Astroparticle Physics 62 (2015) 230–240

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

A model of the cosmic ray induced atmospheric neutron environment

Merlin Kole [a,b,*], Mark Pearce [a,b], Maria Muñoz Salinas [a,c]

[a] KTH Royal Institute of Technology, Department of Physics, 10691 Stockholm, Sweden
[b] The Oskar Klein Centre for Cosmoparticle Physics, AlbaNova University Centre, 10691 Stockholm, Sweden
[c] Ecole Polytechnique, Palaiseau, France

ARTICLE INFO

Article history:
Received 17 June 2014
Received in revised form 3 October 2014
Accepted 6 October 2014
Available online 14 October 2014

Keywords:
Atmospheric neutrons
Monte Carlo
Cosmic rays
Instrumental background

ABSTRACT

In order to optimise the design of space instruments making use of detection materials with low atomic numbers, an understanding of the atmospheric neutron environment and its dependencies on time and position is needed. To produce a simple equation based model, Monte Carlo simulations were performed to obtain the atmospheric neutron fluxes produced by charged galactic cosmic ray interactions with the atmosphere. Based on the simulation results the omnidirectional neutron environment was parametrized including dependencies on altitude, magnetic latitude and solar activity. The upward- and downward-moving component of the atmospheric neutron flux are considered separately. The energy spectra calculated using these equations were found to be in good agreement with data from a purpose built balloon-borne neutron detector, high altitude aircraft data and previously published simulation based spectra.

1. Introduction

Instruments flown on balloon-borne and Earth-orbiting satellites experience radiation from a wide range of particles with a galactic, solar, magnetospheric or atmospheric origin [1]. The neutron component is mainly produced in cosmic ray induced showers in the Earth's atmosphere. The production energies for neutrons range from ~0.1 MeV to ~10's of GeV. After production the neutrons are thermalised due to scattering interactions with atmospheric nuclei, resulting in an energy spectrum ranging from eV energies up to 10's of GeV. The non-thermal component of this neutron spectrum is an important source of background for experiments making use of detection materials with low atomic numbers, e.g. plastic scintillators. Examples include X-ray polarimeters operating on balloon experiments, see for example [2,3], in earth orbiting satellites [4], or balloon-borne Compton telescopes [5]. A second source of measurement background, found in a wider range of experiments, stems from neutron-induced activation of both active and passive materials in the detector [6]. Reducing the neutron-induced background through active shielding is inefficient due to the non-ionizing behaviour of neutrons, while passive shielding from neutrons results in a significant mass increase of the payload. As a result an irreducible and variable background resulting from neutrons is often unavoidable. During the design phase of the instrument an understanding of the incoming neutron flux is therefore needed to optimise the signal to background of the experiment.

The spectral shape and the energy integrated flux of atmospheric neutrons varies strongly with altitude. The energy integrated flux has additional dependencies on the magnetic latitude and solar activity. For Earth orbiting satellites and long duration balloon experiments the latitude, solar activity and altitude may not be constant during the mission, resulting in a variable neutron-induced background rate. An understanding of how the neutron flux and spectral shape changes throughout the mission is therefore important. The neutron flux is largest and most influenced by solar activity in the polar regions, where long duration stratospheric balloon flights are conducted [7].

Recently published studies have verified that the atmospheric neutron environment can be simulated accurately using different Monte Carlo packages, see for example [8–12]. The Monte Carlo based packages PLANETOCOSMICS [13] and a combination of Geant4 [14] and MCNP [15] are used respectively in [11,12] to simulate the neutron flux dependent cosmogenic nuclei production rates. The neutron production rates are simulated for a more general purpose using Geant4 [14], PHITS [16] and a combination of CORSIKA [17], MCNP [15] and MCNPX [18] respectively in [8–10]. In particular the work presented in [8] provides a look-up table for neutron spectra at particular altitudes, all cut-off rigidities and all solar activities, which are shown to match spectra as

* Corresponding author at: KTH Royal Institute of Technology, Department of Physics, 10691 Stockholm, Sweden. Tel.: +46 85 537 8186; fax: +46 85 537 8216.
E-mail address: merlin@particle.kth.se (M. Kole).

http://dx.doi.org/10.1016/j.astropartphys.2014.10.002
0927-6505/

measured on ground and on high altitude flights. In [9] analytical functions are furthermore provided describing the neutron energy spectra over a wide energy range for altitudes below 20 km. Also in [9] the results are shown to be in good agreement with spectra measured on ground and at flight altitudes.

The aim of this paper is to present a relatively simple model which provides the spectrum of the non-thermal neutron component, for all altitudes exceeding 5 km, which can easily be implemented in, for example, Geant4 based simulations of balloon-borne and Earth-orbiting instruments. Such a model can, for example, be used to study the effect of variations in position and solar activity on the neutron flux impinging on an astrophysics experiment. For this purpose a Monte Carlo data based set of equations describing the atmospheric neutron flux in the energy range of 8 keV–1 GeV for altitudes exceeding 5 km, all magnetic latitudes and all solar activities is presented. The directional dependency of the neutron flux on altitude and energy is of additional importance, especially for balloon-borne experiments. The direction of momentum is therefore included in the model. Section 2 provides a brief overview of the atmospheric neutron environment. This is followed by a description of the performed Monte Carlo simulations in Section 3. Section 4 presents the results of these simulations and the resulting parametrized model and comparisons with results from other models and measurement data. The energy spectrum is divided into an upward and downward moving component in Section 5. Finally Section 6 discusses the neutron environment specifically for high latitude balloon-borne instruments using a comparison with data from a purpose-built neutron detector.

2. Atmospheric neutrons

The majority of atmospheric neutrons are produced in hadronic air showers induced by cosmic ray protons or helium nuclei [19]. A second source is electromagnetic air showers induced either by cosmic gamma rays or electrons. The hadronic component of electromagnetic showers in which neutrons are produced is, however, small. Atmospheric neutrons can also be produced by radioactivity in the Earth. Due to the high atmospheric density at low altitudes, which results in a relatively short mean free path for these neutrons, the contribution from the Earth is only relevant in the lower part of the troposphere. Only production through hadronic air showers is therefore considered here.

Within hadronic air showers the highest energy neutrons are produced by charge-exchange interactions between cosmic ray nuclei and atmospheric nuclei [19]. The resulting neutrons will carry approximately the momentum of the incoming protons, and will therefore preferentially move downwards in the atmosphere. The cross section for this process is not relevant at sub-GeV energies, as a result neutrons produced through this mechanism typically have kinetic energies exceeding 1 GeV.

In hadronic air showers the majority of neutrons are produced in the sub-GeV region through head-on collisions of cosmic rays with atmospheric nucleons. During the collision, a nucleon within the atmospheric nucleus gains momentum and forms an intranuclear cascade [20]. In this cascade different particles are created, the energy of which, due to the Pauli Exclusion Principle, must exceed the highest occupied energy level in the nucleus. As a result, the intranuclear cascade results in neutrons with energies ranging from 10's to 100's of MeV. Due to the high energies involved, the majority of the momenta of the produced neutrons are directed towards the Earth's surface.

The intranuclear cascade is followed by the emission of particles from the excited remnant nucleus. In this process, often referred to as evaporation, the nucleus moves to its ground state energy by emitting hadrons and photons. The emission of hadrons, including neutrons, continues until the excitation level drops below 10's to 100's of keV, after which the remaining energy is lost through photon emission [20]. The neutrons produced through evaporation have typical energies around 1 MeV. The emission from the nucleus proceeds isotropically within the rest frame of the nucleus. The resulting neutron emission is therefore expected to be more isotropic than those coming from the two previously described processes.

After production, neutrons lose energy by scattering off atmospheric nuclei. The energy loss and cross section increase with the decreasing mass of the atmospheric nucleus the neutron interacts with. The process of energy loss, referred to as thermalisation, continues until the energy of the neutron is equal to that of the average energy of the atmospheric nuclei surrounding it. The momentum vector changes at each scattering interaction. As a result, the direction of the neutrons becomes more isotropic during thermalisation. The density gradient of the atmosphere furthermore has an influence on the momentum vector after many scatterings. As a result of this gradient the majority of the scattered neutrons are expected to move upwards in the upper stratosphere.

A typical differential neutron energy spectrum multiplied by the neutron energy, as measured at an altitude of ~ 20 km and a magnetic latitude of 58°, is shown in Fig. 1. By multiplying the spectrum with the energy, the evaporation and intranuclear cascade production energy regions become clearly visible at the respective energies of ~ 1 MeV and ~ 100 MeV.

The amplitude of the spectrum is not only expected to vary with altitude, but also with magnetic latitude and solar activity. The Earth's magnetic field shields the equator from all charged cosmic rays with a rigidity below $\sim$15 GV, whereas in polar regions the cut-off is below 1 GV. As a result, the neutron flux is highest at the magnetic poles. The solar magnetic field, frozen in the solar wind, further shields the Earth from cosmic rays. This effect can be expressed using the force-field approximation [22]. The modulation of the Local Interstellar Spectrum (LIS) by solar activity is approximated by a potential term ϕ. Typical values of ϕ, for solar maximum and solar minimum periods, are respectively 1250 MV and 350 MV [23]. The exact value of ϕ depends on the model used for the LIS [24]. For the work presented here, the proton LIS from [25] was used. Furthermore both the solar activity and the Earth's magnetic field have the largest effect on the lowest energy charged cosmic rays. The dependencies from these two magnetic fields are therefore coupled, meaning that the effects from solar activity are most pronounced at the magnetic poles. Due to the relatively small dependency of the proton-air cross section on energy (for protons with energies exceeding 1 GeV) the shape of the differential neutron energy spectrum does not vary significantly with magnetic latitude and solar activity. The spectral shape in the sub-GeV region can therefore be assumed to only vary with altitude. This can be seen in, for example, [21] where measured spectra are presented for different magnetic latitudes and nearly identical altitudes.

3. Simulations

In order to simulate the atmospheric neutron environment the PLANETOCOSMICS simulation package [13], which incorporated Geant4.9.5.p02 [14] for particle interactions, was used. The QGSP_BIC_HP [26] physics list, which uses the Binary Cascade Model to handle protons and neutrons with energies between 20 MeV and 10 GeV and the G4NDL4.0 data set [27], to handle scattering interactions of neutrons with energies below 20 MeV, was used. Neutron capture reactions and neutron decay are furthermore taken into account in the simulations. The simulations presented here made use of a spherical model of the Earth