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Small-angle neutron scattering (SANS) studies of the vortex lattice in type II superconductors

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Abstract

The last 15 years or so have seen a number of important published studies of the vortex lattice (VL) in type II superconductors. Superconductors are a complex and diverse range of materials such as the high-temperature superconductors (e.g. $YBa_2Cu_3O_{7-\delta}$, $Bi_2Sr_2CaCu_2O_{8+\delta}$, $La_{2-x}Sr_xCuO_{4+\delta}$, $Nd_{2-x}Ce_xCuO_{4+\delta}$), magnetically ordered ([rare-earth]Ni_2B_2C), two-band (MgB_2, $NbSe_2$), heavy-fermion and unconventional materials ($CeCoIn_5$, UPt_3, $PrOs_4Sb_{12}$, Sr_2RuO_4), non-local superconductors ([RE]Ni_2B_2C, V_3Si, $Ca_3Rh_4Sn_{13}$), as well as 'classic' materials such as Nb. Phenomena such as non-locality, order parameter symmetry, multi-component superconductivity, VL melting, static and dynamic response of the VL to driving forces and disorder are topical and continue to be investigated. Here we present a summary of some of these works.

Keywords: Superconductor; Vortex lattice; Small-angle neutron scattering

The diffraction of neutrons by the periodic arrangement of magnetic field—the vortex lattice (VL), in type II superconductors has proved to be a powerful technique. The pioneering experiments of Cribier et al. [1] were in fact the first direct observation of the VL in Nb, albeit in reciprocal space, and even pre-dates the first real space imaging of the VL by Bitter decoration by Essman and Träuble [2].

The length scales associated with the hexagonal VL plane spacing, d, are typically much larger than the neutron wavelengths, λ, (e.g. $\lambda\sim10\,Å$) available for diffraction measurements (e.g. $d\sim0.13\,\mu m$ @ $B=0.1\,T$). Diffraction from the VL therefore occurs at small angles and experiments are usually best performed on a small-angle neutron scattering (SANS) instrument. Using a wavelength spread of 10%, collimation defined by source and sample apertures separated typically by $\sim$20 m, the diffracted intensity is measured on a pixilated area detector a further $\sim$20 m from the sample. The diffraction measurement can be set up in one of two possible geometries. The more usual geometry is to align the magnetic field, B, such that it is almost parallel to the neutron beam direction. This has the advantage that all first-order Bragg peaks are accessible by only small rotations or tilts of the magnet/cryostat system. An alternative arrangement is to align the magnetic field perpendicular to the neutron beam, either horizontally or vertically. In this geometry much larger rotation angles (e.g. 60° for a hexagonal VL) are required in order to scan between two first-order Bragg peaks and is therefore often more convenient in a cryomagnet system to use a vertical magnetic field. To maximize intensity for any particular diffraction spot a rocking curve should be performed by tilting or rotation of the sample, cryostat and magnet together about a horizontal or vertical axis to satisfy the Bragg condition for that spot. Background measurements taken with the sample in the normal state (e.g. $T>T_c$ or $B>B_{c2}$) are subtracted from each pattern prior to analysis.

The structure of the VL in an isotropic type II superconductor was calculated by Abrikosov [3] by analysis of the surface energy at a normal/superconductor boundary. Abrikosov erroneously (and rather famously) initially determined that a square VL would constitute the minimum in free energy. Subsequent re-analysis showed in

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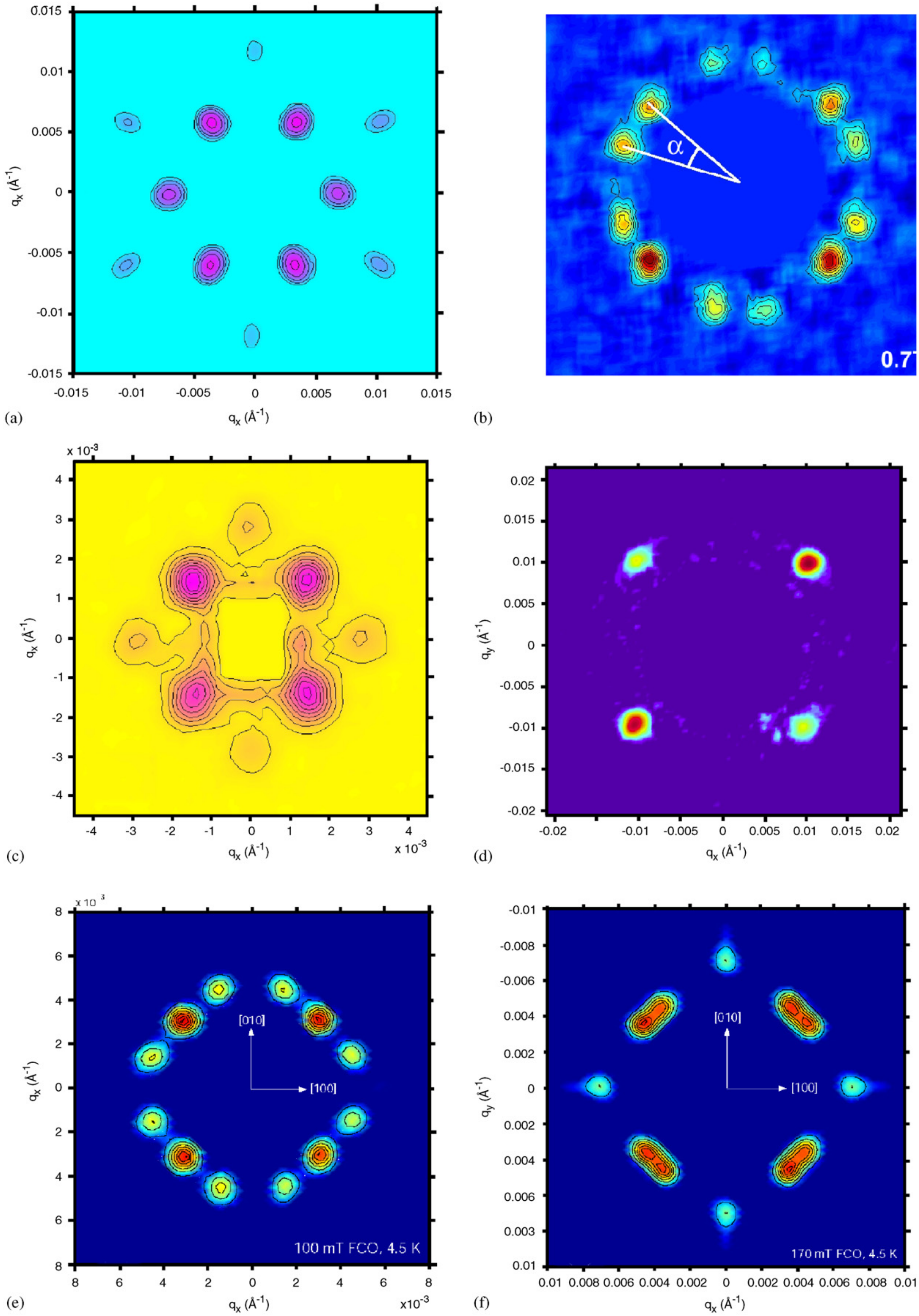

Fig. 1. Small-angle diffraction images of the VL: (a) Hexagonal VL in Nb at 3.2 K, 0.2 T with $B\|[1\,1\,1]$ [4]; (b) two-domain hexagonal VL in the two-band superconductor MgB_2 at 2 K, 0.7 T with $B\|c$ [8]; (c) square VL in the unconventional superconductor Sr_2RuO_4 at 50 mK, 0.025 T, $B\|c$ [10]; (d) square VL in the high temperature superconductor $La_{2-x}Sr_xCuO_4$ at 2 K, 1.2 T with $B\|c$ [11], (e and f) Low- and high-field rhombic VL in YNi_2B_2C at 4.5 K, $B\|c$ at (e) 0.1 T and (f) 0.17 T [18–20].