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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