Charge Conservation and the Lifetime of the Electron*

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(Received 7 July 1965)

New lower limits on the electron lifetime have been set by experiments sensitive to two kinds of non-charge-conserving decay processes for orbital electrons. The lifetime of the K electrons in iodine for a process without photons among the decay products has been shown to be $>2\times10^{21}$ yr and the lifetime for the process $e^-\rightarrow\nu_e+\gamma$ to be $>4\times10^{22}$ yr.

I. INTRODUCTION

THE law of charge conservation is associated with the invariance of the total Lagrangian under a gauge transformation and is generally taken to be absolute. However, regardless of how attractive a law may appear theoretically, its validity rests on experimental evidence. The danger in the application of conservation laws to unexplored domains can be seen in the dramatic failure of parity conservation for weak interactions.

Conservation laws and their experimental basis have been discussed by Feinberg and Goldhaber,[1] who point out in connection with experimental tests of these laws that violations are best sought in situations where distinctive transitions forbidden by the law in question could be observed. As a test of charge conservation we chose to study the stability of the electron because particles of smaller rest mass are uncharged, and the possibility for a distinctive consequence is enhanced in this case.

If we remove the constraint imposed by charge conservation but retain all the other conservation laws, the electron is free to decay into a photon and a neutrino, a neutrino and two antineutrinos, or such other combinations of photons, neutrinos, and antineutrinos which conserve energy, momentum, spin, and lepton number (with the proper distinction between muon and electron neutrinos). The simultaneous violation of two or more of the conservation laws is not inconceivable, but it is clearly necessary to specify the violation in order to devise an experimental test.

The reaction $e^-\rightarrow\nu_e+\gamma$ is interesting to consider because it is the simplest one in which both weak and electromagnetic interactions are represented, except for removal of the singularity associated with the charge. The reaction requires the violation of only one of the abovementioned conservation laws, namely charge conservation and, though we make no use of the fact in the present work, the gamma ray would be circularly polarized, thus providing a possible means of identification.

A particularly attractive experimental test of the electron lifetime has been carried out by der Mateosian and Goldhaber.[1,2] Its appeal lies in the wide range of electron decay processes encompassed. The electron is assumed to decay leaving a vacancy in the parent atom without interacting with the remaining atomic electrons. The detectable clue left by decay of the initially bound electron would be the subsequent filling of the vacancy in the atomic shell from which it disappeared. For example, emission of characteristic x radiation and Auger electrons would be readily detectable if the electron vacancy would occur in the K shell of an iodine atom situated in a NaI(Tl) crystal. Their experiment consisted of a background spectrum accumulation for $6\frac{1}{2}$ h with a shielded 4×5 in. NaI(Tl) crystal, and the assignment to electron decay of all events within about 7 keV of a barium K x-ray calibration peak (32.8 keV). They deduced a limit on the electron lifetime in excess of 10^{18} years.

A portion of the present paper is concerned with an attempt to increase this lower limit by reduction of the detector background and by identification of background components due to sources such as K^{40} and Ra^{226} contamination.

We center the search for electron decay at the K-edge of 33.2 keV. The reasoning is that the energy released as the iodine atom purged itself of inner shell vacancies would total 33.2 keV, the full K ionization energy. Since the relaxation process occurs in much less time than the 0.25 μsec characteristic of NaI(Tl) pulses, the entire characteristic x-ray cascade and/or Auger electrons totaling 33.2 keV would be detected as a single pulse. It can be argued that the detector response is nearly independent of the particular combination of K, L, M, ⋯, x rays and Auger electrons released.

This discussion must be modified if the decay products of the electron are also captured by the crystal, as would sometimes occur if one or more of the products were photons. In this case the 33.2 keV would be added to the coincident photon energy. Accordingly, the escape probability for decay-product photons must be considered in any estimate of the efficiency of a NaI(Tl) crystal for detection of the hole in the iodine K shell.

If in our search for electron decay we look for a particular set of electron decay products rather than a K-shell vacancy alone, some generality is lost. How-

* Supported in part by the U. S. Atomic Energy Commission.
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[1] G. Feinberg and M. Goldhaber, Proc. Natl. Acad. Sci. U. S., 45, 1301 (1959).
[2] E. der Mateosian (private communication).

ever, we gain the advantage of being able to monitor all electrons in the crystal instead of just the iodine K electrons: There are now 64 candidate electrons per NaI molecule instead of 2. Since neutrinos offer negligible chance for detection, we concentrate on the photon as the only detectable electron decay product. Because of the greater number of electrons and the higher energy of the photons ($\sim\frac{1}{2}mc^2=255$ keV) it is possible to set a more stringent lower limit on the electron lifetime against this decay mode than for K-shell vacancies, and der Mateosian and Goldhaber set a lower limit of 10^{19} years.

On the basis of NaI(Tl) background spectra published by other workers concerned with low-level counting,[3–5] we infer lower limits up to $\sim 10^{21}$ years.

As with the K-shell vacancy, this paper describes efforts to increase the lower limit associated with the $\nu_e+\gamma$ mode by paying further attention to background reduction and the identification of contaminants.

II. THE EXPERIMENT

A primary concern in the design of a detection system for electron decay events is to reduce the background. The electron lifetime τ_e is calculated from the expression $\tau_e=N/R$, where N is the number of eligible electrons being monitored, and R is their decay rate.[6] Since all unexplained background events near the appropriate energy must be recognized as candidates for electron decay, the rate of these unexplained events should be kept as small as possible.

A second consideration in detector design is the efficiency for the radiation in question, a number which depends on assumptions made about the decay process. For example, a detector capable of efficiently recording the 33.2-keV events associated with the K-shell vacancy would at the same time have to permit the escape of decay products which would otherwise add their energy to the 33 keV and obscure it. Neutrinos have a negligible interaction probability, but photons of the expected energies travel on the average only about 1 cm in NaI before losing energy. Hence a study involving only 33.2-keV events in a large ($\gg$1 cm) NaI crystal is most sensitive to the cases in which no decay-product photons are involved. As to the detection efficiency for the nonphoton decay mode, it is very close to 100% because the low-energy x rays and electrons involved travel less than 0.4 mm in NaI.

Efficiency and background considerations indicate that a crystal 3 in. long and 3 in. in diameter is suited both to measurements at 33.2 and 255 keV. Its efficiency for absorption of 255-keV photons born uniformly throughout the crystal is calculated to be 59%.

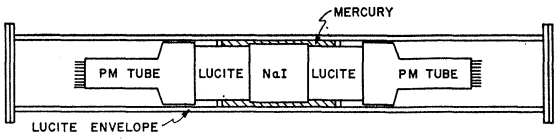

FIG. 1. The 3-×3-in. crystal detector.

The crystal, mounted in a double end-window housing, was obtained from the Harshaw Chemical Company. A number of low-background features were incorporated into the assembly: type 304 stainless steel housing of notably lower radioactivity than the usual aluminum[4]; MgO reflector, somewhat less radioactive than Al_2O_3[4,7]; quartz windows, much less radioactive than glass[4]; and a natural potassium content of the crystal guaranteed by Harshaw to be $<0.8\pm0.2$ ppm.

The double window permitted an approximate measurement of the contribution to background made by the notorious radioactivity of the photomultiplier tubes themselves.[4] That is, one tube could be used to measure the background rate with and without the other tube present. This difference method measures the background contribution of the tube only approximately because scattering and absorption by the tube alter the background from other sources. The double window also permitted coincidence operation of two photomultipliers as a means of reducing tube noise.

The photomultipliers were backed away from the crystal with 3 in. long by 3 in. diameter Lucite light pipes. The consequent reduction in solid angle subtended by the photomultipliers at the crystal, coupled with the attenuation of the radiation by the Lucite, reduced the photomultiplier contribution to the background sufficiently to permit the economy of glass envelopes as opposed to those made of the lower background but more costly quartz.[4]

The photomultipliers selected were $3\frac{1}{2}$ in. E.M.I. type 9531 S, a low-noise tube. The pins were soldered directly to the voltage divider to avoid the possibility of noisy contacts.

The optically coupled system of phototubes, light pipes, and crystal was sealed in a Lucite tube and partially surrounded with triple-distilled mercury (Fig. 1). Aluminized Mylar isolated the light pipes and crystal from the mercury. The Lucite tube served to contain the components as an integral unit and protect them from contamination within an easily cleaned surface. All components were carefully washed with detergent and handled with clean rubber gloves during assembly. The need for these precautions was not ex-

[3] William H. Ellet and Gordon L. Brownell, Nucl. Instr. Methods, 7, 56 (1960).
[4] L. D. Marinelli, C. E. Miller, H. A. May, and J. E. Rose, Advan. Biol. Med. Phys. 8, 81 (1962).
[5] R. W. Perkins, J. M. Nielsen, and R. N. Diebel, Rev. Sci. Instr. 31, 1344 (1960).
[6] More precisely, $\tau_e=N/R=(AMn\epsilon/W)/R$ where A is Avogadro's number, M is the NaI mass in grams, n is the number of electrons per NaI molecule, ϵ is the detection efficiency, and W is the molecular weight of NaI.
[7] B. Grinberg and Y. LeGallic, Intern. J. of Appl. Radiation Isotopes 12, 104 (1961).

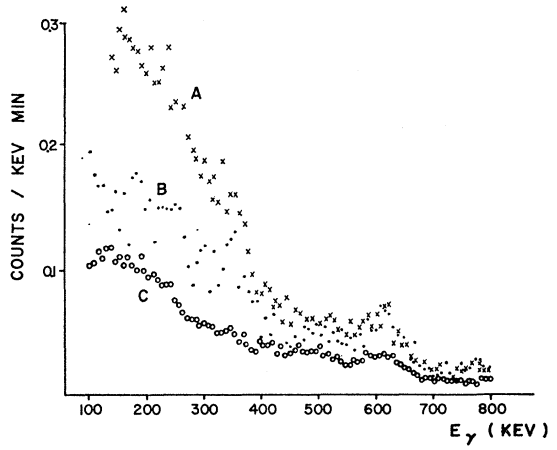

FIG. 2. Three- by three-in. crystal; medium energy background; A: Iron shield lined with $\frac{1}{8}$-in. virgin lead; B: Lead removed; C: Light pipes inserted.

perimentally established here, but it has been reported[8] that fingerprints from supposedly clean hands can contribute 20 counts/min to background in a large crystal.

With respect to the extensive use of Lucite, it should be remarked that no radioactivity has been observed[9] to be associated with Lucite except traces from charged radon daughters electrostatically attracted to its surface.

The detector was suspended by strings at the center of a 9-in.-thick iron shield with inside dimensions 26×26 in. at the base by 27 in. high. The shield was constructed of tiers of iron billets of 3-in. square cross section. It is the same shield used in an earlier experiment and has been described in detail.[10]

Cosmic rays were reduced to $1/(m^2 \text{ min})$ by virtue of a location 585 m underground in a mine of the Morton Salt Company.

With the two photomultipliers balanced and summed, a resolution of 10.7% full width at half-maximum (FWHM) was measured for the 661-keV gamma ray from Cs^{137}. For accumulation of the energy spectrum near 255 keV the two photomultipliers were connected in parallel and the output fed through a single preamplifier and amplifier to a 400-channel analyzer. The system was calibrated with a Cs^{137} source daily except on weekends when the mine was closed. Drift of the system was held to less than 1% during data accumulation.

Since a successful reduction in background by the addition to an iron shield of a $\frac{1}{8}$-in. virgin lead lining had been reported in the literature,[4] the iron shield was initially so lined.

In the first arrangement the photomultipliers were coupled directly to the crystal windows, and no mercury was present. Spectra were then accumulated at medium energy (Fig. 2) and high energy (Fig. 3).

In order to check the effectiveness of the lead lining it was removed and a second spectrum accumulated (Fig. 2). A large drop in count rate toward the low end of the medium-energy spectrum indicated that the "low-background, virgin lead" contained considerable activity. Since efforts to clean the lead surface were unsuccessful, the lining was not used during the remainder of the experiment.

Insertion of the Lucite light pipes brought about a significant background reduction both at medium and high energies (Figs. 2 and 3). When the light pipes were inserted, however, the drop in background was much less than the relative reduction in solid angle subtended at the crystal by the photomultipliers. The implication is that with the light pipes in position the photomultipliers were no longer a major source of background. For this reason the background change associated with the removal of one photomultiplier was not investigated.

As the final step in background reduction, the crystal was surrounded with triple-distilled mercury which occupied the space between the crystal and the Lucite envelope and partially covered the light pipes (Fig. 1). The thickness of mercury was 0.48 cm at the crystal, and 0.80 cm at the light pipes. Mercury was not extended farther along the light pipes toward the radioactive photomultipliers because it would then scatter gamma rays from the photomultipliers into the crystal. A background spectrum was accumulated at medium energy with the light pipes and mercury in place. As seen in Fig. 4, the reduction in background effected by the mercury was substantial.

The medium-energy background level realized with this system is the lowest level, per gram of NaI, known to have been achieved in an inert shield. A level lower by a factor of 2 at 255 keV for a 5- ×5-in. NaI crystal in an 18- ×18-in. plastic scintillator anticoincidence

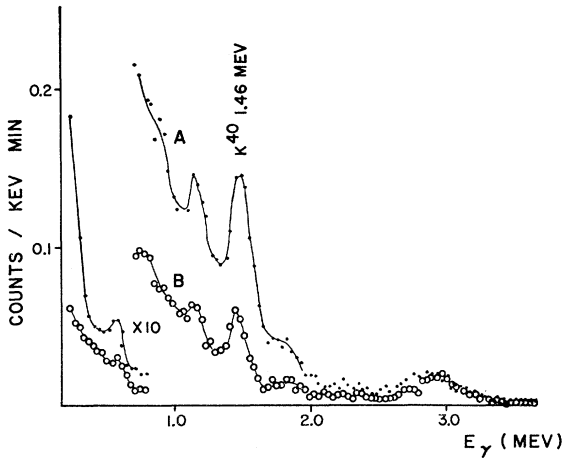

FIG. 3. 3- ×3-in. crystal; high-energy background; A: In iron shield; B: Light pipes inserted.

[8] C. E. Miller, L. D. Marinelli, R. E. Rowland, and J. E. Rose, Nucleonics **14**, 40 (1956).
[9] H. A. May, (private communication).
[10] C. C. Giamati and F. Reines, Phys. Rev. **126**, 2178 (1962).

guard has been reported by Ellet and Brownell.[11] However, it is clear that an anticoincidence guard is not in itself sufficient to ensure low background: Perkins *et al.*[12] reported a background at 255 keV which was higher per gram of NaI than the bottom curve of Fig. 4 by a factor of 3 for a 3- ×3-in. crystal in a large NaI anticoincidence guard, and by a factor of 4 for a 5- ×5-in. NaI crystal in a large plastic scintillator anticoincidence guard. The detailed reasons for the higher backgrounds in these cases are not known to us. It is significant for the present experiment that although an anticoincidence guard might be effective with a detector for 255-keV electron-decay photons, it would impair the efficiency of a 33.2-keV K-shell vacancy detector in the sense that it would trap decay-product photons, as discussed in the Introduction. Therefore efforts were concentrated on the reduction of background without an anticoincidence guard to assure that the detector would be effective in the 33.2-keV mode in the more generalized sense here envisioned.

The system was operated at medium energy for a total running time of 362 h (Fig. 5, curve A). A statistical accuracy of $\pm 1.4\%$ $(=1/\sqrt{N})$ per channel was achieved.

A high-energy spectrum was accumulated for 25.4 h to help identify sources of background. In order to be able to subtract the contribution due to the generally present K^{40} it was necessary to measure the crystal response to this isotope. Accordingly, 1 kg of natural potassium was placed near the crystal but outside the mercury shield. In this way it was seen that K^{40} contributes to the background, not only at the photopeak, but also from the Compton edge all the way to the lowest detectable energy. An external K^{40} source was chosen because it was determined that most of the background due to this nuclide is from sources external to the crystal and its mercury shield. A K^{40} spectrum at medium energy was accumulated and was normalized to the high-energy K^{40} source spectrum. Thus, when enough K^{40} radiation was subtracted from the high-energy background spectrum to eliminate the 1.46-MeV peak, the medium-energy background spectrum was correctly adjusted by subtracting the same fraction of the normalized medium-energy K^{40} spectrum. Curve D in Fig. 5 shows the amount of K^{40} which a consideration of the spectral shape indicates can be attributed to this isotope.

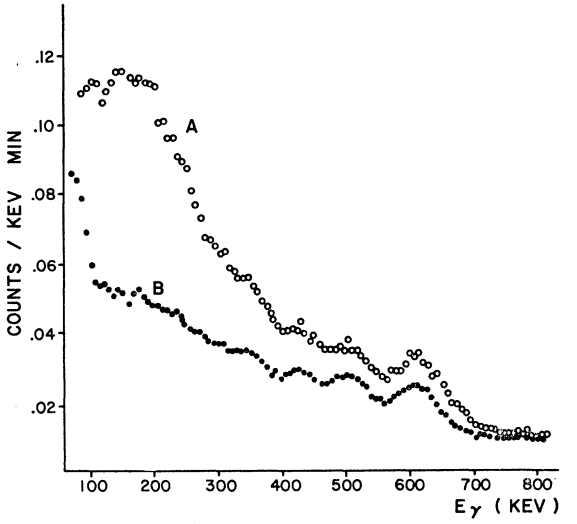

FIG. 4. 3- ×3-in. crystal; medium-energy background; A; In iron shield with light pipes; B: Mercury added.

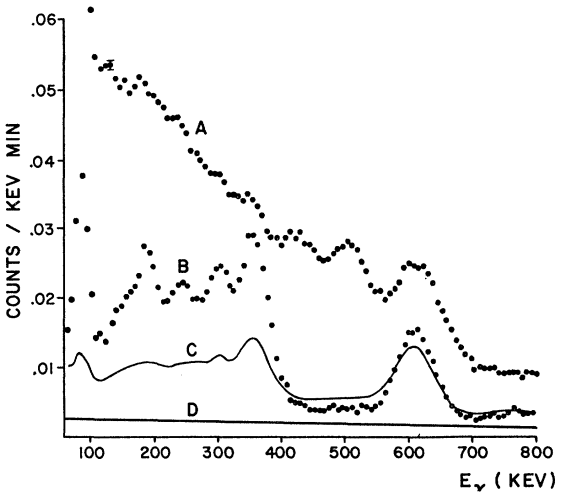

FIG. 5. 3- ×3-in. crystal. Medium energy; A: Background; B: Ra calibration without Hg; C: Ra^{226} source with Hg; D: K^{40} source with Hg.

A high-energy spectrum was taken with a Ra^{226} source. All the peaks in this Ra spectrum are actually due to the daughter, Bi^{214},[13] which also is a daughter of gaseous 3.8-day Rn^{222}. The appearance of these peaks in the background indicated the presence of Rn^{222} but not necessarily the Rn^{222} parent, Ra^{226}. The Rn gas could diffuse into the shield from without. Hence, the subtraction of enough of the Ra source spectrum to eliminate the peaks at high energy does not justify the subtraction of an equal amount of the Ra source spectrum at medium energy where the presence of the 187-keV Ra^{226} line in the background has not been established.

Before subtracting the Ra source spectrum, therefore, we considered the medium-energy background spectrum (Fig. 5) and looked for the 187-keV Ra^{226} peak. It is seen to be just barely perceptible against the general background. How much of the background is contributed by Ra^{226} as well as its spectral shape is a difficult question. The problem of a determination of the contribution of Ra^{226} to the background is complicated by the

[11] William H. Ellet and Gordon L. Brownell, Nucl. Instr. Methods **7**, 56 (1960).

[12] R. W. Perkins, J. M. Nielsen, and R. N. Diebel, Rev. Sci. Instr. **31**, 1344 (1960).

[13] C. E. Crouthamel, *Applied Gamma-Ray Spectrometry* (Pergamon Press, Inc., New York, 1960).

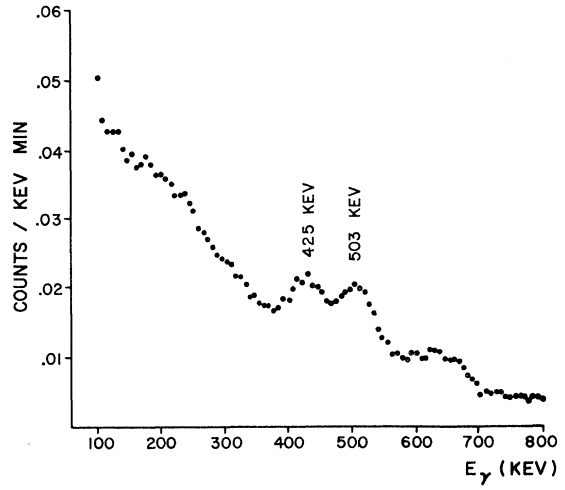

FIG. 6. 3- ×3-in. crystal; medium-energy background with K^{40} and Ra^{226} subtracted.

manner in which the mercury is observed to distort the Ra source spectrum below ~500 keV (curves B and C, Fig. 5) and the uncertainty as to the location of the troublesome Ra^{226}.

The Ra spectrum which was actually subtracted is shown in curve C, Fig. 5. It is the mercury-attenuated Ra test source spectrum scaled to eliminate the 609-keV Bi^{214} peak. The spectrum subtracted does not contain the characteristic rise at low energies seen in curve B, Fig. 5. The medium-energy background spectrum with Ra and K^{40} subtracted (Fig. 6) shows some of the 187-keV Ra^{226} peak remaining, indicating that the amount of Ra source subtracted was conservative. Judging by the shape of the residual spectrum some of the Ra^{226} gamma rays do not traverse the mercury. They may arise within the crystal, or more likely, in the photomultiplier tubes. The mercury-attenuated K^{40} source subtraction was conservative for the same reason: Bremsstrahlung from K^{40} radiation could arise from the photomultipliers and reach the crystal without traversing the mercury.

Care was taken during the subtraction of these Ra and K^{40} backgrounds to avoid the introduction of additional statistical error in the residual background. The source spectra were accumulated with good statistics and smoothed before subtraction.

Two prominent peaks remain in the residual medium-energy background spectrum, one at 425±7 keV, and the other at 503±7 keV (Fig. 6). In the high-energy background spectrum, peaks not associated with the Ra source appear at 1.62±0.03 and 2.91±0.06 MeV. We have not succeeded in identifying the sources responsible for these lines. It was at first thought that they were due to the thorium series which yields photons at 415 keV from $_{82}Pb^{212}$ and at 511 keV from $_{81}Tl^{208}$; the uranium series which gives a 510-keV photon from $_{86}Rn^{222}$; or the actinium series which gives a 425-keV photon from $_{82}Pb^{211}$. All these nuclides can be eliminated as sources of the lines at 425 and 503 keV by the conspicuous absence of strong accompanying lines which would have to appear in the spectrum. The natural decay series offer no photons at 1.62 and 2.91 MeV, nor do any other candidates appear among other naturally occurring nuclides or daughters of nuclides with half-lives $>10^8$ years. The broad 2.91-MeV peak may possibly be due to alpha particles of a somewhat higher energy. (The crystal responds somewhat more poorly to alpha particles than to photons.) The peak at 503 keV might be annihilation radiation (511 keV). Contamination by products of fission or neutron activation may explain the remaining peaks, but without positive identification their complete spectra remain unknown and cannot be subtracted from the background.

A source of background remaining to be discussed is the K^{40} beta spectrum from the 0.8±0.2 ppm natural potassium in the NaI itself. Natural potassium is 0.0119 at.% K^{40}, and K^{40} emits 31 beta rays and 3.4 gammas per sec per gram. On the basis of this information and the shape of the K^{40} beta spectrum, it was concluded that a negligible background, in the vicinity of 1.3×10^{-4} betas per keV per min, would arise between 0 and 1.35 MeV from 0.6-ppm natural potassium and that gamma rays from internal K^{40} contamination are also negligible. These considerations justify the earlier statement that most of the K^{40} radiation comes from outside the NaI.

The counts making up the residual spectrum (Fig. 6) remain as unexplained events. It is significant that this curve has no characteristic peaking at 255 keV. We choose to interpret these events in terms of a limit on the electron lifetime. As is pointed out in Sec. III, the photon spectrum for electrons decaying by $e^- \rightarrow \nu_e + \gamma$ is a delta function at 255 keV for unbound electrons, and is spread out and lowered in energy as the binding energy increases from zero. The most tightly bound are the iodine K electrons, and the spectral broadening of decay photons associated with this binding would be expected to be comparable to the photon energy.[14] The great majority of Na and I elec-

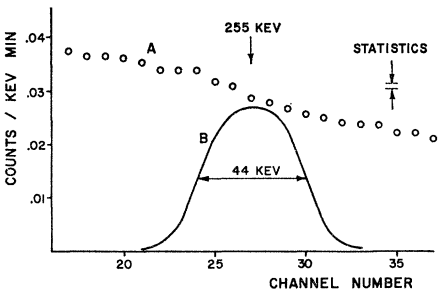

FIG. 7. A: Background near 255 keV; B: Theoretical electron-decay gamma spectrum.

[14] L. L. Foldy (private communication). This calculation of the expected broadening of the photon spectrum was made by specifying certain of the factors present in the transition probability and carrying out a phase-space integration of the resulting photon energy distribution.

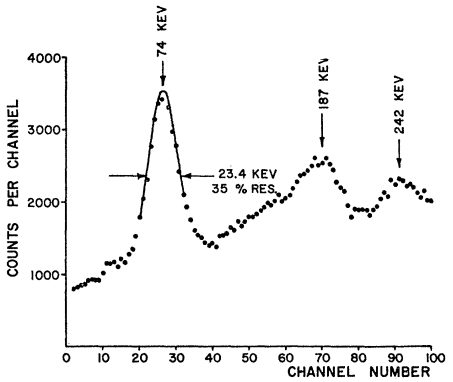

FIG. 8. Resolution for the 74-keV Pb x ray.

trons are much less tightly bound than the iodine K electrons, and in this instance the main cause of broadening would be instrumental. The resolution of the system for the 661-keV Cs^{137} gamma is measured to be 10.7% and the resolution at 255 keV, made on the assumption that resolution is determined by photon statistics, is 17.2% full width at half-maximum. The portion of the residual background near 255 keV after Ra and K^{40} were subtracted was plotted together with the approximate theoretical electron-decay photon spectrum (Fig. 7). The 17.2% resolution gives a 44-keV width to the decay spectrum.

If, as an illustration, *all* the events of Fig. 7 in the 44-keV interval centered at 255 keV are assumed to be electron-decay photons, the lifetime can be calculated as 3×10^{20} years. (See Ref. 6 with $M=1278$ g, $n=64$, $\epsilon=59\%$, $W=149.9$, and $R=6\times10^5$/year).

This value of the lifetime is low for several reasons, among which is the assumption that the only source of decaying electrons is the NaI. Electrons in the surrounding mercury and other materials are equally likely to decay and bathe the crystal in an external flux of 255-keV photons. An additional reason for assigning a higher lifetime limit is that the residual count rate in the 44-keV band at 255 keV cannot possibly be due exclusively to decaying electrons. A portion of the rate in this band is made up of the compounded Compton tails belonging to photopeaks at higher energy, particularly at 425 and 503 keV. In addition, the nearly featureless structure of the residual spectrum at 255 keV indicates a smoothly rising background of bremsstrahlung, backscatter, and indistinct components against which a substantial 255-keV photopeak would be very conspicuous. Statistical fluctuations (Fig. 7) in the counts per channel across the 44-keV band are not sufficient to conceal more than a few per cent of the 255-keV electron-decay photon peak.

The number of counts which can be attributed to electron decay is not specified by the residual spectrum (Fig. 7). However, in the absence of any clearly defined structure, it seems reasonable to associate such a limit with statistical fluctuations which could obscure the spectrum expected from electron decay (curve B, Fig. 7). From Fig. 5 the fluctuation in the number of counts in the energy range 44 keV surrounding the 255-keV peak ($=5\times10^3$/year) yields a lifetime limit $>4\times10^{22}$ years.[15] We note that Fig. 5. gives the background *prior* to subtraction of identifiable impurities. The statistical fluctuation employed is 1.4%/channel divided by $\sqrt{7}$, the number of channels per 44 keV.

The same detector arrangement was used to accumulate a spectrum near 33.2 keV. Because of the increase in photomultiplier tube noise at this energy, the pulse-height analyzer was gated with a coincidence pulse between the two tubes. An upper-level discriminator rejected very large pulses which threatened by means of delay-line reflections to introduce spurious low-energy counts. Visual observation of the two outputs displayed simultaneously on a dual-beam oscilloscope confirmed that the system was functioning properly in the coincidence mode.

The calibration was performed several times each week with the 74-keV Pb x ray from the Ra source. The mercury had to be partially removed for each calibration because it so greatly attenuated the 74-keV x ray.

The resolution for the 74-keV x ray was measured as 35% (Fig. 8). If we assume the resolution to be given by photon statistics we estimate the resolution at 33.2 keV to be 52%. The full width at half-maximum of the expected 33.2-keV peak is therefore 17 keV (Fig. 9).

A spectrum was accumulated at low energy for a total run time of 110 h to give better than 7.6% statistics in each channel (Fig. 9). No subtraction of identified background components has been made in this spectrum. The behavior of the Ra and K source spectra was not investigated at low energy. The Compton tail associated with the 1.46-MeV K^{40} photopeak can be seen from Fig. 5 to be nearly flat rising slowly as the energy decreases. The Compton tail compounded from the many photopeaks of the Ra source is lost

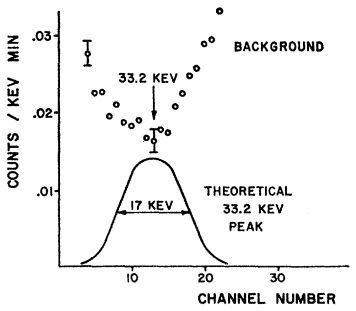

FIG. 9. Low-energy spectrum.

[15] A lifetime of 4×10^{22} years is extremely short if we consider the cosmological consequences of electron disappearance (unaccompanied by disappearance of proton charge as well). This follows because a charge imbalance of as little as two parts in 10^{18} can account for the expansion of the universe [R. A. Lyttleton and H. Bondi, Proc. Roy. Soc. (London) **A252**, 313 (1959)] and from the age, $\sim10^{10}$ years, of the universe, we can argue that the electron lifetime is $>10^{28}$ years. This remark was stimulated by a question of Dr. E. Leach of Case Institute.

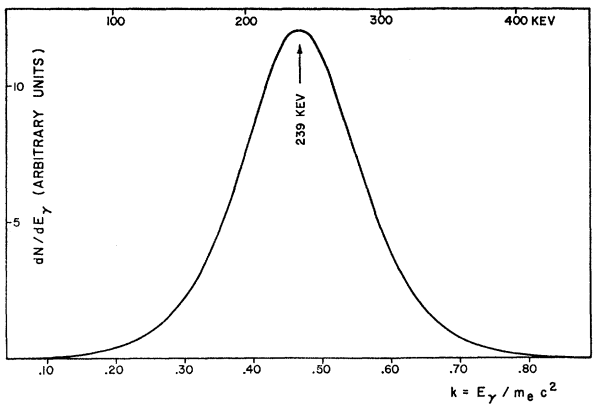

FIG. 10. Gamma spectrum from $e^- \rightarrow \nu_e + \gamma$ for iodine K electrons.

under the peaks between 74 and 400 keV (Fig. 5, curve C) but is at least as high at 33.2 keV as it is near 500 keV, below the 609-keV Bi^{214} photopeak. The important point in this discussion is that the various known backgrounds do not exhibit structure of the kind which would tend to obscure a possible electron decay signal. As an estimate of the lower limit on electron lifetime from these data, we ascribe to electron decay the statistical fluctuation in the number of counts seen in the 17-keV energy region around the 33.2-keV peak. The number of decay events in this limit calculation is therefore <4100/year corresponding to a lifetime $>2\times10^{21}$ years.

III. AN ALTERNATIVE APPROACH

We present now an alternative approach which failed to give as stringent limits but which may in principle be capable of important improvements.

As is evident from conservation of energy and momentum if the decay $e^- \rightarrow \nu_e + \gamma$ occurs for a free electron at rest, the photon and neutrino will have equal and opposite momenta, and will share equally the rest energy of the electron. The resulting photon spectrum will be a delta function at $\frac{1}{2}mc^2 = 255$ keV.

If the decaying electron is bound in an atom, some of the momentum, in general, will be shared by the nucleus. The result is a broadening of the photon spectrum and a downward shift of its peak from $\frac{1}{2}mc^2$ to $\frac{1}{2}(mc^2 - E_b)$, where E_b is the binding energy. The more tightly bound the electron, the greater will be the expected broadening of the photon spectrum.

If the process occurs, in particular for iodine K electrons, 33.2 keV will be released as low-energy x rays and Auger electrons in coincidence with a gamma ray of $\sim$239 keV in accordance with the spectrum of Fig. 10 calculated by Foldy.[14] The gamma ray, by virtue of its higher energy, has a much greater mean free path in NaI (14 mm) than the radiations associated with the K-shell vacancy (0.4 mm). Consequently, the x rays and Auger electrons are more likely to be trapped in the crystal where they are born, whereas the gamma rays within a centimeter or so of the crystal surface have a good chance of escaping. Hence, we can hope to effect a significant discrimination against background by looking for 33.2-keV events in one crystal in coincidence with $\sim$239-keV events in a second, nearby crystal.

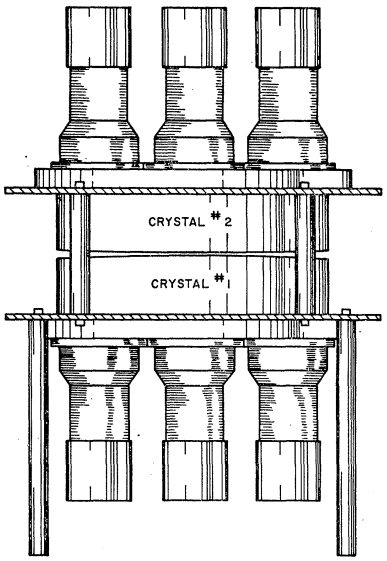

FIG. 11. The coincidence detector consisting of two NaI(Tl) crystals 11½ in. in diameter, 3 in. thick.

A search for this coincidence was actually made with the pair of NaI(Tl) crystals shown in Fig. 11. They were located in the same underground iron shield occupied earlier by the detector of Fig. 1.

The electron lifetime limit for this postulated decay mode obtained by this coincidence method was $>7\times10^{21}$ years, a factor of 6 lower than the single-crystal result. We attribute this poorer result in part to the intrinsic factors: (1) Only K electrons were eligible candidates for decay, and only those near the surface of one of the crystals. (2) The gamma spectrum from iodine K electrons is expected to be much broader than from the other electrons. However, the most troublesome factor experimentally is that despite the distinctive character of the coincidence required there is an unexpectedly high degree of correlation in the background due to multiple Compton scattering between the two crystals. Removal of all inert material between crystals could be effective in reducing these events.

ACKNOWLEDGMENTS

We wish to thank Professor L. L. Foldy for helpful discussions and for his calculation of the photon spectrum. We also express our appreciation to the Morton Salt Company for the courteous treatment we received at their Fairport Harbor mine.