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Instruments to study fast neutrons fluxes in the upper atmosphere with the use of high-altitude balloons

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Abstract

The successful circumpolar flight of the X-ray polarimeter PoGOLite in the northern hemisphere during the summer campaign of 2013 inspired us, the team consisting mostly of students and senior researchers, to develop a Modular Monitor of the Cosmic Neutral Emission (MMCNE) prototype that can be flown on the high-altitude balloons to study two components of neutral emission, namely spectra of neutrons and of gamma-rays in the upper layers of Earth atmosphere. Instrument modular concept, and some of the simulated detection characteristics for the selected layout will be presented in this paper.

Keywords: Albedo neutrons; Cosmic rays; Solar cosmic rays; Solar flares; Terrestrial gamma flashes; High altitude balloons

1. Introduction

Dedicated measurements of neutron fluxes in the upper atmosphere to verify the CRAND (Cosmic Ray Albedo Neutron Decay) model of the inner radiation belt formation were carried out in the 1970's (Kanbach et al., 1974; Preszler et al., 1972, 1974). These experiments used a fast neutron scattering technique to measure an energy and direction of the incoming neutrons (Gollnitz et al., 1969; Grannan et al., 1972; Koga et al., 1979; Lockwood et al., 1979). We intend to use this neutron scattering method for neutron detection, e.g., method that is similar to the gamma-quanta Compton scattering detection concept that was used in COMPTEL telescope (Ryan et al., 1993; Schoenfelder et al., 1993). Namely, we plan to combine neutron detection with the Compton scattering technique to have a capability to detect atmospheric and cosmic gamma-rays, as well as to detect albedo and, hopefully, solar neutrons during high-altitude balloon flight. Solar energetic particles (SEP) can be also detected with this instrument with the properly adjusted trigger criteria. Solar energetic particles might penetrate into Earth polar zone where MMCNE will be flying. Large solar flares, those that can cause a radiation hazard at the Earth, can provide a substantial amount of solar neutral emission, namely of gamma-rays and neutrons as well, that can be detected by an instrument like MMCNE flying on sufficiently high altitudes.

Registration time of the solar neutral emission detected near the Earth can be quite simply connected with the time and place of neutrons generation during the solar flare, and consequently might help to measure the Solar Energetic Particles (SEP) spectra and the place of their generation.

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An unambiguous detection of solar neutrons implies necessity to use a neutron telescope with directional capability. Such telescopes to detect solar fast neutrons at energies from a few MeV up to 100 MeV with moderate energy and angular resolution are under development at SINP MSU.

Because we plan to use MMCNE for detection of different components of the neutral emission, we are developing different concepts of the MMCNE that are varying in their performance and ability to detect neutrons and/or gamma rays. Those concepts differ in the dimensions of scintillating fibers used for tracking, and in the scintillator used for the calorimeter.

At present we are using fibers with cross section of $3.0 \times 3.0\ \mathrm{mm}^2$ of Saint-Gobain production, and of $1.5 \times 1.5\ \mathrm{mm}^2$ and $0.25 \times 0.25\ \mathrm{mm}^2$ of Kuraray production. For use as a pixellated calorimeter we are testing $LaBr_3$:Ce, $CeBr_3$, LYSO, YSO and Ce:GAGG. Some results of the calibration measurements to verify performance of $LaBr_3$:Ce, and $CeBr_3$ based calorimeter pixels were already published (Iyudin et al., 2009, 2013), and the papers describing performance of LYSO, YSO and Ce:GAGG based pixels of MMCNE calorimeter are under preparation.

2. Neutron detection by MMCNE

Neutrons interact in a plastic scintillator either by elastically scattering from hydrogen (*n–p*), or by interacting with carbon (*n–C*). The (*n–p*) events are most useful for the neutron flux and spectra analysis. The kinematics of non-relativistic elastic scattering (*n–p*) implies that the scattered neutron and proton momenta are mutually orthogonal. This kinematic criterion also helps to distinguish (*n–p*) scatter events from (*n–C*) events. This is very helpful at neutron energies exceeding ~50 MeV at which probability of (*n–C*) interactions becomes higher then that of (*n–p*) elastic scattering. This criterion is used to select a sequence of two (*n–p*) elastic scattering in the detector volume to make a full kinematic analysis of the neutron scatter event and to derive a direction from which neutron was coming into detector. If both recoil protons in a double scatter event can be measured, then the energy and incident direction of the neutron are uniquely determined.

In early experiments dedicated to atmospheric neutrons study mostly a bulk plastic scintillators were used, see Grannan et al. (1972) and Frye et al. (1988), to detect fast neutrons of different origin with the use of elastic scattering of neutrons.

Rather than using a block of plastic scintillator, which provides limited spatial information, one can use orthogonally oriented plastic scintillating fibers that will form a sufficient volume to have a reasonable probability for a fast neutron detection. In this case one will need an image of neutron scatter event via registration of the recoil proton track and energy deposition. The timing information can be used to define a sequence of two elastic scattering events, and, in some cases, even provide a means to independently derive the energy of the neutron after first scatter event.

The scintillating fibers serve both as scattering targets and as a light pipelines for the event imaging. The dimensions of a fiber define the minimal detectable energy of the neutron.

Fig. 1 illustrates different event types produced by particles interacting with scintillating fibers, and Fig. 2 shows the principle of a fast neutron registration, that will be used by MMCNE.

Independent of the target material a simple relation (1) holds for the elastic scattering in the non-relativistic case, where *A* is atomic number of a scatter material:

$$\frac{E_R}{E_n} = \frac{4A}{(1+A)^2} \cos^2 \theta_{lab} \tag{1}$$

In Eq. (1) *A* is atomic number of a scatter material, E_R is kinetic energy of the target recoil,and E_n is an energy of incoming neutron, while θ_{lab} is an angle of recoil nucleus impulse relatively to the direction of incoming neutron. Usually a composition of a plastic scintillator is approximately 50% of hydrogen and 50% of carbon. Therefore, most relevant in our case are elastic scattering of a neutron on the hydrogen and carbon. Cross sections of elastic scatter reactions for both elements are given in the Evaluated Nuclear Data File library (ENDF, 2007). For the illustration purpose of both cross-sections behavior depending on the neutron energy we have used a Fig. 3 that is taken from Frye et al. (1985).

In the normal neutron detection mode we assume that the first neutron interaction with the material of scintillating fiber is due to elastic scatter of neutron on hydrogen. It is known that after an elastic scattering event the neutron momentum is nearly perpendicular to the recoil proton momentum. This property of an elastic scattering of neutrons on protons (hydrogen) can be used to proper choose a sequence of events inside of the tracker chamber. If we want to select double scatter events for the detection mode we can consider a starting points of two recoil protons tracks. From the starting positions (fibers) of the two scintillating tracks we deduce the momentum direction of the neutron after its first scattering. The first recoil proton is the one whose track is almost perpendicular to the momentum of scattered neutron. Knowing the energy and the momentum of the second scattered proton, and the momentum direction of a neutron after its first scatter one is able to reconstruct the energy and direction of incoming neutron.

Fig. 3 shows approximate cross section dependence of the neutron scattering by elements of scintillating fibers material.

A similar to MMCNE principle to register solar neutrons will be used also in the telescope of fast neutrons INTERSONG that is planned to be installed on-board of "Interhelioprobe" (Kuznetsov et al., 2015; Kuznetsov, 2015), that is also using an elastic scattering of neutrons