The Limits of Ordinary Matter

Berndt Müller

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in areas of the temporal lobe (*9*), parietal lobe (*12*), and frontal lobe (*3*), as well as at subcortical processing levels (*13*). If a concept is in our mind, even momentarily, neurons in all areas that code properties of this concept enhance their activity at that precise point in time. As a result, the evolution of attentional modulation over time can provide direct insight into the sequence of mental processing steps needed to solve complex cognitive tasks (*14*). Every cognitive task requires the joint activation of many brain areas that need to exchange information, and the widespread nature of attentional signals suggests that they could provide the vehicle for this information exchange (*11*).

Controlling the activity of a particular cell must be associated with changes in the activity of other brain regions that are either necessary for exerting the mind control or that change activity as a consequence. To better understand the functioning of these large-scale attentional networks (see the figure), future studies could combine mind control of cells in one area with monitoring activity in another.

It is also exciting to anticipate the potential applications of mind control for patients. Foremost are the potential prosthetic applications for people with paralysis. But researchers are also exploring the possibility of using mind control to treat other disorders. Subjects can control patterns of brain activity that can be measured noninvasively with magnetic resonance imaging or electroencephalography (*15*). Could depressed patients improve their mood if they are trained to increase the activity of their brain pleasure networks? Neuroscientists are entering into an era where their discoveries are not only of importance to understand brain and mind, but where their findings will be increasingly used to treat brain disease.

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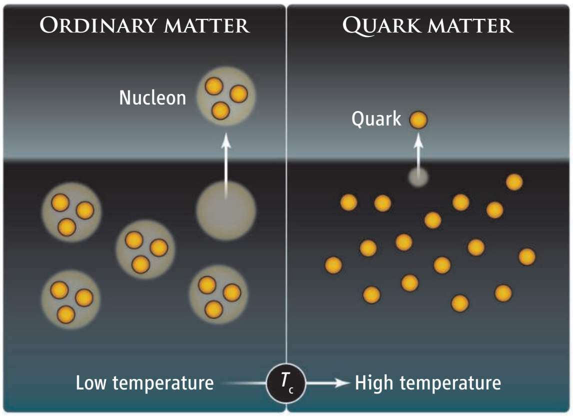
PHYSICS

The Limits of Ordinary Matter

The temperature at which quarks escape the confines of protons and neutrons has been determined from high-energy particle collision data.

Berndt Müller

All ordinary matter consists of protons and neutrons, collectively called nucleons, which are bound together in atomic nuclei, and electrons. The elementary constituents of protons and neutrons, the quarks, almost always remain confined inside nucleons (or any other particle made up of quarks, called hadrons). The fundamental force that binds quarks together—the strong, or "color" force—cannot be overcome unless extremely high-energy conditions are created, such as through heavy-particle collisions. Theoretical simulations based on quantum chromodynamics (QCD) predict that the transition temperature for the appearance of free quarks should occur at 2.0×10^{12} K (an energy of 175 million eV) (*1*, *2*). Since 2000, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has created the necessary conditions to form quark matter in particle collision, but determining the transition temperature under these conditions is challenging. On page 1525 of this issue, Gupta *et al.* (*3*) show that the relevant temperature and energy scales can be extracted from recent experimental studies and find that the transition temperature is in remarkable agreement with theory.



Matter rearrangements. In ordinary matter, quarks can be added or removed only in triplets, but in quark matter, they can be added or removed individually. Gupta *et al.* show how properties associated with such changes can be used to determine the temperature of the transition between these two regimes from particle collision data.

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Detailed information about the nature of the transition can be obtained from theoretical studies of the change in free energy when a quark is added or removed from a finite piece of matter. The free energy function is needed because it includes the effects of temperature and entropy, as well as particle number. In the case of ordinary matter, quarks can be added or removed only in the form of nucleons, that is, in triplets; after the transition to quark matter, quarks can be added or removed individually (see the figure).

This difference in how particles are added manifests itself in an abrupt change in the response of the matter to changes in conserved quantum numbers carried by quarks, in particular, the baryon number (a measure of relative number of quarks and antiquarks). In statistical physics, the response of a system to infinitesimal changes is measured by coefficients called susceptibilities, which carry the information about the nature of the constituents of the matter. The susceptibilities for baryon number and similar conserved quantum numbers, such as electric charge, are predicted to change drastically and characteristically when ordinary matter transitions to quark matter, providing a distinctive fingerprint of the transition (*4*, *5*). For example, a certain ratio of baryon number susceptibilities (the kurtosis, a

Department of Physics, Duke University, Durham, NC 27708, USA. E-mail: muller@phy.duke.edu

measure of the shape of the probability distribution) drops to one-ninth of its normal value over a narrow temperature range.

Not only are enormous accelerators needed to give colliding particles the required energy to create quark matter—a sufficiently large chunk of this extremely hot matter also must be maintained by inertial confinement for a sufficiently long period of time to ensure thermalization and permit the observation of its properties. Experiments conducted at RHIC achieved the needed energy by colliding two large nuclei, such as those of gold, against each other at energies up to 2 trillion eV (2 TeV) (*6*). These studies have shown, surprisingly, that quark matter is not a dilute gaseous plasma of quarks and gluons, the particles that carry the strong force. Instead, a strongly coupled liquid with almost no viscosity, that is, an almost ideal fluid, forms. The emission pattern of protons provides indirect evidence that quarks move independently inside this hot matter.

Direct evidence for the transition temperature and the nature of the transition can be extracted from the data by examining various susceptibilities. Susceptibilities are related to fluctuations of the thermodynamic variables that occur within a fixed volume of matter. In the case at hand, the baryon number susceptibilities can be related to the fluctuations of the number of protons emitted event by event in nuclear collisions (*4*). The emitting volume is not known precisely, so it is necessary to study ratios of baryon susceptibilities corresponding to different orders in the expansion of the free energy (*7*, *8*). These ratios change during the transition from ordinary to quark matter in a characteristic manner and can be used to track the change in the structure of the matter with the change in thermal conditions as the nuclear collision energy is varied (*9*).

Gupta *et al*. went one step further. Numerical QCD simulations of interactions among quarks are carried out for a discretized version of space-time, an approach known as lattice gauge theory. To determine the transition temperature, the lattice simulations must fix the energy scale, which is usually done by comparison with some other observable quantity determined directly or indirectly from experiment. The authors show that the scale, and thus the actual value of the QCD transition temperature, can be determined from the same data used to compare with predictions for the quark susceptibilities, if the data are known over a sufficiently wide parameter range. This new method has been made possible by recent results from the STAR collaboration at RHIC (*10*), which probed matter with the ratio of the baryon chemical potential (the change in energy of the system as the net number of quarks minus antiquarks fluctuates) to the temperature extending over a wide range by varying the collision energy. The values of the temperature and chemical potential reached at each energy were obtained by comparing the measured particle yields with those calculated in the hadron resonance gas model. The value for the transition temperature obtained by Gupta *et al*. (175^{+1}_{-7} MeV) agrees very well with the values obtained by comparison with single-hadron properties.

With many more results expected from the RHIC experiments in the near future, additional insights into the details of the transition from ordinary matter to quark matter are within reach. To fully make use of the data and confirm the conclusions presented by Gupta *et al*., it will be necessary to develop a comprehensive theoretical framework for the creation, evolution, and freeze-out of thermodynamic fluctuations in the matter produced in nuclear collisions that moves at relativistic speeds. This challenge to theorists is commensurate to the experimental challenges that have been overcome by recent detector and accelerator upgrades at RHIC.

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ECOLOGY

Why Did You Lévy?

Daniel Grünbaum

Mussels in intertidal beds use random movement behaviors to optimize formation of patches to balance feeding and mortality.

Nature is full of biological landscapes that seem static to the casual observer, but actually contain highly dynamic spatial features. These features are shaped dramatically, if slowly, by subtle interplays between large-scale population-level patterns and small-scale movements of individual organisms. For spatial ecologists, a challenging aspect of such landscapes is the chicken-and-egg character of the underlying interactions: Organism movements are dictated by the environment, but the environment is strongly affected by organism movements. On page 1551 of this issue, de Jager *et al*. (*1*) reveal how, for mussels in patchy intertidal beds, the ecology of dynamic spatial patterns and the evolution of movement strategies are tightly linked.

Mussels attach to substrate and to each other using byssal threads, a biological material with remarkable mechanical properties secreted by the mussel's foot (*2*) (see the figure). By systematically adding and removing threads, mussels adjust their position and, especially as juveniles, are surprisingly mobile. For those of us to whom "perfection in movement" more readily connotes sprinting cheetahs and soaring albatrosses, de Jager *et al*. have a surprising message: Despite their leisurely locomotion—or perhaps because of it—mussels exhibit economy of movement and savvy behavioral strategies that approach a theoretical ideal as well as, or better than, more visibly athletic species.

De Jager *et al*. combined experiments and theory to quantify relationships between mussel movement behaviors and the patchy distributions in which mussels are often found. Individual mussels have reduced mortality when they are in the immediate vicinity of other mussels, probably because they are less likely to be torn away by currents (*3*, *4*). However, mussels filter-feed on algal cells and other small plankton, and large masses of mussels deplete local food resources. Hence, mussels with many immediate neighbors but few more-distant neighbors—that is, those that are aggregated on short length scales but dispersed on longer length scales—enjoy the best of both worlds. Patchy distributions provide individuals with just this combination of neighbors.

If most members of a population benefit from patchy distributions, it seems inevitable that evolution would shape mussel behavior to produce patches. However, population

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School of Oceanography, University of Washington, Seattle, WA 98195–7940, USA. E-mail: grunbaum@ocean.washington.edu