INVESTIGATIONS ON NUCLEAR PHYSICS WITH ACCELERATED BEAMS OF POLARIZED IONS AT THE NSC KIPT

R.P. Slabospitsky, N.A. Shlyakhov

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

The overview of polarization phenomena studies in NSC KIPT is presented.

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The study of nuclear forces and development of the theory of nucleus is one of the fundamental problems in the science. The features of a nuclear structure and nuclear forces determine after all the chemical and physical properties of elements play a leading role in astrophysics as well as in different applications of nuclear physics in the science and technique.

Nuclear forces depend on the spins of interacting particles and this fact is always taken into account in the development of nuclear models and nuclear reaction mechanism. The spin dependence of nuclear forces leads to different regularities of polarization appearance for the exit particles as well as to the dependence of the reaction cross-section on the incident particles. The investigation of different polarization phenomena with protons and deuterons gives very necessary information on the mechanism of nuclear reactions and nuclear structures. The study of these processes at low energies gives the information on the structure of light nuclei, in particular, 1p- and 2s1d- shell nuclei. Here the level density is still low and one can obtain the data on the level quantum characteristics that is difficult for medium and heavy nuclei, but is very important for the test of different nuclear models. The nuclear reaction mechanism is strongly dependent on the nuclear structure features, because, for example, the new reaction channels are opened with increasing nuclear excitation energy. The nuclear reaction mechanism depends not only on the structure of the compound nucleus being formed but also on the quantum characteristics of the neighboring nuclear levels which arise during the nuclear reaction.

In interactions between low-energy particles and light nuclei the essential role is played by such phenomena as a process of production and decay of compound nucleus, direct process, their interference, anomalous phenomena near the threshold of new channel opening, production of incoming states (intermediate structure), excitation and disintegration of isobar-analog states etc.

The information of these phenomena can be obtained from the investigations of differential cross-sections in the resonance nuclear reactions. However, when the polarization is studied too, the information becomes more unambiguous and in some cases is the only possible one. The polarization is the interference effect and its studying is particularly advantageous for investigation of the resonance interference, the interference of direct and compound, processes and isobar-analog resonance and etc.

The investigation of polarization phenomena is the traditional direction in the Kharkov Institute of Physics and Technology (KFTI) where in 60-ies a great volume of experimental (A.K. Valter, P.V. Sorokin, A.P. Klyucharev, N.A. Skakun et al) and theoretical (G.L. Vysotskij, E.V. Inopin, A.G. Sitenko, L.N. Rosentsveig et al.) investigations were performed. However, the experimental polarization investigation has been carried out by the method of double scattering on polarized particle beams obtained from nuclear reactions. Such a polarized particle beam is characterized by the wide spread of energies and by the low intensity that complicates the precision analyses.

In 1961 the problem of developing the source of the positive polarized ions, creating on its base the injector of the negative polarized hydrogen and deuterium ions and accelerating them in the charge-exchange accelarator with the potential on the conductor of 1.5 MV (PG-30) was posed for the group of scientists: A.Ya. Taranov, R.P. Slabospitsky, I.M. Karnaukhov, O.I. Ekhichev, I.E. Kiselev, I.D. Lopatko, V.Kh. Belyaev. The obtaining of beams of polarized protons and deuterons with high monochromaticity by energy made it possible to begin the fulfillment of the program on the study of light atomic nuclei and investigation of polarization phenomena in resonance nuclear reactions.

The investigation of light nuclei was undertaken in order to obtain the information about quantum characteristics of the compound nucleus levels for testing the different shell models and collective model, and to study the nuclear properties near new channel thresholds, the mechanisms of isobar-analog state production and decay, the production of incoming states, the giant resonances. The task was put also to obtain the information about the peculiarities of polarization phenomena: at the interference of direct and compound processes; in resonance nuclear reactions which occur with excitation of single resonances as well as with excitation of several strongly interference resonances, isobar-analog resonances; on excitation of Ericson fluctuations etc. Investigations on the target nuclei with the zero spin and nonzero spin were aimed for finding the properties of nuclei having different ratio of proton and neutron numbers. To study the compound nucleus levels with different excitation energy the investigations were undertaken with protons and deuterons inasmuch as in the case of deuteron excited are the levels of

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energy by 6…7 MeV higher than for proton. There were taken into account also the peculiarities of the deuteron-nucleus interaction mechanism related to the deuteron specific character, i.e. very low coupling energy, large space between neutron and proton and no coincidence of the center-mass with the center of charge, too. We have planned also the study of different channels of interaction between the incident particle and target nucleus: elastic, non-elastic stripping and pickup reaction.

By now, many problems of the above mentioned programs were solved during investigation of the interactions between polarized protons and nuclei of zero spin (^{12}C, ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca, ^{62}Ni, ^{66}Zn) of nonzero spin (^{7}Li, ^{9}Be, ^{11}Be) and polarized deuterons with nuclei of zero spin (^{12}C, ^{16}O, ^{24}Mg, ^{28}Si, ^{30}Si, ^{32}S), of nonzero spin (^{9}Be, ^{14}N, ^{19}F). The information obtained in our investigations on the interaction of polarized low-energy proton and deuteron beams with light nuclei makes up more than half of that obtained in the whole world.

To get the information on the structure of the atomic nuclei being considered and on the nuclear reaction mechanism the special method was created for obtaining the experimental results and their analysis by comparison with calculated polarization (the analyzing power data). For the experimental procedure we developed the special scattering chambers, detecting and measuring instruments, isotope targets. In what follows we survey and discuss the most valuable results on the investigation of polarized phenomena in the Kharkov Institute of Physics and Technology.

In investigations of polarization effects depending on the density of nuclear excited states, different cases were studied: when the level density is low (the scattering on the nuclei ^{12}C, ^{28}Si, and ^{40}Ca) and the main role is played by the single resonances as an interference of not more than two resonances; when the level density is rather high (the scattering on the nuclei ^{24}Mg, ^{26}Mg, ^{32}S and ^{40}Ca) and the strong interference of some resonances takes place, and in the case (the scattering on the nuclei ^{62}Ni, ^{66}Zn) when in the compound nucleus excited are the isobar-analog states which can be observed simultaneously with the normal ones having very high resonance density.

It is shown that in the first case the measurement of the polarization sign (Fig. 1) is enough to determine unambiguously the total angular momentum of the level and the measurement of the polarization energy dependence allows one to determine with a sufficient accuracy the phase shift that in its turn makes it possible to calculate the polarization maps. These polarization maps calculated for the elastic proton scattering on nuclei ^{12}C and ^{28}Si permitted to use these processes as the analyzers of polarization of the polarized proton beams in the next investigations.

The study of the polarization as an interference effect has a particular significance for the study of properties of a number of resonances, which interfere between them when the level density is rather high. For example, in the case of the elastic scattering of protons with energy of 1.8…2.2 MeV on the nuclei ^{26}Mg, very (Fig. 2) complex dependence on the energy of scattering cross-section and polarization was observed. This dependence is conditioned by the interference of several narrow resonances with two broad resonances, which also interfere between them. Here, the quantum characteristics of narrow resonances are most difficult to determine. It was impossible to do it by measuring only the elastic scattering cross-section. The polarization measurements allowed one to determine the quantum characteristics of all levels of compound nucleus excited at above mentioned proton energies.

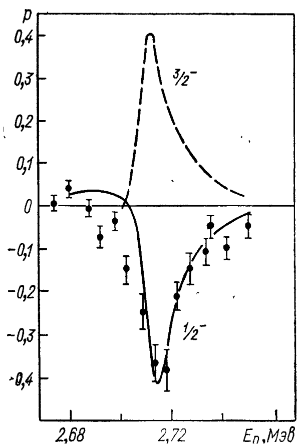

Fig. 1. The dependence of polarization of protons an energy for reaction $^{40}Ca(p, p)^{40}Ca$

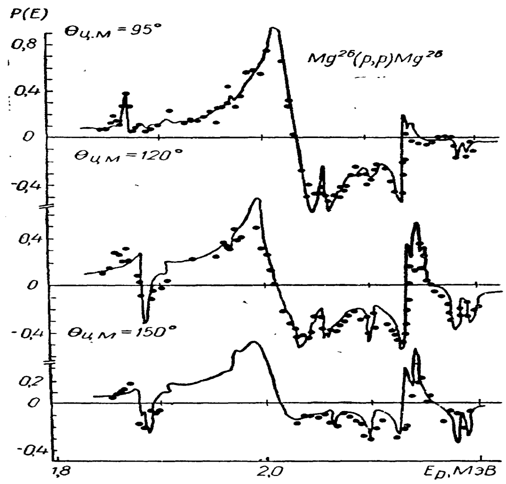

Fig. 2. The dependence of polarization of protons an energy for reaction $Mg^{26}(p, p)Mg^{26}$

The polarization measurement has been helpfull also in investigations of the splitting of the ^{41}Sc one-particle 2p 1/2 state into the multiplet. According to the weakly coupled shell model where the excited states of the ^{40}Ca, as an core have been taken into account one should expect that the one-particle 2 p 1/2 state in the nuclei ^{41}Sc and ^{41}Ca must be splitted into the multiplet of five components. Such a splitting in ^{41}Ca has been really found earlier. The comparison of level schemes of mirror nuclei ^{41}Ca and ^{41}Sc and the calculation results show that in ^{41}Sc the levels of the expected multiplet should be near the excitation energy of 4 MeV. From the cross-section measurement determined were only the orbital moments l=1, and the total momenta have not be found.

The investigations of the polarized proton scattering on ^{40}Ca demonstrated the presence of five resonances being the components of the one-particle 2p 1/2 state and the predictions of the model were confirmed.

When the polarization is studied the situation is appreciably different. It is shown in our works that since the polarization is the interference effect it can be easily measured even for states with the small ratio between proton and total widths. Polarization is observed at small breakdown and allows one to determine the total angular momentum of the compound nuclear isobar-analog state. Thus, the quantum characteristics of ^{63}Cu and ^{67}Ga levels were determined that made it possible, for the first time, to determine also the quantum characteristics of the ^{63}Ni ground state. The investigations on the interaction of polarized protons with zero spin nuclei permitted to determine the quantum characteristics of ^{13}N, ^{25}AL, ^{27}AL, ^{29}P, ^{33}Cl, ^{41}Sc, ^{63}Cu excited states. These data were analyzed by the shell models with the intermediate coupling and surface delta-interaction and by the collective model with weak and close coupling.

On a basis of the information obtained on the quantum characteristics of excited states in about twenty atomic nuclei with 1p- and 2s1d-shells and after their comparison with available calculations by the shell and collective models we established that the nuclei with 1p-shell are described better by the model of shells with intermediate coupling and the nuclei with 2s1d-shell- by the collective model with close coupling. It was shown also that 2p 1/2 state in the nucleus ^{41}Sc is really splitted into 5 components as it was predicted by the collective model with weak coupling and core excitation. For the experimental data be described better, the further development of the models is required.

The investigations of the elastic polarized proton scattering on nuclei with the nonzero spin (^{7}Li, ^{9}Be, ^{11}B) and of the ^{11}B pα--reactions were performed to determine the quantum characteristics of ^{8}Be, ^{10}B, and ^{12}C excited states. It is shown, that polarization investigations of these nuclei as well as of zero-spin nuclei allow determining the quantum characteristics of compound nucleus levels more reliably as compared to the case when investigated were only the differential cross-sections. The nucleus ^{8}Be, ^{10}B, ^{1}C are the self-conjugate nuclei. The study of nuclei of such type is of a great interest for investigation of the states being the analog states in the mirror nuclei of the corresponding triad that is important for the test of the law of nuclear force charge independence.

The particular attention in investigation of the polarized proton interaction with ^{7}Li, ^{9}Be and ^{11}Be was being given to the study of elastic proton scattering processes in the near-threshold (p,n)-reaction region. It is shown that the differential cross-section and the analyzing power of the elastic scattering process have the anomalous behavior near the (p, n)-reaction threshold. In the description of the scattering near the (p, n)-reaction threshold the greater contribution into the process of polarized proton scattering on 1p-shell nuclei gives the S-wave. It may be an important confirmation of the hypothesis on the existence near the threshold of the virtual S-state predicted by the theory.

The interaction of polarized deuterons on zero-spin nuclei (^{12}C, ^{16}O) has been investigated in order to determine the quantum characteristics of compound nuclei ^{14}N and ^{18}F levels and to compare them with calculations by the weak-shell coupling model. The quantum level characteristics were determined from the combined analysis of the elastic deuteron scattering and stripping reaction measurements. The energetic and angular dependences of the vector analyzing power for these processes were measured experimentally. The analysis was performed by comparison of experimental data and theoretical calculations fulfilled with different sets of values obtained for the quantum characteristics of compound nuclear levels. To verify the accuracy of the quantum characteristic values obtained we have calculated also the tensor analyzing powers for the deuteron elastic scattering on ^{12}C and compared them with the data published. The agreement was rather good.

Comparison between quantum characteristics of the compound ^{14}N nuclear levels and different models describing ^{14}N has shown that the description of our results by the model of weak coupling is the best. Unfortunately, the calculation for ^{18}F by the models was performed for the low-lying levels and do not describe the high-excited levels of ^{18}O, i.e. the case of our measurements.

The elastic scattering of polarized deuterons on ^{12}C and ^{16}O was studied to consider the use of this process as an analyzer of the incident deuteron beam polarization. The extended investigation of the energy and angular dependence has shown that the deuteron scattering from ^{12}C can be used as a polarization analyzer, and the deuteron elastic scattering on ^{16}O is convenient for these purposes.

After measuring the analyzing power for the stripping reaction when deuteron interacted with ^{12}C we obtained the possibility to investigate the mechanism of this reaction and to define both qualitatively and quantitatively the relative contribution of the direct process and of the process occurring through the compound nucleus. It was established that at small proton exit angles the reaction occurs mainly through the direct process and the contribution of the compound process is about 20%. The contribution of the processes occurring through the compound nucleus increases with the increasing proton exit angle and at large angles (150°) reaches 80%. These investigations demonstrated the advantages of polarization measurements being very sensitive to the interference of different reaction mechanisms.

For the interaction between the low-energy polarized deuterons with the nuclei ^{9}Be, ^{14}N, ^{19}F, ^{23}Na, ^{24}Mg, ^{26}Mg, ^{28}Si, ^{30}Si, ^{32}S and ^{40}Ca the efforts were directed on the investigation of the intermediate structure resonance. The excitation energy of compound nuclei in these interactions is 12…22 MeV and the excited state density is very high. The levels are very overlapped, thus, the application of the statistic model may be possible. The deviation from the statistic models arises in the case when the life time of single states of a compound nucleus is less than that necessary for the incident particle en-

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ergy statistic distribution between all nucleons of the nucleus. In this case, in the differential cross-sections, averaged over the energy range the broad resonances are observed. These anomalies in the excitation function correlate in a wide range of particle exit angles and for different nuclear decay channels. To describe this cross-section behavior proposed as the model of intermediate structure resonances. If they are the real resonances but not any fluctuations (for example, Ericson's ones or another type) then it should be expected that in polarization effect investigations they are distinct. For the first time we have used for such investigations the polarized deuteron beams.

Considering the data ion the differential cross-sections of the interaction between deuterons and the nuclei ^{14}N and ^{40}Ca, the level density in the compound nuclei ^{16}O, ^{42}Sc and the structure of these nuclei, a quite different dependence of the vector analyzing power for the interaction between deuterons and the nuclei ^{40}Ca and ^{14}N should have been expected. Earlier we have not observed any anomalies for the deuteron - ^{40}Ca interactions and they are wholly described by the statistic model. Also, any anomalies should have not been expected in the energy dependence of the analyzing power on the deuteron energy, moreover, its value must be close to zero. Our measurements show that indeed, the vector analyzing power is zero within the error limits.

Absolutely another pattern should have been expected for the deuteron-^{14}N interaction. In the functions of reaction channel excitation with the proton and (α-particle exit, the broad resonances (hundreds of keV) were observed which, probably, are related to the thin structure of giant resonances (quadrupole and others). Indeed, the Fermi-gas model calculations give in the nucleus ^{16}O at excitation energies between 22 and 23.5 MeV the value of the mean distance between levels about 30 keV, and the mean width of normal levels in this excitation energy range is about 250 keV. Therefore, the individual compound states cannot arise as single resonances. However, one can assume that the broad resonances observed in the excitation functions corresponds to rather simple states, e.g. to the fine structure of giant resonances or to the isobar-analog states. It has not been possible to determine from the differential cross-sections the quantum characteristics of measured broad resonances and to compare them with the thin structure parameters of quadrupole and other giant resonances measured in the photonuclear reactions. In other words, one should expect in the deuteron- ^{14}N interaction the appearance of intermediate structure resonances. It was necessary to show that the study of these resonances requires the polarization investigations. We have performed the measurements on the dependence of the vector analyzing power for different reaction channel on the deuteron energy and particle exit angle. It was shown that the polarization experiment unambiguously confirm the presence of the intermediate structure resonances and allows one to determine their quantum characteristics. These resonances are related to different giant resonances excited in the nucleus ^{16}O: the dipole resonance, the fine structure of the isoscalar quadrupole resonance and the fragmentation of the main E3-components over the more complex states. One of the resonances is interpreted as a well-known double-analog state. These resonances are related to different giant resonances excited in the nucleus ^{16}O: the dipole resonance (Fig. 3), the fine structure of the isoscalar quadrupole resonance and the fragmentation of the main E3-components over the more complex states. One of the resonances is interpreted as a well-known double-analog state.

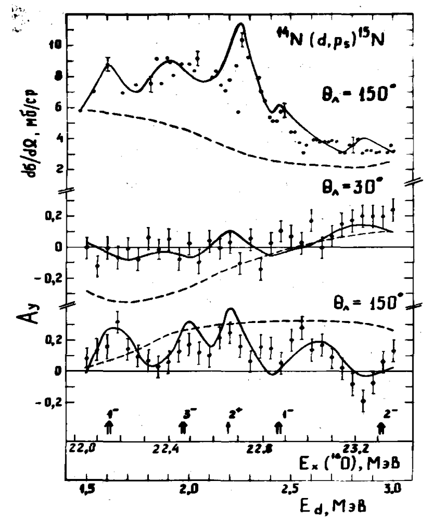

Fig. 3. The differential cross-section and vector analyzing power vs energy for reaction $^{14}N(d, p_5)^{15}N^*$

In the excitation functions with nonpolarized deuterons, the resonance for two proton exit channels (main and first excited channels) was observed at Ed=2.225 MeV that can be explained by the creation of the incoming state which interferes with the direct stripping process. On the other hand, at this deuteron energy the neutron channel onto the excited (7.14 MeV state) of $^{31}P^*$ is opened. This state is an isobar analog of the first excited nucleus ^{31}Si being populated in the reaction with proton exit. Besides, the optical and shell models predict that there is the 2*p*-neutron one-particle state at zero (threshold) energy for the nuclei with A-30. There fore, the anomaly in the cross-section for the first excited state of the nucleus ^{31}Si at Ed=2.2 MeV may be explained by the 2*p*-neutron resonance with the close coupling of channels where the components of one multiple are excited. However, this approach does not explain the presence of the resonance at the same energy in the excitation function for the ground state of the nucleus ^{31}Si. The polarization experiment should answer whether the anomaly is observed only in the excitation function for one or for both groups of exit protons. Then, in the first case the anomaly may be related to the neutron threshold and in the second one to the incoming state.

The polarization investigations and their analysis show that the more probable reaction mechanism is the excitation of the incoming 2^+ state which interfere with the direct stripping process. However, the fact that this incoming state is observed at deuteron energy when the neutron channel is opened indicates on the compound nuclear resonance enhancement due to the new channel opening. Such a phenomenon was predicted by the different models of the threshold phenomena. Detailed bibliography of the works on polarization carried out in KFTI can be found in the preprint: R.P. Slabospitsky, "Investigation on polarized proton and deuteron beams at the Kharkov Institute of Physics and Technology" (Short review), KFTI 93-33, Kharkov-1993.

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