Vestnik Otdelenia nauk o Zemle RAN, VOL. 4, NZ9001, doi:10.2205/2012NZ_ASEMPG, 2012

# Meteoritic nanodiamonds and primary cosmic rays

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Isotopic anomalies of xenon in the nanodiamonds of chondrites testify to the rigid radiation and magneto hydrodynamic conditions at the last supernova explosion prior to formation of the Solar system.

*Key words: cosmic rays, astrophysical sources, shock waves, diffusive acceleration, meteoritic nanodiamonds, isotopic anomalies*

**Citation:** Ustinova, G. K. (2012), Meteoritic nanodiamonds and primary cosmic rays, *Vestn. Otd. nauk Zemle, 4*, NZ9001, doi:10.2205/2012NZ_ASEMPG

**Problems of origin of cosmic rays.** The origin of cosmic rays is one of the key present-day problems. Potential sources of cosmic rays can be both in the Galaxy (e.g., supernova outbursts, pulsars, explosions in the nucleus of the Galaxy), and in the Metagalaxy (e.g., close superclusters of galaxies, quasars) [*Berezinskii et al., 1990*]. Numerous models considering different astrophysical objects, combinations of them, and accompanying processes as possible sources of cosmic rays are developed. An adequacy criterion of models is their ability to reproduce the observed spectrum and composition of primary cosmic rays (PCRs), the energy range of which extends up to ~$10^{21}$ eV to date [*Haungs, 2009*]. Characteristic features of the PCR spectrum are changes of the spectral index, i.e., kinks of the spectrum at ~$10^{15}$–$10^{17}$ eV, at ~$10^{16}$–$10^{18}$ eV, and at the highest energies ≥$10^{19}$ eV, as well as the gradual enrichment of the spectrum with heavy ions: above $10^{17}$ eV the spectrum consists almost entirely of iron. There are two approaches to the interpretation of experimental data: nuclear physical and astrophysical. In the nuclear physical interpretation, observed features of the PCR spectrum are connected with the possible formation of new particles, new interactions, or new states of matter (e.g., quark-gluon plasma) at energies ≥$10^{15}$ eV, which could influence the spectrum character and PCR composition. However, recent experiments at the Large Hadron Collider (LHC) at the energy of the incident particle ≥$10^{16}$ eV did not show any deviations from the standard model of particles and interactions [*LHC News, 2010*], so this fact allows giving preference to the astrophysical aspect.

**Universal mechanism of cosmic ray acceleration:** The main sources of PCR in our Galaxy are supernova outbursts [*Berezinskii et al., 1990*]. A reliable justification of this hypothesis was the discovery of the universal mechanism of cosmic ray acceleration in shock waves accompanying supernova outbursts [*Berezhko, Krymsky, 1988*]. While the ejected matter of the supernova moves in the turbulent interstellar medium, a shock wave forms; it represents a magneto-hydrodynamic discontinuity, at the front of which in the matter compression region, the regular magnetic field undergoes a jump, and in addition, the stochastic magnetic field of the plasma turbulence develops; this creates scattering centers for the diffusive scattering of charged particles. The physical meaning of the acceleration mechanism is the following: as a result of the diffusive scattering, charged particles can repeatedly cross the compression region at the wave front, getting an energy increment in generated inductive electric fields; i.e., the longer particles are held in the wave front region, the more they are accelerated. In other words, the larger the particle velocity and, therefore, its path before the scattering, the more often and from larger distances the particle can return to the front region and get the velocity increment. As a result, the particle power-law energy spectrum forms: $F(E) \sim E^{-\gamma}$ with the index $\gamma = (\sigma + 2)/(\sigma - 1)$, where $\sigma$ is the degree of matter compression at the shock front [*Berezhko, Krymsky, 1988*]. Obviously, in strong shock waves (at $\sigma >> 1$), a very hard spectrum of accelerated particles (with $\gamma \to 1$) can be formed. Similarly, heavy ions with a large path will have a priority of acceleration; this leads to the enrichment of the spectrum with heavy ions proportionate to $A/Z$, where $A$ is the mass number and $Z$ is the ion charge.

In fact, the process of the diffusive acceleration of particles by shock waves is the knocking-out of new particles from the background plasma by the shock wave and the transferring of particles from the low-energy region of the spectrum to its high-energy part. This leads to the increase of fluxes of nuclear-active particles above the threshold energy of nuclear reactions and, accordingly, to the increase of the rate of isotope production in spallation reactions (see [*Ustinova, 2007*] and references therein). In addition, the change of the energy spectrum of nuclear-active particles leads to the change of the weighted spectrum-averaged cross sections for the production of many isotopes, excitation functions of which are sensitive to the particle spectrum shape. As a result, in reservoirs reprocessed by shock waves, for example, in expanding shells of supernovas, absolutely different isotopic and elemental ratios than those in matter not affected by such reprocessing are formed. Indeed, in samples of extraterrestrial matter, numerous isotopic anomalies that could have been caused by such violations of isotopic ratios are observed [*Ustinova, 2002; 2007; 2011a*].

**Isotopic anomalies of xenon in relic nanodiamond grains,** identified in carbonaceous and nonequilibrium ordinary chondrites [*Huss, Lewis, 1995*], are of particular interest. For meteoritic nanodiamonds, a bimodal character of xenon release is observed: mainly as the Xe-$P_3$ component with the almost-solar isotopic composition and as the anomalous Xe-*HL* component with the exotic isotopic composition (enriched about twice with light $^{124}$Xe, $^{126}$Xe isotopes and heavy $^{134}$Xe, $^{136}$Xe isotopes). Besides the processes of nucleosynthesis, all xenon isotopes could be produced in reactions of spallation of neighboring Ba, Cs, Ce, and La nuclei by high-energy particles [*Ustinova, 2007; 2011a*]. The anomalous Xe-HL in meteoritic nanodiamonds was formed simultaneously with nanodiamonds themselves during the shock wave propagation at the last supernova explosion before the formation of the Solar System [*Ustinova, 2011a*]. Indeed, since the conversion of the protosolar nebula into the protostar was accompanied by huge changes in the physical state of the matter, all of the previously synthesized nanodiamond grains, even if preserved, should have lost all their noble gases. But the last supernova was not the SnII [*Ustinova, 2007*]. The absence of excesses of heavy extinct radionuclides (products of the *r*-process) in CAI of carbonaceous chondrites with a formation interval of ~1 million years indicates that the last supernova during the formation of the Solar System was the carbon-detonation supernova SnIa which was devoid of both a heavy core and a hydrogen shell [*Ustinova, 2007*]. During its explosion, all of the rock-forming elements up to the iron peak are synthesized, but products of the *r*-process are absent. This fact puts spallation reactions in the key role of the generation of isotopes of xenon captured by nanodiamonds.

The modeling of rates of xenon isotope production in spallation reactions of neighboring Ba, Cs, Ce, and La nuclei by high-energy protons with different spectrum hardness (at variations of $\gamma$ from 1.1 to 6) shows [*Ustinova, 2011a*] (see rows 3 and 6 of the table 1) that the isotopic ratios observed in chondrites in the Xe-*HL* component are higher than the corresponding isotopic ratios in the Xe-$P_3$ component [*Huss, Lewis, 1995*] almost as much as isotopic ratios of xenon generated under hard radiation conditions of the matter reprocessing by shock waves ($\gamma$ = 1.1, for example, in expanding shells of supernovas) are higher than those in the matter not affected by such reprocessing ($\gamma$ = 3, for example, in the main volume of the protosolar cloud). This reveals the spallogenic nature of both anomalous and normal components of xenon and points to the different hardness of the energy spectrum of nuclear-active particles as the major cause of the difference in their isotopic systems.

The table 1 implies that spallation reactions are insufficient only for the generation of the heaviest $^{134}$Xe and $^{136}$Xe isotopes, and an additional nucleogenetic source is required. However, the most favorable for the synthesis of the nanodiamond front of the explosion shock wave was enriched with these isotopes because of the preferential acceleration of just heavy isotopes of the medium [*Berezhko, Krymsky, 1988*], in particular, of products of the *r*-process from previous explosions of SnII, at the shock front. Thus, during the nanodiamond synthesis in the shock wave from the SnIa explosion, the xenon produced in spallation reactions by protons which were accelerated by the shock wave was captured, and heavy isotopes of xenon from preceding explosions of supernovas, with which the wave front was enriched, were captured. This is what formed the anomalous Xe-*HL* component. The Xe-$P_3$, could be captured simultaneously, but most likely, this component was implanted later during the uniform mixing of the matter of the supernova and the protosolar cloud by supersonic turbulence.

The table 1 also allows comparing the observed isotopic ratios of the xenon in the Xe-*HL* component with theoretical ones at $\gamma = 1.1$ (row 7) and the observed isotopic ratios of the xenon in the Xe-$P_3$ component with theoretical ones at $\gamma = 3$ (row 8). It is seen well that the xenon preserved in the nanodiamond is significantly heavier than the originally generated xenon, and almost to the same extent for both components. The latter suggests that processes that led to such weighting occurred after the formation of these components, most likely, during the accretion. Indeed, the multiple acts of partial recrystallization of nanodiamond grains at the stage of the young Sun were accompanied by the diffusion and escaping of xenon from destroyed traps, cracks, and other disturbances of the crystal lattice and, consequently, led to the gradual enrichment of the isotopic system of the preserved xenon with heavy isotopes in comparison with its original isotopic system during the generation.

**Table 1.** Isotopic ratios of Xe in the observed Xe-*HL* [a] and Xe-$P_3$ [a] components in nanodiamonds of chondrites and the similar ratios, generated by the shock wave accelerated nuclear-active particles with various hardness of the energy spectrum $F(>E_0) \sim E^{-\gamma}$: at $\gamma = 1.1$ and $\gamma = 3$

| N | Xe components | $\frac{^{124}Xe}{^{132}Xe}$ | $\frac{^{126}Xe}{^{132}Xe}$ | $\frac{^{128}Xe}{^{132}Xe}$ | $\frac{^{129}Xe}{^{132}Xe}$ | $\frac{^{130}Xe}{^{132}Xe}$ | $\frac{^{131}Xe}{^{132}Xe}$ | $\frac{^{134}Xe}{^{132}Xe}$ | $\frac{^{136}Xe}{^{132}Xe}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | *Xe-HL* [a] | 0.0084 | 0.0057 | 0.091 | 1.06 | 0.154 | 0.844 | 0.636 | 0.7 |
| 2 | $Xe\text{-}P_3$ [a] | 0.0045 | 0.004 | 0.081 | 1.04 | 0.159 | 0.823 | 0.377 | 0.31 |
| 3 | $\frac{Xe-HL^{a}}{Xe-P_3^{a}}$ | **1.86** | **1.43** | **1.12** | **1.02** | **0.97** | **1.03** | **1.85** | **2.26** |
| 4 | $Xe\ (\gamma \sim 1)$ | 0.58 | 1.38 | 3.16 | 4.16 | 1.29 | 9.61 | 0.036 | 0.0065 |
| 5 | $Xe\ (\gamma = 3)$ | 0.31 | 0.90 | 2.69 | 4.44 | 1.18 | 10.44 | 0.026 | 0.0045 |
| 6 | $\frac{Xe\ (\gamma \sim 1)}{Xe\ (\gamma = 3)}$ | **1.87** | **1.53** | **1.17** | **0.94** | **1.09** | **0.92** | **1.38** | **1.44** |
| 7 | $\frac{Xe\ (\gamma \sim 1)}{Xe-HL^{a}}$ | 69.05 | 242.11 | 34.73 | 3.92 | 8.38 | 11.39 | 0.057 | 0.0093 |
| 8 | $\frac{Xe\ (\gamma = 3)}{Xe-P_3^{a}}$ | 68.89 | 225.00 | 33.21 | 4.27 | 7.42 | 12.69 | 0.069 | 0.0145 |

[a] According to data from [*Huss, Lewis, 1995*].

**Magneto hydrodynamic conditions in the early Solar system:** The obtained results demonstrate the quantitative estimations of isotope anomalies in the primordial matter due to the diffusive acceleration of cosmic rays by shock waves; these estimations represent a subtle tool for studying processes in the early Solar System [*Ustinova, 2011a*]. The magneto hydrodynamic conditions of particle acceleration at the stage of the free expansion of the shock wave during the SnIa explosion are concretized for the first time. The experimental evidence for the formation of the power law spectrum of particles with the index $\gamma = 1.1$ indicates that the degree of matter compression at the front of the explosion shock wave from the SnIa explosion was $\sigma = 31$, which corresponds to the Mach number $M \sim 97$ at $\sigma \sim M^{3/4}$ [*Ustinova, 2011b*]. This implies that the interstellar magnetic field ($B \sim 10^{-5}$ G), which is proportionate to the degree of compression, increased by a factor of 31 at the shock wave front, and the maximum energy of accelerated particles, which is proportionate to the magnetic field, increased by the same factor. Since the mean interstellar magnetic field is sufficient to accelerate protons to $\sim 10^{14}$ eV [*Berezinskii et al., 1990*], the energies of $\sim 3 \cdot 10^{15}$ eV were reached at the acceleration by the explosion shock wave. Further investigations should show how these energies were modified during the further evolution of the shock wave in accompanying processes, what fraction they contributed to the total PCR spectrum from different sources, and for what part of the spectrum they turned out to be the most operative. Indeed, the effects of high radiation conditions are observed in the extinct radionuclides in some refractory grains of the Ca and Al rich inclusions (CAI) of carbonaceous chondrites (see Figs. 1 and 2 for $^{26}$Al and $^{53}$Mn, respectively), as well as they follow from the abundances of isotopes of the light elements Li, Be and B (Fig.3) [*Ustinova, 2002*]. Since the interval of CAI formation is ~ 1 My [*Srinivasan et al, 1996*], the stage of free expansion of explosive shock wave was long enough and should make noticeable contribution to the formation of the highest energy part of integral spectrum of the primary cosmic rays.

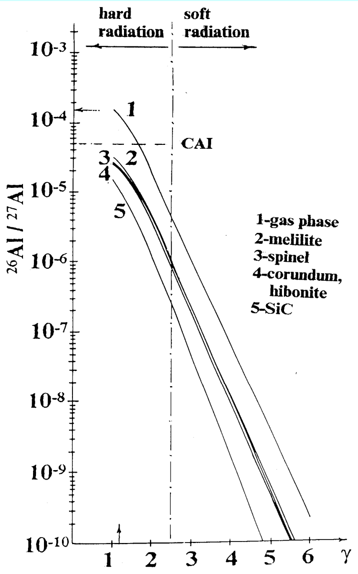


**Fig. 1** The observed range of $^{26}Al/^{27}Al$ in CAI of carbonaceous chondrites reaches ~$10^{-3}$ (while the canonic value, marked by the dashed line, is $5\cdot10^{-5}$), which corresponds to $\gamma$ ~1.

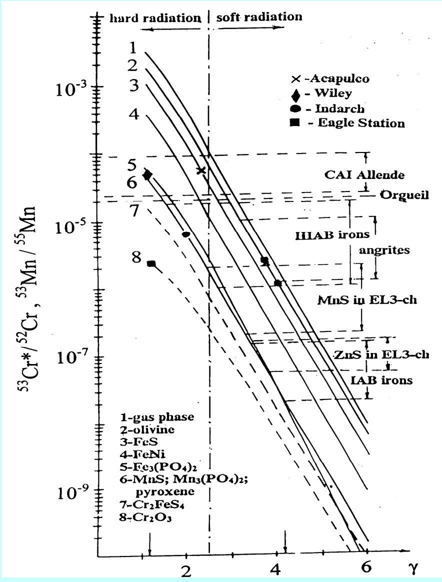


**Fig. 2** In CAI of the Allende carbonaceous chondrite, as well as, in some differentiated meteorites, the minerals with the $^{53}Mn/^{55}Mn$ relation, formed in spallation reactions at $\gamma$ ~1 are observed.

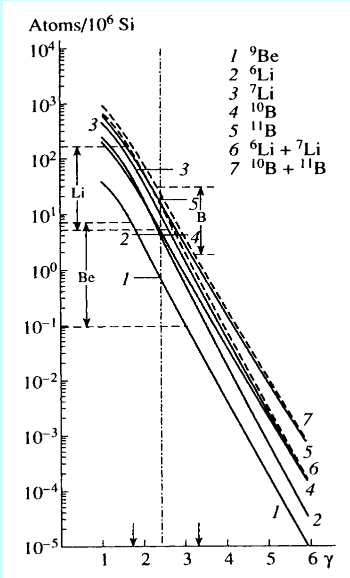


**Fig. 3** The measured range of abundances of Li, Be and B isotopes, in particular, $^{7}Li$, could be produced in spallation reactions with the shock wave accelerated particles if $\gamma$ ~1.

*This work is supported in part by the Program No. 22 of Fundamental Research of Russian Academy of Sciences.*

## References

Berezinskii, V. S., S. V.Bulanov, V. A. Dogiel', V. L. Ginzburg, and V. S. Ptuskin (1990). *Astrophysics of Cosmic Rays;* Elsevier: Amsterdam.

Berezhko, E. G., and G. F. Krymsky (1988). Acceleration of cosmic rays by shock waves. *Sov. Phys. Usp. 31*, pp. 27–51.

Haungs, A. (2009). *High-light talk 31st ICRC* Lodz. http://icrc2009.uni.lodz.pl/dl.php?fname=haungs.pdf

Huss, G. R., and R. S. Lewis (1995). Presolar diamond, SiC, and graphite in primitive chondrites: Abundances as a function of meteorite class and petrologic type. *GCA 59*, pp. 115–160.

LHC News (2010). http://elementy.ru/LHC/news

Srinivasan, G., S. Sahupal, A. A. Ulyanov, and J. N. Goswami (1996). Ion microprobe studies of Efremovka CAIs: II. Potassium isotope composition and $^{41}Ca$ in the early Solar system. *GCA* 60, pp. 1823–1835.

Ustinova, G. K. (2002). Mechanisms of Isotopic Heterogeneity Generation by Shock Waves in the Primary Matter of the Solar System, *Geochem. Intern., 40*, pp. 915–932.

Ustinova, G. K. (2007). On the problem of the Solar system origin: The regularities of noble gas fractionation in shock waves. *Sol. System Res. 41*, pp. 231–255.

Ustinova, G. K. (2011a). Production of anomalous Xe in nanodiamond in chondrites during the last supernova explosion predating the origin of the Solar system. *Geochem. Intern., 49,* pp. 555–567.

Ustinova, G. K. (2011b). Effects of the diffusive acceleration of particles by shock waves in the primordial matter of the Solar system. *Doklady Physics 56,* pp. 219–223.