fissility $\beta = 31.5 \pm 0.5$. Although fusion at near-barrier energies seems to be influenced by what happens during deep interpenetration, at lower energies the weak-contact dynamics enable these cold, heavy nuclei to fuse with relative ease.

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Rejection of Evidence for Nonzero Neutrino Rest Mass from Double Beta Decay

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Previous evidence from double beta decay (DBD) of ^{128}Te and ^{130}Te required neutrinoless DBD involving a neutrino rest mass of $\hat{m}_\nu \sim 34$ eV (~ 10 eV in the most recent theoretical treatment) or else a strong violation of lepton-number conservation ($\eta \neq 0$) due to a $(V+A)$ admixture. The DBD rate ratio of ^{128}Te and ^{130}Te has been redetermined. The present result is consistent with $\hat{m}_\nu = \eta = 0$. The experimental limits still allow Majorana decay at levels of $\hat{m}_\nu \leq 5.6$ eV or $\eta \leq 2.4 \times 10^{-5}$ (95% confidence). The DBD half-life for ^{128}Te is $T_{1/2}(^{128}\text{Te}) > 8 \times 10^{24}$ yr (2σ).

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Double beta decay (DBD) may occur with neutrino emission (2ν, Dirac decay) or without neutrinos (0ν, Majorana decay). Neutrinoless DBD is made possible either by a right-handed leptonic current admixture[1] (violation of lepton-number conservation, amplitude η) or by an implicit helicity breaking due to a nonzero mass of the electron neutrino ($\hat{m}_\nu \neq 0$).[2-4] The presence or absence of measurable decay rates $\lambda_{0\nu}$ puts stringent limits on η and $\hat{m}_\nu$. Even very small values of $\eta, \hat{m}_\nu$ lead to effectively enhanced decay rates since Majorana decay is promoted by a phase-space factor $\sim 10^6$ relative to Dirac decay. DBD is thus considered to be "the most sensitive test for lepton-quark symmetry."[5]

DBD has been experimentally observed so far by the geochemical method.[6-11] This method yields effective decay rates $\lambda_\Sigma = \lambda_{0\nu} + \lambda_{2\nu}$ and one cannot distinguish between Majorana and Dirac decay. Limits on η have nevertheless been inferred from $\lambda_{0\nu} < \lambda_\Sigma$. These limits suffered, however, from the uncertainties of the nuclear matrix elements and hence the theoretical decay-rate predictions. Pontecorvo[12] pointed out that the situation is much improved if decay-rate ratios of pairs of similar nuclei such as ^{128}Te-^{130}Te (or ^{80}Se-^{82}Se) are considered because the ratio of their respective relevant nuclear matrix elements should be near unity. In addition, the ratio $\rho_{0\nu} = {}^{128}\lambda_{0\nu}/{}^{130}\lambda_{0\nu}$ becomes much larger than

$\rho_{2\nu} = {}^{128}\lambda_{2\nu}/{}^{130}\lambda_{2\nu}$. This is because the decay energy of ^{128}Te (869 keV) is much lower than that of ^{130}Te (2533 keV). Even very small Majorana-decay contributions cause a drastic increase of the measurable ratio $\rho = \rho_\Sigma = {}^{128}\lambda_\Sigma/{}^{130}\lambda_\Sigma$ above the base level $\rho_{2\nu}$. Consequently, $\rho_{exp} = \rho_\Sigma > \rho_{2\nu}$ if Majorana decay occurs at all.

Equally important are the experimental advantages in determining a decay-rate ratio rather than absolute rates. The geochemical method of DBD detection is based on the measurement of DBD product nuclei which have accumulated during long geological times in natural minerals rich in the parent nuclei. Tellurium minerals contain both ^{128}Te and ^{130}Te, and DBD produces ^{128}Xe* and ^{130}Xe*. (Throughout this paper an asterisk denotes excess over the atmospheric abundance of the same isotope in the sample.) The ratio $\rho = {}^{128}\lambda_\Sigma/{}^{130}\lambda_\Sigma$ is directly deduced from isotope ratio measurements. Errors in the effective accumulation time (absolute age error, or incomplete gas retention over geological time) or in the absolute Xe calibration will cancel.

Previous determinations of ρ gave the following results:

$\rho \leq 295\times10^{-4}$ (1σ) (Ref. 9);

$\rho \leq 194\times10^{-4}$ (1σ) (Ref. 10);

$\rho \leq 111\times10^{-4}$ (1σ) (Ref. 10);

$\rho \leq 5\times10^{-4}$ (1σ) (Ref. 13);

$\rho = (6.29\pm0.20)\times10^{-4}$ (Ref. 11);

$\rho = (6.37\pm0.41)\times10^{-4}$ (Ref. 11).

TABLE I. Xenon extracted from 4.494 g native tellurium, Goodhope Mine. (Melt fraction; 2 h at 480°C.)

	Sample	Atmosphere
^{124}Xe	0.3556± 0.0280[a]	0.3537
^{126}Xe	0.3208± 0.0208	0.3300
^{128}Xe	7.152± 0.036	7.136
^{129}Xe	146.9± 0.6	98.32
^{130}Xe	424.86± 1.69	15.136
^{131}Xe	113.36± 0.48	78.9
^{132}Xe	100	100
^{134}Xe	39.11± 0.48	38.79
^{136}Xe	33.39± 0.46	32.94
	After fission correction	
^{128}Xe$_{fc}$	7.175± 0.043	7.136
^{130}Xe$_{fc}$	426.25± 1.7	15.136

[a]All isotopes are measured relative to ^{132}Xe; errors stated are 1σ. ^{132}Xe component of sample is 460.5 $\times 10^{-14}$ cm^3/g.

The positive result of Hennecke, Manuel, and Sabu[11] is far above the theoretically expected ratio for Dirac decay ($\rho_{2\nu} \sim 2\times10^{-4}$).[5] It seemed to indicate the occurrence of Majorana decay and was interpreted by the authors in terms of $\eta \neq 0$. [The theoretical expectation values for $\rho_{0\nu}$ alone are between 62×10^{-4} ($\hat{m}_\nu = 0$) and 420×10^{-4} ($\eta = 0$).[5]]

With the advent of a quantitative theoretical formalism concerning the implicit helicity breaking by $m_\nu \neq 0$,[2-5,14] values of $\hat{m}_\nu \sim 34$ eV,[2] or, most recently, of $\hat{m}_\nu \sim 10$ eV,[4,5] have been inferred from the ρ of Ref. 11 (for $\eta = 0$).

In view of another observation (tritium end-point energy determination) calling for a non-vanishing neutrino rest mass of that same order[15] these data became extremely important and made an experimental confirmation desirable. We have redetermined ρ (and $^{130}\lambda_\Sigma$) in a mass spectrometric investigation of xenon in a sample from the same Precambrian tellurium ore which we used fourteen years ago, when DBD occurrence in nature was first unambiguously demonstrated for ^{130}Te.[6] The results are summarized in Tables I and II. Some experimental details are given

TABLE II. Partitioning of Xe components [units of 10^{-14} (cm^3 STP)/g] and deduced DBD quantities.

	Melt extraction	Total[b]
^{129}Xe$_{Exc}$	223.6±2.7	251.6±3.1
^{131}Xe$_{Exc}$	158.7±2.2	178.9±2.5
^{129}Xe$_{Exc}$/^{131}Xe$_{Exc}$	1.409±0.026	1.406±0.026
^{132}Xe$_{measured}$	460.5	614.7
^{132}Xe$_{Fission}$	1.47 ±1.47	
^{132}Xe$_{F.corr.}$	459 ±18[a]	
^{130}Xe*	1887 ±74[a]	2113 ±83[a]
^{128}Xe*	0.18(±)0.20[a]	0.20(±)0.22[a]
$^{128}\lambda_\Sigma(10^{-26}y^{-1})$[c]		$2.75\ ^{+\ 3.0}_{-\ 2.75}$
$^{130}\lambda_\Sigma(10^{-22}y^{-1})$[c]		2.67 ± 0.29
$R_{exp} \equiv {}^{128}$Xe*/^{130}Xe*		(0.95(±)1.04)·10^{-4}
$\rho = {}^{128}\lambda_\Sigma/{}^{130}\lambda_\Sigma$ [d]		(1.03(±)1.13)·10^{-4}

$^{130}T_{1/2} = (2.60\pm0.28)\cdot10^{21}$y;

$^{128}T_{1/2}/{}^{130}T_{1/2} = \rho^{-1} = 9710$ (mean)
> 4425 (+ 1σ)
> 3040 (+ 2σ)

[a]Inclusive absolute calibration error.
[b]Inclusive sum of five preheating steps.
[c]Age = (1.31 ± 0.14) $\times 10^9$ yr.
[d]Obeying ^{128}Te/^{130}Te = 0.922.

later.

Our result for the absolute half-life of ^{130}Te is $^{130}T_{1/2} = (2.60 \pm 0.28) \times 10^{21}$ yr. This agrees well with earlier measurements from different laboratories.[6,10] For $\rho = {}^{128}\lambda_\Sigma / {}^{130}\lambda_\Sigma$ we find $[1.03 \pm 1.13] \times 10^{-4}$ and cannot confirm the results of Ref. 11. In terms of $^{128}T_{1/2}$ our result $^{128}T_{1/2} \geq 8 \times 10^{24}$ yr (2σ) conflicts with $^{128}T_{1/2} = (1.54 \pm 0.17) \times 10^{24}$ yr.[11]

Our results are fully compatible with Dirac decay alone. Any possible contribution from Majorana decay is limited to values $\hat{m}_\nu \leq 5.6$ eV and $\eta \leq 2.4 \times 10^{-5}$ (95% confidence).

The allowed region for combinations of $\hat{m}_\nu \neq 0$, $\eta \neq 0$ is shown in Fig. 1 both for the result of Ref. 11 and for ours. The two results are incompatible. Also shown in Fig. 1 are the respective limits obtained from the search for neutrinoless DBD in a coincidence experiment with ^{82}Se.[4,5,16] The deduction of limits on m_ν and η from the data benefits from recent advances in our theoretical understanding of the relation between 0ν and 2ν matrix elements[4] and in the treatments of the DBD phase space.[4,5] The present analysis has been taken from a report by Doi *et al.*[5] that incorporates these improvements. The major remaining theoretical uncertainty is the value of the ratio $\xi = |M_{GT}{}^{0\nu} / M_{GT}{}^{2\nu}|$. The ξ value used [$\xi(128) \approx \xi(130) = 1.69$][4] is conservative (see, e.g., Ref. 17) unless there are unrecognized large cancellations in the nuclear theory, a possibility which could explain a disagreement of theoretical and experimental matrix elements for ^{82}Se and ^{130}Te.[18] This caveat remains and cannot be resolved at present.

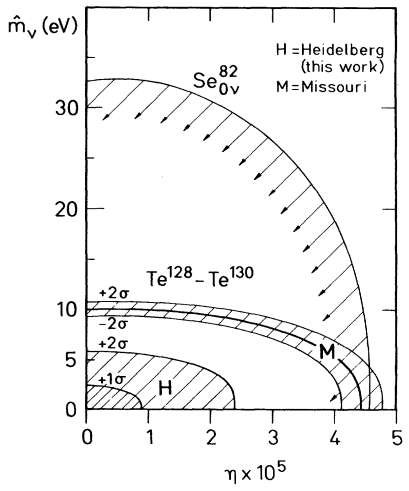

FIG. 1. Allowed regions in the $(\hat{m}_\nu, \eta)$ plane deduced from the measured ratio ρ of this work after theoretical treatment following Ref. 5. The neutrino rest mass is $\hat{m}_{\nu e} \leq 5.6$ eV (2σ). Note that the results of this work are incompatible with those of Ref. 11 ("Missouri") treated the same way. The ^{82}Se curve is calculated from the limit for $^{82}\lambda_{0\nu}$ set by Cleveland *et al.* (Ref. 16) in their direct counting experiment (1σ).

For details of the $\rho(\hat{m}_\nu, \eta)$ dependence we refer to Refs. 4, 5, and 19. In this Letter we give for better perception a numerically simplified approximation:

$$\rho \approx 1.97 + \hat{m}_\nu{}^2 + (\tfrac{1}{2}\eta)^2,$$

with $\hat{m}_\nu$ in units of $10^{-5} m_e$ (= 5.11 eV), η in units of 10^{-5}, and ρ in units of 10^{-4}. The approximation is valid for $\hat{m}_\nu \times \eta \leq 10$ in the same units. Note that the inferred neutrino rest mass (for $\eta = 0$) equals the square root of the difference of the experimentally determined ratio ρ and the respective ratio expected for Dirac decay alone ($\hat{m}_\nu = \eta = 0$). This illustrates the intrinsic power of the Te-ratio system. Deduced values are independent of absolute calibrations, ore ages, or gas retention properties.

In summary, from the results of our study we exclude a Majorana mass of the electron neutrino in excess of 5.6 eV at the 95% confidence level.

Experimental details and the complete results will be reported in a more comprehensive paper.[19] In this Letter we confine ourselves to the essentials.

The available sample was a compact piece of freshly appearing native tellurium from the Goodhope mine (Colorado). It was preserved from our earlier study.[6] The chemical analysis confirmed its purity [Te, (100 ± 0.6)%]. The K-Ar age of the ore had been determined earlier to be $(1.31 \pm 0.14) \times 10^9$ yr.[6] It should be mentioned here that both the K-Ar and the Te-Xe systems are based on rare-gas retention. In our context the time of gas retention is more relevant than the geological mineralization age if they should differ at all.

We have used our standard procedures for high-sensitivity mass spectrometric rare-gas analysis. The sample was preheated in a high-vacuum extraction line in five steps; 4 h each at 100, 200, 250, 300, and 330 °C. The Xe was analyzed in each step. Afterwards the sample was melted for 2 h at 480 °C ("melt extraction"). 89.3% of the total radiogenic ^{130}Xe* was released in the melt run (Table II) which gave $^{130}\text{Xe}^*/^{130}\text{Xe}_{\text{atm}} = 27$. Table I contains the results. The errors stated are 1σ statistical errors from n subse-

quent ratio determinations with ^{132}Xe serving as reference isotope ($n = 80$ for ^{128}Xe, ^{130}Xe, and ^{132}Xe; $n = 40$ for the other isotopes). Before and after the sample numerous air xenon standards of widely differing quantities [$(70-14\,000)\times10^{-14}$ cm^3 STP ^{132}Xe] were analyzed. This served to check the reproducibility of isotope ratio determinations, to determine the mass fractionation $(0.32\pm0.02)\%$/u, and to perform absolute sensitivity calibration.

Table II contains the results of the decomposition of the measured Xe into its components. As known from earlier studies of Xe in tellurium ores[7,9,11] these are as follows. (i) Xe of atmospheric composition: ^{132}Xe, ^{134}Xe, and ^{136}Xe are entirely atmospheric except for a small amount of U-fission Xe. (ii) Resonance-neutron-capture Xe: $^{129}Xe_{exc}$, $^{131}Xe_{exc}$. The observed ratio $^{129}Xe_n/^{131}Xe_n \sim 1.4$ is typical.[7,20] (iii) Radiogenic xenon (DBD): ^{128}Xe*, ^{130}Xe*. (iv) Fission xenon from ^{238}U: minor amounts of ^{136}Xe, ^{134}Xe, ^{132}Xe, ^{131}Xe; no ^{128}Xe, ^{130}Xe (shielded isotopes). The relevance of U-fission Xe is limited to the slight reduction of $^{132}Xe_{atm}$. This is the reference isotope needed to infer the atmospheric quantities of $^{128}Xe_{atm}$ and $^{130}Xe_{atm}$ above which ^{128}Xe* and ^{130}Xe* appear as excess. The fission contributions are deduced from the known isotopic compositions of Xe_{fiss} and of Xe_{atm} for ^{132}Xe, ^{134}Xe, and ^{136}Xe. The quantities are in accordance with a very low U-concentration of the ore (≤ 40 parts per 10^9).

The excess ^{130}Xe* is undisputably due to DBD (see Refs. 6–8 for exclusion of other sources of $^{130}Xe_{exc}$).

The possible excess of ^{128}Xe* is limited to $(0.20^{+0.22}_{-0.20})\times10^{-14}$ (cm^3 STP)/g (1σ). Before assigning this excess to DBD it would be necessary in principle to exclude all other possible sources of excess ^{128}Xe. Examples are neutron capture on traces of ^{127}I in the ore or experimental artifacts such as the "memory" effect. These potential sources of larger apparent ^{128}Te decay constants must be definitely excluded before a positive result on ^{128}Xe* is assigned to DBD. However, all these potential sources of error can only increase ^{128}Xe*. In our case the measured quantity leads only to an upper limit of the ^{128}Te decay constant, and hence these effects could only reduce this upper limit even further. Therefore we assume $^{128}Xe^* = {}^{128}Xe_{DBD}$. This is the most conservative assumption with respect to the inferred half-lives and theoretical consequences (Table II).

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