ABSTRACT

This theoretical proposal is founded on the core concept to stimulate experimental effort that can lead to revolutionary advances in quantum simulation and sensing by the development of new protocols to control atom-light interactions in cavity systems loaded with long-lived multi-level atoms. These are atoms with rich atomic structure and a lifetime much longer than the time that takes photons to escape out of the cavity. They include fermionic alkaline-earth atoms and other with similar structure, such as Sr and Yb, which are currently the basis of the most precise atomic clocks. The goal is to gain theoretical understanding over these complex systems and use their large number of degrees of freedom, coupled by different optical cavity modes, to generate coherent elastic interactions of many atoms over long times as well as highly entangled steady-states under driven and dissipative conditions. The internal levels will serve as synthetic dimensions and will be used to encode bosonic or fermionic degrees of freedom which can be cooled down efficiently via optical pumping.

The successful development of the research will deploy solid, carefully conceived and practical protocols that allow for the exploration of the rich physics and the unique opportunities offered by multi-level atoms in cavities, which can lead to revolutionary transformations relevant to DOD mission. They include:

i) Advance current state-of-the-art atomic clocks and interferometers via protocols that build up quantum correlations at exponentially fast rates, making them robust to undesirable but always present decoherence sources;

ii) Realize synthetic materials that feature strong correlations and/or non-trivial topological behaviors;

iii) Prepare and characterize robust dark states featuring large-scale entanglement for memory storage and sensing applications;

iv) Design ultra-narrow light sources largely insensitive to the problems that affect modern-day most stable lasers.

The proposed research is challenging since multi-level atoms are significantly more complex than two-level atoms, however, the PI is in a position to accomplish these ambitious goals taking advantage of state-of-the-art numerical and analytical methods, recently developed in her group, in combination with a close collaboration with leading cavity experiments at JILA and MIT. It is instructive to place the scope of this research effort in the context of quantum simulation. First, theory will guide experiments in regimes where theoretical predictions can be made and used to verify experiments. Next, experiments will be done in regimes whose dynamics are inaccessible to current theoretical methods, and finally those experiments will enable improved theoretical methods capable of reproducing the observed dynamics and with enriched predicting power.

Broader impacts of the proposed research include, besides the training of graduate students and postdocs who will become future scientific leaders, potential revolutionary transformations relevant to DOD mission. They include on the one hand, the realization of exotic synthetic quantum states of matter and light that can push the frontiers of material science and feature non-trivial quantum behaviors. On the other, the development of unprecedentedly accurate atomic clocks, and interferometers not only for improved traditional timekeeping and gravimetry applications but also for precision tests of fundamental physics, searches for new physics, and the exploration of connections between quantum mechanics and gravity.