Experiment 817: β-NMR Investigation of Type-II Superconductors

(Z. Salman, (Oxford University), D. Wang and R.F. Kiefl (UBC)

One of the most remarkable properties of a superconductor is the vortex lattice, which if formed in the presence of an applied magnetic field. Much has been learned about vortices and the vortex lattice since it was first predicted by Abrikosov in 1957. Nevertheless, vortices are complex objects with properties that are still not fully understood. In recent years muon spin rotation (μSR) has been used extensiviely to measure the magnetic field distribution in the vortex state, which is a sensitive probe of vortex structure and the vortex lattice. For example μSR results in $NbSe_2$ have shown that the vortex core shrinks due to depopulation of the core bound states but the low temperature core radius is still significantly larger than predicted in the quantum limit. Recently there has been considerable work on the role of delocalized quasiparticles associated with the cores and the interaction between vortices, particularly in multiband superconductors such as $NbSe_2$, where there is more than one superconducting gap.

In this experiment we are investigating the vortex state of $NbSe_2$ (T_c=7.0 K) and other superconductors using depth resolved β-detected NMR of ^{8}Li. While μSR is primarily a bulk probe, β-NMR can be used to investigate the vortex lattice much closer to the surface, i.e. on the scale of the vortex lattice spacing $a_0 = 1546/\sqrt{B_{ext}[mT]}$nm . In general, we expect vortices and vortex interactions to be different near a surface or interface due the discontiunous nature of the superconductor.

Fig.1a. shows the β-NMR spectrum in the normal state of $NbSe_2$ in a magnetic field of 300 mT applied along the c-axis. Above T_c the lineshape is nearly independent of magnetic field, temperature and implantation depth. After field-cooling below T_c, the resonance broadens asymmetrically (Fig.1b) and exhibits all the characteristic features of a triangular vortex lattice. In particular, note the most probable frequency, or cusp frequency, shifts by an amount Δ_c below the normal state frequency. The cusp frequency (or magnetic field) arises from Li located midway between two adjacent vortices. In addition, there is also a high frequency tail which corresponds to the magnetic field distribution near the vortex core. The high frequency cutoff, which is shifted by an amount Δ_v above the normal state frequency, corresponds to the field at the vortex core. The curve in Fig. 1b is a fit to the vortex lineshape model taking into acocunt the close proximity to the surface. The best fit gives a London penetration depth λ=230(30) nm and a vortex core radius ρ=13(1) nm. These parameters are close to what is observed from μSR in the bulk $NbSe_2$ at the same temperature and field, indicating at this field the vortex lattice is similar to that deeper inside the sample.

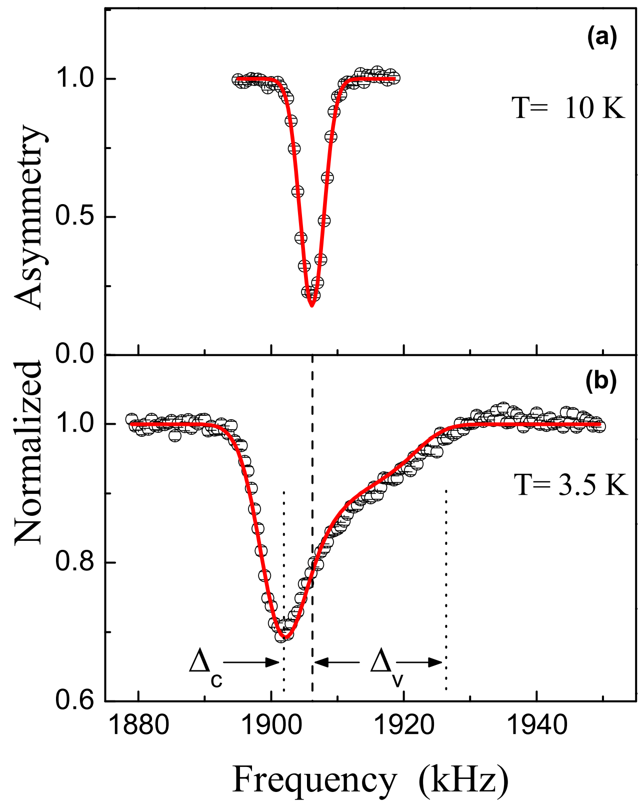

Fig. 1. (a)The β-NMR spectrum in the normal state of $NbSe_2$ at 10 K in a magnetic field of 300 mT applied along the c-axis. The beam energy of 20 keV corresponds to a mean implantation depth $\langle z \rangle = 85$ nm. The observed Gaussian line broadening is attributed to ^{93}Nb nuclear moments. (b) The same conditions as (a) except field cooled to 3.5 K or $0.5T_c$. The asymmetric lineshape is characteristic of a triangular lattice of magnetic vortices.

Fig.2 shows the β-NMR lineshape in a much lower magnetic field of 10.8 mT. Note the line is slightly narrower in Fig. 2b compared to 2c. This is predicted in a simple model of vortices near a surface. The most surprising result is the remarkable similarity of lineshapes in Figs 1 and 2, given the magnetic fields differ by a factor of 27. In particular, in Fig.2, note the observed cutoff at a frequency Δ_v above the normal state frequency, corresponding to the frequency at the vortex. The small value of Δ_v in Figs.2b and 2c can only be explained by a very extended vortex. The curves are a fit to the vortex lineshape model assuming a depth independent λ nm and ρ nm. The best fit is with $\lambda = 167(15)$ nm and $\rho = 77(10)$ nm. Thus the core size at this field is much larger than the coherence length and what is measured in high field. A plausible explanation is that in a lower field the vortices are further apart and thus interact more weakly. This would lead to enhanced thermal vibrations in low field. It is likely that multiband effects also contribute to the giant vortices we observe in $NbSe_2$. These results point to the need for a comprehensive theory of the vortices and their interactions, which includes both electronic and vibrational excitations.

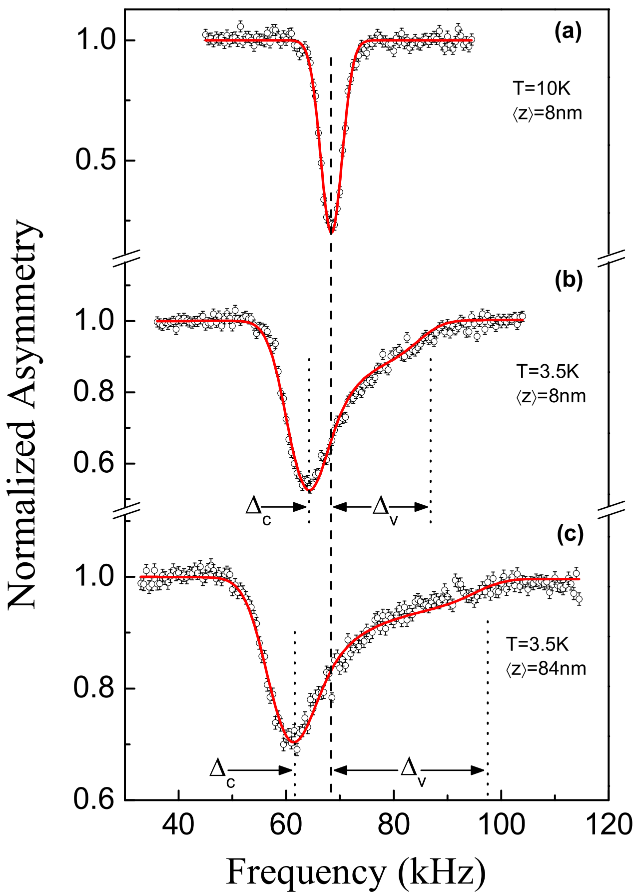

Fig. 2 β-NMR resonances in $NbSe_2$ in a low magnetic field of 10.8 mT. (a) In the normal state at 10 K with a beam energy corresponding to a mean implanta nm. (b) The same conditions as (a) except field cooled to $0.5T_c$. (c) The same temperature and magnetic field as (b) but the mean implantation depth is about 10 times larger.

Publications

1. D. Wang, M.D. Hossain, Z. Salman, D. Arseneau, K.H. Chow, S. Daviel, T.A. Keeler, R.F. Kiefl, S.R. Kreitzman, C.D.P. Levy, G.D. Morris, R.I. Miller, W.A. MacFarlane, T.J. Parolin, H. Saadaoui, "β-Detected NMR of ^8Li in the Normal State of $2H - NbSe_2$", Physica B, **374-375**, 239-242 (2006).

2. Z. Salman, D. Wang, K. H. Chow, M.D. Hossain, S.R. Kreitzman, T.A. Keeler, C.D.P. Levy, W.A. MacFarlane, R.I. Miller, G.D. Morris, T.J. Parolin, H. Saadaoui, M. Smadella, and R.F. Kiefl,"Giant Vortices Below the Surface of $NbSe_2$ Detected Using Low Energy β-NMR", submitted to PRL.

Theses:

1. Near surface vortex lattice in $NbSe_2$ studied with low energy beta-NMR, Dong Wang, M.S. thesis, Department of Physics and Astronomy, UBC, 2006.