PROCEEDINGS OF SCIENCE

Hands on LUNA: Detector Simulations with Geant4

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For the evaluation of measurements performed at the Laboratory for Underground Nuclear Astrophysics (LUNA), knowledge of the response of the detectors and a detailed understanding of the background contributions to the measured spectra are essential. Monte Carlo simulations of the radiation transport on the basis of Geant4 are important tools used in LUNA to evaluate these points.
In this hands-on project an existing simulation of a bismuth germanium oxide (BGO) detector was studied, updated and extended. The resulting code was tested by performing a feasibility study for a measurement of the radioactive backgrounds originating from within the BGO detector with a germanium detector.

PoS(GSSI14)022

Gran Sasso Summer Institute 2014 Hands-On Experimental Underground Physics at LNGS - GSSI14,
22 September - 03 October 2014
INFN - Laboratori Nazionali del Gran Sasso, Assergi, Italy

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1. Nuclear Astrophysics Underground with LUNA

The Laboratory for Underground Nuclear Astrophysics (LUNA) is a facility for the measurement of nuclear cross sections, with a focus on reactions of astrophysical interest. At the core of the current setup is an accelerator with a terminal voltage of 400 kV and a radiofrequency ion source that can provide protons or alpha particles. [1]

An important factor for the sensitivity of experiments measuring radiation from reactions with small cross sections are radioactive backgrounds. A big advantage of LUNA in this respect is its location at the Gran Sasso National Laboratories (LNGS), where the rock overburden greatly reduces the flux of cosmic muons and their (direct or indirect) contributions to the observed background spectrum. Another source of radioactive background is natural radioactivity in materials around the detector and the detector materials itself. Independent of the location, the beam used in an experiment can cause other reactions besides the one under investigation, further adding to the background.

A detailed understanding of the observed backgrounds is crucial to correctly infer the signal from the measured (total) spectra. The identification of the separate background contributions is also essential to design effective measures for further background reduction.

2. Gamma Radiation Detectors Used in LUNA

Detectors of different types have been used in experiments at LUNA. The focus in this project was on a bismuth germanium oxide (BGO) scintillation detector, which has been used for gamma ray detection in different experiments at LUNA [2] and is also scheduled for multiple studies in the near future.

This detector consists of six optically isolated BGO crystals (about $52\,\mathrm{cm}^2 \times 28\,\mathrm{cm}$ each) in a steel housing. The detector is cylindric and has a borehole in its center to insert beamline and target. The detector geometry is shown in Figure 1. The crystals are arranged around the borehole, parallel to the cylinder axis, providing a large solid angle coverage around the target. Further adding to the detection efficiency for gamma rays are the high density ($\rho = 7.1\,\mathrm{g/cm^3}$) of BGO and the large atomic number of bismuth ($Z = 83$), favoring photoelectric absorption; a disadvantage is the moderate energy resolution [3].

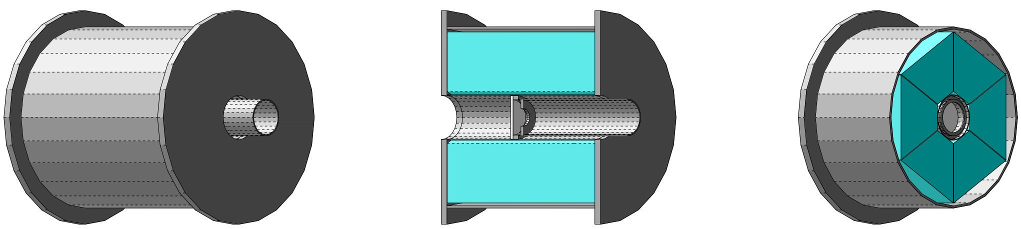


Figure 1: Exterior view (left) and cross sections of the BGO detector geometry – crystals (cyan), housing and parts of the beam line with target (gray) – as implemented for the simulation (see next Section).

Each crystal is equipped with either one or two photomultiplier tubes (PMTs). The individual readout yields the energy depositions for each segment of the detector. Summing the signals from the individual crystals increases the probability for the detection of the complete gamma energy released following a reaction, whereas the spectra of the single crystals can yield more information about the individual gamma rays emitted in cascades.

Another detector type widely used at LUNA are high purity germanium (HPGe) detectors. These detectors can provide a roughly two order of magnitude better energy resolution than BGO. However, due to the properties of germanium ($Z = 32$, $\rho = 5.3\,\mathrm{g/cm^3}$) and generally smaller dimensions compared to the BGO detector described above, their full energy peak efficiency for gamma radiation is significantly smaller than for the BGO detector.

3. Detector Simulations

3.1 Existing BGO Detector Simulation and Updates

A working simulation for the BGO detector already existed and was used for example to determine the detector response to gamma cascades coming from reactions in the target, and to gamma radiation from environmental background [4]. The simulation code was based on Geant4 [5] version 9.6, implemented the BGO detector geometry as shown in Figure 1 and used the appropriate physics lists to simulate electromagnetic interactions. In the course of this project different parts of this simulation were updated and various features added.

The code was updated to work with Geant4 version 10.0 and to utilize the multi-threading support that was introduced with this version, allowing to run more efficiently on machines with multiple cores. The simulation made use of the ROOT framework for storing the simulated results, which proved to be a difficulty, as parts of this framework are not thread-safe [6]. Hence access to ROOT data structures was kept as mutually exclusive between threads, so that these actions do not run in parallel. When the actual simulation of an event requires much more time than saving the result, which is typically the case here, this limitation does not strongly reduce the benefits of parallelization.

The geometry and the primary particle generators were implemented in a more modular way, to simplify the addition of new geometric objects or primary particle generators. New macro commands were introduced for geometry objects (such as the BGO detector) to enable, place and rotate each single object. Another set of macro commands was added to control the settings for the generation of primary particles and their positions. With these changes it is possible to realize different setups without the need to alter the code itself.

3.2 BGO Detector Backgrounds, Simulation and Results

Figure 2 shows the combined spectrum of several background measurements (without beam) during the $^{25}\mathrm{Mg}(\mathrm{p},\gamma)^{26}\mathrm{Al}$ campaign [7]. The spectrum shows the sum of all crystals and was acquired in about one month total measurement time. Particularly interesting is the part of the spectrum above about 6 MeV, as the Q-values of future reactions to be studied at LUNA fall into this region. Background events in this region are attributed mostly to (n,γ) capture reactions of neutrons on detector materials [8] and currently subject of more detailed studies.

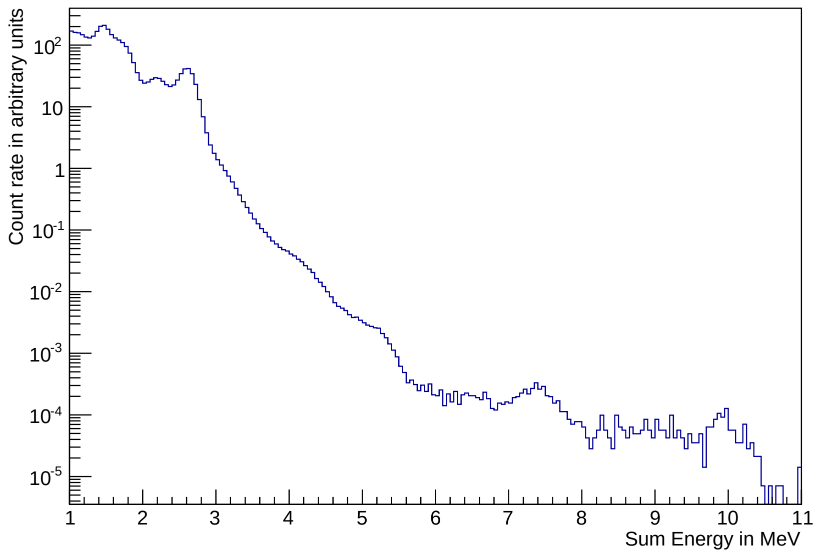


Figure 2: Background spectrum (sum energy of all six crystals) for the BGO detector.

The feasibility to detect gamma rays from the cascades following (n,γ) reactions in the BGO detector with an HPGe detector was considered to test the application of the simulation. Such a detection would provide a clear signature of the capture events. The detection of other gamma lines could point to sources of background in the BGO detector that have not been considered yet.

The simulated setup consists of the BGO detector and a simplified HPGe detector (a cylindrical piece of germanium with a borehole, in an aluminum casing) in different configurations, shown in Figure 3. In all cases the HPGe was brought as close as possible to the BGO. However, the HPGe detector under consideration does not fit into the BGO detector's borehole.

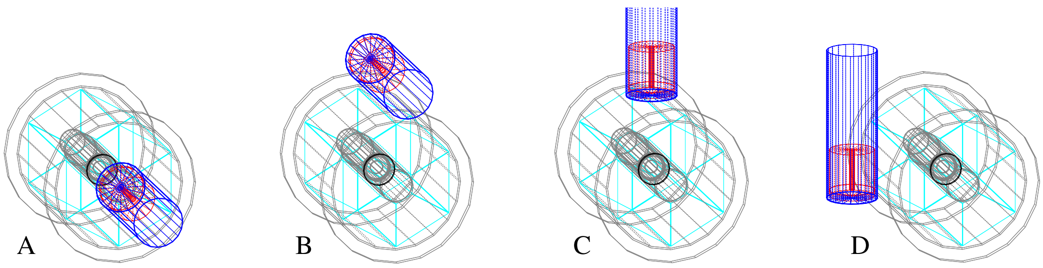
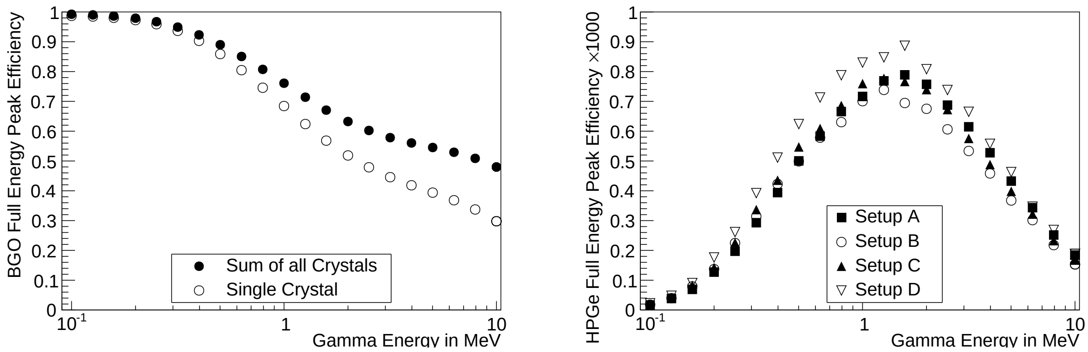


Figure 3: Simulated setups of the BGO (cyan) and HPGe (red) detectors with their housings.

The simulation was extended to have the option to sample the primary particle position homogeneously within volumes of a given material. Using this position generator, monoenergetic gamma rays were simulated within the BGO crystals. The energy deposition in the individual crystals and in the germanium volume were stored, and evaluated after completion of the simulation. The full energy peak efficiency, i. e. the fraction of events with an energy deposition in sensitive parts of the detector equal to the initial gamma ray energy, were evaluated for a single BGO crystal, for the sum of all BGO crystals and for the HPGe detector.

The results for the full energy peak efficiencies at different gamma energies are shown in Figure 4. The BGO detector shows large efficiencies for these internal gamma rays, decreasing for larger gamma energies. The HPGe full energy peak efficiency is determined by the probability of the gamma ray to escape the BGO without energy loss and the efficiency to detect the full gamma energy in the germanium, yielding an efficiency curve with a maximum at about 2 MeV in the simulations. Due to the efficient gamma ray absorption in BGO, the properties of germanium and the small solid angle coverage of the HPGe, even at the maximum of its efficiency curve the germanium detector has an almost three orders of magnitude smaller full energy peak efficiency than the BGO. The relative differences in efficiency between the various HPGe positions are smaller than 20%, with the largest efficiencies for the configuration with the HPGe alongside the BGO and perpendicular detector axes (setup D, cf. Fig. 3).



a) BGO, single crystal and sum

b) HPGe at different positions

Figure 4: Full energy peak efficiencies of the two detectors obtained in the simulation.

These results for monoenergetic gammas can not be applied directly in the context of neutron captures, as this would require information about the gamma cascades (which influence the detection efficiencies via summing effects). However, the much smaller full energy peak efficiency of the HPGe compared to the BGO detector found in the simulation and the low event rates in the high-energy range of the measured BGO spectrum attributed to neutron captures suggest that it is not feasible to detect single gammas from these captures in a realistic time – even assuming that the HPGe itself does not detect background from other sources than the BGO.

4. Summary and Outlook

The simulation of the BGO detector has been updated and extended. It can be used to evaluate different questions regarding the BGO detector response, including the simulation of the signal from target reactions, the beam-induced background from target impurities, or the simulation of intrinsic and external backgrounds for studies of the detector background model. The macro commands for geometry and primary generator allow for changes in the simulated setup without changing the source code. New geometries or particle generators can be added to the simulation code in a modular way. However, more complex demands for future simulations may require further extensions of the source code structure.

5. Acknowledgements

The authors acknowledge the IT division at LNGS for providing computing resources (U-LITE) that have contributed to the results reported within this paper. Further computing resources were provided by the Gran Sasso Science Institute.

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