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Condensed matter physics in the 21st century: The legacy of Jacques Friedel

One-dimensional physics in the 21st century

La physique unidimensionnelle au XXI^{e} siècle

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ABSTRACT

This paper presents a brief introduction to some of the systems and questions concerning one-dimensional interacting quantum systems. Historically, organic conductors and superconductors – a field extremely active in the "Laboratoire de physique des solides" in Orsay, in a good part thanks to the influence of Jacques Friedel, played a crucial role in this field. I will describe some of the aspects of this physics and also review some of the very exciting theoretical and experimental developments that took place in the 1D world in the last 15 years or so.

RÉSUMÉ

Cet article constitue une courte introduction à une sélection de questions et de systèmes expérimentaux ayant trait à la physique des systèmes quantiques en interaction. Historiquement, les conducteurs et supraconducteurs organiques – un domaine extrêmement actif au sein du Laboratoire de physique des solides à d'Orsay, en grande partie grâce à l'influence de Jacques Friedel, ont joué un rôle crucial dans ce domaine de recherche. Je décrirai certains des aspects de cette physique et épasserai également en revue certains des développements, tant du point de vue théorique qu'expérimental, qui se sont produits dans le monde des unidimensionnels pendant la dernière quinzaine d'années.

1. Introduction

Solids exhibit strong quantum properties, and are in fact quantum systems one can touch! This is due to the extremely high energy scales of the Fermi energy that allow the system to remain degenerate even at ambient temperatures [1]. A remarkable consequence is for example the existence of the Friedel oscillations [2,3] occurring even for free electrons, and which shows that even a local disturbance of the electron fluid leads to long-range density oscillations.

These effects are considerably amplified when interactions are present. In "high" dimension (read three-, two- being a very special case), one can find an escape route by incorporating the effects of interactions in the parameters (such as the mass) of new excitations that "resemble" the free electrons. This is the famous Landau Fermi liquid theory [4–6] that has

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been the cornerstone of our understanding of solids for a good part of the 20th century. With it we can eliminate the main complicated term in the many-body interacting electron problem and bring back the solid in the reassuring realm of "free" particles. This allows us to study much smaller perturbations – such as, e.g., the electron–phonon interaction – with a chance of success and to understand instabilities such as superconductivity and charge density waves.

However, the situation is radically different when the system is one-dimensional. In that case, there is no way for the electrons to avoid each other and it is easy to see (an experience that anyone stuck in a waiting line has already made) that there are no individual excitations possible, but only collective motion of all the particles in the system. The properties of the Fermi surface that led to Friedel excitations in the first place are at their utmost in one dimension, and as a consequence the amplification of the quantum effects by interactions at its best (or worst). This makes the one-dimensional system have a physics of their own, and a remarkable laboratory to study the effects of interactions.

This physics has of course been extensively studied both theoretically and experimentally in a large variety of systems and at a large number of places. Unravelling the secrets of the one-dimensional quantum world was a considerable challenge, both from the fundamental point of view but also in view of potential new materials exhibiting these remarkable properties. In the beginning of the 1980s, under the influence of Jacques Friedel, the "Laboratoire de physique des solides" in Orsay was a paradise in that field. In particular, among other remarkable lines of research, superconductivity was discovered in a novel class of organic materials, synthesized by K. Bechgaard, by D. Jérome and collaborators [7]. It was thus a fantastic place to learn about this field, especially in contact with exceptional young theorists such as H.J. Schulz. I caught there during my PhD the one-dimensional virus and thus it is quite natural for me to discuss in this article some aspects of this remarkable physics of one-dimensional systems.

The plan of this article is as follows. In Sec. 2 I will give an extremely brief reminder of the Tomonaga–Luttinger liquid, the generic model describing one-dimensional interacting quantum systems. In Sec. 3 I will discuss the organic superconductors. I will not focus too much on the organic superconductors per se, since they will be covered in much more details in the articles written by D. Jérome and J.-P. Pouget in this issue, but will start with them as a remarkable example of one-dimensional systems. I will especially point out the open issues that remain in my opinion with these materials. In Sec. 4 I will discuss the large number of breakthroughs that were accomplished in the last 15 years or so in the one-dimensional world both on the theoretical side and on the experimental one. Finally, some conclusion will be put in Sec. 5. As a disclaimer, this article cannot and do not pretend to be exhaustive. It aims to present a few selected highlights whose choice is somewhat subjective and corresponds to my own interests in the subject.

2. A zest of theory – the Tomonaga–Luttinger liquid

I will not here recall all the properties of one-dimensional systems, since extensive literature exists on the subject (see, e.g., [8–10]). I will just give here a brief digest of the salient properties, pertinent in the context of this chapter and refer the reader to the existing literature, either on fermions or bosons, on the subject for more details and references.

As briefly mentioned above, the individual excitations do not exist in one dimension. Thus the description of, e.g., fermionic systems in terms of the standard Landau quasiparticles is failing. Instead one has a fully different set of properties that went globally by the name of Tomonaga–Luttinger liquid [11]. The main characteristic of such a TLL are as follows.

1. **Collective excitations:** Only collective excitations exist. These excitations are analogous to sound waves, i.e. density oscillations, but the oscillating density is the electronic density or some other density (e.g., spin density). They are characterized by a velocity u. For noninteracting fermionic particles, u corresponds to the Fermi velocity v_{F}, but assumes a different (renormalized) value in an interacting system. Remarkably, the existence of sound-like excitations is quite general, and applies also to physical systems of bosons (cold atoms) and to insulating magnetic materials as well.
2. **Quasi-long-range order:** A one-dimensional system is poised at the verge of an instability but, because quantum fluctuations usually prevent the breaking of a continuous symmetry, the system is usually only having *quasi*-long-range order, even at zero temperature, with power-law-decreasing correlation functions. For example, for antiferromagnetic spin chains with an anisotropy between the z axis and the xy plane (so-called XXZ spin chain), the correlation functions read [8] in the absence of external magnetic field:

$$\begin{aligned} \langle S^z(x)S^z(0)\rangle &= \frac{1}{x^2} + (-1)^x A_z \left(\frac{1}{x}\right)^{2K} \\ \langle S^-(x)S^+(0)\rangle &= (-1)^x A_x \left(\frac{1}{x}\right)^{\frac{1}{2K}} + B_x \left(\frac{1}{x}\right)^{\frac{1}{2K}+2K} \end{aligned} \tag{1}$$

   Similar formulas are valid for fermions and bosons. The number K is a dimensionless number that depends on the interactions. The amplitudes A, B are non-universal numbers depending on the precise microscopic model and the interactions.
3. **Tomonaga–Luttinger liquid:** The above constitute the essence of a Tomonaga–Luttinger liquid that describes the generic behavior of an interacting one-dimensional system [11]. Its asymptotic properties (i.e. the ones for large distances and/or large time differences) are fully determined by the knowledge of the two numbers: the velocity u and the Luttinger parameter K. This last number is dimensionless and controls the decay of *all* the correlation functions as is obvious