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PoGOLino: A scintillator-based balloon-borne neutron detector

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ABSTRACT

PoGOLino is a balloon-borne scintillator-based experiment developed to study the largely unexplored high altitude neutron environment at high geomagnetic latitudes. The instrument comprises two detectors that make use of LiCAF, a novel neutron sensitive scintillator, sandwiched by BGO crystals for background reduction. The experiment was launched on March 20th 2013 from the Esrange Space Centre, Northern Sweden (geomagnetic latitude of 65°), for a three hour flight during which the instrument took data up to an altitude of 30.9 km. The detector design and ground calibration results are presented together with the measurement results from the balloon flight.

1. Introduction

A detailed understanding of the atmospheric neutron environment is necessary for radiation protection studies linked to air travel and space tourism, as well as the phenomena of single event upsets in avionics [1]. Furthermore, for Earth-orbiting and balloon-borne experiments making use of low Z detection materials, high energy neutrons may produce an irreducible background when scattering in the detector. Data on of the neutron environment at high latitude balloon altitudes is however lacking. An example of an experiment subject to an irreducible neutron induced background is the PoGOLite instrument of which PoGOLino is a spin-off [2]. PoGOLite is a balloon-borne X-ray polarimeter which makes use of plastic scintillators to detect both the scattering and photoabsorption location of incoming X-rays. Plastic scintillators have a high Compton scattering cross-section for hard X-rays, but also for elastic neutron scattering. At the float altitude of PoGOLite, 40 km, the background induced by neutrons is larger than the expected signal despite the use of a 300 kg passive polyethylene shield used to reduce the incoming high energy neutron flux. Due to this irreducible background and the long duration circumpolar flight path of the instrument, a detailed knowledge of the neutron environment at high altitudes and its dependencies on location and solar activity is of great importance.

Neutrons are produced in the Earth's atmosphere in air showers resulting from interactions of cosmic rays with atmospheric nuclei. Within the shower neutrons are produced either by weak interaction processes, in internal cascades in the nuclei or by the evaporation of these nuclei after the initial interaction. The production energy of neutrons from these processes range from as low as ~ 0.1 MeV, for evaporation, to a maximum of 10's of GeV for weak interaction processes. After production, the neutrons are moderated to sub-eV energies by scattering off atmospheric nuclei. The different production processes and the atmospheric moderation result in a complex relationship between the neutron energy spectra, directional dependence and altitude. The neutron environment furthermore depends on the incoming cosmic ray spectrum which in turn varies with latitude and solar activity, further adding to the complexity of the atmospheric neutron environment.

As a result of the large number of dependencies on the neutron environment, accurate predictions of it rely on Monte Carlo simulations which are validated using experimental data. For

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low latitudes such high altitude data exists as a result of, for example, several measurements performed during balloon missions launched from Palestine, Texas [3,4]. Experimental data at high altitudes is however lacking for high latitudes where, as a result of the Earth's magnetic field, the neutron flux is the highest and most sensitive to solar activity. Interest in accurate predictions for these altitudes is further increased as a result of the recent popularity of balloon flights from high latitude locations such as the McMurdo Station in Antarctica and the Esrange Space Centre in Northern Sweden. Acquiring more data of the neutron environment at these locations is therefore necessary in order to validate and develop Monte Carlo based atmospheric neutron models.

The increasing price of ^{3}He, the traditional material used for neutron detection, has prompted the development of novel neutron detectors. Among these, the recently developed Lithium Calcium Aluminium Fluoride (LiCAF) scintillator crystal allows compact, mechanically simple, lightweight and efficient detector systems to be developed. LiCAF scintillator crystals can be combined with high Z scintillators in a Phoswich (phosphorous sandwich) configuration, a combination of several different scintillators read out using a single photomultiplier tube (PMT), to reduce instrumental background. The high detection efficiency per unit volume allows for a small detector whereas the scintillation crystal-based detection mechanism allows for a mechanically simple instrument with respect to, for example, gas-based detectors. This combination of features makes LiCAF ideal for balloon-borne neutron measurements.

The PoGOLino instrument contains two neutron detectors, one of which is embedded in a moderating material, resulting in a high efficiency for high energy neutrons whereas the second detector remains unshielded resulting in a high efficiency at low energies, thereby giving insight into the spectral shape of the incoming spectrum. By keeping the instrument lightweight and designing it for autonomous operation, it is optimized for piggyback flights on other balloon experiments.

PoGOLino was launched on March 20th 2013 from the Esrange Space Centre in Northern Sweden. Data was collected both during the ~2 h ascent phase and during the additional 1 h spent at the float altitude of 30.9 km.

In the following section a detailed description of the instrument will be provided, followed by results of the on-ground calibration measurements. The 2013 flight is then described and the flight measurement results are compared to simulated data.

2. Instrument design

LiCAF was chosen as the scintillator material for the PoGOLino experiment to maintain a low mass while ensuring a high neutron detection efficiency. LiCAF is a novel, low Z, inorganic scintillator material with a high ^{6}Li content developed at Tokuyama corporation, Japan. Neutron detection proceeds through the reaction $^6\mathrm{Li} + \mathrm{n} \rightarrow {}^4\mathrm{He}$ (2.73 MeV) $+$ ^{3}T (2.05 MeV). The cross-section for this process for thermal neutrons is 940 barn. The low Z value of the material, which results in a relatively low cross-section for photon interactions, and the monoenergetic signal from neutron capture makes LiCAF suitable for performing pulse height based photon/neutron discrimination. Both a cerium and a europium doped version of LiCAF exists. Cerium doped LiCAF has a decay time of 40 ns and a light yield of 3.5×10^3 photons/neutron capture [5]. Europium doped LiCAF has a longer decay time, 1600 ns, but has the advantage of a high light yield of 3×10^4 photons/neutron capture [6]. Due to the relatively low counting rates expected at float altitudes, on the order of 10 Hz, a short decay time is not required for PoGOLino. Europium doped LiCAF, which has the advantage of a higher light yield, was therefore chosen as a detection material. The emission wavelength from Eu:LiCAF is 370 nm making it compatible with Bismuth Germanium Oxide (BGO) scintillators in a Phoswich configuration. In the Phoswich Detector Cells (PDCs) used in PoGOLino, a hexagonal LiCAF scintillator with a thickness of 5 mm and a side length of 16 mm is used. The high detection efficiency per unit volume of LiCAF ensures an expected total number of neutron detections of order 10^3 for a 300 s measurement for this size of scintillator. Assuming a balloon ascent velocity of 1 km/300 s this will enable PoGOLino to perform neutron flux measurements with a statistical error on the order of a few percent within a 1 km ascent. To reduce instrumental background from photons and charged particles the LiCAF scintillator is placed between two 40 mm thick BGO crystals which form an anticoincidence system. The BGO crystals used for PoGOLino were produced by the Nikolaev Institute of Inorganic Chemistry. BGO was chosen for its high Z value which results in a high photoabsorption cross-section. Since the decay time of BGO emission is 300 ns, pulse shape discrimination can be used to distinguish between the LiCAF events and BGO events. The assembly of 3 scintillator crystals is read out by a PMT of the type Hamamatsu Photonics R7899EGKNP originally developed for the PoGOLite mission [7]. Fig. 1 shows an assembled PDC together with the individual components. PoGOLino contains two such PDCs. One is shielded by a polyethylene cylinder with a radius of 8.5 cm while the other remains unshielded. The unshielded detector is sensitive to thermal neutrons whereas, due to neutron moderation by the polyethylene, the shielded detector is sensitive to neutrons over a wider energy range, thereby making PoGOLino sensitive in two different energy regimes. Aside from these two PDCs, the PoGOLino instrument has a third PDC in which the LiCAF crystal is replaced by a plastic EJ-204 scintillator, produced by Eljen Technology with the same geometry as the LiCAF crystals. The data from this PDC will be used for the study of neutron interactions in EJ-204. Such interactions are expected to form the main background for the polarization measurements of the PoGOLite experiment [8].

The energy dependence of the neutron capture efficiency of the two LiCAF-BGO PDCs was simulated using Geant4 [9], a C++ based software toolkit developed to simulate particle interactions in matter. The version of Geant4 used for this work is 4.9.6. This version was used with the QGSP_BIC_HP physics list together with the neutron high precision thermal scattering data libraries. Results are presented in Fig. 2. Due to the limited moderation of the LiCAF material itself the neutron capture cross-section as a function of energy of the unshielded detector, shown in blue, is

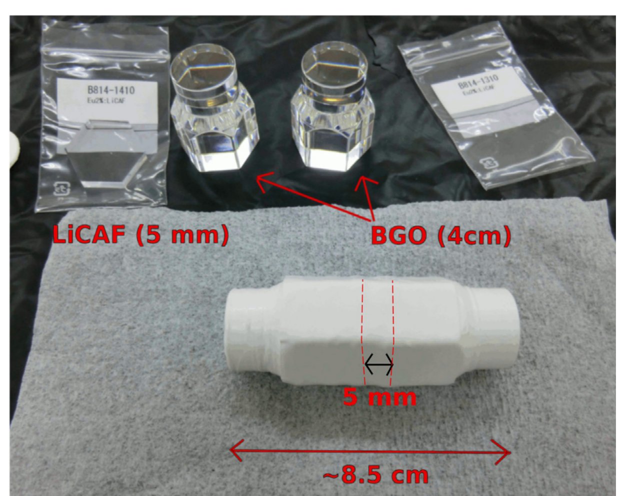

Fig. 1. An assembled PDC in front of the three individual crystals.