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Neutron excess number and nucleosynthesis of heavy elements in type Ia supernova explosion

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Supernovae of the type Ia produce very powerful burst of light, which can be observed to high redshift. This fact is very attractive for cosmological applications. For supernova light curve modelling it is very important to know the amount of Fe and Ni, formed during the explosion. In this paper we explore both the chemical composition of the ejected supernova shells and the possibility of weak r-process under increased neutron excess number based on a set of trajectories of tracer particles, calculated in a hydrodynamical model of SNIa explosion. It is shown that no r-process elements are synthesized in the considered supernova model, even for an increased neutron excess number ($Y_e \sim 0.4$) because of the slow evolution of temperature and density along chosen trajectories. The results of explosive nucleosynthesis are discussed.

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Supernovae of the type Ia (SNIa) are currently used as "standardizable candles" to determine distances to distant galaxies. The discovery of accelerating expansion of the universe [1, 2] using SNIa showed the importance of these objects. Now they continue to be used to refine the parameters and constraints on the evolution of the Dark Energy.

During explosive nucleosynthesis of the SNIa a major part of new formed elements belong to the iron peak, including radioactive ^{56}Ni. The maximum luminosity of SNIa and the shape of the light curve depend strongly on the radioactive nickel isotope ^{56}Ni formed during explosive nucleosynthesis. Therefore, in addition to hydrodynamic simulations and modeling of the light curve, the calculations of explosive nucleosynthesis are important since they give the abundance and distribution of ^{56}Ni produced in the explosion.

Modelling full nucleosynthesis simultaneously with the explosion hydrodynamics of SNIa is a very difficult task, which has yet to be resolved. Usually these two processes are divided into the hydrodynamic part in which only energy release is treated on a small network of nuclear reactions. The detailed nucleosynthesis is considered later in a post-processing according to the calculated histories of temperature, density, and other characteristics of matter in tracer particles.

Different stages of nucleosynthesis in the consecutive stages of presupernova evolution, during the explosion of a supernova or in expanding ejecta are usually modeled separately, which leads to additional initial conditions and problems of cross-linking the numerical setup of the problems. We have developed a model realizing the full network of nuclear reactions taking into account all reactions not only with neutrons, protons, alpha particles, and photons, but also the processes of combustion of carbon, oxygen, silicon, and weak interactions. The model has been applied to the ivestigation of the whole picture of the evolution of the chemical composition from the nucleosynthesis on the stage of presupernova at high densities and temperatures up to the final stages of nucleosynthesis in the ejected layers (with the number of electrons per baryon, i.e. the parameter $Y_e = \langle Z/A \rangle$, close to 0.5).

The basic idea of SNIa explosion models is simple (in the single degenerate scenario): the mass of the white dwarf in a binary system grows as a result of accretion of

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matter from the companion. The increasing mass leads to the star contraction, and when the mass approaches the Chandrasekhar limit, runaway thermonuclear reactions in the central part of the star set in due to the thermal instability in the plasma with degenerate electron gas [3–5]. The runaway leads to explosion and complete disruption of the white dwarf.

The incineration of the white dwarf with the mass of $1.4 M_\odot$ consisting of equal amounts of ^{12}C carbon and ^{16}O oxygen to pure $1.399 M_\odot$ of ^{56}Ni would lead to the release of the thermonuclear energy of about $2.19 \cdot 10^{51}$ erg which would result in the complete destruction of the original white dwarf [6, 7]. Subtracting the gravitational binding energy of the white dwarf ($\approx (5-6) \cdot 10^{50}$ erg), and considering the fact that not all matter is burned to form Fe and Ni (intermediate elements such as Mg, Si, S, Ca are also partially formed), implies the observed explosion energy $\sim 10^{51}$ erg. The energy released in the decay chain $^{56}\mathrm{Ni} \to {}^{56}\mathrm{Co} \to {}^{56}\mathrm{Fe}$ explains the light curve. The detailed analysis of the observed light curves and spectra allows one to determine density and composition [8, 9] and confirms that at the explosion of the normal bright SNIa the CO-white dwarf is completely destroyed. Complete combustion of the white dwarf leads to the formation of heavier elements, preferably of the iron group, on average in an amount of $(0.6–0.8) M_\odot$, and lower amounts of intermediate-mass elements: Si, S, Ar, and Ca.

During thermonuclear burning of carbon and oxygen at the initial stage of explosive nucleosynthesis in the above type Ia supernova explosion scenario [10, 11] the formation of new nuclei and elements proceeds, in general, due to reactions with charged particles. With the drop in temperature, density and the rate of the nucleosynthesis, after the termination of α-process [12] the formation of new nuclei can go on, if a sufficient number of free neutrons is available, via a dynamic r-process [13]. The process of formation of the heavy nuclei (with $Z > 26$) before the r-process with an excess of neutrons significantly reduces the demands on both the neutron source (it requires minimal number of free neutrons) and on seed nuclei – they are produced in reactions with charged particles.

Numerous investigations and simulations of SNIa explosions (see [3, 14] and citations in these papers) show that the composition of the white dwarf is close to $Y(^{12}\mathrm{C}) \approx Y(^{16}\mathrm{O}) \approx 0.5$. The detailed analysis of the synthetic spectra and light curves of SNIa obtained from the modeling of explosions and the comparison with observations imply that the nucleosynthesis calculations with such an initial composition of the SNIa core is also close to the observed one in the outer layers. It is found also that the changes in the initial composition have weak influence on the final results of nucleosynthesis. On the other hand, the changes in nucleosynthesis conditions strongly dependent on the rate of the accretion in presupernova [14, 15]. That is why in this paper the nucleosynthesis along different trajectories is considered under assumption of constant initial composition of $\mathrm{C + O}$ core.

In addition to calculating the yields of the iron group elements in these models, it was also interesting to examine the yields of heavy elements, produced beyond the iron peak by neutron flux after freeze-out of reactions with charged particles.

For the conditions that we consider in the expanding ejecta, when $T_9 < 5$ and $\rho < 10^8$, the value of Y_e changes on the time scale comparable with the hydrodynamic scale during freeze-out due to different reactions driven by the weak interactions. After the freeze-out phase, when neutron density is high enough for the r-process, Y_e grows mainly due to beta decay.

There are at least 2 groups of the r-process scenarios [16, 17]. The first group supposes nucleosynthesis of heavy elements with atomic masses $A > 120$ in the environment of a very high free neutron number. Such conditions can be reached in neutron star mergers [18, 19] or in jets [20]. The details of a typical scenario from the second group, in which chemical elements in the mass range $60 < A < 120$ can be formed, are not known yet. There are some models which can be included in the group: the model of helium flash [21, 22]; neutrino-induced nucleosynthesis in the shells of collapsing SN [23], and formation of the conditions for weak r-process in central parts of a low mass SNIa, if there is a shell with high neutron excess $\eta = (N-Z)/A$ or, accordingly, with small $Y_e = (1-\eta)/2$ [24, 25], during deflagration of a CO-core [26, 27].

In [13, 27] it was supposed that formation of chemical elements with masses $60 < A < 120$ can occur in low mass supernovae not only in (n,γ)-reactions, but mostly in the reactions with charged particles at least at the beginning of the process of rapid nucleosynthesis, [28], which is the transition stage from explosive nucleosynthesis to the r-process.

In present work we investigate explosive nucleosynthesis on the basis of three-dimensional hydrodynamical simulations in type Ia supernovae (model c3-3d-256-10) [29], in the framework of which the profile parameters of 10000 trajectories were calculated. The model c3-3d-256 gives the powerful enough explosion to be qualify as the typical SNIa explosion and is a good candidate at least to explosion strength and remnant composition. The trajectories of the model were defined for different equally spaced tracer particles. From the important for nucleosynthesis point of view we consider 10 representative trajectories, different mainly by maximum temperature reached on these trajectories. Nucleosynthesis calculations have been done for these trajectories described by profiles $\rho(t), T_9(t)$ taking into account strong, electromagnetic and also new for our model weak interactions, important for values of T_9 more than 5. Different final abundances for some trajectories (defined by tracer particles) are shown at the Fig. 1.

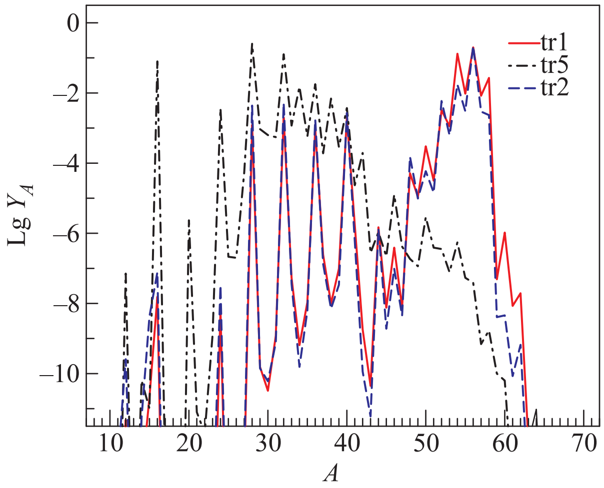

Fig. 1. (Color online) Logarithm of isotope abundances Y_A when temperature drops below value $T_9 \sim 1$ for some trajectories, along which the maximum value of T_9 was equal 3.2 (tracer particle 5), 5.3 (tracer particle 2), 7.6 (tracer particle 1), marked at the figure as tr5, tr2, and tr1 accordingly; $Y_e^0 = 0.498$

Usually α- and the r-process are considered separately. This leads to difficulties for evolution in the matching point. To avoid this, we applied the full nuclear net model [23] to the investigation of nucleosynthesis starting from conditions based on c3-3d-256-10s model, computed by MPA supernova group, [29] in different shells with model and parametric values of Y_e from ~ 0.5 down to 0.46 and calculated evolution of element composition during NSE, alpha-process and r-process (for smaller Y_e) phases.

For the correct description of nucleosynthesis (especially the explosive one) in the inner layers of ejecta, under the influence of the neutron flux, it is important to know the value of $Y_e = \langle Z/A \rangle$, which varies in the reactions of the weak interaction in layers where there is explosive burning, i.e. in process of electron and positron capture, beta decay, and neutrino/antineutrino capture. At high temperatures ($T_9 > 5$) and high density ($\rho \geq 10^8\,\mathrm{g\,cm^{-3}}$) [3], weak reactions of electron and positron captures on nucleons and nuclei leads to decreasing of Y_e and result in changes of final abundances, especially isotopes Fe, Co, Ni (see Fig. 1, abundances with mass numbers $A \approx 54-56$). Except previously considered reactions $\nu_e + n \leftrightarrows p + e^-$ and $\tilde{\nu}_e + p \leftrightarrows n + e^+$ the captures of electrons and positrons by nuclei were considered either.

Results of nucleosynthesis calculations for the typical composition of C + O core $Y_{\mathrm{C}} = 0.5$, $Y_{\mathrm{O}} = 0.475$, and $Y_{\mathrm{Ne}} = 0.025$ (model c3-3d-256-10s [29]) are shown at Figs. 2 and 3. For different shells the most abun-

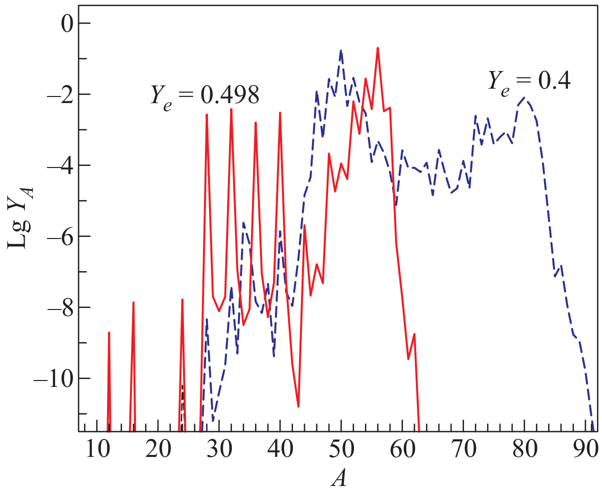

Fig. 2. (Color online) Logarithm of isotope abundances, derived in explosive nucleosynthesis for SNIa with C/O core and initial value of $Y_e = 0.498$ (line) and for the nucleosynthesis along the same trajectories, but for the increased neutron excess, i.e. lower $Y_e = 0.401$ (dashed line) for tracer 2 (where T_9 reaches 3.2)

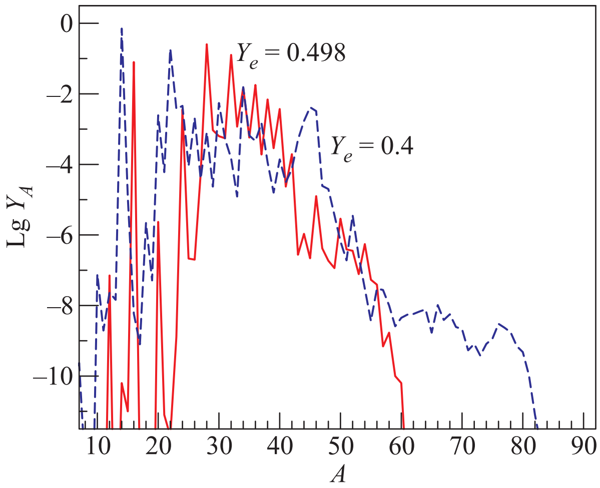

Fig. 3. (Color online) The same as at Fig. 2, but for tracer 5 (where maximum value of T_9 reaches 5.3)

dant nuclei are different: Si and neighbors (Fig. 2, the shell is far from the core) or Fe/Ni (Fig. 3, the shell is closer to the core). At the same figures the impossibility of heavy nuclei formation in the r-process are shown. The possible source of neutrons in supernova explosions is still unknown, and the value of Y_e was artificially decreased down to values, when free neutrons fraction is sufficient to support the r-process (see, for example [30]). The r-process nucleosynthesis should run in the explosive scenario with short nucleosynthesis duration time $\tau_r \sim n \cdot 0.1$ s. When neutron excess was increased (dashed lines at Figs. 2 and 3), a significant amount of nuclei with atomic masses up to $A \approx 80$ is formed. This result confirms previous parametric calculations of nucleosynthesis [13], but present results based on hydrodynamical trajectories, do not confirm the artificial scheme of the r-process, called rbc-process [26], which intended to explain the simultaneous nucleosynthesis of Fe-peak nuclei and r-process nuclei as well.

In conclusion we would like to emphasize that the growth of abundance yields of heavier nuclei with increasing of neutron excess in present nucleosynthesis calculations in exploding shells reproduce the abundance of nuclei with $A \sim 80$, formed in static nucleosynthesis [13], but heavier nuclei do not form. For nucleosynthesis nuclei formation the faster expansion of the shells is needed [31, 30].

Our present calculation of nucleosynthesis give the detailed distribution of iron peak isotopes and the obtained distributions of nickel and iron allow us to compute synthetic light curves on a very reliable basis. This will be the subject of our future research.

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