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COSMOGENIC AND RADIOGENIC NOBLE GASES IN THE SOŁTMANY L6 CHONDRITE

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Abstract: We measured the concentrations and isotopic compositions of He, Ne, Ar, Kr, and Xe in a 60.36 mg sample of the Sołtmany meteorite (L6), which fell in northeastern Poland in 2011. The Kr and Xe data suggest a mixture of atmospheric contamination and Q. Using cosmogenic ^{21}Ne and ^{38}Ar concentrations, Sołtmany's cosmic-ray exposure (CRE) age was determined to be ~29.2 Ma. The preatmospheric radius for Sołtmany was equal to or less than approximately 15 cm and the sample studied here most likely came from close to the preatmospheric surface of the meteoroid. While the ^{40}Ar gas retention age is about 4137 Ma, the ^{4}He gas retention age is 1610 Ma, suggesting loss of a major ^{4}He fraction likely during an impact and/or degassing event on the Sołtmany parent body prior to the ejection of the Sołtmany meteorite ~29.2 Ma ago.

Keywords: noble gas, cosmic ray exposure age, preatmospheric radius, gas retention age

INTRODUCTION

The L6 chondrite Sołtmany fell on April 30th, 2011 near the small village of Giżycko in the northeastern part of Poland. The meteorite penetrated the edge of a roof and was immediately recovered. The total mass of Sołtmany is about 1066 g (Karwowski et al., 2011).

In this study, we analyzed the concentrations and isotopic compositions of the noble gases He, Ne, Ar, Kr, and Xe in a 60.36 mg sample of Sołtmany. The goal of this work was to decipher the cosmic-ray exposure history of Sołtmany, i.e., the cosmic-ray exposure (CRE) age, the preatmospheric size, and the shielding depth of the studied sample, and to determine whether or not the new data fit into the existing exposure age histogram for L-chondrites (e.g., Wieler, 2002; Herzog, 2003). In addition, we studied the thermal history of Sołtmany and the meteorite's source region on its parent body by analyzing the cosmogenic ^{3}He/^{21}Ne ratio and the ^{4}He and ^{40}Ar gas retention ages.

EXPERIMENTAL

We analyzed the He, Ne, Ar, Kr, and Xe isotopic concentrations of the L6 chondrite Sołtmany. Noble gas extraction and mass spectrometric measurements of a bulk sample with a mass of 60.36 mg were performed at the University of Bern following standard procedures (e.g., Eugster et al., 1993; Huber et al., 2008; Leya et al., 2013). Briefly, the sample was wrapped in aluminum foil before being loaded into the all-metal (except for a glass window) noble gas extraction and purification system. To reduce atmospheric surface contamination the sample was pre-heated in vacuum at about 100 °C for one day. The sample was degassed in one temperature step at 1750 °C in a Mo crucible and the evolved gases were cleaned by admission to different getters and a He-Ne fraction, an Ar fraction, and a Kr-Xe-fraction were separated from each other using activated charcoal held between –120 °C and –196 °C. The different noble gas fractions, HeNe, Ar,

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Table 1. Measured and cosmogenic He and Ne concentrations (10^{-8} cm^3STP/g) and isotope ratios in bulk material of the L6 chondrite Sołtmany.

Sample	Mass	^{3}He	^{4}He	^{20}Ne	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	$^{21}Ne_{cos}$	$(^{22}Ne/^{21}Ne)_{cos}$
Sołtmany	60.36	35.9	585	8.23	0.881	0.863	8.06	1.15

The ^{3}He and ^{4}He concentrations are corrected for blank contributions and instrumental mass discrimination (15.8%). The Ne data are corrected for instrumental mass discrimination (0.1%/amu) and interferences but not for blank contributions. Uncertainties are 5% for gas amounts and about 1% for isotope ratios.

and KrXe, were measured sequentially using a static noble gas mass spectrometer. The gas concentrations were determined by peak height comparisons with standards having known amounts of He, Ne, Ar, Kr, and Xe.

Procedural blanks were determined with the same extraction procedure as for the sample: by analyzing 40–60 mg of aluminum foil, which is similar in mass to that used to wrap the sample. These so-called aluminum blanks were used only for the blank correction of ^{3}He and ^{4}He. For Ne, Ar, Kr, and Xe, the data were used only to check whether or not the blank is of atmospheric composition. We subtracted the blank values for He, Ne, and Ar using a two-component deconvolution (see below). All isotope ratios have been corrected for instrumental mass discrimination, ^{20}Ne has been corrected for interferences from $H_2{}^{18}O$ and $^{40}Ar^{2+}$, and ^{22}Ne has been corrected for interferences from $CO_2{}^{2+}$. Krypton and Xe in Sołtmany are essentially a mixture of atmospheric contamination, Kr and Xe from phase Q (noble gases host phase defined by Lewis et al. (1975)), and minor cosmogenic contributions. Since the deconvolution of the different Kr and Xe components suffered from the rather large uncertainties of the measured Kr and Xe concentrations, the Kr and Xe data are not discussed here. The noble gas concentrations and isotope ratios for He and Ne are given in Table 1. The data for Ar are given in Table 2.

Table 2. Measured and cosmogenic Ar concentrations (10^{-8} cm^3STP/g) and isotope ratios in bulk material of the L6 chondrite Sołtmany

Sample	Mass	^{36}Ar	^{40}Ar	^{36}Ar/^{38}Ar	$^{38}Ar_{cos}$
Sołtmany	60.36	1.25	5 148	1.00	1.15

The Ar data are corrected for instrumental mass fractionation (0.5%/amu) and interferences but not for blank contributions. Uncertainties are 5% for gas amounts and about 1% for isotope ratios.

RESULTS

Cosmogenic He, Ne, and Ar

The low ^{20}Ne/^{22}Ne ratio of 0.88, which includes blank contributions, indicates that the measured Ne is purely cosmogenic and contains no significant amounts of solar and/or primordial Ne. We made minor corrections for trapped Ne assuming that the trapped component is atmospheric contamination. The correction was performed using a cosmogenic ^{20}Ne/^{22}Ne endmember ratio of 0.82 ± 0.02, which is identical within uncertainties to the preferred value of 0.80 ± 0.03 for chondritic meteorites (Eugster et al., 2007) and an atmospheric endmember with ^{20}Ne/^{22}Ne and ^{21}Ne/^{22}Ne ratios of 9.80 (Eberhardt et al., 1965) and 0.02878 (Heber et al., 2009), respectively. Note, this and the following cosmogenic gas fractions are labeled with an index "cos". The trapped corrections for ^{21}Ne and ^{22}Ne/^{21}Ne are less than 1%. Cosmogenic $^{21}Ne_{cos}$ and $(^{22}Ne/^{21}Ne)_{cos}$ are given in Table 1. Since there is no solar and/or primordial Ne we can safely assume that the measured ^{3}He is entirely cosmogenic.

The measured ^{36}Ar/^{38}Ar ratio of 1.00 is higher than the cosmogenic ^{36}Ar/^{38}Ar ratio of ~0.63 (Wieler, 2002), indicating significant contributions of trapped Ar, either primordial and/or atmospheric. Considering the high petrographic type of Sołtmany (L6), we assume that the Ar is a mixture of trapped atmospheric contamination and cosmogenic Ar with ^{36}Ar/^{38}Ar ratios of 5.319 and 0.62, respectively. The correction for trapped ^{38}Ar is about 10%.

When discussing $(^3He/^{21}Ne)_{cos}$ as a function of $(^{22}Ne/^{21}Ne)_{cos}$, the value measured for Sołtmany plots (Fig. 1) slightly below the empirical correlation line given by Nishiizumi et al. (1980), indicating a ^{3}He deficit of about 25%. About 50% of the cosmogenic ^{3}He was originally produced as radioactive ^{3}H (e.g., Leya and Masarik, 2009), which β-decayed to ^{3}He. ^{3}H is supposed to diffuse much faster than ^{3}He; the deficit of 25% most likely indicates ^{3}H diffusive losses of about 50%. Such diffusive losses might indicate that Sołtmany had an orbit with a perihelion close to the Sun.

Note that noble gas data alone are not enough to uniquely restrict the size of the meteorite and the position of the studied sample. A possible way to determine the preatmospheric radius using only the cosmogenic ^{22}Ne/^{21}Ne ratio is given by the empirical

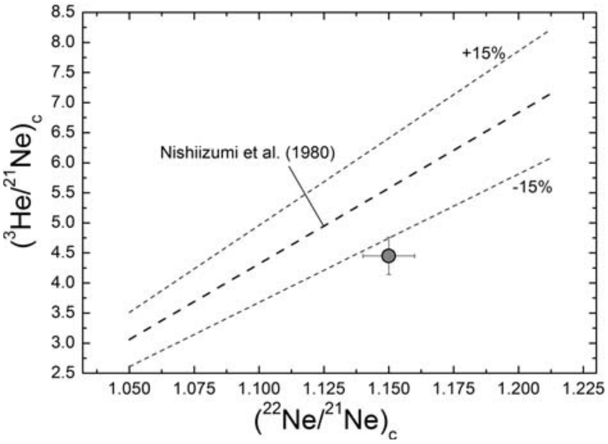

Fig. 1. ($^{3}He/^{21}Ne)_c$ vs. ($^{22}Ne/^{21}Ne)_c$ (Bern plot). Also shown is the empirical correlation line for chondrites as given by Nishiizumi et al. (1980). The dashed lines represent the ±15% variations from this correlation

correlation from Bhandari et al. (1980). Unfortunately, this correlation is only valid in a certain range of nuclear track densities and nuclear track data are not available for Sołtmany. However, radionuclide data measured via non-destructive γ-spectrometry (e.g., ^{52}Mn, ^{22}Na, ^{26}Al) and especially the absence of any detectable ^{60}Co activity indicate a preatmospheric radius of less than ~20 cm for Sołtmany (Laubenstein et al., 2012). With this a priori information we can use the empirical correlation between the preatmospheric mass of a meteorite and its ($^{22}Ne/^{21}Ne)_{cos}$ ratio (Bhandari et al., 1980) and calculate a preatmospheric mass for Sołtmany of about 36 kg. Using a bulk density for Sołtmany of 3.475 g/cm^3 (Szurgot et al., 2012), which is almost identical to the average density for L-chondrites of 3.35 g/cm^3 (Britt and Consolmagno, 2003), we obtain a preatmospheric radius of about 13.5 cm, which perfectly confirms the radionuclide data (Laubenstein et al., 2012). With a preatmospheric mass for Sołtmany of about 36 kg and the about 1 kg found on the Earth, only about 3% of the original mass made it to the Earth surface, which is lower than the average of 15–20% (Bhandari et al., 1980; Alexeev, 2004).

Having demonstrated that Sołtmany had a preatmospheric radius smaller than about 15 cm, we can safely use the empirical correlations between $^{21}Ne_{cos}$ and $^{38}Ar_{cos}$ production rates and the shielding indicator ($^{22}Ne/^{21}Ne)_{cos}$ (Dalcher et al., 2013) to determine the CRE age of Sołtmany. With the measured ($^{22}Ne/^{21}Ne)_{cos}$ ratio of 1.15, we obtain a ^{21}Ne production rate of 0.285×10^{-8} cm^{3}STP/g/Ma. Using now the $^{21}Ne_{cos}$ concentration of 8.06×10^{-8} cm^{3}STP/g (Table 1) we calculate a CRE age based on cosmogenic ^{21}Ne, T_{21}, of 28.3 Ma. Doing the same exercise with cosmogenic $^{38}Ar_{cos}$, we calculate a production rate of 0.0384×10^{-8} cm^{3}STP/g/Ma and with the $^{38}Ar_{cos}$ concentration of 1.15×10^{-8} cm^{3}STP/g/Ma we obtain a CRE age based on ^{38}Ar, T_{38}, of 30.0 Ma, which is in good agreement with T_{21}. The average value for the CRE age for Sołtmany is 29.2 Ma (N = 2) with an uncertainty of about 10%.

The exposure age histogram for L-chondrites shows a major peak at 40 Ma and three minor peaks at 5 Ma, 15 Ma, and 28 Ma (e.g., Wieler, 2002). However, Herzog (2003) argues that there is only one strong peak for the L-chondrites at about 40 Ma and a possible peak at about 5 Ma. The author also suggests that, instead of the peak at about 15 Ma, there is a broad hump between 20–30 Ma with a maximum at about 28 Ma. Our estimate of the CRE age for Sołtmany of 29.2 Ma supports this argument.

Radiogenic ^{4}He and ^{40}Ar

As discussed above, Sołtmany lost ^{3}He and/or ^{3}H, possibly due to solar heating at small perihelion distances. In addition to the loss of cosmogenic gases, radiogenic gases (e.g., ^{4}He and ^{40}Ar) can be lost either during impacts or other thermal events on the meteorite parent body and/or due to terrestrial weathering (e.g., Scherer & Schultz, 2000). Since Sołtmany is an observed fall, any losses due to terrestrial weathering should be negligible.

To estimate the radiogenic ^{4}He abundance, measured ^{4}He is corrected for cosmogenic using the relationship between ($^{3}He/^{4}He)_{cos}$ and ($^{22}Ne/^{21}Ne)_{cos}$ given by Leya and Masarik (2009). The correction is about 26%. Note that we can estimate only an upper limit for the ^{4}He age because of the assumption that all ^{4}He (corrected for cosmogenic ^{4}He) is of radiogenic origin. We did not correct ^{4}He for a potentially trapped component. Using U and Th concentrations of 10 and 42 ppb, respectively, as measured by non-destructive γ-spectrometry (Laubenstein et al., 2012) we calculate a ^{4}He gas retention age for Sołtmany of about 1610 Ma (Tab. 3). Note that the values of U and Th are in good agreement with those of average concentrations for L-chondrites given by Wasson and Kallemeyn (1988), Lodder and Fegley (1998), and McSween and Huss (2010).

Using the measured ^{40}K concentration of 840 ppm for Sołtmany (Laubenstein et al., 2012), which is similar to the average ^{40}K concentration for L-chondrites of 858 ppm (Kallemeyn et al. 1989), and the measured ^{40}Ar concentration (Table 2) we calculate a ^{40}Ar gas retention age of 4137 Ma (Tab. 3). Interestingly, the ^{40}Ar gas retention age is relatively high, indicating that Sołtmany comes from a region of the L-chon-

Table 3. Cosmic ray exposure ages and gas retention ages for the L6 chondrite Sołtmany (all in Ma)

Sample	$T_{GCR}(^3He)^1$	$T_{GCR}(^{21}Ne)$	$T_{GCR}(^{38}Ar)$	$T_{ret}(^4He)$	$T_{ret}(^{40}Ar)$
Sołtmany	20.4	28.3	30.0	1610	4137

[1] The $T_{GCR}(^3He)$ age has been calculated using the correlation $^3He/^{21}Ne$ vs. $^{22}Ne/^{21}Ne$ (Dalcher et al., 2013) and the ^{21}Ne production rate used to calculate $T_{GCR}(^{21}Ne)$. All ages have uncerainties of about 10%.

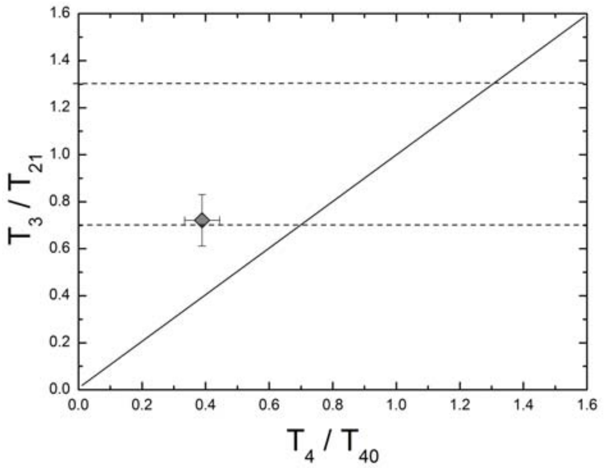

Fig. 2. Ratio of cosmogenic exposure ages T_3/T_{21} vs. ratio of gas retention ages T_4/T_{40}. Meteorites plotting on the solid line with slope 1 (but off from the ratios of 1) lost ^3He and ^4He during the cosmic-ray exposure time. Meteorites lying to the left of the solid line (like in case of Sołtmany) lost radiogenic ^4He before their cosmic-ray exposure, either at or before break-up of their parent body. Meteorites plotting to the right of the correlation line indicate trapped solar ^4He. Data plotting in-between the two horizontal lines show no or only minor indications of ^3He and/or ^3H diffusive losses.

drite parent body that did not suffer degassing during the 470 Ma break-up event (e.g., Swindle and Kring, 2008). The ^{40}Ar gas retention age is about 2.5 times higher than the ^4He gas retention age, indicating significant losses of radiogenic ^4He (Fig. 2). Based on the radiogenic ^{40}Ar gas retention age, the estimated loss of radiogenic ^4He is about a factor of 3.4. The estimated deficit of cosmogenic ^3He is about 25%, which could be due to diffusive losses such as those that would be experienced by a ~15 cm diameter meteoroid with a relatively small perihelion distance. The same diffusion event(s) that led to this ^3He deficit could also account for the loss of about 25% of the radiogenic ^4He. If this is true, the radiogenic ^4He concentration at the time of ejection of Sołtmany from its parent body was about 540 cm^3STP/g, i.e., still a factor of about 2.7 too low to bring ^4He and ^{40}Ar gas retention ages into agreement. From the data we cannot decide when and how Sołtmany lost its radiogenic ^4He. It is conceivable that some radiogenic ^4He, but none of the radiogenic ^{40}Ar, has been lost either in the asteroidal break-up event at 470 Ma and/or at the meteoroid-forming event at 29.2 Ma.

CONCLUSIONS

We measured the concentrations and isotopic compositions of He, Ne, Ar, Kr, and Xe for Sołtmany, the L6 chondrite that fell recently in Poland. The Kr and Xe data are too uncertain to constrain the cosmic-ray exposure history of Sołtmany. Based on cosmogenic $^{21}Ne_{cos}$ and $^{38}Ar_{cos}$ concentrations, together with the $(^{22}Ne/^{21}Ne)_{cos}$ ratio, we determined a CRE age for Sołtmany of 29.2 Ma, a preatmospheric size of less than about 15 cm, and we conclude that the studied sample resided close to the preatmospheric surface of the meteoroid. In addition, we detected a $^3He_{cos}$ deficit of about 25%, most likely due to solar heating at small perihelion distances. The ^{40}Ar gas retention age of 4137 Ma is significantly higher than the ^4He gas retention age, indicating that this part of Sołtmany's parent body lost a major fraction of its radiogenic ^4He, most likely during an impact and/or degassing event before or at the ejection of the Sołtmany meteorite 29.2 Ma ago.

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