

NUCLEAR EFFECTS OF SUPERNOVA-ACCELERATED COSMIC RAYS ON EARLY SOLAR SYSTEM PLANETARY BODIES. B. S. Meyer, L.-S. The, and J. Johnson, Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978 (mbradle@clemson.edu).

Introduction: Evidence from ^{60}Fe strongly suggests that the Solar System formed in proximity to nearby massive stars (e.g., [1]). Gamma rays emitted by the explosion of a nearby massive star early in the Solar System's history have been invoked to explain the discrepancy between the Pb-Pb and Lu-Hf ages of meteorites [2]. The idea is that such gamma rays excite ^{176}Lu from its ground state into excited states which subsequently decay either back down to the ground state (half-life against beta decay of 3.73×10^{10} years) again or to the 3.7 hour isomer at 123 keV excitation. The effect is then to accelerate the beta decay of any ^{176}Lu exposed to the gamma rays and thereby make the apparent Lu-Hf age greater than the Pb-Pb age.

The difficulty with this scenario is that gamma rays have a shallow penetration depth. This suggests that the acceleration of the beta decay due to excitation by gamma rays would have to occur when the ^{176}Lu resided in very small bodies, most likely dust grains [2]. Consequently, the Hf anomalies would then have to survive as the grains were incorporated into larger meteorite parent bodies.

We and collaborators have proposed that the acceleration of the beta decay of ^{176}Lu instead comes from excitation by secondary particles produced from ultrarelativistic cosmic rays accelerated by supernova shocks [3,4]. Data indicate that roughly 5% of the ^{176}Lu needs to have had its beta decay accelerated [4] in the affected meteorite parent bodies.

Cosmic rays are accelerated as particles, primarily protons, are repeatedly scattered off of inhomogeneities in magnetic fields [5]. Fermi originally imagined the cosmic rays to be accelerated by inhomogeneities in the interstellar magnetic field, but it is now strongly suspected that they are instead accelerated by such inhomogeneities in supernova shocks [6,7]. Models show that supernova shocks can accelerate cosmic rays to 100s of TeVs [8].

Cosmic-Ray Penetration in Solid Bodies: As high-energy protons reach the early Solar System, they can impinge on planetary bodies. These protons will travel meters to tens of meters into the rock before interacting with a nucleus. Such an interaction will create a hadron shower of several hundred particles, particularly protons, neutrons, and pions. The pions themselves will travel a short distance before decaying into longer-lived muons. As the charged particles travel through the rock, they lose energy by pair production and Bremsstrahlung at high energy and by ionization at

low energy. Figure 1 shows the energy deposition resulting from a 1 TeV proton incident on a block of aluminum. The bulk of the energy is deposited in the first few meters of the block, but some energy is deposited as deeply as 10-14 meters. For a 100 TeV proton, the energy deposition is as deep as 100-200 meters.

energy density ($\text{GeV}/\text{cm}^3/\text{primary}$)

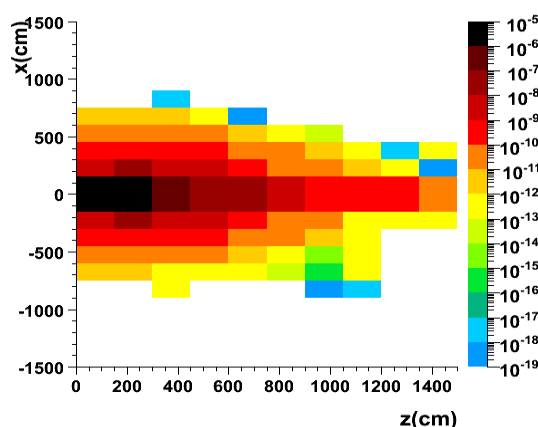


Fig. 1: Energy density resulting from a 1 TeV proton impinging on a block of aluminum as computed in a Monte-Carlo calculation with the Fluka code [9,10].

Nuclear Effects: As the ultrarelativistic particles from the hadron shower traverse the rock, they can excite nuclei by Coulomb excitation. Alternatively, the Bremsstrahlung radiation generated as they pass by nuclei can also excite other nuclei to excited states. In most cases, the nuclei so excited will de-excite to their ground states by emitting new gamma rays. In some cases, however, the nuclei in question have relatively long-lived isomers that will beta decay before de-exciting to the ground state. ^{26}Al , ^{113}Cd , ^{176}Lu , and ^{182}Hf are among such nuclei. We have used the Clemson University Nuclear Astrophysics group's liblvs code [11] to calculate, for example, that if ^{26}Al is excited from its ground state to its eighth excited state at 2.365 MeV, it will subsequently de-excite 46.3% of the time to its ground state but 53.7% of the time to its 228 keV isomeric state. This isomeric state will beta decay before de-exciting to the ground state. The result is that excitation of ^{26}Al can accelerate the beta decay of ^{26}Al . Table 1 shows the percentage decay to the ground or isomeric state when ^{26}Al is excited to the each of the first ten excited states above the 228 keV

isomer, as computed with our liblvs-based code. As is evident, the resulting accelerated beta decay depends strongly on the details of the excitation and the nuclear physics governing the de-excitation cascade. The same phenomenon can hold true for other such nuclei. It is worth mentioning that ^{180}Ta will experience a similar acceleration of its beta decay. In this case, however, naturally-occurring ^{180}Ta only exists in its 9- isomeric state. Excitation of ^{180}Ta allows the nucleus to de-excite to its ground state, which only lives for 8 hours.

Energy (keV)	Ground (%)	Isomer (%)
416.85	100	0
1057.74	0	100
1759.03	98	2
1850.62	0.7	99.3
2068.86	100	0
2069.47	21.6	78.4
2071.64	10.6	89.4
2365.15	46.3	53.7
2545.37	44.1	55.9
2660.92	67	33

Table 1

Energetics: To estimate the energetics, we consider that the supernova-accelerated cosmic-ray spectrum is a power law of index ~ 2.5 ranging from 100 MeV to 1 Pev in energy [8]. For such a spectrum, only 1 part in 10^6 of the flux is in cosmic rays with energy greater than 1 TeV. Nevertheless, given a total fluence of supernova cosmic rays of F_0 , such cosmic rays will carry an energy fluence of $3 F_0$ MeV. If this energy is incident on solid bodies in the Solar System and is deposited uniformly into depth L , we find $3 F_0 (L[\text{cm}])^{-1}$ MeV/cm³. Given a ^{176}Lu mass fraction in rock of 10^{-10} and a rock density of 2.55 g/cm³, we find $\sim 10^{12}$ ^{176}Lu atoms per cm³. In order to excite 5% of ^{176}Lu nuclei in depth L to 123 keV, we thus require a fluence $F_0 > 1.5 \times 10^{10} L(\text{cm}) \text{ cm}^{-2}$. For $L = 10 \text{ m} = 10^3 \text{ cm}$, this corresponds to $F_0 > 1.5 \times 10^{13} \text{ cm}^{-2}$. This is clearly an underestimate since it assumes all of the incident energy ends up in ^{176}Lu .

Roughly 10^{50} ergs or $\sim 10^{56}$ MeV of energy from a supernova goes into accelerating cosmic rays (e.g., [8]). While a supernova remnant, the site of cosmic ray acceleration, is \sim parsecs in size and not a point source from the view of a stellar system only parsecs or fractions thereof away, we nevertheless treat it as such in the following estimate for simplicity. The energy fluence in cosmic rays is $\sim 10^{18} (r[\text{pc}])^{-2}$ MeV/cm², where $r[\text{pc}]$ is the distance from the point source in parsecs. Since the average cosmic ray energy for our

assumed spectrum is 300 MeV, the number fluence is $3 \times 10^{15} (r[\text{pc}])^{-2} \text{ cm}^{-2}$. The point source supernova at 1 pc certainly has enough energy to excite the ^{176}Lu nuclei to their 123 keV isomeric state if all energy is directed to ^{176}Lu . The fractional abundance of ^{176}Lu , however, is only about 10^{-12} in the rock. For a fluence of $3 \times 10^{15} \text{ cm}^{-2}$, therefore, a ^{176}Lu nucleus must be excited preferentially by a factor of roughly 10^9 over other abundant isotopes. This may be possible since abundant isotopes such as ^{16}O and ^{28}Si have very high-lying first excited states that may be difficult to excite. Moreover, excitation of these abundant species leads to re-emission of gamma rays that can subsequently excite further nuclei, including ^{176}Lu . Detailed transport calculations are required to follow the cascade of energy from a single ultrarelativistic proton into the various lower-energy states, such as ^{176}Lu excitation and ionization.

Another estimate of the cosmic-ray fluence may come from the current cosmic ray flux in the Solar System. At the Earth's exosphere, the current flux of cosmic rays with energy greater than 1 GeV is $1600 \text{ m}^{-2} \text{ s}^{-1}$ [12]. If we assume this value held over the history of the Solar System, this corresponds to a fluence of about $2 \times 10^{16} \text{ cm}^{-2}$. From the assumed cosmic-ray spectrum, this corresponds to a fluence of $6 \times 10^{17} \text{ cm}^{-2}$ for particles in the range 100 MeV to 1 PeV. Since there is no evidence for cosmic-ray induced effects for meteorites from parent bodies younger than 4.557 Gyr [4], we can assume that the supernova fluence F_0 could be larger than $6 \times 10^{17} \text{ cm}^{-2}$, which is an increase of a factor of at least 4×10^4 over the $1.5 \times 10^{13} \text{ cm}^{-2}$ value above.

Of course an upper limit on the supernova cosmic ray fluence would come from production of short-lived radioactivities. Too large a fluence would overproduce isotopes such as ^{26}Al and ^{41}Ca . The role of modulation caused by the solar wind from the newly formed Sun would play a role in such considerations.

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