T-4
Atomic & Optical Theory

Quantum Chaos in Ion Traps

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Modern technology is rapidly advancing towards a stage at which the quantum mechanical behavior of devices will become both important and exploitable. Applications of quantum mechanics to such fields as communications, cryptography, remote sensing, computation, and even teleportation have attracted considerable attention over the last few years. Some of the main difficulties in developing such quantum technologies are the quantum mechanical instabilities that can occur. These instabilities differ from instabilities in classical systems that are connected with the strong dependence of dynamics on the initial conditions and on the values of parameters: small variations lead to large deviations of the corresponding trajectories. If the speed of this deviation is exponential, the system is chaotic. But for quantum mechanical systems, the notion of a trajectory is not well defined, and so most of the well-developed methods for stability analysis do not apply to quantum dynamics. As was first shown theoretically by Berman and Zaslavsky in the quantum domain, systems that are classically chaotic can have quantum dynamics that are very different from the corresponding classical dynamics. Remarkably, this difference occurs very rapidly, on the logarithmic time-scale known as the “Berman-Zaslavsky time-scale.’’ Another important chaotic phenomenon, which takes place in quantum systems, is quantum nonlinear resonance (QNR). Again, Berman and Zaslavsky were the first to investigate them. Interactions of QNRs are intimately connected to the transition to quantum chaos. In the simplest situations, QNRs occur when a quantum system with non-equidistant spectrum is driven by a resonant perturbation. Isolated QNRs imply stable quantum dynamics; overlapping QNRs cause a transition to quantum chaos. QNRs are very general phenomena in nonintegrable quantum systems, and can be thought of as “quasiparticles” of quantum chaos. Until now, QNR effects have only been experimentally investigated using Rydberg atoms in a resonant microwave field.

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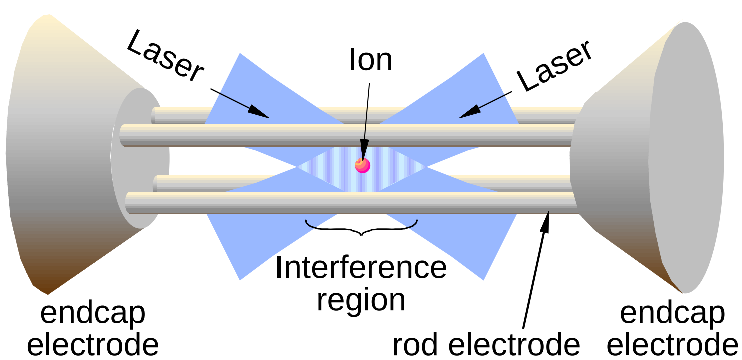

Using radio frequency Paul Traps, devices that confine atomic ions and allow them to be cooled to their quantum ground state using lasers, experimental tests of fundamental principles of quantum mechanics can be carried out. These devices have important technological applications, such as frequency standards or quantum computation. Ions are confined by a combination of a rotating quadrupole potential (induced by the rod electrodes) and a weak electrostatic potential (induced by the conical endcap electrodes). The ions, once trapped, can be cooled by standard Doppler cooling and by an optical pumping method (“sideband cooling”), that can cool multiple ions down to the quantum mechanical ground state of the trapping potential. In an ion trap quantum computer, information can be stored in the internal quantum states of the ions (which constitute the quantum bits, or “qubits” of the computer), and, using ultra narrow bandwidth lasers, quantum gate operations can be realized between pairs of qubits using quantum states of the collective motion of the ions in the harmonic confining potential as a quantum information bus. Currently there is an experimental project underway at Los Alamos to construct a prototype ion trap quantum computer. Because this device is specifically designed to investigate experimentally the preparation, evolution, and measurement of quantum systems with large dimension Hilbert spaces, it represents an ideal opportunity to investigate the problems of dynamical quantum stability, the transition to quantum chaos, and the spectroscopy of quantum nonlinear resonances.

Currently we are theoretically exploring the best means to investigate experimental quantum chaos in an ion trap. One strong possibility is shown in the figure: two lasers, interfering in the vicinity of a single trapped ion, can (if one takes sufficient care on the internal dynamics of the ion) have exactly the same dynamics as a well-know paradigm of chaos, namely the harmonically driven oscillator. Furthermore, the experimental parameters involved are such that this system is definitely quantum-mechanical in nature. For example, the dynamics of an ion in the trap produces a series of sideband quantum levels, corresponding to the ladder states of a quantum harmonic oscillator; these sidebands can be individually resolved using a narrow bandwidth laser. Signatures of quantum chaotic behavior could be detected in measurements of relative populations of these sideband quantum harmonic oscillator states.

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