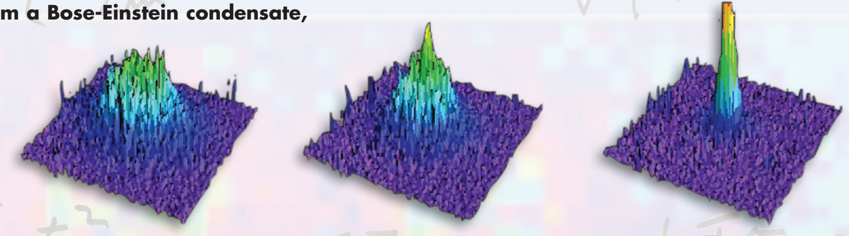
Quantum Science

Los Alamos physicists are studying the quantum behavior of small groups of carefully prepared atoms, ions, and photons. In addition to providing insights into the strange world of quantum mechanics, these studies are paving the way for ultrasensitive gravity sensors, highly random number generators, ultraprecise frequency standards, quantum computers, and unbreakable encryption methods.

Measuring Small Changes in Gravity

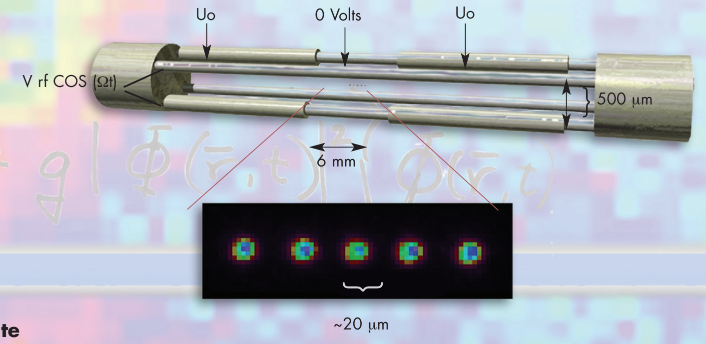


This sequence of three shadow images shows a gas of 200,000 trapped rubidium atoms (blue-green cloud) gradually forming a Bose-Einstein condensate as the temperature is lowered through evaporative cooling. The height of each pixel is proportional to the density of the atoms at that location. The narrow density spike that forms in the center of the second and third plots is an image of the wave function of the Bose-Einstein condensate. Because all the atoms in the condensate occupy the lowest energy state of the atom trap, they have no thermal motion and the wave function is therefore very localized.

When cooled to very low temperatures, a group of gaseous atoms can form a Bose-Einstein condensate, or BEC. In this state, separate quantum-mechanical wave functions of the individual atoms add to produce a single macroscopic wave function, whose amplitude is large enough to be easily detected. As for sound or light waves, the effect of adding two BEC wave functions depends on the amplitude and phase of each. Because the rate at which a BEC wave function's phase increases depends on the local gravitational field, one can measure small changes in gravity by measuring the effect of adding the wave functions of two slightly separated BECs held in a gravitational field. The method is as sensitive as the best laboratory gravity-measurement methods but could be implemented in a small package. Such a sensor could detect underground caves and oil or mineral deposits or help submarines avoid underwater obstacles.

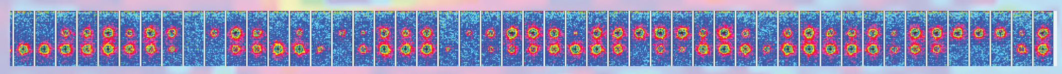
Studying Trapped Ions

Los Alamos physicists study quantum behavior on nearly stationary ions confined in a one-dimensional trap. Ions are forced to the trap's axis by a radio-frequency quadruple field and to the trap's center by a static electric field. Lasers cool the ions to near absolute zero.



This illustration shows the trap and five confined ions. The laser light that cools the ions to near absolute zero also scatters into the camera that took this picture.

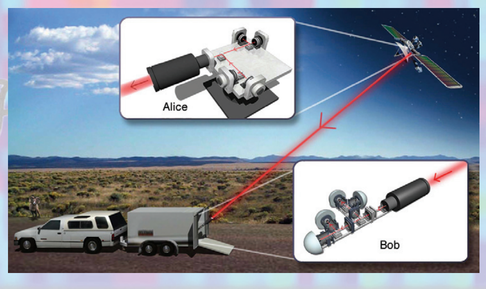
When illuminated by lasers with the right wavelengths, cold trapped ions either cycle between a short-lived state and a ground state while scattering light into the camera or jump to a long-lived state and disappear from view until they jump back to the ground state. According to quantum theory, these jumps occur at random times, so they could be used to make superior random-number generators. Trapped ions could also be used to make ultraprecise frequency standards, to simulate other quantum mechanical systems—such as superconductors—and for quantum computing.



This movie shows two trapped ions illuminated by lasers. The visible ions are cycling to a short-lived state and scattering photons into the camera. The ions that are not visible have jumped to a long-lived quantum state. Whether or not the ions appear in a short frame in our movie is unpredictable.

Distributing Encryption Keys

When a random number called a "key" is added to a numerical message, the message is encrypted. To invert the process, one subtracts the key from the encrypted message. Distributing copies of the key securely is thus crucial to transmitting encrypted messages. In the well-known BB84 key-distribution protocol (BB stands for the inventors' names, Charles Bennett and Gilles Brassard), single, randomly polarized photons are sent from "Alice" to "Bob." Using this protocol, Los Alamos physicists have generated and distributed keys in daylight over distances of up to 10 kilometers. They hope to distribute keys from a satellite to Earth in the near future.



In the BB84 scheme, Alice transmits single, randomly polarized (vertically, horizontally, or diagonally) photons to Bob. To receive each photon, Bob randomly sets his detector to a particular polarization. He detects only the photons whose polarization matches his detector's. Bob tells Alice when he detects a photon, but he does not tell her its polarization. For each photon Bob detects, Alice and Bob separately and secretly write down either 1 or 0, depending on the photon's polarization. The resulting list of 1s and 0s is a random binary number—an encryption key—known only to Bob and Alice. If Eve (an eavesdropper) intercepts the photons, Alice and Bob will know because a statistically significant number of photons will fail to reach Bob. Furthermore, because of the "no-cloning" law of quantum mechanics, Eve cannot copy one of Alice's photons for herself and send the original to Bob. Thus, the laws of quantum mechanics will foil all eavesdropping attempts.

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