theoretical prediction was realized in the lab in an incredibly beautiful way."

Although the quantum phase transition technically occurs only at absolute zero, the atoms in the Munich experiment are sufficiently cold that the quantum fluctuations still dominate the thermal ones.

Number-squeezed states

A year ago, Kasevich, together with coworkers from Yale and the University of Tokyo had done a similar experiment, in one dimension: They formed a BEC, loaded it into a 1D optical lattice and saw the presence and absence of interference patterns as a function of well depth.[5] The emphasis of their experiment was different, however, so that they had far more atoms—on the order of 1000—per lattice site. Kasevich and his coworkers are working on precision interferometry and want to have the large number of atoms to gain greater sensitivity.

In both the Yale–Tokyo and the Munich experiments, the Mott insulating phase was in what is known as a number-squeezed state. That is, one could know with a very high degree of certainty how many atoms occupied each site. The price for such certainty, as dictated by the uncertainty principle, was that the phase was completely unknown. In the present case, the superfluid and Mott insulating phases are characterized by extreme cases of two conjugate parameters: In a superfluid, the phase is known but the number of atoms per site is undetermined, and in a Mott insulator the atom number is known but the phase is completely randomized.

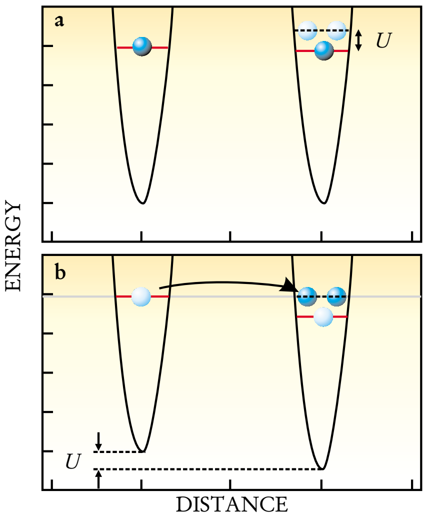

Figure 2. Intersite Interaction. (**a**) Two atoms (dark blue balls) occupy neighboring potential wells. *U* is the energy cost for them to be in the same well (pale blue balls). (**b**) Lowering one well relative to the other allows atoms originally in separate wells (light blue) to occupy the same well (dark blue). (Adapted from ref. 1.)

One prediction of the theory is that the formation of a Mott insulator should be accompanied by the opening of an energy gap in the excitation spectrum; as shown in the top panel of figure 2, it costs an energy *U* to move an atom from the left-hand to the right-hand well. Bloch and his colleagues came up with a clever way to measure this energy gap. With the system in its insulating phase, they applied an energy gradient to the potential wells, which in 2D would be like tilting the egg carton. The effect is shown in the bottom panel of the figure: Once the energy gradient has raised the relative energy of the left-hand well by an amount *U*, the left-hand atom can hop, and both atoms end up on the same site. The tilt threshold that results in such tunneling tells experimenters the value of the energy gap *U*.

As for applications, Zoller said that the Mott insulator should allow interesting chemistry to happen. For example, "One might load exactly two atoms per lattice site and engineer the formation of molecules by way of a photoassociation process." Zoller and Ignacio Cirac (Max Planck Institute for Quantum Optics) have also proposed a scheme to entangle atoms for quantum computation using cold, controlled collisions.[6,7] Zoller views the Mott insulator as an ideal starting point for their scheme.

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Ultracold Neutrons Exhibit Quantum States in the Earth's Gravitational Field

Quantum mechanics is thought to be universal. It ought to apply to particles trapped in the Earth's gravitational field just as it does to electrons trapped in the electric field of an atom. Like atomic electrons, very cold neutrons sitting in a gravitational potential well ought to have quantized energy levels. The experimenter's problem, of course, is that the gravitational force on a neutron at sea level is 19 orders of magnitude weaker than the Coulomb force on an electron in the ground state of the hydrogen atom. Whereas the low-lying hydrogen energy eigenstates are separated by electron volts, the analogous neutron states in a gravitational well would be separated by only picoelectron volts (1 peV = 10^{-12} eV).

Quantization imposes a lower limit on the energy of a neutron trapped in a gravitational potential well.

More than 20 years ago, Vladislav Luschikov and Alexander Frank at the Joint Institute for Nuclear Research in Dubna, near Moscow, suggested that one might exploit the then-new technology of ultracold neutrons to exhibit these gravitationally bound quantum states. Now, at last, a group at the Laue–Langevin Institute (ILL) in Grenoble seems finally to have pulled off this difficult trick. Valery Nesvizhevsky and coworkers report, in a recent paper, that they have clearly demonstrated the 1.4-peV neutron ground state in a gravitational well and have also found hints of the first few excited quantum levels.[1]

It's not just a matter of verifying quantum mechanics in a new observational realm. The techniques developed in this very challenging experiment may eventually be applied to searches for a nonvanishing neutron charge or violation of the equivalence of inertial and gravitational mass. The present experimental upper limit on the neutron's charge is about $10^{-21}\,e$.

At the Laue–Langevin

Nestled in the French Alps, the ILL, with its high-flux research reactor, is a particularly prolific source of

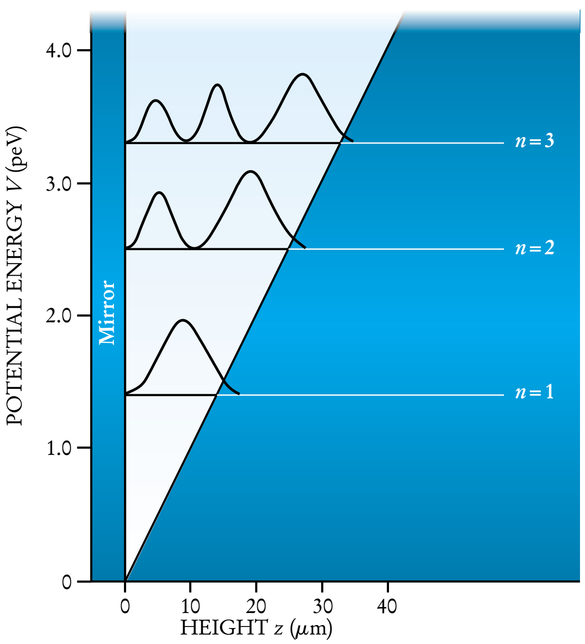

FIGURE 1. GRAVITATIONAL POTENTIAL WELL with walls formed by a mirror for ultracold neutrons and by the Earth's gravity field. The calculated energy levels and wavefunctions (squared) are shown for the three lowest energy eigenstates for a neutron trapped in such a well.

ultracold neutrons. The reactor neutrons are cooled by being made to traverse a liquid-deuterium moderator and then work their way uphill against gravity through piping whose reflecting walls preferentially absorb out the more energetic neutrons. The resulting ultracold neutrons, collimated and concentrated in momentum space by turbines, reach Nesvizhevsky's gravitational well as a horizontal beam with a sprinter's speed of about 10 m/s. But in the vertical direction, transverse to the beam, the effective temperature of the neutron aggregation is only 20 nK, corresponding to an energy of a peV or so.

The experiment's one-dimensional gravitational potential well is shown in figure 1, together with the calculated wavefunctions (squared) of its three lowest-lying neutron energy eigenstates. The one dimension is the height z above the horizontal slab of material that serves as a perfect reflecting mirror for the ultracold neutrons and thus as an impenetrable wall of the potential well. At sufficiently low temperatures, many metal surfaces are perfect neutron reflectors at all angles of incidence.

The second, sloped wall is the potential energy

$$V(z) = mgz$$

due to the gravitational field itself, where m is the neutron mass and g is the acceleration of gravity. Lifting a neutron by 10 μm in the Earth's gravitational field raises its potential by 1.02 peV. The solutions of the Schrödinger equation for such a linear potential are the Airy functions.[2] Note that these wavefunctions penetrate slightly into the classically forbidden region to the right of the sloped potential wall.

The ground-state energy, $E_1 = 1.4$ peV, is the kinetic energy a neutron would gain by falling *classically* onto the mirror from a height of about 14 μm, having reached a final vertical speed of 1.6 cm/s. But the experimenters cannot simply drop neutrons from various micron heights. Instead, they direct the horizontal beam of cold neutrons at the mouth of a 10-cm-long gap between the mirror and an upper surface that either absorbs or scatters out of play any neutron that touches it.[2] (See figure 2.) The vertical spacing between the mirror and the absorber–scatterer can be varied from 0 to 100 μm. A neutron detector at the far end of the gap measures the neutron flux that gets through as a function of the gap height.

The beam is directed at the gap with a slight upward tilt. The range of neutron energies emerging from the ultracold source leaves a significant spread in the vertical-velocity distribution of the entering beam. The gap height then serves as a filter that sets an upper limit on the vertical velocity components of the individual neutrons. Classically, if the absorber–scatterer ceiling does its job perfectly, the largest initial vertical velocity component that can make it through a gap of height z is the velocity a particle would acquire by falling through that height.

But the quantum-mechanical ground state imposes a *lower* limit on the gap height and, in a sense, on the vertical velocity. Semiclassically, a bound neutron of energy E, unencumbered by a ceiling or a horizontal velocity, would continually bounce off the mirror to a height $z = E/mg$. The quantum well cannot, however, accommodate any neutron for which that characteristic bounce height is less than the 14 μm, corresponding to E_1. To put it more quantum mechanically, if the gap is not high enough for the ground-state wavefunction to fit inside, the neutron beam will be scattered away at the gap's entrance.

Quantum threshold

All this assumes that the vertical component of the neutron velocity can be treated independently of the horizontal beam velocity. So, if the experimenters have taken adequate care to eliminate any mechanical or magnetic effects that might couple the velocity components, one expects that the transmission of neutrons through the gap as a function of its height will exhibit a threshold at about the width of the ground-state wavefunction, followed by a sequence of steps at heights corresponding to the widths of the excited-state wavefunctions.

The red curve in figure 3 is the detailed prediction of the neutron flux reaching the detector. The blue curve, with no threshold, is what one would expect simply from geometric and phase-space considerations, without

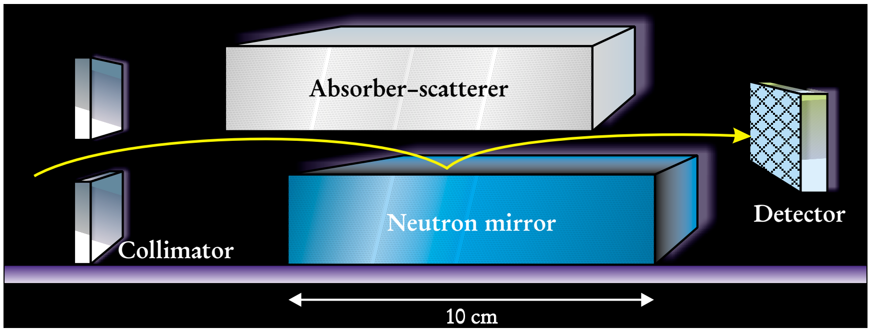

FIGURE 2. SCHEMATIC SETUP of the experiment that detected quantum states of neutrons in a gravitational potential well. A horizontal beam of ultracold neutrons with, on average, a slight upward tilt enters a long, narrow gap of adjustable height between a neutron mirror floor and an absorbing–scattering ceiling. The gap height, much exaggerated in this drawing, limits the vertical velocity component of the entering neutrons. The detector records the fraction of transmitted neutrons as a function of the gap height. (Adapted from ref. 1.)

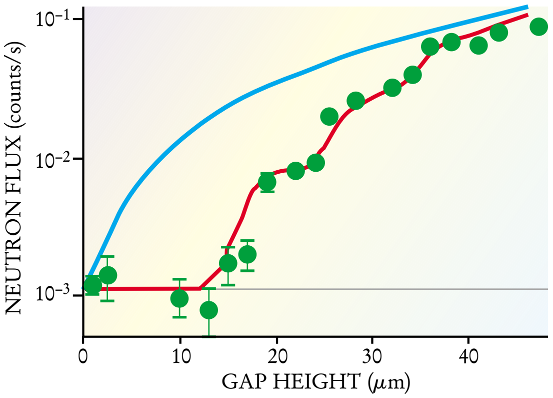

Figure 3. Transmitted neutron flux as a function of gap height in the Laue–Langevin experiment shows a clear threshold near 15 μm and indications of steps at larger gap heights, consistent with the quantum-mechanical prediction (red curve). The blue curve is what one expects simply from the increasing phase-space acceptance of the gap. The horizontal line indicates the detector's background level. (Adapted from ref. 1.)

any quantum effects. The data clearly favor the quantum-mechanical prediction, though the extremely limited statistics can only hint at quantum steps beyond the first. "Our experiment had to select only one in a billion incoming reactor neutrons," Nesvizhevsky told us.

The experiment's energy resolution is not limited only by statistics. The quantum-mechanical uncertainty relation

$$\Delta E \Delta t \gtrsim \hbar$$

also comes into play. The 0.01 s it takes a neutron to traverse the 10-cm-long gap in this experiment limits the energy resolution of the quantum-well eigenstates to 0.07 peV. One could, of course, do a hundred thousand times better if one could keep the neutron trapped in the well for its full lifetime—about 15 minutes.

If the horizontal and vertical neutron motions are sufficiently decoupled, the transmission curve in figure 3 should be independent of the neutron beam velocity. And that is indeed what the experimenters find. Furthermore, the fact that the gap, even when it's less than 10 μm high, has no difficulty transmitting visible light is evidence that its opacity to neutrons at that height is really due to the neutron ground-state energy in the gravitational well. The width of the ground-state wavefunction is, roughly speaking, the de Broglie wavelength corresponding to the vertical momentum component of that state. The much smaller de Broglie wavelength corresponding to the horizontal beam momentum, on the other hand, plays no role at the threshold in figure 3.

"For precision experiments in search of new, unpredicted effects," says Nesvizhevsky, "we will have to find ways of making the neutrons spend more time in the gravitationally bound states. And, of course, we'll need a significant increase in the available density of ultracold neutrons."

Bertram Schwarzschild

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An Energy Recovery Linac Is Seen as a Bright Idea

The popularity of synchrotron radiation facilities continues to grow, spurred by their usefulness for studying the structure and dynamics of materials ranging from membrane proteins to nanocomposites. In response to the growing demand, the newest synchrotron storage rings provide more brilliant radiation beams—that is, beams having greater fluxes of photons per unit area and solid angle—and they allow more room for arrays of magnets that wiggle the electrons, causing them to generate highly collimated beams of radiation.

So where to go from here? Many types of experiments require shorter, more flexible pulses and greater brilliance. For example, pulses as short as 100 femtoseconds would enable studies of structural dynamics, and brighter, better collimated beams would allow the use of smaller samples.

To move forward, researchers at a number of accelerator centers are eyeing an x-ray light source in which electrons are accelerated by what's known as an energy-recovery linear accelerator (ERL) rather than by a synchrotron.[1] Perhaps, they hope, an ERL can produce electron beams with shorter pulses and smaller angular spread—that is, lower emittance—than is possible in a synchrotron (emittance is the product of the beam width and its divergence). Smaller emittance contributes to greater brilliance, both in the electron beam and in the radiation it produces.

▶ Will some future light sources be based on linear accelerators rather than synchrotron storage rings?

Proponents of ERL light sources have been buoyed by the successful performance of an ERL-based, infrared free-electron laser (FEL) with high average current,[2] which has been operating at the Thomas Jefferson National Accelerator Facility since 1999. Researchers face considerable challenges to scale up to the much higher electron energies and currents envisioned for x-ray ERL light sources. But, as Sol Gruner, director of the Cornell High-Energy Synchrotron Source, put it, the Jefferson Lab FEL has at least shown that the concept is not a "pie in the sky" idea.

In today's synchrotron radiation facilities, bunches of electrons race around a storage ring, emitting radiation each time the electrons are bent by a dipole magnet or subjected to the oscillating magnetic field of devices known as wigglers and undulators. Once the electron beam is brought up to the target energy and stored, only a small amount of energy from a radio-frequency (RF) field is required to replace what's lost through the emission of synchrotron radiation.

Recycling energy, not electrons

Whereas a storage ring continually recycles the electron beam, an ERL recycles the energy but not the electrons. As shown in the figure on page 24, an electron bunch is injected from a photocathode gun into a linear accelerator (linac). If the bunch enters at just the right phase, it gains energy from the resonant electromagnetic field in the linac. The electron bunch is then looped back through a path whose length is adjusted so that the bunch re-enters the linac out of phase with the accelerating field and is slowed. Energy is thus given back to the electromagnetic field, and the spent electrons are dumped. One can make a light source from this design