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Lessons after the evidence for $0\nu\beta\beta$ decay

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Abstract
This communication describes the lessons we have to draw after the observation of neutrinoless $\beta\beta$ decay on a 6σ level by the enriched ^{76}Ge experiment in Gran Sasso, for present and future experiments (a) to fulfill the task to confirm the present result (b) to deliver additional information on the main contributions of effective neutrino mass and right-handed weak currents etc. to the $0\nu\beta\beta$ amplitude. It is pointed out that presently running and planned experiments are not sensitive enough to check the present evidence on a reasonable time scale. More important, the only way to get information on the individual contributions of m, η, λ etc to the $0\nu\beta\beta$ amplitude is to go to completely different types of experiments, e.g. mixed-mode β^+EC decay experiments, such as ^{124}Xe decay, on a 10^{27} y sensitivity level.

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1. Final status of search for $0\nu\beta\beta$

What is the main result from the HEIDELBERG-MOSCOW (HM) experiment (see [1–5]).

(1) There is now a $>6\sigma$ signal for $0\nu\beta\beta$ decay.
(2) The neutrino is a Majorana particle.
(3) Total lepton number is violated.
(4) The neutrinos are (if we assume vanishing contributions of right-handed weak currents and of other contributions to the $0\nu\beta\beta$ amplitude, see below) degenerate in mass or (if the LSND result is confirmed) allow existence of a *sterile* neutrino [2, 4].
(5) The $0\nu\beta\beta$ process yields very strong limits for other fields beyond SM physics often very competitive with high energy accelerators (see [6–8]).

To put the experiment into historical perspective, the first (non-geochemical) discovery of $2\nu\beta\beta$ decay, in 1987 with a half-life of 1.1×10^{20} years for ^{82}Se, relied on a 2.2σ signal (35 events) [9].

Now we see this decay process, for ^{76}Ge, in the HM experiment with 160 000 events ($T_{1/2}^{2\nu} = 1.74 \times 10^{21}$ years) [10], i.e. the experimental sensitivity has been increased by a factor of 50 000! This is what *allowed us* to see the $0\nu\beta\beta$ signal, with a half-life of 1.19×10^{25} years, on a $>6\sigma$ cl [2, 5] (without methods to reduce the γ-background on a 4.2σ level). The experiment is the by far the most sensitive $0\nu\beta\beta$ experiment in 13 years and its sensitivity will be unfortunately not reached by other experiments in the quite far future (see below).

It has the largest source strength ever in operation (11.0 kg), the lowest background in such a type of experiment (0.17 counts kg yr keV without pulse shape analysis), the highest efficiency for detection of $\beta\beta$ events (~95%), the highest energy resolution (~3.3 keV), the highest duty cycle and the highest collected statistics (71.7 kg years), i.e. by a factor of 8.2 more than one of the other ^{76}Ge experiments (IGEX) which finished operation in 1999 (see e.g. [11]). Further, the background of the experiment is very well understood from extensive Monte Carlo simulations [10] and from independent analysis by [12].

Of decisive importance for the reduction of the γ-background in the range of the $Q_{\beta\beta}$ value of the $0\nu\beta\beta$ process was, to develop methods of pulse shape analysis which were able to separate $0\nu\beta\beta$ from γ background events. We have developed two independent methods allowing us to project out $0\nu\beta\beta$ events with practically no background from surrounding γ-rays. One is based on application of a neuronal net [2, 5, 13], the other on calculated libraries of pulse shapes of $\beta\beta$-like events, starting from Monte Carlo simulated time history and spatial distribution of $0\nu\beta\beta$ events as a function

[1] Spokesman for HEIDELBERG–MOSCOW, GENIUS-TF and HDMS collaborations, http://www.mpi-hd.mpg.de.non acc/

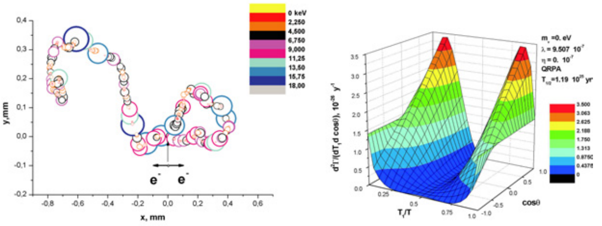

Figure 1. Left: typical calculated event for $0\nu\beta\beta$ decay without photon emission (bremstrahlung). Right: calculated spectral angular correlation for the $\langle\lambda\rangle^2$-term for $0\nu\beta\beta$ decay of ^{76}Ge (see [3]).

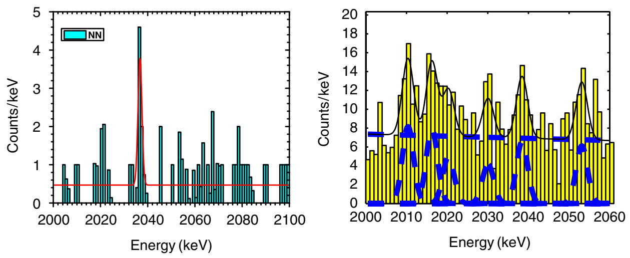

Figure 2. Left: the pulse shape selected spectrum in the range 2000–2100 taken with detectors 2,3,4,5 and the corresponding full spectrum of all five detectors in the range 2000–2060 keV (right), in the period 1995–2003 (see [2, 5]).

of location in the detector (including the dependence on the spectral angular correlation of the emitted electrons) [3, 14] (see figure 1).

Both methods *fulfill the criteria* required to prove observation of neutrinoless $\beta\beta$ decay: (i) select $0\nu\beta\beta$ events at $Q_{\beta\beta}$; (ii) reduce strongly surrounding γ-events. In the period 1995–2003, which delivered the main set of data, the time structure of all events has been measured, using 250 MHz flash ADCs.

We show here in figure 2 the spectrum selected by the neuronal net around $Q_{\beta\beta}$ (to be compared with the measured full spectrum, see [2, 15]). The selected spectrum over the full energy range now is similar in shape to a $2\nu\beta\beta$ spectrum [2]. The signal at $Q_{\beta\beta}$ has a confidence level of 6.4σ (7.05 ± 1.11 events). The other method gives similar results [5].

The energy of the line observed, (see [5]) seems to be slightly below the 'best' value reported for $Q_{\beta\beta}$ [16] of 2039.006 ± 0.050 keV. Other measurements report $Q_{\beta\beta} = 2040.71 \pm 0.52$ keV, 2038.56 ± 0.32 keV and 2038.7 ± 2.2 keV [16].

2. Lessons for present and future

The actual experimental status of double beta research is in 2006 similar to what it was in 2001. There is an observed signal and various experiments trying to check this result (some of them meanwhile stopped operation). What is required: (i) *very good energy resolution*. Not fulfilled by NEMO III and EXO which have 400 and 100 keV, respectively, to be compared to 3.3 keV in the HM experiment [2, 15]. (ii) *Large efficiency*. Nemo III has only 14%, i.e. a 10 kg experiment is effectively only a 1.4 kg experiment. (iii) *The measured spectrum should be shown and analysed over the full energy range* to show that the background is fully understood. (iv) The $2\nu\beta\beta$ spectrum should be measured as well to help normalization of the $0\nu\beta\beta$ matrix element. This is at present not possible with sufficient precision for CUORICINO/CUORE.

2.1. Problems

The main problem is that present and future 'confirmation' experiments partly because of the reasons mentioned are not sensitive enough: a good example is the NEMO III experiment. The half-life limits reached (at a 1.5σ level) of $T^{0\nu}_{1/2} = 1.0 \times 10^{23}$ and 4.6×10^{23} years for ^{100}Mo and ^{82}Se (see [25]) after 389 days of effective measurement are a factor 20 away from the half-lives required to check the HM result on a 1.5σ level. Since the half-life is connected with the measuring time by $T^{0\nu}_{1/2} \sim \sqrt{tM/\delta EB}$, this means that NEMO III would have to measure *more than 400 years, to see the signal on a 1.5σ level*, and correspondingly longer, to see it on a higher cl [15]. CUORICINO: which has the general problem, that it *cannot* distinguish between β and γ-events, and because of its high background cannot see the $2\nu\beta\beta$ spectrum of ^{130}Te, could see the HM signal assuming an uncertainty in the knowledge of the nuclear matrix element [17] of a factor of only 2, within 1 and 30 years on a 1.5σ cl [15]. It can thus *never disprove* the HM result (see also [24]). The large version CUORE with a factor of 16 larger mass also would need many years for a statement on a 6σ level. EXO: the main problem is that *no tracks* are visible in a liquid ^{136}Xe experiment [18]. This kills the main idea of the experiment to separate $\beta\beta$ from γ events, and just reduces it to a complicated calorimeter. Since the other main idea, laser identification of the daughter nucleus, is not (yet) working, the present rather modest aim is to reach a background level as reached in the HM experiment, instead of the factor of 1000 less, projected earlier [19]. GERDA: (the copied GENIUS project proposed in 1997 [20], planning to operate naked ^{76}Ge crystals in liquid nitrogen). Our earlier Monte Carlo calculations promised a large potential for $\beta\beta$ research. The only long-term experience with naked detectors in liquid nitrogen has been collected since then with our GENIUS-test-facility in Gran Sasso. For reasons why any GENIUS-like project will not be able to confirm our evidence in a short time, see our second report in this conference.

Concerning expected information on the ν mass, there is another problem in present experimental approaches. Even if one of these $\beta^-\beta^-$ experiments would be able to confirm the HM result, no *new* information would be obtained.

It is known for 20 years—but surprisingly often overlooked (see e.g. [23])—that a $\beta^-\beta^-$ experiment can give information on the effective neutrino mass *only* under some *assumption* on the contribution of right-handed weak currents (parameters η, λ) or others like SUSY…to the $\beta\beta$-amplitude (see e.g. [6]). *In general* one obtains *only an upper limit on* $\langle m \rangle$. So if neutrino masses are deduced from $0\nu\beta\beta$ experiments, this is always done under the assumption of vanishing η, λ etc. In that sense it is highly premature to compare as often done such a number with numbers deduced e.g. from WMAP or other cosmological experiments, or to use it as a landmark for future tritium experiments other than as an upper limit.

It is unfortunate that even an additional high-sensitive $\beta^-\beta^-$ experiment (e.g. ^{136}Xe) *together* with the ^{76}Ge HM result can give *no* information to decide the individual contribution of $\langle m \rangle$, $\langle \eta \rangle$, $\langle \lambda \rangle$ to the $0\nu\beta\beta$ decay rate. This has been shown already in 1994 [21].

2.2. Proposed way out

In the same paper [21] it has been shown that the only realistic way to get this information on the individual contributions of m, η, λ is to combine the $\beta^-\beta^-$ result from ^{76}Ge (HM), with a very high-sensitivity (level of 10^{27} y) mixed mode β^+EC decay experiment (e.g. of ^{124}Xe).

So it might be wise to combine future efforts to confirm the HM result with a possibility to pin down the various contributions to the $0\nu\beta\beta$ decay amplitude, (*instead of just trying a repetition of existing information*).

3. Summary and outlook

We reached with the HEIDELBERG-MOSCOW experiment [2, 5, 22], what we wanted to learn from our large GENIUS project, proposed in 1997 [20] at a time where a signal was not yet seen—namely observation of $0\nu\beta\beta$ decay. There is now a $>6\sigma$ signal for $0\nu\beta\beta$ decay. The neutrino is a Majorana particle. Total lepton number is violated. Presently running and planned experiments do not seem to be sensitive enough to check the HM result on a reasonable time scale. In particular they *cannot* determine the *neutrino mass* and the contributions of right-handed weak currents.

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