Noble Gases of the 1st and 2nd AO Ryugu Samples Collected by the Hayabusa2 Spacecraft

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Hayabusa2 arrived at the C-type asteroid 162173 Ryugu in June 2018, and successfully collected surface samples from two sampling sites, returning ~5.4 g of samples to Earth on December 6, 2020. Surface samples stored in Chamber A were collected during the 1st touchdown (TD) on Ryugu's surface on February 21, 2019. A crater (diameter of ~14 m) on Ryugu's surface was made using a collision device - denoted "Small Carry-on Impactor (SCI)" on April 5, 2019 [1]. Samples in Chamber C were collected proximal to this artificial crater and are possibly ejecta from the north side of the crater by the 2nd TD on July 11, 2019 [2].

Our studies on the Hayabusa2 samples are based on the measurement of those nuclides produced in asteroidal surface materials by both solar (SCR) and galactic cosmic rays (GCR). Cosmic-ray-produced (cosmogenic) nuclides are used to determine the duration and nature of the exposure of materials to energetic particles [3]. Our goals are to understand both the fundamental processes on the asteroidal surface and the evolutionary history of its surface materials. These processes occur over timescales spanning the present to 10^9 yrs into the past, and are important not only for understanding the history of Ryugu's surface but also for studies of asteroid-meteoroid evolutionary dynamics. For Hayabusa2 samples, there are several specific questions we aim to address: (1) are the Chamber C samples, collected during the 2nd TD, ejecta deposits from the artificial crater, (2) if so, what is the original depth of each recovered sample grain in the Ryugu regolith, and (3) what is the average surface exposure time, mixing rate of regolith materials, and erosion/escape rate of Ryugu's surface? We investigate and utilize cosmogenic radionuclides (^{10}Be, ^{26}Al, ^{36}Cl, and ^{41}Ca) and noble gases, especially cosmogenic ^{21}Ne in Ryugu samples. Expected maximum cosmogenic nuclide concentrations in millimeter-sized (~1 mg in mass) Ryugu sample are a few times 10^5 - 10^7 atoms or lower. These values are higher than the present detection limits of accelerator mass spectrometry (AMS) and noble gas mass spectrometry, but 2 orders of magnitude smaller than normal studies of cosmogenic nuclide measurements in meteoritic materials.

We present here the noble gas isotopic compositions of 6 samples (Table 1) allocated as the 1st and 2nd AO. Noble gases were measured with the system of modified-VG5400 mass spectrometer at Korea Polar Research Institute (KOPRI). The noble gas system had been used to measure the Itokawa samples at the University of Tokyo [4], and then moved to KOPRI afterward in 2015. Noble gases were extracted from each sample using a miniature furnace specially designed for small samples, using a Ta-tube with a Mo-crucible. A sample dropped into the crucible is heated from outside of the Ta-tube by a W-heater. Electric current applied to the W-heater is controlled by a computer program monitoring the heating temperature with a W-Re thermocouple. Samples were installed in a glass-made sample holder, which was set on the furnace and preheated for a day at about 120°C to remove atmospheric noble gas contamination adsorbed on the samples. Stepwise heating was applied to extract noble gases, i.e., 200, 900, and 1700°C for small samples (A0130, C0162, and C0182), and 200, 600, 900, 1200, and 1700°C for larger samples (A0221, C0012, and C0212). The extracted noble gases from each sample were purified and separated into 5 fractions, i.e., He, Ne, Ar, Kr, and Xe, then measured isotope abundances and isotopic ratios for each fraction.

Total values of concentrations of ^{4}He, ^{20}Ne, ^{36}Ar, ^{84}Kr, and ^{132}Xe, and isotope ratios of He, Ne, and Ar obtained by the stepwise heating method are presented in Table 1. Data of Orgueil CI chondrite measured in this work are also presented for comparison. Solar He and Ne with very high concentrations of ^{4}He (14.9 and 9.3×10^{-4} cm^{3}STP/g) and ^{20}Ne (2.0 and 1.5×10^{-3} cm^{3}STP/g) were observed for the aggregate samples A0221 and C0212, respectively. These samples showed ^{20}Ne/^{22}Ne ratios of 12.8–13.7 in the temperature range of 200–900°C. The ratios are close to the value of 13.78 for solar wind (SW) [5]. Release peaks of ^{4}He for these samples were at the heating temperature of 600°C, for which ^{3}He/^{4}He was 3.9×10^{-4}, slightly lower than the SW value of 4.64×10^{-4} [5]. Smaller amounts of SW He and Ne are also indicated in A0130. Neon isotopic compositions for other samples are a mixture of several primitive components, e.g., P1 (Ne-Q), P3 (presolar diamond), and Ne-E(H) (SiC) [6]. Xe isotopic ratios, e.g., ^{130}Xe/^{132}Xe, ^{129}Xe/^{132}Xe, and ^{136}Xe/^{132}Xe, indicate that trapped Xe is mostly Q-Xe component, with a small or negligible contribution of cosmogenic and HL or fissiogenic Xe.

Concentrations of cosmogenic ^{3}He were difficult to calculate, because only a small excess of cosmogenic ^{3}He was observed at the low heating temperatures at 200–900°C for some samples (^{3}He/^{4}He = 5.2, 7.3, 4.9, and 4.8×10^{-4} for A0221, C0012, C0162, and C0212, respectively), and most ^{3}He/^{4}He ratios were between 1.23×10^{-4} for trapped Q-He [6] and 4.64×10^{-4} for SW [5]. Neon isotopic compositions are a mixture of several primitive components, e.g., SW [5], P1 (Ne-Q), P3 (presolar diamond), and Ne-E(H) (SiC) [6], to which a small contribution of cosmogenic ^{21}Ne was detected. Calculated concentrations of cosmogenic ^{21}Ne in excess of the assumed trapped $^{21}Ne/^{22}Ne = 0.029$ are presented in Table 1. The concentrations of cosmogenic ^{21}Ne are $(4.06–11.9)\times10^{-9}$ cm^3STP/g. The concentrations of 11.9 and 9.83×10^{-9} cm^3STP/g for aggregate samples A0221 and C0212, respectively, are higher than those observed for the initial analysis samples, $(1.6–7.8)\times10^{-9}$ cm^3STP/g [7, 8]. Exposure depths were estimated from preliminary measurements of ^{10}Be and/or ^{26}Al in same samples. Then, each production rate P_{21} was obtained by new calculation using the MCNP Code System. Calculated cosmic ray exposure (CRE) ages are shown in Table 1. CRE ages calculated for the samples from Chamber-A are roughly 4 and 11 Myr for A0130 and A0221, respectively. CRE ages for 3 samples from Camber-C, C0012, C0162, and C0182, are in the range of 3–5 Myr, while C0212 has longer CRE age of 8-9 Myr. The CRE ages of 3–5 Myr for the samples from Chamber-A and -C are similar to the reported ages for initial analysis samples, 3–5 Myr [7] and ~5 Myr [8]. Contrary to these grain samples, two aggregate samples A0221 and C0212 with longer CRE ages are enriched in SW-Ne. Samples measured in the present work must have been irradiated heterogeneously by both GCR and SW on the Ryugu's surface before sampling by the Hayabusa2.

Table 1. Concentrations and isotopic ratios of noble gases[1)] in 6 Ryugu samples and Orgueil CI chondrite.

Sample	Mass	Stepwise	^{4}He	^{20}Ne	^{36}Ar	^{84}Kr	^{132}Xe	$^{3}He/^{4}He$	$^{20}Ne/^{22}Ne$	$^{21}Ne/^{22}Ne$	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$	$^{21}Ne_{cosm}$	P_{21} [3)]	T_{21} [3)]
	mg	heating[2)]	$10^{-9}cm^3STP/g$					10^{-4}					$10^{-9}cm^3STP/g$	$10^{-9}cm^3STP/g/Myr$	Myr
A0130	0.2086	3 steps	219000	1230	1600	15.9	19.3	3.84	10.54	0.0654	0.1858	1.79	4.41	1.10-1.20	3.7–4.0
A0221	1.6610	5 steps	1490000	20400	3430	16.9	18.5	3.54	12.85	0.0362	0.1842	0.485	11.9	1.20	9.9
C0012	2.2179	5 steps	97700	472	1530	15.9	19.6	3.59	8.27	0.0978	0.1861	0.419	4.06	1.12–1.20	3.4-3.6
C0162	0.1886	3 steps	118000	706	1430	15.3	17.7	4.46	8.68	0.0984	0.1867	1.34	5.83	1.13–1.17	5.0–5.2
C0182	0.2768	3 steps	93800	432	1370	20.5	17.0	3.80	8.09	0.1280	0.1876	1.18	5.45	1.15–1.20	4.5–4.7
C0212	0.8232	5 steps	932000	15200	2720	16.1	18.7	3.89	12.95	0.0371	0.1849	0.427	9.83	1.12–1.17	8.4–8.8
Orgueil(CI)	1.7205	3 steps	672000	1130	1260	13.0	15.7	3.51	10.08	0.1099	0.1856	2.37	9.37	2.22[4)]	4.22

1) Isotopic ratios of Kr and Xe are not presented.

2) Heating temperatures are 200, 900, and 1700°C for 3 steps, and 200, 600, 900, 1200, and 1700°C for 5 steps.

3) Each depth was estimated based on prelininary measurements of cosmogenic radionuclides. The production rates and CRE ages were not included ±5 % uncertainty of our new calculations and experimental errors.

4) Prodction rate in 4π-geometry for CI chondrites [9].

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