LBL-25687

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

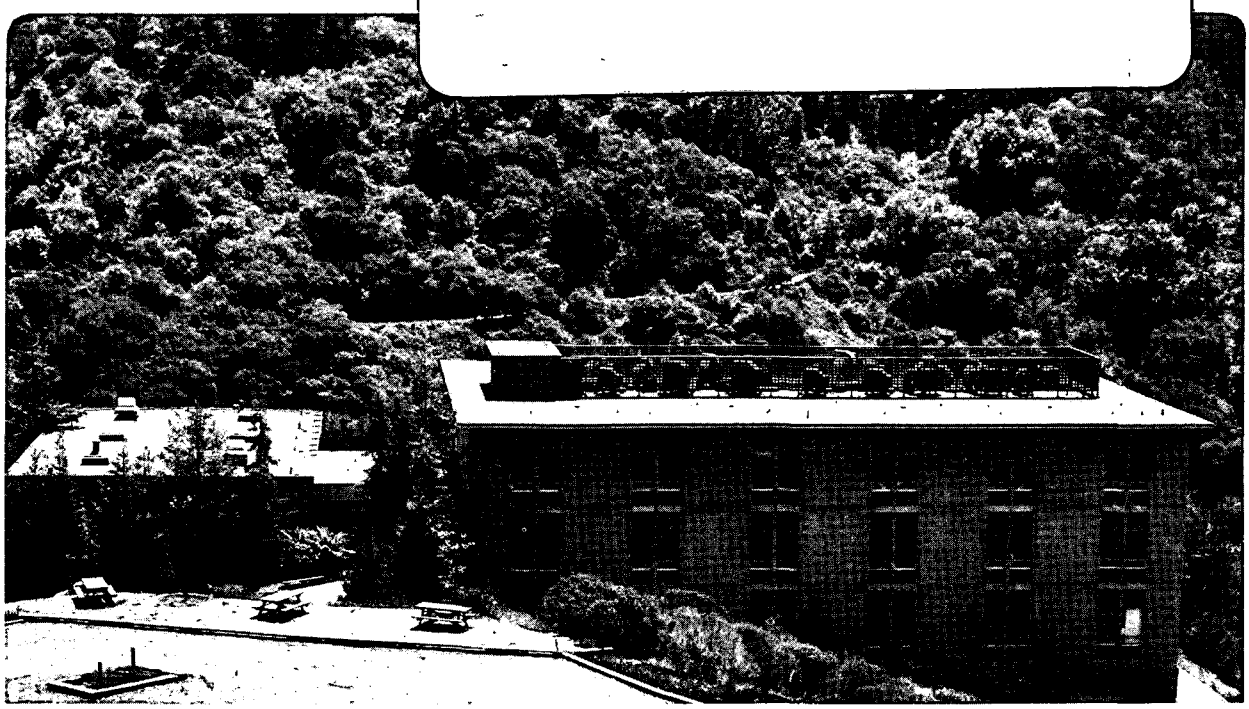
Materials & Chemical Sciences Division

Presented at the Third Symposium on Pan-American Collaboration in Experimental Physics, Rio de Janeiro, Brazil, October 19–23, 1987, and to be published in the Proceedings

1987: Open Problems in Condensed Matter Physics

L.M. Falicov

August 1988



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

To be published in the Proceedings of the
Third Symposium on Pan-American Collaboration
in Experimental Physics, Rio de Janeiro, Brazil,
October 19-23, 1987 (World Scientific)

LBL-25687

1987: OPEN PROBLEMS IN CONDENSED MATTER PHYSICS*

L. M. Falicov

Physics Department, University of California, Berkeley, CA 94720

and

Materials and Chemical Sciences Division,
Lawrence Berkeley Laboratory, Berkeley, CA 94720

August 1988

*Work supported in part by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

1987: OPEN PROBLEMS IN CONDENSED MATTER PHYSICS

L. M. FALICOV

Department of Physics, University of California,
Berkeley, CA 94720

and

Materials and Chemical Sciences Division,
Lawrence Berkeley Laboratory, Berkeley, CA 94720

ABSTRACT

The 1970's and 1980's can be considered the third stage in the explosive development of condensed matter physics. After the very intensive research of the 1930's and 1940's, which followed the formulation of quantum mechanics, and the path-breaking activity of the 1950's and 1960's, the problems being faced now are much more complex and not always susceptible to simple modelling. The (subjectively) open problems discussed here are: (1) high temperature superconductivity, its properties and the possible new mechanisms which lead to it; (2) the integral and fractional quantum Hall effects; (3) new forms of order in condensed-matter systems; (4) the physics of disorder, especially the problem of spin glasses; (5) the physics of complex anisotropic systems; (6) the theoretical prediction of stable and metastable states of matter; (7) the physics of highly correlated states (heavy fermions); (8) the physics of artificially made structures, in particular heterostructures and highly metastable states of matter; (9) the determination of the microscopic structure of surfaces; and (10) chaos and highly nonlinear phenomena.

Nineteen eighty seven has been a very exciting year in physics in general, and in condensed-matter physics in particular. It has also been the year of superlatives, with the prefix super working overtime. The 1987 Nobel Prize in Physics has been awarded to G. Bednorz and A. Muller for their work on high temperature superconductivity. Astrophysicists are fascinated with their new toy: the 1987 supernova in the Magellanic

cloud. High-energy theorists seem to be dazzled by their supersymmetric strings. And high-enery experimentalists, who always have to have twice as much as everyone else, have been busy designing their multibillion-dollar superconducting supercollider.

(1) HIGH-TEMPERATURE SUPERCONDUCTIVITY.

(1a) Introduction.

High-temperature superconductivity has been the science news of the year: the media have never popularized a scientific, health unrelated subject with such intensity, ubiquity and persistence. And physicists, who like most human beings enjoy the limelights, played faithfully their rock-superstar role and delivered, in the New York meeting of the American Physical Society in March of 1987, a difficult to forget session, labelled by the press "The Woodstock of Physics".

Superconductivity is however an old phenomenon. It is a phase, a state of matter (in the sense that ice and steam are phases of water and diamond and graphite are phases of pure carbon) observed in some solids, mostly metals [1-3].

The superconducting state has several characteristic properties:

i. When it exists for a given substance, it exists only at temperatures below a so-called transition temperature, T_c, and in general down to the absolute zero of the temperature scale (0 K = -273.15 °C).

ii. It exhibits d.c. zero resistivity, i.e. infinite conductivity for zero-frequency measurements (an effect discovered in mercury by Kamerlingh Onnes in 1911).

iii. It exhibits, for weak magnetic fields, perfect diamagnetism, i.e. its magnetic susceptibility in Gaussian units is given by

$$X_M = -(1/4\pi) \ , \qquad (1)$$

which means that magnetic flux lines are completely expelled from the superconductor. This effect, known as the Meissner effect, was discovered by Meissner in 1933.

iv. There is a minimum energy value -- called an energy gap [4] -- for exciting the system away from its state of lowest energy (the so-called ground state). This energy gap

$$E_G = 2|\Delta| \ , \qquad (2)$$

was conjectured theoretically by London in 1935, deduced from thermodynamic data in 1946, observed by infrared measurements in 1956 and by electron tunneling in 1960.

v. There is a surprising dependence on the transition temperature, T_c, on the isotopic mass of the atomic nuclei of the superconductor. (It is surprising that a phase which is electric and magnetic in nature, and therefore caused by the electrons, depends in any fashion on the mass of the nuclei). This is the so-called isotope effect, was discovered in 1950, and establishes that

$$M^{\alpha} \cdot T_c = \text{constant} \ , \qquad (3)$$

where M is the nuclear mass and, for various metals, the exponent α takes the values: 0.485 for Pb, 0.415 for Sn, 0.150 for Ti, 0.065 for Ru, and -0.015 for Ir.

vi. Superconductivity, in addition to high temperatures, can be destroyed (with a return to the normal state) by either a large enough electric current $I > I_c$, or a large enough magnetic field $H > H_{c2}$. (It should be mentioned that for intermediate field strengths $H_{c1} < H < H_{c2}$, the magnetic flux lines partially penetrate the superconductor but do not destroy the superconducting state.) The quantities I_c, H_{c1}, and H_{c2} are called the critical current and the critical magnetic fields, respectively.

vii. Superconductivity is a macroscopic quantum phenomenon, with amplitudes and phases associated with the energy gap parameter Δ. Therefore interference and diffraction effects can be achieved, in particular the Josephson effect [3]. These effects can be fruitfully employed in processing, storing, and retrieving information, i.e. in computer technology

(1b) Theory.

The currently, universally accepted theory of superconductivity, known as the BCS theory, was formulated [5] by Bardeen, Cooper and Schrieffer in 1957. The theory in its most general form states that, if metallic mobile electrons interact attractively with each other, then they will condense into a ground state with

(i) an energy gap in the excitation spectrum;

(ii) zero resistivity;

(iii) the Meissner effect; and

(iv) a phase transition to the normal metallic state at a transition temperature T_c.

There is an important issue to resolve. How can two electrons -- which are charged particles with identical negative charges and therefore experience a strong Coulomb-force repulsion -- attract one another? The answer is: by polarizing the crystal lattice! [An instructive simile is the attraction that two billiard balls experience when placed on a rubber membrane: one billiard ball falls readily into the depression caused by the other ball, hence it is attracted by the other ball.] Since the polarization of the solid lattice depends on the mass of the nuclei which form it, the strength of the electron attraction depends on the mass of the nuclei, i.e. there is an isotope effect.

The BCS theory yields, in general, an integral equation for the energy gap parameter Δ, and another integral equation for the transition temperature T_c. These integral equations depend on the electronic structure of the metal, and on the details of the attractive interaction between the electrons. As an example of their theory, Bardeen, Cooper and Schrieffer introduced a very simple model, the so-called BCS model, for which the integral equations can be analytically solved, and that yields

$$\Delta = 1.76\ k\ T_c = 2\ \hbar\omega_D \exp[-1/NV] , \qquad (4)$$

where k is Boltzmann's constant, ω_D is the vibration (Debye) frequency of the lattice, N is the number of available electronic states per unit energy in the solid (density of states at the Fermi level), and V is the strength of the attractive (lattice mediated) electron-electron interaction.

This simple BCS model gives a good idea of how the BCS theory works: the transition temperature can be increased (i) by increasing ω_D, (ii) by increasing N, or (iii) by increasing V. [It should be remarked that the influence of both N and V on T_c is much more dramatic than the simple proportionality of T_c and ω_D.] According to formula (4) there is no maximum transition temperature; T_c can be increased without

limit by finding solids with larger and larger N, V, and ω_D.

In fact formula (4) is not accurate; it is only a simple model. A very good and accurate theory, based on the BCS theory, was developed by Eliashberg and McMillan [6] which, given precise experimental information about the solid lattice vibrations, could accurately -- by numerical methods -- calculate the gap parameter Δ and the transition temperature T_c. This theory, with a precision of a few percent, yields excellent results for the transition temperature T_c and the isotope effect exponent α in several well studied cases, mostly transition metals. Numerical experiments performed with the Eliashberg-McMillan equations produced, for sensible input of lattice vibration spectra, superconducting transition temperatures which never exceeded 40 K. Therefore, although no rigorous limit was established for a maximum superconducting transition temperature, the belief among most specialists was that such an upper bound existed, and that it was in the range of 30 K to 40 K.

(1c) History of the Highest Superconducting Transition Temperatures.

The table below shows the history of the experimentally found highest superconducting transition temperatures:

Year	T_c[K]	Substance	Notes and References
1911	4.2	Hg	[1]
~1913	7.2	Pb	
1933	9.5	Nb	
1941	16.0	NbN	
1953	17.1	V_3Si	
1960	18.05	Nb_3Sn	
1969	20.8	NbAlGe	
1973	23.2	Nb_3Ge	[7]
1986	~30	La-Ba-Cu-O	[8,9]
1986	39	La-Sr-Cu-O	[10]
1987	~92	RE-Ba-Cu-O	RE=various rare earths [11,12]
1987	~230	RE-Ba-Cu-O	not reproducible, unstable! [13]

As can be seen, from 1911 to 1973 the increase in maximum observed transition temperatures was a more-or-less linear fraction of about 0.3K per year. No temperature was found to violate the (wrongly believed) upper bound.

For the sake of comparison it should be rememberd that liquid helium boils at 4.5 K, liquid hydrogen at 20.7 K, liquid neon at 27.2 K, and liquid nitrogen (i.e. liquid air) at 77.4 K. These are the most commonly used refrigerants, and any technology based on superconductivity will have its costs determined, almost exclusively, by the refrigeration costs. The discovery of superconducting Nb_3Ge in 1973 was considered a major breakthrough, since for the first time the liquid-hydrogen barrier was crossed. Needless to say the events of the last few months can be considered, by any standards, fantastic: first, the liquid-neon barrier was broken; soon thereafter the liquid-air temperature was surpassed; and -- if the elusive and unstable very high temperatures reported recently, but easily lost, are both confirmed and stabilized -- it seems that the dream of room-temperature superconductivity is now within accessible reach.

(1d) The New Superconductors.

The 1987 high-temperature superconductors have a combination of properties which are, except for the HUGE VALUES of the CRITICAL TEMPERATURES, the CRITICAL MAGNETIC FIELDS, and the ENERGY GAPS, not really unusual. They are all four- or five-component COPPER OXIDES. They are poor conductors in the normal state. They have a very LOW CRITICAL CURRENT. They exhibit, to a varying degree, an ISOTOPE EFFECT. The various substances exhibit a rich variety of solid-state phases. Some of the phases are ANTIFERROMAGNETIC. Some of the phases are INSULATING. The superconducting phases are VERY ANISOTROPIC, with characteristics which make them look either as layered compounds (i.e. with strong two-dimensional features), or, in some cases, as linear chains (i.e. with one-dimensional characteristics). They are all incredibly easy to manufacture (which makes one wonder why were they not discovered before). They are also difficult to produce in a single phase, and even more difficult to produce as single crystals (all known

single crystals are, as far as the author is aware, twins). But the main fact is that they are, in all respects, traditional superconductors: they exhibit all the features (i) through (vii) discussed in Section I.

Theories, speculations, and explanations for these fascinating substances abound. In fact the 1987 Physics, Chemistry, and Materials Sciences literature has been flooded with papers aiming at either partial or comprehensive elucidation of the superconducting behavior of these oxides. Needless to say, the "theories" are mostly divergent, and clash with one another. As more experimental facts become known and detailed data become available most, if not all, will be discarded. A critical discussion of the merits and drawbacks of the various attempts is, at this point, a rather futile exercise. It is important, however, to underline some of the ideas currently being pursued, and the main features of these theories/speculations:

(i) The new superconductors are layered solids, and this anisotropy may be the dominant feature which produces the high transition temperatures. (There are many other layered superconductors, e.g. $NbSe_2$ either pure or intercalated with other substances, including organic molecules. These "two-dimensional" superconductors have "ordinary" transition temperatures, in the range 5 K to 15 K.)

(ii) The lattice vibrations of these oxides may be unusually soft, with a consequent enhancement of the superconductivity. (This is a common feature of many other superconductors, and leads to high, but "ordinary" transition temperatures, easily explained by the Eliashberg-McMillan equations.)

(iii) The magnetism -- especially the antiferromagnetism -- of these substances may play an unusual and crucial role. (Although antiferromagnetism and superconductivity are known to coexist in some cases, e.g. $ErRh_4B_4$, magnetic moments, and especially ferromagnetic arrangements, tend to destroy, not enhance, superconductivity.)

(iv) These substances are oxides, and the oxygen ion must play a crucial role in the superconductivity. (There are other oxide superconductors, e.g. $LiTi_2O_4$, with a transition temperature of

13.7 K, discovered in 1973, and $BaPb_{1-2}Bi_xO_3$ with a transition temperature of 13 K, discovered in 1975, but they are the exception rather than the rule.)

(v) The electrons may be in these substances very tightly bound in pairs and behave like the atoms of superfluid helium. (This is the so-called "Bose condensation of bipolarons"; most experimental evidence seems to be against this type of explanation.)

(vi) The repulsion between the electrons caused by the Coulomb forces, coupled to their motion in the solid lattice, must produce a repulsion at short distances, but could produce an attraction at intermediate distances which may lead to a superconducting state. (It should be noted that the Coulomb repulsive interaction normally hinders rather than favors the appearance of a superconducting state. In fact the Coulomb repulsion, coupled to quantum-mechanical effects, is responsible for the appearance of the various forms of magnetic ordering, including ferromagnetism and antiferromagnetism.)

(vii) The lattice vibrations do not play (or at most play a minor) role in the superconducting properties of these oxides. (This will be a completely new feature for superconductors: all other superconductors are known to be a consequence of the electron-electron attractive interaction caused by a lattice polarization. An explanation of this sort could take care of the violation of the Eliashberg-McMillan upper bound, but will contradict the observation of the isotope effect in these high transition temperature superconductors.)

(viii) The BCS theory should be discarded for these substances and a new state of matter, with radically different properties should be postulated. (Unfortunately this type of explanation seems to be doomed to failure, since these are, except for the large values of the parameters, ordinary superconductors in all respects. And it should be remembered that the BCS theory is not only one of the most successful physical theories ever formulated, it has great predictive values: in all cases its predictions have been confirmed -- over and over again -- by experiment.)

(1e) Conclusions.

The BCS theory, in all probability, will explain the properties of these new superconducting materials. However, a detailed account of why they have such an unusually high transition temperature will require much more work, mostly careful, well designed, well executed experiments.

The key to the answer to the theoretical questions may be found in the fact that all these materials are ceramics; i.e. BAD CONDUCTORS in their normal phase. In fact, they are "ALMOST INSULATORS", with strange and varied MAGNETIC PROPERTIES. And although the lattice polarization will certainly play a role (as shown by the isotope effect), the detailed motion of the electrons and the short-range Coulomb repulsion may give the unusual characteristics which result in high transition temperatures.

From the point of view of practical applications and their implications in our everyday life, much can be speculated: transmission lines without any power losses, levitated trains, super-supercomputers, new and not-yet-invented devices. But all these innovations will require the solution of complicated (and expensive to solve) materials problems (brittle, hard to handle ceramics; unstable phases; low critical currents) as well as a cool-headed economic analysis which this author is unable to provide.

But, from the point of view of the scientific and technological challenge, the fun has just begun. Hard work lies ahead, but is challenging, exciting work, with potentially enormous rewards.

(2) THE INTEGRAL AND FRACTIONAL QUANTUM HALL EFFECTS.

The discovery in 1980 of the Integral Quantum Hall effect [14] was rewarded by the Nobel Prize in Physics for 1985. It was found that high-mobility electrons, moving with a current J_x along the x-direction in artificially made two-dimensional structures [see (8) below], in the presence of high magnetic fields B_z perpendicular to the structure, developed a Hall voltage V_y such that the Hall resistance $\rho_{yx} = (V_y/J_x)$ developed plateaux whenever

$$\rho_{yx} = h / (\nu\, e^2\, B) \quad ,$$

where h is plancks constant, B the strength of the magnetic field, and ν

= 1, 2, 3, ... a positive integer. The interesting feature of this discovery is that the plateaux depend on the value of the magnetic field and on universal constants, and are independent of the material parameters of the sample.

A surprise followed [15] in 1982, when it was discovered that additional plateaux exist for odd denominator fractional numbers ν = (1/3), (2/3), (1/5), (2/5), ... This involves unusual, correlated states of the two-dimensional electron gas. The path-breaking theory of Laughlin [16] was followed by great activity [16-21]. Electrons confined to a two-dimensional layer in the presence of high magnetic fields are undoubtedly in a highly correlated state. Is this state the traditional Wigner crystal? Is it the fascinating new state [16-20] proposed by Laughlin? Is it another, even more complicated [21] many body state? The question is not yet completely settled, although the odds seem to be in favor of Laughlin's model [16]. The area is very active and interesting results will be forthcoming.

(3) NEW FORMS OF ORDER IN CONDENSED-MATTER SYSTEMS.

For most condensed-matter scientists the idea of order is unequivocally intertwined with periodicity and three-dimensional lattices. X-ray diffraction, Bragg's law, Bloch's theorem and the mathematics of periodic systems are the foundation stones of solid-state physics. It was therefore a rude shock when, in 1985, a new structure for the quenched alloy $MnAl_6$ was reported [22]. This discovery opened up a field presumed to be closed, understood and finished. It produced a bonanza for pure and applied mathematicians (geometers, topologists and group theorists), for X-ray crystallographers and electron microscopists, for metallurgists and materials scientists. The harvest has been rich [22-25]: we now know that sharp diffraction spots can be caused by systems that are not periodic [11], that five-fold symmetries are allowed in ordered (albeit not periodic) systems, and that the mathematics of six-dimensional spaces, when projected onto our ordinary three-dimensional world, produces perhaps real structures, observable in the laboratory. It is a new and fascinating new world, in which the still unanswered question can be found in the title [25] of a commentary paper: Where are the Atoms?

(4) THE PHYSICS OF DISORDER. SPIN GLASSES.

Since Physics is the search for underlying basic order in a complex and seemingly chaotic Universe, it is surprising the fascination that physicists have developed for the study of disorder [26-28]. It should be recognized that disorder and chaos happen to have a fantastic and perverse beauty of their own, enhanced and brought up to its most exquisite form by the mathematical concept of fractal [29-31], a concept which is currently highly in vogue and whose influence in science seems to be destined to be widespread, deep, and lasting.

The study of disordered systems covers all kinds of ill-condensed matter [32], from the traditional fields of ordinary glass [33], amorphous semiconductors [34] and polymers [35], to the most recent studies of growth, aggregation and gelation [31,36]. But the field reaches its most challenging aspects in the study of spin glasses [37-43], an area in which the deceptive simplicity of the formulation and the richness (and difficulty) of the solutions seems to transcend the boundaries of condensed-matter physics to influence areas of applied mathematics [37,40], information theory and even the physiology of the brain [44]. The ideas and concepts derived from this research have opened new vistas: the horizon is not yet on sight.

(5) THE PHYSICS OF COMPLEX ANISOTROPIC SYSTEMS.

In the 1970's and 1980's physicists have learned to be comfortable with systems which lack symmetry, not only disordered systems but also those which are intrinsically directionally asymmetric. In particular, three-dimensional systems that resemble linear chains [45] (quasi-one-dimensional) or layers [46,47] (quasi-two-dimensional) have been and are intensively studied. Their main interest and fascination derives from four features: (i) they can be easily modified and "tailored" [46]; (ii) they present fascinating states of electron broken symmetry, in particular spin-density and charge-density waves [45,47]; (iii) they exhibit unusual magnetic and superconducting behavior; and (iv) they exhibit yet poorly understood nonlinear behaviors in the presence of moderately strong electric and magnetic fields [45-52]. This last effect is, at this time, one of the most active and open questions in condensed matter physics, directly related to other phenomena discussed

here: chaos and nonlinear phenomena, interaction of electrons in solids with high magnetic fields, and the physics of highly correlated states of matter.

(6) THE THEORETICAL PREDICTION OF STABLE AND METASTABLE STATES OF MATTER.

The basic predictive question of condensed-matter theorists (given the chemical composition of a system, can we predict ab initio its stable configuration and all its attendant physical properties?) still remains an unfulfilled dream, but with some glimpses of realization, albeit for very simple systems, now firmly established [53-57]. There are now, in print, firm predictions for new phases of silicon [55,56] and for an insulating state of nickel [57], all under hydrostatic pressure. The $T = 0$ equations of state for simple elemental solids have been reproduced, in good agreement with experiment. Some binary compounds are currently being investigated. The area is buzzing with activity and enthusiasm, which have to be attributed to three developments: (i) our better understanding of the behavior of electrons in periodic potentials [53,58]; (ii) our better understanding of how to replace complicated many-body interactions with a working one-particle potentials (the Local Density Approximation [59]); and (iii) the spectacular development and availability world-wide of inexpensive large-scale computation [60].

(7) THE PHYSICS OF HIGHLY CORRELATED STATES (HEAVY FERMIONS).

The unusual properties of some metallic rare-earth and actinide compounds [61,62], the so-called heavy fermions, has opened a new chapter in the venerable field of the condensed-matter physics of unfilled f-shell elements. Their thermodynamic, electrical, and magnetic properties are so unusual as to defy categorizing them in any of the known types of solids studied thus far. In addition, some of them ($CeCu_2Si_2$ and UPt_3) exhibit unusual superconducting properties [63,64]. This is essentially a new area, poorly understood at present, although directly related to the somewhat older field of fluctuating-valence solids [65,67].

(8) THE PHYSICS OF ARTIFICIALLY MADE STRUCTURES.

Considerable advances in materials technologies [68-70] has permitted the fabrication of complex structures with characteristics different from those found in natural substances and structures. This new technology has produced a new branch of condensed-matter physics [71] which studies the dynamics of electrons in new, artificially constructed situations. The Integral [14] and the Fractional [15] Quantum Hall Effects, discussed in (2), are the most notable examples of this new kind of physics. But the field is much vaster, and includes one- and two-dimensional artificially periodic devices, quantum wells, lasers, switches, tunneling barriers and other tunneling structures, resonating tunneling devices, etc. It deals with the thermodynamics and the electrical, optical and magnetic properties of these systems.

Along different lines, but with similar motivations, the advent of the Diamond Anvil Cell [72] has permitted the application of high pressures to hitherto unexplored areas. New phases of old materials (silicon, for example [55,56]) have been discovered and studied. The dream of repeating natures's diamond trick (the preparation of a highly desirable, highly metastable phase of a common substance) has been revived. We are, as in the times pf the "philosophical stone", trying hard again: an old field is wide open once again, albeit with new and powerful tools.

(9) THE DETERMINATION OF THE MICROSCOPIC STRUCTURE OF SURFACES.

The area of Experimental Surface Science, of great importance to the chemical, construction, and electronic industries, has been an extremely active one for almost two decades. It is populated by a multitude of techniques which explore, in a variety of ways, the microscopic structure of surfaces and interfaces [73]. These techniques constitute, for the uninitiated, a bewildering soup of letters:

AES: Auger Electron Spectroscopy,

ARPES: Angular Resolved PhotoElectron Spectroscopy,

ELS: Energy Loss Spectroscopy,

EM: Electron Microscopy,

ESCA: Electron Scattering for Chemical Analysis,

EXAFS: Extended X-ray Absoption Fine Structure,

FIM: Field-Ion Microscopy,

HEIS: High-Energy Ion Scattering,

HREELS: High-Resolution Electron Energy Loss Spectroscopy,

LEED: Low Energy Electron Diffraction,

LEIS: Low-Energy Ion Scattering,

MEED: Medium Energy Electron Diffraction

MEIS: Medium-Energy Ion Scattering,

PES: PhotoElectron Spectroscopy,

RHEED: Reflection High-Energy Electron Diffraction,

SEXAFS: Surface-Sensitive Extended X-ray Absoption Fine Structure,

SIMS: Secondary-Ion Mass Spectroscopy,

SPPES: Spin Polarized PhotoElectron Spectroscopy,

TDS: Thermal Desorption Spectroscopy.

UPS: Ultraviolet Photoelectron Spectroscopy

XPS: X-ray Photoelectron Spectroscopy.

These techniques are extremely useful and of widespread applicability. They are even more powerful when applied simultaneously (in groups of two, three, four or even more) to tackle a particular structural problem of a particular surface.

The invention in 1983 of STM, the Scanning Tunneling Microscope (with a Nobel Prize in Physics awarded to the invention in 1986) has opened new avenues of research [74,75] in the area of Surface Science, and has brought us closer to achieving another unfulfilled dream: the complete determination of the microscopic structure of surfaces. The new technique has already yielded spectacular results [74-77], and has permitted the determination, by using the microscope not only as an image builder but also as a spectroscopic tool, of complex rearranged structures in silicon and germanium, and of chrage density waves in quasi-one-dimensional and quasi-two dimensional systems. The field is one of intense activity, and tunneling microscopes are sprouting in laboratories all over the world as daffodils in and English spring.

The excitement is even higher because an Atomic Force Microscope [78], based on the STM, has been made to work. It has the advantage of being capable of investigating surfaces of insulators (the STM only works with metals and semiconductors) on an atomic scale, without

damaging the surface.

(10) CHAOS AND HIGHLY NONLINEAR PHENOMENA.

The study of chaotic dynamics [79] and highly non linear phenomena in condensed-matter systems is now in its adolescence; its various subfields are developing in leaps and bounds. The field as a whole has had a strong impulse provided by the concept of fractal [29-31], a seminal idea whose final influence in physics is still to early to assess. The systems studied experimentally [31,36,80] involve semiconductors, metals, magnetic materials, anisotropic solids, and small clusters. The driving forces are non-linear couplings to the outside electric and magnetic fields caused by quasi-particle interactions (electrons, phonons, plasmons, magnons, excitons, polaritons, etc.). The impetus to these new studies come from (i) the idea of universality [81] in non-linear phenomena; (ii) the recognition of the existence of canonical routes to chaos [82]; the application of the idea of fractal [29-31]; and (iv) once more, the availability of high speed, inexpensive, large scale computation [60].

The conclusion to this review should be a note of optimism. Condensed-matter physics in 1987 is in an ebullient state. The Nobel Prizes in Physics in 1985, 1986, and 1987 have been awarded for discoveries in Condensed Matter Physics. New ideas and new problems are exciting and abundant. The major upheaval caused by the discovery of high temperature superconductivity has brought a influx of research funds and new workers to the field. Financial, industrial, and academic support are adequate. Interactions are strong at all levels: between academic and applied research, between industry and universities, between theory and experiment, between instrumentalists and materials researchers, between simple-model builders and heavy-number crunchers, between physicists and their scientific neighbors (chemists, materials scientists, electrical engineers, computer scientists, biologists). The next few years should bring new, important and challenging developments. The future is bright.

References

1. C. Kittel, Introduction to Solid State Physics, 5th edition (Wiley, New York, 1976), Chapter 12.
2. M. Tinkham, Introduction to Superconductivity (McGraw-Hill, New York, 1975).
3. J. Clarke, Amer. J. Phys. 38, 1071 (1970).
4. D. H. Douglass, Jr., and L. M. Falicov, in Progress in Low Temperature Physics, edited by C. J. Gorter (North-Holland, Amsterdam, 1964), vol. 4, p. 97.
5. J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 106, 162 (1957); 108, 1175 (1957).
6. For a comprehensive review of this complex subject, see the various articles in Superconductivity, two volumes edited by R. E. Parks (Dekker, New York, 1969).
7. See the review in Science 183, 293 (1974).
8. J. G. Bednorz and K. A. Müller, Z. Phys. B - Condensed Matter 64, 189 (1986).
9. C. W. Chu, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, and Y. Q. Wang, Phys. Rev. Lett. 58, 405 (1987).
10. R. J. Cava, R. B. van Dover, B. Batlogg, and E. A. Rietman, Phys. Rev. Lett. 58, 408 (1987).
11. M. K. Wu, J. R. Ashburn, C. J. Tong, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu, Phys. Rev. Lett. 58, 908 (1987).
12. See the article "Superconductivity seen above the boiling point of nitrogen," in Search and Discovery, Physics Today, April 1987, p. 17.
13. C. Y. Huang, L. J. Dries, P. H. Hor, R. L. Meng, C. W. Chu, and R. B. Frankel, Nature 328, 403 (1987).
14. K. von Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. 45, 494 (1980).
15. D. C. Tsui, H. L. Stormer, and A. C. Gossard, Phys. Rev. Lett 48, 1559 (1982); H. L. Stormer, A. M. Chang, D. C. Tsui, J. C. M. Hwang, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett 50, 1953 (1983);

16. R. B. Laughlin, Phys. Rev. Lett. 50, 1395 (1983).
17. F. D. M. Haldane and E. H. Rezayi, Phys. Rev. Lett. 54, 237 (1985).
18. D. Yoshioka, B. I. Halperin, and P. A. Lee, Phys. Rev. Lett. 50, 1219 (1983).
19. B. I. Halperin, Phys. Rev. Lett. 52, 1583, 2390(E), (1984).
20. D. P. Arovas, J. R. Schrieffer, and F. Wilczek, Phys. Rev. Lett. 53, 722 (1984).
21. S. Kivelson, C. Kallin, D. P. Arovas, and J. R. Schrieffer, Phys. Rev. Lett. 56, 873 (1986).
22. D. Shechtman, I. Blech, D. Gratias, and J. W. Cahn, Phys. Rev. Lett. 53, 1951 (1985).
23. D. Levine and P. J. Steinhardt, Phys. Rev. Lett. 53, 2477 (1984).
24. V. Elser and C. L. Henley, Phys. Rev. Lett. 55, 2883 (1985).
25. P. Bak, Phys. Rev. Lett. 54, 1517 (1985); Phys. Rev. B 32, 5764 (1985); Phys. Rev. Lett. 56, 861 (1986).
26. R. J. Elliott, J. A. Krumhansl, and P. L. Leath, Rev. Mod. Phys. 46, 465 (1974).
27. D. J. Thouless, Physics Reports 13, 93 (1974).
28. Excitations in Disordered Systems, edited by M. F. Thorpe (Plenum, New York, 1982).
29. B. B. Mandelbrot, Fractals: Forms, Chance and Dimension (Freeman, San Francisco, 1977).
30. B. B. Mandelbrot, The Fractal Geometry of Nature (Freeman, San Francisco, 1983).
31. S. H. Liu, in Solid State Physics, edited by H. Ehrenreich and D. Turnbull (Academic Press, New York, 1986), Volume 39, 207.
32. Ill-Condensed Matter, edited by R. Balian, R. Maynard and G. Toulouse (North-Holland, Amsterdam, 1984).
33. J. C. Phillips, Physics Today 35, No. 2, 27 (February 1982).
34. H. Fritzsche, Physics Today 37, No. 10, 34 (October 1984).
35. P. J. Flory, Principles of Polymer Chemistry (Cornell University Press, Ithaca, 1969), Chapter 14.
36. Kinetics of Aggregation and Gelation, edited by F. Family and D. P. Landau (North-Holland, Amsterdam, 1984).

37. Heidelberg Colloquium on Spin Glasses, edited by J. L. van Hemmen and I. Morgenstern (Springer-Verlag, Berlin, 1983).
38. S. F. Edwards and P. W. Anderson, J. Phys. F 5, 965 (1975).
39. D. Sherrington and S. Kirkpatrick, Phys. Rev. Lett. 35, 1792 (1975).
40. G. Parisi, Phys. Lett. 73A, 205 (1979); Phys. Rev. Lett. 43, 1754 (1979); J. Phys. A 13, L115, 1101, 1807 (1980); Phys. Rev. Lett. 50, 1946 (1983).
41. M. Mézard, G. Parisi, N. Sourlas, G. Toulouse, and M. Virasoro, Phys. Rev. Lett. 52, 1156 (1984).
42. D. J. Thouless, Phys. Rev. Lett. 56, 1082 (1986).
43. D. Chowdhury, Spin Glasses and Other Frustrated Systems (World Scientific, Singapore, 1986)
44. J. J. Hopfield, Proc. Natl. Acad. Sci. USA 79, 2554 (1982).
45. Electronic Properties of Inorganic Quasi-One-Dimensional Compounds, edited by P. Monceau (Kluwer, Dordrecht, 1985).
46. M. S. Dresselhaus, Physics Today 37, No. 3, 60 (March 1984).
47. F. R. Gamble and T. H. Geballe, in Treatise on Solid State Chemistry, edited by N. B. Hannay (Plenum, New York, 1976), p. 89.
48. R. Brusetti, P. Garoche, and K. Bechgaard, Phys. Colloq. C 3, 1051 (1983); F. Pesty, P. Garoche, and K. Bechgaard, Phys. Rev. Lett. 55, 2078 (1985).
49. R. V. Coleman, G. Eiserman, M. P. Everson, A. Johnson, and L. M. Falicov, Phys. Rev. Lett. 55, 863 (1985).
50. L. P. Gor'kov and A. G. Lebed, J. Phys. (Paris), Lett. 45, 943 (1984).
50. M. Héritier, G. Montambaux, and P. Lederer, J. Phys. (Paris), Lett. 45, 943 (1984); G. Montambaux, M. Héritier, and P. Lederer, Phys. Rev. Lett. 55, 2078 (1985).
52. C. A. Balseiro and L. M. Falicov, Phys. Rev. Lett. 55, 2336 (1985); Phys. Rev. B 34, 863 (1986).
53. M. L. Cohen, in Structure and Bonding in Crystals, edited by M. O'Keefe and A. Navrotsky (Academic Press, New York, 1981), Vol. 1, p. 25.
54. M. L. Cohen, Physica Scripta T1, 5 (1982).

55. M. L. Cohen, in Highlights of Condensed-Matter Theory (LXXXIX Corso, Soc. Italiana di Fisica, Bologna, 1985), p. 16.

56. K. J. Chang, M. M. Dacorogna, M. L. Cohen, J. M. Mignot, J. M. Chouteau, and G. Martinez, Phys. Rev. Lett. 54, 2375 (1985).

57. A. K. McMahan and R. C. Albers, Phys. Rev. Lett. 49, 1198 (1982).

58. O. K. Andersen, O. Jepson, and D. Glötzel, in Highlights of Condensed-Matter Theory (LXXXIX Corso, Soc. Italiana di Fisica, Bologna, 1985), p. 59.

59. M. Schlüter and L. J. Sham, Physics Today 35, No. 2, 36 (February 1982).

60. J. E. Hirsch and D. J. Scalapino, Physics Today, 36 No.5, 44 (May 1983).

61. G. R. Stewart, Rev. Mod. Phys. 56, 755 (1984).

62. C. M. Varma, Phys. Rev. Lett. 55, 2723 (1985).

63. F. Steglich, J. Aarts, C. D. Bredl, W. Lieke, D. Meschede, W. Franz, and Schäfer, Phys. Rev. Lett. 43, 1892 (1979).

64. G. R. Stewart, Z. Fisk, J. O. Willis, and D. L. Smith, Phys. Rev. Lett. 52, 679 (1984).

65. Valence Instabilities and Related Narrow Band Phenomena, edited by R. D. Parks (Plenum, New York, 1977).

66. Valence Fluctuations in Solids, edited by L. M. Falicov, W. Hanke, and M. B. Maple (North-Holland, Amsterdam, 1981).

67. Valence Instabilities, edited by P. Wachter and H. Boppart (North-Holland, Amsterdam, 1982).

68. G. H. Vineyard and L. M. Falicov, Rev. Sci. Instrum. 55, 620 (1984).

69. V. Nayaranamurti, Physics Today 37 No.10, 24 (October 1984).

70. L. Esaki, in Recent Topics in Semiconductor Physics, edited by H. Kamimura and Y Toyozawa (world Scientific, Singapore, 1983) p.1.

71. T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. 54, 437 (1982).

72. A. Jayaraman, Rev. Mod. Phys. 55, 65 (1983).

73. G. A. Somorjai, Chemistry in Two Dimensions: Surfaces (Cornell University Press, Ithaca, NY, 1981).

74. G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, Phys. Rev. Lett. 49, 57 (1982); Phys. Rev. Lett. 50, 120 (1983).

75. G. Binnig and H. Rohrer, Sci. Ame. 253, 50 (1985).

76. R. S. Becker, J. A. Golovchenko, and B. S. Swartzentruber, Phys. Rev. Lett. 54, 2678 (1985); R. S. Becker, J. A. Golovchenko, E. G. McRae, and B. S. Swartzentruber, Phys. Rev. Lett. 55, 2028 (1985); R. S. Becker, J. A. Golovchenko, D. R. Hamann, and B. S. Swartzentruber, Phys. Rev. Lett. 55, 2032 (1985).

77. B. Giambattista, W. W. McNairy, C. G. Slough, A. Johnson, L. D. Bell, R. V. Coleman, J. Schneir, R. Sonnenfeld, B. Drake, and P. K. Hansma, Proc. Natl. Acam Sci. USA 84, 4671 (1987).

78. G. Binnig, C. F. Quate, and Ch. Gerber, Phys. Rev. Lett 56, 930 (1986).

79. W. -H Steeb and J. A. Louw, Chaos and Quantum Chaos (World Scientific, Singapore, 1986).

80. C. D. Jeffries, Physica Scripta T9, 11 (1985).

81. M. J. Feigenbaum, J. Stat. Phys. 19, 25 (1978).

82. J. -P. Eckmann, Rev. Mod. Phys. 53, 643 (1981).

Acknowledgment

This work was supported in part at the Lawrence Berkeley Laboratory by the Director, Office of Energy Research, Office of Basic Energy Sciences, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720