Production of Cosmic-Ray-Produced Nuclides in Meteorites

Exposure of material to high-energy particles, protons or neutrons, can cause nuclear transmutations. These reactions lead to the production of numerous secondary nuclides. These secondary nuclides could either be stable or radioactive. Figure 1 illustrates a spallation reaction.

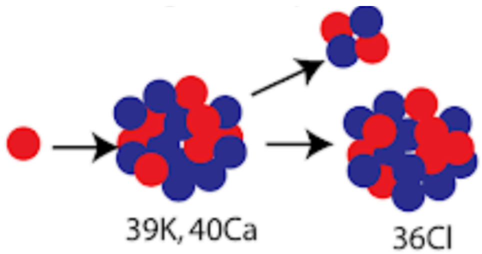

Figure 1

For a stable nuclide, the concentration, C, is a function of the exposure time.

$$C = Pt \qquad (1.1)$$

where

C = concentration of the stable nuclide in atoms/gm

P = production rate of that nuclide in atoms/gm-yr

t = time of exposure

For a stable nuclide, the buildup in concentration is linear in time. Figure 2 illustrates the buildup of a stable cosmogenic nuclide in time.

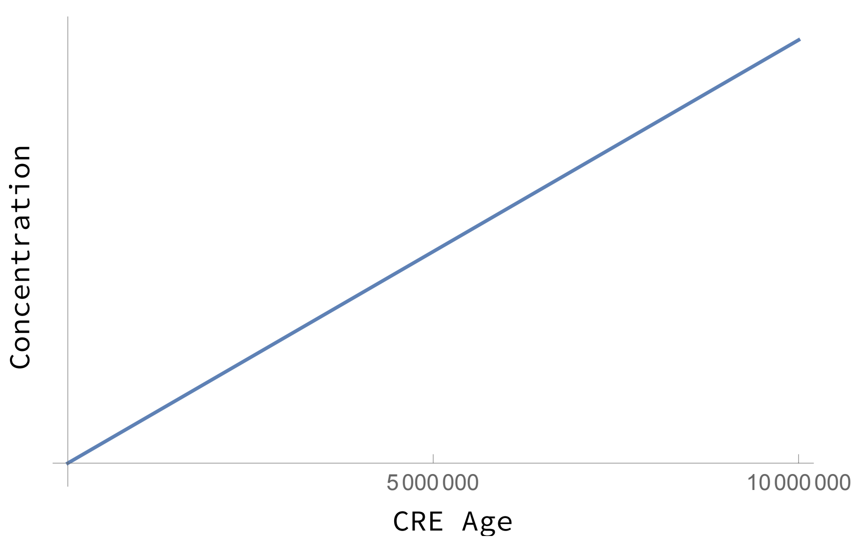

Figure 2

The growth of a cosmogenic radionuclide is different. The growth can be described by a first order differential equation:

$$dN = -\lambda N(t)dt \qquad (1.2)$$

This mathematical relationship expresses the observations of radioactive decay. The number of decays is proportional to the number of atoms of a specific isotope multiplied by the elapsed time. The decay constant, λ, having units of inverse time, expresses how fast or slow a radioactive species decays. The equations that comprise the mathematical model of radioactive decay are known as the Bateman equations. Equation (1.2) can be solved by separation of variables.

$$dN = Pdt - \lambda N(t)dt$$

P is the production rate for the radionuclide; this relationship expresses both production and decay

First separate the variables

$$dN = (P - \lambda N(t))dt$$

$$\frac{dN}{(N(t) - P/\lambda)} = -\lambda dt$$

Integrate both sides

$$\int \frac{dN}{N - P/\lambda} = -\lambda \int dt$$

$\ln(N - P/\lambda) = -\lambda t + k$ where k is the constant of integration

Exponentiate both sides of the equation and rewrite the constant

$$N(t) = Ce^{-\lambda t} + P/\lambda$$

The constant is found by applying initial conditions, in this instance at $N(t = 0) = 0$.

$$0 = Ce^{-0} + P/\lambda$$

$$C = -P/\lambda$$

$$N = P/\lambda - P/\lambda e^{-\lambda t}$$

$$N = \frac{P}{\lambda}(1 - e^{-\lambda t})$$

$A = \lambda N$ where A is the activity, typical units could be decays/sec-kg

$$A = P(1 - e^{-\lambda t})$$

At $t = 0$ consistent with the initial conditions. At $t = \infty$, the activity is equivalent to the production rate, *i.e.* the activity is saturated, or in equilibrium.

Figure 3 shows the buildup of two different radionuclides, one with a shorter half-life. The blue curve is ^{36}Cl, with a .301 Myr half-life, and the yellow curve is ^{10}Be, with a 1.36 Myr half-life. For both radionuclides, the saturation activity is reached after about 5 half-lives. At this stage the activity is the same as the production rate.

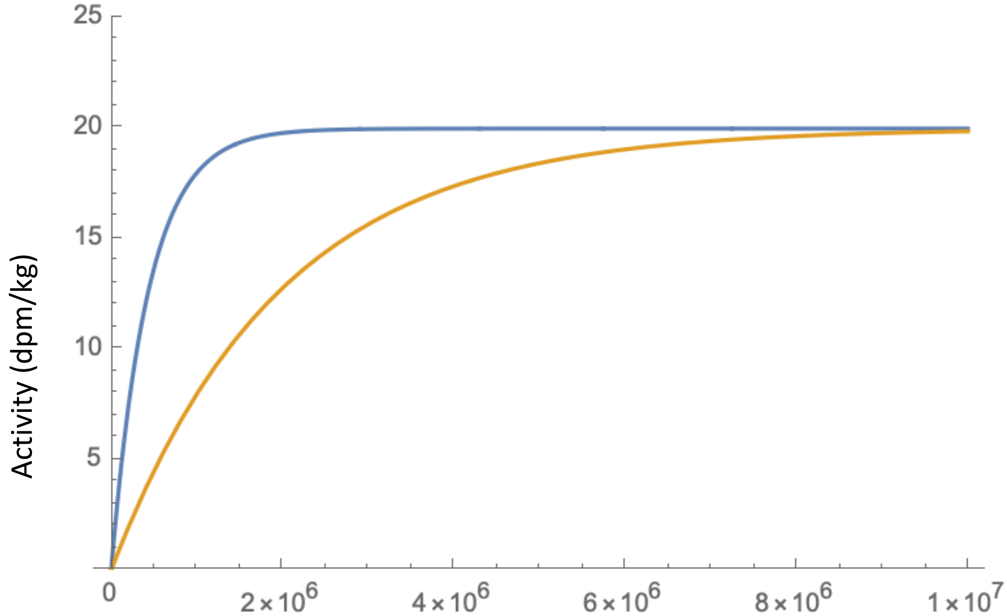

Figure 3

Meteorites exposed to cosmic rays in space are exposed to cosmic rays. Cosmogenic nuclides, both stable and radioactive, provide a measure of the exposure time. For meteorites with shorter exposures, radionuclides can be used. For longer exposure ages, ^{21}Ne is the most commonly used cosmogenic noble gas nuclide measured. For meteorites that have been exposure to cosmic rays for > 8 Myr, the ^{10}Be activity will be saturated, which provides the production rate. The production rates are a function of the radius of meteor and the sample location within the meteor. For the samples, if we measure multiple nuclides we can place some limits on the size of the pre-atmospheric body.