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Study of terrestrial γ-ray background in presence of variable radioactivity from rain water

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ABSTRACT

A number of groups have reported significant reduction in the flux of low energy (0.1–3 MeV) γ-rays in observations carried out during the past total solar eclipses. However, the contribution of the radon induced radioactivity to the overall γ-ray background can become substantial, especially during episodes of rain. Depending upon the pattern of the rainfall radon induced γ-ray background may vary significantly on time scales of ~10 min, making the interpretation of the data in terms of an extraterrestrial effect such as a total solar eclipse rather difficult. A reliable estimate of the low energy terrestrial γ-ray (TGR) background is necessary before attempting to measure the possible contribution of any extraterrestrial phenomenon. The knowledge of the precise energies and branching ratios of radon and other radio-isotope induced γ-rays was exploited to accurately reproduce the TGR background, even in the presence of a large and variable contribution from radon induced radioactivity from fresh rain water. The measurement of the TGR background has paved the way for studying the variation of the soft γ-ray flux during the long duration total solar eclipse that occurred on 22 July 2009 in the middle of the Monsoon season in India.

1. Introduction

In recent times, there have been a number of reports claiming detection of significant variation in the flux of cosmic soft γ-rays, in the sub-MeV to a few MeV range, during the total solar eclipse events. These claims have generated considerable interest due to their potential interpretation of being astrophysical in origin. A group from Kolkata had reported a significant reduction in the flux of cosmic γ-rays in the energy range 0.15–1.35 MeV, during the period of totality. Their experiment was carried out at Diamond Harbour near Kolkata, India during the total solar eclipse of 24 October 1995 [1]. Similarly, another group led by the J.C. Bose Institute had independently reported a large decrease in the flux of soft γ-rays in the energy region 0.3–3.0 MeV, during the same total solar eclipse on 24 October 1995. This group had also offered a possible explanation of the variation in the soft γ-ray flux during total solar eclipse. Their explanation was based on the cooling of the upper layer of atmosphere during the totality resulting in a downward shift of the production layer of the soft γ-rays [2]. However, from the viewpoint of astrophysics it is essential to unambiguously establish the phenomenon before embarking on serious attempts at its explanation.

In a recent work based on the measurements made during the total solar eclipse of 1 August 2008 at Novosibirsk, Russia, we had also reported a variation in the flux of soft γ-rays over a wider energy region of 0.1–4.6 MeV [3]. These measurements were made with two large volume sodium iodide crystal detectors that were more than an order of magnitude larger than the ones used in the earlier studies. The usage of two identical detectors with separate data recording systems ensured that the reported variation was measured in a fully redundant manner by two independent systems, thus increasing the level of confidence in the reliability of the result. The soft γ-ray flux measured on the surface of the Earth consists of two major components that are of, (a) astrophysical, and (b) terrestrial origins. Therefore, the results discussed above primarily relied on the time coincidence of the reported variation with the occurrence of the total solar eclipse. However, in reality the flux of terrestrial γ-rays (TGRs) also displays significant time variation. Therefore, an unambiguous identification of the observed variation with an astrophysical phenomenon can only be claimed provided the TGR background can be accurately and independently determined on the same time scale as that of the astrophysical phenomenon being invoked.

Several experiments such as the underground measurement of the radioactivity [4], rare event observations including the search

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for dark matter [5,6], and of course, the variation of the cosmic soft γ-ray flux during the total solar eclipse events [3,7], all require a precise measurement of the TGR background. As explained earlier, the TGR background fluctuates with time due to several contributing factors, chief among them being the radon decay products during the episodes of rain or snowfall. The TGR rate may increase significantly due to precipitation of the radon decay products along with rain water. The major contributors on a time-scale of $\sim$ 1 h to the soft γ-ray flux being Pb^{214} and Bi^{214}. Bi^{214} is specially significant due to relatively higher energies of the emitted γ-rays. Thus, the measurement of the radioactivity in fresh rain water becomes necessary since the radon decay products are easily transported to the ground during the rainfall. Precipitation may result in a substantial enhancement of the TGR background, ranging from a few to several tens of percent, thus inducing a sizable variation in the TGR background. Such a large and variable contribution can severely affect the aforesaid measurements, necessitating a thorough assessment of its impact.

In the recent past there have been several attempts to measure the contribution of the radon decay products. A dedicated measurement of the radon decay products using a high purity germanium (HPGe) detector showed a huge variation in their concentration during rainfall, ranging from 50 to 1600 Bq l^{-1}. It was also reported that the radon concentration in the clouds from the sea-side storms was significantly less in comparison to that of the land-side storms. It was observed that the measured activity showed significant variation throughout a single rain episode. It was also reported that the enhancement in the TGR background did not correlate with, (a) the rate of rainfall, (b) the duration of the rainfall, and (c) the amount of the rainfall [8]. In another interesting observation a negative correlation between the concentration of the radon decay products and the rainfall rate was reported for several episodes [9].

For measuring the radioactivity due to the γ-rays emitted by the radon decay products a large variety of detectors have been employed by different investigators including, the plastic scintillators, the thallium activated sodium iodide NaI(Tl) crystal detectors, and the HPGe detectors. The choice of a suitable detector is dictated by the optimization of relevant parameters such as the energy resolution, efficiency, durability, portability, and the cost. The plastic scintillators are over an order of magnitude more economical than the NaI(Tl) crystals. On the other hand, the HPGe detectors besides being very expensive also require additional infrastructure for their operation at liquid nitrogen temperatures. However, if the energy resolution of the γ-ray lines is of prime importance then the HPGe may be preferred over the other two types of detectors. On the other hand, if the detection efficiency is a key parameter specially in the cases where the level of radioactivity is rather low, then the NaI(Tl) detectors may offer a better alternative. In the present case after examining various options, a large volume NaI(Tl) detector with an energy resolution of 7 % at 662 keV was selected. The plastic scintillator detectors for their very poor energy resolution and the HPGe detectors due to their exorbitantly high cost were ruled out. During our study, the constant TGR background due to the radioactivity from the building and surroundings was very substantially reduced by using a lead shielding of suitable thickness.

A steady flux of high energy charged particles, namely, the cosmic rays is continuously striking the top of the atmosphere. The interaction of these particles in the upper atmosphere results in the production of a number of secondary mesons including the pions, the kaons, etc. The charged pions and kaons decay to produce muons that form the penetrating component of the secondary cosmic rays which eventually reaches the ground level. Neutral pions decay to produce pairs of γ-rays. The decays of muons lead to the production of electrons and positrons, and which in turn, produce γ-rays through bremsstrahlung. These secondary particles further interact with the atmospheric nuclei, producing more secondaries, resulting in an ever increasing flux of muons and γ-rays of progressively lower energies. Finally, at the observational level on the surface of the Earth, a sizable and steady flux of sub-MeV to a few MeV γ-rays and GeV muons is observed. In addition, the terrestrial radioactive nuclei such as ^{40}K, ^{222}Rn, ^{232}Th, ^{238}U present in the soil and in the surrounding buildings also contribute to the observed flux of the sub-MeV to a few MeV γ-rays [10]. Therefore, the observed γ-ray spectrum in the MeV range consists of a cosmic ray induced component and a component due to the terrestrial radioactivity. Under good weather conditions, no significant variation in the terrestrial component is expected. However, a change in the observed flux of soft γ-rays of astrophysical origin could result in a variation in the measured flux of γ-rays.

2. The experimental setup

The TGR background level normally does not change over time interval of an hour except in the presence of radon and its decay products [11]. Thus, in general the variability in TGR background may be attributed to the presence of radon. To address the issue of radon induced γ-ray background, several measurements of radioactivity from the fresh rain water were carried out. The purpose of this study was to measure the spectrum of the radioactivity contained in the fresh rain water, and in future exploit this information to analyze the data collected during the total Solar eclipse of 22 July 2009 which was affected by several episodes of rains. Here, the challenge was to suitably analyze the recorded energy spectrum, where each γ-ray peak rode over a complex continuum background that varied from one rain episode to the next. In the case of the spectrum with a single peak, the data can be fitted by a Gaussian function using a standard platform such as the ROOT framework [12]. However, in the present case the estimate of the strength of the signal in the presence of a complex background that varied for each episode of rain was a major challenge. The TGR spectrum contained several γ-ray lines along with an associated Compton continuum. If one uses a sufficiently large number of variables then any observed profile can be successfully reproduced; however, such an approach would be arbitrary and ad-hoc, and different workers may end up with radically different parameterizations. In such a scenario it would become extremely difficult to estimate the significance of a signal due to an incorrect or inadequate description of the TGR background.

In the present context, it was found that the basic ROOT framework while perfectly capable of fitting a few peaks became inconvenient to use when a large number of peaks had to be fitted. However, another associated graphics and statistical toolkit RooFit [13] offered an effective framework for the present analysis which involved fitting of a large number of peaks. RooFit can be used quite effectively in view of its many advanced features of data modeling with the necessary provisions to analyze statistical distributions, and to perform likelihood fits, etc. RooFit also produces plots of excellent quality, and allows a precise calculation of the number of events in a distribution. For complex fits it contains a number of built-in classes designed to enable easier fitting of the data. These plots may also be accessed through ROOT, thus allowing the use of various utilities under it. From version 5 onwards, RooFit has been included as part of the standard ROOT distribution.

When studying the TGR background a prior knowledge of several of the parameters made the task of estimating the background possible. The knowledge of the radio-isotopes present in the rain water including the energies and branching ratios of the emitted γ-ray lines [14] was used for estimating the contribution from the rainfall. This was done by first collecting fresh rain water on the roof of the laboratory building in Mumbai, and then by using this information to devise a robust scheme with the aid of RooFit to reproduce the measured energy spectrum.

A metal funnel with a large collection area (2.4 m $\times$ 2.4 m) was installed on the roof of the laboratory building in Mumbai for the collection of fresh rain water as shown in Fig. 1. The large area funnel