

GRANT NO N00014-90-J-1322
AN EXPERIMENTAL STUDY OF QUANTUM CHAOS
January 1, 1990- December 31, 1995
Daniel Kleppner, Principal Investigator

FINAL REPORT

The work under this grant comprised experimental and theoretical studies of quantum chaos. The scientific accomplishments are described in the publications.

SCIENTIFIC PUBLICATIONS

- 1 New Class of Universal Correlations in the Spectra of Hydrogen in a Magnetic Field, B.D. Simmons, A. Hashimoto, M. Courtney, D. Kleppner and B.L. Altshuler, *Phys. Rev. L* **71**, 2899 (1993).
- 2 Long-period orbits in the Stark spectrum of lithium, Michael Courtney, Hong Jiao, Neal Spellmeyer, and Daniel Kleppner, *Phys. Rev. Lett.* **73**, (1994) 1340.
- 3 Closed Orbit Bifurcations in Continuum Stark Spectra, Michael Courtney, Hong Jiao, Neal Spellmeyer, and Daniel Kleppner, J. Gao and J.B. Delos *Phys. Rev. Lett.* **74**, 1538 (1995).
- 4 Core-Induced chaos in diamagnetic lithium, Michael Courtney and Daniel Kleppner, *Phys. Rev. A.*, **53**, 178 (1995).
- 5 Classical, Semiclassical, and Quantum Dynamics in the Lithium Stark System, Michael Courtney, Neal Spellmeyer, Hong Jiao and Daniel Kleppner, *Phys. Rev. A.*, **51**, 3604, 1995.
- 6 Recurrences Associated with A classical Orbit in the Node of A Quantum Wavefunction, John A. Shaw, John B. Delos, Michael Courtney and Daniel Kleppner, *Phys. Rev. A.* **51**, 3695 (1995)

CONFERENCE PROCEEDINGS

- C1 Quantum Chaos and Laser Spectroscopy, D. Kleppner, in Proceedings of the International School of Physics Enrico Fermi, CXX Course "Frontiers in Laser Spectroscopy", Varenna, Italy, ed. T. Hansch, and M. Inguscio (Il Nuovo Cimento), North-Holland, New York, 1994.
- C2 Quantum Chaos and Laser Spectroscopy, D. Kleppner, *Atomic Physics 13*, ed. H. Walther, T.W. Hansch, and B. Neizert, (AIP, 1993) pp. 417-424.
- C3 Quantum Chaos and Rydberg Atoms in Strong Fields, Michael Courtney, Hong Jiao, Neal Spellmeyer, and Daniel Kleppner, Drexel Conference Proceedings (9/94), to be published.

THESES

Michael Courtney, Ph.D. thesis. Rydberg atoms in Strong Fields: A Testing Ground for Quantum Chaos, M.I.T., November 1994.

Hong Jiao, Ph.D. theses. Experimental and Theoretical Aspects of Quantum Chaos in Rydberg Atoms in Strong Fields, M.I.T., November 1995.

HONORS

Michael Courtney was one of five finalists in the competition for outstanding Ph.D. research in AMO physics sponsored by the American Physical Society Division of Atomic, Molecular and Optical Physics.

Daniel Kleppner is the 1995-96 recipient of the James Rhyne Killian, Jr., Faculty Achievement Award of the Massachusetts Institute of Technology.

PERSONNEL

In addition to the P.I., three graduate students have been involved with the research, Michael Courtney (Ph.D. 1994), Hong Jiao (Ph.D. Nov. 1995), and Neal Spellmeyer (AASERT support). In addition, Professor John Brandenberger from Lawrence University participated during the academic year 1995-1996 with supplementary support from the NSF for visiting professors from undergraduate institutions. One MIT undergraduate participated in the research in the spring and summer of 1995.

Collaborators include Professors John Delos (William and Mary), Karl Welge (Bielefeld) and Boris Altshuler (MIT).

SUMMARY OF FINDINGS

Our principal achievement has been the development of high resolution periodic orbit spectroscopy (recurrence spectroscopy) which we applied to the problem of the lithium atom in an electric field. Gutzwiller's periodic orbit theory [1 (references above)] provides the most powerful tool that we currently possess for bridging the gap across the semiclassical region that separates the quantum and classical worlds. Its power derives from its ability not only to relate detailed (as contrasted to statistical) features of quantum structure to classical behavior, but also to gain insight into the classical behavior, for instance the development of chaos, from quantum structure. Recurrence spectroscopy is based on the principles of closed orbit theory [2], a modification of periodic orbit theory due to Delos and his co-workers.

Our work on the lithium Stark problem was motivated on the following considerations. The hydrogen atom in an electric field- the hydrogen Stark problem- has analytic solutions both classically and quantum mechanically. Because closed orbit theory can be applied in complete detail, the problem is ideal for testing its limits, particularly the important question of the theory's convergence. Lithium behaves like hydrogen except

for the effect of its small ionic core. In many regions the two atoms behave identically. However, unlike hydrogen, lithium can display irregular motion. The irregular features- expressed by the development of new classical orbits in certain areas- can be observed in detail and simply related to hydrogenic behavior. Consequently, this system is also well suited for studying the onset of chaos, for instance the proliferation of periodic orbits that characterizes a chaotic system.

Closed orbit theory has been applied to the hydrogen Stark problem in great depth by Gao and Delos [3]. They classified the classical periodic orbits systematically, identified the creation each new orbit by a bifurcation process, and predicted the recurrence spectra. We have confirmed many of these predictions in publication P2, above, where we report observations of spectra in which more than 100 recurrences of a primitive orbit were observed. Of particular interest was the identification of periodic orbits that are not found in the hydrogen spectrum. These were identified as arising from scattering of the electron from the ionic core. In this process the electron is scattered by the core from one hydrogenic orbit to another. Consequently, the action of the new orbit is the sum of the action of the previous orbit. Because actions can be determined to very high precision, the orbit assignment is unambiguous.

The role of core scattering in lithium turned out to provide a new insight into the onset of chaos in lithium. As one considers orbits of greater and greater action, the number of core-scattered orbits grows. Single, double and even triple scattering was observed. Successive core scattering leads to the exponential growth of orbits with period- the proliferation of orbits- that is characteristic of irregular systems. This process is discussed both experimentally and theoretically in [P5].

Gao and Delos [3] have shown that at positive energy the hydrogen Stark problem displays only one periodic orbit, leading to a simple sinusoidal modulation of the absorption spectrum. As the energy is decreased below zero, new orbits suddenly appear at the bifurcation points. The energy and action of these bifurcations can be determined exactly. Each new orbit leads to a periodic oscillation in the photo absorption spectrum. (At the bifurcation point the new orbit has the same period as its primitive, but as the energy is varied, their periods differ.) As the energy is decreased further, the number of bifurcations increases, the recurrence spectrum becomes more and more complex, and its Fourier transform, which is the photo absorption spectrum, takes on the aspect of the true quantum spectrum.

We have studied this bifurcation process in detail in [P3]. At the bifurcation point periodic orbit theory diverges, and the behavior requires a quantum treatment. (There is a close analogy to optics: ray optics fails at a focus and diffraction theory is required.) We found excellent agreement with predictions of Delos and Shaw [4]. on the shape of a recurrence in the vicinity of a bifurcation. In particular, the so-called "ghost" orbits, precursors in the recurrence spectrum of a new orbit before its classical bifurcation point, were clearly identified. The existence of this phenomenon had been anticipated by Kus, Haake and Delande [5].

The behavior of chaotic systems at positive energy has received relatively little attention. We have addresses this issue in [P7], which associates irregular motion with "chaotic ionization", ionization which takes place on a wildly varying time scale that displays fractal behavior.

With respect to experimental progress, we have developed methods for carrying out scaled energy spectroscopy with high precision. We are currently implementing a diode laser excitation scheme which will reduce, though not eliminate, our dependence on dye lasers.

The two students working on the experiment, Hong Jiao and Neil Spellmeyer, spent two weeks in the summer of 1995 working with the group of Professor Karl Welge at the University of Bielefeld, Germany, under the sponsorship of the Humboldt Foundation.

Finally, from this research a new direction for study has emerged: this is the investigation of the effect on the quantum spectrum of a Rydberg atom on an electric field of an oscillating electric field whose period matches that of a classically allowed orbit. This represents a new type of resonance spectroscopy in the area of semiclassical theory.

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Dan Kleppner
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