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Experimental test of charge conservation and the stability of the electron*

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A new experimental lower limit of 5.3×10^{21} years for the mean lifetime of the electron for decay into nonionizing particles is reported. A finite value for this lifetime would have implied a breakdown of the law of charge conservation. The experimental technique consists of a search for the internally-absorbed 11.1-keV x-ray and Auger-electron cascade which would follow the decay of a K-shell electron in a germanium atom in a high-resolution Ge(Li) detector.

We are reporting an experimental test of the law of conservation of electric charge. The experimental basis of conservation laws has been discussed by Feinberg and Goldhaber,[1] who suggested the possibility of electron decay as a test of electric charge conservation. This is an appropriate place to look for electric charge nonconservation, since (according to present knowledge) the electron has the lowest rest mass of any particle carrying an electric charge. If energy conservation is valid, the electron, therefore, can decay only if electric charge is not conserved.

At the present time, the highest limit on the electron mean lifetime is[2] $\tau_e > 4 \times 10^{22}$ y. This experiment was sensitive only to the decay mode $e^- \rightarrow \nu_e + \gamma$. Any other decay mode of the electron could not have been seen. It is therefore of interest to perform experiments making minimum assumptions, or, at least, different assumptions about the particular mode by which the electron decays.

The present experiment is sensitive to all electron decay modes in which the decay particles escape from the detector and its anticoincidence shield without depositing energy. An example of such a decay permitted by all known conservation laws except charge conservation would be $e^- \rightarrow 2\nu_e + \bar{\nu}_e$. The result of the experiment is expressed as a lower limit for the mean lifetime of the electron for such decay modes.[3]

The first experiment of this kind was performed by der Mateosian and Goldhaber,[4] who used a NaI(Tl) scintillation detector to look for the x-ray and Auger-electron cascade which would follow the decay of a K electron of one of the iodine atoms inside the scintillation crystal. Because the range of the radiations emitted is much less than the crystal dimensions, the total energy released in the detector by such an event would be 33.2 keV, the K ionization energy of iodine. The limit obtained for the electron lifetime was $\tau_e > 10^{18}$ y.

In 1965, this experiment was repeated by Moe and Reines,[2] who quoted a lower limit of $\tau_e > 2 \times 10^{21}$ y. However, as discussed in the Appendix of the present paper, the lower limit achieved by Moe and Reines was, in our opinion, only $\tau_e > 10^{20}$ y. The experimental technique used was quite similar to that of der Mateosian and Goldhaber. The improvement over the value obtained in Ref. 4 was due to a longer running time as well as to a reduced background made possible by a location 585 m underground in a salt mine and by painstaking attention to detector and shielding design.

In the present experiment we have made use of the high-resolution solid-state detector technology now available to improve[5] the lower limit on the electron lifetime by a further factor of 50. The experimental technique consists of a search for the internally absorbed 11.1-keV x-ray and Auger-electron cascade which would follow the decay of a K-shell electron in one of the germanium atoms of a Ge(Li) γ-ray spectrometer crystal. Although the volume of our Ge(Li) crystal was smaller than that of the NaI(Tl) crystal of Ref. 2, an improved limit was obtained for three reasons: (1) The detector resolution of 1 keV was higher than the 17-keV resolution of the NaI(Tl) detector; (2) the running time was increased by a factor of 10; and (3) the behavior of the background in the region of interest was much smoother, thereby allowing the application of a least-squares-fitting procedure to the data. In addition a more satisfactory method of calibration of the detector and of determination of the detector response to the process of interest was used.

The experiment was performed in the counting facility of the University of Maryland nuclear chemistry laboratory. The experimental area is shielded only by several floors of a conventional building from cosmic rays. The arrangement of the experiment is shown in Fig. 1. The Ge(Li) detector was surrounded by an anticoincidence shield consisting of two large cylindrical NaI(Tl) scintillation detectors. All events depositing more

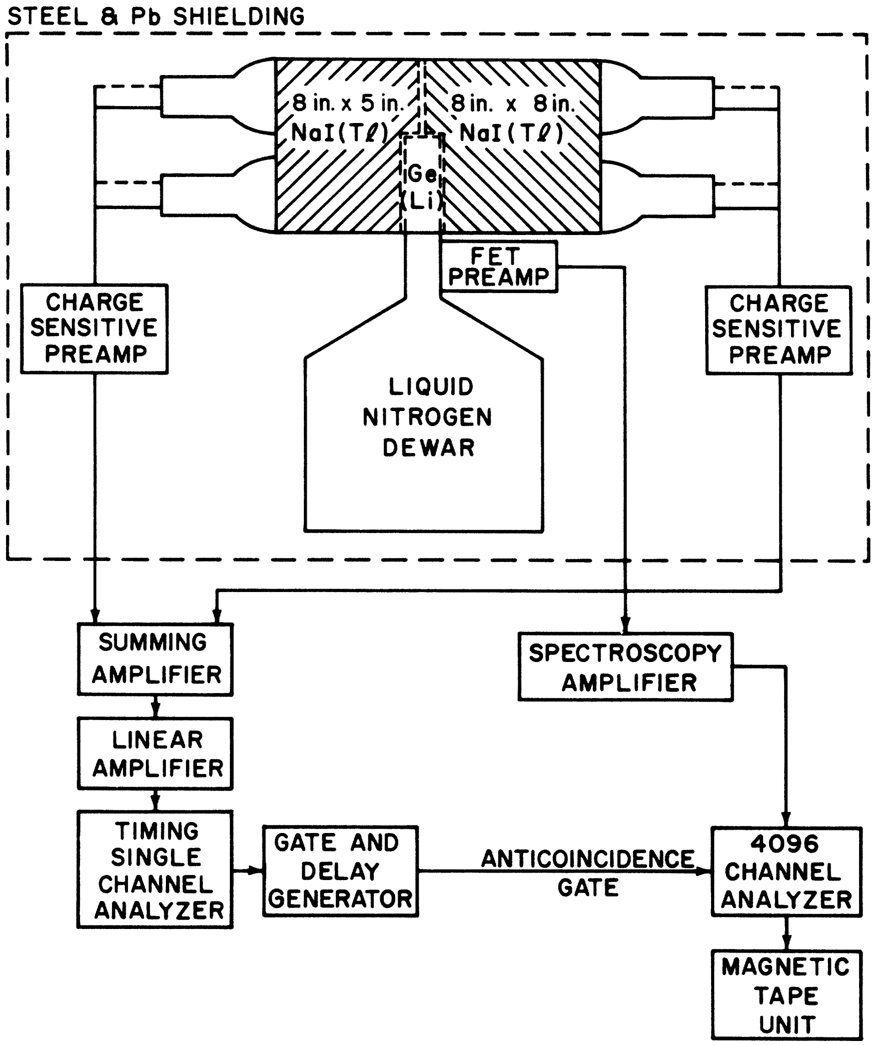

FIG. 1. Schematic drawing of the anticoincidence-shielded Ge(Li) spectrometer and associated electronics.

than 20 keV of energy in the NaI(Tl) detectors caused the anticoincidence gate of the 4096-channel analyzer to be closed. A blocking time of 700 μ sec was found to give optimum reduction of the background. The system dead time introduced by the blocking signal was measured to be 3.2%. The entire anticoincidence-shielded detection system was placed inside a cave whose walls consisted of a 10-cm thickness of Pb and a 10-cm thickness of steel.

The true coaxial Ge(Li) detector (Princeton Gamma-Tech serial No. 711) had a nominal active volume of 66.1 cm^3, a resolution of 2.0 keV at 1.33 MeV and a peak to Compton ratio (without Compton anticoincidence) of 36 : 1 at 1.33 MeV. Since the FET preamplifier (Princeton Gamma-Tech model PG-11) was uncooled, resolution at low energy was limited by electronic noise. The observed pulser width was 1.05 keV.

The results obtained after 1185.3 h of running time are shown in Fig. 2. Most of the peaks have been identified as due to members of the naturally occurring ^{238}U, ^{235}U, and ^{232}Th radioactive decay chains. The occurrence of these peaks is consistent with the observations of other workers involved in low-background measurements with Ge(Li) detectors.[6-9] We attribute these peaks to the presence of radioactive impurities in the materials surrounding the detector, and to the presence of radioactive gases (^{222}Rn and ^{220}Rn) in the air of the laboratory.

The feature of prime interest in these data is the peak clearly visible in channel 117. Using external radioactive test sources, a preliminary

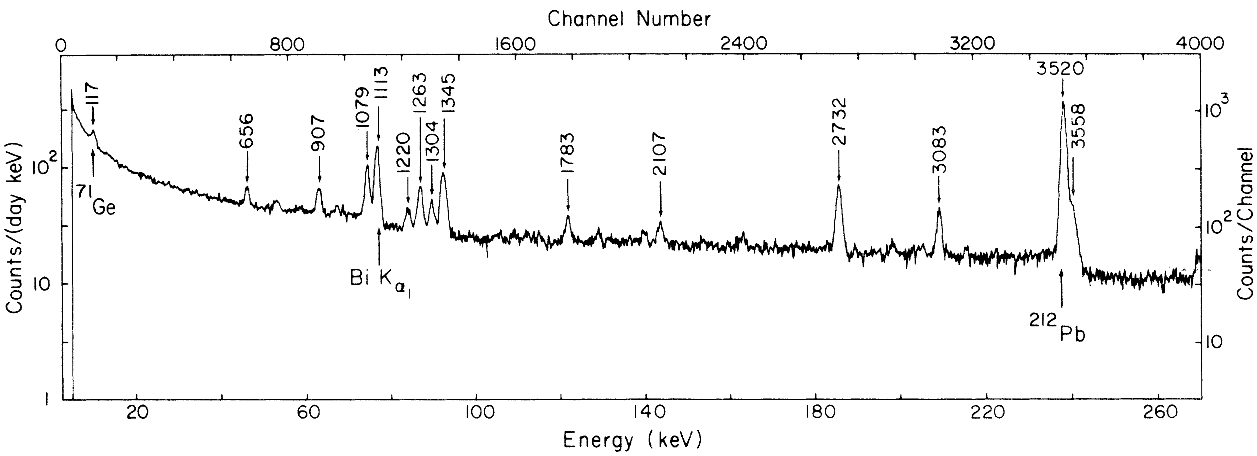

FIG. 2. Background spectrum obtained with the system shown in Fig. 1 after 1185.3 h of running time.

calibration based upon an extrapolation of a linear fit to the 88.0-keV line of ^{109}Cd and the 22.1-keV K_α line of Ag established the energy of this peak as 10.5 ± 0.4 keV. Because the cryostat window was too thick to allow observation of the 14.4-keV line of ^{57}Co, it is evident that the source of the 10.5-keV radiation must have been internal to the cryostat. We attribute this line to the x-ray and Auger-electron cascade which follows K-electron capture by the nuclide ^{71}Ge. The energy which would be released in the detector by such an event is 10.367 keV, the K ionization energy of Ga, in good agreement with the observed value of 10.5 ± 0.4 keV. The evidence upon which we base this conclusion follows.

When this line was first observed after 315.8 h of running time, its intensity was 3.5 ± 0.5 counts/h. At this point, since cosmic-ray-generated-neutron capture on ^{70}Ge (relative isotopic abundance 20.7%) was suspected as the source of the activity, Cd shielding was placed around the detection system inside the cave. The activity was then observed to decrease with a period in reasonable agreement with the 11.4-day half-life of ^{71}Ge. About 34 days after the Cd shielding was added, the count rate of the 10.5-keV line had decreased to 1.2 ± 0.5 counts/h. This result indicates that some of the neutrons being captured by ^{70}Ge atoms had energies above the Cd cutoff energy. It is also likely that (n, xn) and similar reactions on the heavier Ge isotopes were responsible for some of the ^{71}Ge activity.

The occurrence of the ^{71}Ge electron-capture line is fortunate in that it provides a virtually exact method of determining the detector response to electron decay events. The mean free path of thermal neutrons in natural Ge is about 10 cm. The Ge(Li) crystal is therefore effectively transparent to neutrons, and the ^{71}Ge activity is uniformly distributed throughout the volume of the crystal, a distribution exactly matching that of the electron decay events being sought. Energy-response problems associated with variations in charge-collection efficiency are thereby eliminated.

At the conclusion of the experiment, a 10-mCi Ra-Be neutron source was brought in close proximity to the detector for 3 h in order to produce ^{71}Ge activity for detector calibration. The data resulting from that activation are shown in Fig. 3. The count rate for the K-capture peak is 40.3 ± 1.8 counts/h. A six-parameter nonlinear least-squares fit was made to these data assuming a Gaussian peak on a quadratically varying background. The free parameters were the peak height, location, and width and the three coefficients of the background. The fitted curve is also shown in Fig. 3. The region of the fit extended from chan-

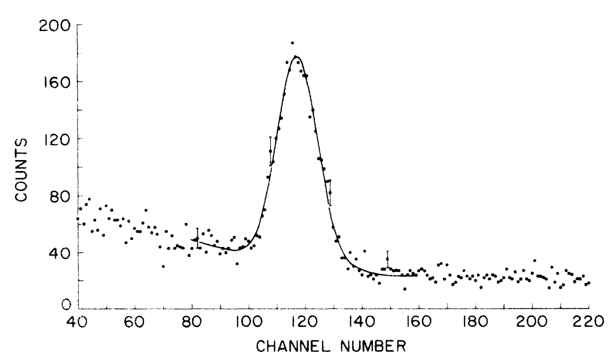

FIG. 3. The low-energy region of the spectrum obtained after thermal neutron activation of the Ge(Li) crystal. The peak is the 10.367-keV electron-capture line of ^{71}Ge used for detector calibration. The solid line is the result of a six-parameter least-squares fit to the data. The running time was 64.639 h.

nels 80 to 159. The reduced χ^2 was an acceptable 0.795. The parameters of interest from this calibration are the full width at half maximum (16.81 $\pm$0.56 channels or 1.13 keV) and the centroid (channel 117.61$\pm$0.20).

Using this information together with an energry scale derived from the 238.62-keV line of ^{212}Pb and the 77.11-keV Bi K_{α_1} line (see Fig. 2), it follows that the electron decay signal should be a Gaussian of width 16.81 channels centered on channel 128.59. A five-parameter fit assuming two Gaussian peaks with fixed widths and centroids on a quadratic background was then performed on the final data. The free parameters were the electron-capture peak height, the electron-decay peak height, and the three background parameters. The fitted region extended from channels 60 to 159. The final data together with the fitted curve are shown in Fig. 4. The reduced χ^2 was 0.987. In Fig. 5 are shown the deviations of the data points from the fit of Fig. 4 in units of the standard deviation. No systematic deviations between the data and the fitted curve are apparent. The value obtained from this fit for the area of the electron-capture peak is 2689$\pm$186 counts and for the electron-decay peak, -20 ± 165 counts.

We therefore find no evidence of electron decay and assign an upper limit of 145 counts to this process at an 84% confidence level.

Assuming 66.1 cm^3 as the active volume of the crystal, there are 5.87×10^{24} K-shell electrons under observation. The lower limit for the mean lifetime of the electron is then $(5.87\times10^{24}/145)\times1185.3/1.032$ h or 5.3×10^{21} y. (The factor of 1.032 is a correction for the system dead time.) No evidence for a breakdown of the law of charge conservation is found.

A preliminary result of this experiment has appeared previously.[10]

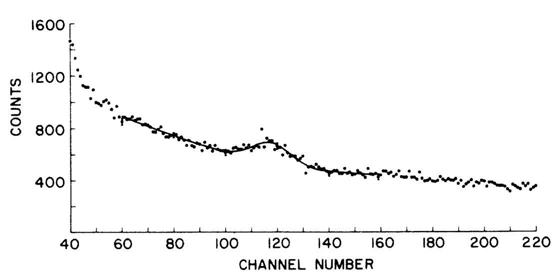

FIG. 4. The low-energy region of the spectrum of Fig. 2 showing the electron-capture line of ^{71}Ge. The channel corresponding to electron decay is 128.59. The fitted curve was obtained by varying the electron-capture peak height, the electron-decay peak height, and three parameters for the background.

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APPENDIX: DISCUSSION OF THE RESULT OF MOE AND REINES (REF. 2)

In Fig. 6 we have redrawn the data of Moe and Reines (Fig. 9 of Ref. 2) in order to discuss their claim of a lower limit of 2×10^{21} y for the mean lifetime of the electron for decay into nonionizing particles. They obtained this value by taking as an upper limit for the number of electron decays observed the square root of the total number of counts in a band 17 keV wide centered on 33.2 keV (the K ionization energy of iodine). With roughly 2400 total counts, this amounts to about 50 counts. Because of the dip in the background occurring precisely in the region of interest, however, this procedure is in our judgement erroneous. In order to illustrate this, we have shown in Fig. 7 the result of subtracting a Gaussian peak centered on 33.2 keV whose full width at half maximum is 17 keV and whose area is 1200 counts, or 50% of the total area. This figure demonstrates that the general shape of the background thus obtained is essentially *indistinguishable* from that of Fig. 6 as long as there exists no theoretical or phenome-

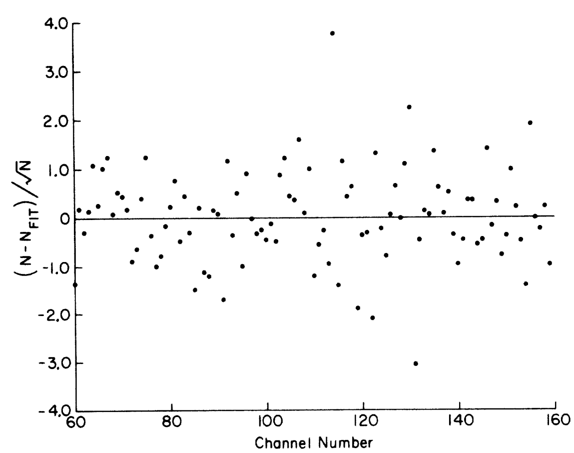

FIG. 5. The deviations of the data points of Fig. 4 from the fitted curve in units of the standard deviation.

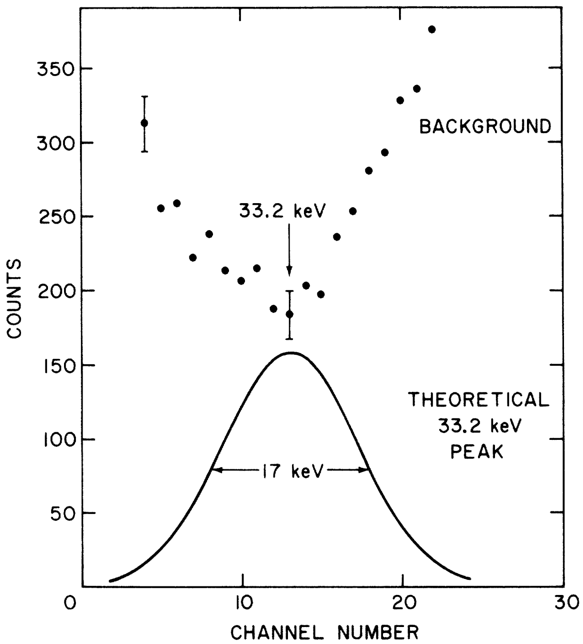

FIG. 6. The data obtained in Ref. 2 on electron decay. This is a redrawing of Fig. 9 of that reference.

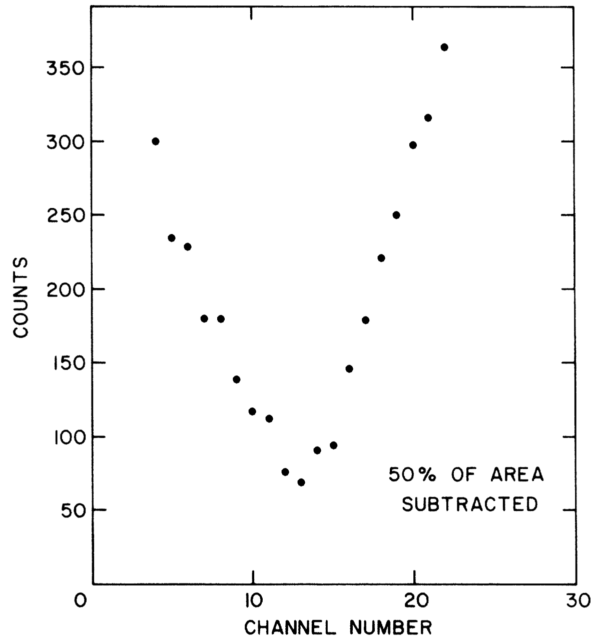

FIG. 7. The data of Fig. 6 after subtraction of a Gaussian peak centered on 33.2 keV whose full width at half maximum is 17 keV and whose area is 1200 counts.

nological prediction or experimental measurement of the behavior of the background. The number of counts to be attributed to electron decay is therefore not 50, as claimed in Ref. 2, but could be, in our estimate, as high as 1200 counts. The lower limit on the electron lifetime obtained in Ref. 2 for these modes is therefore not 2×10^{21} y, but 10^{20} y.

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