The analysis of P-even angular correlations of fission fragment from $^{235}U(n,f)$ - and $^{239}Pu(n,f)$ - reaction induced by s- and p-wave neutron resonance interference.

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Relation between A.Bohr's "fission channels" and fission modes is during last decades a subject of some theoretical and experimental investigations [1-3]. It was shown [2] the wave function of a transition state $J^{\pi}K$ (generalized A.Bohr's fission channel) can be represented as an expansion over the wave functions of distinct fission modes with the coefficients depending on deformation of fissioning system.

The new approach [4] to a description of nuclear fission induced by low energy neutrons based on the standard reaction theory joints naturally the extended concept of transition states [2] and a consistent description of angular correlations of fission products observed in the experiments [5-9] Using a modified helicity representation for fission product channels c_f introduced firstly by V.Strutinski [10] a summation over huge number of c_f channels taking place in real experiments has been carried out [4,11] in the framework of a pole expansion of the S-matrix. It was shown how P-even and P-odd correlations of fission products could "survive" and the "reduced" S-matrix defined for the "observed" $J^{\pi}K$ multi mode channels f was obtained in consistent way. This multi level S-matrix equivalent to "ad hoc" introduced Reich – Moore S-matrix allows one to describe the observed interference effects in the total and differential cross sections of (n,f)-reaction. Very recently on the basis of correct account for total parity of fission product channels in a helicity representation the new formulas for fission product angular correlation were obtained [12].

These formulas are used below for analysis of experimental data on angular anisotropy of fission fragments from resonance neutron induced fission of aligned nuclei ^{235}U [9] and P-even angular correlations for $^{235}U(n,f)$ reactions [8]. In the framework of the approach [4,12] outlined above the differential cross section of (n,f)-reaction could be written in the form:

$$\frac{d\sigma_{nf}(E)}{d\Omega_f}=\frac{1}{4\pi}\{\sigma_{nf}^{(0)}(E)+\sigma_{nf}^{(1)FB}(E)(\vec{n}_f\vec{n}_k)+\sigma_{nf}^{(1)RL}(E)p_n(\vec{n}_f[\vec{n}_k\vec{n}_s])+$$
$$+\sigma_{nf}^{(2)}(E)f_2P_2(\vec{n}_f\vec{n}_I)\}, \qquad (1)$$

where

$$\sigma_{nf}^{(0)}=\pi\lambda\!\!\!^{-2}\sum_{J^{\pi}}g_J\sum_{lj}\sum_{K}|S_J(ljE\to K\pi f)|^2=\sum_{J^{\pi}}\sigma_{nf}^{(0)J^{\pi}}(E) \qquad (2)$$

is the total fission cross section expressed as a sum of the spin-separated components.
Other terms of (1) can be expressed as

$$\sigma_{nf}^{(1)}=\pi\lambda\!\!\!^{-2}\sum_{J^{\pi}}\sum_{J'j}\pi_0 g_J(-1)^{\frac{3}{2}-j}\sqrt{6(2j+1)}\times$$
$$\times U(IjJ1,J'\tfrac{1}{2})\,\mathrm{Im}\big((1-i\beta_j)\times$$
$$\times\{-C_{J010}^{J'0}S_{J'}^{*}(1j\to 0f)S_J(0\tfrac{1}{2}\to 0f)+$$
$$+\sum_{K>0}C_{JK10}^{J'K}S_{J'}^{*}(1j\to Kf)S_J(0\tfrac{1}{2}\to Kf)\}\big) \qquad (3)$$

and

$$\sigma_{nf}^{(2)} = \pi\lambda^2 G \sum_{J^\pi}\sum_{J'j}\sum_{K} g_J U(\frac{1}{2}IJ'2,JI) C_{JK20}^{J'K} S_{J'}^{*}(0\frac{1}{2}E \to K\pi f) S_J(0\frac{1}{2}E \to K\pi f) . \quad (4)$$

Here the quantum numbers l and j are orbital and total momenta of incident neutron, I is a spin of target nucleus, $\vec{n}_i$ ($i = k,s,I,f$) denotes unit vectors of neutron momentum and spin, a target nucleus spin and a fission product relative momentum, respectively. The coefficients $\beta_j = 1$ for $j = \frac{1}{2}$ and $\beta_j = -0.5$ for $j = \frac{3}{2}$, p_n is neutron beam polarization, f_2 is alignment of target nuclei,

$$G = \frac{15 I^2}{\sqrt{(2I-1)I(I+1)(2I+3)}} ,$$

$U(IjJQ, J'I)$ and $C_{JKQ0}^{J'K}$ are Racah and Clebsh-Gordon coefficients respectively.

In the framework of the same theoretical approach it is possible to obtain the next expression for P-odd part of the differential cross section:

$$\frac{d\sigma_{nf}^{PV}(E)}{d\Omega_f} = \frac{1}{4\pi}\sigma_{nf}^{(1)PV}(E) 3\tau'_{10}(s)(\vec{n}_f \vec{n}_s) , \quad (5)$$

where

$$\tau'_{10}(s) = \frac{1}{\sqrt{3}} p_n$$

$$\sigma_{nf}^{(1)PV} = \pi\lambda^2 [-\frac{2}{2I+1}\sqrt{\frac{I(+1)}{3}} \sum_{\pi=\pi_0,-\pi_0} \pi \times$$

$$\times \mathrm{Im}\{S^{*}_{I+\frac{1}{2}}(0\frac{1}{2} \to 0 - \pi f) S_{I-\frac{1}{2}}(0\frac{1}{2} \to 0\pi f)\} +$$

$$+ 2\pi_0 \sum_{JJ'} g_J U(I\frac{1}{2}J1, J'\frac{1}{2}) \sum_{K>0} C_{JK10}^{J'K} \mathrm{Im}\{S_{J'}^{*}(0\frac{1}{2} \to K - \pi_0 f) S_J(0\frac{1}{2} \to K\pi_0 f)\}] \quad (6)$$

and π_0 is the parity of target nucleus so $\pi = (-1)^l \pi_0$.

It is important to note that the study P-even and P-odd angular correlations caused by an interference of s- and p-wave reaction amplitudes provides a direct information on the parity dependence of the fission barriers for $J^\pi K$ channels. The experimental investigation of such correlations has been carried out by Dubna – Gatchina collaboration for target nuclei ^{235}U and ^{233}U (see refs. {8] and [13]) and has been finished recently [14] for ^{239}Pu target nucleus. For P-even correlations the experiments of two types were fulfilled. In the first type of the experiments an energy dependence of fission fragment yield difference along and opposite to the direction of unpolarized incident neutron momentum ("forward-back")

$$\alpha^{FB} = \frac{N^F - N^B}{N^F + N^B} . \quad (7)$$

was measured. In the second type of experiments the asymmetry of fission fragment emission in a respect to the plane formed by the spin of polarized neutron and its momentum

$$\alpha^{RL} = \frac{N^R - N^L}{N^R + N^L} \quad (8)$$

was investigated.

Using the formulas (1) – (3) one can obtain the next expressions for the coefficients α^{FB} and α^{RL} ($\alpha^{RL} = -\alpha^{LR}$) which can be applied for analysis of experimental data.

The forward-back asymmetry can be written as

$$\alpha^{FB} = \frac{A}{B} , \quad (9)$$

where

$$A = \sum_J g_J \sum_{J'j} \sum_K Z(JJ'Kj)[\cos\Delta\phi(\mathrm{Re}W_1 \,\mathrm{Im}W_0 - \mathrm{Im}W_1 \,\mathrm{Re}W_0) + \\ + \sin\Delta\phi(\mathrm{Re}W_1 \,\mathrm{Re}W_0 + \mathrm{Im}W_1 \,\mathrm{Im}W_0)], \qquad (10)$$

$$B = \sum_{Jl} g_J \sum_K |W_l(JK)|^2 \qquad (11)$$

and the right-left asymmetry can be expressed in the form:

$$\alpha^{RL} = \frac{C}{B},$$

where

$$C = p_n \sum_J g_J \sum_{J'j} \sum_K Z(JJ'Kj)\beta_j[\cos\Delta\phi(\mathrm{Im}W_1 \,\mathrm{Re}W_0 - \mathrm{Re}W_1 \,\mathrm{Im}W_0) + \\ + \sin\Delta\phi(\mathrm{Re}W_1 \,\mathrm{Re}W_0 + \mathrm{Im}W_1 \,\mathrm{Im}W_0)]$$

In these formulas the S-matrix was taken in the form

$$S^J_{nfl} = 2e^{-i\phi_l}W \text{ with } W = [(I-K)^{-1}]_{nf},$$

where for the matrix elements K_{nf} the expression

$$K_{nf} = -\frac{1}{4}\sum_\lambda \frac{\Gamma_{\gamma\lambda}\sqrt{\Gamma_{n\lambda}\Gamma_{f\lambda}}}{d_\lambda} + \frac{i}{2}\sum_\lambda \frac{(E_\lambda - E)\sqrt{\Gamma_{n\lambda}\Gamma_{f\lambda}}}{d_\lambda}$$

$$d_\lambda = (E_\lambda - E)^2 + \Gamma^2_{\gamma\lambda}/4$$

was used. Here the multi indexes n and f are defined as $n \equiv \{ljJ\}$ and $f \equiv \{J^\pi K\}$. The index λ enumerates compound states of fissioning nucleus. In the formulas (10) – (13) Z is a combination of geometric coefficients, $\Delta\phi = \phi_1 - \phi_0$, $\phi_0 = ka$, $\phi_1 = ka - \arctan(ka)$, a is the potential scattering radius in an entrance channel, $k = k_n$.

In the following analysis the parameters of S-matrix for s-wave fission are extracted from ref. [15] for ^{235}U and from ref. [16] for ^{239}Pu and are kept fixed during the fit procedure. The energy dependence of the experimental coefficients $\alpha^{FB}(E)$ and $\alpha^{LR}(E)$ was fitted to obtain information on the positions and parameters of the p-wave resonances lying in the energy interval under consideration..

The range of S-matrix for s- and p-wave fission in principle is different. In entrance channels the range is estimated in an apparent way but for exit channels a situation is not trivial. The interference terms in formulas for α^{FB} and α^{LR} have the same projections K for the s- and p-wave fission but in the total p-wave fission cross section the additional $J^\pi K$ channels could contribute. But these channels could be forbidden according to the angular momentum and parity conservation laws for the s-wave fission. These additional resonance parameters should be included in the fit to preserve the unitarity of corresponding S-matrix.

The result of new fit of $\alpha^{FB}(E)$ and $\alpha^{LR}(E)$ values for the case $^{235}U(n,f)$-reaction are shown in fig.1. It is seen that a quality of the fit is approximately the same as in the previous analysis [17] carried out with something different formulas for α^{FB} and α^{LR} which are revised now [12] to include more correct description of a total parity in exit fission channels. Such result could be explained by the fact that a lot of free parameters for p-wave resonances are used in fitting of experimental data which have in turn very complicated dependence on neutron energy.

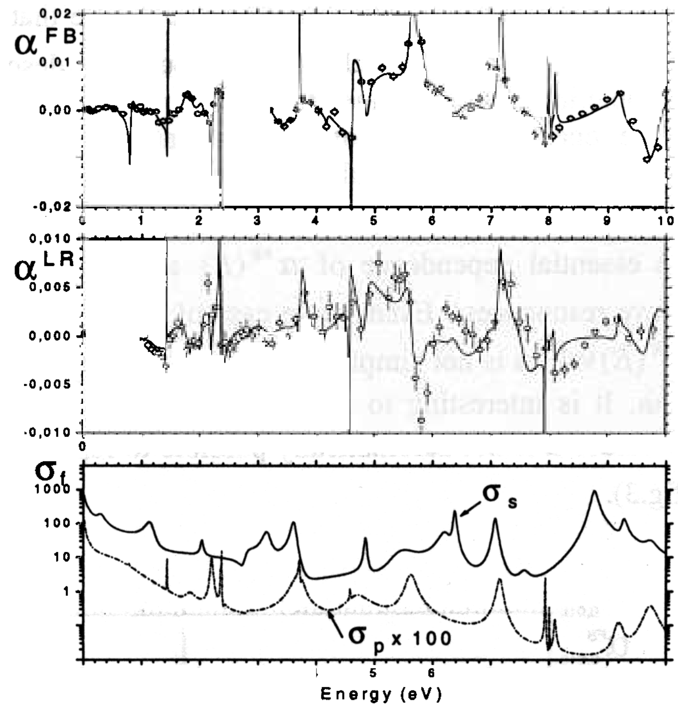

Fig.1. The fit of experimental values of $\alpha^{FB}(E)$ and $\alpha^{LR}(E)$ for ${}^{235}U(n,f)$-reaction, realized with s-wave and p-wave fission cross sections shown in lower part of the figure.

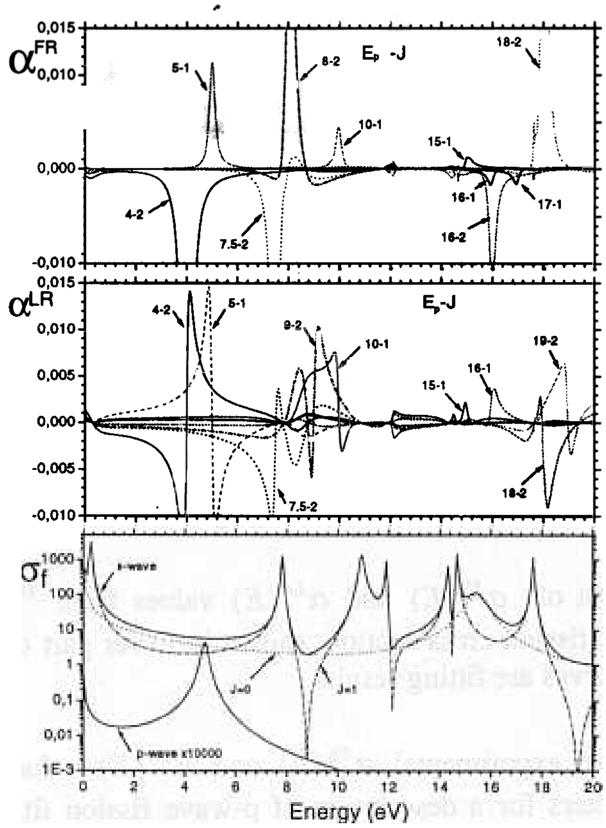

Fig.2. The test calculations of the $\alpha^{FB}(E)$ and $\alpha^{LR}(E)$ dependences for ${}^{239}Pu(n,f)$-reaction carried out with one p-wave resonance. The different curves correspond to the various positions and spins of the assumed p-wave compound state.

The case of $^{239}Pu(n,f)$-reaction is something more simple that $^{235}U(n,f)$-one because only an account of the $1^{+}0$ and $0^{+}0$ fission channelsis enough for description of the respective cross sections. To get some intuition on influence of different parameters of p-wave resonances onto the value and the energy behavior of the correlation coefficients some methodical calculations have been carried out. The results are presented in fig. 2. It is seen that energy behavior of $\alpha^{FB}(E)$ and $\alpha^{LR}(E)$ has strong dependence on the value of p-wave resonance spin. Also one can see the essential dependence of $\alpha^{FB}(E)$ and $\alpha^{LR}(E)$ on relative position of interfering s- and p-wave resonances. Even in the case of $^{239}Pu(n,f)$-reaction a simultaneous fit of $\alpha^{FB}(E)$ and $\alpha^{LR}(E)$ values is not simple due to the fact that two $0^{+}0$ channels contribute [16] for s-wave fission. It is interesting to note that if one fit reproduces in some way the experimental $\alpha^{FB}(E)$ values it is not automatically possible to reproduce the experimental data for $\alpha^{LR}(E)$ too (see fig.3).

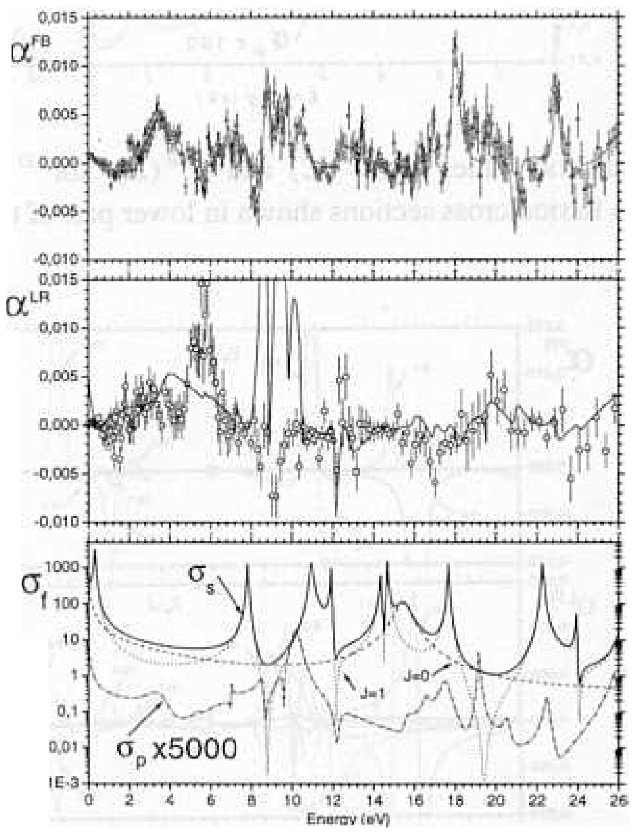

Fig.3. The preliminary fit of $\alpha^{FB}(E)$ and $\alpha^{LR}(E)$ values from $^{239}Pu(n,f)$-reaction realized with s-wave and p-wave fission cross section, shown in lower part of the figure. The points are experimental data, the curves are fitting results.

Now the joint analysis of experimental $\alpha^{FB}(E)$ and $\alpha^{LR}(E)$ values is continued to obtain a consistent set of parameters for a description of p-wave fission fitting respective interference effects. After completion of such analysis it will become possible to derive some conclusions on parity dependence of fission barriers for fixed number of $J^{\pi}K$.

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EPITHERMAL NEUTRON ACTIVATION ANALYSIS FOR DEVELOPING SELENIUM-, IODINE-, AND CHROMIUM-CONTAINING PHARMACEUTICALS BASED ON BLUE-GREEN ALGAE *SPIRULINA PLATENSIS* MATRIX

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Neutron activation analysis was successfully used to substantiate developing of selenium-, iodine-, and chromium-containing pharmaceuticals based on blue-green algae *Spirulina platensis,* which is widely used in fundamental and applied biotechnology. This algae was chosen as a matrix for these pharmaceuticals due to its fast growth, non-toxicity, assimilability (85-95%), high protein content (60-70%), well-balanced amino acid compositions, richness in vitamins, and a great variety of biologically active agents in appreciable amounts. The ability to biotransform and endogenously add the desired elements producing complexes easily assimilated by a human organism is a distinctive feature of *Spirulina platensis* [1, 2].

As a preliminary stage of research, the background levels of the elements in cells of *Spirulina Platensis* biomass cultivated in a standard nutrient medium with distilled water were studied by epithermal neutron activation analysis (ENAA) at the fast pulsed reactor IBR-2.

The concentrations of 31 macro-, micro- and trace elements (namely Na, Mg, Al, Cl, K, Ca, Sc, V, Cr, Mn, Fe, Co, Ni (using (*n, p*) reactions), As, Br, Zn, Rb, Mo, Ag, Sb, I, Ba, Sm, Tb, Tm, Hf, Ta, W, Au, Hg, and Th) ranging from 10^{-3} up to 10^{5} ppm were determined (Fig. 1).

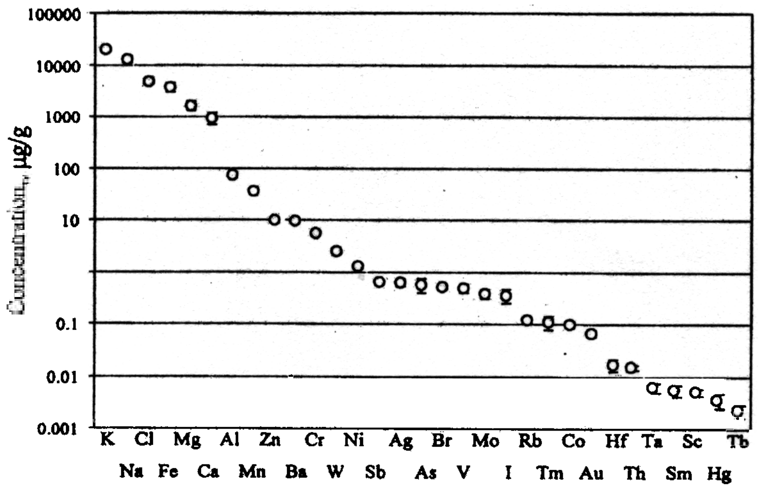
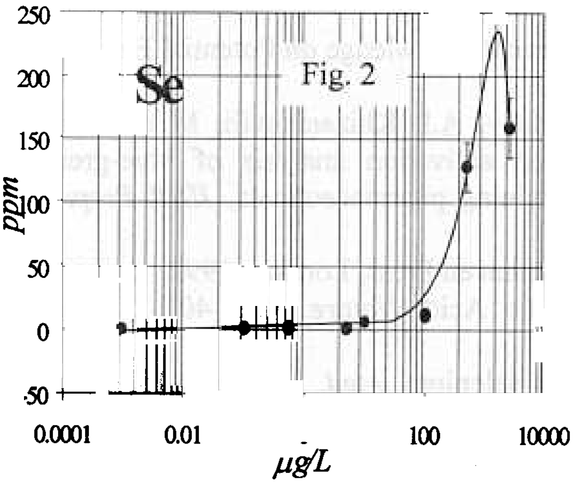


Fig. Background concentrations of macro-, micro- and trace elements in the *Spirulina platensis* biomass [3].

It is evident that the cultivated *Spirulina Platensis* biomass does not contain toxic elements in concentrations above the tolerance levels and such product can be utilized as a matrix for the manufacturing of pharmaceuticals based on it (see http://www.spirulina.com/spbnutrition.htlm).

The deficiency of certain elements and compounds in the human organism is the cause many ailments [4]. One of such elements is selenium. Selenium is a component of some enzymes, proteins and is incorporated in the 21st amino acid, selenocysteine, which plays a unique part in the readout of genetic information during the synthesis of proteins [5-7]. A low level of selenium may cause such diseases as cancer, cardiomyopathy, anemia, *etc.*

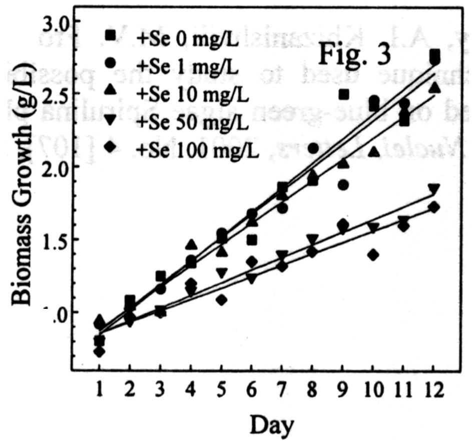
Another equally important element is iodine. It is a vitally important element for the function, development and growth of the human organism. Iodine affects metabolism enhancing the oxidation-reduction processes. Iodine deficiency results in dysfunction of the thyroid and is reduction of the level of intellectual development [8]. For experimental investigation of the possibility of creation of Se- and I-containing pharmaceuticals, a method for cultivation of the *Spirulina* biomass in nutrient medium with the given concentration of loading is developed [9, 10].

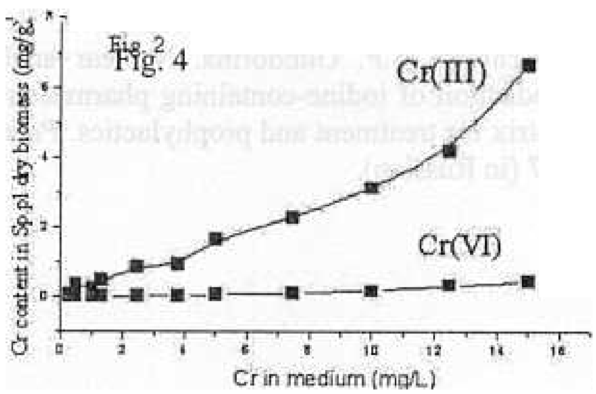


The dynamics of Se and I accumulation by *Spirulina Platensis* in the process of its cultivation was studied. A polynomial relationship between the accumulation of selenium and iodine in the Spirulina biomass and their concentration in the nutrient medium is found. The concentration of selenium in the *Spirulina* biomass versus its concentration in the nutrient medium is shown in Fig. 2.

On the basis of the results obtained, the physiological doses of Se and I in the *Spirulina* biomass required for manufacturing medical and prophylactic preparations were determined.

The influence of different doses of selenium on the growth of Spirulina cells, on the chlorophyll content and on the total protein are studied. The range of selenium concentration was 0.5–15 mg/L. It is shown that the increase of the Se concentration in the given range practically does not influence the growth of the *Spirulina platensis* biomass and its natural properties (Fig. 3).





However, in the case of large doses of Se in the Spirulina biomass a decrease of chlorophyll and total protein contents was observed In the process of Spirulina biomass cultivation with biogenically bound chromium it was established that the Cr^{+6} (in the form of $K_2Cr_2O_7$) reduce the growth of cells and the content of chlorophyll and total protein, while Cr^{+3} (in the form of $Cr(CH_3COO)_3$) stimulates the biomass growth (Fig. 4). Thus Spirulina cells actively accumulate Cr^{+3} and do not bind Cr^{+6}.

The study carried out allow to optimize the concentrations of Se, I and Cr in the nutrient medium for obtaining their predetermined doses in *Spirulina platensis* biomass intended to be used as bioactive nutrients for medical purposes.

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