Levitation in Physics

E. H. Brandt

Several physical effects allow free floatation of solid and even liquid matter. Materials may be levitated by a jet of gas, by intense sound waves, or by beams of laser light. In addition, conductors levitate in strong radio-frequency fields, charged particles in alternating electric fields, and magnets above superconductors or vice versa. Although levitation by means of ferromagnets is unstable, superconductors may be suspended both above and below a magnet as a result of flux pinning. Levitation is used for containerless processing and investigation of materials, for frictionless bearings and high-speed ground transportation, for spectroscopy of single atoms and microparticles, and for demonstrating superconductivity in the new oxide superconductors.

The phenomenon of levitation has always attracted wide attention. Although magicians have perfected tricks to demonstrate seemingly free floatation of objects and parapsychologists investigate levitation claimed to have been caused by supernatural mental forces, physicists have studied a series of effects that allow true levitation of solid and even liquid matter. The problem here is not so much to find invisible contact-free forces. Force fields with action at a distance abound in physics. The main problem in the physics of levitation is stability: the levitated body should not slip sideways but should be subjected to restoring forces in all directions horizontally and vertically when it is slightly displaced from its equilibrium position. In this article I discuss intrinsically stable levitation mechanisms. Levitation stabilized by sensing and controlling the position electronically I shall not discuss here.

The search for systems that exhibit stable levitation poses an interesting physical problem. In 1842 Earnshaw (*1*) proved that stable levitation or suspension is impossible for a body placed in a repulsive or attractive static force field in which force and distance are related by an inverse square law. Examples of such systems are the forces between electric charges, magnetic monopoles, and gravitating masses. From Earnshaw's theorem one might conclude that levitation of charged or magnetic bodies is not possible, but this is not generally true. For example, dynamic phenomena may stabilize the levitation in oscillating force fields. This stabilization may be illustrated with a pendulum that consists of a stiff rod with a weight attached. Usually, the pendulum has only one stable equilibrium position at the lower resting point. When its pivot is subjected to vertical oscillations, however, the upper turning point (the position of farthest travel) also may become a position of stable equilibrium. Similarly, stable levitation is possible for charged particles in a quadrupolar electric field that oscillates, for example, at a frequency of 60 Hz (see below). Furthermore, quantum effects allow the stable levitation of electrons and of atoms carrying a magnetic moment in electric or magnetic fields.

Earnshaw's theorem applies only to individual particles. Extension of the analysis to dielectric and magnetizable bodies, both of which involve dipoles, shows that stable levitation is possible for diamagnetic and superconducting bodies in static magnetic fields (*2*, *3*). The levitation of superconductors is a most conspicuous phenomenon. It is really static (requires no energy input), quiet, and exceedingly stable. A superconductor levitated above a permanent magnet (see Fig. 1) or a magnet levitated above a flat superconductor may have a continuous range of stable equilibrium positions or orientations that allow it to levitate motionless as if it were stuck in sand. The invisible frictional force that holds it fast originates from the pinning of the magnetic flux inside the superconductor. This phenomenon will be described at the end of this article.

Other types of stable levitation include aerodynamic, acoustic, optical, electric, magnetic, and radio-frequency (rf) levitation. Some of these methods are used for the containerless melting and processing of metals or ceramics even at temperatures above 2000 K, for zone refining and degassing in ultrahigh vacuum, and for studies of creep and plastic deformation caused by centrifugal forces in a rapidly spinning niobium sphere. Some of these levitation methods allow contact-free positioning of samples in experiments in space or

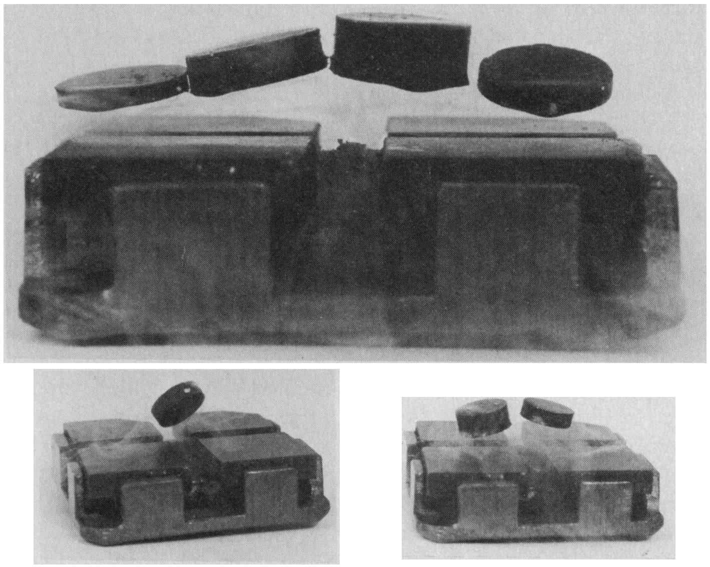

Fig. 1. Disks (12 mm in diameter) of the oxide superconductor YBa$_2$Cu$_3$O$_{7-\delta}$ levitated above a permanent magnet with one central north pole and four south pole sections. The vertical and horizontal inhomogeneity of the magnetic field in connection with the pinning of magnetic flux lines inside the superconductor causes strong friction that damps oscillation and rotation of the disk and holds it rigidly levitated within a continuous range of possible stable positions and orientations.

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are used in spectroscopy of microparticles and single atoms or ions. Technical applications include frictionless bearings and high-speed ground transportation.

Aerodynamic Levitation

In aerodynamic levitation a spherical specimen is lifted by a fluid jet. Stability in the vertical direction results from the divergence of the jet, which leads to a decreasing drag with increasing height. In the transverse direction this levitation is stable because the jet is deflected toward an off-axis specimen. This asymmetry, or the increased Bernoulli force at the side where the flow is faster, produces a centering force that leads to stable levitation of a ball even by a tilted jet of water or air (Fig. 2). Because of the friction of the fluid at its surface, an off-axis sphere rotates rapidly; the resulting Magnus force leads to an additional (retarded) centering force that further increases the lateral stability. Both the Bernoulli and the Magnus forces are caused by the Bernoulli pressure $-\rho v^2/2$ in a fluid with density ρ and local velocity v.

Levitation by subsonic and supersonic free jets of air or argon at pressures down to 1 torr has been used to heat beads of hard materials (steel, glass, or boron nitride) with diameters of ≈ 4 mm in a containerless fashion. Heating to temperatures above 2000 K is achieved by an elliptical radiant heater (*4*) or by laser radiation (*5*). Sapphire spheres were melted in this way; upon melting, the liquid sphere remained stable for 5 to 10 s; then radial oscillations appeared and grew until the specimen struck and stuck to the nozzle (*5*). Such vibrational instabilities appear to thwart the effective aerodynamic levitation of liquids (*5, 6*).

A further application of aerodynamic levitation is the contact-free positioning of nonconducting samples under the condition of microgravity in space (*6, 7*). A sphere in a constricted tube with air flow (see Fig. 2) exhibits a stable equilibrium position close to the constriction because it is both blown away from the nozzle by drag and drawn to it by an upstream Bernoulli force. This simple levitator is essentially independent of orientation and gravity.

In a delicate experiment (*8*) intended to produce targets for the SHIVA laser fusion facility at Lawrence Livermore National Laboratory, a collimated hole structure made of glass was utilized to direct streams of argon molecules at a pressure of 0.02 to 0.4 torr on a hollow glass microsphere with a diameter of 100 to 200 μm and a mass of less than 1 μg. This system levitated the microsphere to a height of 150 μm and allowed it to be coated with a 3-μm-thick homogeneous layer of copper by dc sputtering.

Acoustic Levitation

A second method for the containerless processing of insulators is levitation by high-intensity sound waves. In contrast to levitation in fluid jets, this elegant (but noisy) method allows stable levitation even of liquid drops or shells (*9, 10*). Even steel balls 1 cm in diameter have been levitated by a 1-kW siren operating at 3260 Hz (*11*). The theory of acoustic levitation is well understood (*12*). In essence, the gravitational force is counteracted by a steady-state acoustic radiation force, which is the result of a nonlinear effect in the laminar flow around a body whose size is much smaller than the wavelength of sound. The force that attracts the levitated body to maxima in the sound intensity originates from a gradient in $-\rho\langle v^2\rangle/2$. This is just the time-averaged Bernoulli pressure and the (negative) energy density of the wave. The radiation force is much larger in standing than in running waves.

In typical experiments, the high-intensity ultrasonic field is that of a standing wave of 20 to 40 kHz generated by a piezoelectric transducer, for example, prestressed lead zirconate-titanate (PZT) disks (*9*), faced by a flat or concave reflector (Fig. 3). Configurations with one rotationally symmetric axis allow free access to the sample along all perpendicular directions. The axial and radial variation of the acoustic pressure must be tailored to maximize the stability of the levitated sample.

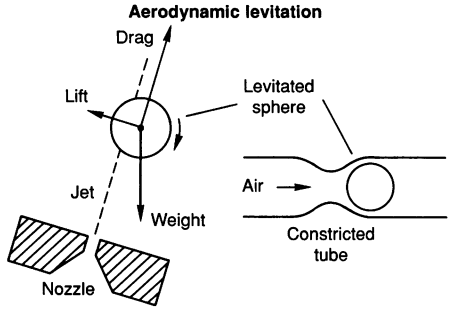

Fig. 2. (**Left**) Drag and lift on a sphere levitated in an inclined jet of air. (**Right**) A constricted tube levitator working with or without gravity.

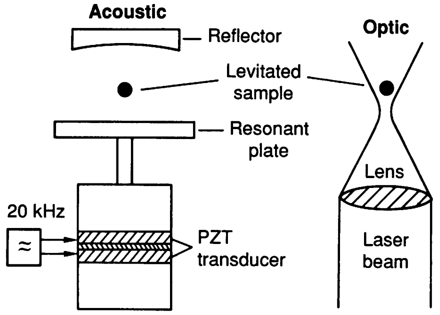

Fig. 3. (**Left**) Acoustic levitation in a standing sound wave. (**Right**) Optical levitation of a dielectric particle in a vertical laser beam. Other positions of stable levitation are possible in opposing beams or with different beam modes.

Acoustic levitation has been used to determine the properties of molten materials in their stable and metastable states. Undercooling to 0.7 times the melting temperature has been achieved (*9*), and the equilibrium shape and stability of liquid drops and shells were studied (*9, 10*). The shells were generated by injecting gas into a levitated drop. From the decay rate of the shape oscillations one can determine the viscosity of the liquid. Surface tension–dominated fluid dynamic phenomena, found with free liquids in the low gravity of space, can be studied by acoustic levitation in a liquid host that compensates for gravity (*9*). Additional interesting applications were discussed at a recent conference of the Acoustical Society of America (*13*).

Optical Levitation

Radiation pressure exerted on matter by light was probably first suggested by Kepler in 1619 when he used this hypothesis to explain why comet tails always point away from the sun. Today we know that this explanation was correct and that light absorbed, reflected, or diffracted by a body exerts a force on it that is proportional to its intensity. The problem of a plane wave diffracting around a transparent spherical particle was first solved by Mie (*14*), and from this exact solution of Maxwell's equations Debye calculated the force on the particle (*15*). The resulting expression is a power series in $x = 2\pi R/\lambda$, where R is the radius of the particle and λ is the wavelength of light. With increasing x, the force oscillates more and more rapidly as a result of resonances caused by multiple scattering of the light inside the particle. In the limit $x >> 1$, the radiation pressure on large absorbing particles is just given by the energy density in the light, which is similar to the case of the sound wave discussed above. The pressure on reflecting particles is higher (for an ideal flat mirror by a factor of 2) because reflection reverses the momentum of light.

With the advent of laser light sources of high intensity, spectral purity, and spatial coherence, optical levitation of microparticles became possible in the laboratory (*16, 17*). Two methods have been used to trap particles, (i) vertical laser beams (see Fig. 3) and (ii) two opposing horizontal laser beams with nearly coinciding foci. Particles up to 120 μm were either dropped into the zone of stable levitation or thrown up by a piezoelectric vibrating support until one of them became trapped. Various positions of stable levitation exist near the focus, depending on the diameter and mode of the beam and on the size and refractive index n of the particle (*17–19*). Small transparent particles with $n > 1$ are attracted to the focus because the laser field (in the "TEM_{00}" mode) decreases in all directions away from the focus. Reflecting and opaque particles are also attracted. Even assemblages of more than a dozen spheres can be trapped and locked in stable rigid arrays in a single beam (*20*). Gas bubbles in water can be held in a stable equilibrium by the downward-directed beam of a laser operated in a mode that gives an irradiance minimum at the center of the beam (*21*). The optical resonances predicted by Mie (*14*) have been observed in glycerol with water droplets levitated by a laser beam (*22*). More applications to microparticles and bacteria have been discussed by Ashkin (*18*) and by Ashkin and Dziedzic (*19*) ("optical tweezers").

A fascinating application of optical levitation is the trapping of a few or even single atoms by a laser beam (*23*). On the one hand, the radiation pressure resulting from the absorption of photons by the atom (real excitations) pushes the atom along the beam. On the other hand, when the laser field is tuned below the absorption frequency, a dipolar force (gradient force) pulls the atom into the strongest part of the field. This mistuning leads to virtual excitations of the atom, which decelerate the light in a manner similar to the effect of a positive refractive index. If the laser beam is tightly focused and is tuned far enough away from the absorbing frequency, then the dipolar force can overcome the radiation pressure and the atom can be trapped.

Trapping of atoms is possible only if the atoms are "cooled," that is, if their thermal motion is very slow. Free atoms can be cooled and even stopped if a laser beam is directed against an atomic beam (*23*). If the laser beam is appropriately tuned, its radiation pressure will slow down the atoms (*24*) until they are "cold" enough to be trapped in optical, electric, or (very shallow) magnetic traps. Optical cooling and trapping of ions and atoms have been used primarily for spectroscopy, but further applications are suggested in the reviews (*23*).

Electric Levitation

The four levitation methods discussed thus far create dissipative states of stationary equilibrium and thus require the input of energy. Is dissipation-free levitation possible by a static electric field? A stable equilibrium requires that any small displacement of the body leads to restoring forces. Equivalently, the potential $U(\mathbf{r})$ of the force vector $\mathbf{F} = -\nabla U$ must have a local minimum at the equilibrium position. The particle then remains stationary or oscillates in a potential well. Now let us consider two cases. First, a particle with charge q in an electric field $\mathbf{E} = \nabla\phi$ has the potential energy $U = -q\phi$, where ϕ is the electrostatic potential. Second, an uncharged particle with volume V and dielectric constant ε in a medium with dielectric constant ε_0 exhibits an energy $U = -(V/2)(\varepsilon - \varepsilon_0)E^2$. This result follows from the dipolar force $V(\mathbf{P}\cdot\nabla)\mathbf{E}$, the polarization $\mathbf{P} = (\varepsilon - \varepsilon_0)\mathbf{E}$, and the relation $(\mathbf{E}\cdot\nabla)\mathbf{E} = (1/2)\nabla E^2$.

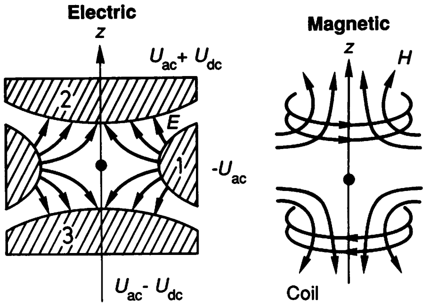

Fig. 4. (**Left**) Levitation of a charged particle in a quadrupolar electric field E oscillating at 60 Hz (U_{ac}). Electrode 1 is a ring with hyperbolic cross section, and electrodes 2 and 3 are hyperboloids. The arrows denote field lines of E. A small constant field (U_{dc}) compensates for the weight of the particle. (**Right**) Levitation of a diamagnet, or of an atom carrying a magnetic moment, in a static quadrupolar magnetic field H generated by two coaxial coils with opposing currents (magnetic trap).

If the particle is surrounded by a medium containing no space charge, then the Maxwell equations $\nabla\cdot\mathbf{E} = 0$ and $\nabla \times \mathbf{E} = 0$ apply; from these it follows that $\nabla^2\phi = 0$ and $\nabla^2 E^2 \geqq 0$. Because $\varepsilon \geqq \varepsilon_0$ (negative polarizabilities are never observed), one concludes that charged bodies exhibit $\nabla^2 U \equiv U_{xx} + U_{yy} + U_{zz} = 0$ and dielectric bodies $\nabla^2 U \leqq 0$. Therefore, in both cases at least one of the three curvatures U_{xx}, U_{yy}, or U_{zz} must be negative and U cannot have an isolated minimum. Stable levitation by an electrostatic field in vacuum or air is thus not possible. However, stable levitation of gas bubbles in water ("particles" with $\varepsilon < \varepsilon_0$) is possible.

The above impossibility does not apply to time-dependent electric fields. Various cases of stable levitation are indeed possible in oscillatory electric fields.

1) At high frequencies ν, the relation $\nabla^2\phi = 0$ is replaced by $\nabla^2\phi = (2\pi\nu/c)^2\phi$, where c is the velocity of light. It is essentially the different relation that allows the levitation of dielectric particles with extension larger than or comparable to the wavelength c/ν of the electromagnetic field, which is the case in the optical levitation discussed above.

2) The magnetic field generated by time-dependent electric fields makes possible the rf levitation of conducting bodies by induced eddy currents.

3) Even at low frequencies of $\nu \approx 60$ Hz, where $\mathbf{E}$ may be treated as quasi-static (that is, $\nabla^2\phi = 0$ holds), stable levitation of a charged particle is possible because of an interesting dynamic effect (*25*). In a sinusoidally time-varying force field whose strength is proportional to the distance from a central origin, dynamic stabilization occurs that is analogous to alternating gradient focusing in particle optics. For example, in a quadrupolar field $\phi(x,y,z,t) = A(x^2 + y^2 - 2z^2)\sin\omega t$, where A is a constant and the angular frequency $\omega = 2\pi\nu$ (see Fig. 4), a particle of charge q and mass m oscillates vertically (along z) with a phase shift (with respect to ϕ) such that, after time averaging, a positive restoring force $F = -K\langle z\rangle$ results. For weak ac fields the effective spring constant is (*26*) $K = 8A^2q^2/\omega^2 m$. If the displacement caused by gravity $\langle z\rangle$ is compensated by an additional dc field, then the particle can be brought back to the point $x=y=z=0$, where $\mathbf{E} = 0$ and where its oscillation amplitude thus vanishes. Such dynamic traps have been applied to study the photoemission of microparticles (*26, 27*) and to trap cold ions (*23*). For the trapping of ions or electrons, frequencies of several megahertz are required (*25*).

4) Another type of dynamic electric suspension uses an LCR circuit (L = inductance, C = capacitance, R = resistance) tuned such that the attractive force between the capacitance electrodes increases with increasing distance (*3*). This principle has been applied to vacuum gyroscopes (*28*).

5) Quantum effects allow the stable levitation of electrons above the surface of liquid helium at a distance of $\approx 10^{-8}$ m (about 30 atomic spacings). The electrons can move freely parallel to this

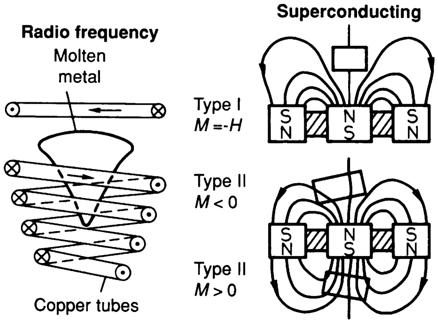

Fig. 5. (**Left**) Levitation of a liquid metal in a radio-frequency field of 400 kHz. The coil consists of water-cooled copper tubes. The counter winding above the sample stabilizes levitation. (**Right, top**) Levitation of a type I superconductor in the perfect Meissner state above permanent magnets of cylindrical or other symmetry. A type I superconductor has only one stable equilibrium position and may oscillate or orbit about it without damping. (**Right, bottom**) Levitation of a type II superconductor above or below the same permanent magnet. A range of stable equilibrium positions and orientations exists as a result of hysteresis effects caused by flux-line pinning. The levitated sample expels part of the magnetic flux (internal field H_i < external field H). The suspended sample attracts magnetic field lines because some flux is trapped in it ($H_i > H$).

surface and form a two-dimensional lattice (Wigner crystallization), which exhibits novel physical properties and provides the lateral stabilization (*29*).

Magnetic Levitation

Truly stable levitation without consumption of energy is possible only in magnetic fields. As with the electrostatic field, one can show that the potential energy of a magnetizable body with permeability μ in a static magnetic field $\mathbf{H}$ in a medium containing no current is $U = -(V/2)(\mu - \mu_0)H^2$ (μ_0 is the permeability of free space) and that $\nabla^2 H^2 \geqq 0$ always holds. The strict inequalities $\nabla^2 E^2 \geqq 0$ and $\nabla^2 H^2 \geqq 0$ mean that static electric or magnetic fields cannot have isolated maxima (*30*). They may well have isolated minima, for example, between two equal electric or magnetic poles as shown in Fig. 4. Because stability requires $\nabla^2 U > 0$, we see that in static magnetic fields paramagnets ($\mu > \mu_0$) and ferromagnets ($\mu >> \mu_0$) cannot levitate freely but diamagnets ($\mu < \mu_0$) and superconductors ($\mu = 0$) can. These are repelled by magnetic poles and attracted to field minima.

Another type of magnetic levitation is the result of a quantum effect. Cold (*24*) neutral atoms with their magnetic moments oriented parallel to $\mathbf{H}$ may be trapped in a minimum of the magnetic field (Fig. 4). The force is the same as that used in the famous Stern-Gerlach experiment to deflect atoms (*31*). A classical magnet would flip and orient its magnetic moment antiparallel to $\mathbf{H}$ and would then be ejected from the minimum. In contrast, a quantum magnet exhibits a finite lifetime in this energetically unfavorable excited state.

Whereas the levitation of diamagnetic beads of bismuth or graphite (*2*) seems to be of no more than academic interest, the levitation of superconductors is most spectacular and promising. Many tons may be lifted, as has been demonstrated in Japan and Germany by full-scale prototype models of high-speed trains (*32*). For the application of magnetic and superconducting levitation to high-speed bearings and ground transportation, the reader is referred to the review by Jayawant (*3*). For such large-scale applications, stability and damping in the horizontal and vertical directions is particularly important. As for trains, several types of magnetic levitation have been successfully tested.

1) Levitation by strongly repulsive permanent magnets must be combined with rollers for horizontal guidance or with controlled electromagnets.

2) Levitation with superconductors may be based on the perfect diamagnetism in the Meissner state that allows stable levitation of a superconductor in magnetic fields generated, for example, by a superconducting coil.

3) Alternatively, the levitation may rely on the repulsion between a superconducting magnet and a conducting plate or guideway on which it moves (*32*). This repulsion originates from the eddy currents in the plate that cause both lift and drag. Interestingly, the drag (caused by the ohmic loss in the plate) decreases as the velocity of the vehicle increases. This is so because at high velocities almost all the energy in the eddy currents generated by the front end of the magnet is regained when the rear end of the magnet passes by; at low velocities part of the wake of the eddy current has decayed by then.

4) Levitation may use the eddy currents generated in a conducting plate by an ac coil. Such ac levitation systems may also provide the propulsion of the vehicle by a linear induction motor.

5) Suspension with controlled dc electromagnets has become feasible with the appearance of high-power electronics. Although not as elegant as the other levitation techniques, this method is reliable and provides the only levitation system for ground transport that continues to be used in Germany (*33*).

Radio-Frequency Levitation

An important levitation technique for applications in materials science is the levitation of solid or liquid metals in strong rf fields generated by a coil of appropriate shape (Fig. 5). This levitating mechanism is related to magnetic levitation. The rf field induces eddy currents in the surface of a conductor, the field of which cancels the applied field inside the specimen. An rf field of frequency ν, therefore, penetrates a specimen with electric conductivity σ only to within the skin depth $\delta = (\pi\sigma\mu\nu)^{-1/2}$. If δ is much smaller than the radius R of a spherical sample, the rf field is screened from the interior even as a magnetic field is screened from a superconductor in the Meissner state. The sphere is then expelled from the rf field H_{rf} by a force $\mathbf{F} = -\pi\mu_0 R^3 \nabla H_{\text{rf}}^2$ (*30*).

This levitation technique has been applied to containerless melting and zone refining of metals (*34*) and has been used for the calorimetry of liquid metals (*35*). It was further used to decarburize and degas monocrystalline niobium spheres up to 9 mm in diameter in ultrahigh vacuum (*36*). The levitated niobium sphere starts to rotate and spins faster and faster until it deforms plastically as a result of centrifugal forces. The origin of this spinning is not completely understood. The spinning may be controlled by applying a transverse dc magnetic field that induces eddy currents in the specimen, and the combination of rf levitation and eddy current damping has been used to study the plastic deformation and steady-state creep of a niobium crystal at high temperatures in a contact-free way (*36*).

Superconducting Levitation

The stable levitation of a superconductor above a permanent magnet or vice versa has fascinated physicists since the discovery of the phenomenon of superconductivity in 1911 (*37*). Strong repulsive forces cause a very stable and quiet levitation, which, apart from cooling, requires no energy input. With the discovery of copper oxide–based superconductors (*38*), which remain superconducting up to critical temperatures T_c of 90 K (*39*) or even 125 K (*40*), the demonstration of levitation became even more impressive. Whereas conventional superconductors must be cooled to liquid helium temperatures (4.2 K) in an expensive cryostat, the oxides may be operated in inexpensive liquid nitrogen, which boils at 77 K under atmospheric pressure.

Type I superconductors. Usually the observed levitation is ascribed to the perfect diamagnetism ($\mu = 0$) of a superconductor in the Meissner state. This is indeed true for most pure metals, for example, lead or tin. At temperatures $T < T_c$ and applied magnetic fields $H < H_c(T)$ depending on T, these type I superconductors expel all magnetic flux from their interiors. The screening currents, which achieve this by exactly compensating the applied field in the interior by their own field, flow in a thin surface layer of thickness $\lambda \approx 0.1$ μm [the London penetration depth for weak magnetic fields (*41*)]. Levitated type I superconductors have one stable equilibrium position about which they may oscillate, rotate, or orbit with almost no damping (Fig. 5 and the two upper plots in Fig. 6).

Type II superconductors. More important for applications are type II superconductors, which exhibit a different magnetic behavior. Most alloys, the metals niobium and vanadium, and the new oxides belong to this class. Type II superconductors have a Ginzburg-Landau parameter $\kappa > 0.707$, whereas type I superconductors exhibit $\kappa < 0.707$ (*41, 42*). Because the new oxides exhibit $\kappa \approx 100$, they are of extreme type II. Type II superconductors are in the Meissner state at very low fields $H < H_{c1}(T)$ and become normally conducting in the bulk at quite high (compared to type I superconductors) fields $H > H_{c2}(T) \approx (2\kappa^2/\ln \kappa)H_{c1}(T)$. For the oxides, $\mu_0 H_{c1}$ is of the order of 100 G and $\mu_0 H_{c2}$ is extrapolated to over 10^6 G at $T = 0$. As T approaches T_c, both H_{c1} and H_{c2} vanish.

The flux-line lattice. In the large-field range $H_{c1} < H < H_{c2}$ magnetic flux penetrates a type II superconductor in the form of magnetic flux lines. These are tiny current vortices of radius λ carrying one quantum of magnetic flux $\phi_0 = 2.07 \times 10^{-7}$ G-cm^2. The flux lines repel each other and in the ideal case form a regular triangular lattice. This flux-line lattice was predicted from Ginzburg and Landau's successful theory of superconductivity (*42*) by Abrikosov (*43*). Later it was observed in an electron microscope after the superconducting sample was decorated with tiny ferromagnetic particles ("magnetic smoke") in niobium (*44*) and recently also in the oxides (*45*). Brandt and Essmann have recently reviewed this field (*46*).

Flux-line pinning. In a real type II superconductor the flux lines are pinned by inhomogeneities in the material, for example, by crystal lattice defects, grain boundaries, or precipitates of a different phase (*47*). This flux pinning has several important consequences. The first effect of pinning is that when an electric current is applied to a pin-free (ideal) type II superconductor, the flux lines will be moved by a Lorentz force. Moving flux lines, however, induce a voltage drop, and the superconductor would then no longer be ideally conducting. Pinning of flux lines is thus essential for applications of type II superconductors.

The maximum loss-free current density j_c that the pinned flux lines can support has been studied by numerous experiments and theories (*48*). The forces exerted by individual pins must be calculated from microscopic theories and then be summed statistically to yield the average pinning force density $j_c B$. This summation depends sensitively on the elastic and plastic properties of the flux-line lattice, as can be seen from the following arguments. An ideally rigid flux-line lattice cannot be pinned by randomly positioned pins because its flux-line positions are not correlated with the pins. The average pinning force thus vanishes. In the opposite limit, a very soft flux-line lattice completely adjusts to the pins such that each pin can exert its maximum force. As yet, a generally applicable summation theory does not exist, but for weak pins the "theory of collective pinning" has proven successful (*49*). Pinning in the granular oxides has been reviewed elsewhere (*50*).

Magnetization curves. A second effect of flux pinning is that the field inside the superconductor depends on its previous history. The magnetization curves of a real type II superconductor are thus hysteretic (see the two lower plots in Fig. 6). In an increasing field the sample contains less flux than at the same H value in a decreasing field. At zero applied field, $H = 0$, flux may be trapped such that the specimen behaves as a permanent magnet. Flux trapping in decreasing fields leads to the free suspension of a superconductor not only above (*51*) but also below (*52*) a permanent magnet.

Hysteretic forces. A third consequence of flux pinning is the existence of hysteretic magnetic forces. Hysteresis of both the vertical and the horizontal levitation forces (*53*) and of the torque on a rotating superconductor (*54*) has been measured recently in the oxides. The force on a small superconductor of volume V magnetized parallel to $\mathbf{H}$ is $\mathbf{F} = \mu_0 V M(H) \nabla H$ ($H = |\mathbf{H}|$). From this expression the hysteretic force field, in principle, may be calculated when the magnetization curve $M(H)$ and the spatially varying field $\mathbf{H}(\mathbf{r})$ are known. For example, if $\mathbf{H}$ is a dipolar field, one has $H \sim z^{-3}$ and $\nabla H \sim z^{-4}$ along the vertical z axis and the vertical levitation force is $F = CM(H)H^{4/3}$, where C is a constant (*55*).

This model, depicted in Fig. 6, illustrates that a continuous range of stable equilibrium positions may exist, not just two stable positions as supposed by various investigators (*51, 53*). When the superconductor is pushed down onto the magnet and released, it returns to its lowest equilibrium position provided pinning is weak. It also lifts off when it is cooled below T_c on the magnet. However, when pinning is stronger, the superconductor in both cases does not lift off but stays on the magnet. For even stronger pinning the superconductor has a continuous range of stable equilibrium positions both above and below the magnet. It may then be levitated or suspended. Suspension has indeed been observed recently (*52*).

Friction in a levitated superconductor. A fourth effect of the pinning, or rather of the unpinning, of flux lines is a strong frictional force

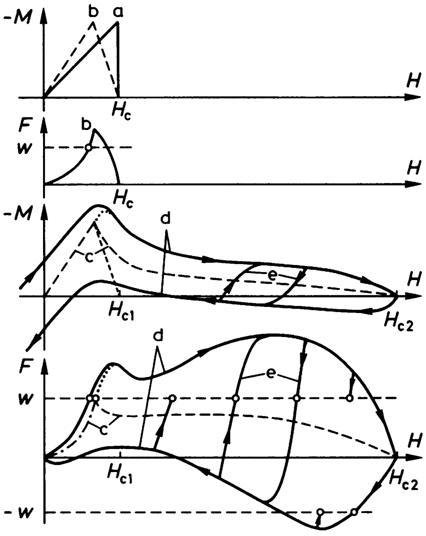

Fig. 6. Magnetization $M = H_i - H$ (internal minus external field) of superconductors and the levitation force on these in a dipolar field of local strength H, F = const. × $MH^{4/3}$. The levitation height z is related to H by $H \sim z^{-3}$. Stable levitation or suspension is possible at points (denoted by circles) where $F(H)$ has a positive slope and intersects the lines $F = \pm w$ (w is sample weight). At intersections with a negative slope the equilibrium is unstable in the vertical direction. Curve a: Type I superconductor, long cylindrical sample parallel to the field, ideal Meissner state for $H < H_c$. Curve b: Same as curve a but for spherical samples. Because of demagnetization effects, the flux starts to penetrate at the equator when $H = (2/3)H_c$. Curve c: Type II superconductors without flux-line pinning, "ideal" magnetization curve of a sphere. Curve d: The same superconductor with pinning. The dotted line is the virgin curve. When H is cycled between $-H_{c2}$ and H_{c2}, then $M(H)$ is symmetric to the origin. This hysteretic "real" magnetization curve yields one stable levitation point ($F > 0$), reached by approaching the magnet from above, and one stable suspension point ($F < 0$), reached by lowering the superconductor from the magnet. Curve e: Many more stable positions (in fact, a continuous range) may be reached by pushing the sample toward or away from the magnet. The resulting small change in H causes a large relative change in M (along a hysteresis loop) because initially the internal field stays constant until the flux lines unpin.

experienced by levitated type II superconductors. This internal friction is most spectacular when the superconductor is levitated above a magnet of low symmetry, for instance, with four south pole sections and one central north pole (Fig. 1). Motion in such strongly inhomogeneous fields changes the magnetic flux through the superconductor and leads to unpinning of flux lines. Unpinning occurs first at the specimen surface and then deeper in the bulk. The "plucked" flux lines jump to new equilibrium positions. During such jumps they dissipate part of their elastic energy (i) by eddy currents that must pass through the normal conducting vortex core and (ii) by the relaxation of the superconducting order parameter at the rim of the vortex core (*41*). The resulting frictional force may be calculated from the hysteresis loops in the irreversible magnetization curve.

Rigid levitation. As a consequence of this "dry friction," a levitated type II superconductor behaves as if it were stuck in sand. It can be pushed to a wide range of positions and orientations and then will remain there rigidly, without swinging or rotating. Such rigid levitation is also observed when a permanent magnet floats above a type II superconductor with sufficiently strong pinning. This spectacular friction is unique to superconducting levitation. In some ways this effect is more fascinating than the levitation itself. One can "feel" the existence and pinning of flux lines directly by pushing a levitated oxide superconductor with one's finger.

Orbiting. Above magnets with a rotationally symmetric vertical axis, a superconductor even with strong pinning and of odd shape can orbit about this axis for a long time, damped only weakly by the eddy currents it induces in the magnet or its holder. In its orbit it always turns the same surface toward the symmetry axis, just as the moon does when orbiting the earth. During this type of motion any point on the surface of the specimen "sees" a time-independent magnetic field. Therefore, no flux will move and no energy is dissipated.

Swinging. Weakly damped swinging of a levitated superconductor is possible near the symmetry axis of the magnet or near the points where H changes only quadratically in at least one spatial direction. The damping increases rapidly with increasing amplitude of the oscillation. Such an amplitude-dependent hysteretic damping has been observed also in cantilevered vibrating "reeds" (*56*). When a superconducting reed or beam is cooled below T_c in an applied longitudinal field, the frequency and attenuation of its flexural vibrations increase drastically by factors up to 10 and 10^4, respectively.

Applications. Because it is necessary to cool conventional superconductors with liquid helium, superconducting levitation has found application mainly in physics laboratories. Flux pinning and flux creep in superconductors may be investigated by levitation (*53, 54*), and prototypes of trains levitated by superconducting coils exist (*32*). Several high-precision experiments use levitated superconductors.

For a precise absolute determination of the quantum of flux ϕ_0, an aluminum cone 1 mm in diameter coated with (superconducting) lead is levitated above a superconducting coil (*57*). The levitation height is measured by a laser interferometer, the coil current by a superconducting quantum interference device (SQUID), and the coil voltage by counting the voltage steps in a Josephson junction (each step equals ϕ_0 times the applied rf). From these data ϕ_0 can be calculated.

Future directions. Sensitive levitation systems with tiny niobium spheres are being used in the search for fractional electric charges $\pm e/3$ (e is the charge on the electron) (*58*). Their detection would indicate the existence of free quarks, elementary particles that theorists believe to be bound inside atomic nuclei.

The discovery of the oxide superconductors has also led to educational levitation kits. Recently levitation has been used to measure the transition temperature T_c of very small oxide crystals under a microscope and to separate particles of different T_c (*59*). Intensive research on high-temperature superconductors may lead to new ideas for the application of superconducting levitation and suspension.

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60. I thank my colleagues, in particular U. Essmann, for helpful discussions about this topic.

Contingent Genetic Regulatory Events in T Lymphocyte Activation

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Interaction of antigen in the proper histocompatibility context with the T lymphocyte antigen receptor leads to an orderly series of events resulting in morphologic change, proliferation, and the acquisition of immunologic function. In most T lymphocytes two signals are required to initiate this process, one supplied by the antigen receptor and the other by accessory cells or agents that activate protein kinase C. Recently, DNA sequences have been identified that act as response elements for one or the other of the two signals, but do not respond to both signals. The fact that these sequences lie within the control regions of the same genes suggests that signals originating from separate cell membrane receptors are integrated at the level of the responsive gene. The view is put forth that these signals initiate a contingent series of gene activations that bring about proliferation and impart immunologic function.

ALTHOUGH THE PRECURSORS FOR MOST T CELLS ARISE IN the bone marrow, only after migration to the thymus do they differentiate to express receptors capable of interacting with antigen (*1*). Thymic differentiation involves the rearrangement of genes encoding the antigen receptor (*2*) and the expression of a group of T cell surface proteins that divide mature T cells into those that suppress and those that enhance antibody production (*3*). After the rearrangement of antigen receptor genes, T cells are subject to selective mechanisms in the thymus that lead to the survival of cells able to respond to foreign antigen and the death of cells recognizing self-antigen (*4*). After these critical events, the T lymphocyte migrates through the peripheral blood to other tissues and remains quiescent until it comes into contact with its cognate antigen. A 7- to 10-day process then begins that results in cell division and immunologic functions such as cytotoxicity and the production of lymphokines that induce antibody production by B cells and control the growth of granulocyte and macrophage precursors. The initiation of this process requires a complex interaction of the antigen receptor with the combination of antigen and self-histocompatibility molecules on the surface of antigen-presenting cells. These complex requirements can in part be met by relatively simple stimuli such as calcium ionophores, plant lectins, and antibodies to the antigen receptor that are felt to mimic the effects of physiologic interactions with the T cell receptor. In addition, agents that activate protein kinase C (PKC), such as phorbol myristate acetate (PMA), are felt to mimic a requirement for accessory cells and their products. These aspects of T cell activation have been the subject of several recent reviews (*5*).

Along this pathway to immune function the T cell undergoes morphologic changes (blastogenesis) at about 12 hours, divides by 24 to 48 hours, and then differentiates as genes are sequentially activated for several days. More than 70 molecules are specifically regulated during this process (Table 1). These regulatory events begin within minutes of contact with antigen and continue for at least 10 days. By analogy to viral systems they can be roughly divided into immediate, early, and late genes, although sufficient information is not available to categorize every molecule listed. Table 1 presents data obtained primarily from human peripheral blood T cells; however, data are also included from murine nonmalignant T cell lines that may have differences in the degree or kinetics of induction of the molecules listed.

This complex sequence of gene activations leading to immunologic function can be approached by making analogies to several well-studied systems of differentiation. Generalities learned from these systems include the concept of commitment, after which differentiation progresses in a relatively autonomous way, and the concept of contingent regulatory events that provide temporal order to the process of morphologic and functional change. Commitment is used here to denote a programming event that may not be irreversible (*6*). Contingency simply indicates that a later event is dependent on an earlier event without implying a direct mechanism. These fundamental levels of control generally act by regulation of genes that commit a cell to a specific pathway of differentiation or allow it to proceed along a pathway. Recent developments have made it

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