Collisional effects in exotic atom spectroscopy: *ab initio* calculations for fundamental physics tests

This project focuses on exotic helium atoms—unique quantum systems in which one of the electrons in a helium atom is replaced by another subatomic particle such as a pion, kaon, or antiproton. Exotic helium atoms can exist in metastable states—unusually stable configurations that persist long enough to allow for their detailed examination using spectroscopic methods. Spectroscopy investigates how atoms interact with light, resulting in a spectrum—a recorded image of radiation spread across various wavelengths. Characteristic elements of the spectrum are the spectral lines, whose positions, intensities, and shapes provide information about the internal structure of the atom. The accuracy of spectroscopic measurements is limited, among other things, by collisions of exotic atoms with surrounding helium atoms, which cause the broadening and shifting of spectral lines. A thorough theoretical understanding of these effects is crucial for the reliable interpretation of experimental spectra of exotic atoms. These studies are of fundamental importance as they allow testing of the Standard Model—the contemporary theory of interactions between elementary particles.

The primary goal of this project is to present a detailed description of how collisions affect the spectral lines of exotic helium atoms. Unlike previous attempts to study collision effects, this project will be based entirely on quantum theory: solving the Schrödinger equation for the exotic atom-helium system will provide insights into how collisions perturb the energetic structure of exotic atoms and their translational motion, leading to changes in the shape of spectral lines. The results of this project will serve as reference data for enhancing the accuracy of experimental measurements in exotic atom spectroscopy, significantly impacting various fields of atomic physics. More precise spectroscopic measurements of exotic helium atoms will allow, among other things, the determination of the masses of exotic particles (antiprotons, pions, and kaons) with unprecedented precision. Comparisons of the antiproton mass with the proton mass will also test the fundamental symmetry proposed by the Standard Model—the CPT symmetry. An important aspect of the project will also be the first application of quantum scattering calculations to study collisional perturbation of two-photon transitions — spectral lines formed as a result of exotic atoms interacting with two quanta of electromagnetic radiation. Measurements using two-photon spectroscopy play a crucial role in studies of the energy structure of exotic atoms.

Additionally, this project will explore the behavior of exotic atoms in extreme conditions, such as ultralow temperatures where helium transitions to a superfluid state. In these conditions, an abrupt and unexplained narrowing of spectral lines has been observed. Understanding this phenomenon could significantly enhance the precision of spectroscopic measurements, leading to even more accurate tests of quantum theory.