Neutron Capture ^{36}Cl in Ryugu Samples

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Hayabusa2 arrived at the C-type asteroid 162173 Ryugu in Jun. 2018, and successfully collected surface samples from two sampling sites, returning ~5.4 g of samples to Earth on Dec. 6, 2020. The surface samples stored in Chamber A were collected by the 1st touchdown (TD) on Ryugu's surface on Feb. 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 Apr. 5, 2019 [1]. The 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 Jul. 11, 2019 [2].

Our studies are based on the measurement of those nuclides produced in asteroidal surface materials by cosmic rays - 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. Our goals are to understand both the fundamental processes on the asteroidal surface and the evolutionary history of its surface materials. With this information we hope to better understand 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 in the Ryugu regolith, and (3) what is the surface exposure time, mixing rate, and erosion/escape rate of Ryugu's surface? To answer these questions, we were allocated and received 2 particles from Chamber A (A0105-19 and -20) and 6 particles from Chamber C (C0106-09, -10, -11, -12, C0002-V01, and -V02) for measurements of cosmogenic radionuclides and noble gases. Each sample is several hundred μm in size.

As a part of initial analysis of Ryugu we have measured cosmogenic ^{10}Be ($t_{1/2}$ = 1.36 x 10^{6} yr) [3], ^{26}Al (7.05 x 10^{5} yr) [4], and stable noble gases [5] in above samples. The Table 1 summarizes ^{26}Al, ^{10}Be, and cosmogenic ^{21}Ne concentrations in each sample. Based on those measurements, we found that sampling depth of A0105-19 was 10-15 g/cm^{2} and A0105-20 was ~5 g/cm^{2}. The exposure ages of both A0105 samples were 6.4-7.5 Myr. The chamber A samples were exposed to cosmic rays at Ryugu's near surface (~10 cm), as expected, and had similar exposure ages of ~7 Myr. On the other hand, the four C0106 particles were exposed at depth of ~50, 110, 130, and 145 g/cm^{2} respectively and had exposure ages of ~1.6, 3.2, 4.5, and 5.8 Myr respectively. Our results indicate that Chamber C samples are mixture of particles ejected from various depths on Ryugu by the SCI impact. It is noteworthy that all four particles had different exposure ages on Ryugu. Exposure depths of each sample are also shown in Table 1.

To further study of the exposure condition of Ryugu surface materials, we analyzed cosmogenic ^{36}Cl (3.01 x 10^{5} yr). After dissolution of each sample with a few drops of HF-HNO_3 mixture, Cl was separated as AgCl prior to Be and Al separation [3, 4]. After chemically purified AgCl, the concentration of ^{36}Cl was measured by accelerator mass spectrometry (AMS) at Purdue University [6], using a ^{36}Cl AMS standard [7] for normalization. The concentrations of ^{36}Cl (dpm/kg) in each Ryugu sample are shown in Table 1 along with that of Nogoya CM2 chondrite for validation. The ^{36}Cl concentrations in all Ryugu samples are more than an order of magnitude higher than that of Nogoya. The dominant production pathway for ^{10}Be and ^{26}Al is by high-energy neutron spallation reactions. Although ^{36}Cl can be produced by both thermal neutron capture reaction, ^{35}Cl (n,γ) ^{36}Cl, and high-energy neutron spallation on K, Ca, and Fe, the thermal neutron production of ^{36}Cl is dominant owing to the high H and Cl concentrations in Ryugu. Using the MCNP Code System [8], we calculated GCR production rate of ^{36}Cl by spallation reactions for a body having a 2π geometry with Ryugu's chemical compositions [9]. The obtained production rates are 5.4 ^{36}Cl atom/min/kg at surface to 3.3 at ~150 g/cm^{2}. The thermal neutron production of ^{36}Cl is calculated by subtracting spallation contribution from measured value and normalized to Cl concentration in Ryugu and shown in Table 1 as $^{36}Cl_{th}$. We adopted a Cl concentration of 780 ppm [9]. The measured ^{36}Cl concentrations in Ryugu are extraordinarily high. Among carbonaceous chondrites, only the CI chondrite Orgueil is higher, having 160 ± 1 dpm/kg (unpublished), assuming exposure in a 4π geometry. This corresponds to 220 ± 3 dpm ^{36}Cl /g Cl assuming 700 ppm Cl in Orgueil.

Assuming a chemical compositions for each particle the same as the bulk analysis of Ryugu [9], the thermal neutron produced ^{36}Cl in Ryugu is maximum at slightly below 100 g/cm^{2} or between depth of C0106-10 and -11. The depth of maximum production for the low-energy neutron capture reaction on Ryugu is shifted toward surface compared to that of the Moon (~150 g/cm^2). This occurs because Ryugu contains high H (0.94 %) and C (4.6 %) [9] which are effective moderators of neutrons. Since we don't have exact Cl concentration in each particle, it is hard to compare observed ^{36}Cl concentration to model calculation such as MCNP code system at present. Although we are planning measurements of thermal neutron capture ^{41}Ca ($t_{1/2}$ = 0.10 Myr) in Ryugu, it requires larger sample size than this work because low thermal neutron capture cross section on ^{40}Ca compared to that of ^{35}Cl (0.43 b vs. 43.6 b) and lower AMS sensitivity of ^{41}Ca measurements.

Table 1. Cosmogenic nuclide ^{36}Cl, ^{26}Al, ^{10}Be, and ^{21}Ne concentrations in Ryugu samples and Nogoya CM2 chondrite.

Sample	Mass (μg)	Depth[a] (g/cm^2)	^{36}Cl[b] (dpm/kg)	$^{36}Cl_{th}$[c] (dpm/g Cl)	^{26}Al[d] (dpm/kg)	^{10}Be[e] (dpm/kg)	$^{21}Ne_c$[f] (10^{-9} cm^3 STP/g)
A0105-19	242.9	5	31.1±2.3	33±3	27.1±1.1	12.76±0.37	7.55
A0105-20	206.1	10-15	28.9±1.9	30±2	33.3±1.8	12.75±0.29	7.75
C0106-09	122.8	50	72.0±6.2	86±8	23.3±1.4	7.10±0.30	1.79
C0106-10	154.3	110	116.5±6.9	144±9	25.7±1.3	7.48±0.26	3.58
C0106-11	189.8	130	23.4±2.5	26±3	25.5±1.2	7.21±0.43	5.07
C0106-12	959.8	145	24.2±0.9	27±1	23.8±0.7	7.36±0.33	6.54
C0002-V01	45.3	125	30.1±4.3	34±6	24.9±1.9	8.29±0.95	-
C0002-V02	11.1	125	11±13	-	21.9±5.1	7.87±1.80	-
Nogoya CM2	459.4	-	2.2±0.5	-	-	2.09±0.13	-
Nogoya CM2	343.7	-	2.2±0.6	-	7.7±0.5	2.12±0.09	-
Nogoya CM2	204.9	-	0.6±1.0	-	9.1±0.6	2.00±0.13	-

[a]Estimated depth based on ^{10}Be and ^{26}Al [4]; [b]This work; [c]After subtraction of spallation component (see text); [d][4]; [e][3]; [f][5].

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