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ISSN : 2454 – 308X | Volume : 03 , Issue : 09 | October – December 2017

MANY-BODY PHYSICS

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Abstract:

The study of many-body physics has provided a scientific playground of surprise and continuing revolution over the past half century. The serendipitous discovery of new states and properties of matter, phenomena such as superfluidity, the Meissner, the Kondo and the fractional quantum hall effects, have driven the development of new conceptual frameworks for our understanding about collective behaviour, the ramifications of which have spread far beyond the confines of terrestrial condensed matter physics- to cosmology, nuclear and particle physics. Here, we are selectively reviewing some of the developments in this field, from the cold-war period, until the present day. With the discovery of new classes of collective order, the unfolding puzzles of high temperature superconductivity and quantum criticality, the prospects for major conceptual discoveries remain as bright today as they were more than half a century ago.

ISSN 2454-308X
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Emergent Matter: a new Frontier

Since the time of the Greeks, scholars have pondered over the principles that govern the universe on its tiniest and most vast scales. The icons that exemplify these frontiers are very well known - the swirling galaxy denoting the cosmos and the massive accelerators used to probe matter at successively smaller scales- from the atom down to the quark and beyond. These traditional frontiers of physics are largely concerned with reductionism: the notion that once we know the laws of nature that operate on the smallest possible scales, the mysteries of the universe will finally be revealed to us[1].

Over the last century and a half, a period that stretches back to Darwin and Boltzmann- scientists have also become fascinated by another notion: the idea that to understand nature, one also needs to understand and study the principles that govern collective behavior of vast assemblies of matter. For a wide range of purposes, we already know the microscopic laws that govern matter on the tiniest scales. For example, a gold atom can be completely understood with the

Schrodinger equation and the laws of quantum mechanics established more than seventy years ago [2]. Yet, a gold atom is spherical and featureless- quite unlike the lustrous malleable and conducting metal which human society so prizes. To understand how crystalline assemblies of gold atoms acquire the properties of metallic gold, we need new principles {principles that describe the collective behavior of matter when humungous numbers of gold atoms congregate to form a metallic crystal.

In this paper, we will talk about the evolution of our ideas about the collective behavior of matter since the advent of quantum mechanics, hoping to give a sense of how often unexpected experimental discovery has seeded the growth of conceptually new ideas about collective matter [3]. Given the brevity of the article, I must apologize for the necessarily selective nature of this discussion. In particular, I have had to make a painful decision to leave out a discussion of the many-body physics of localization and that of spin glasses. I do hope future articles will have opportunity to redress this imbalance. The past seventy years of development in many-body physics has seen a period of unprecedented conceptual and intellectual development. Experimental discoveries of remarkable new phenomena, such as superconductivity [4], superfluidity, criticality, liquid crystals [5], anomalous metals, antiferromagnetism and the quantized Hall effect, have each prompted a renaissance in areas once thought to be closed to further fruitful intellectual study.

Indeed, the history of the field is marked by the most wonderful and unexpected shifts in perspective and understanding that have involved close linkages between experiment, new mathematics and new concepts.

We will discuss three eras:-

- The immediate aftermath of quantum mechanics|
- Many-body physics in the cold war
- The modern era of correlated matter physics.

Over this period, physicists' view of the matter has evolved dramatically- as witnessed by the evolution in our view of electricity" from the idea of the degenerate electron gas, to the concept of the Fermi liquid, to new kinds of electron fluid, such as a the Luttinger liquid or fractional quantum Hall state. Progress was not smooth and gradual, but often involved the agony, despair and controversy of the creative process. Even the notion that an electron is a fermion was controversial. Wolfgang Pauli, inventor of the exclusion principle [6] could not initially envisage that this principle would apply beyond the atom to macroscopically vast assemblies of degenerate electrons; indeed, he initially preferred the idea that electrons were bosons. Pauli arrived at the realization that the electron fluid is a degenerate Fermi gas with great reluctance, and at the end of 1925 [7] gave way, writing in a short note to Schrodinger that read

"With a heavy heart, I have decided that Fermi Dirac, not Einstein is the correct statistics, and I have decided to write a short note on paramagnetism."

Unsolved riddles of the 1930's

The period of condensed matter physics between the two world-wars was characterized by a long list of unsolved mysteries in the area of magnetism and Vol. 4, 2003 Many Body Physics: Ferromagnetism had emerged as a shining triumph of the application of quantum mechanics to condensed matter. So rapid was the progress in this direction, that Neel and Landau quickly went on to generalize the idea, predicting the possibility of staggered magnetism, or antiferromagnetism in 1933.

In a situation with many parallels today, the experimental tools required to realize the predicted phenomenon, had to await two decades, for the development of neutron diffraction. During this period, Landau became pessimistic and came to the conclusion that quantum fluctuations would most probably destroy antiferromagnetism, as they do in the antiferromagnetic 1D Bethe chain – encouraging one of his students, Pomeranchuk, to explore the idea that spin systems behave as neutral fluids of fermions [8]. By contrast, superconductivity remained unyielding to the efforts of the finest minds in quantum mechanics during the heady early days of quantum mechanics in the 1920s, a failure derived in part from a deadly early misconception about superconductivity. It was not until 1933 that a missing element in the puzzle came to light, with the Meissner and Ochensfeld discovery that superconductors are not perfect conductors, but perfect diamagnets. It is this key discovery that led the London brothers to link superconductivity to a concept of rigidity" in the many-body electron wave function, a notion that Landau and Ginzburg were to later incorporate in their order parameter treatment of superconductivity [9]. Another experimental mystery of the 1930's, was the observation of a mysterious resistance minimum" in the temperature dependent resistance of copper, gold, silver and other metals [10-11]. It took 25 more years for the community to link this pervasive phenomenon with tiny concentrations of atomic size magnetic impurities- and another 15 more years to solve the phenomenon [12] - now known as the Kondo effect- using the concepts of renormalization.

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