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Double beta decay of ^{128}Te

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The half-life of ^{128}Te relative to the half-life of ^{130}Te has been found to be $t_{1/2}^{128}/t_{1/2}^{130} = (1.59 \pm 0.05) \times 10^3$ by measurement of the $\beta\beta$-decay products, ^{128}Xe and ^{130}Xe, in a geologically old (2.46×10^9 yr) telluride ore. These results yield an upper limit on the lepton nonconservation parameter, $\eta \leq 0.8 \times 10^{-4}$.

[RADIOACTIVITY $\beta\beta$-decay ^{128}Te; measured $T_{1/2} = 1.5 \times 10^{24}$ yr; deduced $\eta \leq 0.8 \times 10^{-4}$. Detected excess ^{128}Xe in old Te ore.]

I. INTRODUCTION

The process of double β decay, $(A, Z) \rightarrow (A, Z \pm 2)$, may occur spontaneously in cases where decay to the intermediate isobaric nucleus $(A, Z) \rightarrow (A, Z \pm 1)$ is energetically prohibited or strongly inhibited by a large spin change.[1] There have been no direct experimental observations of the double β decay processes, but mass-spectrometric measurements of the daughter product which accumulated in geologically old ores of selenium[2] and tellurium[3] have provided convincing evidence for the natural occurrence of two double β decays, $^{82}\text{Se} \xrightarrow{\beta\beta} {}^{82}\text{Kr}$ and $^{130}\text{Te} \xrightarrow{\beta\beta} {}^{130}\text{Xe}$. The simulation of double β decay from reactions induced by solar neutrinos,[4] $^{82}\text{Se}(\nu, e^-)^{82}\text{Br}(\beta^-)^{82}\text{Kr}$ and $^{130}\text{Te}(\nu, e^-)$-$^{130}\text{I}(\beta^-)^{130}\text{Xe}$, has been shown to occur far too rarely to account for a significant fraction of the observed excesses of ^{82}Kr or ^{130}Xe.

Experimentally measured rates of $\beta\beta$ decay are useful in defining the nature of the neutrino and the degree of lepton conservation in weak nuclear interactions.[5] Rosen and Primakoff[1] have shown that the theoretically predicted half-lives for $\beta\beta$ decay vary by several orders of magnitude, depending on whether the decay is a second-order process of ordinary β decay that occurs with the emission of two neutrinos, e.g.,

$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e \ , \tag{1}$$

or a second-order process in which no net neutrinos are emitted (the neutrino emitted in the first step is readsorbed in the second step), e.g.,

$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e \rightarrow (A, Z+2) + 2e^- \ . \tag{2}$$

The latter process would be nonconserving of leptons and could only occur if $\bar{\nu}_e \equiv \nu_e$.

More recently, Pontecorvo[6] has suggested that $\beta\beta$ decay may occur through a first-order process involving the superweak interaction postulated by Wolfenstein[7]:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- \ . \tag{3}$$

Smith, Picciotto, and Bryman[8] have further developed a model for neutrinoless $\beta\beta$ decay in a first-order superweak interaction and calculated a coupling constant for the interaction equal to about 10^{-13} of the Fermi coupling constant. Both Pontecorvo[6] and Smith *et al.*[8] note that their models predict $\beta\beta$-decay rates for ^{128}Te which are capable of accounting for the excess ^{128}Xe reported in old Te minerals by Takaoka and Ogata.[9] Primakoff and Rosen[10] have also acknowledged that the $\beta\beta$-decay lifetime for ^{128}Te reported by Takaoka and Ogata[9] is appreciably less than the lifetime expected for the two neutrino process represented by Eq. (1). They[10] suggest that $\beta\beta$ decay is predominantly no neutrino, and thus violates lepton conservation, but that $\beta\beta$ decay is nevertheless a second-order weak process.

The $\beta\beta$-decay half-life of ^{128}Te reported by Takaoka and Ogata[9] has received considerable attention,[5,6,8,10-14] although these authors cautioned that the apparent excess of ^{128}Xe which they observed might be due to a background in the mass spectrometer. In an effort to better establish the half-life of ^{128}Te, we have analyzed the xenon extracted by stepwise heating of a relatively large sample of gold tellurides from Kalgoorlie lodes, Western Australia. Turek[15] has established the age of gold mineralization for this area to be $(2,460 \pm 80) \times 10^6$ years by the ^{87}Rb-^{87}Sr dating

method. Earlier analyses[16] in our laboratory of xenon from this ore revealed a larger ratio of excess ^{130}Xe to trapped ^{130}Xe than had ever been observed in any tellurium mineral. Further, the xenon spectrum revealed no enrichment of the heavy isotopes from fission, an expedient situation when looking for products of extremely rare nuclear events since interfering reactions induced by the decay of uranium and its decay products will be minimal.

II. EXPERIMENTAL METHOD

Samples. Dr. G. A. Travis of the Western Mining Corporation, Australia provided us a 10 g specimen of relatively pure tellurides from Kalgoorlie lodes. The specimen contains a mixture of tellurides, the dominant phases probably being coloradoite and krennerite.[17] Sample 1 was a single piece of this specimen weighing 3.791 g. The xenon was extracted from sample 1 and analyzed in a Reynolds-type[18] mass spectrometer in order to determine the ratio of radiogenic ^{130}Xe, the $\beta\beta$-decay product of ^{130}Te, to radiogenic ^{128}Xe, the $\beta\beta$-decay product of ^{128}Te. Two smaller samples were prepared as aliquots from another part of the original specimen which had been crushed to -50 mesh size. Sample 2, weighing 0.2919 g, and sample 3, weighing 0.3070 g, were irradiated in a local reactor with monitors of tellurium and iodine to an integrated flux of $\approx 2\times10^{13}$ n cm^{-2}. After allowing time for the precursors of stable xenon isotopes to decay, analyses of xenon from these two irradiated samples and their monitors were used to identify the effects of neutron induced reactions on the isotopic spectrum of xenon. The ratio of excess ^{131}Xe (the stable decay product of neutron capture on ^{130}Te) to radiogenic ^{130}Xe in these two irradiated samples was used to define the parent: daughter ratio which had been produced from the $\beta\beta$ decay of ^{130}Te over the 2.46×10^{9} yr history of this ore.

Irradiation. Prior to the irradiation sample 2 and sample 3 were weighed, encapsulated in separate Vycor irradiation tubes, evacuated to $\approx10^{-5}$ Torr, and then sealed under vacuum. Each irradiation tube contained a break-seal by which it could be attached to a vacuum manifold for gas extraction after the irradiation. In this way the irradiated samples were continuously isolated from the atmosphere from the time of encapsulation until completion of the xenon analysis.

Two monitors, each containing a mixture of iodine and tellurium, were encapsulated in similar Vycor irradiation tubes with break-seals. Each monitor was prepared by weighing ≈0.1 g reagent grade Te, transferring this to the irradiation tube, and then using a pipette to add 1 ml of a standard KI solution containing 0.8143 mg KI per ml. The monitors were freezed dried, then brought to room temperature, evacuated to $\approx10^{-5}$ Torr, and sealed under vacuum.

The four sealed Vycor irradiation tubes, each containing a sample or a monitor, were encapsulated individually in aluminum cans. These were mounted in a rotary device and irradiated for 133 min at an average distance of ≈10.2 cm from the core of a local swimming-pool-type reactor. The reactor was operating at a 1 kW power level and produced an average thermal neutron flux of $\approx 3\times10^{9}$ n cm^{-2} sec^{-1} at the rotary device.

Xenon analyses. The extraction and analysis of xenon from sample 1, the unirradiated 3.791 g sample, was completed about six months prior to extraction and analysis of xenon from the two smaller irradiated samples, sample 2 and sample 3, and the latter analyses preceded by a few days the extraction and analysis of xenon from the two irradiation monitors. This sequence of analyses permitted us to utilize the results from the unirradiated sample in deciding the integrated neutron flux to be used on sample 2 and sample 3 and the relative amounts of iodine and tellurium to be used in the irradiation monitors. This order of analyses also corresponds to increasing relative amounts of pile-produced xenon isotopes and thus minimizes systematic errors which might arise from "memory" of anomalous xenon isotopes in the analyzer tube of the mass spectrometer.

Gases were extracted from all samples and monitors by resistance heating in Vycor tubes. Sample 1 was mounted in an upper side-arm chamber of the extraction bottle, the pressure was reduced to $\approx10^{-9}$ Torr, and the lower part of the extraction bottle was heated to 600 °C. The xenon released by heating the empty Vycor tube was collected and analyzed to monitor the cleanliness of the system. The sample was then dropped into the lower part of the extraction bottle and the xenon extracted at three different temperatures; 250, 350, and 600 °C. The sample had completely melted and partially vaporized at 600 °C. The extent to which xenon was extracted by this procedure was checked by a final heating of the sample to 750 °C.

The extraction and analysis of xenon from the irradiated samples, sample 2 and sample 3, followed essentially the same procedure used for the unirradiated sample, except that only two extraction temperatures, 250 and 600 °C, were employed. It was observed that gases extracted from the irradiated samples contained a larger component of atmospheric xenon than the unirradiated sample. This is understood in terms of the following differences in experimental procedures.

(i) The irradiated samples had been crushed to −50 mesh and thus had a higher ratio of surface area: volume than did the single piece of unirradiated tellurides designated sample 1.
(ii) The irradiation chambers had only been evacuated to $\approx 10^{-5}$ Torr prior to the irradiation, and there was no additional pumping prior to the extraction of xenon. Each irradiation capsule was attached to the vacuum manifold of the sample system via a break-seal. After the pressure in the vacuum manifold had been reduced to $\approx 10^{-9}$ Torr, the manifold was isolated from pumping and the seal to an irradiation capsule broken. The gases were then extracted from the sample by heating of the irradiation capsule.

Thus, the gases from the irradiated samples contained a component of xenon which remained on the surfaces of the sample and the Vycor within the irradiation capsules at $\approx 10^{-5}$ Torr, whereas the unirradiated sample had been evacuated to $\approx 10^{-9}$ Torr and then dropped into a previously degassed Vycor tube for heating.

The irradiation monitors were attached to the sample system via break-seals. The procedure used for the extraction and analysis of xenon from each monitor is as follows. After the pressure in the sample system had been reduced to $\approx 10^{-9}$ Torr, the system was isolated from pumping, the seal to an irradiation monitor broken, and the gases extracted by heating the monitor to 750 °C. The gases released from the monitor were mixed with a standard volume of air prior to gas cleanup in order that the amounts of pile-produced ^{128}Xe and ^{131}Xe could be determined in the mass spectrometer by isotope dilution.

The xenon was analyzed in a Reynolds type 11.4 cm sector mass spectrometer, operating in the static mode. Each xenon spectrum was scanned 10 times and the isotopic compositions reported here were corrected for mass spectrometer memory by extrapolating the observed ratios to the time of xenon entry into the spectrometer. The entire mass region from $A = 122$ to $A = 136$ was scanned in the first two sweeps of each spectrum. For all extraction temperatures the amounts of ^{124}Xe and ^{126}Xe released from the tellurides were near the detection limit of the mass spectrometer, and the mass region below ^{128}Xe was not swept in subsequent scans of the spectrum in order to minimize the effects of memory and spectrometer pumping on the isotope analysis. The first two sweeps of the light mass region of each spectrum showed no evidence of anomalous peaks in this region where hydrocarbon or tellurium contamination would be most easily observed. No evidence of interferences at mass 128 due to "tailing" from the more abundant xenon isotope was observed.

The sensitivity and mass discrimination of the mass spectrometer were determined before and after the analyses of xenon from each sample by analyzing xenon in standard air volumes. The procedures used in our laboratory for purification of xenon, mass spectrometric analysis, data reduction and error analysis have been described earlier.[16,19]

III. RESULTS AND DISCUSSION

Table I shows the results of our analyses on Xe released from sample 1, an unirradiated single piece of Kalgoorlie tellurides weighing 3.791 g. The abundances of ^{124}Xe and ^{126}Xe are not reported in Table I, but a conservative estimate (from two scans of this mass region for each analysis) is that the ^{124}Xe/^{132}Xe ratios and ^{126}Xe/^{132}Xe ratios in the tellurides are identical to their atmospheric values, within a factor of 3. By stepwise heating, we were able to isolate at 600 °C a fraction of Xe which is highly enriched in anomalous isotopes from tellurium. In this temperature fraction ^{130}Xe is enriched by almost three orders of magnitude over its atmospheric value,[20] and ^{128}Xe, ^{131}Xe, and ^{129}Xe are each enriched by about a factor of 2. The enrichment of radiogenic ^{130}Xe in this temperature fraction is greater by factors of $10^1 - 10^3$ than the enrichment of radiogenic ^{130}Xe reported for all other analyses of Xe in Te ores. The enrichments of ^{131}Xe and ^{129}Xe can be explained by resonance neutron capture[21] on ^{130}Te and ^{128}Te, respectively.

The excess of ^{128}Xe, ^{130}Xe, and ^{131}Xe relative to atmospheric xenon[20] and the concentrations of the reference isotope ^{132}Xe are given at the bottom of Table I in units of cm^3 STP per gram of ore. The ratio of (excess ^{128}Xe) : (excess ^{130}Xe) = $(5.8 \pm 0.2) \times 10^{-4}$ is about 50 times smaller than the ratio reported by Takaoka and Ogata,[9] but agrees with our results from other analyses on Te ores where upper limits on radiogenic xenon[16,19] were ^{128}Xe/^{130}Xe $\leq 9.3 \times 10^{-3}$ and ^{128}Xe/^{130}Xe $\leq 3.2 \times 10^{-3}$. We therefore conclude that the large excess of ^{128}Xe observed by Takaoka and Ogata[9] was primarily from some source other than the $\beta\beta$ decay of ^{128}Te.

Kirsten[22] recently brought to our attention some unpublished data on xenon isotopes released from a native tellurium ore from the Good Hope mine in Colorado. According to Kirsten, the xenon released from this ore at 650 °C shows an upper limit value for the ratio (excess ^{128}Xe): (excess ^{130}Xe) $< 4.6 \times 10^{-4}$. However, the xenon released at 650 °C from Good Hope tellurium was enriched in ^{130}Xe by less than a factor of 10, whereas ^{130}Xe is enriched by more than a factor of 700 in the xenon released from Kalgoorlie tellurides at 600 °C (Ta-

TABLE I. Xenon released by stepwise heating of sample 1, 3.791 g Kalgoorlie telluride.

Mass No.	Extraction temperature 250°C	350°C	600°C	750°C	Atmosphere [a]
128	7.9 ± 1.1	7.4 ± 0.2	13.4 ± 0.2	7.1 ± 0.1	7.14
129	98.9 ± 0.3	98.9 ± 0.3	234.5 ± 0.6	99.0 ± 0.4	98.3
130	32.9 ± 0.2	70.3 ± 0.2	10822 ± 32	50.9 ± 0.4	15.2
131	79.5 ± 0.5	79.6 ± 0.3	133.1 ± 0.3	79.6 ± 0.9	78.8
132	≡100	≡100	≡100	≡100	≡100
134	38.8 ± 0.1	39.0 ± 0.3	39.2 ± 0.2	39.1 ± 0.1	38.8
136	33.2 ± 0.2	32.9 ± 0.1	33.4 ± 0.1	33.3 ± 0.2	33.0
Content of ^{132}Xe ($\times 10^{-13}$ cm^3 STP/g)	4.73 ± 0.17	4.76 ± 0.18	4.71 ± 0.17	6.39 ± 0.24	
Excess ^{130}Xe ($\times 10^{-14}$ cm^3 STP/g)	8.4 ± 0.3	26 ± 1	5090 ± 190	23 ± 1	
Excess ^{128}Xe ($\times 10^{-15}$ cm^3 STP/g)	3.6 ± 5.2	1.2 ± 0.9	29.5 ± 1.5	−0.3 ± 0.7	
Excess ^{131}Xe ($\times 10^{-14}$ cm^3 STP/g)	0.3 ± 0.2	0.4 ± 0.2	25.6 ± 1.0	0.5 ± 0.6	

[a] See Ref. 20.

ble I). If the xenon released from Good Hope tellurium at 650°C contained the same ratio of (excess ^{128}Xe): (Excess ^{130}Xe) that we observed in a 600 °C fraction of sample 1, the ^{128}Xe/^{132}Xe ratio would have been enriched by only 1.0%. In view of the fact that a 1% enrichment in an isotope ratio is within the 3σ detection limit[23] for high sensitivity mass spectrometers commonly used in noble gas studies, and further considering the much higher precision for excess ^{128}Xe afforded by the xenon released at 600 °C from Kalgoorlie tellurides, we will consider the possibility that the enrichment of ^{128}Xe and ^{130}Xe result from the double β decay of ^{128}Te and ^{130}Te, respectively. Nevertheless, we must consider other possible origins for excess ^{128}Xe in tellurium ores,[24] including three α-induced reactions, ^{126}Te$(\alpha, 2n)$, ^{125}Te(α, n), ^{124}Te(α, γ), a neutrino-induced process, ^{128}Te(ν, e^-)-^{128}I(β^-), reactions induced by cosmic ray primaries and secondaries, such as ^{128}Te$(p, n)^{128}$I(β^-) and ^{128}Te$(d, 2n)^{128}$I(β^-), and neutron capture on iodine, ^{127}I$(n, \gamma)^{128}$I(β^-).

In considering reactions induced by α particles, it should be noted that α decay of Th and U in surrounding rocks is not expected to make a significant contribution to ^{128}Xe because of the short range of α particles ($\approx$0.02 cm for 8 MeV α particles in this ore). From the ^{136}Xe/^{132}Xe ratios in Table I and the decay parameters of uranium,[25] we calculate that this ore has a uranium content of 3.5 ± 2.6 ppb if there has been quantitative retention of fission xenon produced within the ore. For a typical Th : U ratio $\approx$3, the total number of α's produced over the 2.46×10^9 yr history of this ore is $\approx 6\times10^{13}$ α's/g. Assuming that all α particles in a particular decay series have the reaction cross section on Te as estimated by Takaoka and Ogata[24] for the most energetic α particle in that decay series (the actual cross sections will be much smaller for the less energetic α's due to a $\approx$14 MeV Coulomb barrier of the Te nucleus for α particles), it can be shown that α-induced reactions on Te will produce no more than 10^{-3} of the excess ^{128}Xe released at 600 °C. For the neutrino flux and cross sections given by Bozoki and Lande[4] and Takaoka and Ogata,[24] we calculate that the fraction of excess ^{128}Xe which could be produced by the ^{128}Te$(\nu, e^-)^{128}$I$(\beta^-)^{128}$Xe reaction is less than 10^{-5} for solar neutrinos[4] and less than 10^{-3} for high energy neutrinos from cosmic ray secondaries.[24]

For the telluride sample used in this study, the ^{126}Te$(p, n\beta^-)^{126}$Xe reaction and the ^{126}Te$(d, 2n\beta^-)$-^{126}Xe reaction can be used to approximate upper limits on the total production of ^{128}Xe from the ^{128}Te$(p, n\beta^-)^{128}$Xe and the ^{128}Te$(d, 2n\beta^-)^{128}$Xe reactions. Assuming a normal isotopic composition for tellurium and xenon originally trapped within the ore, then initially (^{126}Te/^{126}Xe) = 12.6 (^{128}Te/^{128}Xe). If ^{126}Te and ^{128}Te have equivalent cross sections for both the (p, n) and the $(d, 2n)$ reactions, and if 44% of the intermediate ^{126}I decays to stable ^{126}Xe, then the ^{126}Xe/^{132}Xe ratio presently trapped in tellurium ores will be 5.5 times

more sensitive than the $^{128}Xe/^{132}Xe$ ratio as an indicator of $(p, n\beta^-)$ and $(d, 2n\beta^-)$ reactions. Since no enrichment of $^{126}Xe/^{132}Xe$ was observed ($^{126}Xe/^{132}Xe < 0.01$ in all temperature fractions), this upper limit on excess ^{126}Xe suggests that no more than 30% of the excess ^{128}Xe released at 600 °C can be attributed to $(p, n\beta^-)$ or $(d, 2n\beta^-)$ reactions on ^{128}Te. Although the above calculation does not set very stringent limits on the production of excess ^{128}Xe by (p, n) and $(d, 2n)$ reactions on ^{128}Te, we suspect that these cosmic-ray-induced reactions have made a negligible contribution to the excess ^{128}Xe for the following reasons:

(i) Takaoka and Ogata[24] have noted that nuclear reactions induced by protons and deuterium ions will not be effective due to large energy loss of these particles in surrounding rocks.

(ii) We are not aware of any reports of (p, n) or $(d, 2n)$ reactions in subsurface minerals, such as the telluride sample used in this investigation, although reactions induced by the more penetrating cosmic-ray-produced neutrons have been detected in a few surface rocks.[26-28]

Analyses of xenon in the two pile-irradiated samples, sample 2 and sample 3, were used to estimate the possible role of natural neutron-induced reactions in producing the excess ^{128}Xe observed in the 600 °C fraction of sample 1. The isotopic compositions of xenon from the irradiated samples are presented in the upper part of Table II, and the concentrations of the reference isotope ^{132}Xe and the excesses of ^{128}Xe, ^{130}Xe, and ^{131}Xe are shown in the lower part of Table II. From a comparison of the data in Table I and Table II, it will be noted that the irradiation caused excess ^{131}Xe to increase by about a factor of 500, but the excess ^{128}Xe increased by only a factor of 2. These results show that irradiation by neutrons having the energy spectrum available in the pile cannot account for the excess ^{128}Xe released by sample 1 (Table I). Further, it seems highly unlikely that epithermal resonance effects and differences between the energy spectrum of neutrons in the tellurides during their history and the energy spectrum of neutrons in the pile can account for the ≈400-fold difference observed between the ratio of (excess ^{131}Xe): (excess ^{128}Xe) in the natural tellurides (Table I) and in the pile-irradiated tellurides (Table II).

Thus, it appears from the above considerations that $\beta\beta$ decay of ^{128}Te is the most likely source for excess ^{128}Xe observed in the 600 °C fraction of the unirradiated tellurides. From the ratio of excess ^{128}Xe to excess ^{130}Xe in the 600 °C fraction of the unirradiated sample, and assuming a normal isotopic composition for Te, we calculate the half-life of ^{128}Te ($t_{1/2}^{128}$) relative to the half-life of ^{130}Te ($t_{1/2}^{130}$) to be

$$t_{1/2}^{128}/t_{1/2}^{130} = (1.59 \pm 0.05) \times 10^3 \ . \qquad (4)$$

Many possible sources of systematic errors in measurements of the individual half-lives for $\beta\beta$ decay, such as errors in the ore age, in the tellurium determination, or in measurement of the xenon content, will not affect[3] the experimental value of $t_{1/2}^{128}/t_{1/2}^{130}$. A comparison of the measured

TABLE II. Xenon released by stepwise heating of neutron-irradiated Kalgoorlie telluride.

Mass No.	Sample 2(0.2919 g) 250°C	Sample 2(0.2919 g) 600°C	Sample 3(0.3070 g) 250°C	Sample 3(0.3070 g) 600°C	Atmosphere [a]
128	7.0± 0.1	8.0± 0.1	7.6± 0.1	8.0± 0.1	7.14
129	97.3± 0.3	110.6± 1.1	97.6± 0.3	108.3± 0.5	98.3
130	18.9± 0.2	1141 ± 8	30.8± 0.2	924 ± 7	15.2
131	87.6± 1.1	3565 ± 24	104.0± 0.6	2462 ± 23	78.8
132	≡100	≡100	≡100	≡100	≡100
134	38.7± 0.2	39.1± 0.4	38.9± 0.3	39.0± 0.6	38.8
136	32.9± 0.2	33.0± 0.2	33.0± 0.2	33.2± 0.1	33.0
Content of ^{132}Xe ($\times 10^{-13}$ cm^3 STP/g)	103 ± 7	43 ± 3	28 ± 2	59 ± 4	
Excess ^{130}Xe ($\times 10^{-14}$ cm^3 STP/g)	38 ± 3	4840 ± 340	44 ± 3	5360 ± 370	
Excess ^{128}Xe ($\times 10^{-15}$ cm^3 STP/g)	−14 ± 10	37 ± 5	13 ± 3	51 ± 7	
Excess ^{131}Xe ($\times 10^{-14}$ cm^3 STP/g)	91 ± 13	15 000 ± 1050	71 ± 5	14 060 ± 960	

[a] See Ref. 20.

$t_{1/2}^{128}/t_{1/2}^{130}$ ratio with that predicted from theory has the added advantage of eliminating uncertainties in the theoretically predicted decay rates due to the nuclear matrix elements for $^{128}\text{Te} \rightarrow {}^{128}\text{Xe}$ and $^{130}\text{Te} \rightarrow {}^{130}\text{Xe}$, if one accepts the usual assumption[8,10] that these elements are approximately equal. In this manner the $t_{1/2}^{128}/t_{1/2}^{130}$ ratio predicted for the different models can be approximated as a function of the energy released for the two decays. Recent mass measurements by Kerr and Bainbridge[29] and the equations presented by Rosen and Primakoff[1] yield $t_{1/2}^{128}/t_{1/2}^{130} = 8\times10^{3}$ for the second-order process of ordinary β decay [Eq. (1)], and $t_{1/2}^{128}/t_{1/2}^{130} = 1.4\times10^{2}$ for the no neutrino second-order process [Eq. (2)]. The observed value, as shown by Eq. (4), is intermediate to the values predicted by these two models. However, the ratio shown by Eq. (4) is not consistent with the relative decay rates predicted for the first-order process involving the superweak interaction constant [Eq. (3)], which yields $t_{1/2}^{128}/t_{1/2}^{130} = 20$ for the equations presented by Smith *et al.*[8]

The relative half-lives of ^{128}Te and ^{130}Te from Eq. (4) can be used to estimate the extent of lepton nonconservation in the $\beta\beta$-decay processes. Assuming equal matrix elements for ^{128}Te and ^{130}Te, the relative half-lives which we observed yield an upper limit on the lepton nonconservation parameter discussed by Primakoff and Rosen[10] of $\eta = 0.8\times10^{-4}$.

Analyses of xenon from the two irradiation monitors indicated that the irradiation had produced $(3.06\pm0.26)\times10^{-10}$ cm^3 STP of ^{131}Xe per g Te. These results were used to calculate the amount of Te associated with the excess ^{130}Xe in each of the 600 °C fractions of the irradiated samples (Table II). For an ore age of $(2.46\pm0.08)\times10^{8}$ yr,[15] the ratios of (excess ^{130}Xe): (Te) yielded values for the half-life of ^{130}Te of $t_{1/2}^{130} = (1.05\pm0.04)\times10^{21}$ yr and $t_{1/2}^{130} = (0.89\pm0.11)\times10^{21}$ yr, respectively, for sample 2 and sample 3. The average value for these two determinations and the $t_{1/2}^{128}/t_{1/2}^{130}$ ratio shown in Eq. (4) corresponds to a half-life for ^{128}Te, $t_{1/2}^{128} = (1.54\pm0.17)\times10^{24}$ yr. Although incomplete retention of xenon produced by $\beta\beta$ decay in this ore should not affect the value given for the relative half-lives in Eq. (4), nor the value of $\eta \leq 0.8\times10^{-4}$, any correction for loss of radiogenic ^{130}Xe and ^{128}Xe would shorten the half-lives of ^{130}Te and ^{128}Te.

Our results on the half-lives of both ^{128}Te and ^{130}Te are near the lower limit of the half-lives predicted[1] for a second-order decay process of ordinary β decay, as represented by Eq. (1), but are a few orders of magnitude greater than the half-lives predicted[1] for the second-order process involving no net neutrino emission, as represented by Eq. (2). Thus, our experimental values for the relative half-lives, $t_{1/2}^{128}/t_{1/2}^{130} = 1.6\times10^{3}$, and for the individual half-life values, $t_{1/2}^{128} = 1.5\times10^{24}$ yr and $t_{1/2}^{130} = 1.0\times10^{21}$ yr, are in general agreement with the values predicted for $\beta\beta$ decay via a second-order process of ordinary β decay.

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