New Limits on the Neutrino Mass, Lepton Conservation, and No-Neutrino Double Beta Decay of ^{76}Ge

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A continuing search for the no-neutrino mode of the double beta decay of ^{76}Ge has resulted in a new lower limit $T_{1/2}{}^{0\nu} \geq 1.7\times10^{22}$ yr. This value corresponds to a 90% confidence level determined with a maximum-likelihood analysis of the energy interval 2041 ± 2 keV. Combined with recent shell-model calculations, the data imply $m_\nu \leq 10$ eV and a limit on lepton nonconservation $|\eta| \leq 2.4\times10^{-5}$. In the context of the shell model, the data imply that the electron neutrino is not a Majorana mass eigenstate.

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The renewed interest in no-neutrino double beta decay $(Z,A)\rightarrow(Z+2,A)+2\beta^-$ is primarily due to the important impact that experimental knowledge of the neutrino mass and lepton conservation will have on the development and testing of the gauge theories of the fundamental interactions. In-depth reviews of these important topics by Primakoff and Rosen[1] and by Frampton and Vogel[2] have recently appeared in the literature. Reviews of the double beta decay process itself give the history up to 1977.[3]

New enthusiasm for this subject was stimulated by Lubimov *et al.*[4] who reported a neutrino mass ($14 \leq m_\nu \leq 46$ eV) with a confidence level (CL) of 99.7%, based on measurements of the shape of ^{3}H beta spectrum. If their lower limit is combined with the results of extensive shell-model calculations by Haxton, Stephenson, and Strottman,[5] one concludes that no-neutrino double beta decay of ^{76}Ge should occur with a half-life of less than 8×10^{21} yr. At this half-life it would not have been observed in the experiment performed almost a decade ago by Fiorini *et al.*[6] and more recently by Bellotti *et al.*[6] In the early search two data sets resulted from counting with a well-shielded 68.5-cm^3 Ge(Li) detector under Mont Blanc. The more recent result of the Milano group is 3.2×10^{21} yr at a 90% CL,[6] which implies $m_\nu \leq 22$ eV when interpreted with Eq. (3) given later. The present search was a by product of an effort to improve the sensitivity of ^{76}Ge double beta decay experiments to a level allowing both no-neutrino and two-neutrino processes to be observed. The results of our experiments indicate that we understand the sources of the background and eventually can improve the radiopurity of the experiment significantly.

In light of the half-life predicted with use of the measured lower limit $m_\nu \geq 14$ eV (Ref. 4) and the calculations,[5] it seems worthwhile to make another analysis based on our new experimental limit, which is more than a factor of 5 greater than the previous one. Further motivation for presenting these results concerns the order of magnitude disagreement between the calculated half-life[5] for the total double beta decay of ^{82}Se, which is 3.07×10^{19} yr, and that obtained from the geological measurements of Srinivasan, Alexander, and Manuel,[7] 2.76×10^{20} yr. The calculated half-life is, however, in agreement with a recent value of $(1.0\pm0.4)\times10^{19}$ yr, measured by Moe and Lowenthal[8] with a sophisticated cloud-chamber technique. This controversy will probably not be settled easily, and hence, it is important to consider all of the available experimental information on double beta decay.

The apparatus used in this investigation is an intrinsic Ge detector in a commercially available low-background cryostat inside of a NaI(Tl) anticoincidence shield, inside of a complex bulk shield. The effective volume of Ge was determined with well-known dE/dx relations. Monte Carlo calculations verified that about 25% of the electrons originating in the outer 2.64 mm of Ge escape. This reduces the effective volume 5.6% from 132 cm^3 to 125 cm^3. Data were accumulated for a total of 4054 h in counting periods of several days each. The detector resolution was 4 keV at 2615 keV and 3.4 keV in the region of the Q value of the decay which has recently been reported by Wapstra to be 2040.9 ± 2.5 keV.[9] The data from the various sets were combined after minor energy renormalization, to correct for slight gain shifts, by use of a computer code which determines the number of channels between the centroids of the 2614-keV ^{208}Tl peak, from the decay of ^{228,232}Th, and the 1460-keV peak due to ^{40}K contamination. The data sets are then each normalized to 1 keV/channel. This procedure ensures that when the data sets are combined, only events of the same energy are added. The energy resolution quoted above was determined from the final summed data and therefore represents the proper value for the entire experiment. This procedure is the correct way to combine the results of different experiments. The experimental half-life $T_{1/2}$, the number of atoms N, the total data collection time T, and the number of counts c, in some selected energy range, which can be attributed to double beta decay, are connected by the simple relation

$$T_{1/2} = 0.693 N T \epsilon / c . \qquad (1)$$

The efficiency ϵ contains the probability that electrons deposit all of their energy in the active volume of the detector as well as accounting for the fraction of real events which fall inside of the energy interval used to obtain c. These factors are 0.947 and 0.86, respectively, in our case.

In the present experiment no statistically significant peaks were observed in the data, which contained an average of 32.4 counts/keV, in the region of interest (see Fig. 1). The γ-ray peaks which appear as background in the data were used to obtain the energy resolution, thus determining the energy interval which contains any chosen fraction of the peak. A very crude approximation assumes that the most real events which could be hidden in the statistical fluctuations of the background, B, is simply $\sqrt{B}$ with a 68% confidence limit. This approach is unsatisfactory for several reasons. For example, it is

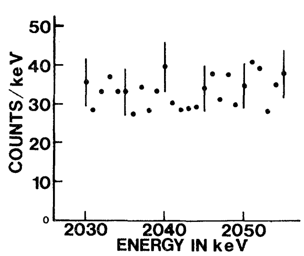

FIG. 1. Raw data from 2032 to 2055 keV for 4054-h count.

not possible to optimize the signal to background ratio by selecting an optimum energy-bin width.

We can accomplish a more meaningful interpretation because we have invested a significant effort in reproducing the background γ rays with the correct relative intensities. Radioactive sources of ^{228,232}Th, ^{226}Ra, ^{234m}Pa, ^{60}Co, ^{137}Cs, ^{40}K, and a PuBe neutron source were placed at a variety of locations, with energy degraders of varying thicknesses, until their proper line shapes and relative intensities observed in long background experiments were achieved. The resulting reference spectra were normalized to the background peaks in the data to obtain an artificial synthesis of the continuum due to radioactive background with good statistics. This continuum contains only part of the background from cosmic rays, namely that due to delayed cosmic-ray neutrons. The remaining cosmic-ray continuum was fitted by a function of the form $y = ax^b$, where x is proportional to the energy. The components of the background in the region near 2041 keV were as follows: ^{226}Ra (44%), ^{228,230}Th (22%), neutrons (13%), and remaining cosmic-ray continuum (21%). The mean background in the region of interest was thus determined to be 33.2 ± 1.2 counts/keV whereas the average of the data from the long measurement of the search was 32.4 ± 5.7 counts/keV. The statistical analyses of the data near the Q value were based on a maximal-likelihood technique which exploits the fact that the number of $\beta^-\beta^-$ decay counts y, added to the number of background counts x, will be a Poisson distribution. Because the mean value $x = 33.2 \pm 1.2$ is known, the probabilities that hypothesized values y are contained in a chosen energy interval can be calculated. In the region centered at 2041 keV, the value $y = 8$ corresponds to a probability of 90% that the total $x + y$ would be greater than that observed. This value of y implies $T_{1/2} \geq 1.7 \times 10^{22}$ yr.

In the case that the leptonic current explicitly contains a term which violates lepton number conservation, while also $m_\nu \neq 0$, the current is written

$$j_\mu{}^L \propto \psi_e{}^\dagger(x)\gamma_4\gamma_\mu\{(1+\gamma_5) + \eta(1-\gamma_5)\} \times [\psi_\nu(x) + \psi_{\bar{\nu}}(x)] , \qquad (2)$$

where the mass is contained in the "four component," Majorana neutrino spinor.[1] In the case of decays between ground states ($0+ \to 0+$), the process can be driven by two mechanisms, namely, neutrino mass and chiral mixture, and these are coherent. Haxton and Stephenson have derived the following expression for the no-neutrino, double beta decay rate of ^{67}Ge:

$$\lambda = (2.47\times10^{-21}\ \mathrm{sec}^{-1}) \times[\eta^2 + 1.54\xi^2\{1+\eta^4 - 0.253\eta^2\} - 0.585\ \xi\{\eta - 0.82\ \eta^3\}], \tag{3}$$

where $\xi \equiv m_\nu/m_e$. The curve shown in Fig. 2 encloses portions of the η-ξ plane consistent with the experimental half-life limit of $T_{1/2} \geq 1.7\times10^{22}$ yr. We see $\xi \leq 1.94\times10^{-5}$, which implies $m_\nu \leq 10$ eV and $|\eta| \leq 2.4\times10^{-5}$. A similar analysis has been done for energies from 2032 to 2055 keV, and the results appear in Table I. The above theoretical expression for λ is a refinement of the results given in Ref. 5 and predicts half-lives about 30% longer than predicted by the approximate formulas given in Ref. 5. A discussion of theoretical details and comparison with experiment is given by Doi *et al.*[10] and by Haxton.[11]

In light of the discrepancy between the theoretical predictions[5] and the mean value of the geological determinations[12] of $T_{1/2}(^{82}\mathrm{Se}) = (1.45\pm0.15)\times10^{20}$ yr, it is interesting to hypothesize that the shell model overestimates the decay rates by the factor 4.7. It should be emphasized that this assumption is intended to produce a conservative argument, sensitive only to the ratio of matrix elements, and there is no compelling evidence at this time to justify this reduction. Nevertheless, if we do implement this scaling by assuming that the same factor applies to ^{76}Ge, our limits based on the data become $m_\nu \lesssim 22$ eV and $|\eta| \lesssim 5.2\times10^{-5}$ at 90% CL. These values represent the most constraining limits resulting from a direct counting experiment distinguishing between two-neutrino and no-neutrino decay, and which are essentially free from nuclear theory uncertainties.

The present results can be used to shed light

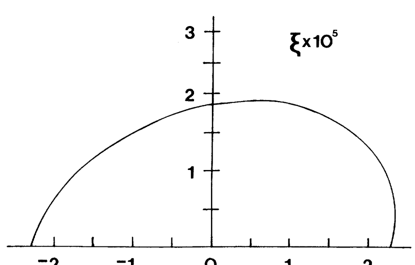

FIG. 2. An elipse on the ξ-η plane implied by measured limits on the rate λ. This can be expressed in polar coordinates as $r^{-2}(\theta) = 1.12\times10^{-23}\{1.27 - 0.27\cos2\theta - 0.29\sin2\theta\}T_{1/2}(y)$.

on the ^{128}Te-^{130}Te controversy. If we use the lower limits on the parameters η and ξ from the geological determinations of Hennecke and co-workers[13] with Eq. (3), we see $T_{1/2}{}^{0\nu}(^{76}\mathrm{Ge}) \leq 4.9\times10^{21}$ yr corresponding to 28 counts in our energy bin, whereas, our sensitivity was less than 8 counts. If we use the upper limits $|\eta| \leq 2.4\times10^{-5}$ and $\xi \leq 1.1\times10^{-5}$ from the measurements of Kirsten,[12] Eq. (3) implies $T^{0\nu}(^{76}\mathrm{Ge}) \geq 1.5\times10^{22}$ yr, which is slightly below our experimental limit. If the shell-model calculations are correct, our data strongly support the measurement of Kirsten of the ratio of the half-lives of ^{128}Te and ^{130}Te. If however, we must divide Eq. (3) by the factor 4.7, discussed above, then the values of Hennecke and co-workers of η and ξ imply $T_{1/2}{}^{0\nu}(^{76}\mathrm{Ge}) \cong 3\times10^{22}$ yr. In this case the question cannot be settled by our present results. The nuclear structures of ^{82}Se and ^{76}Ge are similar, and the case of ^{82}Se is valuable for determining the degree to which the shell-model calculations[5] overestimate, or possibly underestimate, the decay rate of ^{76}Ge. If, on the other hand, the cloud-chamber measurement of $T_{1/2}(^{82}\mathrm{Se})$ is correct, it would be necessary for us to multiply Eq. (3) by a factor greater than 2 and the ^{128}Te-^{130}Te controversy would be clearly settled in favor of the results of Kirsten.

Finally, we must recognize the fact that the lower limit of the mass observed by Lubimov *et al.*[4] is not necessarily the same as that observed in no-neutrino double beta decay, so that we are actually putting a limit on a superposition of Majorana mass eigenstates as discussed by Wolfenstein.[14] A cumbersome but more correct

TABLE I. Limiting values of $T_{1/2}{}^{0\nu}(^{76}\mathrm{Ge})$ and $\overline{m}_\nu$ (90% CL).

Energy bin	$T_{1/2} \geq$ (yr)	$\overline{m}_\nu \leq$ (eV)
2032	1.57×10^{22}	10.7
2034	1.78×10^{22}	9.7
2036	2.52×10^{22}	8.2
2038	1.47×10^{22}	10.7
2040	1.65×10^{22}	10.1
2042	1.85×10^{22}	9.6
2044	1.72×10^{22}	9.9
2046	1.26×10^{22}	11.6
2048	1.18×10^{22}	12.0
2050	1.03×10^{22}	12.8
2052	1.11×10^{22}	12.3
2055	1.31×10^{22}	11.4

notation would be $\langle m^{\mathrm{Maj}}\rangle_\nu$ which is constrained to be less than 10 eV, with 90% CL, by our data. The limiting half-life reported here, when considered with the shell-model calculations of Ref. 5 and the direct mass measurement of Ref. 4, strongly implies that the electron neutrino is not a Majorana mass eigenstate. This conclusion was reached earlier in Ref. 5 on much weaker experimental constraints.

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Complete Particle-Core Multiplets Populated in ^{99}Ru by the (^{3}He, $2n\gamma$) Reaction

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Extensive sets of yrast and nonyrast states in ^{99}Ru have been populated by the reaction ^{98}Mo(^{3}He, $2n\gamma$)^{99}Ru. The population of nonyrast states is attributable to the characteristics of the reaction rather than the specifics of the nuclear structure involved. Several complete particle-core multiplets have been successfully interpreted with a particle-rotor model.

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(HI, $xn\gamma$) reactions have been used extensively to study the band structure of nuclei. These reactions, however, preferentially populate states of maximum angular momentum at a given energy (yrast states). In an odd-A nucleus these frequently correspond to the most aligned coupling of the core and odd-particle angular momenta. Conceptually different nuclear models frequently give similar predictions for yrast states; hence differentiation of disparate models requires the population of a more complete set of nuclear states. Light-particle-induced reactions have traditionally been used to populate nonyrast states. Standard reactions generally populate

