PHYSICS

Sparse Crystals

John Schiffer

Ordinary solids as we know them are made of atoms packed a few angstroms apart, interacting through their electrons in a regime where quantum mechanical effects are important. There is, however, another kind of classical solid where quantum mechanics may often be completely neglected: a contained array of like-charged particles whose Coulomb repulsion causes them to be equally spaced in a crystalline lattice. Such an infinite solid forms a cubic lattice. The first to observe this simple crystalline state in the laboratory, in a cloud of about 100,000 ions spinning rapidly in an ion trap, was a group at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. The details are reported by Itano *et al.* on page 686 of this issue (*1*).

There was a period of intense interest in such systems about 100 years ago when early work on x-ray diffraction demonstrated both the crystalline structure of matter and the wave nature of x-rays. It was calculated that the lowest state of such a purely Coulombic solid would be body-centered cubic. The quantum mechanical form of such a solid was later treated by Wigner (considering electrons in sodium metal) in the 1930s, the formative years of quantum mechanics, adapting the ideas and principles to the realm that became solid-state physics. The classical limit for infinite matter is precisely what Itano *et al.* observed in their experiment (*1*).

Such a state of matter does not exist in pure form in nature on Earth, although it has relatives. Opal, for instance, is opalescent because charge impurities in a neutral matrix condense in a regular array with spacings that are several times the wavelength of visible light, causing diffraction. However, the presence of the matrix complicates this system. Also, the outer crust of neutron stars, where bare iron nuclei are compressed by gravitational pressure, is believed to have this crystalline form.

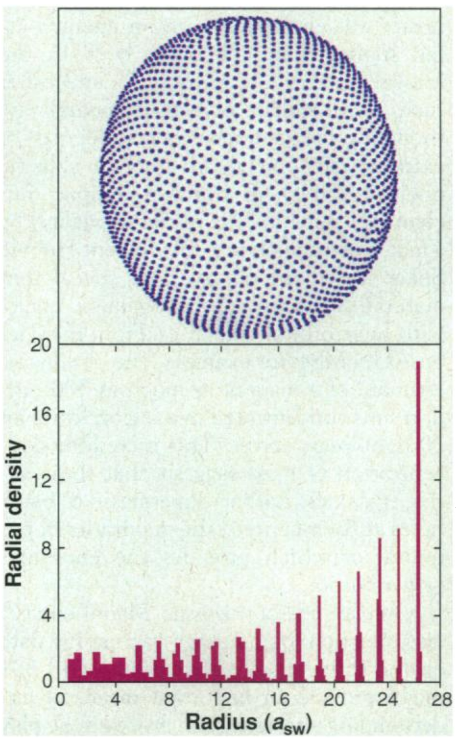
With the rapid developments in the technology of ion traps, it has been possible to contain a collection of ions in a combination of electric and magnetic fields. In Penning traps, the cloud rotates in a magnetic field, which confines it in two dimensions, with electrostatic containment in the third; Paul traps use radio-frequency field gradients to give a time-averaged confining potential. In such traps, the distances between ions are typically tens of micrometers, some 100,000 times larger than the distances between atoms in a solid, and thus, the densities are 10^{15} lower.

The first simulations of the freezing temperature for such a "solid," with densities corresponding to a vacuum of 10^{-8} torr, were done with the advent of large computers at Livermore in the 1960s (*2*). The temperatures required for producing a crystalline solid out of such a "one-component plasma" (*3*) are in the millikelvin range. In the last decade, with the development of the techniques of laser cooling, it has become possible to produce such low temperatures in a plasma, but only with ions in which the required cooling transitions are available. The 1997 Nobel Prize in Physics was awarded to Chu, Phillips, and Cohen-Tannoudji (*4*) for the physics emerging from the laser cooling of neutral atoms. Simulations of finite ion clouds (*5*, *6*), later confirmed by experiments (*7*, *8*), indicated that the form of crystallization was not in the cubic form but instead in a set of concentric spherical or spheroidal shells (see figure), with approximate hexatic ordering characteristic of liquid crystals within each shell. Early experiments on substantial ion clouds by the group of Wineland *et al.* at the NIST laboratory in Boulder (*7*) and by Walther at the University of Munich (*8*) showed structures that were identical to those in the simulations.

For 'sufficiently large' clouds, the influence of the curved surface imposed by the confinement of a finite cloud must disappear. Somewhere beyond 20 shells, the interior of a cold cloud would have to settle into the cubic order that is the lowest state of infinite systems. The competition between the two forms of ordering is sufficiently complex that all that is available are rough estimates by Dubin of the University of California at San Diego (*9*) of how deep in the interior such a transition would occur. The limitations, even of supercomputers, have not permitted sufficiently large systems to be studied in numerical simulations with the required precision.

Even though the spacing between ions in such a solid is sufficiently large that they could be resolved optically, the rapidly rotating clouds make this impractical. The Boulder work makes use of the technique that was used by Laue to show the crystalline nature of matter, x-ray diffraction. Instead of x-rays, the distances are such that the diffraction of visible light is feasible; in fact, the same laser light that is used to cool the ion cloud is diffracted.

Because the spacings are several tens of wavelengths, the Bragg scattering occurs at very small angles, which required the development of special techniques. Originally, because of the rapid rotation of the ion cloud, the diffraction pattern showed up as a set of rings, analogous to the powder pattern in normal x-ray diffraction (*10*). It was unclear whether this pattern was primarily the result of the rapid rotation or whether there were multiple crystals in the cloud. However, experimenters have now learned to do stroboscopic measurements, locking in their detection system with the rotational phase of the cloud. This technique permits the Bragg pattern to be observed when the crystal is of the right ori-



Seeing shells in an ion cloud. Simulation of the outer surface of a 20,000-ion cloud confined in an isotropic trap (**top**), and the radial density of the ion cloud (**bottom**), showing a series of concentric spherical shells. The work of Itano *et al.* (*1*) is for clouds of more than 100,000 ions, with the curved shell layers giving way to the cubic order in the interior.

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entation with respect to the laser beam. Further, this feature provides a handle to determine the precise frequency of rotation of such a crystal. This measurement could be crucial in the utilization of the transitions in these ions as possible frequency (time) standards, because their containment in the trap keeps them free of any environmental interactions, and the effects of rotation can be corrected if they are precisely controllable.

A new state of infinite solid matter is apparent in these experiments; the matter is certainly "visible" because of the fluorescence of the ions in laser light, and yet its density is that of what would normally be considered a respectable vacuum. The question of what may be done with this form of matter remains to be seen. The applications to time standards are promising, but perhaps there are other, more far-fetched applications on the horizon. Could ions in such a solid be linked by resonant photon exchange between them? This possibility may introduce additional classes of phenomena. Or could one engineer such materials with perhaps different species of ions imbedded as impurities, or perhaps eventually in a regular array, allowing new properties to be developed? At the moment, these possibilities are still speculative but, the field is moving rapidly.

References and Notes

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ASTROPHYSICS

What the Wild Things Are

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In 1962, Schmidt discovered that the bright quasi-stellar radio source known as 3C-273 was not a star at all. From its redshift, he found that it was as far away as the most distant galaxies (*1*). Its intrinsic luminosity was enormous, with an energy output higher than any other body in the known universe. Now, 3C-273 and other such quasi-stellar objects (quasars) are thought to be members of a broader class of extragalactic objects, the active galactic nuclei (AGNs), in which a compact nucleus may outshine the rest of the galaxy by a factor of as much as 1000. Recent Hubble Space Telescope observations reveal that material swirls around these galactic nuclei with huge orbital velocities. From the data on AGN M84, for example, one obtains an estimate of a mass of as much as 300 million suns concentrated in a region less than 20 light years across. This incredible concentration of mass suggests that these active galaxies harbor supermassive black holes at their centers, the gravitational potential of which provides the enormous power output.

On page 684 of this issue, Mannheim (*2*) discusses how high-energy gamma ray data on the active galaxy Markarian (Mrk) 501 might provide an important means of understanding the energetic processes at play in these enigmatic objects. In keeping with the energy of AGNs, the debate surrounding their mechanisms is vigorous, and I shall consider Mannheim's conclusions from a somewhat different perspective.

The most extreme members of the family of AGNs, the BL Lac objects and optically violent variable quasars (collectively known as the blazars), show dramatic variability in their emission on incredibly short time scales ranging from days down to less than 1 hour. These observations imply a very compact emission region limited by causality to have an extent less than the product of the speed of light and the variability time scale. Shortly after the discovery of the extragalactic nature of quasars, Rees (*3*) pointed out that an outflow with a relativistic velocity could decrease (Doppler shift) the apparent variability time scales: Blazars appear to correspond to AGNs in which the relativistic jet happens to be pointed nearly in our direction, and we are being provided with a view of the energetic processes in a very small region, probably near the base of the jet close to the central engine.

The broadband spectra of blazars (stretching over eight orders of magnitude in wavelength, from the radio to x-ray wavebands) is nothing like the ordinary thermal black-body radiation emitted by more mundane astrophysical objects such as our own sun. This nonthermal emission is well described by synchrotron radiation emitted by a population of energetic electrons, an effect caused by the bending of electron trajectories in the relatively strong magnetic fields in the jet.

Gamma ray emissions from blazars are another story, however. Emission has been seen at energies greater than 100 MeV from some 50 AGNs, including 3C-273 (*4*). The energy of these photons lies well above the point at which the relatively well understood synchrotron spectrum appears to cut off, signifying a new component of the spectral energy distribution in these objects. It came as a surprise that over the entire electromagnetic spectrum, the power output for many of these objects is peaked in the high-energy gamma ray waveband. Perhaps still more surprising was the discovery that the high-energy emission of some of these objects (Mrk 421 and Mrk 501) extended up to 10^{12} eV (*5*, *6*).

For Mrk 421 and Mrk 501 (and other similar objects referred to as the x-ray selected BL Lacs), the emission from the radio up to the high-energy x-ray waveband is almost certainly synchrotron emission produced as electrons gyrate in the relatively strong magnetic fields in an AGN jet. However, the origin of the gamma ray emission is still poorly understood. Models in which electrons or protons dominate the gamma ray emission have been proposed, but as pointed out by Mannheim (*2*), they lead to different predictions of magnetic field strength and Doppler factor. Because these are potentially observable quantities, we have a possible means of discriminating between these models. In a constant magnetic field, particles of a given momentum are deflected by a perpendicular force, which produces an angular acceleration, and this in turn results in electromagnetic radiation. Furthermore, particles of high momentum gyrate in circular orbits of larger radii. From these basic deductions, a number of important conclusions can be reached that have a direct bearing on the question of proton versus electron models.

The decay in the synchrotron emission caused by the declining population of energetic electrons is referred to as "synchrotron cooling." In a magnetic field, a proton,

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