Small-Angle Neutron Scattering (SANS) Studies of Superconducting UPt$_3$’s Vortice Lattice

Joseph Hlevyack
2012 NSF/REU Program
Physics Department, University of Notre Dame

Advisor:
Morten R. Eskildsen, Ph.D.

Graduate Student Collaborators:
William Gannon
Catherine Rastovski
Pinaki Das, Ph.D.
Abstract

\textit{UPt}_3\textit{ is a type-II, heavy-fermion superconductor characterized by a mixed state threaded with vortices that each carry quantized magnetic flux. Using Small-Angle Neutron Scattering (SANS) experiments, the vortex lattice (VL) was analyzed at various applied magnetic fields and temperatures, including settings in the C and A phases of the $H\text{--}T$ diagram. In particular, the temperature dependence of the form factor—the Fourier transform of the magnetic flux modulation—was closely analyzed, and comparisons between two experiments indicate that the form-factor results were reproducible. The experiments also resolved a question about the existence of a new superconducting state existing in the multi-phase $H\text{--}T$ diagram.}

1 Introduction

Superconductors are materials that have a virtually zero electrical resistance below some critical temperature,\textsuperscript{1} which can range from a few mK to over 100 K. Since zero electrical resistance means no energy dissipation via heat, superconductors are promising technologically in electrical circuits. Yet, our understanding of superconductors is far from complete, and studying superconductors with low critical temperatures is important to better understand the superconducting state.

Superconductors are divided into two classes: type-I and type-II. Type-I superconductors are exclusively characterized by the Meissner effect, where below a critical temperature $T_c$ and applied magnetic field $H_{c1}$, the superconductor completely expels the applied field. Type-II superconductors, on the other hand, are characterized by two states: the Meissner state and the “mixed” state. The mixed state is bounded by two critical magnetic fields $H_{c1}$ and $H_{c2}$, below which the Meissner state exists and above which the normal state appears. See Fig. 1(a). The mixed state’s hallmarks are the penetration of the bulk by flux-lines or vortices—whirpools of supercurrents—that each carry quantized magnetic flux. One quantum of magnetic flux is $\phi_0 = 2070 \text{ T*nm}^2$.

\textsuperscript{1}Once this critical temperature is reached, there is also some critical applied magnetic field below which the superconducting state can exist.
UPt₃ is a heavy-fermion superconductor characterized by three superconducting phases termed A, B, and C; these three phases meet at a tetracritical point in the $H - T$ phase diagram as in Fig. 1(b). Huxley et.al. [3] studied how UPt₃’s flux-line lattice is oriented with increasing temperature. Additionally, Kleiman et.al. [4] observed that, besides having “conventional quantization,” UPt₃’s VL exhibits distorted hexagonal symmetry; their study predicts that Fermi-surface and gap anisotropies—meaning that measurements are directionally dependent—could explain UPt₃’s anisotropy. Finally, according to Joynt and Taillefer [2], the coupling between magnetism and superconductivity is the weakest point in any theory about UPt₃. In this respect, all of these studies reveal why UPt₃ is an interesting superconductor.

This particular study used SANS experiments to analyze the UPt₃’s VL. The principle behind this experiment arises from quantum mechanics. Since the neutron has a spin, it has a magnetic moment. Because of a varying magnetic potential energy in the VL, the neutrons are diffracted. Moreover, a neutron has a characteristic wavelength related to its momentum. When neutrons encounter the VL, they scatter in a manner akin to crystal X-ray diffraction. In its elementary form, the Bragg condition for lattice scattering is given.
by

\[ \lambda = 2d \sin \theta, \] (1)

where \( \theta \) is half of the scattering angle, \( \lambda \) the neutron’s wavelength, and \( d \) the VL spacing. Because a neutron’s de Broglie wavelength is perhaps on the order of 10 Å while the VL spacing is 1000 Å, SANS is an ideal technique to analyze the VL. That is, it is ideal because the scattering angle is small; the order-of-magnitude estimates show that \( \sin \theta \approx \theta = \lambda/(2d) = 10/2000 = 5 \times 10^{-3} \).

The SANS setup is summarized in Fig. 2. The neutrons go through a velocity selector that regulates which neutrons pass through the instrument and are then collimated. They interact with the sample, and the scattered neutrons fall upon a detector while the unscattered neutrons are absorbed by a beamstop [5]. To satisfy the Bragg conditions for scattering from the VL planes, the sample and magnets are tilted together at small angles. If the scattering intensity is plotted versus the tilt angle, a “rocking” curve is generated. More details about this curve appear in the studies considered below.

2 The Experiments

The two SANS studies were conducted at the Paul Scherrer Institute (PSI) in Villigen, Switzerland. One study in August 2011 was conducted with SANS-I while the other was
done with SANS-II in May 2012. Parts of each experiment were devoted to understanding UPt$_3$’s $H - T$ phase diagram. Since the symmetry of the lattice is well-documented, only two diffraction spots were imaged to save time. The applied field was set parallel to the crystal’s $a^*$ axis for the parts of the experiments discussed below.

2.1 SANS-I Experiment: August 2011

For the SANS-I experiment, the sample was cooled down to a temperature as low as 43 mK using a dilution refrigerator. The applied magnetic field $H$ was ramped up to about 3.0 T—well above the critical-field $H_{c2}$ transition. Then the field was dropped down and oscillated about the desired setting to set up the VL. The neutrons’ wavelength was set at 6 Å, and the detector distance was 16.0002 m.

Rocking-curve data was collected at multiple field and temperature settings. During the analysis, the data were fitted with Gaussian and Lorentzian curves, and the Full-Width-Half-Maximum (FWHM) of each curve was determined from the fit. Nonetheless, all of the rocking curves did not necessarily have good resolution. The limited resolution arises from the sample size as well as the instrument itself.

With the applied field constant, some others were taken at various temperatures to check if the rocking curves were broadening as the temperature increased.\(^2\)

Two scans of the temperature dependence of the peak’s intensity were done for a 0.4-T setting; this explored the transition through the tetracritical point. Fig. 3(a) shows one of the 0.4-T temperature scans. Notice the linearity in the plot at low temperatures (up until about 300 mK or so) and the positive curvature as the VL transitions from the $B$ phase into the normal state in Fig. 3(a).

Fig. 3(b) shows the temperature dependence for $H = 0.2$ T, and it represents a transition

\(^2\)This was done since it was assumed that the rocking curve’s FWHM was constant for a peak’s form-factor analysis; this issue will be explored.
Figure 3: Temperature dependence of the average peak intensity for three different field settings (SANS-I).

from the $B$ to $A$ phases and then into the normal state. Observe that the linear relationship between the peak’s intensity and temperature still occurs at lower temperatures (i.e., while UPt$_3$ is in the $B$ phase); positive curvature also appears as it did for the 0.4-T scan.

 Nonetheless, there is a difference between Figs. 3(a) and 3(b). Notice the “bump” in the plot at higher temperatures (starting around 450 mK) for the temperature dependence in Fig. 3(b); it is absent in Fig. 3(a). This raised the question of whether a new phase had been discovered, and it motivated the SANS-II experiment.
A final temperature scan was done at 0.75-T—well into the $C$ phase. Fig. 3(c) shows the resulting temperature analysis. Because of poor signal-to-noise readings, more measurements with higher count rates will be needed in the future to explore this field-temperature regime. Nonetheless, measurements in this high-field regime were unprecedented.

### 2.2 SANS-II: May 2012

For the SANS-II experiment, the sample was cooled with a dilution refrigerator. In some cases, the temperature was as low as 65 mK. To prepare the VL, the applied magnetic field was ramped up well above the $H_{c2}$ transition, then dropped down and oscillated about the final field setting. The detector’s distance was 6.2 m, and the neutrons’ wavelength was about 8 Å.

One of the experiment’s aims was to expand upon the SANS-I’s VL study, which showed a “bump” in the 0.2-T temperature dependence. The sample’s temperature was lowered to 65 mK and then increased while the applied field was kept constant at 0.2 T. Fig. 4 displays the resulting temperature scan. More data was collected in the higher-temperature regime, and it is concluded that the “bump” that characterized the curve in the 0.2-T scan from SANS-I disappeared with better statistics.
Unfortunately, background noise is prominent at higher temperatures for this experiment. Background subtraction often resulted in a small negative intensity. Nothing could be done to eliminate this problem.

## 2.3 Form-Factor Comparisons

By comparing the temperature dependence of the form factors, we can see how reproducible the results are between the two experiments. Recall that the form factor is the Fourier transform of the magnetic-flux modulation. In theory and practice, both experiments should yield similar temperature dependences in the form factors at a particular field setting—0.2 T in this case. Generally, the form factor can be found by manipulating the following relationship:

$$R = \frac{2\pi \gamma^2 \lambda_n^2 t}{16\phi_0^2 q \cos \eta_Q} |h(Q)|^2,$$

where $R$ is the peak’s reflectance—the peak’s integrated intensity divided by the direct beam’s intensity, $\gamma = 1.91$ the neutron’s gyromagnetic ratio, the neutrons’ wavelength $\lambda_n$, the form factor $h(Q)$, the Lorentz correction $\cos \eta_Q$, the scattering vector $q$, the sample thickness $t$, and $\phi_0$ the flux quantum (2070 T*nm$^2$).

Briefly, to do a form-factor analysis, rocking-curve data must have been collected for the field setting considered. During a temperature scan, multiple rocking curves are taken at a few temperatures to check if the rocking curves are broadening as the temperature increased. This is done because during the analysis, it would be assumed that the Full-Width-Half-Maximum (FWHM) was constant throughout the temperature scan.

When choosing an FWHM, it is customary to look at the “base”-temperature rocking curve and use its FWHM for the analysis. For any rocking curve, the FWHM can be obtained

\[^3\eta_Q\text{ can be obtained from angular measurements in the diffraction pattern. In this case, it can be thought of as a “spot” angle.}\]
Figure 5: Temperature dependence of the form factor (at “low” temperatures) for both the SANS-I and SANS-II experiments at $H = 0.2$ T.

from a fit to the curve. This requires another assumption—the kind of curve fit, for rocking curves can be fitted with a Gaussian, Lorentzian, or Voigt (the best-fit) curve. For simplicity, a Gaussian fit was assumed. At a particular temperature, by knowing the FWHM and a scattering peak's maximum intensity, the integrated intensity of each scattering peak can be generated. From this, the reflectance $R$ can be determined once the direct beam’s intensity is known. Assuming that all other quantities have been analyzed, the form factor can be determined.

Fig. 5 shows the temperature dependence of the form factor from both experiments. Notice that there is some difference between the form factors, but in general, it seems that the form factors from each experiment have a linear dependence with temperature. Differences probably arise based upon detector calibration as well as any errors in the assumption. Moreover, the rocking curve used for the SANS-II analysis had large error bars, causing some more differences to arise.
3 Summary

This study investigated UPt$_3$’s VL via SANS experiments, focusing upon the characteristics of the VL at various points in the $H - T$ diagram. These experiments looked at multiple state transitions. In particular, the VL was analyzed at an unprecedented applied field setting of 0.75 T—well within the superconducting $C$ phase. Additionally, the SANS-II experiment resolved any question about the possible existence of another superconducting state; statistics from this experiment seem to suggest that there is not another state.

References


