Quantum scars in the motion of Rydberg atoms

A theoretical & numerical internship closely related to experiments devised at LKB/Collège de France

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Students from the *Quantum Physics*, *Theoretical Physics*, and *Condensed Matter* divisions of the ICFP–M2 program are welcome to apply for this internship, which will lead to a PhD for the successful candidate.

This internship proposal, and the PhD project to which it will lead, are theoretical. Their aim is to identify novel *many–body quantum scars* affecting Rydberg atoms [1] arranged in long chains, and to devise a protocol for their observation at Collège de France. This work will involve a close collaboration between theorists and experimentalists, and the candidate will take part in regular meetings and discussions with the experimental group.

Many classical systems may be brought into a chaotic regime, where the classical trajectory followed by the system strongly depends on the initial condition [2]. A particle moving in a stadium–shaped billiard, an atom in a magnetic field, coupled pendula . . . etc. may all exhibit chaotic dynamics. One may naively expect the quantum system corresponding to a classical chaotic system to behave even more erratically. However, that is not always true: some classically chaotic systems have a quantum counterpart whose dynamics is regular and which does not thermalise. This counterintuitive phenomenon, called *quantum scarring*, was discovered with a single particle in a stadium billiard [3], and has recently been observed at Harvard in the internal–state dynamics of a chain of many interacting atoms [4].

We expect quantum scars to also occur in the quantum dynamics of the long chains of Rydberg atoms which will be produced in an experiment under construction at Collège de France in Paris [5]. Just like in the Harvard experiment, this new experiment will involve strongly–interacting atoms, so that its description must account for many–body effects. An important difference is that the atoms in this new experiment are free to move, which will allow for the first analysis and observation of a many–body scar in the spatial dynamics of the system.

The candidate will characterise the quantum scars occurring in a model involving two interacting atoms confined in a unidimensional trap (Fig. 1a). This involves three steps. **1.** The key ingredient leading to a quantum scar is the existence of periodic trajectories in the classical system (Fig. 1b). These will be identified using a well–established algorithm that the intern will be taught and that they will implement in the language of their choice (C++, Python, . . .). **2.** The classical periodic trajectories leave a visible 'scar' on some of the stationary states of the quantum system (Fig. 1c). These eigenstates, and their corresponding energies, will be calculated using free software such as FreeFEM. The distribution of the eigenenergies will be analysed to look for signatures of chaos in the quantum system. **3.** The quantum scar is expected to be more stable than the classical periodic orbit. The intern will demonstrate this through numerical simulations of the evolution in time of a quantum wavepacket launched along the classical trajectory.

During their PhD, the candidate will analyse the case of a long Rydberg chain, through the identification of many–body trajectories periodic both in time and in space. Importantly, a protocol for the observation of the quantum scars will be devised in close collaboration with experimentalists: their signature will be sought in the behaviour of the system under the evaporative cooling scheme proposed specifically for the new experiment [5]. A more direct signature will be provided by spatially–resolved fluorescence imaging [6], which will be available in future experiments.

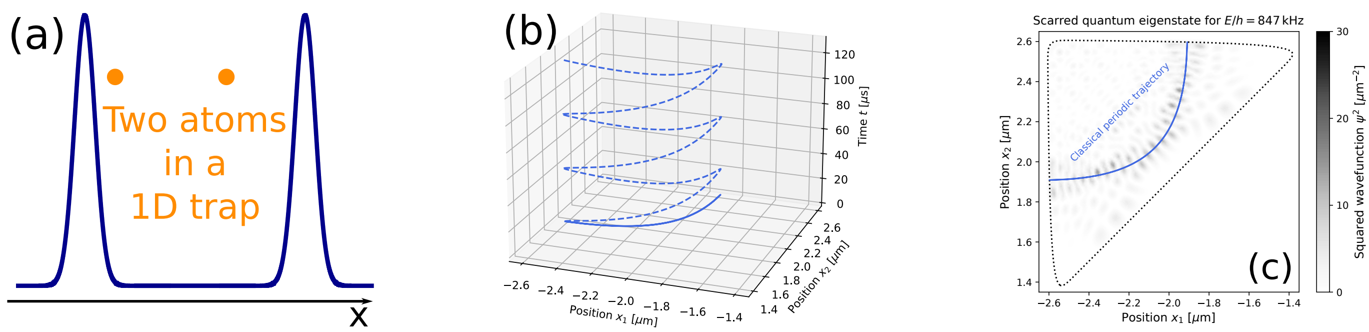

Figure 1 *(a)* Two interacting Rydberg atoms confined in a unidimensional "flatbottom" potential. *(b)* A classical periodic trajectory for the two atoms. *(c)* A quantum eigenstate (grey scale) scarred by the periodic trajectory (blue line).

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