NOBEL: NOnlinear BEhavior of Rabi frequency in poLar systems

Through the decades of exploration of the world of interactions of light with matter, plenty of theories have been developed and experiments performed. They lead to groundbreaking results, not only providing a basic understanding of the elemental building blocks of nature but also enabling practical applications such as fiber-optic communication used in many houses to provide internet connection, LASERs (light amplification by stimulated emission of radiation) incorporated in various types of devices, e.g., in CD and DVD players, or distance sensors, or OCT (optical coherence tomography) used in medicine to make 3D images of biological tissues (e.g., retina or coronary arteries).

Understanding the mechanisms underlying these cutting-edge technologies is possible thanks to the simplified physical models that represent real-life, incredibly complicated systems such as atoms, molecules, crystals, etc. This approach is often sufficient to understand the physical mechanisms of effects observed in nature and to predict new phenomena under nonstandard conditions. In quantum mechanics, one of such is a widely used two-level model, where the complex structure of the physical object (e.g., atom) is reduced to a system with only two possible states - ground and excited. It allows us to quantitatively describe a plethora of problems, especially if we are interested in the interactions with light. One of the most important effects, particularly significant for the NOBEL project, can be described by the use of the two-level model is Rabi flipping or Rabi oscillations.

To understand the idea of this process, imagine that our system (for example, an atom) is in the ground state at the beginning and we want to excite it. Excitation means that we have to deliver a portion of energy to it so it can change its state. This can be done by illuminating it with a laser with a strictly matched frequency. Once we succeed, the atom is in the excited state, however, if we do not switch off the laser the atom wants to go back to the ground state, and eventually does. We end up at the starting point, hence the atom again wants to go up to the excited state. This flipping between states is called Rabi oscillations and lasts as long as light provides energy to the system, and the frequency of these transitions depends on the laser's intensity -- brighter light gives faster oscillations.

Different systems respond differently to the illumination with light - some require small light intensities to start oscillating while others have to interact with significantly stronger light to achieve the same frequency of flipping. Nevertheless, the rule is usually the same - the frequency of Rabi oscillations is proportional to the laser's field amplitude even for its very high values. There are, however, more special cases in which the rule does not hold for all amplitudes - polar systems. As an example, in many molecules, the average position of the positive nucleus and the average position of the negatively charged electrons are separated. This polarization of charges, which is an intrinsic feature, leads to the emergence of the permanent electric dipole moment and makes this molecule a polar system. Under illumination with light, such systems perform Rabi oscillations as well, however, for very strong light intensities they start to behave in a nonlinear manner, contrary to the regular ones. Our preliminary results suggest that increasing the light intensity may not increase the Rabi frequency anymore. Possible scenarios assume the existence of ranges of intensities where Rabi oscillations do not change their value at all (robust regime) or even decrease it and eventually reach zero (collapse regime).

The investigation of such nonintuitive regimes is the main subject of the NOBEL project. For now, the bottleneck that prevents exploring these effects experimentally and exploiting them in applications is related to the fact that for typical systems the corrections originating at the polar geometry are relatively weak. The nonlinear Rabi frequency dependence on the light intensity would be significant in the specific realization of the strong light-matter coupling regime. This unique combination of polar systems and the strong coupling has been poorly studied so far. We would like to provide a comprehensive theoretical description of these effects, and with the support of numerical calculations find real-life candidates for the observation of these effects as the outcome. This would be the starting point for the design of future experiments.

Besides the fundamental character of this project, a good understanding of Rabi oscillations in the described regime may lead to several potentially useful applications. One can think about sensitive field measurement where small changes in the light intensity guide to a significant difference in the system's dynamics. Another possible scenario involves a considerable change of the field that does not affect the Rabi frequency, making the dynamics more robust and giving foundations for the long-lasting quantum memories that can be used, e.g., in realizations of quantum computers.