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Sub-Barrier Interaction between Deuterons and $^{58,\,62}$Ni Nuclei

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Abstract—The interaction between deuterons and $^{58,\,62}$Ni nuclei at energies of E_d = 3.5, 4.5 and 5.16 MeV is investigated. The discrepancy between measured scattering elastic cross section and the Rutherford ones is higher than the value calculated theoretically by considering deuterons polarization and Coulomb breakup. Analysis of measured cross section of $^{58,\,62}$Ni(d, p) reaction and the results of calculation of Coulomb breakup cross section integrated over neutron emission angles shows that that the dominant mechanism of proton formation is the reaction of neutron transfer to the target nucleus.

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INTRODUCTION

The interaction of weakly bound nuclei with nuclei over a wide range of masses at sub-barrier energies is of interest since it is possible to observe the dynamic effects affecting the internal degrees of freedom in a weakly bound system. In this energy range, the processes caused by Coulomb interaction are manifested considerably, and they can be used in investigating the structural features of weakly bound nuclei. One example of such a process is a weakly bound nucleus breaking up into nucleons or clusters in the Coulomb field of the target nucleus.

In some theoretical approaches to describe the Coulomb breakup of weakly bound neutron-excess nuclei, a model in which such nuclei consist of two clusters, charged and neutral [1–4], is used. If the Coulomb breakup of neutron-excess nucleus ^{6}He is considered in the context of the theory presented in [4], we can correctly reproduce the experimental data [5, 6] on ^{6}He elastic scattering by ^{209}Bi [5] and ^{208}Pb [6] nuclei at sub-barrier energies.

As for testing the models developed for investigating weakly coupled exotic nuclei, it is logical that we study the sub-barrier interaction for the simplest weakly coupled nucleus: a deuteron. In this work, we present the results from our investigation of deuteron elastic scattering and the (d, p) reactions of $^{58,\,62}$Ni nuclei at E_d = 3.5, 4.5, and 5.16 MeV.

We should point out that such processes as deuteron breakup and the most intensive process of elastic scattering at sub-barrier energies have yet to be studied properly. The elastic scattering of deuterons by the medium and heavy nuclei of ^{124}Sn, ^{130}Te, ^{138}Ba, ^{140}Ce, ^{142}Nd, and ^{208}Pb, along with the (p, d) reactions on the above nuclei were investigated in [7] at energies lower than the Coulomb barrier and the respective nucleus. In [7], however, information was obtained for several points of the angular distribution of scattering cross sections and (p, d) reactions. For elastic scattering d + ^{208}Pb at θ_d ranging from 40° to 150° and at E_d = 7.3 MeV [8], it was found that the scattering cross section for higher angles was lower than the results calculated by considering the deuteron breakup. From the energy spectrum for protons in [8], it can be seen that protons are formed mainly due to the ^{208}Pb(d, p)^{209}Pb reaction, and not due to breakup reaction ^{208}Pb(d, p)n^{208}Pb.

The reaction of neutron stripping has been investigated in detail for nuclei with mass number $A \approx 60$, and particularly for Ni isotopes with deuteron energies close to the Coulomb barrier. The aim of such investigations was to obtain spectroscopic information on the exciting states for nuclei with mass number $(A + 1)$. For example, in $^{62,\,64}$Ni(d, p)$^{63,\,65}$Ni reactions at E_d = 7.5 MeV [9], which is higher than the Coulomb barrier, the spectroscopic characteristics of several dozens of levels of ^{63}Ni and ^{65}Ni nuclei have been determined due to the high resolution of proton spectra measurement. The spectroscopic characteristics for the Coulomb stripping reaction $^{58,\,62,\,64}$Ni(d, p)$^{59,\,63,\,65}$Ni at sub-barrier energy E_d = 2.9 MeV for the low excited states $^{59,\,63,\,65}$Ni [10], at which the energy of outgoing protons is higher than the Coulomb barrier, revealed anomalies caused by the multistep mechanism of its formation, and by interference from one- and multistage processes.

In this work, we investigate the Coulomb scattering of deuterons, the Coulomb breakup, and neutron stripping at d + $^{58,\,62}$Ni interaction in the area of sub-barrier energies. The aim of our investigation was to determine how the last two processes affect elastic scattering.

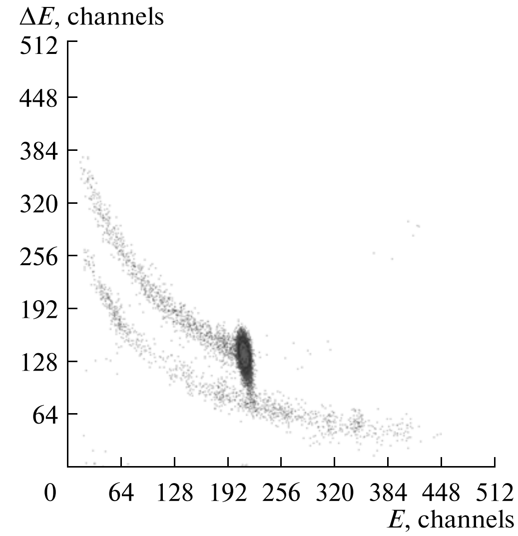

Fig. 1. 2D ΔE–E spectrum for the products of d + ^{62}Ni interaction, measured at $E_d = 5.16$ MeV and $\theta_d = 50°$.

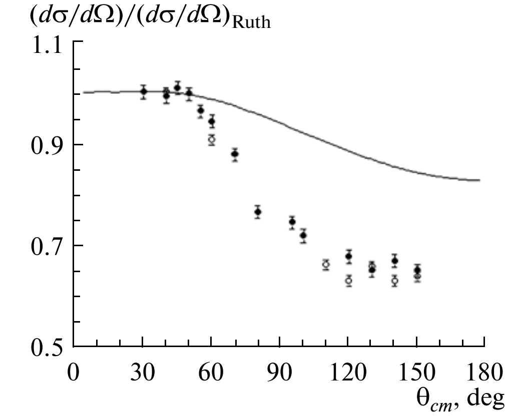

Fig. 2. Differential cross sections of the elastic scattering of deuterons. ● is d + ^{62}Ni; ○ is d + ^{58}Ni. Deuteron energy $E_d = 5.16$ MeV. The bold line corresponds to the theoretical calculations performed with allowance for the Coulomb breakup of deuterons.

EXPERIMENTAL

The differential cross sections of deuteron scattering and the (d,p) and (d,p)n reactions for ^{58,62}Ni nuclei were measured on the tandem EG-10K electrostatic generator at the Institute for Nuclear Research, Academy of Sciences of Ukraine, at $E_d = 3.5$, 4.5, and 5.16 MeV.

In this experiment, we did not intend to obtain the high energy resolution needed for identifying and determining the excitation cross section of separate neighboring levels of ^{59,63}Ni nuclei in proton spectra. To accomplish this, we would need an energy resolution of ~15 keV. Seventy-eight levels of the ^{63}Ni nucleus were identified with such resolution in [9] at excitation energies of up to 5.2 MeV. At sub-barrier energies, the formation of cross sections for each ^{59,63}Ni state in (d, p) reactions are quite small [9, 10], and it is difficult to examine simultaneously both the elastic scattering and the (d, p) reactions without a magnetic spectrometer. In addition, high resolution for deuteron energy is not required to separate the contribution of elastic and inelastic scattering by ^{58,62}Ni nuclei, since the energies of the first excited states of ^{58}Ni and ^{62}Ni are 1.454 and 1.172 MeV, respectively. These factors designated the selection of thick, self-supporting targets (~5 mg/cm^2) ^{58,62}Ni for measuring the cross sections of scattering and (d,p) reactions.

Differential cross sections were measured for angles θ ranging from 40° to 150°. The reaction products were detected by two (ΔE–E) semiconductor detector telescopes with thicknesses of ~20 and 500 μm, respectively. If we use thin ΔE detectors, we can lower the threshold of energy detection; for protons, it is ~1.1 MeV. The beam intensity is controlled with a Faraday cup and two detectors placed in the reaction chamber at fixed angles θ = 27° and 150°.

The system for data accumulation used in our experiment was described in detail in [11]. The information was analyzed using software that performs all of the procedures needed for identifying particles, for generating the energy spectra, and for calculating the differential cross section of elastic scattering and reactions, the products of which are detected along with particle scattering.

Figure 1 shows a 2D ΔE–E spectrum measured during interaction between deuterons and ^{62}Ni nuclei. In addition to the intense peak of deuteron scattering, there is a pronounced yield of protons; this could be due to deuteron breakup and the ^{62}Ni(d, p)^{63}Ni reaction.

RESULTS AND DISCUSSION

Differential cross sections of elastic scattering were determined by integrating spectra over elastic scattering peak. To obtain the absolute values of the cross sections, we normalized them to Rutherford cross sections for small scattering angles. Figure 2 shows the angular distributions of deuteron elastic scattering by ^{58,62}Ni nuclei at a deuteron energy of 5.16 MeV. From Fig. 2 we can see that the cross sections of deuteron elastic scattering are close for ^{58,62}Ni isotopes. The considerable discrepancy between the measured differential cross sections and the Rutherford cross sections at θ > 60° could be due to deuteron breakup or to other reactions, e.g., (d, p). From Fig. 2, we can see that the Coulomb breakup does not completely explain the observed reduction in the scattering cross section. Figure 3 presents the variation in the elastic cross section obtained for deuteron elastic scattering by ^{58}Ni nuclei at all three values of the deuteron energies. As was expected, the discrepancy between the measured and the Rutherford cross sections, and the

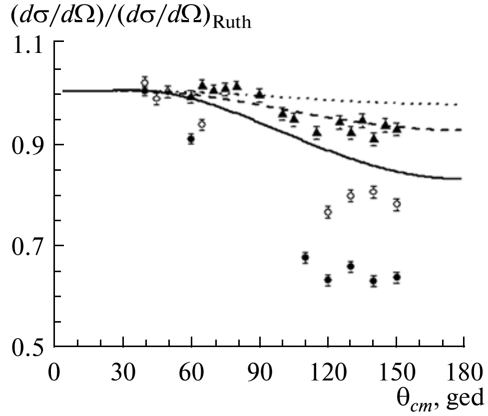

Fig. 3. Differential cross sections of the elastic scattering of ^{58}Ni(d, d)^{58}Ni (●) for $E_d = 5.16$ MeV; (○) for $E_d = 4.5$ MeV; (▲) for $E_d = 3.5$ MeV [10]. The theoretical calculations for $E_d = 5.16$ MeV (bold line), $E_d = 4.5$ MeV (dashed line), and $E_d = 3.5$ MeV (dotted line) are presented.

results from calculations performed with allowance for the Coulomb breakup, grows as the energy rises. At an energy of 5.16 MeV, which is close to the Coulomb barrier for deuterons and $^{58,\,62}$Ni nuclei, it is not only the Coulomb forces that can influence the breakup process, but nuclear forces as well. In the case of lower energies, e.g., at $E_d = 3.5$ MeV (about half the value of the Coulomb barrier), deuteron breakup should be due only to Coulomb interaction.

To understand why the variation in scattering cross sections is so high (a Coulomb breakup cannot produce such variation), we analyzed the proton spectra, which can be generated by the products of breakup reaction (d, p)n or by neutron stripping (d,p). In the first case, the continuous wide distribution at energies ranging from zero to 2.9 MeV (deuteron beam energy $E_d = 5.16$ MeV) should be visible in the proton spectrum. In the second case, the discrete spectral structure corresponding to the ground and excited states of $^{59,\,63}$Ni nuclei formation shall be observed.

Figure 4 shows the proton energy spectrum for the ^{62}Ni(d, p)^{63}Ni reaction, measured at $E_d = 5.16$ MeV and $\theta_p = 80°$. Since the thickness of the E detector is not sufficient to totally absorb the protons with energies corresponding to the ground and low excited states of ^{63}Ni nucleus formation, its contribution to the presented spectrum is not visible. In Fig. 4, the peaks that correspond to the contribution from excitation of energy states (or the excitation of a group of states) for the ^{63}Ni nucleus is marked by arrows (the numerical values are the excitation energy for the ^{63}Ni nucleus given in MeV), the bold line represents the calculations for its summed contribution with allowance for the target thickness, performed using the Monte Carlo method.

The solid line in Fig. 4 in the area of $E_d < 2.5$ MeV corresponds to the calculated contribution from deuteron breakup using the algorithm presented in [12]. To estimate this contribution, three-time differential cross sections of Coulomb breakup calculated according to [12] and with allowance for the target thickness were integrated over all angles of neutron emission. In the proton spectra in the area of $E_p < 2.9$ MeV, a contribution from the highly excited unbound state of the ^{63}Ni nucleus and the unbound (singlet) state of deuteron is also possible. We can identify these processes if the statistical accuracy of measuring inclusive proton spectra is high, and if we investigate (d, pn) reactions in correlation experiments.

The angular distributions of differential cross sections for $^{58,\,62}$Ni(d, p) reactions, obtained by integrating the measured proton spectra (at $E_d = 5.16$ MeV) over the full energy range including the contribution from reaction $^{58,\,62}$Ni(d, p)n, are presented in Fig. 5. The same data for ^{58}Ni(d, p) reactions at $E_d = 3.5$; 4.5 and 5.16 MeV are shown in Fig. 6. In Figs. 5 and 6, the

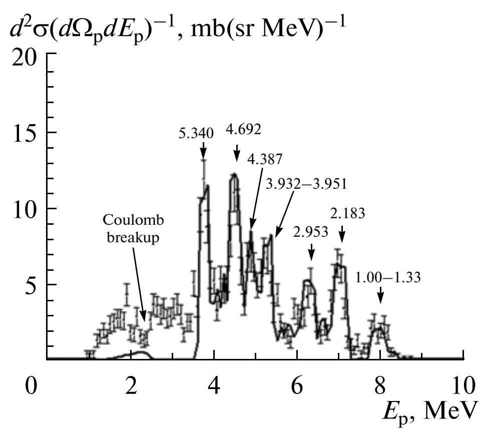

Fig. 4. Proton spectrum for ^{62}Ni(d, p) reaction measured at $E_d = 5.16$ MeV and $\theta_d = 80°$. The bold line corresponds to the contribution from the ^{62}Ni(d, p)^{63}Ni reaction at excitment levels of ^{63}Ni and from the Coulomb breakup reaction ^{62}Ni(d, pn)^{62}Ni.

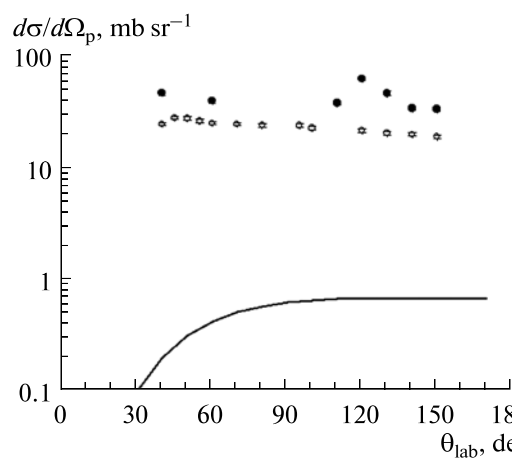

Fig. 5. Differential cross sections for Ni(d, p) reactions at a deuteron energy of 5.16 MeV: (○) ^{62}Ni(d, p); (●) ^{58}Ni(d, p). The bold line represents the results from calculating the contribution from Coulomb deuteron breakup.

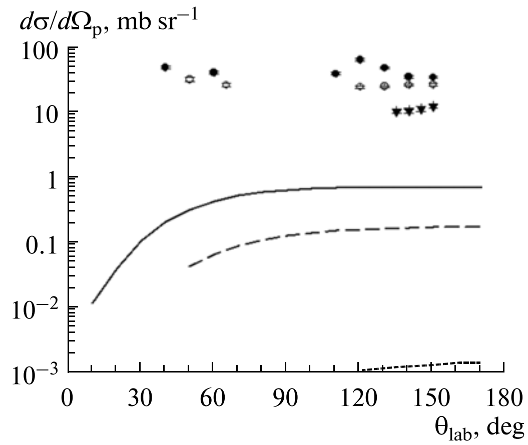

Fig. 6. Differential cross section of the ^{58}Ni(d, p) reaction: (●) $E_d = 5.16$ MeV; (○) 4.5 MeV; (▲) 3.5 MeV. The lines represent the theoretically calculated contributions from a Coulomb breakup: the bold line is for $E_d = 5.16$ MeV; the dashed line is for E_d= 4.5 MeV; the dotted line is for E_d= 3.5 MeV.

respective theoretical calculations considering only the Coulomb breakup for deuterons are represented by the lines.

The calculated and experimental data were compared, and it was seen that the measured values for differential cross sections of the ^{58,62}Ni(d, p) reaction are considerably greater than the contribution from the Coulomb breakup of a deuteron.

If we assume that (d,p) and (d,p)n reactions describe the processes responsible for the discrepancy between our elastic cross section and the Rutherford cross section, the number of formed protons should be equal to the number of deuterons that dropped out from the channel of elastic scattering (we ignore inelastic scattering and the interference of different processes). To verify this assumption, the cross sections of ^{62}Ni(d, p) reaction integrated over the angle of proton emission were compared to the difference between the Rutherford and the measured cross sections of deuteron elastic scattering. These integral values were equal within the accuracy of measurement.

CONCLUSIONS

Our experimental investigations of the interaction between deuterons and ^{58,62}Ni nuclei at sub-barrier energies of $E_d = 3.5$; 4.5, and 5.16 MeV show that the discrepancy between the measured elastic cross section and the Rutherford cross section is considerably greater than the theoretical estimates obtained by considering the Coulomb breakup of deuterons.

We analyzed the proton spectra for ^{58,62}Ni(d, p) reactions in order to determine possible reasons for the observed discrepancy. We found that the dominant process of proton formation is the reaction of neutron transfer to the target nucleus. The observed discrepancy between the measured elastic cross section and the Rutherford cross section is thus due mainly to the process of neutron transfer, and not to the Coulomb breakup of a deuteron.

The results obtained in this work agree with the data in [8], where the sub-barrier interaction d + ^{208}Pb was investigated, and require additional detailed theoretical investigations to be conducted; they could prove useful in studying the sub-barrier interaction of weakly bound nuclei, which are more complicated nuclei than deuterons.

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