Prospects of Using the Complicated ('flaky') Neutron-Optical Potential

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Abstract: *The big work on research of thin structure of neutron-optical potential for heavy nuclei has been done.*

Motivation of this research is connected with necessity of an explanation of following phenomena:

1.Presence enough sharp fluctuation of parameters of potential by studying of their power dependence which at neutron energies more than 0.5 MeV appear to be very close, for example, for lead and uranium nuclei.

2.Correlation of structures in energy dependence of any characteristics of interaction of neutrons with nuclei: full cross sections, cross sections of fission, kinetic energy of products of fission and etc.

3.Equidistant arrangement of correlating structure similar under the form not in scale of energies but in a scale of lengths of waves of neutrons.

4.Small-angle neutron scattering of MeV neutrons by heavy nuclei.

The assumption of possibility to explain the observable phenomena by diffraction of neutron waves on spatially divided structures of a nucleus with inevitability has raised the question about existence of correlations in cross sections for various radiations, for example, neutrons and gamma beams, at coincidence of their lengths of waves. The first attempts to find such correlations have crowned success and are the most difficulty refutable proof of existence of spatially divided nuclear structures.

Figure 1 shows two variants of the optical potential real part, obtained in the work [1] in result of a detailed search, where at every integration step of Schrodinger equation the ordinate of the potential is considered to be a free parameter. At that, an apprehension can arise that in such search procedure a risk exists of the terms values of potential departing into the physically unreal area of the parametric space.

Nevertheless, this risk might be brought to a minimum: firstly, the ordinates of the potential should be announced as free only after the approximation of the experimental data had been obtained using it (i.e. the squared search functional is in the minimum, and the optimal value of the volume integral of a required potential had been acquired). Secondly, radical methods of search should not be applied, e.g., random search, when the random number generator can 'throw' the parameter set to the physically unreal area of the parametric space.

A more time consuming but a more dependable method of cyclic enumeration of parameters with their small increments at each search step was used in the work [1]. In this case, a departure from already found minimum of the quadratic search functional is practically impossible.

The work [1] emphasizes that at the initial stage of the search, the experimental material was used for full cross-sections and differential cross-sections of neutron scattering by lead to large and small angles [2]. In the aftermath, small-angle scattering was excluded from the consideration. Thus, further, to evaluate the neutron electric polarizability with a new potential the verification of its peripheral part is to be carried out.

It can be said that the search of the nuclear potential was performed as a search for its more complicated form. The idea of heavy nuclei 'neutron coat', for instance, compelled the authors of the work [2] to use the real part of the potential in the form of two Woods-Saxon terms. The investigation of the nuclear charge density distribution by way of research of high energy electrons scattering ($E_e \sim 120 \div 180$ MeV) by Hofstadter et al [3,4] lead to the conclusion of a possibility to reduce protons density in the center of the nucleus. This result

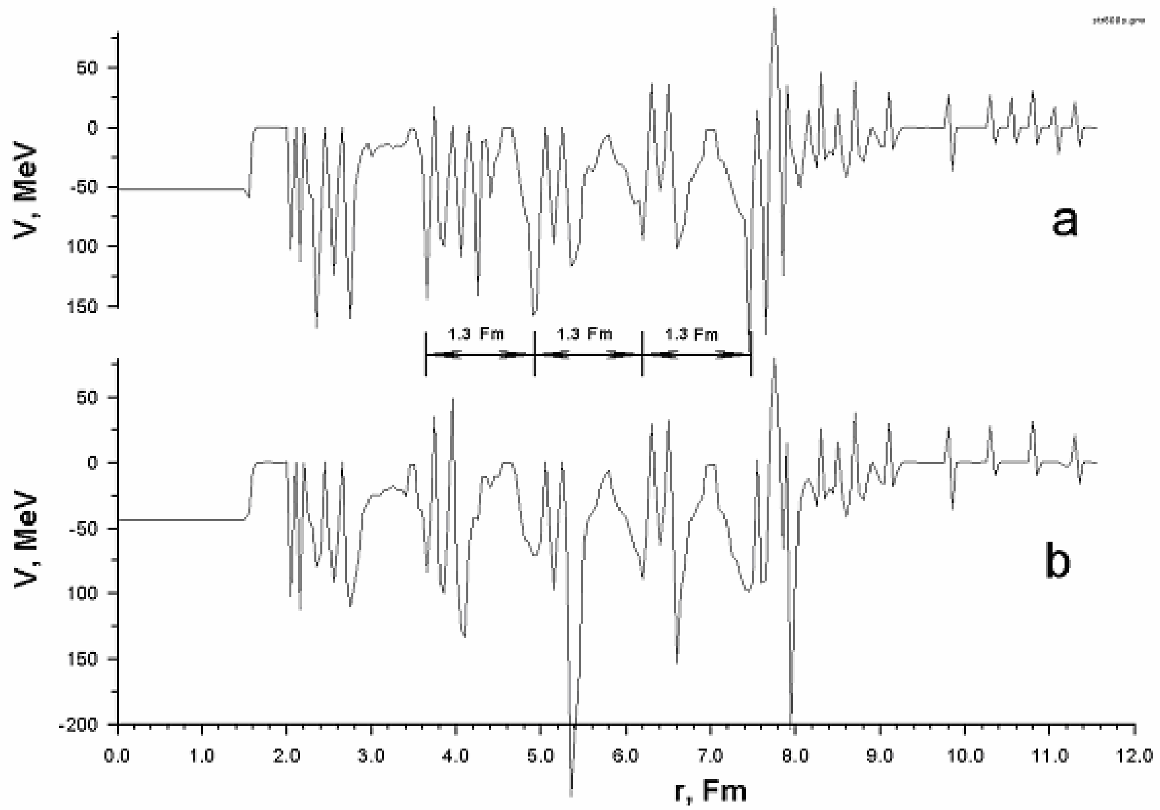

Fig. 1

The real part of the nuclear-optical potential from the work [1] (see the text).

was more surely registered for gold nuclei, and was not marked for lead-208.

With account of these results, the work [5] on the possibility of scattering very high energy protons ($E_p \sim 1$ GeV) by nuclei also comes to the conclusion of a possibility to reduce protons density in the center of the nucleus. The work [6] considered the possibility to introduce analytically the decrease of a potential hole assuming of the real part of the potential in the 'bottle bottom' form.

The authors of the work [7] realized this idea using the real part of the potential as the sum of three members:

$$-V=\sum_{i=1}^{3} V_i/(1+\exp((r-r_i)/a_i)) .$$

The initial values of the parameters V_3 and r_3 were: $V_3 = 0$, $r_3 = 3$Fm

In the automatic search process these parameters acquired the values: $V_3 = -4.45$ MeV, $r_3 = 2.75$ Fm (for uranium) and $V_3 = 3.25$ MeV, $r_3 = 2.56$ Fm (for lead) which provided the decrease of a potential's pit depth in the central area of the nucleus by the range of about 4 MeV. This decrease disappears very rapidly with the growth of the distance from the nucleus center (parameter $a_3 = 0.1$ Fm).

It is marked in the work that the increase of a_3 parameter up to 0.2 Fermi doubles the squared search functional for angular distributions of neutrons with a wave length of $2 \div 3$ Fm. This suggested the idea of existing of structural elements with rapidly changing with radius in the nuclear potential and served a stimulus for conducting a detailed research of the optical potential radial dependence [1]. One of the found variants of the real part of the potential is presented in the work [8].

It turned out that the potential possesses a 'flaky' (almost periodical) structure, the elements of which do not have an over high 'hardness'. The work [1] shows that each of these elements can deform at coincidence of its radial address with the indicated wave length $\lambda/2\pi$ of the oncoming neutron.

In view of the above, it can be possibly noted that the most suitable instrument for the nuclear structure investigation could have been a detailed examination of cross-sections of neutrons scattering with not so high energy (e.g. 0.05 MeV $\leq E_n \leq$ 25 MeV). At using very high energy particles, as it is correctly noted in the work [5], we can obtain the picture of localization of individual nucleons in the kernel, but the structures being the result of their interaction will be scarcely evaluated accurately. Most probably, they will be deformed or even destructed.

Reviewing the prospect of a more precise determination of neutron electric polarizability, it needs to assess – if all the possibilities had been used in already completed works. There, the correlation is marked of deviations from the theory of the experimental small angle cross-sections with energy dependence of the real part of the nuclear amplitude [9]. That indicated the interferential nature of the deviations which were maximal at neutrons energy of 1 ÷ 2 MeV. It is not surprising that propositions were expressed to repeat the measurements of differential cross-sections namely at these neutrons energies [10].

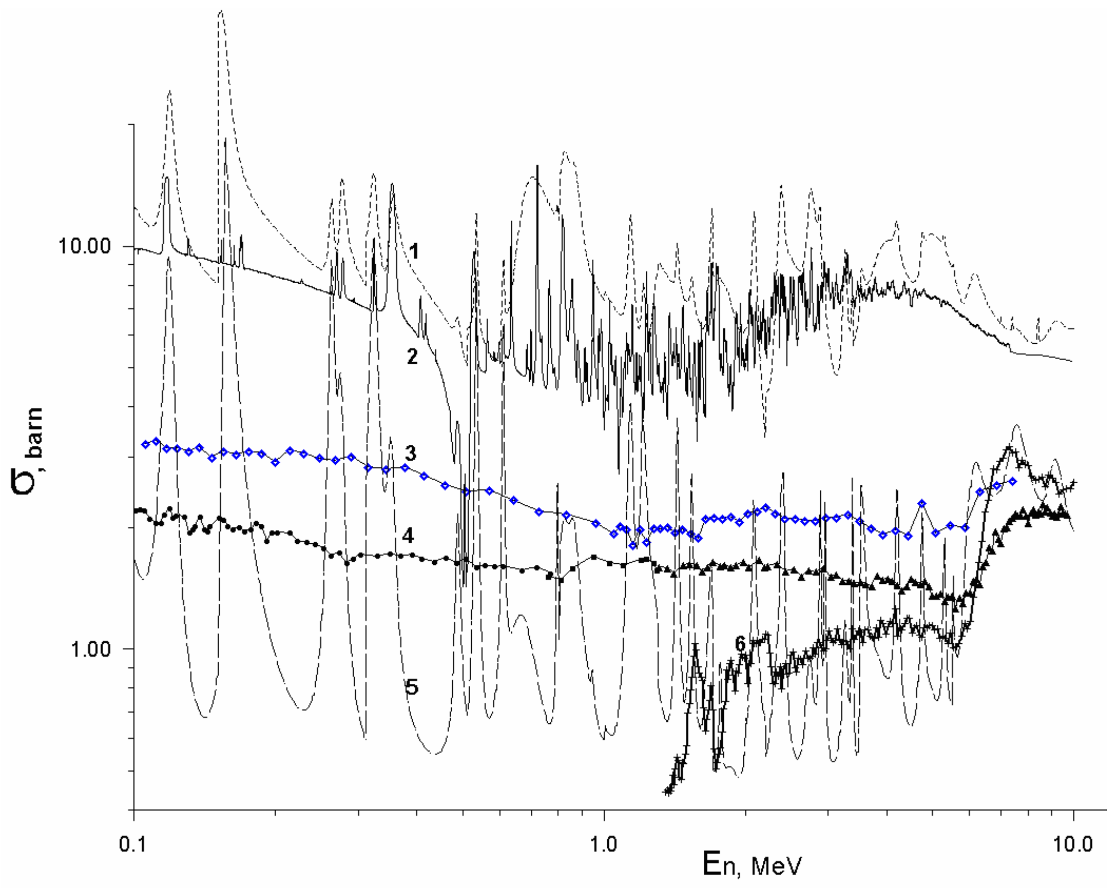

Fig. 2

Comparison of the cross-sections calculated applying the optical model with the 'flaky' potential (dotted curves) with experimental data for heavy nuclei (see the text).

At the assessment of neutron polarizability, the analysis of cross-sections takes place, which cross-sections are averaged in a certain energy interval. But, as was noted in the works [11, 12], the elements of the full cross-section resonant structure should be also taken into account

For assessing the resonant structures in the cross-sections the complicated (‘flaky’) potential of the optical model could be used, as shown in Fig. 1. Its possibilities are illustrated in Fig. 2, where the results are shown of the adjustment of the potential to describe the full cross-sections massive measured in Los-Alamos [13]. The massive contained 11 thousand values of σ_t in the range of neutron energy from 0.1 to 12 MeV. In the result of the averaging procedure it was reduced to 300 values (it is represented in the figure by continuous curve with number 2). The dotted curve under number 1 is the result of calculations of full cross-sections with ‘flaky’ potential [1]. It is worth to note a considerable consent in the behavior of the averaged σ_t with the calculated cross-sections values. Moreover in the energies range of about 0.5—1 MeV the calculation also reproduce separate narrow resonances.

Curves 3 and 4 represent the cross-sections of fissions of Cm-247 [14] and U-235 [15,16],correspondingly. On the curve 6 the cross-sections of fission of Th-232 [17] are shown, elevated by an order, for a better compactness of the figure. Curve 5 is the cross-section of the compound nucleus formation, normalized in such way that its resonances allowed to track the structures correlation in the calculated and experimental cross sections in a better way, and also the structure correlation of experimental cross sections for various heavy elements with the structures in lead σ_t. These correlations are discussed in detail in the work [18]. They also became one of the stimulus of the search for spatial structures in the nuclear potential as the source of additional diffraction effects in the cross sections. Especially meaningful in this respect are the correlation of structures in neutron cross sections and photo-nuclear reactions cross-sections at coincidence of neutron and γ ray wave lengths. The examples of such correlations are given in the works [1, 18]. We reproduce one of them in this work in Fig.3.

The degree of correlation of the structures presented in Fig. 2 is increasing with the growth of neutrons energy since for these neutrons the role of diffraction effects becomes more important in the inner nucleus ‘layers’, which are practically similar with heavy nuclei. At the decrease of the energy the correlation for fission cross-sections remains notable, whereas the correspondence in the positions of resonances with those in lead cross section diminishes, since the peripheral part of the potential comes into play, perhaps, reflecting the presence of nucleonic ‘stratosphere’, which is more poor for lead than for other heavy nuclei.

At the adjustment of the potential its terms [curve a) in Fig. 1] was taken with a certain change: the central part with the depth of about 50 MeV, left from Woods-Saxon potential, was replaced by small (nearly zero) values. Energy dependence is tracked anew of the real spin-orbital and imaginary part of the potential, K_{re}, K_{so}, K_{IM} coefficients are found, by which the depths of these parts were multiplied in 12 energy intervals, into which all the energy range was divided (from 0.1 to 12 MeV). The interval limits in Table 1 are identified as E_1 and E_2 ($E_1 < E_n \leq E_2$).

Table 1

E_1, MeV	0.1	0.15	0.31	0.51	0.8	1.0	1.3	1.7	2.2	2.9	3.5	5.5
E_2, MeV	0.15	0.31	0.51	0.80	1.0	1.3	1.7	2.2	2.9	3.5	5.5	12
K_R	0.60	0.30	0.23	0.34	0.40	0.39	0.40	0.44	0.49	0.49	0.10	0.10
K_{S1}	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.2	0.1
K_{S2}	2.17	6.16	6.18	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.0	0.0

The said multipliers were calculated by the table data as $K_{RE}=K_R E_n$, $K_{SO}=K_{S1}E_n+K_{S2}$, E_n is neutron energy. What concerns the imaginary part, its energy dependence rate is approximated analytically by the formula :

$$K_{IM} = 0.0031/E_n^{1/2} + \sum_{l=1}^{3} K_{Im\,l} \cdot E_n \cdot \exp(B_l)/(1+\exp(B_l))^2$$

Here $B_l = |E_n - E_l|/A_l$, and the rate of attenuation of exponents A_l was changing its values at threshold values of E_l: $A_l = A_{l1}$ at $E_n < E_l$ and $A_l = A_{l2}$ at $E_n \geq E_l$.

The parameters of this formula are specified in Table 2.

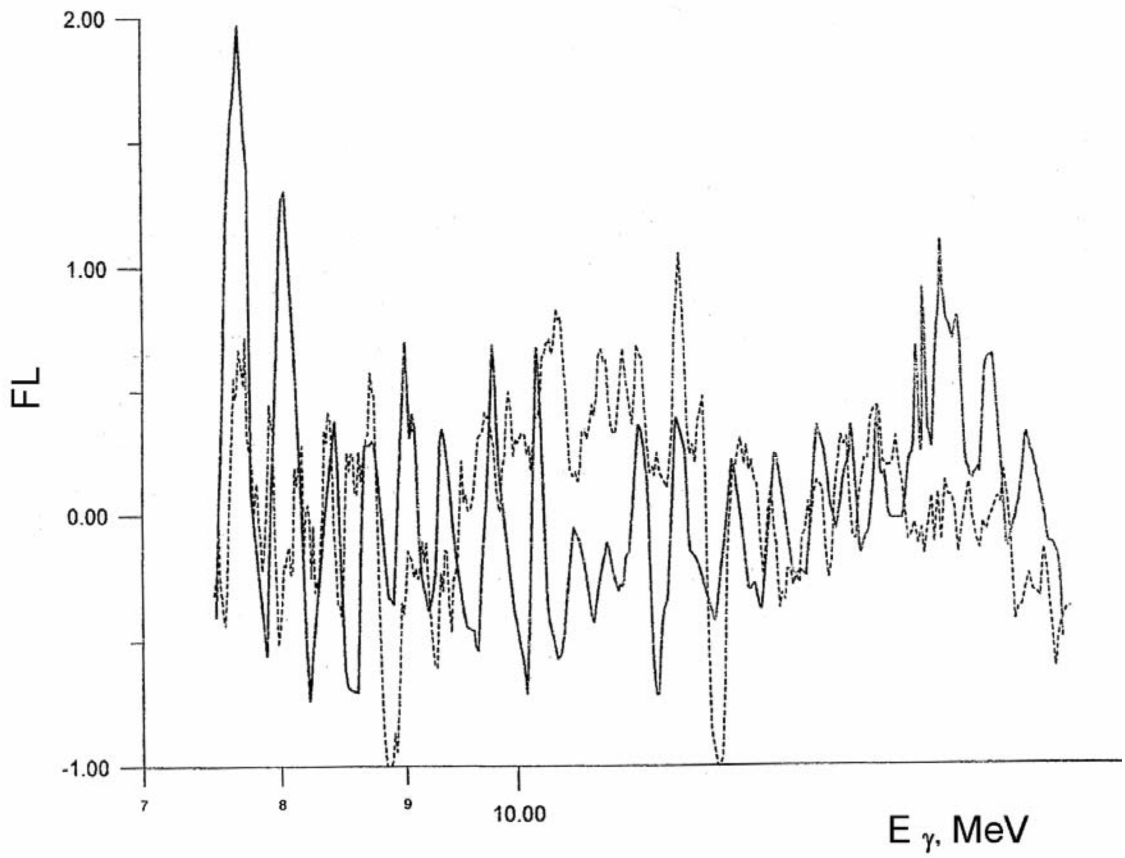

Fig. 3

Comparison of fluctuations of U^{235} fission cross-section by neutrons with the energy of ≈ 0.08 MeV [29] (dotted curve) and the cross-section of the interaction of gamma-rays with lead σ in the gigantic resonance area [30] (continuous curve).

It is worth noting that some juxtaposition of full cross-section structures of neutrons interaction with lead and 'flaky' potential structures had been already presented in the said work [8].

Table 2

ℓ	1	2	3
K_{lml}	0.037	0.09	0.24
E_l, MeV	0.27	1.40	7.0
A_{l1}, Fm	0.004	0.215	0.4
A_{l2}, Fm	0.48	1.0	2.0

It was stressed in the work [11] that the sensibility to the change of the positions (‘addresses’) of resonances acquired in the calculation of the energy scale, first of all, of the real part of the potential, makes the reproduction of these ‘addresses’ the most reliable criterion of the found terms of the potential real part (and hence, the nucleon density distribution in the nucleus). Further, it could be reasonable to work on detailing the ‘flaky’ potential peripheral structure to get the assessment of neutron polarizability.

The question inevitably is also raised about the atomic nucleus structure in view of the ‘flaky’ organization of the optical potential. Of course, we can further consider that within the divided limits nucleons go on moving almost independently, with a little ‘residual’ interaction. But we can accept another radical variant – cluster organization of nucleon membranes, when nucleons are tied similar to carbon nuclei in fullerenes.

The concept of cluster in atomic nuclei was introduce Blokhinsev still in the middle of 1950s during his work in Obninsk and published in 1958 [19] in connection with discovery of emission of clusters from nuclei at high energies protons incident upon them.

Are there any hints to that in the experiment? The work [20] reviews a triple fission of Cf-252 nuclei with escape from the neck of the fissile nucleus of light nuclei from tritium to carbon. The yield of a major part of masses (H-3, He-6, He-8, Li, Be, B) corresponds its statistical evaluations, whereas the output of He-4 and C-12 excess these evaluations by two orders. The authors of the work make the conclusion of the cluster nature of the yield excess, i.e. admit that these two nuclei already exist in the form of a cluster before the escape from the neck of the fissile nucleus. But when we recall that numbers 2 and 6 are the first in the row of the occupation numbers of nucleon shells of the nucleus, it would be reasonable to assume that ready clusters also exist in the nucleus for the next occupation numbers.

As the argument in favor of existence of spatial spherical nucleon ‘flaky’ in the nucleus the possibility can serve to get the numbers occupation sequence, clearly from the geometry point of view. Assuming that the maximum number of nucleons that can accommodate in the layer is proportional to the sphere space with the radius equal to the layer radius, and also that the layers are positioned in the nucleus equidistantly, the following table of occupation of nuclear shells by nucleons can be compiled (see Table 3, V.Anikin) .

In the cluster variant, the number of nucleons in the shells is proportional to the square of its radius R_n. Non-dimensional values $\boldsymbol{B}$ in the table, giving the correct occupation numbers by the formula $\boldsymbol{N} = \boldsymbol{B}^2 – 0.25$ can be selected at any length measuring unit, though the right distances ($\boldsymbol{R_n} – \boldsymbol{R_{n1}}$ ~ 1.3 Fermi) between the shells found at the adjustment of the optical potential are obtained at applying the length units of 1.3 Fermi.

It is shown in the table that the ‘magical’ numbers, if referred to the nuclei with occupied shells, can be obtained only with the omission of certain shells. It is, perhaps, related to proton shells of the heavy nuclei, and is connected with the necessity of the nuclear attraction and Coulomb repulsion forces balance.

Table 3

Shell number N	1	2	3	4	5	6	7	8
$B=R_n$ / Length unit	**1.5**	**2.5**	**3.5**	**4.5**	**5.5**	**6.5**	**7.5**	**8.5**
Fill number $N=B^2$--0.25	**2**	**6**	**12**	**20**	**30**	**42**	**56**	**72**
Magic numbers:								
2	2							
8	2	6						
20	2	6	12					
28	2	6	-	20				
50	2	6	12	-	30			
82	2	6	12	20	-	42		
126	2	6	12	20	30	-	56	
184	2	6	12	20	30	42	-	72

Then, taking into account that the nucleus sometimes is decomposed mainly to deuterons or alpha-particles in the reaction with energetic particle, a temptation emerges to create the alpha-particle or deuteron model of the nucleus. At the same time it would be reasonable to assume that the nucleons positioned in the nucleus shell in the ‘chessman’ order are capable to form various clusters depending on lengths of the waves excited on the nucleus shell by the incoming particle.

Of course, while accepting the cluster structures, it would be necessary to change the approaches to solving a lot of problems concerning the nucleus structure: distances between nucleons inside the nucleus, calculation of the nucleus level density, where the cluster component should have been sharply raised. Some works have already indicated the necessity of accounting the influence of clusters on the atomic nucleus features, in particular, on the nuclear level density (see e.g. [21-24]).

In addition as show the analysis [25] in the determination of the polarizability of the fast neutron scattering by heavy nuclei one should consider the impact of nuclear charge form factors. Such consideration should be especially actual in the case of ‘flacy’ potential. Must also bear in mind that in [12] was shown that the polarizability of the electron shell of a heavy atom may give appreciable contribution to the anomalous scattering of neutrons at energies of several MeV. For the neutron polarizability obtained in this case the order of 10^{-42} cm^3. This means that the electric polarizability of the neutron was observed in experiments on neutron scattering at small angles in heavy nuclei already in 1957 (first job [26]) i.e. one-two years after the hypothesis of it and sooner than the polarizability of the proton in the experiments on the γp-scattering [27], conducted in 1960. Detection of polarizability (i.e. deformation) of the nucleon (as well as first (1953-1957) Hofstadter’s experiments) was direct evidence of the spatial expansion of the nucleon.

It should be noted that W-type structures of the ‘flaky’ potential can be considered as zero approximation of assessments of potentials (n, p)-interaction (external part of the structure, more distant from the nucleus center) and (n, n)-interaction (internal part of the W-structure).

Such conception could be justified if to consider that the protons and neutrons form a single shell where the protons are offset by Coulomb forces to the nuclear periphery. Both the potentials (n, p) and (n, n) have limited height repulsive kerns in the center.

Conclusion

The fact of existing of correlating resonant structures in the cross-sections for various radiations (e.g. neutrons and gamma-rays), at coincidence of their wavelengths and not energies, indicates that the atomic nucleus has space-divided nucleons complexes. Such correlation can hardly be explained by anything but the waves diffraction on the same nucleon structures. The examples of similar correlations are given in the works [1], [18] and in this work (see Fig. 3).Some correlation effects in resonance structure of different nuclides are considered for instance in [28] and other publication of these authors.

A detailed adjustment for the experiment of the optical potential gives the picture of nucleon density distribution in the nucleus only in a first approximation.

At the same time, as Fig. 2 of this work shows, the approximation turns out to be acceptable since it allows replicating not only the general nature of the averaged resonance structures, but also some narrow resonances in the full cross-sections. The necessity of future work is evident to ascertain the details of the potential and their physical interpretation. A substantial contribution in such ascertaining could be made by the description of precisely measured angular distribution of scattered neutrons. It might be noted that such measurements can be accomplished, e.g., in the Institute for Physics and Power Engineering in Obninsk where the accelerators are available, which are able to provide neutron currents from kiloelectronvolt single units to 15 MeV.

The authors are grateful for the discussion of the above matters to O.D. Kazachkovskiy, B.D. Kuzminov, P.P. Dyachenko and B.I. Fursov, and also to A.V. Gulevich – for the attention and the interest to the work.

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