Neutrino Mass Limits from a Precise Determination of $\beta\beta$-Decay Rates of ^{128}Te and ^{130}Te

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Double beta decay of ^{128}Te has been confirmed and the ratio of half-lives for $\beta\beta$ decay of ^{130}Te and ^{128}Te has been determined as $^{130}\mathrm{Te}_{1/2}/^{128}\mathrm{Te}_{1/2}=(3.52\pm0.11)\times10^{-4}$ by ion-counting mass spectrometry of Xe in ancient Te ores. The Xe measurements, combined with common Pb dating, yield a ^{130}Te half-life of $(2.7\pm0.1)\times10^{21}$ yr and thus a ^{128}Te half-life of $(7.7\pm0.4)\times10^{24}$ yr. These results give limits on the effective Majorana mass of the neutrino (<1.1-1.5 eV) and right-handed currents ($|\langle\eta\rangle|<5.3\times10^{-8}$) comparable to the best obtained from direct neutrinoless $\beta\beta$-decay searches. They also imply new limits on nonstandard Majorons not constrained by measurements of the Z^0 decay width.

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In recent years a considerable amount of effort has been devoted to the study of $\beta\beta$ decay of various nuclei. The motivation has been provided by the implication of such studies for the Majorana mass of the neutrino, the possibility of right-handed currents in weak interactions and violation of lepton number conservation, and more generally for the physics beyond the standard model of electroweak interactions. We present here the main results of our study of $\beta\beta$ decay of tellurium, which provides some of the most stringent constraints available on these issues.

In this paper we are concerned with the following possible decays,

$$^{128}\mathrm{Te}\rightarrow{}^{128}\mathrm{Xe}+2e^-+2\bar{\nu}\ (0.87\ \mathrm{MeV})\,, \quad (1a)$$

$$^{128}\mathrm{Te}\rightarrow{}^{128}\mathrm{Xe}+2e^-+0\bar{\nu}\,, \quad (1b)$$

$$^{128}\mathrm{Te}\rightarrow{}^{128}\mathrm{Xe}+2e^-+0\bar{\nu}+\phi\,, \quad (1c)$$

where ϕ is the Majoron, and the analogous decay modes for ^{130}Te (2.53 MeV). The advantages that the system of Te isotopes provides in the geochemical determination of the lifetimes and for the interpretation of the data in terms of neutrino mass, etc., have been well recognized [1,2]. The decay product Xe is a noble gas with an extremely low abundance in most terrestrial rocks, typically with a mass fraction $<10^{-14}$. Ores of native Te or with high Te content (such as $\mathrm{AuTe_2}$) are available with ages in excess of 10^9 yr, so that a relatively high abundance of the daughter Xe is accumulated. Contributions to ^{128}Xe and ^{130}Xe through nuclear interactions are far less than those from $\beta\beta$ decay in Te ores shielded from cosmic rays by more than 10 m overburden of rock [3]. The only significant interference for these isotopes is from Xe initially trapped in the sample at the time of ore formation (generally having the composition of atmospheric Xe). All of these points permit an accurate determination of the amounts of ^{128}Xe and ^{130}Xe generated in Te $\beta\beta$ decay. One disadvantage of the geochemical method, however, is that it cannot directly determine the $\beta\beta$-decay mode but only the sum of the contributing decay channels.

From the point of view of interpreting the observed lifetimes of ^{128}Te and ^{130}Te, the rather large difference in their decay energies simplifies the analysis. The phase-space dependence of the 2ν decay rate of a given nucleus can be represented as a polynomial in T_0 (where T_0 is the total kinetic energy carried off by the leptons) that varies sharply as T_0^7 to T_0^{11}. The 0ν $\beta\beta$ process varies somewhat less rapidly as $T_0\langle m\rangle^2$ to $T_0^5\langle m\rangle^2$, where $\langle m\rangle$ is the effective Majorana mass of the neutrino [4]. This implies that the relative contribution of 0ν $\beta\beta$ decay to the ^{128}Te decay is much larger than that for ^{130}Te for reasonable values of $\langle m\rangle$. These advantages provided by the Te system have prompted many groups to study it, and although the decay of ^{130}Te is well established, there has existed a long-standing controversy over whether $\beta\beta$ decay of ^{128}Te has actually been observed. Several studies by the University of Missouri at Rolla group [5] have led to positive claims, but work on Te from the Colorado Good Hope Mine by the Heidelberg group [1] does not support those observations.

We have measured the Xe isotopic composition in several samples, some also taken from the same ore deposits studied by these two groups, in order to resolve this question. Attention was focused on two crucial problems, namely, reduction of the level of trapped initial Xe in the Te ores and establishment of reliable sample ages. First, we note that a significant fraction of the initially trapped Xe is probably present in fluid inclusions and other defects in the Te ores. We found that a sizable fraction of the trapped Xe could be released by crushing the sample into a fine powder *in vacuo,* and the mass spectrum of this Xe could thus be checked for the presence of mass fractionation, etc. On the other hand, the radiogenic and

TABLE I. Ages and relative and absolute $\beta\beta$-decay half-lives for Te ores.

Sample	Radiogenic ^{130}Xe (10^{-12} cm^3/g Te)	Common Pb age (10^9 yr)[a]	$T_{1/2}^{130}/T_{1/2}^{128}$ (10^{-4})	$T_{1/2}^{130}$ (10^{21} yr)	$T_{1/2}^{128}$ (10^{24} yr)
Native Te (American Mine, CO)	21.20	1.66	3.59 ± 0.24	3.2	9.2
Native Te (Good Hope Mine, CO)	23.37	1.60	3.41 ± 0.29	2.8	8.0
Native Te (Vulcan Mine, CO)	23.77	1.61	3.44 ± 0.18	2.8	7.9
Altaite; $PbTe_2$ (Mattagami Lake, Quebec)	42.62	2.67	4.70 ± 0.58	2.6	7.3
Krennerite; $(Au,Ag)Te_2$ (Kalgoorlie, Australia)	93.73		3.48 ± 0.23		
Mean value			3.52 ± 0.11[b]	2.7 ± 0.1[c]	7.7 ± 0.4[c,d]

[a]Computed using the two-stage Stacey-Kramers [22] common Pb evolution model.
[b]Mean ratio of half-lives and 1σ error in mean. Data are corrected ($\leq 15\%$) for cosmic-ray-muon contributions to Te-derived ^{128}Xe [9].
[c]American Mine data excluded from mean due to apparent 10% Xe loss from this ore [9]. Stated uncertainty is for 1σ dispersion about the mean.
[d]Computed from $T_{1/2}(130)$ and mean half-life ratio given in (b).

fissiogenic Xe are relatively tightly bound in the crystal lattice and are released at elevated temperatures and completely only upon sublimation of the sample. Thus, apart from indicating the composition of the initially trapped Xe, the crushing procedure makes the signals of the less abundant Xe components in the sample stand out more clearly against the reduced background of this gas. In our experiments we devised the means of crushing the samples into fine powders, and then transferring them into a quartz oven without any break in the vacuum. The complete release of Xe was effected by the standard procedure of stepwise heating. The Xe isotopic composition for each extraction step was measured using a high-sensitivity ion-counting mass spectrometer [6] which had not been used for any previous analyses except of atmospheric Xe, thus ensuring that the analyses of the Te ores were not affected by spectrometer "memory" effects caused by release of previously implanted Xe. Second, we have attempted to improve the specification of sample ages by determining the common Pb ages by thermal ionization mass spectrometry [7], instead of relying only on the age deduced from geological context, or on techniques involving lighter noble gases such as Ar or He that are likely to be unreliable for such samples [8]. The list of samples used in the present study, their ages, Te $\beta\beta$-decay half-lives, and Xe concentrations are given in Table I. Additional experimental details are discussed elsewhere [9].

The ratios of isotopes ^{128}Xe/^{132}Xe and ^{130}Xe/^{132}Xe as obtained for the various stages of Xe extraction for all the samples are shown in Fig. 1. The ^{132}Xe data and ^{128}Xe data have been corrected for minor contributions from ^{238}U spontaneous fission and from reactions induced by cosmic-ray muons and their secondaries on Te, respectively [9]. The amounts of ^{128}Xe and the ^{130}Xe from $\beta\beta$ decay of ^{130}Te are linearly correlated and yield a consistent radiogenic ^{128}Xe/^{130}Xe ratio for all samples studied. The least-squares line ($\chi^2 = 1.04$) passes through the point corresponding to the composition of Xe in air and the slope of the line gives the ^{128}Xe/^{130}Xe ratio generated from Te $\beta\beta$ decay as $(3.30 \pm 0.10) \times 10^{-4}$, corresponding to a ratio of ^{130}Te to ^{128}Te half-lives of $(3.52 \pm 0.11) \times 10^{-4}$. The fact that ^{128}Xe/^{132}Xe ratios in the stepwise-heating data are often substantially in excess of the atmospheric value assures us that radiogenic contributions to ^{128}Xe are definitely observed. More detailed analysis shows that there are no other nuclear reactions contributing significantly to the production of ^{128}Xe [9];

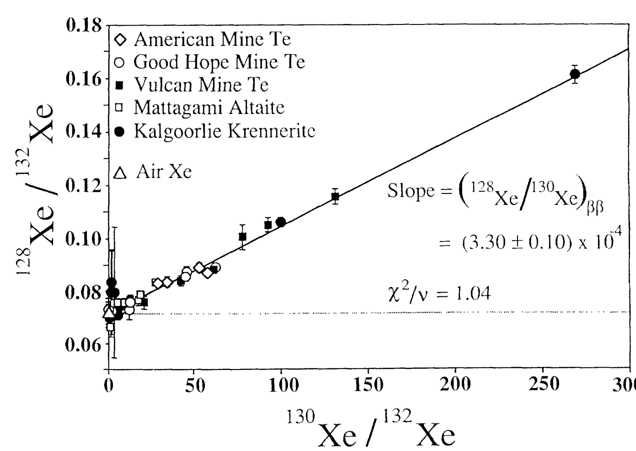

FIG. 1. Xe data for vacuum crushing and stepwise heating of ancient Te ores (see Table I). The data are consistent with a mixture of Xe from air and from $\beta\beta$ decay of ^{128}Te and ^{130}Te. See text for discussion.

in particular, the most prolific likely interference from $^{127}I(n,\gamma)$ can be ruled out because the neutron fluences for our samples vary by an order of magnitude (on the basis of differences in $^{129}Xe/^{131}Xe$ from neutron capture) but the corrected $^{128}Xe/^{130}Xe$ ratios have a dispersion of only a few percent about their mean value. We note that our mean half-life ratio of $(4.02 \pm 0.09) \times 10^{-4}$, exclusive of corrections for cosmic-ray-muon reactions, is in good agreement with the values $(4.2 \pm 0.8) \times 10^{-4}$ and $(4.4 \pm 0.8) \times 10^{-4}$ recently reported by Lee, Manuel, and Thorpe [5] for krennerite and altaite. In that work, however, no measurements of ^{126}Xe were made, precluding assessment of muon-induced contributions to ^{128}Xe. In comparing our Good Hope Te results with those of Kirsten, Richter, and Jessberger [1], we attribute the failure of the Heidelberg group to detect ^{128}Te $\beta\beta$ decay to a much greater concentration of atmospheric Xe in their sample.

By summing over all of the Xe emitted at various temperatures and subtracting out the initial trapped Xe and a small correction to the ^{128}Xe from cosmic-ray-muon-induced reactions, the absolute amounts of ^{128}Xe and ^{130}Xe generated by $\beta\beta$ decay of Te are established. From these it is straightforward to calculate the half-lives for these decays (given in Table I). The weighted averages correspond to decay widths for these two nuclides of

$$^{128}\Gamma_{tot} = (9.0 \pm 0.5) \times 10^{-26}\ \mathrm{yr}^{-1}\,,$$
$$^{130}\Gamma_{tot} = (2.6 \pm 0.1) \times 10^{-22}\ \mathrm{yr}^{-1}\,. \qquad (2)$$

The implications of these results are briefly discussed below.

(a) The $\beta\beta$ decay of ^{128}Te has been firmly established and its half-life has been determined to be $(7.7 \pm 0.4) \times 10^{24}$ yr without any ambiguity due to trapped Xe interferences. This is the longest radioactive lifetime ever to have been measured.

(b) Theoretical calculations [10–15] fail to correctly reproduce the long half-lives determined for ^{128}Te and ^{130}Te and underestimate them by 1 to 2 orders of magnitude, pointing to a real suppression in the 2ν decay rate of these isotopes.

(c) Despite the inaccuracy of the absolute 2ν-decay-rate calculations implied by comparison of theory with the present experimental results, most $\beta\beta$-decay models predict a *ratio* of 2ν decay widths, $\rho_{2\nu} = \Gamma_{2\nu}^{128}/\Gamma_{2\nu}^{130}$, which is in fair agreement with observation. In particular, these models give $\rho_{2\nu} \gtrsim 2 \times 10^{-4}$, compared to our result $\rho_{total} = (\Gamma^{128}/\Gamma^{130})_{total} = (3.52 \pm 0.11) \times 10^{-4}$. While it is tempting to ascribe any difference between the total decay ratio and the predicted 2ν decay ratio to the presence of neutrinoless decay channels in ^{128}Te decay, we resist doing so because the theoretical calculations generally overestimate the 2ν matrix elements for both ^{128}Te and ^{130}Te by large factors, with widely varying results. However, most calculations of the 0ν matrix elements are in fair agreement, at least on a factor-of-2 level, and we can have better confidence in using the measured ^{128}Te decay rate *alone* to set limits on the neutrinoless decay rate. We thus take the total decay width $\Gamma_{total}^{128} = (9.0 \pm 0.5) \times 10^{-26}$ yr^{-1} as a conservative upper bound on the 0ν decay width,

$$\Gamma_{0\nu}^{128} \leq \Gamma_{total}^{128}\,, \qquad (3a)$$

whence a lower limit on the half-life for 0ν decay of ^{128}Te is given by the experimentally determined ^{128}Te half-life,

$$(T_{1/2}^{128})_{0\nu} \geq (7.7 \pm 0.4) \times 10^{24}\ \mathrm{yr}\,. \qquad (3b)$$

In theoretical calculations of 0ν $\beta\beta$ decay [4,10–14], the relationship between the decay half-life and neutrino mass is usually presented in the form

$$[(T_{1/2}^{128})_{0\nu}]^{-1} = C_{mm}\langle m\rangle^2 + C_{m\eta}\langle m\rangle\langle\eta\rangle + C_{\eta\eta}\langle\eta\rangle^2 + \cdots\,, \qquad (4)$$

where $\langle m\rangle$ is the effective Majorana mass of the neutrino and $\langle\eta\rangle$ the parameter which scales with the assumed strength of the right-handed weak leptonic currents. The coefficients C are tabulated by various authors. Using the lower limit on the neutrinoless decay half-life [Eq. (3b)] and neglecting right-handed currents, we obtain (Table II) a range of upper limits on the Majorana neutrino mass with Eq. (4), from < 1.1 eV to < 1.5 eV for various estimates of C_{mm}. We also derive the limit $|\langle\eta\rangle| < 5.3 \times 10^{-8}$ on the basis of coefficients calculated by Suhonen, Khadkikar, and Faessler [14], which give the least restrictive of the estimates. These limits are comparable to the best currently obtained from direct neutrinoless $\beta\beta$-decay searches.

(d) The standard Majoron is now ruled out by the LEP measurements of the Z^0 decay width [16]. However, nonstandard Majorons have been postulated that would evade the LEP limits but nonetheless contribute to $\beta\beta$ decay. To illustrate the sensitivity of our ^{128}Te measurements to three-body decays, we give the standard Majoron coupling $|\langle g_B\rangle|$ corresponding to our total ^{128}Te half-life of 7.7×10^{24} yr for the Majoron process [17] with 0ν $\beta\beta\phi$ in the final state [Eq. (1c)],

$$|\langle g_B\rangle| < 3 \times 10^{-5}\,. \qquad (5)$$

TABLE II. Upper limits on the effective Majorana neutrino mass (eV). Derived from observational limit $T_{1/2}^{0\nu} > 7.7 \times 10^{24}$ yr for ^{128}Te $\beta\beta$ decay, with $|\langle\eta\rangle| = 0$.

Theory (Ref.)	Upper Limit on $\langle m_\nu\rangle$
Haxton [4] [a]	1.1
Tomoda [13]	1.1
Suhonen [14]	1.5

[a] Calculated with $g_A/g_V = 1.0$

A coupling at this limit would then generate the following rates in other $\beta\beta$-decay nuclei:

$$T_{1/2}(^{48}\mathrm{Ca}) > 3.8\times10^{23}\ \mathrm{yr}\,,$$
$$T_{1/2}(^{76}\mathrm{Ge}) > 4.9\times10^{23}\ \mathrm{yr}\,,$$
$$T_{1/2}(^{82}\mathrm{Se}) > 7.1\times10^{22}\ \mathrm{yr}\,, \qquad (6)$$
$$T_{1/2}(^{100}\mathrm{Mo}) > 3.7\times10^{21}\ \mathrm{yr}\,,$$
$$T_{1/2}(^{150}\mathrm{Nd}) > 2.1\times10^{21}\ \mathrm{yr}\,.$$

The $\beta\beta$-decay Majoron searches [18–20] that have been performed using these nuclei have yielded bounds far less stringent than those of Eq. (6). Although nonstandard Majoran models may involve somewhat different nuclear physics, qualitatively it is clear that the total ^{128}Te decay rate is presently the best constraint on three-body decays.

(e) In our experiments we have observed excess ^{126}Xe generated by cosmic-ray muons and their secondaries [3,9]; we note that any Te ore that is to be used in a test of the standard solar model as proposed by Haxton [21] should be shielded by $\sim$4400 meters of water equivalent of rock to reduce the cosmic-ray contributions to below 10% of the neutrino-induced production of ^{126}Xe.

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