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# Bose Metal in Atomically Thin $NbSe_2$?

**Unveiling Resilient Superconducting Fluctuations in Atomically Thin $NbSe_2$ through Higgs Mode Spectroscopy**
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*Recommended with a Commentary by Daniel Arovas, University of California, San Diego*

In the beginning was the scaling theory of localization. Boomer physicists[1] were raised to believe that there are no two-dimensional metals because any amount of disorder leads to localization and insulating behavior[2]. They understood that fine-tuned metallic behavior could manifest at the quantum critical point of a superconductor-insulator transition, tuned by magnetic field or disorder, and early experiments on superconducting films seemed to confirm this picture: superconducting on one side of the transition, insulating on the other, and a critical metallic state right at the transition. But starting around 1990, experiments suggesting that there was not a critical metallic state, but rather an entire metallic phase, began to accumulate. This anomalous metallic state (AMS) was unusual because, *inter alia*, its conductivity $\sigma_{xx}(T \to 0)$ leveled off at values much below those given by Drude theory in the normal state. Another anomaly is the observed power-law scaling $R_{xx} \sim (H - H_0)^{\alpha(T)}$ of resistance *versus* field. Fig. 1 depicts a rough sketch of the general features of the phase diagrams presented in the recent literature on this subject (the familiar bulk phase diagram is included for contrast). The regime in which the unusual metallic phase of interest is observed is labeled AMS.

If the AMS is a distinct phase of matter, what exactly is it? Spoiler alert: we still don't know, although there have been many substantial ideas discussed in the literature. One possibility, prompted by the proximity to *bona fide* superconductivity is some melange of Cooper pairs and mobile unpaired electrons [1, 2]. Another suggestion is a 'Bose metal', *i.e.* a metallic phase of constituent Cooper pairs in which both charge and phase degrees of freedom are disordered [3]. An elaboration of this idea considers the possibility of a metallic phase glass [4]. A yet more exotic proposal is that of the non-Fermi liquid vortex metal [5].

Du *et al.* [6] have studied highly crystalline samples of atomically thin $NbSe_2$ both via electrical transport ($R_{xx}$ and $R_{yx}$) as well as optical Higgs mode spectroscopy as a function

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[1] Such as your humble correspondent.

[2] The case of strong spin-orbit coupling (class AII) is a notable exception in which there is a metal-insulator transition.

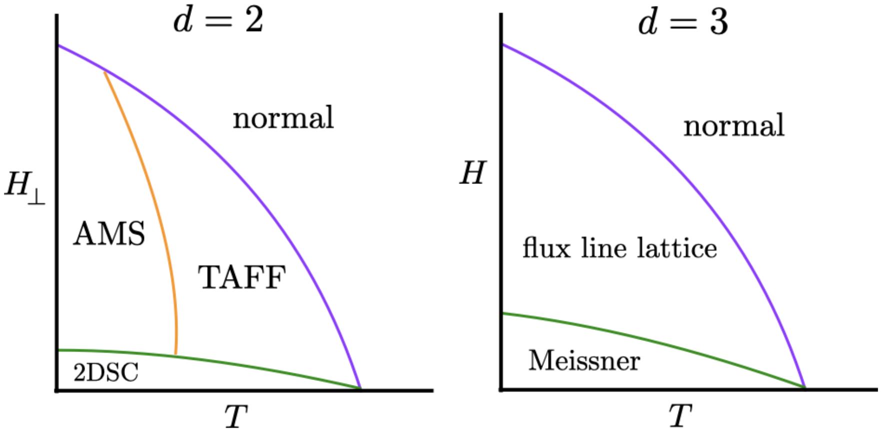

Figure 1: Very rough sketches of phase diagrams for crystalline 2d (left) and 3d (right) type-II superconductors in an external magnetic field. Abbreviations: AMS = anomalous metallic state, TAFF = thermally assisted flux flow, 2DSC = two-dimensional superconductor.

of perpendicular field and sample thickness. Recent work on 2D crystalline $TiSe_2$ observed an AMS in longitudinal transport [8]. In 2D crystalline $NbSe_2$, the superconducting state was found to be fragile and the AMS somewhat elusive [7]. Du *et al.* found that both transport and optical spectroscopy confirmed the existence of an extended range of magnetic field over which the AMS is present, characterized by finite $R_{xx}$, vanishing $R_{yx}$, and a clear superconducting Higgs mode resonance which is thickness-dependent. Since the Higgs mode is associated with amplitude fluctuations of the superconducting order parameter, its observation provides evidence that there is a bosonic aspect to the AMS.

Fig. 2 shows a typical device image and longitudinal resistance curves $R_{xx}(T)$ for samples of four different thicknesses. From the thickness dependence of the slope $dR_{yx}/dH$ at $T = 100\,\text{K}$, a hole density of $n = 1.4 \times 10^{22}\,\text{cm}^{-3}$ was inferred, consistent with the bulk value, and independent of sample thickness.

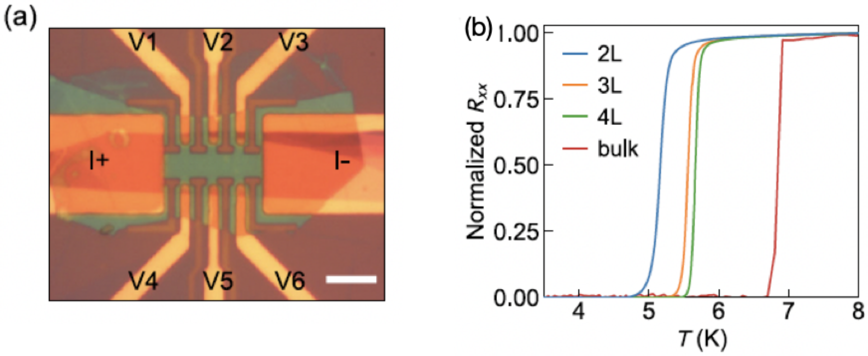

Figure 2: (a) Optical image of a trilayer $NbSe_2$ device. I± electrodes are the current source and $V1$ through $V6$ are voltage probes. (b) The resistive superconducting transition in 2-layer, 3-layer, 4-layer, and bulk samples.

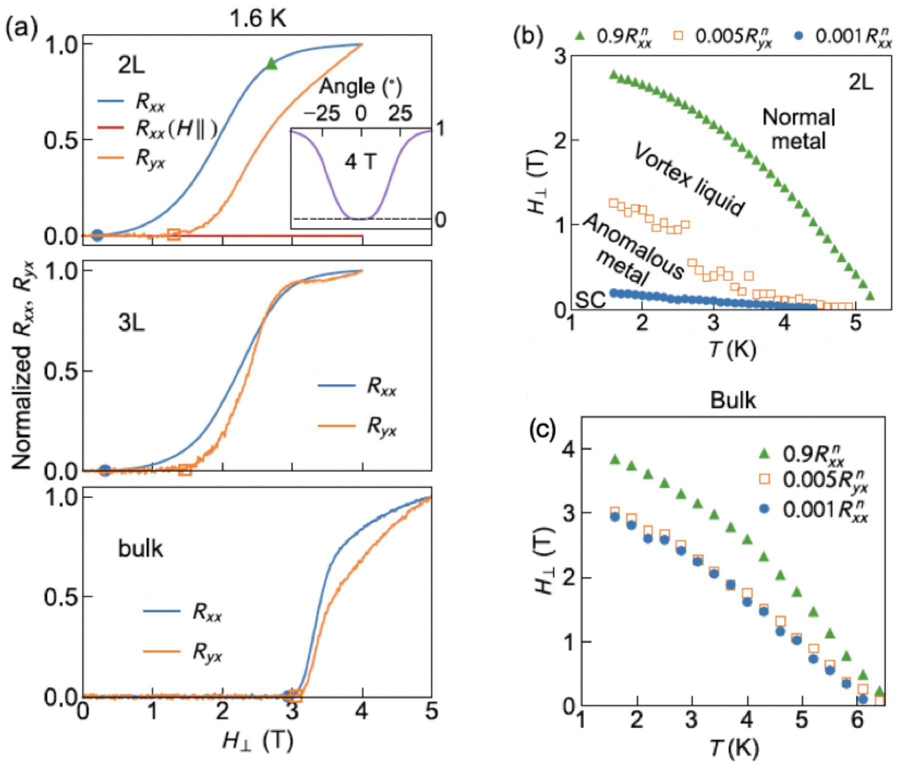

Figure 3: (a) Dependences of $R_{xx}$ and $R_{yx}$ on transverse magnetic field $H_\perp$ for varying thicknesses (bilayer, trilayer, bulk) at $T = 1.6\,\mathrm{K}$. The inset in the top panel shows that the normalized $R_{xx}$ vanishes when the field is rotated to lie in the plane of the sample.The circles, squares, and triangle mark $0.001\,R^{\mathrm{n}}_{xx}$, $0.005\,R^{\mathrm{n}}_{yx}$, and $0.9\,R^{\mathrm{n}}_{xx}$, respectively, where $R^{n}_{xx/yx}$ is the corresponding normal state value at $T = 1.6\,\mathrm{K}$ and $H_\perp = 4\,\mathrm{T}$ or $5\,\mathrm{T}$. (b) $(T, H_\perp)$ phase diagram for bilayer $\mathrm{NbSe_2}$. (c) $(T, H_\perp)$ phase diagram for bulk $\mathrm{NbSe_2}$.

The three panels of Fig. 3a show $R_{xx}$ and $R_{yx}$ as a function of $H_\perp$ for bilayer, trilayer, and bulk samples at a temperature $T = 1.6\,\mathrm{K}$. Symbols mark the values $0.001\,R^{\mathrm{n}}_{xx}$, $0.005\,R^{\mathrm{n}}_{yx}$, and $0.9\,R^{\mathrm{n}}_{xx}$, where $R^{n}_{xx/yx}$ are the normal state values (see figure caption). These define upper bounds for the critical fields $H^\perp_{M1}$ and $H^\perp_{M2}$ where $R_{xx}$ and $R_{yx}$, respectively, become finite, through the relations $R_{xx}(H^\perp_{M1}) = 0.001\,R^{\mathrm{n}}_{xx}$ and $R_{yx}(H^\perp_{M2}) = 0.005\,R^{\mathrm{n}}_{yx}$ . The perpendicular upper critical field is defined via $R_{xx}(H^\perp_{c2}) = 0.9\,R^{n}_{xx}$. This leads to the phase diagrams in panels (b) and (c). The anomalous metal phase is defined by the region $H^\perp_{M1} < H_\perp < H^\perp_{M2}$. When $H^\perp_{M2} < H_\perp < H^\perp_{c2}$ both resistances $R_{xx}$ and $R_{yx}$ are finite, and they obey a scaling relation $|R_{yx}| \propto R^{\alpha}_{xx}$ with $\alpha \sim 2$, roughly independent of sample thickness. For $H^\perp_{M1} < H_\perp < H^\perp_{M2}$ we have $R_{xx} > 0$ but $R_{yx} = 0$. The vanishing of $R_{yx}$ is interpreted as reflecting a particle-hole symmetry in the anomalous metal phase.

To further probe and characterize the AMS, Higgs mode spectroscopy was performed. Recall that the Higgs is identified with amplitude fluctuations $\delta|\Delta|$ of the superconducting order parameter, while the phase fluctuations are associated with $\delta\,\mathsf{arg}(\Delta)$. Observing the Higgs in superconductors is a somewhat subtle issue, since it is a scalar which does not couple

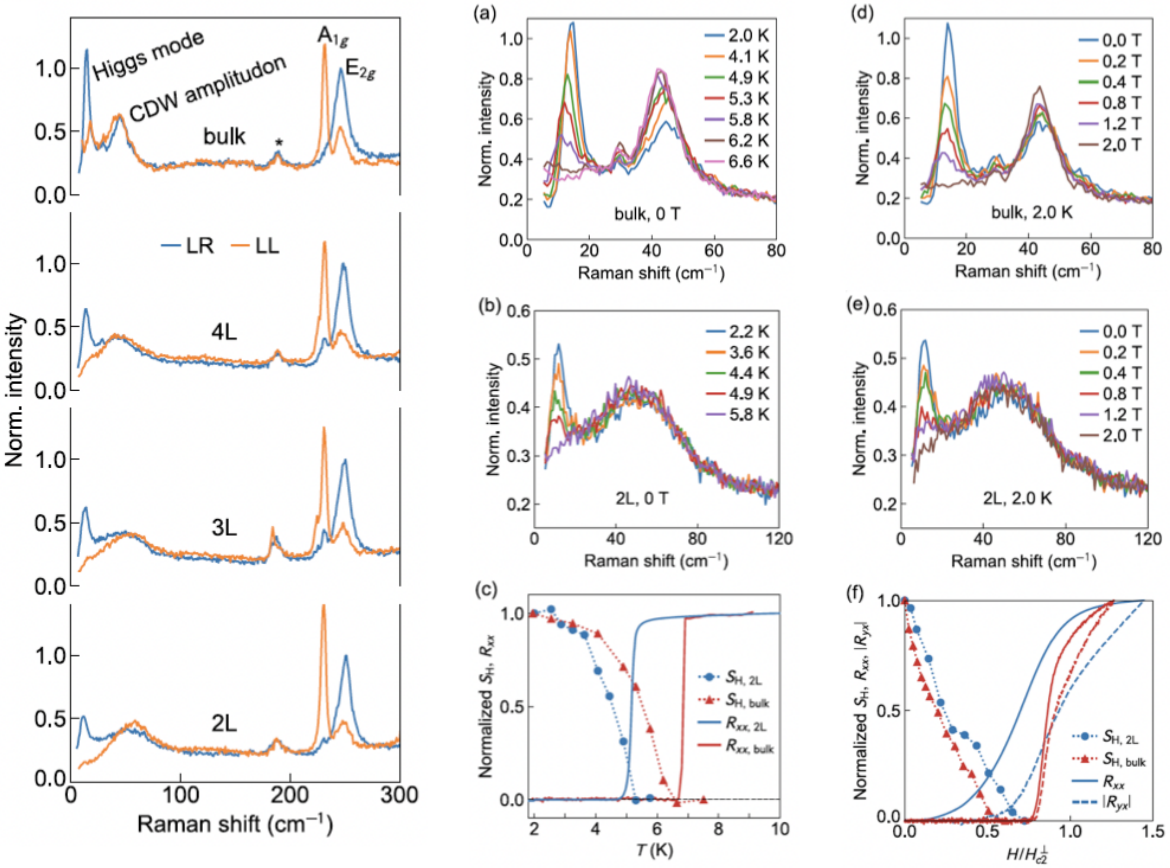

Figure 4: Left: Raman spectra for $NbSe_2$ with varying thicknesses, measured at $T = 2.0\,\mathrm{K}$ in the LR and LL polarization configurations. Center: Temperature dependence of the Raman spectra for bulk (a) and bilayer (b) $NbSe_2$ at $H_\perp = 0\,\mathrm{T}$. (c) Temperature dependence of the normalized Higgs mode spectral weight (symbols) and $R_{xx}$ (solid lines) for bilayer (blue) and bulk (red) samples. Right: Field dependence of the Raman spectra for bulk (d) and bilayer (e) $NbSe_2$ at $T = 2.0\,\mathrm{K}$. (f) Reduced field dependence of the normalized Higgs mode spectral weight (symbols) and $R_{xx}$ (solid lines) for bilayer (blue) and bulk (red) samples.

directly to current[3] and only weakly to charge, due to an effective particle-hole symmetry in the BCS state. However, in superconductors where there is also a charge density wave instability, the Higgs is observable via Raman spectroscopy because it couples to a soft Raman-active phonon of the CDW at temperatures $T < T_c < T_{\mathrm{CDW}}$ [9]. This is consistent with the fact that no clear Higgs peak is observed in isostructural superconducting $NbS_2$, where there is no CDW order.

The left panel of Fig. 4 shows Raman spectra in flakes of four different thicknesses at $T = 2.0\,\mathrm{K}$, measured in the LL and LR polarization configurations, corresponding to the $A_{1g}$ and $E_{2g}$ vibration channels, respectively. The high frequency modes at $\sim 200\,\mathrm{cm}^{-1}$ are Raman-active phonons. The Higgs and CDW amplitude modes have energies $\hbar\omega_{\mathrm{H}} \approx 1.5\,\mathrm{meV}$

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[3] At least not in the absence of disorder, which would break translational invariance and allow such a coupling.

and $\hbar\omega_{\mathrm{A}} \approx 5.5\,\mathrm{meV}$, respectively, with some thickness dependence (moreso for $\omega_{\mathrm{A}}$ than for $\omega_{\mathrm{H}}$). For bulk NbSe$_2$, the Higgs mode are associated with the superconducting phase, rendered visible in the Raman spectra because in the CDW-SC state the CDW modifies the Higgs mode, facilitating its detection [9]. The Higgs mode persists down to the bilayer structure. Panels (a) and (b) show the temperature dependence of the zero field Raman spectra for bulk and bilayer NbSe$_2$. As $T$ is increased starting from $2\,\mathrm{K}$, the Higgs spectral weight $S_{\mathrm{H}}(T)$ vanishes concomitantly with the onset of finite $R_{xx}$ in both bilayer and bulk samples (panel (c)). Panels (d) and (e) show the field dependence of the Raman spectra at $T = 2.0\,\mathrm{K}$. As panel (f) shows, in the bulk sample the Higgs spectral weight decays to zero as $H_\perp$ is increased from $H_\perp = 0$ before $R_{xx}$ and $R_{yx}$ become finite. By contrast, for the bilayer, the Higgs spectral weight remains finite even while $R_{xx}$ is increasing, and only dies out when $R_{yx}$ begins to increase. Du *et al.* thereby conclude that the nature of the vortex state in bulk and atomically thin NbSe$_2$ must differ substantially.

Do the observations here of a persistent Higgs mode in the AMS regime $H^\perp_{M1} < H_\perp < H^\perp_{M2}$ warrant belief in the existence of a Bose metal? The authors judiciously refrain from making any such claim, but the Higgs spectroscopy in concert with the longitudinal transport and Hall measurements suggest that Cooper pairs are somehow playing an essential role. Still, despite the observed “resilient superconducting fluctuations,” the AMS is not a superconductor, and just what it is we still do not know.

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