International Journal of Recent Research and Review, Vol. IX, Issue 2, June 2016
ISSN 2277 – 8322

On the Issue of *p*-Nucleus Synthesis Possibility at Quasi-Equilibrium Stages of Massive-Star Evolution

I.V. Kopytin[1], Imad A. H. Al-Hayali[2]
[1]*Department of Theoretical Physics, Voronezh State University, Universitetskaya pl. 1, Voronezh, 394006 Russia*
[2]*Department of Physics , Mosul University, Mosul, Iraq*
Email: i-kopytin@yandex.ru, imad_ahmad2003@yahoo.com

Abstract: Based on the previously presented model of the synthesis process of p-nuclei considering quasi-equilibrium stages of the evolution of massive stars, the calculations of their abundances were made. We consider high-temperature stages of silicon and oxygen burning in massive stars when the temperature of the matter reaches the "nuclear" values 0.2-0.5 MeV in energy units. It is shown that during the burning the observed "sun" abundances can be obtained for 27 from the 33 p-nuclei. In these calculations it is significant to take into account all types of thermal nuclear β-transition (electron and positron), nuclear photobeta decay and the effect of almost complete ionization of atoms of the matter by strong heating.

Keywords— p- nucleus, abundances, β-transition, supernova

I. INTRODUCTION

Recently we have proposed a model of the process of synthesis of p-nuclei at the quasi-equilibrium stages of the evolution of massive stars [1]. There the synthesis of stable even-even p-nucleus (A, Z +2) in the triad of nuclei (A, Z), (A, Z +1) and (A, Z +2) passes through the chain of beta- transitions (A and Z are mass and charge numbers). A feature of this chain is that firstly, for the beta-transition (A, Z) → (A, Z +1) there is the energy barrier and therefore under terrestrial conditions even-even nucleus (A, Z) is also stable. Secondly, the odd-odd nucleus (A, Z +1) is multidecay, i.e, for it under terrestrial conditions it is possible positron beta decay (plus electron capture) (A, Z +1) → (A, Z) and electron beta decay (A, Z +1) → (A, Z +2). In extremely hot medium, high-temperature field stimulates the beta-decay of a stable nucleus (A, Z), i.e., overcoming above mentioned energy barrier. It happens due to the opening channels of thermal beta decay (beta transitions from the excited states of a nucleus (A, Z)) and photobeta decay (endothermic beta transitions in the electromagnetic field). The temperature field for the same reason will change its branching coefficient for multi-decay nucleus (A, Z +1). It determines the fraction of the electron beta-decay in complete decay rate for the nucleus (A, Z +1). Final output of p-nuclei will depend exactly on full rates of electron beta decay (A, Z) → (A, Z +1) and (A, Z +1) → (A, Z +2). Its calculation was made on the basis of the system of kinetic equations for the chain of beta transitions taking into account the temperature dependence of their rates in extremely hot medium.

In work [1], the stage of burning the oxygen layer in the massive medium when the temperature can reach $3T_9$ (the notation $T_n = 10^n$ K) was considered. There was calculation of abundances of all 33 p-nuclei for the synthesis of which there is the energy barrier though the beta-decay channels. It turned out that we could get "solar" abundance for 20 of them if we start with the "solar" abundances of pramother nuclei (A, Z). For the quasi-equilibrium stages of the evolution of massive stars such result was obtained for the first time. It happens, in our opinion, due to the complex approach. In it for all links in the chain of beta-decays in the calculation of their full rates at the same time thermal beta and photobeta transitions were taken into account.

There is possibility of improvement the proposed model, which allows, in principle, to increase the yield of the p-nuclei for which it was not enough. Firstly, in this process of synthesis it is possible to evaluate the role of the next stage in the evolution of a massive star - silicon burning. In this case the temperature of the matter reaches even higher values - $5T_9$, which corresponds to about 0.5 MeV in energy units. With increasing temperature, the full rate of beta transitions tends to increase. Particularly the value of full rate electron beta transition of the first stage (A, Z) → (A, Z +1) increases too much, typically in one to two orders at the temperature rise from $3T_9$ to $5T_9$. Therefore, even if the stage of silicon burning (one day) is much shorter than the stage of oxygen burning (5 months), the final yield of p-nuclei may be greater than the time of oxygen burning layer.

Secondly, the rate of the reverse decay (A, Z +1) → (A, Z) was calculated in [1] taking into account the electron capture from excited states of the nucleus (A, Z +1). Its total rate in extremely hot medium was comparable to total rate of positron decay but for some multidecay isotope (A, Z +1) it was far superior to it and the total rate of subsequent electronic beta transition (A, Z +1) → (A , Z +2). In these cases, the branching coefficient for the nuclei (A, Z +1) is anomalously low, and the yield of p- nuclei is deficient. However, as it was shown in [2, 3], in extremely hot medium the degree of ionization of atoms including the K-shell is large and the capture of atomic nucleus electrons will be difficult. Accounting for this effect for multidecay nuclei with anomalously small quantities of the branching coefficients can significantly increase the proportion of their electronic beta decay. Due to this fact the final yield of some p-nuclei will increase which will connect them, perhaps to those 20 p-isotopes for which the proposed model has given the observed abundance.

The purpose of the research is to consider the process of p-nuclei synthesis at the high temperature stage of silicon burning in a massive star using the proposed in [1] model. Also it will also be explored how the suppression of the process of capture by the nucleus of atomic electrons due to the ionization of atoms in extremely hot medium affects the results of calculation of the abundances of p-nuclei. In this case, both stages of the evolution massive stars - oxygen burning and silicon burning will be considered.

II. BASIC EQUATIONS OF THE MODEL OF THE PROCESS OF SYNTHESIS OF p- NUCLEI

Let's consider a chain of beta-decays $(A,Z) \leftrightarrow (A,Z+1) \rightarrow (A,Z+2)$. In it under terrestrial conditions a pramother nucleus (A, Z) and p-nucleus $(A, Z+2)$ is stable and the intermediate odd-odd nucleus $(A, Z+1)$ is multibeta-decay. Heating the medium stimulates the beta-decay of a nucleus (A, Z), which enables the implementation of the whole chain of the beta processes. Their rate will depend on the medium temperature. It as well as the duration of the stage, which examines the beta process will determine the final abundance. The latter one can be found from the system of kinetic equations written for the above chain of beta-decays as shown in equation 1. The analytical solution of this system for the final abundance of p-nucleus (A, Z +2) has the form

$$N(\tau) = N_0\left\{1 - \frac{1}{2}\left[e^{\left(-\frac{\delta_{+}\tau}{2}\right)} + e^{\left(-\frac{\delta_{-}\tau}{2}\right)}\right] - \frac{\lambda_{123}}{\delta} sinh\left(\frac{\delta\tau}{2}\right) e^{\left(-\frac{\lambda_{123}\tau}{2}\right)}\right\} \quad ..(1)$$

Here, τ is duration of the stage, N_0 is initial abundance of pramothe progenitor nuclei (A, Z),

$$\delta = (\lambda_{123}^2 - 4\lambda_1\lambda_3)^{1/2};$$

$$\delta_{\pm} = \lambda_{123} \pm \delta ;\ \lambda_{123} = \lambda_1 + \lambda_2 + \lambda_3$$

λ_1 is the total rate of electron beta-transition $(A, Z) \rightarrow (A, Z+1)$, λ_2 is the total rate of reverse beta transition $(A, Z+1) \rightarrow (A, Z)$ (it includes a positron beta transition and electronic K-capture) and λ_3 is total rate of electron beta transition $(A, Z+1) \rightarrow (A, Z+2)$. All these rates depend on medium temperature. Let's give the formulas for calculating these rates of beta processes.

$$\lambda_1 = \lambda_{tot}^{(\beta^-)}((A, Z); T) + \lambda_{tot}^{(\gamma\beta^-)}((A, Z); T); \quad ..(2)$$

$$\lambda_2 = \lambda_{tot}^{(\beta^-)}((A, Z+1); T) + \lambda_{tot}^{(\varepsilon_K)}((A, Z+1); T); \quad ..(3)$$

$$\lambda_1 = \lambda_{tot}^{(\beta^-)}((A, Z+1); T) + \lambda_{tot}^{(\gamma\beta^-)}((A, Z+1); T); \quad ..(4)$$

Total rate $\lambda_{tot}^{(\xi)}((A, Z_i); T)$ β- process ξ ($\xi = \beta^-$, $\gamma\beta^-$, β^+ or ε_K) for nuclear (A, Z_i) in the medium heated to a temperature T is given by

$$\lambda_{tot}^{(\xi)}((A, Z_i); T) = \sum_{a,b} P(E_a, T)\, \lambda_{a\rightarrow b}^{(\xi)}\left((A, Z_i); \Delta_{ab}^{(\xi)}\right) \quad ..(5)$$

$P(E_a, T)$ is the occupation probability of a-th state of the nucleus (A, Z_i) with total spin j_a and with energy E_a measured from its ground state:

$$P(E_a, T) = \frac{2j_a + 1}{G(T)} \exp(-E_a / kT) \qquad ,.(6)$$

k is the Boltzmann constant and $G(T)$ is the statistical sum:

$$G(T) = \sum_a (2j_a + 1)\exp(-E_a / kT) \qquad ..(7)$$

$\lambda^{(\xi)}_{a\to b}((A, Z_i); \Delta^{(\xi)}_{ab})$ is the partial transition rate from the state a of the parent nucleus (A, Z_i) to the state b of the daughter nucleus (A, Z_f) with energy E_b measured from the energy of its ground stat either, $\Delta^{(\xi)}_{ab}$ is energy of the transition.

Confine ourselves only to subsequently allowed beta transitions as the most intense beta transitions. An analysis of the level schemes of studied isotopes shows that this condition can always be done. We consider beta transitions between excited states of the even-even nuclei (A, Z) and $(A, Z+2)$ on the one hand, and the odd-odd nucleus $(A, Z+1)$, on the other hand. Because of the complexity of their structure, a large number of β-transitions and difficulties with the choice of appropriate nuclear models we will use the average values of the nuclear matrix elements as in [1]. They are obtained from the expression for the given lifetime of the allowed beta transition $f_0 t_{1/2}$ if we take a typical value $\lg f_0 t_{1/2}$ in the interval 4.0-5.5 for the allowed transitions of unrelieved type.

The partial rates of beta transitions in the "natural" system of units $\hbar = c = m_e = 1$ where c is rate of light and m_e is electron mass can be calculated using the following formulas.

1. *Electron beta-transition $(A, Z_i)\to(A, Z_i+1)$ ($\xi=\beta^-$; in our task $Z_i=Z$ or $Z+1$)*

$$\lambda^{(\beta^-)}_{a\to b}\left((A, Z_i); \Delta^{(\beta^-)}_{ab}\right) = \frac{\ln 2}{\langle f_0 t_{1/2}\rangle}\int_1^{\Delta^{(\beta^-)}_{ab}} E(E^2 - 1)^{1/2}(\Delta^{(\beta^-)}_{ab} - E)^2 F_0(Z_i + 1, E)\,dE \qquad ..(8)$$

Here, $\Delta^{(\beta^-)}_{ab} = Q_\beta + E_a - E_b$, where $Q_\beta = M(A, Z_i) - M(A, Z_i + 1)$ is the energy released at β^- - transition between the ground states of the mother and daughter nuclei; ($M(A, Z)$ is the atomic mass of the nucleus (A, Z)), $F_0(Z, E)$ is the Coulomb Fermi function (we used an analytical expression for it and a table of values from [4]). The given average lifetime of the allowed β-transition of the unrelieved type $\langle f_0 t_{1/2}\rangle$ should be set by selecting a particular value from the interval $10^{4.0} - 10^{5.5}$ c.

2. *Positron beta transition $(A, Z+1)\to(A, Z)$ ($\xi=\beta^+$)*

The calculation of the partial rate $\lambda^{(\beta^+)}_{a\to b}((A, Z+1); \Delta^{(\beta^+)}_{ab})$ can also be made using the formula (8) substituting in its left part $Z_i = Z+1$ and replacing everywhere $\Delta^{(\beta^-)}_{ab}$ by $\Delta^{(\beta^+)}_{ab} = Q^{(+)}_\beta + E_a - E_b$, where $Q^{(+)}_\beta$ is the energy released by β^+-transition between the ground states of nuclei $(A, Z+1)$ and (A, Z): $Q^{(+)}_\beta = M(A, Z+1) - M(A, Z) - 2$ (β^+-transition will occur only if $\Delta^{(\beta^+)}_{ab} > 0$). In addition, it is necessary to use the Coulomb Fermi functions for the β^+-decay in the right-hand side of (8), in the argument of which in this case Z must stand instead of $Z_i + 1$ (this function is also tabulated in [4]).

3. *Electron photobeta decay ($\xi=\gamma\beta^-$)*

In accordance with [1, 5, 6], the expression for the partial rate of photobeta transition can be written as

$$\lambda^{(\gamma\beta^-)}_{a\to b}\left((A, Z_i); \Delta^{(\beta^-)}_{ab}\right) = \frac{\alpha \ln 2}{\pi \langle f_0 t_{1/2}\rangle}\int_{\Delta^{(\gamma\beta^-)}_{ab}}^{\infty} \frac{d\omega}{\omega}\frac{G(\omega, \Delta^{(\gamma\beta^-)}_{ab})}{e^{(\omega/kT)} - 1} \qquad ..(9)$$

where α = 1/137.04 is the fine structure constant, and $\Delta^{(\gamma\beta^-)}_{ab} = Q_\beta + E_a - E_b$ is the energy threshold for photobeta transition.. As opposed to β^-- decay now it can be $Q_\beta < 0$ and endothermic process of photobeta decay will be possible only under the condition $\omega > \Delta^{(\gamma\beta^-)}_{ab}$.

$$G(\omega, \Delta^{(\gamma\beta^-)}_{ab}) = \int_1^{\omega - \Delta^{(\gamma\beta^-)}_{ab} + 1} (\omega - E - \Delta^{(\gamma\beta^-)}_{ab} + 1)^2 \{2(\omega - E)(E^2 - 1)^{1/2} + (\omega^2 - 2\omega E + 2E^2)\ln[E + (E^2 - 1)^{1/2}]\} F_0(Z_i + 1, E)\,dE \qquad ..(10)$$

4. K-Electron capture ($\xi=\varepsilon_K$)

The capture of electrons by the nucleus will be considered only with the K-shell of the atom as the most intense one. The rate of this process can be calculated by the formula

$$\lambda_{a\to b}^{(\varepsilon_K)}((A,Z+1);\Delta_{ab}^{(\varepsilon_K)}) \approx \frac{\pi \ln 2}{2\langle f_0 t_{1/2}\rangle}(\Delta_{ab}^{(\varepsilon_K)})^2 \beta_K^2 \qquad ..(11)$$

Where, $\Delta_{ab}^{(\varepsilon_K)} = Q_\beta^{(+)} + 1 - |E_K| + E_a - E_b$, $Q_\beta^{(+)}$ was defined above and β_K and E_K are respectively the Coulomb amplitude of the wave function and the energy of the bound *K*-electron (for them in [4] there is a table of values). In (11) the factor is omitted that takes into account the electron exchange since the *K*-shell of its value is almost equal to one. In extremely hot medium where the atoms are ionized, it is necessary in the formula (11) to make a correction that takes into account the degree of occupation of the atom K-shell, the nucleus of which is experiencing the *K*-capture.

III. CALCULATION RESULTS AND DISCUSSION

The stage of burning silicon in a massive star was considered. Although its duration is only one day, the temperature of the star matter can reach a value $5T_9$. For this maximum value of temperature by the formulas of the preceding section, we calculated the abundances for 33 *p*-nuclei (*A, Z* +2). For the initial abundances of N_0 progenitor nuclei (*A, Z*), "solar" values were used. The calculation results are in Table 1 (column a). For comparison, the maximum temperature for $3T_9$ there are abundances of p-nuclei (column a), previously to the same model calculated for the stage of oxygen burning in [1] with the same values N_0 (duration of stage is 5 months).

Comparison of the theoretical abundances in the columns *a* indicates that at the end of stages yields of p-nuclei in both cases are almost comparable in magnitude. In [1] it was found that for 13 p-nuclei the synthesis through the beta-decay channel at the stage of oxygen burning is not effective. These nuclei are ^{78}Kr, ^{92}Mo, ^{96}Ru, ^{112}Sn, ^{124}Xe, ^{130}Ba, ^{136}Ce, ^{144}Sm, ^{156}Dy, ^{162}Er, ^{184}Os, ^{190}Pt, ^{196}Hg. Table 1 shows that for them the abundances calculated for the stage of oxygen burning (column a) differ from the "solar" ones by value orders. Accounting of additional possibility of synthesis of these isotopes at the stage of silicon burning does not eliminate the discrepancy. Note that for the remaining 20 *p*-isotopes overestimated values of the theoretical abundances in comparison with "solar" ones, sometimes quite strongly, should not be confused. Firstly, they have been obtained for the maximum temperature. It was supposed the temperature permanence during the whole stage. Secondly, in the calculations we have used maximum value of the nuclear matrix element which corresponded $\lg f_0 t_{1/2}$=4.0. Such values as $\lg f_0 t_{1/2}$ rather correspond to the values of the nuclear matrix elements calculated by the single-particle model of the nucleus. However, the structure of the excited states in both even-even nuclei (*A, Z*) and (*A, Z* +2) and in odd-odd nuclei (*A, Z* +1) is far from the single-particle. Accordingly, the value $\lg f_0 t_{1/2}$ is closer to 5.5 or even more. In this case, theoretical values of abundances shown in Table 1 should be reduced by one or two orders of magnitude. And, finally, thirdly, "solar" abundances of grandparent nuclei (*A, Z*) have been used as the basis, which at the beginning of the considered stages could be different. In principle, because of the variation of all listed parameters within reasonable limits or even some of them it is possible to get "solar" abundances of *p*-isotopes.

Let's consider the role of electron capture in this model of synthesis process of p-nuclei. It contributes to the total rate of the decay of multidecay nuclei (*A, Z* +1) and consequently to the values of abundances $N(\tau)$ of *p*-nuclei (*A, Z* +2) defined by the formula (1). Under terrestrial conditions, the proportion of electron capture can be significant, as evidenced by the experimental data about the decay properties of multibeta-decay isotopes (A, Z +1 (see, for example, the table of isotopes [7].) It as a rule usually takes place during taking into account the temperature dependences of the beta processes by the formulas of the previous section [8].

Effect of ionization of atoms in the beta process in extremely hot medium has been discussed in works [2, 3]. In [2] there are also tables of occupation of atomic *K*-shell for the different densities of matter and temperature $1T_9$ that is close to considered ones by us. From these tables it is clear that even for $T = 1T_9$ and density 10^4 g/cm^3 the occupation of the *K*-shell even in relatively heavy atom of Osmium (Z = 76) is only 0.0848 instead of 2.0 under terrestrial conditions. Accordingly, the probability of *K*-capture in this case decreases about in 25 times. In the work [2] it was shown that during high heating of the star matter, beta transformation of nuclei through the channel of electron capture if occurs, then only with negligible small probability. This result remains valid even taking into account the capture of free electrons which are always present in the matter of a massive star.

Let's estimate the degree of influence of the electron capture on values of the abundances obtained by the considered model. The abundances of *p*-nuclei were calculated again using (1) - (7), but only now in the formula (3) the second term is not taken into account. The maximum temperature stages of oxygen burning ($T = 3T_9$) and silicon burning ($T = 5T_9$) in a massive star were considered again. The calculation results are shown in Table 1 (column b). As expected, inhibition of *K*-electron capture in extremely heated medium increases the final yield of *p*-nuclei. It happens because the proportion of the electron beta transition (A, Z +1) → (A, Z +2) of the multibeta-decay nuclei (A, Z +1) increases which leads to p-isotopes. In some cases, when this electron beta transition was strongly suppressed in the background of electron capture, the increase of abundances is especially noticeable. It happens for T for *p*-nuclei ^{136}Ce, ^{144}Sm, ^{156}Dy, ^{162}Er, ^{184}Os, ^{190}Pt and ^{196}Hg. As a result, "solar" values for the abundances of these isotopes at the stage of oxygen burning can be obtained as for twenty previously listed ones. And only for 6 *p*-nuclei ^{78}Kr, ^{92}Mo, ^{96}Ru, ^{112}Sn, ^{124}Xe and ^{130}Ba the beta decay mechanism for their synthesis is not effective, at least in this model. This particularly applies to the *p*-isotope ^{96}Ru, for which the value of theoretical abundances by 3 orders less than the observed one.

IV. CONCLUSION

The proposed model of the process of nucleosynthesis lets gets observed abundances, in principle, for 27 of the 33 *p*-nuclei. Feature of the model is a complex examination of all types of beta decay in the triad "stable nucleus - multibeta-decay nucleus - stable p-nucleus" taking into account the influence of high temperature field on it inside a massive star. The obtained results contradict the conventional opinion that at the quasi-equilibrium stages of star evolution cannot explain the appearance of the isotopes, poor neutrons - so-called bypassed nuclei. In fact, for most of these isotopes the last term is losing its meaning. In fact, nucleosynthesis of *p*-elements at hot stages of the massive star evolution naturally continues the synthesis of *s*-nuclei at more cold stages. Now, however, it can only take place in the electromagnetic field without participation of neutrons.

Under the effect of high temperature field stable nuclei become beta -active. As it turned out, the energy of this field is sufficient to overcome the required intensity of the energy threshold, which prevents the synthesis of *p*-nuclei at the quasi-equilibrium stages. Thus, the synthesis of chemical elements including *p*-isotopes from the stage of helium burning naturally moves to high temperature of stages of oxygen and silicon burning. By the pre-supernova and supernova stages, most of *p*-elements will exist already in the observed proportions to the corresponding *s*-elements. This allows them to take into account their already not zero concentration studying nucleosynthesis at the pre-supernova stage and during the solution of the kinetic equations at the supernova explosion.

V. REFERENCES

[1] Kopytin I V, Kornev A S and Hussain I A . LXIII Intern. Conf. "Nucleus 2013". Fundamental Problems of Nucl. Phys. and Atomic Power Engineering. October 8-12, 2013, Moscow,Russia. – Book of Abstr. – S.-Pb., 2013. – P. 42.

[2] Bahcall J N 1964 *Astrophys. J.* 139 318

[3] Takahashi K and Yokoi K 1987 *Atomic Data Nuclear Data Tables* 36 375

[4] Behrens H and Ëanecke J 1969 Landolt-Bornstein: Numerical Data and Functional Relationships in Science and Technology: New Series. Nuclear physics and technology. Numerical tables for beta decay and electron capture ed H Schopper (Springer-Verlag: Berlin–Heidelberg–New-York)

[5] Shaw P R, Clayton D D and Michel F C 1965 *Phys. Rev.* 140 B1433

[6] Kopytin I V and Hussain I A 2013 *Phys. Atom. Nucl.* 76 476

[7] Firestone R B, Shirley V S, Frank Chu S Y, Baglin C M and Zipkin J 1996 *Tables of Isotopes* 8th ed (Wiley: New York)
[8] Kopytin I V and Hussain I A 2013 *Phys. Atom. Nucl.* T.76, *N2* 11.-C. 1379-1387.
[9] Lodders K, Palme H and Gail H-P 2009 *Abundances of the elements in the solar system* In *Landolt-Bornstein: New Series, Astronomy and Astrophysics* ed J E Trumper vol VI/4B (Springer-Verlag: New York) chap 3.4 p 560–630

Table I

The calculated abundances of *p*-nuclei
(the value of the parameter $\langle f_0 t_{1/2} \rangle_0 = 10^4$ c as used; *a* is the calculation with accounting *K*-capture, *b* is without it). The experimental data ("solar" abundances) were taken from [9]
(they are normalized to $N(Si)=10^6$)

Prog. nucleus (*A, Z*)	*p*-nucleus (*A, Z*+2)	"solar" abundance Foremother nuclei *N*(*A, Z*) exp.	"solar" abundance *p*-nuclei *N*(*A, Z*+2) exp.	Abundance of *p*-nuclei (*A, Z*+2) theory			
				Oxygen burring		Silicon burring	
				$3\cdot10^9$ K; τ = 5 мес.		$5\cdot10^9$ K; τ = 1 сут.	
				a	*b*	*a*	*b*
$^{74}_{32}Ge$	$^{74}_{34}Se$	41.2	0.60	0.679	0.791	0.609	0.692
$^{78}_{34}Se$	$^{78}_{36}Kr$	16.04	0.20	$1.7\cdot10^{-4}$	$3.5\cdot10^{-4}$	$6.9\cdot10^{-4}$	$1.5\cdot10^{-3}$
$^{80}_{34}Se$	$^{80}_{36}Kr$	33.48	1.30	30.7	32.5	17.2	18.2
$^{84}_{36}Kr$	$^{84}_{38}Sr$	31.78	0.13	0.708	1.13	0.724	0.934
$^{92}_{40}Zr$	$^{92}_{42}Mo$	1.848	0.370	$2.9\cdot10^{-3}$	0.014	$2.8\cdot10^{-4}$	$5.8\cdot10^{-4}$
$^{94}_{40}Zr$	$^{94}_{42}Mo$	1.873	0.233	1.85	1.85	1.86	1.87
$^{96}_{42}Mo$	$^{96}_{44}Ru$	0.425	0.099	$3.3\cdot10^{-7}$	$3.2\cdot10^{-5}$	$1.2\cdot10^{-6}$	$8.4\cdot10^{-5}$
$^{98}_{42}Mo$	$^{98}_{44}Ru$	0.622	0.033	0.483	0.622	0.366	0.415
$^{102}_{44}Ru$	$^{102}_{46}Pd$	0.562	0.0139	0.0219	0.171	$7.8\ 10^{-3}$	0.064
$^{106}_{46}Pd$	$^{106}_{48}Cd$	0.371	0.020	$7.5\cdot10^{-4}$	0.371	0.159	0.233
$^{108}_{46}Pd$	$^{108}_{48}Cd$	0.359	0.014	0.073	0.103	0.014	0.020
$^{110}_{46}Pd$	$^{110}_{48}Cd$	0.159	0.197	0.158	0.159	0.137	0.137
$^{112}_{48}Cd$	$^{112}_{50}Sn$	0.380	0.035	$1.7\cdot10^{-3}$	$5.2\cdot10^{-3}$	$1.8\cdot10^{-3}$	$5.3\cdot10^{-3}$
$^{114}_{48}Cd$	$^{114}_{50}Sn$	0.452	0.024	0.372	0.452	0.220	0.269
$^{120}_{50}Sn$	$^{120}_{52}Te$	1.175	0.005	$3.5\cdot10^{-3}$	0.015	$7.2\cdot10^{-3}$	0.030

${}^{124}_{52}Te$	${}^{124}_{54}Xe$	0.226	0.007	$3.4\cdot10^{-7}$	$1.1\cdot10^{-5}$	$3.0\cdot10^{-6}$	$9.8\cdot10^{-5}$
${}^{126}_{52}Te$	${}^{126}_{54}Xe$	0.889	0.006	0.211	0.321	0.046	0.068
${}^{130}_{54}Xe$	${}^{130}_{56}Ba$	0.239	0.005	$1.4\cdot10^{-5}$	$1.6\cdot10^{-4}$	$2.3\cdot10^{-5}$	$3.1\cdot10^{-4}$
${}^{132}_{54}Xe$	${}^{132}_{56}Ba$	1.438	0.005	0.176	0.871	0.048	0.232
${}^{136}_{56}Ba$	${}^{136}_{58}Ce$	0.351	0.002	$4.5\cdot10^{-5}$	$1.8\cdot10^{-3}$	$3.4\cdot10^{-5}$	$1.4\cdot10^{-3}$
${}^{138}_{56}Ba$	${}^{138}_{58}Ce$	3.205	0.003	1.42	3.20	2.62	3.12
${}^{144}_{60}Nd$	${}^{144}_{62}Sm$	0.203	0.008	$2.5\cdot10^{-6}$	$4.4\cdot10^{-3}$	$1.3\cdot10^{-6}$	$1.2\cdot10^{-4}$
${}^{152}_{62}Sm$	${}^{152}_{64}Gd$	0.071	0.0007	0.0251	0.029	$9.5\cdot10^{-3}$	0.011
${}^{156}_{64}Gd$	${}^{156}_{66}Dy$	0.0736	0.0002	$3.2\cdot10^{-6}$	$8.5\cdot10^{-4}$	$2.1\cdot10^{-6}$	$5.4\cdot10^{-4}$
${}^{158}_{64}Gd$	${}^{158}_{66}Dy$	0.0894	0.0004	0.060	0.089	0.045	0.060
${}^{162}_{66}Dy$	${}^{162}_{68}Er$	0.1028	0.0004	$4.2\cdot10^{-5}$	$5.5\cdot10^{-3}$	$1.2\cdot10^{-5}$	$3.6\cdot10^{-3}$
${}^{164}_{66}Dy$	${}^{164}_{68}Er$	0.1141	0.0042	0.044	0.114	0.043	0.082
${}^{168}_{68}Er$	${}^{168}_{70}Yb$	0.071	0.0003	$3.3\cdot10^{-4}$	0.018	$1.2\cdot10^{-5}$	$4.3\cdot10^{-3}$
${}^{174}_{70}Yb$	${}^{174}_{72}Hf$	0.0821	0.0003	$6.1\cdot10^{-3}$	0.080	$1.0\cdot10^{-3}$	0.013
${}^{180}_{72}Hf$	${}^{180}_{74}W$	0.0547	0.0002	0.029	0.054	0.047	0.054
${}^{184}_{74}W$	${}^{184}_{76}Os$	0.0420	0.0001	$1.4\cdot10^{-8}$	$6.4\cdot10^{-4}$	$3.3\cdot10^{-8}$	$6.4\cdot10^{-6}$
${}^{190}_{76}Os$	${}^{190}_{78}Pt$	0.179	0.0002	$1.6\cdot10^{-6}$	0.011	$9.7\cdot10^{-7}$	$3.6\cdot10^{-4}$
${}^{196}_{78}Pt$	${}^{196}_{80}Hg$	0.322	0.0010	$6.0\cdot10^{-5}$	0.046	$2.8\cdot10^{-5}$	$3.8\cdot10^{-3}$