The age of meteorite formation by the ^{176}Lu-^{176}Hf system and accelerated decay of ^{176}Lu by cosmic-ray neutrons

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A meta-stable isotope ^{176}Lu decays to ^{176}Hf with a half-life of (3.719+-0.007)x10^{10} yr [1]. The ^{176}Lu-^{176}Hf system could be used as a nuclear chronometer for the ages of formation of parent bodies of meteorites. It has been also used for the study of crust mantle evolution of various planetary bodies such as Earth, Moon, Mars, and the asteroid Vesta. However, the formation ages of some meteorites such as eucrites and angrites evaluated by the ^{176}Lu-^{176}Hf system are older than the age of the oldest solid grains, Calcium-aluminium-rich inclusion (CAI), in the solar system. These results clearly show that there is unresolved mechanism leading excess of ^{176}Hf.

To explain the older ages, several models have been proposed [2]. Recently, Iizuka et al. found that some Ryugu samples show excess of 176Hf and this is the evidence for removement of Lu in water flow [3]. The parent body of Ryugu was formed behind the H2O snow line with ice, whereas there is no evidence that Vesta and the parent body of angrites have rich water. Another possible mechanism is the accelerated decay of ^{176}Lu with cosmic gamma-ray irradiation [4]. There is an isomer at 123 keV in ^{176}Lu which decays to ^{176}Hf with a half-life of approximately 3.7 h. When ^{176}Lu is irradiated by high energy gamma-rays, intermediate states in ^{176}Lu are excited by absorption of gamma-rays and subsequently a part of the intermediate states decay to the isomer decaying to ^{176}Hf. When the decay of ^{176}Lu is accelerated, the isotopic abundance of ^{176}Lu relative to ^{175}Lu should decrease because the isotopic abundance of ^{175}Lu is kept under the gamma-ray irradiation. However, the measured ^{176}Lu/^{175}Lu ratios in meteorites do not show decreased ratios [5].

Hayakawa et al. [1] have proposed another accelerated decay with cosmic-ray neutron irradiation. The isotopic abundance anomalies caused by cosmic neutrons irradiation have been widely reported. In this model, neutrons are produced by nuclear reactions including spallation reactions with high-energy cosmic rays such as protons and alpha particles on the surface of parent bodies of meteorites. The energies of the neutrons decrease through multiple scattering on other atomic nuclei. Excess of the isotopic abundance of ^{176}Hf is made by two nuclear reaction paths. First, the isomer in ^{176}Lu is produced by neutron capture reactions on the stable isotope ^{175}Lu, and the isomer decays to ^{176}Hf. Second, inelastic scattering with high-energy neutrons on the ground state of ^{176}Lu forms a compound nucleus of ^{177}Lu, and a part of ^{177}Lu decay to the isomer in ^{176}Lu through neutron inelastic scattering; the isomer decays to ^{176}Hf. We have calculated the detailed isotopic abundance change of ^{176}Hf using the equation presented in Ref. [3]. In this process, the meta-stable ground state of ^{176}Lu is produced by neutron capture reaction on 175Lu and the calculated result shows that the ^{176}Lu/^{175}Lu ratio does not decrease in typical neutron fluences, which were obtained from the isotopic abundance analyses of Sm and Er in eucrites. This result indicates that even if the measured ^{176}Lu/^{175}Lu ratio is not lower than the chondritic value it does not indicate that accelerated decay did not occur. We also calculated the expected isotopic abundances of Hf with assumed neutron fluences and evaluated the ages that can be obtained from Hf and Lu isotopic abundance without modification of cosmic-neutron irradiations. We found that the evaluated older ages for the eucrites can be explained by this mechanism.

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