The recent discovery of room-temperature superconductivity (RTSC) at pressures of several megabars has led to intensive efforts to probe the origin of superconducting (SC) electron pairs. Although the signatures of the SC phase transition have been well established, few reports of the SC properties of RTSCs have been published because of the diamond anvil cell (DAC) environments. Here, we report the first direct evidence of two SC gaps in Y metal via point-contact
spectroscopy (PCS) in DAC environments, where a sharp peak at the zero-bias voltage in the
differential conductance is overlaid with a broad peak owing to Andreev reflection. Analysis based
on the Blonder-Tinkham-Klapwijk (BTK) model reveals the existence of two SC gaps: the larger
gap $\Delta_L$ is 3.63 meV and the smaller gap $\Delta_S$ is 0.46 meV. The temperature dependence of the two
SC gaps is well explained by the BCS theory, indicating that two-band superconductivity is
realized in Y metal. The successful application of PCS to Y in DAC environments is expected to
guide future research on the SC gap in megabar high-$T_c$ superconductors.

The discovery of superconductivity in hydrogen-rich materials has attracted great interest because
of their high superconducting (SC) transition temperatures ($T_c$) [1-7]. An organic-derived carbonaceous
sulfur hydride (C-S-H) system was recently discovered to exhibit superconductivity at 288 K and 267
GPa (2.67 Mbar) [6]. The $T_c$ of the rare-earth (RE) metal hydrides REH$n$ (RE=La, Y) occurred at
temperatures above 200 K at pressures of several megabars, where the RE atom hosts a clathrate-like
hydrogen cage structure [1-3]. Yttrium (Y), which participates in the megabar superhydride superconductors YH$n$ with a $T_c$ of 243 K [2,3] exhibits superconductivity under pressure at temperatures
as high as 20 K, one of the highest $T_c$s among the elemental superconductors. At an external pressure
of 11 GPa, Y transforms into the superconducting state below 1.2 K [8]. AC magnetic susceptibility
measurements showed that the pressure-induced superconducting transition temperature monotonically
increased to 20 K at 100 GPa [9,10]. In contrast, first-principles calculations predicted that $T_c$ decreases
at pressures above 100 GPa [11]. Very recently, electrical resistivity measurements of Y indicated that
$T_c$ decreased above the megabar pressure range, verifying the prediction of a peak in $T_c$ near 100 GPa
[12]. Although the $P$-$T$ phase diagram of the SC state of Y is well established [12,13], SC properties
such as the upper critical field and SC gap, which are important for understanding the mechanism of its
superconductivity, have not been studied.
Here, we report the point-contact spectroscopy (PCS) of Y metal in a diamond anvil cell (DAC) environment for the first time. The PCS measurements, which were performed as a function of both temperature and magnetic field at 48.6 GPa, revealed that the differential conductance \( \frac{dI}{dV} \) of Y is best described by a conventional s-wave superconducting order parameter with two SC gaps, i.e., \( \Delta_L(0) = 3.63 \text{ meV} \) and \( \Delta_S(0) = 0.46 \text{ meV} \). The SC gap-to-\( T_c \) ratio, \( 2\Delta_L(0)/k_B T_c \), for the larger gap is 8.2, which is much higher than the 3.53 expected for a weakly coupled BCS superconductor; instead, it is comparable to that of strongly correlated superconductors such as high-\( T_c \) cuprates, heavy fermions, and Fe-based compounds [14]. In support of the unusual superconductivity, the initial slope of the upper critical fields at \( T_c \) is \(-1.54 \text{ T/K} \) at 48.6 GPa, which is ten times that of the two-gap superconductor MgB\(_2\) [15] and larger than that of the Fe-based superconductor LiFeAs [16]. The successful development of the PCS technique in DAC environments not only revealed the strongly coupled superconductivity of elemental metallic Y, but is also expected to provide a much-needed approach to guide efforts to understand the realization of SC properties of room-temperature superconductors in megabar environments.

The electrical resistivity of Y under pressure is plotted as a function of temperature in Fig. 1(a). The resistivity at 21.1 GPa decreases with decreasing temperature, exhibiting metallic behavior. But, the signature of the SC phase transition was not found at temperatures above 6 K. Increasing pressure to 35.4 GPa causes the resistivity to drop sharply to zero at 9.9 K owing to the SC transition. A further increase in pressure gradually enhances \( T_c \) to 19.1 K at 90.2 GPa, above which \( T_c \) decreases slightly with pressure. Figure 1(b) displays the dependence of \( T_c \) on pressure, where the results obtained in this work are represented by star symbols, and the other data were obtained from previous ac magnetic susceptibility (30–125 GPa) and resistivity measurements (80–166 GPa) [12]. Even though the \( T_c \) obtained in this work is slightly higher than that in previous studies, the pressure dependence of \( T_c \) and
the positions of a peak near 100 GPa are similar.

The change in the pressure-induced SC state of Y in the presence of a magnetic field at 33.4 and 48.6 GPa is displayed in Fig. 2(a) and 2(b), respectively. At 33.4 GPa, the resistivity sharply increases at 7.7 K, reaches a maximum at 7.5 K, and drops to zero at 6.7 K. We note that a hump-like feature near $T_c$ was often observed in disordered superconductors, which may have been caused by deformation during the compression process in this case [3,17]. Upon increasing the magnetic field, the SC phase is highly robust against an external field as high as 3.5 T, which is more than one order of magnitude higher than that of Pb with similar $T_c$. At 48.6 GPa, the resistivity reveals a peak below 10.0 K and decreases to zero at 9.3 K owing to the SC phase transition. At 9 T, which is the strongest magnetic field available in this work, the SC phase is still robust and the onset of $T_c$ occurs at 3.9 K.

The magnetic field dependence of $T_c$ determined as the onset of superconducting phase transition is plotted in Fig. 2(c) for both pressures. The initial slope (dotted lines) of the upper critical field at $T_c$, $d(\mu_0H_{c2})/dT$, is $-0.76$ and $-1.54$ T/K at 33.4 and 48.6 GPa, respectively. The single-band Werthamer-Helfand-Hohenberg (WHH) formula in the dirty-limit, i.e., $\mu_0H_{c2}(0) = -0.69d(\mu_0H_{c2})/dT|_{T=T_c}$ [18], gives upper critical fields $\mu_0H_{c2}$ at 0 K of 3.67 and 10.20 T, respectively. The SC coherence length $\xi(0)$ estimated from the relation of $\mu_0H_{c2}(0) = \Phi_0/2\pi\xi(0)^2$ is 9.5 and 6.4 nm at 33.4 and 48.6 GPa, respectively, where $\Phi_0$ is the flux quantum. A kink-like feature in $\mu_0H_{c2}(T)$ near 5.5 K at 48.6 GPa, indicated by the arrow, is a deviation from the prediction for a single-band $s$-wave scheme [19]. Taken together with the large initial slope of the upper critical field at $T_c$, these anomalous behaviors of upper critical fields suggest that superconductivity of Y emerging under high pressure is atypical.

Figure 3 shows the dependence of conductance $dI/dV$ on bias voltage at 48.6 GPa, which is
obtained from point-contact spectroscopy (PCS) results. The signature of Andreev reflection owing to the presence of an SC gap is shown in Fig. 3(b), where the broad peak in dI/dV is overlaid with a small peak near zero-bias voltage [20,21]. The solid and dashed lines are best fits based on the Blonder-Tinkham-Klapwijk (BTK) model for a single and two s-wave SC gaps, respectively, indicating two-gap superconductivity in elemental metallic Y. To take into account the dip feature observed near 10 mV, an inter-grain Josephson effect (IGJE) is introduced to the modified BTK model [22]:

$$dI/dV(V) = G_0 \left( \frac{dV_{BTK}}{dI} + w_I \frac{dV_{IGJE}}{dI} \right)^{-1}$$  \hspace{1cm} (1)$$

where $G_0$ is the differential conductance in the normal state, and $w_I$ is the IGJE weight. The introduction of IGJE not only causes a dip, but also broadens the dI/dV profile, making it difficult to extract a precise value of the SC energy gap without performing numerical simulations. The first term of Eq. (1) corresponds to the modified BTK formula for two-band s-wave SC pairing symmetry (denoted as bands L and S), which is expressed as

$$\left. \frac{dI}{dV} \right|_{BTK} = w_L \left. \frac{dI}{dV} \right|_{band \ L} + (1-w_L) \left. \frac{dI}{dV} \right|_{band \ S}$$  \hspace{1cm} (2)$$

Here, the contribution from each band is evaluated using the modified BTK formula [21]:

$$\left. \frac{dI}{dV} \right|_{band \ i} = \frac{1}{1+Z_i^2} \int_{-\infty}^{+\infty} df \sigma_p(E; Z_i, \Delta_i, \Gamma_i) dE, \quad i = L, S$$  \hspace{1cm} (3)$$

where $f(E)$ is the Fermi function and $\sigma_p(E; Z_i, \Delta_i, \Gamma_i)$ is proportional to the sum of probabilities of the tunneling processes at the normal-superconductor interface, including Andreev and normal reflections. The free parameters $Z_i$, $\Delta_i$, and $\Gamma_i$ account for the interface barrier strength, SC energy gap, and lifetime broadening parameters, respectively. The second term of Eq. (1) is a contribution from the IGJE, which is the solution of the Fokker-Planck partial differential equation for a resistively shunted junction model with current fluctuations caused by thermal noise in the small capacitance limit [22] (see SI for details).
The dependence on temperature of \( \frac{dI}{dV} \) divided by its normal-state value at 10.5 K, \( \frac{(dI/dV)_{10.5\, K}}{(dI/dV)_{10.5\, K}} \), is selectively displayed in Fig. 3(c) with an offset for clarity. With increasing temperature, the broad peak from Andreev reflection is gradually suppressed and disappears at temperatures above \( T_c \) of 10.4 K, whereas the smaller zero-bias peak is not clearly observed for \( T > 5 \) K. Figure 3(d) is a color contour plot of the normalized conductance on the \( T-V \) axes, where green (red) represents larger (smaller) values. The smaller zero-bias peak is depicted as a hatched area in the low-\( T \) and low-\( V \) regimes, and is surrounded by a regime of enhanced Andreev reflection. The suppressed IGJE regime in dark yellow surrounds the SC phase. The field evolution of \( \frac{dI}{dV} \) divided by the value at 8.5 T is shown in Fig. 3(c) at a fixed temperature of 5 K, where the normalized conductance is displayed with an offset for clarity. The Andreev reflection spectrum is progressively suppressed with increasing magnetic field and disappears at approximately 7.5 T. A contour plot of the normalized conductance along the \( H-V \) axes, as shown in Fig. 3(f), reveals that the enhanced \( dI/dV \) is significantly suppressed in comparison with the \( T \)-dependent \( dI/dV \), indicating that the dependence on magnetic field of the SC state is different from that of temperature.

The dashed lines in Fig. 3(c) and 3(e) are least-squares fits of data to the modified BTK+IGJE model with contributions from the two SC gaps and IGJE terms (see SI for the parameters obtained from the best fits). Excellent agreement between the experimental datasets and model simulations in both the \( T \)- and \( H \)-dependent evolution of the Andreev reflection spectroscopy attests to the existence of two \( s \)-wave SC gaps for elemental metallic Y.

Figure 4(a) illustrates the extracted SC energy gaps versus temperature for two different point contacts P1 and P2 of Y at 48.6 GPa. During the fitting process, it was assumed that the weight of band L is 75%, regardless of the temperature. The SC energy gaps \( \Delta_L \) (band L) and \( \Delta_S \) (band S) are similar
for P1 (open symbols) and P2 (solid symbols). As shown in the inset of Fig. 4(a), the dependence on reduced temperature \(T/T_c\) of the reduced gap \(\Delta(T)/\Delta(0)\) is similar for both the smaller and larger SC gaps, indicating that they have a similar origin. The solid lines are best fits obtained from theoretical calculations based on the quasi-classical Eilenberger weak-coupling formalism with two isotropic SC gaps, where \(\Delta_l(0)\) and \(\Delta_q(0)\) are 3.63 and 0.45 meV, respectively [23]. In the calculation, the effective coupling matrix, \(\lambda_{nm}(n, m = L, S)\), describes the renormalized coupling to each band, including electron-phonon and Coulomb interactions (see SI for details). The diagonal components of the coupling matrix that describe the intraband coupling are \(\lambda_{LL} = 0.383\) and \(\lambda_{SS} = 0.045\), whereas the off-diagonal components for the interband coupling are \(\lambda_{LS} = 0.013\) and \(\lambda_{SL} = 0.039\), indicating that the two bands are strongly coupled. The magnetic field dependence of the energy gap at \(T = 5.0\) K obtained from the modified BTK+IGJE model is shown in Fig. 4(b) for contact P1. As shown in the inset of Fig. 4(b), the reduced gap, \(\Delta(H)/\Delta(0\ T)\), versus the reduced field, \(H/H_{c2}\), is well described by the power-law form \(\Delta(H) \propto (1 - H/H_{c2})^{0.5}\) (dashed line), which is often used to describe the field dependence of an isotropic BCS gap [24].

The ratio of the SC gap-to-\(T_c\), \(2\Delta(0)/k_BT_c\), serves as a criterion for the strength of the SC coupling constant relative to the BCS value of 3.53 for weak-coupling conventional superconductors. This ratio is significantly higher for unconventional superconductors such as high-\(T_c\) cuprates, heavy-fermion superconductors, and Fe-based superconductors [14]. In general, the gap ratio in multigap superconductors also deviates from the BCS value, with the ratio being above and below the weak-coupling limit for large and small SC gaps, respectively. For example, it is 4.3 and 1.8, respectively, for the large and small gaps of a MgB\(_2\) single crystal [25] and 4.4 and 1.9, respectively, for optimally doped Ba(Fe\(_{1-x}\)Co\(_x\))\(_2\)As\(_2\) [26]. Being similar to other multigap superconductors, the SC gap ratio of Y at 48.6 GPa (\(T_c = 10.3\) K) is 8.2 and 1.0 for the large and small gaps, respectively. The significant deviation of the gap ratio from the BCS value indicates that the pressure-induced superconductivity of Y arises from
strongly coupled electron-boson interactions and raises the possibility of unconventional superconductivity in this $d$-electron metallic element.

The gradual, pressure-induced increase in $T_c$ of Y was previously ascribed to $s$-$d$ transfer, where electron transfer from the $s$-band to the $d$-band occurs because the $s$-orbital shifts to higher energy faster than the $d$-orbital [27,28]. The $s$-$d$ transfer, linked with the crystal structure sequence hcp – $\alpha$-Sm type – dhcp – dfcc [29], is expected to increase the density of states at the Fermi energy and the electron-phonon coupling, leading to enhanced superconductivity. The observation of two SC gaps in Y at high pressure may be attributed to $s$-$d$ transfer because the increase in electronic density of states in the $d$-band may change the electronic band structure accompanied by structural transitions [29]. Considering the limited studies on the electronic band structure and SC gap functions of Y at high pressure [11,30], further experimental and theoretical studies can be expected to be important to deepen our understanding of the emergent multigap superconductivity of Y metal under pressure.

In conclusion, this is the first report of pressure-induced multigap superconductivity of elemental metallic Y based on point-contact spectroscopy in a diamond anvil cell environment. The differential conductance of Y at 48.6 GPa reveals a narrow zero-bias peak overlaid with a broad Andreev reflection spectrum in the SC state, which is best explained by the modified BTK model with two superconducting gaps of 3.63 and 0.46 meV. The ratio of the SC gap-to-$T_c$ is 8.2 and 1.0 for the large and small gap, respectively, which differ significantly from the BCS value of 3.53 and indicate that Y is a strongly coupled superconductor. A signature of superconductivity in the electrical resistivity of Y at 48.6 GPa is observed even at 9 T, which is approximately two orders of magnitude higher than that of other elemental superconductors, such as Pb with a similar $T_c$. The initial slope of the upper critical field at the $T_c$ is $-1.54$ T/K, which is ten times that of the two-gap superconductor MgB$_2$, but is close to that of other strongly correlated compounds. Taken together with substantial deviation of the SC gap ratio from
the BCS value, the anomalously large upper critical field suggests that the superconducting properties of elemental metallic Y could possibly be of an unconventional nature.

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**Figure Captions**

**FIG. 1. Electrical resistivity and P-T phase diagram of Y at different pressures**

(a) Pressure–temperature evolution of the resistivity of Y. The inset displays the resistivity over the entire temperature range (6–300 K) at which measurements were conducted at various pressures up to 109.4 GPa. (b) P-T phase diagram of Y obtained from resistivity (circle symbol) and ac susceptibility (square symbol) measurements under pressure. The star symbols refer to our resistivity data in the symmetric cell (blue) and miniature Be-Cu cell (red). The resistivity measurements of $T_c$ from refs. [8, 12] are represented as navy and olive circles, respectively. $T_c$ collected from ac susceptibility is indicated by square symbols [9, 10]. The dashed lines indicate the structural phase boundaries measured at room temperature [13]. As the pressure increases, the phase transition sequence for the crystal structure is hcp – $\alpha$-Sm type – dhpc – dfcc – oF16. The inset shows a photograph of the van der Pauw configuration at 109.4 GPa.

**FIG. 2. Upper critical fields of Y under pressure**

Electrical resistance of Y as a function of temperature for representative magnetic fields at 33.4 GPa in (a) and 48.6 GPa in (b). (c) Temperature dependence of the upper critical fields, $\mu_0H_{c2}(T)$, at 33.4 (black squares) and 48.6 GPa (blue hexagons), where $T_c$ is determined to be the temperature at which the resistance deviates from normal state behavior. We note that the $T_c$ onset is consistent with that determined from PCS (see Fig. S4 in the SI). The dotted lines are the initial slope of $\mu_0H_{c2}(T)$ near $T_c$ at each pressure and the arrow marks a kink in $\mu_0H_{c2}(T)$.

**FIG. 3. Quasi-particle scattering spectra at 48.6 GPa**

(a) Schematic diagram of point-contact spectroscopy on Y inside the diamond anvil cell. Injected
electrons flow through a sharp-cut Pt tip and form Cooper pairs in the superconductor, leaving the retroreflected hole on the normal electrode side. The normal/insulating grain boundaries between superconducting grains consist of an effective Josephson junction. (b) Normalized differential conductance, \((dI/dV) / (dI/dV)_{10.5\,\text{K}}\), at 2.0 K as a function of the bias voltage. The solid and dash-dotted lines are best fits to two-band s-wave and single-band s-wave models, respectively. (c) Temperature evolution of \((dI/dV) / (dI/dV)_{10.5\,\text{K}}\) from 2.0 to 10.4 K. All the curves are displayed with an offset for clarity. (d) Contour plot of \((dI/dV) / (dI/dV)_{10.5\,\text{K}}\) of temperature \((T)\) vs. bias voltage \((V)\), where green (red) represents larger (smaller) differential conductance. (e) Magnetic field evolution of the normalized \(dI/dV\) curves at 5.0 K. All the curves are displayed with an offset for clarity. (f) Contour plot of \((dI/dV) / (dI/dV)_{10.5\,\text{K}}\) of magnetic field \((H)\) vs. bias voltage \((V)\), where green (red) represents larger (smaller) differential conductance. The dotted lines in (c) and (e) are best fits of data to the modified BTK model with two-gaps plus inter-grain Josephson effects (see the main text for details).

**FIG. 4. Dependence of the superconducting gap of Y on the temperature and magnetic field at 48.6 GPa**

(a) Temperature dependence of the two superconducting (SC) energy gaps obtained from different contacts P1 (open symbols) and P2 (solid symbols) at 48.6 GPa. The gray and red lines are the best fits using the two-band s-wave BCS framework (see the main text for details). The inset shows the reduced SC energy gaps for contacts P1 and P2 versus reduced temperature. (b) Field dependence of the two extracted SC energy gaps obtained from contact P1 at 5.0 K and 48.6 GPa. The dashed lines are best fits to the phenomenological model: \(\Delta(H) \propto (1-H/H_{c2})^{0.5}\). The reduced SC energy gaps versus the reduced magnetic field are shown in the inset.
Figures

(a) Figure 1a

(b) Figure 1b

Figure 1
Figure 2
Figure 3
Figure 4

(a) Graph showing the relationship between temperature (K) and the energy gap (Δ) as a function of field. The inset graph shows the normalized energy gap (Δ/Δ(0)) versus the ratio of temperature to critical temperature (T/Tc).

(b) Graph showing the relationship between field (T) and the energy gap (Δ) as a function of pressure. The inset graph shows the normalized energy gap (Δ/Δ(5 K)) versus the ratio of field to critical field (H/Hc2).

Y, P=48.6 GPa
Y-P1, T=5.0 K

$\Delta(H) \propto \left(1 - \frac{H}{H_{c2}}\right)^{0.5}$