Supplementary Information for "Enhanced and robust superconductivity in $La_{0.8}Sr_{0.2}NiO_2$ membranes compressed up to 210 GPa"

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1. Pressure determination for the investigated sample

Given that this study involves ultrahigh-pressure measurements, we used a secondary pressure scale based on the Raman shift at the center of the loaded diamond anvil tip to determine the sample pressure [1,2]. Figure S1a presents an optical image of the sample at 205 GPa, showing the relative positions of the $La_{0.8}Sr_{0.2}NiO_2$ membrane, the electrodes, and the gasket hole. Figure S1b shows the evolution of the diamond Raman spectrum measured at the anvil center as the pressure increased from 132 to 210 GPa. The cutoff shifts continuously toward higher wavenumbers with increasing pressure, confirming that pressure was successfully applied to the sample[1,2].

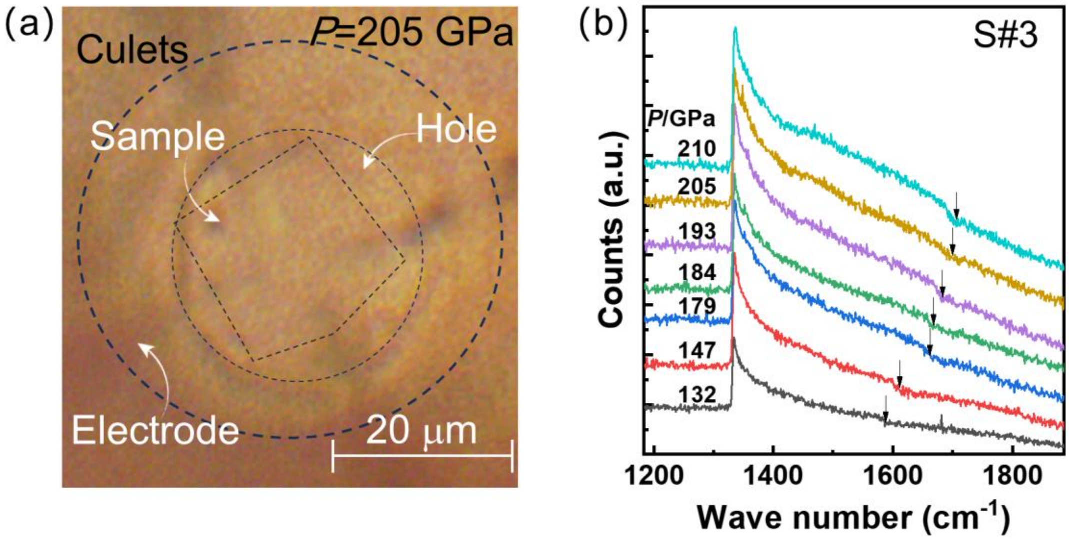

Figure S1 Sample configuration within the diamond anvil cell and diamond Raman spectra under various pressures. The black arrows indicate the continuous shift of the high-frequency cutoff of the diamond Raman peak toward higher wavenumbers with increasing pressure.

2. Determination of the superconducting transition temperatures

To facilitate comparison with the $Nd_{0.85}Sr_{0.15}NiO_2$ results[1], we employed two criteria to determine the superconducting transition temperature (T_c): the 0.5% resistance drop ($T_c^{99.5\%R}$) and the two-line intersection method ($T_c^{2\ line}$). Figure S2 presents the temperature-dependent resistance data for sample S#1 at 146 GPa, sample S#2 at 147 GPa, and sample S#3 at 147 GPa.

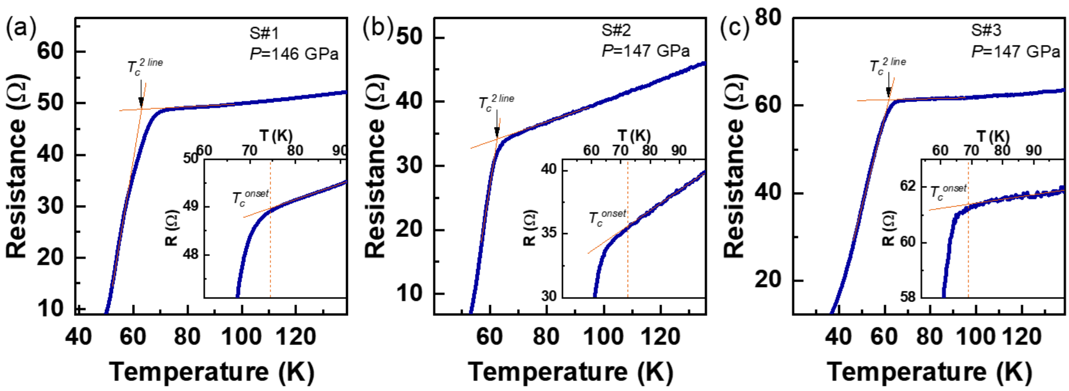

Figure S2 Determination of the superconducting transition temperature. Temperature-dependent resistance curves for (a) sample S#1 at 146 GPa, (b) sample S#2 at 147 GPa, and (c) sample S#3 at 147 GPa. In each main panel, $T_c^{2\ line}$ denotes the transition temperature determined by the two-line intersection method. The corresponding insets zoom in on the temperature region near the superconducting onset, illustrating the determination of T_c^{onset} using the 0.5% resistance drop criterion.

3. Determination of the midpoint transition temperature (T_c^m) and evaluation of superconductivity enhancement using T_c^m as a criterion

Unlike conventional superconductors, the superconducting transitions in our samples are all broad (Figs. 1-2), which makes the very notion of T_c ambiguous. In conventional superconductors that conform to the mean-field, Bardeen-Cooper-Schrieffer (BCS) theory, the transitions are much sharper. For example, in Nb, $T_c \approx 9$ K, while the transition width ΔT_c is on a 10 mK scale, so that $\Delta T_c/T_c < 0.001$. In contrast, in a freestanding $La_{0.8}Sr_{0.2}NiO_2$ membrane, from Fig. 1c we can estimate that the transition onsets at about 16 K and ends at about 12 K, so that $\Delta T_c \approx 4$ K and $\Delta T_c/T_c \approx 0.3$.

To make this quantitatively accurate is not straightforward. Naturally one would define the transition width as $\Delta T_c = T_c^{onset} - T_c(R{=}0)$. The problem with this is how to determine accurately T_c^{onset} and $T_c(R{=}0)$. For T_c^{onset}, the result depends on (i) how we define the "normal-state $R(T)$ dependence in the absence of superconductivity", *i.e.*, to what hypothetical functional form and within which T interval we fit the $R(T)$ data above T_c, and (ii) how we choose the "departure point" – 0.5%, 1%, or 10% (the smaller, the higher T_c^{onset}). Likewise, the value of $T_c(R{=}0)$ is also subject to uncertainty; it depends on the experimental noise floor which varies from one to another setup. Ironically, if the same sample were measured by three groups, with the voltage noise floors δV of 1 mV, 100 nV, and 10 nV, respectively, the group that performed the best measurement (with 10 nV precision) would report the worst result (the lowest T_c). This is nicely illustrated in Ref. 3 which measured $R(T)$ in a thin $YBa_2Cu_3O_7$ film, tracked the resistance decreasing over eight orders of magnitude, and showed that it remained finite down to the lowest T. In such a situation $T_c(R=0)$ should be more correctly called T_c^{offset}, with the explicit understanding that, like T_c^{onset}, it is also ambiguous and subjective. Indeed, that also translates to uncertainty in $\Delta T_c = T_c^{onset} - T_c^{offset}$.

A better choice is to take a derivative of the $R(T)$ dependence and determine T_c^m as the temperature at which the d$R(T)$/dT function reaches the maximum, and δT_c as the full width at half maximum of the peak in d$R(T)$/dT. Then, we can use T_c^m as the proxy for the representative "critical temperature". While not ideal, this definition is at least not subjective.

With this choice, we can objectively discuss an important question, so far brushed under the carpet: when an enhancement of superconductivity under pressure is reported, does T_c really increase, or the transition just gets broader, driving the apparent T_c^{onset} higher? To answer this, we plotted the $T_c^m(P)$ data (see Fig. 3), which clearly proves the former.

4. Reproducibility of robust superconductivity in highly compressed $La_{0.8}Sr_{0.2}NiO_2$ membranes

A successful resistance measurement requires overcoming two major experimental challenges: (1) transferring the investigated membrane, only a few nanometers thick, onto a diamond anvil with an extremely small culet diameter (50 - 100 μm, comparable to the diameter of a human hair), and (2) preventing damage to both the membrane and its electrodes caused by deformation of the sample hole under ultrahigh compression. Once these issues are resolved, reproducible measurements of the pressure-induced evolution of T_c can be achieved, as demonstrated by our three independent experimental runs (see Fig. 2).

References

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