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Lepton Conservation in the Double β Decay of ^{82}Se†

B. T. Cleveland, W. R. Leo, C. S. Wu, L. R. Kasday,* and A. M. Rushton‡
Department of Physics, Columbia University, New York, New York 10027

and

P. J. Gollon
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

J. D. Ullman
Department of Physics and Astronomy, Lehman College of the City University of New York, New York, New York 10468

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We report an experimental investigation of the lepton-nonconserving neutrinoless double β decay of ^{82}Se. The half-life of this decay mode is found to be greater than 3.1×10^{21} yr at a 68% confidence level. By use of the reported total lifetime of ^{82}Se obtained from recent mass-spectrometric measurements, an upper limit of 9% on the branching ratio for neutrinoless decay is estimated. This corresponds to an upper bound of $\sim 3 \times 10^{-4}$ for the lepton-nonconservation amplitude if a two-nucleon mechanism is assumed.

The law of lepton conservation may be critically tested by observation of nuclear double β ($\beta\beta$) decay. The decay may occur completely by way of a lepton-conserving two-neutrino mode,

$$(Z,A) \to (Z+2,A) + 2e^- + 2\bar{\nu},$$

or partially via a lepton-nonconserving no-neutrino mode,

$$(Z,A) \to (Z+2,A) + 2e^-.$$

If the no-neutrino mode is totally absent, then, as Lee and Wu[1] have shown, there must exist a way of assigning a lepton number L_e to the neutrinos such that the algebraic sum of L_e is always conserved in all weak interactions. Double β decay, at present, offers the most sensitive test of this conservation law.

Mass-spectrometric studies of ^{82}Kr abundances in geologically old selenium ores by Kirsten and Müller[2] and more recently by Srinivasan *et al.*[3] have presented convincing evidence that ^{82}Se does undergo $\beta\beta$ decay. While this type of experiment is extremely sensitive, it is inherently unable to distinguish directly the two decay modes as only the presence of the daughter nuclei is detected. An unequivocal determination of the decay mode can be made by a measurement of the sum-energy spectrum of the two emitted electrons. In the two-neutrino mode this energy distribution would be continuous as the available energy is shared by the electrons and neutrinos. In the no-neutrino mode, however, the available energy is carried off by the two electrons so that their sum-energy spectrum would appear as a sharp peak at the full energy release for the reaction—3.0 MeV in the case of ^{82}Se. A measurement of the electron sum-energy spectrum in this energy region and the derived lifetime for the no-neutrino decay mode is reported in this Letter.

The apparatus used to detect the two decay electrons had a sensitivity comparable to that of the geological experiments. The selenium source formed the center plate of a helium-filled double-gap streamer chamber with an array of sixteen unwrapped plastic scintillation counters placed against the thin windows on each side (see Fig. 1). The streamer chamber was fired if two and only two scintillation counters registered coincident pulses whose individual and sum energies exceeded set limits. The tracks that were produced on both sides of the source were photographed through the transparent scintillation counters and a third camera was used to record an oscilloscope display of the scintillator pulse-height data. A magnetic field of 370 G with an rms deviation over the chamber volume of 3% made possible an unambiguous interpretation of the tracks of almost all chamber events. Since the apparatus and measurement technique were similar to that used in an earlier experiment[4] with ^{48}Ca, the reader is referred to that paper for a more detailed description.

The apparatus was housed in a salt mine situated at a depth of 600 m below ground level. The surrounding salt was found to be virtually free of radioactive substances (with the exception of ^{40}K) and the rock overburden provided excellent shielding against cosmic rays. The total background rate was two or more orders of magnitude less than at an uncontaminated location at Columbia University.

The source contained approximately 46 g of metallic selenium powder enriched to 56.5% of ^{82}Se. The selenium was purified by precipitation of radium with separated ^{138}Ba and by multiple passes through ion-exchange columns. It was measured to have an activity of less than 3.5 dis/min for ^{40}K and less than 0.25 dis/min for various other suspected contaminants. The selenium was further ground with a ball mill, suspended in lacquer, and laminated between two thin sheets of aluminum foil by a specially developed procedure. The total source thickness was measured to be equivalent to 58 mg/cm^2 of aluminum with an rms deviation of 8%. Energy losses of electrons (from $\beta\beta$ decay) emitted within a source of this thickness were found by a Monte Carlo calculation to have an appreciable effect upon the sum-energy spectrum. With scintillator resolution taken into account, this calculation indicated that the energy distribution for the no-neutrino decay process in this experiment would appear as a peak centered at 2.75 MeV with a width $\sigma \simeq 0.3$ MeV.

The data consisted of photographs of events which satisfied the requirements of the electronics and were of sufficient brightness to be recorded by the film. The vast majority of these events were background induced—many of these being due to the Compton scattering of an ambient γ ray in a scintillator with the recoil electron passing through the chamber and hitting a second counter. Such events were readily distinghished from possible $\beta\beta$ events by the track curvature.

Selection of possible $\beta\beta$ events was made by a visual scan of the film for frames with the correct signature of $\beta\beta$ decay: two and only two tracks leaving the source from a common vertex. Only about one event in 300 satisfied these criteria. In 1300 h of live running time, 201 events of this type were found (see Table I). Many of these, however, were caused by double-scattering processes within the source.[5] These events were dif-

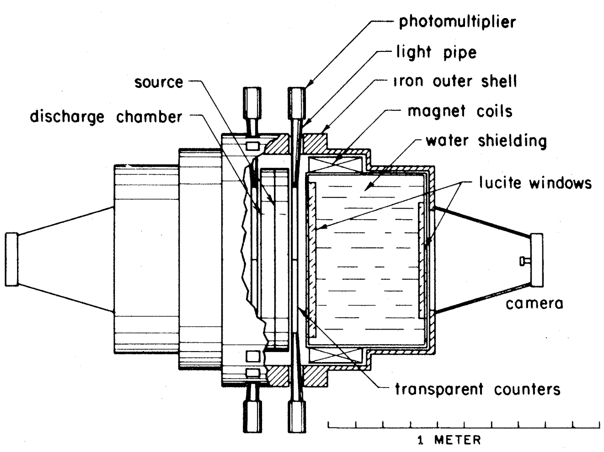

FIG. 1. Cross-sectional view of the apparatus.

TABLE I. Results of scan for no-neutrino events.

Total number of events	65 500
Two-track events with the signature of $\beta\beta$ decay	201
Events with both track lengths $\geq$ 1 cm	183
Events with both track sagittas $\geq$ 0.5 mm	148
Events with scintillator energy consistent with energy derived from track curvature	96
Events with energy between 2.43 and 3.17 MeV	0

ficult to distinguish from true $\beta\beta$ events, but a number of them could be identified by an energy-consistency check between the energy as recorded by the scintillators and the energy as calculated from the measured track curvature.

Track analysis was most difficult for those events in which an electron was emitted with high energy or at a small angle to the chamber axis. The track curvature in such cases was difficult to determine reliably. Consequently, only those events in which both tracks made an angle of greater than 21° to the chamber axis were accepted. (This corresponded to track lengths greater than 1 cm as seen on the scanning table.) A more subtle problem was that due to the biases of our scanners in recognizing track curvature. Since the magnetic field was relatively weak, the curvature of tracks produced by high-energy electrons was not large enough to avoid ambiguous interpretation by the scanners. This made necessary the imposition of a minimum-sagitta requirement of 0.5 mm on the track curvature to replace the unknown and subjective cutoff imposed by the limited abilities of the human eye.

The geometric efficiency, using the theoretical energy spectrum[6] for the no-neutrino mode, and including self-absorption and the track requirements discussed above, was found by a Monte Carlo calculation to be 28.5%. The track-producing efficiency of the chamber was measured to be close to 100% and the scanning efficiency was found to be no less than 90%. In the search for no-neutrino events, the region of interest was restricted to the range between 2.4 and 3.2 MeV. This region constituted 75% of the area under the expected energy distribution. (Enlarging this region substantially would have permitted the acceptance of a large number of lower-energy events produced by background mechanism.) If this energy-selection efficiency is combined with the above factors, the overall detection efficiency becomes 19%. As shown in Table I, no events were found in this energy region.[7]

At a confidence level of 68%, this null result implies the following lower limit on the half-life for no-neutrino $\beta\beta$ decay of ^{82}Se:

$$T_{1/2}^{0\nu} \geqslant 3.1\times 10^{21}\ \text{yr}.$$

Combining this with the measurement of the overall half-life by Srinivasan *et al.*[8] of $(2.76 \pm 0.88)\times 10^{20}$ yr, we find the branching ratio, R, to be

$$R = \frac{\text{no-neutrino rate}}{\text{total } \beta\beta \text{ rate}} \lesssim 9\%.$$

This is the first experimentally determined branching-ratio limit in $\beta\beta$ decay.

Pontecorvo, in order to explain the anomalous ratio of the ^{128}Te to ^{130}Te lifetimes, has proposed[9] that $\beta\beta$ decay is the first-order effect of a new lepton-nonconserving "superweak" interaction. More recent and accurate measurements[10] of the tellurium lifetimes have, however, not shown this anomaly, and since the present branching ratio indicates that the $\beta\beta$ decay of ^{82}Se is in fact predominantly a two-neutrino process, this suggestion of Pontecorvo loses much of its attractiveness.

A limit on the fraction α of the weak-interaction amplitude that does not conserve leptons can be set by making the approximations[11] that (1) the nuclear matrix elements for no-neutrino and two-neutrino $\beta\beta$ decay are comparable, and (2) the available phase space for the neutrinoless mode is enhanced over that for the two-neutrino mode by a factor on the order of 10^6. Then

$$T_{1/2}^{2\nu}/T_{1/2}^{0\nu} \simeq 10^6\alpha^2.$$

But since $T_{1/2}^{0\nu}/T_{1/2}^{2\nu} = (1-R)/R$, the above experimental limit on R can be used to conclude that[12]

$$\alpha \lesssim 3\times 10^{-4}.$$

In previous estimates of α, lifetimes based on theoretically calculated nuclear matrix elements were used; this may introduce an uncertainty in the value of α of as much as an order of magnitude. The best of these results using a two-nucleon mechanism, $\alpha \lesssim 10^{-3}$, was made by Bardin *et al.*[4] for ^{48}Ca and Fiorini *et al.*[13] for ^{76}Ge. The result on ^{82}Se, as reported here, does not involve explicit theoretical estimates of the nuclear matrix elements and therefore sets not only a lower but also a sharper limit on α.

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*Present address: Department of Psychology, Columbia University, New York, N. Y. 10027.

‡Present address: Department of Physics, College of William and Mary, Williamsburg, Va. 23185.

[1]T. D. Lee and C. S. Wu, Annu. Rev. Nucl. Sci. 15, 381 (1965).

[2]T. Kirsten and H. W. Müller, Earth Planet. Sci. Lett. 6, 271 (1969).

[3]B. Srinivasan, E. C. Alexander, Jr., R. D. Beaty, D. E. Sinclair, and O. K. Manuel, Econ. Geol. 68, 252 (1973).

[4]R. K. Bardin, P. J. Gollon, J. D. Ullman, and C. S. Wu, Nucl. Phys. A 158, 337 (1970).

[5]For instance, Compton scattering of an ambient γ ray in the source followed by a second Compton scattering or a Møller scattering with detection of the scattered photon and at least one electron. See Ref. 4, p. 341, processes (F) and (G).

[6]E. Greuling and R. C. Whitten, Ann. Phys. (N. Y.) 11, 510 (1960).

[7]The events that were found outside this energy region will be discussed elsewhere.

[8]The total half-life measured by Srinivasan *et al.* (Ref. 3) is about twice as large as that of Kirsten and Müller (Ref. 2). In order to set an upper limit on the branching ratio, the result reported by Srinivasan *et al.* is used.

[9]B. Pontecorvo, Phys. Lett. B 26, 630 (1968).

[10]E. W. Hennecke, O. K. Manuel, and D. D. Sabu, Phys. Rev. C 11, 1378 (1975).

[11]H. Primakoff and S. P. Rosen, Rep. Prog. Phys. 22, 121 (1959).

[12]A much less reliable estimate can be obtained by assuming the $N^*(1236)$ mechanism proposed by Primakoff and Rosen. [See H. Primakoff and S. P. Rosen, Phys. Rev. 184, 1925 (1969).] By use of their theoretically calculated expression, we find $\alpha \lesssim 10^{-4}$, which is of the same order as obtained by Hennecke, Manuel, and Sabu (Ref. 10) from their recent measurements with tellurium.

[13]E. Fiorini, A. Pullia, G. Bertolini, F. Capellani, and G. Restelli, Nuovo Cimento Soc. Ital. Fis. A 13, 747 (1973).

Exact Classical Solution for the 't Hooft Monopole and the Julia-Zee Dyon*

M. K. Prasad and Charles M. Sommerfield

Sloane Physics Laboratory, Yale University, New Haven, Connecticut 06520

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We present an exact solution to the nonlinear field equations which describe a classical excitation possessing magnetic and electric charge. This solution has finite energy and exhibits explicitly those properties which have previously been found by numerical analysis.

Recently 't Hooft[1] has proposed a model for a magnetic monopole which arises as a static solution of the classical equations for the SU(2) Yang-Mills field coupled to an SU(2) Higgs field. The model has been extended by Julia and Zee[2] so that the monopole becomes a dyon, possessing both electric and magnetic charge. The purpose of this note is to present an exact analytic solution for a particular version of these models.

The Lagrangian density for the model is[3]

$$\mathfrak{L} = -\tfrac{1}{4}F^{\mu\nu a}F_{\mu\nu}{}^{a} - \tfrac{1}{2}\Pi^{\mu a}\Pi_{\mu}{}^{a} + \tfrac{1}{2}\mu^2\varphi^a\varphi^a - \tfrac{1}{4}\lambda(\varphi^a\varphi^a)^2, \tag{1}$$

where

$$F_{\mu\nu}{}^{a} = \partial_\mu A_\nu{}^a - \partial_\nu A_\mu{}^a + e\epsilon^{abc}A_\mu{}^b A_\nu{}^c, \tag{2}$$

and

$$\Pi_\mu{}^a = \partial_\mu \varphi^a + e\epsilon^{abc}A_\mu{}^b\varphi^c. \tag{3}$$

The field equations in the static limit where all time derivatives are zero are

$$\partial_i F^{\mu i a} + e\epsilon^{abc}A_i{}^b F^{\mu i c} = e\epsilon^{abc}\Pi^{\mu b}\varphi^c, \tag{4}$$