Backgrounds in a BGO detector underground

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Abstract. For the measurement of reactions with small cross sections as aimed for in the Laboratory for Underground Nuclear Astrophysics (LUNA) at the Gran Sasso National Laboratory (LNGS), low detector background levels are compulsory. Background measurements with a BGO detector used at LUNA have been evaluated to develop a model of the contributions in the region of interest for ongoing and planned measurements. Conclusions from this model and implications for further background reduction for this detector setup are discussed. A customized lead shielding against environmental backgrounds is described.

1. Challenges in direct measurements of small cross sections

The relevant energy region for nuclear reactions in stellar scenarios is given by the Gamow window. Direct measurements of nuclear reactions in or close to this energy region are often very challenging as the cross sections for these processes fall rapidly with decreasing energy. The Laboratory for Underground Nuclear Astrophysics (LUNA), located at the Gran Sasso National Laboratory (LNGS) is dedicated to measurements of such reactions. Two factors are crucial to achieve this: a large detection efficiency for the signal of the reaction and a small background in the signal region of interest.

2. The Bismuth Germanium Oxide (BGO) detector at LUNA

An important tool for the detection of \((p, \gamma)\) reactions at LUNA is a BGO detector \cite{1}. BGO efficiently absorbs gamma rays thanks to its density and the large atomic number of bismuth. Its scintillation properties allow the subsequent detection of the absorbed radiation. A disadvantage to other gamma ray detection techniques is the moderate energy resolution. The detector at LUNA has six crystal segments that are aligned axially around the borehole for the beamline. The setup allows to place the target in the center of the detector and achieve a close to \(4\pi\) solid angle coverage. The crystals are optically isolated and coupled to PMTs that are read out individually to obtain six single crystal spectra. When coincident events in the individual crystals are added, a total detector spectrum can be obtained. This spectrum imitates one large crystal and maximizes the efficiency for detection of the complete gamma ray energies. Hence, the region of interest in the total detector spectrum for a \((p, \gamma)\) reaction is usually given by the \(Q\) value of the reaction under study. The single crystal spectra can yield additional information on the individual gamma rays emitted in the reaction.
3. Background contributions
Without dedicated efforts, the background signal in the detector can easily be the limiting factor for the sensitivity of a measurement. An understanding of the different background contributions is necessary to choose an appropriate background reduction strategy. Two primary sources contribute to the background in a radiation detector: radioactive decays and cosmic rays.

The radioactive component stems primarily from natural radioactivity in the form of primordial decay chains and $^{40}$K. It contributes to the detected environmental gamma ray background, but also to the ambient neutron flux via $(\alpha, n)$ reactions. Particle $(\alpha$ and $\beta)$ radiation will typically not be detected from sources outside the detector, due to its limited range. It can be relevant, however, for intrinsic radioactivity inside or on the scintillator.

Cosmic rays, in particular penetrating muons, contribute by direct detection or via secondary processes that produce gamma rays or neutrons. At LNGS, the cosmic component is dominated by muons, whose flux is about a factor $10^6$ lower than on surface. This reduction is also directly reflected in the muon-induced backgrounds, e.g. for high-energy gamma rays (see [2] for a comparison with this detector on surface and underground).

Thermal neutrons constitute a large fraction of the environmental neutron flux at LNGS (cf. e.g. [3]). For the studied detector these neutrons can contribute significantly to the background via $(n, \gamma)$ reactions, typically with large $Q$ values, in or close to the active detector volume.

4. Modeling of a background spectrum acquired underground
Background spectra were acquired during multiple runs in the course of the $^{25}$Mg$(p, \gamma)$ campaign at LUNA (cf. [4]) with an accumulated real time of approximately one month. These data, acquired without additional shielding around the detector, were used as the basis for the development of the background model. Focus of the model was the energy region above 6 MeV given by the $Q$ values of the reactions to be studied.

Simulations of the detector setup are required to determine the energy deposition in the detector caused by different background sources. They have been performed with a simulation based on Geant4 [5]. The detector geometry had been implemented and tested previously (cf. e.g. [4]). The radioactive decay process provided by Geant4 was used to generate the primary particles from the decays of the different radioactive nuclides. A custom primary particle generator was used for the radiative capture of thermal neutrons, creating the deexcitation gamma cascades according to the level schemes of the daughter nuclei as far as the branchings were known. Contributions from the radioactive nuclides were simulated homogeneously distributed throughout the surrounding rock, the steel parts of the detector and the BGO crystals. The radiative neutron captures were simulated homogeneously throughout the volumes, neglecting the self-shielding of the detector. For each simulated contribution, the energy deposition in the BGO crystals was saved, separately for electrons and for $\alpha$ particles.

The detector response to the energy deposition has to be modeled to derive a simulated signal that can be compared to the measured spectrum. The quenching effect, leading to a lower scintillation light yield of $\alpha$ particles compared to electrons of the same energy, was modeled using Birks' law as described in [6]. To account for the detector resolution, the visible energy deposition after quenching was smeared with a Gaussian response with an energy-dependent resolution $\sigma$. A quadratic relation between the visible energy deposition and the detector signal (ADC channel) was assumed.

Several assumptions had to be made to limit the number of free parameters when combining the large number of individual contributions to obtain the total spectrum. The decay chains were assumed to be in equilibrium. Intrinsic radioactivity was treated only as a function of material, possible differences in radiopurity between separate parts have been neglected. Pile-up, i.e. the random summing of energy depositions from independent decays or reactions, has been considered for each combination of two or three physical events occurring within a certain
time window for a single detected event, based on the rates of the contributions.

As a result, neutrons from \((n,\gamma)\) reactions in BGO and the steel parts of the setup have been identified as the main contribution to the backgrounds for energies of 6-12 MeV. In the range of circa 4-6 MeV, pile-up events were the largest contribution.

5. Customized lead shielding
A lead shielding around the detector can suppress the detection of environmental gamma rays. Even though many of the reactions studied with the BGO detector at LUNA have \(Q\) values above the direct contribution of environmental gamma rays, the region of interest for these reactions can be affected by pile-up from random coincidences of environmental background events.

The use of a stationary shielding using lead bricks is not practical for this setup, as the detector has to be moved away regularly to exchange the irradiated target. A customized shielding has been built, consisting of few massive pieces that house the detector and are mounted on rails, such that the whole detector setup can be moved along the beamline to access the target. The setup provides 10 cm of lead around the detector (except for openings for the beamline and for the cables). It is also manufactured to house a HPGe detector (in two different positions) with 15 cm of lead around.

First measurements with the shielding in place showed a reduction of approximately 1 order of magnitude in the count rate around 1 MeV. With the shielding, in combination with a new DAQ that allowed shorter coincidence intervals for the total detector spectrum, the pile-up contribution could be reduced significantly, and the region where neutron-capture reactions are predominant extended to lower energies. A reduction in the number of detected neutron-induced events has been observed as well, presumably mostly caused by the absorption of thermal neutrons on \(^{206}\text{Pb}\) in the shielding.

6. Conclusions and outlook
A model for the background contributions was developed for the LUNA BGO setup, focusing on the high-energy part of the spectrum. A reduction of pile-up events and neutron induced events has been achieved using a customized lead shielding. The identification of radiative neutron capture as the main background contribution at large energies motivates the consideration of an additional neutron shielding.

Updates of the model are ongoing to improve the description over a larger energy range and incorporate the information from shielded background measurements, aiming at a better distinction between external and intrinsic backgrounds. Ultimately the final model will be used to assess the feasibility of a further background reduction to enhance the sensitivity of the presented setup, and therefore allow the measurement of reactions at lower beam energies or reactions with lower \(Q\) values.

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