

DE GENNES WINS NOBEL PHYSICS PRIZE FOR WORK ON COMPLEX SYSTEMS

In 1977 Pierre-Gilles de Gennes of the Collège de France wrote an article for *La Recherche* about the Nobel Prize in Physics that had been awarded that year to John Van Vleck, Philip Anderson and Nevill Mott. In his article, de Gennes categorized each of the three Nobelists according to a scheme suggested to him by the wife of an English colleague: She classified physicists either as golf players, who patiently tap a single ball from hole to hole until the end of the game, or as tennis players, who bound around the court to hit the ball from all directions. By this definition de Gennes is a tennis player. In his career he has studied condensed matter in many forms: ferromagnets, superconductors, liquid crystals, polymers and, most recently, interfacial phenomena. Now this Frenchman has won the Nobel Prize, having been cited more for his overall style of play than for any unique stroke. In announcing the prize, the Royal Swedish Academy of Sciences recognized de Gennes for "discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers." De Gennes received his prize, worth \$1 million, on 10 December.

Born in 1932, de Gennes earned a PhD in physics while working for the Center for Atomic Studies in Saclay in 1958. He had a postdoctoral year at Berkeley in 1959 with Charles Kittel. In 1961 he became a professor of physics at the Université du Paris Sud in Orsay, where he organized a group of experimenters and theorists to study type-II superconductivity. One of his contributions to that field was his prediction of neutron scattering by an array of vortex lines, which was confirmed soon afterwards in an experiment by Daniel Cribier, Bernard Jacrot and coworkers. Another contribution was his prediction that superconductivity persists on the surface of a type-II material even at fields higher than the upper critical magnetic field H_{c2} , the field at which superconductivity disappears in the



Pierre de Gennes explaining some of the work that earned him this year's Nobel Prize.

bulk of the material. The surface remains superconducting until a third critical field, H_{c3} , is reached.

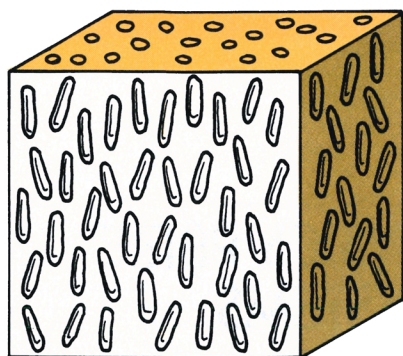
Liquid crystals

Around 1968 de Gennes became fascinated by liquid crystals. Not only were the liquid crystals, in his words, "beautiful and mysterious," but the field was one in which simple experiments were still possible. Many condensed matter physicists had shied away from liquid crystals up to that point because the structures had far less order than the familiar crystalline lattices and because they typically involved complicated organic materials. In the words of Robert Birge-neau of MIT: "De Gennes took a set of organic fluids that, from the outside, looked very complicated, with a literature that was incomprehensible to virtually all physicists, and he figured out how to think about them simply. He knew the right questions to ask: What is the order parameter for this system? What are its symmetries?

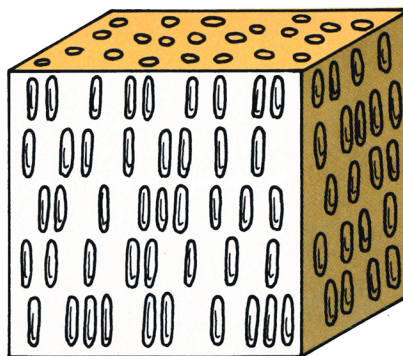
What are its broken symmetries? What are the dynamical consequences of those broken symmetries? A large number of experiments followed naturally from that approach."

Believing in close collaboration between theorists and experimenters and in the benefits of cross-fertilization among physicists, chemists and materials scientists, de Gennes gathered together at Orsay a group that included all of these specialties. This group focused on liquid crystals, which were attracting attention at the time because of their potential industrial applications: Liquid crystals have optical properties that can be easily manipulated, so they are valuable for information displays.

Perhaps the simplest in structure of these liquid crystals are the nematics. In nematics the rod-like molecules tend to line up with their axes along one direction, designated by a vector called the "director," but their spatial placement is random. In other words, in one direction nematics break the



Nematic



Smectic A

Liquid crystals have greater order than isotropic liquids. In nematic crystals (left) rod-shaped molecules tend to align parallel to one direction. In smectic-A crystals, the molecules are additionally organized in planes perpendicular to the direction of orientation.

continuous rotational symmetry of the isotropic liquid. (See the figure on page 18.) Another category of phases of liquid crystals—the smectics—have one additional degree of order imposed on them. For example, in crystals of the smectic-A type, rod-like molecules are oriented along a director, as in nematics, but the molecules are grouped in planes normal to the director; that is, their positions are random in only two directions but have translational order in the third dimension. Thus smectic-A materials act like a solid parallel to the director and have the structure of a liquid in the other two dimensions.

Because the molecules of a smectic-A liquid crystal group lie in planes spaced at regular intervals, the crystal can be described by a density wave along the director. De Gennes took the amplitude and the phase of this density sine wave as the two components of an order parameter for the system. (In critical phenomena an order parameter is a macroscopic variable characterizing the symmetry that is broken at a phase transition. One example is the net magnetization of a ferromagnetic system, which is zero in the disordered phase and nonzero in the ferromagnetic state.) When de Gennes wrote the expression for the free energy of the nematic-smectic-A phase transition he found that it was analogous to the Landau-Ginzburg description of a superconductor. In the latter case the order parameter is the wavefunction of the Cooper pair, and the magnetic vector potential $\mathbf{A}$ replaces the nematic director. Because both superconductors and smectic-A liquid crystals have two-component order parameters, they belong to the same universality class of critical phenomena. De Gennes's description of the second-order nematic-smectic-A phase tran-

sition has been largely verified by experiment.

It turns out that there are three subtle differences between the smectic-A phase and superconductors. The first concerns the behavior of the coherence length. In superconductors there is one isotropic coherence length that diverges as the transition temperature is approached. In smectic-A materials there are two coherence lengths, one parallel to the director and the other normal to it, and their ratio diverges as the critical transition is approached. Another difference between smectic-A liquid crystals and superconductors concerns the natural length scale of the fluctuations. Fluctuations occur on molecular scales (tens of angstroms) for the former and on the scale of Cooper pairs (thousands of angstroms) for the latter. Thus critical fluctuations begin to appear much farther from the transition point for the nematic-smectic-A transition: Its critical regime is much wider. A third difference is that a superconductor has true long-range order in three dimensions, whereas the density sine wave in a smectic-A liquid crystal decays algebraically with distance, much as in a two-dimensional crystal.

The announcement from the Swedish Academy stated that de Gennes's chief contribution to liquid crystals was his explanation of the anomalous scattering of light from nematic liquid crystals. It had been known that nematics strongly scatter light and appear quite turbid, but the early explanation, based on "swarms," did not seem to make sense. This scattering as well as other features were successfully explained by a fundamental theory developed by de Gennes (in papers published with the Orsay liquid crystal theory group) to describe the static and dynamic be-

havior of nematics. His theory indicated that light was scattered from local reorientations of the nematic director.

Patricia E. Cladis (AT&T Bell Labs) notes that liquid crystals, once confined to niche markets like watches and calculators, now are used in the microelectronic hardware poised to take over from cathode ray tubes in the electronic display industry. Japan has been especially aggressive in developing liquid crystal displays. Most of today's displays use the "twisted nematic" technique, in which an electric field $\mathbf{E}$ forces the liquid crystal to change from a helical arrangement, which rotates the polarization of light, to a uniaxial arrangement, which does not alter the polarization.

Polymers

Around 1971, soon after de Gennes accepted a chair in condensed matter physics at the Collège de France, he went through another phase transition and began to explore polymer physics. Polymers ostensibly have far less structure than liquid crystals, but de Gennes was still able to apply the principles of critical phenomena to them. One example of critical phenomena is the behavior of a magnetic system near a critical point: There are fluctuations of the local magnetization, with a maximum size called the correlation length ξ . Near the critical temperature ($T \rightarrow T_c$), ξ diverges as $(T - T_c)^{-\nu}$, where the exponent ν typically has a value of $2/3$.

De Gennes, building on the ideas of Paul Flory and others, showed that the behavior of a single polymer coil, floating in a good solvent, has a deep similarity to these fluctuations. The analog of the temperature shift $T - T_c$ is the inverse of the polymer's molecular weight M : Long chains (large M) correspond to temperatures very close to the critical value. The coil size R is related to M by $R \approx M^\nu$, and the exponent ν can be predicted by the same renormalization-group methods that have been successful for phase transitions. Later, de Gennes's ideas were extended to solutions of overlapping coils by Jacques des Cloizeaux of Orsay, whose work inspired a whole generation of new experiments.

De Gennes's second contribution to polymer science concerned the dynamics of polymer motion. For years scientists had been puzzled over how a mass of polymer coils that is not in solution is able to flow even though the chains are expected to be strongly entangled. Researchers needed to be able to characterize the molecular motions that result in macroscopic

flow in order to understand the viscoelastic properties of a polymeric solution. De Gennes's answer was that the polymers "slither" like snakes, and his model is consequently called the "reptation" model (from the Latin *reperere*, meaning "to creep"). A chain does not move forward in a straight line; instead, its random local Brownian movements lead it to progress gradually along its own contorted contour. In this way the haphazard motions of parts of a chain result in a much smaller forward progress of the center of mass of the whole molecule.

De Gennes told us that his work on polymers owes a heavy debt to Sam Edwards of Cambridge University, England. In the early 1960s Edwards noted that polymers obey laws similar to quantum field theory, and he was able to solve them in the limit of high concentrations. (He collaborated in some of this work with Carl

Freed of the University of Chicago.) Edwards also introduced a mean-field approach, by which one concentrates on one polymer and represents the effect of all the others on it by an average interaction. Edwards told us that de Gennes then realized that he could extend the study of polymers to dilute solutions by using scaling mechanisms.

Edwards also laid the groundwork for the reptation model by suggesting that polymers are hemmed in by all the other molecules in a polymer melt at high concentration and that each chain behaves as if it were confined to a tube with its axis curved in arbitrary arcs: The walls of the tube correspond to the restrictions imposed by the surrounding polymers. De Gennes pushed this model further to analyze the snake-like motion of the polymer as it wiggles along its tube. The polymer leaves one tube

section by diffusion and creates another section as it winds its way through the solution.

De Gennes told us that over the last ten years he has been thinking less in terms of complex mathematics and more in terms of scaling laws. His education in that approach, he says, comes largely from Leo Kadanoff of the University of Chicago. Kadanoff in turn is impressed by the ingenious ways in which de Gennes has extended the ideas of scaling in unexpected directions. Kadanoff's Chicago colleague Thomas Witten notes that all de Gennes's diverse accomplishments embody a single style of reasoning: He strips away all possible formalism to explain the phenomenon at hand with maximum economy and simplicity. This style is well expressed in the elegant scaling arguments for which de Gennes is famous.

—BARBARA GOSS LEVI

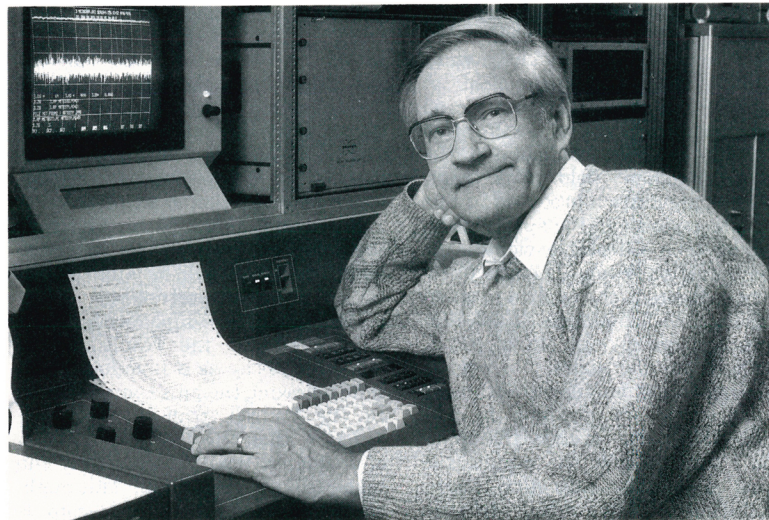
NOBEL CHEMISTRY PRIZE RECOGNIZES THE IMPORTANCE OF ERNST'S NMR WORK

Richard R. Ernst of the Swiss Federal Institute of Technology (ETH) in Zurich was reviewing research proposals on a flight from Moscow to New York, on his way to collect Columbia University's 1991 Louisa Gross Horwitz Prize, when the captain informed him he had won the 1991 Nobel Prize in Chemistry. While the news was not important enough to interrupt screening of the in-flight movie, Ernst did go forward to the cockpit to receive the radioed congratulations of the Royal Swedish Academy of Sciences, the president of Switzerland and participants in a party organized on his behalf in Zurich.

In announcing the award the academy cited Ernst's "contributions to the development of the methodology of high-resolution nuclear magnetic resonance spectroscopy." In the 46 years since the invention of nmr, a number of researchers have made highly significant advances, and consequently the first thing Ernst asked the captain was, "Who are the other two?"

"I could imagine several feasible combinations of winners where I would be only one of two or one of three," Ernst told us.

However, Ernst stands out especially because of two important developments: Fourier-transform nmr spectroscopy in the mid-1960s and two-dimensional nmr in the 1970s. He also proposed an nmr tomography method that now forms the basis of one of the most widely used magnetic



Richard R. Ernst in front of a spectrometer that is used to record two- and three-dimensional nmr spectra.

resonance imaging techniques for clinical studies.

Early work

The first nmr experiments were carried out in 1945 by groups led by Felix Bloch at Stanford and Edward L. Purcell at Harvard. (Bloch and Purcell won the 1952 Nobel Prize in Physics for this work.) Nmr makes use of the nuclear Zeeman effect: In an applied magnetic field of the order of several tesla, different orientations

of the nuclear spins have energies that differ by amounts corresponding to radio frequencies. When the nuclei are exposed to radio waves of the correct frequency, transitions between the levels can be excited. Most of the earliest experiments involved continuous-wave radio signals swept slowly through a range of frequencies; at the resonant frequencies absorption or dispersion by the sample is detected, either by the coil producing the radio waves or by a separate

ETH, ZURICH