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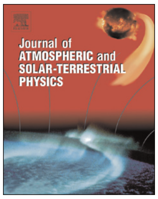

Study of radiation dose induced by cosmic-ray origin low-energy gamma rays and electrons near sea level

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ABSTRACT

For a long time, it has been known that low-energy continuous gamma radiation is present in open air at the Earth's surface. In previous investigations it was assumed that this radiation is produced almost exclusively by gamma photons emitted due to the natural radioactivity, which are backscattered by air above ground. We show that significant amount of this radiation (related to energy region 30–300 keV) that peaks at about 90 keV, is produced by cosmic-rays, with the photon flux of about 3000 m^{-2} s^{-1}. We find that the contribution of this omnipresent low-energy gamma radiation of cosmic-ray origin, including the corresponding low-energy electron flux, to the doses of general population are non-negligible components of overall doses induced by cosmic rays near sea level.

1. Introduction

The production of soft component of secondary cosmic rays at sea level (photons and electrons) is caused by the electromagnetic particle showers, generated in the atmosphere by decays of neutral and charged π mesons, as well as interactions of the very penetrating muons, all initially produced by high-energy primary cosmic-rays (Ackermann et al., 2011; Apel et al., 2008; Binns, 2011; Hafner, 1964; Sigl, 2001; Tavernier, 2010). In addition, the interaction of cosmic rays with Earth atmosphere leads to the complex dynamic changes in it, including influence on electrical environment of atmosphere, lightning discharges, cloud formation, etc. (Erlykin and Wolfendale, 2011; Usoskin et al., 2004; Velinov and Mateev, 2008; Bazilevskaya et al., 2000; Singh et al., 2011).

The shower development by pair production is stopped when the transferred energy drops below 1.02 MeV (the minimal energy needed for electron-positron pair creation). Although below this energy there is no production a new electrons by pair effect, the photons with energies below 1.02 MeV can generate new electrons, for instance, 1 MeV photon still can create Compton electrons. At these lower energies electrons and photons propagate decoupled: electrons termalize mostly by collisions with atomic electrons in air (the bremsstrahlung production probability is negligible at such low energies), while photons transfer their energies to atomic electrons via the photo-effect or multiple Compton scattering. Thus both, electrons and photons can produce new free electrons in the air through interactions with atomic electrons.

Thus Earth's atmosphere, although relatively dense and consequently efficient in absorption of high-energy cosmic radiation, leads to the production of intensive photon and electron ultra-low energy continuous radiations at ground level (with photon flux that peak around 90 keV). This energy maximum in cosmic-origin photon flux can be seen (Fig. 14 of Mitchell et al., 2009) after appropriate subtraction of contribution of air backscattering of environmental gamma rays (Swarup, 1980), a process which also give energy maximum at about 90 keV. On the other hand, due to the interactions of low-energy photons via photo-effect and Compton-effect in the air (Compton scattering is, for ~100 keV photons, very important for air where the atomic number is low), the maximum in electron flux is expected at significantly lower energies. These ultra-soft ionizing components of cosmic radiation were seldom studied in detail, especially their contributions to doses received by somatic human tissue. This is especially important because previous analyzes and estimations of doses from charged-particle and photon components of cosmic radiation have primarily incorporated the altitude (Dachev, 2013) and latitude effects, and taken into account the dominant contribution (~85%) of cosmic muons (with energies 1–20 GeV) to the cosmic-origin dose equivalent rate at ground level, as well as a possible muon flux enhancement according to extragalactic shock model (Atri and Melott, 2011). Only the doses of cosmic radiations at low

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altitudes with energies above 1 MeV were measured, neglecting the contribution of electrons (Rasolonjatovo et al., 2002). Distinguishing this cosmic-origin low-energy radiation from other contributing components (such as air backscattering of environmental gamma rays emitted by natural radioactivity of the ground (Swarup, 1980)) which cover the same energy region below 300 keV, is a difficult task. Whereas the intensity of air backscattering component depends only on radioactivity of the ground (which is strongly dependent on particular location, i.e. local rock and soil composition), the low-energy cosmic component near sea level may show only temporal variability due to slight changes of the primary cosmic-ray flux. The latitude effect of the soft cosmic ray radiation at the near sea level is negligibly small (Stozhkov et al., 2009).

Some attempts to investigate natural low-energy gamma-ray background using gamma spectrometry method are reported in (Mitchell et al., 2009). In this work the absolute value of the low-energy cosmic-origin gamma flux is not reported (just the relative contributions of different component, including cosmic-ray origin component to the low-energy gamma region are analyzed at the site of measurement). It should be emphasized that the *relative* contribution of cosmic-ray origin photon flux to the total intensity of low-energy gamma flux from upper hemisphere at particular measurement site is strongly dependent on local radioactivity of ground which leads to the increase of air-backscattering effect of gamma rays arising due to natural radioactivity of soil and rocks. This can be reason for discrepancy of conclusions among experiments conducted at different locations, although the *absolute* values of cosmic-origin low-energy fluxes can be similar at these locations.

In our work both contributions, from ultra-low-energy photons and from electrons, to the whole body and surface tissues are analyzed and estimated separately, having in mind the different penetrating properties of these types of ionizing radiations.

According to recent calculations (Desorgher et al., 2005; Makhmutov et al., 2007), as well as experimental results (Bazilevskaya et al., 2012; Bazilevskaya et al., 2013), electron flux at the near-ground air is 8–10 times less than photon flux at energies about 100 keV. Precisely speaking, these experiments are restricted to the measurement of electron flux with energy of electrons above 200 keV. However, electrons with lower energies have small effective path and are absorbed in several cm of air. On the other hand the mean free path of photons in the same energy range is several tens of meters and consequently, at lower energies the number of electrons decreases relative to the number of photons.

2. Experiment

2.1. Laboratory measurements

In order to study the contributions of cosmic rays to the low-energy continuous part (30–300 keV) of background gamma-ray spectra, we used the big-volume (380 cm^3 of active volume) extended-range High-Purity germanium detector (HPGe), shielded from environmental radiations coming from the lower hemisphere by heavy 15 cm thick lead shield, and widely open for the radiations coming only from the upper hemisphere, Fig. 1.

The influence of Pb shield, due to production of secondary particles within Pb shield by cosmic-ray muons, on acquired background gamma spectrum, given in Fig. 1, is negligible. This can be concluded from the spectrum obtained when Ge detector is completely shielded from environmental gamma rays (i.e. when cover of Pb shield is also present above detector). In such situation the count rate of detector (mainly induced by secondary particles of cosmic-ray muons interacting with Pb shield) in the energy region of 30–300 keV is ~0.6 counts/s (only ~3% of count rate when cover of Pb shield is removed). There is no contribution for production of X-ray fluorescence in mentioned energy region, since the passive shield has a inner lining to stop Pb X-fluorescence lines (75–85 keV). Lining materials are low-background tin (with thickness of 1mm and high purity copper with a thickness of 1.5 mm. Also, the Sn X-rays (25–28 keV) are reduced by copper. The intensity of neutron induced lines at 66.7 keV from 72Ge(n, γ) 73mGe, 139.7 keV from 74Ge(n, γ)74mGe and 198.9 keV from 70Ge (n, γ)71mGe) are 0.00159 counts/s, 0.00189 counts/s and 0.00249 counts/s, recounts/sspectively (negligible small comparing to 14.8 counts/s obtained for situation described in Fig. 1).

The arrangement shown in Fig. 1 prevented the gamma radiation arising from concrete slab below the detector shield, as well as from the walls of the laboratory to directly reach the detector.

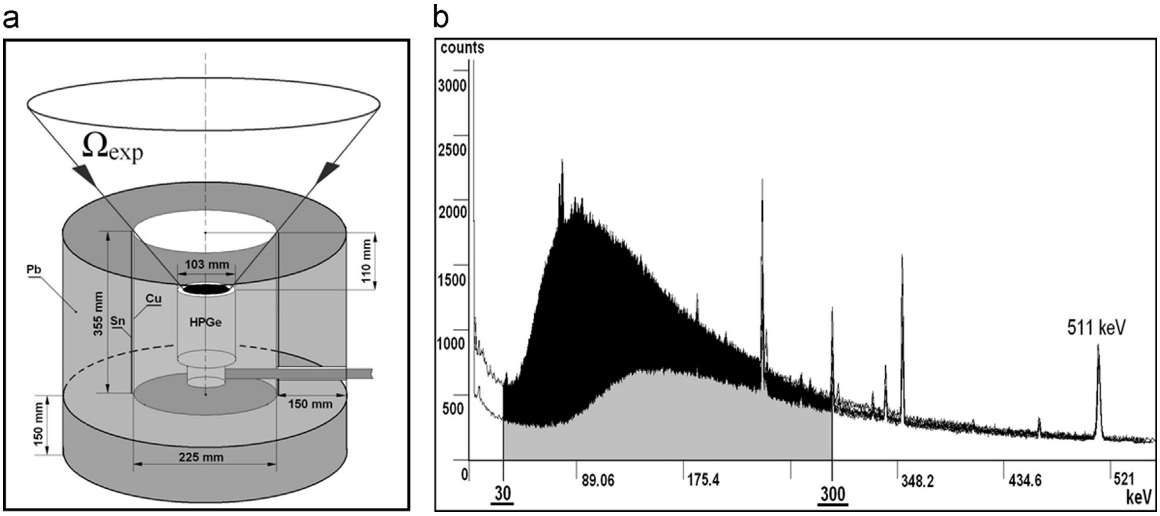

Fig. 1. Experimental setup for study of cosmic origin photons contribution to the low-energy continuous region of background gamma-ray spectrum (a) Schematic view of extended-range HPGe detector in lead shield, open only for detection of incident radiation at detector within solid angle $\Omega_{exp} \approx 1.1$ sr, (b) Low-energy part of background gamma spectrum, acquired by HPGe detector which was open for radiation coming within solid angle $\Omega_{exp.}$ Net intensity of continuous spectral distribution in the region 30–300 keV is 14.8 counts/s and it is marked by black. The contribution of Compton-scattered gamma rays of higher energies in detectors' active volume to this region is found to be about 44% of total intensity (area presented in gray).