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Nuclear astrophysics studies at the LENA facility: The γ-ray detection system

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Abstract

The detection system of The Laboratory for Experimental Nuclear Astrophysics is described, including methods for measuring weak capture-γ-ray resonances. Improved γγ-coincidence techniques are detailed, as well as the reduction of cosmic muon-induced background in the energy region of $E_\gamma = 0.6-9.0\,\mathrm{MeV}$ by the use of compact cosmic muon anti-coincidence shields. These techniques reduced background count rates in the regions of $E_\gamma = 0.6$–3.0 and 3.0–9.0 MeV with respect to unshielded singles count rates by factors of 3600 and 21, respectively.

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1. Introduction

At energies relevant to stellar nucleosynthesis, charged particle interactions such as proton or α capture are highly suppressed due to the Coulomb barrier. Hence, in experimental nuclear astrophysics, it is important that low count rates are observable. The count rates of interest are often lower than those of environmental background, and therefore, methods to distinguish between background counts and those from the reaction of interest must be developed. Low-level γ spectroscopy has been summarised in Ref. [1].

In order to reduce background count rates, active and passive methods can be used. Passive methods include placing the experiment deep underground in conjunction with using very low-activity shielding, reducing high-energy, cosmic muon-induced background by orders of magnitude [2,3]. Active methods require the use of other detectors to distinguish between background and the counts of interest.

The Laboratory for Experimental Nuclear Astrophysics (LENA) is a low-energy accelerator facility dedicated to nuclear astrophysics. It is designed for the measurement of very weak cross-sections of reactions relevant to nucleosynthesis. In this work, we will discuss the detection system employed at LENA. We will outline the methods used for reducing background and increasing detection efficiency for measuring weak capture-γ-ray cross-sections of reactions important in stellar nucleosynthesis. This work follows from Ref. [4], with significant improvements to the methodology and detectors used. Simply subtracting background from data is not desirable for statistical reasons [5]. Consequently, background reduction is essential to the measurement of low-energy capture resonances. LENA uses a combination of passive, and active shielding with coincident techniques for background reduction in low-energy resonant capture measurements. Although detector arrays such as Gammasphere [6] or Euroball [7] are commonly used for coincident techniques, a compact

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system is desired in our case. In order to improve the detection efficiency, close geometry between source and detector is essential. This introduces summing effects for cascade decays which need to be addressed. Here, we will use coincidence summing to introduce an effective method of finding detector efficiencies, and will show how coincidence summing can be accounted for in resonance strength determinations.

Throughout this work, all quantities are given in the laboratory system unless mentioned otherwise.

2. General considerations

2.1. Background considerations

The sensitivity of a counting experiment is inversely proportional to the square root of the background rate and directly proportional to the signal rate. Limitations in detector technologies and economic concerns limit the improvements on signal strength. Therefore, background rates must be reduced as much as possible to improve sensitivity. A discussion of the sources of background radiation can be found in Ref. [1] and will be summarised here.

The sources of background radiation are: (i) environmental radioactivity, such as the discrete peaks arising from the decay of ^{40}K and ^{208}Tl. (ii) Radio impurities in apparatus material, such as ^{238}U and its decay products (including ^{210}Pb). (iii) Rn gas, which is present in the air. (iv) Cosmic rays, which produce many secondary particles in the upper atmosphere, the most important of these being highly penetrating muons and neutrons. Muons create background events through various mechanisms. Background counts can arise in the detector by direct ionisation, pair-production, bremsstrahlung and nuclear interactions. Muons are attenuated with a mean length of about $2\,\mathrm{kg\,cm^{-2}}$ [1]. It has also been shown that the intensity of tertiary neutrons, produced by muon interactions in the lead shielding increases with lead shielding thickness. These neutrons can then induce γ-ray background in the detector. Here we will present a method of using anti-coincidence requirements to significantly reduce muon-induced background in the detector. (v) Neutrons from natural fission and (α, n) reactions. The neutrons from these reactions induce secondary γ-ray background in the detectors. A singles germanium detector spectrum showing contributions from some of these background sources can be seen in Fig. 1.

The majority of these environmental background sources can be suppressed with the use of passive shielding, such as lead shields, and the coincidence techniques discussed in the following section. However, cosmic-ray-induced background cannot be removed easily in this way. Cosmic-ray muons and neutrons are highly penetrating, and thus passive shielding is not very effective. Coincidence techniques will also not work sufficiently because muons can pass through the coincidence apparatus, depositing some amount of energy in multiple counters, thereby producing true coincidences.

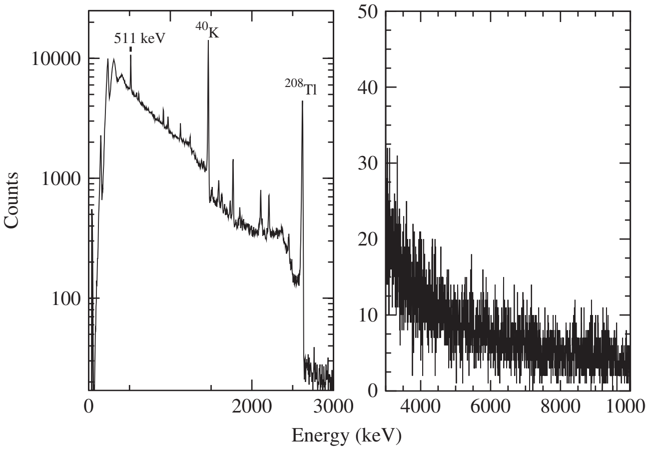

Fig. 1. 140% HPGe room background spectrum with passive shielding for a running time of 17 h.

One possible method of reducing background from these highly penetrating sources is to place the equipment deep underground. Sufficient amounts of rock shielding can stop high-energy muons and neutrons, and therefore reduce the background in the detector. Background rates reported from other laboratories, both at sea level, and underground are presented in Section 4.

2.2. Coincidence detection scheme

As described in Ref. [4], the decay strength of most capture reactions of astrophysical interest is fragmented as a result of many lower lying levels giving rise to $\gamma\gamma$-cascades [8,9]. Experience shows that these $\gamma\gamma$-cascades frequently decay through the first excited state(s) with excitation energies that are usually less than $E_x \approx 3.0\,\mathrm{MeV}$. The decay strength is then concentrated as these states decay to ground. The presence of multiple γ-rays means that coincidence techniques can be used to reduce the background considerably. As an example, consider a hypothetical situation in which an excited nucleus decays by emitting two photons, a 3 MeV γ-ray in coincidence with a 6 MeV γ-ray. It is then possible to gate on a 2D coincidence spectrum of energy detected in one counter (e.g. a Germanium detector) vs. the energy in another counter (e.g. a NaI(Tl) annulus). This is shown in Fig. 2.

Most of the room background originates from γ-rays from ^{40}K (1461 keV) and ^{208}Tl (2615 keV). Scattering of photons from the NaI(Tl) annulus into the high-purity Ge (HPGe) detector or vice versa will also create background in the coincidence spectrum. Other coincident background originates from cosmic muon interactions, which deposit energy in both the NaI(Tl) and the HPGe counters. Two diagonal lines can be drawn immediately in the 2D coincidence spectrum. Disregarding all events located below the lower line, with $E_{\mathrm{sum}} = E_{\mathrm{Ge}} + E_{\mathrm{NaI}} = 3.5\,\mathrm{MeV}$ will remove the majority of room background. It is not possible for a summed energy of greater than 9 MeV to be produced by the reaction in question, so these events must