## The study of atomic nucleus

The nature provided us with a huge variety of atomic nuclei ranging from hydrogen up to the heaviest actinides. Each of them is a quantum system composed of protons and neutrons, together called nucleons. At first glance, nuclei differ from each other only by proton and neutron numbers, therefore one may expect that their characteristics would not change much from one to another. Nothing could be further from the truth. Each of these tiny systems is unique and shows a plethora of fascinating phenomena. What makes nuclear physics even more interesting is the fact that in laboratories scientist have observed only a small sample of nuclei that are expected to be bound. Those unseen, however, are not unimportant -- they are predicted to be involved in stellar processes, which are crucial in the formation of matter, the nucleosynthesis. At present, the only way to study them is through theoretical calculations, which are not limited by the current experimental techniques. However, this approach is not a *panacea* for all the ills, since atomic nucleus, as a many-body system, evades an exact description -- an analytical solution simply does not exist. Hence, the only way to describe it in a quantitative manner is turning to approximate methods. One of the most commonly used, the mean field approach, treats nucleons as noninteracting particles moving in an effective potential well, the mean field, which originates from the other nucleons. Being successful in describing the bulk properties of nuclei, like their masses and radii, this method has a handful of significant limitations. In contrary to electrons in an atom, which are immersed in the external Coulomb potential of the nucleus, the nucleons are self-bound. This results in spontaneous breaking of fundamental symmetries, like the rotational one, which hinders studies of subtle nuclear structure effects. Required is restoration of the broken symmetries, that is done in approaches going beyond the mean-field approximation. In this project we adopt one of them, the density functional theorem, to account for unexplained character of the nuclear interaction.

Since protons are positively charged and neutrons, as their name indicates, are neutral, having the Coulomb repulsion as the only interaction between nucleons, we would not ever encounter atomic nuclei as bound systems. However, we do observe them, which indicates the existence of an attractive force that keeps them from falling apart, the strong nuclear interaction. A self-explanatory way of studying it, the nucleon-nucleon scattering, provides a lot of information about the nature of this force. As mentioned, it is attractive, except for very short distances at which it becomes repulsive preventing nucleons to fall one on another. In contrary to the Coulomb interaction, which is long-distance, the nuclear force affects only neighbouring nucleons, that is why, we do not witness its effects in every day life. However, all these conclusions, when applied directly to description of nuclei, are not sufficient as the nuclear matter modifies the nucleon-nucleon interaction and other phenomena, like shell effects (analogous to those in noble gases) further complicate the picture. On the other hand, theory has its own problems since derivation of the nucleon-nucleon interaction from the quantum chromodynamics describing the interaction of quarks, which are constituents of nucleons, is not yet achievable, not to mention tackling a complex nucleus as a whole. Again physicists have to make use of approximate methods and, basing on the experimentally observed effects, construct a phenomenological nuclear force. Giving up the generality, is by no means inaccurate. Effective interactions have been developed for more than 50 years probing the nuclear structure more and more deeply and in this work we want to contribute to this common effort.

## Isospin symmetry

As was already pointed out, the study of atomic nuclei is a constant process of simplifying the complex theoretical description without loosing physical understanding of assumptions made and results obtained. One of the most influential approaches, the concept of isospin, was introduced in the 1930s by Wigner. As protons and neutrons are both constituents of nuclei, why not describing them within one formalism. According to Wigner, they are simply two states of a nucleon, the only difference between them is due to newly proposed quantum number, the isospin. If a system of nucleons remains the same after interchange of protons and neutrons, it is isospin symmetric, what greatly simplifies its description. Sad to say, that such an elegant concept is also an another approximation. The isospin symmetry is broken by the slight difference in masses of proton and neutron and, what is the most significant, by the Coulomb interaction which acts only between two protons. This is not the end of the complications. It turns out that also the strong force contributes to the isospin-symmetry violation.

This was first observed in the already mentioned nucleon-nucleon reactions. Detailed study of neutron-neutron, neutron-proton and proton-proton scattering proved that the interaction strength depends on nucleons involved. The differences are relatively small, in the range of 1-2.5%, however, they are significant in the precise study of nuclear properties. The most evident sign, that neglecting them in theoretical models is invalid, comes from the calculation of Nolen and Schiffer. In the late 1960s they performed a systematic study concerning mirror nuclei[1]. They intended to account for differences between the binding energies[2] in such pairs present in the experimental data. Up to then, this effect was understood as only due to the Coulomb interaction, which clearly makes a system with more protons less bound and is the main player breaking isospin symmetry. However, it turned out that this force alone, even after applying detailed corrections, is not sufficient to reproduce the data. The further research encouraged the belief that this anomaly can be explained only by a proper introduction of the isospin-symmetry-violating part of the strong nuclear interaction, what will be a main goal of the project.

## Atomic nucleus as a laboratory

Each nucleus, showing unique behaviour depending *only* on the number of protons and neutrons, can be treated as a tiny laboratory. What can be studied there is not only the nuclear physics itself, but also the particle physics describing the fundamental concepts of matter and the astrophysics explaining the formation of elements in the Universe.

The project is mainly devoted to investigate the strong nuclear interaction, in particular its isospin-symmetry-breaking part which will be implemented in our model. As a first test of our approach, we plan to account for the Nolen-Schiffer anomaly and verify if the Coulomb force together with the modified nucleon-nucleon interaction are capable of reproducing the experimental binding energy differences. Afterwards, the further study of nuclei with similar number of protons and neutrons, in which the isospin-symmetry-violation effects are the most significant, will be undertaken. We hope that the systematic and detailed research will bring important results and shed a new light on the present perception of the nucleon-nucleon interaction.

Besides the scientific impact, the project will contribute to the development of the HFODD code, which is one of the trademarks of the Warsaw nuclear theory group. Started in the capital city of Poland, HFODD has become a unique tool for nuclear physics calculations extended and used by scientists all around the world. What is more, it is available on the public domain.

Knowing the model to the finest details provides a rare opportunity to go beyond the nuclear physics and tackle the fundamental aspects of the particle physics. A perfect field for such interdisciplinary research is the beta decay, which is responsible for transforming proton into neutron or *vice versa*, being governed by the weak interaction. This process is really sensitive with respect to the isospin quantum number and any impurities due to the Coulomb or strong interactions have to be handled with the highest precision. However, the game is worth the candle. The results of such study provide a stringent test for the Cabibbo-Kobayashi-Maskawa matrix (Nobel prize 2008), which is one of the key concepts of the Standard Model of elementary particles describing the principles of our Universe.

Furthermore, the nuclear physics provides data for stellar calculations. The demand exceeds the supply, since nuclei involved in the astrophysical processes are beyond the experimental accessibility. Hence, their properties, like binding energies, have to be calculated with theoretical models. The rapid proton capture process, which is responsible for the synthesis of heavy elements, goes through nuclei with similar number of protons and neutrons. Therefore, our model, with the strong interaction violating the isospin symmetry, is a prefect tool for determining binding energies and other structural information. The results will, in turn, contribute to the more precise calculations of stellar process and explaining the nucleosynthesis.

[1] Mirror nuclei are a pair of nuclei in which the number of protons in the first element is equal to the number of neutrons in the second one and the number of protons in the second element is equal to the number of neutrons in the first one.

[2] Binding energy is the energy required to disassemble a nucleus into separate neutrons and protons.