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DEUTERONS INTERACTION WITH NUCLEI ^{208}Pb AT SUB-BARRIER ENERGIES

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The sub-barrier interaction of deuterons with ^{208}Pb nuclei has been experimentally studied. Considerable difference of measured elastic cross sections from Rutherford ones and from theoretical calculations that take into account the processes of deuteron polarizability and breakup in the Coulomb field of ^{208}Pb nucleus was revealed. Energy proton spectra from (d, p) reactions have been also analyzed. It was shown that the process of neutron transfer occurs with essentially bigger probability than Coulomb breakup of deuterons.
Keywords: deuteron elastic scattering, deuteron breakup, heavy nuclei, transfer reactions.

Introduction

Study of weakly bound nuclei interaction is important because of essential influence of dynamic effects caused by nuclei spatial patterns. Deuteron Coulomb breakup at sub-barrier energies is one of the simplest cases when such effects can take place. Some theoretical models [1, 2] consider "deuteron-like" cluster structure of neutron rich nuclei, for example ^{6}He with dineutron configuration and strongly bound α-cluster as a "proton".

This experiment was performed with the aim to test the model, which is based on adiabatic approximation and used for the description of deuteron and "deuteron-like" nuclei scattering and Coulomb breakup [1 - 4]. This model successfully reproduces the energy dependence of backward (θ_d = 140º, 150º and 160º) d + ^{208}Pb scattering measured with high accuracy in the energy range E_d = 3 - 7 MeV [5] and angular distributions of differential cross sections of ^{6}He + ^{209}Bi [3] and ^{6}He + ^{208}Pb [4] elastic scattering measured at near and sub-barrier energies [6, 7], but can not explain the non-monotonic behaviour in the middle angular range of ^{6}He + ^{208}Pb scattering at E(^{6}He) = 14 and 16 MeV [8].

It is necessary to note that existing experimental data for sub-barrier scattering of deuterons by heavy nuclei are very scarce nowadays. Besides data obtained in [5], the cross sections of d + ^{208}Pb scattering were also measured at the angles θ_d = 50º, 140º and 170º and different deuteron energies (E_d = 7.0, 8.0, 9.0, 10.0 and 11.0 MeV) [9]. Therefore, there are no data for full range of scattering angles.

Experiment

The measurements were carried out with the deuteron beam accelerated to the energy 7.3 MeV at tandem electrostatic generator ESG-10K (Institute for Nuclear Research, Kyiv). Thick (11 mg/cm^2) self-support ^{208}Pb target was used in the experiment. Differential cross sections of deuteron elastic scattering and (d, p) reaction were measured in the angular range θ = 50º - 150º. Deuterons and protons were registered by two ΔE-E telescopes of semiconductor detectors ~ 20 and ~ 500 microns thick. The low energy threshold of registration was possible owing to the utilization of thin ΔE-detectors. Deuteron beam intensity was controlled with Faraday cup and two monitor detectors, which were installed in the reaction chamber at the fixed angles θ = 27 and 150°.

Typical ΔE-E spectra, which were measured at forward and backward angles, are shown in Fig. 1. Corresponding deuteron spectra as a sum of signal amplitudes from E and ΔE detectors are shown in Fig. 2. Besides the peaks of elastically scattered deuterons the relatively narrow peak near deuteron energy ~ 3.5 MeV is observed in the spectrum at θ_d = 150º. This peak can be caused by inelastic scattering with the excitation of lowest ^{208}Pb* levels. Monte Carlo calculation performed for the excitation (with equal cross sections) of two levels of ^{208}Pb nuclei with E_x = 2.6 MeV and E_x = 3.5 MeV illustrates the possibility of "narrow" peak formation as a sum of two wide spectral distributions (see insert in Fig. 2, *b*). The excitation of ^{208}Pb nucleus with E_x ~ 2.6 – 3.5 MeV, which must be low probable at sub-barrier energies, was also observed at the study of sub-barrier ^{6}He + ^{208}Pb interaction [8].

Data acquisition system that was used in the experiment is described in [10]. Data analysis was done by software that is intended for the execution of procedures which are necessary for identification of registered reaction products and reconstruction of their energy spectra. The operation with two-dimensional matrix with the size up to 1024 × 1024 channels is possible, that improves the mass separation of reaction products in ΔE - E spectra. Data acquisition system can be also used for coincidence measurements of events from eight pair of ΔE - E telescopes.

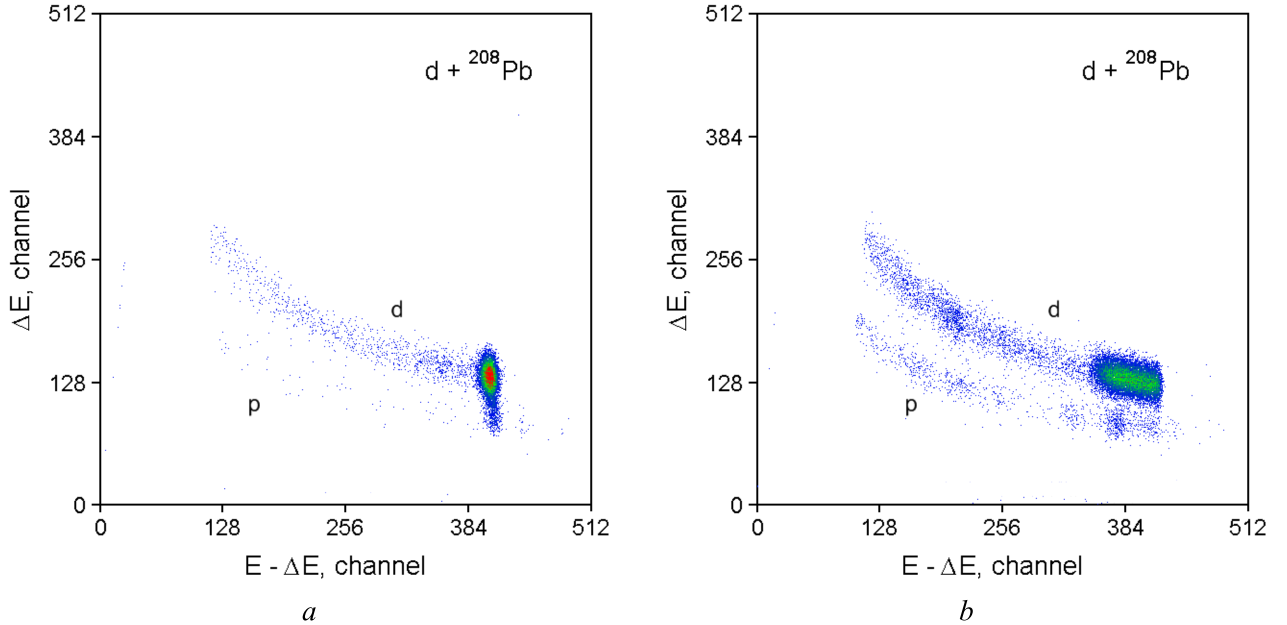


Fig. 1. Two-dimensional plots of ΔE-E spectra measured at θ = 50º (*a*) and θ = 120º (*b*).

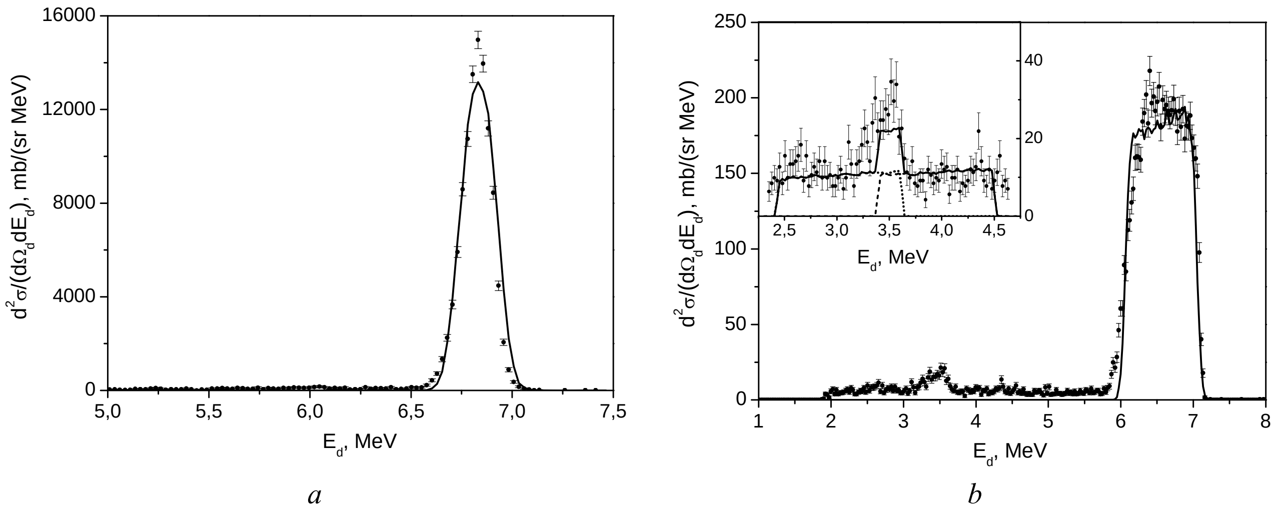


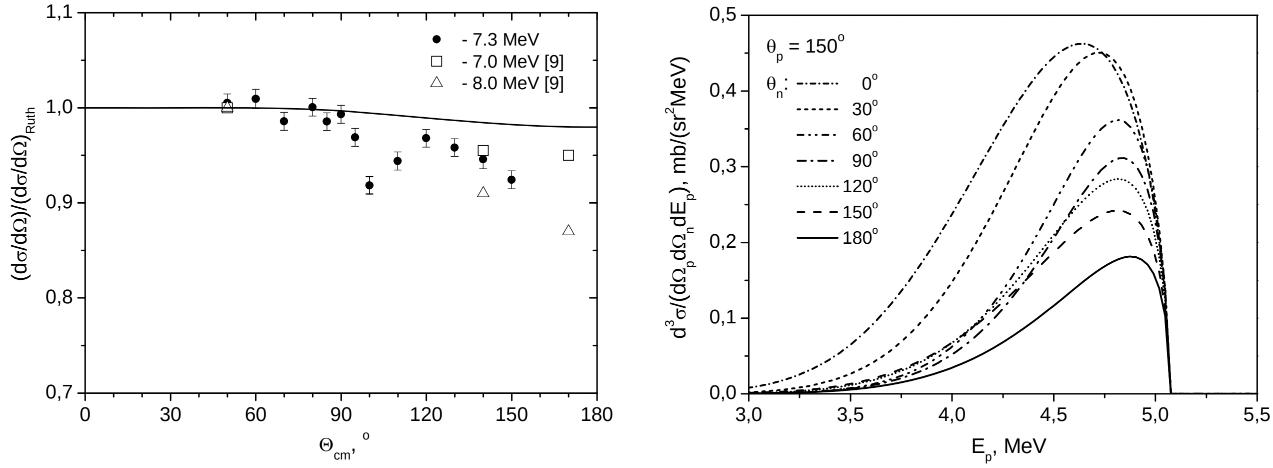
Fig. 2. Deuteron energy spectra measured for d + ^{208}Pb scattering at E_d = 7.3 MeV, θ_d = 60º (*a*) and θ_d = 150º (*b*). The peaks correspond to the elastic scattering. Solid curves show the peaks shape calculated by Monte Carlo method with taking into account the target thickness. Solid line in the left corner of right figure corresponds to the calculated total contribution of inelastic scattering with the excitation of two Pb* levels with E_x = 2.6 MeV (dashed line) and E_x = 3.5 MeV (dotted line).

Results and analysis

The differential cross sections of elastic scattering were determined by integrating of energy spectra over the observed peaks (see Fig. 2) and normalizing the cross section values, measured at forward angles, to the cross section of Rutherford scattering. Considerable deviation between measured differential cross sections and Rutherford ones is observed at the middle and backward angles (Fig. 3).

The experimental data agree with differential cross sections obtained at close energy (E_d = 7.0 and 8.0 MeV [9]) but sufficiently differ from theoretical calculation that takes into account deuteron polarizability and breakup processes [1, 2]. Angular dependence of measured differential cross sections of elastic ^{208}Pb(d, d) scattering is non-monotonic, as in the case of ^{58}Ni(d, d) and ^{124}Sn(d, d) scattering, studied at sub-barrier deuteron energies E_d = 3.5 - - 5.5 MeV [11]. Similar behaviour of angular distributions of differential cross sections was observed also for sub-barrier elastic scattering of more complicated nucleus ^{6}He with neutron halo structure [8]. This feature of weakly bound nuclei scattering had no theoretical explanation until now.

The proton spectra were analyzed with the aim to check the grounds for such unexpected differences

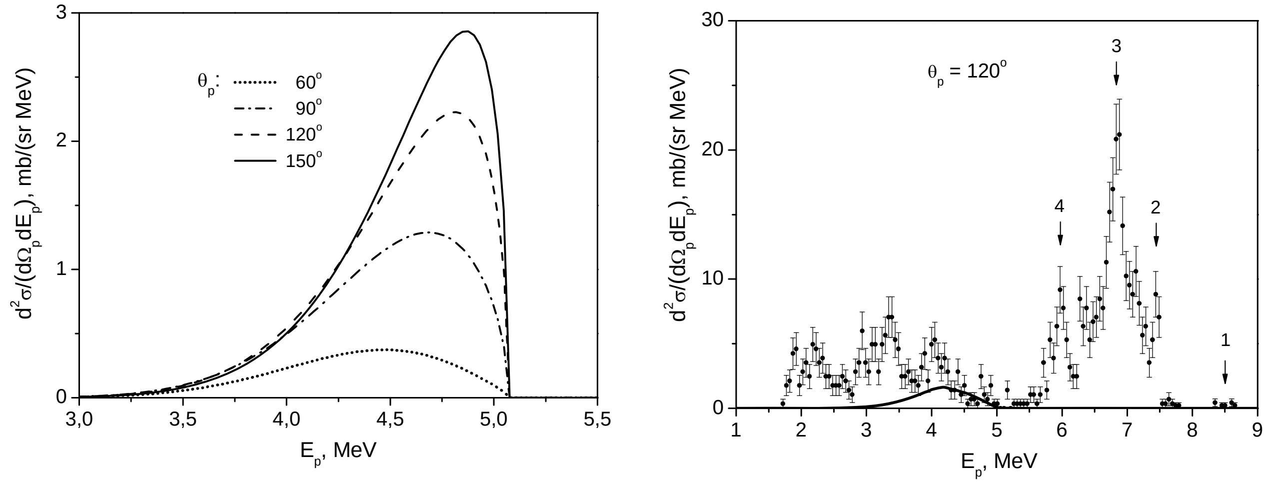


a *b*

Fig. 3. *a* – The angular distribution of differential cross sections of d + ^{208}Pb elastic scattering measured at E_d : ● – 7.3 MeV (this work); □ – 7.0 MeV [9]; Δ – 8.0 MeV [9]. Solid line is the result of theoretical calculation with two-cluster adiabatic approximation [1, 2]. *b* – Triple differential cross sections of deuteron breakup calculated according to [12] for the fixed angle θ_p = 150º and different neutrons angles θ_n.

between measured elastic scattering cross sections and Rutherford ones. Protons in the exit channel of d + ^{208}Pb reaction can be observed as the products of deuteron Coulomb breakup or neutron transfer reaction ^{208}Pb(d, p)^{209}Pb. Wide continuous energy distribution of protons and peak structure of their spectra are expected for the first and second process, respectively.

The triple differential cross sections of deuteron breakup calculated according to [12] for the fixed angle of proton emission and different neutrons angles are shown in Fig. 3, *b*. For the estimation of possible breakup contribution to the measured inclusive spectra of protons the calculated differential cross sections $d^3\sigma/(dE_p d\Omega_p d\Omega_n)$ were integrated over the all possible neutron emission angles Ω_n. Obtained double differential cross sections for some angles θ_p are shown in Fig. 4, *a*. For the comparison with measured inclusive spectra of protons the target thickness was taken into account in the calculations using Monte Carlo method. One can see in Fig. 4, *b* that the contribution of stripping reaction is much higher than the probability of Coulomb breakup. Measured spectra contain the protons from deuteron breakup, but this process is not dominant.



a *b*

Fig. 4. *a* – Inclusive spectra of protons from deuteron breakup ^{208}Pb(d, p)n^{208}Pb at E_d = 7.3 MeV calculated for different angles θ_p. *b* – The proton energy spectrum measured at θ_p = 120º, E_d = 7.3 MeV. Solid curve shows the spectrum of protons from deuteron Coulomb breakup calculated using the model described in [12]. Marked peaks correspond to the energy levels of ^{209}Pb nucleus from ^{208}Pb(d, p)^{209}Pb reaction: *1* – ground state; *2* – E_x = 0.78 MeV; *3* – E_x = 1.57 MeV; *4* – E_x = 2.54 MeV.

The formation of several states of ^{209}Pb nucleus was observed in the proton spectra. The ground and excited states of ^{209}Pb with $E_x \leq 2.54$ MeV were also observed in the ^{208}Pb(d, p)^{209}Pb reaction studied earlier at sub-barrier deuteron energies $E_d = 7.0$, 8.0, 9.0, 10.0 and 11.0 MeV in [9] and at $E_d = 8.0$ MeV in [13, 14]. The cross sections for the ground state of ^{209}Pb, which was obtained in this work at $E_d = 7.3$ MeV and $\theta_p = 140^o$ (~ 0.1 mb/sr), agree with previous data at $E_d = 7.0$ MeV [9].

Neutron transfer to the excited states of ^{209}Pb nucleus with energy $E_x \geq 2.54$ MeV can contribute to the proton spectra at $E_p < 5$ MeV (see Fig. 4, *b*). However, the group of events near 2.0 - 2.5 MeV can be also caused by the formation of unbound singlet deuterons. The coincidence measurements of protons and neutrons are required to verify this assumption. The role of formation of singlet deuterons in the Coulomb field of heavy nuclei is considered in [15] for (d, p*f*) reactions.

Neutron stripping is also important at the interaction of more complicated weakly bound nuclei. For example, the population of the ground and excited states of ^{209}Pb with $E_x \leq 2.54$ MeV was clearly observed in the $^9Be + ^{208}Pb \rightarrow ^{209}Pb + \alpha + \alpha$ reaction at near-barrier energy of ^{9}Be [16].

Conclusions

The sub-barrier interaction of deuterons with ^{208}Pb nuclei has been experimentally studied at $E_d = 7.3$ MeV. Measured differential cross sections of deuteron elastic scattering at backward angles essentially differ from the values of Rutherford scattering. The theoretical calculation with consideration of the deuteron polarizability and breakup in the Coulomb field of ^{208}Pb nucleus predicts considerably lesser decreasing of cross sections with the growth of scattering angle. Non-monotonic change of experimental cross sections at the middle angles of scattering is also not reproduced by this theory. Similar behaviour of angular dependence was also observed for ^{58}Ni(d, d) and ^{124}Sn(d, d) scattering studied at sub-barrier deuteron energies [11].

Energy proton spectra from ^{208}Pb(d, p) reactions have also been analyzed with the aim to check the main mechanism of proton production at d + ^{208}Pb interaction. According to the calculations the main yield of protons from deuteron breakup must be observed at backward angles. However, the measured backward proton yield is mostly caused by the neutron stripping reaction ^{208}Pb(d, p)^{209}Pb. From this we can assume that the neutron transfer is dominant mechanism of ^{208}Pb(d, p) reaction at $E_d = 7.3$ MeV. The formation of singlet deuterons in the Coulomb field of heavy nuclei is also possible.

The obtained results show the necessity of detailed complex study of deuteron scattering, (d, p) and (d, pn) reactions at sub-barrier energies.

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ВЗАЄМОДІЯ ДЕЙТРОНІВ З ЯДРАМИ ^{208}Pb ПРИ ПІДБАР'ЄРНИХ ЕНЕРГІЯХ

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Експериментально досліджено підбар'єрну взаємодію дейтронів з ядрами ^{208}Pb. Виявлено суттєві відмінності виміряних перерізів пружного розсіяння від резерфордівських, а також від теоретичних розрахунків, що враховують процеси поляризованості та розщеплення в кулонівському полі ядра ^{208}Pb. Аналізувались також енергетичні спектри протонів з (d, p) реакцій. Показано, що процес передачі нейтронів відбувається з суттєво більшою ймовірністю, ніж кулонівське розщеплення дейтронів.

Ключові слова: пружне розсіяння дейтронів, розщеплення дейтронів, важкі ядра, реакції передач.

ВЗАИМОДЕЙСТВИЕ ДЕЙТРОНОВ С ЯДРАМИ ^{208}Pb ПРИ ПОДБАРЬЕРНЫХ ЭНЕРГИЯХ

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Экспериментально исследовано подбарьерное взаимодействие дейтронов с ядрами ^{208}Pb. Обнаружены существенные отличия измеренных сечений упругого рассеяния от резерфордовских, а также от теоретических расчетов, учитывающих процессы поляризованости и расщепления в кулоновском поле ядра ^{208}Pb. Анализировались также энергетические спектры протонов из (d, p) реакций. Показано, что процесс передачи нейтронов происходит с существенно большей вероятностью, чем кулоновское расщепление дейтронов.

Ключевые слова: упругое рассеяние дейтронов, расщепление дейтронов, тяжелые ядра, реакции передач.

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