NOBLE GASES IN THE CHELYABINSK METEORITES.

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Introduction: The Chelyabinsk meteorite fell in Russia on February 15, 2013 and was classified as LL5 chondrite. The diameter before it entered the atmosphere has been estimated to be about 20 m [1]. Up to now, numerous fragments weighing much greater than 100 kg in total have been collected. In this study, all noble gases were measured for 13 fragments to investigate the exposure history of the Chelyabinsk meteorite and the thermal history of its parent asteroid.

Experimental method: One fragment C3-2, and twelve fragments from commercially obtained Chelyabinsk meteorites (HR-1 to HR-12) were used in this study. The HR samples are from an unknown source and unknown location in the strewn field. Small chips weighing about 30 mg were taken from each Chelyabinsk fragment for noble gas analysis. A stepwise-heating noble gas extraction method (T = 600, 1000, 1300 or 1400, and 1700°C) was applied to four C3-2 chips (2 bulk samples, one light and one dark color portion), HR-1 (bulk), HR-7 (light), and HR-7 (black). Noble gases in the bulk samples from other fragments were extracted by total melting at 1700°C. The noble gases were measured with a modified-VG5400 (MS-3) mass spectrometer at the University of Tokyo. The concentration of ^{81}Kr ($T_{1/2}$ = 0.23 My) was measured for the HR-7 (bulk), the sample weighing 501.8 mg with relatively high concentrations of cosmogenic noble gases.

A chip weighing 19.7 mg taken from C3-2 was irradiated by neutrons using the research reactor of Kyoto University for Ar-Ar and I-Xe dating. Hb3gr and Shallowater meteorite were used as standard samples for Ar-Ar and I-Xe, respectively. Noble gases were extracted by stepwise heating and measured with a modified VG3600 mass spectrometer at the Radioisotope Center, University of Tokyo.

Results and discussion: Cosmogenic He, Ne and ^{38}Ar were clearly observed in the eleven HR samples. The samples from C3-2 and HR-11, on the other hand, show very low concentrations. This indicates that the C3-2 and HR-11 fragments were derived from inside the large meteoroid, while the other HR samples were from shallower parts of the pre-atmospheric body. The ^{3}He/^{4}He ratios of the C3-2 and HR-11 samples are in the range of primordial or solar wind He and relatively low concentrations of ^{4}He, suggesting negligible effect from cosmic-ray irradiation as well as almost perfect loss of radiogenic ^{4}He. Presence of cosmogenic He in the HR samples is evident, but the concentrations are rather low compared with those in most ordinary chondrites. Neon and Argon isotopic ratios also show a clear difference between the C3-2 and HR samples. The HR-7 fragment had black portions larger than the typical scale of melt veins [1]. This material showed the highest concentration of ^{40}Ar among the samples measured in this work, which indicates enrichment in K in the black material. Concentrations of ^{40}Ar in the merasured fragments, however, are distinctly lower than those in unshocked ordinary chondrites. A rough estimation of the K-Ar age for the samples shows young ages of about 1,000 My or less, which may be the time of a violent shock event, possibly the one that left the numerous melt veins in the meteorites.

The shielding depth against cosmic-ray bombardment for each sample, and the cosmic-ray exposure age for the Chelyabinsk meteoroid are estimated based on the cosmogenic noble gas compositions measured in this work. Although the concentration of ^{81}Kr was measured for the sample HR-7 (bulk), the usual Kr-Kr method could not be applied due to the low concentration of cosmogenic Kr isotopes in the sample. Because the concentration of ^{81}Kr, 1.6×10^{-14} ccSTP/g, is in the range of the equilibrium level for ordinary chondrites, this fragment should have been at a shallow depth in the preatmospheric body. Calculation of the depth profile of ^{81}Kr concentration under the condition of 2π-geometry irradiation, following the method in Hohenberg *et al.* [2], indicates that the observed concentration of ^{81}Kr corresponds to a shielding depth of about 1 g/cm^2, very close to the surface of preatmospheric body. In the calculation, the average concentrations of Rb, Sr, Y and Zr for other LL-chondrites [3] were adopted. The expected production rate of cosmogenic ^{21}Ne under the same shielding condition of 1 g/cm^2 is calculated to be 2.29×10^{-9} ccSTP/g/My (2π-geometry) following Hohenberg et al. [2]. Combined with the measured concentration of cosmogenic ^{21}Ne, 2.76×10^{-9} ccSTP/g for the sample HR-7 (bulk), the cosmic-ray exposure age is calculated as 1.2 My. Measured concentrations of cosmogenic ^{21}Ne for other samples from the same fragment, HR-7 (light) and HR-7 (black), are 2.45 and 2.98 × 10^{-9} ccSTP/g, respectively, and give similar exposure ages.

In order to know shielding depths for the other samples, the ^{21}Ne production rate ratios were calculated by normalizing to the sample HR-7 whose shielding depth was ca. 1 g/cm^2. The depth profile of the ^{21}Ne production rate is shown in Fig. 1, where the production rate was calculated in the range from surface to 500 g/cm^2 (equivarent to ca. 150 cm), following Hohenberg *et al.* [2], and extrapolated to about 400 cm in depth. The calculated ^{21}Ne production rate ratios for the measured samples range from 1.39 to 0.003, which corresponds to the depth from surface to ~300 cm beneath the surface of the Chelyabinsk meteoroid. An average density of 3.3 g/cm^3 [1] was used in the calculation. These data show that the diameter of the Chelyabinsk pre-atmospheric body was larger than 6 m at least, which supports other estimates of about 20 m in diameter [1]. If that is the case, however, we can expect that fragments will be recovered derived from deeper parts of the meteoroid that would have negligible effects from cosmic-ray bombardment.

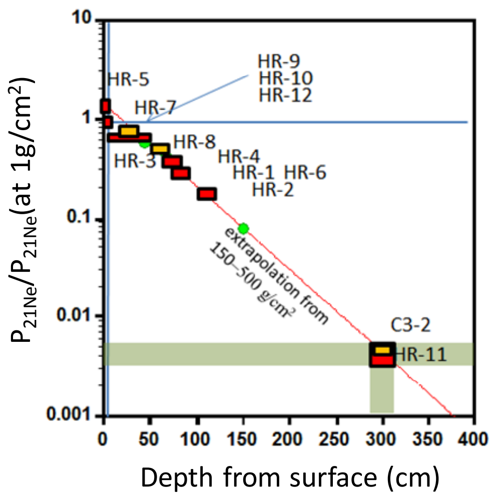

Fig. 1. Estimation of depth from the surface for each fragment in the preatmospheric body of the Chelyabinsk meteoroid.

Ar-Ar age spectrum shown in Fig. 2 shows no clear plataou age, and complex heating events which degassed radiogenic ^{40}Ar at about 1500–2000 My and at recent, <100 My. The latter event might have caused partial loss of Ar. The age spectrum is consistent with the K-Ar age of about 1000 My infered from the total melting analyses described above. Plot of ^{129}Xe/^{130}Xe vs. ^{128}Xe/^{130}Xe in Fig. 3 does not show an isochrone for the Chelyabinsk meteorite, which indicates almost perfect resetting of ^{129}I-^{129}Xe system and low concentration of I (~0.7 ppb). The results of Ar-Ar and I-Xe dating show heavy impact event(s) occured on the parent asteroid for the Chelyabinsk meteorite after the decay of ^{129}I ($T_{1/2}$ = 15.7 My).

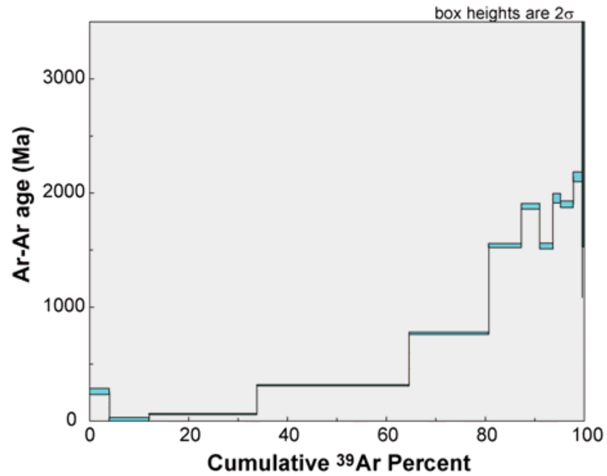

Fig. 2. Apparent age as functions of cumulative percent of ^{39}Ar released from the Chelyabinsk meteorite.

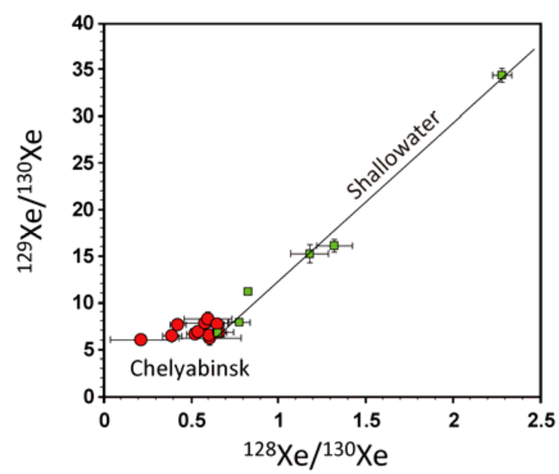

Fig. 3. Correlation of ^{129}Xe/^{130}Xe with ^{128}Xe/^{130}Xe (red data for Chelyabinsk meteorite and green data for Shallowater meteorite).

Acknowledgements: Neutron irradiation of the Chelyabinsk sample for Ar-Ar and I-Xe dating was performed with a nuclear reactor of Kyoto University.

References: [1] Popova O. P. *et al.* (2013) *Science* **342**, 1069–1073. [2] Hohenberg et al. (1978), P*roc. Lunar Planet, Sci. Conf. 9th,* 2311–2344. [3] K. Lodders and B. Fegley, Jr. (1998) *The Planetary Scientist's Companion*, Oxford Univ. Press.