Preface

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Preface

'With a heavy heart, I have been converted to the idea that Fermi–Dirac, not Einstein–Bose is the correct statistics. I wish to write a short note on its application to paramagnetism.'

W Pauli (letter to Schrödinger, December 1926) [1].

Recent advances in materials science have re-opened a great debate about the nature of metals. For almost forty years, 'Landau–Fermi liquid theory' has provided the mainstay of our understanding of the metallic state. While Fermi liquid theory provides an astonishingly successful description of conventional metals, it has become increasingly clear that the behaviour of many complex materials, such as the cuprate superconductors, certain f-electron materials and low-dimensional conductors, lie outside the its well-explored confines, suggesting that fundamentally novel and unexpected kinds of metallic behaviour occur in nature.

As Pauli's letter shows above, even the Fermi liquid began life as a subject of controversy. Fermi liquid theory is now well established; the important question is how to go beyond it. What is the essential issue? The theorist will tell you that we are really looking for new kinds of metallic fixed points; the experimentalist, that we are interested in discovering, characterizing and understanding new kinds of metals. The past few years have seen tremendous advances on both fronts. Theoretically, we have discovered and established the properties of a number of classes (or 'fixed points') describing non-Fermi-liquid behaviour. Some examples include:

- The one-dimensional Luttinger liquid, in which the spin and charge excitations of the electronic fluid decouple into new quasiparticles called 'holons' and 'spinons' [2].
- A conventional metal at a zero-temperature critical point. At such a 'quantum critical' point, fluctuations become sufficiently long-ranged in space and time that the interaction they induce is singular enough to destabilize the Fermi liquid ground state [3, 4].
- Non-trivial impurity models, such as the two-channel Kondo model [5–8].
- The Chern–Simons theory of the half-filled Landau level and the closely related gauge theory of the 't–J' model [9, 10].

On the experimental side, many classes of materials with properties apparently inconsistent with Fermi liquid theory have been discovered, including:

- High-temperature superconductors.
- Quasi one- and two-dimensional conductors.
- Many metallic alloys containing elements such as Ce or U with partially filled f-shells.
- Edge states of quantized Hall systems.

This is only a partial list of recent advances; furthermore, it is likely that there are new kinds of non-Fermi liquid behaviour yet to be discovered. This proof by example that non-Fermi liquid behaviour exists has led to a new sub-field of physics and many lively debates. On the theoretical side, many of the examples known involve rather special situations (e.g. low dimensionality, criticality, high symmetry); pressing questions arise relating to the possibility of extending this anomalous behaviour to more general models. On the experimental side, the connection between the realized non-Fermi liquid materials and the various theoretical models is by no means clear. When a real material with anomalous properties is encountered, the resulting debate centres on whether it falls into one of the pre-existing categories: is it a more conventional system in disguise (due to real-world effects such as disorder), or is it a new kind of non-Fermi liquid fixed point, as yet uncharacterized [11–13, 15]?

Over a six month period in the spring of 1996, a group convened at the Institute for Theoretical Physics in Santa Barbara to study 'Non-Fermi Liquid Physics'. The programme was conceived as a way of bringing diverse theoretical and experimental efforts in this area together, framing the debate and identifying the open questions in the field. *The International Conference on Non-Fermi Liquid Behaviour in Metals* was held in June 1996 to conclude the programme. This volume contains a collection of papers that were written by conference or programme participants. In its preparation, we have been mindful of the youthfulness of this field. We feel it is vital to try to represent the fervor of scientific debate and discussion; thus we have tried to select articles which polemically or pedagogically describe possible resolutions of problems at the forefront of this field of research. Issues addressed in subsequent pages include:

- Quantum critical phenomena. The existing theories seem to account for the properties of transition metal ferromagnets [12], yet the various heavy-fermion systems on the brink of antiferromagnetism, such as $CeCu_{6-x}Au_x$ [13], Ce_7Ni_3 [14] and $CePd_2Si_2$ [12, 15], show a marked deviation from the theoretical predictions. The $T^{1.2}$ dependence of the resistivity of $CePd_2Si_2$ over two decades is particularly dramatic in this respect. Could it be that disorder is affecting the nature of the magnetic fixed point? Both theoretical [17, 18] and experimental [19] investigations of the interplay between disorder and quantum spin fluctuations are featured here. Another exciting possibility is that the interplay of the Kondo effect with the quantum critical behaviour produces a new kind of fixed point [12]. A related perspective is offered by Klein's group [16] who argue that even the classical critical behaviour of the resistivity of 'bad metal' systems is not understood.
- The wide variety of non-Fermi liquid behaviour in f-electron materials reviewed by Maple and coworkers [11, 20, 21] continues to fascinate. Both optical [22] and neutron data [23] highlight the presence of anomalous spin and transport properties in several of these compounds. Here the debate takes many forms. One new idea aired at the meeting [24, 25] is that many of the observed properties might be understood as a consequence of a broad distribution of Kondo temperatures. These authors recognize, however, that this can only be part of the story. Others have argued for a more intrinsic origin of the non-Fermi liquid behaviour, such as the quadrupolar Kondo effect or some other single-ion origin [26, 27], or perhaps a wholly new kind of lattice non-Fermi liquid behaviour [28].
- Nowhere is the debate about possible non-Fermi liquid behaviour more fierce than in the discussion of the normal state of the cuprate superconductors. Experimentalists brought many new results to bear on this discussion at this meeting, including new insights into the nature of the spin-gap in under-doped cuprates [29] and the anomalous temperature dependence of Hall current relaxation time [30]. Each of these measurements spurs its own debate. Is the spin gap a reflection of novel spin pairing, as discussed by Anderson [31] or is it a reflection of a more conventional kind of Cooper pairing (with long-range order suppressed by fluctuation effects)? Alternatively, could it arise through gapping of the Fermi surface by antiferromagnetic fluctuations [32]? Likewise,

is the presence of two relaxation rates seen in the optical Hall and conductivity measurements [30] a reflection of severe Fermi-surface anisotropy in the scattering rates [32], or does it arise from the formation of a new kind of fluid, where the Hall and electric currents relax in intrinsically different fashions [33, 34]?

- Experimental manifestations of one-dimensional non-Fermi liquid behaviour, such as spin–charge decoupling, are still very much sought after as discussed by Allen and coworkers [35]. One area of active debate is the effect of interchain coupling on one-dimensional conductors, and whether spin–charge decoupling is robust against these effects [33]. Another area of interest is whether non-Fermi liquid behaviour can give rise to new kinds of correlation, such as odd-frequency pairing [37].
- Half-filled Landau level. Although the Fermi surface of composite fermions was initially characterized as a non-Fermi liquid, there is a growing school of thought that argues that the physical response functions of the composite Fermi surface may be described by a modified version of Landau–Fermi liquid theory, whereby the quasiparticles are subject to a singular 'gauge' interaction. This discussion is reviewed by Simon [36].

Above all, we hope that this volume will be a source book for the field, offering something to interested readers, future students and participants in non-Fermi liquid physics. In closing, we would like to thank the staff of the ITP for their gracious assistance in organizing the non-Fermi liquids programme, and in particular, acknowledge the support of the National Science Foundation (grant No PHY94-07194), which provided the funds that made the whole event possible.

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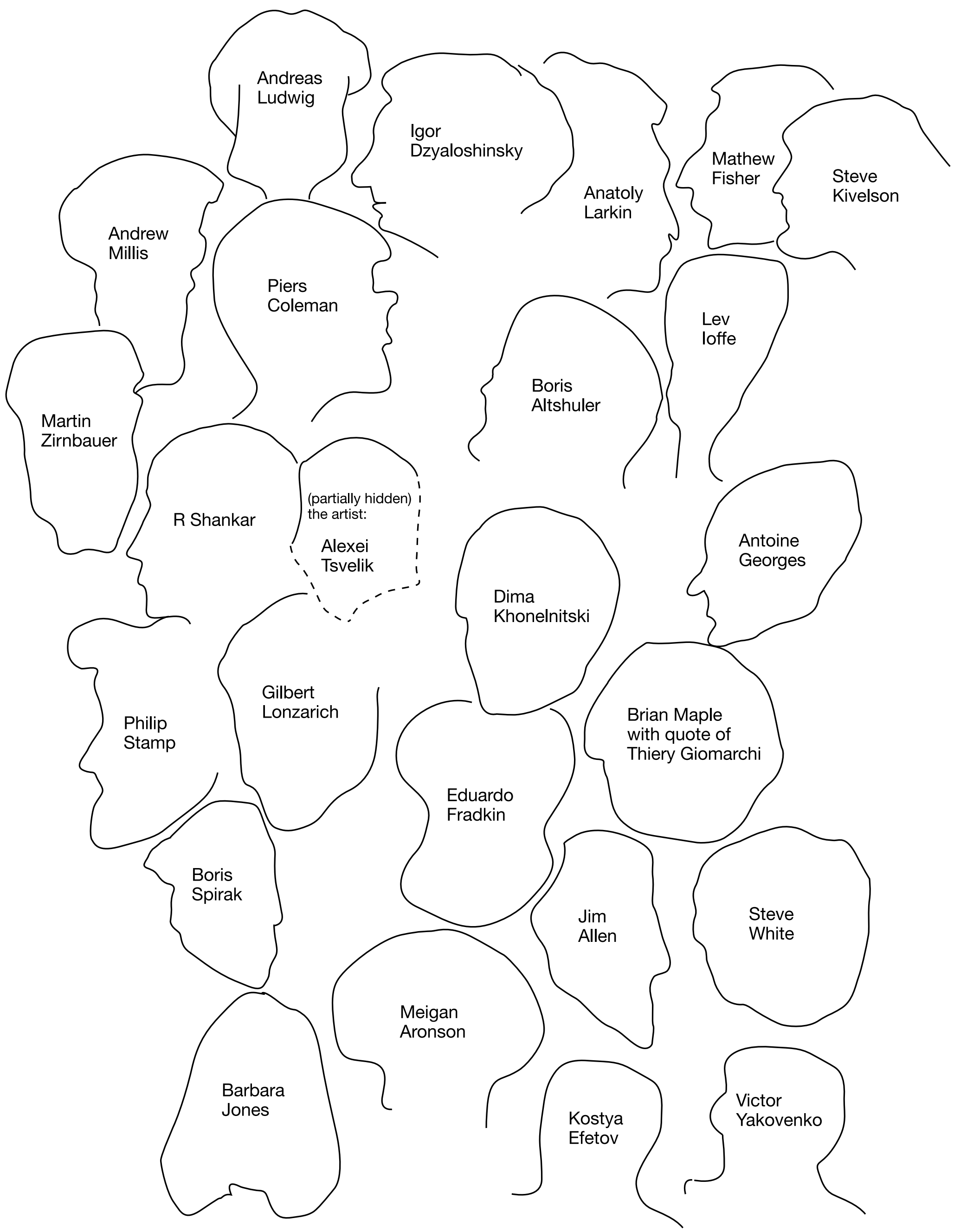
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