Noble gases in presolar diamonds III: Implications of ion implantation experiments with synthetic nanodiamonds

Gary R. HUSS1*, Ulrich OTT2, and Alexey P. KOSCHEEV3

1Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i at Mānoa 1680 East-West Road, Post 504, Honolulu, Hawai‘i 96822, USA
2Abteilung Geochemie, Max-Planck-Institut für Chemie, Postfach 3060, 55020 Mainz, Germany
3Karpov Institute of Physical Chemistry, ul. Vorontzovo Pole 10, Moscow, 105064, Russia
*Corresponding author. E-mail: ghuss@higp.hawaii.edu
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Abstract – A series of experiments carried out by Kosc heev et al. (1998, 20 01, 2004, 2005) showed that the bimodal release of heavy noble gases from meteoritic nanodiamonds can be reproduced by a single implanted component. This paper investigates the implications of this result for interpreting the noble gas compositions of meteoritic nanodiamonds and for their origin and history. If the bimodal release exhibited by meteorite diamonds reflects release of the P3 noble gas component, then the composition inferred for the pure Xe-HL end member changes slightly, the excesses of heavy krypton isotopes that define Kr-H become less extreme, evidence appears for a Kr-L component, and the nucleosynthetic contribution to argon becomes much smaller. After correction for cosmogenic neon inherited from the host meteorites, the neon in presolar diamonds shows evidence for pre-irradiation, perhaps in interstellar space, and a nucleosynthetic component perhaps consistent with a supernova source. After a similar correction, helium also shows evidence for presolar irradiation and/or a nucleosynthetic component. For the case of presolar irradiation, due to the small size of the diamonds, a large entity must have been irradiated and recoiling product nuclei collected by the nanodiamonds. The high $^{3}$He/$^{21}$Ne ratio (~43) calls for a target with a (C + O)/heavier-element ratio higher than in chondritic abundances. Bulk gas + dust (cosmic abundances) meet this criteria, as would solids enriched in carbonaceous material. The long recoil range of cosmogenic $^{3}$He argues against a specific phase. The excess $^{3}$He in presolar diamonds may represent trapped cosmic rays rather than cosmogenic $^{3}$He produced in the vicinity of the diamond crystals.

INTRODUCTION

Presolar diamonds are nanometer-sized diamonds that occur in abundances of up to 1500 ppm in the fine-grained material of primitive chondritic meteorites (Lewis et al. 1987; Huss and Lewis 1994a; 1995; Huss et al. 2003). They are characterized by, and were originally identified through the study of, their isotopically distinct noble gas components. The most well-known of these components are Xe-HL, Kr-H, and Ne-A2 (Huss and Lewis 1994a). A presolar origin for the diamonds is indicated by isotopic anomalies in noble gases, tellurium, palladium, barium, and strontium relative to normal solar system materials. For example, Xe-HL, Kr-H, and the compositions of tellurium, palladium, barium, and strontium are consistent with contributions from supernovae (e.g., Lewis et al. 1987, 1991; Huss and Lewis 1994a; Richter et al. 1998; Maas et al. 2001). An isotopically less-exotic noble gas component (P3) is released from nanodiamonds at low temperatures. The P3 component is also distinct from what we think are normal solar system noble gases, again implying an origin outside of the solar system (Huss and Lewis 1994a). On the other hand, the carbon composition of the nanodiamonds is within the range of solar system carbon, as may be nitrogen, if the $^{14}$N/$^{15}$N ratio of the solar system is similar to that measured in Jupiter’s atmosphere (Owen et al. 2001), in a carbon-bearing osbornite (TiN) condensate from a CAI (Meibom et al. 2007), and some lunar soil samples (Hashizume et al. 2000). In addition, the isotopically most-anomalous noble gas components such as Xe-HL are carried in only a tiny fraction of the diamonds (literally one in a million), so some workers argue that the diamonds may not be dominantly presolar, but that most of them originated inside the solar system (e.g., Dai et al. 2002). Although we cannot solve the problem of the origin of meteoritic nanodiamonds here, we will use the term “presolar diamond” to describe them as a means of clearly distinguishing them from...
nanometer-sized synthetic diamond that will play a key role in this paper.

One thing that has prevented resolution of the origin of the meteoritic nanodiamonds has been the inability to model in detail the isotopic compositions of the anomalous components. This may be because the measurements are made, by necessity, on collections of billions of individual diamond grains, which may have come from many different sources. We will never be able to solve this problem because a minimum of ~30,000 xenon atoms is required to obtain a precise xenon isotopic composition, and this requires on the order of $3 \times 10^{10}$ diamonds. However, a better understanding of how the noble gases are released would permit a better characterization of the noble gas components. Verchovsky et al. (2000) and, more importantly for this paper, Koscheev et al. (1998, 2001, 2004, 2005) carried out experiments in which ionized noble gases were implanted into synthetic nanodiamonds. In this paper, we will compare the results of noble gas measurements of presolar diamonds with the results of two studies that implanted noble gases into synthetic nanodiamonds (Koscheev et al. 2001, 2004). In the Koscheev et al. (2001) study, the implanted noble gases were extracted from the diamonds and measured using the same experimental protocol that is typically used to measure presolar diamonds. The Koscheev et al. (2004) study used a different measurement protocol, releasing the gas by continuous heating, but the resulting gas-release profiles are similar. The similarities in gas-release behavior between the presolar and synthetic nanodiamonds are striking, and if the behavior of the synthetic nanodiamonds can be taken as representative of presolar diamonds, some very interesting implications arise. These implications are the subject of this paper. A preliminary discussion of these implications was given previously (Huss et al. 2000). We also take the opportunity to officially report the data described in preliminary form by Koscheev et al. (2004).

**SUMMARY OF THE OBSERVATIONS**

**Presolar Diamonds**

Presolar diamonds contain three isotopically distinct noble gas components, all of which contain all five noble gases (Huss and Lewis 1994a). The P3 component is released between 200 °C and 900 °C during stepped-heating (pyrolysis) experiments and has isotopic compositions that are similar to, but distinct from, the major noble gas component in meteorites, P1 (Table 1). The HL component is released between 1100 and 1600 °C, and all five noble gases have isotopic ratios that are very different from those in the P1 component. For example, Xe-HL exhibits large enrichments of both the heaviest and lightest isotopes, while Kr-H shows an elevated $^{86}\text{Kr}/^{84}\text{Kr}$ ratio (Huss and Lewis 1994a). The P6 component is quantitatively considerably smaller than the other two. It is released at slightly higher temperature than the HL component, and its isotopic compositions, while not well constrained, appear to be similar to, but again distinct from, those of the P1 component. Diamond separates from CI and CM2 chondrites may incorporate a small amount of nanometer-sized SiC, which releases its gases above 1600 °C (Huss and Lewis 1994a). These high-temperature releases are not relevant to this paper and will not be discussed further.

An example of the release patterns for the noble gases in diamonds from primitive, unmetamorphosed chondrites is shown in Fig. 1. For argon, krypton, and xenon there is a clear bimodal gas release. The low-temperature release has been designated as P3, and the HL and P6 components make up the

### Table 1. Comparison of isotopic compositions of noble-gas components in presolar diamonds with P1 gases.

<table>
<thead>
<tr>
<th>Component</th>
<th>$^{20}\text{Ne}/^{22}\text{Ne}$</th>
<th>$^{21}\text{Ne}/^{22}\text{Ne}$</th>
<th>Component</th>
<th>$^{3}\text{He}/^{4}\text{He}$</th>
<th>$^{38}\text{Ar}/^{36}\text{Ar}$</th>
<th>$^{40}\text{Ar}/^{36}\text{Ar}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne-P3</td>
<td>8.910 (57)</td>
<td>0.029 (1)</td>
<td>P3</td>
<td>≤0.000135 (10)</td>
<td>0.1900 (10)</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>Ne-A2 (= HL + P6)</td>
<td>8.500 (57)</td>
<td>0.036 (1)</td>
<td>HL</td>
<td>0.000170 (10)</td>
<td>0.2270 (30)</td>
<td>&lt;0.08</td>
</tr>
<tr>
<td>Ne-P1 (Ne-Q)</td>
<td>10.7 (2)</td>
<td>0.0294 (10)</td>
<td>P1 (Q)</td>
<td>0.000159 (4)</td>
<td>0.1890 (7)</td>
<td></td>
</tr>
<tr>
<td>Kr-P3</td>
<td>0.0065 (10)</td>
<td>0.0399 (4)</td>
<td>= 0.2035</td>
<td>0.2036 (5)</td>
<td>0.3111 (6)</td>
<td></td>
</tr>
<tr>
<td>Kr-HL</td>
<td>0.0043 (10)</td>
<td>0.0308 (10)</td>
<td>= 0.1600</td>
<td>0.1993 (10)</td>
<td>0.3603 (18)</td>
<td></td>
</tr>
<tr>
<td>Kr-P6</td>
<td>0.0035 (8)</td>
<td>0.0205 (10)</td>
<td>= 0.2017</td>
<td>0.3130 (30)</td>
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<tr>
<td>Kr-P1</td>
<td>0.0067 (6)</td>
<td>0.0401 (3)</td>
<td>= 0.2025</td>
<td>0.3074 (9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xe-P3</td>
<td>0.00451 (6)</td>
<td>0.00404 (4)</td>
<td>0.0806 (2)</td>
<td>1.042 (4)</td>
<td>0.1591 (2)</td>
<td>0.8232 (10)</td>
</tr>
<tr>
<td>Xe-HL</td>
<td>0.00842 (9)</td>
<td>0.00569 (8)</td>
<td>0.0905 (6)</td>
<td>1.056 (2)</td>
<td>0.1544 (3)</td>
<td>0.8442 (13)</td>
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<tr>
<td>Xe-P6</td>
<td>0.00438 (25)</td>
<td>0.00444 (28)</td>
<td>0.0890 (20)</td>
<td>1.114 (8)</td>
<td>0.1660 (11)</td>
<td>0.8214 (47)</td>
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<td>Xe-P1</td>
<td>0.00467 (6)</td>
<td>0.00414 (5)</td>
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<td>1.040 (2)</td>
<td>0.1630 (4)</td>
<td>0.8212 (12)</td>
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</table>

1Diamond data from Huss and Lewis (1994a). Data for Kr-P1 and Xe-P1 from Huss et al. (1996). Data for He-P1, Ne-P1, Ar-P1 from closed-system oxidation of Allende (He) and Murchison (Ne, Ar) HF/HCl residues (Wieler et al. 1991, 1992). One-sigma uncertainties are shown in parentheses. Uncertainties on literature compositions are as listed in the source. 2Ne-A2 is a pseudo-component consisting of Ne-HL and Ne-P6. 3Compositions assuming P6 is approximately isotopically “normal.”

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For neon, the low-temperature release is very much smaller and does not really define a peak, but the neon released at low temperature is isotopically quite distinct from that in the HL component (Table 1, Fig. 1). Helium also does not have a clear bimodal release, but the isotopic composition changes with temperature. Note that the five gases have high-temperature release peaks where mean release temperatures differ by only a few degrees between helium at the low end and xenon at the high end. Natural heating processes can release the low-temperature P3 component almost quantitatively from the diamonds while having little effect on the HL component (Huss and Lewis 1994b).

**Synthetic Nanodiamonds**

Several studies have implanted noble gases into synthetic nanodiamonds (Koscheev et al. 1998, 2001, 2004, 2005; Verchovsky et al. 2000). In this paper, we work with the results of two of the Koscheev et al. experiments. The synthetic diamonds used in these experiments were produced by shock detonation and have a size distribution very similar to that of meteoritic diamonds (Daulton et al. 1996; Maul et al. 2005).

In the experiment of Koscheev et al. (2001), a single component containing helium, argon, krypton, and xenon was implanted into the diamonds at ~700 eV. The samples were then measured for noble gas abundances and isotopic compositions by stepped pyrolysis using an experimental protocol similar to that used to measure presolar diamonds. The release profiles for helium, argon, krypton, and xenon obtained by Koscheev et al. (2001) exhibit a striking resemblance to the release pattern for the presolar diamonds (Fig. 2). Argon, krypton, and xenon have a clear bimodal release, and the two release peaks occur at the same temperatures as in presolar diamonds. The helium release is also very similar to presolar diamonds, with a large release at ~1000 °C. The gas release is accompanied by mass-dependent
isotope fractionation that decreases from argon to krypton to xenon, as expected based on the mass difference between the isotopes (Koscheev et al. 2001).

Koscheev et al. (2004) took a different approach, measuring the gas release as a function of temperature in dynamic mode. In this experiment, the sample of synthetic nanodiamonds implanted with a mixture of helium, neon, argon, krypton, and xenon ions was heated linearly at a rate of ~7 °C/minute and the partial pressures of the released noble gases were measured. This was done in the noble-gas-only system at Mainz (e.g., Schwenzer et al. 2007), but because of the large gas amounts, a quadrupole mass spectrometer (Balzers Prisma) was used for analysis rather than a standard magnetic sector, noble gas mass spectrometer. The gases were introduced into the mass spectrometer at a low rate through a calibrated valve as the sample chamber was continuously pumped. To distinguish $^{20}\text{Ne}$ from doubly-charged $^{40}\text{Ar}$ ($m/z = 20$) in the mass spectra, doubly charged $^{20}\text{Ne}$ ($m/z = 10$) was measured to characterize the neon release. Release rate profiles for each gas were calculated from the measured “release curve” (the dependence of partial pressure of noble gas on time or temperature) using the following equation describing vacuum pumping:

$$Q_i/V = P_i(S_i/V) + dP_i/dt$$  \hspace{1cm} (1)

$Q_i$ is the gas release rate, $V$ is the volume of the vacuum chamber, $P_i$ is the pressure, $S_i$ is the pumping rate, and the index “$i$” denotes the noble gas. The time constant of pumping $(V/S_i)$ for each noble gas was calculated from the decay curve after introducing the calibrated noble gas mixture into the vacuum system (it varied from 111 seconds for helium to 648 seconds for xenon; the measured Xe/He ratio, 648/111 = 5.84, is very close to the theoretical value of 5.74). Using these data, the value $Q_i/V$ for each gas as a function of time (temperature) was determined. The curves in Fig. 3 represent these data plotted in ordinary stepped form. The size of each step is proportional to the gas amount released over ~12 minutes during linear heating with a rate of 7 °C/min.

In the discussions to follow, we will primarily be concerned with the data collected by Koscheev et al. (2001), because these data were collected by the same experimental protocol as those for the meteoritic nanodiamonds. Experimental artifacts should thus be minimized. The Koscheev et al. (2004) study provides neon data that fills a gap in the Koscheev et al. (2001) data set. We report the data from the Koscheev et al. (2004) study for the first time here (Table 2, Fig. 3).

**IMPLICATIONS OF THE EXPERIMENTAL RESULTS**

The release patterns shown in Figs. 1 and 2 are strikingly similar. The pattern shown by the continuous release is also similar (Fig. 3). Because the bimodal release in synthetic
nanodiamonds is generated using a single component, we must consider the possibility that the bimodal release from presolar diamonds also results from a single component and that the P3 component dominates the high-temperature release as well. If this is the case, then the isotopically anomalous component in the presolar diamonds must be very much smaller and much more isotopically extreme than previously believed. It has been known for some time that the measured isotopic compositions of krypton and xenon in presolar diamond are not as extreme as the theoretical end members. Based on isotopic arguments, one can conclude that up to 90% of the xenon and 50–97% of the krypton in the HL component may belong to an isotopically “normal” component intimately intermixed with the exotic gases (Huss and Lewis 1994a and references therein). The release curves from the synthetic nanodiamonds may support this conclusion.

**Xenon**

Argon, krypton, and xenon in the synthetic diamonds show systematic shifts in isotopic composition as a function of release temperature. Because the light isotopes are released somewhat more easily than the heavy isotopes, the gas released at higher temperature is increasingly depleted in the light isotopes. Figure 4 shows the degree of mass-dependent fractionation observed for xenon in the synthetic diamonds as a function of temperature. The flat line at unity represents the weighted mean of the measured compositions of the first four (200–500 °C) steps and can be considered analogous to the Xe-P3 composition in meteoritic diamonds. The 500 °C step is essentially unfractio nated, but the 1400 °C step shows a mass fractionation of ~0.99% per amu.

A typical way to graphically display the anomalous Xe-HL component is to normalize the measured composition to a composition that we believe to represent solar system xenon. In such a plot, isotopic abundances that match the chosen normalizing composition plot on the X-axis, and isotopes with excesses plot above the X-axis. Figure 5 is an example of
such a plot, but rather than plotting several measurements of the Xe-HL component normalized to a single composition, we plot a single measurement of Xe-HL normalized to several different isotopically “normal” components. For example, relative to solar xenon, $^{136}$Xe is enriched in HL by about 150%. When normalized to the P3 component, the enrichments in heavy isotopes are slightly smaller and the enrichments of light isotopes slightly larger than when normalized to P1. When a fractionated P3 component is used, based on the mass-fractionation behavior exhibited by xenon released from synthetic nanodiamonds (Fig. 4), the filled symbols result. While it makes some difference which “normal” component one chooses, the basic picture remains the same, and differences are minor on the scale of Fig. 5.

The isotopic composition of the Xe-HL in meteoritic nanodiamonds represents a mixture of the isotopically “exotic” component and a “normal” component that can be thought of as average gas from all nucleosynthetic sources. Traditionally, the “exotic” component has been thought to be a product of nucleosynthesis in a supernova, with the $r$-process or something like it responsible for the H component and the $p$-process responsible for the L component (e.g., Heymann and Dziczkaniec 1979, 1980; Clayton 1989). Neither of these processes (with the exception of the photodisintegration version for explaining Xe-L) produces $^{130}$Xe, so one can calculate the end-member composition by assigning all of the $^{130}$Xe to a “normal” component and subtracting the associated amounts of the “normal” component from the other isotopes.

Figure 6 shows in solid symbols the composition of Xe-H inferred by subtracting three “normal” components, Xe-P3, mass-fractionated Xe-P3, and solar xenon, from the measured Xe-HL. Changing the underlying component results in slight, but noticeable differences in the calculated Xe-H composition. These slight differences become important when one tries to discriminate between models for the formation of the Xe-H component. The open symbols and dashed lines in Fig. 6 show three model calculations for processes that might have generated the Xe-H composition (assuming that it is a single composition, not a mixture from several sources). The two neutron-burst calculations (Howard et al. 1992; Meyer et al. 2000—see complete predictions including xenon at http://nucleo.ces.clemson.edu/pages/tables) show significant deviations from the observed composition, outside of the range exhibited by the natural samples under any of the assumptions used to make Fig. 6. The model that seems to match the xenon observations best is the rapid-freeze-out model proposed by Ott (1996). In this model, xenon from the $r$-process is separated from iodine and tellurium within hours after synthesis, while part of the xenon is still held up in radioactive precursors. Ott’s model requires that a small amount of fully developed $r$-process xenon be added to the freeze-out xenon to match the inferred natural composition. However, by using fractionated Xe-P3 as the

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**Fig. 4.** The isotopic composition of xenon released as a function of temperature from the synthetic diamonds is plotted, normalized to the weighted mean of the four lowest-temperature steps (200–500 °C). The 500 °C step is essentially unfractionated compared to this “initial” composition, but with increasing release temperature, the xenon becomes isotopically heavier, with the fractionation reaching 0.99% per amu in the 1400 °C step. This mass fractionation reflects an interplay between the process of implantation and the release during pyrolysis. Example 1σ error bars are shown for the 500 °C step.

**Fig. 5.** The isotopic composition of Xe-HL as measured by Huss and Lewis (1994a) is plotted normalized to four different “normal” components, solar xenon (Pepin et al. 1995), Xe-P1 (= Xe-Q) (Huss et al. 1996), Xe-P3 (Huss and Lewis 1994a), and Xe-P3 mass fractionated by 0.99% as found in the 1400 °C step of the experimentally implanted diamond. The normal components plot along the base of the diagram. The level of the inferred isotopic anomaly changes depending on which “normal” component is used for the normalization. We chose $^{130}$Xe to normalize the compositions because it is unaffected by $r$-process and other rapid neutron capture processes.
underlying component, the required amount of fully developed \( r \)-process xenon is reduced to \( \sim 4 \% \) (Fig. 6) from \( \sim 7 \% \) required for solar xenon (Ott, 1996). Ott’s model appears to account not only for the xenon composition, but also for the tellurium composition inferred for the diamonds (Richter et al. 1998).

Krypton

Krypton from synthetic nanodiamonds shows similar mass fractionation behavior to xenon, except that the degree of mass fractionation is higher. Figure 7 shows the degree of mass-dependent fractionation observed for krypton in the synthetic diamonds as a function of temperature, normalized to the weighted mean of the measured compositions of the first four (200–500 °C) steps. As with xenon, the degree of mass fractionation increases with temperature, reaching \( \sim 1.44\% \) per amu in the 1400 °C step. The degree of mass fractionation of krypton relative to xenon is slightly less than expected from a 1/mass dependence.

Figure 8 shows the krypton data for Orgueil diamonds as a function of temperature normalized to the composition of Kr-P3 derived by Huss and Lewis (1994a). The low-temperature steps, from which the Kr-P3 composition is derived, plot on the horizontal line at 1.00, while the high-temperature steps show excesses of heavy isotopes and no excesses at \( ^{86}\text{Kr} \). However, if one compares the high-temperature Orgueil steps to the high-temperature releases from the synthetic diamonds, normalized to their four low-temperature steps, the patterns for Orgueil high-temperature steps can be interpreted as a superposition of mass-fractionated Kr-P3 and an HL component showing excesses at both high- and low-mass isotopes.
fractionation of an underlying Kr-P3 component, and if much of the gas in these steps is in fact mass fractionated Kr-P3, then the inferred excesses of $^{83}$Kr, $^{84}$Kr, and $^{86}$Kr relative to fractionated Kr-P3 that should be assigned to Kr-H are considerably smaller, and a small excess in $^{80}$Kr appears. Data for $^{78}$Kr from Orgueil diamonds is not sufficiently precise to reveal the potential excess of $^{78}$Kr.

It is difficult to accurately evaluate the sizes of the isotopic anomalies due to a nucleosynthetic component in krypton because we do not know the composition of the underlying fractionated component very well. Figure 9 shows the 1235 °C, 1420 °C, and 1600 °C steps from Orgueil diamonds, those that are dominated by the Kr-H component, compared to calculated compositions for mass fractionated Kr-P3 in the same steps based on the mass fractionation observed in synthetic nanodiamonds. The calculation was done by evaluating the degree of mass fractionation for argon, krypton, and xenon from the synthetic nanodiamonds for each temperature step and deriving a mass-dependence function for the fractionation. The best fit to the data can be expressed as:

$$\text{Fractionation (amu)} = c \times \text{mass}^{-0.8067}$$

which is slightly less than a 1/mass dependence. The inferred excesses of $^{80}$Kr, $^{83}$Kr, $^{84}$Kr, and $^{86}$Kr relative to the calculated P3 compositions are similar to those inferred from Fig. 8 and support the suggestion that anomalous krypton contains a Kr-L component.

**Argon**

The $^{38}$Ar/$^{36}$Ar ratio in Orgueil diamonds increases with release temperature through the 1600 °C step (with an excursion to a higher value for the 1235 °C step) and then gradually decreases at higher temperatures (Fig. 1). The Orgueil data, normalized to the composition of Ar-P3 from Table 1, are compared to data for implanted synthetic nanodiamonds, normalized to the weighted mean of the first four steps, in Fig. 10. The two data sets show similar overall trends. Huss and Lewis (1994a) inferred that Ar-HL has a higher $^{38}$Ar/$^{36}$Ar ratio than Ar-P3. However, the close similarity of the data sets in Fig. 10 suggests that we may be looking almost entirely at mass fractionation of Ar-P3. The excursion from the fit through the data for the 1235 °C step in the Orgueil data, the step with the biggest $^{134}$-136Xe excesses, may contain a nucleosynthetic Ar-HL component. Uncertainties are 1σ.

**Neon**

In the Orgueil diamonds, neon does not show the strongly bimodal release shown by the heavier gases. The experiments reported by Koscheev et al. (2001) unfortunately did not
include neon, but the Koscheev et al. (2004) experiment did. Figure 3 shows their data for all five noble gases implanted into synthetic diamonds and released during continuous (rather than stepped) heating. Argon, krypton, and xenon show the same bimodal release as was shown by the stepped heating experiments (Fig. 2). Helium shows a single release in between the two peaks of the heavier gases, as it did in the stepped heating experiments (Fig. 2). Neon shows a very muted bimodal release, with the low-temperature peak consisting of a shoulder on the high-temperature release. This is similar to the neon release profile from Orgueil diamonds during stepped heating (Fig. 1), again suggesting that neon in presolar diamonds is dominated by a single component.

We can estimate the neon isotopic fractionation that should have been observed had neon been included in the Koscheev et al. (2001) experiments based on the characteristics of the other gases. Using the power-law mass dependence described by Equation 2, we have calculated the expected mass fractionation for $^{20}\text{Ne}/^{22}\text{Ne}$ in Ne-P3. This calculation gives an expected mass fractionation in the 1420 °C step of ~3.3% per amu. We compare the result of these calculations with the measured data for neon in Orgueil diamonds in Fig. 11. The measured data and the calculated ratios follow very similar trends, suggesting that neon may also be dominated by a single component, Ne-P3. The higher ratios for Orgueil diamonds in the two lowest-temperature steps probably reflect the presence of atmospheric neon ($^{20}\text{Ne}/^{22}\text{Ne} = 9.8$) adsorbed on the sample. The offset to higher values for the intermediate steps may reflect an additional component, which would be $^{20}\text{Ne}$-rich compared to fractionated Ne-P3. This could be a nucleosynthetic component. It is unlikely to be a contribution from Ne-P1, the neon component that accompanies the most abundant heavy noble gas component in chondrites (P1 or Q gases) and has a $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of ~10.7. This is because Ne-P1 only comprises ~10% of the neon in the bulk meteorites and effectively all of it would have to be in the diamonds to shift the composition of Ne-P3 as indicated in Fig. 11.

When $^{21}\text{Ne}/^{22}\text{Ne}$ is added to the mix, the picture becomes more complicated. Calculated compositions for mass fractionated Ne-P3 based on Equation 2 define a trend with a positive slope on a Ne 3-isotope plot (Fig. 12). In contrast, the natural diamonds follow trajectories with a moderate negative slope. The neon data for diamonds from four meteorites define four distinct trajectories in Fig. 12. For this discussion, only the intermediate-temperature steps (from ~800 °C to ~1600 °C) are of interest. The low-temperature steps are contaminated by atmospheric neon and cosmogenic neon, and the highest-temperature steps for Orgueil (CI), Murchison (CM2), and Murray (CM2) diamonds are contaminated by Ne-E, presumably from tiny SiC grains that were not completely separated from the diamonds (Huss and Lewis 1994a; Huss et al. 2003). In addition, Ne-P3 in loosely bound sites has largely been degassed from the Leoville (CV3) diamonds during parent body metamorphism (Huss and Lewis 1994b), so cosmogenic neon is more visible in the low-temperature steps for Leoville diamonds.

Neon-21 is a rare isotope whose abundance can be shifted significantly by the addition of cosmogenic neon produced by spallation reactions due to interactions with cosmic rays. For this reason, it is used widely to measure cosmic ray exposure ages of meteorites. Huss and Lewis (1994a) showed that cosmogenic neon incorporated from the host meteorite, systematically shifts the $^{21}\text{Ne}/^{22}\text{Ne}$ ratios in diamonds from different meteorites. As the exposure age of the host meteorite increases, the neon compositions move to the right in Fig. 12. Consider first the data for diamonds from Murchison, which has a cosmic-ray exposure age of 1.8 million years (Herzog et al. 1997). The contribution of cosmogenic neon should be the smallest of the samples shown, and the 625 °C and 780 °C steps plot close to the array defined by mass fractionated Ne-P3. For Murray and Orgueil, the low-temperature steps are displaced to the right, indicating larger contributions of cosmogenic neon, as expected from the exposure ages of the host meteorites. Leoville has the longest exposure age and most of the low-temperature P3 gases have been lost during parent-body metamorphism. Thus, the somewhat larger amount of cosmogenic neon relative to the
other meteorites has a much larger effect on the low-temperature steps. Mass fractionation of Ne-P3 plus addition of cosmogenic neon (plus air neon in the very lowest-temperature steps) can explain the data for steps below ~800 °C. Diamonds from Orgueil, Murchison, and Murray have their full complement of low-temperature Ne-P3. Low-temperature Ne-P3 was largely outgassed from the Leoville diamonds by parent-body metamorphism. The data show evidence for a component enriched in 21Ne relative to mass-fractionated Ne-P3 that is released primarily above ~1000 °C. This could be a nucleosynthetic component or evidence for presolar cosmic-ray irradiation, or both.

The data for the ~800 °C to ~1600 °C steps tell a more complicated story. First, all of the data for these temperature steps are shifted significantly to the right of the Ne-P3 fractionation array, indicating the presence of a component enriched in 21Ne. The spread in the direction of cosmogenic neon between the four data sets for presolar diamonds is consistent with their cosmic ray exposure ages, but is smaller for these steps than for the low-temperature steps, consistent with a smaller relative contribution of cosmogenic neon from the host meteorite in the higher-temperature steps. Even so, the 800–1600 °C steps contain >95% of the cosmogenic neon inherited by the diamonds from the host meteorites. There is a significant additional 21Ne-rich component that needs an explanation. In order to evaluate what this 21Ne enrichment represents, it is necessary to correct for the contribution of cosmogenic neon from the host meteorite.

Figure 13 summarizes two ways to calculate and account for the cosmogenic 21Ne produced in the host meteorite and released in the intermediate-temperature steps. One method is to assume that all 22Ne is in the P3 component, subtract fractionated Ne-P3 from each temperature step, and then sum the residual 21Ne for each sample. Those results can then be plotted against the cosmic ray exposure age for the host meteorite. The amount of excess 21Ne in the diamonds prior to irradiation in the host meteorite during its travel to Earth can be estimated in two ways. Assuming that the irradiation of the host meteorites produced 21Ne at essentially the same rate, then the intercept of a regression line through the data gives an estimate of the amount of pre-existing excess 21Ne. Alternatively, because carbon is ~1.5× more efficient at trapping cosmic-ray produced neon than is bulk chondrite material (SRIM Code; Ziegler 2004), one can subtract 1.5× the bulk cosmogenic 21Ne content of the host meteorite to get the amount of pre-existing excess 21Ne (plotted as open symbols). The two methods give similar results, implying that ~5×10^−8 ccSTP/g of presolar excess 21Ne is carried in the diamonds. Steps used in the calculation: Murchison: 780–1495 °C; Murray: 880–1495 °C; Orgueil: 865–1600 °C; Leoville: 945–1710 °C.
the diamonds is the same as in the other components of the meteorite and to subtract that amount from the total $^{21}\text{Ne}$ remaining after subtracting fractionated Ne-P3. A slightly better calculation is to assume $\sim 1.5 \times$ the concentration in the other components because, according to the SRIM code (Ziegler 2004), the stopping power of pure carbon is higher than that of material with chondritic composition by that amount. The results of this calculation are shown in the open symbols in Fig. 13. The four samples define a band that includes the intercept of the regression line (shaded region in Fig. 13). The two calculations suggest that the amount of excess $^{21}\text{Ne}$ present in the diamonds when they entered the host meteorites was $\sim 5 \times 10^{-8}$ ccSTP/g.

One possibility for the origin of this excess $^{21}\text{Ne}$ relative to fractionated Ne-P3 is that it reflects a presolar irradiation (e.g., Huss et al. 2000). There are problems with this suggestion. For example, the isotopic shifts are quite large, particularly for the high-temperature steps, and the release pattern is different from that inferred from comparing diamonds from different meteorites; the low-temperature fraction seems to be missing. Perhaps this reflects loss of $^{21}\text{Ne}$ that was trapped in less retentive sites during the long history in interstellar space. The tiny diamond crystals would have experienced thermal excursions of $> 50$ K when hit by UV photons (Draine 2003). Alternatively, the $^{21}\text{Ne}$ content of the Ne-P3 component may be overestimated, and the low-temperature gas may actually be present. Also, $^{21}\text{Ne}$ is not produced by spallation of carbon, the major element in the diamonds. The target elements must have been heavier than carbon. Heavier elements such as Si and Mg might have accumulated on the diamond surfaces as grain mantles, but the thermal excursions experienced by the diamonds are thought to preclude the development of significant grain mantles. Probably most important, recoil lengths for spallation reactions are considerably longer than the longest dimension of the diamond grains (e.g., Ott and Begemann 2000). If the diamonds were accreted onto surfaces of interstellar silicate grains during the growth of grain mantles in interstellar clouds, recoiling cosmogenic neon from the silicates might have been trapped in the diamond crystals, but even then the size of the silicates might not be enough. We will expand on this aspect in more detail below in the helium section.

In spite of these problems, as a thought exercise, we have tried to estimate the exposure age of presolar diamonds from the excess $^{21}\text{Ne}$, assuming that the $\sim 5 \times 10^{-8}$ ccSTP/g of intrinsic $^{21}\text{Ne}$ is from cosmic ray exposure in interstellar space. We will assume that the $^{21}\text{Ne}$ is acquired by recoil from an equivalent mass of average galactic solids, which we will assume to be chondritic in composition. We make no attempt to define the geometric relationships between the diamond and the average galactic material. We simply assume a suitable relationship. Using chondritic abundances from Lodders (2003) and production factors from Reedy (1989) for interstellar cosmic rays, we find that the observed excess of $^{21}\text{Ne}$ relative to fractionated Ne-P3 could have been produced in $\sim 20$ million years. This is not an unreasonable number for a presolar exposure for the bulk diamonds, but it should not be taken as a valid estimate of the duration of presolar exposure. There are huge uncertainties in the calculation. For example, it makes no attempt to account for trapping efficiency, it does not define the geometric relationship between the diamonds and the source of the spallogenic $^{21}\text{Ne}$, and the composition assumed for average galactic solids may bear little resemblance to the composition of actual sources of $^{21}\text{Ne}$. But the fact that the result is plausible indicates that presolar exposure cannot be ruled out.

A possible alternative explanation of the excess $^{21}\text{Ne}$ in the 800–1600 °C steps is that the diamonds contain a nucleosynthetic neon component that is significantly enriched in $^{20}\text{Ne}$ and $^{21}\text{Ne}$ compared to fractionated Ne-P3. These are the steps that also contain the HL component in the heavier gases. The O/Si and O/Ne zones of a 25 M⊙ supernova model are significantly enriched in $^{20}\text{Ne}$ over the starting composition, but $^{21}\text{Ne}$ is only moderately enriched in the O/Ne zone and is depleted in the O/Si zone, resulting in very high $^{20}\text{Ne}/^{21}\text{Ne}$ ratios (Meyer et al. 1995). The O/C zone in the same model is enriched in $^{21}\text{Ne}$ and $^{22}\text{Ne}$ relative to $^{20}\text{Ne}$, but the $^{20}\text{Ne}/^{21}\text{Ne}$ ratio is still over 100. The ratio of excess $^{20}\text{Ne}$ to excess $^{21}\text{Ne}$ inferred for the 800–1600 °C steps in the diamond samples is $\sim 5$. The excess $^{20}\text{Ne}$ in these steps (Fig. 11) appears to require a nucleosynthetic component. If mass fractionated Ne-P3 does in fact dominate these steps, and if stellar models are not able to match the $^{20}\text{Ne}$ and $^{21}\text{Ne}$-rich component inferred to accompany the fractionated Ne-P3, then it appears that the excess $^{20}\text{Ne}$ and $^{21}\text{Ne}$ represent a mixture of a nucleosynthetic component that supplied most of the $^{20}\text{Ne}$ and a cosmic-ray produced component that supplied most of the $^{21}\text{Ne}$.

**Helium**

The $^{3}\text{He}/^{4}\text{He}$ ratio increases with increasing release temperature (Fig. 14). Diffusive mass fractionation of He-P3 depletes $^{3}\text{He}$ and the $^{3}\text{He}/^{4}\text{He}$ ratio decreases with temperature. The calculated fractionation using the model summarized in equation 2 reaches $\sim 12\%$ per amu at 1420 °C. To first order, the observed compositions for Orgueil and Leoville diamonds do not match expectations for diffusively fractionated He-P3.

Higher ratios are produced by addition of $^{3}\text{He}$, and spallation reactions in the host meteorite efficiently produce $^{3}\text{He}$. Because $^{3}\text{He}$ is $\sim 10^4$ times less abundant than $^{4}\text{He}$, the addition of cosmogenic helium from the host meteorite has a large effect on the $^{3}\text{He}/^{4}\text{He}$ ratio, particularly in steps with low gas content. There was also a relatively large helium blank in the mass spectrometer used by Huss and Lewis (1994a). Thus, the lowest- and highest-temperature steps both have large...
Fig. 14. The measured $^3\text{He}/^4\text{He}$ ratios in the temperature steps from presolar diamonds from Orgueil (CI), Leoville (CV3), and Bishunpur (LL3.1) are compared to the ratios expected from mass-dependent fractionation of He-P3, using the mass dependence described in Equation 2. The $^3\text{He}/^4\text{He}$ ratios are higher in the 800–1600 °C steps from the presolar diamonds relative to the model predictions. Note that the ratio for He-P3, from Huss and Lewis (1994a), is an upper limit on the true ratio, so the fractionated P3 values are also upper limits, while inferred excesses are lower limits. Data are from Huss and Lewis (1994a).

errors and do not reflect the intrinsic helium in the samples. These steps are not plotted in Fig. 14. The most reliable data come from the same intermediate-temperature steps used above to calculate excess $^{21}\text{Ne}$. These steps had high gas contents and thus low relative contributions from host-meteorite helium and blank. Figure 14 shows the data for three diamond separates. Orgueil diamonds have a full complement of P3 gases and thus are less affected by extraneous components. The data for the intermediate-temperature steps for all three samples plots at a $^3\text{He}/^4\text{He}$ ratio of $\sim 1.6 \times 10^{-8}$, significantly higher than even unfractonated He-P3. The cosmic-ray exposure ages for Orgueil, Leoville, and Bishunpur are 4.5 Ma, 7.1 Ma, and ~9 Ma, respectively (Mazor et al. 1970; Heymann and Mazor 1968). But, unlike the case for neon, the factor-of-two difference in exposure age is not reflected in the $^3\text{He}/^4\text{He}$ ratio of the intermediate-temperature steps. This is not surprising because with a cosmic ray production rate of $\sim 1.6 \times 10^{-8}$ ccSTP/(g Ma) (Eugster 1988), the recently produced concentrations of $\sim 7$, 11, and $14 \times 10^{-8}$ ccSTP/g are dwarfed by the apparent excesses of $^3\text{He}$, as discussed below for the case of Orgueil.

Cosmogenic $^3\text{He}$ acquired by recoil from the surrounding bulk meteorite must have essentially the same concentration as the bulk meteorite. This is because the grain size of the diamonds is very much smaller than the recoil length of spallogenic helium and because the diamonds are finely dispersed in the matrix (Banhart et al. 1998; Dai et al. 2002). With some of the expected $\sim 7 \times 10^{-8}$ ccSTP/g of recent $^3\text{He}$ certainly released already at lower temperature, we subtract $\sim 4 \times 10^{-8}$ ccSTP/g, which leaves an intrinsic excess $^3\text{He}$ content of $\sim 2.16 \times 10^{-8}$ ccSTP/g.

Huss et al. (2000) suggested, as discussed above for $^{21}\text{Ne}$, that the difference between the $^3\text{He}/^4\text{He}$ ratios for the presolar diamonds and those for mass-fractionated He-P3 could reflect a presolar irradiation. Although $^3\text{He}$ is produced by spallation reactions on the carbon that makes up the diamond, the excess $^3\text{He}$ relative to He-P3 cannot be caused by addition of cosmogenic helium produced in the diamonds themselves because the tiny diamond crystals cannot retain the helium produced within them. Thus, as with neon, accumulation of cosmogenic $^3\text{He}$ in presolar diamonds would require that the diamonds were part of some larger object so that recoiling $^3\text{He}$ can stop within the diamonds. A clue to the nature of such a possible larger object is provided by the remarkably high abundance ratio of the inferred presolar cosmogenic $^3\text{He}$ and $^{21}\text{Ne}$ (~43). Chondritic matter irradiated as grains smaller than one centimeter gives a $^3\text{He}/^{21}\text{Ne}$ ratio of ~11, using cosmic abundances from Lodders (2003) and production rates of Reedy (1989). Higher ratios can be achieved only by having a higher abundance of elements lighter than neon, on which no spallation neon is produced, relative to those of the important target elements (Mg, Al, Si) for neon (or—unlikely—predominantly heavy elements like Fe). To arrive at the $^3\text{He}/^{21}\text{Ne}$ ratio of ~43, more than 90% of the $^4\text{He}$ would have to have been produced on the light elements. Carbonaceous material would qualify, for example a target consisting of some 70% carbon and the rest in chondritic proportion. So, if in the interstellar medium the diamonds were surrounded by (or attached to) some type of predominantly graphitic material, this might explain the observations. For our specific example the inferred $^{21}\text{Ne}$ exposure age would increase to ~60 Ma, i.e., about a factor of three compared to a chondritic target.

A problem with this scenario is that whatever the type of larger object (plus associated nanodiamond) is, it must be large enough to retain the cosmogenic $^3\text{He}$ (and $^{21}\text{Ne}$, as discussed above). Our best estimate for the average recoil range of directly produced cosmogenic $^3\text{He}$ is ~15 µm, where the definition is that 50% of recoils have a larger range, 50% a smaller range. This is roughly 10 times that of $^{21}\text{Ne}$. Tritium, the radioactive precursor for about half of cosmogenic $^3\text{He}$ (Leya et al. 2004), has a recoil range that is larger by another factor ~4 (see Appendix). These ranges are not only much higher than the size of the ~0.0026 µm nanodiamonds, but also much larger than the size of “typical” (submicron) interstellar grains (Mathis et al. 1977; Draine...
2003). This problem may be overcome if the source of the cosmogenic $^3$He is the dust and gas of the interstellar medium itself. The gas phase contains much of the carbon and oxygen making up cosmic abundances.

Another process that may be equally or even more important than cosmic ray spallation reactions is the trapping of cosmic rays, at least for $^3$He. Just as the grains (diamonds or composite) cannot avoid being hit by cosmic rays initiating nuclear reactions, they also cannot avoid being hit by secondary nuclei produced by cosmic ray interactions with other dust grains and with the gas in the interstellar medium. These several MeV nuclei can travel quite some distance in the vast (almost) empty reaches of the interstellar medium or even leave the Galaxy, and in fact as a rule will become included in the galactic cosmic rays as secondaries and can be trapped by grains. In the galactic cosmic rays arriving here today, the ratio of the secondary nuclei $^3$He/$^{21}$Ne is on the order of $\sim 300$. This follows from the observed elemental ratio He/Ne of $\sim 300$ (Simpson 1983; Lund 1984) and from the fact that the isotopic abundances of both $^4$He (e.g., Ahlen et al. 2000; Wang et al. (2002) and $^{21}$Ne (e.g., Israel et al. 2005) are about 10%. The reason for the high ratio is that $^3$He (like deuterium) is mostly the product of $^4$He breakup (e.g., Mewaldt 1989), with spallation on heavier nuclei making a small addition, while $^{21}$Ne is exclusively spallogenic. Hence, the predominant sources of excess $^3$He and $^{21}$Ne in our diamonds may well be different–trapped GCR versus spallation recoil. In principle, it is possible to calculate a “cosmic ray trapping (CRT) age” from these data (Ott and Huss 2008). Given all the assumptions involved in deriving the abundance of excess $^3$He, in calculating an age from this, and in deriving the $^{21}$Ne age, the result will have to be taken with a grain of salt, however. We will deal with the aspect of cosmic ray trapping in detail in a forthcoming paper.

An alternative to the cosmogenic origin is that the higher $^3$He/$^4$He ratios in intermediate-temperature steps could reflect a nucleosynthetic HL component, as in the other gases. The excess $^3$He is accompanied by much more $^4$He that may not be in the P3 component, as assumed above. However, $^3$He is not produced in supernovae or their precursor massive stars (Meyer et al. 1995). Stars burn their initial inventory of deuterium to $^3$He while still on the pre-main sequence. In traditional stellar models, low-mass stars ($<3$ M$_\odot$) create $^3$He pockets in their interiors during main-sequence burning and the $^3$He is subsequently brought to the surface during first dredge-up (Iben 1967; Sackmann and Boothroyd 1999). The abundances of $^3$He in the model envelopes range from $\sim 30 \times$ the initial abundance in 1 M$_\odot$ stars to $\sim 2 \times$ the initial abundance in 3 M$_\odot$ stars. The higher temperatures in more-massive stars destroy any $^3$He that was once present. When the hydrogen burning due to deep extra mixing (cool bottom processing) is taken into account, most of the $^3$He produced by low-mass stars is destroyed (Sackmann and Boothroyd 1999). Thus, except for rare instances, stellar nucleosynthesis does not produce $^3$He, and the $^3$He/$^4$He ratio in the Galaxy decreases slowly with time (Sackmann and Boothroyd 1999).

Based on our current understanding, it is not possible to accept or reject either the cosmogenic or the nucleosynthetic hypothesis for the excess $^3$He. The decreasing apparent relative abundance of the isotopically anomalous nucleosynthetic component from xenon to krypton to argon, coupled with the high abundances of helium and neon in the diamonds, would seem to argue against the nucleosynthesis model for the origin of excess $^3$He and $^{21}$Ne relative to mass fractionated P3. But the mechanism for production and incorporation of cosmogenic helium and neon into the diamonds is not obvious either. Another possibility is that the P3 and HL components in helium both represent an average helium composition of the environments where the diamonds formed or in interstellar space, and that the difference in the $^3$He/$^4$He ratio reflects a nucleosynthetic HL component from xenon to krypton to argon.

SUMMARY AND CONCLUSIONS

The experimental data obtained by Koscheev et al. (2001, 2004) imply that the bimodal release of argon, krypton, and xenon from presolar diamonds may be primarily due to a single component, P3. If this is true, then the following implications arise:

1. The inferred Xe-HL composition shifts slightly, perhaps enough to change the nucleosynthetic process inferred to produce the component.
2. The inferred magnitude of the Kr-H isotopic shift decreases, and evidence appears for Kr-L.
3. The isotopic effects in argon are largely accounted for without calling on a nucleosynthetic component, although a small nucleosynthetic contribution may be present.

Our analysis also shows:

4. The measured neon compositions of presolar diamonds are significantly affected by cosmogenic neon acquired from the host meteorite, more strongly than previously realized.

Although the helium and neon releases in the experimental data are not as clearly bimodal, if a single component dominates these gases, then:

5. The neon isotopic composition in the intermediate-temperature steps may indicate presolar irradiation, where cosmogenic neon was produced in interstellar dust grains to which the diamonds had accreted in grain mantles. In addition, a distinct nucleosynthetic component may be present that has characteristics consistent with a supernova origin (as for argon, krypton, and xenon).

6. Excess intrinsic $^3$He relative to the expected composition of fractionated He-P3 seems to be present in presolar diamonds in an abundance that is much larger than can be accounted for by cosmogenic $^3$He produced in the host meteorite during its recent cosmic ray exposure.
nucleosynthetic component is unlikely, but cannot be ruled out. Similar to the case of $^{21}$Ne, the excess $^3$He may also have originated through spallation reactions as recoil nuclei that were collected by the tiny nanodiamonds. In this case, the high ratio of excess $^3$He to $^{21}$Ne requires production on a (C + O)-rich target, perhaps dust and gas of the interstellar medium rather than a specific phase to which the diamonds were attached. Trapping of cosmic rays may also have been involved.

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**APPENDIX**

The effect of recoil in estimating presolar exposure ages from $^{21}$Ne in silicon carbide has been controversial, with Tang and Anders (1988) using a much shorter range (–0.1 µm) than determined in the experiment (~2.5 µm) of Ott and Begemann (2000), who measured the neon actually retained in irradiated SiC grains in the range 0.3 to 5.5 µm. There are no equivalent data for $^3$He in the literature that can be directly applied, and it is not possible to extrapolate from neon to helium as Ott and Begemann (2000) did to estimate the spallation xenon range (see also Ott et al. 2005). This is because the dominant nuclear processes that lead to spallation $^{21}$Ne (a large fragment) and spallation $^3$He (a light fragment) are different.

The most relevant data for the case of $^3$He produced on carbon seem to be those of Greiner et al. (1975), who studied the momentum distribution of isotopes produced by fragmentation of $^{12}$C and $^{16}$O projectiles. Note that their data have been used by Ray and Völk (1983) for estimating the recoil range of spallation $^{21}$Ne produced on Si and spallation $^{38}$Ar produced on Fe, and that these are what Tang and Anders
(1988) used in calculating presolar exposure ages for silicon carbide. There are two misconceptions, however, in the application by Ray and Völk (1983), which explain the discrepancy between their range value and the directly determined recoil losses of Ott and Begemann (2000):

a) According to Greiner et al. (1975) the emission of secondaries is almost isotropic in the projectile rest frame. The Greiner et al. equation that Ray and Völk apply is for the “average” momentum and close to zero because the direction of emission is included in the averaging. In simple words, in their approach two emitted nuclei with the same momentum value and opposite direction will average to zero in momentum (and recoil loss). In reality, they do not average to zero recoil loss, of course, since both nuclei will recoil out of a grain of interest, if the numerical value of their momentum is large enough. In addition, the Ray and Völk application only takes into account the average momentum in the direction parallel to the projectile and ignores the momentum components orthogonal to it.

b) The data from Greiner et al. (1975) used by Ray and Völk are valid for the case of “projectile residues” (light nuclei) and not “target residues” (Morrissey 1989) such as $^{21}$Ne from $^{28}$Si. In fact, the linear relation shown in Fig. 3 of Morrissey (1989) between the average recoil momentum $p_{\text{rms}}$ and target-residue mass difference predicts for this case an average momentum of $\sim 400$ MeV/c, which corresponds to an energy of $\sim 4.1$ MeV and an implied recoil range in SiC (calculated using the SRIM code; Ziegler 2004) of $2.2 \mu$m, in excellent agreement with the $2.5 \mu$m determined by Ott and Begemann (2000).

Coming back to the case of $^3$He, the Greiner et al. (1975) data show a Gaussian distribution for the isotropic distribution of the momentum projected onto the beam axis in the frame of the projectiles $^{12}$C and $^{16}$O, and the situation should be essentially the same in the laboratory system in the case of protons hitting these nuclei as targets. The distribution is characterized by a Gaussian width of 145 MeV/c. This means that 50% of the projected momenta are $<98$ MeV/c; 50% are larger than $\sim 98$ MeV/c, which we define as the “average” value. Multiplying this value by the $\sqrt{3}$ gives the mean momentum (Morrissey 1989), which then is $\sim 170$ MeV/c. The corresponding energy of the $^3$He nuclei is $\sim 5.2$ MeV and the range in diamond (density $3.5$ g/cm$^3$) is $\sim 15 \mu$m according to the SRIM code (Ziegler 2004). Of course, roughly half of cosmogenic $^3$He is produced via radioactive tritium ($^3$H) as a precursor (e.g., Leya et al. 2004). For tritium the data of Greiner et al. (1975) show a virtually identical momentum distribution as for $^3$He, but over most of the energy range the range of tritium is $\sim 4\times$ that of $^3$He so that the mean range of $^3$H is of the order of 60 $\mu$m.