Non-destructive analysis of C-type asteroid Ryugu using negative Muon: Determination of bulk chemistry of Ryugu samples

*K. Terada[1], T. Nakamura[2], K. Ninomiya[1], T. Osawa[3], T. Takahashi[4], Y. Miyake[5], S. Takeshita[5], I. Umegaki[5], I. Chiu[1], M. K. Kubo[6], A. Taniguchi[7], T. Wada[2], S. Watanabe[8], H. Yurimoto[9], T. Noguchi[7], R. Okazaki[10], H. Yabuta[11], H. Naraoka[10], K. Sakamoto[8], S. Tachibana[4], S. Watanabe[12], Y. Tsuda[8] and J-PARC Muon Team[13]

[1]Osaka University, [2]Tohoku University, [3]Japan Atomic Energy Agency, [4]The University of Tokyo, [5]High Energy Accelerator Research Organization, [6]International Christian University, [7]Kyoto University, [8]Japan Aerospace Exploration Agency, [9]Hokkaido University, [10]Kyushu University, [11]Hiroshima University, [12]Nagoya University and [13]Japan Proton Accelerator Research Complex

We have been developing a non-destructive Muonic X-ray analysis for extraterrestrial materials [1, 2, 3, Figure-1(a)]. Since muon has a mass about 200 times greater than that of an electron, negative muon behaves as a heavy electron in the sample. In the classical Bohr model, orbital radii of negative leptons (electron and/or muon) around an atomic nucleus are inversely proportional to the lepton mass, and therefore a muon trapped by an atom has an orbit closer to the atomic nucleus than electrons due to its ~200 times heavier mass (Figure-1(b)). As a result, muon-induced characteristic X-rays have about 200 times higher energies than those associated with the orbital transition of electrons. For instance, electron-induced Kα–X-ray of C has an energy of 0.3 keV, whereas muonic Kα–X-ray of C has an energy of 75 keV, which is large enough to penetrate a rock sample of about 1 cm in size without significant self-absorption. Another advantage is that the position at which the characteristic X-rays are generated (i.e. the depth of penetration from the sample surface) can be controlled by controlling the momentum of the incident muons, making it possible to non-destructively analyse the chemical composition inside a material from light elements to heavy elements.

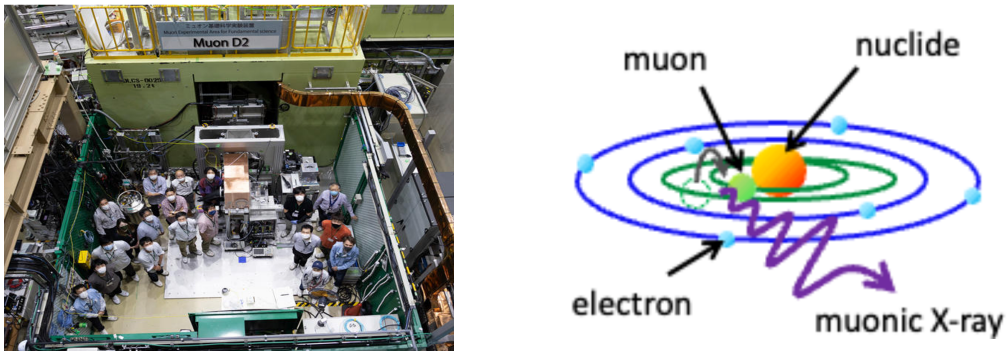

Figure 1. (a) Muon beam line at J-PARC, (b) Schematic view of muon-induced characteristic X-ray.

Ten coarse Ryugu samples (A0026, A0064, A0067, A0094, C0002, C0025, C0033, C0061, C0076, and C0103), which were allocated to the initial analysis STONE team, have been investigated at J-PARC MUSE (Japan Proton Accelerator Research Complex, MUon Science Establishment) [4]. Because of the muon beam size (more than 3 cm in diameter), we obtained a bulk elemental abundance of total 122.86 mg (17.72 mg from chamber-A and 105.14 mg from chamber-C). For comparison, pellets of the meteorites Murray (CM2; 306.5 mg) and Orgueil (CI; 195 mg) were also measured. In order to avoid the contamination from atmosphere (N and O), during the analysis, samples were set in the chamber which was filled with helium [3]. Figure-3 shows the muonic X-ray spectra from Ryugu and Orgueil. Significant Muonic X-rays of C, N, O, Na, Mg, Si, S and Fe were detected from Ryugu and Orgueil. Signals of Cu and Be, originated from the inside shield of vacuum chamber, the sample holder and the detector windows, were also detected.

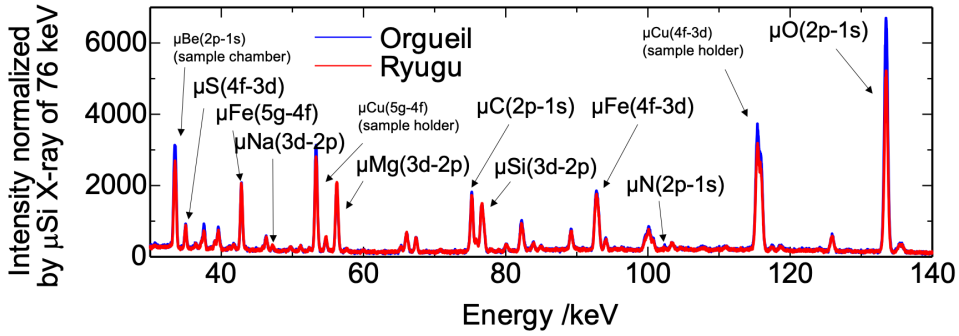

Figure 2. Muonic X-ray spectra of Ryugu and Orgueil (CI)

We calculated elemental mass ratios X/Si (X=C, N, O, Na, Mg, S, and Fe) of Ryugu samples from relative intensity ratios of muonic X-rays using Murray with known X/Si ratios. The obtained mass ratios of C, N, O, Na, Mg, S and Fe relative to Si are 0.338±0.008, 0.019±0.009, 3.152±0.099, 0.039±0.006, 0.890±0.021, 0.510±0.019, and 1.620±0.040, respectively. These elemental ratios are in a good agreement with the reported values for CI chondrites [5] and the conventional solar abundance [6], except for the 25% lower O/Si for Ryugu relative to CI (Figure-3). This means that Ryugu is depleted in oxygen by 11.3 % by mass compared to CI, assuming similar Si concentration for Ryugu to CI chondrites. The Ryugu samples were prepared and analyzed in low oxygen conditions (< 0.1%) and at low dew points (< -50°C), thus the very low oxygen concentration is indigenous feature. This result is consistent with [7], which was obtained from a chamber-A grain (~1 mg). Lesser water content in Ryugu samples relative to CI chondrites [7] is likely the main factor for the low oxygen concentration.

Thus, we have succeeded in a non-destructive Muonic X-ray analysis for Ryugu sample, including light elements such C, N and O. This innovative technique will also be powerful for sample returns from the C-type asteroid Bennu and/or from the Martian satellite Phobos, which are expected to be enriched in organic matter.

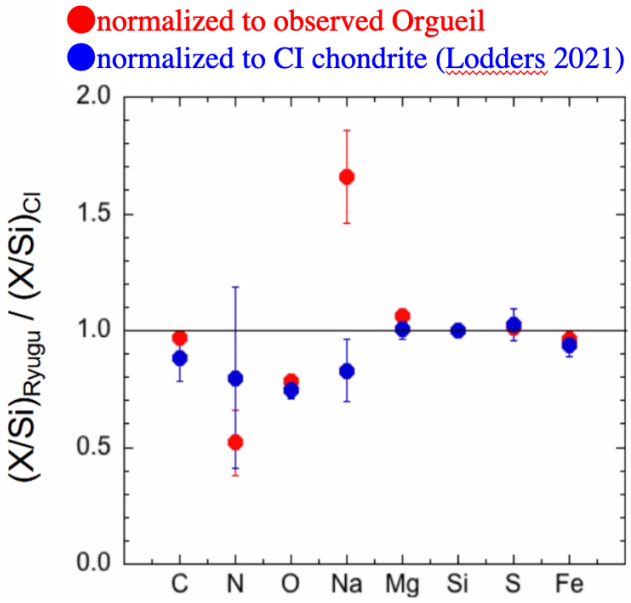

Figure3. Elemental ratios of Ryugu to normalized to Orgueil and CI chondrite

References

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