e$ has no clear advantage over that for the decay $e^- \to \gamma + \nu_e$, which is an easier experiment. However, a sensitive search for x rays alone would probe all possible decay modes whereas our experiment is sensitive to only one.

II. EXPERIMENTAL DESCRIPTION

The design of this spectrometer evolved from several prior generations of low-level spectrometers. The sources of background from a 1983 state-of-the-art NaI(Tl) anticoincidence-shielded intrinsic germanium spectrometer[18] were identified. The diode was removed from the anticoincidence shield and placed within a bulk lead shield which resulted in significantly reduced background due to ^{226}Ra and its daughters. An active anticosmic shield[19] was included in the bulk lead shield which reduced the cosmic-ray-induced component of the background by about a factor of 300.

The remaining background was then systematically traced. The aluminum end cap, diode cup, support hardware, and electronic parts close to the detector were found to be the primary sources of primordial and man-made radioactivity. The isotopes ^{228}Ac, ^{212}Pb, and ^{208}Tl from the ^{232}Th chain, ^{234m}Pa from the ^{238}U chain, ^{235}U, and ^{40}K were the significant primordial contributors with ^{137}Cs and ^{60}Co being the only discernible man-made radionuclides. Prospective construction materials were assayed for radionuclide contamination using two 30-cm-diameter-by-20-cm-thick NaI(Tl) detectors as described earlier.[20] Aluminum was the major source of primordial radioactivity, with capacitors, resistors, field-effect transistors (FET's), and rubber O rings being smaller contributors.[19] The stainless-steel screws contained ^{60}Co.

Three types of copper were analyzed, and the one with the least amount of radioactivity (<0.00003 disintegrations/min g) was used to replace the aluminum and stainless steel in the cryostat. Brass screws replaced the stainless-steel screws, and indium was used for the O-ring vacuum seal. The FET was modified to exclude the contaminated component, and the preamplifier was placed outside the shield. The resulting reduction in radioactive background was more than 3 orders of magnitude for the primordial radioactivities mentioned above.

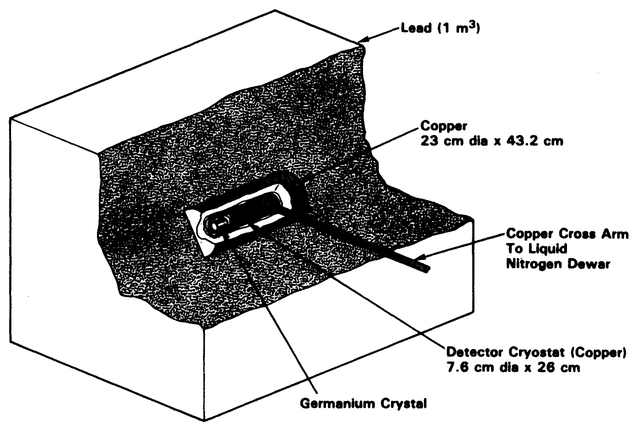

FIG. 1. Geometrical configuration of the Ge detector and inner copper shield.

The experiment was conducted with no special shielding between the low-background lead and the copper cryostat. A significant low-energy bremsstrahlung spectrum was observed from the β decay of the ^{210}Bi daughter of ^{210}Pb present in the lead shielding bricks themselves. An inner shield of pre–World War II steel was tried but was found to be contaminated with radioactive isotopes of thorium and radium albeit at levels which would be undetectable in previous low-background experiments. Later a copper inner liner, shown in Fig. 1, was installed which is 7.3 cm thick on the sides and 7.6 cm thick on the ends. This reduced the background in the 255-keV region by a factor of 12.7. In addition it provides nearly seven times the effective electron density within the range of the detector as does the lead. It is interesting to note that the experiment is sensitive enough to detect the 1124-keV line from the decay of ^{65}Zn present in the crystal due to the cosmic-ray-generated neutron reaction ^{70}Ge$(n,\alpha 2n)^{65}$Zn. This line is the sum of the 1115.5-keV transition in ^{65}Cu, following the electron capture of ^{65}Zn, and the Cu K x ray. Cosmogenically produced ^{54}Mn, ^{56}Co, ^{58}Co, ^{59}Fe, and ^{60}Co are also observed in the Cu liner. The specific activities of these isotopes in the copper liner are given in

TABLE I. Primary reactions of cosmic-ray neutrons with the copper liner and the equilibrium concentrations of daughter-isotope decays in disintegrations/min kg.

Reaction	Specific activity	Reaction	Specific activity
^{63}Cu$(n,\alpha 2n)^{58}$Co	0.05	^{63}Cu$(n,\alpha 4n)^{56}$Co	0.006
^{63}Cu$(n,2\alpha 2n)^{54}$Mn	0.02	^{63}Cu$(n,\alpha p)^{59}$Fe	0.004
^{63}Cu$(n,\alpha)^{60}$Co	0.01	^{63}Cu$(n,\alpha 3n)^{57}$Co	<0.002

Table I. The existence of detectable levels of these isotopes demonstrates that experimentalists involved in ultralow-background measurements must be cognizant of cosmogenic radionuclide production in their construction materials. This will be the limiting factor for low-background experiments above ground. Recently the copper lines have been replaced by lead bricks fabricated from 400-yr-old lead.

III. RESULTS AND ANALYSIS

Data were collected for 8850 h in the configuration shown in Fig. 1. The spectrum in the vicinity of 255 keV is shown in Fig. 2. The background count rate in the region of interest is 1.9×10^{-2} counts/keV h. This can be compared to 1.5 counts/keV h in the experiment of Kovalchuk, Pomanski, and Smolnikov[12] which until now claimed the most stringent limit on τ_e. A better measure of the relative merit of two experiments can be made by comparing the quantity

$$\epsilon N_e t/\sqrt{B} \ , \tag{1}$$

where ϵ is the weighted detection efficiency for the 255-keV γ rays from electron decay, N_e is the total number of electrons, t is the time, and B is the total background in one full width at half maximum in the detector for the 255-keV γ. These values are 4.3×10^{23} yr and 1.3×10^{25} yr for the experiment of Ref. 12 and this experiment, respectively.

An expression for the limit on the mean life set by the present experiment can be written as

$$\tau_e \geq \frac{(\epsilon_1 N_1+\epsilon_2 N_2)t}{c} \ , \tag{2}$$

where N_1 and N_2 are the numbers of electrons in the Ge detector and copper inner shield, respectively, and ϵ_1 and ϵ_2 are the corresponding overall detection efficiencies for the 255-keV γ ray. The quantity c is the maximum number of counts in the peak at 255 keV attributed to electron decay and t is the counting time. The numbers of electrons are $N_1=1.92\times10^{26}$ and $N_2=2.81\times10^{28}$. The efficiencies were calculated using Monte Carlo techniques developed earlier.[21,22] They are $\epsilon_1=0.52$ and $\epsilon_2=0.0078$. The total counting time is 8850 h or 1.01 yr. Equation (2) is then simply $\tau_e \geq (3.19\times10^{26})(t/c)$. There is no peak at 255 keV; the mean count is 163 keV^{-1}, and the resolution is 1.9 keV FWHM. This would place a limit of $c \lesssim 21$ and $\tau_e > 1.5\times10^{25}$ yr. This improvement over the result given in Ref. 12 would be expected from the figure-of-merit arguments given earlier. The data were subjected to a standard maximum-likelihood analysis with the result that $c \lesssim 14$, at a 68% confidence limit, which corresponds to $\tau_e \simeq 2.3\times10^{25}$ yr. This analysis, however, neglects the important effect of Doppler broadening due to the average kinetic energy of orbital electron motion. This effect is very significant for K- and L-shell electrons in Ge and Cu and must be considered in M-shell electron decay as well.

The Doppler broadened line shape was calculated by assuming that the electrons had a temperature corresponding to the expectation value of kinetic energy associated with a given energy level. According to the virial theorem, $\langle E_{\mathrm{kin}}\rangle = -\frac{1}{2}\langle E_{\mathrm{pot}}\rangle$ in the case of a Coulomb potential.[23] The Doppler line shape is given by[24]

$$I(E)=\frac{1}{(2\pi)^{1/2}\sigma}e^{-(E-E_0)^2/2\sigma^2} \ , \tag{3}$$

where $\sigma=(kT/m_e c^2)^{1/2}E_0$. Here k is the Boltzmann's constant, T is the absolute temperature, m_e is the electron mass, and E_0 is the γ-ray energy from the decay of the electron in a given level. This can easily be expressed as

$$\sigma/E_0=4.47\times10^{-2}[E_B\ (\mathrm{keV})]^{1/2} \ , \tag{4}$$

where E_B is the absolute value of the binding energy.

There are seven different subshells involved for both the Ge and Cu electrons. As a result the predicted γ-ray line is a sum of fourteen different Gaussian lines. This is expressed as

$$I(E)=\sum_i \frac{n_i}{(2\pi)^{1/2}\sigma}\exp[-(E-E_{0i})^2/2\sigma_i{}^2] \ , \tag{5}$$

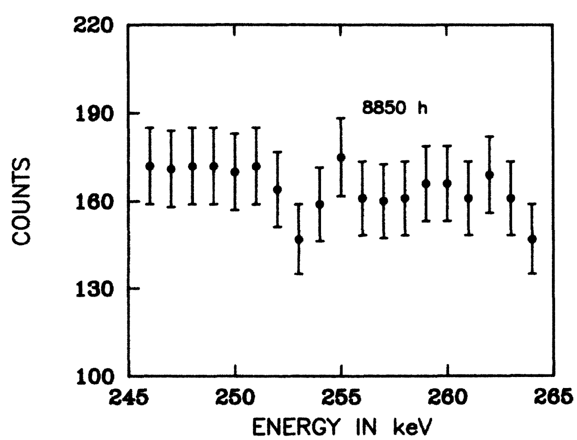

FIG. 2. Background spectrum of the 135-cm^3 ultralow-background spectrometer in the 255-keV region.

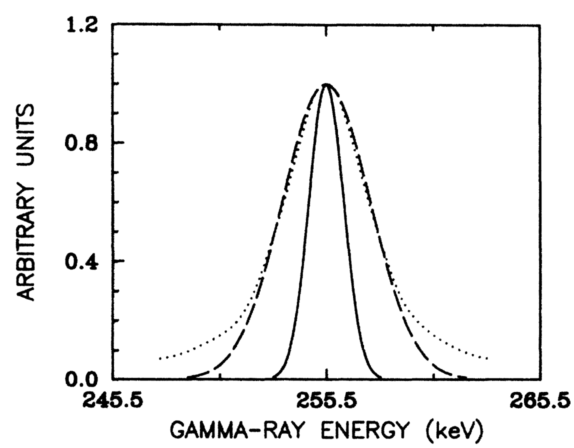

FIG. 3. Calculated composite γ-ray line from the decay $e^-\rightarrow\gamma+\nu_e$. The calculation includes binding energy shifts and instrumental and Doppler broadening. The solid curve is the instrumental line shape. The dotted curve is the Doppler-broadened composite line. The dashed curve is a Gaussian with the same FWHM as the Doppler-broadened composite line.

TABLE II. Limits on the electron mean life for various confidence intervals computed by maximum likelihood.

Confidence level	λ(C.L.) (counts)	Mean life τ_e (yr)
0.68	≤ 21	$\geq 1.5\times 10^{25}$
0.90	≤ 30	$\geq 1.1\times 10^{25}$
0.95	≤ 37	$\geq 8.6\times 10^{24}$
0.997	≤ 57	$\geq 5.6\times 10^{24}$

where the index i runs over the K shells through the M_5 shells of both Cu and Ge. The quantity n_i is the fraction of electrons in the ith shell.

The K- and L-shell electrons are almost completely lost from the analysis because of severe Doppler broadening. The decay of Cu K-shell electrons, for example, gives rise to a γ ray of 251.0 keV with a Doppler width of $\sim$80 keV FWHM. The decay of Cu L-shell electrons gives rise to a line at 255.0 keV with a Doppler width of 27 keV FWHM. The widths of the γ-ray lines from M_1-shell electrons is about 10 keV whereas that for M_2 and M_3 electrons is approximately 6 keV. The calculated composite line, including all occupied subshells, is shown in Fig. 3. The results of maximum-likelihood analyses, using this Doppler broadened line shape, are given in Table II. The agreement of the 68%-C.L. value in the table and the rough approximation given above without including Doppler broadening is coincidental.

IV. PROJECTED ULTIMATE SENSITIVITIES

The results of the present measurements are interesting because they extend the previous limit significantly. In our current search for $\beta\beta$ decay of ^{76}Ge, plans call for reducing the background significantly in the low-energy region and for constructing a large detector ($\sim$1440 cm^3) (Refs. 25 and 26). One-half of this detector has already been assembled; however, current cryogenic techniques used to shield the detector and cold finger from infrared radiation are incompatible with the ultralow-level background required. When new cryogenic developments are completed and this detector is installed in the mine it will represent a far more sensitive search for electron decay.

If the background can be reduced one order of magnitude and data accumulated for 5 yr, the resulting limit on τ_e would be $\gtrsim 2.5\times 10^{27}$ yr. If the background can be reduced by 2 orders of magnitude, the projected 5-yr sensitivity would be $\tau_e \gtrsim 1\times 10^{28}$ yr. Finally, there are other groups attempting ultrasensitive searches for ^{76}Ge $\beta\beta$ decay, and if these groups were eventually to achieve the same low levels of background in the low-energy region, the ultimate world limit could be on the order of 10^{29} yr.

ACKNOWLEDGMENTS

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[1]G. Blewitt *et al.*, Phys. Rev. Lett. **55**, 20 (1985).

[2]H. Georgi and S. L. Glashow, Phys. Rev. Lett. **32**, 438 (1974).

[3]T. W. Kephart and N. Nakagawa, Phys. Rev. D **30**, 1978 (1984).

[4]H. Primakoff and S. P. Rosen, Ann. Rev. Nucl. Part. Sci. **31**, 145 (1981).

[5]A. Y. Ignatiev, V. A. Kuzmin, and M. E. Shaposhnikov, Phys. Lett. **84B**, 315 (1979).

[6]M. B. Volóshin and L. B. Okun', Pis'ma Zh. Eksp. Theor. Fiz. **28**, 156 (1978) [JETP Lett. **28**, 145 (1978)].

[7]L. B. Okun', *Leptons and Quarks* (North-Holland, Amsterdam, 1982), p. 181.

[8]L. B. Okun' and Y. B. Zeldovich, ITEP Report No. 79, 1978 (unpublished).

[9]G. Feinberg and M. Goldhaber, Proc. Natl. Acad. Sci. U.S.A. **45**, 1301 (1959).

[10]M. K. Moe and F. Reines, Phys. Rev. **140**, 992 (1965).

[11]R. I. Steinberg, K. Kwiatowski, W. Maenhout, and N. S. Wall, Phys. Rev. D **12**, 2582 (1975).

[12]E. L. Kovalchuk, A. A. Pomanski, and A. A. Smolnikov, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 163 (1979) [JETP Lett. **29**, 145 (1979)].

[13]M. Goldhaber, in *Unification of Elementary Particles and Gauge Theories,* edited by D. B. Cline and F. Mills (Harwood Academic, New York, 1977), p. 531.

[14]F. Reines and H. W. Sobel, Trans. N.Y. Acad. Sci. **40**, 154 (1980).

[15]E. Bellotti, M. Corti, E. Fiorini, C. Liguori, A. Pullia, A. Sarracino, P. Sverzellati, and L. Zanotti, Phys. Lett. **124B**, 435 (1983).

[16]F. Reines and H. W. Sobel, Phys. Rev. Lett. **32**, 954 (1974).

[17]R. D. Amado and H. Primakoff, Phys. Rev. C **22**, 1338 (1980).

[18]N. A. Wogman, I.A.E.A. Proc. Ser. **252**, 1 (1981).

[19]J. H. Reeves, W. K. Hensley, R. L. Brodzinski, and P. Ryge, IEEE Trans. Nucl. Sci. **NS-31**, 697 (1984).

[20]N. A. Wogman, D. E. Robertson, and R. W. Perkins, Nucl. Instrum. Methods **50**, 1 (1967).

[21]F. T. Avignone III, Nucl. Instrum. Methods **174**, 555 (1980).

[22]F. T. Avignone III and T. W. Donnelly, Nucl. Instrum. Methods **179**, 163 (1981).

[23]J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, *Molecular Theory of Gasses and Liquids* (Wiley, New York, 1954), p. 41.

[24]Robert D. Cowan, *The Theory of Atomic Structure and Spectra* (University of California Press, Berkeley, 1981), p. 20.

[25]F. T. Avignone III, R. L. Brodzinski, D. P. Brown, J. C. Evans, Jr., W. K. Hensley, H. S. Miley, J. H. Reeves, and N. A. Wogman, Phys. Rev. Lett. **54**, 2309 (1985).

[26]R. L. Brodzinski, D. P. Brown, J. C. Evans, Jr., W. K. Hensley, J. H. Reeves, N. A. Wogman, F. T. Avignone III, and H. S. Miley, Nucl. Instrum. Methods **A239**, 207 (1985).

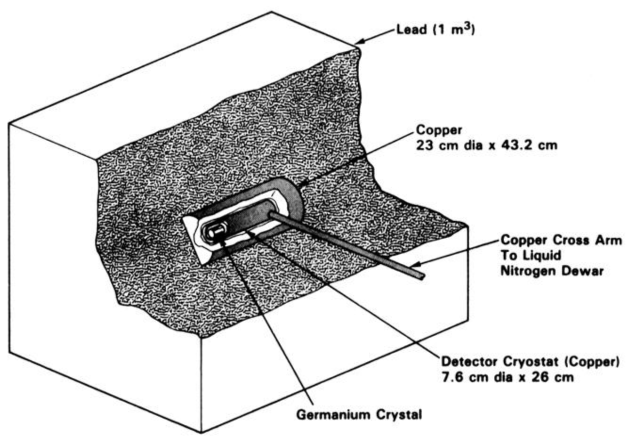

FIG. 1. Geometrical configuration of the Ge detector and inner copper shield.