*Status of the Heidelberg–Moscow $\beta\beta$–Experiment using enriched ^{76}Ge +, *)*

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The search for the $\beta\beta0\nu$-decay is at present the most powerful tool for investigating a Majorana mass of the neutrino. The Heidelberg-Moscow group has now 16.9 kg of 86% enriched ^{76}Ge at its disposal. End of July 1990 the first phase of the experiment has been started in the Gran Sasso underground laboratory.
The results after 135.1 days of data taking with a 980 g detector are: background around 2 MeV B=0.5 counts/keV·y·kg, half life limit for the $\beta\beta0\nu$-decay to the ground state of ^{76}Se $T_{1/2}>3.8\cdot10^{23}y$ (90% c.l.). A possible $\beta\beta0\nu$-decay to the first excited state can be excluded with $T_{1/2}>1.8\cdot10^{23}y$ (90% c.l.). The statistical significance of these results is 3.9 mol·y.

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1. Introduction

The successful test of the standard model at LEP raises the question whether this model is the ultimate description of nature or whether there is new physics beyond. One key for our understanding of nature could be the physics of the neutrino, from which only very little is known up to now. It is still an open question whether the neutrino is a Dirac or a Majorana particle and whether it carries a finite rest mass.
Many models of grand unification (GUT's, SUSY's...) are predicting a non-vanishing Majorana mass of the neutrino, which has to be zero in the standard model since no right-handed neutrinos are available. Unfortunately these predictions are strongly divergent ranging from 10^{-11} eV to values of the order of 1 eV [1].
In a recent paper S. Glashow showed that also the possible existence of 17 keV neutrinos does not neccessarily imply that neutrinos are Dirac particles.[2]
The investigation of the neutrinoless nuclear ββ-decay is up to now the most sensitive probe of a possible Majorana mass of the neutrino. At present this mass is tested to be smaller than ~1.7 eV.
Double beta decay which is one of the rarest processes in nature is expected to proceed mainly via two decay modes:

$$(\beta\beta 2\nu) \qquad A(Z) \Rightarrow A(Z+2) + 2e + 2\bar{\nu}_e \qquad (1)$$

$$(\beta\beta 0\nu) \qquad A(Z) \Rightarrow A(Z+2) + 2e \qquad (2)$$

It should become observable in those nuclei where ordinary alpha or beta decay is forbidden (for example in the case of ^{76}Ge). The measurement of the decay rate of process (1), which is allowed in the standard model and has been already observed, is important to check theoretically calculated nuclear matrix elements and consequently the understanding of nuclear structure. The electrons emitted in this process have a continuous energy spectrum.
The so far unobserved ββ0ν-decay would require massive Majorana neutrinos and consequently imply physics beyond the standard model. Through a measured half life (or limit) the effective Majorana mass $\langle m_\nu \rangle$ of the neutrino (or a limit for it) can be deduced using theoretically calculated nuclear matrix elements for example from ref. [3]. A discussion of $\langle m_\nu \rangle$ and its dependence on the mixture of the different mass eigenstates can be found in ref. [4]. Since process (2) is a two body decay the summed energy of the electrons should be a discrete line at the Q-value of the decay (E=2040.71 keV).
A new generation of ββ-experiments can test the neutrino mass down to ~0.1 eV through the use of large amounts of isotopically enriched source materials and test a class of left right symmetric GUT models (for the latter see[1]).
The collaboration between the MPI in Heidelberg and the KIAE in Moscow has 16.9 kg of Ge metal enriched to 86% in ^{76}Ge at its disposal. The natural abundance of this isotope is only 7.8%.
In this experiment semiconductor detectors made from the isotopically enriched Ge are used simultaneously as source and detector for electrons emitted in the ββ-decay of ^{76}Ge. The strong enrichment helps to increase the source strength

without simultaniously raising the sensitivity towards background radiation as would be the case if simply a larger amount of natural Ge would be used. This fact is reflected in the figure of merit of this experiment given in units of the half life limit $T_{1/2}$ [y] deduced if no peak can be found at the correct energy after measuring time t [y].

$$T_{1/2} > (4.18 \cdot 10^{24} kg^{-1}) \cdot \frac{a}{f} \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \quad (3)$$

a : isotopical abundance of ^{76}Ge
M : active mass of the detector [kg]
B : average background at the energy of the peak [counts/keV·y·kg]
ΔE: energy resolution (FWHM) [keV]
The factor f connects the limit to a confidence level (c.l.). f=1.35; 3.62; 8.74 corresponds to 68%, 90% and 99.9% c.l. respectively. This conservative choice of f is derived from the concept of minimal detectable activity described for example in ref. [5]. In this approach the risc of rejecting the peak hypothesis if it is true and accepting the nopeak hypothesis if it is wrong (this is not the same) is included in the limit.
In a less conservative approach which measures only the first risc, f is equal to 0.48; 1.28; 3.09 for 68%, 90% and 99.9% c.l. respectively. In the literature f is often used in an undefined way.
The isotopical abundance is obviously the most effective parameter to increase the sensitivity. Since the hypothetical peak lies in the energy range of the natural radioactivity and the expected count rate is extremely small (for $T_{1/2} > 8 \cdot 10^{23}$y lower than 6 counts/kg·y) the background reduction is the biggest experimental challange. The experiment claiming at present still the most stringent half life limit for the ββ0ν-decay has an average background around 2 MeV of B=1.2 counts/keV·y·kg [6]. The lowest background reported in the literature is B=0.3 counts/keV·y·kg [7].

2. Experimental set up

In the first phase of our experiment a 980 g p-type enriched HP Ge detector with an active mass of about 927 g is used to study the ββ-decay. Approximately 10.5 mol ^{76}Ge are contained in this first detector. As far as the source strength is concerned even this first detector is one of the biggest ^{76}Ge ββ-experiments in operation. The HP crystal was grown at ORTEC (USA). At 2 MeV this detector has an energy resolution of ΔE=3.0 keV. It is the first HP detector from enriched Ge ever operated.
All detector parts have been carefully selected for lowest activity with existing low-level Ge spectrometers [8].
The cryostat of the detector is made from electrolytic copper. To avoid activation through the cosmic radiation the copper was obtained directly from the producer and than quickly stored underground. No soldering was done near the

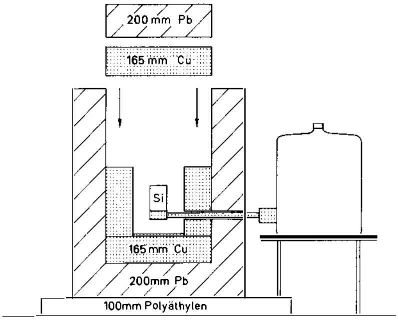

Fig. 1 Cross section of the set up. The inner cavity is now filled with LC2 grade Pb.

crystal. The detector endcap is made from a zone refined Si crystal. To avoid surface contaminations all detector parts were etched or electropolished before assembling. The cryostat system was mounted under cleanroom conditions. The FET is located at a remote position. Charcoal made from coconuts selected for their low Ra content serves as a molecular sieve. The development of the low-level cryostat was done in cooperation with CANBERRA (Belgium).
Fig. 1 depicts a cross section of the set up.
The detector is surrounded by a passive shielding composed of 20 cm low-activity lead, 16.5 cm electrolytic copper and 10 cm radio pure so-called LC2 grade lead.
Special care was taken to remove the air containing Rn from the inner cavities of the shielding. The whole set up is surrounded by an airtight steel container. The shielding is always flushed with nitrogen gas giving a constant excess pressure to the steel box.
The experiment is located in the Gran Sasso underground laboratory of the INFN (Istituto Nazionale di Fisica Nucleare) in Italy with a shielding thickness of about 3500 m w.e. The muon-flux is reduced by six orders of magnitude. The INFN has constructed a special low-level building for this experiment to allow clean, stable and quiet working conditions.
To control the systematic errors during the long measuring time data taking is done in an event-by-event mode. Together with the detector signal several control signals are recorded like: high voltage applied to the crystal, temperatures of the electronic components, status of the electrical network and absolut time of the event. Through these additional parameters the data can be checked for correlations with external parameters. The time distribution of the events offers the possibility to identify artificial signals. The temperatures can be used for a software stabilisation of the calibration drifts. Weekly calibration measurements with ^{60}Co and ^{228}Th sources are performed to check the performance and stability of the experiment.

3. Experimental Results

The results of 135.1 days of data taking will be discussed. This measuring time corresponds to a statistical significance of 3.9 mol·y. In Fig. 2 the background spectrum from 100 to 2700 keV is shown. The integral countrate in this interval is 0.05 counts/min·kg. A major part of the background is composed from the cosmogenic isotopes $^{57,58,60}Co$, ^{54}Mn and ^{65}Zn. They were formed via the interaction of the cosmic radiation with the Cu (mainly absorption of neutrons) and the Ge (mainly spallation) while being exposed above ground. Radioisotopes decaying by EC can be distinguished to originate from Ge or Cu by giving either the total decay energy (inclusive follow up x-rays) or the x-ray escape peak respectively. In this way the $^{57,58}Co$, ^{54}Mn and ^{65}Zn activities can be located. This is very important for a reliable Monte Carlo simulation of the detector.

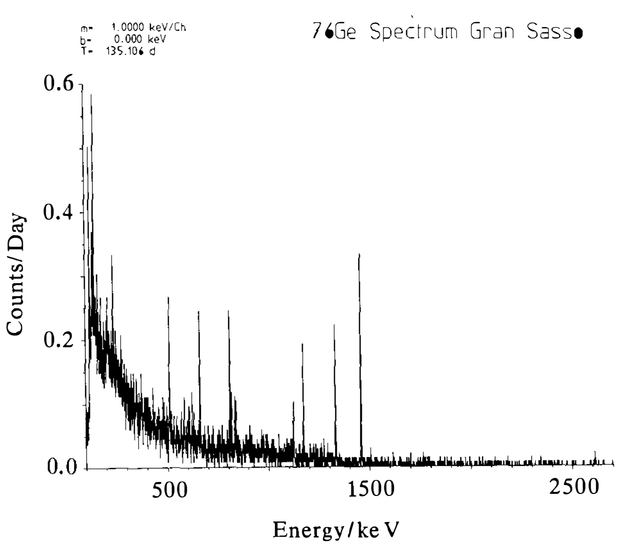

Fig.2 Background spectrum of the enriched detector.

From man-made radioactivity only ^{137}Cs is present. Above the E=1461 keV γ-line of the ^{40}K decay no strong lines are visible after 135 days.

The background around 2 MeV is mainly formed by Compton scattered γ-quanta emitted from isotopes of the natural ^{232}Th and ^{238}U decay chains. At present only members of the Th chain are visible. The absence of lines of the U chain shows that the Rn system works quite efficiently. ^{68}Ge is in contrast to experiments working with natural Ge no problem here because its target isotope ^{70}Ge in the cosmic ray reaction $^{70}Ge(n,3n)\,^{68}Ge$ is reduced by about 3 or-

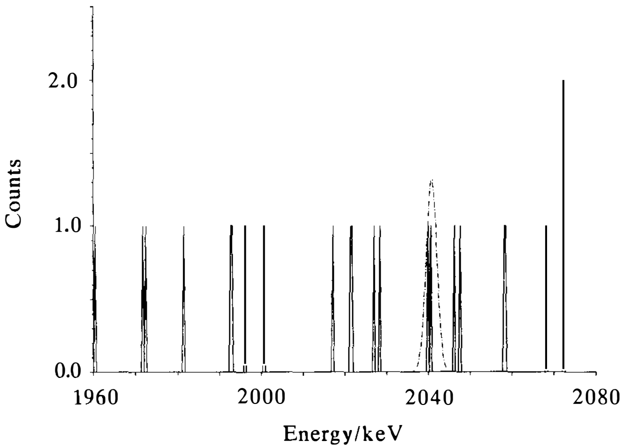

Fig. 3 Background around 2 MeV. The dotted curve represents the excluded $\beta\beta0\nu$-signal of 4.2 counts.

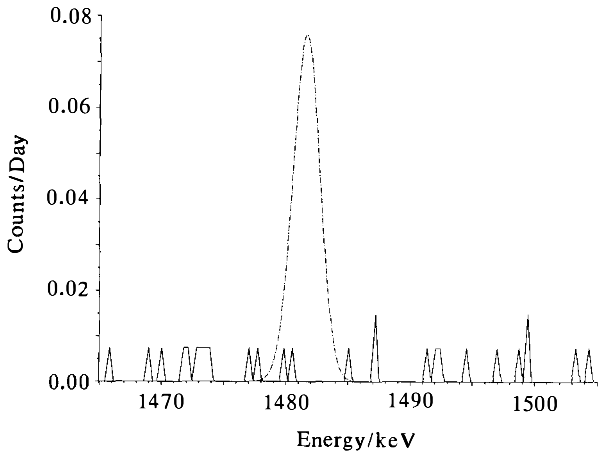

Fig. 4 Background around 1.48 MeV. The dotted curve shows the signal which should be there if the signal of ref.[10] would be ββ0ν-decay.

ders of magnitude in the enrichment process. In Fig. 3 the energy range around 2 MeV is displayed. The average background there is B=0.5 counts/keV·y·kg. Since the number of counts contained in this intervall is still extremely small the method recommended by the particle data group[9] for a Poisson process with background was applied to calculate the half life limit for the ββ0ν- decay to the ground state of ^{76}Se. The result after 135.1 days is $T_{1/2}>3.8\cdot10^{23}$y (90% c.l.).
This corresponds to a limit of 2.4 eV for the Majorana mass of the neutrino. The data were also checked for a possible ββ0ν-decay of ^{76}Ge to the first excited ($J=2^+$) state of ^{76}Se. Observation of such a decay would require right handed admixtures to the weak interaction because of conservation of angular momentum. Such a decay should result in a line at the decay energy lowered by the energy of the excited state. The probability for the total escape of deexcitation γ-quanta with an energy of E=559 keV has been calculated with a Monte Carlo program (based on the CERN code GEANT 3) to be 43% for our detector. In a recent publication a French group reported a coincidence signal which could be identified with the discussed ββ0ν-decay to the first excited state. Their published half is $T_{1/2}=1\cdot10^{22}$y ± 50% [10]. Even if a half life at the upper end of the 3σ-error bar of ref. [10] is assumed ($T_{1/2}=2.5\cdot10^{22}$y) we should find according to the exponential decay law 28 events. Fig. 4 shows the spectrum around the energy of the peak at E=1482 keV. The dotted curve corresponds to the peak which should be there if the coincidence signal of ref. [10] would be ββ0ν-decay. We find only 3 events in the energy interval of the peak. The average background in this energy range is in our experiment B=1.8 counts/keV·y·kg. Therefore ββ0ν-decay of ^{76}Ge to the first excited state can be excluded to have a half life as large as reported in ref. [10]. Since the background is very low, a statistical fluctuation can not explain the discrepancy. From our spectrum we deduce a half life limit of $T_{1/2}>1.8\cdot10^{23}$y (90% c.l.).
With the data available at this moment we can give a half life limit for the ββ2ν-decay of $T_{1/2}>7.5\cdot10^{20}$ y (90% c.l.).

4. Future Perspectives of the Heidelberg-Moscow experiment

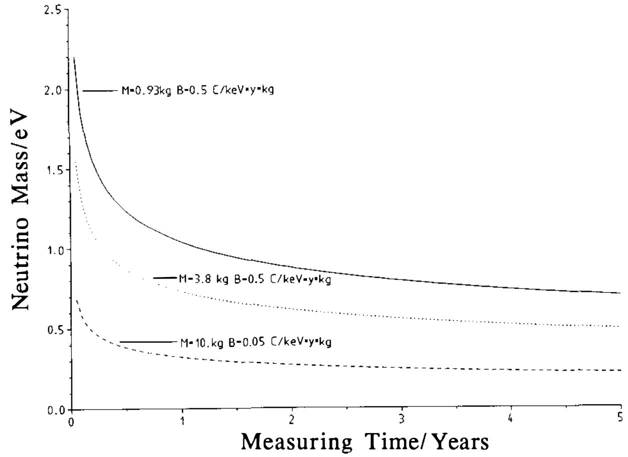

Fig. 5 Neutrino mass limit for different experimental parameters.

To estimate the perspectives of the described experiment the neutrino mass limits (90% c.l.) deduced via the discussed $T_{1/2}$-formula (conservative f) and the matrix elements from ref [3] are plotted as a function of the measuring time in Fig. 5. The solid curve represents the sensitivity of the discussed detector. Even with this first detector it will be possible to reach the results of the leading experiment [6] within one year.

Currently a second enriched detector with a mass of 2.9 kg is under construction. In a test cryostat this detector has an energy resolution of 2.0 keV.
The pointed curve shows the sensitivity of the experiment if this new detector will have the same background as the previous one. With this source strength neutrino masses below 1 eV can be probed. A third detector grade enriched crystal with a mass of 3.3 kg has been recently grown at ORTEC.
To test new ideas for a further background reduction a detector made from natural Ge was equiped with a crystal holder and cap made from zone refined Si. Test measurements with this detector are performed in the Gran Sasso lab. In a second step it is planned to replace the LC2 grade Pb shielding bricks by Ge bricks. For this purpose ~400 kg of semiconductor purity Ge is available.
In the dashed curve the potential of the full-scale experiment is estimated. If ~10 kg detector mass and a factor ~10 background reduction are assumed mass limits around 0.2 eV can be reached.

Through the use of highly enriched source materials ββ-experiments can probe the Majorana neutrino mass beyond today's possibilities. The first phase of the Heidelberg- Moscow experiment is in operation in the Gran Sasso underground lab. since July 1990. The background characteristic and the source strength makes this first enriched HP Ge detector to one of the most sensitive systems searching for the ββ-decay of ^{76}Ge. Further enriched detectors are in preparation. The time scale of the full experiment is approximately 5 years.

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