DEPTH-DEPENDANT SOLAR COSMIC RAY INDUCED COSMOGENIC PRODUCTION RATES.
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Introduction: Meteoroids in space are irradiated with solar (SCR) and galactic cosmic rays (GCR). Both types of cosmic rays induce, among others, spallation reactions that result in the production of so-called cosmogenic nuclides. By analyzing the cosmogenic nuclide content in meteorites, exposure ages, shielding depths, and terrestrial residence times can be determined if the relevant production rates are known.

SCRs penetrate only the upper few g/cm$^2$ of a given meteoroid because the SCR flux densities are highest at energies below 200 MeV/amu. In contrast, the majority of GCR particles has an energy in the range of a few GeV, leading GCR particles to penetrate up to meters into the meteoroid and therefore to produce cosmogenic nuclides over a large range of shielding depths. Production rates due to GCR can be modeled reliable for most cosmogenic nuclides in ordinary chondrites, carbonaceous chondrites, and iron meteorites [1,2].

Since most meteoroids lost their upper few g/cm$^2$ due to ablation when passing through the Earth’s atmosphere, cosmogenic nuclides produced by SCRs are very often not important for cosmogenic nuclides studied in typical size meteorites. However, returned lunar samples as well as certain meteorites (especially shergottites) show a combined record of SCR and GCR induced effects. Here we calculate depth dependent SCR production rates of cosmogenic helium, neon, and argon isotopes in shergottites and lunar material.

Methods: For the model calculations we use a rigidity SCR spectrum with an incident particle flux ($J_0$) of 100 cm$^{-2}$ s$^{-1}$ and a rigidity ($R_0$) of either 100 MV or 125 MV. The SCR spectrum with $R_0 = 125$ MV is the same as used by [3] for SCR production rates in interplanetary dust particles, however, here we consider all SCR incident angles. Therefore the reported production rates are not valid for small particles like IDPs and micrometeorites.

For calculating the stopping of SCR particles we use the chemical compositions of the Apollo 15 drill core at various depths [4] and of shergottites [e.g., 5]. The stopping of SCR protons is calculated using the Bethe-Bloch equation in the parameterized form presented by [6]. For modeling, the meteoroid or the lunar sample is divided into sections of 0.001 g cm$^{-2}$ thickness and the stopping power, which depends on the chemical composition, is calculated in each of these slices. The total stopping at a given depth is then the sum of the stopping in all preceding slices. To calculate the whole spectrum at a given depth, we consider SCRs up to 400 MeV and calculate the stopping with an energy resolution of 0.05 MeV. Subsequently, the spectra are binned into steps of 1 MeV. Finally, we assume for all calculations here, that the radius of the irradiated meteoroid is infinity, hence we irradiate a flat (2π) geometry isotropically from all angles, which is equivalent to the assumption that no SCR particle will penetrate from the back. We slice the angles into steps of 2° for all calculations. All numerical integrations (slicing the meteoroid, energy resolution, and irradiation angle integration) converge well, indicating that the numerical resolution of the calculation is sufficient. The spectra at various depths were then used in the SCR production rate model by [3] to calculate the cosmogenic production of $^3$He, $^{21}$Ne, and $^{36}$Ar.

Results & Discussion: In Figure 1 we compare the depth dependant production rates for $^{21,22}$Ne modeled for lunar samples with literature values [7]. For the comparison we scaled the empirical literature data [7] to the same particle flux as used in our model. While we predict almost the same production rate at the surface, our production rates at higher depths are slightly lower than the empirical values. Considering that our model calculations are based on state-of-the-art stopping calculations and our best knowledge of

![Figure 1: Comparison of our production rates with published values [7].](image-url)
the relevant nuclear cross sections (all cross sections are experimentally determined) we consider the agreement between the two datasets reasonable and our data as superior.

Figure 2 and 3 show depth dependent production rates for $^4$He, $^{21}$Ne, and $^{36}$Ar in the Apollo 15 drill core and in Shergotty, respectively. The modeled production rates are for a SCR spectrum with a rigidity of 100 MV and 125 MV. A SCR spectrum with $R_0 = 125$ MV has a higher amount of energetic particles than a SCR spectrum with $R_0 = 100$ MV, therefore penetrating deeper into the meteoroid. Consequently, the production rates for higher rigidity spectra decrease slower with shielding depth than the production rates for SCR spectra with low rigidity.

Cosmogenic nuclides measured in shergottites [8,9] can best be explained by a combination of GCR and SCR induced effects. Garrison et al. [9] argued that the $^{21}$Ne/$^{22}$Ne ratio in shergottites is too low to be explained by a GCR component only. Typical modeled GCR $^{21}$Ne/$^{22}$Ne ratios for shergottites are around 0.8, while most of the measured ratios are lower. The modeled $^{21}$Ne/$^{22}$Ne SCR production rate ratios vary between 0.57 and 0.68 and between 0.58 and 0.69 for $R_0 = 100$ MV and $R_0 = 125$ MV spectra, respectively. The ratios show a strong depth dependency in the depth range from 0 to about 18 g cm$^{-2}$. The $^{21}$Ne and $^{22}$Ne production rates in this depth range both decreases by a factor of about 50.

This range of $^{21}$Ne/$^{22}$Ne ratios is significantly lower than the range for GCR induced effects but is in agreement with recent data (see [8] at this meeting).

**Summary & Conclusions:** We presented a model to calculate cosmogenic nuclides produced by SCR. Here we focus on two different chemical compositions and two different spectra but the model can easily be extended to other shapes of the SCR spectrum and other target chemistries.

We show that the shielding dependency of the production rates depends on the rigidity of the SCR spectrum. We also modeled the $^{21}$Ne/$^{22}$Ne ratios for typical shergottites. The ratio is significantly lower than the value for GCR induced effects, confirming literature [9] and current data [8] for martian meteorites.

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