Available online at www.sciencedirect.com
ScienceDirect
PHYSICS LETTERS B
Physics Letters B 644 (2007) 109–118
www.elsevier.com/locate/physletb

A new experimental limit for the stability of the electron

H.V. Klapdor-Kleingrothaus [*,1], I.V. Krivosheina [2], I.V. Titkova [3]

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany

Received 4 July 2006; received in revised form 9 November 2006; accepted 13 November 2006

Available online 27 November 2006

Editor: V. Metag

Abstract

A lower limit of $> 1.22 \times 10^{26}$ yr (68% c.l.) has been determined for the mean life time of electron decay via the branch $e^- \to \gamma + \nu_e$. The limit was deduced from the spectra measured in the period 1995–2003 with the full set-up of 5 enriched ^{76}Ge detectors of the Heidelberg–Moscow $\beta\beta$ experiment in the Gran Sasso underground laboratory. One of the detectors, and the setup 1 consisting of four detectors show an indication of a signal on a 1.4σ C.L. The best limit given by a single detector is 1.93×10^{26} yr. The result is the by far sharpest limit obtained with Ge detectors. When comparing it with other limits, e.g. that from Borexino [H.O. Back, et al., Phys. Lett. B 525 (2002) 29] it may be essential to note that the present limit has been deduced from the raw data without any treatment of the background, and also, that the energy resolution in the present experiment is much larger than in the other most sensitive experiments. Combined with the best laboratory limit on the photon mass the present result gives the following restriction for *charge nonconservation*: $\epsilon_{e\nu\gamma} < 0.86 \times 10^{-98}$ (68% c.l.) or $< 1.14 \times 10^{-97}$ (90% c.l.).

PACS: 13.35.-r; 13.40.Hq; 14.60.Cd; 11.30.-j; 29.40.Wk

Keywords: Stability of the electron; Charge nonconservation; Heidelberg–Moscow experiment; High purity Ge detectors

1. Introduction

The standard model of elementary particle physics is in excellent agreement with all experimental results obtained with accelerators. Looking for physics beyond the standard model the search for rare events in testing fundamental laws of physics have been shown to be rather promising (see, e.g. [1–3]). One of the possible tests is that of charge conservation. In the context of gauge field theories, the invariance of the Lagrangian under a given gauge transformation corresponds to the conservation of some specific type of charge. In some grand unified theories, for example, terms appear in the Lagrangian which break the global gauge invariance associated with baryonic charge leading to proton decay at some level. In the electroweak sector the local gauge invariance of the Lagrangian corresponding to the equations of quantum electrodynamics dictates strict electric charge conservation and a massless photon. According to this class of theories we do not expect electrons to decay, because there is no lighter charged lepton, and the decay into photons and/or neutrinos requires the violation of charge conservation. No conservation of the electric charge will only be possible if the Lagrangian of QED contains terms which destroy global as well as local gauge invariance.

There are two possible ways of observing the electron decay in Ge semiconductor detectors: the search for the 255.5 keV γ-rays coming from the decay $e^- \to \nu_e + \gamma$, and looking for the decay $e^- \to \nu_e + \nu_e + \bar{\nu}_e$. The second decay mode creates K-shell X-rays which are, even with a very low-background large detector, difficult to measure. Thus we searched for the decay mode $e^- \to \nu_e + \gamma$ using the data collected in the period 1995–2003 (56.66 kg yr) by the enriched germanium detectors of the Heidelberg–Moscow $\beta\beta$ experiment [1–3]. Ear-

* Corresponding author. Tel.: +49 (0)6221 516 262; fax: +49 (0)6221 516 540.
E-mail address: h.klapdor@mpi-hd.mpg.de (H.V. Klapdor-Kleingrothaus).
URL: http://www.mpi-hd.mpg.de.non_acc/.
[1] Spokesman of Heidelberg–Moscow, GENIUS-TF and HDMS Collaborations.
[2] On leave from Radiophysical-Research Institute, Nishnii-Novgorod, Russia.
[3] On leave from JINR, Dubna, Russia.

0370-2693/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.physletb.2006.11.013

Table 1
The present limits for the mean life time τ (till 2006) for the electron decay for the decay mode $e^- \to \nu_e + \gamma$. Presented are all experiments from 1959 which measured this mode. The energy resolution is given for the case without and with Doppler-broadening in keV. Indicated is also the structure of the analysed data—raw data or after background subtraction

Type of the detector	Mass (kg)	Resolution (keV)	Backgr. (keV kg yr)$^{-1}$	Raw data	Limits τ (yr) (c.l.) mode: $e^- \to \nu_e + \gamma$	Ref., Year
NaI	5	–	–	–	$> 1.0 \times 10^{19}$ (68%)	[4], 1959
NaI	1.4	44 (–)	~ 21020	No	$> 4.0 \times 10^{22}$ (68%)	[5], 1965
NaI	6	43 (–)	$\sim 3 \times 10^5$	Yes	$> 3.5 \times 10^{23}$ (68%)	[6], 1979
Ge (Li)	0.69	~ 1.5	1500	Yes	$> 3 \times 10^{23}$ (68%)	[17], 1983
HPGe	0.71	1.9 (5.13)	240	Yes	$> 1.5 \times 10^{25}$ (68%)	[7], 1986
HPGe	3.1	2.5 (7.6)	25.8	Yes	$> 2.4 \times 10^{25}$ (68%)	[8], 1993
HPGe	2.2	1.8 (5.3)	10–80	Yes	$> 3.7 \times 10^{25}$ (68%)	[9], 1995
LXe (DAMA)	6.5	–	–	Yes	$> 1.0 \times 10^{25}$ (90%)	[23], 1996
LXe (DAMA)	6.5	78 (80)	0.04	Yes	$> 3.4 \times 10^{26}$ (68%)	[24], 2000
CTF ($C_{16}H_{18}$) (Borexino)	4170	72 (–)	0.06	No	$> 4.6 \times 10^{26}$ (90%)	[10], 2002
HPGeII	10.96	2.3 (7.7)	25	Yes	$> 1.93 \times 10^{26}$ (68%)	This work, 2006

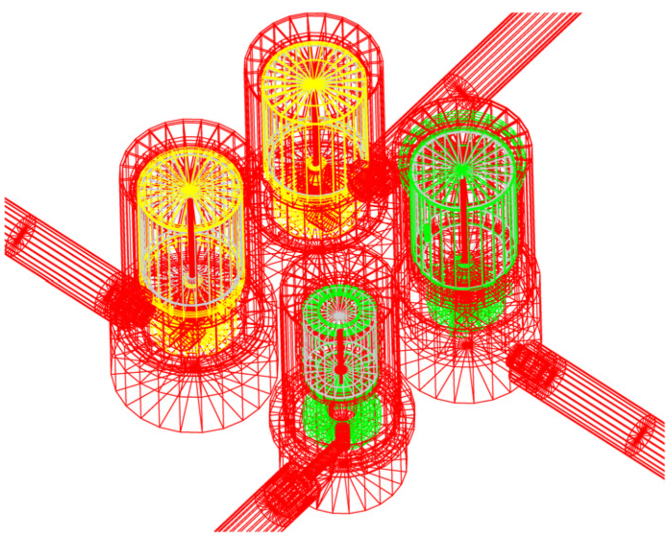


Fig. 1. Geometry of the setup 1 of the Heidelberg–Moscow experiment, containing four of five enriched detectors (detectors 1, 2, 3, 5). The germanium detectors (grey) are mounted in copper cryostats (red). The detector holder system consists of teflon (green) and vespel (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

lier searches for electron decay have been performed with NaI detectors [4–6], Ge detectors [17,7–9], liquid Xe [23,24] and $C_{16}H_{18}$ [10], yielding lower half-life limits in the range 10^{23}–10^{26} yr (see Table 1).

The sharpest limit is given according to Table 1 by Borexino [10]. However, in deduction of the life time limit from the Borexino data some major uncertainties may have entered into the analysis, since 1. The background whose origin seems not to be fully known has been parameterized by six parameters—and it has to be assumed to behave linearly down to low energies 2. Strong and perhaps not unique cuts have been applied to reduce the contamination of the spectrum in the range of interest by betas and gammas from ^{40}K and from ^{14}C 3. It is not clear that threshold effects on the spectrum in the range of interest are really excluded 4. There do not exist direct measurements of the dependence between light yield of the electrons and their energy for the scintillator used in Borexino 5. The energy resolution in the Borexino experiment is by a factor of 30 worse than that of the present Ge experiment. These points may make it useful to have an independent experiment, as presented in this Letter, not suffering from all these potential drawbacks.

Table 2
Main parameters of the ^{76}Ge detectors in the Heidelberg–Moscow experiment (November 1995 till May 2003)

	ANG1	ANG2	ANG3	ANG4	ANG5
Active mass, kg	0.920	2.657	2.324	2.295	2.666
Measurement times, days	2090.61	1894.11	2079.46	1384.69	2076.34
^{76}Ge content, %	85.9	86.6	88.3	86.3	85.6

2. Experimental setup

The search for the rare electron decay requires a detector with ultralow background, not to loose the expected weak signal of the expected ~ 255.5 keV γ-line of the decay in the background radiation. The enriched germanium detectors of the Heidelberg–Moscow $\beta\beta$ experiment [11,13,1,2] which has been used for search for neutrinoless double-beta decay give such possibility as byproduct.

The experiment operated in the Gran Sasso underground laboratory five p-type high-purity enriched ^{76}Ge detectors (Fig. 1) with total active mass of 10.96 kg, corresponding to 125.5 mol of ^{76}Ge in the period August 1990–November 2003. The experiment and its shielding have been described in detail in [12,13,1–3,14], to which we refer for experimental details.

For the analysis with respect to electron decay we use the data taken in the period November 1995 till May 2003 (see Table 2).

3. Data analysis and results

The idea of the present work is to search for γ rays with ~ 255.5 keV energy which could accompany the possible de-

Table 3
Detection efficiencies for germanium and copper for both setups

	Detector	P_{Ge}, %	P_{Cu}, %
Setup 1	ANG1	30.824	–
	ANG2	63.548	4.620
	ANG3	61.514	–
	ANG5	64.439	6.940
	Full setup 1	55.471	–
Setup 2	ANG4	60.862	–
Full setup: (setup 1 + setup 2):		58. 166	–

Table 4
Numbers of atoms and Doppler-broadened FWHM for all detectors

		Number of atoms:		**FWHM, keV:**	
	Detectors	Ge	Cu	ME case	AE case
Setup 1	ANG1	0.730×10^{25}	4.562×10^{25}	7.83	9.67
	ANG2	2.231×10^{25}	8.966×10^{25}	7.70	9.47
	ANG3	1.844×10^{25}	7.523×10^{25}	7.67	9.57
	ANG5	2.116×10^{25}	7.252×10^{25}	7.63	9.37
	Full setup 1	6.921×10^{25}	2.830×10^{26}	7.7	9.5
Setup 2	ANG4	1.821×10^{25}	8.371×10^{25}	7.73	9.5
Full setup: (setup 1 + setup 2):		8.742×10^{25}	3.667×10^{26}	7.70	9.47

cay of any electron in germanium and in its surroundings, by analyzing the spectra collected during the measurement time with these detectors (see Table 2). The exact value of the total energy deposited in the detector depends on the place where the electron decay occurs. If it happens outside the sensitive volume of the detector the deposited energy is simply equal to the energy released by the photon: $E_t = \frac{m_e c^2 - E_b}{2}$, where $m_e c^2$ keV is the electron mass and E_b is the binding energy of the decaying electron in the corresponding atomic shell. If the electron decay occurs in the sensitive volume of the detector, the energy deposited in the detector is a sum of the photon energy E_γ and of the energy released by the X-rays or Auger electrons following the atomic deexcitation (with total energy of E_b): $E_t = \frac{m_e c^2 - E_b}{2} + E_b = \frac{m_e c^2 + E_b}{2}$. Data for binding energies are taken from [15]. To obtain the lower limit for the mean life time τ of the electron decay we write

$$\tau \geqslant \frac{t}{\lambda} \cdot (P_{\mathrm{Cu}} N_{\mathrm{Cu}} + P_{\mathrm{Ge}} N_{\mathrm{Ge}}), \tag{1}$$

where $N_{\mathrm{Cu,Ge}}$ are the number of electrons in the copper cryostat and germanium detector, respectively, $P_{\mathrm{Cu,Ge}}$ are the detection efficiencies for the 255.5 keV γ-ray and t is the measuring time. The efficiencies were calculated with the aid of the GEANT4 program [16]. For ANG2 and ANG5 $P_{\mathrm{Cu,Ge}}$ were calculated and used for the mean life time determination, for ANG1, ANG3, ANG4 and the full setup (all five detectors) only P_{Ge} was used for the half-life limit calculations (see Table 3). The quantity λ is the maximum number of electron decay events that can be excluded at the peak position.

To obtain the value λ one has to take into account the Doppler broadening (first mentioned by [17]), resulting from the average kinetic energy of the electrons in their orbital motion [7–9,24], or—in the language of atomic and solid state physics—being due to the Compton profile of the bound electrons, i.e. their linear moments [26]. This effect is not negligible, for instance, for Ge K-shell electrons a Gaussian line centered at 261.05 keV with width (full width at half maximum (FWHM)) equaling 91.37 keV will be expected, for copper the values are 251.01 keV and 79.01 keV, respectively. On the other hand for Ge M5-shell electrons a Gaussian line centered at 255.51 keV with FWHM 4.59 keV is expected. The lines expected from different atomic shells for germanium and copper atoms are presented in Fig. 2.

The Doppler broadening is calculated here (following [7–9, 24]) under the assumption that the electrons have a temperature corresponding to the expectation value of the kinetic energy in a given energy level, and that the virial theorem $\langle E_{\mathrm{kin}} \rangle = -\frac{1}{2}\langle E_{\mathrm{pot}} \rangle$, is fulfilled. The Doppler line shape is then given by,

$$I(E) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(E - E_t)^2}{2\sigma^2}\right], \tag{2}$$

with $\sigma = E_t \sqrt{\frac{kT}{m_e c^2}}$, where k is Boltzmann's constant, T is the absolute electron temperature. This can be expressed in terms of the absolute binding energy of the electron, $\sigma = 4.47 \times 10^{-2} E_t \sqrt{E_b(\mathrm{keV})}$. The full line shape can be expressed as

$$I(E) = \sum_{\mathrm{Cu},i} \frac{n_i}{\sqrt{2\pi}\sigma_i} \exp\left[-\frac{(E - E_{t,i})^2}{2\sigma^2}\right] \cdot N_{\mathrm{at}}(\mathrm{Cu}) + \sum_{\mathrm{Ge},i} \frac{n_i}{\sqrt{2\pi}\sigma_i} \exp\left[-\frac{(E - E_{t,i})^2}{2\sigma^2}\right] \cdot N_{\mathrm{at}}(\mathrm{Ge}) \tag{3}$$

with $\sigma_i = 4.47 \times 10^{-2} E_{t,i} \sqrt{E_{b,i}(\mathrm{keV})}$, where n_i is the fraction of electrons, the index i runs over the used atomic shells. The number of atoms (N_{at}) for germanium and copper are presented in Table 4.

We have done two types of analysis: at first we took into account only M-shell electrons for the copper and germanium (ME case), in the second analysis we used all shell electrons (AE case). The overall FWHM's for all detectors arising from Doppler broadening are presented in Table 4 for the ME and AE cases. The expected lines for one detector are shown in Fig. 3. The situation is very similar for the other detectors. The effect of the *intrinsic* resolution of the detectors is negligible within a few percent, and has been neglected.

The measured spectra (after calibration) for all detectors separately, for setup 1 and for the full setup are presented in Figs. 4, 5. The calibration was done by using known background lines in that energy range from ^{212,214}Pb. The typical energy resolution is about 2.1 keV.

3.1. *Determination of limits for electron decay events*

3.1.1. *One sigma approach*

The maximum number of electron decay events has been determined in three ways. First, it has been evaluated by using the so-called 'one sigma approach' in which the excluded number of events due to the effect searched for is estimated

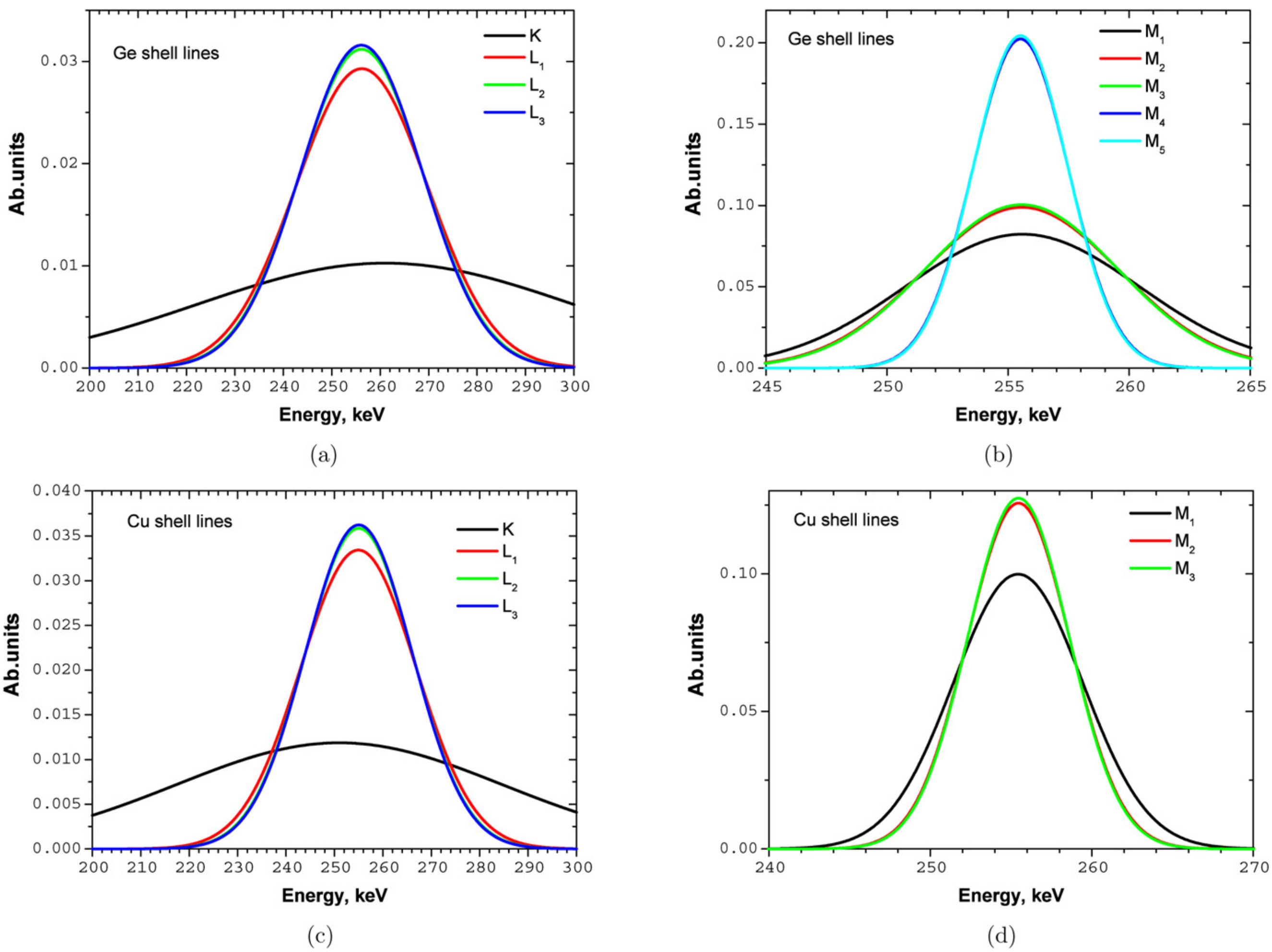


Fig. 2. Lines expected from decay of electrons in different atomic shells for germanium and copper atoms.

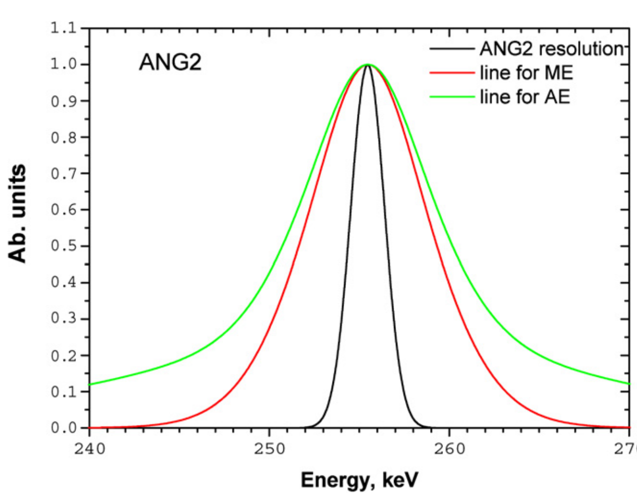


Fig. 3. The expected line shape at 255.5 keV when only M-shell/all shell electrons are taken into account. The black curve shows for comparison the detector resolution without Doppler broadening.

simply as the square root of the number of background counts in a suitably chosen energy window ΔE (see, for example [18]). This method, inspite of its simplicity, gives the right scale of the sensitivity of the experiment. For example, for ANG2 3045 and 3684 counts are present in the spectrum of Fig. 4 within the maximal sensitivity intervals 250.161–260.957 keV (for the ME case) and 248.768–262.002 keV (for the AE case) which contain 90% of the expected peak; thus, the square root estimated gives $\lambda < 61.31/67.44$ events (ME/AE cases). Using these values, the number of electrons in the germanium ($4.909 \times 10^{26}/7.1408 \times 10^{26}$ for ME/AE cases) and in the copper ($1.704 \times 10^{27}/2.600 \times 10^{27}$), the measuring time and the calculated efficiencies, we obtain the mean lifetime limit $\tau > 3.306 \times 10^{25}/4.416 \times 10^{25}$ yr (ME/AE cases). In the same way, the mean lifetime limits for all detectors, for setup 1 and for the full setup were obtained (see Table 5).

3.1.2. Analysis by maximum likelihood method and the least squares method

Second we used the approximate analytical maximum likelihood technique [18,19] to fit the experimental spectrum in the neighborhood of the peak searched for. We fitted the energy range 210–310 keV, assuming a linear background and 3 lines (and 4 lines for ANG4 and the full setup) from ^{212,214}Pb (see Figs. 4, 5), and the Doppler-broadened expected line. The numbers of electron decay events, calculated according to the maximum likelihood analysis, due to an effect, which can be

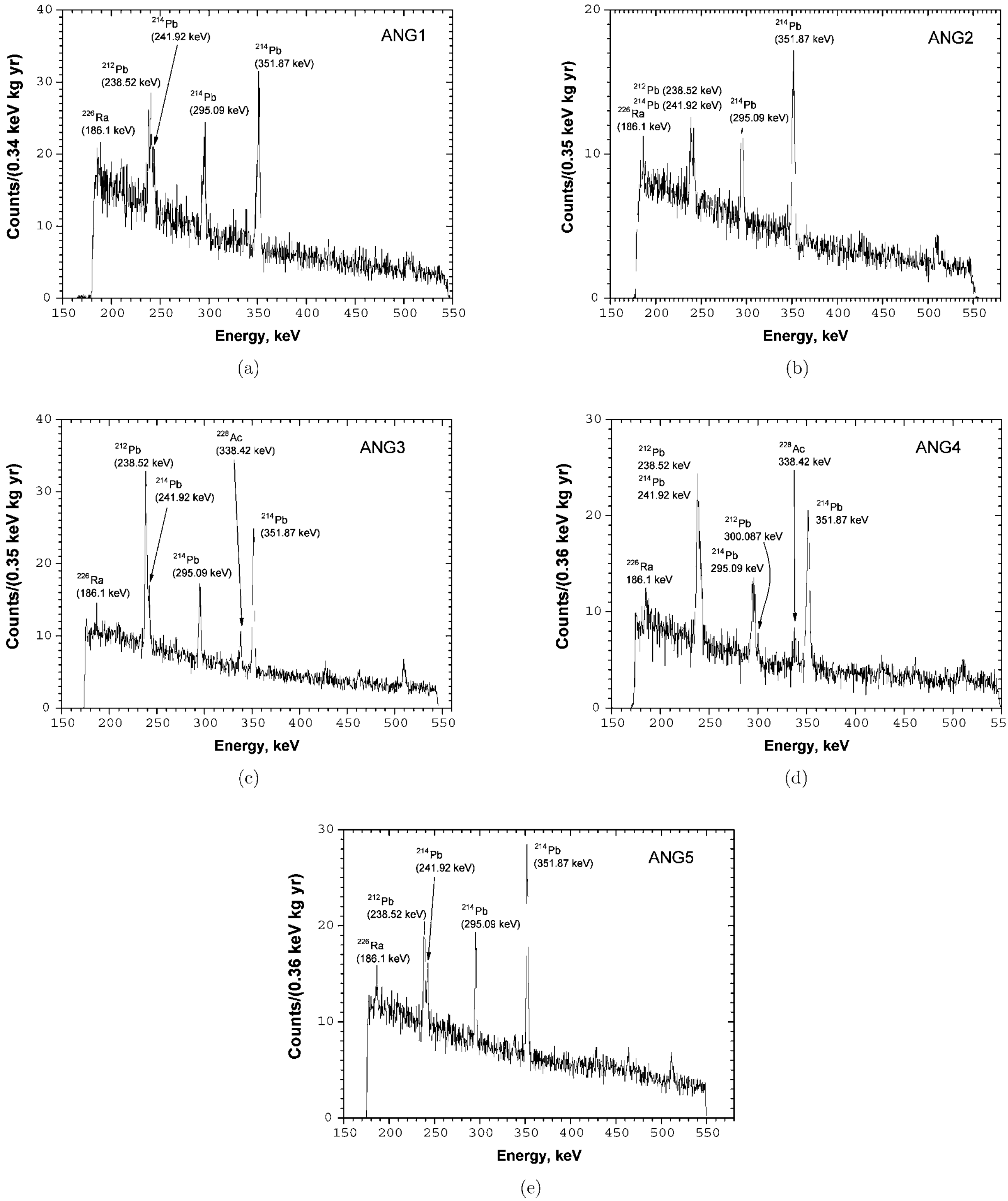


Fig. 4. Measured spectra for all five detectors of the Heidelberg–Moscow experiment in the energy range of interest for the process $e^- \to \nu_e + \gamma$.

excluded at 68% (90%) C.L. [19,20] and the mean life-time limits for the ME/AE cases are presented in Table 6.

Finally, the λ value was determined by using the standard least squares procedure. The fitting curves are shown in Figs. 6–9. As for the maximum likelihood fit, the Gaussian centroids are fixed at the values $E_1 = 238.52$ keV, $E_2 = 241.92$ keV, $E_3 = 295.09$ keV and $E_4 = 300.087$ keV [15]. From the fit, ANG1, ANG3, ANG4 and ANG5 give no evidence of an effect (line) near 255 keV. (In ANG2 and setup 1 there is a small peak in the energy region of the electron decay.) The peak areas (counts), number of the events due to the effect which can be excluded at 68% (90%) C.L. [19], and the mean life-time limit for the ME–AE cases are presented in Table 7.

The mean life time limit for the electron decay mode $e^- \to \gamma + \nu_e$ after 6.038 yr of effective measuring time of the full Heidelberg–Moscow setup is $T_{1/2} > 1.222 \times 10^{26}/7.662 \times 10^{25}$ yr (68%/90% C.L.) if we are taking into account only M-shell electrons for germanium, and $T_{1/2} > 1.138 \times 10^{26}/9.385 \times 10^{25}$ yr (68%/90% C.L.) for the case, when all electrons are taken into account. The best limit obtained from a single detector is 1.93×10^{26} yr. We see a small peak in the energy region near 255.5 keV, at a $1.42\sigma/1.29\sigma$ (for ANG2/setup 1), corresponding to a mean life time of $(4.51 \pm 3.18) \times 10^{25}$ yr.

4. Conclusions

From the analysis of the data of the Heidelberg–Moscow $\beta\beta$ experiment we derive one of the sharpest limits for the stability of the electron for the process $e^- \to \gamma + \nu_e$.

Setups 1 + 2 together yield a lower mean life time limit of 1.2×10^{26} yr. The best limit from a single detector comes from detector 4 with 1.93×10^{26} yr. This is the by far best limit—about one order of magnitude stronger—than those obtained in previous Ge experiments (see Table 1), and it is one of the best limits in general.

If comparing this limit with the presently sharpest claimed limit given by Borexino [10], of 4.6×10^{26} yr, it may be essential to note that the present limit has been deduced from the data without any uncertainties resulting from any treatment of the background (see Section 1). It might be noted further that the present experiment stands out by its high energy resolution from the other most sensitive recent experiments (see Table 1).

As discussed e.g. in [24] there is currently no self-consistent and noncontradictory theory describing possible violations of the charge conservation and allowing to suitably parameterize information from the experimental lifetime limits. If one introduces however, following [21], a charge nonconservation parameter by assuming that the weak interaction Lagrangian includes a small charge nonconservation part having the usual form, but with a neutrino replacing the electron in the lepton current; then

$$L_{\mathrm{CNC}} = \frac{1}{2} e \epsilon_{e\nu\gamma} \bar{\Psi}_e \gamma_\mu (1-\gamma_5) \Psi_\nu A^\mu + \text{h.c.}, \tag{4}$$

where the parameter $\epsilon_{e\nu\gamma}$ gives a measure of the charge nonconservation. The transition probability for the electron decay $e^- \to \gamma + \nu_e$ can be written, according to [22], as:

$$\lambda^{\mathrm{CNC}}_{e\nu\gamma} = \epsilon^2_{e\nu\gamma} \frac{\alpha}{32\pi} \frac{m_e c^2}{\hbar} \left[1 + \left(\frac{m_e}{m_\gamma}\right)^2\right] \approx \epsilon^2_{e\nu\gamma} \frac{\alpha}{32\pi} \frac{m_e c^2}{\hbar} \left(\frac{m_e}{m_\gamma}\right)^2, \tag{5}$$

Table 5
Calculated values of the maximum number of electron decay events that can be excluded at the peak position (λ) and respective limits of the lifetimes in the frame of the 'one sigma approach' (90% of expected peak)

		λ, counts		**Lifetime limit, yr**	
	Detectors	ME case	AE case	ME case	AE case
Setup 1	ANG1	49.229	55.255	5.760×10^{24}	7.464×10^{24}
	ANG2	61.313	67.440	3.306×10^{25}	4.416×10^{25}
	ANG3	63.945	71.552	2.224×10^{25}	2.890×10^{25}
	ANG5	73.148	80.359	3.076×10^{25}	4.121×10^{25}
	Full setup 1	125.485	140.330	4.064×10^{25}	5.286×10^{25}
Setup 2	ANG4	46.081	51.568	2.008×10^{25}	2.611×10^{25}
Full setup: (setup 1 + setup 2):		133.551	149.443	4.179×10^{25}	5.530×10^{25}

Table 6
Calculated values of the maximum number of electron decay events that can be excluded at the peak position (λ) and respective limits of the mean lifetimes τ in the frame of the analytical maximum likelihood technique

		λ (68%/90% C.L.), counts	
	Detectors	ME case	AE case
Setup 1	ANG1	13.777/18.943	16.441/21.104
	ANG2	32.204/48.610	60.627/81.109
	ANG3	20.889/30.695	47.836/55.551
	ANG5	12.518/20.793	17.620/28.728
	Full setup 1	80.754/104.842	132.532/187.610
Setup 2	ANG4	6.841/16.248	17.826/38.365
Full setup: (setup 1 + setup 2):		41.169/60.153	69.129/105.817
		Lifetime limit (68%/90% C.L.), yr	
	Detectors	ME case	AE case
Setup 1	ANG1	$2.058 \times 10^{25}/1.497 \times 10^{25}$	$2.513 \times 10^{25}/1.954 \times 10^{25}$
	ANG2	$6.295 \times 10^{25}/4.170 \times 10^{25}$	$4.912 \times 10^{25}/3.671 \times 10^{25}$
	ANG3	$6.807 \times 10^{25}/4.632 \times 10^{25}$	$4.326 \times 10^{25}/3.723 \times 10^{25}$
	ANG5	$1.797 \times 10^{26}/1.082 \times 10^{26}$	$1.880 \times 10^{26}/1.153 \times 10^{26}$
	Full setup 1	$6.315 \times 10^{25}/4.864 \times 10^{25}$	$5.597 \times 10^{25}/3.954 \times 10^{25}$
Setup 2	ANG4	$1.352 \times 10^{26}/5.698 \times 10^{25}$	$7.554 \times 10^{25}/3.510 \times 10^{25}$
(setup 1 + setup 2):		$1.380 \times 10^{26}/0.944 \times 10^{26}$	$1.195 \times 10^{26}/0.781 \times 10^{26}$

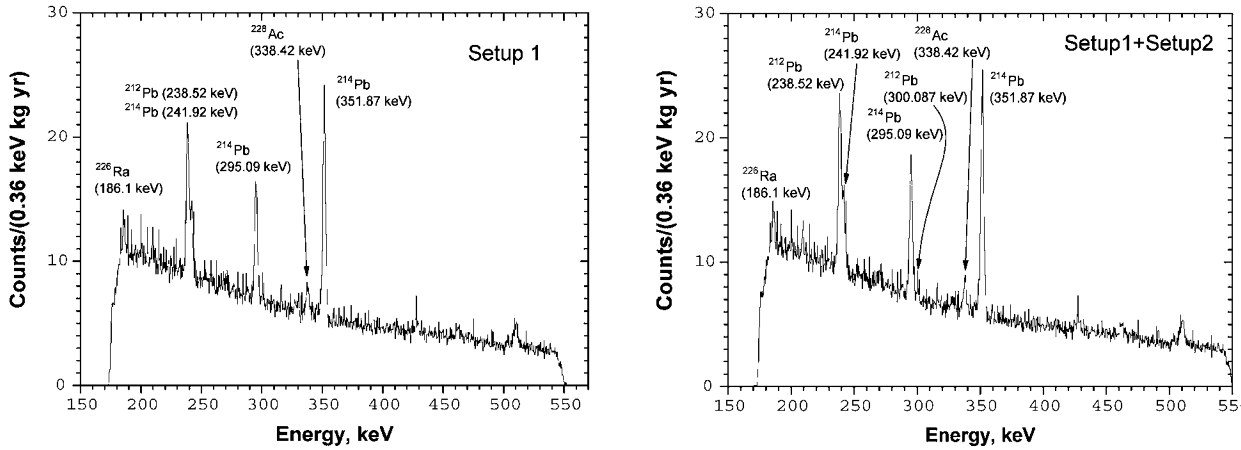


Fig. 5. Measured spectra for the full setup of the Heidelberg–Moscow experiment, and setup 1 separately, in the energy range of interest for the process $e^- \to \nu_e + \gamma$.

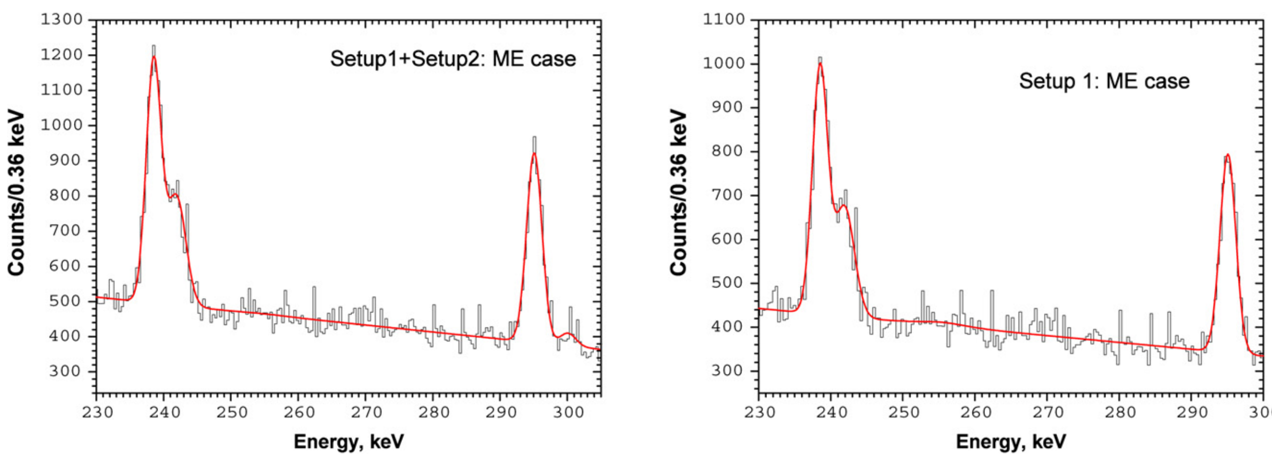


Fig. 6. Full spectrum with the least-squares fitting curve for the ME case for setups 1 and $1+2$ of the Heidelberg–Moscow experiment, in the range around the expected signal from e^- decay.

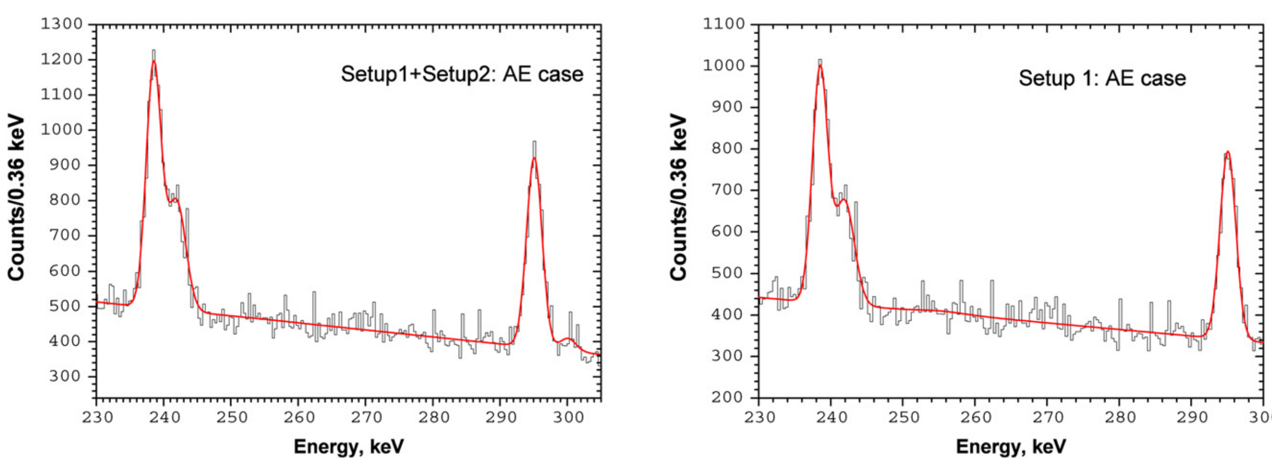


Fig. 7. Full spectrum with the least-squares fitting curve for the AE case, setups 1 and $1+2$ of the Heidelberg–Moscow experiment, in the range around the expected signal from e^- decay.

where α is the fine structure constant. According to [24] $\epsilon^2_{e\nu\gamma}(\frac{m_e}{m_\gamma})^2 = \frac{5.6\times 10^{-25}}{\tau}$ and thus the experimental limit for the full setup $1+2$ leads to the bound $\epsilon^2_{e\nu\gamma}(\frac{m_e}{m_\gamma})^2 = 4.59 \times 10^{-51}/0.73 \times 10^{-50}$ (68%/90% C.L.) for the ME case and $\epsilon^2_{e\nu\gamma}(\frac{m_e}{m_\gamma})^2 = 4.92 \times 10^{-51}/0.60 \times 10^{-50}$ (68%/90% C.L.) for the AE case. If we combine the latter expression with the best laboratory limit on the photon mass $m_\gamma < 7 \times 10^{-19}$ eV [25], we obtain the following restrictions for charge nonconserva-

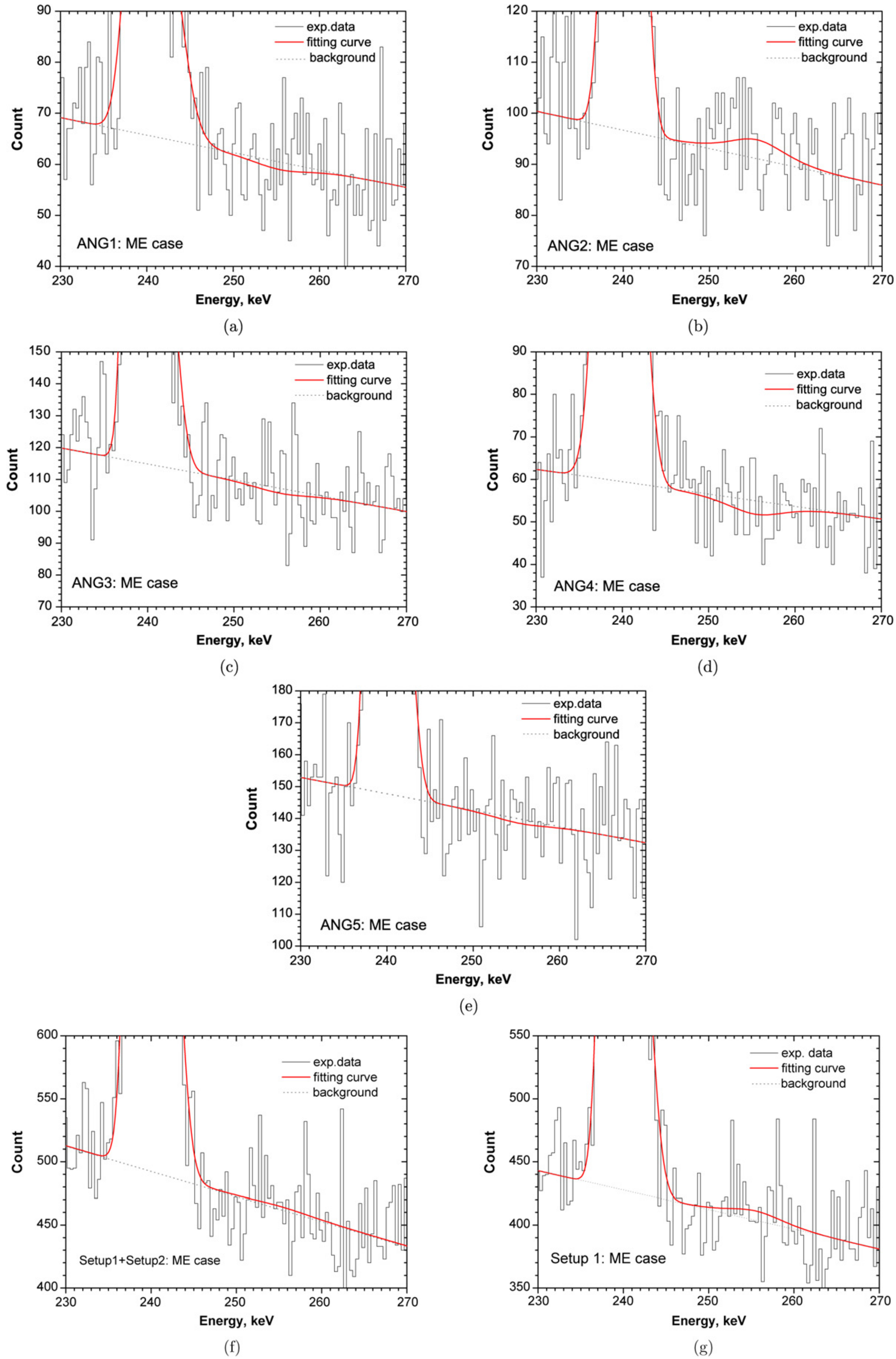
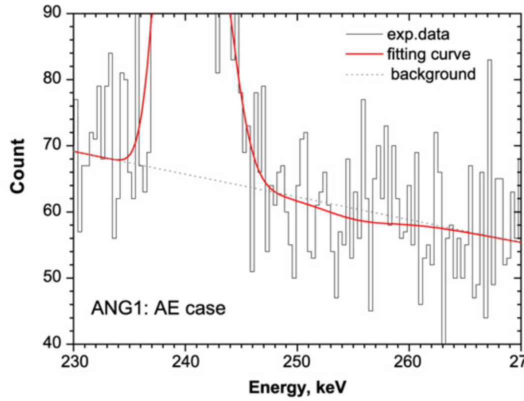
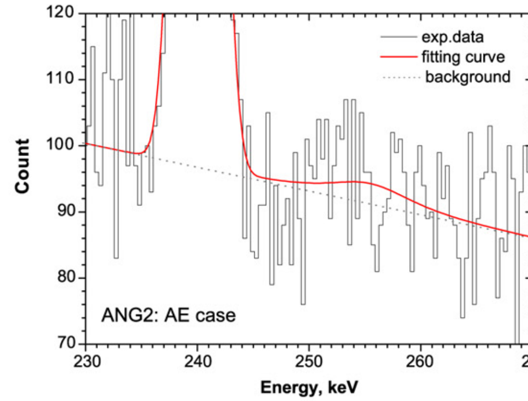


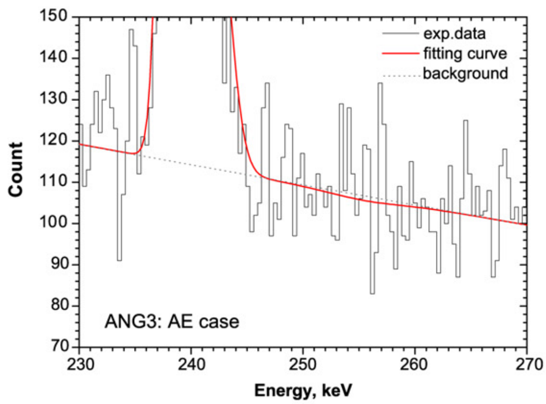
Fig. 8. Spectrum in the energy region of interest for e^- decay (counts/bin) over the full measuring time (see Table 2) with the least squares fitting curve for the ME case, for all five detectors, and setups 1 and $1+2$ of the Heidelberg–Moscow experiment (zoom of Fig. 6, which shows the full fitted range only for Figs. 8(f), (g)).



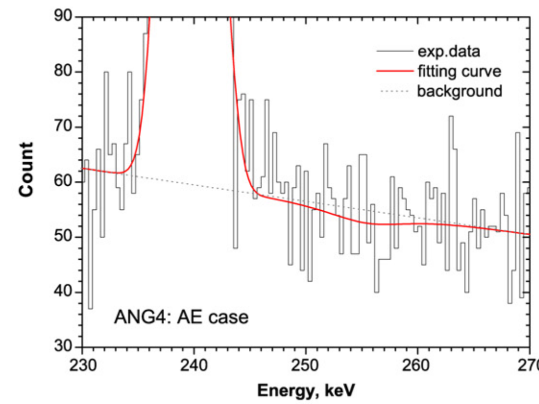
(a)



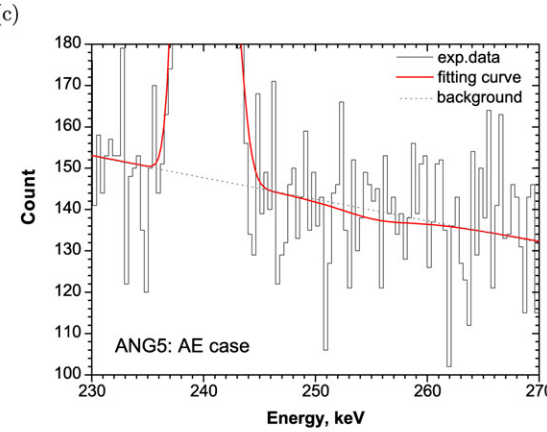
(b)



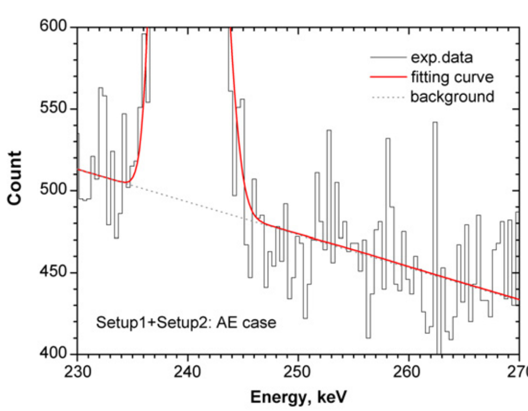
(c)



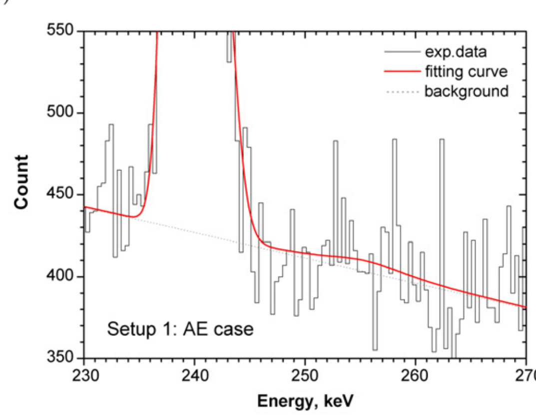
(d)



(e)



(f)



(g)

Fig. 9. Spectrum in the energy region of interest for e^- decay (counts/bin) over the full measuring time (see Table 2) with the least squares fitting curve for the AE case, for all five detectors, and setups 1 and $1+2$ of the Heidelberg–Moscow experiment (zoom of Fig. 7, which shows the full fitted range only for Figs. 9(f), (g)).

Table 7
Results calculated in the frame of the standard least squares procedure

Detectors	$\frac{\chi^2}{NDF}$ ME/AE case	Peak area ME/AE case, counts	**λ (68%/90% C.L.), counts**	
			ME case	AE case
ANG1	1.422/1.423	-38.187 ± 51.077/ -83.759 ± 90.216	13.216/22.850	12.350/22.824
ANG2	0.991/0.992	89.444 ± 63.058/ 146.341 ± 110.710	38.354/51.138	64.772/86.362
ANG3	1.275/1.243	-38.301 ± 67.374/ -57.914 ± 118.130	13.216/22.850	21.295/37.497
ANG5	1.393/1.391	-33.273 ± 75.947/ -111.978 ± 132.749	14.343/24.867	19.764/35.699
Setup 1	2.092/2.095	185.881 ± 144.264/ 293.838 ± 273.878	83.392/111.531	138.429/189.972
ANG4	1.339/1.368	-76.249 ± 47.401/ -114.450 ± 83.968	4.789/9.065	10.386/20.771
Setups 1 + 2	2.143/2.144	45.587 ± 153.863/ 26.670 ± 292.608	46.501/74.146	72.604/88.052

Detectors	**Lifetime limit (68%/90% C.L.), yr**	
	ME case	AE case
ANG1	$2.146 \times 10^{25}/1.241 \times 10^{25}$	$3.340 \times 10^{25}/1.807 \times 10^{25}$
ANG2	$5.285 \times 10^{25}/3.964 \times 10^{25}$	$4.598 \times 10^{25}/3.448 \times 10^{25}$
ANG3	$1.076 \times 10^{26}/0.622 \times 10^{26}$	$9.712 \times 10^{25}/5.516 \times 10^{25}$
ANG5	$1.569 \times 10^{26}/0.905 \times 10^{26}$	$1.676 \times 10^{26}/9.277 \times 10^{25}$
Setup 1	$6.115 \times 10^{25}/4.572 \times 10^{25}$	$5.358 \times 10^{25}/3.905 \times 10^{25}$
ANG4	$1.933 \times 10^{26}/1.021 \times 10^{26}$	$1.297 \times 10^{26}/6.483 \times 10^{25}$
Setups 1 + 2	$1.222 \times 10^{26}/0.766 \times 10^{26}$	$1.138 \times 10^{26}/0.939 \times 10^{26}$

tion: for the ME case $\epsilon^2_{e\nu\gamma} < 0.86 \times 10^{-98}/1.14 \times 10^{-98}$ and for the AE case $\epsilon^2_{e\nu\gamma} < 0.92 \times 10^{-98}/1.13 \times 10^{-98}$ at 68%/90% C.L.

Acknowledgements

The authors acknowledge the support from BMBF and DFG (RFBR 06-02-04009) and RFFI (RFBR 06-02-04003) of this project. I.V. Titkova thanks personally Dr. A.V. Derbin for useful and friendly discussions.

References

[1] H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, et al., Phys. Lett. B 586 (2004) 198.
[2] H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina, et al., Nucl. Instrum. Methods A 522 (2004) 371.
[3] H.V. Klapdor-Kleingrothaus, in: Proceeding of the 2nd Scandinav, Neutrino Workshop, SNOW2006, Stockholm, Sweden, 2–6 May 2006;
H.V. Klapdor-Kleingrothaus, Phys. Scr. T 127 (2006) 40.
[4] G. Feinberg, M. Goldhaber, Proc. Natl. Acad. Sci. USA 45 (1995) 1301.
[5] M.K. Moe, F. Reines, Phys. Rev. 140 (1965) 992.
[6] E.L. Kovalchuk, et al., JETP Lett. 29 (1979) 145.
[7] F.T. Avignone III, et al., Phys. Rev. D 34 (1986) 97.
[8] Heidelberg–Moscow Collaboration, Phys. Lett. B 298 (1993) 278.
[9] Y. Aharonov, et al., Phys. Rev. D 52 (1995) 3785;
Y. Aharonov, et al., Phys. Lett. B 353 (1995) 168.
[10] H.O. Back, et al., Phys. Lett. B 525 (2002) 29.
[11] H.V. Klapdor, Proposal, Internal Report, MPI-1987-V17, September 1987.
[12] H.V. Klapdor-Kleingrothaus, et al., Eur. Phys. J. A 12 (2001) 147.
[13] Heidelberg–Moscow Collaboration, M. Gunther, et al., Phys. Rev. D 55 (1997) 54.
[14] Ch. Dörr, H.V. Klapdor-Kleingrothaus, Nucl. Instrum. Methods A 513 (2003) 596.
[15] D.R. Lide, Handbook of Chemistry and Physics, eightyfifth ed., CRC Press, 2004–2005.
[16] GEANT4 Collaboration, http://geant4.web.cern.ch/geant4.
[17] E. Bellotti, et al., Phys. Lett. B 124 (1983) 435.
[18] P.R. Bevington, D.K. Robinson, Data Reduction and Error Analysis for the Physical Sciences, third ed., McGraw–Hill, 2003.
[19] Particle Data Group, Review of Particle Physics, Phys. Lett. B 592 (2004).
[20] G.J. Feldman, R.D. Cousins, Phys. Rev. D 57 (1998) 3873.
[21] J.N. Bahcall, Rev. Mod. Phys. 50 (1978) 881;
J.N. Bahcall, Neutrino Astrophysics, Cambridge Univ. Press, Cambridge, 1993, p. 360.
[22] M. Suzuki, Phys. Rev. D 38 (1988) 1544.
[23] P. Belli, et al., Astropart. Phys. 5 (1995) 217.
[24] P. Belli, R. Bernabei, C.J. Dai, et al., Phys. Rev. D 61 (2000) 117301.
[25] J. Luo, et al., Phys. Rev. Lett. 90 (2003) 081801;
J. Luo, et al., Phys. Rev. Lett. 91 (2003) 149102;
Particle Data Group, J. Luo, et al., Phys. Lett. B 592 (2004) 1.
[26] W.A. Reed, P. Eisenberger, Phys. Rev. B 6 (1972) 4596.