Background reduction in neutrinoless double beta decay experiments using segmented detectors—A Monte Carlo study for the GERDA setup

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Received 14 July 2006; received in revised form 11 September 2006; accepted 23 October 2006

Abstract

The identification of gamma radiation is essential for a new generation of double beta decay experiments. The GERmanium Detector Array, GERDA, located at the INFN Gran Sasso National Laboratory (LNGS) in Italy, uses germanium, enriched in $^{76}\text{Ge}$, as source and detector, and aims at a background level of less than $10^{-3}$ counts/(kg keV y) in the region of the $Q_{\beta\beta}$-value. For the first time highly segmented detectors will be installed in a double beta decay experiment. A detailed GEANT4 Monte Carlo study was performed to evaluate the background reduction achievable by anti-coincidence cuts between crystals and segments.

Within the overall geometry of GERDA, the segmentation scheme considered here provides around an order of magnitude of extra background reduction.

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PACS: 23.40.-s; 14.60.Pq; 29.40.-n

Keywords: Double beta decay; Germanium detectors; Segmentation

1. Introduction

Neutrinoless double beta decay ($\text{0}\nu\beta\beta$) is a second-order weak process which is predicted to occur, if the neutrino is a massive Majorana particle [1]. The half-life of the process is a function of the neutrino masses, their mixing angles, and CP phases. An observation of the process would therefore give information about the absolute neutrino mass scale. The search for the $\text{0}\nu\beta\beta$-process has become especially important after the evidence for a non-zero neutrino mass from flavor oscillations [1] and the recent claim of an observation of neutrinoless double beta decay [2] based on data of the Heidelberg–Moscow experiment [3].

(High-purity) Germanium crystals can be used as source of $\text{0}\nu\beta\beta$-decays and detectors simultaneously [4,3,5]. Experiments which aim at the observation of rare decays are limited in sensitivity by the observed number of background events. A low background surrounding is therefore essential for the success of all $\text{0}\nu\beta\beta$-experiments.

The Germanium Detector Array, GERDA [6], is a new double beta decay experiment which will be installed in Hall A of the INFN Gran Sasso National Laboratory (LNGS), Italy. It searches for neutrinoless double beta decay in the germanium isotope $^{76}\text{Ge}$. The main design feature is to use a cryogenic liquid (nitrogen or argon) as cooling medium and as shield against gamma radiation which has dominated the background in earlier experiments [3,5]. An array of bare germanium detectors, enriched in the isotope $^{76}\text{Ge}$ to a level of about 86\%, will be suspended inside a cryogenic volume using a minimum of material. The cryogenic volume is surrounded by a
buffer of ultra-pure water acting as an additional gamma and neutron shield. A muon veto system is designed to identify the muon-induced background. With this design, a background index of less than $10^{-3}$ counts/(kg keV y) at the $Q_{bb}$-value of 2039 keV is envisioned. A phased approach is chosen for the experiment. In the first phase detectors that were previously operated by the Heidelberg-Moscow [3] and IGEX [5] collaborations will be redeployed. The detectors have a mass of approximately 2 kg each. The detectors for phase II are still under design, but are expected to be of similar dimensions.

It is possible to segment germanium crystals and read out each of the segments separately [7]. The increased granularity of the detection volume allows for the identification of particular physics processes. In this paper a Monte Carlo study of germanium detectors is presented in which the background reduction for segmented and unsegmented detectors in the GERDA setup is compared. Section 2 introduces the underlying physics processes and expected signatures in germanium detectors. Section 3 motivates the segmentation of germanium detectors. A Monte Carlo simulation of different physics processes is presented in Section 4. The analysis method which is used to compare the background reduction for both scenarios (segmented and unsegmented detectors) is discussed in Section 5. The results are summarized in the same section. Conclusions and an outlook are given in the last section.

2. Physics processes and signatures

The $0\nu\beta\beta$-decay process has, in addition to the daughter nuclei, two electrons and no neutrinos in the final state. The sum of the kinetic energies of the electrons is therefore approximately equal to the $Q$-value of the decay. For the germanium isotope $^{76}\text{Ge}$ this is $Q_{bb} = 2039\text{ keV}$ [8]. Electrons in the relevant energy range dominantly deposit their energy in germanium via ionization. The range of these electrons is of the order of millimeters (see e.g. tables in Ref. [9]). Since the germanium detectors under consideration have a volume of the order of 400 cm$^3$, the energy of the electrons will be fully contained within a small volume of the crystal, if no hard bremsstrahlung is present. The signature of $0\nu\beta\beta$-decay events is thus a peak at the energy of 2039 keV.

Two types of background processes are distinguished. Energy can be deposited in the crystals by the products of the decay of radioactive isotopes or muon-induced neutrons and electromagnetic cascades. The latter are discussed elsewhere [10] as is the overall neutron flux from radioactive elements in the surrounding bed-rock. The former is subject of this paper.

All radioactive materials with $Q$-values larger than $Q_{bb}$ are potential background sources for the $0\nu\beta\beta$-decay process. A fraction of the released energy can be deposited inside a detector, such that the measured energy is around the $Q_{bb}$-value. Photons in the MeV range predominantly deposit their energy via Compton scattering. Their absorption length is of the order of centimeters. Considering the size of the germanium crystals under study, processes with photons in the final state are likely to deposit only a fraction of the total energy inside one detector. The signature of the signal and the main background signatures are classified according to the particles in the final state.

- **Class I**: Two electrons. This class encompasses the neutrinoless and neutrino accompanied double beta decay processes ($0\nu\beta\beta$ and $2\nu\beta\beta$, respectively). If the energy resolution is better than about 10 keV, the two modes of double beta decay can be separated, since the energy region around the $Q_{bb}$-value is not populated by the $2\nu\beta\beta$-decay process. The two electrons deposit their energy locally, i.e. on a millimeter scale.

- **Class II**: Photon(s) and electron. This class contains all $\beta^-$-decay processes accompanied by the emission of one or more photons which occur inside the detector or close to its surface. The energy of the electron is deposited locally, whereas the photon scatters and not all of its energy is necessarily deposited inside the detector. An example for this class is the decay of $^{60}\text{Co}$ inside the germanium.

- **Class III**: Photon(s) and positron. Similar to Class II, this class contains all $\beta^-$-decay processes accompanied by the emission of one or more photons inside the detector. The positron deposits most of its energy locally and annihilates. The photons (the two 511 keV gammas plus any additional photons) scatter and mostly do not deposit all of their energy inside one detector. The most prominent example for this class is the decay of $^{68}\text{Ge}$ inside the germanium.

- **Class IV**: Photon(s) only. If the decay occurs outside the germanium detectors, $\alpha$-particles or electrons can be stopped before they reach the crystals. Most prominent examples are the decays of $^{208}\text{TI}$ and $^{214}\text{Bi}$ which come from radio-impurities in the detector surrounding.

- **Class V**: $\alpha$-particles. Surface contaminations with $^{210}\text{Pb}$ or other isotopes which decay via $\alpha$-emission can contribute to the background. $\alpha$-particles in the 2–10 MeV range deposit their energy on a 5–50 μm scale. $\alpha$-particles emitted at the surface therefore potentially deposit only a fraction of their initial energy inside the active volume of the crystal.

3. Germanium detectors

The semiconductor properties of germanium detectors are well known [11]. The very high purity—the number of impurities is of the order of $10^{10}$/cm$^3$—allows the construction of large individual detectors with excellent energy resolution. Suitable detector crystals for Phase II of the GERDA experiment are true coaxial cylinders with an outer diameter and height of 8 cm, respectively. The inner diameter is 1 cm.
A rather novel technique is the segmentation of germanium crystals. Segmentation is done in the azimuthal angle $\phi$ and the height $z$. The potential of segmented germanium detectors for the use in double beta decay experiments has also been investigated by the MAJORANA collaboration [12] using Monte Carlo techniques [13]. A so-called clover detector, four germanium crystals with two longitudinal segments each, is currently under study by the MAJORANA collaboration. Segmentation also allows the tracking of $\gamma$-rays which Compton-scatter in the detector. This feature is explored by the AGATA [14] and GRETA [15] collaborations.

The segments are chosen to be large compared to the scale of the energy deposition for electrons (millimeter) and therefore have a large probability to contain the total energy of $Q_{\beta\beta}$ of the $0\nu\beta\beta$-decay process. This results in an improved distinction from physics processes in which the energy deposition is distributed over a larger volume (such as Compton scattering of photons). An improved identification of photon events (Classes II–IV) and thus background reduction is expected by using coincidence cuts between the segments of one or more crystals.

The choice of the segmentation scheme depends on three factors: (1) the physics processes involved; (2) the technical feasibility; and (3) the side-effects, such as an increased amount of material due to extra electronics. Simple considerations like the mean free path of the relevant photons being in the centimeter range suggest dimensions of the order of centimeters. The current detector design foresees a six-fold segmentation in $\phi$ and a three-fold segmentation in $z$. Detectors with this design can be reliably produced and the additional material required can be kept under control.

4. Monte Carlo Simulation

A Monte Carlo study was performed in order to quantify the improvement of the background reduction with segmented detectors. The simulation is performed using the MaGe package, a GEANT4 [16] based tool which simulates the GERDA geometry and all relevant physics processes (especially low-energy electromagnetic models). A description of implemented physics processes and models can be found in Ref. [17]. MaGe was developed in cooperation with the MAJORANA project to support both experiments. Details are described elsewhere [18].

4.1. Geometry

The simulated GERDA infrastructure and an array of detectors are shown in Fig. 1. An array of 21 identical detectors, placed hexagonally in strings of three detectors each, is assumed. The infrastructure is a simplified version of GERDA. The detectors are simulated as previously described, i.e., they have a height of 8 cm, an inner diameter of 1 cm and an outer diameter of 8 cm. The detectors are segmented into 6 $\phi$- and 3 $z$-segments each. Unsegmented detectors are simulated by summing the energy deposits of all segments in one detector. The vertical distance between two crystals is 5 cm and the distance of closest approach between two strings is 2 cm. The crystal array is placed inside a 3-walled copper cryostat with an outer radius of 2 m and a height of 5 m, filled with liquid nitrogen. The cryostat itself is surrounded by a water tank with a diameter of 10 m and a height of 8.90 m. Optionally, liquid argon can be used as cooling medium. Its density is higher than that of liquid nitrogen and the absorption of photons is improved. Since no qualitative change in the detection process is anticipated the simulation is carried out with liquid nitrogen as cooling medium only.

4.2. Data Sets

Between $10^5$ and $10^6$ events are simulated for every background component. Each unstable nucleus under consideration is placed randomly inside the geometrical component under study. Subsequently, the decay products are propagated through the GERDA geometry and the energy deposited inside the detectors is recorded. The improvement in background reduction due to the segmentation depends on the signature of the underlying...
physics process. The classes of signatures of the signal and background processes are listed in Section 2. Representative processes for each class are selected. For decays inside the germanium crystals these are the $\nu\bar{\nu}$-decay process (Class I), the decay of $^{60}$Co (Class II) and the decay of $^{68}$Ge (Class III). The decay of $^{208}$Tl inside the detector holders serves as an example for Class IV. The decay of $^{210}$Pb nuclei on the surface of the crystals is given as an example for Class V. For the background estimate for the GERDA experiment all relevant isotopes are simulated.

5. Results

The results of the Monte Carlo simulation are presented in the following.

5.1. Scale of energy depositions

A measure of the volume of the energy deposition in an event is the radius $R_{90}$ within which 90% of the total energy deposited is contained. To begin with, the center-of-energy-deposition for the energy deposited is calculated for each event as

$$\bar{x}_{\text{c.o.e.d.}} = \frac{\sum_i E_i \bar{x}_i}{\sum_i E_i}$$ (1)

where the sum runs over all individual energy deposits in germanium. Afterwards, the energy deposits are ordered according to their distance to the center-of-energy-deposition. Summing over all energy deposits with increasing distance, $R_{90}$ is defined as the distance of the particular energy deposit which is the first that satisfies the requirement that the sum of energies is larger than 90% of the total energy.

Fig. 2 (top) shows the distributions of $R_{90}$ for the considered processes without a cut on the total energy deposited. For the $\nu\bar{\nu}$-decay process, the distribution has a strong peak in the millimeter range. This reflects the range of the electrons in germanium at the relevant energy. The distribution ranges up to the centimeter scale due to events with hard bremsstrahlung in the final state. The distributions for Class II and III processes show a peak at several centimeters. This is expected due to the range of the photons which undergo Compton scattering. The shouder towards lower radii is due to photons which only deposit part of their energy in the crystal. A second, much smaller peak in the micrometer range is visible. This is due to electrons which come from decays of $^{208}$Tl in the holder structure and are not stopped in the liquid nitrogen. The distribution for Class V events ranges from the micrometer to the centimeter scale. The sharp peak at 1 µm is an artifact of the simulation due to the threshold for the production and tracking of $\gamma$-rays.1 The peak at around 10 µm is due to the range of $\alpha$-particles in the relevant energy region. The distribution above 10 µm is due to $\gamma$-rays and bremsstrahlung photons.

Fig. 2 (bottom) shows the distribution of $R_{90}$ for Classes I–IV in the region from 0.1 mm to 10 cm. The total energy for the events in these distributions is required to be within a window of ±50 keV around $Q_{\beta\beta}$. The difference in $R_{90}$ for the signal process and the chosen background processes is more pronounced compared to Fig. 2 (top). Note the deposition varies from the sub-micrometer to the centimeter range. Again, a smaller peak in the micrometer range is visible. It is due to electrons which come from decays of $^{208}$Tl in the holder structure and are not stopped in the liquid nitrogen. The distribution for Class V events ranges from the micrometer to the centimeter scale. The sharp peak at 1 µm is an artifact of the simulation due to the threshold for the production and tracking of $\delta$-rays.1 The peak at around 10 µm is due to the range of $\alpha$-particles in the relevant energy region. The distribution above 10 µm is due to $\gamma$-rays and bremsstrahlung photons.

A variation of threshold parameters did not have an effect on the simulation results presented in the following.
change in the x-scale. Similar calculations with a different setup [19] are compatible with the results obtained in this study.

As can be seen in Fig. 2 the range of the photons involved in the processes under study is indeed approximately 2–3 cm. In the chosen segmentation scheme, considering the size of the crystals, the size of a single segment is comparable with a sphere of radius 1.4 cm. The simple considerations that led to the choice of the segmentation scheme are thus confirmed.

5.2. Multiplicities and suppression factors

Segmentation is used to identify and reduce events with photons in the final state by requiring an anti-coincidence between segments.

The crystal multiplicity, $N_c$, is defined as the number of crystals in an event which have measured energies larger than 10 keV. Similarly, the segment multiplicity, $N_s$, is defined as the number of segments in an event which have measured energies larger than 10 keV. The segments do not necessarily have to belong to the same crystal. Distributions of the crystal/segment multiplicity for the processes selected in Section 4.2 are displayed in Fig. 3 (left/right). Events from all five classes predominantly show energy deposition in only one crystal. However, for Classes I and V the multiplicity drops faster than for Classes II–IV. The segment multiplicities for Classes II–IV drop off only beyond a multiplicity of three. Again, the multiplicities drop significantly faster for the classes without photon emission. The distributions behave as expected from the distributions of $R_{\vec{Q}}$. The segment multiplicities show that the segment size is large compared to the size of energy depositions from electrons from the signal process and comparable to the range of photons in background events.

The distributions of the energy deposited inside the detectors are shown in Fig. 4 for the processes selected in Section 4.2. For each process the total energy measured in all events (total energy spectrum) is shown as well as the spectrum of events after anti-coincidence cuts between crystals (single crystal spectrum, $N_c = 1$) and between segments (single segment spectrum, $N_s = 1$). The top left histogram shows the energy distributions for the $0\nu\beta\beta$-decay process. Most of the events deposit energy at the $Q_{\beta\beta}$-value, although a tail towards lower energies is present due to bremsstrahlung. Since the range of electrons is small compared to the size of the crystals and segments, anti-coincidence requirements change the energy spectrum only slightly. Eighty-seven percent of the signal events deposit their energy within a 10 keV window around $Q_{\beta\beta}$.

The top right histogram shows the spectra for $^{60}$Co. The two characteristic lines from the de-excitation of $^{60}$Ni as well as the summation peak are visible in all three cases. The lines are broadened due to the additional electron that is emitted in the decay.

The suppression factor, SF, is defined as the ratio of the number of events which have a measured total energy in a 10 keV window around $Q_{\beta\beta}$ and the number of events which, in addition, fulfill the respective anti-coincidence requirement. This is either an anti-coincidence between crystals (SF$_c$) or between segments (SF$_s$).

For $^{60}$Co the single crystal spectrum reflects a clear suppression of the process with a suppression factor for crystal anti-coincidence of SF$_c = 3.2$. The single segment spectrum shows a further suppression. In comparison to the total energy spectrum, the suppression factor is SF$_s = 38.3$.

The middle left histogram of Fig. 4 shows the energy spectra for $^{68}$Ge. As in the case of $^{60}$Co the single crystal and single segment spectra are suppressed. The suppression factor is SF$_c = 2.4$ for the single crystal spectrum and SF$_s = 18.0$ for the single segment spectrum. In comparison to $^{60}$Co the suppression is not as strong since only one photon is present in the final state of the decay of $^{68}$Ge ($^{68}$Ga),\(^2\) and $^{68}$Ge decays via electron capture into $^{68}$Ga which subsequently decays via $\beta^+$ decay.

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Please cite this article as: I. Abt et al., Background reduction in neutrinoless double beta decay experiments using segmented detectors—A Monte Carlo study for the GERDA setup, Nuclear Instruments and Methods in Physics Research A (2006), doi:10.1016/j.nima.2006.10.188
Fig. 4. Energy spectra of the five selected processes (top left: $0\nu\beta\beta$, top right: $^{60}$Co, middle left: $^{68}$Ge, middle right: $^{208}$Tl, bottom left: $^{210}$Pb). The black solid line corresponds to the total energy in all crystals. The gray solid line indicates the energy deposited in one crystal requiring only one crystal to fire ($N_c = 1$). The gray dashed line is the spectrum of energy deposited in one segment requiring exactly one segment to fire ($N_s = 1$). The numerical values for the suppression factors can be found in Table 1.
Table 1
Summary of suppression factors for single crystal (SFs) and single segment (SFs) anti-coincidence requirements for a representative selection of isotopes

<table>
<thead>
<tr>
<th>Material</th>
<th>Source</th>
<th>Class</th>
<th>SFs</th>
<th>SFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germanium</td>
<td>Bi</td>
<td>II (e⁻ + γ)</td>
<td>1.8 ± 0.1</td>
<td>5.5 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>Tl</td>
<td>II (e⁻ + γ)</td>
<td>2.6 ± 0.4</td>
<td>13.0 ± 3.7</td>
</tr>
<tr>
<td></td>
<td>Co</td>
<td>II (e⁻ + γ)</td>
<td>3.2 ± 0.1</td>
<td>38.3 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>Ge</td>
<td>III (e⁺ + γ)</td>
<td>2.4 ± 0.1</td>
<td>18.0 ± 1.4</td>
</tr>
<tr>
<td>Detector holder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>Bi</td>
<td>IV (γ)</td>
<td>2.8 ± 0.5</td>
<td>6.0 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>Tl</td>
<td>IV (γ)</td>
<td>2.2 ± 0.4</td>
<td>4.6 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>Co</td>
<td>IV (γ)</td>
<td>6.7 ± 0.2</td>
<td>157.2 ± 26.7</td>
</tr>
<tr>
<td>Teflon</td>
<td>Bi</td>
<td>IV (γ)</td>
<td>2.2 ± 0.3</td>
<td>12.8 ± 3.7</td>
</tr>
<tr>
<td></td>
<td>Tl</td>
<td>IV (γ)</td>
<td>2.5 ± 0.3</td>
<td>10.0 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>Co</td>
<td>IV (γ)</td>
<td>3.8 ± 0.1</td>
<td>106.3 ± 7.6</td>
</tr>
<tr>
<td>Cables</td>
<td>Kapton</td>
<td>Bi</td>
<td>II (IV) (γ)</td>
<td>3.3 ± 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tl</td>
<td>II (IV) (γ)</td>
<td>3.1 ± 0.7</td>
</tr>
<tr>
<td>Electronics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Tl</td>
<td>IV (γ)</td>
<td>1.5 ± 0.3</td>
<td>2.9 ± 0.6</td>
</tr>
</tbody>
</table>

A detector unit consists of the crystal, a holder structure (copper and Teflon), Kapton cables and electronics. The electronics is placed about 30 cm above the detector array.

The suppression of multiple energy deposits is therefore smaller.

The middle right histogram shows the energy spectra for 208Tl in the copper of the detector holder. The suppression factor for the single crystal spectrum is SFs = 2.2. The single segment spectrum is further suppressed with a suppression factor of SFs = 4.6.

The spectra from the decay of 210Pb on the surface of the detectors is shown in the bottom left histogram of Fig. 4. As expected, the anti-coincidence requirements do not change the spectrum significantly since α-particles have a range which is small compared to the size of the detectors and the segments.

In order to quantify the benefit of segmentation, the simulation was carried out for the main sources of radioactive background expected in the GERDA experiment. The suppression factors achieved by anti-coincidence requirements between crystals and between segments are calculated for different isotopes located in different components. The results are summarized in Table 1. Note that the class of background an isotope belongs to depends on its position.

As expected Class V events do not show an improved suppression by requiring anti-coincidence between segments. The suppression factors for Class II to IV events for segment anti-coincidence are much larger than the suppression factors for crystal anti-coincidence. The ratio of the segment and crystal suppression factors ranges from 3 to 12 for Class II events and is 8 for Class III events. For Class IV events the ratio ranges from 2 to 30. 60Co events with their two photons in the final state are particularly well suppressed.

The suppression factor for the decay of 208Tl strongly depends on the position of the isotope. For radio-imurities inside or close to the crystal (germanium, detector holder) the suppression factor is larger than for those in a larger distance to the crystal (cables, electronics). This is due to the electrons in the final state which do not reach the detector in the latter case.

The suppression factors depend on the geometrical acceptance. A study for a single crystal is in preparation where data from a segmented prototype detector will be compared to Monte Carlo data.

6. Conclusions and outlook

A Monte Carlo study of an array of 21 germanium crystals arranged according to the GERDA design was performed. The background rejection based on anti-coincidence requirements for segmented and unsegmented germanium detectors was compared. Events with photons in the final state are significantly better identified, if segment anti-coincidences are used. The improvement for the particularly interesting case of 60Co inside the crystals is about one order of magnitude.

The segments cannot be chosen arbitrarily small because bremsstrahlung photons from electrons can enlarge the volume over which energy is deposited in 0νββ-events. The use of simple anti-coincidence cuts between segments decreases the signal efficiency with an increasing number of segments, whereas the suppression factor for photon events increases.

Combining the results obtained from the Monte Carlo simulation presented here and material screening measurements the background index for the GERDA experiment is predicted to be dominated by events from radioactive decays in the detector suspension and the cabling. The very first design simulated for this study would yield a background index of 3 × 10⁻³ counts/(kg·keV·y). With the guidance from the Monte Carlo both the design of the cables and the suspension system have been modified. The improved layout provides background reduction to the desired level.

A further identification of background events is expected from the analysis of the evolution of the electrical pulses coming from the germanium detectors. These so-called pulse shape analysis techniques have been established in recent double beta decay experiments and will also be applied in the analysis of data from the GERDA experiment.

A prototype detector of the GERDA Phase II design is currently under study. The identification of photon events will be investigated in detail and compared to Monte Carlo simulation.
Acknowledgments

The authors would like to thank the MAJORANA Monte Carlo group for their fruitful collaboration and cooperation on the MAGe project. The authors would also like to thank Igor Barabanov and Peter Grabmayr for their helpful comments. This work has been supported by the EU FP6 project Ilias and the INFN.

References