

should allow the work of many other types of human information and decision-making agents to be automated. These may well include travel agents, loan officers, insurance agents, telephone operators, and many others. The technology provides artificial intelligence and computer science with a tool that goes beyond the now classical expert system.

Since these software agents have built-in architecture and mechanisms for consciousness, they may actually turn out to be sentient. This issue is the subject of current research aimed at locating consciousness in nervous systems. Success at finding criteria for sentience would help solve the problem for humans and animals. Struggling with these provocative questions about artificial sentience may add, in yet another way, to knowledge of human consciousness.

For background information see COGNITION; CONSCIOUSNESS; SOFTWARE in the McGraw-Hill Encyclopedia of Science & Technology. Stan Franklin

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### Crystalline plasma

A plasma is matter in an ionized state. The assumption is often made that such matter is necessarily in a fluid state, and this is the case most often observed. However, cold, highly correlated ion plasmas confined in a vacuum by magnetic and electric fields have recently been observed to crystallize into lattice patterns that depend on the sizes and shapes of the plasmas. These studies are relevant to the understanding of dense astrophysical objects, such as neutron stars and white dwarfs, in which plasmas having similar properties are believed to exist.

**One-component plasmas.** The one-component plasma (OCP) is an idealized theoretical model of matter consisting of a single species of charged particles embedded in a uniform, neutralizing background of opposite charge. It is the simplest system in which crystallization of an ion plasma occurs. The thermodynamic properties of an infinite homogeneous OCP are determined by a dimensionless parameter  $\Gamma = q^2(4\pi\epsilon_0akT)^{-1}$ , which is a measure of the ratio of the electrostatic potential energy of neighboring particles [about  $q^2/(4\pi\epsilon_0a)$ ] to the kinetic energy per particle (about  $kT$ ). Here,  $q$  is the charge of the particles,  $\epsilon_0$  is the permittivity of the vacuum,  $k$  is the Boltzmann constant, and  $T$  is the

temperature. The Wigner-Seitz radius  $a$  is a measure of the average interparticle spacing and is defined in terms of the density  $n$  by  $4\pi a^3/3 = n^{-1}$ ; that is, the average number of particles in a sphere of radius  $a$  is equal to 1. When  $\Gamma$  is much less than 1, the OCP is said to be uncorrelated; when  $\Gamma$  is greater than or approximately equal to 1, it is said to be strongly coupled or strongly correlated. When  $\Gamma$  is greater than a value  $\Gamma_{\text{crit}}$  equal to about 170, the OCP is predicted to crystallize, forming a body-centered cubic (bcc) lattice.

These results hold for an infinite OCP. For finite-sized systems, the spatial arrangement of the particles may be something other than a bcc lattice. Numerical simulations of as many as tens of thousands of particles have shown that solidified, finite OCPs have layered structures. In the case of a sphere, for example, an approximate two-dimensional hexagonal lattice forms at the outer surface. A series of concentric spherical layers of particles forms inside the sphere. For a sufficiently large number of layers, the spatial arrangement of the particles near the center should form a bcc lattice, as for the infinite OCP. This number may be about 30, according to theoretical estimates. Numerical simulations have not yet verified this transition from a layered structure in the outer regions to a bcc lattice in the central region directly, since the number of particles required is around  $10^5$ , which is too large for current computers to handle. Other geometries have also been investigated theoretically, for example, one in which the particles are confined to a cylindrical region that is unbounded along the axis of the cylinder. In this case, the structure consists of a series of coaxial cylinders.

**Astrophysical applications.** In some dense astrophysical bodies, the electrons form a degenerate Fermi gas. That is, the electrons have the maximum density allowed by the Pauli exclusion principle, which prevents two electrons from occupying the same quantum state. At sufficiently high pressures, the Pauli principle, not Coulomb repulsion, limits the density of the electrons. Under these conditions, the electrons form a uniformly charged background, in which the fully stripped ions move. The ions, being much more massive than the electrons, remain non-degenerate even at pressures much higher than those needed to force the electrons into a degenerate state. If there is only a single ion species, the system resembles an OCP.

A neutron star is a gravitationally collapsed stellar object with a mass on the order of that of the Sun but with a radius of only about 10 km (6 mi). The core consists of degenerate neutrons. The crust of a neutron star is believed to consist mainly of iron nuclei embedded in degenerate electrons. When the density is high enough and the temperature low enough, the iron nuclei are predicted to freeze into a solid. It is not known whether this is a bcc crystal, as for the idealized OCP, or a disordered solid.

A white dwarf is a star that no longer generates energy by thermonuclear reactions and is stabilized

against gravitational collapse by the pressure of degenerate electrons. The interiors of white dwarfs are believed to consist of a mixture of carbon and oxygen nuclei embedded in a degenerate electron gas. Thus, rather than being a one-component plasma, the core is a binary ionic plasma with some other minor ionic components. At high enough densities and low enough temperatures, such a mixture should crystallize. Knowledge of the details of the crystallization process is needed to estimate the age of a white dwarf from its observed luminosity. For example, if the carbon and oxygen nuclei separate into different regions of the core before crystallizing, heat is released that slows the cooling process.

Estimates of the age of the universe are based on the Hubble constant, which is a measure of the rate of expansion of the universe. Hubble-constant measurements have varied, indicating an age of the universe between about 10 and 20 billion years, though recently they have been converging on a value of about 12 billion years. The estimated ages of the oldest white dwarfs are from about 9 to 15 billion years. Of course, the age of the universe must be greater than that of any star, so both the Hubble-constant measurements and the estimates of white dwarf ages need to be refined to make sure that they are not in contradiction.

**Experiments.** Crystallization of plasmas has been observed in ion traps, which are devices that confine charged particles by various configurations of electric and magnetic fields. A collection of a single species of ions in a trap is similar to a finite OCP, where the trap fields take the place of the uniform, neutralizing background. In order to lower the temperatures enough for crystallization to occur, laser cooling has been used. Laser cooling is a method of reducing the temperature of atoms or ions by the use of resonant light pressure. In its simplest form, called Doppler cooling, the frequency of a laser is tuned slightly below the frequency of a strong atomic resonance. Ions with velocities directed against the laser beam scatter light at a higher rate than those moving with the beam, and lose kinetic energy.

A radio-frequency or Paul ion trap confines charged particles with the use of spatially nonuniform, alternating electric fields. Crystallization of ions has been observed in such traps, notably at the Max Planck Institute for Quantum Optics in Germany, at the University of Aarhus in Denmark, and at the U.S. National Institute of Standards and Technology (NIST). However, while layered structures have been observed, the plasmas were not large enough to allow the observation of the infinite OCP structure.

Recent work at NIST has resulted in the production of crystallized ion plasmas in Penning traps that are large enough in all three dimensions for the bcc lattice structure expected for the infinite OCP to be observed. A Penning trap uses a static, uniform magnetic field superimposed on a quadrupolar electrostatic potential to confine charged particles in all three dimensions. A collection of a single type of

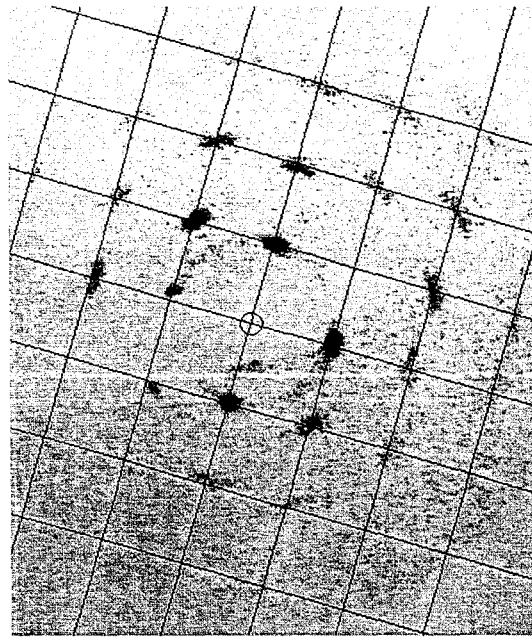


Fig. 1. Diffraction pattern of a beryllium ion plasma, showing the square grid pattern characteristic of a bcc lattice irradiated along a fourfold symmetry axis. The open circle marks the position of the undeflected beam. The grid spacing corresponds to an angular deviation of  $2.54 \times 10^{-2}$  rad. The ion density is  $3.83 \times 10^8 \text{ cm}^{-3}$ . (Reprinted from W. M. Itano et al., *Bragg diffraction from crystallized ion plasmas*, *Science*, 279:686–689, January 30, 1998)

ion in a Penning trap has properties equivalent to an OCP, aside from an overall rotation about an axis parallel to the magnetic field direction.

Diffraction of collimated radiation (radiation whose particles are nearly parallel) by the ordered atoms of a crystal is called Bragg scattering. The incident beam is scattered in a discrete set of directions, from which the lattice structure of the crystal can be inferred. Ordinarily, x-rays are used for Bragg scattering; but for ion plasmas confined in Penning traps, it is convenient to use the same laser radiation used to cool the ions. **Figure 1** shows a diffraction pattern observed in the forward-scattered 313-nanometer laser radiation that has passed through an approximately spherical plasma of about  $5 \times 10^5$  trapped beryllium-9 ( $^9\text{Be}^+$ ) ions. The square array of spots is the signature of a cubic lattice irradiated along one of the fourfold symmetry axes. Precise measurements of the plasma density and the scattering angles show that the pattern is due to a bcc lattice and not to a simple cubic (sc) or a face-centered cubic (fcc) lattice. A diffracted beam is expected at each intersection of the grid lines overlaid on the image. Some spots are obscured by a beamstop. In order to obtain this image, it was necessary to synchronize the detection with the 126-kHz overall rotation frequency of the plasma. For spherical plasmas having approximately 200,000 ions or more, the diffraction patterns were consistent with bcc ordering. It is also possible to study the spatial ordering by direct optical imaging of the individual ions.

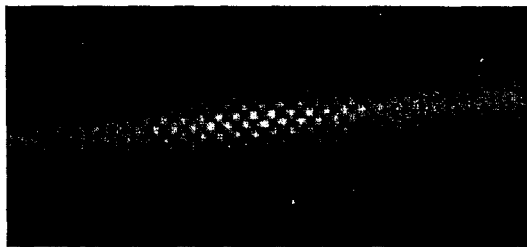


Fig. 2. Image of a  ${}^9\text{Be}^+$  ion plasma, illuminated by a laser beam perpendicular to the magnetic field, showing the presence of a bcc crystal in the central region. The horizontal extent of the image is 0.5 mm. (After T. B. Mitchell et al., *Direct observations of the structural phases of crystallized ion plasmas*, *Phys. Plasmas*, 6:1751–1758, May 1999)

Figure 2 shows a view in a direction parallel to the magnetic field of the fluorescence from a narrow laser beam directed through a plasma. A bcc crystal is observed in the central region. Other lattice types, including fcc and hexagonal-close-packed (hcp), are observed in very flat plasmas.

Future experiments might include a measurement of the melting temperature of the trapped-ion crystals and of the details of the spatial structure changes during the melting transition. Another area for experimental study is the crystallization of a binary ionic mixture, for example,  ${}^9\text{Be}^+$  with aluminum-27 ( ${}^{27}\text{Al}^{3+}$ ). These ions have nearly the same charge-to-mass ratio and hence will tend to remain mixed rather than undergoing centrifugal separation. It is not known how such a mixture will crystallize—in particular, whether like ions will group together or will remain mixed with the others in a kind of alloy. The results of such a study might yield some insights into the structure of the interiors of white dwarfs.

For background information see CRYSTAL STRUCTURE; CRYSTALLOGRAPHY; PLASMA (PHYSICS); SUN; X-RAY CRYSTALLOGRAPHY; X-RAY DIFFRACTION; WHITE DWARF STAR in the McGraw-Hill Encyclopedia of Science & Technology. Wayne M. Itano

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### Deoxyribonucleic acid (DNA) microarrays

The Human Genome Project, the effort to decode the entire deoxyribonucleic acid sequence of humans, is showing how much of the makeup of cells remains to be elucidated. DNA is the blueprint of life and encodes all of the genes which are expressed from the genome in the form of messenger ribonucleic acid

(mRNA). The mRNA is translated by cellular machinery into proteins. Determining the sequence of the entire genome allows a comprehensive analysis of all genes, and hence proteins, that make up cells, tissues, and the entire organism. There is now access to the complete genome sequence of over a dozen bacterial genomes and the complete sequence of small genome eukaryotes such as yeast (*Saccharomyces cerevisiae*, 6200 genes encoded in about 12 million base pairs), worm (*Caenorhabditis elegans*, 18,000 genes encoded in about 80 million base pairs), and fruit fly (about 200 million base pairs). By late 2001, highly accurate sequencing of the human genome (about 3 billion base pairs encoding an estimated 100,000 genes) will be available due to recent increases in sequence production from government-funded laboratories. The mouse genome, generally considered one of the best models for human diseases, will be sequenced before 2005.

This avalanche of sequencing information will provide a comprehensive view of genes. However, the sequence data from the smaller-genome yeast and worm are quite humbling. Even with the vast amount of prior gene information and two decades of highly focused molecular biology experimentation, it is possible to guess the function of only a third of all the 6200 genes identified in yeast. The rest are a complete mystery. Therefore, there are vast frontiers of biology not yet explored by modern tools. The problem will be more severe as the much larger human genome is completed and the sequence of approximately 100,000 genes is determined. The era of individual gene cloning, which has dominated human genetics, is coming to an end, and a new era of discovering functions for all of the genes identified is beginning. In the efforts to identify the function of each of these 100,000 genes in the human genome, tools that allow the sampling of many genes in individual assays are needed. Two key technological advances since 1995, oligonucleotide and complementary DNA (cDNA) microarrays, allow testing to determine which genes are turned on in a given cell and to what level.

**Gene expression.** The set of genes that are turned on in a cell and the timing of the activation of the genes are key events in determining the cell type. The cell responds to its local environment frequently by sending messages to the cell nucleus to change which genes are turned on or off. This process is extremely important in all developmental processes and in the responses of cells to changes in the environment. Because of this, a major clue to a gene's function is in what cell type it is found and when it is turned on. Since their inception in 1995, gene expression microarrays are providing unprecedented analysis of gene expression levels—a critical measurement in the diagnosis, prognosis, and management of cancer and other diseases. The application of DNA microarray technologies will provide vast quantities of data regarding how genes are used to build tissues and how genes are affected in disease processes.