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Has neutrinoless double β decay of ^{76}Ge been really observed?

Yu.G. Zdesenko *, F.A. Danevich, V.I. Tretyak

Institute for Nuclear Research, MSP 03680 Kiev, Ukraine

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Abstract

The claim of discovery of the neutrinoless double beta ($0\nu2\beta$) decay of ^{76}Ge [Mod. Phys. Lett. A 16 (2001) 2409] is considered critically and firm conclusion about, at least, prematurity of such a claim is derived on the basis of a simple statistical analysis of the measured spectra. This result is also proved by analyzing the cumulative data sets of the Heidelberg–Moscow and IGEX experiments. Besides, it allows us to establish the highest worldwide half-life limit on the $0\nu2\beta$ decay of ^{76}Ge:

$$T_{1/2}^{0\nu} \geqslant 2.5\ (4.2) \times 10^{25}\ \text{yr} \quad \text{at 90\% (68\%) C.L.}$$

This bound corresponds to the most stringent constraint on the Majorana neutrino mass:

$$m_\nu \leqslant 0.3\ (0.2)\ \text{eV} \quad \text{at 90\% (68\%) C.L.}$$

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The observation of the $0\nu2\beta$ decay would be a clear evidence for a new physics beyond the standard model (SM) of electroweak theory[1] and an unique confirmation of the Majorana nature of the neutrino [3–5]. Another issue of the $0\nu2\beta$ decay search is the reconstruction of the neutrino mass spectrum, which could provide a crucial test of neutrino mixing models [6,7] tightly connected with the solar neutrino problem [8].[2]

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* Corresponding author.

E-mail address: zdesenko@kinr.kiev.ua (Yu.G. Zdesenko).

[1] The $0\nu2\beta$ decay violates lepton number (L) conservation, while many extensions of the SM incorporate L violating interactions and, hence, could lead to this process. A non-vanishing $0\nu2\beta$ decay rate requires neutrinos to be massive Majorana particles, independently of which mechanism induces it [2].

[2] The solar data, especially latest results of the Super-Kamiokande [9] and Sudbury [10] Neutrino Observatories, provide evidence that there is a non-electron flavor active neutrino component in the solar flux [11]. These data, the measured deficit of the atmospheric muon neutrino flux [12] and the result of the LSND accelerator experiment [13], all may be explained by means of neutrino oscillations, requiring nonzero neutrino masses in the range $0.01 \leqslant m_\nu \leqslant 1$ eV [6,7]. However, oscillation experiments are sensitive to the neutrino mass difference, while only the measured $0\nu2\beta$ decay rate can give the absolute scale of the effective Majorana neutrino mass.

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Therefore, it is obvious that discovery of the $0\nu 2\beta$ decay would be an extraordinary event of the highest importance for the modern physics. However, despite the numerous efforts, which are continuing since 1948 [14], this process still remains unobserved (see latest reviews [3,4,15,16]. Nevertheless, due to tremendous progress in experimental sensitivity achieved during last decade, the impressive half-life limits for 0ν mode were set in direct measurements with several nuclides: $T_{1/2}^{0\nu} \geqslant 10^{22}$ yr for ^{82}Se [17], ^{100}Mo [18]; $T_{1/2}^{0\nu} \geqslant 10^{23}$ yr for ^{116}Cd [19], ^{128}Te, ^{130}Te [20], ^{136}Xe [21]; and $T_{1/2}^{0\nu} \geqslant 10^{25}$ yr for ^{76}Ge [22,23]. These results have already brought the most stringent restrictions on the values of the Majorana neutrino mass ($m_\nu \leqslant 0.4$–5 eV), the right-handed admixture in the weak interaction ($\eta \approx 10^{-8}$, $\lambda \approx 10^{-6}$), the neutrino-Majoron coupling constant ($g_{\mathrm{M}} \approx 10^{-4}$), and the R-parity[3] violating parameter of minimal supersymmetric (SUSY) standard model ($\varepsilon \approx 10^{-4}$), which allow one to reduce the number of acceptable theoretical models and to address the multi-TeV energy range that is the focus of accelerator experiments [3–6].

It is important to note that highest $T_{1/2}^{0\nu}$ bounds for ^{76}Ge were obtained in two different experiments, which were performed by the Heidelberg–Moscow (HM) [22] and IGEX [23] Collaborations. These experiments belong to the class of 2β decay search involving an "active" source technique, in which Ge detectors containing ^{76}Ge candidate nuclei serve as source and detector of 2β decay events simultaneously. If the $0\nu 2\beta$ decay occurs in this "active" source, the sharp peak at the energy $Q_{\beta\beta} = 2039.01(5)$ keV [24] would be observed in the background spectrum of the detector (the width of peak is determined by the energy resolution).

The IGEX was operating three 2-kg enriched in ^{76}Ge to $\approx 86\%$ high purity (HP) Ge semiconductor detectors in the Canfranc Underground Laboratory (Spain). The shield consisted of super low-activity lead, and a plastic scintillator to veto cosmic muons. With the pulse shape analysis (PSA) applied to the data the background rate in the energy range 2.0–2.5 MeV was equal to ≈ 0.06 counts/(yr kg keV). The combined energy resolution for the $0\nu 2\beta$ peak was 4 keV. Analysis of 116.75 mol yr (or 8.87 kg yr in ^{76}Ge) of data yields a lower bound of $T_{1/2}^{0\nu} \geqslant 1.57 \times 10^{25}$ yr at 90% C.L. [23].

The HM experiment in the Gran Sasso Underground Laboratory (Italy) uses five HP Ge detectors (enriched in ^{76}Ge to 86%) with a total active mass of 10.96 kg (125.5 moles of ^{76}Ge). The shield and PSA of the data reduces the background rate to the value of ≈ 0.06 counts/(yr kg keV) in the range 2000–2080 keV. The energy resolution at the energy of 2039 keV is 4.0 keV. The total statistics is 54.98 kg yr (or 47.28 kg yr in ^{76}Ge). After 24 kg yr (or 20.8 kg yr in ^{76}Ge) of data with PSA, a lower half-life limit of $T_{1/2}^{0\nu} \geqslant 1.6 \times 10^{25}$ yr at 90% C.L. has been set for ^{76}Ge [22]. In 2001 this limit was slightly improved up to $T_{1/2}^{0\nu} \geqslant 1.9 \times 10^{25}$ yr (90% C.L.) by analyzing 35.5 kg yr of data with PSA [25].

Suddenly, in December 2001 the discovery of the neutrinoless 2β decay of ^{76}Ge with half-life of 1.5×10^{25} yr (95% confidence interval of (0.8–18) $\times 10^{25}$ yr) has been claimed [1].[4] Instantaneously, important physical implications of such a discovery were discussed in publications [27–31]. However, this claim was immediately criticized [32,33]. In particular, it was shown [32] (by an analysis of the intensities of the ^{214}Bi peaks in the background spectrum), that the peak fitting procedure, used in [1], produced spurious peaks near the $Q_{\beta\beta}$ energy, thus the paper [1] does not support the claim of evidence for $0\nu 2\beta$ decay (see, however, reply [34]). Similar conclusion about absence of evidence for $0\nu 2\beta$ decay in the published data [1] was also derived in Ref. [33], where the data fit procedure, similar to those used by authors [1], was repeated for the different energy intervals.

In the present Letter we will demonstrate with the help of simple numerical analysis of the measured spectra [1] that mentioned claim of discovery cannot be proved by the standard statistical test.

In fact, here we deal with well-known task in the experimental physics and communication engineering, which can be formulated as follows: "How to recognize effect/signal in the presence of back-

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[3] R-parity is defined as $R_p = (-1)^{3B+L+2S}$, where B, L and S are the baryon and lepton numbers, and the spin, respectively.

[4] Surprisingly, this claim (based on the data collected during about ten years in the course of the HM collaboration experiment) has been made only by the four co-authors [1], and then in the next publication by the three persons [26].

ground/interference?" In case of the 2β decay research this task is additionally complicated by two circumstances:

(a) Measured count rate (which includes background and effect searched for) is extremely low, consequently, final statistics is very poor. For instance, in the HM experiment [22] some tens of counts were collected in the energy region of interest after about 10 years of measurements (see Fig. 1). Poor statistics makes it difficult to use standard or newly developed statistical methods for analysis of experimental data/spectra and peak search, and for calculation of the confidence intervals or upper limits (see, e.g., Refs. [35–44]).[5]

(b) Expected background can be estimated only approximately, while, for example, the procedure recommended by Particle Data Group for calculating the confidence intervals or upper limits [40] is valid "*only for the case with exactly known background expectation*" [44]. At first sight, it seems that background in such experiments could be measured independently with a blank detector (which is similar to working one, but does not contain 2β candidate nuclei), or at least could be simulated. However, it is practically not so simple for many reasons. For instance, tiny variance of the residual radioactive contaminations of the detectors, different isotopic composition (resulting in different cosmogenic activation), etc., all will lead to the different background of the detectors. Hence, when dealing with intrinsic activities of several counts per ≈ 50 kg yr, it is extremely difficult to guarantee an absolute identity of the detectors and their background. Monte Carlo simulation of the set up (shielding, detectors, etc.) cannot fully solve this problem too.[6]

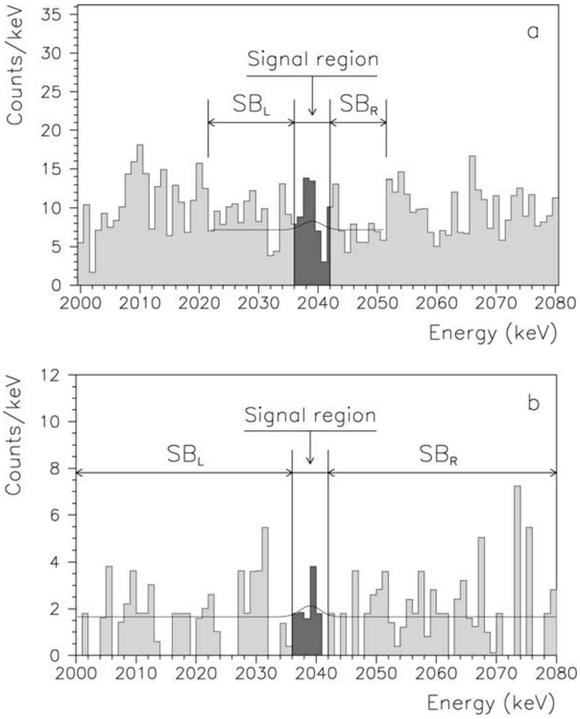

Fig. 1. Background spectra collected in the HM experiment (as they given in [1]): (a) sum spectrum of the HP ^{76}Ge detectors 1–5 with the total statistics of 54.98 kg yr; (b) sum spectrum of the HP ^{76}Ge detectors 2, 3, 5 operated with PSA for the total statistics of 28.05 kg yr. SB_L and SB_R are the left and right sidebands chosen for our analysis and smooth lines represent the fitting curves (see text).

Therefore, background in this type of 2β decay experiments ("active" source technique) is estimated from the same data sample by analyzing the left and right sidebands, i.e., regions which are located near the signal region and which contain no signal events. The choice of the sidebands is extremely important [42]. If sidebands are chosen much larger than signal region, and if background behaves there as a smooth function, the estimate of background can be treated as accurate.[7] "*However, if the areas of signal and sidebands regions are comparable, ... it ... overestimates the significance of a signal for numbers of observed events larger than back-*

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[5] Even hypothesis of Poisson nature of signal and background is weakly justified at super-low statistics, when they became to be quasi-stationary processes [39].

[6] The super-low activity nature of the 2β decay research and complexity of the apparatus used make it quite unrealistic to perform high precision simulation of the background. The different assumptions/approximations made of necessity at each step of simulation and inaccuracy of computer programs will result in non-controlled increase of final systematic errors.

[7] Even so, one has to remember that this estimate is based on belief that background in signal region is the same as in sidebands, but, at least in principle, it may be not true in some cases.

ground, increasing the probability of a 'discovery' " [42]. Note that this precaution was written before publication [1].

As an example, the possible choice of sidebands is shown in Fig. 1 for the two samples of data collected in the HM experiment [22,25]. In both cases the width of the signal region is fixed to 6 keV as compromise between requirements of the maximal efficiency and minimal background. It contains about 92% of the expected peak of the $0\nu2\beta$ decay of ^{76}Ge with the FWHM $= 4.0$ keV determined by the energy resolution of the detector. In the spectrum without PSA (see Fig. 1(a)) there are two peculiarities, which can be considered as indications on the possible peaks at the energy 2010 and 2054 keV. Taking this fact into account, the width of the left sideband, SB_L, is chosen as 14.5 keV (from 2021.5 to 2036 keV), the width of the right sideband, SB_R, as 9.5 keV (from 2042 to 2051.5 keV). Consequently, $\mathrm{SB}_L + \mathrm{SB}_R = 24$ keV is four times larger than signal region (Fig. 1(a)). The total number of counts in sidebands is 198, thus expected background in 6 keV bin is $B = (49.5 \pm 3.5)$ counts. For the data with PSA (Fig. 1(b)) the corresponding widths are $\mathrm{SB}_L = 36$ keV, and $\mathrm{SB}_R = 38$ keV (i.e., 74 keV in total), where there are 126.7 counts, thus the expected background in 6 keV interval equals to $B = (10.3 \pm 0.9)$ counts.

The effect would be recognized if the actual number of counts collected in signal region exceeds background with the certain statistical significance. It seems that in ^{76}Ge experiments, where a Gaussian peak on smooth background is searched for, geometrical criteria of peak shape could help in identification of the effect. Unfortunately, in reality it is not so because: "*Shape criterion does not work at super-low statistics at all*" [38] (see also review on mathematical methods of the analysis of experimental spectra [39]).[8]

Let us perform a simple statistical test of the HM data [1,22,25] presented in Fig. 1(a) (54.98 kg yr). There are 55.2 ± 7.4 counts in the signal region of 6 keV (from 2036 to 2042 keV). Comparing this value with expected background 49.5 ± 3.5 counts, one can calculate the difference between gross signal, S, and background: $\Delta = S - B = 5.7 \pm 8.2$ counts, which gives no evidence for the effect.

Similarly, for HM spectrum with PSA (28.1 kg yr) shown in Fig. 1(b) there are 10.8 counts in the 6 keV signal region, hence the difference is $\Delta = 0.5 \pm 3.4$ counts, that is again in agreement with absence of the effect.

For completeness of our analysis of the HM data we also determine the half-life limit for the $0\nu2\beta$ decay of ^{76}Ge, which is calculated on the basis of known formula: $\lim T^{0\nu}_{1/2} = \ln 2\,\epsilon\, N\, t / \lim S$, where N is the number of ^{76}Ge nuclei; t is the measuring time; ϵ is the detection efficiency; and $\lim S$ is the number of effect's events, which can be excluded with a given confidence level on the basis of measured data. From our result, $\Delta = 5.7 \pm 8.2$ counts, the value of $\lim S$ is estimated as 19.2 (13.9) counts at 90% (68%) C.L. Then, taking into account Nt product (54.98 kg yr or 47.28 kg yr in ^{76}Ge) and the detection efficiency ($\epsilon = 0.92$), a half-life bound $T^{0\nu}_{1/2} \geqslant 1.2\ (1.7) \times 10^{25}$ yr at 90% (68%) C.L. is obtained. In addition, the value of $\lim S$ was determined by using the standard least square procedure [45], where the experimental energy distribution was fitted in the energy interval 2022–2051 keV by the sum of linear background and the $0\nu2\beta$ decay peak being sought (Gaussian with the FWHM = 4 keV centered at 2039 keV). It yields (fitting curve is depicted in Fig. 1(a)) the area of the $0\nu2\beta$ decay peak equal to 4.8 ± 8.1 counts, and consequently the value of $\lim S = 18.1\ (12.9)$ counts at 90% (68%) C.L., which translates to practically the same half-life bounds.[9] Similarly, for the data with PSA (28.1 kg yr or 24.17 kg yr in ^{76}Ge) we get from the difference $\Delta = (0.5 \pm 3.4)$ counts the $\lim S$ as 6.1

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[8] Therefore, the statistical significance is the only criterion, which is substantial for the effect recognizing in the super-low activity experiments, consequently the actual ratio "signal to background" is the "gold key" for that. Nevertheless, authors [1] insist that their sophisticated mathematical procedure is able to find in the super-low activity spectrum the peaks, which are not seen by eyes: "*This is the reason, that the method can do more the naked eye*" [34]. In our opinion the peak, by whom discovery is manifested, has to be seen by naked eyes of physicists. Otherwise it must be firmly proved that background has a hole just in the signal region.

[9] Fit with more complicated background model (the linear function plus two possible peaks at the energy 2010 and 2054 keV) yields the area of the first peak 28 ± 9 counts (at 2010 ± 1.2 keV), the area of the second one 25 ± 10 counts (at 2054 ± 1.2 keV), and the area of the $0\nu2\beta$ peak 2.0 ± 6.8 counts. Very similar results were also obtained with parabolic function included in the background model instead of linear one.

Table 1
Results obtained by the simple statistical analysis of data (and by fit) for the different energy intervals chosen (see text for definitions)

Data set	Chosen energy interval	Fit of data	Simple $S-B$ procedure		
(figure)	keV	Effect area	S	B	$\Delta = S - B$
		counts	counts	counts	counts
HM data with PSA	2000–2080	2.0 ± 3.1	10.8 ± 3.3	10.3 ± 0.9	0.5 ± 3.4
(Fig. 1(b))	2005–2075	1.5 ± 3.0	10.8 ± 3.3	10.8 ± 1.0	0 ± 3.4
	2010–2070	2.1 ± 3.2	10.8 ± 3.3	10.2 ± 1.1	0.6 ± 3.5
	2015–2065	2.2 ± 3.4	10.8 ± 3.3	10.3 ± 1.2	0.5 ± 3.5
	2020–2060	1.7 ± 3.4	10.8 ± 3.3	10.8 ± 1.4	0 ± 3.6
	2025–2055	1.8 ± 3.4	10.8 ± 3.3	10.8 ± 1.6	0 ± 3.7
	2030–2050	1.9 ± 3.6	10.8 ± 3.3	10.8 ± 2.2	0 ± 3.9
	2031–2049	3.3 ± 3.6	10.8 ± 3.3	9.3 ± 2.2	1.5 ± 3.9
	2032–2047	6.5 ± 3.8	10.8 ± 3.3	5.7 ± 2.0	5.1 ± 3.9
HM + IGEX data with PSA	2020–2062	-0.7 ± 5.2	17.7 ± 4.2	24.5 ± 2.0	-6.8 ± 4.7
(Fig. 4(b))	2022–2060	-0.3 ± 5.3	17.7 ± 4.2	23.8 ± 2.1	-6.1 ± 4.7
	2024–2058	-0.5 ± 5.3	17.7 ± 4.2	22.5 ± 2.2	-4.8 ± 4.8
	2026–2056	-1.0 ± 5.4	17.7 ± 4.2	23.0 ± 2.4	-5.3 ± 4.9
	2028–2054	-0.8 ± 5.4	17.7 ± 4.2	22.3 ± 2.6	-4.6 ± 5.0
	2030–2052	$+0.3 \pm 5.4$	17.7 ± 4.2	20.6 ± 2.8	-2.9 ± 5.1
	2032–2050	$+1.7 \pm 5.5$	17.7 ± 4.2	16.8 ± 3.1	$+0.9 \pm 5.3$
	2032–2048	$+2.1 \pm 5.5$	17.7 ± 4.2	16.8 ± 3.3	$+0.9 \pm 5.4$

(3.9) counts at 90% (68%) C.L., which corresponds to the half-life limit $T_{1/2}^{0\nu} \geqslant 2.0\ (3.1) \times 10^{25}$ yr at 90% (68%) C.L.[10]

Remarkably, all half-life limits, which we obtained by using our simple method of analysis and by fitting procedures, are in a good agreement with those established by the HM Collaboration [22,25]. However, on the contrast with Ref. [1], where the 2.2σ and 3.1σ effect ($0\nu2\beta$ decay of ^{76}Ge) has been found, our simple statistical analysis (and fit procedure as well) give no indications for that. In our opinion, the only explanation for the (2–3)σ signal "seen" by authors [1] is their specific choice of the energy interval for the fitting procedure. Indeed, sideband regions in [1] are very small as compared with the width of signal region ($\mathrm{SB}_L \approx \mathrm{SB}_R \approx 6$ keV), hence, in accordance with above-mentioned remarks [42] the background estimate of Ref. [1] cannot be considered as correct. To prove this statement even more firmly we have repeated both—simple statistical analysis and data fits—for the different energy ranges, beginning from our initial sideband widths and reducing them step by step down to $\mathrm{SB}_L \approx \mathrm{SB}_R \approx 6$ keV. Results of analysis of the HM data set with PSA (Fig. 1(b)) are presented in Table 1. They evidently prove absence of any indications for the effect obtained by both our methods for all energy interval chosen except for the last one 2032–2047 keV, which is practically the same as used in Ref. [1]. Thus, one can conclude that claimed (2–3)σ "effect" is only due to the unique (and incorrect) choice of the fitting interval made in [1].

Nevertheless, one can point out that small positive excess of counts in signal region is also found by our analysis and ask the question: "What is the probability that possible effect was missed?" To answer this question we will follow a procedure, which consists in the test of a simple statistical null hypothesis, H_0, against a simple alternative hypothesis, H_1, that effect exist [35,37,41]. When doing it there are two types of errors:

Type I Reject the null hypothesis H_0 when it is true. The probability of Type I error is the risk of "*false detection*" (it is called *size* of the test and is usually denoted by α).

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[10] The fit of the PSA spectrum in the region 2000–2080 keV by the maximum likelihood method (it was used because of very low statistics of this sample of data) by the sum of linear (parabolic) background and the $0\nu2\beta$ decay peak gives the area of the latter as 2.0 ± 3.1 counts (see Fig. 1(b)). It corresponds to similar $\lim S$ values: 7.0 (5.1) counts at 90% (68%) C.L.

Type II Accept the null hypothesis H_0 when alternative hypothesis H_1 is true. The probability of Type II error is the risk of "*false non-detection*" and is usually denoted by β. The value $\pi = 1 - \beta$ is called *power* of the test (it is a probability to reject H_0 when H_1 is true, that is a probability of "*right detection*").

Therefore, the procedure of effect recognizing is forced to accept some risk. Obviously, it is desirable to find a test, which always provides a maximal probability of "*right detection*" π (i.e., a minimal β) at any certain probability of "*false detection*" α. It is called a *uniformly most power* test.[11] In our case mentioned risks can be controlled by introduction of the critical level, L_C, and the minimum detection limit, L_D, which depend on the background and are defined as follows [35,36,46]: L_C is the minimal signal for which probability of "*false detection*" is less than α,[12] and L_D is the minimum signal for which probability of "*false non-detection*" is less than β, keeping at the same time previously fixed value of α. These definitions are illustrated in Fig. 2(a), where two probability density functions are shown—one for background, B, second for the measured gross signal, S, which activity above background corresponds to L_D. From this figure the expressions for L_C and L_D can be written as: $L_C = k_\alpha \sigma_b$, and $L_D = L_C + k_\beta \sigma_s = k_\alpha \sigma_b + k_\beta \sigma_s$, where σ_b and σ_s are standard deviations of the background and the measured gross signal, k_α and k_β are quantiles of the standardized normal distribution corresponding to probabilities $(1 - 2\alpha)$ and $(1 - 2\beta)$. Using these formulae, the values of L_C and L_D can be calculated for the measured background/gross signal and for different combinations of the acceptable risks, α and β. Then, a null hypothesis, H_0, can be tested against an alternative hypothesis, H_1, by comparing obtained set of L_C and L_D values with the measured difference $\Delta = S - B$.

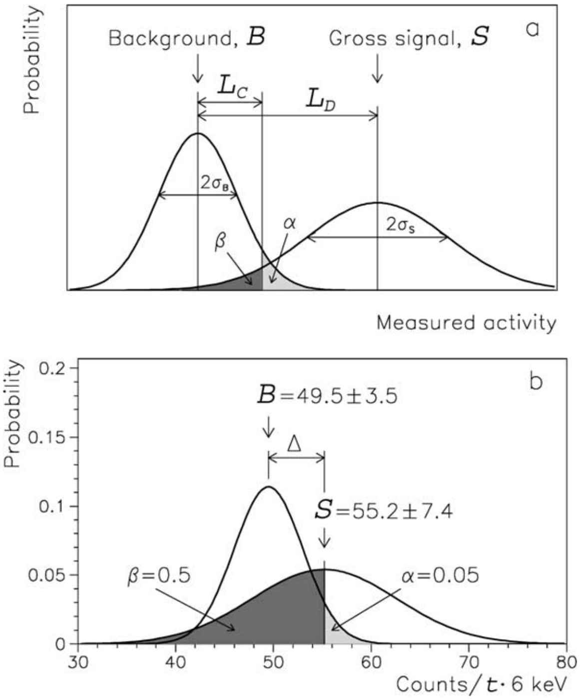

Fig. 2. (a) Relationship between critical level, L_C, minimum detection limit, L_D, and both types of errors, α and β (see text) shown in curves of two probability density functions: for measured background B and gross signal S, which activity above background corresponds to L_D. (b) The probability density functions for B and S count rates (normalized on the 6 keV energy interval and duration of experiment t) derived in our analysis of the HM data sample (54.98 kg yr).

For the data sample of the HM experiment (54.98 kg yr) we have $B = 49.5$, $\sigma_b = 3.5$, $S = 55.2$ and $\sigma_s = 7.4$ counts. Supposing that probabilities of both types of errors are equal (such a rule is widely used in order to minimize both risks and to prevent possibility of a subjective choice), we get $L_C = 5.7$ and $L_D = 17.9$ counts for $\alpha = \beta = 0.05$; $L_C = 4.5$ and $L_D = 14.0$ counts for $\alpha = \beta = 0.10$; $L_C = 3.5$ and $L_D = 10.9$ counts for $\alpha = \beta = 0.17$; etc. Comparing these values with measured difference $\Delta = 5.7 \pm 8.2$ counts, we can conclude that alternative hypothesis about existence of the effect is in clear contradiction with the available experimental data. It is also illustrated in Fig. 2(b), where two probability density func-

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[11] Unfortunately, it is difficult to find such a test because of absence of the informative/positive definition of the effect [38]. More exactly, in accordance with the Neyman–Pearson lemma a uniformly most power test does not exist in general, if the alternative hypothesis is two-sided [41]. However, it exists if the class of tests is restricted in appropriate way [43].

[12] In fact, L_C is the lowest upper limit, which can be, in principle, reached in experiment with given level of background. To some extent it is similar to definition of "sensitivity" recommended by Particle Data Group [44].

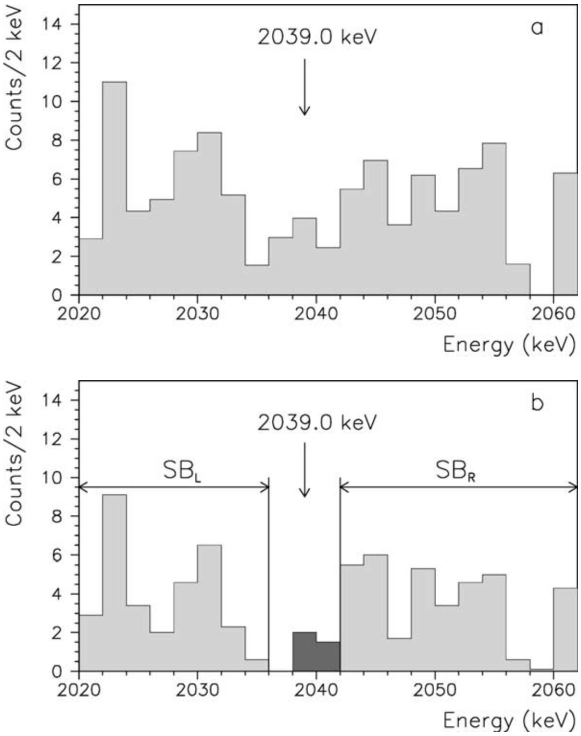

Fig. 3. Background spectra collected in the IGEX experiment with the total statistics of 8.87 kg yr in ^{76}Ge [23]: (a) sum spectrum of the HP ^{76}Ge detectors without application of PSA; (b) sum spectrum of the HP ^{76}Ge detectors with PSA.

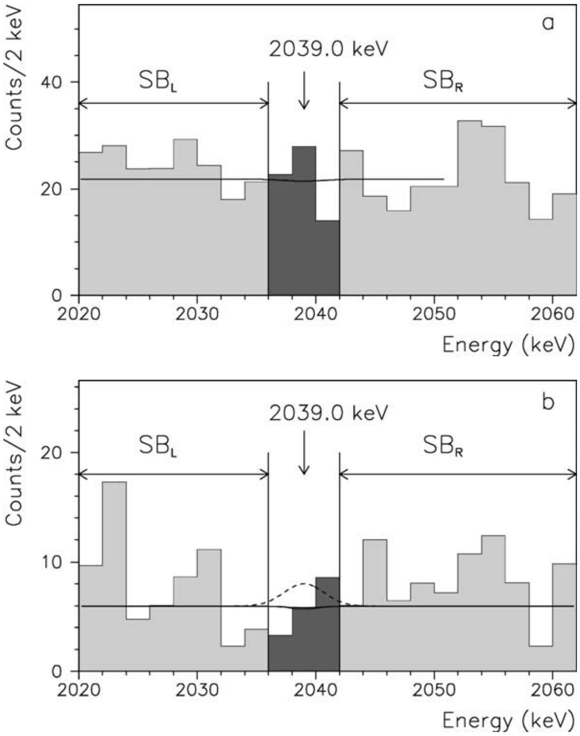

Fig. 4. Background spectra of the HP ^{76}Ge detectors obtained on the basis of the cumulative data sets of the HM and IGEX experiments: (a) sum spectrum without application of PSA (total statistics of 56.16 kg yr in ^{76}Ge); (b) sum spectrum with PSA (totally 39.4 kg yr in ^{76}Ge). Fits (see text) are shown by smooth curves. Dashed curve is the $0\nu2\beta$ decay peak of ^{76}Ge with $T_{1/2}^{0\nu} = 2.5 \times 10^{25}$ yr excluded at 90% C.L.

tions for the measured B and S are depicted. For example, with requirement that probability of "*false detection*" α must be less than 0.05, we get the risk of "*false non-detection*" $\beta = 0.5$ (hence, a probability of "*right detection*" $\pi = 0.5$), or with requirement of the reasonable value of error $\beta = 0.22$, we obtain the risk of "*false detection*" $\alpha = 0.5$. Obviously, neither statement about such a "discovery" can be accepted in normal experimental practise (we can predict the existence of the effect by flipping the coin as well).

However, if the neutrinoless 2β decay of ^{76}Ge exists at the level, which is slightly below the present level of sensitivity of experiments, it would become seen with the larger statistics, thus we have to wait for another five-ten years of measurements. Fortunately, there is a chance to increase the available statistics right now by combining the data of the HM experiment [22,25] with those of the IGEX [23], whose sum spectra, corresponding to 8.87 kg yr in ^{76}Ge, are shown in Fig. 3. Such a combination is indeed possible because both experiments use the same technique: HP Ge semiconductor detectors with the energy resolution of about 4.0 keV at 2 MeV and with very similar level of background.[13] The cumulative sum spectra (IGEX plus HM) are depicted in Fig. 4: (a) without PSA (54.98 kg yr of the HM [1] plus 8.87 kg yr in ^{76}Ge of the IGEX [23]); (b) with PSA (35.5 kg yr of the HM [25] plus 8.87 kg yr in ^{76}Ge of the IGEX [23]).

Let us repeat our simple statistical test for the effect with the cumulative spectrum without PSA depicted in Fig. 4(a). It is seen from this figure that behaviour of

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[13] We have also performed statistical test and estimate of the half-life limit with the IGEX data. For example, with the PSA spectrum (Fig. 3(b)) the $T_{1/2}^{0\nu}$ bound in the range of $(1.1\text{–}1.6) \times 10^{25}$ yr at 90% C.L. was obtained, that is in accordance with the IGEX result [23].

background is rather smooth, except one peculiarity at the energy 2054 keV (estimated area of the possible peak is 44 ± 8 counts). The signal region is fixed from 2036 to 2042 keV, where 64.6 ± 8.0 counts are contained. The width of the left sideband, SB_L, is 16 keV (2020–2036 keV), the width of the right sideband, SB_R, is 20 keV (2042–2062 keV), that is 36 keV in sum or six time larger than the signal region. The total number of counts in both sidebands is 417 ± 20 (or 373 ± 22 if taking into account the possible peak), thus expected background in 6 keV bin is 69.5 ± 3.4 (or 62.2 ± 3.7) counts. Consequently, the difference between gross signal and background is $\Delta = -4.9 \pm 8.7$ (or 2.4 ± 8.8) counts. Similarly, the χ^2 fit in the energy region 2020–2051 keV with the linear background yields -1.5 ± 8.2 counts in the anticipated $0\nu 2\beta$ decay peak.[14] Corresponding half-life limits are in the range $T_{1/2}^{0\nu} \geqslant (2.0\text{–}2.3) \times 10^{25}$ yr at 90% C.L. and $T_{1/2}^{0\nu} \geqslant (3.2\text{–}3.8) \times 10^{25}$ yr at 68% C.L.

For the data with PSA (Fig. 4(b)), there are 147 counts in both sidebands (their widths are the same: $\mathrm{SB}_L = 16$ keV, and $\mathrm{SB}_R = 20$ keV), so the expected background in 6 keV interval equals to 24.5 ± 2 counts. The signal region contains 17.7 ± 4.2 counts, hence the difference is $\Delta = -6.8 \pm 4.7$ counts. The χ^2 fit with linear background yields -0.7 ± 5.2 counts for the area of effect searched for (see Fig. 4(b)).

Again, constancy and reliability of results obtained with both spectra were tested and proved by repeating simple statistical analysis and fitting procedure for different sidebands (see Table 1, where results of such a test of PSA data are presented).

Thus, we can conclude that despite an increased statistics (by factor of ≈ 1.2 without PSA and ≈ 1.6 with PSA), the analysis of the cumulative data sets of the HM and IGEX experiments also gives no evidence for the 2039 keV peak, which can be associated with the neutrinoless 2β decay of ^{76}Ge.[15] At the same time it is interesting to note that weak peak at the energy 2054 keV is slightly enhanced in the sum spectrum without PSA (see for comparison Fig. 1(a) and Fig. 4(a)).

At last, we determine the half-life limit for the $0\nu 2\beta$ decay of ^{76}Ge on the basis of the sum HM [25] and IGEX spectrum with PSA (totally 39.4 kg yr in ^{76}Ge) depicted in Fig. 4(b). First, from the experimental difference $\Delta = -6.8 \pm 4.7$ counts the value of $\lim S$ is estimated as 7.5 (4.7) counts at 90% (68%) C.L., from which, taking into account the detection efficiency ϵ and the total Nt product, the half-life bound is derived as $T_{1/2}^{0\nu} \geqslant 2.6\ (4.2) \times 10^{25}$ yr at 90% (68%) C.L. Besides, the value of $\lim S$ was estimated by the least square fit of the energy distribution by the sum of linear background and $0\nu 2\beta$ decay peak being sought (fitting curve is presented in Fig. 4(b)). It yields the area of the $0\nu 2\beta$ decay peak -0.7 ± 5.2 counts. Conservatively accepting the latter as 0 ± 5.2 counts, the value of $\lim S = 8.7$ (5.2) counts at 90% (68%) C.L. is derived, which corresponds to the half-life limit $T_{1/2}^{0\nu} \geqslant 2.5\ (4.2) \times 10^{25}$ yr at 90% (68%) C.L.

As one can see, both methods—simple statistical approach and fitting procedure—repeated in the different energy intervals (see Table 1), give us practically the same bounds, proving by that the reliability of obtained results. The final half-life limit is set as: $T_{1/2}^{0\nu} \geqslant 2.5\ (4.2) \times 10^{25}$ yr at 90% (68%) C.L., which is the highest worldwide bound on the $0\nu 2\beta$ decay half-life published up-to-date (see review [15]). It allows us to establish the most stringent constraints on the neu-

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[14] Here and farther, when calculating the value of $\lim S$, we conservatively treat such a negative difference or area of the $0\nu 2\beta$ decay peak as zero: e.g., -4.9 ± 8.7 counts is accepted as 0 ± 8.7 counts.

[15] Even in case, if 2039 keV peak would be firmly registered, the absence of any background processes, which can imitate such a peak, must be proved. Indeed, there are near 50γ lines in the 2037–2041 keV energy interval [47,48], belonging to short-lived isotopes, part of which can be produced by cosmic muons or neutrons in the detectors and shielding materials. For example, in the thermal neutron capture on ^{63}Cu (abundance $\delta = 69.2\%$) the prompt γ quanta with $E_\gamma = 2037.5$ keV (relative yield $I_\gamma = 0.51\%$) are emitted, on ^{65}Cu ($\delta = 30.8\%$)—γ quanta with $E_\gamma = 2039.3$ keV ($I_\gamma = 0.20\%$) [49]. Neutron capture in ^{76}Ge produces ^{77}Ge ($T_{1/2} = 11.3$ h, $Q_\beta = 2702$ keV), whose β decay is accompanied by γ with $E_\gamma = 2037.8$ keV ($I_\gamma = 0.114\%$). If ^{77}Ge is created in a dead layer of Ge detector (∼ 1 mm thickness [1]), the low-energy electron could escape the detection, while γ can be registered in the same or neighbouring detector. Similarly, ^{73}Ge in a dead layer could yield γ lines with $E_\gamma = 2037.0$ keV ($I_\gamma = 0.46\%$) and $E_\gamma = 2040.5$ keV ($I_\gamma = 0.08\%$). The processes discussed above are faint, thus all mentioned γ lines should be very weak and probably they may be excluded by analyzing the measured spectrum in the whole energy range. Anyhow, this problem would arise in the future large-scale experiments with ^{76}Ge (GEM [50], GENIUS [51] and Majorana [52]), if 2039 keV peak will be observed there.

trino mass, lepton non-conservation parameters, etc., by comparing obtained $T_{1/2}$ limit with the theoretical half-life value, which can be derived on the basis of different nuclear matrix elements (NME) calculations for ^{76}Ge. For example, using calculations [53][16], we get restrictions on the neutrino mass and right-handed admixtures in the weak interaction as: $m_\nu \leqslant 0.36$ eV, $\eta \leqslant 3.5 \times 10^{-9}$, $\lambda \leqslant 5.5 \times 10^{-7}$ at 90% C.L., and neglecting right-handed contribution, as $m_\nu \leqslant 0.31$ (0.24) eV at 90% (68%) C.L. Besides, in accordance with Ref. [54] the value of the R-parity violating parameter of the minimal SUSY standard model is restricted by obtained $T_{1/2}$ limit as $\varepsilon \leqslant 2.7 \times 10^{-4}$ at 90% C.L. (calculations [55] give more stringent result: $\varepsilon \leqslant 1.1 \times 10^{-4}$).

In conclusion, with the help of a simple statistical analysis of the background spectra measured by the HM and IGEX experiments, it was clearly shown that claim of “discovery” of the $0\nu2\beta$ decay of ^{76}Ge [1] is at least premature. In order to really make such an important discovery we surely need much more statistics in mentioned experiments and/or new projects with higher sensitivity. The next generation of the super-high sensitivity 2β decay experiments, like CAMEO [58], CUORE [59], EXO [60], GEM [50], GENIUS [51], MAJORANA [52] will certainly shed light on this problem, providing at the same time crucial tests of the key theoretical models of the modern astroparticle physics.

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