Phase sensitive measurements on the bulk phase of Sr_2RuO_4

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Low-temperature scanning SQUID measurements

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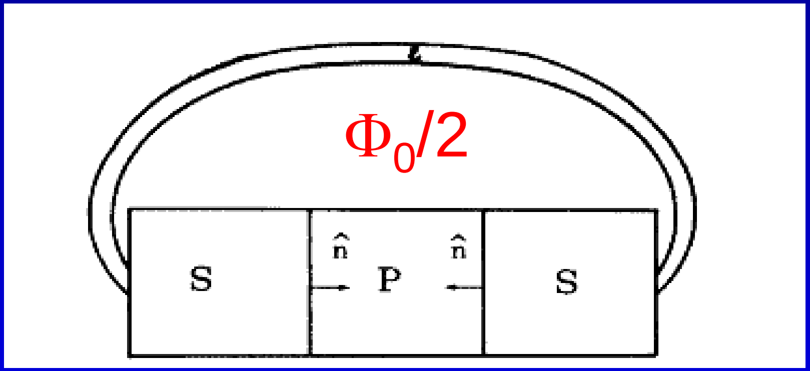
Phase-sensitive test for odd-parity pairing

V.B. Geshkenbein, A.I. Larkin, A. Barone, Phys. Rev. B 36, 235 (1987).

$$j_s \propto \left\langle \mathrm{Im}\left[\Psi_s^* \vec{d}\cdot(\vec{n}\times\vec{k})\right]\right\rangle_{average}$$

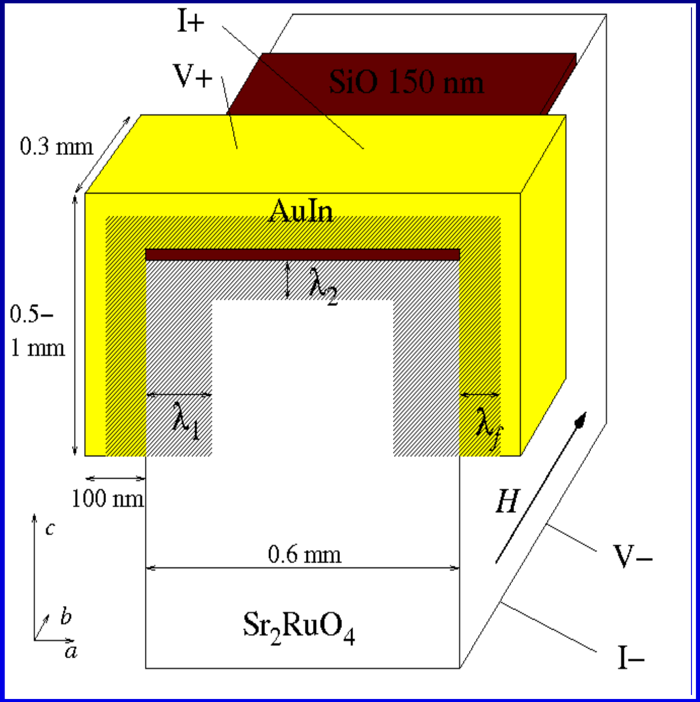


Expected experimental signatures:

- I_c is a minimum in the interference pattern at zero total flux.
- Presence of a spontaneous half-flux quantum, $\Phi_0/2$.

Experiment proposed originally for heavy fermions has not been carried out.

Preparation of a $Sr_2RuO_4/Au_{0.5}In_{0.5}$ SQUID



Experimental signature for P-wave pairing:

- I_c is a minimum in the interference pattern at zero total flux.

Photo credit: John Passaneau

Consideration on the measurement

The total flux threading the SQUID

$$\Phi = \Phi_{\text{ext}} + \Phi_{\text{ind}} + \Phi_{\text{bgr}} + \Phi_{\text{trap}}$$

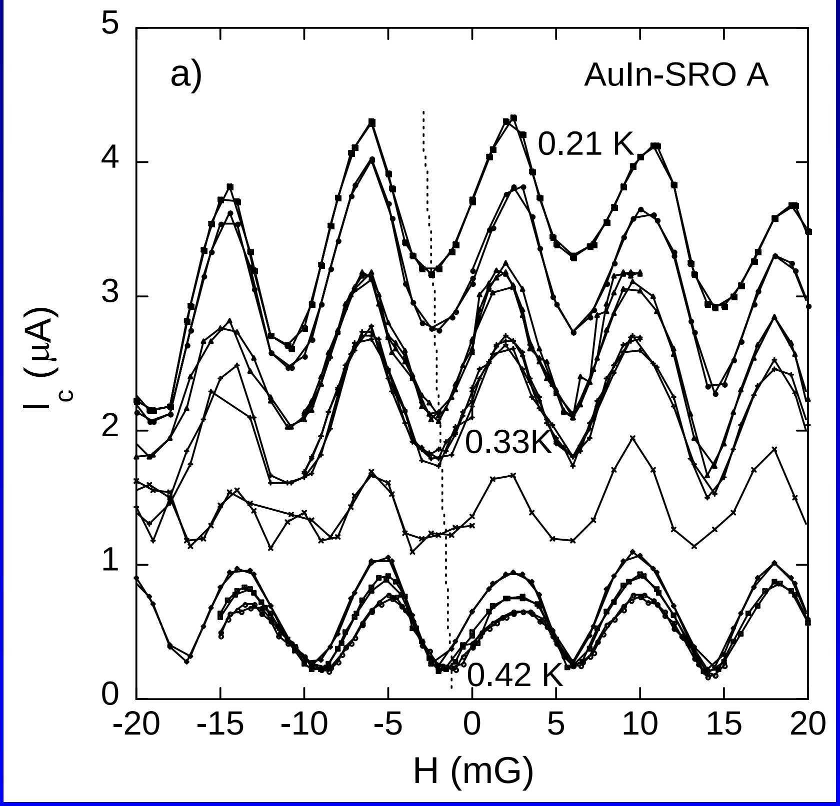
To determine if $I_c(\Phi = 0)$ is a minimum, we need $\Phi \to \Phi_{\text{ext}}$.

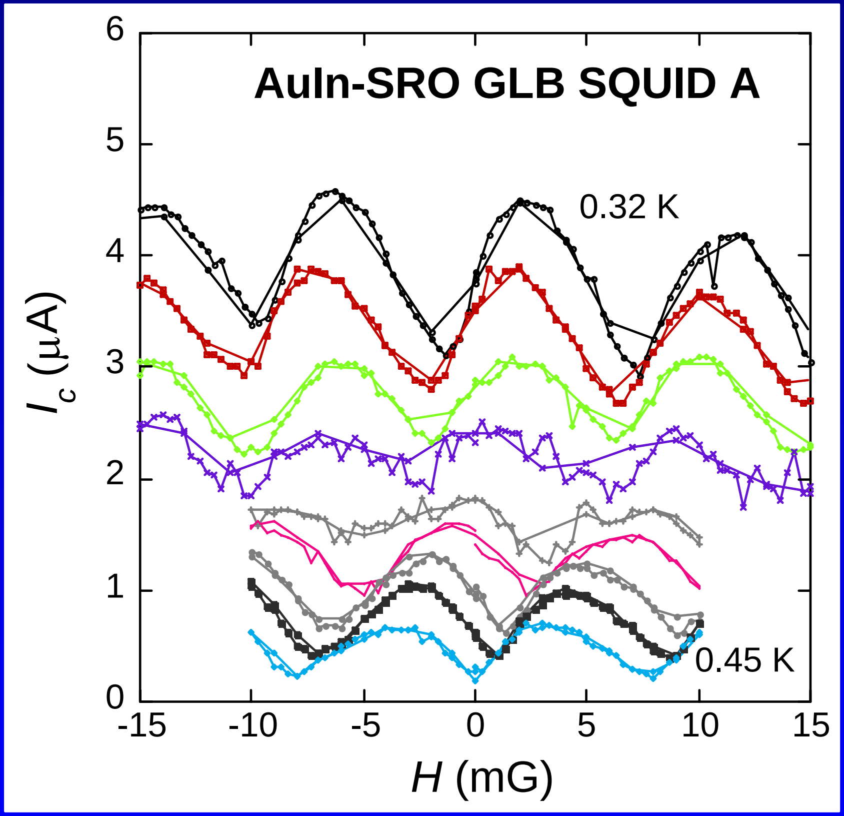
Goal: To get rid of trapped vortices or vortex-antivortex pairs, and unwanted multiple domains.

- Search for a symmetric $I_c(\Phi)$ pattern.
- Watch out for possible vortex jumps.
- Cool and warm the sample repeatedly with a computer controlled slow rate!

Samples are not created equal!

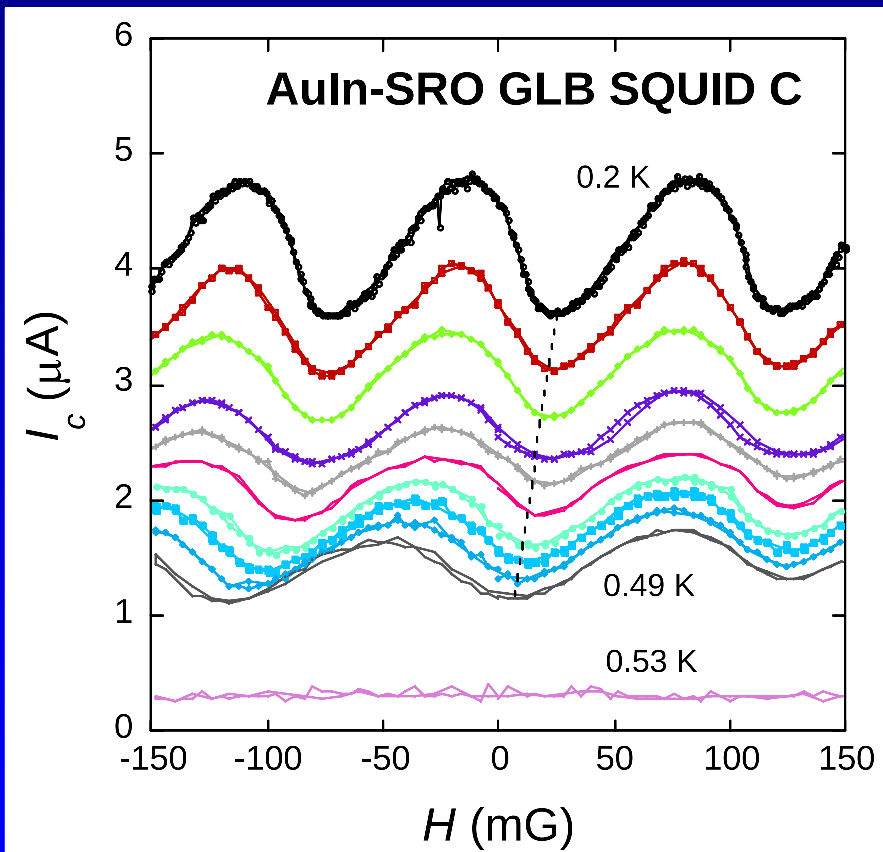
$I_c(\Phi=0)$ in the quantum interference pattern of an opposite-side $Sr_2RuO_4/Au_{0.5}In_{0.5}$ SQUID

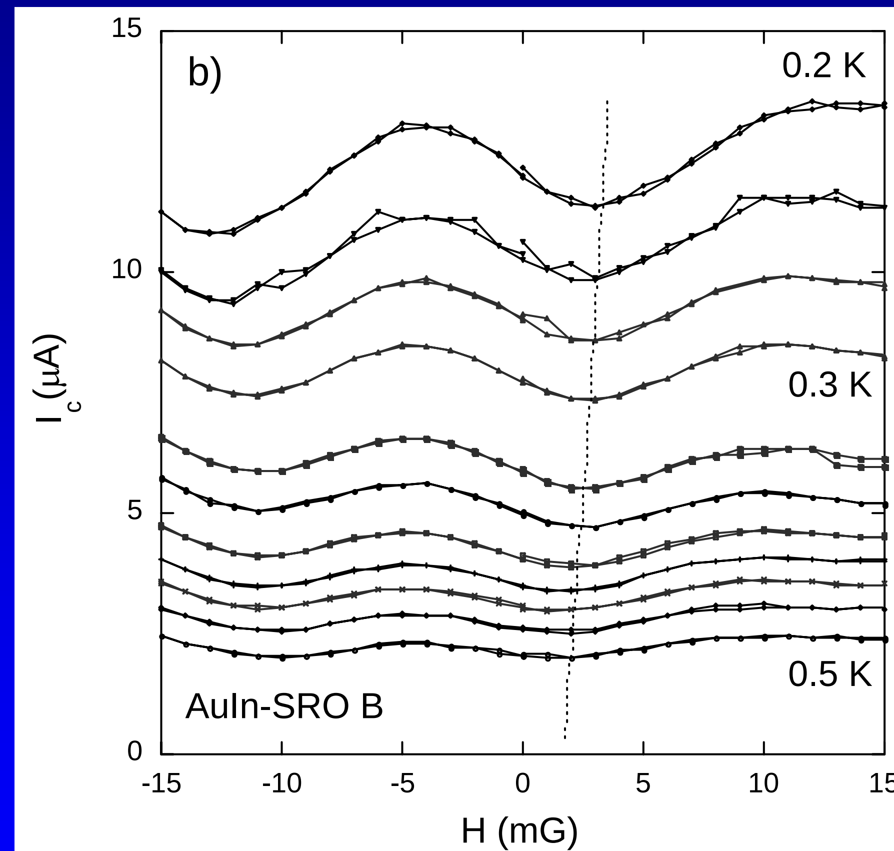




- $T \to T_c$, Φ_{ind} approaches zero, $\Phi = \Phi_{ext} = HA \Rightarrow I_c\ (\Phi=0)$ is a minimum!
- Reasonable shift due to reduction in I_s, $\Delta\Phi = L\Delta I_s$!

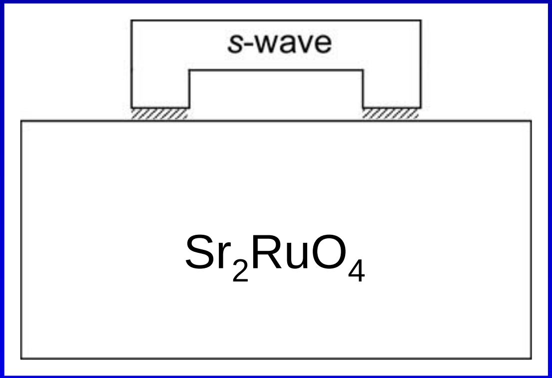
More opposite-side $Sr_2RuO_4/Au_{0.5}In_{0.5}$ SQUIDs

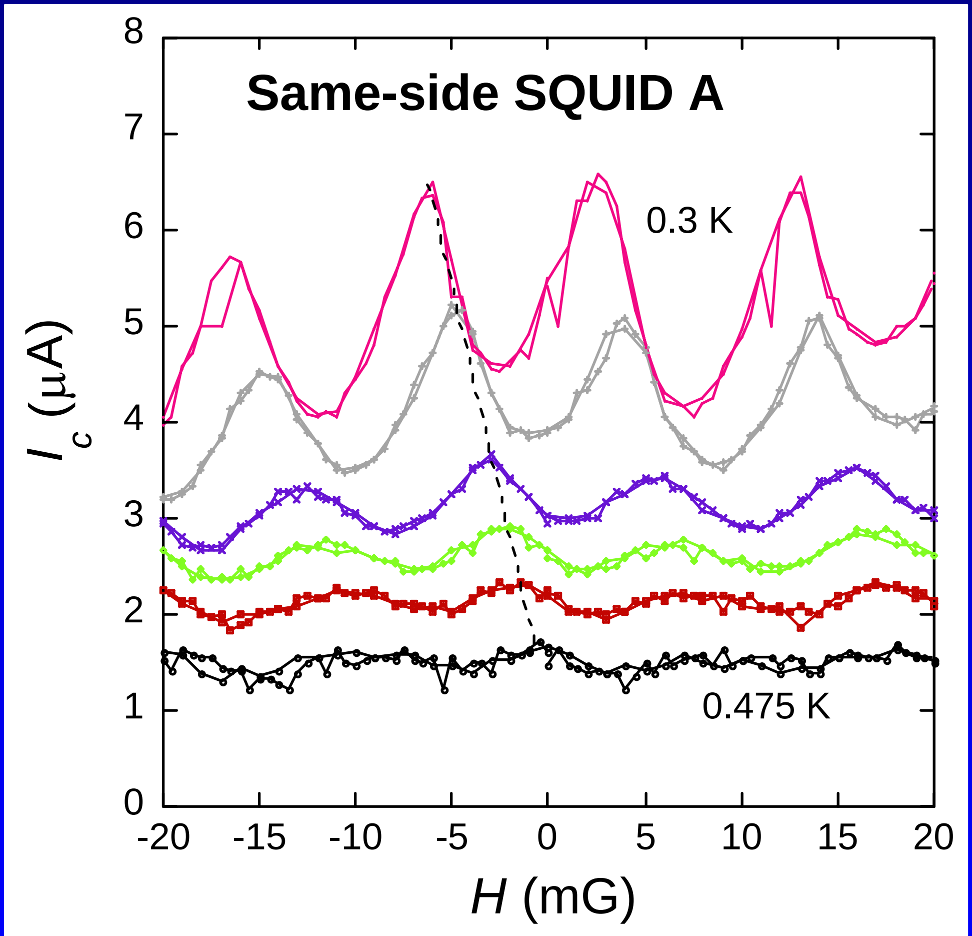




For both samples, $I_c(\Phi = 0)$ is a minimum!

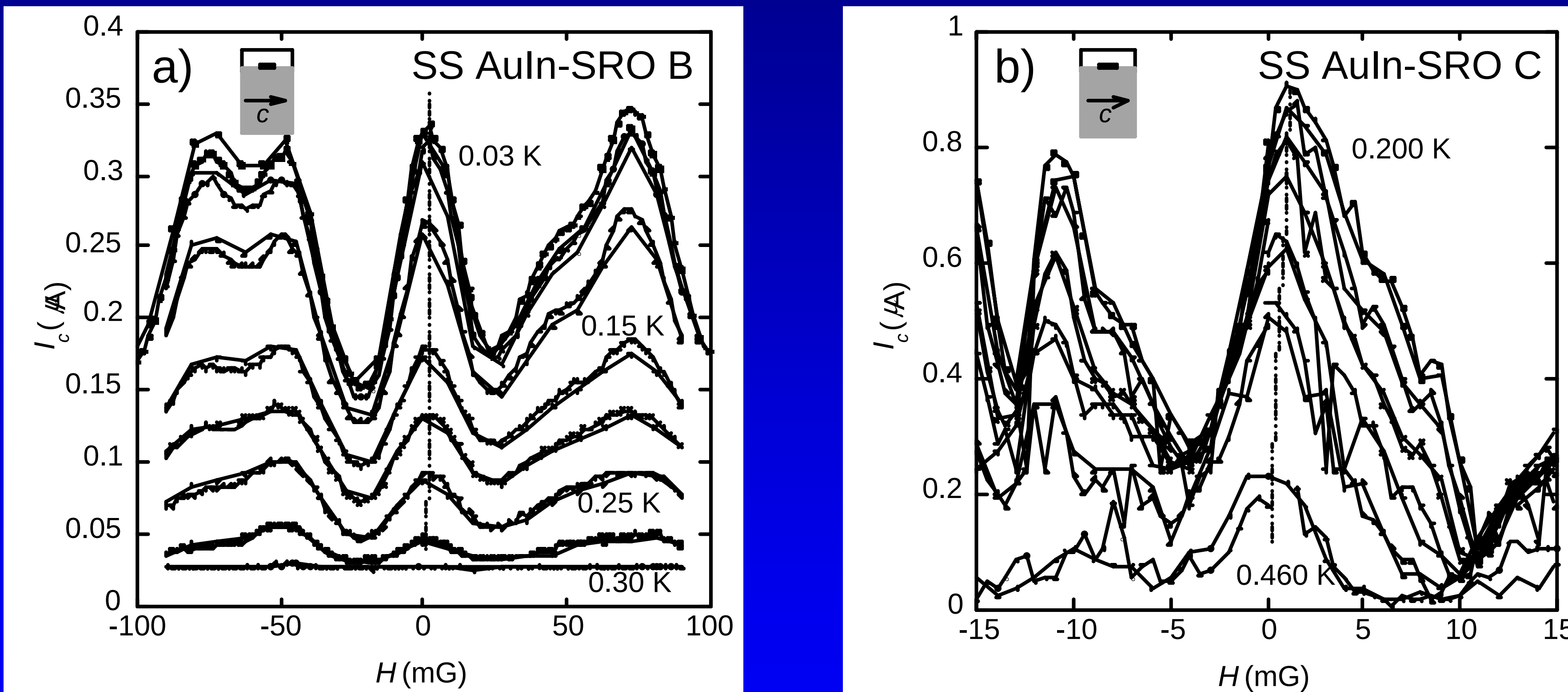
Control experiments: Same-side SQUIDs





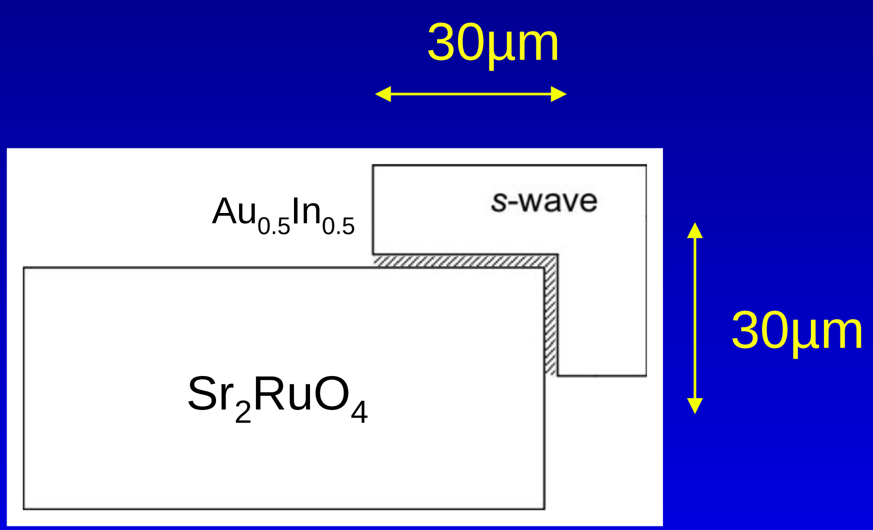
$I_c(\Phi = 0)$ is a maximum!

More same-side SQUIDs



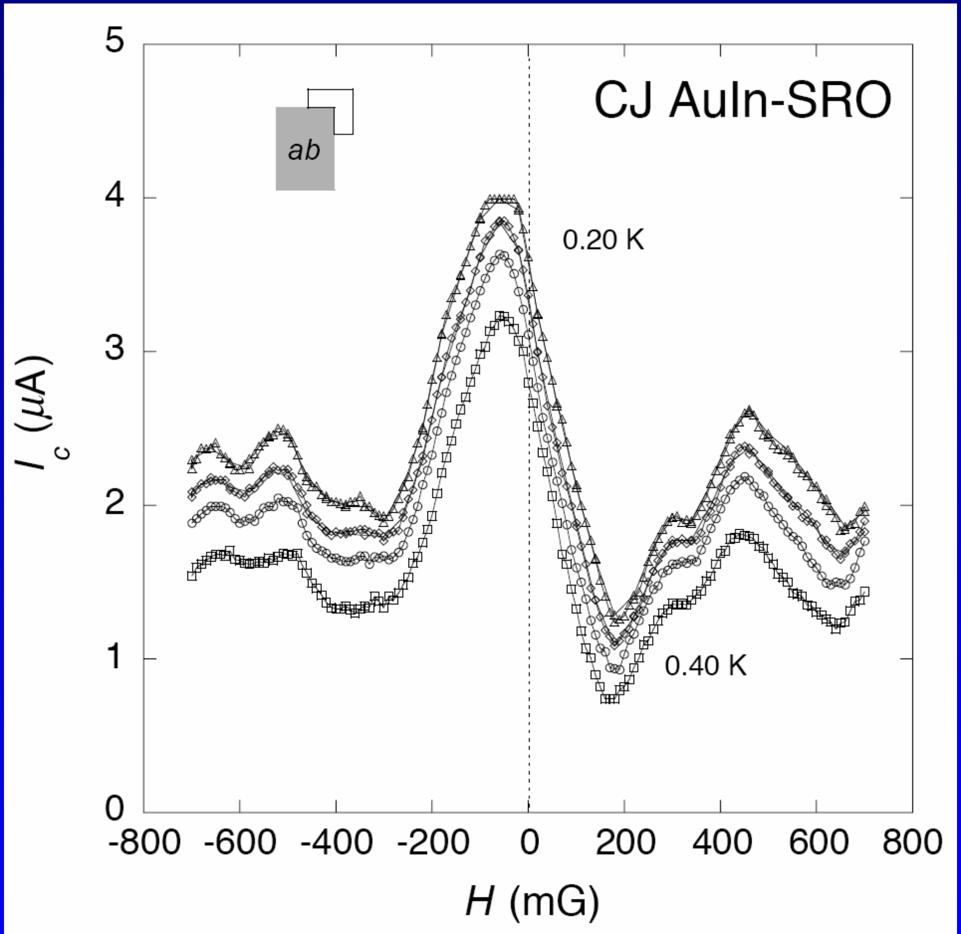
For both samples, $I_c(\Phi = 0)$ is a maximum!

$Sr_2RuO_4/Au_{0.5}In_{0.5}$ corner junction I



We expect:

- For *d*-wave, $I_c(\Phi = 0)$ is minimum.
- For *p*-wave $I_c(\Phi = 0)$ is neither a maximum or minimum!



Conclusion on pairing state in bulk Sr_2RuO_4

The phase of the superconducting order parameter in Sr_2RuO_4 changes by π under inversion, and $\pi/2$ under 90º rotation (shown later), showing that Sr_2RuO_4 is an odd-parity superconductor.

Nelson, Mao, Maeno, and Liu, Science 306, 1151 (2004).

Within Rice-Sigrist scheme of pairing states in two dimensions, this and our other measurements, the above result suggests that the pairing state in Sr_2RuO_4 is that of the Γ^{-}_{5}.

State	*d*-vector
Γ^{-}_{1}	$\boldsymbol{x}k_x + \boldsymbol{y}k_y$
Γ^{-}_{2}	$\boldsymbol{x}k_x - \boldsymbol{y}k_y$
Γ^{-}_{3}	$\boldsymbol{x}k_y - \boldsymbol{y}k_x$
Γ^{-}_{4}	$\boldsymbol{x}k_y + \boldsymbol{y}k_x$
Γ^{-}_{5}	$\boldsymbol{z}(k_x \pm i\, k_y)$

T.M. Rice and M. Sigrist,
J. Phys. Cond. Matt. 7, L643 (1995).