

Limits on the Majorana Neutrino Mass in the 0.1 eV Range

L. Baudis, A. Dietz, G. Heusser, H. V. Klapdor-Kleingrothaus,* I. V. Krivosheina,† St. Kolb, B. Majorovits, V. F. Melnikov,‡ H. Päs, F. Schwamm, and H. Strecker

Max-Planck-Institut für Kernphysik, P.O. Box 10 39 80, D-69029 Heidelberg, Germany

V. Alexeev, A. Balysh, A. Bakalyarov, S. T. Belyaev,* V. I. Lebedev, and S. Zhukov

Russian Science Centre, Kurchatov Institute, 123 182 Moscow, Russia

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The Heidelberg-Moscow experiment gives the most stringent limit on the Majorana neutrino mass. After 24 kg yr of data with pulse shape measurements, we set a lower limit on the half-life of the $0\nu\beta\beta$ decay in ^{76}Ge of $T_{1/2}^{0\nu} \geq 5.7 \times 10^{25}$ yr at 90% C.L. (after PDG98 [C. Caso *et al.*, *Eur. Phys. J.* **C3**, 1 (1998)], the sensitivity of the experiment being $T_{1/2}^{0\nu} \geq 1.6 \times 10^{25}$ yr at 90% C.L. We thus exclude an effective Majorana neutrino mass greater than 0.2 eV (0.39 eV sensitivity), using the matrix elements of A. Staudt, K. Muto, and H. V. Klapdor-Kleingrothaus, *Europhys. Lett.* **13**, 31 (1990). This limit sets strong constraints on degenerate neutrino mass models.

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Neutrinoless double beta ($0\nu\beta\beta$) decay is an extremely sensitive tool to probe theories beyond the standard model (see [1]). While the standard model exactly conserves $B - L$, $0\nu\beta\beta$ decay violates lepton number, and $B - L$, by two units. The simplest mechanism which can induce $0\nu\beta\beta$ decay is the exchange of a Majorana neutrino between the decaying neutrons. Alternatively, any theory that contains lepton number violating interactions can lead to the process. Independently of the underlying mechanism, an observation of the $0\nu\beta\beta$ decay would be an evidence for a nonzero Majorana neutrino mass [2]. There are several indications for nonzero neutrino masses, the most stringent ones come from solar and atmospheric neutrino experiments. In particular, the confirmation by Super-Kamiokande of the atmospheric neutrino deficit [3] provides strong evidence for neutrino oscillations, although also other solutions are possible [4]. If a neutrino as a hot dark matter (HDM) component is taken into account, then fitting the atmospheric, solar, and HDM scales with three neutrinos is possible only in the degenerate mass scenario, where all neutrinos have nearly the same mass, of the order of $\mathcal{O}(\text{eV})$ [5]. This would lead to an amplitude for $0\nu\beta\beta$ decay mediated by the neutrino mass which is accessible by the present sensitivity of the Heidelberg-Moscow experiment.

The Heidelberg-Moscow experiment operates five p -type HPGe detectors in the Gran Sasso Underground Laboratory. The Ge crystals were grown out of 19.2 kg of 86% enriched ^{76}Ge material. The total active mass of the detectors is 10.96 kg, corresponding to 125.5 mol of ^{76}Ge , presently the largest source strength of all double beta experiments. Four detectors are placed in a common 30 cm thick lead shielding in a radon-free nitrogen atmosphere, surrounded by 10 cm of boron-loaded polyethylene and with two layers of 1 cm thick scintillators on top. The remaining detector is situated in a separate box

with 27 cm electrolytical copper and 20 cm lead shielding, flushed with gaseous nitrogen and with 10 cm of boron-loaded polyethylene below the box. A detailed description of the experiment and its background is given in [6]. For a further reduction of the already very low background of the experiment, a pulse shape analysis (PSA) method was developed [7]. The analysis distinguishes between multiple scattered interaction in the Ge crystal, so called multiple site events (MSE), and pointlike interactions, i.e., single site events (SSE). Since double beta decay events belong to the SSE category, the method allows one to effectively reduce the background of multiple Compton scattered photons. The probability of correct detection for a SSE is 75%, and 74% for a MSE [7].

Figure 1 shows the total spectrum of the five enriched detectors of the Heidelberg-Moscow experiment, with a statistical significance of 41.55 kg yr. Because of the good energy resolution of the detectors, the γ activities can be easily identified via their specific lines. The neutron background can be estimated from measurements with and without the neutron shielding, while the effect of muons can be deduced from the scintillator measurements in coincidence with Ge detectors. In the region of interest for the $0\nu\beta\beta$ decay in ^{76}Ge (Q value = 2038.56 ± 0.32 keV [8]) the dominant background originates from the Compton continuum of the ^{208}Tl line (2615 keV), the summed ^{60}Co line (2506 keV), and some ^{214}Bi lines (2119, 2204, 2248, and 2293 keV) (all together about 60% of the total background), from neutron-induced (about 30%) and muon-induced (about 10%) events.

For the evaluation of the $0\nu\beta\beta$ decay we consider both data sets, with and without pulse shape analysis. We see in none of them an indication for a peak at the Q value of the $0\nu\beta\beta$ decay. The total spectrum of the five detectors with a statistical significance of 41.55 kg yr contains all the data with the exception of the first 200 d

of measurement of each detector. The interpolated energy resolution at the energy of the hypothetical $0\nu\beta\beta$ peak is 3.85 ± 0.16 keV. To estimate the expected background in the $0\nu\beta\beta$ region, we take the energy interval from 2000 to 2080 keV. The expected background in the 3σ peak interval, centered at 2038.56 keV, is 78 ± 3 events, whereas the number of measured events in the same peak region is 68. This number is below the expectation and might be due to peaks in the background interval, which are however too weak to be identified. To extract a half-life limit for the $0\nu\beta\beta$ decay we make the assumption, as recommended by [9], that the number of measured events equals the background expectation. With the achieved energy resolution, the number of excluded events in the 3σ peak region is 15.9 (9.52) with 90% C.L. (68% C.L.), resulting in a half-life limit of (for the $0^+ \rightarrow 0^+$ transition)

$$\begin{aligned} T_{1/2}^{0\nu} &\geq 1.3 \times 10^{25} \text{ yr}, & 90\% \text{ C.L.} \\ T_{1/2}^{0\nu} &\geq 2.1 \times 10^{25} \text{ yr}, & 68\% \text{ C.L.} \end{aligned}$$

We consider now the data with pulse shape measurements, with a statistical significance of 24.16 kg yr and an energy resolution at 2038.56 keV of 4.2 ± 0.17 keV. The expected number of events from the background left and right of the peak is 13 ± 1 events, the measured number of events in the 3σ peak region is 7. Considering again the number of expected events instead of the number of measured ones [9], we can exclude 7.17 (4.71) events with 90% C.L. (68% C.L.). The limit on the half-life is

$$\begin{aligned} T_{1/2}^{0\nu} &\geq 1.6 \times 10^{25} \text{ yr}, & 90\% \text{ C.L.} \\ T_{1/2}^{0\nu} &\geq 2.8 \times 10^{25} \text{ yr}, & 68\% \text{ C.L.} \end{aligned}$$

Obviously the pulse shape data are now not only competitive with the complete data set, but they deliver more stringent lower limits on the half-life of the $0\nu\beta\beta$ decay. The pulse shape analysis reduces the background in the interesting energy region by a factor of 3 [background in-

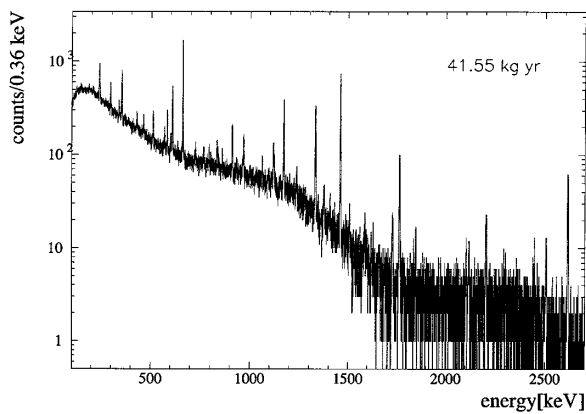


FIG. 1. Sum spectrum of all detectors of the Heidelberg-Moscow experiment with 41.55 kg yr for the energy region between 100 and 2700 keV.

dex without PSA: (0.18 ± 0.02) events/(kg yr keV), with PSA: (0.06 ± 0.02) events/(kg yr keV)]. This reduction factor is due to the large fraction of multiple Compton scattered events in the $0\nu\beta\beta$ decay region.

Figure 2 shows the combined spectrum of the five detectors after 41.55 kg yr and the SSE spectrum, corrected for the detection efficiency, after 24.16 kg yr. The solid lines represent the exclusion limits for the two spectra at the 90% C.L.

In addition we report the limits obtained by evaluating the SSE data with the new method proposed by the Particle Data Group 98 [10]. The number of excluded events for an observation of seven events and a background expectation of 13 is 2.07 (0.47) with 90% C.L. (68% C.L.) (see Tables III and V in [11]). The resulting upper limits for the half-life of the $0\nu\beta\beta$ decay are the following:

$$\begin{aligned} T_{1/2}^{0\nu} &\geq 5.7 \times 10^{25} \text{ yr}, & 90\% \text{ C.L.} \\ T_{1/2}^{0\nu} &\geq 2.5 \times 10^{26} \text{ yr}, & 68\% \text{ C.L.} \end{aligned}$$

The sensitivity of the experiment, as defined in [11], is again obtained by setting the measured number of events equal to the expected background. With 7.51 (4.71) excluded events at 90% C.L. (68% C.L.), the half-life limit is

$$\begin{aligned} T_{1/2}^{0\nu} &\geq 1.6 \times 10^{25} \text{ yr}, & 90\% \text{ C.L.} \\ T_{1/2}^{0\nu} &\geq 2.5 \times 10^{25} \text{ yr}, & 68\% \text{ C.L.} \end{aligned}$$

Figure 3 shows the SSE spectrum and the excluded peaks (upper limit and sensitivity) with 90% C.L.

Using the matrix elements of [12] and neglecting right-handed currents, we can convert the lower half-life limit into an upper limit on the effective Majorana neutrino mass. The obtained limits are shown in Table I. The Heidelberg-Moscow experiment is thus, at present, giving the most stringent upper limit on the Majorana neutrino

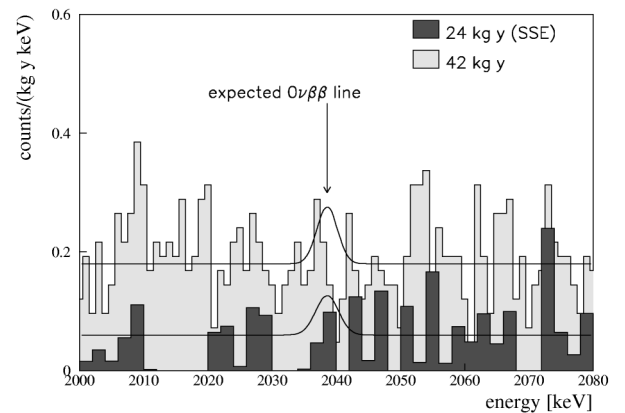


FIG. 2. Sum spectrum of all five detectors with 41.55 kg yr and SSE spectrum with 24.16 kg yr in the region of interest for the $0\nu\beta\beta$ decay. The curves correspond to the excluded signals with $T_{1/2}^{0\nu} \geq 1.3 \times 10^{25}$ yr (90% C.L.) and $T_{1/2}^{0\nu} \geq 1.6 \times 10^{25}$ yr (90% C.L.)

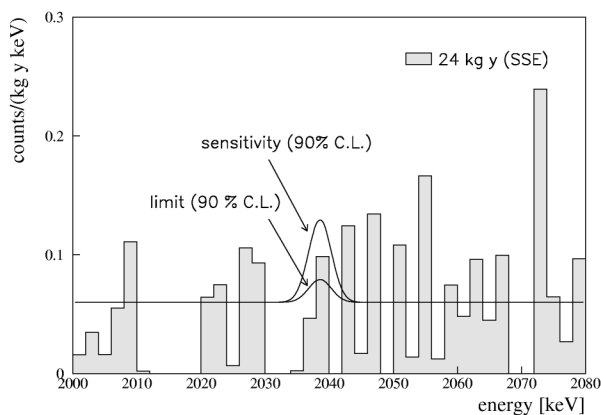


FIG. 3. SSE spectrum after 24.16 kg yr and the corresponding excluded signal and sensitivity of the experiment, at 90% C.L. after [10].

mass, of 0.2 eV at 90% C.L. (0.1 eV at 68% C.L.) (after PDG98 [10]). The sensitivity of the experiment is 0.38 eV at 90% C.L. [10]. This is equal to the limit obtained with the method proposed by PDG96 [9] (see Table I).

Table II gives a list of the limits from the presently most sensitive experiments on double beta decay and a comparison between different matrix element calculations. It should be mentioned that the calculations of [22] do not use a realistic nucleon-nucleon force, those of [21] use too small a configuration space (leaving out the important spin-orbit partners), and the recent calculation of [24] does not fulfill the Ikeda sum rule. This favors the matrix elements of [12,23] (for a discussion, see also [1]). Some further confidence in the matrix elements of [12] might be derived from the fact that the $2\nu\beta\beta$ decay half-life of ^{76}Ge [27] has been predicted correctly [28] within a factor of 2 (the $2\nu\beta\beta$ decay matrix element within $\sqrt{2}$).

The limit on the effective Majorana neutrino mass given by the Heidelberg-Moscow experiment is about an order of magnitude lower than for other double beta experiments. This is the result of the high source strength, good energy resolution, high material purities combined with the efficiency of the pulse shape analysis, and, last, but not least, the excellent long-term stability of the experiment.

TABLE I. Limits on the effective Majorana neutrino mass from the $0\nu\beta\beta$ decay of ^{76}Ge for the matrix elements from [12].

	$T_{1/2}^{0\nu}$ (yr)	$\langle m \rangle$ (eV)	C.L. (%)
Full data set	$\geq 1.3 \times 10^{25}$	≤ 0.43	90
	$\geq 2.1 \times 10^{25}$	≤ 0.33	68
SSE data after [9]	$\geq 1.6 \times 10^{25}$	≤ 0.38	90
	$\geq 2.8 \times 10^{25}$	≤ 0.29	68
SSE data after [10]	$\geq 5.7 \times 10^{25}$	≤ 0.20	90
	$\geq 2.5 \times 10^{26}$	≤ 0.10	68
Sensitivity	$\geq 1.6 \times 10^{25}$	≤ 0.38	90
	$\geq 2.5 \times 10^{25}$	≤ 0.30	68

After about another five years of measurement, assuming no other improvement in the present background index, the Heidelberg-Moscow experiment will be able to explore the half-life of the $0\nu\beta\beta$ decay up to some 10^{26} yr in the best case. For a significant improvement of the experimental sensitivity, a much lower background counting rate and a higher source strength are required.

A major step forward in this field would bring the new project proposed by our group, GENIUS (Germanium in liquid Nitrogen underground setup) [1,29], which would operate enriched Ge crystals directly in liquid nitrogen. The goal is to reduce the background by about 3 orders of magnitude by removing essentially all materials from the vicinity of the measurement crystals. It was shown that Ge detectors work reliably in liquid nitrogen [29,30], also detailed Monte Carlo simulations of the various expected background components [30] confirm the possibility of obtaining a counting rate of 0.3 events/(ton yr keV) in the $0\nu\beta\beta$ region. GENIUS is conceived to test the neutrino mass down to the level of 0.01 eV and lower.

In conclusion, already in the present stage, the Heidelberg-Moscow experiment is setting the most stringent limit on the Majorana neutrino mass and is testing the predictions of degenerate neutrino mass models. For example, in models which try to accommodate the solar

TABLE II. Limits on the half-lives of the $0\nu\beta\beta$ decay and on the effective Majorana neutrino mass for different matrix element calculations for the best existing experiments with half-life limits $>10^{21}$ yr.

Isotope	$T_{1/2}^{0\nu}$ (yr)	C.L. (%)	$\langle m \rangle$ (eV)
^{48}Ca	$\geq 9.5 \times 10^{21}$	76 [13]	≤ 13 [12]
^{76}Ge limit	$\geq 5.7 \times 10^{25}$	90	≤ 0.20 [12], 0.56 [21], 0.52 [22], 0.19 [23], 0.4 eV [24], 0.17 eV [25], 0.22 eV [26]
^{76}Ge sensitivity	$\geq 1.6 \times 10^{25}$	90	≤ 0.38 [12], 1.07 [21], 0.93 [22], 0.36 [23], 0.77 [24], 0.32 eV [25], 0.41 eV [26]
^{82}Se	$\geq 9.5 \times 10^{21}$	90 [14]	≤ 7.9 [12], 15.7 [21], 24 [22], 8 [23], 7.8 eV [25], 8.6 eV [26]
	$\geq 2.7 \times 10^{22}$	68 [15]	≤ 4.7 [12], 9.4 [21], 14.4 [22], 4.75 [23], 4.6 eV [25], 5.1 eV [26]
^{100}Mo	$\geq 5.2 \times 10^{22}$	68 [16]	≤ 4.9 [12], 4.34 [22], 2.2 [23], 2.2 [24]
^{116}Cd	$\geq 3.2 \times 10^{22}$	90 [17]	≤ 3.9 [12], 4.26 eV [26]
^{130}Te	$\geq 5.6 \times 10^{22}$	90 [18]	≤ 2.9 [12], 3.43 [22], 3.1 [23], 2.88 [24], 1.69 [25], 3.59 [26]
			≤ 2.2 [12], 5.2 [21], 2.7 [22], 1.8 [23], 3.12 [26]
^{136}Xe	$\geq 4.4 \times 10^{23}$	90 [19]	≤ 2.2 [12], 5.2 [21], 2.7 [22], 1.8 [23], 3.12 [26]
^{150}Nd	$\geq 1.22 \times 10^{21}$	90 [20]	≤ 5.2 [12], 6.7 [26]

and atmospheric neutrino problems while considering the neutrino as a hot dark matter candidate with a mass of a few eV, the small angle Mikheyev, Smirnov, Wolfenstein (MSW) solution is practically ruled out [31]. For the large angle MSW solution, an effective Majorana neutrino mass smaller than 0.2 eV would need an unnatural fine-tuning to account for a relevant neutrino mass in a mixed hot and cold dark matter cosmology [32].

This, as well as other implications for physics beyond the standard model, such as left-right symmetric models, supersymmetry, leptoquarks, and compositeness will be discussed in detail elsewhere.

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*Author to whom correspondence should be addressed.

†On leave from the Radiophysical Research Institute (NIRFI), Nishnij Novgorod, Russia.

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