Physics Letters B 283 (1992) 32–36
North-Holland

PHYSICS LETTERS B

The Heidelberg–Moscow double beta decay experiment with enriched ^{76}Ge. First results

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Received 15 January 1992

The status of the Heidelberg–Moscow ββ-experiment using isotopically enriched ^{76}Ge is reported. The results of 14.8 mol yr (or 1.29 kg yr) of operation are presented. From these data a new half life time for the ββ0ν-decay of ^{76}Ge to the ground state of ^{76}Se of $T_{1/2} > 1.4(2.5)\times10^{24}$ yr with 90% (68%) CL can be deduced. For a possible neutrinoless decay to the first excited state a half life of $4.3(8.2)\times10^{23}$ yr can be excluded with 90% (68%) CL.

The investigation of the neutrino is still one of the most challenging fields of contemporary physics. There are many long standing open questions in our understanding of this particle: Does the neutrino carry a finite rest mass? Is the neutrino a Dirac or Majorana particle? Does a small right-handed admixture to the weak interaction exist? None of these questions has so far been answered (see e.g. ref. [1]). The investigation (nonobservation) of the lepton number violating neutrinoless double beta (ββ0ν) decay yields up to now the most stringent limits for these unknown parameters. Many experimental studies are devoted to this exotic decay (for a review of the different experiments see e.g. ref. [2]).

In general two ββ-decay modes are discussed:

$$A(Z,N)\to A(Z+2,N-2)+2e^{-}+2\bar{\nu}_e \quad (\beta\beta2\nu)\,, \tag{1}$$

$$A(Z,N)\to A(Z+2,N-2)+2e^{-} \quad (\beta\beta0\nu)\,. \tag{2}$$

The ββ2ν-decay, resulting in a continuous spectrum of the electrons is allowed in the standard model and has been directly observed for several nuclides [3–5]. It is an important probe of the theoretically predicted decay rates, since it is parameter-free from the particle physics side. The ββ 0ν-decay rate depends besides the nuclear matrix element also on unknown physics. While the observation of this decay would prove the existence of massive Majorana-neutrinos the nonobservation of it allows the deduction of limits, since the nuclear physics part of the decay rate can be reliably calculated [6,7]. The signature of this decay would be a peak in the sum energy spectrum of the electrons at the Q-value of the decay. The detection of the ββ 0ν-decay to the first excited state in ^{76}Se, which has a spin of $J=2^{+}$, would require a right-handed admixture to the weak interaction [8].

In the following we will focus on the ββ 0ν-decay mode. Our results for the ββ 2ν-mode will be discussed in a separate article. Those potential ββ-emitters which can be simultaneously used as source and detector of the emitted electrons offer the best experimental conditions. In this way large amounts of

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source material can be used without suffering strong self-absorption losses.

Through the use of large amounts of isotopically enriched source material second generation $\beta\beta$-experiments can probe neutrino masses down into the sub-eV range. The Heidelberg–Moscow collaboration can use in the described experiment 16.9 kg of enriched Ge with a ^{76}Ge abundance of 86%. The natural abundance of ^{76}Ge is only 7.8%. Ge semiconductor detectors made from the isotopically enriched Ge are used as source and detector of the electrons emitted in the $\beta\beta$-decay of this isotope. These detectors have an excellent energy resolution which is very favourable for a sensitive search for the discrete spectrum of the $\beta\beta$ 0ν-decay. Since $\beta\beta$-decay is one of the rarest processes known in nature the background reduction is the biggest experimental challenge. The fact that the Q-value ($E_0 = 2038.56$ keV [9]) of the $\beta\beta$-decay of ^{76}Ge lies in the energy range of the natural radioactivity makes it even more difficult.

The use of the highly enriched material allows to concentrate the source strength on relatively small detectors and consequently limit their sensitivity towards background radiation. This advantage is reflected in the figure of merit of the experiment given in units of the half lifetime $T_{1/2}$ (yr) to be extracted from the background fluctuation if no peak will be present after the measuring time t (yr),

$$T_{1/2} > (4.18 \times 10^{24}\ \mathrm{kg}^{-1})\,\frac{a}{f}\sqrt{\frac{Mt}{B\,\Delta E}}, \qquad (3)$$

where a is the isotopical abundance of ^{76}Ge, M the active mass of the detector (kg), B the average background at the energy of the peak (counts/keV yr kg), ΔE the energy resolution (FWHM) (keV). The factor f connects the limit to a confidence level (CL). $f = 3.62$ (1.35) for 90% (68%) CL if the minimum detectable activity and $f = 1.81$ (0.68) for 90% (68%) CL if the minimum detectable count rate is estimated. The enrichment factor a is the only parameter not connected through the square root to the sensitivity.

Currently two HP Ge detectors made of enriched ^{76}Ge are available in the described experiment. The first (#1), which has an active mass of 0.927 kg, has been operated for 250.8 d. This detector has an energy resolution of 2.5 keV at 1.3 MeV. The second detector (#2), which has an active mass of 2.758 kg, was the biggest Ge detector ever made at the time of its production in 1991. The measuring time available from it is 86.9 d, the energy resolution at 1.3 MeV is 2.4 keV. The energy threshold of detector #1 is at 110 keV. Detector #2 can be operated with a threshold of 12 keV.

Concentrating the available Ge in the biggest possible detectors has several experimental advantages. (i) The ratio of the Ge-mass (high radiopurity) to the mass of the cryostat parts (less radiopurity) is optimized. (ii) The background around the hypothetical $\beta\beta$ 0ν-peak is mainly formed by Compton scattered γ-quanta emitted by the members of the ^{232}Th and ^{238}U decay chains. The spectral shape of this background is a flat continuum. The good peak-to-Compton ratio of big detectors (43:1 for detector #1 and 93:1 for detector #2) can help to concentrate the background into the peaks and consequently to remove it from the energy region of interest.

A third enriched detector (#3) with a mass of 2.447 kg and a peak-to-Compton ratio of 89:1 has recently been produced. After being installed in its low-level cryostat it will be ready for data taking in 1992. The usable rest of detector grade Ge-metal is sufficient to pull another 3 kg crystal in 1992.

Both detectors are surrounded by passive shields. That of detector #1 has 10 cm LC2 grade Pb, 16.5 cm electrolytic Cu and 20 cm of low activity Boliden Pb. This setup has already been described elsewhere [10]. Detector #2 is mounted together with a detector made from natural Ge in a shield composed of 10 cm of LC2 grade Pb and 20 cm of Boliden Pb. The experiment is operated in the Gran Sasso underground laboratory (LNGS). The LNGS has a shielding thickness of 3500 m of water equivalent which reduces the penetrating myonic component of the cosmic radiation by 6 orders of magnitude. Since the surrounding rock is mainly dolomite the neutron flux is very low in this location [11]. For Rn suppression the shields are equipped with air-tight steel cases on the outside and are flushed with nitrogen gas. All cryostat parts were only made from carefully selected materials as electrolytic Cu, zone refined Si and Teflon. These materials have very low intrinsic concentrations of radioactive isotopes. The material selection was done with existing low-level Ge spectrometers (see ref. [12]). In order to avoid surface contaminations the cryostat parts were etched before their assembly. The final assembly was done under cleanroom conditions. All LC2 grade Pb bricks forming the inner part of the shielding were etched as well.

Fig. 1 depicts the combined background spectrum of both detectors. The total measuring time is 1.29 kg yr (kg of Ge), corresponding to a statistical significance of 14.8 mol yr (mol of ^{76}Ge). The background around 2 MeV (averaged from 1960 to 2080 keV) is $B_1 = 0.40$ counts/keV yr kg. The background around 1.48 MeV (averaged from 1465 to 1700 keV) is $B_2 = 1.13$ counts/keV yr kg. The two used detectors are differing significantly in their background. Detector #1: $B_1 = 0.57$ counts/keV yr kg and $B_2 = 1.61$ counts/keV yr kg; Detector #2: $B_1 = 0.28$ counts/keV yr kg and $B_2 = 0.93$ counts/keV yr kg. Since the bigger detector contains the main part of the Ge and has the lower background, the background in the combined spectrum will decrease with the measuring time.

Besides the natural radioactivity (^{40}K, ^{232}Th and ^{238}U) also man-made activities as ^{134,137}Cs and cosmogenic radioactivity from ^{54}Mn, ^{57,58,60}Co and ^{65}Zn are identified in the spectrum shown in fig. 1. All peak-count rates of the big detector are lower than those of the first detector. The biggest improvement was achieved for the isotopes ^{40}K and ^{137}Cs (improvement factor of 5.9 and 6.6 respectively) which cause the strongest lines in the spectrum of detector #1. The available data show no indication for a ββ 0ν-decay either to the ground or to the first excited state. The energy resolution of our experiment at the decay energies is estimated from a linear fit of the FWHM of the strongest lines in the background spectrum. In comparison to an also tested square-root fit the linear model gives a higher confidence level as well as the more conservative result. The resulting energy resolution in the sum spectrum is 3.0 keV and 3.4 keV for the decay to the excited and the ground state, respectively.

The evaluation intervals corresponding to the 3σ-interval of the hypothetical ββ0ν-peaks are containing four events for the decay to the ground state and eleven events for the decay to the first excited state, respectively. Since our background is still too low to use the usual approximation of the Poisson- through the Gauss-distribution (as used to derive inequality (3)) we use the method recommended by the Particle Data Group for a Poisson distributed signal superimposed to background [13] to estimate the number of excluded ββ 0ν-events. For the ground state decay we can exclude in this way 4.40 (2.41) events with 90% (68%) CL. Under the assumption that the exponential decay law is valid we can convert the above result into a half life limit of $T_{1/2} > 1.40$ $(2.56) \times 10^{24}$ yr, 90% (68%) CL. Fig. 2 shows the measured spectrum around the hypothetical ββ 0ν-peak together with the signal excluded with 90% CL.

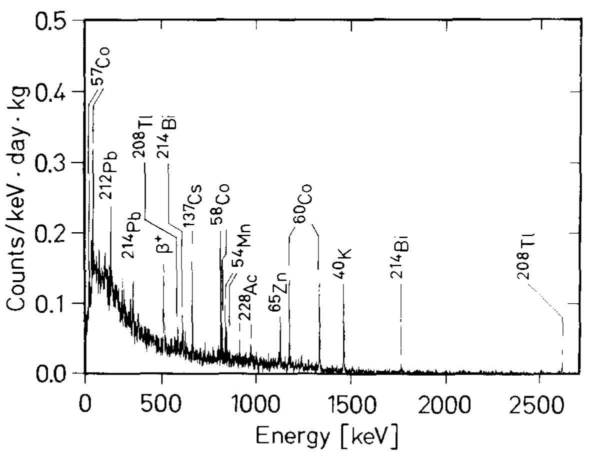

Fig. 1. Combined background spectrum of the enriched detectors. The presence of peaks demonstrates the excellent resolution and stability of the experiment. Measuring time is 1.29 kg yr.

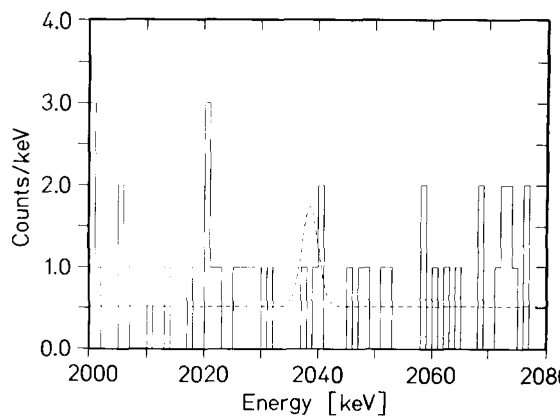

Fig. 2. Energy range around the hypothetical ββ 0ν-peak. No peak is present after a measuring time of 1.29 kg yr. The dotted line represents the excluded signal at a confidence level of 90%.

Table 1
The following parameters are listed: a, N (source strength; amount of decaying isotope), Nt (where t is the measuring time), B (average background at the decay energy in units of the amount of the decaying isotope), FWHM (energy resolution at the decay energy), $T_{1/2}$, $\langle m_\nu \rangle$ (effective Majorana neutrino mass), $\langle \lambda \rangle$ (effective right-right-handed admixture to the weak interaction) and $\langle \eta \rangle$ (effective left-right-handed admixture to the weak interaction).

Experiment	Sample	a	N (mol)	Nt (mol yr)	B (counts keV^{-1} mol^{-1} yr^{-1})	FWHM (keV)	$T_{1/2}$ (10^{24} yr)	$\langle m_\nu \rangle$ (eV)	$\langle \eta \rangle \cdot 10^8$	$\langle \lambda \rangle \cdot 10^6$
Caltech–Neuchâtel PSI [a)]	^{76}Ge	0.078	6.3	9.4	2.2	3.2	0.29	3.7	3.6	5.7
UCSB–LBL [b)]	^{76}Ge	0.078	7.3	22.6	1.1	3.3	1.2 (0.8) [c)]	1.6 (1.9)	1.6 (1.9)	2.5 (3.1)
Yerevan–ITEP [d)]	^{76}Ge	0.85	13.3	14.5	0.19	3.7	1.0	1.7	1.7	2.8
Heidelberg–Moscow	^{76}Ge	0.86	42.2	14.8	0.035	3.4	1.4	1.5	1.5	2.3
Milano [e)]	^{136}Xe	0.64	20.7	14.6	2.2	124	0.02	14.9	11.1	20.3
Caltech–Neuchâtel PSI [f)]	^{136}Xe	0.63	26.6	10.3	0.002	164	0.25	3.3	2.4	4.5

a) Ref. [15]. b) Ref. [16].
c) If the remeasured decay energy is taken into account, refs. [5,9] obtain this result. Our analysis of this experiment yielded a similar result.
d) Ref. [5]. e) Ref. [17]. f) Ref. [18].

Through a Monte Carlo program (based on the CERN code GEANT3) the probability for the total escape of the 559.1 keV γ-quanta emitted at the decay of the first excited state of ^{76}Se was calculated to be 37.6% for the combined data. This results in a half life limit for the ββ 0ν-decay to the first excited state of $T_{1/2} > 4.39(8.22) \times 10^{23}$ yr with 90% (68%) CL. Busto et al. [14] published evidence for a coincidence signal which they interpreted as a possible ββ 0ν-decay to the first excited state with a half life of $T_{1/2} = 10^{22}$ yr ± 50%. Even the upper end of their 3σ-error of $T_{1/2} = 2.5 \times 10^{22}$ yr should correspond to 92.9 events in the evaluation interval of our spectrum. By this 28.0σ disagreement it has to be concluded, that the coincidence signal found by Busto et al. must have other causes than ββ 0ν-decay.

Using the matrix elements of ref. [6] we deduce from the half life limit of the ββ 0ν-decay to the ground state new upper limits for the Majorana mass of the neutrino as well as for possible right-handed admixtures to the weak interaction. Table 1 contains the experimental parameters and results of this experiment in comparison to other large scale ββ-experiments. From table 1 it is obvious that the Heidelberg–Moscow setup shows at present the most advantageous experimental parameters of all compared ββ-experiments. Together with the enriched detector #3 a source strength of ~ 70 mol of ^{76}Ge will be available in 1992. The full scale of this experiment will correspond to ~ 100 mol ^{76}Ge. The developed technology together with the exceptional source strength of this experiment will allow us to test Majorana neutrino masses down to ~ 0.2 eV within approximately 5 years of measurement.

The development of the low-level cryostats is done in cooperation with CANBERRA (Belgium), while ORTEC (USA) grows the Ge crystals. The authors are especially grateful to Dr. V. Prusakov, Dr. A. Tchelzov and Dr. A. Tihomirov – without their efforts in the field of isotope separation this experiment would have been impossible. This work is supported by the Bundesministerium für Forschung und Technologie der Bundesrepublik Deutschland and the State Committee of Atomic Energy of the USSR. The authors greatly acknowledge the generous support the INFN, and in particular by Professor E. Bellotti. M.B. is supported by the Konrad-Adenauer-Stiftung.

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