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## Noble gases in ureilites: Cosmogenic, radiogenic, and trapped components

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**Abstract**—Abundances and isotopic compositions of Ne (in bulk samples only), Ar, Kr, and Xe have been investigated in 6 monomict, 3 polymict, and the diamond-free ureilite ALH78019 and their acid-resistant, C-rich residues. Isotopic ratios of Kr and Xe are very uniform and agree with data for ureilites from the literature. The measured ratio  $^{38}\text{Ar}/^{36}\text{Ar}$  showed large variations due to an experimental artifact. This is shown to be connected to the pressure dependence of the instrumental mass discrimination, which for ureilites with their low abundance of  $^{40}\text{Ar}$  is different from that of the usual air standard. This observation necessitates a reassessment for the recently reported  $^{36}\text{Ar}$  excesses due to possible decay of extinct  $^{36}\text{Cl}$  in the Efremovka meteorite.

Trapped  $^{22}\text{Ne}$  in the range of  $(1.4\text{--}2.5) \times 10^{-8}$  cc STP/g is present in bulk ureilites. A Ne three-isotope plot for polymict ureilites indicates the presence of solar Ne.  $^{21}\text{Ne}$ -based cosmic ray exposure ages for the 10 ureilites studied range from 0.1 Ma (for ALH78019) to 46.8 Ma (for EET83309).

All ureilites may have started with nearly the same initial elemental ratio  $(^{132}\text{Xe}/^{36}\text{Ar})_0$ , established in the nebula during gas trapping into their carbon carrier phases (diamond, amorphous C) by ion implantation. Whereas diamonds are highly retentive, amorphous C has suffered gas loss due to parent body metamorphism. The correlation of the elemental ratios  $^{132}\text{Xe}/^{36}\text{Ar}$  and  $^{84}\text{Kr}/^{36}\text{Ar}$  along the mass fractionation line could be understood as a two-component mixture of the unaffected diamond gases and the fractionated (to varying degrees) gases from amorphous C. In this view, the initial ratio  $(^{132}\text{Xe}/^{36}\text{Ar})_0$  is a measure of the plasma temperature in the nebula at the formation location of the carbon phases. Its lack of correlation with  $\Delta^{17}\text{O}$  (a signature of the silicate formation location) indicates that carbon phases and silicates formed independently in the nebula, and not from a carbon-rich magma.

The elemental ratios  $^{132}\text{Xe}/^{36}\text{Ar}$  and  $^{84}\text{Kr}/^{36}\text{Ar}$  in carbon-rich acid residues show a decreasing trend with depth (inferred from carbon consumption during combustion), which can be interpreted as a consequence of the ion implantation mechanism of gas trapping that leads to greater depth of implantation for lighter mass ion.

The similarity between trapped gases in phase Q in primitive chondrites and the C phases in ureilites—for both elemental and isotopic compositions—strongly suggests that phase Q might also have received its noble gases by ion implantation from the nebula. The slight differences in the elemental ratios can be explained by a plasma temperature at the location of phase Q gas loading that was about 2000 K lower than for ureilite C phases. This inference is also consistent with the finding that the trapped ratio  $^{129}\text{Xe}/^{132}\text{Xe}$  ( $1.042 \pm 0.002$ ) in phase Q is slightly higher, compared to that of ureilite C phases ( $1.035 \pm 0.002$ ), as a consequence of in situ decay of  $^{129}\text{I}$ , and becomes observable due to higher value of I/Xe in phase Q as a result of ion implantation at about 2000 K lower plasma temperature. Copyright © 2003 Elsevier Ltd

### 1. INTRODUCTION

Ureilites are an enigmatic group of achondrites and show both igneous and primitive features. In terms of mineralogy, texture, lithophile element chemistry, and Sm-Nd systematics they appear to be highly fractionated rocks: either magmatic cumulates (Berkley et al., 1976; Berkley, 1989; Goodrich et al., 1987) or partial melt residues (Boynton et al., 1976; Scott et al., 1993) and thus the product of planetary differentiation processes. They also contain some minor components, which have several primitive characteristics that are unlikely to have survived extensive igneous processing on a parent body. These include high abundance of carbon that contains large amounts of fractionated primordial noble gases (residing mostly in diamond) and metal with high abundance of trace siderophile elements, both of which are typical of undifferentiated, chon-

dritic material (Spitz and Boynton, 1991). In addition to these primitive signatures carried by minor components, ureilites contain the oxygen isotope signature of primitive chondrites (Clayton and Mayeda, 1988). Broadly, ureilites can be classified into two subgroups: polymict and monomict. Polymict ureilites are characterized by their brecciated nature and the presence of lithic clasts and mineral fragments of rock types other than those found in the main group of ureilites (MGUs), monomict ureilites.

The relative abundance pattern of noble gases in ureilites is of the fractionated “planetary” type as it is in carbonaceous chondrites (Weber et al., 1971; Wilkening and Marti, 1976; Göbel et al., 1978), though gas contents vary considerably (for example, Xe contents vary by a factor of  $\sim 100$  in bulk samples; Göbel et al., 1978). Analysis of separated fractions of the carbonaceous matrix or vein material showed the noble gases to be enriched at least 600-fold relative to the silicates, and demonstrated that the gases are largely contained in carbon (Weber et al., 1971, 1976; Göbel et al., 1978). In diamond-bearing ureilites, diamond is the principal gas carrier and

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