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76-GE

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THE HEIDELBERG-MOSCOW DOUBLE BETA DECAY EXPERIMENT WITH ENRICHED ^{76}GE: STATUS AND PERSPECTIVES

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Abstract:

Double beta decay probes beyond standard model physics. Status and perspectives of the HEIDELBERG-MOSCOW double beta decay experiment which is undertaken in the GRAN SASSO laboratory, are presented. Of the 16.9 kg of enriched (86%) ^{76}Ge in hands of the cooperation, ~ 12 kg have been converted into detectors (or crystals). At present 6 kg of detectors are in operation for data taking. The significance of the experiment at present is 2649 kg · d. Present limits for 0νββ decay to the g.s. and first excited state of ^{76}Se, respectively, are:
$T_{1/2}^{0\nu}(0^+ \to 0^+) > 1.9 \times 10^{24}$ y and $T_{1/2}^{0\nu}(0^+ \to 2^+) > 8.0 \times 10^{23}\, y$ with 90% c.l. These values are the most stringent directly measured 0νββ half life limits known up to now. They correspond to an effective neutrino mass limit of $< m_\nu > < 1.1$ eV. On the other hand we seem to observe a systematic excess of counts beyond the expected background precisely at the 0νββ ($0^+ \to 0^+$) transition energy. For the neutrinoless decay with majoron emission a half life of 1.7 x 10^{22} y can be excluded leading to an upper limit for the neutrino-majoron coupling of $< g_{\nu\chi} > < 1.8 \cdot 10^{-4}$ (90% c.l.). The background around 2 MeV is b = 0.2 counts/kg y keV for the total array. The experiment opens new perspectives for the investigation of exotic processes like electron decay, solar axions and dark matter. It was, e.g., possible to improve the existing cross section limits for WIMP masses above ~ 150 GeV and to exclude Dirac neutrinos in the range 26 GeV to 4.7 TeV as the dominant component of the dark halo. The new ββ-technology has found also application in high resolution balloon and satellite gamma-ray astronomy.
Concerning the matrix elements for ββ decay a major step beyond the frequently used QRPA model has been made by applying the Operator Expansion Method (OEM).

1. INTRODUCTION

The neutrino mass m_ν is one of the key quantities for the structure of grand unified

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theories [1,2]. Predictions for m_ν cover the wide range between 10^{-11} and several eV. Double beta ($\beta\beta$) decay yields at present the sharpest limits on the electron neutrino mass. The future (next 5 years) of $\beta\beta$ experiments will be dominated by use of enriched detectors, ^{76}Ge playing a particularly favourable role here [3,4], and enriched source material such as ^{136}Xe (see [5]), ^{100}Mo [6], ^{116}Cd [7] (Fig. 1). Such experiments can probe the neutrino mass in the next years down to about 0.1 eV. They are complementary to solar neutrino experiments like GALLEX and SAGE, which could be sensitive to a difference of masses of neutrinos of different flavour, but do not measure the electron neutrino mass directly.

For deduction of an (effective) neutrino mass (limit) from a measured 0ν decay rate (limit) calculation of nuclear matrix elements is required. Neglecting right-handed weak currents

$$\left[T_{1/2}^{0\nu}(0_i^+ \to 0_f^+)\right]^{-1} = (M_{GT}^{0\nu} - M_F^{0\nu})^2 G_1 \frac{<m_\nu>^2}{m_e}$$

After the major step of recognizing the importance of g.s. correlations for their calculation [8], in recent years the main groups used the QRPA model. It was found that in most cases the uncertainties of the model were tolerable in the case of $0\nu\beta\beta$ decay (see [9]). The problem of QRPA - extreme dependence of the calculated rate (particularly for 2ν decay) on the choice of the renormalization of the particle-particle force, g_{pp}, seems recently to have been solved by applying the so-called Operator Expansion Method (OEM) [10,11].

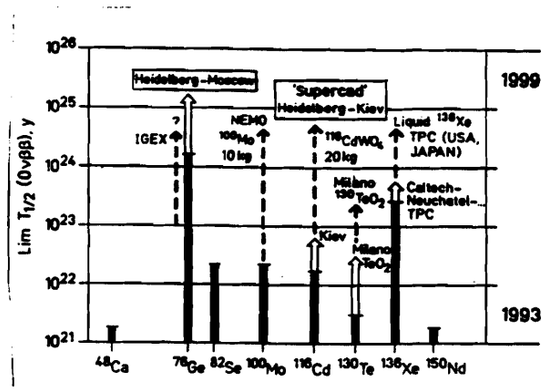


Fig. 1:
Present situation and perspectives of the most promising $\beta\beta$ experiments. Only for the isotopes shown $0\nu\beta\beta$ half life limits > 10^{21} y have been obtained. The thick solid lines correspond to the present, 1993, status, open bars and dashed lines to 'safe' and 'less safe' expectations for 1999, respectively (from [7]).

2. STATUS OF THE HEIDELBERG-MOSCOW EXPERIMENT

Use of enriched ^{76}Ge (86%) instead of detectors from natural Ge (containing 7.8% of ^{76}Ge) could explore the half life of $0\nu\beta\beta$ decay up to $\geq 10^{25}$ years and correspondingly the neutrino mass down to ~ 10^{-1} eV, probing a class of left-right symmetric GUT models with a right-handed Majorana mass term of about 1 TeV, based on $SU(2)_L \otimes SU(2)_R \otimes U(1)$ (see [1], [3]) The HEIDELBERG-MOSCOW $\beta\beta$ experiment [3] makes

use of 16.9 kg of ^{76}Ge metal enriched to 86%, corresponding to 14.5 kg of the isotope ^{76}Ge. Up to now one enriched detector of ~ 1 kg, another of 2.9 kg (the largest ever produced Ge-detector at that time) and another three detectors (or crystals) of 2.5, 2.9 and 3.5 kg, respectively, have been produced. The first detector is running in the GRAN SASSO Underground Laboratory in Italy since end of July 1990, the second since September 1991, the third since August 1992.

0ν-decay: The results of the first 2649 days x kg of measurement are:
$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+) > 1.9 \times 10^{24}$ (90% c.l.), (Fig. 2), the corresponding limit for the neutrino mass is $m_\nu < 1.1$ eV. The HEIDELBERG-MOSCOW experiment thus yields now the most stringent limit for the 0νββ half life of ^{76}Ge and the sharpest limit for the neutrino mass from detector experiments (for details see [3]). On the other hand we observe (Fig. 3) a systematic excess of events beyond the expected background precisely at the energy of a 0νββ $(0^+ \rightarrow 0^+)$ transition (present significance ~ 2σ). This coincides with the observation of a stagnating 0νββ half-life limit (Fig. 4) as function of measuring time (Fig. 4) inspite of decreasing background. These effects require further attention. For their further investigation we have developed [12] a method of pulse shape analysis which will allow rejection of ~ 80% of multiple (non-ββ) events.

The background level which characterizes the quality of the set-up is 0.36 events/kg year keV (Fig. 2) in an 80 keV interval around the hypothetical 2038.5 keV 0νββ-line for the total spectrum, and ~ 0.2 events/kg year keV at present. As an upper limit for aββ transition to the first excited state of ^{82}Se which should occur at 1479.5 keV, we deduce a half-life limit $T_{1/2}^{0\nu}(0^+ \rightarrow 2^+) > 8.0 \times 10^{23}$ (90% c.l.), i.e. far beyond the half-life of 2.5 x 10^{22} years claimed by [13] (Fig. 2).

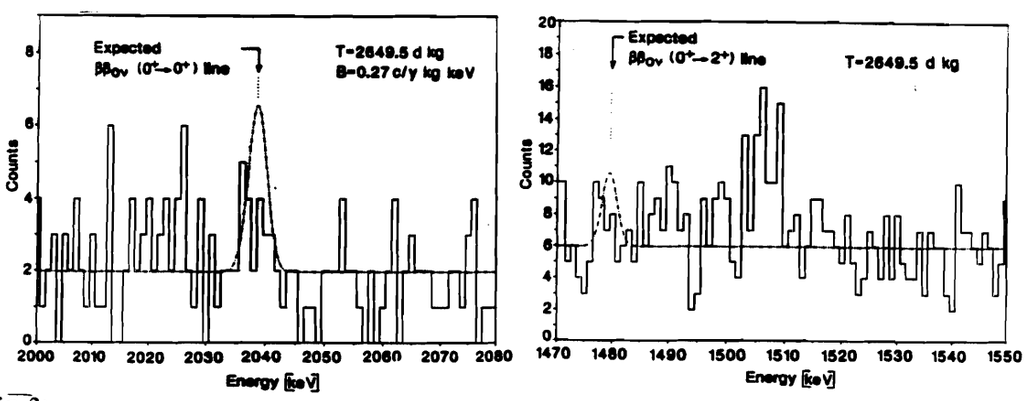
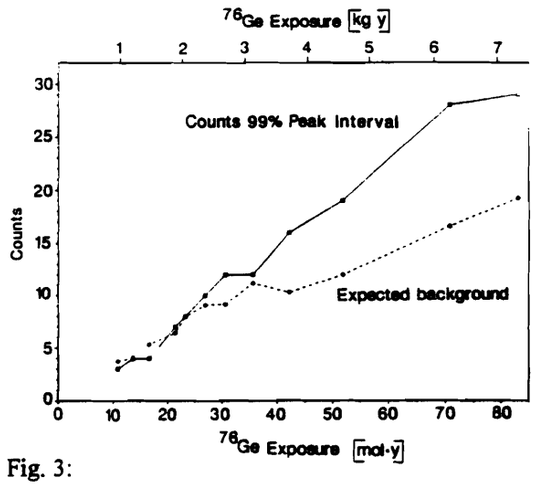


Fig. 2:

Details of the spectrum of the HEIDELBERG-MOSCOW collaboration in the region of neutrinoless double beta decay to the ground and first excited state of the daughter nucleus after a measuring time of 2649 kg d. Dashed lines excluded with 90% c.l.



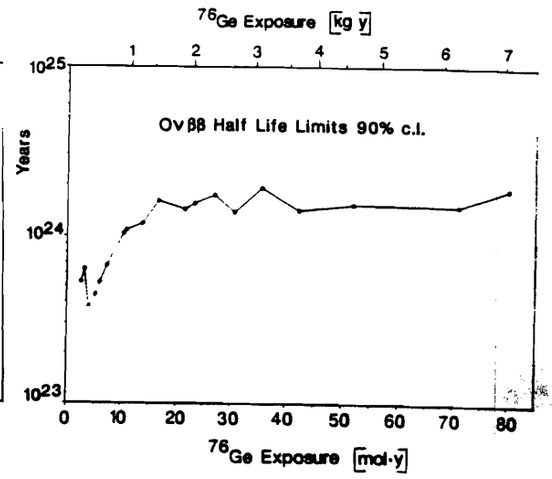


Fig. 3:

Number of expected background counts (dashed line) and measured total number of counts (solid line) in the 3σ energy range of a $0\nu\beta\beta\,(0^+ \rightarrow 0^+)$ transition of ^{76}Ge, as function of measuring time in the HEIDELBERG-MOSCOW experiment. The expected background is extrapolated from 30 keV ranges left and right from the centroid energy (2038.6 keV). The deviation under a no-line hypothesis between observed and expected counts corresponds to 2σ (from [22]).

Fig. 4:

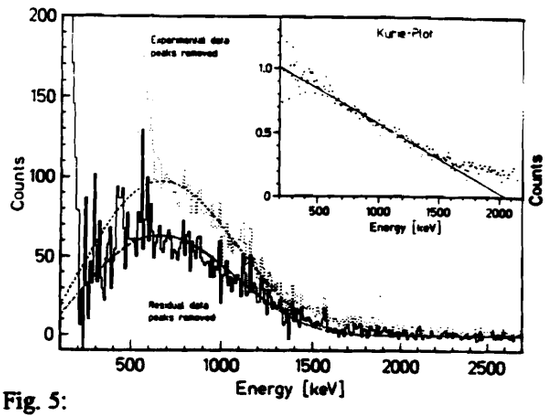
Deduced $0\nu\beta\beta$ half-life limit for ^{76}Ge as function of measuring time in the HEIDELBERG-MOSCOW experiment (from [22]).

2ν-decay: For $2\nu\beta\beta$ decay subtraction of the background contributions from cosmogenically produced isotopes, natural decay chains, ^{210}Pb etc. from the spectrum measured with the second detector in 527 kgd yields [14] the spectrum shown in Fig. 5 and $T_{1/2}^{2\nu}(0^+ \rightarrow 0^+) = (1.42 \pm 0.03(stat) \pm 0.13(syst))10^{21}$ y. This is probably the first undoubtable evidence for this up to now rarest nuclear decay mode.

0νχ-decay: For Majoron-accompanied, $0_{\nu\chi}$, ββ decay, subtraction of the 2ν-spectrum from Fig. 5 leads to the spectrum of Fig. 6 and an upper limit $T_{1/2}^{0\nu\chi} > 1.7 \times 10^{22}$ y (90% c.l.) and for the neutrino-majoron coupling constant to $< g_{\nu\chi} > < 1.8 \times 10^{-4}$ (90% c.l.) [15] thus excluding some recently discussed [16] indication of this decay mode.

e⁻-decay: As a by-product of the ββ-experiment we obtain [17] for the decay mode $e^- \rightarrow \gamma + \nu_e$ $T_{1/2} > 1.63 \times 10^{25}$ y (68% c.l.) which is the sharpest laboratory limit existing.

In total we hope to have 12 kg of enriched detectors in operation in the Gran Sasso by end of 1994. These would correspond to a non-enriched Ge experiment of at least 1.2 tons. In five years of measurement we could probe the neutrino mass down to ~ 0.1 eV.



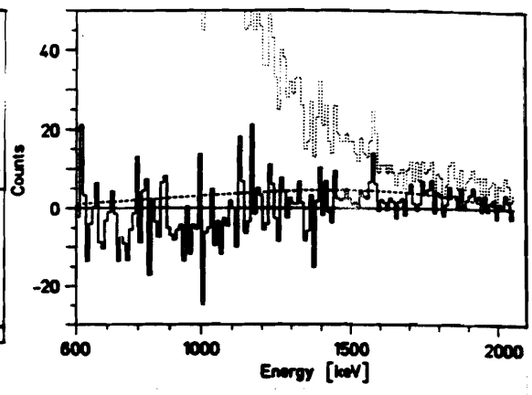


Fig. 5:

Measured spectrum after 527 kg d (dotted curve, lines cut out) with the second detector, the resulting spectrum after subtraction (see [14]) of the background (solid histogram), and a fitted 2ν spectrum with $T_{1/2}^{2\nu} = 1.42 \times 10^{21}$ y (lower dashed-dotted curve). The dashed curve corresponds to a half-life of 0.9 times 10^{21} y claimed by [24].

Fig. 6:

Spectrum remaining after subtraction of the 2ν spectrum from the solid histogram of Fig. 5, together with a calculated 0νχ-spectrum with $T_{1/2}^{0\nu\chi} = 1.66 \times 10^{22}$ y (dashed curve). Also shown is the measured spectrum (dotted histogram).

3. CALCULATION OF ββ MATRIX ELEMENTS, OEM

The method of OEM (Operator Expansion Method) [10,11] does not explicitly use the intermediate energy spectrum. This is the essential advantage over QRPA, since in this way the dependence on the pp force (which affects the distribution of β strength in the intermediate nucleus) is drastically reduced.

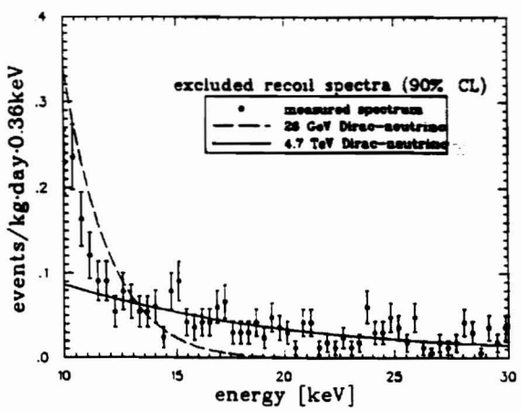
In OEM the matrix element involves the bare nucleon-nucleon interaction without any adjustable parameter. The wave functions of initial and final states we take from QRPA. The results obtained for ^{238}U of $T_{1/2}^{2\nu,calc} = 0.9 \times 10^{21}$ y shows that the far-reaching conclusions drawn [18] from a recent experimental result seem not to be on stable grounds.

4. APPLICATION OF ββ-TECHNOLOGY TO DARK MATTER SEARCH AND γ-LINE ASTROPHYSICS

The results of the HEIDELBERG-MOSCOW experiment show for the first time that the technology of production of enriched HP Ge detectors can be handled. This has promising consequences for dark matter search and galactic γ-spectroscopy satellite missions (see [3,19-21]). Enriched ^{76}Ge and ^{73}Ge detectors would allow to improve the LEP limits on Dirac- and Majorana WIMPs (weakly interacting massive particles). Use

of enriched ^{70}Ge detectors in the ESA project INTEGRAL (International Gamma Ray Astrophysics Laboratory) would allow to reduce the β-background dominating in orbit, by an order of magnitude [20]. This has recently been checked in balloon flights [21]. The INTEGRAL satellite mission aims at the study of a variety of astrophysical questions by high resolution γ-spectroscopy.

The HEIDELBERG-MOSCOW experiment allowed for the first time a search for dark matter with isotopically enriched material. Data taken with a 2.9 kg detector in 166 kgd were used to set limits on spin-independently interacting WIMPs. A background level of 0.102 ± 0.005 events/ kg · d · keV was achieved (average value between 11 and 30 keV), which is better by a factor of 5-7 than in other dedicated dark matter experiments with Ge detectors (Fig. 7). The existing cross section limits for WIMP masses above ~ 150 GeV were improved (Fig. 8) and Dirac neutrinos could be excluded as the dominant component of the dark halo in the mass range 26 GeV to 4.7 TeV [22].



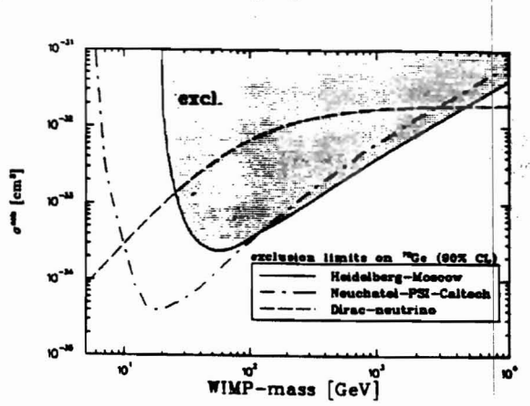


Fig. 7:

Low energy spectrum of the second enriched detector corresponding to a measuring time of 165.6 kgd. The background counting rate in the energy range 11-30 keV is 0.102 ± 0.005 events/kg d keV. Also shown are the expected recoil spectra of Dirac neutrinos with 26 GeV (dashed line) and 4.7 TeV (solid line) (from [22]).

Fig. 8:

Exclusion limits for elastic scattering cross sections of WIMPs on ^{76}Ge from the HEIDELBERG-MOSCOW experiment (solid line), compared with the best result obtained with a natural Ge detector [23] (dashed-dotted line). WIMPs of a given mass with cross sections σ^{coh} beyond the lines are excluded. The expected cross section for Dirac neutrinos with standard weak coupling is shown as a dashed line.

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