transfer its electron polarization to the helium nuclei by hyperfine interaction in collisions.

Noble gases

What's so special about ^{3}He and ^{129}Xe? They turn out to be the only noble gas isotopes with spin-½ nuclei. One could polarize the nuclei of the hydrogen isotopes and other gases by this kind of optical pumping and collisional spin exchange. But only in the noble gases, with their perfectly symmetrical, closed electron shells, does the nuclear polarization last for hours and even days. In ordinary reactive atoms, molecular configurations formed in collisions couple to the nuclear spins and promptly depolarize them. Furthermore, the chemical inertness of the noble gases makes them harmless inhalants (except for radioisotopes like ^{133}Xe) for clinical applications. The spin-½ nuclei are essential for mri. Spinless nuclei like ^{4}He obviously don't experience magnetic resonance, and spins higher than ½ involve electric quadrupole moments that promote depolarization.

The subject lay largely dormant until 1978, when Bruce Grover at Litton Industries, trying to devise a nuclear-magnetic-resonance gyroscope, succeeded in polarizing ^{129}Xe and krypton-83 nuclei with optically pumped rubidium. "Grover's work rekindled my interest in this field," Happer told us. Undertaking a systematic study of the spin-exchange mechanisms from alkali vapors to noble gas nuclei, Happer and colleagues Nat Bhaskar and Thomas McClelland were able to achieve 5% nuclear polarization of ^{129}Xe with a tunable laser in 1982. In all the earlier work, the optical pumping had been done with lamps.

Before turning its attention to mri applications, the Princeton group in 1988 began to work on creating polarized ^{3}He targets for nuclear and particle physics. That work, led by Cates, culminated a few years later in the building of a foot-long, 9-atmosphere ^{3}He target with a nuclear polarization of about 35% at the business end of the two-mile-long Stanford linear accelerator. High-energy experiments carried out with this target have contributed crucial information about the role of quarks in the spin structure of the neutron.[3]

"Achieving that level of polarization required, at the time, an expensive, powerful laser system that our little atomic physics group could never have afforded," recalls Happer. "The relatively generous funding for high-energy physics came to the rescue." But in just the last year or two the availability of small, efficient diode-laser arrays has made it possible to do optical pumping for mri at modest expense.

A breathing guinea pig

The thoracic cross section of a guinea pig shown on page 17 is, Johnson told us, the first hyperpolarized magnetic resonance image ever made with a living, breathing animal. (The guinea pig imaged several months earlier for reference 1 had just been "euthanized.") It was made at Duke, by Robert Black, Hunter Middleton and coworkers, with inhaled ^{3}He polarized to about 20%. The picture is actually a composite of the ^{3}He lung scan (shown in shades of blue) and a conventional ^{1}H mri scan of the rest of the body. The ^{3}He scan took less than 20 seconds. (The scans are synchronized with the animal's breathing.) Obtaining comparable signal-to-noise for lung tissue with conventional mri takes much longer, and then one still doesn't see the inhaled gas. "This is the only lung-imaging technique I know of," says Johnson, "that promises both high resolution *and* capability for functional studies."

The 20% ^{3}He nuclear polarization was obtained by several hours of optical pumping with circularly polarized laser light tuned to 795 nm, the appropriate excitation wavelength for rubidium, the alkali vapor mixed in with the helium at about a part per million. The nuclear polarization thus achieved lasts for several hours. Collisions with the wall of the containing vessel contribute significantly to depolarization. "Much of our effort has gone into learning how to make the walls benign," Happer told us. "With carefully prepared walls we can get relaxation times of days, which lets us pump the helium beyond 50% nuclear polarization."

In ^{129}Xe, the noble gas used in last year's mri experiments at Stony Brook, one can maintain the nuclear polarization for days without having to worry about collisions, simply by freezing the gas. Xenon has the potentially attractive property of lipophilia: Unlike helium or water, it is readily absorbed by fatty tissue. The hydrophobia of lipids presents imaging problems for conventional mri. Another promising attribute of ^{129}Xe for mri is its very large "chemical shifts." In the magnetostatic field of an mri scanner, the resonant precession frequency of a hydrogen nucleus has a very slight dependence on its immediate molecular environment. Such chemical shifts can be exploited to identify biochemical details in magnetic resonance imaging. The chemical shifts of the ^{129}Xe nucleus turn out to be orders of magnitude higher than those of hydrogen.

No listing of the virtues of xenon for mri would be complete without mentioning that inhaling xenon, which has well-known anesthetic properties, produces a subjectively pleasant effect. "There's been no shortage of volunteers for the human trials planned for Duke," Happer told us. "We're still quite far from knowing whether any of this will prove to be clinically useful," he notes. "But in the current political climate it's important to point out that it all began as curiosity-driven physics research. If we had set out simply to find a better way to image lungs, we wouldn't have gotten this far."

BERTRAM SCHWARZSCHILD

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Sodium Atoms Kicked by Standing Waves Provide a New Probe of Quantum Chaos

Several features of quantum chaos have been demonstrated in a system of sodium atoms interacting with a modulated standing wave of light. The system can be tuned continuously from a regime that can be described classically to one where a quantum description is necessary.

The question of how to quantize a system whose classical dynamics is chaotic has long been a puzzle. The hallmark of classical chaos is sensitive dependence on initial conditions: A small perturbation of the system changes its evolution in a way that grows exponentially with time. But in quantum mechanics a small perturbation of the initial state will in general be mapped into a small perturbation of the final state. In recent years the study of quantum systems whose underlying classical dynamics is chaotic has been an active area of research.[1]

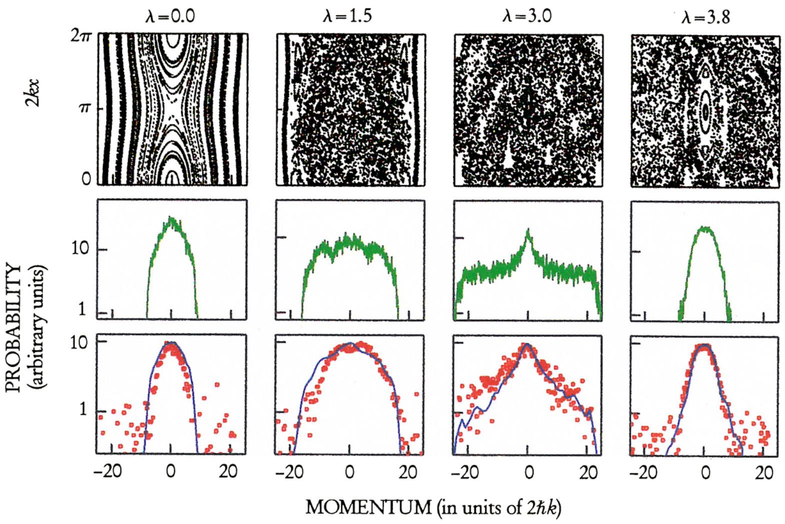
On the experimental side, it is difficult to set up a system that falls squarely in the quantum regime, is suitably isolated from the environment (dissipation tends to destroy quantum effects) and yet has nonlinearities of the type needed for chaotic classical dynamics. Recently, however, a group led by Mark Raizen at the University of Texas at Austin has performed a series of experiments involving just such a system. Their experiments use ultracold sodium atoms interacting with a standing wave of laser light.[2,3] The standing wave periodically imparts a "kick" of momentum to each atom, replicating a kicked rotor. Shmuel Fishman of the Technion, in Haifa, Israel, told us: "The kicked rotor is the standard system used in theoretical investigations of quantum chaos for driven systems. Mark Raizen's experiments are the first experimental realization of that system."

By altering the characteristics of the standing wave the researchers can vary the system from a regime where the classical dynamics is chaotic to one that is predominantly stable. For stable regimes and regimes where there are substantial islands of stability, the classical and quantum predictions coincide and are borne out by the experiments. In the more fully chaotic regimes the experiments confirm the quantum predictions, which differ substantially from the classical ones.

In particular the group has seen a novel quantum phenomenon known as dynamical localization: Classically, the momenta of the atoms should diffuse, but quantum mechanically the diffusion halts after an interval known as the quantum break time. The effects of dynamical localization have been seen before, in experiments such as those of Peter Koch and coworkers (State University of New York at Stony Brook) and James Bayfield and coworkers (University of Pittsburgh), which look at the ionization of highly excited ("Rydberg") hydrogen atoms being driven in a microwave cavity or in a waveguide.[4] Raizen's experiments, however, have explored the time evolution of the localization process.[5] "We observe the diffusion for short times, followed by dynamical localization after the quantum break time," he told us.

Raizen says his group has also observed quantum resonances, an effect predicted to occur when the interval between kicks coincides with a characteristic time of the freely evolving quantum state of the atoms. Roderick Jensen (Wesleyan University) likes the high degree of experimental control possible with Raizen's system. "Their experiments can straddle both the boundary between chaotic and regular motion and the interface of classical and quantum mechanics. This is a very exciting frontier where theory has made a number of interesting predictions and experiment has yielded many surprises," he says.

The experimenters on the Austin team are Raizen, Fred Moore, John Robinson and Cyrus Bharucha; the theorists are Qian Niu, George Georgakis, Bala Sundaram, Robert Jahnke and Paul Williams.



CLASSICAL AND QUANTUM DYNAMICS of sodium atoms in a modulated standing wave of wavenumber k for different values of the modulation amplitude λ. Black images are phase-space diagrams, green curves are classically predicted momentum distributions, blue curves are quantum Floquet predictions, and red boxes are experimental data. Note the logarithmic vertical axes for the distributions. The momentum units, $2\hbar k$, correspond to a single "kick." At $\lambda = 0$ the classical phase space is integrable and the atoms' momentum distribution is trivially localized. At $\lambda = 1.5$ the phase space is chaotic but momentum growth is limited by the resonant kick boundary. At $\lambda = 3.0$ only very small islands of stability remain in the phase space (causing the central peak in the classical curve). The data, however, confirm the quantum prediction of an exponentially localized momentum distribution. At $\lambda = 3.8$ the classical phase space is almost integrable again. (Adapted from ref. 3.)

Kicked rotors and Rydberg atoms

The classical kicked rotor consists of an arm rotating about a pivot at one end. The rotation takes place in the absence of gravity, but periodically a force like gravity is turned on for an instant, imparting an impulse, or kick, to the rotor. As Eric Heller of Harvard University explained to us, "The motion becomes chaotic and diffusive if the kicking is strong enough because the size of each kick depends on the rotor's angle at that instant and the rotor's period bears no special relation to the kicking period."

The comparative simplicity of the kicked-rotor system combined with the richness of its dynamics makes it ideal for quantum studies. In 1979 Giulio Casati (University of Milan), Boris Chirikov, Felix Izrailev (Budker Institute of Nuclear Physics, Novosibirsk) and Joseph Ford (Georgia Institute of Technology) showed numerically that the quantum and classical motions of the kicked rotor could be very different. Fishman, with Daniel Grempel (Laue–Langevin Institute, Grenoble) and Richard Prange (University of Maryland), drew a connection to the phenomenon of Anderson localization: In a disordered lattice quantum effects suppress the classically expected diffusion of electrons. Reference 6 reviews these theoretical developments.

Casati and coworkers showed that Rydberg atoms driven by sufficiently high-frequency microwaves can be related to the quantum kicked rotor by a sequence of approximations. Koch says his group is indebted to Casati and his coworkers "for convincing us to push our experiments to high scaled frequencies to study this physics." (See reference 7 for a detailed review of the microwave work.)

Koch's group experimentally demonstrated the stabilizing effect of dynamical localization in 1988, and Bayfield's group obtained similar results.[4] (The work of both groups grew out of microwave ionization experiments begun by Bayfield and Koch at Yale University in the mid-1970s.) In 1991 Herbert Walther's group at the Max Planck Institute for Quantum Optics in Garching, Germany, saw the stabilizing effect of dynamical localization in the microwave ionization of rubidium Rydberg atoms in a waveguide. Koch and Walther also studied the effects of external noise on dynamical localization.

The signal of localization in these experiments is that for sufficiently high values of the scaled driving frequency, the real (quantum) atom becomes significantly more stable (that is, harder to ionize) than is predicted by classical computations (in which there is an onset of chaos). However, the interpretation of the microwave ionization results and the connection to analytic theory is more complicated than in Raizen's work—many experimental details are, of necessity, neglected by the theories. As Koch says, "The phenomenon of dynamical localization is interesting physics, but it is most definitely not the entire story of these systems."

Modulated standing waves

In 1992 Robert Graham, Martin Schlautmann (University of Essen, Germany) and Peter Zoller (University of Innsbruck, Austria) proposed a system that models the kicked rotor more directly than the Rydberg-atom systems do.[8] In their system atoms interact with a standing wave produced by two laser beams directed in opposite directions along the x axis. The phase of one of the laser beams is modulated, for example by reflecting it off an oscillating mirror, which causes the standing wave itself to oscillate back and forth along the x axis.

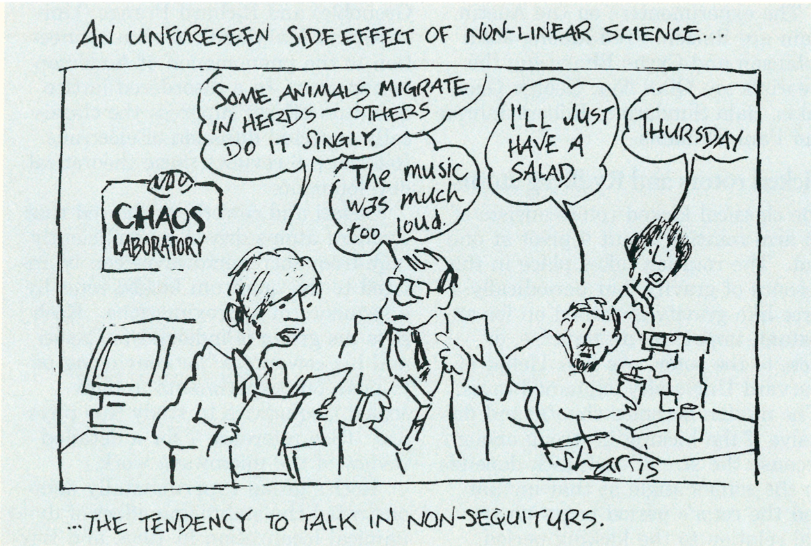
If the laser frequency is detuned somewhat from a transition of the atoms, then the dominant interaction is a coherent two-photon process: An atom in the ground state absorbs a photon from one beam and is immediately stimulated to emit a photon into the other beam. The change in momentum from the absorbed to the emitted photon imparts a "kick" along the x axis to the atom.

As Raizen explained to us, an atom in the standing wave receives the biggest kick at those moments when its x component of velocity v_x matches the velocity of the modulated standing wave, which occurs twice each cycle. The modulated system is not an exact analog of the kicked rotor, however, because the kicks are not delta functions and they don't occur with a single period. Also, once an atom's v_x exceeds the maximum velocity of the modulated standing wave, it is effectively decoupled from the standing wave. (This is called the resonant kick boundary.)

In the original proposal of Graham and his coworkers, one would pass a beam of atoms transversely through such a standing wave and observe how the atoms were deflected. Raizen's group has instead set up a clever variation of this system that gives them much more experimental control.[2,3] They first trap and cool their sodium atoms in a three-dimensional magneto-optic trap (see PHYSICS TODAY, September 1994, page 19); this leads to a spatially confined sample of ultracold atoms. The magneto-optic trap is then turned off and the standing wave is turned on for, say, 10 microseconds. The kicking of the standing wave causes diffusive growth in the x component of the atoms' momenta. The standing wave is then turned off, allowing the atoms to freely expand with whatever momenta they have acquired. At the end of this free-expansion period (typically 2 milliseconds) an "optical molasses" is turned on, freezing the atoms in place. The experimenters now observe the spatial distribution of the atoms via fluorescence and use the time of flight to deduce their earlier momentum spread.

To understand and interpret the experimental results detailed theoretical analyses of the system were done independently by Raizen's group[3] and by the group of Wolfgang Schleich at the University of Ulm in Germany.[9] Both analyses clearly showed that it is possible to switch the system between a nearly integrable regime and one that is classically chaotic. One does this by varying the amplitude of the standing wave's oscillation along the x axis, which is an important control parameter. This amplitude is related to a dimensionless parameter λ that appears in the Hamiltonian, and the system exhibits a variety of dynamics as λ is altered. (See the figure on page 19.) For small λ the classical system is stable and the classical and quantum predictions agree. As λ increases, the classical phase space becomes increasingly disordered, but islands of stability remain. Again the classical and quantum predictions largely agree and are borne out: The atoms diffuse in momentum up to the resonant kick boundary. At certain high values of λ (for example, $\lambda = 3.0$, as shown), the phase space is almost entirely chaotic. For such values the quantum predictions differ from the classical by showing localization: A sizable proportion of the atoms are localized to momenta well below the classical kick boundary.

In this modulated system, Raizen told us, although there are classically chaotic regimes the classical phase space is complicated by recurrences of islands of stability for many values of λ. Koch points out that such regimes of "mixed" dynamics are the generic case in nature and he considers the understanding of their quantum counterparts to be a key part of his Rydberg atom research. Raizen and his group will also be pursuing many studies of the mixed regime, but their most recent experiment has focused on purely chaotic dynamics and has realized the quantum kicked rotor more exactly. To do this, they replaced the modulated standing wave with a standing wave that is turned on in pulses.[5] Typical pulse times are around 50 nanoseconds—the shorter the pulse, the more closely it approximates a true delta



kick, but if the pulses are too short each one contains too little energy. The group has varied the time between pulses from 1.5 microseconds up to tens of microseconds.

With this system they have observed the momentum distributions after various evolution times and they have seen the transition from classical diffusion in momentum space (at extremely short times) to the localization that occurs after the quantum break time.[5] "Theorists have made some very specific predictions," Raizen told us, "relating the diffusion rate during the initial diffusive phase, the break time and the localization length—the spread in momentum space that occurs. By observing the time evolution of this process we've verified some of those predictions for the first time."

They have also seen quantum resonances in the pulsed system. In between kicks the phase of an atom's quantum state evolves like that of a free particle: $e^{-(it/\hbar)(p^2/2m)}$. Quantum resonances were predicted to occur when the period of the kicks matches the period of this phase, and Raizen's group has observed this. One signal is a dramatic change in line shape at the resonant pulse periods.[5]

Numerous other experiments are possible using either the modulated or the pulsed system. The effective Planck's constant $\hbar'$ of the quantum kicked rotor is an adjustable parameter in the experiment. This should enable the study of questions related to the correspondence principle in the limit of small $\hbar'$. (The Rydberg-atom experiments have also studied this.) It is also possible to study the effects of noise and dissipation on dynamical localization.

Another phenomenon of particular interest, Raizen told us, is the Anderson problem. In condensed matter physics this is the transition from an insulator to a conductor in three dimensions. Casati, Italo Guarneri (University of Milan) and Dima Shepelyansky (Budker Institute, Novosibirsk) have shown that one can obtain a system equivalent to the Anderson problem in three dimensions by taking a one-dimensional kicked rotor and modulating the amplitude of the kicks with two frequencies that are incommensurate with the kicking frequency. Localization in momentum space in the rotor system is the analog of an electron being pinned in an insulator. "We're setting up to study this next," Raizen told us.

Graham P. Collins

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Astronomical Image Processing May Improve Breast Cancer Diagnostics

Medical and astronomical researchers have collaborated to apply sophisticated image processing techniques to detect microcalcifications in mammograms.

Over the last few decades, astronomical image processing has become extremely sophisticated, encompassing image reconstruction and restoration, image filtering, object detection and classification. A collaboration from the Space Telescope Science Institute, in Baltimore; Johns Hopkins University; and the Lombardi Cancer Research Center at the Georgetown University Medical Center, in Washington, DC, is hoping to apply some of these methods to detect telltale signs of breast cancer in a digitized mammogram. The project was catalyzed over a year ago by Benjamin Snavely, program director for advanced technologies and instrumentation in the NSF division of astronomical sciences, which recently awarded the collaboration a $50 000 grant from the Small Grants for Exploratory Research Program.

Finding a faint star in a blurry image amid other emission sources turns out to be similar to finding a microcalcification amid the complex background structures in a mammogram. Clusters of microcalcifications are one of several types of objects whose presence in mammograms is indicative of breast cancer; they appear as faint, pointlike spots. According to Matthew Freedman (Georgetown), a member of the collaboration, roughly one-third of breast cancer cases have microcalcifications no larger than 50–100 microns in size. Currently mammography shows microcalcifications of about 250 microns or larger; one can't usually see the smaller ones without image processing.

Workers at Space Telescope Science Institute developed a large collection of image processing software after the spherical aberration in the Hubble Space Telescope's primary mirror became apparent soon after launch in April 1990. The software was intended to compensate for the telescope's loss of dynamic range and spatial resolution, Robert Hanisch of STScI told us.

At Georgetown radiologists are conducting a clinical trial of whole-breast digital mammography based on storage phosphor imaging technology. The system's detection capability is limited by noise from the random flux of x-ray photons, by structural feature noise (due to normal anatomical structures that resemble microcalcifications) and by the presence of breast ligaments.

In preliminary studies Freedman gave Hanisch and Richard White (STScI) four digital mammogram images; on two of them Freedman showed them where the microcalcification clusters were and with the other two he told them nothing. Hanisch and White first tried Fourier domain filtering on the images, but the approach failed to spot only the microcalcifications—the fibrous nature of the breast tissue, the edge of the breast and the edge of the exposure frame all contribute to the highest spatial frequencies in the Fourier transform.

The procedure that did work was a three-stage process. First Hanisch and White used the well-known image processing technique called unsharp masking, in which one smooths the image heavily and then subtracts the smoothed image from the original image. The result was that features in the brightest regions of the image were overemphasized. So the second step was to improve the filtering by normalizing the image variances. The third step was to apply an adaptive filter to smooth regions where there are no statistically significant data values above