ON ORIGIN OF Xe-HL IN METEORITIC NANODIAMONDS. Galina K. Ustinova , Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow V-334, 119991 Russia; E-mail: ustinova@dubna.net.ru

Xenon in the Presolar Diamonds: The finest grains of nanodiamonds identified in the carbonaceous and nonequilibrium ordinary chondrites are the most abundant relic grains, for which, as well as for the silicon carbide and graphite, the presolar origin is assumed [1].They could be apparently formed by condensation in cool stellar atmospheres or in the extreme *PT*-conditions of reprocessing the matter by shock waves at the supernova explosions [2]. The supposition of the presolar nature of the nanodiamond grains is based on the distinctive isotopic anomalies of the noble gases, which were trapped by the grains at their synthesis and growth or they were impregnated into the grains later [1].

Apparently, the xenon anomaly is the most intriguing and the widely discussed one. In the case of the presolar diamonds the bimodal behavior of the xenon release is observed: mainly as the Xe-P_3 component with the normal isotopic composition in the low temperature range, and as the anomalous Xe-*HL* component with an exotic isotopic composition in the high temperature range [1]. In comparison with the solar xenon, the Xe-*HL* component is about twice enriched with the light neutron-deficient isotopes ^{124}Xe, ^{126}Xe, as well as with the heavy neutron-rich isotopes ^{134}Xe, ^{136}Xe. In the 9-isotopic system of xenon, different isotopes were formed in different nucleosynthesis processes. The heavy neutron-rich isotopes ^{131,132,134,136}Xe are the products of the *r*-process; they can also be formed in the fission of ^{244}Pu and ^{238}U. The $^{128–130}$Xe isotopes are the products of the *s*-process, but ^{129}Xe can also be radiogenic because of the decay of the extinct radionuclide ^{129}I. Finally, the neutron-deficient isotopes ^{124,126}Xe are products of the *p*-process. At the same time, all isotopes of Xe may have cosmogenic components, formed in the spallation reactions of Ba, Cs, Ce, and La with high-energy particles.

The protosolar matter was mainly formed from matter of a giant gas–dust nebula, which, during its 10-Myr lifetime before collapse had been uniformly mixed with the products of nucleosynthesis of about ten supernovae by supersonic turbulence [3]. Namely from the results of such mixing, one should deduce the primordial isotopic composition of many noble gases, and, first of all, the heavy xenon. In the process of further evolution of the matter, the isotopic relations of gases might be changed, being subjected to different mechanisms of fractionation, which, for the most part, were delimited by the different spatial and temporal intervals for the different gases in different objects. Because of different location and different temperature of release, the Xe-P_3 and Xe-*HL* components are considered to be formed as individual components before their implantation into the diamond grains, which, besides, was different in time: while the Xe-*HL* implantation was rather transient, the Xe-P_3 implantation was prolonged in time [4]. Therefore, the Xe-P_3 reservoir was rather permanent, whereas the Xe-*HL* reservoir was, apparently, of short duration. Since the Xe-*HL* component is observed only in nanodiamonds and it is absent in other presolar relics of meteorites, it is natural to suppose that this component was formed under the same conditions, in which the nanodiamond was synthesized, in particular, under the conditions of shock-wave reprocessing of the matter at the supernova explosions. Hence, it appears logically that just the regularities of fractionation and peculiarities of change of the noble gas isotopic relations during the propagation of strong shock waves [5,6], represented the cause of the exotic isotopic composition of Xe-*HL*.

Shock Wave Effects in the Noble Gas Isotopic Systems: There are two key factors of the shock wave impact on the isotopic composition of medium of their propagation: at the front of shock waves the enhancement of the rigidity of the spectrum of nuclear-active particles (1) and its enrichment with heavier ions (2) take place.

(1) A tremendous explosive wave and supersonic turbulence led to the acceleration of particles in the cosmic plasma with the formation of a power law energy spectrum $F(>E_0) \sim E^{-\gamma}$ of very high hardness ($\gamma \rightarrow 1$) [7,8]. A shock wave picks up new particles from the background plasma and pumps over the particles from the low-energy part of the spectrum to its high-energy part. This leads to an increase in fluxes of nuclear active particles with energies above E_0 by 1–2 orders of magnitude, and, accordingly, to the increase of spallation production rates of isotopes [5,6]. Since the spectrum of nuclear active particles is changed due to shock-wave acceleration, for many isotopes, whose excitation functions are sensitive to the form of the energy spectrum of particles, the weighted spectrum-averaged production cross sections vary as well. As a result, the isotopic and elemental ratios in reservoirs reprocessed by shock waves, for instance, in the expanding supernova shells, should be quite different from those in the matter not touched by such reprocessing.

(2) Another remarkable feature of magneto hydrodynamic acceleration of particles at the shock-

wave front is the enrichment of their spectrum with heavy ions. In the case of multiply charged ions, their path before scattering is a function of rigidity $R=p/Ze$ (where p is the momentum of particles proportional to A and Ze is the ion charge) and, hence, the acceleration efficiency depends on the A/Z ratio: ions with higher A/Z (a large free path) come to the preshock area (acceleration region) from farther distances, and, therefore, are accelerated more frequently [9,10]. The inferences of the contemporary nonlinear kinetic theory of shock wave acceleration of particles in supernova remnants [8, 10] testify that the enrichment of the spectra of particles with heavy nuclei depends on the parameters of supernovae (on the quantity of the nucleosynthesis products with certain values of A and Z), as well as on the parameters (on the power) of the explosive (collisionless) shock waves, e.g. on the injection rate into the acceleration regime, which also is a function of the rigidity of particles, and, therefore, a function of A/Z too.

Xe-*HL*: The above mentioned peculiarities of impact of explosive shock waves from the supernova explosion on the change of the isotopic ratios and fractionation of matter at the fronts of shock waves had manifest themselves strongly in the isotopic compositions of noble gases [5,6]. There is a comparison in the table below: by how many times the isotopic ratios in Xe-HL are higher than in Xe-P3 (* according to the data of [1]) and by how many times the isotopic ratios of cosmogenic xenon generated at the front of shock waves (at $\gamma\sim1$) are higher than those in the case of the calm medium ($\gamma=3$). The best agreement is for light neutron-deficient isotopes, which are mostly produced in spallation and other reactions with protons (*p*-process). It serves as a natural evidence of genesis of the light Xe-*L* component just in the rigid radiation conditions of the pre-fronts of the explosive shock waves. Moreover, as seen from the table, the characteristic *s*-process features of the relations of the medium-mass isotopes of xenon can be formed also in spallation reactions with protons accelerated at the front of the explosive shock waves. This conclusion is very important. The point is that *s*-process is absent at the supernova explosion, which violates the unity of the conception of synthesis of nanodiamonds with the observed xenon isotope relations in that process: one should attract a possibility of the preliminary generation of Xe-*S* in atmospheres of AGB stars and artificial models of required mixing of the matter [11].

Ratios	^{124}Xe/^{132}Xe	^{126}Xe/^{132}Xe	^{128}Xe/^{132}Xe	^{129}Xe/^{132}Xe	^{130}Xe/^{132}Xe	^{131}Xe/^{132}Xe	^{134}Xe/^{132}Xe	^{136}Xe/^{132}Xe
Xe-HL*/Xe-P3	1.86	1.43	1.12	1.02	0.97	1.03	1.85	2.26
Xe($\gamma\sim1$)/Xe($\gamma=3$)	1.87	1.53	1.17	0.94	1.09	0.92	1.38	1.44

As follows from the table, the spallation reactions at the front of the shock waves are insufficient only for the production of the heaviest isotopes ^{134,136}Xe, and an additional nucleogenetic source is required. It is natural that the local regions of supernova remnants before their complete mixing with the matter of protostar nebula or interstellar medium are enriched with the products of nucleosynthesis, in particular, with heavy neutron-rich isotopes of xenon generated in *r*-process. In its turn, transient local regions of pre-fronts of the explosive shock waves are the most enriched reservoirs of these isotopes, supplementing the formation of the heavy component Xe-*H*.

The compression ratio of matter in the pre-front range is the unlimited function of the Mach number and it can reach the values exceeding the average compression ratio $\sigma\sim4$ in shock waves by several orders of magnitude (at $M = 330$, $\sigma \approx 77$) [8]. Withal, the temperature behind the front of such a shock wave decreases by 2.5 times. Similar conditions could be considered as ideal for rapid synthesis and condensation of the diamond crystals and their simultaneous enrichment with heavy Xe-*H*, as well as with light Xe-*L*, i.e. at simultaneous formation of the exotic Xe-*HL* component. It should be emphasized that synthesis of nanodiamonds and their enrichment with anomalous Xe-*HL* in the conditions of shock wave propagation from the supernova explosions are possible in the extreme *PT*-conditions of the pre-front range, as well as due to nucleation in the underpressure range behind the shock front and due to irradiation of the carbonaceous grains with high energy particles. The Xe-P_3 could be trapped too, but, most likely, that component was implanted later under the homogeneous mixing of the matter by supersonic turbulence, and this implantation continued up to the accretion of the meteorite parent bodies.

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