Investigation of the Majoron-Accompanied Double-Beta Decay Mode of ^{76}Ge

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We have examined the double-beta decay mode accompanied by Majoron emission. After 223 days of measurement corresponding to about 615 kg d or 19.3 mol yr of exposure we find a lower half-life limit for this decay channel of $T_{1/2}^{0\nu\chi} > 1.66(1.99) \times 10^{22}$ yr [90% (68%) C.L.] yielding a new limit for the Majoron-neutrino coupling of $\langle g_{\nu\chi} \rangle < 1.8 \times 10^{-4}$ (90% C.L.).

A test of the fundamental nature of neutrinos (Dirac or Majorana particle) can be done by double-beta decay research. Usually three possible decay modes are discussed:

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

$$^{Z}A \rightarrow {}^{Z+2}A + 2e^-, \qquad (2)$$

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

The first decay mode can be understood as a process of second-order Fermi theory, while the second one is not possible in the standard model. The observation of this decay would require massive Majorana neutrinos, if the forces are described by gauge theories. The Majorana term breaks lepton number conservation by two units, and therefore also baryon number minus lepton number, $B - L$. There are three possibilities to break $B - L$ in theory [1]: explicit $B - L$ breaking, meaning the Lagrangian contains $B - L$ violating expressions; spontaneous breaking of a local $B - L$ symmetry; spontaneous breaking of a global $B - L$ symmetry. Associated with the third possibility is the existence of a massless Nambu-Goldstone boson called the Majoron χ. There exist different possibilities to generate Majorana mass terms in extensions of the standard model and therefore also different Majoron models characterized by their weak isospin. By using an additional Higgs triplet Gelmini and Roncadelli [2,3] proposed a model leading to the so-called triplet Majoron. Because it should contribute [3] two neutrino flavors to the Z^0 width it seems to be ruled out by the recent measurements at LEP [4]. Also doublet Majoron models seem to be ruled out, which would contribute half a neutrino width. Nevertheless the existence of singlet Majorons [5] or a mixture of singlet and doublet Majorons is possible. Since Majorons couple to neutrinos it might occur in double-beta decay (see, e.g., [6]). Moreover the model of singlet Majorons has recently experienced growing interest due to the attempt to build possible neutrino mass schemes involving a 17 keV neutrino [7].

The corresponding diagram for Majoron emission in double-beta decay (hereafter the $0\nu\chi$ mode) is shown in Fig. 1. Since it is a three-body decay the energy spectrum is continuous. The sum energy spectrum of both electrons has a maximum around 1500 keV for ^{76}Ge. In deriving a half-life limit we have used the second enriched detector of the Heidelberg-Moscow $\beta\beta$ experiment [8] used to measure the electrons emitted in the $0\nu\chi$ decay. The mass of the detector is 2.88 kg where the fraction of the decaying isotope ^{76}Ge is 86% compared to only 7.8% in natural Ge. The measuring time was 223 d.

To obtain limits on the Majoron spectrum we use the following procedure. Out of the measured spectrum we make a cutoff of all observed spectral lines. The surrounding background is extrapolated into the line regions. This reduces the integral count rate by about 5%. In the region from 1.5–2.1 MeV only the weak 1764.5 keV line of ^{214}Bi is removed. In addition we subtract the Compton continua of the cosmogenically produced isotopes in the copper parts of the crystal holder (^{57}Co, ^{58}Co, ^{54}Mn, and ^{60}CO) and in the crystal (^{57}Co, ^{58}Co, ^{54}Mn, and ^{65}Zn), identified by their characteristic γ lines and the full absorption peaks shifted by the x-ray energy. In the energy interval from 2000 to 2880 keV the corresponding con-
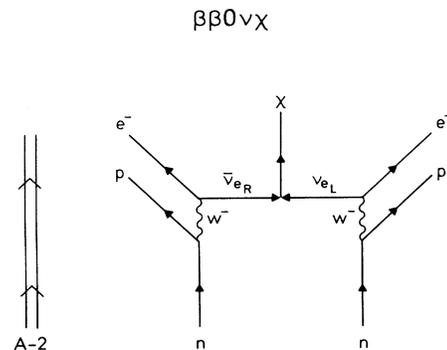
ββ0νχ

FIG. 1. Feynman diagram for double-beta decay with the emission of a Majoron.
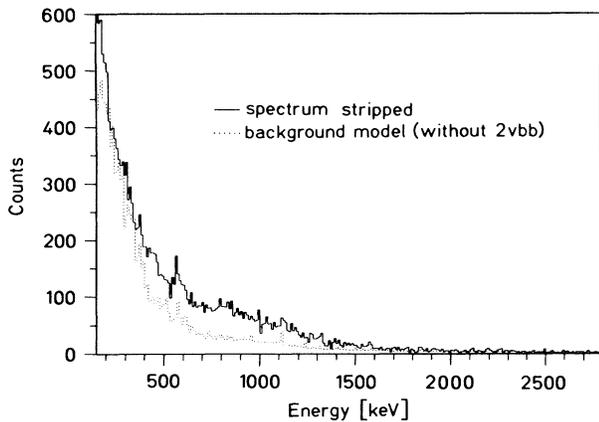
FIG. 2. Comparison of the measured spectrum without lines (solid curve) and the contribution of all the background components described in the text (dotted curve). It is clearly visible that it is not the case that the whole spectrum can be caused by these components.
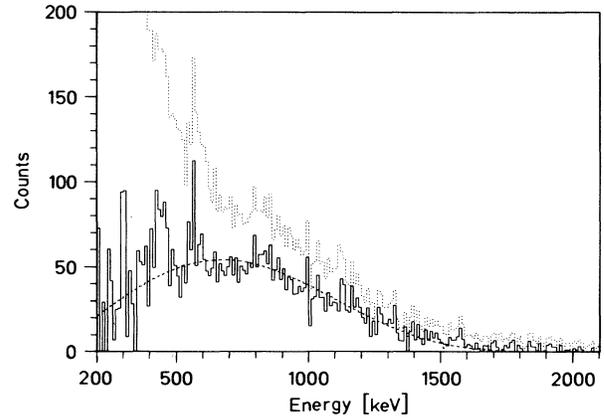
FIG. 3. Comparison of the measured (dotted curve) and background-subtracted (solid curve) spectrum. Especially the part below 800 keV experiences some modification. For comparison a calculated $2v$ spectrum with a half-life of $T = 1.43 \times 10^{21}$ yr is shown (dashed curve), which is the major background component.

tinuous contributions lead to a correction of the order of 14% and 1.5%, respectively. The continuous background of the natural decay chains $(4N, 4N+2)$ identified by the observed γ lines is also subtracted (10.2% correction). We further simulated the ^{210}Bi (a ^{210}Pb daughter) bremsstrahlung spectrum, dominating the energy range up to 1.1 MeV and contributing 33.8% to the measured background, but having a negligible effect on the Majoron spectrum. The ^{210}Pb content of the lead shielding was measured by low-level α spectroscopy to be 0.36 ± 0.03 Bq/kg. A quantitative treatment of the ^{210}Pb spectrum is important for the analysis of the $2v\beta\beta$ decay. All these background contributions are calculated with the help of the Monte Carlo code GEANT3 (version 3.14), which was checked experimentally with an x-y scan of the detector using collimated γ sources. Because not all of the background above 2 MeV originates from the discussed components, we determined the remaining averaged background between 2.1 and 2.5 MeV (0.23 count/keV) and subtracted a corresponding background over the whole energy range (in total a correction of 4%). This correction is a conservative limit, because at lower energies there will be additional contributions from Compton scattering. The sum of all these contributions in comparison with the measured spectrum is shown in Fig. 2. Two groups [9,10] have reported evidence for the $2v\beta\beta$ decay which was later confirmed [11]. The reported half-lives were all about 1×10^{21} yr. Figure 3 shows our measured spectrum with and without subtraction of the background model and also a theoretically calculated $2v$ spectrum assuming $T^{2v}_{1/2} = [1.43 \pm 0.04(\text{stat}) \pm 0.13(\text{syst})] \times 10^{21}$ yr. This is the value we derive for the $2v\beta\beta$ decay by a maximum likelihood fit. It will be discussed elsewhere [12].

The energy range from 1.1 to 2.05 MeV contains

74.5% of the theoretical $0v\chi$ spectrum. In this range there are still 208 remaining events corresponding to a difference from zero at a confidence level of 98%. Figure 4 shows the solid curve of Fig. 3 after further subtraction of the $2v$ spectrum. However, the analysis of the logarithmic likelihood ratio shows that there is not good agreement with the expected form of a Majoron spectrum. Interpreting the result as an upper limit for this decay mode, we find $T^{0v\chi}_{1/2} > 1.66(1.99) \times 10^{22}$ yr 90% C.L. (68% C.L.). (This value would still increase when subtracting the continuous part of the background produced by ^{56}Co, ^{60}Co, and especially ^{68}Ge in the crystal.) This half-life limit can be converted into a limit for the neutrino-Majoron coupling constant
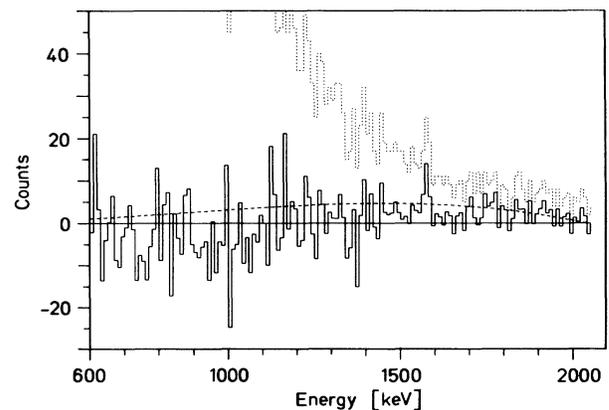
FIG. 4. Remaining spectrum (solid curve) after subtraction of the $2v$ mode, and a calculated $0v\chi$ spectrum with a half-life of $T = 1.66 \times 10^{22}$ yr (dashed curve). Also shown is the measured spectrum (dotted curve).

TABLE I. Half-life limits for the $0\nu\chi$ decay and the corresponding limits for the neutrino-Majoron coupling constant for several isotopes.

Isotope	Experiment	$T_{1/2}$ (10^{21} yr)	$10^4 \langle g_{\nu\chi} \rangle$	Ref.
^{76}Ge	MPIK-KIAE	16.6(90%)	1.8	
^{76}Ge	ITEP	10(68%)	2.2	[9]
^{76}Ge	UCSB-LBL	1.4(90%)	5.8	[16]
^{76}Ge	PNL-USC	6.0	2.8	[10]
^{76}Ge	Cal.PSI-Neu.	1.0(90%)	6.9	[17]
^{100}Mo	LBL-MHC-UNM	0.33(90%)	6.2	[18]
^{136}Xe	ITEP	0.19(68%)	12.5	[19]
^{136}Xe	Cal.-PSI-Neu.	7.2(90%)	2.0	[20]
^{82}Se	UCI	1.6(68%)	12.5	[21]
^{150}Nd	INR	0.07(68%)	1.9	[22]
^{48}Ca	ITEP	0.72	5.1	[23]
^{128}Te [a]	Washington Univ.-Tata	7700	0.3	[24]

[a]Geochemical experiment.

$$T_{1/2}^{-1} \, [\text{yr}^{-1}] = |M_{\text{GT}} - M_F|^2 F^{0\nu\chi} \langle g_{\nu\chi} \rangle|^2 , \tag{4}$$

where

$$\langle g_{\nu\chi} \rangle = \sum_{ij} g_{\nu\chi} U_{ei} U_{ej} . \tag{5}$$

This results in a neutrino-Majoron coupling constant of $\langle g_{\nu\chi} \rangle < 1.75(1.60) \times 10^{-4}$ (90% and 68% C.L., respectively).

A comparison of experimental limits for Majoron emission half-lives in double-beta decay and coupling constants determined for several isotopes is given in Table I. Another value for the coupling constant of about 3×10^{-4} was discussed in [13]. All phase space factors $F^{0\nu\chi}$ [14] and all the matrix elements used in Table I are taken from [15]. Neglecting the contribution of heavy neutrino exchange the nuclear matrix element is identical to that of the neutrinoless double-beta decay (see also the discussion in [14]).

Concluding, we have examined the possibility of Majoron emission in the double-beta decay of ^{76}Ge. The Heidelberg-Moscow experiment setup to probe the neutrino mass down to about 0.1 eV yields, with only part of its final ^{76}Ge source strength, a stringent limit for $\beta\beta 0\nu\chi$ decay.

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