ЯДЕРНА ФІЗИКА

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DEUTERON INTERACTION WITH ^{124}Sn NUCLEI AT SUB-BARRIER ENERGIES

The measurements of cross sections for deuteron elastic scattering and (d, p) reaction on ^{124}Sn nuclei have been performed with aim to study the features of sub-barrier deuteron interaction with heavy nuclei. Experimental data were obtained on the electrostatic Tandem accelerator EGP-10K of the Institute for Nuclear Research (Kyiv) at the deuteron beam energies E_d = 4.0; 5.0 and 5.5 MeV. Cross sections of deuteron elastic scattering were calculated in approach where the deuteron interaction potential with heavy nuclei at sub-barrier energies has been constructed in the framework of single folding model using the complex dynamic polarization potential. It is shown that the account of finite deuteron size leads to the increasing the nuclear potential in outer region of interaction and significantly improves the description of the experimental data. The calculations of elastic scattering cross sections were performed without any variations of the nuclear potential parameters. The analysis of measured integral cross sections of the ^{124}Sn(d, p) reaction and calculated cross sections of deuteron breakup reaction ^{124}Sn(d, p)n^{124}Sn shows the dominant contribution of the neutron transfer reaction in the processes of the formation of protons and elastic scattering cross sections.

Keywords: deuteron, ^{124}Sn nucleus, sub-barrier energies, deuteron elastic scattering, deuteron breakup, transfer reaction.

Introduction

Investigation of deuterons interaction with heavy atomic nuclei at sub-barrier energies showed a significant effect of polarizability and the breakup processes on the elastic scattering cross sections [1 - 3]. While the elimination of the incident particle from the elastic channel for the forward scattering angles (θ ≤ 90°) is adequately described by taking into account polarization and breakup in the Coulomb field of the target nucleus, at the angles over 90° the deviation from the Rutherford cross section is substantially larger than that provided by the theory. Attempts to describe the experimental data by fitting the potential parameters of the standard optical model lead to non-physical values of these parameters.

To explain this phenomenon, a model treats in a unified way the elastic scattering, polarization and the breakup in the target nucleus field was developed [2, 3]. In this model, it was assumed that the deuteron moving along the Coulomb orbit can pass from it stationary state into some quasi-stationary state adiabatically. This state has a certain width, is polarized and can decay to free n-p pair.

The proposed approach allows to calculate the complex binding energy of the incident particle and a wave function of corresponding polarized state. The imaginary part of the resulting binding energy is used for the construction of the so-called electric optical potential (EOP). However, the elastic scattering cross section calculations with EOP and comparison with experimental data [4, 5] showed that the observed deviations from the Rutherford cross sections are not explained by taking into account only the possibility of the incident particle breakup in the electric field of target nucleus.

Therefore, it has been suggested that due to the deuteron finite size and the asymmetric distribution of its charge and mass, the external field can polarize the deuteron, stretching it along the field direction, that allows to penetrate into the region of the nuclear interaction in spite of the fact that the energy of the incident particles are essentially sub-barrier and classical Coulomb turning point is far away from the nucleus.

The inclusion of nuclear interaction leads to the possibility of nuclear reactions passing and in particular (d, p) reaction. This fact was confirmed experimentally [4, 5]. In the deuterons elastic scattering by nickel and lead nuclei with simultaneous measurements of proton emission it was found unexpectedly high yield of protons, significantly greater than it would be expected from the breakup reaction.

In this paper an approach which can significantly improve the agreement of the calculated and experimentally observed cross sections of deuteron elastic scattering at sub-barrier energies is proposed. The calculations performed within this approach are compared with experimental data for elastic scattering of deuterons by ^{124}Sn nuclei at the energies 4.0, 5.0 and 5.5 MeV. The role of deuteron break-up and neutron transfer processes at sub-barrier energies are also analyzed using the data for the proton yields in the ^{124}Sn(d, p) reaction at E_d = 4.0 and 5.0 MeV.

It should be noted that there is no experimental data for deuteron elastic scattering and (d, p) reaction measured simultaneously in the wide angular range for ^{124}Sn. Existing data in the energy region around the Coulomb barrier are limited by the values of the elastic scattering cross sections for several points of the angular distribution (see, for example, [6, 7]). More detailed study was performed for ^{124}Sn(d, p) reaction as well as for ^{116,117,122,123}Sn(d, p) reactions [7].

The article is organized as follows. In the next section the experimental setup for deuteron elastic scattering measurements is shortly described. Next, the basis of the theoretical approach to the description of the deuterons elastic scattering with taking into account their polarizability and the breakup in the electric field of the target nuclei is considered. Thereafter, the main results, their analysis and discussion are presented. Finally, a brief summary is given.

Experiment

The measurements were carried out with the deuteron beam accelerated to the energy E_d = 4.0, 5.0 and 5.5 MeV at the Tandem Electrostatic Generator ESG-10K (Institute for Nuclear Research, Kyiv). Thick self-support ^{124}Sn (5 mg/cm^2) target was used in the experiment. The differential cross sections of (d, d) and (d, p) reactions were measured in the angular range of θ = 30^o - 160^o. Deuterons and protons were registered by two ΔE-E telescopes of semiconductor detectors with the thicknesses ~ 20 and ~ 500 μm, respectively. The low energy threshold of registration was reached owing to the utilization of thin ΔE-detectors. Deuteron beam intensity was controlled with Faraday cup and a monitor detector, which was installed in the reaction chamber at the fixed angle θ = 150^o.

The utilized data acquisition system is described in [4, 5, 8]. Data analysis was done by software that is designated for execution of procedures which are necessary for identification of registered reaction products and reconstruction of their energy spectra.

The theoretical approach

The process of deuteron scattering by the target nucleus in the coordinates system $\vec{R}$ and $\vec{r}$ is described by general three-particle equation

$$\left[E-\hat{K}_{\vec{R}}-\hat{K}_r-V_n\left(\vec{r}_n\right)-V_p\left(\vec{r}_p\right)-V_C\left(\vec{r}_p\right)-V_{np}\left(r\right)\right]\Psi\left(\vec{R},\vec{r}\right)=0\,, \quad (1)$$

where $\vec{R}$ is the deuteron center of mass radius-vector; $r_n=\left|\vec{R}+\vec{r}/2\right|$ and $r_p=\left|\vec{R}-\vec{r}/2\right|$ are the neutron and proton coordinate, respectively; $\vec{r}$ is internal coordinate of deuteron; E_d and $E=E_d-\varepsilon_0$ are kinetic and total energies of deuteron, respectively, $\varepsilon_0=\hbar^2\alpha^2/2\mu$ is the free deuteron binding energy; $\hat{K}_{\vec{R}}$ is the operator of deuteron center of mass kinetic energy; $\hat{K}_r$ is the operator of deuteron internal energy; V_C is the Coulomb potential;. $\Psi\left(\vec{R},\vec{r}\right)$ is the deuteron total wave function; V_n and V_p are neutron and proton nuclear interaction potentials, respectively; V_{np} is nucleon-nucleon interaction potential in the deuteron.

Using the adiabatic approximation [2] and the results of [9 - 11], equation (1) can be reduced to the form

$$\left[E_d-\hat{K}_{\vec{R}}-\bar{V}_N\left(R\right)-\delta V\left(R\right)+V_C\left(R\right)\right]\chi_d\left(\vec{R}\right)=0\,, \quad (2)$$

where $\bar{V}_N\left(R\right)=N\left\langle\varphi_{\vec{R}}\left(r\right)\middle|V_n\left(r_n\right)+V_p\left(r_p\right)\middle|\varphi_{\vec{R}}\left(r\right)\right\rangle$ is the single folded potential of deuteron nuclear interaction with the nucleus target [9]; $\delta V\left(R\right)$ is the complex potential takes into account the polarizability and the breakup of the deuteron [3]; $\chi_d\left(\vec{R}\right)$ is the deuteron relative motion wave function, $\varphi_{\vec{R}}\left(\vec{r}\right)$ is the distorted internal deuteron wave function in the external Coulomb field [3]. In this paper, in order to simplify the calculations an approximate analytical representation for $\varphi_{\vec{R}}\left(\vec{r}\right)$ [11] have been used

$$\varphi_{\vec{R}}\left(r\right)=\sqrt{\alpha/2\pi}r^{-1}e^{-\alpha r}\left[1-\beta\left(\vec{n}_R\cdot\vec{n}_r\right)\left(\alpha r\right)^2\right], \quad (3)$$

where $\beta\approx F_R/\left(8\alpha\varepsilon_0\right)$; $F_R=Z_Te^2/R^2$ is external force acting on the deuteron; $\vec{n}_R$ and $\vec{n}_r$ are unit vectors which determine the direction of the corresponding vectors.

In the calculations the free nucleon-nucleus interaction potentials (V_n, V_p) was chosen [12]. In fact, the deuteron is a bound particle and its constituent particles interaction with nuclei becomes weaker and this is a known problem [13]. Therefore, the normalization factor N, which should take into account this feature, is introduced. In the following calculations, this factor was assumed to be N = 1.

The results of calculations of the deuteron interaction potentials with tin nuclei in a single folding model in comparison with deuteron zero-size model potential is shown in Figs. 1 and 2, where real and imaginary part of the nuclear interaction potentials are presented.

The simple estimates show that in the energy range under consideration the classical Coulomb turning point for this system of interacting particles is located at the distance of ~ 14 Fm. It is easy to see that the folding procedure leads to a significant strengthening of nuclear potentials (both real and imaginary parts) in the peripheral region of interaction.

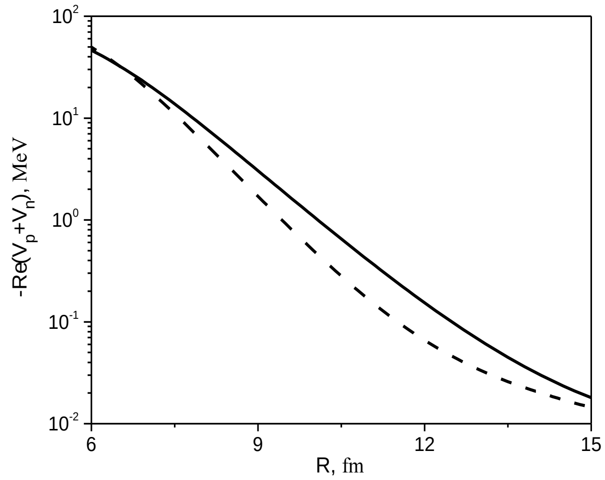

Fig. 1. The radial dependence of the real part of single folded (solid line) and zero-size (dash line) deuteron nuclear potential.

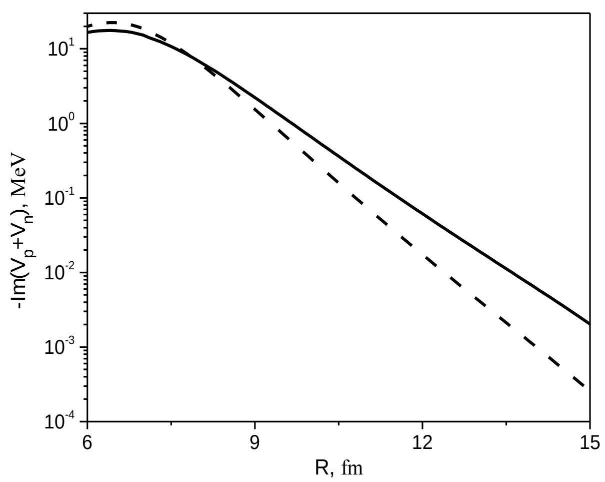

Fig. 2. The radial dependence of the imaginary part of single folded (solid line) and zero-size (dash line) deuteron nuclear potential.

Results and discussion

The differential cross sections of deuteron elastic scattering by tin nuclei were determined by integrating of energy spectra over the observed scattering peak and by normalizing the cross section values, measured at the forward angles, to the cross sections of Rutherford scattering (see [4, 5]). Angular distributions of differential cross sections for $^{124}Sn(d, d)$ elastic scattering measured at the energies of 4.0, 5.0 and 5.5 MeV are shown in Fig. 3. Considerable deviation of the measured differential cross sections and Rutherford ones is observed at the middle and backward scattering angles at E_d = 5.0 and 5.5 MeV. It was also found non-monotonic behavior of the differential cross sections of elastic scattering. Similar behavior was observed in angular dependence of elastic scattering on ^{124}Sn nuclei at the deuteron energy E_d = 5.55 MeV [7]. As it was expected, the differences between scattering cross sections and Rutherford cross sections decreases with energy decreasing, that is clearly shown in Fig. 3 and from data obtained at E_d = 4.55 MeV [7]. At the energy E_d = 4.0 MeV the scattering cross sections are already close to the values of Rutherford scattering cross sections.

The results of the calculations by the method described above are also shown in Fig. 3. Calculations of elastic scattering cross sections were performed with using the optical model with complex potential by code GENOA [14] without any variations of the nuclear potential parameters.

As can be seen in Fig. 3, a substantial part of the deviation from the Rutherford scattering cross section is described by taking into account the deuteron polarizability and breakup as well as the absorption of the particles constituting the deuteron in the peripheral region of interaction (direct reactions). This result is significantly different from that obtained in [4, 5, 15] where the deuteron elastic scattering by nuclei of nickel, lead and tin was investigated with taking into account only the breakup and polarizability of the deuteron in the field of target nuclei.

The differential cross sections of the $^{124}Sn(d, p)$ reaction at E_d = 4.0 and 5.0 MeV were also measured. The proton spectra were integrated over full range of proton energy (E_p > 1.8 MeV). The triple differential cross sections of deuteron break-up calculated according to [16] were integrated over the neutron emission angle and the proton energy for the estimation of possible break-up contribution to the proton yield from the $^{124}Sn(d, p)$ reaction. It is easy to see that the proton yield from (d, p) reaction is much greater than from breakup reaction (Fig. 4).

This conclusion is consistent with that obtained previously [4, 5] at the investigation of deuteron scattering and (d, p)-reactions on ^{58,62}Ni and ^{208}Pb nuclei at sub-barrier energies.

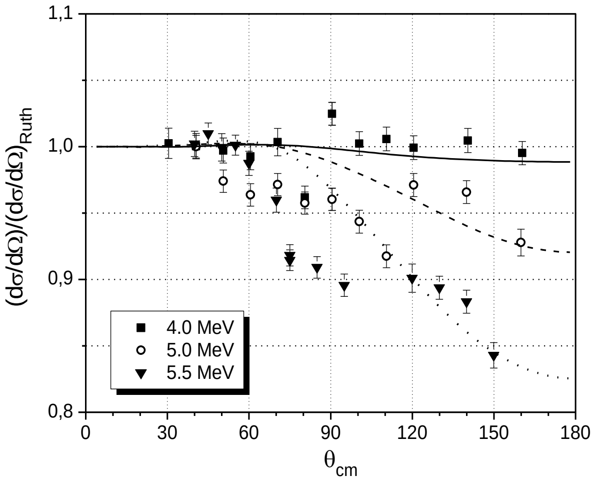

Fig. 3. The differential cross sections of ^{124}Sn(d, d) elastic scattering. The experimental values are shown by squares, triangles and open circles. The lines correspond to the results of theoretical calculations for the deuteron energies of 4.0 MeV (solid line), 5.0 MeV (dashed) and 5.5 MeV (dashed-dotted).

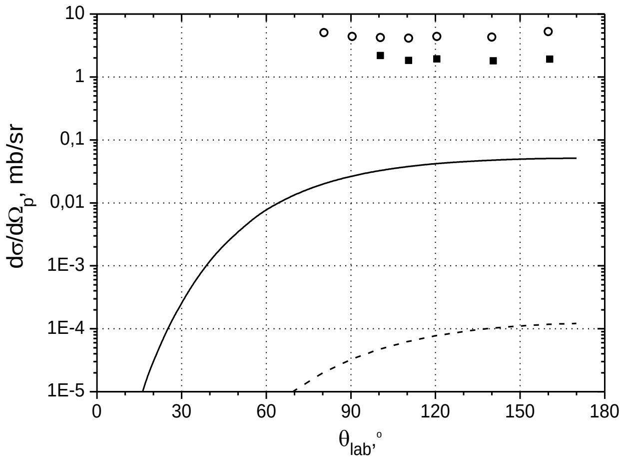

Fig. 4. The differential cross sections of ^{124}Sn(d, p) reaction. Open circles and squares correspond to the measured integral yield of protons at $E_d = 5.0$ MeV and 4.0 MeV, respectively. Solid and dashed lines show the calculated integral (over neutron emission angle and proton energy) Coulomb break-up cross sections at the deuteron energies 5.0 and 4.0 MeV, respectively.

The value of integrated proton yield from ^{124}Sn(d, p) reaction measured at $E_d = 5.0$ MeV is consistent with the data obtained for the cross sections of reaction ^{124}Sn(d, p)^{125}Sn at the close energy $E_d = 5.55$ MeV [7]. The sum of excitation cross sections measured at the proton angle $\theta_p = 160°$ for 44 levels of ^{125}Sn nucleus with $E_x \leq 5.06$ MeV (see Table 3 in [7]) is 6.6 mb/sr. The integrated proton yield at $E_d = 5.0$ MeV and $\theta_p = 160°$ is equal 5.3 mb/sr (see Fig. 4). This value is consistent with the total cross section of (d, p) reaction at 5.55 MeV, given the tendency of the reaction cross sections decrease with decreasing energy of the incident deuterons.

Conclusions

The sub-barrier interaction of deuterons with ^{124}Sn nuclei has been studied at energy of deuterons 4.0, 5.0 and 5.5 MeV. It was shown that the measured differential cross sections of elastic scattering at the middle and backward angles significantly differ from the Rutherford cross sections even at sub-barrier energies.

An approach with the interaction potential of the incident particle with the target nuclei in a model of single folding was used for the theoretical interpretation of the experimental data. It is shown that taking into account the finite size of the incident deuteron leads to the significant increasing the potentials in the peripheral region, which enabled to significantly improve the description of the experimental data. The calculations were performed without any variations of the nuclear potential parameters. At the same time, this model does not describe the non-monotonic behavier of the angular dependence of the elastic scattering cross sections which was experimantally observed at E_d = 5.0 and 5.5 MeV.

The calculations of differential and integral (over the neutron emission angles and the proton energy) cross sections of deuteron breakup reaction ^{124}Sn(d, p)n^{124}Sn and their comparison with integral proton yield indicate the dominant contribution of the neutron transfer reaction in the formation of protons in the final state and elastic scattering cross sections.

Performed study has shown that there are many interesting and unexplained features of the weakly bound particles interaction. Therefore the detailed complex study of the elastic scattering, breakup and other direct reactions at sub-barrier energies will provide more information about nuclear forces and the dynamic properties of the weakly bound nuclei in the external fields.

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ВЗАЄМОДІЯ ДЕЙТРОНІВ З ЯДРАМИ ^{124}Sn ПРИ ПІДБАР’ЄРНИХ ЕНЕРГІЯХ

Виконано вимірювання перерізів пружного розсіяння дейтронів та (d, p)-реакцій на ядрах ^{124}Sn з метою дослідження закономірностей підбар’єрної взаємодії дейтронів з важкими ядрами. Експериментальні дані були отримані на тандем-генераторі ЕГП-10К Інституту ядерних досліджень НАН України при енергіях пучка дейтронів E_d = 4,0; 5,0 і 5,5 МеВ. Перерізи пружного розсіяння дейтронів розраховано в наближенні, в якому потенціал взаємодії дейтронів з важкими ядрами при підбар’єрних енергіях побудовано в рамках моделі однократної згортки з використанням комплексного потенціалу динамічної поляризовності. Показано, що врахування скінченності розмірів дейтрона призводить до значного посилення ядерного потенціалу в периферійній області взаємодії і суттєво поліпшує опис експериментальних даних. Обчислення перерізів пружного розсіяння виконувалося без варіації будь-яких параметрів. Аналіз виміряних інтегральних перерізів реакції ^{124}Sn(d, p) та розрахованих перерізів реакції розщеплення дейтронів ^{124}Sn(d, p)n^{124}Sn вказує на визначальний вклад реакції передачі нейтрона в процеси утворення протонів і формування перерізів пружного розсіяння.

Ключові слова: дейтрон, ядро ^{124}Sn, підбар’єрні енергії, пружне розсіяння дейтронів, розщеплення дейтронів, реакції передач.

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ВЗАИМОДЕЙСТВИЕ ДЕЙТРОНОВ С ЯДРАМИ ^{124}Sn ПРИ ПОДБАРЬЕРНЫХ ЭНЕРГИЯХ

Выполнены измерения сечений упругого рассеяния дейтронов и (d, p)-реакций на ядрах ^{124}Sn с целью исследования закономерностей подбарьерного взаимодействия дейтронов с тяжелыми ядрами. Экспериментальные данные получены на тандем-генераторе ЭГП-10К Института ядерных исследований НАН Украины при энергиях пучка дейтронов $E_d = 4{,}0$; 5,0 і 5,5 МэВ. Сечения упругого рассеяния дейтронов рассчитаны в приближении, в котором потенциал взаимодействия дейтронов с тяжелыми ядрами при подбарьерных энергиях построен в рамках модели однократной свертки с использованием комплексного потенциала динамичной поляризуемости. Показано, что учет конечного размера дейтрона приводит к значительному усилению потенциалов в периферийной области взаимодействия и существенно улучшает описание экспериментальных данных. Расчет сечений упругого рассеяния выполнялся без вариации каких-либо параметров. Анализ измеренных интегральных сечений реакции ^{124}Sn(d, p) и рассчитанных сечений реакции расщепления дейтронов ^{124}Sn(d, p)n^{124}Sn указывает на определяющий вклад реакции передачи нейтрона в процессы образования протонов и формирования сечений упругого рассеяния.

Ключевые слова: дейтрон, ядро ^{124}Sn, подбарьерные энергии, упругое рассеяние дейтронов, расщепление дейтронов, реакции передач.

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