STUDY OF THE MECHANISMS OF INTERACTION OF FAST NEUTRONS WITH ^{93}Nb NUCLEI

I. O. KORZH, M. T. SKLYAR, T. I. YAKOVENKO

Institute for Nuclear Research, Nat. Acad. Sci. of Ukraine
(47, Nauky Prosp., Kyiv 03028, Ukraine)

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The comparison and analysis of literary experimental data on the total cross-sections and scattering cross-sections of fast neutrons by ^{93}Nb nuclei are performed. The applicability of the optical-statistical approach version based on the spherical optical model (SOM), model of excited core (MEC), and statistical model (SM) for the description of experimental cross-sections of the interaction of neutrons with ^{93}Nb nuclei in the energy range 0.2 — 15 MeV is studied. The conclusion about the mechanism of elastic and inelastic neutron scattering by Nb nuclei in a broad range of energies is drawn from the adequate description of experimental data.

Introduction

The use of Nb as a structural material of nuclear reactors and its possible utilization in thermonuclear power units have stimulated the execution of a huge volume of measurements and calculations of neutron cross-sections, first of all, the total cross-sections and scattering cross-sections of fast neutrons.

Up to now, the scientific literature presents the significant experimental information about the total cross-sections and scattering cross-sections of fast neutrons by Nb nuclei. The analysis of this information showed that, despite the presence of appreciable distinctions in the data on inelastic neutron scattering, the experimental data of various authors and laboratories well agree with one another. Such consistent data are of great value, because they promote the establishment of a reliable library of evaluated data and the execution of theoretical analysis of the cross-sections of neutron-nucleus interaction.

Despite the large efforts in the development of theoretical approaches to the description of the cross-sections of interaction of fast neutrons with nuclei, no complete comprehension of the mechanism of scattering of neutrons by Nb nuclei was reached. This is related to the fact that the models which are able to quantitatively predict the cross-sections of scattering of neutrons by odd nuclei are else insufficiently tested. For Nb nuclei, the theoretical interpretation of direct inelastic scattering meets considerable difficulties. For example, the optical-statistical approach well developed by us and others, which is based on SOM, method of strongly coupled channels (MSCC), and modern variants of SM, does not suitable for the theoretical description of inelastic scattering cross-sections, because these methods are unable to take the direct component into account for odd nuclei. Now only the MEC [1] can be used for the interpretation of direct inelastic scattering by odd nuclei. In [2], we fruitfully used this model in the theoretical interpretation of inelastic scattering of neutrons by Cu nuclei in a wide range of energies. Therefore, the goal of this work is to study the applicability of a variant of the optical-statistical approach, which is based on SOM, MEC, and modern variants of SM, to the description of the total cross-sections and cross-sections of scattering of neutrons by Nb nuclei in the energy range 0.2 — 15 MeV by using our and literary experimental data on the cross-sections of interaction of fast neutrons with Nb nuclei.

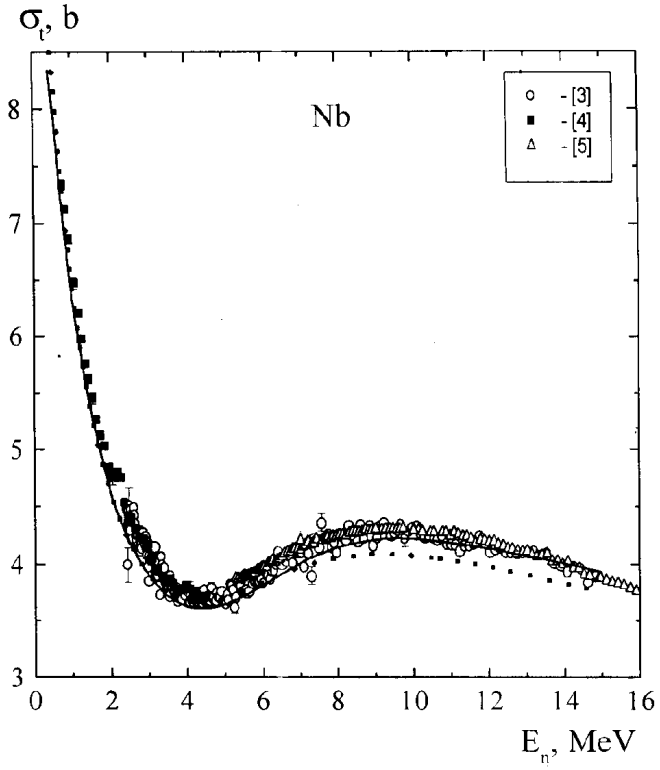

Fig. 1. Energy dependence of the total cross-sections of interaction of fast neutrons with Nb nuclei. Points — experiment, curves — calculations of the cross-sections within SOM: the continuous line — with the parameters derived in this work, the dotted line — with averaged parameters (1)

1. Analysis of Experimental Data on the Total Cross-sections and Cross-sections of Scattering of Neutrons by Nb Nuclei in the Energy Range 0.2 — 15 MeV

The facts that Nb has one isotope and belongs to the structural materials of nuclear reactors promoted the accumulation of a significant experimental information on the cross-sections of interaction of neutrons with Nb nuclei in a wide range of energies. For example, the total cross-sections of interaction of neutrons with Nb nuclei were studied for about five decades, and now we have a lot of reliable information for the region of energies of the reactor spectrum. As an example of experimental information on the total σ_t cross-sections of interaction of neutrons with Nb nuclei, Fig. 1 shows the most systematic data from works [3—5] for the neutron energy range 0.2—15 MeV. As seen, the experimental data of these works agree with one another in the limits of experimental errors in the common energy interval and reliably reproduce the energy dependence of the total cross-sections in the neutron energy region under investigation.

As for the cross-sections of elastic scattering $\sigma_{\rm el}$ of neutrons by Nb nuclei, they have not reached the completeness and accuracy of $\sigma_t(E)$ despite both the facts that the experiments on studying the angular and energetic dependence of the elastic scattering cross-sections were begun almost simultaneously with those on $\sigma_t(E)$ and the availability of systematic data in the energy region under study. The database of the differential cross-sections of elastic scattering of neutrons by Nb nuclei is rather significant up to now (more than thirty publications). Therefore, Fig. 2 presents not all the known data [6—11] on the angular distributions of elastic scattering of neutrons by Nb nuclei, but some part of them sufficient for the illustration of tendencies in a change in the anisotropy with increase in the neutron energy in the energy range under study. Fig. 2 demonstrates that the data on $\sigma_{\rm el}(\theta)$ of various authors well agree with one another and the angular distributions of elastic scattering of neutrons reveal a smooth change in the anisotropy with a change in the neutron energy. The comparison of the data obtained by different authors from different laboratories on the integral cross-sections of elastic scattering of fast neutrons by Nb nuclei [6—22] is given by Fig. 3. As seen, the results of works where the cross-sections were measured in the region of energies less than 3 MeV satisfactorily agree with one another and with the difference between the total cross-section and the inelastic scattering cross-section. At energies more than 3.5 MeV, the dispersion of experimental data on $\sigma_{\rm el}(E)$ is more than that at lower energies. However, significant systematic differences in the data on $\sigma_{\rm el}(E)$ are observed only at energies of 9—11 MeV [8, 14]. Fig. 3 shows that the integral cross-sections of elastic scattering of neutrons quite smoothly vary with a change in the energy of neutrons.

At least two tens of works studied the cross-sections of inelastic scattering of neutrons by Nb nuclei. They contain the results of measurements of the cross-sections of inelastic scattering of neutrons with excitation of separate lowest levels of Nb nuclei in the energy region up to 5 MeV. The measurement of the inelastic scattering cross-sections was performed with the use of two methods: the method of direct registration of inelastically scattered neutrons by time-of-flight and the method of registration of γ-quanta which accompany the inelastic scattering of neutrons. Both methods are relative. Therefore, to determine the absolute value of cross-sections, one uses the reactions which are standards. The use of the single system of standards

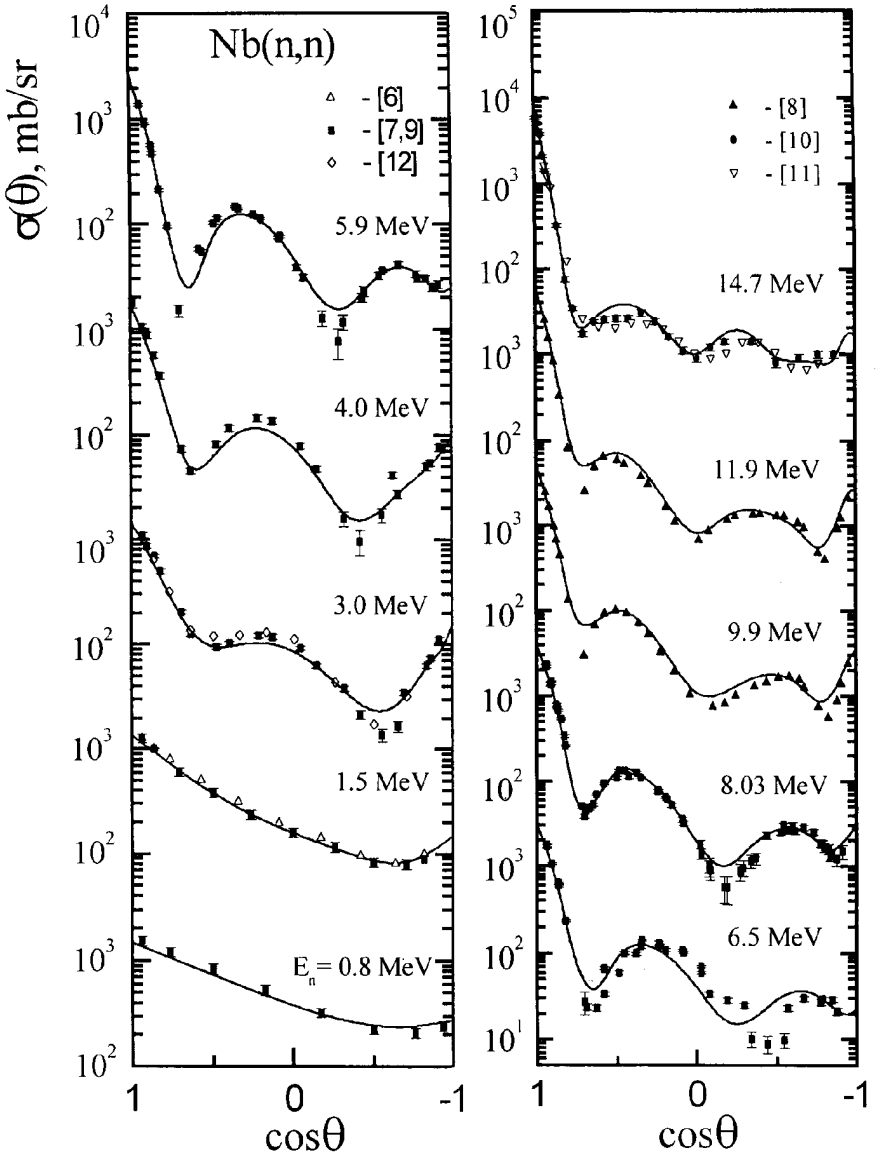

Fig. 2. Differential cross-sections of elastic scattering of neutrons by Nb nuclei in the energy range 0.8 — 14.7 MeV. Points — experimental data, curves — calculations within SOM and SM with the parameters derived in this work

becomes possible only at the end of 1980s. For this reason, it was impossible to compare the results of early works without the reduction of the cross-sections of inelastic scattering to a uniform system of standards. In [23], the results of early experiments using both methods were reduced to a uniform system of standards. This analysis and the calculations by SM underlie the evaluation of the inelastic scattering of neutrons with excitation of the first seven levels of a Nb nucleus. We used the evaluated data as a database of the neutron inelastic scattering cross sections with excitation of five lowest levels of positive parity. The evaluated data of two libraries, BROND-2 [32] and ENDF/B-VI [33] are given in Fig. 4 by, respectively, dashed and dotted lines. In addition to the data on the cross-sections of inelastic scattering with excitation of separate levels, the literature contains the data on the total cross-sections of inelastic scattering of neutrons by Nb nuclei in the energy range 0.5—14.5 MeV presented in Fig. 5. They were obtained by direct measurements and by calculations based on the data on partial cross-sections [12, 24—31]. Fig. 5 presents also the evaluated data from

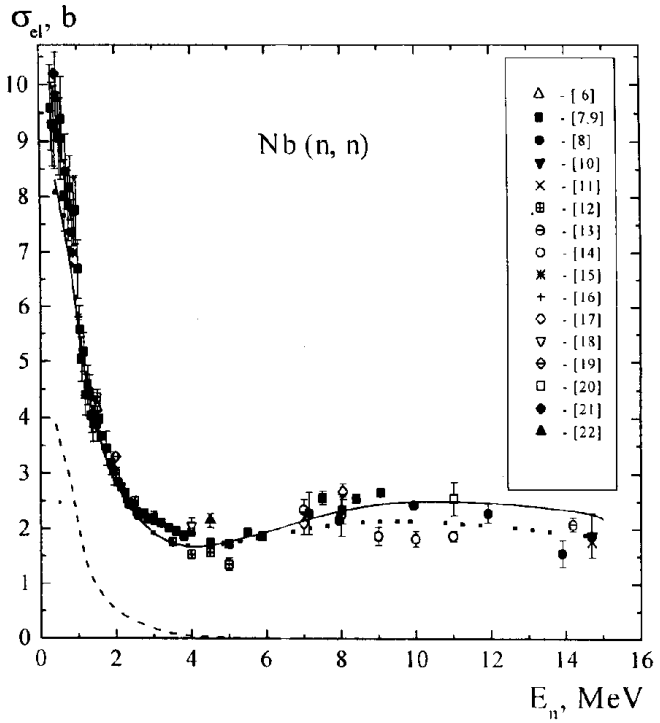

Fig. 3. Energy dependence of the cross-sections of elastic scattering of neutrons by Nb nuclei. Points — experimental data, the continuous and dotted curves — calculations within SOM and SM with the parameters derived in this work and with parameters (1), respectively; the dashed line — within SM with the parameters derived in this work

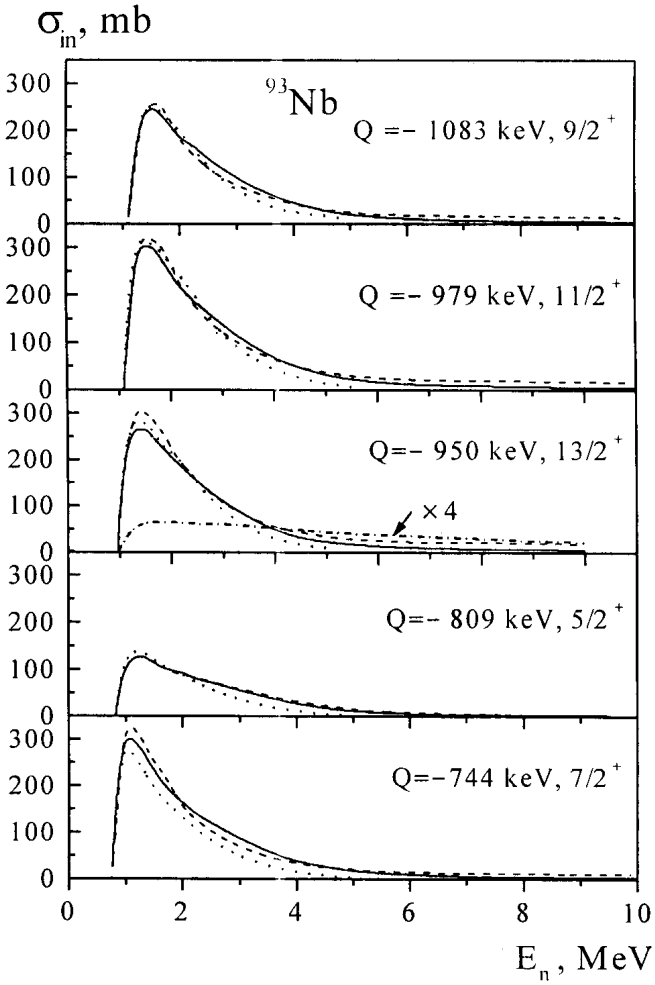

Fig. 4. Energy dependence of the cross-sections of inelastic scattering of neutrons with excitation of the first five positive-parity levels of a Nb nucleus. The dashed and dotted lines — evaluated data of BROND-2 and ENDF/B-VI, respectively; the continuous and dash-dotted lines — calculations within SM and MEC and only within MEC, respectively

the libraries BROND-2 and ENDF/B-VI. As seen, the evaluated data well reflect the contemporary state of available experimental data.

From the analysis of the above-presented data on the cross-sections of interaction of fast neutrons with Nb nuclei, we conclude that they are sufficient, by their number and quality, for the theoretical analysis in the frame of the optical-statistical approach with the aim to investigate the mechanism of interaction of neutrons with Nb nuclei in a wide energy range.

2. Theoretical Analysis of the Experimental Data on the Cross-sections of Interaction of Fast Neutrons with Nb Nuclei

The theoretical analysis of the experimental data on the cross-sections of interaction of fast neutrons with Nb nuclei is performed in the frame of the optical-statistical model based on SOM, MEC, and modern variants of SM. The calculations of cross-sections within these models are based on the use of a single set of parameters of the optical potential (OP). As a starting set of OP parameters, we took the averaged parameters from [34], where they were efficiently applied to the theoretical analysis of the experimental differential and integral cross-sections of elastic and inelastic scattering of neutrons by even-even nuclei with middle atomic masses in the energy range 0.5 — 9.0 MeV:

$V_c = (48.7 - 0.33E)$ MeV, $W_c = (7.2 + 0.66E)$ MeV,

$V_{s0} = 7.5$ MeV,

$a_v = 0.65$ fm, $a_w = 0.47$ fm, $a_{s0} = 0.65$ fm,

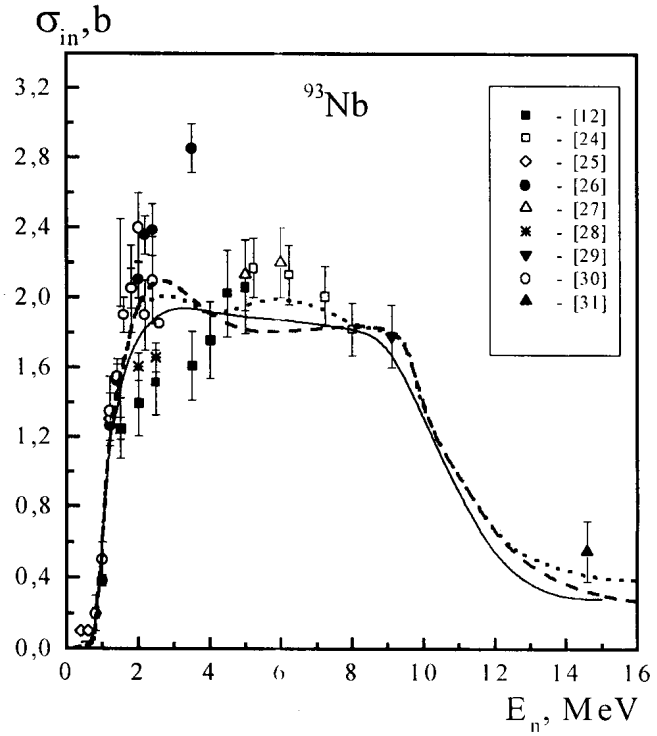

Fig. 5. Total cross-sections of inelastic scattering of fast neutrons by Nb nuclei. Points — experimental data. The dashed and dotted lines — evaluated data of BROND-2 and ENDF/B-VI, respectively; the continuous line — the results of calculations performed in this work

$$r_v = 1.25\,\text{fm},\quad r_w = 1.25\,\text{fm},\quad r_{s0} = 1.25\,\text{fm}. \qquad (1)$$

The compound components of the cross-sections of elastic and inelastic scattering of neutrons by Nb nuclei in the region of excitation energies, where the parameters of levels (up to 1.7 MeV) are well known, were calculated within the Hauser—Feshbach—Moldauer model [35, 36] by the LIANA program [37]. At higher excitation energies, the calculations of the cross-sections of scattering through a compound nucleus were realized by the STATIS program [38], where the channels with excitation of both the discrete and continuous spectra of levels of a nucleus were taken as competitive channels of inelastic scattering. The characteristics of levels of the discrete spectrum of a ^{93}Nb nucleus were taken from work [39]. The density of levels was calculated by the combined Gilbert—Cameron formula [40] with parameters $a = 10.9$ MeV^{-1} and $U_0 = 0.72$ MeV.

The direct component of scattering of neutrons by Nb nuclei was described within MEC. In this model, the excited states of a Nb nucleus for excitation energies 0.7—1.1 MeV with spins from $1/2^+$ to $13/2^+$ are

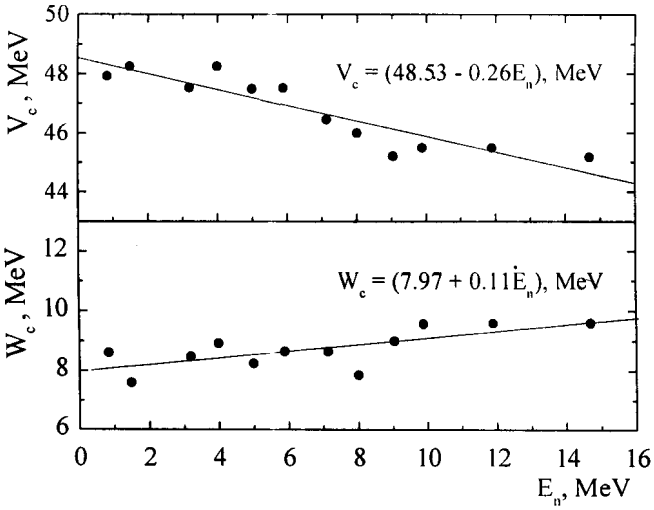

Fig. 6. Energy dependence of the parameters of optical potential V_c and W_c according to the results of this work

interpreted as the terms of a multiplet of levels under the coupling of the one-photon 2_1^+-excitation in ^{92}Zr ($E = 934.48$ keV and $\beta_2 = 0.1$ [41]) with one-particle proton state $1g_{9/2}$ in ^{93}Nb. The center-of-weights of a quintet in a ^{93}Nb nucleus (934 keV) well coincides with the position of level 2_1^+ of the neighbor even-even nucleus ^{92}Zr. In addition, the sum of reduced probabilities of the electromagnetic transitions to the states which belong to this quintet is close to the probability of the electromagnetic transition to state 2_1^+ of a nucleus ^{92}Zr [28] . Such an agreement indicates that the averaged characteristics of excited states of a Nb nucleus can be considered in the model of weak coupling of an odd proton in shell $1g_{9/2}$ with an excited state of the even-even core of ^{92}Zr. The cross-section of direct excitation of any level of the quintet is defined by the formula

$$\frac{d\sigma}{d\Omega}(J_p \to J) = \frac{2J+1}{(2J_c+1)(2J_p+1)}\frac{d\sigma}{d\Omega}(J_0 \to J_c), \qquad (2)$$

where J_p is the spin of the ground state of the odd nucleus, J is the spin of its excited state, J_0 is the spin of the ground state of the core, and $\frac{d\sigma}{d\Omega}(J_0 \to J_c)$ is the cross-section of direct excitation of the core. The cross-section of direct excitation of a collective level of the core is calculated within MSCC by the ECIS-94 program [42]. In the calculations of cross-sections within this method, we decreased the value of the imaginary part of the OP (1) by 20%.

The comparison of the results of calculations of the total cross-sections, integral, and differential cross-sections of elastic scattering within SOM with the set

of parameters (1) with experimental data showed a good agreement at energies lower than 7 MeV. At higher energies, the theoretical cross-sections are less than experimental ones. This is clearly seen in Figs. 1 and 3, where the theoretical cross-sections are shown by dotted lines. To improve the description of the total cross-sections and cross-sections of elastic scattering in the energy region under study, by using the GENOA program [43], we sought such values of the parameters V_c and W_c, for which the value of χ^2 reaches a minimum under fitting the calculated values of σ_t and $\sigma_{\rm el}(\theta)$ to the relevant experimental ones. At this stage of search for the values of V_c and W_c, other parameters in (1) were held constant. The parameters V_c and W_c determined in such a way are given in Fig. 6. According to our data, the energy dependence of V_c and W_c can be written as

$$V_c = (48.53 - 0.26E_n)\ \text{MeV},$$

$$W_c = (7.97 + 0.11E_n)\ \text{MeV}. \qquad (3)$$

In what follows, the systematic calculation of the total cross-sections and cross-sections of scattering is performed with the use of OP parameters in the form (1) except for V_c and W_c whose energy dependence is taken as (3). The results of calculations of the cross-sections of interaction of fast neutrons with Nb nuclei with the above-discussed parameters and the experimental data are presented in Figs. 1—5.

It is seen from Figs. 1—3 that the theoretical energy dependences of the total cross-sections and cross-sections of elastic scattering well agree with experiment, which testifies to the well-founded approach accepted by us in the description of the cross-sections of scattering of fast neutrons by Nb nuclei. The results of calculations of the energy dependence of the integral cross-sections of excitation of 5 levels of a ^{93}Nb nucleus (their characteristics are: $E_1 = 0.744$ MeV $(7/2^+)$, $E_2 = 0.809$ MeV $(5/2^+)$, $E_3 = 0.950$ MeV $(13/2^+)$, $E_4 = 0.979$ MeV $(11/2^+)$, and $E_5 = 1.083$ MeV $(9/2^+)$) well agree with the evaluated data [32, 33] in a wide energy range. The calculated total cross-sections of inelastic scattering within SOM and SM with the corrections for the contribution of open channels of the reactions (n, p), (n, α), and $(n, 2n)$ [33] also well agree with the experimental evaluated data [32, 33], which is demonstrated by Figs. 4 and 5.

The results of calculations of the cross-sections of scattering of neutrons by ^{93}Nb nuclei in the wide energy range indicate that the compound mechanism of scattering significantly contributes to the cross-sections of elastic scattering only in the energy range up to 5 MeV and dominates in the cross-sections of inelastic scattering almost in the whole energy range under study. The cross-section of direct excitation of level 2_1^+ of a ^{92}Zr nucleus reaches a maximum value of about 60 mb at an energy of 1.7 MeV and decreases smoothly to 30 mb at an energy of 7 MeV. These values of the cross-section are distributed between members of the quintet of levels of a ^{93}Nb nucleus in the proportion 0.16 : 0.12 : 0.28 : 0.24 : 0.20. As was expected, components of the direct interaction for them are small by absolute value and dominate only at energies larger than 7 MeV.

Conclusions

We have carried out the comparison and analysis of the experimental data on the total cross-sections and cross-sections of scattering of fast neutrons by ^{93}Nb nuclei. It is shown that the totality of experimental data on the cross-sections of the interaction of neutrons with Nb nuclei can be adequately described in the frame of the optical-statistical approach based on SOM, MEC, SM, and the individual set of the OP parameters. The results of theoretical analysis are used for the study of mechanisms of elastic and inelastic scattering of fast neutrons by ^{93}Nb nuclei.

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ДОСЛІДЖЕННЯ МЕХАНІЗМІВ ВЗАЄМОДІЇ ШВИДКИХ НЕЙТРОНІВ З ЯДРАМИ ^{93}Nb

І.О.Коржс, М.Т.Скляр, Т.І.Яковенко

Р е з ю м е

Проведено порівняння і аналіз експериментальних даних з повних перерізів і перерізів розсіяння швидких нейтронів ядрами ^{93}Nb. Досліджено застосовність варіанта оптико-статистичного підходу, основу якого становлять сферична оптична модель, модель збудженого остова та статистична модель, для опису експериментальних перерізів взаємодії нейтронів з ядрами ^{93}Nb в області енергій 0,2 — 15 МеВ. Із адекватного опису експериментальних даних зроблено висновки про механізми пружного і непружного розсіяння нейтронів ядрами ніобію в широкій області енергій.