Outstanding Problems of Presolar Diamond in Meteorites

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Abstract. Diamond is the first mineral type of presolar grains that were isolated from meteorites, yet it is one of the least understood presolar grain types. An isotopically anomalous component Xe-HL is carried by diamond and is characterized by excesses in both the light, p-process only isotopes (124 and 126) and the heavy, r-process only isotopes (134 and 136). These excesses are always correlated although physical settings of these two processes are quite different and there is little reason to always correlate each other. Furthermore, the r-process Xe and the p-process Xe in diamond inferred from Xe-HL are quite different from what is derived from the solar system abundance as well as stellar models. Further studies are needed to investigate these outstanding problems for over three decades.

Keywords: presolar diamond, isotopic anomalies, meteorites, supernovae, p-process, r-process
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INTRODUCTION

Meteorites formed 4.6 billion years ago along with other solar system objects. Until the late sixties, it was believed that the solar nebula, from which the planets and meteorites formed, was completely homogenized and that the Solar System was isotopically uniform. This idea began to be questioned when Black and Pepin [1] analyzed Ne in a fragment from the Orgueil meteorite by stepwise heating and found that $^{20}Ne/^{22}Ne$ ratios in high temperature fractions (800 – 1000°C) were much lower (down to 4, air: 9.8) than those commonly observed in meteorites, indicating the presence of a ^{22}Ne-rich component. This component was named Ne-E because alphabets from A to D had already been taken for other Ne components. In subsequent studies, upper limits of $^{20}Ne/^{22}Ne$ of Ne-E became even lower, and this convinced many that some meteorites contain stardust that survived the solar system formation. Other isotopically anomalous noble gas components were also found in meteorites. Xe-HL shows enrichment in both *l*ight (124 and 126) and *h*eavy (134 and 136) isotopes [2]. Kr-S and Xe-S are characterized by enrichment in the s-process only isotopes [3]. A quest for the minerals that contain these noble gas components ultimately led the discovery of presolar grains, opening up a new field of astronomy [e.g., 4].

Presolar grains are defined as stardust that formed in the stellar outflow or ejecta, and was later incorporated in meteorites. This implies that presolar grains are older than the Solar System, a very reason we call *pre*solar grains. Presolar grains identified to date include diamond [5], SiC [6, 7], graphite [8], oxides [9], silicates [10-12], Si_3N_4 [13] and refractory carbides [14]. Their abundances range from a few hundred ppm (diamond, silicates) to a few ppb (Si_3N_4). Of them diamond was the first mineral type that was isolated and identified from meteorites [5], yet it is the least understood carbonaceous type of presolar grains. One of the reasons is that diamonds are very small (average 3nm [15]) and only bulk (≡aggregates of grains) analysis is possible.

In this paper, we will review outstanding problems of presolar diamonds relevant to nucleosynthetic processes in stars.

PRESOLAR DIAMOND

Outstanding Problems of Presolar Diamond

Diamond is the carrier of Xe-HL that is characterized by enrichment in the p-process only isotopes, 124 and 126, and the r-process only isotopes, 134 and 136 (Fig. 1). Excesses in the light isotopes and those in the heavy isotopes are separately called Xe-L and Xe-H, respectively. Interestingly, Xe-L and Xe-H are always positively correlated: the higher the former, the higher the latter. This correlation has been observed in all diamond separates from any kinds of meteorites.

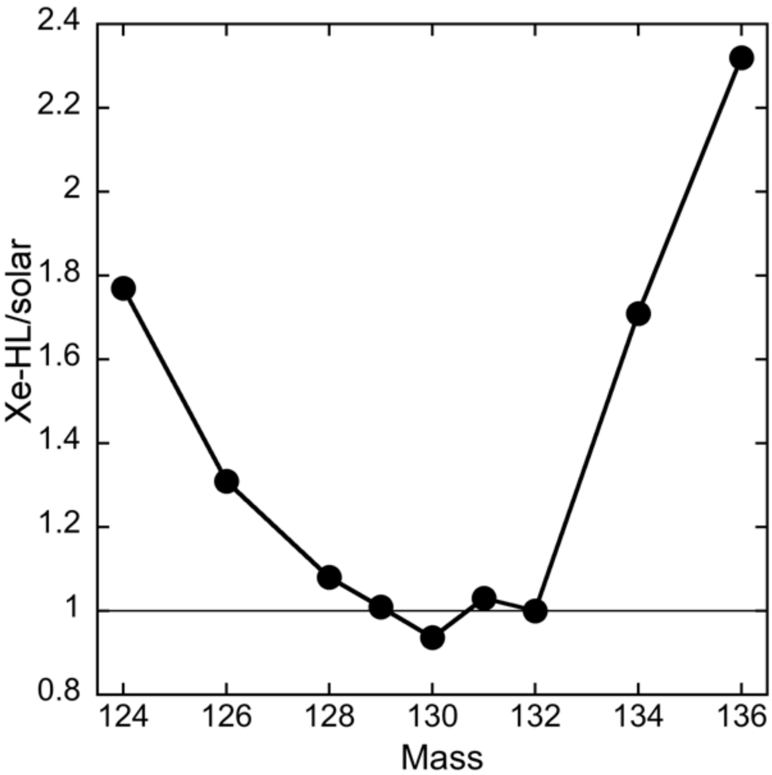

FIGURE 1. The Xe-HL pattern [16]. Xenon isotopes are normalized by ^{132}Xe and the solar ratios. Excesses in the p-process only isotopes and the r-process only isotopes are always observed together.

The close association of the two different nucleosynthetic processes is indeed odd. The p-process is considered to occur in the O/Ne zone in supernovae [17]. It is photo-disintegration processes [(γ,n), (γ,p) and (γ,α)] of pre-existing neutron-rich nuclei under high temperature ($T > \sim 2\times10^9$ K). The r-process is thought to occur in neutrino-driven winds from the neutron star of core-collapse supernovae [18], although the "hot bubble (high entropy)" region which is believed to appear just after the creation of a newly-born proto-neutron star in the core-collapse supernova explosion, neutron star – neutron star binaries, and neutron star – black hole binaries are other candidates. Thus, the isotopes produced by the two completely different processes, which are expected to happen in different physical settings, do not always have to be correlated as what has been observed in diamonds.

Furthermore, the r-process Xe and the p-process Xe inferred from Xe-HL are not what are expected either from the solar system abundance or from stellar models. Assuming that Xe-HL comprises the p-process Xe, the r-process Xe and solar Xe (Xe-HL contains 128 and 130 that are s-process only isotopes. Therefore, Xe-HL must contain a component other than those originated from the p-process and the r-process), Ott [19] inferred the 134/136 ratio of the r-process Xe in diamond to be 0.699 and the 124/126 ratio of the p-process Xe in diamond to be 2.205. These ratios are markedly different from the p-process and the r-process Xe in the Solar System: the r-process 134/136 is derived to be 1.207 after a small correction for the s-process Xe in SiC (although 134 is dominantly produced by the r-process, a small amount of 134 is produced by the s-process) [19]. The p-process Xe in the Solar System is 1.157, taking the ratio of 124 and 126 from the solar abundance. Model calculations of supernovae also predict ratios close to the p-process Xe in the Solar System: Rayet et al. [17] derived 124/126 ratios of stars with mass between 13 and 25 M_{sun} range from 0.952 to 1.188.

Studies on Presolar Diamond

Theoretical Studies

A first attempt to quantitatively explain the Xe-H pattern was made by Howard et al. [20]. They invoked a neutron burst (where the neutron density is lower than that of the r-process), selected one neutron irradiation history, and successfully reproduced Xe-H. Later, Ott [19] proposed the "rapid separation scenario" where unstable precursors with different half-lives are separated from Xe at a proper time to produce the Xe-H pattern: ^{136}Te ($T_{1/2}$ = 17.5 s) and ^{136}I ($T_{1/2}$ = 1.39 m) decay to ^{136}Xe, while ^{134}Te ($T_{1/2}$ = 42 m) and ^{134}I ($T_{1/2}$ = 53 m) decay to ^{134}Xe. The precursors of ^{136}Xe have shorter half-lives than those of ^{134}Xe. If Te and I are separated from Xe before ^{134}Te and ^{134}I completely decay, ^{136}Xe becomes more abundant than ^{134}Xe. The "correct" time for the separation is 8000 seconds after the r-process takes place. Ott [19] applied the same approach to explain Xe-L. This scenario, however, requires very precise timing of the separation. Diamonds in meteorites are undoubtedly formed in more than one supernova. According to this scenario, the separation should have taken place at the "right" time in most supernovae that produced diamonds in meteorites. It is not probable, if not impossible, that most supernovae experienced the same "separation" time.

Another scenario proposed to explain Xe-H is to mix material experienced neutron-burst and solar Xe [21]. However, Xe-L left unexplained in this scenario.

In any case, it has not been satisfactorily explained either why Xe-L and Xe-H are always correlated or why the p- and r-process Xe in diamond are different from those derived from the solar system abundance or stellar models.

Experimental Studies

Compared with huge isotopic anomalies of Xe, those of other heavy elements in diamond are bewilderingly small. Lewis et al. [22] reported Ba and Sr analysis of an Allende diamond separate, using a procedure of cold combustion of diamonds. The highest isotopic anomaly found in Ba is 6.0±1.5 ε in $^{137}Ba/^{138}Ba$ (both isotopes are s- and r-process isotopes){$\varepsilon \equiv [(^{137}Ba/^{138}Ba)_{diamond}/(^{137}Ba/^{138}Ba)_{solar} - 1]\times 10000$} and that in Sr is 120±1 ε in $^{87}Sr/^{88}Sr$ (^{87}Sr: s-process-only isotope, ^{88}Sr: s- and r-processes isotope). Since the Sr and Ba concentrations in the separate was very low, they dismissed the possibility that extremely anomalous Sr and Ba are diluted with a huge amount of normal Sr and Ba because of their low concentrations.

Tellurium isotopic ratios in presolar diamonds were analyzed by Richter et al. [23] and Mass et al. [24]. The r-process only isotopes, ^{128}Te and ^{130}Te show slight excesses [$\delta(^{128}Te/^{124}Te) = 4.0 \pm 1.5$ ‰, $\delta(^{130}Te/^{124}Te) = 9.3 \pm 2.8$ ‰]{$\delta(^{128}Te/^{124}Te)$ ‰ $\equiv [(^{128}Te/^{124}Te)_{diamond}/(^{128}Te/^{124}Te)_{solar} - 1] \times 1000$} [24]. Palladium also shows an elevated $\delta(^{110}Pd/^{104}Pd)$ value of 9.4 ± 5.7 ‰ (^{110}Pd is a r-process only isotope, while ^{104}Pd is an s-process only isotope) [24]. These anomalies are much smaller than those of Xe. Yet they are qualitatively consistent with the rapid separation model as well as the neutron burst model.

CONCLUSIONS

Diamond is the carrier of an isotopically anomalous Xe component, Xe-HL, and the first mineral type of presolar grains that was isolated from meteorites in 1987. Yet it is one of the least understood presolar grain types. A close association of excesses in the p-process only isotopes, 124 and 126, and those in the r-process only isotopes, 134 and 136, is puzzling. Furthermore, the r-process and the p-process in diamond are different from what is derived either from the solar system abundance or from stellar models. Further studies are needed to unlock these outstanding problems.

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