Superconducting pairing symmetries in the 3-K phase of Sr$_2$RuO$_4$

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KITP, UCSB. December 12, 2007
Acknowledgement

Penn State
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Single crystal growth
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Low-temperature scanning SQUID measurements
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Work supported by DOE
Ru in Sr$_2$RuO$_4$: The 3-K phase


Surprising enhancement of $T_c$!

$T_{c\text{bulk}} = 1.5$K  \quad T_{c\text{Ru}} = 0.5$K  \quad T_{c}^{*} \leq 3$K

$H_{c2}^{c} = 0.075$T  \quad H_{c} = 69$G  \quad H_{c2}^{c} = 1.0$T

$H_{c2}^{ab} = 1.5$T  \quad H_{c2}^{ab} = 3.6$T

Early interests:

- Insight into the mechanism of superconductivity in Sr$_2$RuO$_4$?
- Phenomenology of interfacial unconventional superconductivity.
Andreev surface bound states in the 3K phase


Single-crystal cleave (break) tunnel junctions

Superconductivity in the 3-K phase is also unconventional!
Pairing symmetries of Ru embedded in Sr$_2$RuO$_4$

An unconventional mesoscopic superconducting system that gives rise to some unique physical phenomena not available in conventional mesoscopic superconductors.

Mixed pairing state at the lowest temperatures?
Ru microdomains do remember that it is an $s$-wave superconductor to begin with:
$V_{l=0} > V_{l=1}$

$T_0 < T < T_c^{3K}$
$T_{c\text{ bulk}} < T < T_0$
$T_c^{\text{Ru}} < T < T_c^{\text{bulk}}$
$T < T_c^{\text{Ru}}$
Mixing of two pairing states!
Proximity effect at an $s$- and $p$-wave interface at zero temperature

Theoretical work
Yip, De Alcantara Bonfim, Kumar, 1990.

In the $T = 0$ limit, physics is similar to conventional superconductors.
Experiment I: Pressed In on almost pure \( \text{Sr}_2\text{RuO}_4 \) crystal (\( ab \) face)

Ru microdomains involved in the pressed In junction will be small in size. Only few of them will be present at the junction.
Temperature dependent tunneling resistance
Behavior above the intrinsic $T_c$ of Ru

Observation of a zero-bias conductance peak (ZBCP)

$\Rightarrow$ Andreev surface bound states
$\Rightarrow$ proximity induced, small unconventional pairing in Ru
Opening of a superconducting energy gap in Ru

\[ I(V) = \int_{-\infty}^{+\infty} N(E)N'(E+eV)[f(E) - f(E+eV)]dE \]

\[ N(E) = \text{Re} \frac{|E| + i\Gamma}{\sqrt{(|E| + i\Gamma)^2 - \Delta^2}} \]

\[ \Delta_{\text{Ru}}(0) = 0.1\text{meV?} \]

\[ T = 0.1\text{ K} \]
If Ru is a BCS weak-coupling superconductor, we expect

\[ \Delta = 1.76k_B T_C = 1.76k_B (0.5K) \approx 0.072\text{meV} \]

Is Ru weak coupling superconductor? Ru gap has never been determined before!
Experiment II: Tunneling into a single Ru domain

The Ru microdomain is large compared with $\xi^{214}(0) \approx 0.066 \, \mu m$
Origin of the anomalously large energy gap

For Ru inclusion of a size only several times larger than the \( T = 0 \) coherence length of the 3K phase, the interplay between the condensation energy and the kinetic energy due to gradient of the order parameter becomes important.

\[
\Delta_{\text{Ru}} = \Delta_s + i\Delta_p
\]

If \( \Delta_s \approx \Delta_p \approx 0.072 \text{ meV} \)

\[ \Rightarrow \Delta_{\text{Ru}}(0) = 0.102 \text{ meV!} \]

A chiral mixed pairing state? Not forbidden by symmetry Consideration because this occurs in a mesoscopic sample.
Different critical field for the $s$- and $p$-wave pairing?

$H \parallel ab$ (along the junction plan)

Therefore the field can penetrate the Ru surface into which tunneling occurs easily.

Field suppresses the gap at $H = H_c^{Ru} = 69$ G, making.

$$\Delta_{Ru} = \Delta_p \approx 0.072 \text{meV}$$

Results were reproduced in another sample.
Effects of a perpendicular magnetic field

1) Interplay between the chiral and field-induced current near the Ru/Sr$_2$RuO$_4$ interface? How is the current induced?

2) Vortex physics?

$H \perp ab$

Field modulates the gap in a non-monotonic way!

Physical origin?
Conclusion

• In a Ru microdomain embedded in Sr$_2$RuO$_4$, there may be a mixed pairing state below 0.45 K.

• Ru-Sr$_2$RuO$_4$ provides a fascinating arena for studying the physics of unconventional, odd-parity superconductivity!