DEPTH VARIATIONS OF SPALLOGENIC NUCLIDES IN METEORITES*, R. C. Reedy, Los Alamos Scientific Laboratory, Los Alamos NM 87545; G. F. Herzog, Dept. of Chemistry, Douglass College, Rutgers Univ., New Brunswick, NJ 08903; and E. K. Jessberger, Max-Planck-Institut fur Kernphysik, D-6900 Heidelberg FDR.

The interaction of energetic cosmic-ray particles with meteorites produces a variety of radioactive and stable nuclides, including isotopes of the rare gases. The production rate of a nuclide in a sample of a meteorite is a function of the composition of the sample and of the flux of cosmic-ray particles to which it was exposed. The flux of particles depends on the size and shape of the meteorite, the depth of the sample in the meteorite, and the orbit of the meteorite about the sun. Measurements of rare gases in cores from two large meteorites, Keyes (1) and St. Severin (2), have shown variations of production rates and isotope ratios with depth.

Two approaches have been used to calculate the effects of the depth of a sample on the production rates of spallogenic nuclides. One method (3,4) takes the distribution of nuclides measured in thick targets bombarded by beams of high-energy protons and then transforms the measurements to isotropic irradiations of spherical objects. The second approach (5,6) involves the calculation of the flux of nuclear particles as a function of depth and energy, φ(d,E). Thin-target cross sections are used to determine the production rate of a given species at a depth d, \( P(d) \), using the relation

\[
P(d) = \sum_i N_i \int \phi(d,E) \sigma_i(E) \, dE,
\]

where \( N_i \) is the number of atoms of target i and \( \sigma_i(E) \) is the cross section for particles with energy E reacting with target i to produce the nuclide in question. This approach has been used successfully by Reedy and Arnold (5) to calculate the production rates of radionuclides in the moon. The Reedy-Arnold lunar galactic-cosmic-ray (GCR) model has calculated the shape of the production profiles as a function of depth very well, but often it has been off in absolute magnitude by factors of 30% or more (7). This paper extends the Reedy and Arnold lunar model (5) to calculations of the production rates of rare-gas isotopes in meteorites. Production rates are calculated for the L-chondrite Keyes since the depth profiles for the rare gases He, Ne, and Ar (1) and for Al-26 (8) have been measured.

The abundances of target elements assumed for these calculations were (in weight percents): Na (0.55), Mg (14.8), Al (1.18), Si (19.5), K (0.085), Ca (1.31), and Fe (22.2). The cross sections for Al-26 were those of (5) and for the rare-gas isotopes (except neon) were those described in (9). The cross section for the production of Ne-21 from magnesium by 14-MeV neutrons was recently measured to be about 155 mb (Reedy, Herzog, and Jessberger, paper in preparation). Cross sections for neon isotopes from other targets have been changed from those in (9) to give better agreement with measured neon isotope ratios from mineral separates.

The fluxes of GCR particles above 1 GeV/nucleon as a function of depth were calculated using the same approach as in (6). The meteorite was assumed to be spherical and the preatmospheric radius for Keyes was assumed to be 35 cm (1), or 120 g/cm^2. The fluxes of incident primary GCR particles were increased by 1.1 above those used by (6) to account for the increase in GCR par-
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Particles for distances from the sun greater than 1 A.U. The calculated flux of particles above 1 GeV as a function of depth in Keyes is shown in Fig. 1. The profile is much flatter than that calculated for the moon (5) since the meteorite is exposed to GCR particles on all sides and, having a radius similar to the interaction length of GCR particles, most locations have particles coming from all directions. The spectrum of particles as a function of energy was assumed to be the same as that used in (5), which involves a function with a shape parameter \( \alpha \). Figure 1 shows the values of \( \alpha \) as a function of depth in Keyes as determined from fitting the measured Al-26 data of (8). (The Reedy-Arnold model successfully fitted the Al-26 activities measured in lunar samples.) Since more than 5 cm of surface was lost by ablation, production by solar cosmic rays should be negligible and was not calculated.

Fig. 1. The parameters for the GCR flux as a function of depth in the Keyes L-chondrite. The top curve is the shape parameter and the bottom curve is the integral flux of particles with energies greater than 1 GeV/nucleon. Depths in g/cm\(^2\) are from the surface of the preatmospheric body; those in cm are from the present surface.

The calculated production rates for He-3, Ne-21, and Ar-38 as a function of depth were fitted to the measured data by multiplying the calculated production rates by various exposure ages. The resulting theoretical profiles are shown with the measured data of (1) in Figs. 2 and 3. Also compared in Fig. 3 are the calculated and measured ratios of Ne-22/Ne-21. The shapes of the depth profiles for these three rare gases are in very good agreement with the observed profiles (the measured Ar-38 data have too much spread to establish the observed trend). The calculated He-3/Ne-21 profile is similar to, but only 0.66 of, the observed one. The calculated ratio of (C1-36+Ar-36)/Ar-38 is about 0.70 for all depths. The calculated ratio Ne-20/Ne-22 varied from 0.87 at the surface to 0.97 at the center and the calculated production ratio Al-26/Ne-21 varied from 0.46 to 0.42. The worst agreement is for the Ne-22/Ne-21 ratio for the samples nearest the surface. The reasons for this discrepancy are not known, but it is possibly due to the cross sections used to calculate the Ne-22 production rates or to the assumed sphericity.

The exposure ages used to determine the fits shown in Figs. 2 and 3 are considerably larger than those reported for Keys by (1), 24 My for He-3 and 23 My for Ne-21, and by (8), 18.5 My for Ne-21. In fitting the H-3 profiles for lunar rocks, the Reedy-Arnold GCR production rates were estimated by (7) to be low by a factor of 1.4. Including this factor, the He-3 age would be 34 My, in good agreement with the Ne-21 and Ar-38 ages of 31 and 34 My, respectively. The reasons for the discrepancies between the ages calculated here

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and those calculated using traditional production rates are not known.

The calculated ratio for the direct production of He-3 to that for H-3
is about 1.1. About 53% of the (He-3+H-3) atoms are made by particles with
energies below 1 GeV. The ratio of the production rates of Na-22 to the rates
for direct production of Ne-22 ranges from 1.77 to 1.55. For Ne-21, (Ne-22+
Na-22), and Ar-38, about 50%, 35%, and 50%, respectively, of the production
is by particles with energies below 100 MeV. In Keyes, the major target
element for (He-3+H-3) production is O (about 53%), for Ne-21 and (Ne-22+
Na-22) it is Mg (76 and 68%), and for Ar-38 it is Ca (about 66%).

These calculations show the details of the mechanisms for the spallation
production of nuclides in meteorites. Such production rate calculations
will help to improve exposure age determinations and other studies of the history
of a meteorite by allowing better corrections for chemistry, depth, and size
in interpreting measurements of spallogenic nuclides.

References: *This work was supported in part by funds from NASA.
clear Reactions in Astrophysics, Ed. by B. S. P. Shen, pp. 169-245, Benjamin,

Figs. 2&3. Calculated (solid lines) and measured (symbols, (1)) concentrations
or ratios for spallogenic rare-gas isotopes as a function of depth in Keyes.