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Measurement of the $\beta\beta 2\nu$ decay of ^{76}Ge

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From the data taken with one of the enriched detectors of the Heidelberg–Moscow $\beta\beta$ experiment a half-life of $T^{2\nu}_{1/2} = (1.42 \pm 0.03(\mathrm{stat}) \pm 0.13(\mathrm{syst})) \times 10^{21}$ yr for the two-neutrino double-beta ($\beta\beta 2\nu$) decay of ^{76}Ge is derived. The ^{76}Ge exposure is 19.3 mol yr. This result represents the first high statistics measurement and probably the first undoubtable evidence of this extremely rare nuclear decay mode. The measured decay rate is in good agreement with the theoretical predictions.

1. Introduction

Among the different methods to identify non-zero neutrino masses the search for the $B-L$ symmetry violating, neutrinoless double beta decay plays a unique role, because of its large sensitivity, and since it distinguishes Dirac from Majorana neutrinos.

Double-beta ($\beta\beta$) decay is an extremely rare second-order weak decay, which changes the nuclear charge by two units. A discussion of the physics of the different possible decay modes can be found in previous publications [1,2].

An observation of the neutrinoless decay modes either with emission of two electrons ($\beta\beta 0\nu$) or with an additional hypothetical Goldstone boson, the so-called Majoron ($\beta\beta 0\nu\chi$), would have far-reaching consequences, since it requires non-standard model physics. Although extremely sensitive this method has the drawback that the deduction of the neutrino mass or of the neutrino–Majoron coupling has to rely on theoretically calculated nuclear matrix elements.

This article will focus on a measurement of the allowed two-neutrino double-beta ($\beta\beta 2\nu$) decay. The decay rate of the $\beta\beta 2\nu$ decay does not depend on any unknown particle physics parameter as the $\beta\beta 0\nu$ modes do. The $\beta\beta 2\nu$ decay is further much more sensitive on details of the wave functions of the involved nuclei than $\beta\beta 0\nu$ decay [3,4]. Measurements of $\beta\beta 2\nu$-decay rates therefore are a particularly sensitive test whether nuclear physics can reliably parametrize such second-order weak processes.

From the experimental side the detection of the $\beta\beta 2\nu$ mode is in principle more difficult than of the $\beta\beta 0\nu$ decay. While the latter one has a clear experimental signature in the form of a peak at the decay energy of $E_0 = 2038.56$ keV, the former, resulting in a continuous sum energy spectrum of the emitted electrons, is more difficult to distinguish from background.

$\beta\beta 2\nu$ decay has already been observed for several isotopes, but all previous experiments either showed low statistical significance or an unfavourable signal-to-background ratio. The aim of this experiment was to use the exceptional source strength and the extremely low background of the enriched detectors of the Heidelberg–Moscow Collaboration to perform the

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first high-statistics measurement of the $\beta\beta 2\nu$ decay.

2. Experiment

In the Heidelberg–Moscow $\beta\beta$ experiment Ge semiconductor detectors, made from isotopically enriched Ge, are used simultaneously as source and high resolution calorimetric detectors for the electrons emitted in the $\beta\beta$ decay of ^{76}Ge. The isotopical abundance of ^{76}Ge is 86% compared to only 7.8% in natural Ge. We have measured the isotopical composition of the enriched detectors by accelerator mass spectroscopy.

At present the Heidelberg–Moscow Collaboration is operating three enriched HP detectors of 6.29 kg total and 6.0 kg active mass in the Gran Sasso underground laboratory in Italy. This corresponds to a source strength of 68.7 mol ^{76}Ge. The shielding thickness of the laboratory is 3500 m water equivalent. A fourth enriched detector of 2.87 kg, increasing the source strength to 100 mol is under construction and will be installed in 1993. The aim of this experiment is to probe the mass range down to 0.2 eV.

The detectors are now operated in a common shield of 10 cm highly radiopure LC2-grade Pb followed by 20 cm of less clean Boliden Pb. The cryostats are made from electrolytic Cu. All construction materials were carefully selected. During the detector production all parts were stored underground when not being processed to avoid its activation by the cosmic radiation. The detectors including the Ge diodes were exclusively surface transported to avoid the high cosmic ray flux during flights. To reduce surface contaminations the cryostat parts and the inner Pb shield were etched with analytical grade HNO_3. The cryostats were assembled in a cleanroom.

For the analysis of the $\beta\beta 2\nu$ decay data taken with the second enriched detector from October 1991 to August 1992 have been used. During this period the enriched detector of 2.88 kg total and 2.76 kg active mass was operated together with a detector from natural Ge in a common shield. The measured spectrum (measuring time 1.68 kg yr) is shown in fig. 1. This data taking period ended with the installation of the third enriched detector, when the shielding was completely rearranged. In the energy intervals 100–2700 keV, 500–1500 keV and 2000–2100 keV the measured counting rates were 6.36, 5.07 and 0.29 counts/keV yr kg, respectively.

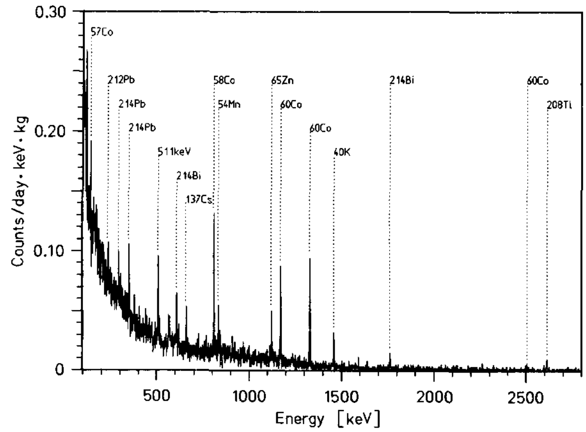

Fig. 1. Measured spectrum of the second enriched detector. The binwidth is 1 keV, the measuring time is 1.68 kg yr. The strongest lines are labeled.

The data have been taken in an event-by-event mode using 13 bit ADCs. Several control parameters as absolute time of the event, temperature of the electronics and applied high voltage were measured simultaneously.

The short-term energy resolution of the detector, measured with a ^{60}Co source, is $\Delta E = 2.4$ keV at 1.33 MeV. The stability of the electronics was monitored through weekly calibration measurements with a ^{228}Th source. During the 310 real-time days of measurement the amplification shift was 0.8%. These shifts were off-line corrected using a software recalibration. As a result the energy resolution at 1.33 MeV is $\Delta E = 3.4$ keV after 223 d data taking, whereas the uncorrected data have $\Delta E = 13.4$ keV. The energy calibration showed excellent linearity over the full measuring period.

Since a measurement of the spectral shape is the most important criterion to identify a $\beta\beta 2\nu$ signal a large number of events is crucial for a reliable analysis. In general the $\beta\beta 2\nu$ spectrum is superimposed to continuous background as Compton continua of γ-lines, bremsstrahlung emitted by the construction materials and β-activities of the Ge detectors itself. The excellent energy resolution of Ge detectors helps to concentrate the γ-background into the peaks and to identify the emitting isotope. Thus it is advantageous to make the detectors as large as possible, to obtain a good peak to Compton ratio.

The different background components have to be identified and then unfolded from the measured spectrum quantitatively. The unfolding can be done reliably only if the measured spectrum is not dominated by background. It should be pointed out, that the subtraction of big numbers, as it was necessary in some previous experiments, is not a reliable method to obtain information about a weak effect.

3. Data analysis and results

In a first step 27 identified peaks were removed from the measured data by fitting the continuous background on both sides of each peak and then extending the continuum into the peak region. The resulting "stripped" spectrum represents the continuous component of the measured spectrum. 15.5% of the counts were thus eliminated in the energy interval of interest from 500 to 1500 keV, containing 72% of the $\beta\beta 2\nu$ intensity. In table 1 the number of simulated background events is compared to the 7219 counts contained in this interval of the stripped spectrum.

To unfold the continuous background a Monte Carlo background model based on the CERN code GEANT 3.14 was developed. For its construction it is most important to know the localization of the different background components, since magnitude and shape of the simulated continuum depends on the geometry and density of the part in which the contamination is placed.

Table 1
Localization, absolute activity and contribution of the radioactive impurities to the measured background in the evaluation interval.

Isotope	Localization	Activity (μBq/kg)	Fraction (%)
^{54}Mn	Ge	4	0.3
^{57}Co		2	0
^{58}Co		6	0.4
^{65}Zn		20	1.3
^{54}Mn	Cu	27	1.0
^{57}Co		57	0
^{58}Co		152	3.4
^{60}Co		118	13.6
^{232}Th	Cu	36	3.5
^{238}U		70	5.6
^{137}Cs	Cu	20	0.3
^{210}Pb	LC2 Pb	3.6×10^5	6.7
^{40}K	LC2 Pb	140	3.3

^{54}Mn, ^{57,58}Co and ^{65}Zn decaying totally or partly by EC were identified through their characteristic γ-lines shifted by the energy of the deexitation X-ray to be inside the Ge crystal. The measured peak intensities were used to normalize the activities. Those activities having no EC branch cannot be identified inside the crystal.

^{54}Mn and ^{57,58,60}Co activities are located in the Cu parts of the cryostat system. This assumption was cross-checked through an independent experiment with a detector made from natural Ge using a 2200 kg Cu probe of the same production lot with and without inner LC2-grade Pb lining. The measured peak intensities were used to normalize the MC simulation. The two latter components are cosmogenic activities produced when the materials were above ground (see table 1).

^{210}Pb contained in the LC2-grade Pb of the shield is contributing through the bremsstrahlung of its daughter ^{210}Bi, which β-decays with an endpoint energy of $E_0 = 1.16$ MeV, to the $\beta\beta 2\nu$ background. A quantitative analysis of this component is difficult, since the low energetic radiation characterizing this decay was not identified in the spectrum, due to absorption in the cryostat. The absolute activity was therefore measured by low-level α-spectroscopy of the ^{210}Po decay (a ^{210}Bi daughter). The deviation of the shape of the electron spectrum of the ^{210}Bi decay from an allowed decay was taken into account.

Both natural decay chains are contributing through the Compton continua of numerous γ-lines to the $\beta\beta 2\nu$ background. Since several of these lines are identified in the measured spectrum, their relative intensities can be used to locate the contamination. A placement in the Cu of the cryostat showed the best agreement with the experimental data. A placement in the LC2-grade Pb could be ruled out in that way, resulting in limits for its ^{232}Th and ^{238}U activities of 286 and 245 μBq/kg, respectively. The absolute activities of the Cu were normalized to the measured peak intensities. A placement in the Ge could be ruled out by the absence of high energetic α-lines in the measured spectrum. Residual uncertainties in the localization were included into the systematic error.

^{40}K localized by neutron activation in the LC2-grade Pb, and ^{137}Cs have only a minor influence on the continuous background. The measured peak intensities were used to determine the absolute activities. The simulated Cs background is nearly independent from the placement.

To account for the residual background from 2.1 to 2.8 MeV a phenomenological constant background of 0.15 c/keV yr kg, extended to lower energies had to be introduced. It contributes 3.5% of the continuous background. This component can be understood qualitatively as inelastic neutron scattering on the construction materials of the detector and the lead shield. If the measured neutron flux of ref. [5] is used to scale the simulated spectrum resulting from neutrons produced through (α, n) reactions in the walls of the tunnel we find a flat continuum contributing 5.9% of the events in the evaluation interval. Since the measured neutron flux is rather unsafe a straight line was chosen to account for this background component in order to leave the shape of the background model unchanged.

The sum of the discussed components represents the background model, which thus has been constructed from experimental quantities. It has not been fitted to the measured continuum. From the difference of measured and background counts, according to the discussed model, we deduce a signal to background ratio of 1.3:1 in the evaluation interval, showing that we performed indeed an ultra low background experiment.

To understand whether these non-background events are due to ββ2ν decay we have to investigate their spectral shape. The solid spectrum in fig. 2 shows the residual data after subtracting the background model from the experimental data (peaks removed), while the dotted spectrum shows the measured spectrum. The continuous curves are theoretically calculated ββ2ν spectra. The lower one is in a wide energy range in good agreement with the residual data. It results from a maximum-likelihood fit of our data, yielding a half-life of $T^{2\nu}_{1/2} = (1.42 \pm 0.03(\text{stat})) \times 10^{21}$ yr. The statistical error was evaluated from the logarithmic likelihood ratio, which shows parabolic behaviour.

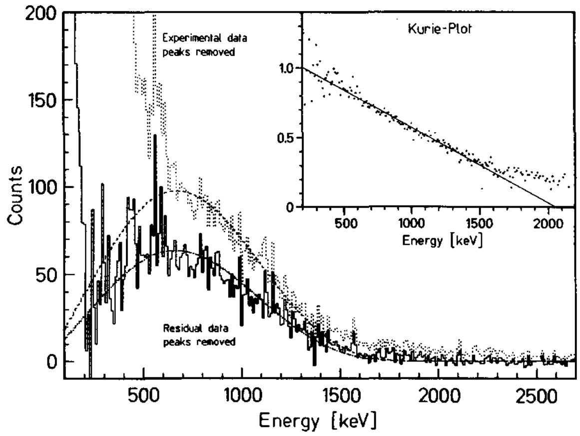

Fig. 2. The dotted spectrum shows the measured continuous background, while the solid spectrum depicts the residual data after background unfolding. The binwidth is 10 keV. The continuous curves are calculated ββ2ν-spectra, with half-lifes of $T^{2\nu}_{1/2} = 0.92$ and 1.42×10^{21} yr. In the insert the residual data have been linearized like in a Kurie plot using the shape of the ββ2ν decay.

The ββ2ν spectra of fig. 2 were calculated using the known ββ decay energy. Since the statistics of our data is good enough (4135 events are contained in the evaluation interval of the residual spectrum) we can determine the experimental endpoint using a ββ Kurie plot. Linear regression yields an endpoint energy of 2051 ± 20 keV. The good linearity and the correct endpoint energy shows the excellent agreement of measured and theoretical spectral shape.

Several single β-decay candidates as e.g. ^{60}Co (inside the crystal), $^{68,77}Ge$, ^{90}Sr and ^{234}Pa were simulated in different materials to test, whether they could produce a similar spectrum. All tested isotopes are either leading to a strongly non-linear ββ Kurie plot or to a wrong endpoint energy.

A similar analysis done with the data taken with the first enriched detector of 0.93 kg mass, operated in a separate shield, yields $T^{2\nu}_{1/2} = (1.55 \pm 0.09(\text{stat}) \pm 0.2(\text{syst})) \times 10^{21}$ yr. The ^{76}Ge exposure of this result is 7.3 mol yr, but the signal to background ratio of 1:3.7 is less advantageous.

The data of the control detector made from natural Ge could not be used as a ββ-blank, since the different peak counting rates showed that the background composition of both detectors is not identical.

Since the evaluated half-life is very large the measured counting rate should be constant in time. Thus a further consistency test can be done through the behaviour of the integral counting rate in the evaluation interval as a function of time, displayed in fig. 3. The full measuring time was divided into 30 d intervals. The background model was defined at the end of the measuring period, then only tabulated half-lives were used to calculate its time dependence. Experimental and residual data do not show strong fluctuations, although a decrease of the counting rate in the first 107.7 d of measurement can be seen.

If a two-parameter ML fit, leaving the half-life and the endpoint energy as free parameters, is performed we find for the last 115.3 d (corresponding to a ^{76}Ge exposure of 10.0 mol yr), when the counting rate was constant, $T_{1/2}=(1.58\pm0.08)\times10^{21}$ yr and $E_0=2039\pm43$ keV in comparison to $T_{1/2}=(1.41\pm0.05)\times10^{21}$ yr and $E_0=2053\pm29$ keV if the full measuring time is used. The final decision whether the decline of the counting rate, which is a 10% effect, is due to short-lived unidentified background components or an artefact (the systematic error is not included in the error bars of fig. 3) needs the evaluation of the full amount of data. Any unidentified background component would lead to even longer half-life values.

The systematic error of the measurement includes the uncertainties due to the localization of ^{137}Cs, ^{232}Th and ^{238}U (2.1%), statistical errors of the measured peaks used to normalize the model (3.4%), the error

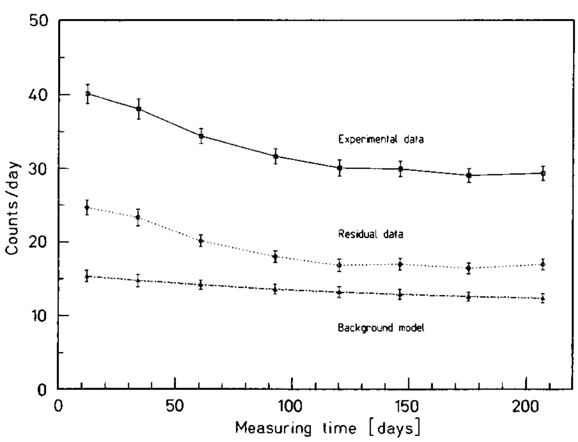

Fig. 3. Time dependence of the integral counting rate from 500 to 1500 keV. Peaks were removed.

of the ^{210}Pb activity measurement (1%) and the error of the simulated detector response (5.1%), yielding a total systematic error of 9.2%. All errors were added quadratically, except the contribution of the detector simulation, which was added linearly. The latter one was determined experimentally with a calibrated collimated ^{133}Ba source. The detector was scanned with this source in 19 steps in axial and 14 steps in radial direction. This experiment also showed that the fiducial volume of the detector is known within 5% accuracy.

If the full amount of data (nothing subtracted) available at present, corresponding to a ^{76}Ge exposure of 70.8 mol yr, is analyzed we find an average background of 0.3 counts/keV yr kg in the energy interval from 2000–2100 keV. From the absence of a significant peak at the ββ-decay energy we conclude that the half-life of the ββ0ν decay has to be larger than 1.5×10^{24} yr with 90% CL. Using the nuclear matrix elements of ref. [3] and neglecting possible right-handed admixtures to the weak interaction this result corresponds to an upper limit of 1.3 eV for the Majorana mass of the neutrinos.

In table 2 all exclusive measurements of ββ2ν-decay half-lives are summarized. Obviously the result presented in this paper connects for the first time a large number of evaluated events with good signal to background ratio. The measurements of refs. [7,10], done with a time projection chamber, reported very large $S:B$ values. On the other hand the source strengths used in this experiment are extremely small, resulting in a small number of counts. It seems to be difficult to understand the spectral shape of a broad continuum with less than 100 counts. The other experiments show small $S:B$ values, making those results sensitive to even small uncertainties in the background estimation. This should result in large systematical errors.

The upper curve of fig. 2 corresponds to a half-life of 9.2×10^{20} yr measured in an earlier experiment using also 86% enriched Ge [6], but having a measuring time of only 0.69 mol yr. Their result was evaluated under the assumption that the detector background is only due to ^{210}Pb. Since our raw data is in good agreement with their published result and the existence of additional background has been shown experimentally their assumption is questionable.

Table 2
Comparison of all exclusive measurements of $\beta\beta 2\nu$ decays. S:B denotes the signal to background ratio in the evaluated energy interval. The percentage denotes the fraction of the total $\beta\beta 2\nu$ intensity contained in this interval. The number of events used to derive the half-life is also given.

Isotope	Reference	$T_{1/2}^{2\nu}$ ($\times 10^{20}$ yr)	Interval (keV)	(%)	Number of events (counts)	Exposure (mol yr)	S:B
^{82}Se	UC Irvine [7]	$1.1^{+0.8}_{-0.3}$	1300–2000	34	36	0.150	3.6:1
^{100}Mo	Osaka [8]	$0.115^{+0.03}_{-0.02}$	700–1600	62	336	0.136	1:5.5 [a]
^{100}Mo	INR [9]	$0.033^{+0.02}_{-0.01}$	560–1810 [a]	78	645 [a]	0.041	–
^{100}Mo	UC Irvine [10]	$0.116^{+0.034}_{-0.008}$	800–2000	71	67	0.018	7.4:1
^{76}Ge	ITEP–Yerevan [11]	9.0 ± 1	700–1200	43	2284	11.53	1:10
^{76}Ge	PNL–USC [12]	$11.3^{+6.1}_{-2.9}$	300–2100 [a]	90	758	2.05	1:10 [a]
^{76}Ge	PNL–USC–ITEP [6]	$9.2^{+0.7}_{-0.4}$	500–1500 [a]	73	225 [a]	0.679	–
^{76}Ge	Heidelberg–Moscow	$14.2 \pm 0.3^{\text{stat}} \pm 1.3^{\text{syst}}$	500–1500	73	4135	19.27	1.3:1

[a] Geometrically estimated from the figures of the corresponding publication.

In summary, the discussed data show strong evidence for the existence of the $\beta\beta 2\nu$ decay of ^{76}Ge with a half-life of $T_{1/2}^{2\nu} = (1.42 \pm 0.03(\text{stat}) \pm 0.13\ (\text{syst})) \times 10^{21}$ yr. The systematic error was determined quantitatively for the first time in an experiment of this type, showing that its magnitude is not negligible.

The present result represents the first high-statistics measurement of $\beta\beta 2\nu$ decay. Experimental and calculated nuclear matrix elements of ref. [3] agree within 40%. The result deviates from an earlier experiment [6].

It has been shown experimentally that nuclear physics can parametrize the $\beta\beta 2\nu$ decay of ^{76}Ge, giving higher reliability to the constraints placed on non-standard model parameters as the Majorana mass of the neutrinos and a Majoron neutrino coupling. Data taking of the experiment continues. With the measured background and energy resolution a non-observation of the $0\nu\beta\beta$ decay will probe neutrino masses down to 0.2 eV within five years.

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