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Nuclear magnetic resonance in high magnetic field: Application to condensed matter physics

Résonance magnétique nucléaire en champs magnétiques intenses : application à la physique de la matière condensée

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ABSTRACT

In this review, we describe the potentialities offered by the nuclear magnetic resonance (NMR) technique to explore at a microscopic level new quantum states of condensed matter induced by high magnetic fields. We focus on experiments realised in resistive (up to 34 T) or hybrid (up to 45 T) magnets, which open a large access to these quantum phase transitions. After an introduction on NMR observables, we consider several topics: quantum spin systems (spin–Peierls transition, spin ladders, spin nematic phases, magnetisation plateaus, and Bose–Einstein condensation of triplet excitations), the field-induced charge density wave (CDW) in high-T_c superconductors, and exotic superconductivity including the Fulde–Ferrel–Larkin–Ovchinnikov superconducting state and the field-induced superconductivity due to the Jaccarino–Peter mechanism.

RÉSUMÉ

Dans cette revue, nous décrivons les opportunités offertes par la résonance magnétique nucléaire (RMN) pour étudier les propriétés microscopiques des nouveaux états quantiques de la matière induits par les champs magnétiques intenses. Nous mettons l'accent sur les expériences réalisées dans des bobines résistives (jusqu'à 34 T) ou hybrides (jusqu'à 45 T), qui ouvrent un large accès à ce type de transitions quantiques. Après avoir introduit les quantités observables par RMN, nous considérons plusieurs domaines de recherche : les systèmes de spins quantiques (la transition de spin–Peierls, les échelles de spin, les phases nématiques de spin, les plateaux d'aimantation et la condensation de Bose–Einstein des excitations triplets), l'onde de densité de charge induite sous champ dans les supraconducteurs à haute T_c, et la supraconductivité exotique, avec la phase

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supraconductrice Fulde–Ferrel–Larkin–Ovchinnikov et la supraconductivité induite sous champ de type Jaccarino–Peter.

1. Introduction

Since its discovery just after the second World War, the nuclear magnetic resonance (NMR) technique has known a tremendous development in chemistry, biology and imaging for medical applications (MRI). This development was founded on three pillars: the development of superconducting magnets providing extremely stable and homogeneous (10^{-10}) magnetic fields up to 23.4 T (1 GHz for proton resonance), the continuously increasing power of computers, and the development of high-frequency and high-power electronics. Most of the experiments performed in the world concern structural information and are usually performed around room temperature (in particular for biology and MRI) in diamagnetic systems. The situation is quite different for NMR applied to solid-state physics, where temperature, pressure and magnetic field are essential thermodynamic variables. The homogeneity and stability requirements are much less stringent than mentioned above, and usually fall in the range 10^{-5}–10^{-3}, depending on the systems under study, so that in many cases all-purpose high-field resistive magnets, available only in few dedicated facilities in the world, can be used up to field values up to 35 T, or even 45 T in a hybrid magnet. In this case, high magnetic fields are not used to increase the sensitivity or the resolution of NMR spectroscopy, but as a physical variable able to induce phase transitions, even at zero temperature (the so-called quantum phase transitions) and to access new (quantum) phases of condensed matter [1]. Electrons in the matter couple with the magnetic field H through their spin and orbit. In this latter case, it is convenient to define a typical magnetic length $l_B = \sqrt{\hbar/eB} = \frac{25\,\text{nm}}{\sqrt{B\,[\text{T}]}}$, such as $2\pi l_B^2 B = \phi_0 = h/e$, where e is the absolute value of the electron charge, and ϕ_0 the elementary flux quantum, and to compare it to some typical distance of the system under study. The most well-known examples are the critical field H_{c2} in a superconductor of type II and the Integer Quantum Hall Effect (IQHE) and the Fractional one (FQHE) in 2D electron gas. In the first case, the comparison between the coherence length ξ of the Cooper pairs and the (superconducting) quantum flux $\phi_{0s} = h/(2e)$ gives the upper critical field $H_{c2} = \phi_{0s}/2\pi(\xi(T))^2$ [2]. In the second case, the IQHE plateaus correspond to incompressible phases, in which the number of electrons per flux quanta is an integer [3]. A similar picture can be used for the FQHE [4] with composite fermions [5,6]. As far as the coupling with the spins are concerned, it is the Zeeman energy that has to be compared with the relevant energy scale in the system under consideration. Examples range from quantum spin systems, in which the characteristic energies derive from the exchange couplings J's, to the Pauli limit in superconductors when the Zeeman energy overcomes the pairing energy of Cooper pairs. More generally, application of magnetic field allows one to generate new quantum phases and, until recently, NMR has been the only technique allowing a microscopic investigation of their structure and excitations for field values above 17 T. This is now changing, with the new possibilities for X-rays to do experiments under pulsed magnetic fields up to 30 T [7] and for neutron scattering up to 27 T [8]. Comparing results obtained by these techniques with those obtained by NMR opens a new fascinating area of research.

In this paper, we will review some of the NMR contributions to the physics in high magnetic fields performed by the authors [9–39] using resistive magnets at the "Laboratoire national des champs magnétiques intenses" (LNCMI, Grenoble, France). Some experiments requiring magnetic fields up to 45 T were performed at the National High Magnetic Field Laboratory (NHMFL) at Tallahasse (Florida, USA), and we also discuss recent NMR results obtained in pulsed magnetic field up to 55 T at the LNCMI of Toulouse (France).

2. NMR observables

Without entering into details of how NMR is actually performed [40–44], we will limit the presentation to its basic principles in order to explain what physical quantities can be observed [16]. In a typical configuration, NMR relies on the Zeeman interaction

$$\mathcal{H}_Z = -\boldsymbol{\mu}_n \cdot \mathbf{H}_n \tag{1}$$

of the magnetic moment of nuclei (of selected atomic species) $\boldsymbol{\mu}_n = \hbar\gamma_n \mathbf{I}_n$, where γ_n and $\mathbf{I}_n$ are the gyromagnetic ratio and the spin of the nucleus, to obtain an information on the local magnetic field value $\mathbf{H}_n$ at this position. The experiment is performed in a magnetic field $H_0 \sim 10$ T, whose value is precisely known (calibrated by NMR), and which is perfectly constant in time and homogeneous over the sample volume. A resonance signal is observed at the Larmor frequency corresponding to transitions between adjacent Zeeman energy levels $\omega_{\text{NMR}} = \gamma_n H_n$, allowing very precise determination of $\mathbf{H}_n$, and therefore of the local, induced, so-called "hyperfine field" $\mathbf{H}_{\text{hf}} = \mathbf{H}_n - \mathbf{H}_0$ (as γ_n is known from calibration on a convenient reference sample). This hyperfine field, produced by the electrons surrounding the chosen nuclear site, is a signature of the local electronic environment. On the other hand, nuclei that have a spin $I > 1/2$ have a non-spherical distribution of charge, and possess a quadrupolar moment that couples to the electric field gradient (EFG) tensor produced by the surrounding