because they often reflect an increase in the number of households. If this increase could be stabilized at roughly the same level as population growth, the adverse effects might also stabilize. But could this be achieved? That depends on possible explanations for why household sizes have fallen in the first place. Some of these explanations are as follows. First, all other factors remaining the same, falling birth rates reduce population size, but do not affect the number of households; hence, household size is reduced. Second, increased material standards of living have an effect. Extended households are observed in countries in an early stage of development[13]. When these countries attain a higher standard of living, some institutions — such as social-security systems — provide the assurance against risks that were formerly supplied by the extended household.

Third, social, economic and cultural theories of demographic behaviour point to a variety of reasons why individuals prefer to live in small households[14–16]. These include less adherence to strict norms; less religiosity and increased individual freedom on ethical issues; female education, which has led to women having greater economic independence and also facilitates divorce; more assertiveness in favour of symmetrical gender roles; the contribution of women to the labour market; increased economic aspirations; and residential autonomy. Fourth, population ageing reduces household size. This is a direct consequence of two facts: increased longevity leads to longer periods of time when children do not live with their parents; and the greater mortality of men, together with

the usual age difference between spouses, results in many widows who live alone.

Smaller households, then, are the result of processes that cannot be reversed (such as modern contraception and liberalization from norms) or that we value for a number of reasons (such as women's emancipation). So policy interventions will have to focus on the average household resource consumption, in order to combat the adverse effects of smaller households. ∎

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Condensed-matter physics

Tunable colloidal crystals

William B. Russel

Microscopic particles dispersed in a solvent — a colloidal dispersion — can be a useful model for phase transitions and crystal nucleation. A colloid that can be 'tuned' using an electric field is a valuable new tool.

Fundamental advances in colloid science often depend on physical models, which are made by dispersing carefully tailored particles, less than a micrometre in size, in pure aqueous or organic liquids. Such dispersions can be characterized by methods such as light scattering and confocal microscopy, and the physical and chemical interactions between the particles, responsible for intriguing phases such as colloidal crystals (which behave like atomic solids), can be precisely controlled. On page 513 of this issue, Yethiraj and van Blaaderen[1] describe a new model system that can be tuned with an electric field to display phase transitions and unexpected crystalline structures.

Colloidal crystals first attracted interest

in the 1960s. In studies of the light scattered from dilute dispersions, a transition was detected from a disordered fluid to an ordered body-centred-cubic (b.c.c.) crystal when the screened (or reduced) Coulomb repulsions between the colloidal particles extended to length scales greater than the lattice spacing[2]. In fact, this transition can be controlled: adding a small amount of salt decreases the range of the repulsive force, because the salt dissociates into ions that enhance the screening. As a result, the volume fraction (or density) of particles at the transition increases, and a denser, face-centred-cubic (f.c.c.) crystal structure is favoured. Adding even more salt leads to 'hard-sphere' transitions — as though the
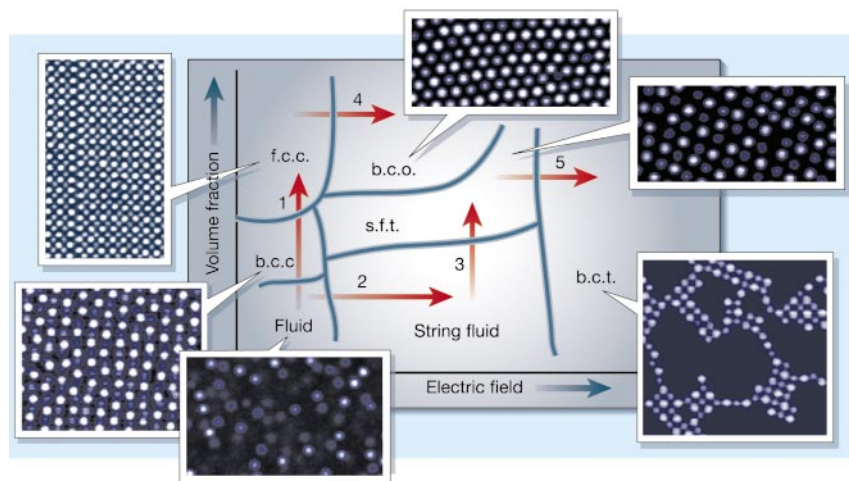
particles were effectively hard spheres, with no Coulomb repulsion. Then, entropy — generally considered to be a measure of disorder — favours the f.c.c. crystal, as the number of configurations available to a particle localized about a lattice site in the f.c.c. crystal exceeds those accessible in a disordered fluid or the b.c.c. crystal[3].

Although hard-sphere behaviour of polymer-based colloids could be achieved in model systems, there was a drawback: those colloids were opaque at even moderate densities, so little could be learned about their structure from light scattering. More transparent dispersions were sought, such as silica spheres coated with short hydrocarbon chains in a nonpolar solvent that eliminates surface charge[4]. In the 1980s, these organophilic silicas and the aqueous lattices sufficed for many studies of fluid-to-crystal transitions and other colloidal phenomena. But small silicas could not easily be made highly uniform in size and there can be extra, van der Waals attractions between the larger ones, so better colloidal hard spheres were sought. Eventually a standard emerged: poly(methylmethacrylate) (PMMA) spheres coated with a low-molecular-weight polymer[5].

In a solvent that also contains soluble polymer, neighbouring spheres are pushed together by osmotic pressure due to expulsion of polymer chains from small gaps between the particles. This attractive force increases roughly linearly with polymer concentration and can easily cause a dilute gas-like dispersion to condense into a colloidal fluid, and then into a solid f.c.c. crystal. In reality, the hard spheres pass through an intermediate, random hexagonal close-packed (r.h.c.p.)[6] phase and only slowly convert to the f.c.c. structure. For larger colloids or smaller polymer chains, the transition directly from 'gas' to f.c.c. crystal is more favourable[7].

Thus long-range attractions or repulsions yield condensed phases with low density and coordination number, such as dense fluid or b.c.c. crystal phases. Short-range repulsions and attractions produce denser f.c.c. crystals with higher coordination number. But crystals with lower coordination numbers than the b.c.c. phase or more complex structures have not been achieved with spheres of a single size. Yethiraj and van Blaaderen[1] confront this issue by devising a model system in which the forces between particles can be tuned, combining a soft repulsion with a long-range, anisotropic attraction.

The authors laced PMMA spheres (with radii between 1 and 2 μm) with fluorescent dye and dispersed them in an organic mixture whose refractive index and density were chosen to aid confocal imaging of the spheres. The solvent also preserves sufficient dielectric contrast for an applied electric field to induce strong dipole–dipole inter-

Figure 1 **How to tune your colloidal crystal.** Yethiraj and van Blaaderen[1] have devised a model colloid whose structure can be effectively 'tuned' by varying the applied electric field and the volume fraction, or density, of colloidal particles. At low field values, increasing the volume fraction (1) causes the random, fluid arrangement of colloidal particles to take on body-centred cubic (b.c.c.), then face-centred cubic (f.c.c.) crystal structures (shown in the insets). Increasing the electric field at fixed volume fraction (2), however, transforms the colloid into a string fluid structure. If the volume fraction is then increased (3), a space-filling tetragonal (s.f.t.) structure results. Alternatively, starting from high volume fraction with f.c.c. structure and increasing the electric field (4) produces the body-centred orthorhombic (b.c.o.) state. From the s.f.t. state, if the electric field is pushed up still further (5), the colloidal crystal takes on another, more open structure, known as body-centred tetragonal (b.c.t.).

actions, and the dye imparts charge and generates weak electrostatic repulsions that can be moderated by adding a soluble salt. So the interaction potential superposes a hard-sphere repulsion (considered to have infinite magnitude and zero range), an exponentially decaying repulsion (of finite magnitude, with its decay length dependent on salt concentration) and an orientation-dependent dipolar attraction/repulsion (with magnitude proportional to the electric field strength, and range comparable to the particle radius). The result is a three-dimensional phase diagram defined by the volume fraction, the range of the dipolar force and the strength of the electric field.

Yethiraj and van Blaaderen first sampled one plane of the phase diagram, looking at the effects of varying volume fraction and range of the electrostatic repulsion, in the absence of an electric field. They found fluid-to-b.c.c.-to-f.c.c. transitions for soft repulsions, fluid-to-f.c.c. transitions for harder electrostatic repulsions, and fluid-to-r.h.c.p. transition for nearly hard spheres, consistent with earlier results.

But then, looking at the variation with volume fraction and electric field, they found richer phase behaviour. At low values of electric-field strength, increasing the volume fraction induces a fluid-to-b.c.c.-to-f.c.c. sequence (Fig. 1). But maintaining a low volume fraction and increasing the field strength instead leads across a phase boundary from the isotropic fluid to a disordered phase in which the spheres condense into strings. Then, increasing the volume fraction at intermediate field strength drives a first-order transition, forming a space-filling

tetragonal (s.f.t.) crystal. More interesting still are the solid–solid transitions Yethiraj and van Blaaderen observed by increasing the field strength from the f.c.c. crystal to a body-centred orthorhombic (b.c.o.) structure, and then from the s.f.t. crystal to a body-centred tetragonal (b.c.t.) structure, the phase that

had been generally expected for hard spheres in a strong electric field. The tunability of the system through the electric field also means that the process can be reversed to observe complex melting phenomena, as one or more phase boundaries are traversed.

Yethiraj and van Blaaderen's model system, incorporating tunable dipolar attraction and soft repulsion, has revealed several new phase transitions for colloidal crystals. The newly identified crystalline phases, s.f.t. and b.c.o., as well as the b.c.t. phase expected in electric fields, represent anisotropic distortions of the b.c.c. lattice into more open structures with lower coordination numbers. Converting these fragile colloidal crystals into robust solids could have technological implications, and further tuning of the pair potential should reveal even more interesting crystal structures. ■

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Behavioural genetics

Family matters

David Haig

Differential activation of genes inherited from mothers and fathers will manifest itself as conflict in families. The effects are being explored experimentally with mice.

The evolution of maternal care involves a complex interplay between the genetic interests of mothers and those of offspring, with offspring predicted to favour higher levels of care than those favoured by mothers[1]. This interaction is further complicated by the possibility of conflict within offspring genomes through a phenomenon known as genetic imprinting[2], and of conflicts within maternal genomes between genes that are inherited by a particular offspring and genes that are not[3]. A study by Hager and Johnstone (page 533 of this issue[4]) reveals some of the genetic complexities behind how these conflicts are resolved.

Imprinting is an important concept in this context. Two copies — alleles — of a gene are inherited by offspring, one from the father and one from the mother. In imprinting, some modification of the DNA sequence,

such as the addition of a methyl group to cytosine residues, means that one copy of the gene is inactivated and so only the paternally or maternally inherited version is expressed. Natural selection on genes expressed in offspring favours the solicitation of higher levels of maternal care when the gene is inherited from a father than from a mother because, in the former case, the allele has less 'interest' in the mother's future reproduction. This asymmetry sets up the possibility of a three-way conflict within offspring genomes — among unimprinted genes, maternally expressed imprinted genes (when the allele inherited by the offspring from its father is silent), and paternally expressed imprinted genes (when the allele inherited by the offspring from its mother is silent). For interpreting Hager and Johnstone's study, the important point is that the influence of