required protein, E2, a ubiquitin-conjugating enzyme (Ubc). In yeast, there are 13 Ubcs. Only one of these, Ubc6p, is a transmembrane protein, although it has some overlapping specificity with the soluble Ubc, Ubc7p. These two enzymes participate in the ubiquitination of both soluble and membrane-bound substrates. The new work reports that an ER protein, Cue1p, is required to recruit the soluble Ubc7p to the membrane. A deletion of Cue1p gives the same phenotype for ER degradation as a deletion of Ubc7p, suggesting that Ubc7p must be assembled with Cue1p to be active. In a yeast strain defective for ubiquitination of misfolded proteins, the latter are stabilized and remain in the lumen of the ER. This result suggests that attachment of ubiquitin may be required to drive unidirectional export of unfolded proteins from the ER.

If the presence of a ubiquitin branch on a protein can contribute to the unidirectional export of proteins from the ER, it may also be able to block import through the translocon. For ubiquitination to occur during cotranslational import into the ER, the seal between the ribosome and the membrane must be broken to allow access of the Ubcs to the protein. Evidence suggests that the ribosome seal can be broken during the translocation of transmembrane proteins without compromising the ER permeability barrier (*7*). This would allow for the ubiquitination and degradation of a misfolded transmembrane protein to begin before translation has terminated. Does this occur and could this serve to degrade improperly inserted membrane proteins? Given the rapid rate of recent progress in the fields of ER translocation and degradation, answers to these enigmas should come soon.

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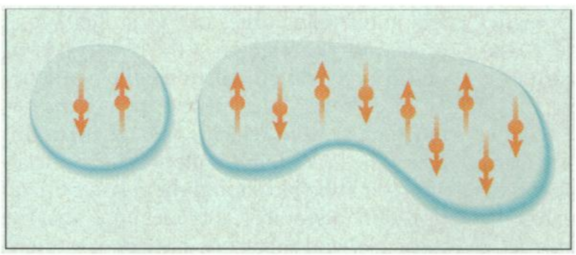
QUANTUM PHYSICS

Artificial Atoms: New Boxes for Electrons

Paul L. McEuen

An atom can be thought of as a spherically symmetric box for electrons, where the walls of the box are set by the attraction of the electrons to the positively charged nucleus. The energy-level structure of electrons in these atomic boxes have been a central testing ground of quantum mechanics. For example, reproducing the measured hydrogenic spectrum of the one-electron atom was one of the first tests of the Schrödinger equation. Similarly, the excitation spectra of multielectron atoms have been key to the development of many of the more advanced ideas in multiparticle quantum mechanics. Now, similar experiments are being done on quantum dots (*1*).

These are small solid-state systems with discrete charge states and energy level structures that are reminiscent of atomic systems. Unlike in real atoms, however, a variety of geometries in these "artificial atoms" are possible, including one-dimensional (1D) rods (*2*), 2D pancakes (*3*, *4*), and 3D spheres (*1*). For example, on pages 1784 and 1788 of this issue, Kouwenhoven and colleagues at Delft Institute of MicroElectronics and Submicrotechnology and Nippon Telegraph and Telephone (*5*) and Stewart and co-workers at Stanford University (*6*) report on detailed studies of 2D quantum dots. In the former, a high-symmetry dot of a few electrons was studied, and in the latter, a low-symmetry dot containing many electrons was probed. These measurements demonstrate that many of the cherished ideas from atomic physics can be directly applied to artificial atoms. They also show, however, that artificial atoms offer new challenges to our understanding of interacting multiparticle quantum systems. In the related report on page 1792, Schedelbeck *et al.* (*7*) explain how two coupled dots were used to create artificial molecules.



Electrons in boxes. (**Left**) Schematic illustration of two electrons in a 2D circular quantum dot (quantum dot helium). In the ground state, the spins are oppositely oriented, but in the excited state, they can be in the same direction (triplet state) or in opposite directions (singlet state). (**Right**) Schematic of many electrons in an irregularly shaped 2D quantum dot. The states are expected to be complex, and the ground state may have a net spin polarization.

To probe the energy level spectra, the first two groups took electrical measurements on individual quantum dots using a technique developed in the early 1990s, where the dot is incorporated into an electronic device resembling a transistor (*4*). Current-voltage (*I-V*) measurements on these quantum-dot transistors directly probe the ground- and excited-state energies of electrons in the dots. Further, the charge state of the dot, that is, the atomic number of the artificial atom, can be controlled by a voltage applied to a nearby metallic gate. In this manner, the whole periodic table for a particular type of artificial atom can be studied in a single device.

In real atoms, the behavior of the ground and excited states is well known. For hydrogen, with one electron, the spectrum is given by the shell structure calculated by undergraduate physicists the world over. For the next simplest atom, helium, things get more difficult. The shell structure remains, but the coulomb interaction between the electrons complicates matters. For example, the coulomb repulsion plus the restrictions placed on the system as a result of the Pauli exclusion principle lead to the so-called exchange interaction, which favors a spin alignment of electrons in the atom. This ordering results, for example, in a splitting of the first excited state of He into a triplet state, where the electron spins are parallel, and a singlet state, where the spins are antiparallel. The exchange interaction is also the origin of Hund's rule in larger atoms with many electrons. This rule favors a spin-polarized, that is, magnetic, ground state for atoms with a partially filled shell.

In the experiment of Kouwenhoven *et al.* (*5*), the spectra of the first few electrons added to a circular quantum dot [resembling a pancake (see figure)] are studied. The dot is like a 2D atom and exhibits a shell structure whose states can be characterized by radial and angular momentum quantum numbers (*3*). The magnetic field dependence of the levels can be used to identify the angular momentum of the

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states, just as in real atoms. The experiments show that the energies of pancake hydrogen (one electron on the dot) follow a simple model of noninteracting electrons that is easy to calculate. For pancake helium (two electrons on the dot), the effects of coulomb interactions are evident, and the exchange-induced splitting between singlet and spin triplet excited states is clearly seen. Further, the addition of a magnetic field B leads to a crossing of the spin triplet excited state with the ground state, resulting in a different spin-polarized ground state at finite B, as had been seen by previous researchers (*3*, *8*). The analogous transition in real helium would only happen at nearly a million teslas because true helium is orders of magnitude smaller than its artificial counterpart, and a much larger field is thus needed to perturb its electron orbits. For pancake dots with more electrons, Hund's rules properly predict the behavior of the ground- and excited-state spectra, both at zero and finite B (*9*).

It is possible to do much better than just give a qualitative account of the results using the notions of 2D shell structure and exchange. Exact calculations of the spectra are possible for just a few electrons on the dot, and the quantitative agreement between theory and experiment is remarkable. These experiments beautifully illustrate that for a high-symmetry quantum dot of a few electrons, the ideas of atomic physics coupled with many-body quantum calculations can give a relatively complete qualitative and quantitative description of the observed behavior.

In the experiments of Stewart *et al.* (*6*), the dot was irregularly shaped and contained many electrons (see figure). As a result, there is no shell structure, and a simple classification of the quantum states in terms of their symmetries is not possible. Further, the large number of electrons, about 200, in this extremely "transuranic" artificial atom far exceeds the number that can be treated by exact calculations. As a result, many basic questions about the level structure remain a mystery. For example, it is not known whether the ground state of the dot is nonmagnetic, if the electrons fill up the quantum states in spin up–spin down pairs (*10*), or whether it is partially magnetic, if some spins are aligned as a result of the exchange interaction. It is also not known if the energy levels of a dot with $N + 1$ electrons bear any resemblance to the same dot with N electrons because the differing coulomb interactions may completely reorganize the states.

The experiments of Stewart *et al.* begin to address these questions. They examined the magnetic field dependence of the ground and excited states of this dot. The observed behavior is complex, showing many level crossings with increasing B. Nevertheless, there remains a strong correlation between the ground state of the $N + 1$ electron quantum dot and the first excited state of the N electron dot over a significant range of N. This relation means that the coulomb interactions do not completely reorganize the states. Surprisingly, it also implies that only one electron is added to each quantum level. One reason for this behavior may be that these electrons all have the same spin due to the exchange interaction. If this is true, then the dot is partially magnetic. Recent calculations by Stopa (*11*) support to this conclusion. Still, these experiments raise as many questions as they answer. A direct measurement of the magnetization of the dot would be highly desirable, as would more detailed studies of the correlations between the states of the dot with different numbers of electrons.

The systematic exploration of artificial atoms is thus well under way. The studies discussed above, combined with measurements of other geometries such as spherical dots (*12*) or 1D carbon nanotubes (*2*), are revealing how electrons behave in all confined geometries, not just in old-fashioned atoms. The next step is obvious: to assemble these atoms into artificial molecules (*13*) and solids (*14*). For example, Schedelbeck report in this issue on optical measurements of a quantum dot molecule (*7*). This two-dot molecule contains a single electron-hole pair, or exciton. It is thus analogous to the simplest real molecule, the positively charged hydrogen molecular ion. The optical spectrum clearly reveals the bonding and antibonding states of this artificial molecule, with the strength of the bonding determined by the distance between the two dots.

In spite of such recent achievements, much more work remains to be done in this area. The lack of uniformity of the artificial-atom building blocks and the relative crudeness of the assembly techniques imply that the molecular and solid-state physics of artificial atoms are fields for the next millennium.

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