ON THE NUCLEONS MOTION IN THE NUCLEUS AS BEING DUE TO REALISTIC INTER-NUCLEONIC FORCES

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This paper deals with the possible motion of nucleons in the nucleus, which is due to realistic inter-nucleonic forces. This approach provides new or more substantiated conclusions about the nuclear structure than those based on the effective interaction of nucleons, while the shell model of the nucleus may lead to questionable conclusions regarding the nuclear structure and nuclear reaction mechanisms.

PACS: 21.30.-x, 21.10.-k, 21.60.Cs

1. INTRODUCTION

High-accuracy data on two-nucleon forces acting in the nucleus have been obtained in recent years. These data enable one to gain more reliable information on the nuclear structure and the nuclear reaction mechanisms than the information derived on the basis of effective nucleon-nucleus interaction. For illustration, Fig.1 shows the CD-Bonn data for the realistic NN potential [1, 2]. They were derived from the phase analysis of the experimental data on elastic (p, p) and (n, p) scattering in the energy range up to 350 MeV for the total momentum $J \leq 4$ of the NN system (notation: $^{2S+1}L_J$, S-spin, L-orbital momentum of two-nucleonic system). The positive phase value corresponds to inter-nucleonic attraction, while the negative phase value corresponds to nucleon-nucleon repulsion. As the nucleon scattering energy E_N tends to zero, the $^3S_1$ phase goes to 180^0, and this corresponds to the bound state of the np system, i.e., the deuteron. It is necessary to point out that nucleon modification is possible in the nucleus [3]. However, if this nucleon modification in the nucleus does exist, then it will also occur at two-nucleon scattering, and consequently, will be taken into account phenomenologically, too.

A distinctive feature of the inter-nucleonic forces is that they depend not only on the inter-nucleon distance r, but also on the quantum configuration of the nucleon system, which is determined by the orbital momentum L, spin S and isospin T of the system. The dependence of the NN potential on the quantum configuration of the two-nucleon system may be more considerable than the dependence on the distance r. Besides, $3N$ forces are also at work in the nucleus [4, 5]. Therefore, the nuclear wave function, which is dependent only on the distance r, may be inconsistent with reality.
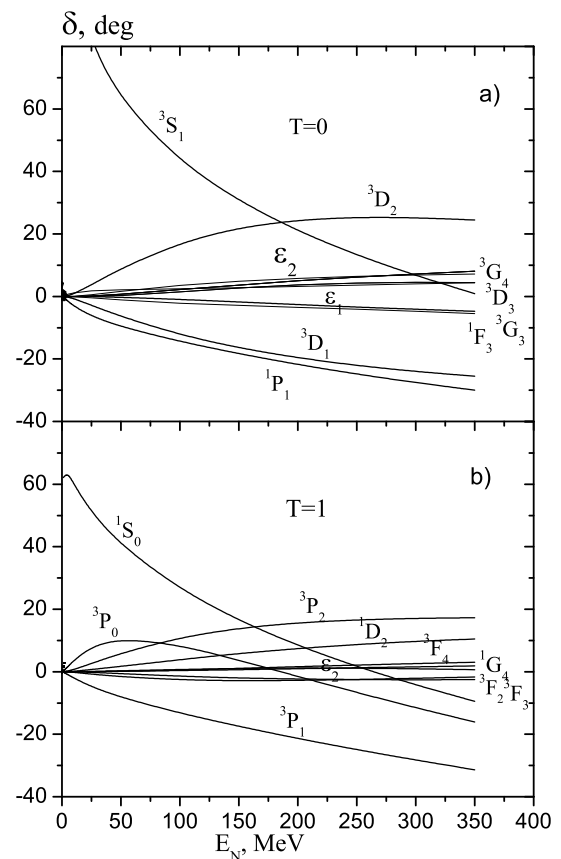

Fig.1. *Phases δ and mixing parameters ϵ of NN scattering: a) (n, p) scattering with isospin T=0 and b) (n, p), (p, p) and (n,n) scattering with T=1 in the CD-Bonn nucleon-nucleon potential. Insignificant differences between phases in the T=1 states are not shown in the figure*

2. NUCLEON PAIRING AND CLUSTERING OF NUCLEUS

Using the NN potentials from refs. [1] and [6], and also the $3N$ forces UrbanaIX [4] and Tucson-

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Melbourne [5]), the authors of ref. [7] have calculated the binding energies, the probability of states with nonzero orbital momenta of nucleons, and the nucleon momentum distribution in the ^{4}He nucleus. The calculations of the nucleon momentum distribution and other mentioned parameters are in good agreement with the available experimental data. This distribution is shown in Fig.2 as a function of relative energy E_N of two nucleons.
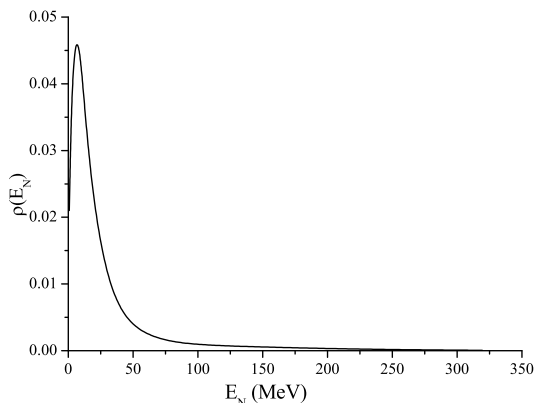

Fig.2. *Nucleon energy distribution in the ^{4}He nucleus. The functions are normalized to $\int f(E_N)dE_N = 1$*

The comparison between Fig.1 and Fig.2 suggests the conclusion that for the most part of time the nucleons stay in the states with zero orbital momenta. The neutron-proton pairing in the $T=1$ state and also neutron-neutron, proton-proton pairings, take place in the $^1S_0$ state, i.e., in the state with antiparallel spins, while the pairing of neutron with proton at $T=0$ occurs in the $^3S_1$ state. The pairing takes place in a wide range of relative energies of nucleons, i.e., is dynamic. The paired nucleons are bosons, and therefore, the Pauli principle doesn't forbid the basic part of the nucleons of the nucleus to be in the paired states.

The attraction between nucleons having zero orbital momenta can lead to nuclear clusterization. The $3N$ forces also have an effect of attraction. This makes an additional contribution to clusterization of the nucleus. The formation of several similar three-nucleon clusters can be suppressed in accordance with the Pauli principle. However, after attraction of the fourth nucleon, the three-nucleon cluster would not impede a further clusterization of the nucleus. For example, the paired neutron from the neutron-proton pair in the $^3S_1$, $T=0$ state takes on the other neutron in $^1S_0, T=1$ state, while the proton of the mentioned pair joins with the other proton in the same state (Fig.3,a); that leads to cluster formation in the $^1S_0$ state. Similarly, a cluster can appear due to $^1S_0, T=1$ couplings (Fig.3,b). Also, the clusters can form from four neutrons or four protons by means of $^1S_0, T=1$ couplings (Fig.3,c). The possibility of formation of more complex nucleonic clusters is not excluded, in

particular, cluster from 8 neutrons. It is possible, that this is connected to the fact that nuclei ^{40}Ca and ^{48}Ca are magic.
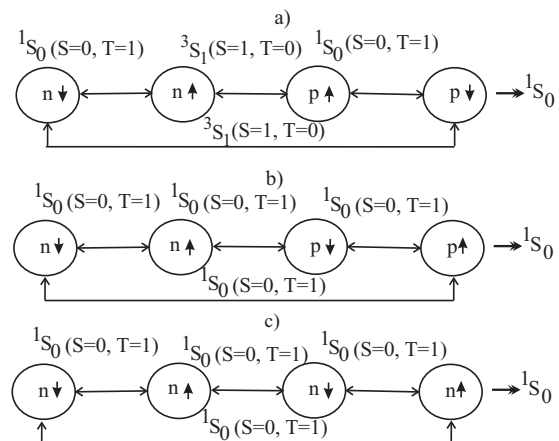
Fig.3. *Schemes of $^1S_0$ α-cluster formation*

Pairing of nucleons and clusterization of nuclei are confirmed by numerous experimental data. Thus, the nucleus represents essentially the boson system, and this makes the application of the shell model to the nucleus unreasonable.

3. NON-CENTRAL STRONG INTERACTION OF NUCLEONS

Non-centrality of strong interaction leads to the fact that in the process of intranuclear motion the nucleon spin-flip may take place. For example, with spin-flip of one nucleon in the ^{4}He nucleus, the nuclear spin will take on the $S=1$ value. At that, according to the laws of conservation of total momentum and parity of the nucleus ^{4}He, we have $J^\pi = 0^+$, the total orbital momentum of nucleons would have to change and take on the $L=1$ value. That leads to the emergence of states with non-zero orbital momenta of nucleons in the lightest nuclei. The laws of conservation of total momentum, parity, and also, the Pauli principle, permit only two values of orbital momentum of nucleons in the deuteron, viz., $L=0$ and $L=2$. In the rest of the nuclei with A$\geq$3 there are infinitely many states with non-zero orbital momenta [7]. However, with increase in the orbital momentum of the nucleon the probability of the mentioned state decreases (see Fig.1). Therefore, later on, the nucleon will return to its original state, provided that it remained unoccupied by another nucleon. Similarly, spin-flips of two nucleons may occur, and the ^{4}He nucleus will appear in the $S=2$ and $L=2$ state. The probabilities of states with non-zero orbital momentum of the nucleons of the lightest nuclei have been calculated in [8].

When constructing the effective interaction of nucleons, the curves in Fig.1 are averaged, including the $3N$ forces, which can also lead to the nucleon spin-flip. As a result, the nuclear shell model predicts the total momenta J and the spins S of all even-even nuclei to be zero. The experimental data obtained from the studies of the ^{4}He$(\gamma, p)^3$H and ^{4}He$(\gamma, n)^3$He reactions

with emission of one nucleon, show that in these reactions the multipole transitions with the spin $S=1$ of the final-state of the particle system take place. Their contribution is about $\sim 10^{-2}$ of the total reaction cross-section. The experimental information about these $S=1$ transitions can be obtained, in particular, in the collinear geometry, in which the contribution of dominant transitions with the spin $S=0$ is absent. In theoretical [9] and experimental [10] works, the occurrence of $S=1$ transitions was attributed to the fact that the electromagnetic interaction caused a spin-flip of the hadronic particle system, and that spin-flip was due to the contribution of mesonic exchange currents (MEC). It should be noted that the MEC contribution depends on the photon energy [11].

The calculation [7] based on realistic inter-nucleonic forces has shown that the ground state of the ^{4}He nucleus can be in the states with non-zero orbital momenta of nucleons, and the spin of the ^{4}He nucleus can take the values $S = 0$, 1 and 2. Consequently, the transitions with spin $S=1$ of the final-state of the particle system can originate from the initial state of the ^{4}He nucleus with spin $S=1$ without spin-flip of the nucleon in the process of reaction. In this case the ratio of the total cross-section of $S=1$ transitions to the total cross-section of the reaction can be independent of the photon energy [12].

The analysis of the experimental data (Fig.4) has suggested the conclusion that, within the statistical error, the ratio of the reaction cross-section in the collinear geometry to the cross-section of the electrical dipole transition with $S=0$ at the angle of nucleon emission $\theta_N = 90^0$ (ν_p and ν_n) in the photon energy range $22 \leq E_\gamma \leq 100$ MeV does not depend on the photon energy (despite the fact that in this photon energy range, the total cross-section of the reaction ~ 15 times). The average ν_p and ν_n values in the mentioned photon energy range were calculated to be $\nu_p = 0.01 \pm 0.002$ and $\nu_n = 0.015 \pm 0.003$, respectively. The calculations took into account the errors in the measurement of the polar angle of nucleon emission in the mentioned reactions [12]. The available experimental data are in agreement with the theoretical calculation [7], and also, with the assumption that the $S=1$ transitions can originate from P-states of the ^{4}He nucleus.

Thus, the conclusion about spin flipping during the reaction, made on the basis of the nuclear shell model, raises doubts. The conclusions about the nucleon knocking-out from s- and p-shells of the nucleus may also be open to question.

The presence of states with non-zero orbital momenta of nucleons in the lightest nuclei is due to the tensor part of the NN potential, and also, $3N$ forces. Consequently, similar effects must be observed unexceptionally in all the nuclei, including their excited states, too.
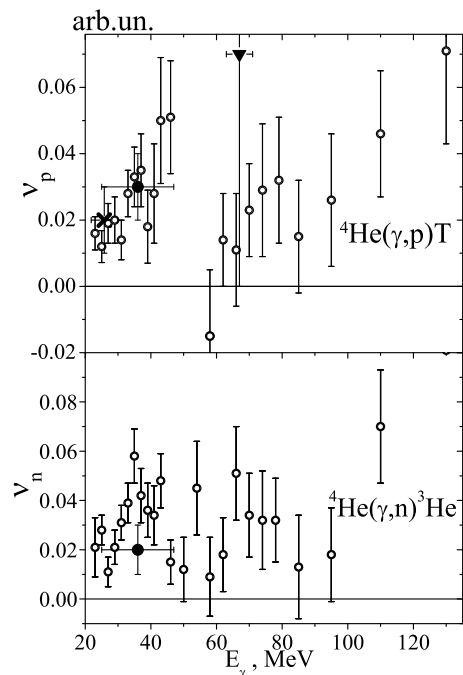
Fig.4. Ratio of the reaction cross-section in the collinear geometry to the cross-section of the electrical dipole transition with $S = 0$ at the nucleon emission angle $\theta_N = 90^0$. Closed points: Balestra et al. [13]; triangle: Jones et al. [14]; open points: Arkatov et al. [15]; cross: Shima et al. [16]

It can be assumed that with an increase in the number of nucleons A in the nucleus, the number of nucleons with flipped spins also increases. This increase for the nucleus with the number of nucleons A relative to the nucleus with the number of nucleons A-1 can be estimated from the contribution of D-wave to the deuteron wave function, i.e., $\sim 5\%$. In the general case, the spin of the nucleus with the number of nucleons A can take on integer values in the interval $0 \leq S \leq A/2$ provided that A is even, or half-integer values in the interval $1/2 \leq S \leq A/2$ provided that A is odd. The total orbital momentum of the nucleons L must take the values in accordance with the laws of conservation of the total momentum and parity of the ground state of the nucleus or its excitation level.

It can be supposed that in the process of pairing the odd neutron or the odd proton in odd-odd medium and heavy nuclei generally appears to be in the states with non-zero orbital momentum. Therefore, in these nuclei the odd proton and the odd neutron cannot be paired in the $^3S_1$ state. Perhaps for this reason, only very light odd-odd nuclei are stable.

4. SPIN-ORBIT INTERACTION OF NUCLEONS IN THE NUCLEUS

The spin-orbit interaction of nucleons leads to an additional contribution to the potential energy of the nucleus. Within the framework of the nuclear shell model this energy can be calculated by the expres-

sion:

$$U_{SO} = -b\left(\frac{\hbar}{Mc}\right)^2 \sum_{i=1}^{A} \frac{1}{r_i}\frac{\partial V_i}{\partial r_i}(\vec{l_i}\cdot\vec{s_i}),\qquad(1)$$

where V is the spherically symmetrical potential, l is the orbital momentum, s is the nucleon spin. However, to bring into agreement with the experiment, expression (1) should be multiplied by the spin-orbit interaction constant of nucleons b. For medium and heavy nuclei the constant comes up to $b \sim 10$, and this value increases with increasing A. The origin of the constant may be attributed to the fact that in the medium and heavy nuclei the significant number of nucleons is in the spin-flip states. For example, let us assume that in the ^{208}Pb nucleus ten nucleons are in the spin-flip states, i.e., the nucleus spin is $S = 10$. Then the total orbital momentum of the nucleons must be $L = 10$. This can give rise to a substantially higher contribution of the spin-orbit nucleon interaction than that predicted by the nuclear shell model. This can be a part of the reason for the origin of the constant b of the spin-orbit nucleon interaction.

5. CONCLUSIONS

Two competing processes are at work in the nucleus. On the one hand, the realistic inter-nucleonic forces result in nucleon pairing and nucleus clustering. On the other hand, the non-centrality of the strong nucleon interaction and the $3N$ forces cause spin-flips of the nucleons, and consequently, the decay of the formed nucleon pairs and their clusters. The nucleus spin S and the total orbital momentum of the nucleons L are random variables, with the distribution dependent on the specific nucleus.

Despite a considerable MEC contribution to the total cross section of the reaction, the contribution of the spin-flip of the hadronic particle system as a result of electromagnetic interaction may be suppressed.

The nuclear shell model may lead to doubtful conclusions about the nuclear structure and mechanisms of nuclear reactions.

The author gratefully acknowledges a fruitful discussion with Drs A.F.Khodyachikh and E.A.Skakun.

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О ДВИЖЕНИИ НУКЛОНОВ В ЯДРЕ, ОБУСЛОВЛЕННОМ РЕАЛЬНЫМИ МЕЖНУКЛОННЫМИ СИЛАМИ

Ю. П. Ляхно

Обсуждается возможное движение нуклонов в ядре, обусловленное реальными межнуклонными силами. Это позволяет получить новые или более обоснованные выводы о структуре ядра, чем на основе эффективного взаимодействия нуклонов. Оболочечная модель ядра может привести к сомнительным выводам о структуре ядра и механизмах ядерных реакций.

ПРО РУХ НУКЛОНІВ В ЯДРІ, ОБУМОВЛЕНИЙ РЕАЛЬНИМИ МІЖНУКЛОННИМИ СИЛАМИ

Ю. П. Ляхно

Обговорюється можливий рух нуклонів в ядрі, обумовлений реальними міжнуклонними силами. Це дозволяє здобути нові або більш обґрунтовані висновки про структуру ядра, ніж на основі ефективної взаємодії нуклонів. Оболонкова модель ядра може привести до сумнівних висновків про структуру ядра і механізми ядерних реакцій.