HELIUM PRODUCTION OF PROMPT NEUTRINOS ON THE MOON.

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Introduction: The subject of conducting fundamental physics and astronomy experiments on the lunar surface continues to be of interest in the planetary science community. Such an inquiry necessarily requires an analysis of the backscatter albedos produced by Galactic cosmic rays (GCRs) when they directly impact the lunar regolith. Unlike the Earth, this happens because the Moon has only a tenuous exosphere. Such secondary radiation constitutes a background that obscures and interferes with measurements conducted in the normal sense of laboratory physics on Earth. Our previous investigations [1-2] using recent enhancements in the Monte Carlo program known as FLUKA [3] included the production of charged particles, neutrons, photons, and neutrinos by the impact of Galactic protons. That investigation is extended here to include the effect of ionized helium, ^{4}He, or α–particles. Because high-energy GCRs excite planetary regoliths into giving rise to charmed mesons, neutrinos are produced. Thus a connection is established for the GCR helium production of prompt neutrinos on the Moon using the physics of charm.

Method: Developments in high-energy physics (HEP) and astrophysics have been intimately involved with the science of CRs since the onset of all three disciplines. It is therefore natural that advanced HEP technology used in designing the world's particle accelerators should find its way into space investigations by means of CR astrophysics.

In addition to fundamental physics experiments themselves, this includes hardware instrumentation and detectors as well as computer software design-and-analysis tools. The latter utilize transport codes for the propagation of particle scattering and nuclear fragmentation events. One such method is the Monte Carlo technique, and many such codes currently exist.

Monte Carlos: FLUKA (an acronym from the German, for "Fluctuating Cascade") is the radiation transport code chosen for the study, modified with an advanced 3-D graphics geometry package [3]. That software is used in conjunction with an object-oriented (OO) physics analysis infra-structure that is currently evolving at CERN known as ROOT [4]. A multi-processor Linux-based architecture is used for launching the FLUKA-Executing-Under-ROOT or FLEUR simulation packages in this study.

Table 1. Lunar Surface Model

Element	Atomic Weight	Z	Percent Weight
O	16.00	8	43.47
Si	28.09	14	20.86
Al	26.98	13	9.63
Fe	55.85	26	9.08
Ca	40.08	20	8.93
Mg	24.31	12	5.54
Ti	47.88	22	1.46
Na	22.99	11	0.32
Cr	52.00	24	0.22
Mn	54.94	25	0.16
K	39.10	19	0.15
P	30.97	15	0.09
S	32.07	16	0.09

Model: Preliminary exploration of the Moon during the Apollo and Luna programs resulted in a thorough investigation of actual regolith material returned from a number of landing sites [5]. The model adopted here for the lunar surface is taken to be the average of the chemical composition of soils found over all such sites. A generic regolith for the present analysis is thus defined, being the same model as used in [1-2]. Table 1 gives the resulting weight percentages calculated by element. These are the 13 elemental abundances, having atomic mass A and charge Z, measured to be present on the Moon with more than a trace. Biogenic elements (H, C, and N) have been neglected. The lunar surface model is assumed to have a mean density of 2.85 g cm^{-3} [6] and a negligible magnetic field.

The Monte Carlo geometry consists of a collisional tracking volume described earlier [1-2]. A cylindrical tube comprised of a thin wafer of vacuum (tracking medium 1) is followed by a homogeneous mixture of the lunar surface material in Table 1 (tracking medium 2). The differential CR flux is taken from Simpson [7] to be α–particles (ionized ^{4}He) obeying a power-law spectrum $dN \sim E^{-\gamma} dE$ with $\gamma = 2.7$. The incident flux (having 4-momenum p_μ whose energy is E) impacts the regolith at an angle θ with respect to the zenith.

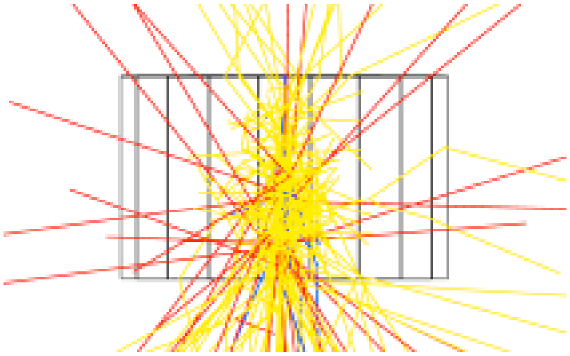

Figure 1. Cascade and albedo backscatter

Results: Figure 1 shows the dynamics of GCR impacts. A CR-induced particle cascade (lines going down) and albedo backscatter (lines going up) are produced, viewing the cylindrical volume (radius and height = 170 cm) of pie-shaped sectors of regolith from its side. A charged primary nucleus incident from the zenith at □ = 0 with energy *E* = 100 GeV is shown producing prompt neutrinos (red), protons (blue), and other particles (yellow).

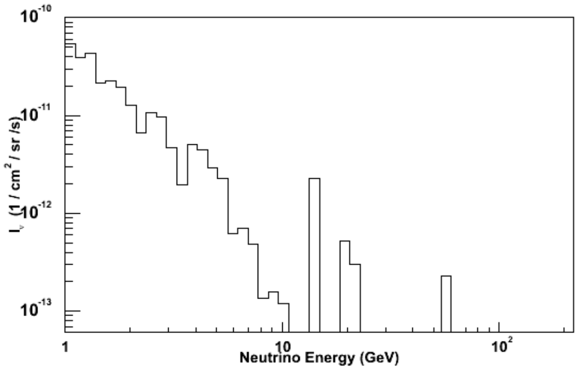

Figure 2. Neutrino flux *I*_ with onset of charm

Similarly, Figure 2 and Figure 3 illustrate the prompt neutrino flux production *I*_ by the lunar surface commencing above 1 GeV, as a result of 40 GeV – 8 TeV incident □–particles. At energies below 10 GeV, the neutrino flux is due primarily to pions (π-mesons) and kaons (*K*-mesons), seen to drop exponentially and cutting off at 10 GeV. At energies higher than 1 GeV, the prompt decay of charmed *D*-mesons into neutrinos begins to emerge, first suppressed by the lower-energy background and then appearing above 10 GeV. Figure 3 is re-scaled using units of E^3I_ in order that the higher-energy prompt neutrino spectrum has more emphasis. This provides a means for comparison with the results of Volkova [8,1] who earlier studied protons in the GCR flux. The statistics result from 100,000 primary □–particle events, and additional FLUKA runs are in progress to improve the spectrum above 10 GeV.

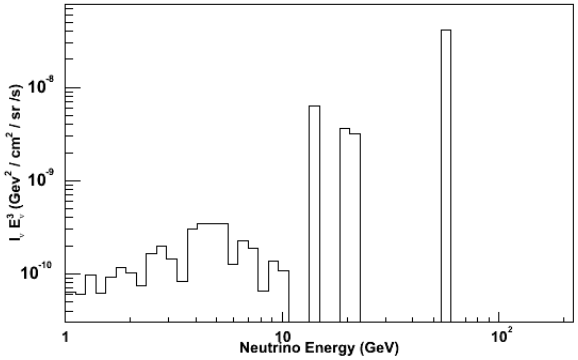

Figure 3. Re-scaling of flux in Fig. 2 as E^3I_

Conclusions: Charmed meson decay is shown to result in prompt neutrino production by the surface of the Moon when excited by high-energy Galactic helium particles. This extends earlier Monte Carlo investigations [1-2] using the latest available enhancements in FLUKA.

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