CONTRIBUTIONS OF DIRECT PROCESSES TO THE CROSS-SECTIONS FOR FAST-NEUTRON SCATTERING BY MANGANESE NUCLEI

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The applicability of a variant of the optical-statistical approach to the description of experimental total, elastic, and inelastic cross-sections for neutron scattering by manganese nuclei in the energy range 0.2—12 MeV has been studied for the first time. The variant is based on the spherical optical model (SOM), the coupled-channels method (CCM), the excited-core model (ECM), and modern variants of the statistical model (SM). The results of the adequate description of the experimental data set were used to study the contributions of the direct mechanism and the mechanism of scattering through a compound nucleus to the elastic and inelastic scattering of fast neutrons by manganese nuclei.

1. Introduction

Natural manganese is a monoisotope element (100% of ^{55}Mn) with the well-known structure of excited states up to the excitation energy of 3.6 MeV. Moreover, the ^{55}Mn nucleus is found near the peak of the S_0-strength function. Owing to those manganese characteristics, the study of the cross-sections for the interaction between fast neutrons and manganese nuclei seems reliable enough and interesting from the viewpoint of researching the mechanisms of interaction. In addition, manganese is included into the group of medium atomic weight elements (Ti—Cu), being one of the important dopants. For practical applications and for studying the mechanisms of interaction between fast neutrons and manganese nuclei, regular data concerning the interaction cross-sections for neutrons in a wide energy range are necessary.

The analysis of the available body of experimental information on the cross-sections for fast neutrons—manganese nuclei interaction showed that, actually, the data are regular enough only for total cross-sections. Information dealing with the cross-sections of elastic and inelastic neutron scattering by manganese nuclei is very scarce. This may be related to the existence of a low-lying level with $Q = -0.126$ MeV in a manganese nucleus, the inelastic and elastic scattering on which can hardly be separated from each other experimentally. Only work [1] reported the results of regular and reliable enough studies of the cross-sections for elastic neutron scattering by ^{55}Mn nuclei. The authors used their data to determine the parameters of the optical potential (OP). Nevertheless, while calculating the OP parameters, the cross-sections of scattering through the compound nucleus mechanism were estimated in the framework of the SM and taking no account of the influence of the resonance width fluctuations. Literature experimental data on the cross-sections of inelastic neutron scattering by manganese nuclei cover only the range of neutron energies lower than 4.5 MeV. The results of regular studies of inelastic neutron scattering cross-sections were reported only in work [2]. The authors analyzed their data in the framework of the SM in order to study the influence of the resonance width fluctuations on the cross-sections of inelastic scattering through the compound nucleus mechanism. At the same time, the role of the direct mechanism of inelastic neutron scattering by manganese nuclei, as well as by the majority of odd nuclei, remained unexplored till now. However, the results of our works [3,4] obtained for the neighbor odd nuclei evidence for the necessity to consider both the mechanism of inelastic scattering through a compound nucleus and the direct scattering mechanism in the framework of the ECM [5].

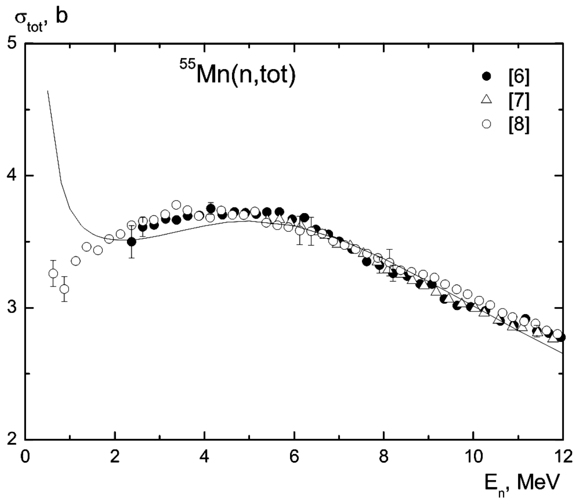

Fig. 1. Energy dependence of the total cross-section of fast-neutron interaction with manganese nuclei. The points denote the experimental data of works [6—8]. The curve corresponds to the results of calculations by the SOM using parameters (1)

Therefore, this work is aimed at carrying out the theoretical analysis of the body of experimental data on the cross-sections for fast-neutron interaction with ^{55}Mn nuclei in the framework of the optical-statistical approach based on the SOM, CCM, ECM, and SM, and at estimating, on the basis of the results of this analysis, the contributions of direct processes to the neutron scattering cross-sections in a wide range of energies.

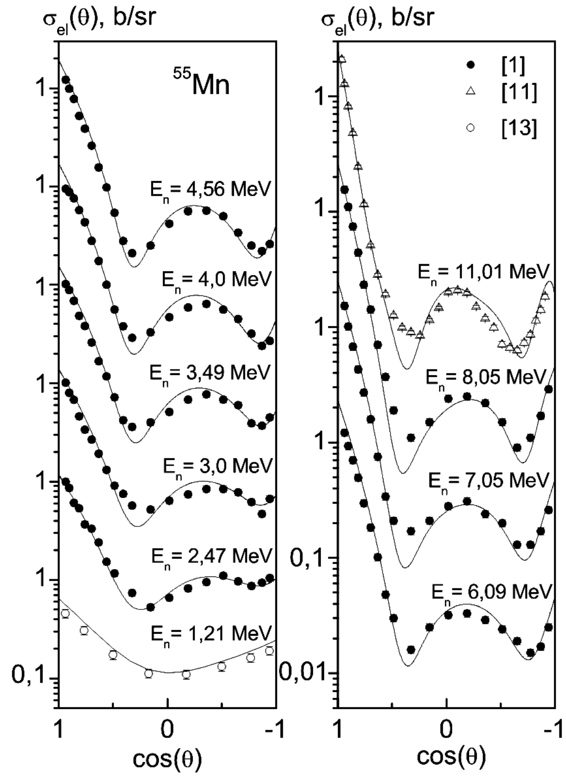

Fig. 2. Differential cross-sections of elastic neutron scattering by manganese nuclei. The points denote the data of works [1, 11, 13]. The curves correspond to the results of calculations by the SOM and SM

2. Cross-sections for the Interaction of Fast Neutrons with Manganese Nuclei

In contrast to its neighbors in the Mendeleev Periodic table, namely, chrome and iron, the nuclear properties of manganese have not been studied enough. Today, regular and reliable data for manganese nuclei are available only for total scattering cross-sections in the range of reactor spectrum energies [6—8]. The data of those works were obtained with a high energy resolution. Therefore, to compare them with one another and with the cross-sections calculated in the framework of the optical model, we averaged those data within the energy interval of about 250 keV. The averaged results of the regular works are shown in Fig. 1. From the figure, one can see that those data are mutually consistent within the limits of experimental errors and reliably illustrate the energy dependence of the total cross-section in a wide energy range.

As for the cross-sections for elastic scattering of fast neutrons by manganese nuclei, the necessary completeness and accuracy have not been reached till now. Regular data on differential cross-sections for elastic neutron scattering by manganese nuclei were obtained only in work [1]. The data of this work do not contradict the fragmentary data of works [9, 10]. To illustrate the tendency in the anisotropy variation with the energy growth, Fig. 2 exhibits the angular distributions of elastically scattered neutrons, plotted in accordance with the data of works [1, 11, 13]. It is evident that the angular distributions of elastically scattered neutrons manifest smooth dependences of the anisotropy on the neutron energy; therefore, they are suitable for finding the OP parameters. The energy dependences of the integral cross-sections of elastic scattering are depicted in Fig. 3, from which it is evident that the integral cross-sections of elastic neutron scattering, according to the results of works [1, 9, 10—13], change weakly as the neutron energy varies.

In works [2, 14—17], the cross-sections of inelastic neutron scattering with the excitation of five lowest-lying levels of a ^{55}Mn nucleus were measured at a plenty

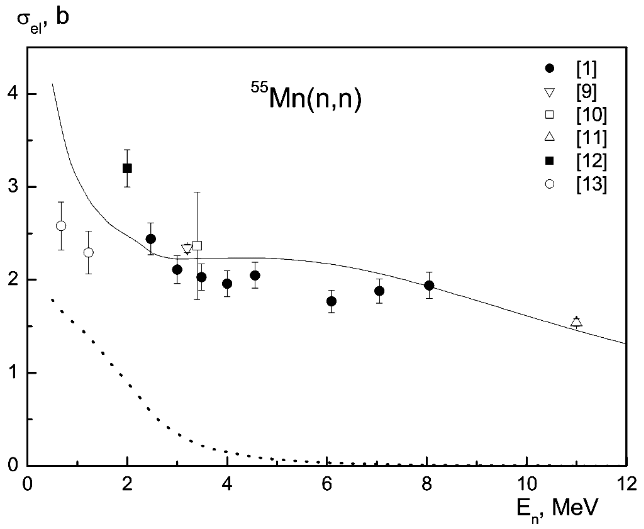

Fig. 3. Energy dependence of the cross-section of elastic neutron scattering by manganese nuclei. The points denote the experimental data of works [1,9,10—13]. The curves correspond to the results of calculations by the SOM and SM (solid curve) and by the SM (dotted curve) using parameters (1)

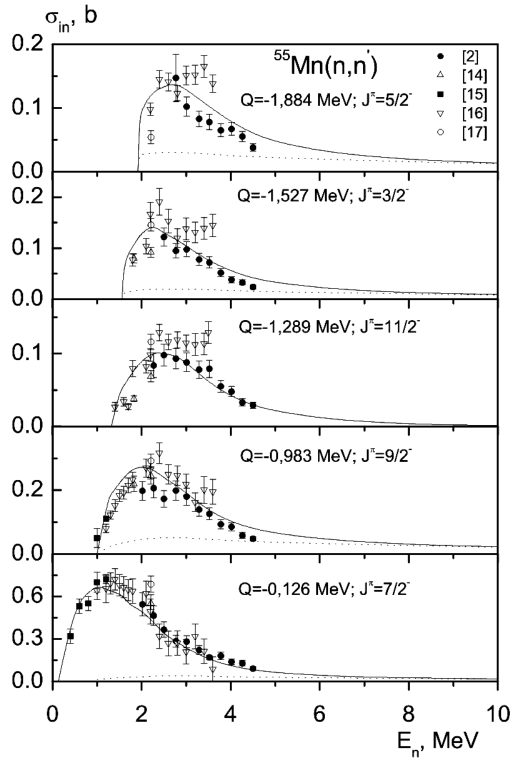

Fig. 4. Energy dependence of the cross-sections of inelastic neutron scattering with the excitation of five levels of a ^{55}Mn nucleus. The points denote the experimental data of works [2, 14—17]. The curves correspond to the results of calculations by the SM and ECM (solid curves), and by the ECM (dotted curves)

of points with different energies lower than 4.5 MeV. The data of those works are compared in Fig. 4. One can see from the figure that the data of work [16], which were obtained by registering the yield of γ-quanta that accompany the inelastic neutron scattering, noticeably exceed the regular data obtained by the direct registration of inelastically scattered neutrons using the time-of-flight method. At energies above 4.5 MeV, literature data on the cross-sections of inelastic neutron scattering are absent. Besides the data on partial cross-sections of inelastic scattering, there are the data on differential cross-sections of inelastic scattering with the excitation of the second to fifth levels of manganese at a neutron energy of 3 MeV [18]. The shape of the experimental angular distributions of inelastically scattered neutrons obtained in that work testifies that the mechanism of scattering through a compound nucleus prevails at this energy.

The analysis of the experimental data on cross-sections of fast-neutron interaction with manganese nuclei allows us to draw a conclusion that there are enough the experimental data describing the total and elastic scattering cross-sections to determine the OP parameters and to study the mechanisms of scattering in a wide energy range.

3. Theoretical Description of the Cross-sections for Fast-neutron Interaction with Manganese Nuclei

The theoretical analysis of the experimental data obtained for the cross-sections of fast-neutron interaction with nuclei under study was fulfilled in the framework of the optical-statistical approach, which is based on the SOM, CCM, ECM, and modern variants of the SM. This approach allows one to take effectively into account the direct and compound mechanisms of scattering. The use of a common set of the OP parameters forms the basis for the corresponding calculations of the cross-sections in the framework of those models. Earlier [3, 4], we showed that the averaged OP parameters that were taken from work [19] and successfully applied by us earlier to the theoretical analysis of the experimental total cross-sections and the cross-sections of fast-neutron scattering by even-even nuclei of medium atomic weights cannot be applied effectively to the ^{51}V and ^{63,65}Cu nuclei, neighbor to manganese. Therefore, in order to achieve an adequate description of the total cross-sections and the cross-sections of elastic scattering within the studied energy range, we used the GENOA computer code [20] for determining such values of the parameters V_c and W_c, for which the value of χ^2 attained its minimum, while fitting the calculated values of σ_t and $\sigma_{el}(\theta)$ to the relevant experimental ones. At this stage of finding the values of the parameters V_c and W_c, the other parameters remained fixed, with the same values as in work [4]. The values of the parameters V_c and W_c, which were determined in such a way for the manganese nucleus and are shown in Fig. 5, were used for searching their energy dependences. According to our data, the OP parameters for the manganese nucleus are as follows:

$$V_c = (50.12 - 0.50E_n)\ \text{MeV};\quad W_c = 8.43\ \text{MeV};$$

$$V_{s0} = 7.5\ \text{MeV};$$

$$a_V = a_{s0} = 0.65\ \text{fm},\quad a_W = 0.47\ \text{fm},$$

$$r_V = r_W = r_{s0} = 1.25\ \text{fm}. \qquad (1)$$

The following regular calculations of the total cross-sections and the cross-sections of fast-neutron scattering by ^{55}Mn nuclei were carried out by making use of those OP parameter values.

The parameters of the SM, in the framework of which the compound components of scattering cross-sections are calculated, include the penetrability factors, calculated by the optical model, and the characteristics of excited nuclear levels. The compound components of neutron scattering cross-sections in that range of excitation energies, where the nuclear level characteristics were known well (up to 3.608 MeV [21]), were calculated in the framework of the Hauser—Feshbach—Moldauer model [22] with the help of the LIANA computer code [23] suitable for calculating cross-sections in the case where there is no dynamic coupling between reaction channels. At higher excitation energies, the calculations of cross-sections for scattering through the compound nucleus mechanism were carried out in the framework of the Hauser–Feshbach model [24]. Relevant corrections were made for the level width fluctuations in the form proposed in work [25]. For this purpose, the STATIS computer code [26], where the channels with the excitation of both the discrete and continuous spectra of nuclear levels were considered as the competitive exit channels of inelastic scattering, was made use of. At energies of several MeV, the energy dependences of the compound cross-sections are

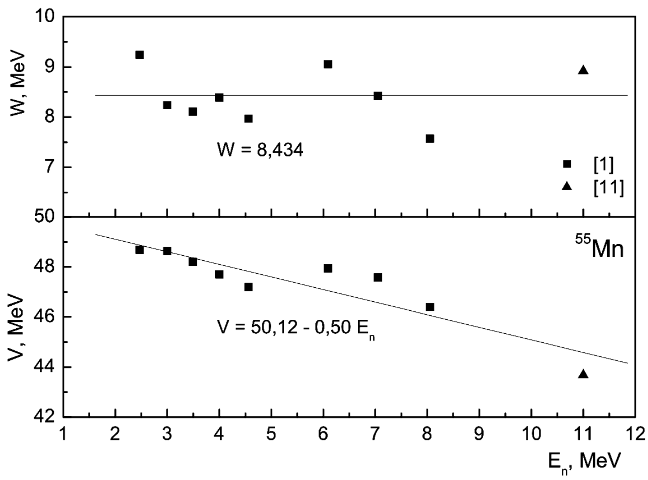

Fig. 5. Energy dependences of the OP parameters V_c and W_c for the manganese nucleus obtained from the analysis of experimental data in works [1,11]

substantially governed by the density of excited levels. The level density for the ^{55}Mn nucleus was calculated in the framework of the back-shifted Fermi gas model with the parameters of work [27] ($a = 5.6$ MeV and $\Delta = -1.62$ MeV).

In order to describe the direct component of the inelastic neutron scattering by ^{55}Mn nuclei, we used the ECM. In this model, the lowest-lying excited states of the ^{55}Mn nucleus with spins from $1/2^-$ to $9/2^-$ are regarded as the members of a level multiplet, provided the coupling between the single-phonon 2^+-excitation of the ^{54}Cr core level ($Q = -0.835$ MeV, $\beta_2 = 0.25$ [29]) and the single-particle proton state $f_{5/2}$ in the ^{55}Mn nucleus. In the weak-coupling model, the cross-section of the direct excitation of any of the multiplet levels is equal to

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

where J_p and J are the spins of the odd nucleus in the ground and excited states, respectively, J_0 is the spin of the core ground state, and $\frac{d\sigma}{d\Omega}(J_0 \to J_c)$ is the cross-section of the direct excitation of the collective level of the core. The latter quantity is calculated by the method of strongly coupled channels, making use of the ECIS-94 computer code [28]. Calculations of direct neutron scattering by ^{54}Cr nuclei were carried out using the averaged OP parameters taken from work [19]. While calculating the cross-sections by the method of strongly coupled channels, the magnitude of the imaginary part of the OP was reduced by 15%.

In Figs. 1–4, we compare the results of our calculations of the total cross-sections, the differential and integral cross-sections of elastic scattering, and the integral cross-sections of inelastic scattering of fast neutrons by ^{55}Mn nuclei with experimental data. The figures demonstrate that the values calculated for the total cross-sections, as well as for the differential and integral cross-sections, of elastic neutron scattering by ^{55}Mn nuclei agree well with the experimental data in a wide range of energies above 1 MeV, and that the results of calculations of the energy dependence of the excitation cross-section for four lowest-lying levels of the ^{55}Mn nucleus ($Q = -0.126$ MeV and $J^{\pi} = 7/2^{-}$; $Q = -0.983$ MeV and $J^{\pi} = 9/2^{-}$; $Q = -1.527$ MeV and $J^{\pi} = 3/2^{-}$; $Q = -1.884$ MeV and $J^{\pi} = 5/2^{-}$) describe the experimental data satisfactorily. In Fig. 4, the results of calculations of the dependence $\sigma_{in}(E_n)$ for a level with the parameters $Q = -1.289$ MeV and $J^{\pi} = 11/2^{-}$, making allowance for only the scattering through the compound nucleus stage, are shown.

The adequate description of the cross-sections of neutron scattering by manganese nuclei in a wide range of energies allowed the reliable conclusions concerning the mechanisms of scattering to be drawn. For example, from Figs. 3 and 4, it is evident that the compound mechanism gives an essential contribution to the elastic scattering cross-sections in the energy range extending to about 6 MeV, and it dominates at the excitation of the level multiplet at energies up to 5 MeV. The calculated cross-section of the direct excitation of level 2_1^+ of the ^{54}Cr nucleus reaches its maximal value of about 150 mb at an energy of 2.5 MeV and smoothly decreases to about 80 mb at an energy of 8 MeV. These values of cross-sections are distributed among the members of the studied multiplet of the ^{55}Mn nuclear levels in the proportion 0.27 : 0.33 : 0.13 : 0.2. From Fig. 4, it is seen that the corresponding components of the direct interaction are small by absolute value and dominate only at energies above 6 MeV.

4. Conclusions

1. The comparative analysis of experimental data on the cross-sections of the neutron interaction with manganese nuclei has been done in a wide range of energies. According to the results of the analysis, the conclusion has been made that the body of consistent experimental data is enough to be the basis for the theoretical analysis aiming at determining the set of the OP parameters and to study the mechanisms of fast-neutron scattering by manganese nuclei.

2. On the basis of the theoretical analysis of experimental data, the values for the OP parameters have been obtained, and the applicability of the variant of the theoretical approach, suitable for the description of cross-sections for neutron scattering by odd nuclei, has been studied. The SOM, CCM, ECM, and SM constitute the basis of this approach. In the framework of this approach, a possibility for the adequate description of the total cross-sections and the cross-sections of fast-neutron scattering by ^{55}Mn nuclei has been demonstrated.

3. The results of the theoretical analysis were used to study the mechanisms of neutron scattering by manganese nuclei in a wide range of energies. The compound mechanism of scattering has been shown to contribute substantially to the cross-sections of elastic neutron scattering in the energy range to 6 MeV, and the compound mechanism has been demonstrated to dominate in the inelastic scattering cross-sections at energies lower than 5 MeV. At higher energies, neutrons are inelastically scattered through the mechanism of direct scattering with the excitation of the multiplet of nuclear levels under consideration.

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ДОСЛІДЖЕННЯ ВНЕСКУ ПРЯМИХ ПРОЦЕСІВ У ПЕРЕРІЗИ РОЗСІЯННЯ ШВИДКИХ НЕЙТРОНІВ ЯДРАМИ МАРГАНЦЮ

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Р е з ю м е

Вперше досліджено застосовність варіанта оптико-статистичного підходу, основою якого є сферична оптична модель, метод зв'язаних каналів, модель збудженого остова та сучасні варіанти статистичної моделі, до опису експериментальних повних перерізів і перерізів пружного та непружного розсіяння нейтронів ядрами марганцю в області енергій 0,2—12 МеВ. Результати адекватного опису сукупності експериментальних даних використано для вивчення у досліджуваному діапазоні енергій внеску прямого механізму і механізму розсіяння через складене ядро в пружне та непружне розсіяння швидких нейтронів ядрами марганцю.