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WHY IS THE CONCLUSION OF THE GERDA EXPERIMENT NOT JUSTIFIED?

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The first results of the GERDA double-beta experiment in Gran Sasso were recently presented. They are fully consistent with the HEIDELBERG–MOSCOW experiment, but *because of its low statistics cannot prove anything at this moment*. It is no surprise that the statistics is still far from being able to test the signal claimed by the HEIDELBERG–MOSCOW experiment. The energy resolution of the coaxial detectors is a factor of 1.5 worse than in the HEIDELBERG–MOSCOW experiment. The *original goal* of background reduction to 10^{-2} counts/kg/y/keV, or by an order of magnitude compared to the HEIDELBERG–MOSCOW experiment, *has not been reached*. The background is *only* a factor of 2.3 lower if we refer it to the experimental line width, i.e., in units counts/kg/y/energy resolution.

With pulse shape analysis (PSA) the background in the HEIDELBERG–MOSCOW experiment around $Q_{\beta\beta}$ is $4 \cdot 10^{-3}$ counts/kg/y/keV [1], which is *a factor of 4 (5 referring to the line width) lower* than that of GERDA with pulse shape analysis.

The amount of enriched material used in the GERDA measurement is 14.6 kg, only a factor of 1.34 larger than that used in the HEIDELBERG–MOSCOW experiment. The background model is oversimplified and not yet adequate. It is not shown that the lines of their background can be identified. GERDA has to continue the measurement for about further 5 years, until they can responsibly present an understood background. The present half-life limit presented by GERDA of $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ y (90% confidence level, i.e., 1.6σ) is still lower than the half-life of $T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \cdot 10^{25}$ y [1] determined in the HEIDELBERG–MOSCOW experiment.

Недавно были представлены первые результаты эксперимента GERDA по поиску двойного бета-распада в подземной лаборатории Гран-Сассо. Эти результаты полностью согласуются с экспериментом HEIDELBERG–MOSCOW и *в силу низкой статистики не могут что-либо сегодня доказать или опровергнуть*. Не удивительно, что эта статистика все еще далека от того, чтобы дать возможность проверить наличие сигнала, обнаруженного в эксперименте HEIDELBERG–MOSCOW. Энергетическое разрешение коаксиальных детекторов GERDA примерно в 1,5 раза хуже, чем у детекторов эксперимента HEIDELBERG–MOSCOW. GERDA *не выполнила изначальную задачу* — достичь понижения фона до уровня 10^{-2} событий/кг/лет/кэВ, т. е. примерно на порядок лучше, чем в эксперименте HEIDELBERG–MOSCOW. Имеющийся уровень фона *всего лишь* в 2,3 раза ниже, если его соотносить с шириной экспериментальной линии, т. е. брать в единицах событие/кг/лет/(энергетическое разрешение).

С учетом же анализа формы импульса (PSA) фон эксперимента HEIDELBERG–MOSCOW в области $Q_{\beta\beta}$ составляет $4 \cdot 10^{-3}$ событий/кг/лет/кэВ, что примерно *в четыре раза ниже (или в пять раз ниже, если сравнивать с шириной линии)*, чем в эксперименте GERDA с учетом анализа формы импульса.

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Масса обогащенного материала, используемого в измерениях эксперимента GERDA, составляет 14,6 кг, что всего лишь в 1,34 раза больше, чем в эксперименте HEIDELBERG–MOSCOW. Описание фона слишком упрощено и пока еще неадекватно. Не показано, что коллаборация способна идентифицировать свои фоновые линии. Для того чтобы полностью понять и адекватно описать фон, эксперимент GERDA должен продолжить измерения еще в течение ~ 5 лет. Опубликованный недавно экспериментом GERDA предел на время полураспада $T^{0\nu}_{1/2} > 2{,}1 \cdot 10^{25}$ лет (90 %-й уровень достоверности, т. е. 1,6σ) все еще ниже, чем измеренное в эксперименте HEIDELBERG–MOSCOW значение времени полураспада $T^{0\nu}_{1/2} = 2{,}23^{+0{,}44}_{-0{,}31} \cdot 10^{25}$ лет.

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INTRODUCTION

Nuclear double-beta ($\beta\beta$) decay is one of the flagships of nonaccelerator particle physics searching for beyond-Standard-Model physics underground [2]. For many years (since 1992) the HEIDELBERG–MOSCOW experiment using the first enriched high-purity ^{76}Ge detectors dominates the field in sensitivity [3].

However, recently some fresh breeze arose in the field. The EXO and the KamLAND-Zen experiments looking for $\beta\beta$ decay of ^{136}Xe reached half-life limits of order of 10^{25} y (1.6 and $1.9 \cdot 10^{25}$ y (90% C.L.), respectively) [4]. These results are consistent with HEIDELBERG–MOSCOW [1] within 1 or 2σ with the matrix elements of [5]. They unfortunately suffer, however, from low energy resolution (~ 30 times less than Ge detectors).

These days the GERDA experiment in Gran Sasso reported its first results [6, 7]. It used the idea of the GENIUS Project [8], namely installing naked Ge detectors in liquid nitrogen or liquid argon. Operating 14.6 kg of enriched ^{76}Ge — of them 10 kg from the HEIDELBERG–MOSCOW experiment — GERDA derived after exposure of 1.5 y a lower limit of $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ y at 90% confidence limit (1.6σ) from their pulse-shape selected spectrum. On this basis they claim «refuting of the HEIDELBERG–MOSCOW signal at high probability» [6]. To this experiment and this conclusion we have the following comments.

GENERAL DEFICIENCIES OF THE EXPERIMENT AND THE ANALYSIS

Half-Life and Double Line. The conclusion that the result of the HEIDELBERG–MOSCOW experiment (a signal at a 6.4σ C.L. [1]) is refuted is *wrong*.

The reason is very simple. The authors of [6, 7] compare their result to the line at ((2038.1–2038.5)$\pm$0.5(stat.)$\pm$1.2(syst.)) keV in the *full* (not PSA-treated) spectrum taken by HEIDELBERG–MOSCOW (exposure 71.7 kg $\cdot$ y), see [9]. They ignore the result, given in [1], that this line at $Q_{\beta\beta}$ in the HEIDELBERG–MOSCOW experiment is *a double* line which cannot be resolved by the energy resolution of a Ge detector. *Two lines* of almost equal intensity occur at 2037.5 and 2039.3 keV. They can be separated, however, by pulse shape analysis (PSA), since the first one consists essentially of single site events as expected for a $0\nu\beta\beta$ line, the second essentially of multiple site events, as expected for a gamma line. Their intensities are 11.0 ± 1.8 and 10.3 ± 3.3, respectively, adding to the line found in the full (not PSA-treated) spectrum of 19.6 ± 5.4 events obtained after 51.39 kg $\cdot$ y (the time during which the time structure of pulses has been recorded in the HEIDELBERG–MOSCOW experiment). The $0\nu\beta\beta$ half-life is consequently $(2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ y [1], and not $(1.19^{+0.38}_{-0.22}) \cdot 10^{25}$ y as deduced in [9] from the full spectrum and as assumed in the GERDA report.

Therefore, in their window around $Q_{\beta\beta}$ GERDA should expect (3.1 ± 0.8) events only (but *not* 5.9 ± 1.4 (1σ error!) as they claim). This signal should be searched at an energy of (2037.5±0.5(stat.)±1.2(syst.)) keV, where the single site line is found, *not* at 2039 keV where we observe the multiple γ-line.

The fact that the line at $Q_{\beta\beta}$ in the full spectrum in the HEIDELBERG–MOSCOW experiment is a double line has been observed independently also by I. Kirpichnikov [10]. He found further indication of a tiny third line at ~ 2034.5 keV, unresolved from the line seen at 2038.5 keV. It shows up also in our spectrum of multiple site events rejected by PSA (see Figs. 5 and 6 of DARK2007 Proc. [1, 2]). He claimed that the lines at 2039.3 and 2034.5 keV each are a sum line of two consecutive gamma transitions (as it is the case also for the 2016.7 keV line — see below and [12]). He also showed that this is supported by the GEMMA Experiment [11]. So their existence does not contradict the findings of Gromov et. al [13] and Dörr et al. [14] that there is *no* gamma transition of this energy in known radioactive isotopes.

Concluding, GERDA has to compare its 1.6σ limit of $2.1 \cdot 10^{25}$ y to the HEIDELBERG–MOSCOW 6.4σ signal of single site events yielding $T_{1/2} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ y [1]. This means that the GERDA limit is lower than the HEIDELBERG–MOSCOW half-life, and is fully consistent with HEIDELBERG–MOSCOW, but *because of its low statistics GERDA cannot prove anything at this moment*.

In their slides 54–57 [6] they show their 90% upper limit. This is *not* a fit, but simple superposition of a Gaussian line with fixed energy, intensity and width on the background. In the upper parts of slides 56, 57 [6], they compare this to their expectations from the erroneously assumed half-life for the HEIDELBERG–MOSCOW experiment [9] — and *not* at the energy position where the line has been observed. The *correct* expectation from HEIDELBERG–MOSCOW [1] is shown in Fig. 1 of this paper, which should replace the

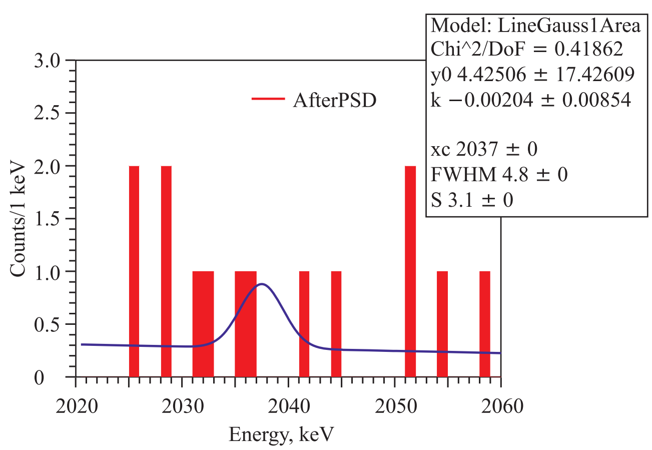

Fig. 1. GERDA spectrum *after* pulse shape discrimination (PSD), from [6,7]. The solid line corresponds to the correct expectation from the HEIDELBERG–MOSCOW experiment [1,2] (see text)

dotted red line in the slides 56, 57 of [6]. In Fig. 1, from the 5 parameters of the fit program all, *except the two background parameters*, are fixed: position of the line and its expected intensity *according to* [1], FWHM according to GERDA experimental resolution.

No contradiction to the GERDA result can be seen here.

But even the discrepancy between the limit of $T_{1/2} > 2.1 \cdot 10^{25}$ y (90% C.L., i.e., 1.6σ level) of GERDA and the half-life of $1.19 \cdot 10^{25}$ y, which they assumed erroneously, is less than the 2σ uncertainty of this half-life (which is $(1.19^{+1.08}_{-0.39} \cdot 10^{25}$ y). Already this certainly would *not* justify the strong statement of refuting the HEIDELBERG–MOSCOW result.

Background and Background Model Building. It has been mentioned that *the main goal* of reaching a background of 10^{-2} counts/kg/y/keV, or by an order of magnitude lower than in the HEIDELBERG–MOSCOW experiment, was *not reached* by GERDA. The background of GERDA in the energy window 2000–2060 keV around $Q_{\beta\beta}$ is 0.031 counts/kg/y/keV. This is a factor of 3.5 lower than the HEIDELBERG–MOSCOW background of 0.113 ± 0.007 counts/kg/y/keV [9]. It is, however, only by a factor of 2.3 smaller than HEIDELBERG–MOSCOW, if we refer to the line width, i.e., in units of counts/kg/y/energy resolution. It is the latter value which defines the sensitivity of the experiment concerning background (without PSA). *With* pulse shape analysis the background in the HEIDELBERG–MOSCOW experiment is $\sim 4 \cdot 10^{-3}$ counts/kg/y/keV [1] around $Q_{\beta\beta}$ (range 2000–2060 keV). This is *a factor of 4 (5, when referring to the line width) lower* than that found by GERDA with PSA.

A general criticism has to be made concerning the treatment of background by GERDA, which is completely unsufficient at this moment. The main point is that they do not show that all lines in the spectrum are understood. The spectra are shown in [6, 7] — except for a range of $\sim 1900{-}2200$ keV around $Q_{\beta\beta}$ — *only binned into energy bins of 5 keV*. This is hardly adequate to an energy resolution of 4.8 keV. More critical is that they compare most part of their spectra *in a 30 keV binning* to a background model averaging also over 30 keV. This means that, for most part of the spectrum, individual gamma lines are not shown and their intensities were not determined or at least are not listed. In this way the usual procedure of localizing the sources of radioactive impurities in the setup cannot be applied. Further, in such a way it cannot be checked whether there exist lines in the spectrum not included in their background model. Strange is also that they (their slide 55, from [6]) exclude «lines» at 2104 and 2119 keV from their background — at least the first of them being not visible. If the 2104 and 2119 keV lines are accepted as lines, then there are *many* lines in their 2 keV-binned spectrum to be accepted and to be explained.

Also about the background in the *individual* detectors nothing can be said in this way. It is clear that under such circumstances the background cannot yet be claimed to be understood.

In the HEIDELBERG–MOSCOW experiment more than 70 lines have been seen and *identified* in the spectrum [13, 14]. A special investigation of the background around $Q_{\beta\beta}$ and of the intensity ratios of the ^{214}Bi lines, some of which occur in the window around $Q_{\beta\beta}$ (range 2000–2100 keV), has been performed with a ^{226}Ra source [12]. In particular, the effect of true coincidence summing on the intensities has been studied, in particular, for the line at 2016.7 keV, which as $E0$ transition can be seen only as sum line of two consecutive gamma transitions — as the line identified at 2039.3 keV (see above).

Concerning their background models: The comparison between measured spectrum and calculated background in the GERDA reports, in spite of the smoothening of the data in 30 keV bins — which *suppresses* local deviations — shows differences up to a factor of 2 and more (a factor of 2.3 in the region around $Q_{\beta\beta}$!) (Slides 33, 34 in [6]). This raises the question whether these models are sufficient.

Highly surprising is the statement that a so-called minimal background model *not* including lines from ^{214}Bi should be sufficient. ^{214}Bi was found in the HEIDELBERG–MOSCOW experiment to yield the famous lines closest to $Q_{\beta\beta}$ [9,12], and is clearly seen also by GERDA (e.g., at 2204 keV), and seems to show up also already in the region around $Q_{\beta\beta}$.

Figure 2 shows a fit which could complement their full spectra shown in slides 54, 55, 56 (lower part) of [6].

Besides the strong ^{214}Bi line at 2204 keV, some lines of low statistics (between 1 and 2σ) are indicated in the range around $Q_{\beta\beta}$ (2000–2120 keV) at energies corresponding to ^{214}Bi lines (2016.7 keV, not resolvable from 2010.7 and 2021.9 keV Bi lines), 2052.9, 2119 keV. A line at 2065 keV is not understood. Also a line at 2037.5 keV is indicated, not separable from 2034.5 and 2039.3 keV lines. Its intensity of (4.9 ± 3.8) counts is consistent with the expectation from HEIDELBERG–MOSCOW [1,2], which is (4.4 ± 1.0) counts, adding the expectations from the 2037.5 keV line and for half of the 2039.3 keV line (because of lower background of GERDA without PSD). In case GERDA would not see the 2039.3 keV line, the expected value from HEIDELBERG–MOSCOW would be 3.1 ± 0.8, both being fully consistent with the above given fit. Considering the *number of events* to be expected in the GERDA spectrum before PSD, in a region of 2 FWHM (4.6σ) around 2037.5 keV, a value of (8.9 ± 1.8) events is expexted, with the background of 0.5 counts per keV determined by the fit in Fig. 2. The observed value of events in this range is 10. So, the present GERDA result is fully consistent with the result of HEIDELBERG–MOSCOW [1,2].

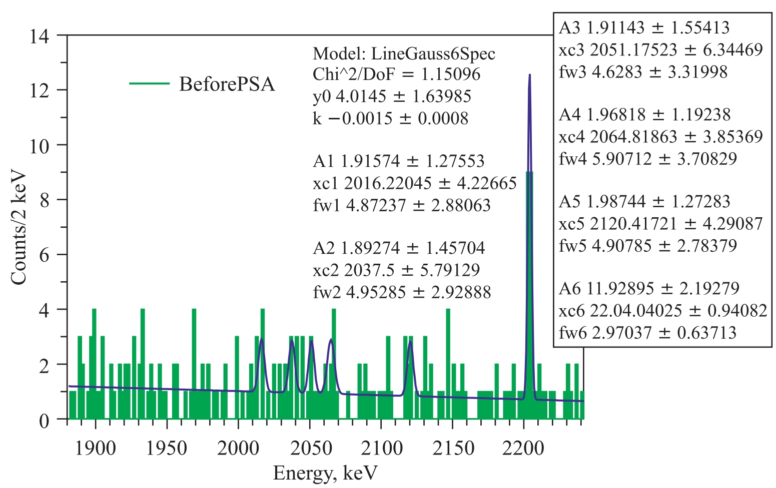

Fig. 2. GERDA spectrum *before* PSD with 2 keV binning (from [6,7]). Besides the strong ^{214}Bi line at 2204 keV, our fit finds indications of lines (on $1{-}2\sigma$ level) at known positions of ^{214}Bi lines 2016.7 keV (not separable from 2010.7 and 2021.8 keV), 2052.9, 2119 keV. Further, it finds a line at 2037.5 keV (not separable from lines 2034.5 and 2039.3 keV). (The parameter «A» of the fit is connected with the intensity «N» by $N = S/2$, $S = A(\mathrm{FWHM}/2)\sqrt{\pi/\ln 2}$. The other parameters are self-explainable (see text))

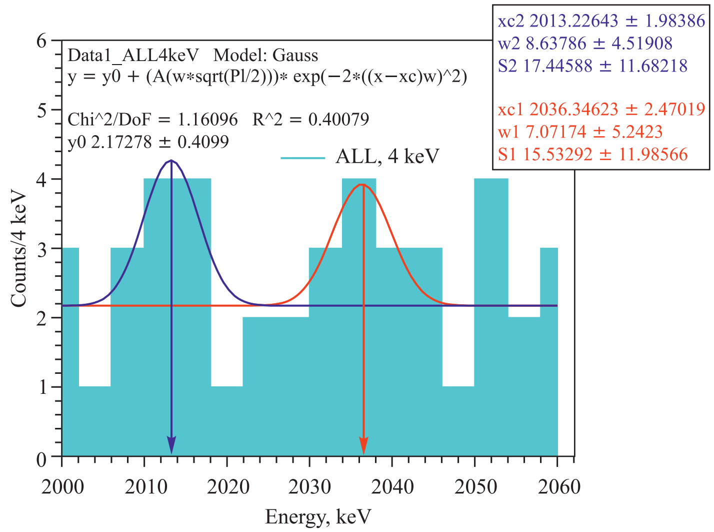

Fig. 3. The GERDA spectrum *before* PSD, with 4 keV binning and our fit. Two structures arise around 2014 keV (unresolved ^{212}Bi — 2010.7, 2016.7, 2021.8 keV), and a broad unresolved structure covering the range 2034–2040 keV (lines 2034.5, 2037.5, 2039.3 keV). (In the fit «S» determines the number of counts N in the line, $N = S/4$)

Figure 3 shows the full GERDA spectrum (before PSA) with a binning of 4 keV. Two structures dominate the spectrum, a broad line at the location of the unresolved ^{214}Bi lines at 2010.7, 2016.7 and 2021.8 keV (known from the HEIDELBERG–MOSCOW experiment) [9], and a broad unresolved structure covering the range 2034 to 2040 keV, which includes the lines 2034.5, 2037.5 and 2039.3 keV known from HEIDELBERG–MOSCOW [1]. The fit yields for the second line $E = (2036.4 \pm 2.5)$ keV and an intensity of (3.9 ± 3.0) events, consistent with the expectation (see above) of (4.4 ± 1.0) events. A word of caution: It should be mentioned, however, that different ways of 4 keV binning can give rather different result. Thus, Figs. 2 and 3 show that at the low statistics GERDA has at present, and with the low energy resolution the GERDA detectors have, at this moment it is premature and marginal to search for resolved lines in this region. The *statistics* of GERDA at present is *simply not sufficient* to check the result of the HEIDELBERG–MOSCOW experiment. But what is found is consistent with the expectation from HEIDELBERG–MOSCOW [1, 2].

The GERDA report claims no excess of signal counts above background. However, even according to their Table (Slide 52 in [6]) an excess *is there*.

Unusual is that the authors show and determine the background spectrum not over the full measuring time (November 2011 until May 2013) but only until January 2013 [6, 7, 18]. The reason should be given: Why 4–5 months of statistics remained unused? One would need some further proof that the background during the period January to May 2013 was the same as in the period before!

Detector Resolution and Stability of Electronics. The energy resolution and its time stability of the coaxial detectors through 1.5 years of operation is rather modest, the energy of the 2614.5 keV Th line floating between -1.4 and $+2.5$ keV around the average value. The average resolution lies for the different detectors between 4.2 and 5.8 keV, and averaged over the detectors is 4.8 keV. This is a factor of 1.5 worse than the resolution of the *same* detectors during eight years of measurement in the HEIDELBERG–MOSCOW experiment, which was 3.27 keV [9]. The reason should be given. This could also indicate some time instability of the electronics in the GERDA experiment. No analysis of a possible temperature dependence of the setup and electronics is mentioned.

Pulse Shape Analysis. The training of the neuronal net for GERDA is done with the method given in [16] using the 1592.5 keV double escape line of the 2614.5 keV ^{228}Th line for simulating single site events, and the 1612 keV total absorption peak from the ^{228}Th daughter nuclide ^{212}Bi for multiple site events. Unfortunately, the time structure of all individual events in the relevant range of energy around $Q_{\beta\beta}$ is *not* shown by GERDA. The reduction of the γ-background is rather modest (order of factor 2).

There are, however, still differences between $0\nu\beta\beta$ (and $2\nu\beta\beta$) events and DE–γ-events in time structure and size (partial volumes in the Ge detector inside which the energy of the events is released), see Monte Carlo simulations in [15].

These differences of $0\nu\beta\beta$ events of different effective neutrino mass m and right-handed current parameters θ, λ from single site (DE) γ events are such that even with the typical spatial resolution of a large Ge detector it might not be excluded to separate $0\nu\beta\beta$ events sharper from any kind of γ-event, if the neuronal net could be properly «calibrated».

In [1] this has been tried in some empirical way, with the result of a drastic further reduction of the *whole* γ-background to $\sim 4 \cdot 10^{-3}$ counts/kg/y/keV (see [1] and also Fig. 3 (left) in [9]). With this reduction the candidate $0\nu\beta\beta$ line stands out clearly of the background.

Problems with Detectors in Liquid Argon? Despite GERDA operated its detectors in liquid argon in shrouds of very thin copper (does this mean that it is tried to *not* use naked detectors?) already two detectors could not be used. This led to the fact that instead of 17.7 kg of enriched material only 14.6 kg have been used (not much more than the 10.9 kg used in the HEIDELBERG–MOSCOW experiment). As reason was given too high leakage current. Nothing is said in the report about the behaviour of the leakage currents of the other detectors as function of running time in the liquid argon.

The experience from our GENIUS Test Facility, in which we operated six (nonenriched) naked Ge detectors over the period of three years in Gran Sasso was the following [19, 20]: Limited long-term stability of naked detectors in liquid nitrogen as a result of increasing leakage current. After three years none of the six detectors was working any more with the nominal leakage current. Three of the detectors did not work any more at all.

CONCLUSIONS

The most sensitive double-beta decay experiments *at present under operation*, EXO and KamLAND-Zen [4] and GERDA [6, 7] reported lower limits for neutrinoless double-beta decay on a 90% C.L., which are consistent with the 6.4σ signal delivered by the HEIDELBERG–MOSCOW experiment [1]. All of these experiments plan improvements of their sensitivity. The future SNO+ experiment with the $\beta\beta$ emitter ^{130}Te still is only under discussion [17]. It is obvious that it will take quite some more years, until checking of the HEIDELBERG–MOSCOW positive result becomes possible.

In the case of EXO and KamLAND-Zen, the modest energy resolution of $\sim$ 90 keV may make serious problems in the moment where indications of a signal might be found — remember the lines close to the $0\nu\beta\beta$ line from HEIDELBERG–MOSCOW.

In the case of GERDA:

1. The treatment of background data, which at present is on an unacceptable level, should be improved considerably. It is not acceptable that no list of identified lines and intensities exists and consequently no comparison with expectations. Consequently, no satisfactory localization of the radioactive impurities in the setup could be performed. It is further not acceptable that lines remain unexplained in the spectrum.

2. The statistics of the experiment has to be decisively improved before any relevant statements can be made, to avoid premature conclusions as in the present report.

3. The reasons for the limited energy resolution of the detectors have to be explained, and the resolution has to be improved to an acceptable level.

4. The time structure of their events in the relevant energy range around $Q_{\beta\beta}$ should be individually shown, and also their fits by their pulse shape approximation library (as has been done in [1]).

5. In view of the experience with GENIUS-TF [19, 20], the development of the leakage currents of the detectors as function of time should be shown. After two detectors already did not work because of too high leakage current in the present run of GERDA, it should be made sure that not more detectors will be lost by the operation in liquid argon.

Because of its similar background and detector mass, *GERDA would require similar measuring times* as HEIDELBERG–MOSCOW to get comparable statistics.

Some outlook on the future of $\beta\beta$ experiments is given in [20].

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