as just dating a rock. Instead, all methods rely on models of varying complexity involving assumptions difficult to verify and parameters difficult to measure. In addition, radiometric dating is generally formulated in terms of chemical events such as fractionation between parent and daughter elements. In the real history of Earth, the relevant chemical changes likely must be treated as protracted processes rather than instantaneous events. Perhaps most fundamentally, different isotopic systems record different chemical changes, and the relations of any of these changes to physical processes such as impact and accretion of mass remain uncertain.

For example, compared with the sun or undifferentiated meteorites, Earth is depleted in moderately volatile elements (for example, Rb) relative to refractory elements (for example, Sr). In undifferentiated materials, the Rb/Sr ratio is relatively high and so too is the rate of growth of the $^{87}Sr/^{86}Sr$ ratio due to decay of ^{87}Rb. At some point, Earth's materials experienced a transition to the much lower present Rb/Sr ratio and thus to much slower growth of $^{87}Sr/^{86}Sr$. The initial $^{87}Sr/^{86}Sr$ ratio for a volatile-poor planet such as Earth is usually taken to reflect the time of this transition, which is commonly considered to have occurred in a dispersed state before planetary accretion but which may be argued to have occurred as a result of accretion. The same might be true for the U (refractory)–Pb (volatile) system, but there is an added complication. If most of Earth's Pb is in the core, then our Pb chronology—which relies on outer Earth materials—might instead be dating core formation. The I-Pu-Xe system may be dating preaccretionary volatile separation as Pu is refractory, I is volatile, and Xe is even more volatile. But it might alternatively record loss of atmosphere after accretion was completed, for example, in a major late impact. Hf and W are both refractory but Hf is strongly lithophilic ("rock-loving") and W is moderately siderophilic ("metal-loving"). Their separation is usually taken to reflect metal-silicate fractionation, that is, core formation. If Hf-W separation occurred early, while ^{182}Hf was still present, the silicate will display excess ^{182}W and the metal will be deficient in ^{182}W (see the figure). In contrast, if separation occurred only late, after ^{182}Hf had already decayed, silicate and metal will both have the same composition. W in Earth's mantle has the same composition as W in undifferentiated meteorites (see the figure), thus indicating late core formation, but again this must be qualified by the possibility that it was only the last few percent of the W to accrete experienced such late metal-silicate formation.

If the moon were an independent planet, we would likely conclude that it was older than Earth. Similar to Earth's estimated age, the oldest lunar rocks (*9*), likely representing the first rocks formed from a lunar magma ocean, are about 100 million years younger than the solar system. But the moon's initial $^{87}Sr/^{86}Sr$ ratio is very low (*10*), indicating that it was depleted in volatiles within a few million years of the formation of the solar system. Also, in contrast to Earth, some of the moon's surface rocks do contain excess ^{182}W (see the figure), indicating preservation of reservoirs since the time when ^{182}Hf was still extant and could generate excess ^{182}Hf after metal-silicate fractionation. If the moon was indeed formed by a giant impact when the still-accreting Earth was struck by a planetary body nearly half its size (*11*), it seems most likely that this impact occurred about 100 million years after the solar system formed, that the moon was made largely from the impactor, and that the impactor had previously enjoyed an existence as an independent planetary body for a considerable time.

To help tie down the details, we need not so much more isotopic data but a better understanding of how the physical events that define planetary histories affect the chemical events and the radionuclide systems by which we reconstruct geological time. For testing the giant impact scenario (*1*) in particular, it would be useful to have a quantitative theory for whether a preexisting atmosphere is lost in the impact, whether preexisting planetary structures (core, mantle, and crust) are reequilibrated after such an impact, and how much of the moon comes from the impactor and how much comes from the target.

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PERSPECTIVES: CONDENSED MATTER PHYSICS

Pumping Electrons

B. L. Altshuler and L. I. Glazman

We usually associate electric current with a dissipative motion of electrons (*1*): The energy provided by an external source eventually becomes heat. However, examples of a current flowing without dissipation are also well known. For instance, a static magnetic field magnetizes a metal specimen by causing edge electric currents (Landau diamagnetism) (*1*). Moreover, a static magnetic flux threading a metallic ring induces a persistent current (*2*). The electrons remain in equilibrium, and energy does not dissipate. Pumping is also a way of transferring electric charges, but it is qualitatively different from both mentioned mechanisms. An experimental investigation of electron pumping through a quantum dot is reported by Switkes *et al.* (*3*) on page 1905 of this issue.

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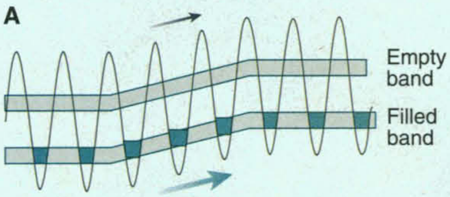
In pumping, periodic (ac) perturbations of the system yield a dc current. This current, though not an equilibrium response to an external perturbation, may be entirely adiabatic: The system always remains in the ground state. In contrast to the more familiar dissipative rectification of ac current, the charge transferred in each cycle of adiabatic pumping is independent of the period T. Therefore, at large T, pumping dominates.

A remarkably clear theoretical example of adiabatic electron pumping was given by Thouless (*4*). For simplicity, consider spinless electrons in a one-dimensional channel, subject to a potential $U(x)$ periodic along the channel: $U(x + a) = U(x)$. Provided the number of electrons na per period a equals an integer N, the lowest N bands of the energy spectrum are full while the higher bands are empty. Now let the potential move with some small velocity, $U(x,t) = U(x - vt)$. At each point x the potential $U(x,t)$ varies periodically with time, because $U(x)$ is translationally symmetric. If electrons follow adiabatically the variation of the potential, then a current $I = nev$ is induced. Over the period $T \equiv a/v$, a quantized charge $Q \equiv IT = Ne$ is transferred through any cross section of the channel (*4*).

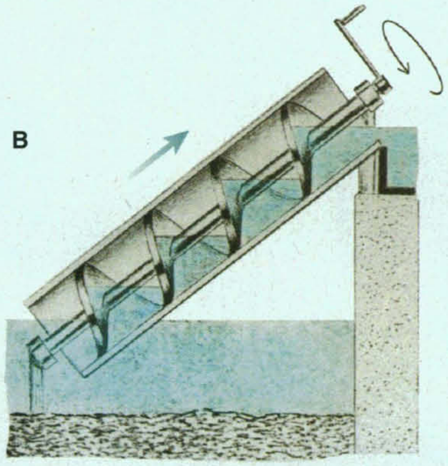
The quantization of the pumped charge is quite robust and survives, for example, in the presence of an additional smooth static potential (see the figure, panel A). The quantization holds, provided the "usual" dc conductance through the channel always remains at zero. Finite temperature and finite length of the system yield a nonzero conductance. The resulting electron counterflow, which is an analog of a leak in a water pump, affects the value of the total current. Indeed, the electron pump is quite reminiscent of the famous Archimedean screw (see the figure, panel B). Among other things, the pumped electric current may run against the applied bias.

Around and about. Adiabatic Thouless pumping of electrons (**A**) and water pumping by Archimedean screw (**B**). Shift of the potential by one period in A is similar to one turn of the screw handle in B (black arrows).

A



B



Recently (*5*) electron pumping by a traveling potential created by an acoustic wave in a semiconductor device was demonstrated. The Coulomb repulsion between the electrons residing in the minima of the moving potential enhances the energy gaps and thus improves the current quantization. This enhancement, known as Coulomb blockade, may eventually enable the use of the electron pump as an electron counter. Pumping electrons one by one was realized in a chain of Coulomb blockaded metallic islands separated by tunnel junctions (*6*).

The Thouless pump is a simple but insightful example. Although the potential varies periodically in time, something changes in the system after each cycle: Every potential minimum gets shifted by the period a. There would be no charge transfer if each minimum returned to its original position: A standing wave does not generate a dc current. On the other hand, the traveling wave $U(x - vt)$ can be presented as a superposition of standing waves. In the simplest case of $U(x) = U_0 \sin(2\pi x/a)$, the traveling wave potential is $U(x - vt) = U_1(t) \sin(2\pi x/a) + U_2(t) \cos(2\pi x/a)$ with $U_{1,2}(t) = U_0 \cos(2\pi t/T + \phi_{1,2})$ and $\phi_{1,2} = 0, \pi/2$. Therefore, although each standing wave alone is unable to pump the charge, two of them together can do it.

The time evolution of the potential can be described in terms of the "trajectory" $\partial\mathcal{U}$ of the system in the plane of parameters U_1,U_2. For the Thouless pump, $\partial\mathcal{U}$ is a circle. It turns out that the pumping takes place in a much more general situation. There should be two (or more) adiabatic perturbations, $U(x,t) = U_1(t)f_1(x) + U_2(t)f_2(x)$, with arbitrary (different from each other) spatial dependencies $f_{1,2}(x)$. At nonzero phase difference $\phi = \phi_1 - \phi_2 \neq 0$ between U_1 and U_2, the trajectory $\partial\mathcal{U}$ encircles a nonzero area in the parameter space; this is the condition for pumping to occur. Its importance has been clearly demonstrated by Switkes *et al.* (*3*) in their experiment with a quantum dot. To illustrate the meaning of this condition, consider first a quantum particle subject to a weak magnetic field. With each winding along a closed trajectory, it acquires a phase equal to the magnetic flux through the trajectory in units of h/e (the Aharonov-Bohm effect). This phase can be measured directly and causes, for example, the anomalous magnetoresistance (*7*). Berry demonstrated (*8*) that the Aharonov-Bohm phase is an example of a more general phenomenon. Suppose the Hamiltonian of a closed quantum system depends on parameters $U_i(t)$, which evolve adiabatically with time, and after a period T return to their original values. Simultaneously, the wave function of the system may acquire an additional phase (Berry phase), which depends on $\partial\mathcal{U}$. Similar to the Aharonov-Bohm phase, the Berry phase can be thought of as a flux (*9*) of some effective "magnetic field," known as an adiabatic curvature in the mathematical literature (*10*), through the contour $\partial\mathcal{U}$. The difference is that both the contour and the "magnetic field" exist in the parameter space rather than in the real space. The pumped charge is a "magnetic flux" too. It can be presented either as a contour integral of some "vector potential" along $\partial\mathcal{U}$, or as an integral of the effective "magnetic field" over the area inside $\partial\mathcal{U}$. This field can be specified (*11*, *12*), given the dependence of the electron scattering amplitudes on U_i. Therefore, the pumped charge is determined by the size and shape of "trajectory" $\partial\mathcal{U}$, changes its sign with the phase difference ϕ, but does not depend on the distribution of "velocities" dU_i/dt along the "trajectory."

The quantization means that small deformations of $\partial\mathcal{U}$ do not affect the pumped charge. This is possible only if the generalized magnetic field vanishes in some domain of the parameter plane. In general it is not zero, and the charge is not quantized (*13*). A nice example for such a behavior is provided by small open conductors with quenched disorder. Properties of such (mesoscopic) systems are known to exhibit mesoscopic (sample-specific) fluctuations. The fluctuations of the pumped charge turn out to be much bigger than its averaged value (*13*). These fluctuations result from the electron interference and are generically of quantum nature, as in the Switkes *et al.* case. The magnitude and even the sign of the pumping current depend, for instance, on a weak magnetic field that affects the interference pattern for the electron waves. The measurements of Switkes *et al.* (*3*) agree with the main predictions (*11*, *13*) at small pumping amplitudes. The amplitude dependence of the pumped current is yet to be understood.

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