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Superconducting Penetration Depth Through a Van Hove Singularity: Sr_2RuO_4 Under Uniaxial Stress

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A plethora of experiments in Sr_2RuO_4 have reached conflicting conclusions about the symmetry of the superconducting gap. To probe the gap's structure in k -space, we use strain to continuously tune the band structure through a Van Hove singularity (VHS) while imaging the superconductivity with scanning SQUID microscopy. We find that the superfluid density peaks at the VHS and that the temperature dependence of the penetration depth is T^2 -quadratic over the entire measured range of strain ϵ . These results are consistent with a gap structure that has vertical line nodes, experimentally confirming that non-local effects in the Meissner screening can lead to T^2 behavior and clarifying the nature of the low-energy excitations in Sr_2RuO_4 .

Strontium ruthenate (Sr_2RuO_4) is an unconventional superconductor [1–8]. The metallic normal state is well understood [9], but a complete understanding of the superconducting order parameter remains elusive. The majority of evidence suggests line nodes in the superconducting gap $\Delta(k)$ [10–15], but the low-temperature penetration depth $\lambda(T)$ is ambiguous. With line nodes, the change in penetration depth with temperature, $\Delta\lambda(T)$, is usually expected to be T -linear for clean samples and T^2 with impurity scattering [16]. $\Delta\lambda(T)$ in Sr_2RuO_4 follows T^2 [17–19], but strong impurity scattering is not expected; Sr_2RuO_4 is one of the cleanest known correlated electron materials [20]. Ref. [17] pointed out that non-local electrodynamics may give $\Delta\lambda(T) \propto T^2$ [21] for Sr_2RuO_4 over a substantial temperature range even in the clean limit because it is only marginally a type-II superconductor with $\kappa = \lambda/\xi \approx 2.9$ at low temperature, where ξ is the coherence length. If this hypothesis is confirmed, it would strengthen the case considerably for line nodes in the order parameter of Sr_2RuO_4 .

Uniaxial stress along [100] tunes the γ Fermi surface sheet through a Lifshitz transition (see Fig. 1 and Ref. [23]) and an associated Van Hove singularity (VHS). The superconducting critical temperature, T_c , increases from $T_{c0} = 1.5$ K to a peak of 3.5 K [22, 24] at the VHS, accompanied by a 20-fold increase in the out-of-plane upper critical field H_{c2} [22, 25]. This tunability provides a route to test the non-local hypothesis through stress-induced variation in κ .

In fact, alternative hypotheses can be constructed for the strain dependence of the $T \rightarrow 0$ superfluid density λ^{-2} of Sr_2RuO_4 . Ref. [26] suggests that the quasiparticle mass renormalization on the γ sheet is a consequence of the proximity of

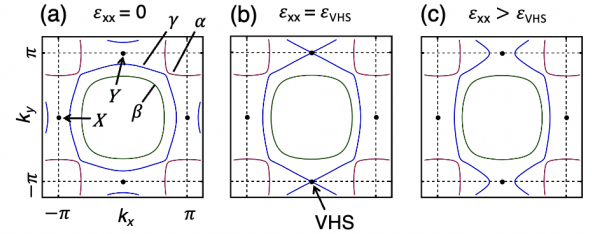


FIG. 1. Quasi-two-dimensional Fermi surface calculations of Sr_2RuO_4 under representative ϵ_{xx} strains [22]. (a) Zero strain, showing the two electron-like bands γ and β and the hole-like band α . Points labeled X and Y indicate high-symmetry points. (b) Strain-tuned to the Lifshitz transition. The VHS occurs on the γ band at the Y points. (c) Strained beyond the Lifshitz transition.

the Fermi level to the VHS. Tuning to the VHS could cause a further increase in the effective mass m^* , thereby decreasing $\lambda(0)^{-2}$ through the relation $\lambda^{-2} = 4\pi n_s e^2 / m^* c^2$, where n_s is the number density of superconducting electrons. Alternatively, an increase in the superconducting gap Δ_0 could reduce the effects of impurities and/or of non-locality in the Meissner screening, leading to an increase in $\lambda(0)^{-2}$. If the coherence length were strongly reduced, then $\Delta\lambda(T)$ would become T -linear. In this Letter, we report scanning SQUID measurements of $\Delta\lambda(\epsilon, T) \equiv \lambda(\epsilon, T) - \lambda(0, 0)$ in Sr_2RuO_4 across the VHS. To aid interpretation of these data, we also report measurements by scanning tunneling microscopy (STM) of Δ_0 on strained Sr_2RuO_4 .

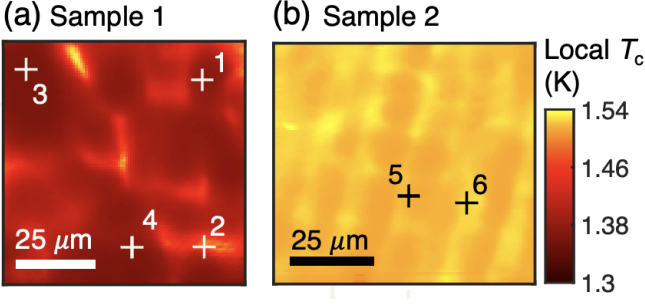


FIG. 2. Local T_c maps in a region of (a) sample 1 and (b) sample 2. Markers indicate the positions at which the temperature and strain dependence of the penetration depth was measured.

We used SQUID susceptometers [27] with a flux-sensitive pickup loop with an inner radius r_{PL} of $1\ \mu\text{m}$ and a concentric field coil with an inner radius r_{FC} of $2.5\ \mu\text{m}$. A low-frequency (893 Hz) alternating current applied to the field coil generates a local field. Near a superconductor, the Meissner response screens the field, reducing the mutual inductance M of the pickup-loop/field-coil pair, measured in units of Φ_0/A , where $\Phi_0 = h/2e$ is the flux quantum. Changes in M vs. T allow determination of the local T_c , defined as the onset of measurable diamagnetism ($\Delta M < 0$), as well as the quantity $\Delta\lambda(\epsilon, T)$ [28]. We bring the SQUID sensor into light mechanical contact with the sample surface to prevent drift in the SQUID-sample separation.

We applied *in situ* tunable strain using a piezoelectric-driven device similar to previous reports [29, 30]. We convert a capacitive measure of displacement to strain by setting the strain to be zero at the minimum T_c and to $\epsilon_c = -0.44\%$ at the peak T_c [31]. We measured two samples from separate batches cut into pieces $\approx 2\ \text{mm}$ in length.

We first obtained maps of local T_c near zero strain by imaging ΔM near T_c [32]. Sample 1 [Fig. 2(a)] shows $T_c = 1.36$ – $1.4\ \text{K}$ with a few regions having T_c up to $1.5\ \text{K}$. Sample 2 [Fig. 2(b)] is more homogeneous and has $T_c = 1.51$ – $1.54\ \text{K}$. We suspect that variations of T_c , both locally and between samples, result mainly from ruthenium deficiency during sample growth [33] [34]. It is unclear why the T_c inhomogeneity appears random in sample 1 but stripy in sample 2. We note that a high density of dislocations can increase T_c up to $3\ \text{K}$ [35]. We find no local enhancement of T_c significantly higher than $1.5\ \text{K}$, indicating that any dislocations present are too dilute to strongly affect the unstressed T_c .

Figures 3(a) and (b) show $\Delta\lambda(\epsilon, T)$ plotted against $(T/T_c)^2$. For fixed T/T_c , the curves show a clear reduction in penetration depth as ϵ_c is approached [Fig. 3(a)] and a subsequent increase in penetration depth for strains beyond ϵ_c [Fig. 3(b)]. For fixed ϵ , T^2 fits describe the data well for $T < 0.5T_c$ over the entire strain range.

In Fig. 3(c), the T_c at two selected points is plotted against applied strain. The local T_c for each strain is the temperature at the maximum in dM/dT [32]. The T_c vs. strain curves for sample 1 and sample 2 approximately track each other; however, the difference between T_c of the two samples shrinks as T_c increases, consistent with the general expectation that

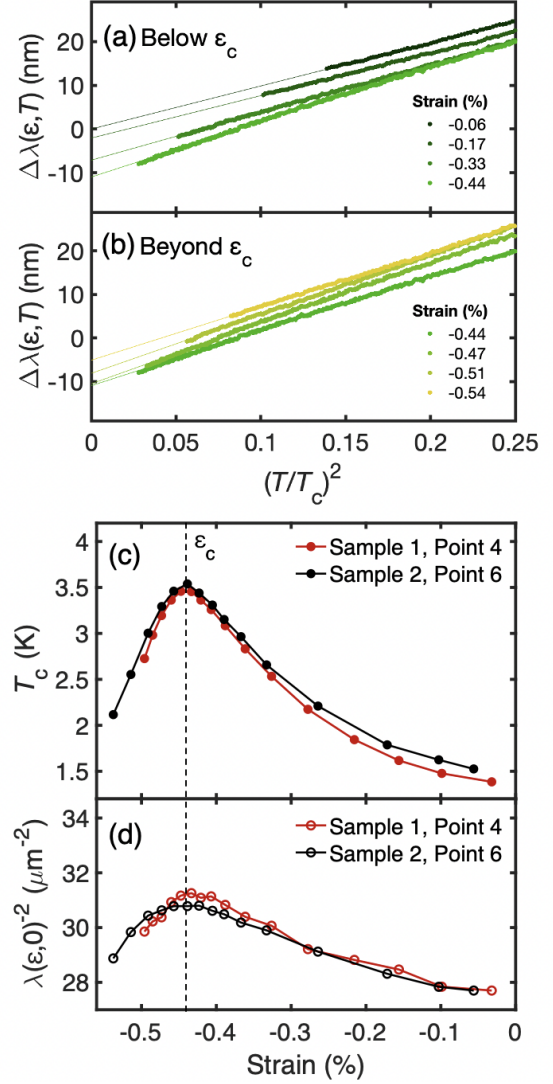


FIG. 3. (a) and (b) $\Delta\lambda(\epsilon, T)$ for ϵ (a) less than ϵ_c and (b) greater than ϵ_c for sample 2. Solid lines are T^2 fits. (c) Local T_c versus ϵ measured on sample 1 (red) and 2 (black). (d) $\lambda(\epsilon, 0)^{-2}$ versus ϵ for sample 1 (red) and sample 2 (black). At the minimum strain, we set $\lambda(\epsilon, 0)^{-2} = 27.7\ \mu\text{m}^{-2}$ [17].

higher T_c corresponds to reduced sensitivity to defect scattering. Although a small amount of dislocations are expected even in exceptionally clean samples, we do not expect the applied strain to strongly interact with these dislocations for two reasons: (1) The local strains produced by dislocations will be disordered and will, on average, not align with the externally applied strain. (2) The elastic limit of Sr_2RuO_4 at low temperature is $> 2\ \text{GPa}$ [36], while the stress corresponding to the peak in T_c is estimated to be well below $1\ \text{GPa}$ [31], and so the applied stress in our measurements will not mobilize dislocations. Figure 3(d) shows the strain dependence of the zero-temperature superfluid density $\lambda(\epsilon, 0)^{-2}$. Under increasing compression, $\lambda(\epsilon, 0)^{-2}$ increases monotonically up to ϵ_c , where it reaches a maximum, then decreases for strains beyond ϵ_c . The peak in $\lambda(\epsilon, 0)^{-2}$ corresponds to a 12–18% in-

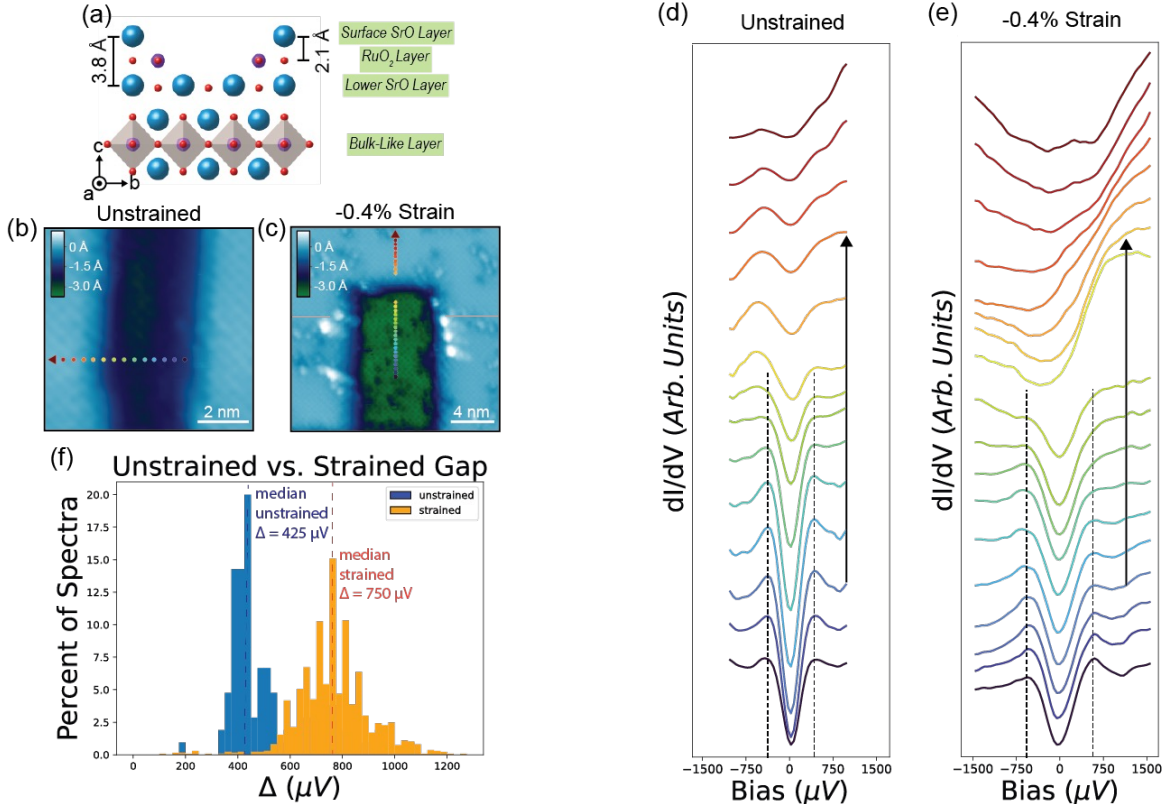


FIG. 4. Superconducting gap in the lower SrO layer. (a) The crystal structure showing subsurface layers (b) Topographic image of a defect (dark blue and green area) on an unstrained sample exposing the RuO_2 layer at a depth of ≈ 2.1 Å. (c) Topographic image of a defect (green area) on a strained sample exposing the lower SrO layer at a depth of ≈ 3.4 Å. See Ref. [32] for details for determining the depth. Colorbar indicates topographic depth relative to the surface SrO layer (light blue area) (d) Waterfall plot of dI/dV spectroscopy data measured at the points indicated in (b). (e) Waterfall plot of dI/dV spectroscopy data measured at the points indicated in (c). The dashed lines indicate values of Δ_0 for spectra inside the trench as determined by a peak-finding algorithm; $400 \mu\text{V}$ and $575 \mu\text{V}$ for the strained and unstrained sample respectively in panels (d) and (e). a.u.: arbitrary units. (f) Histogram of Δ_0 values obtained by a peak-finding algorithm on many spectra inside the trenches for both unstrained (blue) and strained (orange) Sr_2RuO_4 . Dashed lines indicate the median values of Δ_0 ; bins are $25 \mu\text{V}$ wide.

crease from the zero-stress value using $\lambda(0,0) = 190 \text{ nm}$ [17] and a 17-29% increase using $\lambda(0,0) = 124 \text{ nm}$ [37].

For the STM measurements, due to the restricted sample space, strain was applied using a differential thermal expansion cell as in Ref. [23]. We estimate that the applied strain in the sample was $-0.4 \pm 0.1\%$; additional details are given in Ref. [32]. Sr_2RuO_4 has a low elastic limit at room temperature, but by using differential thermal contraction to compress the sample, we expect to remain in the elastic limit because the sample is compressed gradually as it is cooled. Strong evidence that Sr_2RuO_4 does remain in its elastic limit with such a cell is provided by the fact that clean angle-resolved photoemission data could be obtained on samples strained in this way [23]. These data showed that the sample had reached the Van Hove singularity, as expected for a strain of $\approx -0.4\%$. Data from the STM measurements are shown in Fig. 4. As in previous works [38–42], we do not observe a superconducting gap on the top strontium oxide (SrO) surface, possibly because of the surface reconstruction[43–45]. However, we do observe a superconducting gap inside several nanometer-scale trenches, most probably created when the sample was cleaved. In these trenches both the surface SrO layer and the

RuO_2 layer directly below it are removed, thereby exposing the lower SrO layer which provides a window into the bulk properties [see Fig. 4(a)]. Figures 4(b) and (c) show typical topographies while Fig. 4(d) and Fig. 4(e) show spectroscopic linecuts across the trenches in an unstrained and strained sample, respectively.

First, we note that the differential conductance inside the gap is noticeably different between the two samples[Figs. 4(d) and (e)]. The larger in-gap density of states in the strained sample may be due to larger defect scattering because the topographic map [Figs. 4(b) and (c)] of the strained sample shows more defects than that of the unstrained sample.

Next, to estimate the average gap, we analyze more than 200 spectra from dI/dV maps obtained inside the trenches of each sample. We estimate the gap, Δ_0 , as the local maximum identified by a peak finding algorithm[additional spectra are shown in Ref. [32]]. Figure 4(f) shows the distribution of the estimated Δ_0 for the unstrained (blue) and strained (orange) samples. Although the spread is larger on the strained sample, the distributions do not overlap much and the median value of $\Delta_0 = 750 \mu\text{V}$ on the strained sample is significantly larger than the value $\Delta_0 = 425 \mu\text{V}$ on the unstrained sample. This

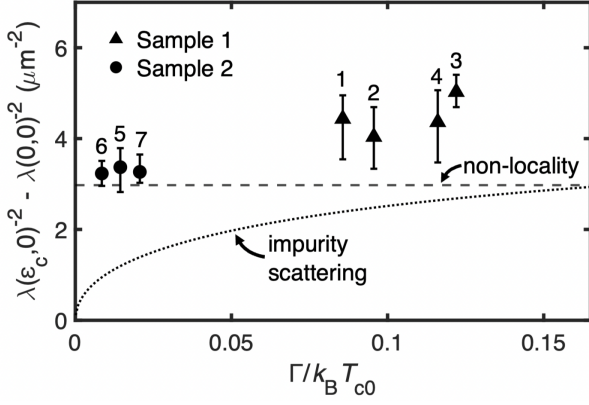


FIG. 5. Increase in $\lambda(\epsilon, 0)^{-2}$ at ϵ_c plotted against the scattering rate Γ normalized by $k_B T_{c0}$. The labels at each marker correspond to the location on the samples indicated in Fig. 2(a) and (b). Point 7 was measured outside the scan range of Fig. 2(b). The prediction from reduced sensitivity to impurities and from reduced non-locality are shown under an assumption that Δ_0 increases in proportion to T_c .

value of Δ_0 for the unstrained sample is similar in magnitude with previous measurements on unstrained Sr_2RuO_4 [46, 47].

In materials with a known gap function and a small in-gap density of states, it may be possible to determine Δ_0 more quantitatively by fitting the dI/dV spectra to a model. That procedure is not possible here because we have a large in-gap density of states and an unknown pairing symmetry with multiple bands. Any model would need many fit parameters, and many models could be made to fit the data. We use the local peak as a proxy for the gap because a coherence peak indicates the presence of pairing, and because the local maximum is a feature that should track with the true gap and can be determined without a model or fit parameters.

We note that the gap measured by STM is likely to be dominated by the α and β sheets. As discussed in Ref. [46], the α and β sheets are dominated by xz and yz orbital weight and the tunneling conductance is likely to be much higher for the xz and yz orbitals than the xy orbital due to their greater extent along the z axis.

Importantly for discussion of the superfluid density, the gap on the α and β sheets is well away from the Van Hove point in k -space (points labeled Y in Fig. 1); due to the low Fermi velocity, carriers near the Van Hove point will not contribute strongly to the superfluid density. We therefore restrict our analysis to regions of the Fermi surface away from the Van Hove point. An enhanced m^* should cause a decrease in superfluid density. In contrast, our results show an increase in $\lambda(\epsilon, 0)^{-2}$, suggesting that any enhancement in m^* near the VHS is too small to have a dominant effect. Angle-resolved photoemission spectroscopy (ARPES) data show no substantial change in band renormalization as the γ sheet is tuned to the VHS by substitution [48] or by uniaxial stress [23]. Therefore, we suppose that m^* on sections of the Fermi surface away from the Van Hove point remains approximately constant as stress is applied.

We suppose further that away from the Van Hove point, the

gap increases in proportion to T_c (the gap is likely substantial at the Van Hove point [49], but the superfluid density is not sensitive to this due to the low Fermi velocity). For a nodal superconductor, an enhanced gap can lead to an increased superfluid density in two ways: (1) reduced sensitivity to impurity scattering and (2) reduced non-local effects in the Meissner screening. For impurity scattering in a d -wave superconductor, the $T \rightarrow 0$ penetration depth $\lambda(0)$ increases from its value in the clean, local limit λ_0 by an amount that depends on the magnitude of the superconducting gap: $\lambda(0) - \lambda_0 \sim \lambda_0 \sqrt{\Gamma/\Delta_0}$, where Γ is the nonmagnetic impurity scattering rate [16]. Studies of T_c on samples with varying levels of impurities [50–53] show a suppression of T_c with increasing impurity concentration that follows an Abrikosov-Gorkov (AG) relation, $\ln(T_{c0}/T_c) = \psi(1/2 + \Gamma/2\pi k_B T_c) - \psi(1/2)$ [54, 55], where ψ is the digamma function and T_{c0} is the clean-limit T_c . Therefore, taking T_c as a measure of Γ , we would expect a greater enhancement of the superfluid density at the VHS for samples that have lower unstressed T_c .

In Fig. 5, we show the increase in $\lambda(\epsilon, 0)^{-2}$ at ϵ_c for each point measured on the samples (see Fig. 2) plotted against $\Gamma/k_B T_{c0}$, where Γ is determined from the AG relation applied to $T_c(\epsilon = 0)$. Measurements on sample 1, which has lower $T_c(\epsilon = 0)$, indeed show a larger increase in $\lambda(\epsilon, 0)^{-2}$ at the VHS. However, the trend of the data does not match the expectation from impurity effects alone. The dotted line in Fig. 5 shows the expectation. It goes to zero in the limit $\Gamma \rightarrow 0$, whereas the strain-induced increase in λ^{-2} for sample 2 remains large, even though Γ is small in this sample.

We now discuss non-local effects. At sufficiently low temperature, non-local effects in the Meissner screening are expected to become important in all nodal superconductors because the coherence length, defined as $\xi(k) = \hbar v_F(k)/\pi \Delta(k)$, diverges along the nodal directions such that $\xi(k) > \lambda_0$ is satisfied near the nodes [21]. Similar to the effect of impurities, the low-temperature behaviour of $\lambda(T)$ becomes quadratic and $\lambda(0)$ increases from λ_0 . In a d -wave superconductor [21], the correction to $\lambda(0)$ can be estimated as $\lambda(0) - \lambda_0 = \lambda_0 \pi \sqrt{2}/16\kappa$. Taking $\lambda(0) = 190$ nm and $\kappa = 2.9$ [17], we estimate $\lambda_0 = 173$ nm; the non-local correction to $\lambda(0)$ is approximately 10% of λ_0 in unstressed Sr_2RuO_4 . T_c increases by a factor of 2.3 between $\epsilon = 0$ and the VHS. If we take κ to increase by this same factor, we find that $\lambda(0)$ decreases by ≈ 10 nm; $\lambda(0)^{-2}$ increases by $\approx 3.0 \mu\text{m}^{-2}$. This increase is consistent with the enhancement in $\lambda(\epsilon, 0)^{-2}$ observed on sample 2 (see Fig. 5). We note that the twenty-fold increase in H_{c2} [22, 25] indicates a greater decrease in ξ_0 by a factor of $\sqrt{20}$. However, the electronic structure of Sr_2RuO_4 tuned to the VHS is highly anisotropic: this increase in H_{c2} could be driven by carriers in the immediate vicinity of the Van Hove point. Because the Fermi velocity approaches zero at these points, they are expected to contribute minimally to the superfluid density.

In summary, the superfluid density in Sr_2RuO_4 peaks, and the penetration depth shows a $\Delta\lambda(T) \sim T^2$ dependence as the system is strain-tuned through the VHS. In addition, the superconducting gap increases with strain going from $\Delta_0 \approx 425 \mu\text{eV}$ in an unstrained sample to $\Delta_0 \approx 750 \mu\text{eV}$ in a sam-

ple strained to near the VHS. That the peak in $\lambda(0)^{-2}$ coincides with the peak in T_c contrasts with the behaviour observed in $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ where $\lambda(0)^{-2}$ reaches a distinct minimum upon tuning to the peak in T_c by chemical doping [56]. Our analysis indicates that the peak in $\lambda(\varepsilon, 0)^{-2}$ is primarily driven by a decrease in non-local effects in the Meissner screening. We note that non-local electrodynamics in Sr_2RuO_4 was recently studied theoretically in Ref. [57] and Ref. [58] reports measurements of H_{c1} in unstressed Sr_2RuO_4 that also highlight the importance of non-local effects. Both the STM and the penetration depth measurements, which are sensitive primarily to regions of Fermi surface away from the Van Hove point, show that tuning to the VHS increases the gap throughout the Brillouin zone, an observation that might be a useful clue on the pairing mechanism in Sr_2RuO_4 .

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