Two-body correlations in the systems of several ultracold atoms of different masses

All known particles can be divided into two very general families: fermions that are constituents of a matter (electrons, muons) and bosons that carry interactions between the matter (photons, the Higgs boson). These families differ with so called spin – the internal angular momentum of a particle which does not have its counterpart in a classical world. From the profound theoretical considerations we know that bosons have the integral spin value (0, 1, 2, …) and fermions the half-integer (1/2, 3/2, …). The properties of these two types of particles are completely different. This comes straightforwardly from the fact that two fermions, in opposing to bosons, cannot occupy the same quantum state. This fact, known as the Pauli exclusion principle, is the foundation of the theory of atomic bonding and the formation of molecules. Due to the fact that bosons do not liable Pauli principle, many of them can be in the same quantum state. This observation is the theoretical principle of operation of the laser.

At a fundamental level the whole matter consists of fermions, but in natural conditions they form stable atoms which are built of protons, neutrons and electrons. Depending on the considered isotope of an atom the total number of all fermions in the atom can be even or odd. If it is even then the total spin of the atom (the sum of spins of all fermions that build the atom) is also even and the whole atom can be treated as a boson. If the number of fermions forming the atom is odd, then the whole atom has fermionic properties. This observation means that in the conditions when atoms are stable the matter can have bosonic properties.

The great achievement of the experimental techniques of the end of 20th century was the development of the methods of trapping and cooling atoms to the temperatures smaller than millionth part of the degree above the absolute zero. Thereby it is possible to precisely control the systems of ultracold atoms and studying their properties in the conditions where the quantum properties are seen. The first Bose-Einstein Condensate, the new state of the matter where macroscopic number of bosons occupy the lowest energy level, has been received in 1995 and has revolutionized the development of atomic physics. The recent experiments have shown that it is also possible to cool down and study various mixtures of bosonic and fermionic atoms (with the same and with different masses), production of one- or two-dimensional effectively systems and controlling the interactions between atoms over the whole range, i. e. from strongly repulsive, through noninteracting, to strongly attractive. These experimental possibilities make this topic extremely interesting from the theoretical point of view. This means that it is possible to produce experimentally the quantum systems that can be described with very simple theoretical models. A big challenge for the physicists was to prepare the ultracold system consisting of the precisely known number of particles. This became possible due to very accurate control of the magnetic field and the laser beam's profile that are used to shape the trap that confines atoms. One can adapt the shape of the trap to let most of the atoms escape and the one that remain will have the smallest energy of all. The system prepared in such a way can be used further to study few atom physics. It is worth noting that in nowadays experiments one can use special detectors that take pictures of an experimental setup with the single atom precision. The above techniques let us compare these few body systems with the theoretical models.

The proposed research project has a theoretical nature but it is inspired by the state of the art experiments in the field of ultracold atoms. The primary goal is to try to understand how the many-body effects are manifested in the systems of small number of particles. The main area of our studies are mixtures of few fermionic particles of different masses which are confined within one-dimensional traps of different shapes. The above issues form part of a broader context of creating a bridge between two- and three-body physics and macroscopic physics.