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Energetic particles in lunar rocks: Production of cosmogenic isotopes

Stepan Poluianov*
Faculty of Science, University of Oulu, Finland
E-mail: stepan.poluianov@oulu.fi

Anton Artamonov
Thule Institute, University of Oulu, Finland

Gennady Kovaltsov
Ioffe Physical-Technical Institute, St. Petersburg, Russia

Ilya Usoskin
Sodankylä Geophysical Observatory and ReSoLVE Center of Excellence, University of Oulu

The era of direct measurements of solar energetic particle (SEP) fluxes is limited to the last few decades and largely overlaps the Modern Grand Maximum of solar activity. However, for many purposes it is important to know the fluxes of SEP on much longer time scale. This can be done only using indirect proxies. Terrestrial ones, such as the nuclides ^{14}C and ^{10}Be in tree trunks and ice cores, may potentially resolve strongest SEP events but cannot evaluate the average SEP flux. On the other hand, lunar rock samples, collected during the Apollo missions and measured later at the Earth, may provide information on the average fluxes of SEP throughout thousands and millions of years in the past. This option had been explored earlier, and here we revisit the approach, using the newly calculated yield functions of cosmogenic nuclide production in lunar rocks and more realistic spectra of solar energetic particles and galactic cosmic rays.

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*Speaker.

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1. Introduction

Studies of content of long-living radionuclides (^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{53}Mn) in lunar rock samples collected by the Apollo missions is a unique method to estimate average fluxes of solar energetic particles and galactic cosmic rays (SEP and GCR, respectively) on long time scales of thousands and millions years [e.g., 1, 2, 3]. The main advantage of the method is the fact that the Moon has no magnetic field or atmosphere, in contrast to the Earth, thus even relatively low-energy particles can reach the surface and cause reactions producing cosmogenic nuclides. The measured distribution of isotopes' concentrations in depth of a lunar rock sample allows one to estimate their average production rates which should be in equilibrium with respective decay rates. Such distributions are different for nuclides produced by SEP and GCR, and this fact helps to disentangle the two factors. Although the method is known since long, the average flux data for SEP and GCR computed from different nuclides are inconsistent [3, 4]. In order to resolve the contradiction we have improved the model of production of ^{14}C and ^{10}Be in lunar rocks and applied more realistic spectra of energetic particles to get new estimates of isotope production rates.

2. Modeling and results

2.1 The model of cosmogenic nuclide production

Production of ^{14}C and ^{10}Be in lunar rock is modelled with a full Monte-Carlo simulation performed by two rival toolkits of particle physics Geant4.10.1 [5, 6] and FLUKA 2011.2c.0 [7, 8] in order to exclude possible programming errors and to verify the embedded physical models. We have simulated a flat rock sample with the composition according to [9]. The sample was assumed to be bombarded by monoenergetic primary protons and α-particles with the isotropic angular distribution. The fluxes of particles, both primaries and secondaries, through surfaces at depths within the range of 0–1000 g/cm^2 were recorded according to their energies. In a series of simulations the primaries had energies in the range of 0.05–100 GeV/nucleon.

In this work we use the yield-function approach described in detail in [10, 11]. The yield function $Y(E_0,d)$ is the average production yield of an isotope at depth d as a result of irradiation of the surface by the unit intensity of primary particles with energy E_0. It can be calculated using the computed fluxes of particles inside the sample and the cross-sections for respective reactions producing the isotope. The cross-sections of reactions for ^{14}C and ^{10}Be caused by protons were taken from [2, 3, 12]. The cross-sections for neutron reaction on O and Si nuclei were taken from [13], and for other nuclei (Na, Mg, Al, Ca, Ti, Fe) they were assumed the same as for protons. The cross-sections for α-particles are taken according to [14]. Using the yield function $Y_i(E_0,d)$ one can calculate the production rate for a given energy spectrum of primary particles $J_i(E)$:

$$Q(d) = \sum_i \int Y_i(E_0,d) \cdot J_i(E_0) \cdot dE_0, \qquad (1)$$

where i is the index of primary particles, protons or alpha-particles.

Figure 1 shows the yield functions for ^{14}C produced by protons and neutrons of a cascade initiated by primary protons with energies 100 and 300 MeV. The effect of secondary α-particles is negligible at these energies. Production of ^{14}C above the depths 10 and 50 g/cm^2 for 100 and 300

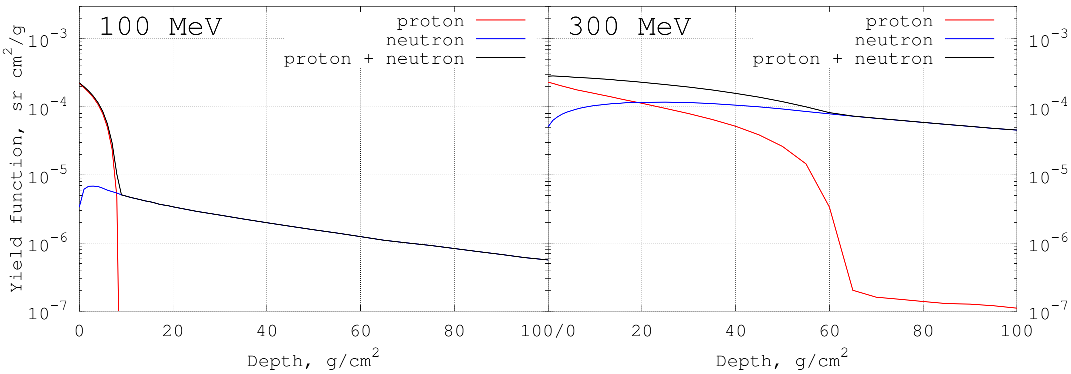

Figure 1: Yield functions of production of ^{14}C by protons and neutrons in lunar rock (primary protons with energies 100 and 300 MeV). Simulation with Geant4.

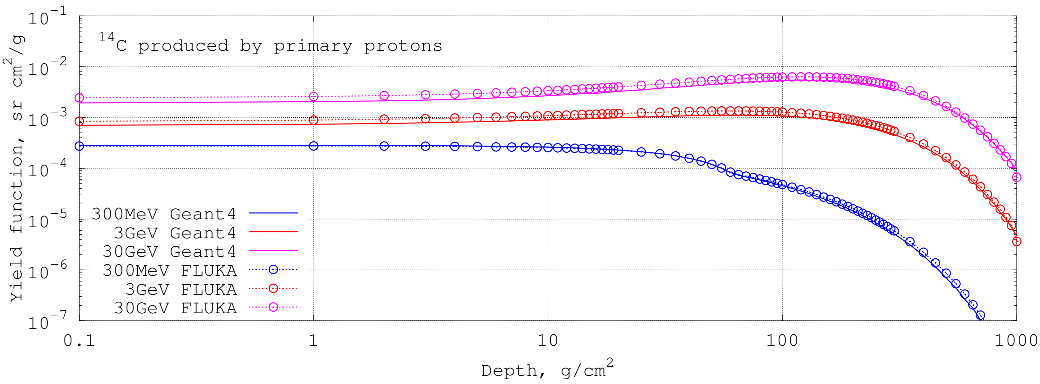

Figure 2: Yield functions of production of ^{14}C by primary protons with energies 300 MeV, 3 and 30 GeV in lunar rock. Simulations with Geant4 and FLUKA.

MeV, respectively, is caused mainly by primary protons, but secondary neutrons become dominant in production in deeper layers. A comparison of yield functions based on simulations done with Geant4 and FLUKA is shown in Figure 2, which depicts the ^{14}C yield functions for primary protons with energies 0.3, 3 and 30 GeV. One can see quite good agreement between the two codes that confirms technical correctness of our modeling at this step.

2.2 Spectra of cosmic rays

The spectrum of energetic particles is the second factor in Equation 1. It is a sum of the GCR and SEP spectra. In order to estimate the spectrum of GCR at the Earth's orbit we use the force-field model [15] so that the differential fluence of cosmic ray nuclei of type i at the Earth's orbit is:

$$J_i(E,\phi) = J_{\text{LIS},i}(E+\Phi)\frac{E(E+2E_0)}{(E+\Phi)(E+\Phi+2E_0)}, \tag{2}$$

where E and E_0 are the kinetic and rest particle's energies per nucleon; $\Phi = \frac{Ze}{A}\phi$; ϕ is the heliospheric modulation parameter; Z, e and A are the charge number, charge of an electron and mass number of a nucleon, respectively; $J_{\text{LIS},i}$ is the local interstellar spectrum taken from [16]. The

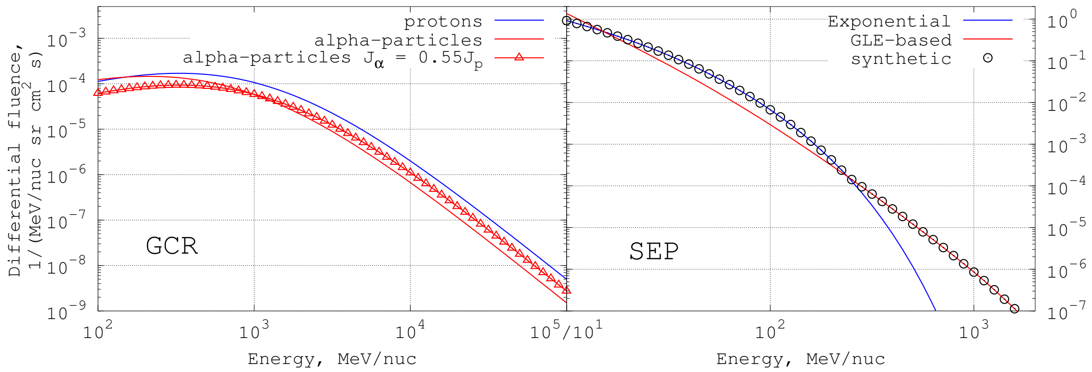

Figure 3: Spectra of galactic cosmic rays (left panel), number of nucleons, and solar energetic protons (right panel) in various models.

computed spectra (in number of nucleons) of GCR protons and nucleons of α-particles for moderate modulation potential $\phi = 500$ MV, corresponding to average solar activity during the present epoch, are shown in Figure 3. Galactic protons and α-particles experience different modulation in the heliosphere because of different Z/A ratios. It is often neglected by assuming that the flux of $\alpha-$particle nucleons are a scaled (with the 0.55 factor) of that of protons [e.g., 17, 18], so that the total differential nucleonic fluence of GCR is $J_{p+\alpha} = 1.55 J_p$. This may lead to essential errors in the results. Here we compute the spectra of protons and α-particles with Equation 2 independently.

Energetic particles coming from the Sun consist mostly of protons with small fraction of α-particles that can be neglected in the analysis. The spectrum of SEP is often assumed as an exponential function of the rigidity [e.g., 1, 2, 3]. In such a case the omnidirectional fluence of protons is

$$F(>R) = F_0 \exp(-R/R_0). \tag{3}$$

The parameters of the equation are defined with the data of observations during the last 60 years: $R_0 = 80$ MV and $F(> 10\text{ MV}) = 134\text{ cm}^{-2}\text{ s}^{-1}$ [19]. This spectrum is shown in the right panel of Figure 3. One can see that it becomes negligibly low above 700 MeV. However, the reconstruction of spectra of strong SEP events accompanied by ground-level enhancements (GLEs) of count rates of the world-wide neutron monitor network [20] show that the SEP spectrum may extend above 700 MeV (the right panel of Figure 3). The GLE-based spectrum is lower than the exponential one at 10–200 MeV. It is the effect of weak SEP events without GLEs, not involved into the computation of the GLE-based spectrum. In order to get a conservative and realistic SEP spectrum, we use the exponential spectrum below 250 MeV and extend it with the GLE-based one above this energy (circles in the right panel of Figure 3). The spectra of SEP and GCR used in this work are gathered together in Figure 4.

2.3 Nuclide production rates

Applying the described yield functions and spectra to Equation 1 we got the production rates of ^{14}C and ^{10}Be by GCR and SEP separately.

The results for ^{14}C produced by GCR are shown in Figure 5. The production rates are plotted there are for three values of ϕ: 300, 500 and 700 MV, which are typical values during the modern

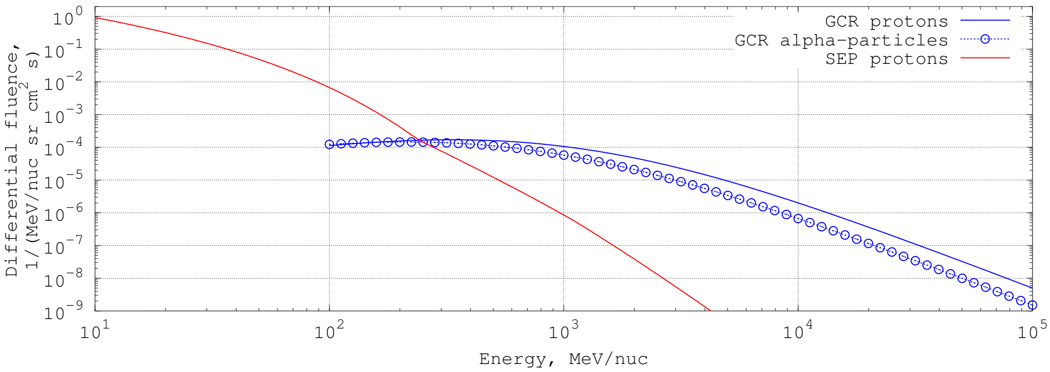

Figure 4: Nucleonic spectra of galactic cosmic rays and solar energetic particles used for further computations.

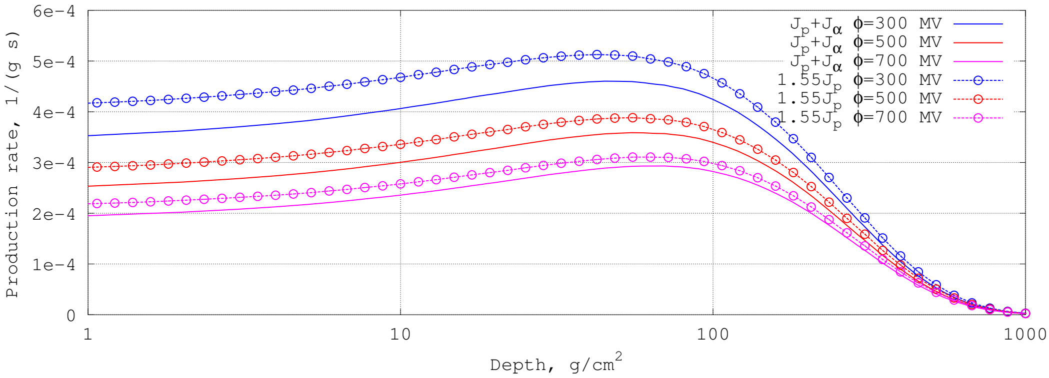

Figure 5: Production rates of ^{14}C by galactic cosmic rays (protons and alpha-particles) for several solar activity levels. The solid lines represent the realistic model of independent computation of proton and α-particle spectra, while the dashed lines with circles represent the model assuming the total spectrum of GCR as 1.55 of the proton spectra.

epoch. In order to show the difference between production rates based on our GCR spectrum and $J_{p+\alpha} = 1.55 J_p$, used in [e.g., 17, 18], we compute and plot the production rate for the last one in Figure 5 as well. One can see that for all ϕ the realistic spectrum yields production rates lower than those for $J_{p+\alpha} = 1.55 J_p$, by 10% in average and up to 17% at the top layer for low activity. Lower production rate leads to higher values of the reconstructed ϕ for the same measured content of the nuclide. In other words, previous studies might underestimated the average level of solar activity based on lunar rock data.

A similar analysis was done for SEPs. Figure 6 depicts production rates of ^{14}C as function of depth, for several assumptions. One is the "synthetic" spectrum of SEP and the other exponential one (both from Fig. 3). Additionally, we show also the production curve that corresponds to earlier used analytical models neglecting development of the nucleonic cascade in rock because of supposedly negligible energy of SEPs [e.g., 1, 2, 3]. The results are different depending on the depth. While the curves are quite close to each other for the top layers (0–5 g/cm^2), because the soft part of the SEP spectra dominates there and its shape is the same (the right panel of Figure 3), more energetic particles become important in deeper layers where the effect of nucleonic cascades

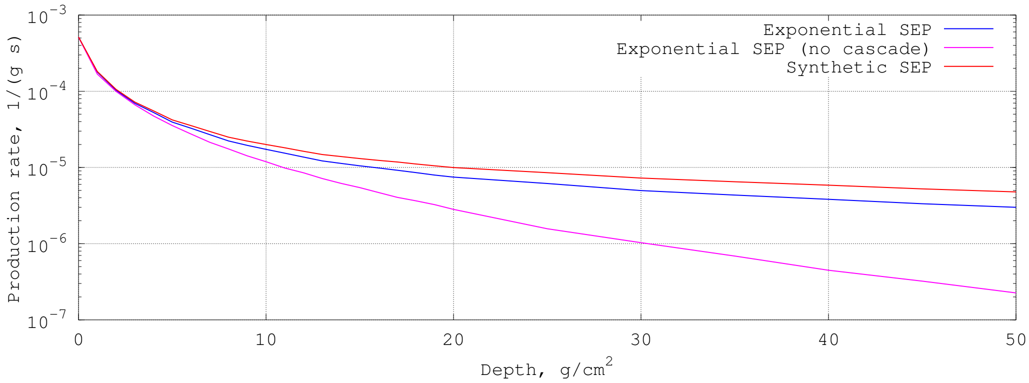

Figure 6: Production rates of ^{14}C in lunar rock by solar energetic particles.

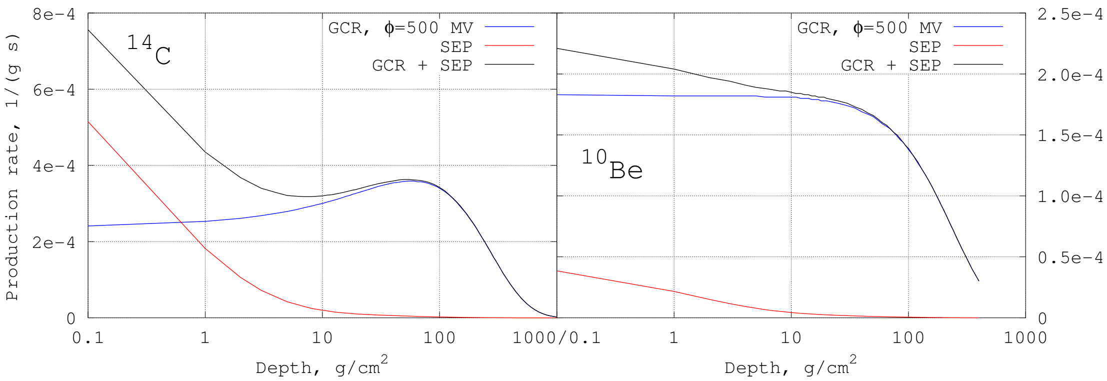

Figure 7: Production rates of nuclides by GCR ($\phi = 500$ MV) and SEP ("synthetic" spectrum). ^{14}C is in the left panel, ^{10}Be is in the right one.

becomes crucial. At 50 g/cm^2, the realistic production rates are greater by more than order of magnitude than the simplified analytical solution. Moreover, a more realistic "synthetic" SEP spectrum yields a significant enhancement (40-50%) of the production rate at moderate depths. about 44% at 50 g/cm^2 over the exponential spectrum. Consequently, including the most energetic particles into the SEP spectrum and taking into account cascades can significantly change the interpretation of the isotope content of lunar rocks at layers deeper than 5 g/cm^2.

Following the same way, the production rates of the isotope ^{10}Be were computed.

The final results for both the nuclides, for GCR and SEP are gathered together in Figure 7. From the left panel of the figure one can conclude that while GCR are mostly responsible for the generation of ^{14}C, solar particles dominate at shallow depths < 8 g/cm^2, because of the high fluxes with lower energy (Fig. 4). This forms two maxima in the production rate curve that theoretically may allow to distinguish the GCR and SEP factors in experimental data. The shape of the total production rate of ^{10}Be differs (the right panel). SEP produce much less ^{10}Be over all the depths, even in top layers. The production by GCR is more or less constant till 20 g/cm^2 and doesn't form a pronounced maximum. These makes it difficult to extract reliable information about solar particles since ^{10}Be is produced mostly by GCR particles. Thus, the content of ^{10}Be is a good base to reconstruct the average flux of GCR in the past.

3. Conclusions

In this work we present the newly computed yield functions of cosmogenic ^{14}C and ^{10}Be in lunar rocks. Applying these yield functions and realistic spectra of GCR and SEP we revisited the production rates for these isotopes. In the subsequent studies comparison with the measured data will be performed.

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References

[1] R. C. Reedy and J. R. Arnold, *Interaction of Solar and Galactic Cosmic-Ray Particles with the Moon*, *J. Geophys. Res.* **77** (1972) 537–555.

[2] A. J. T. Jull et al., *C-14 depth profiles in Apollo 15 and 17 cores and lunar rock 68815*, *Geochim. Cosmochim. Acta* **62** (1998) 3025–3036.

[3] K. Niishiizumi et al., *Solar cosmic ray records in lunar rock 64455*, *Geochim. Cosmochim. Acta* **73** (2009) 2163–2176.

[4] G. A. Kovaltsov and I. G. Usoskin, *Occurrence Probability of Large Solar Energetic Particle Events: Assessment from Data on Cosmogenic Radionuclides in Lunar Rocks*, *Solar. Phys.* **289** (2014) 211–220.

[5] S. Agostinelli et al., *Geant4 — a Simulation Toolkit*, *Nucl Instr. Meth. Phys. Res. A* **506** (2003) 250–303.

[6] J. Allison et al., *Geant4 Developments and Applications*, *IEEE T. Nucl. Sci.* **53** (2006) 270–278.

[7] A. Ferrari et al., *FLUKA: a multi-particle transport code*, *CERN-2005-10, INFN/TC_05/11, SLAC-R-773* (2005).

[8] T. T. Böhlen et al., *The FLUKA Code: Developments and Challenges for High Energy and Medical Applications*, *Nucl. Data Sheets* **120** (2014) 211–214.

[9] R. C. Finkel et al., *Depth variation of cosmogenic nuclides in a lunar surface rock and lunar soil*, *Proc. of 2nd Lunar Sci. Conf.* **2** (1971) 1773–1789.

[10] W. R. Webber and P. R. Higbie, *Production of cosmogenic Be nuclei in the Earth's atmosphere by cosmic rays: Its dependence on solar modulation and the interstellar cosmic ray spectrum*, *J. Geophys. Res.* **108** (2003) 1355

[11] G. A. Kovaltsov and I. G. Usoskin, *A new 3D numerical model of cosmogenic nuclide Be-10 production in the atmosphere*, *Earth Planet. Sci. Lett.* **291** (2010) 182–188.

[12] R. C. Reedy, *Proton cross sections for producing cosmogenic radionuclides*, *Lunar Planet. Sci. Conf.* (2007) 1192.

[13] R. C. Reedy, *Cosmogenic-nuclide production rates: Reaction cross section update*, *Nucl Instr. Meth. Phys. Res. B* **294** (2013) 470–474.

[14] V. Tatischeff et al., *Delayed X- and Gamma-Ray Line Emission from Solar Flare Radioactivity*, *Astrophys. J.* **165** (2006) 606–617.

[15] I. G. Usoskin et al., *Heliospheric modulation of cosmic rays: Monthly reconstruction for 1951–2004*, *J. Geophys. Res.* **110** (2005) A12108.

[16] R. A. Burger et al., *Rigidity dependence of cosmic ray proton latitudinal gradients measured by the Ulysses spacecraft: Implications for the diffusion tensor*, *J. Geophys. Res.* **105** (2000) 27447–27456.

[17] R. Michel et al., *Production of cosmogenic nuclides in meteoroids: accelerator experiments and model calculations to decipher the cosmic ray record in extraterrestrial matter*, *Nucl Instr. Meth. Phys. Res. B* **113** (1996) 434–444.

[18] J. Masarik and J. Beer, *Simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere*, *J. Geophys. Res.* **104** (1999) 12099–12111.

[19] R. C. Reedy, *Update on Solar-Proton Fluxes During the Last Five Solar Activity Cycles*, *Lunar Planet. Sci. Conf.* **43** (2012) 1285.

[20] A. Tylka and W. Dietrich, *A new and comprehensive analysis of proton spectra in ground-level enhanced (GLE) solar particle events*, *Int. Cosmic Ray Conf.* (2009).

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