Pseudogap state in strongly disordered conventional superconductor, NbN

A Kamlapure¹, G Saraswat¹, M Chand¹, M Mondal¹, S Kumar¹, J Jesudasan¹, V Bagwe¹, L Benfatto², V Tripathi¹, P Raychaudhuri¹

¹Tata Institute of Fundamental Research, Homi Bhabha Rd, Mumbai 400005, India
²ICS-CNR and Department of Physics, Sapienza University, Piazzale Aldo Moro 5, 00185 Rome, Italy

E-mail: ask@tifr.res.in

Abstract. We present experimental evidence of the formation of a "Pseudogap" state in a disordered conventional s-wave superconductor, NbN, as the system is driven towards the Anderson Metal-Insulator transition. Series of scanning tunnelling spectroscopy measurements done on films with increasing disorder shows that for strongly disordered samples the dip in the tunnelling spectra at Fermi level persists much above the superconducting transition temperature. We propose that the gap like feature at Fermi level is associated with superconductivity based on the observation of BCS like spectra with dip at Fermi level and diffused coherence peaks after correcting them with Altshuler-Aronov background. We propose a scenario based on phase fluctuations to understand the pseudogap state in strongly disordered NbN films

1. Introduction
One of the intriguing state in the high temperature superconductors is the pseudogap state, the state with finite gap in the DOS at Fermi level above the superconducting transition temperature which evolves continuously from the superconducting energy gap below $T_c$ [1]. The pseudogap state is also observed in newly discovered Iron based superconductors [2]. Recent studies on disordered conventional s-wave superconductors also showed that in presence of strong disorder they form the Pseudogap state [3, 4]. It has been suggested from numerical simulations [10] that in a conventional superconductor, strong disorder gives rise to nanometer sized domains that spontaneously form in a superconductor. Phase fluctuations between these domains can destroy the global superconducting state even if Cooper pairs survive within these domains.

In this paper, we report scanning tunneling spectroscopy (STS) measurements on 3D NbN thin films as the disorder is tuned from the moderately clean limit down to the Anderson metal-insulator transition.

2. Experimental details and data analysis
Thin films of NbN were grown by reactive magnetron sputtering in the mixture of Ar and N₂ over the single crystalline (100) MgO substrate. Disorder in the thin films is controlled by depositing at varying Ar:N₂ ratio and deposition power. Film thickness for all the samples are ≥ 50nm which is much larger than the dirty limit coherence length ($\xi$=4-8nm in our films)[5]. Disorder in the samples is characterized by Ioffe-Regel parameter, $k_Fl$, using the formula
$k_F l = \left( \frac{3 \pi^2}{2} \right)^{2/3} h \left( R_H (285 \, K) \right)^{-1/3} \sqrt{\rho (285 \, K)^{3/2}}$ where $R_H$ is the Hall resistance and $\rho$ is the resistivity, both of which are measured using transport measurements. The range of $k_F l$ varies from 1 to 10.2 in our samples [6].

Temperature evolution of tunneling DOS is investigated through STS measurements in a home built low temperature Scanning tunneling microscope (LT-STM). For that the samples were grown in situ on a specially designed sample holder [4] in a chamber connected to STM and were directly transferred to the STM head for measurements using a set of two manipulators. IV spectra are acquired by sweeping the bias while the feedback is off and recording the tunneling current. The conductance (dI/dV) spectra are acquired using lock-in technique where 100µV alternating voltage of frequency 393.7Hz is modulated in the bias. Spatially averaged spectra at different temperatures are obtained by taking the average of about 20 spectra at 32 equidistant points over the line of length 150nm and then averaging once again.

Representative data for one of the strongly disordered samples ($T_c=2.6\, K$) is shown in Figure 1. Figure 1(a) shows conductance spectra at different temperatures. The spectra show two distinct features: A low bias dip in the conductance associated with superconductivity and a weakly temperature dependent V-shaped background which extends up to high bias. This second feature which persists up to the highest temperature of our measurements arises from the Altshuler-Aranov (A-A) type e-e interactions in the normal state. We observe that the low bias gap feature disappears above 8K and the spectrum at 9.35K has only the broad background. This is clearly seen in the $dG(V)/dV$ versus V curves (Fig. 2(b)) where the symmetric peak-dip structure associated with the low bias feature completely disappears for the spectrum at 9.35K. Therefore to remove the A-A background from the low temperature spectra we subtract the one at 9.35K. Figure 1(c) shows the subtracted spectra and Figure 1(d) shows the colormap of subtracted data with x-axis as the temperature, y-axis as the bias and the colorscale as the normalized conductance value. The data in panel (d) shows that the pseudogap persists up to 6.5K. The temperature up to which the pseudogap persists is defined as $T^*$.

After the STS measurements the samples were taken out of the STM and transport measurements were done on the same samples.

### Figure 1. (a) Normalized conductance curves for the sample with $T_c=2.6\, K$. (b) Derivatives of the conductance curves in panel (a). Few curves are removed for clarity. (c) Normalized conductance curves after subtracting curves in panel (a) from 9.35K data. (d) Surface plot of the subtracted curves of panel (b).

#### 3. Results and discussion

Series of NbN films with increasing disorder were studied using STS. Figure 2 shows the temperature evolution of DOS for four samples with $T_c = 11.9\, K$, 6K, 2K and <300mk. All the plots in this figure are corrected for Altshuler-Aronov background. Second half of each panel shows the R-T data for the same sample. The vertical line on the colormap is the corresponding $T_c$ for given sample. Panel (a) shows that at low temperature spectra consist of dip close to zero bias and two symmetric peaks consistent with BCS density of states. The gap in the spectra vanishes exactly at $T_c$ in accordance with
BCS theory. For the sample with $T_c = 6K$ the gap remains finite up to slightly higher temperature. For strongly disordered sample ($T_c = 2K$) the gap in the electronic spectra at the Fermi level persists all the way up to $6K$ (3$T_c$) showing that it forms the pseudogap state and the corresponding $T^* = 6K$. Similarly for the sample with $T_c < 300mK$, $T^* > T_c$. Thus we conclude that in presence of strong disorder NbN forms a pseudogapped state, which is characterized by a dip in the local tunneling density of state above the superconducting transition temperature.

Observation of pseudogapped state can be explained using phase fluctuation scenario. Superconducting order is characterized by complex order parameter given by $\Delta e^{i\varphi}$, where $\Delta$ is amplitude of the parameter and $\varphi$ is the phase, which is same for the entire sample in the superconducting state. The loss of superconductivity can be because of either vanishing of this amplitude as described by mean field theories like BCS, or because of phase fluctuations [7]. Therefore the relevant energy scales for superconducting transition are $\Delta$ and the superfluid stiffness $J = (\hbar^2 a ns)/(4m^*)$, which is the energy cost for twisting the phase between different parts of the superconductor. Here $a$ is the length scale over which phase fluctuates, $m^*$ is the effective mass of the electron and $n_s$ is the superfluid density measured using penetration depth measurement ($n_s \propto \lambda^{-2}$) [4, 8]. Calculations show that [9] for clean samples ($k_B l > 4$) $J >> \Delta$, showing that phase fluctuations are not important. The superconducting transition happens in this case due to amplitude going to zero. For strongly disordered samples ($k_B l < 4$) we observe that $J \leq k_B T_c$ which makes the system more susceptible to phase fluctuation, resulting in loss of global superconductivity due to phase fluctuations at $T_c$.

Recent theories [10] show that in presence of strong disorder superconductor segregates into phase disconnected islands where superconductivity exists locally, but the global superconducting state is
destroyed because of phase fluctuations between domains. Figure 3 shows the A-A corrected line scans for the same samples thereby describing the spatial distribution of the gap. For the most ordered film with $T_c=11.9\text{K}$, the gap is homogeneous while with increasing disorder the gap becomes inhomogeneous where it forms superconducting domains separated by regions of suppressed superconductivity.

4. Summary

We summarize our results in the form of a phase diagram (see figure 4) which can be distinguished in different regions based on the dominant energy scales. In Region with $(k_f l)>4$ NbN behaves as BCS superconductor and $T_c$ monotonically decreases with increasing disorder. The decrease in the $T_c$ results from two effects. Firstly with increasing disorder, electron motion becomes diffusive thereby increasing the $e-e$ Coulomb repulsion which partially cancels the phonon mediated attractive pairing interaction [11]. Secondly with increasing disorder the electronic states gets localized and one electron bandwidth increases, thereby decreasing density of states ($N(0)$) at Fermi level hence $T_c$ [12].

![Figure 4](image_url)

**Figure 4.** Figure 4: Phase diagram for the 3D NbN as a function of $k_f l$ showing different regimes of disorder.

In the region $1< k_f l<4$ NbN forms a pseudogapped state at temperatures $T_c< T < T^*$. In the pseudogapped state, a gap in the electronic spectrum with broadened coherence peaks is observed in our STS measurements. We conjecture that in this temperature range, the global superconducting state is lost due to phase fluctuations between domains that are seen to spontaneously form in our STS line scans.

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