THE NUCLEOSYNTHESIS OF DEUTERIUM AND HELIUM-3

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We have supposed a new model of the creation of D and ^{3}He in supernova of the first generation. It is based on the idea that a supernova event leads simultaneously to acceleration of particles in the shock wave front and to their interactions with supernova atmosphere matter. The D, ^{3}He, Li, Be, B and by-passed isotopes are created in these interactions. The cosmic abundances of the by-passed isotopes with $A \geqslant 113$ allowed to determine the integral proton flux - $I_p(E_p > 25$ MeV$)=5\times10^{21}$ cm^{-2}, the spectral index - $\gamma = 3$. The calculations of the D and ^{3}He yields in various nuclear reactions at these irradiation conditions show that only the ^{4}He(p,d)^{3}He reaction leads to cosmic abundances of these isotopes on the assumption that all matter has been exposed.

1. Introduction

The nucleosynthesis of D and ^{3}He is possible: (1) during expansion of the hot and dense Universe, (2)in spallation reactions of interstellar matter with galactic cosmic rays, (3)in high-energy ion reactions in shock wave front during explosions of supermassive objects and supernovae of Type II, (4)during momentary processes in active galactic nuclei, and (5)in reactions of interaction of neutrino from collapsing nucleous of supernova. The theoretical models of the expanding Universe explain the main observations of cosmological significance: (1)the red-shifts of distant galaxies, (2)the isotropic distribution of galaxies, (3) the homogeneous distribution of nearby galaxies, (4) the distribution of distant galaxies and radio sources, (5)the microwave background, (6)the X-ray background, and (7)the chemical and isotopic compositions of the initial matter. The D, ^{3}He, ^{4}He, and ^{7}Li cosmological abundances and the microwave background properties are the most informative characteristics for investigation of the physical conditions in the early Universe. The observated tendency of the decreasing of the initial component parts of $Y_p(^4He) \approx 0.22-0.245$, $D/H \approx (2 \div 0.5)\times 10^5$, $^3He/H=(1-2)\times10^{5}$ and $^7Li/H=1\times10^{-9}$ /1/ leads to serious difficulties of the cosmological models. Even the standard isotropic and homogeneous models with the zero lepton number /1,2/ do not allow to obtain the cosmic abundances of ^{4}He and deuterium at anyone entropy value. Therefore the investigation of a possibility of the galactic nucleosynthesis of deuterium is important for the problem of an initial nucleosynthesis in the early Universe.

A few possible classes of objects may be responsible for most of the galactic nucleosynthesis of deuterium. These are: (1)the explosion of supermassive objects, (2)supernovae of Type II, (3)the active galactic nuclei and quasars, and (4)interstellar gas.Two main processes have led to the formation of deuterium. One of them is the spallation in supernova shocks /3, 4/. The propagation of the supernova explosion shock wave in the density gradient of the stellar envelope results in a shock of increasing strength. The acceleration of matter by the shock wave has previously been associated with the formation of cosmic rays. In the peculiar very low density conditions of a presumed red-giant envelope, a strong shock wave, ~ 10 MeV per nucleon in 10^{-3} to 10^{-4} stellar mass fraction, can result in the nearly complete spallation of He plus heaviers to free neutrons and protons. The neutron capture on the protons has led to creation of deuterium.The other group of processes includes the spallation reactions with galactic cosmic rays in the interstellar gas /5,6/.

We have examined a possibility of the creation of deuterium and helium-3 in a massive supernova of the first generation. Our model is based on the idea that a supernova event leads simultaneously to explosive nuclei burning, to acceleration of particles in the front of a shock wave and their interactions with the atoms in supernova atmosphere /7,8/.

2. Nuclear reactions of the synthesis of deuterium and helium-3

We have examined the following nuclear reactions: $H(p,\beta^+)D$, $^4He(p,d)^3He$, $^4He(p,2p)^3H$, $^4He(p,pn)^3He$, $^4He(p,pd)D$, and $^4He(p,2pn)D$ with the threshold energies of ~ 300, 18.32, 19.81, 20.55, 23.75, and 25.97 MeV, respectively. The second reaction is the most probable. Its function dependence of $d\sigma/d\Omega$ from Θ has been only determined at the proton energies of 31.5 MeV /10/, 55 MeV /11/, and 93 MeV /12/. Using the method of graphic interpolation on the energy regions of < 30 MeV and > 100 MeV we have obtained the excitation function for the $^4He(p,d)^3He$ reaction (see Figure, curve 1). The excitation function of the $H(p,\beta^+)D$ reaction has been obtained in accordance with the experimental data /12, 13/ (see Figure, curve II).

The experimental data for the cross sections of the break up reactions of $^4He(p,2p)^3H$, $^4He(p,pn)^3He$, $^4He(p,pd)D$, and $^4He(p,2pn)D$ are absent. However, it was possible to make a comparison of the total cross section of the break up reactions at $E_p = 55$ MeV with

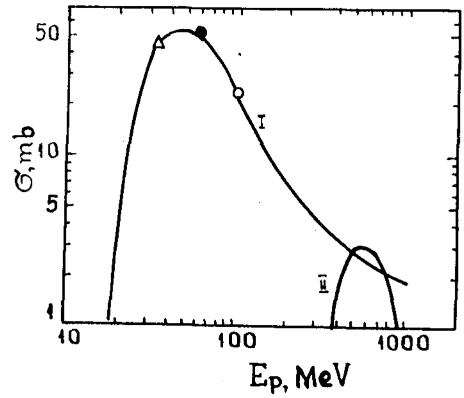

Figure. The excitation functions: I -the $^4He(p,d)^3He$ reaction from /10-12/, II - the $H(p,\beta^+)D$ - reaction from /12,13/. 1-from /10/, 2-from /11/, and 3-from /12/.

corresponding value for the $^4He(p,D)^3He$ reaction /11/. They are equal to 50-80 mb and 40 mb respectively. Hence, the contribution from the break up reactions doubles the yields of deuterium and helium-3. The observed and calculated abundances of deuterium and helium-3 are given in the Table. The calculations have been made at the following parameters: (1) the cosmic abundances of the seed nuclei /9/, (2) $I_p(E_p \geqslant 25MeV) = 5x10^{21}$ cm^{-2}, (3) the spectral index of $\gamma=2.5$. The cross-section of each reaction was averaged according to the energetic spectrum of galactic cosmic rays, as well as averaged according to the isotopic elemental compositions of the irradiated matter.

TABLE. The calculated and observed abundances of deuterium and helium-3 (atoms/10^6 atoms Si)

Target	Isotope	$\bar{\sigma}$, cm^{-2}	N calculated	N observed
^4He	^3He	$38.5x10^{-27}$	$4.2x10^5$	$3.7x10^5$
^4He	D	$38.5x10^{-27}$	$4.2x10^5$	$5.2x10^5$
H	D	$1.4x10^{-30}$	$2.2x10^2$	

These data show that the created in the $^4He(p,D)^3He$ reaction amounts of deuterium and helium-3 are comparable with the cosmic abundances of these isotopes on the assumption that all matter has been exposed. However, if we take into consideration the contribution of the break up reactions then the amount of irradiated matter will decrease up to ~50 per cent.

3. Conclusions

The nucleosynthesis of D and ^3He in supernova of the first generation puts a hard limitation in temperature and chemical composition of the envelopes where it had taken place. The temperatures of the C and O envelopes are high ($T \geqslant 10^7K$) and the D, ^3He, Li, Be, B isotopes, created by spallation reactions with the CNO nuclei, are destroied. Therefore, the D and ^3He creation had taken place only in the atmospheres of the first generation supernova and in interstellar gas which have cosmological composition (hydrogen and helium). The nucleosynthesis of the Li, Be and B isotopes had taken place in nuclear reactions during supernova events of the second generation stars /14/. These data lead to the conclusion that the matter, thrown of the supernova of the first generation, are not exposed to an intensive irradiation in interstellar space. This puts a limitation on models of the galactic structure formation and their evolution.

The D nucleosynthesis in the first generation supernovae not agree with the model of the Galaxy formation in a process of protogalaxy collapse. This model leads to an overproduction of Li, Be and B. To avoid the excess of these elements we examine a model of a homogeneous matter fragmentation with the formation of fragments of $M \sim (10^6 \div 10^8) M_\odot$. The collapse of latter led to formation of massive stars ($M > 100 M_\odot$) of the first generation which have simultaneously evolved. However, these stars have large mass-loss rates and expose the products of nuclear burning at the surface relatively early in their life. This material ejected in the stellar wind can mix with a nearby interstellar gas (and dust) prior to the supernova event. It also leads to an overproduction of Li, Be and B. This problem requires a detailed study.

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