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Cosmogenic ^{7}Be Radionuclide Produced in the Upper Atmosphere by Galactic Cosmic Rays and Solar Energetic Particles

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We calculate the ^{7}Be production rate in the upper atmosphere at the geomagnetic latitude λ=20-30° (Japan) assuming the galactic cosmic ray (GCR) and solar proton spectra in 2002-2004. The global average production rate is 0.043 ^{7}Be/cm^{2} s that is in agreement with the previous ones within a factor of ~2. Intense solar energetic particles associated with an X17/4B solar event on Oct. 28, 2003 produce Be-7 in the polar region but the contribution is not significant because its spectrum is very soft. The latitudinal production rate at λ=20-30° is 0.023 ^{7}Be/cm^{2} s. The measurement of surface ^{7}Be concentration in Tokyo implies that ~1% of ^{7}Be produced by GCR falls to the surface.

1. Introduction

^{7}Be is produced from nuclear interactions of galactic cosmic rays (GCR) with atmospheric N and O nuclei. It is short-lived (half life 53.3 days) and important for a study of air mass motions of a short time scale (~month) in the upper atmosphere [1], [2]. The ^{7}Be production rate depends on the 11-year cycle of solar activity. Further, solar energetic particles (SEP) produced from an extraordinary intense solar event contribute to the ^{7}Be production in the polar region, but the energy spectrum is soft and the frequency and duration of the event are very low and less than a few days.

The ^{7}Be production rate is essential for a comparison with a measurement of surface ^{7}Be concentration. We calculate the ^{7}Be production rate at λ=20-30° (Japan: cutoff energy is 10 GeV) in the atmosphere assuming the energy spectra of GCR and SEP protons and the recent cross sections for ^{7}Be production. The present result is compared with the previous ones and the relation between the ^{7}Be production rate and the surface concentration is studied. Although temporal variations in the surface ^{7}Be concentrtion were reported at many sites in the world, Japan is an indispensable location for a discussion of the air mass motions in the upper atmosphere in the Asian Pacific region [3], [4].

2. ^{7}Be production in the Earth's atmosphere

^{7}Be is mainly produced by nuclear reactions of GCR-produced secondary neutrons with atmospheric N and O nuclei. The energy spectrum of GCR protons at the Earth has been well known to vary with the solar activity and was formulated by the solar modulation parameter Φ [5]. It increases with solar activity level and is estimated from the empirical relation between the Climax neutron monitor data and solar modulation parameter. We evaluate that Φ is 700 MeV in 2002-2004 when the surface ^{7}Be concentration was measured in Tokyo. In addition, an intense solar proton event (X17/4B) occurred on Oct. 28, 2003 within a period of the present ^{7}Be measurement. The solar proton flux is much larger than the GCR proton flux at energies less than 100 MeV. The GCR and solar proton spectra are shown in Figure 1.

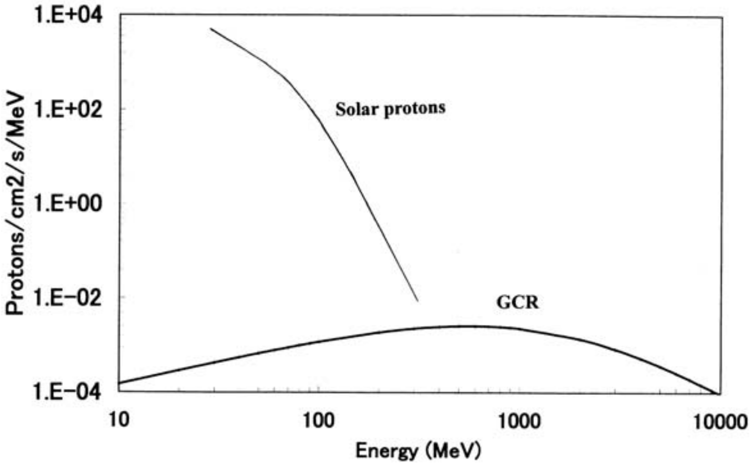

Figure 1. GCR proton spectrum of Φ=700 MeV and solar proton spectrum of a solar event of Oct. 28, 2003.

The revised cross sections for ^{7}Be production from p-N and p-O reactions were given [6], [7]. The cross section for the important p-N reaction is almost constant, except near the threshold energy and essentially independent of energy up to ~1 GeV. GCR protons incident on the Earth's atmosphere develop the nuclear cascade that produces a number of secondary protons and neutrons successively. The interaction mean free path is ~90 g cm^{-2}. These protons and neutrons are equally produced above ~1 GeV and are exponentially attenuated with the atmospheric depth (attenuation mean free path is ~125 g/cm^{2}). The secondary particles of less than a few hundred MeV lose their energies through nuclear spallation reactions. In particular, low-energy protons (<a few tens MeV) rapidly lose energy loss and eventually absorbed by atmospheric nuclei, while the neutrons lose the energies through nuclear reactions. The neutron flux is larger by 2 orders of magnitude than the proton flux. Hence, the ^{7}Be production rate in the atmosphere is proportional to the nuclear cross section and the secondary neutron flux. This proportionality holds throughout the atmosphere, except in the higher atmosphere (<200 g/cm^{2}) from which the neutrons can escape into space.

Assuming Φ is 700 MeV and the cutoff energy is 10 GeV for protons (λ=25°), we simulate the neutron energy spectrum at the atmospheric depth of 20, 200 and 500 g/cm^{2} and the depth distribution of secondary neutrons of energies above 10 MeV. The results are shown in Figure 2 and 3, respectively. We calculate the global average ^{7}Be production rate in the Earth's atmosphere using the following parameters: the energy spectra of GCR and SEPprotons, the cross section of ^{7}Be production in the atmosphere, the fraction of the Earth's surface which is accessible to particle energy corresponding to the cutoff energy at geomagnetic latitude, the yield of ^{7}Be per nuclear spallation reaction, the probability of a particle produces nuclear reaction before the threshold energy by ionization loss and the probability of escape of ^{7}Be to interplanetary space. The calculation is described in detail [8]. Here we consider the possibility of ^{7}Be produced from solar proton event. The frequency of intensive solar proton event is 1-2 events per year in 2002-2004 and the duration is less than a few days. Further, the solar protons are dominant below 100 MeV, suggesting that arrival of solar protons is confined to the polar region with low energy cutoff. Since the range of low-energy protons in the atmosphere is short (for example, 8 g/cm^{2} at 100 MeV), the production of ^{7}Be is restricted in a thin layer at a top of the polar atmosphere. In a case of the solar proton event on Oct. 28, 2003, the contribution to the ^{7}Be production is less than a few % of that of GCR protons.

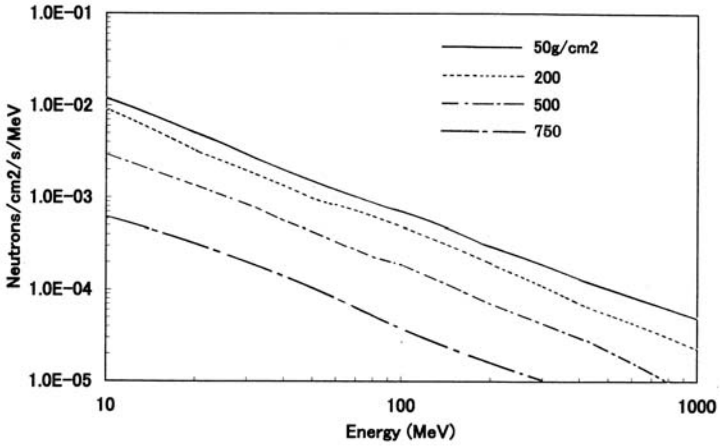

Figure 2. Secondary neutron energy spectra at 50, 200 and 500 g/cm^2 at λ= 25°.

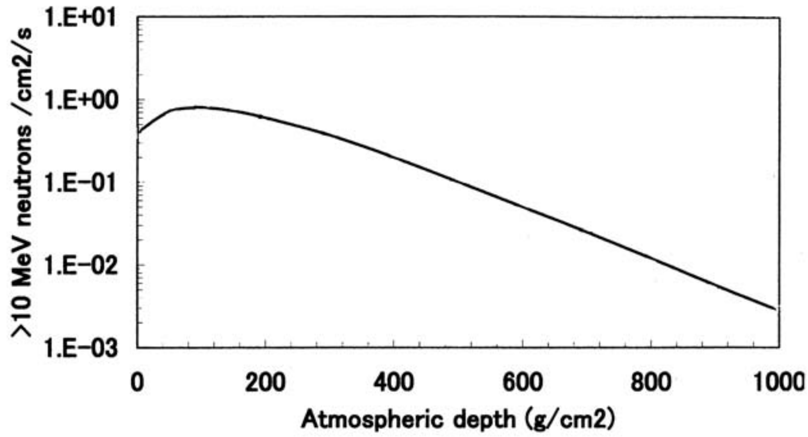

Figure 3. The depth distribution of secondary >10 MeV neutrons at λ=25°.

The global average production rate is 0.043 ^{7}Be/cm^2 s in 2002-2004. The latitudinal ^{7}Be production rate at 20- 30 ° is 0.023 ^{7}Be/cm^2 s. The ^{7}Be production rate per g of air per sec is given as a function of atmospheric depth in Figure 4. Most of ^{7}Be (~70%) are produced in the stratosphere (atmospheric depth <250 g/cm^2) and the rest (~30%) is in the troposphere (atmospheric depth >250 g/cm^2).

3. Discussion

The previous studies of the global average ^{7}Be production rate indicate 0.081 [9], 0.0578 [10], 0.0129 [11], 0.035 ^{7}Be/cm^2 · air mass column s [12]. The present value is in agreement with the previous ones within a factor of ~2. We have continuously measured the surface ^{7}Be concentration in Tokyo since 2000 and the data indicate the surface concentration of (2.0-5.3) x 10^5 ^{7}Be /m^3. This result indicates that ~1% of ^{7}Be produced by GCR contributes to the surface concentration. The surface ^{7}Be concentration is much smaller than those of terrestrial ^{210}Pb and ^{226}Rn that are the decay products of ^{238}U in the Earth's crust. The enhancements of the surface ^{7}Be concentration were measured in spring and autumn. They are thought to be caused by seasonally varying air mass motions.

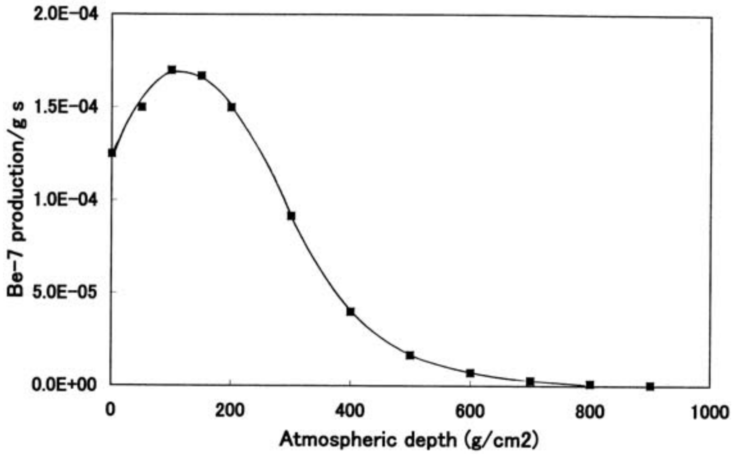

Figure 4. The ^{7}Be production rate as a function of the atmospheric depth at λ=25°.

4. Acknowledgements

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