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Change of Nuclear Beta-Decay Characteristics in Strongly Heated Substance and *p*-Element Synthesis in Massive Stars

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Abstract: For "nuclear" temperatures (in the $(2 – 3)\cdot10^9$ K range) the rate temperature dependences of β processes in massive star matter are obtained. The thermal electron and positron nuclear β decays and electron captures (*K* capture and unbound electron capture) and photobeta decays from ground and excited nuclear states are considered. The quantum degeneracy of electron gas and the ionization of atomic *K* shells in a strongly heated substance are taken into account. For the multidecay odd-odd nuclei the temperature dependences of coefficients defining β^--decay fractions in their total lifetimes are calculated. It is shown that the distinction of this coefficients from the experimental values obtained under "normal" temperatures may be significant. The physical model of the *p*-isotope synthesis in massive star matter is suggested and *p* nucleus abundances are calculated. It is found that during the combustion of oxygen layer in a massive star for 19 from 33 *p*-nuclei it is possible to get their observed 'solar' abundances.

Keywords: photobeta decay, electron gas degeneracy, ionization degree of atomic shell, nuclear synthesis, abundance of p-isotope.

1 Introduction

As it is known, β-decay processes in the standard theory of the origin of chemical elements play an important role [1,2]. The final rate of nucleosynthesis in massive star matter depends on the ratio of β-decay rates and nucleus capture rates of slow (*s*-process) or rapid (*r*-process) neutrons.

The electronic β-decay is especially important in s-process when after the capture of a neutron by an atomic nucleus there is a chain of successive β-decays of daughter nuclei. It ends with a β-stable nucleus, after which it is repeated all over again. s-process is usually realized at relatively high temperatures of stellar matter in the quasi-equilibrium stages of a massive star evolution. This is the stage of helium combustion duration of which is up to 10^5 years when the stellar matter temperature reaches the values of $3T_8$ (hereafter we use the notation, $T_n = 10^n$ K), and oxygen combustion duration of which is up to six months when the substance is heated even more – up to (2–3) T_9, or 200-300 keV in terms of energy.

Although to a lesser degree the β-decay of nuclei is important for the *r*-process which plays a key role in the synthesis of heavy elements in supernovae. In the *r*-process neutron capture rate of nucleus in the reaction (n, γ) is much higher than the rate of the β-decay of the formed radioactive nuclei. Therefore at first few neutrons are captured. After that when the rate of the reaction (n, γ) become in less than the rate of the β-decay the formed nucleus undergoes β-decay after which everything is repeated again. The characteristic time for the *r*-process does not exceed 10^2 s but the stellar matter heating can be strong – up to several T_9. Naturally the rate of the β-decay will also define the rate of *r*-process.

In this work we are interested in β-processes only, in particular, by the effect on their rate of high temperature field of the matter in which they occur. As it was shown above the rate of synthesis of chemical elements at both explosive and quasi-equilibrium stages of a massive star evolution depends on the ratio of β-decay rate and neutron capture rate. During this process the temperature of the stellar matter in terms of energy can reach the "nuclear" values of 300 keV or more. A high temperature field can significantly change β-process rates. This change will affect the final yield of the chemical elements in the process of its synthesis.

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In [3-5] the possibility of changing β-decay properties of the nuclei was first noted. It is because the excited nuclear states can be populated due to the high temperature of matters. As a result β-decay is possible from these states what was not possible at "normal" temperatures. Such β-transitions in contrast to the transitions from the ground state of the nucleus are called thermal β-transitions. Subsequently, in [6] another β-process was proposed which was initiated by a thermal field. This is a photobeta decay. In this case a photon of the thermal field produces a virtual lepton pair and then a positron is absorbed by a nucleus with the emission of antineutrinos. In [3-6] mainly particular questions of nucleus synthesis in stars at quasi-equilibrium stages of their evolution were considered but these studies were not systematic. Subsequently, the physical mechanisms of the thermal β-decay and photobeta decay were used in [7-10] as the base to solve the problem of synthesis of p-nuclei (also known as "bypassed" nuclei). In particular, in [10] for a number of "problem" p-nuclei the possibility of obtaining their observed abundances taking into account both photobeta decay and thermal β-transitions was first investigated. As it turned out this approach explained the observed "solar" abundance of isotopes ^{113}In and ^{115}Sn considering their synthesis only at non-explosive stages. In addition, it was shown that at the high-temperature quasiequilibrium stages of a massive star evolution the channel of the thermal β-decay can be effective for ^{94}Mo and ^{98}Ru p-nuclei and channel of photobeta decay for ^{96}Mo p-nucleus.

The purpose of this study is to systematize various ways of influence of the high temperature field on the rates of nuclear β-decay processes in the matter of a massive star taking into account its physical characteristics. The thermal electron and positron decays of nuclei, thermal captures of atomic and free electrons by nuclei, photobeta decay from the ground and excited states of atomic nuclei will be considered. Corrections in the β-process rates will be introduced. They will consider the quantum degeneracy of the electron gas in the star matter and the degree of ionization of the atomic shell in a high temperature field.

Taking into account all the above mentioned modes of β-decay a physical model of the synthesis of p-nuclei (there are 33 of them) will be formulated and their abundances will be calculated. Only a quasi-equilibrium high temperature stage of the evolution of massive stars will be considered in the model. In this case the synthesis of p-nuclei passes along β-decay chain, $(A, Z)\rightarrow(A, Z+1)\rightarrow(A, Z+2)$, ($A$ and Z are mass and charge numbers of the (A, Z) nucleus). Here, the (A, Z) progenitor nucleus and $(A, Z+2)$ p-nucleus are β-stable nuclei, and for the transition to the p-nucleus it is necessary to overcome the energy threshold that takes place for (A, Z)→(A, Z+1) β-transition. For overcoming this threshold thermal and photobeta transitions in a strongly heated substance will be used. These transitions will be taken into account in the calculation of the β-process rates in all other links of the above β-decay chain.

$(A, Z+1)$ intermediate nuclide is a multibeta-decay nucleus. It has both the electron and positron β-activity and also decay by the way of electron capture. In the calculations of the p-nucleus abundances coefficients representing fraction of $(A, Z+1)\rightarrow(A, Z+2)$ electronic β-decay in the total lifetime of the $(A, Z+1)$ nucleus are usually required. In [9] these coefficients obtained in terrestrial conditions were used. However, in heated medium they depend on the temperature their values may differ from the laboratory values. This effect is also supposed to be studied.

2 Influence of High Temperature Field on Nuclear β-Processes

We will consider the nuclear β-processes in the substance with a given temperature, T. Let us list the effects due to which the thermal field and characteristics of the medium may affect the rates of β-processes:

1. Excited states of atomic nuclei will be populated and the degree of their population can be determined according to the Boltzmann distribution. This effect is significant when the temperature has a "nuclear" scale quantity, and it is more notable for the lowest states. The population of excited states that did not exist at "normal" temperatures under the laboratory conditions opens new channels of thermal β-transitions and there may be a lot of them. The whole picture of the nucleus β-decay can entirely change if the thermal β-transitions have a fewer degree of forbiddances in comparison with β-decay from the ground state of the nucleus. Just such a situation arose for ^{113}Cd→^{113}In and ^{115}In→^{115}Sn β-transitions of the fourth degree of the forbiddances mentioned above which resulted in a strong increase in total β-decay rates of ^{113}Cd and ^{115}In nuclei [10].

2. In the heated quasi-equilibrium medium, there is an electromagnetic field with a Planck spectrum of frequencies. Its photons interacting with a nucleus can also initiate β-decay and this decay can be endothermic. At the expense of the energy of the absorbed photon there is possibility of β-transition from the state of the parent nucleus to the above lying energy states of the daughter nucleus. This can also accelerate the β-process at the expense of β-transition of a fewer degree of forbiddance. In this process photobeta decay has the greatest intensity. It is an electron-positron pair production by a photon in a nuclear field then the absorption of the positron by the nucleus and antineutrinos emission [6]. Note that contrast to nuclear β-decay in the terrestrial conditions in the highly heated medium even β-stable nuclei can decay because of photo beta decay process.

3. There are effects which depend not only on the temperature but also on other physical characteristics of

the medium. Thus for the electronic β-decay the density of the electron gas in the star substance can influence β-decay rate through the Pauli principle. If the density is large then part of the final states for the emitted β-electron will be unavailable. Accordingly, the rates of all modes of electronic β-decay can change. This effect was pointed out in [3] for the first time. Later in [11] it was quantitatively shown as the electronic β-decay rate depends on the ratio of its boundary energy and the Fermi energy of electron gas. Accordingly, through latter we can get the rate dependence on the electron density in the star substance and the temperature. In the star substance there is always a certain amount of free electrons so it is necessary to evaluate the significance of this effect.

4. In the nucleosynthesis process along with electronic β-decay positron β-decay and electron capture from atomic shell of the nucleus can play an important role. In the latter case there are electrons on the low-lying atomic shells under terrestrial conditions and electron capture has no limits on this side. The situation is different in the extremely heated medium (up to the 200-300 keV nuclear temperature). This temperature is much higher than the binding energy of the electron even in the deepest *K*-shell and the atoms are ionized. Of course, if the atomic shell population where there is an electron captured by the nucleus decreases in the conditions of high ionization then it will change the rate of electron capture. The suppression of nuclear electron capture from atomic states because of the ionization of an atom under star conditions was indicated on in [5]. This effect also depends on the temperature and the characteristics of the medium such as the densities of the electron gas and ions the nuclei of which are involved in electron capture.

5. If the electronic capture from the bound atomic states is highly suppressed then it can be also compensated by the effect due to the presence of free electron gas in the star substance. We speak about free electron capture by a nucleus. This phenomenon was studied in [5, 12] and [13] where different approximate expressions for the capture rate were obtained and its dependence on the characteristics of the medium was researched.

Below, we present the modified expressions for the rates of all these processes which will be used to calculate the lifetime of the multidecay nuclei and *p*-element abundances.

3 Rates of Nuclear β-Processes in Strongly Heated Medium

In the medium with the given temperature, *T*, we obtain an expression for the total rate of β-decay. Taking into account the possibility of β-transitions from the excited states of the parent nucleus it is:

$$\lambda_{\xi}[(A,Z_i)\to(A,Z_f);T]=\sum_{a,b,n}P(E_a^{(i)},T)\lambda_{a\to b}^{(n)}[\xi;(A,Z_i)\to(A,Z_f);\Delta_{ab}^{(\xi)}] \quad \ldots\ldots\ldots (1)$$

Here, ξ is the control index that specifies the β-decay mode, Z_i and Z_f are charge numbers of parent and daughter nuclei respectively, $P(E_a^{(i)},T)$ is the population probability for state *a* of the (A, Z_i) parent nucleus at the energy, $E_a^{(i)}$, reckoned from its ground state

$$P(E_a^{(i)},T)=\frac{2j_a^{(i)}+1}{G_i(T)}\exp(-E_a^{(i)}/kT), \quad \ldots\ldots..(2)$$

where $j_a^{(i)}$ is the total spin of (A, Z_i) nucleus in state *a*, *k* is the Boltzmann constant, and G_i *(T)* is the partition function:

$$G_i(T)=\sum_a(2j_a^{(i)}+1)\exp(-E_a^{(i)}/kT)\cdot \quad \ldots\ldots(3)$$

$\lambda_{a\to b}^{(n)}[\xi;(A,Z_i)\to(A,Z_f);\Delta_{ab}^{(\xi)}]$ is the partial rate of the *n*-th-forbidden β-transition from the state, *a*, of the (A, Z_i) parent nucleus to state, *b*, of the (A, Z_f) daughter nucleus, $\Delta_{ab}^{(\xi)}$ is its energy. The specific form of these two values depends on the β-process mode. Below we give explicit expressions for the partial rates of the electrons ($\xi = \beta$) and positron ($\xi = \beta^+$) decay, *K*-electron capture ($\xi = \varepsilon_K$), the capture of free electrons ($\xi = \varepsilon_0$) and photo beta decay ($\xi = \gamma\beta$). In the heated medium the partial rates may also depend on the temperature.

3.1 Electron β-Decay ($\xi = \beta^-$).

The expression for the electron β-decay rate where we also take into account the possibility of β-transitions between the excited states of nuclei is (hereafter, we use the "natural" set of units $\hbar = c = m_e = 1$ where *c* is the speed of light and m_e is the electron mass)

$$\lambda_{a\to b}^{(n)}[\beta^-;(A,Z_i)\to(A,Z_i+1);\Delta_{ab}^{(\beta^-)}]=(2\pi^3)^{-1}\int_1^{\Delta_{ab}^{(\beta^-)}}E(E^2-1)^{1/2}\times \times[\Delta_{ab}^{(\beta^-)}-E]^2F_0(Z_i+1,E)C_{ab}^{(n)}(Z_i+1,E)[1-S(E,T)]dE. \quad ..(4)$$

Here, $\Delta_{ab}^{(\beta^-)}=E_a^{(i)}-E_b^{(f)}+Q_\beta$, where Q_β is the standard (in β-decay theory) notation of the energy released in the β^--transition between the ground states of the parent and daughter nuclei; that is, $Q_\beta=M(A,Z_i)-M(A,Z_i+1)$, where $M(A,Z)$ is the atomic mass of the (A, Z) nucleus, $E_b^{(f)}$ is the energy of state *b* of the (A, Z_f) daughter nucleus reckoned from its ground state. F_0 *(Z, E)* is the Fermi function that takes into account the action of the Coulomb field of the *(A, Z)*

daughter nucleus onto the β electron. We can calculate this function by the formula

$$F_0(Z,E) = 4(2pR)^{2(\gamma-1)} \frac{|\Gamma(\gamma+iy)|^2}{[\Gamma(2\gamma+1)]^2} e^{\pi y}, \quad \text{.....(5)}$$

where Γ(x) is the Euler gamma function; $p = \sqrt{E^2-1}$; R = 3.1x10-3 A1/3 is the radius of the nucleus being considered; $\gamma = \sqrt{1-(\alpha Z)^2}$, with α = 1/137.04 being the fine-structure constant; and y = αZE/p. For the Fermi function the tables are in [14] where there are also explicit expressions of the $C_{ab}^{(n)}(Z,E)$ factor. It is the shape of the spectrum of nth-forbidden β-transition, a→b; it depends quadratically on nuclear matrix elements and the standard combinations of electronic wave functions. Tables of their values are found in [14].

The shape of the spectrum $C_{ab}^{(n)}(Z,E)$ for the most intense allowed β decay (n = 0) which latter are going to be considered has the simplest form

$$C_{ab}^{(0)}(Z,E) = (\left|M_V^{(a\to b)}\right|^2 + \left|M_A^{(a\to b)}\right|^2) L_0(Z,E). \quad \text{.....(6)}$$

Here, $M_V^{(a\to b)} = g_V \int 1$ and $M_A^{(a\to b)} = g_A \int \boldsymbol{\sigma}$ are, respectively, the Fermi and Gamow-Teller nuclear matrix elements for the a→b β-transition (in standard notation), gV and gA being the respective coupling constants. For a purely Coulomb field the function L0 is $L_0 = (1+\gamma)/2 \approx 1$, but for the Coulomb field of a finite-size nucleus the value of this function will be different. However to a high precision, we can set $L_0(Z,E) \approx 1$ in this case irrespective of the decay type.

Finally, in Eq. (4) the factor $[1-S(E,T)]$ takes into account the fact that in the medium where there is β decay some final states in the phase space may be not available for β-electron. This factor allows for the possible degeneracy of the electron gas. For the ideal Fermi gas the function S (E, T) can be taken in the form of the Fermi distribution:

$$S(E,T) = \{1+\exp[(E-E_F)/kT]\}^{-1}, \quad \text{……(7)}$$

where EF is the chemical potential (the electron Fermi energy). It may be found from the normalization condition

$$\rho = (\mu_e/\pi^2 N_A)\int_0^\infty S(E,T)\, p^2 dp. \quad \text{…….(8)}$$

Here, μ_e is the average molar mass per one electron, ρ/μ_e is electron density and N_A is the Avogadro number.

3.2 Positron β-Decay (ξ = β+).

The rate of β+-decay, $\lambda_{a\to b}^{(n)}[\beta^+;(A,Z_i)\to(A,Z_i-1);\Delta_{ab}^{(\beta^+)}]$, can also be calculated by the Eq. (4) if we replace β-⟶β+, $Z_i+1 \longrightarrow Z_i-1$, put factor S (E) is equal to a zero and change $\Delta_{ab}^{(\beta^-)}$ to $\Delta_{ab}^{(\beta^+)} = E_a^{(i)} - E_b^{(f)} + Q_\beta^{(+)}$, where $Q_\beta^{(+)}$ is the energy emitted in the β+ transition between the ground states of the (A, Zi) and (A, Zi-1) nuclei: $Q_\beta^{(+)} = M(A,Z_i) - M(A,Z_i-1) - 2$ (β+ transition will occur only if $\Delta_{ab}^{(\beta^+)}$ >0). In addition for calculating the Coulomb Fermi function by the Eq. (5) it is necessary to replace y by (-y).

3.3 Electron K-Capture (ξ = εK).

The partial rate of electron K-capture of the allowed type (it will only be considered as the most intense) by the (A, Zi) parent nucleus is also modified to take into account the transitions between the excited states of nuclei. It can be calculated by the formula:

$$\lambda_{a\to b}^{(0)}[\varepsilon_K;(A,Z_i)\to(A,Z_i-1);\Delta_{ab}^{(\varepsilon_K)}] = (2\pi)^{-2}(\left|M_V^{(a\to b)}\right|^2 + \left|M_A^{(a\to b)}\right|^2)(\Delta_{ab}^{(\varepsilon_K)})^2 \beta_K^2. \quad \text{.....(9)}$$

Here, $\Delta_{ab}^{(\varepsilon K)} = Q_\beta^{(+)} + 1 - |E_K| + E_a^{(i)} - E_b^{(f)}$ where $Q_\beta^{(+)}$ was defined above, and EK and βK are, respectively, the bound state energy and the Coulomb amplitude of the wave function for a K-electron (there is a table of values in [14] for them). In Eq. (9) the factor considering the electron exchange is omitted as for the K-shell its value is almost equal to the unity.

In the heated medium in the expression Eq. (9) it is necessary to make a correction depending on the temperature and taking into account the degree of ionization of the K-shell of the atom the nucleus of which undergoes K-capture. In fact, this is the fraction of atoms of the considered type which have at least one electron on the K-shell. It can be calculated using the Saha-Boltzmann ionization equation (e.g. see [15]). According to this equation in the conditions of local thermodynamic equilibrium the Nn population of n-th quantum level of the given type i ion is [15]:

$$N_n = N_e N_i (2\pi/m_e kT)^{3/2} \hbar^3 (g_n/2) \exp[(\chi_r - \chi_n)/kT]. \quad \text{…….(10)}$$

Here, Ni and Ne are the concentration of ions and free electrons, respectively; g_n is statistical weight of n-th level (for the energy

level with spin J the statistical weight is equal to 2J+1); χ_r is the energy required to knock out an electron from the ground state of the r-multiple ionized atom, i.e. its ionization potential (table of these potentials for some ions is also in [15]); χ_n is the excitation energy of the n-th state reckoned from the ground state energy.

3.4 Free Electron Capture by Nucleus ($\xi = \varepsilon_0$).

The $\lambda^{(0)}_{a\to b}[\varepsilon_0;(A,Z_i)\to(A,Z_i-1);\Delta^{(\varepsilon_0)}_{ab}]$ rate of free electron capture by nucleus for which it is possible a positron decay of an allowed type under terrestrial conditions can be calculated by the formula obtained in [12]. We take into account the electron capture from *a* excited states of the parent nucleus into *b* state of the daughter nucleus,

$$\lambda^{(0)}_{a\to b}[\varepsilon_0;(A,Z_i)\to(A,Z_i-1);\Delta^{(\varepsilon_0)}_{ab}]=K_{ab}(T)\ln 2/(f_0t_{1/2})_+. \quad \text{.....(11)}$$

Here, $(f_0t_{1/2})_+$ is the reduced lifetime of the positron decay. We take either the value measured in the laboratory conditions or the $<f_0t_{1/2}>_0$ average value (the method of its calculation will be described in the following section). The $K_{ab}(T)$ statistical factor is

$$K_{ab}(T)=\int_{p_o}^{\infty}p^2(E+\Delta^{(\varepsilon_0)}_{ab})^2F_o(Z_i,E)S(E,T)dp, \quad \text{.....(12)}$$

where $\Delta^{(\varepsilon_0)}_{ab}=M(A,Z_i)-M(A,Z_i-1)+E^{(i)}_a-E^{(f)}_b$ and the values of $F_0(Z,E)$ and $S(E,T)$ are defined by Eq. (5) and (7) respectively; p_0=0 if $\Delta^{(\varepsilon_0)}_{ab}>-1$ (exoergic capture) and $p_0=[(\Delta^{(\varepsilon_0)}_{ab})^2-1]^{1/2}$ if $\Delta^{(\varepsilon_0)}_{ab}<-1$ (endoergic capture). For different special cases of the electron gas state the approximate expressions for the $K_{ab}(T)$ factor are in [12, 13].

3.5 Electronic Photobeta Decay ($\xi = \gamma\beta$).

The photobeta decay rate can be calculated by using the formula received in paper [6]. We made corrections in this formula taking into account the influence of the Coulomb field of the daughter nucleus on β-electron and the possibility of photobeta-transitions from the excited states of the parent nucleus and the electron gas degeneracy in the stellar matter

$$\lambda^{(n)}_{a\to b}[\gamma\beta^-;(A,Z_i)\to(A,Z_i+1);\Delta^{(\gamma\beta^-)}_{ab})]= \quad \text{.....(13)}$$
$$=\frac{\alpha}{2\pi^4}\int_{\Delta^{(\gamma\beta^-)}_{ab}}^{\infty}\frac{d\omega}{\omega}\frac{G^{(n)}(\omega,\Delta^{(\gamma\beta^-)}_{ab})}{\exp(\omega/kT)-1}.$$

Here, $\Delta^{(\gamma\beta^-)}_{ab}=M(A,Z_i)-M(A,Z_i+1)+E^{(i)}_a-E^{(f)}_b$ is the energy threshold for the photobeta transition. This process is possible under the condition $\omega > \Delta^{(\gamma\beta^-)}_{ab}$.

$$G^{(n)}(\omega,\Delta^{(\gamma\beta^-)}_{ab})=\int_1^{\omega-\Delta^{(\gamma\beta^-)}_{ab}+1}(\omega-E-\Delta^{(\gamma\beta^-)}_{ab}+1)^2\{2(\omega-E)\times$$
$$\times(E^2-1)^{1/2}+(\omega^2-2\omega E+2E^2)\ln[E+(E^2-1)^{1/2}]\}\times$$
$$\times F_0(Z+1,E)C^{(n)}_{ab}(Z_i+1,E)[1-S(E,T)]dE \quad \text{.....(14)}$$

In Eq. (13) and (14) the α, $F_0(Z,E)$, $S(E,T)$ and $C^{(n)}_{ab}(Z,E)$ factors (including the $C^{(0)}_{ab}(Z,E)$ factor for the most intense allowed β-transition Eq. (6) had been identified before.

The temperature dependence of the $\lambda[\xi;(A,Z_i)\to(A,Z_f);T]$ β-process rates in the heated medium is determined by the $P(E^{(i)}_a,T)$ factors Eq. (1) and by the partial rate dependence of concrete β-processes from factor, $S(E,T)$, Eq. (4), (12) and (14) and factor, $[\exp(\omega/kT)-1]^{-1}$, Eq. (13). In the case of *K*-electron capture Eq. (9) the temperature dependence will become a part of the expression for the rate of this process through an additional factor that takes into account the degree of ionization of the *K*-shell of the atom. Thus, the influence of all these factors on numerical values of the β-transition rates will be determined by the characteristics of the heated medium, in particular, its temperature, density of substance and free electrons.

4 Approximation for Calculation of Nuclear Matrix Element

As it is known, the calculation of the nuclear matrix elements of β-transition is a rather difficult challenge. Unfortunately, there is no satisfactory nuclear model that would make it possible to calculate nuclear matrix elements to a high degree of precision. When thermal β-decays of different types and photobeta decays are considered, the problem is complicated by the inclusion of β-transitions from the excited states of the parent nucleus into the excited states of the daughter nucleus and there could be a lot of such transitions. If the single-particle model of the nucleus or its improved versions can give satisfactory results for β-transitions between the ground states of nuclei then it is difficult to expect it for β-transitions between the excited states of nuclei. Because of the complexity of the low-lying state structure (the low-lying collective states of 2^+ in even-even nuclei may be examples), a large number of β-transitions and the difficulties with the choice of appropriate nuclear models, we prefer to use the average values of the nuclear matrix element as before in [10, 11].

To estimate the values of the nuclear matrix elements its average values were used. They derived from the typical values of the reduced lifetime $f_0t_{1/2}$ of the allowed and first-forbidden β-transitions (f_0 is the integrated Fermi function). This scheme will be used in the given paper. What are more the astrophysical applications of our

calculations are planned. In nuclear astrophysics this approximation is also used (e.g. see [16]). If we are limited by the most intense allowed β-transitions for which the value $\lg f_0 t_{1/2}$ is usually in the 4.0-5.5 range, the nuclear matrix elements will directly determine the reduced lifetime of the β-transition:

$$f_0 t_{1/2} = 2\pi^3 \ln 2 / \left(\left| M_V^{(a\to b)} \right|^2 + \left| M_A^{(a\to b)} \right|^2 \right). \qquad \text{.....(15)}$$

Whence, for the nuclear matrix elements we obtain the estimate

$$\left\langle \left| M_V^{(a\to b)} \right|^2 + \left| M_A^{(a\to b)} \right|^2 \right\rangle = 2\pi^3 \ln 2 / \langle f_0 t_{1/2} \rangle_0, \qquad \text{.....(16)}$$

where $\langle f_0 t_{1/2} \rangle_0$ is the average value of the reduced lifetime of the allowed unfavored β-transition. It must be defined by selecting a specific value from the range of $10^{4.0} - 10^{5.5}$ s.

In the future we will only consider the thermal allowed β-transitions. However, if they do not appear owing to the quantum selection rules in selected energy ranges of the excited states of the parent and daughter nuclei the first-forbidden β-transitions will be considered. It is well known that the spectrum of the majority of such transition has a quasi-allowed shape. For their reduced lifetime Eq. (15) can also be used but it is necessary to make the substitutions for nuclear matrix elements (for more detail, see [10]):

$$M_V^{(a\to b)} \to -g_A \int \gamma_5 + i\xi_c g_A \int \boldsymbol{\sigma}\cdot\mathbf{r},$$
$$M_A^{(a\to b)} \to -g_V \int \boldsymbol{\alpha} + \xi_c g_A \int \boldsymbol{\sigma}\times\mathbf{r} + \xi_c g_V \int \mathbf{i}\mathbf{r}.$$

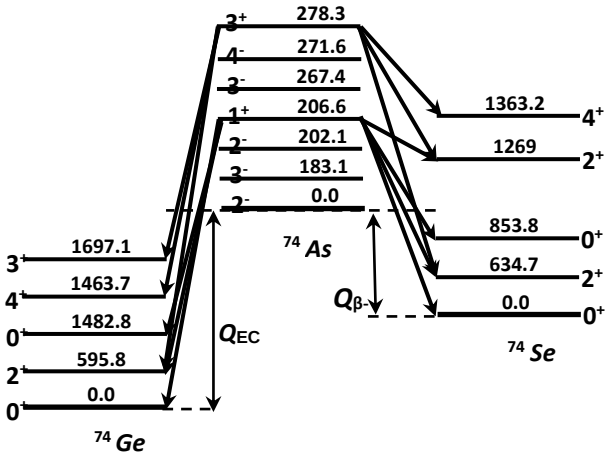

Fig. 1 Parts of level schemes (in keV) of multibeta- decay of the parent nucleus ^{74}As and daughter nuclei ^{74}Ge and ^{74}Se (data taken from [21]). The arrows indicate the allowed β-transitions taken into account in the calculation of the total rate.Q_{EC} = 2562.4 keV, Q_{β^-}= 1353.0 keV.

Here, we give them in the standard notation of a beta-decay theory; $\xi_C = \alpha Z / 2R$ is the Coulomb parameter. Now for the average values of these matrix elements we can again use Eq. (16) only the value $\langle f_0 t_{1/2} \rangle_0$ must be replaced by $\langle f_0 t_{1/2} \rangle_1$. The quantity $\langle f_0 t_{1/2} \rangle_1$ should be chosen taking into account the typical quantities of $\lg f_0 t_{1/2}$ = 7.0-9.0 for the first-forbidden β-transitions i.e. it should be chosen from the range of $10^7 - 10^9$ s.

Thus, in the calculations of the β-transition partial rates of the electron and positron β-decays Eq. (4) and photobeta decay Eq. (13) - (14) the $C_{ab}^{(n)}(Z,E)$ factor will be replaced by the $C_{ab}^{(0)}(Z,E)$ factor which will be calculated by the formula

$$C_{ab}^{(0)}(Z,E) \approx \left| M_V^{(a\to b)} \right|^2 + \left| M_V^{(a\to b)} \right|^2 \approx$$
$$\approx \left\langle \left| M_V^{(a\to b)} \right|^2 + \left| M_A^{(a\to b)} \right|^2 \right\rangle = 2\pi^3 \ln 2 / \langle f_0 t_{1/2} \rangle_0$$

.....(17)

The same substitution of the nuclear matrix elements will be used in the Eq. (9) for *K*-electron capture. For the first-forbidden β-transition the quantity of the $C_{ab}^{(1)}(Z,E)$ factor will be evaluated in the same way

$$C_{ab}^{(1)}(Z,E) \approx 2\pi^3 \ln 2 / \langle f_0 t_{1/2} \rangle_1 . \qquad \text{.....(18)}$$

The quantities of the factors $\langle f_0 t_{1/2} \rangle_0$ and $\langle f_0 t_{1/2} \rangle_1$ must be selected from the above mentioned ranges.

All known multidecay nuclei are classified as odd-odd ones and are listed in Table 1. Accordingly, the daughter nuclei, (*A*, *Z*±1), are even-even. In Table 1 there are experimental quantities of the δ coefficient obtained in terrestrial conditions. This coefficient defines the fraction of electron β-decay in the total lifetime of the nucleus (*A*, *Z*). In fact, the δ coefficient is the ratio of the total rate of electron β-decay of the nucleus to the sum of all of its rate decay modes (electron β-decay and electron capture and positron β-decay if the latter is possible). The data about the decay characteristics of nuclei and their level schemes were taken from [17]. As an example, in Fig. 1 the level schemes of the multidecay parent nucleus, ^{74}As, and daughter nuclei, ^{74}Ge and ^{74}Se, are given.

The results of the calculations of temperature dependence of the coefficients, $\delta(T)$, for multibeta decay nuclei in the high heated medium are also given in Table 1. According to the definition the coefficient, $\delta(T)$, is calculated by the formula

$$\delta(T) = \lambda_{tot}^{(\beta^-)}((A,Z_i);T) / \lambda_{tot}((A,Z_i);T), \quad \text{.....(19)}$$

where

$$\lambda_{tot}^{(\beta^-)}((A,Z_i);T) = \sum_{\xi=\beta^-,\gamma\beta^-} \lambda_\xi[(A,Z_i) \to (A,Z_i+1);T] \text{;.....(20)}$$

$$\lambda_{tot}((A,Z_i);T) = \lambda_{tot}^{(\beta^-)}((A,Z_i);T) + \\ + \sum_{\xi=\beta^+,\varepsilon_K} \lambda_\xi[(A,Z_i) \to (A,Z_i-1);T]. \quad \text{.....(21)}$$

As well as δ, the $\delta(T)$ coefficient determines the fraction of electron β-decay in the total rate of β-decay of the multibeta -decay nucleus in the heated medium.

The isotopes listed in Table 1 are interesting not only by their multibeta-decays. They are intermediate links in the chain of successive β-transitions $(A, Z) \to (A, Z+1) \to (A, Z+2)$ leading to p-nucleus, $(A, Z+2)$. We will consider the quasi-equilibrium stages of the evolution of massive stars within which the temperature of the stellar matter may reach $3T_9$ and even higher. In the above mentioned chain, the total yields of the p-nuclei will depend on the quantities of the coefficients, $\delta(T)$. This is important for the models of the p-nucleus synthesis process which calculate the p-nucleus abundances in different stages of a massive star evolution (e. g. see [7-10]). We will also formulate such a model below.

Table 1. The values of the coefficient $\delta(T)$ for multidecay nuclei
(Experimental data were taken from [17]; 1 – $T = 2T_9$, 2 – $T = 3T_9$)

Nu.	δ (exp.)	δ (theory)		Nu.	δ (exp.)	δ (theory)	
		1	2			1	2
$^{74}_{33}$As	0.34	0.680	0.719	$^{130}_{55}$Cs	0.016	0.011	0.010
$^{78}_{35}$Br	$<10^{-4}$	0.016	0.014	$^{132}_{55}$Cs	0.0187	0.212	0.201
$^{80}_{35}$Br	0.917	0.956	0.941	$^{136}_{57}$La	0	2.8×10^{-3}	2.4×10^{-3}
$^{84}_{37}$Rb	0.038	0.210	0.369	$^{138}_{57}$La	0.336	0.403	0.443
$^{92}_{41}$Nb	$<5\times10^{-4}$	0.018	0.082	$^{144}_{61}$Pm	0	2.0×10^{-4}	4.4×10^{-4}
$^{94}_{41}$Nb	0.986	0.992	0.982	$^{152}_{63}$Eu	0.279	0.878	0.873
$^{96}_{43}$Tc	0	1.3×10^{-5}	6.1×10^{-5}	$^{156}_{65}$Tb	0	8.6×10^{-4}	6.7×10^{-4}
$^{98}_{43}$Tc	1	0.707	0.776	$^{158}_{65}$Tb	0.166	0.675	0.672
$^{102}_{45}$Rh	0.2	0.121	0.112	$^{162}_{67}$Ho	0	4.8×10^{-3}	4.2×10^{-3}
$^{106}_{47}$Ag	<0.01	2.3×10^{-3}	2.0×10^{-3}	$^{164}_{67}$Ho	0.4	0.417	0.389
$^{108}_{47}$Ag	0.972	0.728	0.709	$^{168}_{69}$Tm	10^{-4}	1.3×10^{-3}	0.017
$^{110}_{47}$Ag	0.997	0.993	0.993	$^{174}_{71}$Lu	0	0.068	0.078
$^{112}_{49}$In	0.44	0.181	0.188	$^{180}_{73}$Ta	0.14	0.626	0.532
$^{114}_{49}$In	0.995	0.880	0.822	$^{184}_{75}$Re	0	4.3×10^{-6}	6.3×10^{-6}
$^{120}_{51}$Sb	0	0.160	0.169	$^{190}_{77}$Ir	0	1.1×10^{-4}	1.0×10^{-4}
$^{124}_{53}$I	0	4.3×10^{-4}	7.6×10^{-4}	$^{196}_{79}$Au	0.075	1.1×10^{-3}	1.3×10^{-3}
$^{126}_{53}$I	0.437	0.640	0.640				

In the calculation of the β-process rates we choose the energy ranges of the excited states in the parent and daughter nuclei, (A, Z_i) and $(A, Z_i \pm 1)$, in such a way that there were several allowed β-transitions or photobeta transitions. If it is not impossible, the first-forbidden β-transitions were considered. In Table 1 coefficients, $\delta(T)$, are given for the temperatures of $2T_9$ and $3T_9$. From the data of Table 1 it follows that the coefficient $\delta(T)$ can either increase or decrease with increasing temperature. This is explained by the different temperature dependence both of partial rates of β-processes and their total rates. In their turn, these rates are determined by the characteristics of the quantum states of the parent and two daughter nuclei.

As follows from Table 1, magnitudes of the coefficients, $\delta(T)$, can differ very mach from the values obtained in terrestrial conditions. In many cases (^{78}Br, ^{84}Rb, ^{132}Cs, ^{152}Eu, ^{158}Tb, ^{164}Ho, ^{180}Ta, etc.) the effect of the high temperature field enhances β-decay channel and sometimes (^{92}Nb, ^{120}Sb, ^{174}Lu, etc.) this cannel is even opened. In some cases (^{102}Rh, ^{112}In, ^{196}Au) we can see its attenuation but it is not too strong.

Calculating the rates of β-processes and coefficients, $\delta(T)$, we neglected all the corrections the calculation of which requires knowledge of the free electron density in the heated matter of the star. These corrections are for the degeneracy of the electron gas for the electron β-decay rate and for the possibility of K-shell ionization of the atom the nucleus of which undergoes K-capture. The quantity of the density of free electrons is largely determined by the star model which should be realistic. This presents a certain problem. We research the stage of the oxygen layer combustion in a massive star at the temperature of the matter in the range $(2\text{-}3)T_9$. As shown in [11], possible degeneracy of the electron gas will affect the rate of β-electron transition only if the value of electron concentration, ρ / μ_e, is greater than 10^8 mol/cm^3. It is hardly possible for the stage of the oxygen combustion

5 Calculation of *p*-Element Abundances

In the solution of the well-known problem of the p-nucleus origin (previously they were called "bypassed" nuclei) there has recently been outlined some progress. It is related to the consideration of the possibility of their synthesis in supernova explosions. Here, we are not going to carry out a detailed review of the papers on this topic. We refer only to the reviews [2, 16] and to the papers [10, 18] in which references to other studies on this subject can be found. We only note that, as pointed out in [10, 18], the use of explosive mechanism of the p-element synthesis does not completely cover the problem.

In this paper the p-nucleus synthesis at the quasi-equilibrium stage of a star evolution is researched and the p-nucleus abundances are calculated. The stage of the oxygen layer combustion is considered. Its duration is more than five months and the temperature of the star substance

is completely "nuclear" quantities (200-300) keV. This is enough to intensify the thermal β-transitions and photobeta transitions at all links of the (A, Z)→(A, Z+1)→(A, Z+2) chain going from a stable progenitor nucleus, (A, Z), to stable p-nucleus, (A, Z+2).

The beta-decay characteristics of the multidecay nuclei, (A, Z+1), were calculated above. In the proposed model physical mechanisms of thermal β-transitions and photobeta transitions were used not only for the (A, Z+1)→(A, Z+2) β-decay but also to overcome the energy threshold. It has a place for the β-transition, (A, Z)→(A, Z+1), and in many cases the above mentioned threshold is not small (up to 3 MeV and even more). As it was recently shown in [11] for the β-decay chain, ^{96}Mo→^{96}Tc→^{96}Ru, the high energy threshold (3 MeV) can be overcome by a large number of endothermic photobeta transitions. An appreciable yield of the ^{96}Tc isotope will be obtained during the oxygen layer burning.

We formulate the method for the calculation of the abundances of the (A, Z+2) p-nuclei starting from a stable progenitor nucleus, (A, Z), and using the mechanisms of thermal and photobeta transitions. In principle, it is necessary to solve a system of three differential equations with constant coefficients and assigned initial concentrations of nuclei, (A, Z), (A, Z+1) and (A, Z+2) (in the two latter cases they can take zero values). But it is possible to carry out a short-cut calculation which we will use in what follows.

Let the abundance, $N(A, Z)$, of the (A, Z) nucleus is known. Then, knowing the total rate of electron β-decay, $\lambda_{tot}^{(\beta^-)}((A,Z);T)$, and the duration of the stage, τ, we can receive the abundance, $N(A, Z+1)$, of the (A, Z+1) nucleus using the radioactive decay law:

$$N(A,Z+1) = N(A,Z)\{1-\exp[-\lambda_{tot}^{(\beta^-)}(A,Z);T)\tau]\} \quad \text{……..(22)}$$

The (A, Z+1) nucleus is multibeta-decay and the coefficient $\delta(T)$ determines the fraction of electron β-decay in their total rate. As a result of this β-decay the (A, Z+2) p-nucleus appears. As a rule the total lifetime of the (A, Z+1) nucleus in a heated medium is much less than durations of the quasi-equilibrium stages of star evolution. So the decay of this nucleus is possible to consider as a certain event. Then taking into account the (A, Z+1)→(A, Z+2) β-transition we can calculate the abundance of (A, Z+2) p-nucleus by Eq. (22) introducing into it the $\delta(T)$ coefficient, i.e.

$$N(A,Z+2) = N(A,Z+1)\delta(T). \quad \text{……..(23)}$$

The total β-decay rates, $\lambda_{tot}^{(\beta^-)}((A,Z);T)$ and $\lambda_{tot}^{(\beta^-)}((A,Z+1);T)$, for 33 β-decay chains, (A, Z)→(A, Z+1)→(A, Z+2), were calculated using the Eq. (20), (1), (4) and (13). As well as in the calculation of the coefficients, $\delta(T)$, we chose such energy ranges of the excited states so as there were several allowed β-transitions or photobeta transitions. As an example these β-transitions are shown by arrows in Fig. 2 for triad of p-nuclei, ^{164}Dy, ^{164}Ho and ^{164}Er.

The results of the calculation of the p-nucleus abundances are given in Table 2. In this Table the selected quantities of parameters are pointed out. We chose the stage duration of oxygen layer combustion in a massive star equal to 5 months. In this case the temperature of the star matter reaches (2-3)T_9 that corresponds to the temperature of about 200-300 keV in energy units. The maximum estimation in magnitude of parameter $\langle f_0 t_{1/2}\rangle_0 = 10^4$ s was used. This magnitude corresponds to possible maximum quantities of the nuclear matrix elements of the allowed unfavored β-transitions. However the β-decay matrix elements may be much less. Therefore the magnitude of the $\langle f_0 t_{1/2}\rangle_0$ parameter can be varied in the range of $1.0\cdot10^4$-$3.2\cdot10^5$ s which corresponds to the values of $\lg(f_0 t_{1/2})$ in the range of 4.0-5.5. In our case nuclear states have a complex structure and the value of $\lg(f_0 t_{1/2})$ are more likely near to 5.5. This means that in Table 2 the magnitudes of the calculated abundances could be reduced by maximum in 32 times.

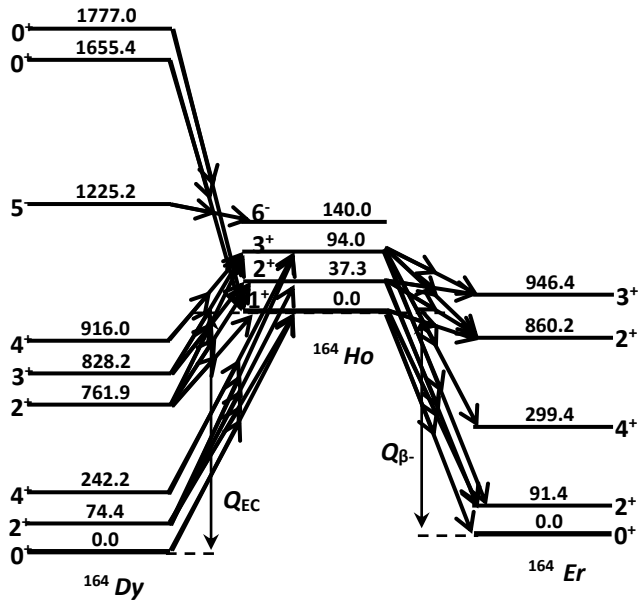

Fig. 2 Parts of level schemes (in keV) of isotopes from the triad, ^{164}Dy, ^{164}Ho and ^{164}Er (data are taken from [21]). The arrows indicate the allowed electron beta and photobeta-transitions taken into account in the calculation of the total rate. Q_{EC} = 986.7 keV, Q_{β^-}= 962.5 keV.

The analysis of the data from Table 2 shows that for 19 p-isotopes from 33 their observed abundances may be very well produced during combustion of the oxygen layer taking account the possible reduction of the calculated abundances. These are isotopes ^{74}Se, ^{80}Kr, ^{84}Sr, ^{94}Mo, ^{98}Ru,

Table 2. Calculated and "solar" values of the *p*-nucleus abundances ($1 - T = 2T_9$, $2 - T = 3T_9$). Parameter values were used: τ = 5 months, $\langle f_0 t_{1/2} \rangle_0 = 10^4$ s. The experimental data were taken from [19]

Progen. nucleus (*A*, *Z*)	*p*-nucleus (*A*, *Z*+2)	Energy threshold Q_{EC} (keV)	Progen. nucleus "solar" abundance *N*(*A*, *Z*) (exp.)	*p*-nucleus "solar" abundance *N*(*A*, *Z*+2) (exp.)	*p*-nucleus abundance *N*(*A*, *Z*+2) (theory)	
					1	2
$^{74}_{32}$Ge	$^{74}_{34}$Se	2562	42.8	0.580	2.5×10^{-3}	0.705
$^{78}_{34}$Se	$^{78}_{36}$Kr	3574	15.8	0.146	1.1×10^{-7}	1.7×10^{-4}
$^{80}_{34}$Se	$^{80}_{36}$Kr	1871	33.4	0.940	0.970	30.6
$^{84}_{36}$Kr	$^{84}_{38}$Sr	2681	23.5	0.128	5.6×10^{-4}	0.523
$^{92}_{40}$Zr	$^{92}_{42}$Mo	2006	2.05	0.634	4.5×10^{-6}	3.2×10^{-3}
$^{94}_{40}$Zr	$^{94}_{42}$Mo	902	2.09	0.361	2.08	2.06
$^{96}_{42}$Mo	$^{96}_{44}$Ru	2973	0.661	0.105	1.4×10^{-10}	5.1×10^{-7}
$^{98}_{42}$Mo	$^{98}_{44}$Ru	1684	0.951	0.036	0.109	0.729
$^{102}_{44}$Ru	$^{102}_{46}$Pd	2323	0.601	0.013	1.5×10^{-4}	0.025
$^{106}_{46}$Pd	$^{106}_{48}$Cd	2965	0.355	0.019	8.0×10^{-4}	7.1×10^{-4}
$^{108}_{46}$Pd	$^{108}_{48}$Cd	1918	0.347	0.014	1.6×10^{-3}	0.071
$^{110}_{46}$Pd	$^{110}_{48}$Cd	893	0.154	0.020	0.153	0.153
$^{112}_{48}$Cd	$^{112}_{50}$Sn	2586	0.373	0.036	7.4×10^{-6}	1.7×10^{-3}
$^{114}_{48}$Cd	$^{114}_{50}$Sn	1453	0.447	0.024	0.143	0.368
$^{120}_{50}$Sn	$^{120}_{52}$Te	978	1.22	5.8×10^{-3}	9.1×10^{-6}	3.6×10^{-3}
$^{124}_{52}$Te	$^{124}_{54}$Xe	3160	0.299	7.4×10^{-3}	1.1×10^{-10}	4.5×10^{-7}
$^{126}_{52}$Te	$^{126}_{54}$Xe	2155	1.22	6.7×10^{-3}	3.4×10^{-3}	0.290
$^{130}_{54}$Xe	$^{130}_{56}$Ba	2983	0.250	4.8×10^{-3}	3.5×10^{-8}	1.5×10^{-5}
$^{132}_{54}$Xe	$^{132}_{56}$Ba	2120	1.52	4.7×10^{-3}	3.4×10^{-3}	0.186
$^{136}_{56}$Ba	$^{136}_{58}$Ce	2870	0.375	2.3×10^{-3}	1.5×10^{-7}	4.8×10^{-5}
$^{138}_{56}$Ba	$^{138}_{58}$Ce	1737	3.44	3.0×10^{-3}	0.510	1.52
$^{144}_{60}$Nd	$^{144}_{62}$Sm	2332	0.188	7.4×10^{-3}	5.4×10^{-9}	$2.3\times\cdot10^{-6}$
$^{152}_{62}$Sm	$^{152}_{64}$Gd	1818	0.064	8.4×10^{-4}	4.9×10^{-4}	0.023
$^{156}_{64}$Gd	$^{156}_{66}$Dy	2444	0.086	1.9×10^{-4}	2.8×10^{-8}	3.7×10^{-6}
$^{158}_{64}$Gd	$^{158}_{66}$Dy	1220	0.104	3.3×10^{-4}	0.066	0.070
$^{162}_{66}$Dy	$^{162}_{68}$Er	2140	0.094	3.1×10^{-4}	4.0×10^{-7}	3.8×10^{-5}
$^{164}_{66}$Dy	$^{164}_{68}$Er	987	0.104	3.6×10^{-3}	0.042	0.040
$^{168}_{68}$Er	$^{168}_{70}$Yb	1679	0.062	2.7×10^{-4}	6.5×10^{-7}	2.9×10^{-4}
$^{174}_{70}$Yb	$^{174}_{72}$Hf	1374	0.064	3.1×10^{-4}	8.6×10^{-4}	4.8×10^{-3}
$^{180}_{72}$Hf	$^{180}_{74}$W	854	0.060	4.0×10^{-4}	0.037	0.032
$^{184}_{74}$W	$^{184}_{76}$Os	1483	0.092	1.2×10^{-4}	1.5×10^{-10}	3.1×10^{-8}
$^{190}_{76}$Os	$^{190}_{78}$Pt	2000	0.182	1.8×10^{-4}	1.7×10^{-8}	1.6×10^{-6}
$^{196}_{78}$Pt	$^{196}_{80}$Hg	1506	0.357	3.1×10^{-4}	1.0×10^{-6}	6.7×10^{-5}

^{102}Pd, ^{108,110}Cd, ^{114}Sn, ^{120}Te, ^{126}Xe, ^{132}Ba, ^{138}Se, ^{152}Gd, ^{158}Dy, ^{164}Er, ^{168}Yb, ^{174}Hf and ^{180}W. For the remaining 13 *p*-isotopes β-decay mechanism does not probably play a significant role in our model of the process of their synthesis. However, the obtained magnitudes of the abundances can be used as initial data for the system of kinetic equations that are solved in the models of the explosive synthesis of chemical elements. Zero values are usually used for the initial concentration of *p*-nuclei on the pre-explosive stage of a star evolution.

6 Conclusion

It has been shown that the effect of the thermal field on the β-processes at the atomic nuclei in extremely heated matter changes strongly their rates and respectively the magnitudes of the coefficients $\delta(T)$ in comparison to their terrestrial values. The $P(E_a^{(i)},T)$ factors that determine the populations of the excited states of the parent nuclei (see Eq. (2)) define the principal dependence of the β-decay rates on the temperature. This fact gives new channels of β-transitions that often have a smaller degree of forbiddenness leading to the change in quantity of the total rate of β-decay. These results are valid at least for the temperatures in the range (2.0-3.0)x10^9 K. Specifically this temperatures are achieved at the stage of an oxygen layer combustion in the massive star matter.

For the same stage the model of the *p*-nucleus synthesis is proposed. The thermal and photobeta decays are its foundation. The observed abundances for the 19 of 33 *p*-nuclei were derived here. Such result was obtained for the first time.

As a rule β-decay mechanism in solving the problem of *p*-element synthesis yields good quantitative results only in special cases. Simultaneous utilization of the mechanisms of the thermal and photobeta decays for the whole links of the chain of successive β-transitions leading to *p*-nucleus makes the progress possible. For the remaining 14 *p*-nuclei the beta-decay mechanism does not seem dominant. But these abundances, even being small, would be able to replace those zero values which are usually taken for *p*-isotopes as initial data at the pre-explosive and explosive stages of massive star evolution.

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