Neutrinoless Double Beta Decay from ^{76}Ge

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Abstract

Neutrinoless double beta decay is one of the most sensitive approaches in non-accelerator particle physics to take us into a regime of physics beyond the standard model. This article is a review of the experiments in search of neutrinoless double beta decay from the most successful emitter isotope ^{76}Ge. Following a brief introduction of the process of double beta decay from ^{76}Ge, the results of the very first experiments IGEX and Heidelberg-Moscow which give indications of the existence of possible neutrinoless double beta decay mode has been reviewed. Then ongoing efforts to substantiate the early findings are presented with the Majorana experiment as a next generation experimental approach which will allow a very detailed study of the $0\nu\beta\beta$ decay mode is discussed.

Keywords: neutrinoless double beta decay, Majorana particle, single-site events, pulse shape discrimination.

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1. Introduction

Neutrinoless double beta decay is one of the most sensitive approaches with great perspectives to test particle physics beyond the Standard Model. There is immense scope to use $0\nu\beta\beta$ decay for constraining neutrino masses, left–right–symmetric models, interactions involving R-parity breaking in the supersymmetric model and leptoquark scenarios, as well as effective lepton number violating couplings. Experimental limits on $0\nu\beta\beta$ decay are not only complementary to accelerator experiments but at least in some cases competitive or superior to the best existing direct search limits. The steadily improving experimental limits on the half-life of $0\nu\beta\beta$ can be translated into more stringent limits on the parameters of these new physics scenarios.

In the process of single beta decay an unstable nucleus decays by converting a neutron in the nucleus to a proton and emitting an electron and an anti-neutrino. For this to be possible the final nucleus must have a larger binding energy than the original nucleus. For the discussed ^{76}Ge, the nuclei with atomic number one higher which is ^{76}As have a smaller binding energy, preventing beta decay from occurring but the nuclei with atomic number two higher which is ^{76}Se has a larger binding energy, so the "double beta decay" process is allowed. In double beta decay two neutrons in the nuclei are converted to a couple of protons, with the emission of two electrons and two anti-neutrinos. For some nuclei, the process could occur as conversion of two protons to neutrons, with emission of two neutrinos and absorption of two orbital electrons (double electron capture). If mass difference between the parent and daughter atoms is more than 1022 keV (two electron masses), another branch of the process becomes possible, with K-capture of an orbital electron and emission of a positron. And, at last, when the mass difference is more then 2044 keV (four electron masses), the third branch of the decay arises, with emission of two positrons ($\beta^+\beta^+$ decay). All these kinds of ββ decay are predicted but have not been observed yet. The processes described above are also known as two neutrino double beta decay, as two neutrinos (or anti-neutrinos) are emitted. Double beta decay, the rarest known nuclear decay process, can occur in these different modes:

$$2\nu\beta\beta\text{ -decay : } A(Z,N) \rightarrow A(Z+2, N-2)+2e^- +2\bar{\nu} \quad (1.1)$$
$$0\nu\ \beta\beta\text{ -decay : } A(Z,N) \rightarrow A(Z+2, N-2) + 2e^- \quad (1.2)$$
$$0\nu(2)\ \chi\ \beta\beta\text{ -decay : } A(Z,N) \rightarrow A(Z+2, N-2)+2e^- + (2)\ \chi \quad (1.3)$$

If the neutrino is a Majorana particle, meaning that the anti-neutrino and the neutrino are actually the same particle then it is possible for neutrinoless double beta decay to occur. In 0νββ decay the emitted neutrino is immediately absorbed (as its anti-particle) by another nucleon of the nucleus, so the total kinetic energy of the two electrons would be exactly the difference in binding energy between the initial and final state nuclei. Experiments have been carried out and proposed to search for the neutrinoless double beta decay mode, as its discovery would indicate that neutrinos are indeed Majorana particles and allow a calculation of neutrino mass. While the two-neutrino mode (1.1) is allowed by the Standard Model of particle physics, the neutrinoless mode (0νββ) (1.2) requires violation of the total lepton number ($\Delta L=2$). This mode is possible only if the neutrino is a Majorana particle, that is, the neutrino is its own antiparticle. The 0ν mode in (1.3) is known as the Majoron neutrinoless mode as it involves the emission of Goldstone bosons called the Majoron which appear in models where the neutrino acquires a Majorana mass via spontaneous breaking of a global lepton number symmetry. The symmetry breaking Goldstone boson in these models is the Majoron, which can be emitted in double beta decay processes.

2. Double Beta Decay: A Rare Process

Weak decays typically involve long decay half-lives, a second-order weak process will involve considerably longer half-lives, and in the case of two-neutrino double beta decay, lifetimes on the order of 10^{18} years or much greater are expected. Considering the age of the universe is only approximately 10^{10} years old, these half-lives are exceedingly difficult to measure. As for the process itself, it arises in certain cases of even-A nuclei, where A is the mass number and is the sum of the number of protons and neutrons ($A = Z + N$). For even-A nuclei, the strong pairing force between like nucleons (neutrons like to be paired with other neutrons in a given nucleus, with the same true for protons), the binding energy of even-even nuclei (even number of protons and even number neutrons) is larger than that of odd-odd nuclei (odd numbers of protons and neutrons). This fact results in two separate parabolas on a plot of binding energy, one parabola for even-even nuclei and one for odd-odd. Consequently, one occasionally finds a situation where two even-even nuclei for a given mass number A are stable against ordinary beta decay. However, the heavier nucleus is not fully stable and can decay to the lighter nucleus via normal double beta decay, a second-order process, whereby the nuclear charge changes by two units. The even-even ^{76}Ge nucleus makes a transition from its 0^+ state (positive parity) to the 0^+ ground state of ^{76}Se with a Q-value of 2039 keV and hence for observing the neutrinoless double beta decay mode we expect to observe a sharp peak at this Q-value energy.

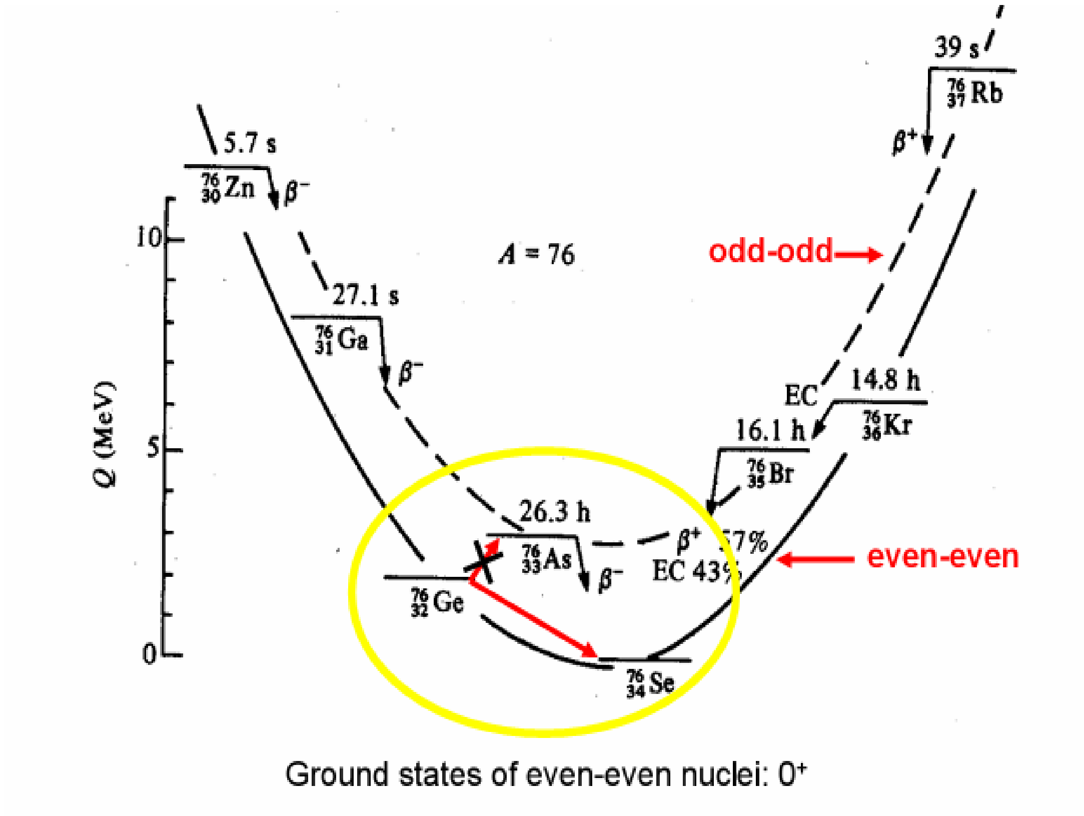

Fig.1: Mass parabola showing allowed and forbidden transition from ^{76}Ge

In the standard model, when a neutron decays it emits a right-handed antineutrino, whereas neutrons absorb left-handed neutrinos. Therefore, for this exchange to occur, the neutrino must be its own antiparticle; that is a Majorana particle. In addition, it must have some mass so it would not be in a pure helicity state. The development of the next standard model of particle physics requires that we form an understanding of these two characteristics of the neutrino. In neutrinoless double beta decay, an antineutrino emitted at the first vertex is absorbed at the second vertex or that a virtual neutrino emitted by a neutron is absorbed by the second neutron participating in the double beta decay. Thus for this non-standard process there is a violation of the total lepton number with ΔL=2.

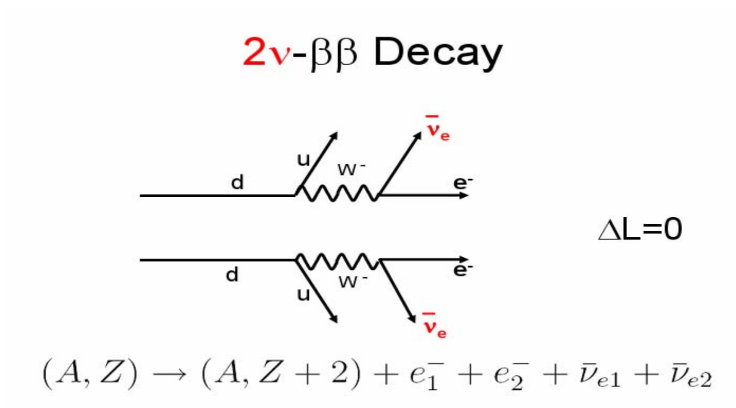

Fig.2: The Feynman diagram showing 2ν double beta decay

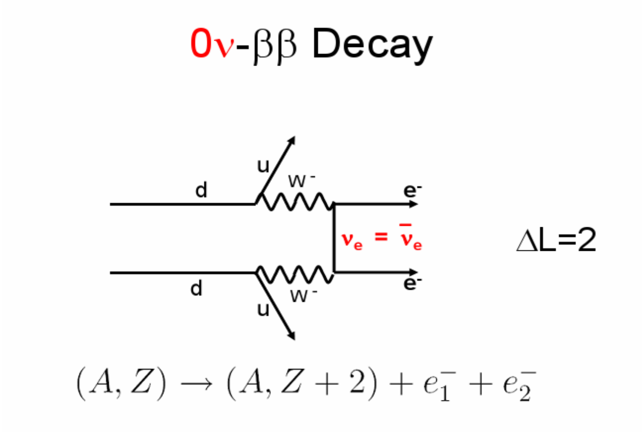

Fig.3: The Feynman diagram showing 0ν double beta decay

The neutrinoless double beta decay experimental approach hopes to determine if the neutrino is a massive Majorana particle. This type of experiment is perhaps the only feasible method for determining if the neutrino is a Majorana or Dirac particle. While 0νββ decay has not yet been experimentally discovered, searches have been conducted for many years, with many continuing today. In fact, the next generation of double beta decay experiments is currently being designed and developed and involves a tremendous increase in the amount of source material to be studied. The next generation ^{76}Ge GERDA experiment at the Gran-Sasso Laboratory has predicted a sensitivity in the half-life of the neutrinoless mode of the order of 10^{26} years while the proposed Majorana experiment has projected to be more sensitive with a half-life of the order of 10^{27} years.

3. Theory of double beta decay

The decay rate for 2ν ββ decay which is allowed in the Standard Model of physics is given in the approximation of weak hadronic current by

$$\left[T_{1/2}^{2\nu}(0^+ \to 0^+)\right]^{-1} = G^{2\nu}(E_0, Z)\left|M_{GT}^{2\nu} - \frac{g_V^2}{g_A^2} M_F^{2\nu}\right|^2 \tag{3.1}$$

The decay rate of the neutrinoless mode is proportional to the squared mass. In other words, the half life is inversely proportional to the squared mass. The decay rate for the process involving the exchange of the Majorana neutrino in the absence of right-handed currents can be expressed as follows:

$$\left[T_{1/2}^{0\nu}(0^+ \to 0^+)\right]^{-1} = G^{0\nu}(E_0, Z)\left|M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu}\right|^2 < m_\nu >^2 \tag{3.2}$$

The M_{GT} and M_F are the nuclear matrix elements of Gamow-Teller and Fermi transitions respectively. The nuclear matrix elements of the $0^+ \to 0^+$ Gamow-Teller and Fermi transition for the two neutrino mode in the second order perturbation theory is given by

$$M_F^{2\nu} = \sum_n \frac{\left\langle 0_f^+ \middle| \sum_j \tau_j^+ \middle| 1_n^+ \right\rangle \left\langle 1_n^+ \middle| \sum_k \tau_k^+ \middle| 0_i^+ \right\rangle}{E_n - E_i + \Delta} \tag{3.3}$$

$$M_F^{2\nu} = \sum_n \frac{\left\langle 0_f^+ \left| \sum_j \overrightarrow{\sigma_j} \tau_j^+ \right| 1_n^+ \right\rangle \left\langle 1_n^+ \left| \sum_k \overrightarrow{\sigma_k} \tau_k^+ \right| 0_i^+ \right\rangle}{E_n - E_i + \Delta} \tag{3.4}$$

where Δ denotes the average energy and is given by $\Delta = (E_i - E_f)/2$ and the Gamow-Teller transition operator and the Fermi transition operator is respectively given by $\sum_j \overrightarrow{\sigma_j \tau_j^+}$ and $\sum_j \tau_j^+$.

A complete orthonormal set of intermediate states have been introduced denoted by $\left|1_n^+\right\rangle$. Thus the two neutrino double beta decay mode has been expressed in terms of single beta transitions through the introduction of intermediate states.
For the neutrinoless mode, the nuclear matrix elements resulting from Fermi and Gamow-Teller transitions are given by

$$M_F^{0\nu} = \left\langle 0_f^+ \left| \sum_{j,k} H(r_{jk}, E)\, \tau_j^+ \tau_k^+ \right| 0_i^+ \right\rangle \tag{3.5}$$

$$M_{GT}^{0\nu} = \left\langle 0_f^+ \left| \sum_{j,k} H(r_{jk}, E)\, \overrightarrow{\boldsymbol{\sigma}_\mathbf{j}} . \vec{\boldsymbol{\sigma}}_\mathbf{k}\ \tau_j^+ \tau_k^+ \right| 0_i^+ \right\rangle \tag{3.6}$$

The function H depends on the distance between the nucleons and approximately has the form

$$H(r,E) = \frac{2R}{\pi r} \int_0^\infty dq \frac{q \sin qr}{\omega\{\omega + E - (E_i + E_f)/2\}} \tag{3.7}$$

where, R= $r_o A^{1/3}$, A being the mass number and r_o=1.2 fm.
The part $G^{2\nu}$ and $G^{0\nu}$ results from integrating over the lepton phase space, and g_V and g_A are the weak vector and axial-vector coupling constants respectively. The $<m_\nu>$ is the effective electron neutrino mass. If the light neutrino (m_j<< few MeV) exchange is the dominant mechanism for the 0νββ-decay process and that both the neutrino currents are left-handed, then the 0νββ-decay amplitude is proportional to the lepton number violating parameters. This effective mass is related to the light neutrino mass eigenvalues (m_j) and the mixing parameters (U_{ej}) and is give by the relation

$$< m_\nu > = \left| \sum_j m_j\, U_{ej}^2 \right| \tag{3.8}$$

The effective light neutrino mass $<m_\nu>$ may be suppressed by a destructive interference between the different contributions in the sum of equation (2.7) if CP is conserved. In this case the mixing matrix satisfies the condition $U_{ej} = U_{ej}^* . \zeta_j$, where $\zeta_j = \pm i$ is the CP parity of the Majorana neutrino ν_j. The absolute value has thus been inserted for convenience, since the quantity inside it is squared in equation (3.8) and is complex if CP is violated.

4. The Experimental Scenario

Experimentally one can distinguish the two modes. In the two neutrino mode the electrons take away only a fraction of the energy Q released in the decay. The sum energy spectrum is continuous, extending from 0 to Q. In the neutrinoless mode the total energy Q is carried away by the electrons, and the sum energy spectrum is a peak centered at Q, with a width given by the instrumental resolution. But this is not so easy since the process of double beta decay is a rare process and this peak would lie under a huge background. The background for the ^{76}Ge case is dominated by natural and cosmogenic radioactivities. The most important naturally occurring isotopes that are potential backgrounds for ββ(0ν) are ^{208}Tl and ^{214}Bi. Some of the ^{214}Bi lines lie very close to this Q-value. Radon is a special problem because it's a gas that emanates from Uranium and Thorium containing compounds and diffuses through many materials also. Experimenters must ensure that the detector volume is kept free of Radon. Because the cosmic ray flux is so high on the surface of the earth, ββ experiments are conducted underground. Going to a deep location and incorporating an anti-coincidence shield can eliminate any prompt events. But in addition to prompt interactions, cosmic rays can produce delayed radioactivity via many nuclear reactions. In particular, while detector materials or the source resides on the surface of the earth, they are exposed to a significant fast (>10 MeV) neutron flux. These fast neutrons can produce large ΔA transitions in nuclei that result in radioactive nuclides and for the ^{76}Ge case the main problem due to this arises from the impurity ^{68}Ge. The ideal 0νββ-decay experiment has the following dream features: the lowest possible background, the best possible energy resolution, the greatest possible mass of the parent isotope, detection efficiency near 100% for valid events, a unique signature and the lowest possible construction cost. Since it is not possible to achieve these properties perfectly, the best solution is to optimize them simultaneously. The best experiments to date are the Ge experiments. The IGEX experiment and the Heidelberg-Moscow experiment have produced the most restrictive limits on the half-life and deduced $m_{<\beta\beta>}$. The results from these two experiments along with a discussion on another proposed ^{76}Ge experiment have been reviewed in the following sections.

5. International Germanium EXperiment (IGEX)

The nuclear Double Beta Decay (DBD) is a unique way to investigate the nature and properties of the neutrino. The neutrinoless decay mode, if it exists, would provide an unambiguous evidence of the Majorana nature of the neutrino, its non-zero mass, and the non-conservation of lepton number. After the definitive confirmation that neutrinos have indeed non-zero mass, as the solar and atmospheric neutrino oscillation results imply, the neutrinoless double beta decay has become a most relevant subject of research because it is a process able to provide, in a relatively short time, the neutrino mass scale and its hierarchy pattern. To achieve high sensitivity limits of the effective Majorana electron neutrino mass derived from the neutrinoless half-life lower bound required for such new objectives, it will require a large number of double beta emitter nuclei, a very low background and a sharp energy resolution in the Q-value region, and methods to disentangle signal from noise.

The International Germanium EXperiment (IGEX) was a typical search for the neutrinoless double beta decay from ^{76}Ge employing large amounts of HPGe detectors, isotopically enriched to 86% in ^{76}Ge. In the first phase of the experiment three detectors of 0.7 kg active volume each were operated: one in the Homestake gold mine (4000 m.w.e.), other in the Baksan Neutrino Observatory (660 m.w.e.) and the other in the Canfranc underground laboratory (Laboratory 2 at 1380 m.w.e.), arriving at a lower bound on the neutrinoless half-life of about 10^{24} years.

In the second phase IGEX took data at the Canfranc Underground Laboratory in Spain at a depth of 2450 m.w.e. in a search of neutrinoless double beta decay. Three Germanium detectors (RG1, RG2 and RG3), of ~2 kg each, enriched to 86% in ^{76}Ge were used. Efforts were made to reduce part of the radioactive background by discriminating it from the expected signal by comparison of the shape of the pulses (PSD) of both types of events. The method was applied to the data recorded by two Ge detectors of the IGEX, which has produced one of the two best current sensitivity limits for the Majorana neutrino mass parameter. The principle for Pulse Shape Discrimination (PSD) is quite simple. In large intrinsic Ge detectors, the charge carriers take 300 - 500 ns to reach their respective electrodes. These drift times are long enough for the current pulses to be recorded at a sufficient sampling rate. The current pulse contributions from electrons and holes are displacement currents, and therefore dependent on their instantaneous velocities and locations. Accordingly, events occurring at a single site (ββ-decay events for example) have associated current pulse characteristics which reflect the position in the crystal where the event occurred. More importantly, these single-site events (SSE) frequently have pulse shapes that differ significantly from those due to the background events that produce electron-hole pairs at several sites by multi-Compton-scattering process, for example (the so-called Multi-Site Events (MSE)). Consequently, pulse-shape analysis can be used to distinguish between these two types of energy depositions since DBD events belong to the SSE class of events and will deposit energy at a single site in the detector while most of the background events belong to the MSE class of events and will deposit energy at several sites.

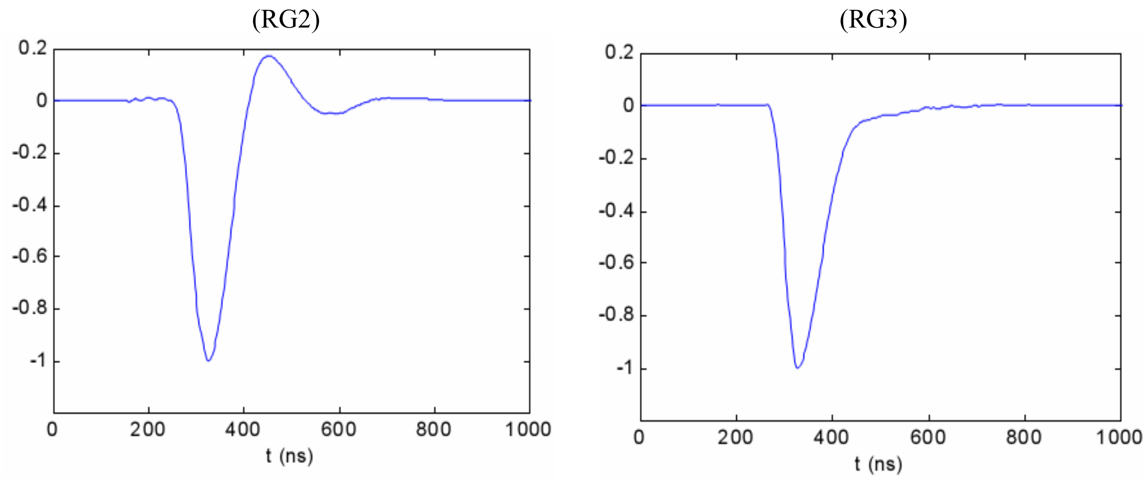

Fig.4: Transfer functions of the preamplifiers for detectors: RG2 and RG3 respectively.

The IGEX detectors worked with modified preamplifier electronics to route and record the current pulses at a very early stage of pre-amplification producing unique high-bandwidth pulse shape signals. Furthermore, to develop PSD techniques it would be highly desirable to obtain an earlier signal, even before it passes through the few unavoidable electronic components at the first stage of the detector preamplifier, to avoid the noise associated, resembling as much as possible to the displacement current of the detector. This allowed the development of algorithms that do not depend strongly on the preamplifier electronics in use. The transfer function of the preamplifier and associated front-end stage was measured for each detector which allowed the reconstruction of the displacement current and an easy comparison to computed pulse shapes.
The detectors in the second phase were installed inside a low background shielding consisting of 40 cm of lead, a PVC box (silicone sealed and flushed with nitrogen), 2mm of cadmium, 20 cm of polyethylene and an active veto (plastic scintillators). A pulse shape discrimination (PSD) technique capable to distinguish single site events (ββ decay events for example) from multisite events (the most dominant background events) was implemented. From here on new limits on the neutrinoless half-life and the neutrino mass parameter are obtained.
The data acquisition system of the IGEX experiment was based on standard NIM electronics, each Ge detector having an independent electronic chain. Preamplifiers were modified for pulse shape analysis and each preamplifier fast-pulse output is routed to a LeCroy 9362 digital oscilloscope (800 MHz analog band-width). The digitized pulse signal covers a total time of 1 μs using 500 points; it is worth noting that the time resolution, of about 100 ns (as inferred from the width of the peaked features or the fall time), limits the ability to resolve nearby features in the pulse such as lobes or discontinuities characteristic of a multiple-site interaction signal. Figure 1

shows the main features of the digitized pulses. These output pulses are taken at the very first stage of the amplification chain, but even so, there is an unavoidable instrumental distortion due to the preamplifier. This has been studied to determine its transfer function h(t). To take into account this distortion in the pulse shape analysis, either the calculated pulse i(t) is folded with the transfer function,

$$o(t) = \int_{-\infty}^{+\infty} \mathrm{i}(\tau).\,\mathrm{h}(\tau - t).d\tau \tag{5.1}$$

or the experimental signal unfolded. The latter allows the recovery of some information lost because of the instrumental distortion. The transfer function of the preamplifiers, h(t), depicted in figure 4, has been directly measured as the response of the preamplifier for a narrow d-like signal. Studies were also made following several methods including analog simulation of the preamplifier circuits and the analysis of the shapes of selected populations of experimental pulses. It was observed that the shape of the rise and the fall of the folded pulses is the same that the shape of the transfer function for those events in which the energy is released in some particular regions of the crystal; in particular, the left side of the transfer function can be deduced by studying pulses of events in the inner and lower part of the crystal, while the right side is derived from those produced in the outer and upper region. Measurements and estimates for the transfer function were found to be in quite good agreement. The pulse shapes of the output signals could be reproduced numerically. An energy deposition in a Ge crystal produces a proportional number of electron-hole pairs, which move towards the electrodes. The induced current i, and consequently the electric pulse taken from the detector, is the sum of the contributions due to each type of charge carriers:

$$\mathrm{i(t)} = \mathrm{i_e(t)}+\mathrm{i_h(t)} \tag{5.2}$$

The PSD method consists in counting the number of lobes of the pulses and rejecting those events having more than two significant lobes or peaks. A Single Site Event (SSE) pulse is expected to have at most two lobes, one due to electrons and the other due to holes. Experimental pulses are first unfolded using the transfer function of the preamplifier. Then, to detect lobes a “mexican-hat” filter F of the proper width is applied to the pulse which is a second derivative of a gaussian distribution.

$$\mathrm{F(t)} = \frac{\sigma^2 - \mathrm{t}^2}{\sigma^4} \times \exp(-\frac{\mathrm{t}^2}{2\sigma^2}) \tag{5.3}$$

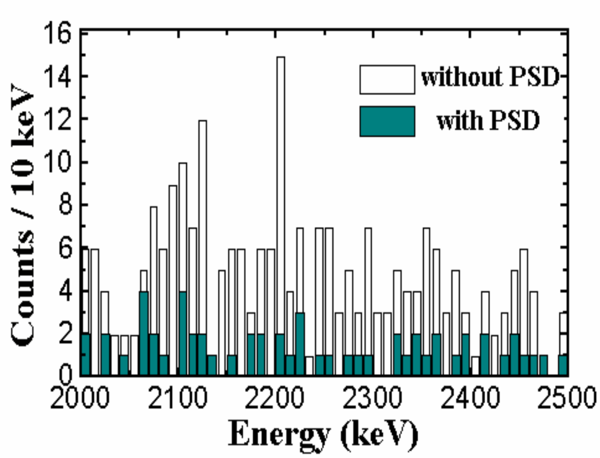

Fig.5: IGEX spectrum with and without the PSD background rejection.

and the filtered signal has a null mean value where there is no lobe in the original signal and a peak where a lobe is present. Thus the idea is to reject all the events having more than two lobes, thus selecting only the single site events which are the double beta decay events.
The IGEX detectors had the initial objective of the detection of the double beta decay of ^{76}Ge. At the end of 1999 certain modifications were made to adapt the detectors to the detection at low energy where the signal of WIMPs (Weak Interacting Massive Particles) is relevant. The shielding, shared by three IGEX detectors (2 kg germanium detectors isotopically enriched to 86% in ^{76}Ge) and the COSME detector, included from inside to outside 40 cm of lead, a PVC box (silicone sealed and flushed with nitrogen), 2 mm of cadmium, plastic scintillators working in anticoincidence with the Ge detectors and 20 cm of polyethylene.

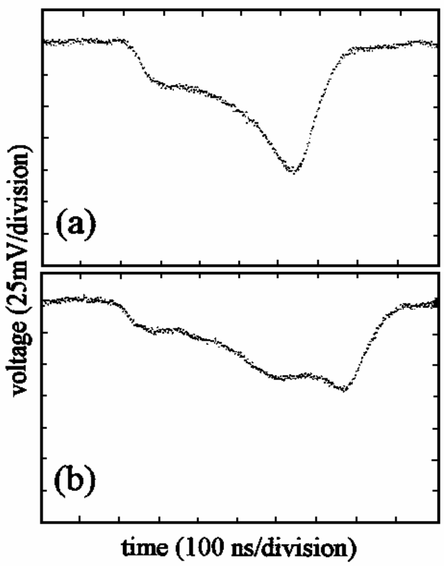

Fig.6: An example of digitized charge collection detail signal preamplifier pulse from a single-site event in (a) and from a multiple-site event in (b) as recorded by the IGEX collaboration.

In addition to the time filtering that eliminates abnormally accumulated events in time, a discrimination technique according to the shape of the event pulse when coming out of the amplifier was implemented. This technique known as Pulse Shape Discrimination (PSD) allows an optimal discrimination of non-desirable events coming from the electronic noise and identifiable through its pulse shape as a random fluctuation of the base line. This Pulse Shape Discrimination technique, to reject the radioactive background in the region in which the double beta decay signal is expected, was developed and applied to the data collected in the IGEX experiment, searching for the neutrinoless double beta decay of ^{76}Ge. As already stated, it is based on the counting of the number of lobes of the pulses, using a proper filter. It has provided a rejection of ~ 60 % of the events in the region of interest, accepting the criterion that those events having more than two lobes cannot be due to a double beta decay event. Accordingly, the improved background levels provided by the PSD technique has allowed the improvement of the limits for the half-life of ^{76}Ge and consequently, the effective electron neutrino mass bound. The shielding modified on July 2001 included only one 2 kg germanium detector inside a more efficient neutron shielding. These techniques of passive and active shielding, along with the extreme radiopurity of the detectors and their components, allowed a low energy background as well as a low enough threshold which are unique in this type of detectors. So, very rigorous contour limits for cross sections and masses of dark matter particles interacting with Ge nuclei through spin-independent interactions can be derived.

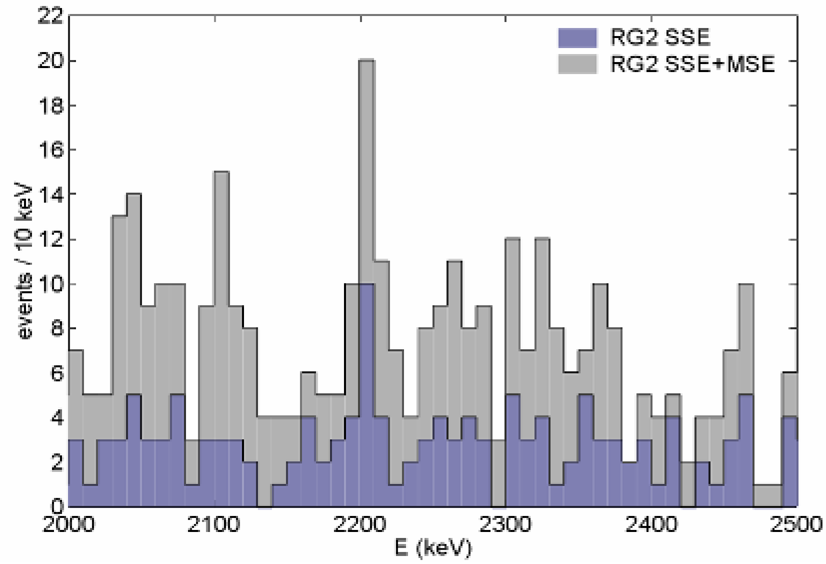

Fig.7: IGEX Background spectra before and after the PSD for detector RG2.

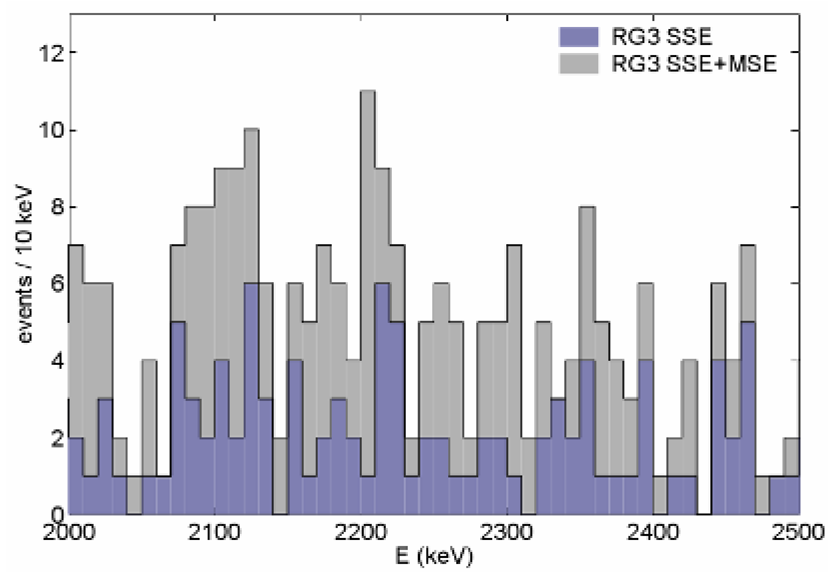

Fig.8: IGEX Background spectra before and after the PSD for detector RG3.

The need to understand and reject backgrounds in Ge-diode detector double-beta decay experiments have given rise to the development of this pulse shape analysis technique in such detectors to discern single-site energy deposits from multiple-site deposits. Te topic of discussion has been extended to segmented enriched Ge detectors to study the effectiveness of combining segmentation with pulse shape analysis to identify the multiplicity of the energy deposits.
Using standard statistical techniques, there are fewer than 3.1 candidate events (90% Confidence Level) under a peak having FWHM = 4 keV and centered at 2038.56 keV. This corresponds to:

$$T_{1/2}^{0\nu}(^{76}Ge) > \frac{4.87\times10^{25}}{3.1}\,yr \cong 1.57\times10^{25}\,yr$$

The requirements for a next generation experiment can thus easily be deduced by reference to

$$T_{1/2}^{0\nu} = \frac{(\ln 2).Nt}{c} \tag{5.4}$$

where N is the number of parent nuclei, t is the counting time, and c is the upper limit on the number of 0νββ-decay counts consistent with the observed background. To improve the sensitivity of $\langle m_\nu \rangle$ by a factor of 100, the quantity N.t/c must be increased by a factor of 10^4. The quantity N can feasibly be increased by a factor of $\sim 10^2$ over present experiments, so that t/c must also be improved by that amount. Since practical counting times can only be increased by a factor of 2 to 4, the background should at least be reduced by a factor of 25 to 50 below present levels. These are approximately the target parameters of the next generation 0νββ decay experiments.

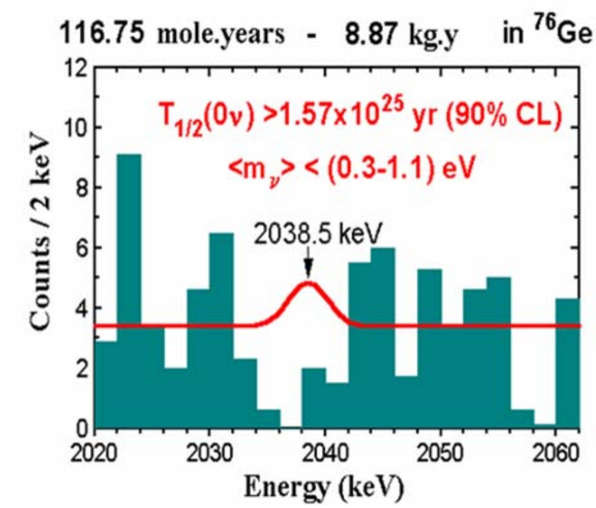

Fig.9: Histogram of the IGEX data in the energy region of interest for the 0ν -ββ decay. The limits on the half-life and neutrino mass parameter are also shown.

The Effective ν Mass: The section of KKDK on effective neutrino mass ("Critical View to the IGEX neutrinoless double-beta decay experiment..." published in Phys. Rev. D, Volume 65 (2002) 092007, by H. V. Klapdor-Kleingrothaus, A. Dietz, and I. V. Krivosheina) begins with: "Starting from their incorrectly determined half-life limit the authors claim a range of effective neutrino mass of (0.33-1.35) eV." In response the IGEX collaboration, came out stating that KKDK selected only the 52.51 mole·years of the IGEX data that had been subjected to PSD and obtained $T_{½}^{0\nu} > 7.1\times10^{24}$ y using the maximum number of counts, 3.1, from the entire 117 mole·years of data which was erroneous and unjustified; in another case, KKDK also decided to arbitrarily use the entire IGEX data set prior to PSD selection. From this they obtained 0ν a bound of $T_{½}^{0\nu} > 1.1 \times 10^{25}$ y. They further state that there is no scientific justification for selecting only PSD corrected data on one hand and totally ignoring the PSD corrected data on the other hand. In the conclusion of KKDK it states: "the IGEX paper - apart from the too high half-life limits presented, as a consequence of an arithmetic error - is rather incomplete in its presentation". In response to this paper the IGEX collaboration published the article "The IGEX experiment revisited: a response to the critique of Klapdor-Kleingrothaus, Dietz, and Krivosheina" where they stated that there was absolutely no arithmetic error and that the analysis of the published IGEX data presented in KKDK is not legitimate. The IGEX group also added that to obtain a much shorter bound on the half-life, they arbitrarily analyzed two ~ halves of the data separately. Instead of having 4.88×10^{25} y in the numerator (ln2 N.t) they used 2.2×10^{25} y. Yet they used the 90% CL upper limit on the number of counts under the peak, obtained by IGEX from all of the data. In another analysis, they ignored the fact that 52.51 mole·years were corrected with PSD and treated the complete uncorrected data set. Naturally, the lower limits on $T_{1/2}^{0\nu}$ (^{76}Ge) obtained by these procedures are lower than that obtained from the analyzed data set by the IGEX group. The response states "the lower limit quoted by IGEX, $T_{1/2}^{0\nu} \geq 1.57 \times 10^{25}$ y, is correct and that there was no arithmetical error as claimed in the Critical View article."

6. The HEIDELBERG - MOSCOW experiment

The Heidelberg-Moscow experiment which operated at the Gran Sasso underground laboratory is now claimed to be the most sensitive neutrinoless double beta decay experiment worldwide. It has contributed in an extraordinary way to the research in neutrino physics and more general beyond standard model physics, and limits for the latter are competing with those from the largest high-energy accelerators. It is expected to keep its outstanding position in non-accelerator particle physics for several years to come, before it may be succeeded by future large projects. Basing to a large extent on the theoretical work of the Heidelberg Double Beta Group, results have been obtained for SUSY models (R-parity breaking, sterile neutrino mass), leptoquarks (leptoquark-Higgs coupling), compositeness, right-handed W boson mass, test of special relativity and equivalence principle in the neutrino sector and others. One of the enriched ^{76}Ge detectors also yielded the most rigorous limits for cold dark matter (WIMP) till date by using raw data. The emphasis on the first indication for neutrinoless double beta decay is found in the Heidelberg-Moscow experiment giving first evidence of the lepton number violation and a Majorana nature of the neutrinos. The neutrinoless double beta decay could answer questions to the absolute scale of the neutrino mass and the fundamental character of the neutrino whether it is a Dirac or a Majorana particle as well as violation of the total lepton number.

With the support of the LNGS the experimental building of the experiment was built between Halls A and B in Gran Sasso Underground Laboratory, into which the first enriched ^{76}Ge detector (the first high-purity enriched ^{76}Ge detector) was installed in July 1990. First preparation work had been done since 1989 in a provisional tent in Hall C. The full set of five enriched ^{76}Ge detectors with a total of 11 kg was finally installed in 1995 and operated since 1996 with a newly developed pulse shape discrimination method.

High purity germanium crystals, enriched by Germanium-76 isotope up to 86% are used as the main detecting elements. Five coaxial detectors with the total weight of 11.5 kg (125 moles in the active volume of detectors) are used. Each detector is located in a separate cryostat made of electrolytic copper with low content of radioactive impurities. The quantity of other designed materials (iron, bronze, light material insulators) is minimized in order to reduce the feasible radioactive impurities contribution to the total background of the detectors. The detectors were located in two separate shielded boxes. One of them, 270 mm thick is made of electrolytic copper (detector #4), the other consists of two layers of lead – inner -100mm of high purity LCD2-grade lead and outer – 200 mm of low background Boliden lead (detectors ## 1,2,3,5). Each setup is coated with stainless steal casing. Non-radioactive pure nitrogen was blown through casings to reduce radon emanation contribution. To reduce neutron background the casing with detectors ##1,2,3,5 was coated with borated polyethylene and two anticoincidence plates of plastic scintillator were located over the casing in order to reduce muon component. The setup was located in Gran Sasso underground laboratory in Italy at a depth of 3500 metres of water equivalent thereby reducing the influence of cosmic rays on background conditions of the experiment. The electronics and the system of collecting data were allowed to record each event – the number (or numbers) of acted detector, amplitude and pulse shape, and anticoincidence veto.

The Heidelberg-Moscow experiment, with five enriched 86%-88% high-purity p-type Germanium detectors, of in total 10.96 kg of active volume, used the largest source strength of all double beta experiments at present, and reached a record low level of background. The detectors were the first high-purity Ge detectors ever produced. The degree of enrichment had been checked by investigation of tiny pieces of Ge after crystal production using the Heidelberg MP-

Tandem accelerator as a mass spectrometer. Since 2001 the experiment was operated only by the Heidelberg group, which also performed the analysis of the experiment from its very beginning.

The sensitivity for the 0ν ββ half-life is $T^{0\nu}_{1/2} \sim a \times \varepsilon \sqrt{\frac{M.t}{\Delta E.B}}$ (and $\frac{1}{\sqrt{T^{0\nu}}} \sim \langle m_\nu \rangle$) (6.1)

With a denoting the degree of enrichment, ε the efficiency of the detector for detection of a double beta event, M the detector (source) mass, ΔE the energy resolution, B the background and t the measuring time, the sensitivity of our 11 kg of enriched ^{76}Ge experiment corresponds to that of an at least 1.2 ton natural Ge experiment. After enrichment - the other most important parameters of a ββ experiment are: energy resolution, background and source strength.

The high energy resolution of the Ge detectors of 0.2% or better, assures that there is no background for a 0νββ line from the two-neutrino double beta decay in this experiment (5.5×10^{-9} events expected in the energy range 2035-2039.1keV), in contrast to most other present experimental approaches, where limited energy resolution is a severe drawback. The efficiency of Ge detectors for detection of 0ν ββ decay events is close to 100%. The source strength in this experiment of 11kg is the largest source strength ever operated in a double beta decay experiment. The background reached in this experiment, is 0.113 ± 0.007 events/kg y keV (in the period 1995-2003) in the 0ν ββ decay region (around $Q_{\beta\beta}$). This is the lowest limit ever obtained in such type of experiment. The statistics collected in this experiment during 13 years of stable running is the largest ever collected in a double beta decay experiment. The experiment took data during ~ 80% of its installation time. The Q value for neutrinoless double beta decay has been determined recently with high precision.

The background of the experiment consists of: (1) primordial activities of the natural decay chains from ^{238}U, ^{232}Th, and ^{40}K; (2) anthropogenic radio nuclides, like ^{137}Cs, ^{134}Cs, ^{125}Sb, ^{207}Bi; (3) cosmogenic isotopes, produced by activation due to cosmic rays during production and transport; (4) the bremsstrahlungs spectrum of ^{210}Bi (daughter of ^{210}Pb); (5) elastic and inelastic neutron scattering; and (6) direct muon-induced events.

The principal application of germanium detectors is gamma ray spectroscopy. High purity Ge is highly advantageous here as a detector. HPGe detectors have an excellent resolution but not as good an efficiency as the scintillator detector in the lower energy gamma region but in $Q_{\beta\beta}$-value region the absolute efficiency is close to 100%. Unlike the LEPS detector, the HPGe detector is used for the detection of gamma rays with the highest resolution available for gamma-ray energies from a few keV up to a 10 MeV. The photoelectric cross section is 60 times greater in Ge than in Si. Cooling of the HPGe detector is necessary only when high voltage is applied. With intrinsic semiconductors it is possible to use n-type semiconductor rather than the p-type required for the lithium drifting process in Ge(Li) detectors.

The detectors, except # 4, were operated in a common Pb shielding of 30 cm, which consisted of an inner shielding of 10 cm radiopure LC2-grade Pb followed by 20 cm of Boliden lead. The whole setup was placed in an air-tight steel box and flushed with radiopure nitrogen in order to suppress the ^{222}Rn contamination of the air. The shielding had been improved in the course of the measurement. The steel box since 1994 was centered inside a 10-cm boron-loaded polyethylene shielding to decrease the neutron flux from outside. An active anticoincidence shielding was placed on top of the setup since 1995 to reduce the effect of muons. Detector # 4 was installed in a separate setup, which had an inner shielding of 27.5 cm electrolytical Cu, 20 cm lead, and boron-loaded polyethylene shielding below the steel box, but no muon shielding. The setup was kept air-tight closed since installation of detector #5 in February'95. Since then no radioactive contaminations of the inner of the experimental setup by air and dust from the tunnel could occur.

H.V. Klapdor-Kleingrothaus, O. Chkvorez, I.V. Krivosheina and C. Tomei at Max-Planck-Institut fur Kernphysik in the Heidelberg-Moscow group presented a paper concerning "Measurement of the ^{214}Bi spectrum in the energy region around the Q-value of ^{76}Ge neutrinoless double-beta decay". In this particular work they performed measurements of the ^{214}Bi spectrum from a ^{226}Ra

source with a high purity germanium detector. Their attention was mostly focused on the energy region around the Q-value of ^{76}Ge neutrinoless double-beta decay (2039.006 keV). The results of this measurement are strongly related to their claim of the first indication for $0\nu\ \beta\beta$ decay of ^{76}Ge. An analysis of the data collected during thirteen years of measurements by the Heidelberg-Moscow experiment, at Gran-Sasso Underground Laboratory, yields a first indication for the neutrinoless double beta decay of ^{76}Ge. An important point of this analysis is the interpretation of the background, in the region around the Q-value of the double beta decay (2039.006 keV), as containing several weak photopeaks. It was suggested and has been shown that four of these peaks are produced by a contamination from the isotope ^{214}Bi, whose lines are present throughout the Heidelberg-Moscow background spectrum.
In this work they performed a measurement of a ^{226}Ra source of activity 95.2kBq with a high-purity germanium detector. The aim of this work was to study the spectral shape of the lines in the energy region from 2000 to 2100keV and, most important, to show the difference in this spectral shape when changing the position of the source with respect to the detector, and to verify the effect of TCS (True Coincidence Summing) for the weak ^{214}Bi lines seen in the Heidelberg-Moscow experiment. The isotope ^{226}Ra appears in the ^{238}U natural decay chain and from its decays also ^{214}Bi is produced. The γ-spectrum of ^{214}Bi is clearly visible in the ^{226}Ra measured spectrum. ^{214}Bi is a naturally occurring isotope produced in the ^{238}U natural decay chain through the β^- decay of ^{214}Pb and α decay of ^{218}At. Subsequently, ^{214}Bi beta decays into ^{214}Po (the branching ratio with respect to the α decay into ^{210}Tl is 99.979%). The decay, however, does not lead directly to the ground state of ^{214}Po, but to its excited states. From the decays of those excited states to the ground state we obtain the well known γ-spectrum of ^{214}Bi which contains more than hundred lines. As one can see in table 1, in the energy region around the ^{76}Ge Q-value of the $0\nu\beta\beta$ decay (2000-2100keV), four γ-lines from the radio-isotope ^{214}Bi and one E0 transition with energy 2016.7 keV are expected. The E0 transition can produce a conversion electron or an electron-positron pair but it could not contribute directly to the γ-spectrum in the considered energy region if the source is located outside the detector active volume.

Energy (keV)	Intensity (%)
2010.71	0.050
2016.7	0.0058
2021.8	0.020
2052.94	0.078
2088.97	0.050

Table 1: γ-lines from ^{214}Bi in the energy region from 2000 to 2100keV.

The intensity of each line is defined as the number of emitted photons, with the corresponding energy, per 100 decays of the parent nuclide. The considerations for the measurement were the efficiency of the detector (which depends on the size of the detector and on the distance source-detector) and the effect called True Coincidence Summing (TCS) effect. The lifetimes of the atomic excited levels are much shorter than the resolving time of the detector. If two gamma-rays are emitted in cascade, there is a certain probability that they will be detected together. If this happens, then a pulse will be recorded which represents the sum of the energies of the two individual photons, instead of two separated pulses with different energies. The TCS effect can result both in lower peak-intensity for full-energy peaks and in bigger peak-intensity for those transitions whose energy can be given by the sum of two lower-energy gamma-rays. In this case, the lines at 2010.7 keV and 2016.7 keV can be given by the coincidence of the 609.312 keV photon (strongest line, intensity = 46.1%) with the 1401.50keV photon (intensity = 1.27%) or with the 1407.98keV photon (intensity = 2.15%). The degree of TCS depends on the probability that two gamma-rays emitted simultaneously will be detected simultaneously. This is a function of the geometry and of the solid angle subtended at the detector by the source. For this reason, the intensities of the two lines mentioned above (2010.71keV and 2016.7keV) are expected to depend on the position of the source with respect to the detector.

The ^{226}Ra γ-ray spectra were measured using a γ-ray spectroscopy system based on an HPGe detector installed in the operation room of the Heidelberg-Moscow experiment at Gran Sasso Underground Laboratory in Italy. The coaxial germanium detector had an external diameter of 5.2cm and was 4.9cm high with the distance between the top of the detector and the copper cap being 3.5cm. The relative detection efficiency of the detector was 23% and an energy resolution of 3.6keV for the energy region of interest in the range 2000-2100keV. The electronics of the system comprised a linear spectroscopy amplifier and an ORTEC MCA board installed in a personal computer. The γ -ray pulses from the preamplifier were shaped into a semi-Gaussian by the amplifier. To reduce pile-ups a shaping time of 2 μsec was chosen. The energy threshold was set at 120 keV to reduce the MCA dead-time. Maximum count rate and dead-time during the measurements were not higher then 10000cps and 13%, respectively.

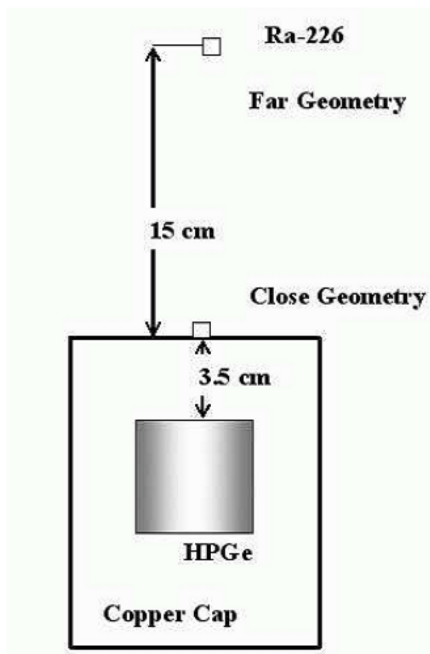

Fig.10: Detector setup for the far geometry and the close geometry measurements.

The measurement of ^{214}Bi spectrum, with a high purity germanium detector, in the energy region around the Q-value of ^{76}Ge neutrinoless double-beta decay (2039.006keV) was done with the ^{226}Ra source used for the measurements positioned, in a first step, directly on top of the copper cap of the detector (close geometry) and, in a second step, 15cm away from the copper cap (far geometry). Figure 10 shows the experimental setup. To collect a high statistics in the considered region, the duration of the measurements were 60000sec and 170000sec for close and far geometries, respectively. The spectra were processed by the Aptec-Demo MCA Analysis Software, allowing separate overlapping γ-lines. The results of the measurements show that, if the source is close to the detector, the intensities of the weak Bi lines in the energy region 2000-2100keV are not in the same ratio as reported by Table of Isotopes.

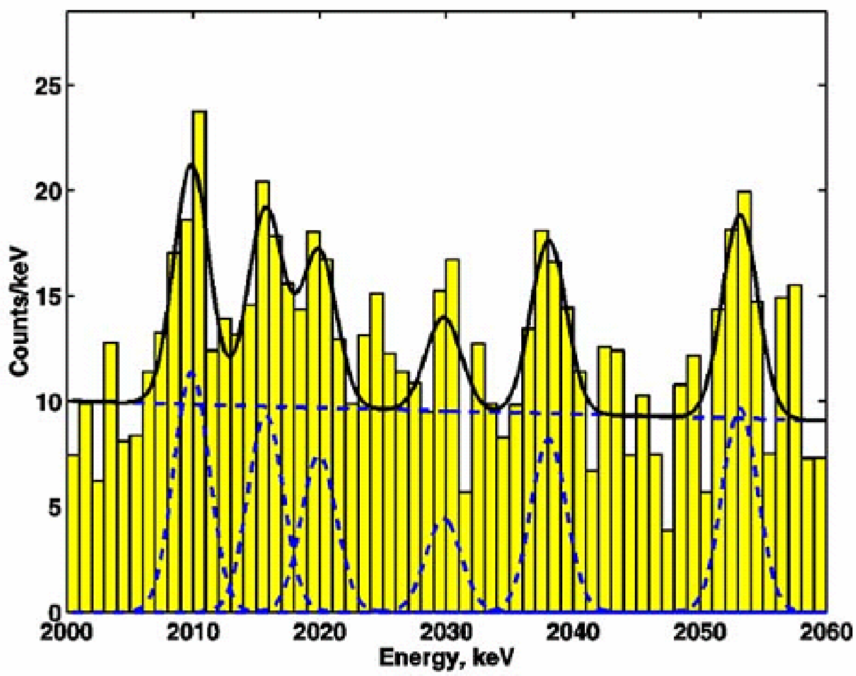

Fig.11: The sum spectrum of the ^{76}Ge detectors 1,2,3,4 and 5 over the period August 1990 to May 2003 in the energy range 2000 to 2060 keV recorded by the Heidelberg-Moscow experiment.

Only with a simulation, which takes into account the True Coincidence Summing Effect and the position of the source with respect to the detector, it is possible to reproduce the measured intensities with good agreement. The analysis of the data collected by the Heidelberg-Moscow experiment, yielding a first indication for the neutrinoless double beta decay of ^{76}Ge, shows that four ^{214}Bi lines are present in the energy region from 2000 to 2080keV (many other strong lines from the same isotope are present in the spectrum), due to the presence of bismuth in the experimental setup, especially in the copper shielding in the vicinity of the Ge crystals.

In a paper by Klapdor-Kleingrothaus, Dietz, Harney, and Krivosheina (referred to as KDHK) evidence is claimed for zero-neutrino double-beta decay in ^{76} Ge. The high quality data, upon which this claim is based, was compiled by careful efforts of the Heidelberg-Moscow collaboration, and is well documented. However, the analysis in KDHK makes an extraordinary claim, and therefore requires very solid substantiation according to another critical assessment article "Comment on Evidence for Neutrinoless Double Beta Decay" by C.E.Aalseth et al. They stated that were a large number of issues that were not addressed in KDHK some of which are:

1. There is no null hypothesis analysis demonstrating that the data require a peak. Furthermore, no simulation has been presented to demonstrate that the analysis correctly finds true peaks or that it would find no peaks if none existed. Monte Carlo simulations of spectra containing different numbers of peaks are needed to confirm the significance of any found peaks.
2. There are three unidentified peaks in the region of analysis that have greater significance than the 2039-keV peak. There is no discussion of the origin of these peaks.
3. There has been no discussion whatsoever of how sensitive the conclusions are according to different mathematical models. There is a previous Heidelberg-Moscow publication that gives a lower limit of 1.9×10^{25} y (90% confidence level). This is in conflict with the "best value" of a newer KDHK paper of 1.5×10^{25} y indicating a dependence of the results on the analysis model and the background evaluation.

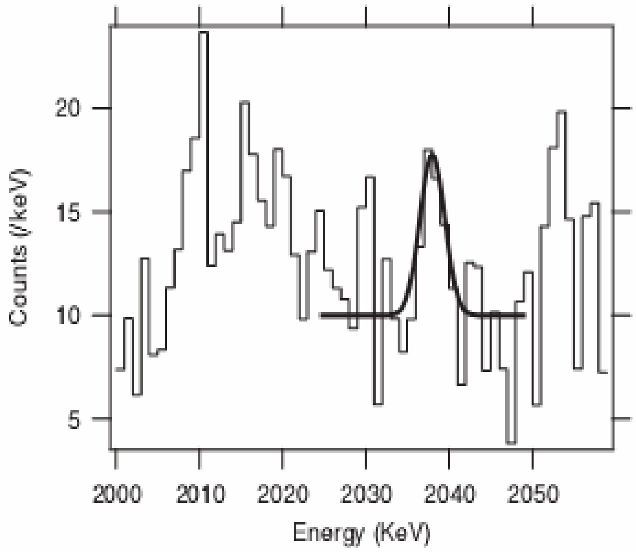

Fig.12: The spectrum from the Heidelberg–Moscow experiment upon which the claim for ββ(0ν) is based.

In this paper they state that a number of other cross checks of the result should also be performed. For example, there has been no discussion of how a variation of the size of the chosen analysis window affects the significance of the hypothetical peak. There is no relative peak strength analysis of all the ^{214}Bi peaks. Quantitative evaluations should be made on the four ^{214}Bi peaks in the region of interest. There is no statement of the net count rate of the peaks other than the 2039-keV peak as well as no presentation of the entire spectrum. Hence it is difficult to compare relative strengths of peaks. There is no discussion of the relative peak strengths before and after the single-site-event cut which is needed to elucidate the model for the origin of the peaks. On the other hand the Heidelberg-Moscow group claims that the signal found at $Q_{\beta\beta}$ is consisting of single site events and is not a γ line. The signal does not occur in the Ge experiments not enriched in the double beta emitter ^{76}Ge, while neighbouring background lines appear consistently in these experiments. On this basis they translated the observed numbers of events into half-lives for neutrinoless double beta decay.

The Heidelberg-Moscow experiment continued regularly from 1990 till 2003 after which it stopped operating due to a halt of the contract with Kurchatov institute on 30 Nov 2003. Since then various calibration measurements with radioactive sources are going on. The analysis of the full data taken with the Heidelberg-Moscow experiment in the period 2 Aug 1990 until 20 May 2003 has been presented. Indeed there has been no explanation so far for the full spectrum with detectors #1,2,3,4,5 in the energy region 2000-2080 keV for the three unknown peaks that appear along with the four ^{214}Bi peaks at 2010.7, 2016.7, 2021.8 and 2052.9 keV and the claimed $Q_{\beta\beta}$ peak at 2039 keV. The completed Heidelberg-Moscow ^{76}Ge Experiment- 71.7 kg.y after 13 years of operation claims for neutrinoless double beta decay evidence presenting their mass limit status as m_ν (eV) = 0.24 - 0.58 (99.997% C.L. or 4.2σ) with the best value of 0.4 eV (95% C.L.).

7. The proposed MAJORANA experiment

While an unambiguous interpretation of all of the neutrino oscillation experiments is not yet possible, it is abundantly clear that neutrinos exhibit properties not included in the standard model, namely mass and flavor mixing. Accordingly, sensitive searches for neutrinoless double-beta decay (0νββ-decay) are more important than ever. Experiments with large quantities of Ge, isotopically enriched in ^{76}Ge, have thus far proven to be the most sensitive, specifically the

Heidelberg-Moscow and IGEX experiments with lower limits in half-life sensitivities 1.9×10^{25} y and 1.6×10^{25} y respectively. A new generation of experiments will be required to make significant improvements in sensitivity one of which is the proposed Majorana Experiment.
The Majorana Experiment is a next-generation ^{76}Ge double-beta decay search which will employ 500 kg of Ge, isotopically enriched to 86% in ^{76}Ge, in the form of ~200 detectors in a close-packed array for high granularity. Each crystal will be electronically segmented, with each region fitted with pulse-shape analysis electronics. A half-life sensitivity of 4.2×10^{27} years or electron neutrino mass $< m_\nu > \sim 0.02 - 0.07$ eV has been predicted after ten years of operation, depending on the nuclear matrix elements used to interpret the data.
The Majorana experiment is proposed for a US deep underground laboratory, and requires very little R&D. It stands on the technical shoulders of the IGEX experiment and other previous successful double-beta decay and low-background experiments. Furthermore, new segmented Ge detector technology has recently become commercially available, along with new pulse-shape discrimination techniques. Several configurations have been evaluated with respect to cryogenic performance and background reduction and rejection. It will concentrate on a conventional modular design using ultra-low background cryostat technology developed by the IGEX. It will also utilize new pulse-shape discrimination hardware and software techniques developed by the Majorana collaboration and detector segmentation to reduce the background.
The Heidelberg-Moscow and IGEX experiments both utilized Germanium enriched to 86% in ^{76}Ge and operated deep underground. The projection is that the Majorana background will be reduced by a factor of 65 over the early IGEX results prior to pulse shape analysis (from 0.2 to ~0.003 $keV^{-1}\ kg^{-1}\ y^{-1}$). This will occur mainly by the decay of the internal background due to cosmogenic neutron spallation reactions that produce ^{56}Co, ^{58}Co, ^{60}Co, ^{65}Zn and ^{68}Ge in the germanium by limiting the time above ground after crystal growth, careful material selection and electroforming copper cryostats. One component of the background reduction will arise from the granularity of the detector array.

Fig. 13: In the adjacent figure, an option for a detector configuration is shown for one module. Each of these modules would have three levels of 19 detectors in close-packed array. Each detector is 62 mm in diameter and 70 mm long with a mass of 1.1 kg. One proposed Majorana module of 57, 1kg detectors in a standard ultra-low background electroformed copper cryostat.

Most of the Compton continuum consists of single Compton scatterings followed by escape of the scattered gamma ray, whereas full-energy events primarily comprises multiple scattering sequences followed by a photoelectric absorption. The peak-to-Compton ratio can therefore be enhanced by requiring a recorded event to correspond to more than one interaction within the detector before its acceptance. In germanium detectors, this selection is usually accomplished by subdividing the detector into several segments (or providing several adjacent independent detectors) and seeking coincident pulses from two or more of the independent segments. When coincidences are found, the output from all detector segments is summed and recorded. The resulting spectrum is made up only of the full-energy peak lying above a featureless continuum that is greatly suppressed and has no abrupt Compton edges. Thus detector segmentation is a very useful technique to suppress the huge Compton background for the $0\nu\beta\beta$ rare event detection.

The next generation Ge experiments must not only be a volume expansion of IGEX or Heidelberg–Moscow, but also must have a superior background rejection and better electronic stability. The summing of 200–250 individual energy spectra can result in serious loss of energy resolution for the overall experiment, but the collaboration has overcome these problems with new Ge technology. In IGEX, instabilities lead to a degradation of 25% in the energy resolution of the 117 mole-years of data. Firstly, detectors electronically segmented into a number of individual volumes in a single n-type intrinsic Ge detector are available from Advanced Measurement Technology (ORTEC) and Canberra Industries. In the ten years since the production of the 2kg IGEX intrinsic Ge detectors, the new technology evolved in these two industrial companies. Secondly, complete digital electronics from X- ray Instrumentation Associates (XIA) have been used by the group to demonstrate unprecedented stability, very low energy thresholds (<1keV) for a 2 kg Ge detector, and a vast improvement in pulse-shape discrimination. Large semi-coaxial n-type detectors have been fitted with a series of azimuthal electrical contacts along their length, and one or more axial contacts in the central hole. After Monte Carlo studies and discussions with detector manufacturers, several configurations are available to the Majorana collaboration to make a good balance between costs, background reduction and production efficiency. The six-by-two configuration in figure 14 was used in the Monte Carlo simulations that produced the data shown in figure 15 for a single detector. The proposed Majorana experiment is based on the early IGEX with reasonable background reduction and cutting methods applied. Efforts are thus on for the search of 0νββ decay that would give a new shape to the standard model of physics.

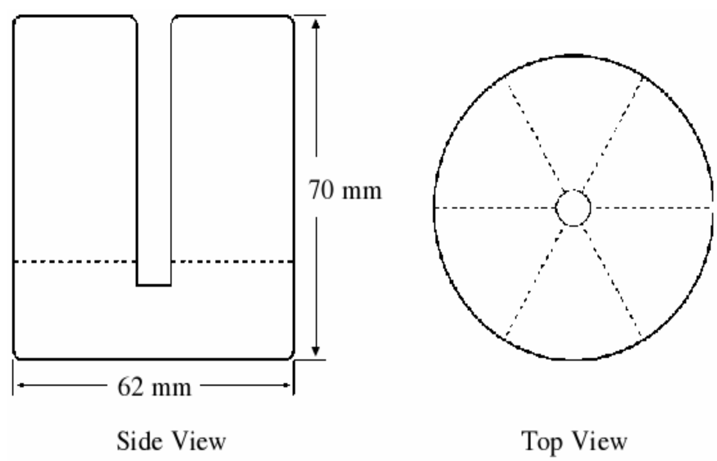

Fig.14: A configuration of the SEGA detector with six-azimuthal-segment by two-axial-segment geometry is shown in the figure.

The internal ^{60}Co modelled in figure 15 is produced by cosmic ray neutrons during preparation of the detector. Formation begins after the crystal is pulled. Its elimination by segmentation and pulse shape analysis is crucial. Current techniques depend entirely on experimental calibration and do not utilize pulse shape libraries. The ability of these techniques to be easily calibrated for individual detectors makes them practical for large detector arrays. A major contributor to this success is the availability of commercial digital spectroscopy hardware. On digitizing a detector pre-amplifier signal, all subsequent operations on the signal are performed digitally. Programmable digital filters are capable of producing improved energy resolution, long-term stability and excellent dynamic range.

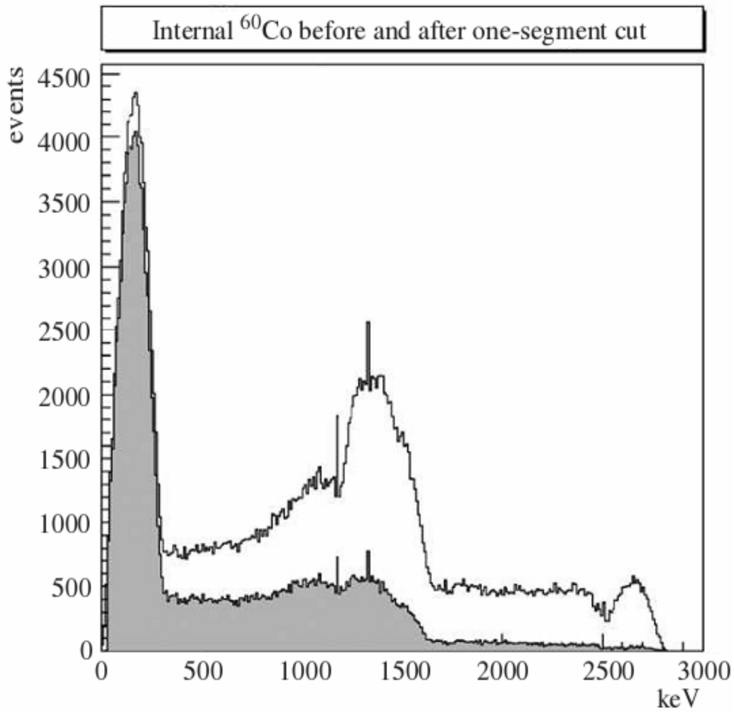

Fig. 15: The results of a detailed Monte Carlo simulation of a contamination of ^{60}Co internal to a Ge detector, created by cosmogenic neutrons while the Ge was on the Earth's surface. The upper spectrum is without suppression, and the lower (dark) spectrum is the result of applying cuts that exclude events that interact in more than one segment.

Since it has been conclusively shown that the limiting background in at least some previous experiments has been cosmogenic activation of the germanium itself, it is necessary to mitigate those background sources. Cosmogenic activity fortunately has certain factors which discriminate it from the signal of interest. For example, while 0νββ -decay would deposit 2 MeV between two electrons in a small volume, internal ^{60}Co decay deposits about 318 keV (endpoint) in beta energy near the decaying atom, while simultaneous 1173 keV and 1332 keV gammas can deposit energy elsewhere in the crystal, most probably both in more than one location, for a total energy capable of reaching the 2039 keV region-of-interest. A similar situation exists for internal ^{68}Ge decay. Thus deposition-location multiplicity distinguishes double-beta decay from the important long lived cosmogenics in germanium. Isotopes such as ^{56}Co, ^{57}Co, ^{58}Co and ^{68}Ge are produced at a rate of roughly 1 atom per day per kilogram on the earth's surface. Below the ground the fast neutron flux is proportional to the cosmic-ray muon flux, so going deeper reduces it but only ^{60}Co and ^{68}Ge have both the energy and half-life to be of concern. Even though the experiments used Ge enriched in ^{76}Ge, the radio-isotope ^{68}Ge was produced in the crystals through the high-threshold reaction, ^{76}Ge(n,9n)^{68}Ge. These fast neutrons can produce large ΔA transitions in nuclei that result in radioactive nuclides. The Majorana collaboration has made joint efforts with the proposed GERDA (GERmanium Detector Assembly) collaboration for the Monte Carlo simulations of background reduction techniques. The GERDA has projected a sensitivity in the half-life of the 0νββ-decay mode by its second phase of running which is in fact less than that of the proposed Majorana experiment.

The deposition-location multiplicity distinguishes ββ-decay from the important long lived cosmogenics in Germanium and to pursue this multiplicity parameter there are two approaches. First, the detector current pulse shape carries with it the record of energy deposition along the electric field lines in the crystal; that is, the radial dimension of cylindrical detectors. This information may be exploited through pulse-shape discrimination. Second, the electrical contacts of the detector may be divided to produce independent regions of charge collection.

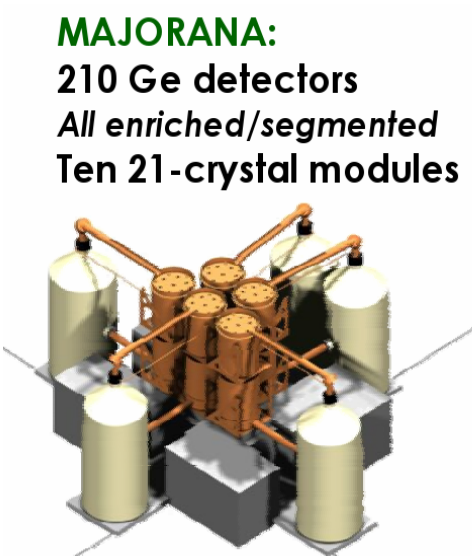

Fig.16: A sketch of the Majorana detection system with 210 enriched and segmented Ge detectors.

Fig.17: The above figure shows a SEGA crystal initial test cryostat.
First (enriched) 6×2 SEGA is operating.
Current: Testing (TUNL); Shallow UG testing at University of Chicago; Operation in Waste Isolation Pilot Plant (WIPP)

A much-superior pulse-shape discrimination method was constructed using a set of parameters calculated from each pulse. The parameters for a single pulse were compared to a distribution collected from a calibration source of interest. Those which agreed to a large extent were kept; and the rest discarded. The acceptance ratio was adjusted during pulse post-processing to optimize cut efficacy. The strength of this approach is that no set of simulated pulses need be maintained; no space charges need be known. It is only required that calibration data be obtained before and after any voltage change, a procedure which is required in any case to periodically check detector gain.
To summarize, the new techniques depend entirely on experimental calibration and do not utilize pulse-shape libraries. The ability of these techniques to be easily calibrated for individual detectors makes them practical for large detector arrays. Calibration for single-site event pulses is trivially accomplished by collecting pulses from thorium ore; the 2614.47-keV gamma ray from ^{208}Tl produces a largely single-site double-escape peak at 1592.47 keV. The PSD discriminator is then calibrated to the properties of the double-escape peak. A slightly improved double-escape peak can be obtained from the ^{26}Al gamma ray of 2938.22-keV. The double-escape appears at 1916.22 keV, only about 120 keV away from the expected region of interest for 0νββ-decay. The obvious and direct use of pulse- shape discrimination and segmentation is the rejection of cosmogenic pulses in the germanium itself. However, the approach should be also effective on gamma rays from the shielding and structural materials. The effects as background of neutrons of both high energy (cosmic muon generated) and low energy (fission and (α,n) from rock) are under consideration by the Majorana group. The segmentation and granularity of the detectors will provide some protection from this lower-order background. These neutrons could also produce other unwanted activities. For instance, ^{3}H and ^{14}C can be produced in nitrogen from

high and low energy neutrons, respectively. Fortunately, the Majorana detectors will not be surrounded by nitrogen at high density. Experimental example pulses in figure 18 show a single-site event from the 1592 keV double-escape peak of the ^{208}Tl 2615 keV line as the top signal and an example multi-site pulse from the full-energy peak of the ^{212}Bi line at 1620 keV as the bottom signal.

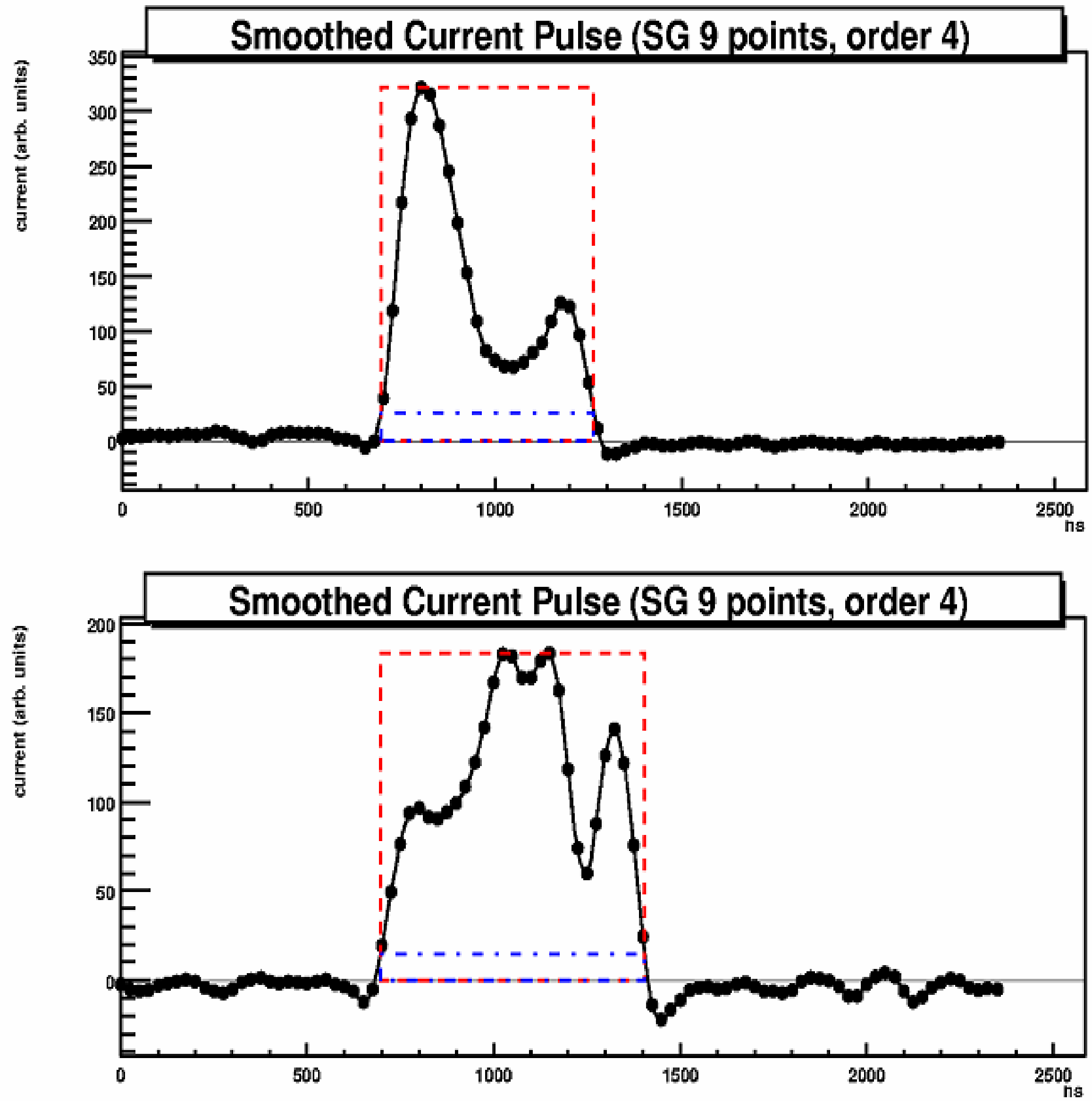

Fig.18: Reconstructed current signal from a 1592-keV double-escape-peak event (top) and a 1620.6-keV full-energy gamma peak event (bottom), with the horizontal scale spanning 2500 ns as shown by the Majorana collaboration.

The Majorana Collaboration has made an extensive analysis of the predicted backgrounds and their impact on the final sensitivity of the experiment. The Majorana experiment represents a great increase in Ge mass over IGEX with new segmented Ge detectors and the latest electronic systems for pulse-shape discrimination. Their conclusion is that with 500 kg of Ge, enriched to

86% in the isotope ^{76}Ge, the Majorana array operating over 10 years including construction time, can reach a lower limit on $T_{1/2}^{0\nu}$ of 4.2×10^{27} years which is more sensitive than the proposed ^{76}Ge GERDA experiment at the Gran Sasso Underground Laboratory. The detector array will have a fiducial mass of 500 kg, containing N = 3.43×10^{27} atoms of ^{76}Ge; a counting time of 10 years, and an energy resolution of 3.0 keV FWHM. The pulse-shape discrimination has a measured single-site-event acceptance fraction of 0.802. The detector-segmentation cut has a calculated single-site-event acceptance fraction of 0.907. The total counting efficiency is then 0.727. Accordingly the sensitivity is projected as:

$$T_{1/2}^{0\nu}(^{76}Ge) = \frac{(0.727)(0.693)(3.43\times10^{27})10}{6}\, yr \cong 4.2\times10^{27}\, yr$$

This projected 0νββ decay half-life corresponds to an upper bound of $< m_\nu >$ of 0.038 ± 0.007eV. One advantage of ^{76}Ge is that it may well be a candidate for a future more reliable microscopic calculation of the 0ν ββ- decay nuclear matrix element.

In conclusion, the Majorana project has been designed in a compact, modular way such that it can be built and operated with high confidence in the approach and the technology. The initial years of construction will allow alternate cooling methods to be employed if they have an advantage and should they be shown to overcome long-term concerns due to surface contamination, muon-induced ions, and diffusion. The technology supporting Majorana signal-processing-based background rejection is ready and shows promise of future improvements. The electrolytic technology of radiopure copper production has improved steadily since the last IGEX system, in which copper support materials played no measurable radiological role. There have been efforts for the cleaning and passivation of copper surfaces to remove contaminated surface radioactivity and prevent oxide formation for generating high purity copper for ultra-low background. Finally, those who enrich germanium have also expressed their enthusiasm and support for the project. Thus, the next generation Majorana project is set to begin operations to determine the effective Majorana mass of the electron neutrino.

8. Conclusion

Neutrinoless double beta decay is thus one of the most sensitive approaches with great perspectives to test particle physics beyond the Standard Model. The 0νββ decay mode, if it exists, can be used for constraining neutrino masses, left–right symmetric models (right-handed W boson mass), SUSY (interactions involving R-parity conserving or breaking SUSY models) and leptoquark scenarios, as well as effective lepton number violating couplings. The leptoquarks are gauge bosons that transform quarks to leptons and induce neutrinoless double beta decay via leptoquark-Higgs coupling. The neutrinoless mode is thus a very sensitive probe to the lepton number violating terms in the Lagrangian such as the Majorana mass of the light neutrinos, right-handed weak couplings involving heavy Majorana neutrinos, as well as Higgs and other interactions involving violation of chirality conservation.

This is one of the most exciting times for neutrinoless double beta decay especially with the most successful emitter ^{76}Ge experiments. In search for neutrinoless double beta decay, the isotope ^{76}Ge as the source material has multiple advantages. It has high resolution (< 4 keV at $Q_{\beta\beta}$) with no background from 2ν mode. A huge leap in sensitivity is possible applying ultra-low background techniques and 0ν- ββ signal discrimination. There can be a phased approach in the experiment with increment of target mass. The source and detector are the same material thereby reducing background and maintaining the 4π geometry. The efficiency near the Q-value is excellent as well. It is also the only way to scrutinize 0ν – DBD claim on short time scale which tests $T_{1/2}$ and not m_ν.

The consequences of Neutrinoless Double Beta Decay can thus be summarized as- [1] Total Lepton number violation: The most important consequence of the observation of neutrinoless double beta decay is that the total lepton number is not conserved which is fundamental for particle physics. [2] Majorana nature of neutrino: Another fundamental consequence is that the neutrino is a Majorana particle. Both of these conclusions are independent of any discussion of nuclear matrix elements. [3] Effective neutrino mass: The matrix element enters when we derive a value for the effective neutrino mass - making the most natural assumption that the $0\nu\beta\beta$ decay amplitude is dominated by exchange of a massive Majorana neutrino. [4] Neutrino oscillations, in particular, are not sensitive to the Majorana CP-violating phases which enter into the expression for the lepton mixing matrix in the case of the massive Majorana neutrinos and which are absent if the massive neutrinos are Dirac particles. Thus, the neutrino oscillation experiments cannot provide information on CP violation caused by the Majorana CP-violating phases and, in the case of CP invariance, on the relative CP parities of the massive Majorana neutrinos and this can be derived from neutrinoless double beta decay.

From future projects one has to require that they should be able to differentiate between a γ and a β signal, or that the tracks of the emitted electrons should be measured and at the same time, as is visible from the present information, the energy resolution should be at least in the order of that of Ge semiconductor detectors, or better. However, if one wants to get an independent evidence for the neutrinoless double beta decay mode, one would probably, wish to see the effect in another isotope capable of double beta decay, which would then simultaneously give additional information also on the nuclear matrix elements. In view of these considerations, future efforts to obtain deeper information on the process of neutrinoless double beta decay would require a new experimental approach, different from all, what is at present pursued.

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