# 論文の内容の要旨

## The initial abundance of niobium-92 in the outer solar system

## （外側太陽系におけるニオブ 92 の初生存在度）

氏名　日比谷　由紀

One of the major goals of cosmochemistry is to understand the origin of short-lived radionuclides, as it is essential for constraining the time-scale and the genealogy of our solar system. Among the short-lived radionuclides, what is of particular interest to this thesis is niobium-92 ($^{92}Nb$). The *p*-process $^{92}Nb$ decays to zirconium-92 ($^{92}Zr$) by electron capture with a half-life of 37 million years. The system is promising chronometer for dating early solar system events accompanied by niobium and zirconium fractionation. Moreover, once the initial abundance of $^{92}Nb$ and its distribution in the early solar system are well established, it provides valuable constraints on the origin of *p*-process nucleosynthesis.

In order to determine the initial abundance of $^{92}Nb$ from one meteorite, we need to calibrate the Nb-Zr chronometer with an absolute precise U-Pb chronometer. Therefore, it is essential to establish a meteorite to which high precision U-Pb chronometer can be applied and in which the initial abundances of $^{92}Nb$ can be determined, the so called “*Time anchor*”. One meteorite must satisfy the following conditions to tie Nb-Zr age to an absolute U-Pb chronology: (1) a precise U-Pb age can be obtained; (2) an internal Nb-Zr isochron age can be obtained; (3) a cooling rate is rapid enough to make the difference of closure temperature between the two chronometers insignificant; (4) the meteorite has not been affected by secondary alternation or exotic components that disturb the ages.

First evidence for live $^{92}$Nb with the initial $^{92}$Nb/$^{93}$Nb of (1.6 ± 0.3) × $10^{-5}$ was reported in rutile in Toluca iron meteorite. Although subsequently proposed initial $^{92}$Nb/$^{93}$Nb vary between $10^{-3}$ to $10^{-5}$, the current paradigm is that the initial $^{92}$Nb/$^{93}$Nb at the solar system formation is (1.7 ± 0.6) × $10^{-5}$, obtained using Nb-Zr *Time anchor* NWA 4590 angrite (U–Pb age: 4557.93 ± 0.36 Ma), and also that $^{92}$Nb was homogeneously distributed in the solar system. However, all of the samples previously studied for internal Nb-Zr isochron dating are thought to have originated from the inner solar system. Thus, it is still unclear whether $^{92}$Nb was homogeneously distributed in the outer solar system such as the accretion regions of carbonaceous chondrites.

Northwest Africa (NWA) 6704 is a recently found achondrite having unbrecciated and fresh igneous texture. The pristine chondrite-like characteristics of this meteorite, coupled with its ancient U-Pb age (4562.76 ± 0.30 Ma), and its igneous texture different from any known achondrite make it ideal for exploring whether it is the first "*Time anchor* from the outer solar system".

The purpose of this study is to evaluate the initial abundance and distribution of $^{92}$Nb in the early solar system, on the largest scale to date. To achieve this goal, the NWA 6704 ungrouped primitive achondrite has been investigated. Developing NWA 6704 as the first *Time anchor* from the outer solar system, and applying the Nb-Zr internal isochron approach, we could determine the initial abundance of $^{92}$Nb in the outer solar system. This allowed us to evaluate the distribution of $^{92}$Nb between the inner and outer solar system, and to provide new constraints on the early solar system chronology and on early solar system processes related to $^{92}$Nb.

In Chapter 2, we developed a new method for combined Cr-Ti isotope analysis applicable to various planetary materials. Both the utility and the validity of the method have been verified by its application to compositionally varied terrestrial and meteorite samples, including terrestrial basalt JB-1b, terrestrial peridotite JP-1, Allende carbonaceous chondrite, and Juvinas non-cumulate eucrite. The developed method enables the combined isotope analyses of 3 μg of Cr and 1.5 μg of Ti, highlighting its potential application to various types of planetary materials.

In Chapter 3, the new method developed in Chapter 2 was applied to NWA 6704, and the origin of this meteorite was investigated in terms of the petrology, geochemistry and $^{187}$Re-$^{187}$Os and O-Cr-Ti isotope systematics. On the basis of our results, we discussed the crystallization process of NWA 6704, the nature and provenance of its parent body, and its potential utility as a "*Time anchor*". Our results indicated that the parent asteroid of NWA 6704 underwent significant but instantaneous melting followed by cooling at a high rate (1–$10^{2}$ ˚C/hour) in the initial stage but a significantly lower rate (<$10^{-4}$–$10^{-2}$ ˚C/hour at below ~1100 ˚C) in the later stage owing to blanketing effect of impact ejecta piled up on the parent body. Furthermore, since the mineral assemblage includes chromite grains with high Nb/Zr, and orthopyroxene and awaruite grains with low Nb/Zr, the internal Nb-Zr isochron can be expected to be obtained. The O, Cr and Ti stable isotope compositions indicated that the parent body of NWA 6704 sampled the same reservoirs to those of carbonaceous chondrites and distinct from the reservoirs of all meteorites previously studied for internal Nb-Zr isochron dating. Consequently, the results revealed that the NWA 6704 ungrouped primitive achondrite is a viable, new "*Time anchor* from the outer solar system".

In Chapter 4, the Nb-Zr internal isochron dating was applied to NWA 6704, and the initial $^{92}$Nb abundance at the start of our solar system was determined. The results yielded an initial $^{92}$Nb/$^{93}$Nb of (2.8 ± 0.3) × $10^{-5}$ at the time of NWA 6704 formation (4562.76 ± 0.30 Ma), which corresponds to an initial $^{92}$Nb/$^{93}$Nb of (3.0 ± 0.3) × $10^{-5}$ at the time of solar system formation. The ratio is distinctly higher than the value in the inner solar system, which significantly affects the interpretation of the Nb–Zr early solar system chronology. This value can serve as the reference point for the Nb–Zr chronometry in the outer solar system. Using the obtained value, we further investigated the nucleosynthetic origin of $^{92}$Nb. The results suggested that the *ν*-process in Type II supernova (SNII) is the most probable origin for $^{92}$Nb, and imply that nuclides synthesized in the last SNII were preferentially implanted or preserved in the outer solar system rather than the inner solar system.