Some Recent Issues in Quantum Magnetism

R. R. P. Singh, W. E. Pickett, D. W. Hone and D. J. Scalapino
Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106

Summary of “Quantum Magnetism” Conference
Institute for Theoretical Physics, Santa Barbara, California, August 16-20, 1999

I. MAGNETISM: OLD AND NEW

Magnetism is an old subject, but it is still full of surprises. It is deeply rooted in experimental phenomena, yet it has also been a perennial source for new theoretical ideas. It is a remarkably rich area in terms of variety of possible new phases, critical phenomena, symmetries of the order parameter, effective dimensionality and variability of experimental control parameters. It has been one of the backbones of modern technology, yet it promises still more technological marvels to come – ranging from nanostorage devices and spin-electronics to quantum computing. The interplay of magnetism with other solid-state phenomena such as superconductivity, structural phase transitions and colossal magnetoresistance, has spurred wide ranging research activities in recent years.

The subject of quantum magnetism dates back to the invention of quantum mechanics itself – starting from the works of Heisenberg, Bethe and others in the 1920s. One of the reasons for the longstanding prominence of the field in theoretical physics is the existence of simple models, which are tractable and yet display detailed quantitative correspondence with real systems. Recent developments in the synthesis of complex materials and in the sophistication and quantitative accuracy of experimental probes, ranging from neutrons to x-rays, optics and NMR, and the development of new techniques such as the use of polarized synchrotron radiation, have reinvigorated the field from an experimental point of view. Recent applications of new theoretical techniques, including Bosonization and conformal field theory, as well as the dramatic improvements in computational techniques ranging from first principles density functional calculations to quantum Monte Carlo simulations and density matrix renormalization group for many-body systems, have opened up the possibility that properties of complex materials can be theoretically predicted – leading to new phenomena and applications.

It may not be an exaggeration to say that the central problem in condensed matter physics in recent years has been high temperature superconductivity in the cuprates, and research in quantum magnetism has had a big boost from the fact that the stoichiometric parent compounds of the high temperature superconducting materials are excellent realizations of quasi-two-dimensional quantum antiferromagnets. Furthermore, even in the superconducting materials there is evidence for spin-fluctuations, spin-gaps and spin-stripes, which are obviously related to quantum magnetism. However, high temperature superconducting materials now comprise only a small subfield of the growing activity in quantum magnetism.

Recent advances in the field of magnetism include experimental realizations of spin chains and ladders, inorganic spin-Peierls materials, materials exhibiting colossal magnetoresistance (CMR), superconducting ferromagnets, organic magnetic materials, nanocrystalline magnetic materials, molecular magnets, and artificial structures – notably, on the mesoscopic scale – which employ magnetic properties to build novel electronic devices. These novel phenomena are based on structural complexity that leads to exchange interactions of varying symmetries and spatial ranges. In many systems exchange interactions compete, resulting in magnetic frustration. Additionally, low dimensional behavior is particularly accessibility in practice in spin systems, because exchange interactions usually are short range. Analogous isolation in mechanical or electrical systems is much more difficult to achieve.

It is such considerations that prompted the development of the program on “Magnetic Phenomena in Novel Materials and Geometries” this Fall at the ITP. We report on the week-long conference that preceded it, which played a role in setting directions for the longer program.

II. OVERVIEW OF MAGNETISM: OLD AND NEW

A special session, devoted to longstanding central problems in magnetism with continuing importance and excitement for current and future science, featured talks by Fisher, Birgeneau, Affleck and Sawatzky. Fisher emphasized the role of magnetism in the understanding of critical phenomena, especially multicriticality and scaling. He discussed the origin of bicritical and tricritical points in magnetic systems. The variety of magnetic systems arising from changes in dimensionality, anisotropy, magnetic field, ferromagnetic versus antiferromagnetic couplings, incommensurate versus commensurate phases, have provided tremendous insight into the subject of phase transitions and classical critical phenomena. The antiferromagnetic next nearest neighbor Ising (ANNNI) model [1] provides a very rich phase diagram, with multiple phases arising out of a special frustrated point at zero temperature. These classical studies may well be relevant to studies of multiple striped phases in doped antiferromagnets, discussed later by Sachdev.

Birgeneau discussed neutron scattering studies of two dimensional quantum Heisenberg antiferromagnets and
their comparisons with theory [3]. As is well known, the correlation length of the spin-half cuprate materials is remarkably well described by the quantum nonlinear sigma (QNLσ) model expressions of Chakravarty, Halperin and Nelson [3] and of Hasenfratz and Niedermeyer (CHNHN) [4]. However, these expressions do not adequately represent the experimental behavior for quasi-2D antiferromagnets with \( S > 1/2 \). This discrepancy is evident on comparison of the CHNHN expressions with high temperature series expansions and Quantum Monte Carlo simulations in the regime where the correlation length is only a few lattice constants. It is now evident that the QNLσ correspondence is strictly valid only at very low temperatures. At those temperatures systems with larger spin can have rather large correlation lengths. Experimental systems always have anisotropies and interplane couplings, which will cut off the two-lengths. Experimental systems with larger spin can have rather large correlation lengths. Experimental systems always have anisotropies and interplane couplings, which will cut off the two-length scales. Hasenfratz has recently discussed a way to incorporate the effects of cutoffs into the theory [5], which allows a description of spin-dependent correlation lengths at shorter length scales.

Birgeneau also discussed recent neutron scattering studies of \( \text{Sr}_2\text{Cu}_3\text{O}_4\text{Cl}_2 \) [6]. This quasi-two-dimensional material presents a fascinating example of the “order-by-disorder” phenomenon, whereby quantum fluctuations lift accidental classical degeneracies and cause spurious Goldstone modes to become gapped, leaving only true symmetry-related Goldstone modes gapless. Neutron scattering experiments have been used to study the excitation spectra of this material, and have validated Shender’s theory of quantum order-by-disorder. Recent theoretical studies of Aharony, Harris and collaborators [7] on the selection of low temperature ordering patterns in various cuprate materials due to quantum fluctuations, anisotropies, and weak interplane couplings further emphasize the importance and generality of these order-by-disorder effects.

Affleck emphasized the importance of logarithms in the low temperature properties of spin-chains. With the development of field-theoretic bosonization techniques, the one dimensional spin problems are now very well understood, including various logarithmic corrections. These logarithms arise due to variables which are marginally relevant in the renormalization group sense, and they appear in many different properties [8]. Perhaps the most important manifestation of such logarithms is the temperature dependence of the uniform susceptibility [8], which approaches its zero temperature value with an infinite slope, rather than continuing the apparently smooth higher temperature behavior first described by Bonner and Fisher [9].

Logarithms have also played a very important role in analyzing numerical data on spin chains. In particular, they lead to slow convergence of numerical approaches. One way to think of the problem is in terms of length dependent effective exponents, which only slowly approach their asymptotic values. However, once the effects of leading logarithms are taken into account, the numerical results show remarkable consistency with theory [10]. There have also been efforts to interpret experimental data on uniform susceptibility and NMR relaxation rates in terms of these logarithmic corrections. However, in these cases their usefulness is less convincing due to the possibly many other perturbations such as impurities and interchain couplings, which can strongly influence the low temperature behavior of these systems.

Sawatzky discussed the importance of orbital degeneracy in understanding magnetic systems. This is an old field, where seminal work was done first by Jahn and Teller and later by Kugel and Khomskii [11]. Recent discoveries of new materials, novel synchrotron based probes which can directly observe orbital ordering, and many technologically important phenomena such as colossal magnetoresistance (CMR) and spin-electronics where orbital degeneracies play a role, have led to a resurgence of interest in these systems. Sawatzky emphasized the importance of orbital degeneracy and ordering in such systems as \( \text{LiVO}_2 \) and \( \text{V}_2\text{O}_3 \) [12]. Understanding many of these oxide materials requires close interplay of electronic structure (LDA and LDA+U versions of density functional theory) and many-body approaches (such as dynamical mean-field theory).

Sawatzky also pointed to some continuing puzzles in the planar insulating cuprate materials. While the spin-1/2 nearest neighbor Heisenberg model, and, in particular, its treatment via spin wave theory, has presented an excellent quantitative picture for the low energy excitations in the cuprate materials, there are still some mysteries related to high energy excitations [13]. First of all, the lineshape and polarization dependence of Raman experiments, which measure 2-magnon spectra, are not fully understood. The same is true for optical absorption experiments. Finally, even in neutron scattering there is substantial spectral weight in multimagnon excitations, as well as evidence that the one-magnon dispersion deviates from the nearest-neighbor Heisenberg spectrum at higher energies [13]. All these deserve further theoretical attention.

### III. Quantum Phases and Quantum Critical Points

One important issue discussed in the conference is related to the nature of “quantum phases” in insulating and doped two-dimensional antiferromagnets [14]. As discussed by Sachdev, these phases can be characterized by the symmetries which are spontaneously broken. Three classes of broken symmetries were considered and are known to arise in some parts of the phase diagram of doped two-dimensional antiferromagnets. Antiferromagnetically ordered phases break spin-rotational
symmetry. The superconducting phases break the $U(1)$ gauge symmetry, whereas dimerized and striped phases break lattice translational symmetry. By generalizing the spin-rotational symmetry from $SU(2)$ to $Sp(N)$, and by studying the large-$N$ limit, Sachdev and Vojta have shown that multiple striped phases, with varying periodicity are possible upon doping, before the system turns into a d-wave superconductor. Striped phases have been observed in many high temperature superconducting materials. They have been argued by Emery, Kivelson and collaborators to result from a competition between tendencies for phase separation and long-range coulomb repulsion. On the other hand, striped phases have also been observed recently in density matrix renormalization group studies of $t$-$J$ models by Scalapino and White, without long-range coulomb interaction and in parameter regimes where there is no phase separation. The mechanism for stripe formation and the interplay of stripes and pairing remains one of the key issues in the field.

The divergence of the correlation length of a system only in the limit $T \to 0$ has been designated “quantum critical” behavior. A “quantum critical point” separates two distinct zero temperature phases (e.g., one magnetically ordered and the other disordered, or one metallic and the other insulating) as some parameter is varied. At these critical points, one expects the temperature to set the characteristic energy scale for the system and dynamical susceptibilities to show scaling in temperature and frequency. Starykh discussed one of the best studied quantum critical systems, namely the spin 1/2 Heisenberg chain. In this case the scaling behavior is complicated by logarithms, which he argued is essential for understanding recent NMR experiments by Takigawa on the material Sr$_2$CuO$_3$. Aeppli presented an example of a quantum critical point in an itinerant-magnetic heavy fermion material, where at the critical point the system shows non-Fermi liquid behavior. The dynamical susceptibility shows very simple scaling in temperature and energy. However, the associated critical exponents are not well understood. Imai discussed NMR measurements in the cuprate materials as one goes from the insulating antiferromagnetic phase to the metallic or superconducting phases upon doping. He pointed out missing intensity in his NMR signals at low temperatures, which he interpreted as evidence for stripe formation. Clearly, quantum phase transitions and quantum critical points in itinerant magnetic systems require further study.

IV. FRUSTRATION

Strongly frustrated magnetic systems provide another class of problems that are not yet well understood. Frustation can have many origins. It can arise from competing ferromagnetic and antiferromagnetic exchange interactions placed randomly in a system as in conventional spin-glasses, or from antiferromagnetic interactions between spins on odd-length loops as happens in triangular and Kagomé lattice antiferromagnets, or from competition between exchange anisotropy and field terms as in the transverse Ising model. It can also come about from competition between superexchange and double exchange terms which favor different spin alignments, or from multiple spin exchange processes of odd and even number of spins. One interesting consequence of this exchange is enhanced entropy at low temperatures and what was termed by Ramirez a “spectral weight down-shift”. A beautiful example of this is the “spin-ice” system Re$_2$Ti$_2$O$_7$, which has a low temperature entropy similar to that associated with the positions of hydrogen in ice as first discussed by Pauling.

Another general consequence of frustration is that fluctuations play a very important role in selecting the ordered state — the phenomenon of order-by-disorder discussed above. Furthermore, in systems with strong quantum fluctuations, accidental degeneracy (beyond what symmetry would dictate) can be lifted by superposition of many states in a resonating valence bond scenario first introduced by Anderson. This in turn results in a gap in the excitation spectrum and possibly excitations with exotic quantum numbers. The talks by Lhuillier and Mila emphasized various quantum spin systems which show spin-gap behavior. In particular, they discussed the spin-half Heisenberg model on the kagomé-lattice, which has intriguing properties. There appears to be a gap in the spin-excitation spectra, but there are many low-lying singlet excitations. The number of singlet states below the lowest triplet appears to grow exponentially with the size of the system. On the other hand, striped phases have also been observed recently in density matrix renormalization group studies of $t$-$J$ models by Scalapino and White, without long-range coulomb interaction and in parameter regimes where there is no phase separation.

V. SPIN GAPS

The problem of spin gaps has attracted considerable attention recently due to the synthesis of a large number of new materials which exhibit behavior characteristic of such gaps, notably thermally activated magnetic susceptibilities. As was pointed out by Khomskii, there are many routes to spin-gap behavior, in systems with spin-rotational symmetry. As proposed first by Haldane, it is now established that spin gaps are generic to quasi-1D Heisenberg spin systems with integer spin per unit cell. A spin gap is also natural when the system consists of finite clusters of spins which have singlet ground states,
which are then weakly coupled to other clusters. Other examples include spin-Peierls, orbitally degenerate, and strongly frustrated spin systems.

Reich discussed several quasi-one- and two-dimensional experimental materials which are strongly dimerized, whereas Kodama presented experimental results on the quasi-2D spin-gap materials CaV$_4$O$_9$ [32] and SrCu$_2$(BO$_3$)$_2$ [33]. Neutron scattering is the most natural tool for studying the spin dynamics of these systems due to its detailed frequency and wavevector resolution. Reich showed that sum rules and single-mode approximations often provide quite accurate quantitative description of the spin dynamics in strongly gapped systems [33]. The material SrCu$_2$(BO$_3$)$_2$ discussed by Kodama is particularly interesting from a theoretical point of view because the spins have an exactly known quantum mechanical ground state [34], its exchange constants put it close to a quantum critical point and it exhibits magnetization plateaus as a function of applied magnetic field [35].

Kotov discussed the nature of elementary excitations and bound states in spin-gap systems [37]. Khomskii and Poilblanc focussed on spin-Peierls systems, especially the inorganic spin-Peierls material CuGeO$_3$ [38][39]. Both interchain couplings and dynamical phonons are important in understanding the properties of these materials. As was evident from these talks, the existence of soliton-like excitations and their bound states is an exciting topic of current research.

VI. SPIN CHAINS AND SPIN LADDERS

Quantum spin chains have long been a pet subject of theorists, as they are mathematically more tractable than higher dimensional systems and exhibit various exotic many-body phenomena. Yet many important results regarding even the spin 1/2 chain have only recently been obtained. Affleck, Eggert and Takahashi [4] found that the uniform susceptibility approaches its T=0 values with an infinite slope, as mentioned above. With the help of the Bethe ansatz, the uniform susceptibility of the spin 1/2 chain is now known very accurately at all temperatures. Johnston described ongoing efforts to develop accurate fits to the susceptibilities and specific heats of uniform and alternating spin 1/2 chains and ladders, to make detailed comparisons between theoretical models and experimental results [40].

Spin ladders allow one to interpolate, by increasing the number of legs, between one and two dimensions [41]. The existence of Cuprate materials which exhibit ladder-like magnetic structure and behavior have further increased interest in these systems. Sierra described variational approaches to studying ladders [42], whereas Solyom discussed different massive and critical phases in these systems [43]. Cabra explained the appearance of magnetization plateaus [44] in quasi-1D spin systems arising from the formation of strongly correlated states at finite magnetizations. Weakly coupled arrays of spin 1/2 chains were discussed by Sandvik [45]. Using a quantum Monte Carlo simulation and a chain mean-field theory, he was able to show that such systems are long range ordered. The question of frustration in such weakly coupled spin chains remains to be explored.

VII. NEW MAGNETIC MATERIALS AND PHENOMENA

Advances in magnetism have long been driven by new materials, from the ancient discovery of native lodestone to more recently studied systems exhibiting novel phenomena such as spin-Peierls behavior. The discovery of interesting new materials continues at a high rate, certainly within the fertile class of oxides which have supplied more than their share of novelties, but also in a variety of other materials.

A. Oxides of Transition Metals

A new system discussed by Keimer is the pseudo-pentenary system $\text{La}_y\text{Y}_{1-y}\text{Ti}_1-x\text{Ca}_x\text{TiO}_3$. With varying $y$, which is thought to tune the bandwidth (or onsite Coulomb repulsion to bandwidth ratio $U/W$) there is an antiferromagnetic to ferromagnetic transition. With varying doping level $x$ there is an insulator-to-metal transition which also depends on $y$, as in the similar manganite system discussed in Sec. IX. This formally $\text{Ti}^{3+}, d^1$ configuration appears to be a prime one for orbital ordering [46], yet structural studies indicate that in the La(Y)-rich regime the $\text{O}_6$ octahedron is undistorted, and there is no change at the magnetic ordering temperature. $\text{YTiO}_3$, on the other hand, is Jahn-Teller distorted and orbitally ordered, as reproduced in the calculations of Sawada and Terakura. [47] The ions at the ends of the transition metal row of the periodic table often show extreme behavior (recall, e.g. that only doped $\text{Cu}^{2+}$ systems have to date been reliably shown to become high temperature superconductors), so the observed special features of this system may reflect new physical phenomenon.

B. Molecular Magnet Crystals

Landee presented an overview of molecular-based magnets, which are either free of oxygen or for which oxygen has no active role. While organic ferromagnets exist, these molecular magnets typically consist of inorganic magnetic molecules which may be sheathed in organic material. An important feature of these materials is their unusually small exchange coupling, weak enough for reasonable applied magnetic fields to have dominating effects. [48] The $\text{Mn}_{12}\text{O}_{12}$ system (“$\text{Mn}_{12}$” (crystalline
Mn$_{12}$O$_{12}$\((\text{CH}_3\text{COO})_{16}\)(H$_2$O)$_4$\) has become a miniclassic, displaying jumps in magnetism in an applied field \cite{49} and unusual relaxation behavior \cite{50} that have become an active area of theoretical study. The CuPzN (copper pyrazine nitrate) system forms a clean, 1D Heisenberg S=1/2 system; however, the ordering temperature T$_N$=70 mK makes it difficult to study at "low temperature" (T<<T$_N$).

The observation of quantization of the magnetization as a function of magnetic field, believed to result from tunneling between different quantum states, in systems in which the individual moments are quite large and therefore expected to behave classically, forms the basis of a field now called quantum tunneling in molecular magnets. As described by Friedman, spin has no explicit kinetic degree of freedom, and the connection between the classical and quantum description must be addressed. Fortunately, very simple and clean samples can be produced that are comprised of identical nanoscale molecular magnets such as Mn$_{12}$ or "Fe$_{8}$" (a similarly complex material with periodically placed magnetic molecules).

Resonant tunneling of the magnetization in molecular magnets results from tuning of energy levels of different S$_z$ states. This phenomenon involves macroscopic relaxation by accumulation of microscopic processes. \cite{51} In many contexts the large local moments (typically S~10) would put one well within the classical regime, but the role of quantum effects is believed to be important and is under active study. Understanding of the thermodynamics and dynamics of these molecular magnets depends on the identification of the symmetry breaking (or lowering) terms in the spin Hamiltonian that governs their behavior.

C. Heavy Fermion Metals

The "heavy fermion" phenomenon has been known for two decades. Metals such as UPt$_3$, UBe$_{13}$, and CeRu$_2$Si$_2$, show very unusual temperature dependences \cite{52} of resisitivity, susceptibility, and heat capacity but finally settle into a vastly enhanced Fermi liquid regime where the carriers have masses of up to 1000 times the free electron mass. It was tempting to interpret the behavior as simply that — an enhanced Fermi liquid, and nothing else. But why does a one particle s-f hybridization model seem to work so well? Why don’t the strong correlations induce Mott localization? Aeppli presented data which indicates that, at least in some cases, much more is going on. In some of these systems, such as CeCu$_{6-x}$Au$_x$, the system can be tuned to drive the characteristic "degeneracy" temperature to zero. \cite{53} This brings in quantum critical behavior, so that the susceptibility becomes simple to model, scaling so as to collapse onto a single universal curve, but one described by a non-analytic function whose origin is still a mystery. Moreover, anomalies are seen at all wave vectors, not just that of the antiferromagnetic order parameter. Kondo singlet unbinding appears to be occurring simultaneously with antiferromagnetism at the quantum critical point.

VIII. HALF METALLIC MAGNETS

The phenomenon of half metallic ferromagnetism was a theoretical discovery by band theorists in the early '80s. \cite{54} In such a system, in which up spin and down spin spectral densities are inequivalent, one spin direction has gapless charge excitations while the other spin direction has a gap in its charge excitation spectrum. Hence one channel is non-conducting while the other is metallic, which has been dubbed "half metallic." Many such ferromagnets (and ferrimagnets) have been predicted, particularly in the Heusler and half-Heusler compounds, but also in perovskites and spinels (Fe$_3$O$_4$). One of the simplest, structurally and electronically, is CrO$_2$. In spite of quite a bit of work, however, it has been difficult to obtain conclusive evidence of half-metallicity in these candidates. The problem is traceable to the difficulty in establishing 100% spin polarization of the charge carriers, \cite{55} either in the bulk of the material, or after ejecting the carriers through a surface or interface, due to extraneous spin scattering.

This situation is beginning to change. Park described spin-resolved photoemission spectra (SRPES) on the CMR system La$_{0.65}$Sr$_{0.35}$MnO$_3$, predicted \cite{56} to be half metallic or very nearly so. With carefully prepared (but not atomically flat) surfaces of a thin film, his group was able to demonstrate \cite{57} that the film ordered magnetically (as seen in the SRPES spectra) at the bulk Curie temperature, and that well below the Curie temperature only electrons of a single spin direction were emitted at or near the Fermi level. Not only is this the first very strong evidence for a half metallic system, but it also buttresses the widespread feeling that the phenomenon of colossal magnetoresistance in the manganites is closely related to its half metallic character. It might be expected that bulk phenomena, such as NMR relaxation times or the low temperature resistivity (due to two-magnon processes), should provide telltale signs of half metallic character. Furukawa indicated why this is not the case, as he argued that $\rho \sim T^{9/2}$ that has been quoted from Ogata's work in the '60s becomes $\rho \sim T^3$ for a more realistic model. \cite{58} This result can be taken as evidence for half metallicity in CrO$_2$.

IX. SPIN/ORBITAL/LATTICE COUPLING

The observation of "colossal magnetoresistance" (CMR) \cite{59} in the manganites, where there is a insulator-to-metal transition at the magnetic ordering (Curie) temperature, has been found to involve several processes,
A fundamental link between transport and magnetic order is provided by Zener’s “double exchange” mechanism, whereby an electron can hop between neighboring magnetic (Mn) ions only if their spins are parallel. The gain in kinetic energy due to the hopping becomes a driving force for ferromagnetic ordering. Experimentally, it has become abundantly clear that the manganites are much more complicated than this; for example, magnetic ordering (and CMR) can be driven by ionic size variations at constant doping level, and structural transformation can be driven even by magnetic field alone. These effects are two manifestations of strong magnetostructural coupling.

Since the carriers in the doped manganites (e.g. La$_{1-x}$Ca$_x$MnO$_3$) occupy the doubly degenerate $e_g$ orbitals of Mn, the question of Jahn-Teller distortion arises, and the Kugel-Khomskii mechanism of “orbital ordering” comes into play. The Mn-O bondlength distortions of LaMnO$_3$ and the resulting magnetic structure (anti-alignment of ferromagnetically aligned layers) can be understood in terms of this mechanism. Maekawa presented a theory of coupled spin and orbital degrees of freedom within a double exchange model, with results that connect orbital ordering tendencies to large response (such as CMR). He illustrated the competing tendencies with phase diagrams where orbital ordering occurs at $x=1/8$, ferromagnetism peaking at $x=1/2$, and antiferromagnetism returning at larger $x$, results that show similarities to observed behavior.

Cheong focused on the observed phenomena at $x=3/8$, which is where the Curie temperature peaks in the CMR systems. Recent work indicates that the system at this concentration phase separates, one phase being metallic and ferromagnetic and the other non-conducting and microscopically charge ordered (stripes separated by a few lattice constants). Due to the strength of the long-range Coulomb interaction charge neutrality can’t be broken on the larger scale of the size of the domains (0.1 to 1 $\mu$m), so both phases must exhibit the global value 3/8 of hole concentration. The insulator-to-metal transition appears to be a percolative phase change. Conductivity is through the ferromagnetic metal domains, whose size can be varied by chemical pressure with the substitution of Pr for La, but with constant carrier concentration $x = 3/8$.

The $x=1/3$ regime, where the CMR effect is strongest, was discussed by D. Singh. At low temperature this is a very good ferromagnetic metal, calculated to be nearly half-metallic. Its structure, both observed and computed, has no Jahn-Teller distortion, consistent with the fact that orbital order is destroyed by easy carrier hopping. As the temperature is raised near and beyond the Curie temperature, where hopping becomes increasingly more difficult due to spin disorder, the observed crystal structure shows no noticeable change. The strong electron-lattice coupling that is so evident at lower doping levels seems to be strongly suppressed in the CMR region of the phase diagram.

X. SPIN CONTROL

A. Spin Electronics

Manipulation of the spin degree of freedom of conduction electrons leads to a new form of electronics, now dubbed spintronics. This form of current and voltage control uses low resistance (hence low voltage and low power consumption) magnetic metals rather than high resistance (high voltage) semiconductors such as Si. The spin-polarized current also offers entirely new possibilities, such as manipulations of electronic signals by magnetic fields or vice versa, or novel effects in ferromagnet/superconductor/ferromagnet sandwiches or multilayers. Quantum information storage and quantum computation are related phenomena that require further study.

A description of the mechanisms and structures of some novel magnetoelectronic devices was provided by M. Johnson. He described two devices: (1) the magne-toquenched superconducting valve, in which a superconducting electronic element is bathed in a fringing magnetic field whose direction is readily controlled by an external field, and (2) the “hybrid Hall device” (hybrid ferromagnet-semiconductor nonvolatile gate), which appears promising as a high density, low power nonvolatile memory device. Johnson also discussed the detection of the degree of spin polarization by detecting the chemical potentials of the ferromagnet at an interface with a semiconductor.

B. Spin Coherence in Semiconductors

The issue of spin polarized carriers in semiconductors has become active due to interest in their possible use in electronics, computing, and information storage. Awschalom described how laser pulses can be used to excite, and then probe, polarized carriers in GaAs. The precession of the spins in an applied field can be used to monitor the spin coherence, which can be unexpectedly long in time and far in space. Lateral transport of spins of up to 100 nm without loss of polarization has been observed. Dramatic effects of magnetic field on spin relaxation have also been seen. In zero field, up and down spins relax equally; upon application of a field, the lifting of the Zeeman degeneracy gives rise to a varying polarization that reflects quantum beating between the Zeeman-split spin levels. A detailed theory of these effects remain to be developed.

XI. CLOSING REMARKS

In 1982 Hurd commented that “magnetism in solids used to be a tidy subject” (emphasis added). It seems now that it can be said that, compared to now,
magnetism in 1982 was a relatively tidy subject. Problems that were in some sense solved (heavy fermions) have not stayed solved, while new questions continually arise. Some longstanding problems may have been put to rest – the susceptibility of the spin-half 1D Heisenberg model, for example. Meanwhile, for each question that is settled, a number of new ones seem to appear.

Copies of the speakers transparencies, audio recording of the presentations and a list of review articles and books on the subject can be found at the ITP web address http://www.itp.ucsb.edu (follow links on magnetism).

This work is supported in part by the National Science Foundation Grant PHY94-07194.

[1] M. E. Fisher and W. Selke, Phys. Rev. Lett. 44, 1502 (1980); W. Selke, Phys. Rep. 170, 213 (1988).
[2] R. L. Leheny et al, Phys. Rev. Lett. 82, 418 (1999); N. Elstner et al, Phys. Rev. Lett. 75, 938 (1995).
[3] S. Chakravarty, B. I. Halperin and D. R. Nelson, Phys. Rev. Lett. 60, 1057 (1988).
[4] P. Hasenfratz and F. Nidermayer, Phys. Lett. 268, 231 (1991).
[5] P. Hasenfratz, cond-mat/9901355.
[6] Y. J. Kim et al, Phys. Rev. Lett. 83, 852 (1999).
[7] T. Yildirim et al, Phys. Rev. Lett. 73, 2919 (1994); ibid, Phys. Rev. Lett. 72, 3710 (1994).
[8] I. Affleck, D. Gepner, H. Schulz and T. Ziman, J. Phys. A 22, 511 (1989); R. R. P. Singh, M. E. Fisher and R. Shankar, Phys. Rev. B 39, 2562 (1989).
[9] S. Eggert, I. Affleck and M. Takahashi, Phys. Rev. Lett. 73, 332 (1994).
[10] J. C. Bonner and M. E. Fisher, Phys. Rev. 135 A640 (1964).
[11] I. Affleck and J. C. Bonner, Phys. Rev. B 42, 954 (1990).
[12] I. Kugel and D. I. Khomskii, Sov. Phys. Usp. 25, 231 (1982).
[13] H. F. Pen et al, Phys. Rev. Lett. 78, 1323 (1997); D. I. Khomskii and G. Sawatzky, Solid State Comm. 102, 87 (1997).
[14] J. Lorenzana and G. A. Sawatzky, J. Superconductivity, 9, 389 (1996).
[15] G. Aeppli, private communication.
[16] S. Sachdev, Quantum Phase Transitions, Cambridge University Press, Cambridge (1999).
[17] M. Vojta and S. Sachdev, Phys. Rev. Lett. 83, 3916 (1999).
[18] O. Zachar, S. A. Kivelson and V. J. Emery, Phys. Rev. B57, 1422 (1998); S. A. Kivelson, E. Fradkin and V. J. Emery, Nature 393, 6655 (1998).
[19] S. R. White and D. J. Scalapino, Phys. Rev. Lett. 80, 1272 (1998); ibid 81, 3227 (1998).
[20] C. S. Hellberg and R. Manousakis, Phys. Rev. Lett. 83, 132 (1999).
[21] A. V. Chubukov, S. Sachdev and J. Ye, Phys. Rev. B 49, 11919 (1994).
[22] O. A. Starykh, R. R. P. Singh and A. W. Sandvik, Phys. Rev. Lett. 78, 539 (1997); V. Barzykin and I. Affleck, J. Phys. A 32, 867 (1999).
[23] M. Takigawa et al, Phys. Rev. B 56, 13681 (1997).
[24] A. Schroder et al, Phys. Rev. Lett. 80, 5623 (1998).
[25] K. Yoshimura et al, Phys. Rev. Lett. 83, 4397 (1999); A. W. Hunt et al, Phys. Rev. Lett. 82, 4300 (1999).
[26] R. Moessner and J. T. Chalker, Phys. Rev. B 58, 12049 (1998).
[27] A. P. Ramirez et al, Nature 399, 333 (1999); R. Siddharthan et al, Phys. Rev. Lett. 83, 1854 (1999).
[28] P. W. Anderson, Mater. Res. Bull. 8, 153 (1973); P. Fazekas and P. W. Anderson, Philos. Mag. 30, 432 (1974).
[29] P. Lecheminant et al, Phys. Rev. B 56, 2521 (1997); C. Wacktmann et al, European Phys. J. B 2, 501 (1998).
[30] F. Mila, Phys. Rev. Lett. 81, 2356 (1998).
[31] F. D. M. Haldane, J. App. Phys. 57, 3359 (1985); Phys. Rev. Lett. 93 A, 464 (1983).
[32] S. Taniguchi et al, J. Phys. Soc. Jpn. 64, 2758 (1995).
[33] H. Kageyama et al, Phys. Rev. Lett. 82, 3168 (1999).
[34] B. S. Shastry and B. Sutherland, Physica B 108, 1069 (1981).
[35] P. R. Hammar et al, Phys. Rev. B 57, 7846 (1998).
[36] S. Miyahara and K. Ueda, Phys. Rev. Lett. 82, 3701 (1999).
[37] V. N. Kotov et al, Phys. Rev. Lett. 80, 5790 (1998).
[38] B. Keimer, private communication.
[39] D. J. Scalapino, D. S. Fisher and P. W. Anderson, Philos. Mag. A 33, 1422 (1998); S. A. Kivelson, E. Fradkin and V. J. Emery, Nature 393, 6655 (1998).
[40] D. I. Khomskii, W. Geertsma and M. Mostovoy, Czech. J. Phys., 46, SUPP6, 3239 (1996).
[41] D. C. Johnston, R. K. Kremer, M. Troyer, X. Wang, A. Klumper, S. L. Budko, A. F. Panchula and P. C. Canfield, preprint.
[42] E. Dagotto and T. M. Rice, Science 271, 618 (1996).
[43] G. Sierra et al, Phys. Rev. B 57, 11666 (1998).
[44] O. Legeza and J. Solyom, Phys. Rev. B 56, 14449 (1997).
[45] D. C. Cabra, A. henceeker and P. Pujol, Phys. Rev. B 58, 6241 (1998).
[46] A. W. Sandvik, Phys. Rev. Lett. 83, 3069 (1999).
[47] B. Keimer, private communication.
[48] H. Sawada and K. Terakura, Phys. Rev. B 58, 6831 (1998).
[49] P. R. Hammar et al, Phys. Rev. B 59, 1008 (1999).
[50] W. Wernsdorfer, R. Sassoli, and D. Gatteschi, Europhys. Lett. 47, 254 (1999).
[51] L. Thomas, A. Caneschi, and B. Barbara, Phys. Rev. Lett. 83, 2398 (1999).
[52] R. Sassoli, D. Gatteschi, A. Caneschi, and M. A. Novak, Nature 365, 141 (1993); J. R. Friedman, M. P. Sarachik, and R. Ziolo, Phys. Rev. B 58, R14729 (1998); J. R. Friedman et al, Phys. Rev. Lett. (1996).
[53] G. R. Stewart, Rev. Mod. Phys. 56, 755 (1984).
[54] R. A. de Groot et al, Phys. Rev. Lett. 50, 2024 (1983).
[55] R. A. de Groot et al, Phys. Rev. Lett. 50, 2024 (1983).
[56] A half metallic band structure was reported earlier by J. I. Horikawa et al, J. Phys. C 15, 2613 (1982).
[57] R. J. Soulen Jr. et al., Science 282, 85 (1998).
[58] W. E. Pickett and D. J. Singh, Phys. Rev. B 53, 1146 (1996).
[56] J. H. Park et al., Nature 392, 794 (1998).
[57] N. Furukawa and K. Hirota, Physica B 241-243, 780 (1997).
[58] R. von Helmolt et al., Phys. Rev. Lett. 71, 2331 (1993); M. McCormack et al., Appl. Phys. Lett. 64, 3045 (1994); S. Jin et al., Science 264, 413 (1994).
[59] J. M. D. Coey, M. Viret, and S. von Molnar, Adv. Phys. 48, 167 (1999).
[60] C. Zener, Phys. Rev. 82, 403 (1951).
[61] S. Ishihara, J. Inone, and S. Maekawa, Phys. Rev. 55, 8280 (1997).
[62] M. Uehara et al., Nature 399, 560 (1999).
[63] W. E. Pickett and D. J. Singh, J. Magn. Magn. Mat. 172, 237 (1997).
[64] D. J. Singh and W. E. Pickett, Phys. Rev. B 57, 88 (1998).
[65] B. E. Kane, Nature 393, 133 (1998).
[66] T. W. Clinton and M. Johnson, J. Appl. Phys. 85, 1637 (1999).
[67] M. Johnson et al., IEEE Trans. Magnetics 34, 1054 (1998).
[68] D. D. Awschalom and J. M. Kikkawa, Physics Today 52, 33 (1999).
[69] C. M. Hurd, Contemp. Phys. 23, 469 (1982).