

2008 APS March Meeting

Session D11: Inhomogeneous Superconductors and Transport

2:30 PM–5:30 PM, Monday, March 10, 2008 Morial Convention Center - RO9

Abstract: D11.00009 : 4:06–4:18 PM

# Isotope Effect in High- $T_c$ Superconductors

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# Major Conclusions<sup>1</sup>

- Correct identification of Pr-on-Ba-site defects as responsible for the oxygen isotope effect (OIE) in Pr-doped  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ .
- Doping causes pair breaking that suppresses  $T_C$  and increases the OIE.
- Monovalent substitutions induce pair breaking due to impurity scattering, which increases the OIE along with reducing  $T_C$ .
- Heterovalent substitutions induce a greater OIE caused by an additional enhancement in the pair breaking rate which scales with the scattering rate.
- Coulomb interactions govern the high- $T_C$  pairing.
- Superconducting hole condensate located in the BaO layers.

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<sup>1</sup> Dale R. Harshman et al., *Physical Review B* **77**, 024523 (2008).

**Researchers based much of their work on Pr doped Y123,  
Believing that Pr substitutes only for Y,  
Leading to incorrect theories and conclusions.**

## **Misinterpretation of Doping Data**

### *Incorrect Assumption*



→ Assume that Pr doped only the Y sites

### *Actual Material*



→ Some ( $y < 5\%$ ) of the Pr actually dopes the Ba sites



When grown as is normally done, Pr-on-Ba-site defects  
Suppress the superconductivity

When grown using a traveling solvent floating zone  
method<sup>1</sup>, These defects are minimized Resulting  
in a  $T_C = 90$  K bulk superconductor

Therefore,  $\text{Pr}^{+3}$  substituting for  $\text{Y}^{+3}$   
i.e., **monovalent** substitution  
Does not affect the superconductivity

Like all rare-earth substitutions for Y

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<sup>1</sup> Z. Zou, et *al.*, Jpn. J. Appl. Phys. **36**, L18 (1997).  
A. Shukla et *al.*, Phys. Rev. B **59**, 12127 (1999).

Since  $\text{Pr}^{+3}$  substituting for  $\text{Ba}^{+2}$  (Heterovalent substitution)  
Strongly suppresses the superconductivity,  
***The charge on the BaO layer is crucial to SC***

## **Problems with Non-Adiabatic Electron-Phonon and Polaron Theories ( e.g., Kresin et al.<sup>1</sup> )**

- o Incorrect assumption regarding Pr-doped Y123
- o Predicts a non-physical singularity at optimum doping
- o Requires adopting (nonexistent) Jahn-Teller and proximity effects to fit the data
- o OIE decreases as the material approaches optimum  $T_C$   
...One would expect the opposite

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<sup>1</sup> V. Z. Kresin, A. Bill, S. Wolf, Yu. N. Ovchinnikov, Phys. Rev. B **56**, 107 (1997).

# Our Approach

- Correct understanding regarding Pr-doping of Y123
- Pair breaking generalized to include **Nonmagnetic disorder**
- Discovered that the OIE can be categorized into **Monovalent** substitution and **Heterovalent** substitution
- Superconductive pairing based on **Coulomb Interactions**

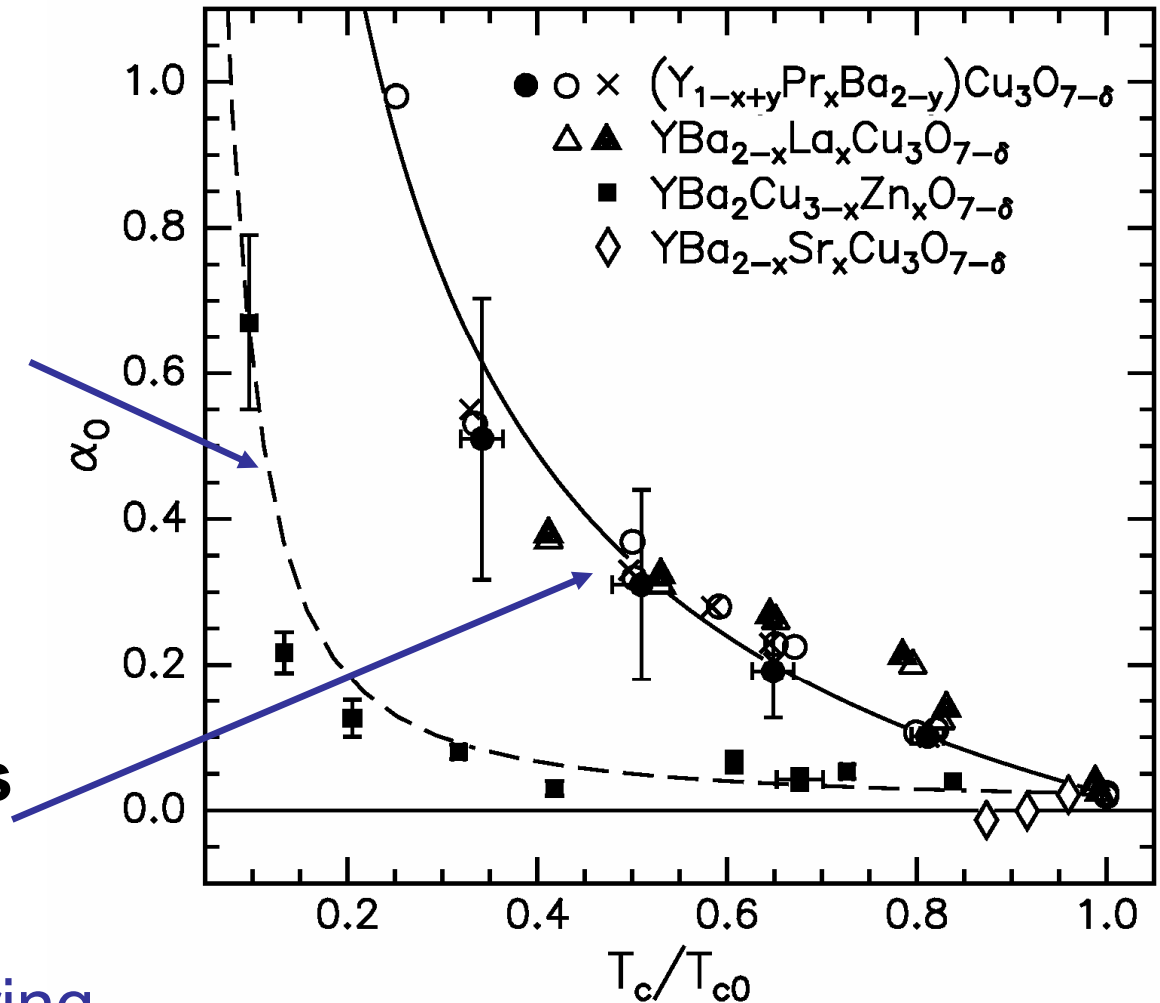
# OIE Coefficients – Transition Temperatures

## Monovalent Substitutions

Since the valence is not changed (to first order) by the substitution, the data follow the standard defect-induced pair-breaking form (dashed curve).

## Heterovalent Substitutions

In this case, the valence is significantly changed, causing enhanced scattering.



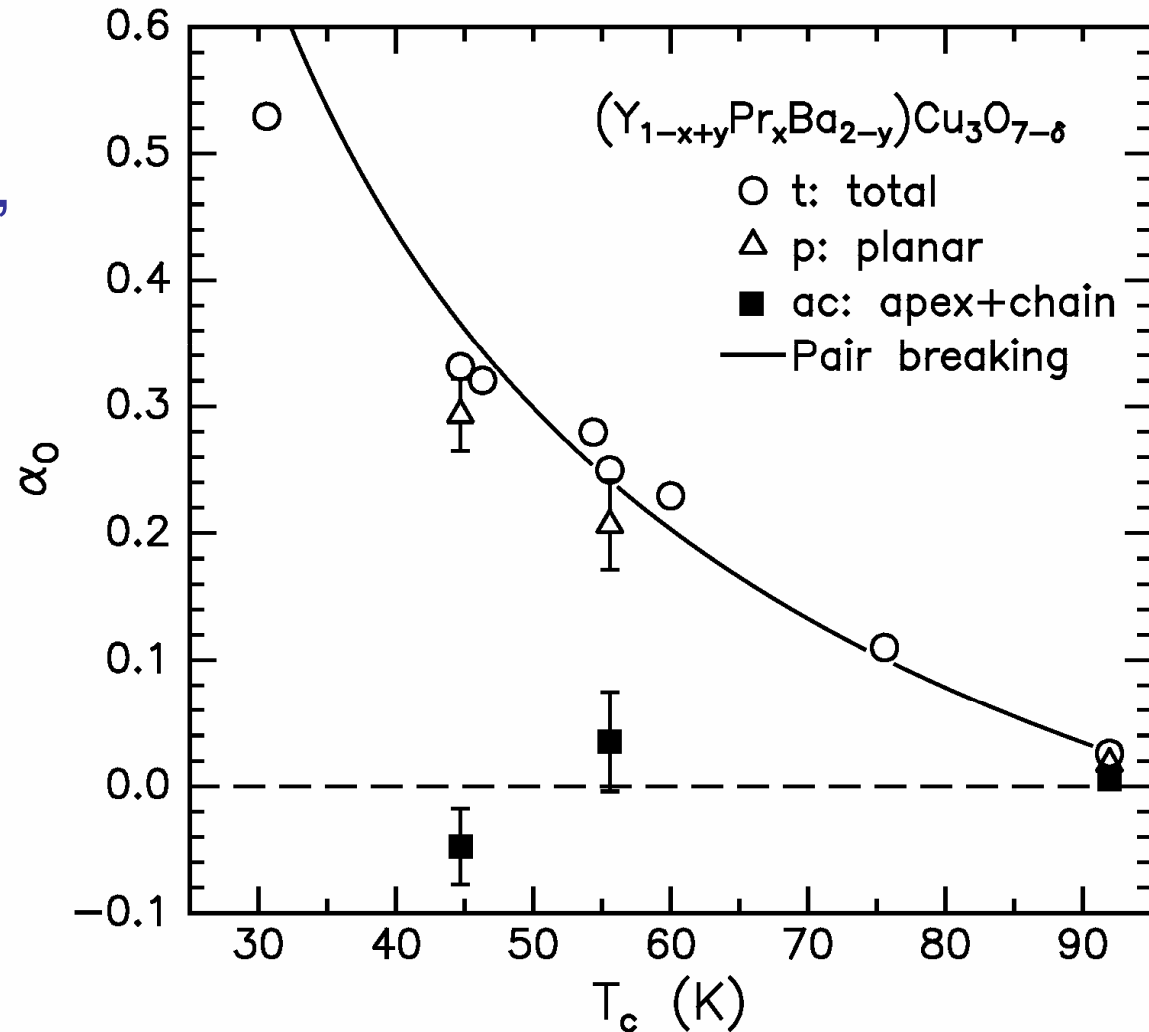
These data fall on the higher curve (solid curve).

Overdoped  $Bi_2Sr_2CaCu_2O_{8+\delta}$  data fall on the solid (enhanced OIE) line, as predicted.

# Site-specific measurements of OIE coefficient

Data show that as Pr-on-Ba-site defects are introduced, the OIE only occurs in the  $\text{CuO}_2$  layers. (It is absent in the BaO layers and CuO chains.)

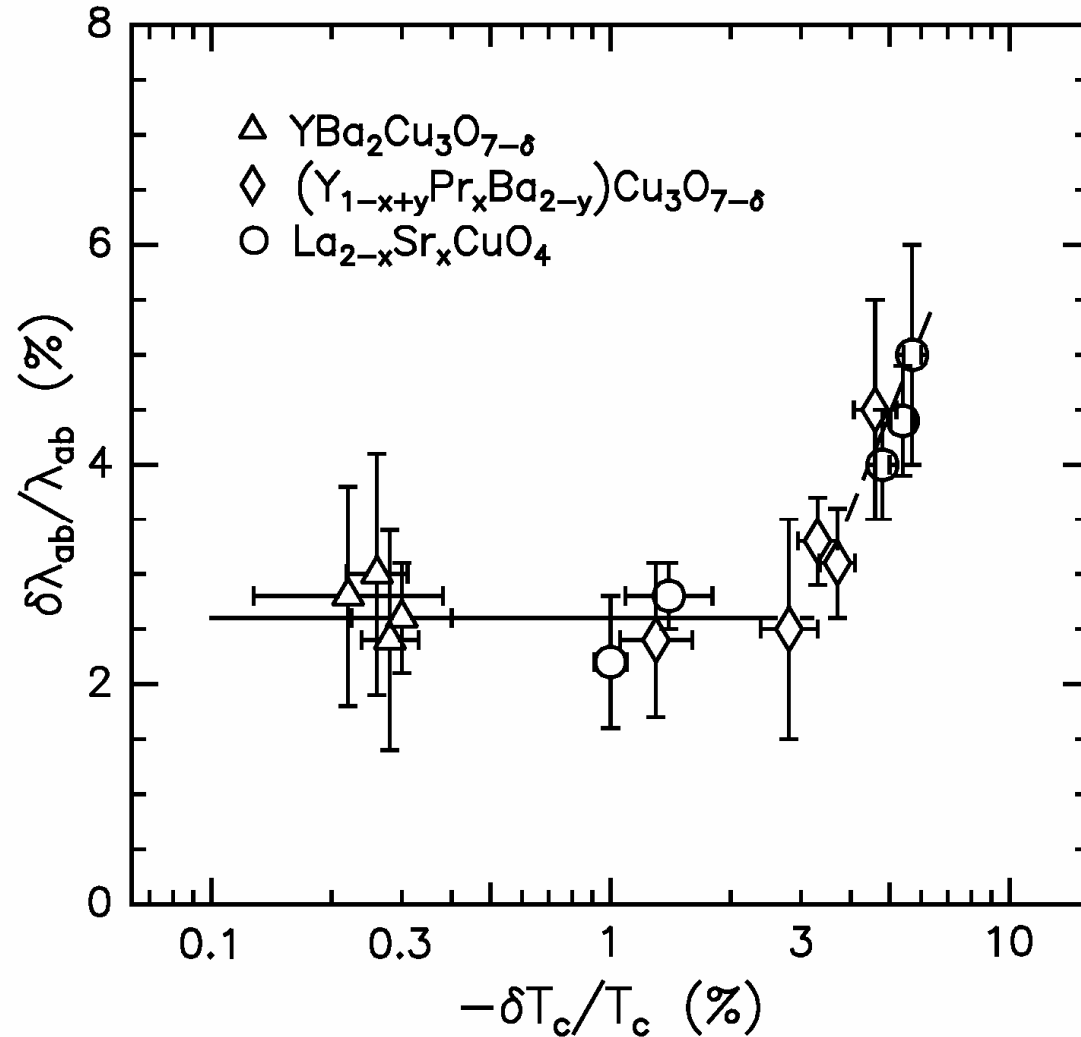
Thus, as we change the charge density in the BaO layers, electron-phonon scattering increases in the  $\text{CuO}_2$  layers.



Data points: H. Keller, Struct. Bond **114**, 143 (2005).



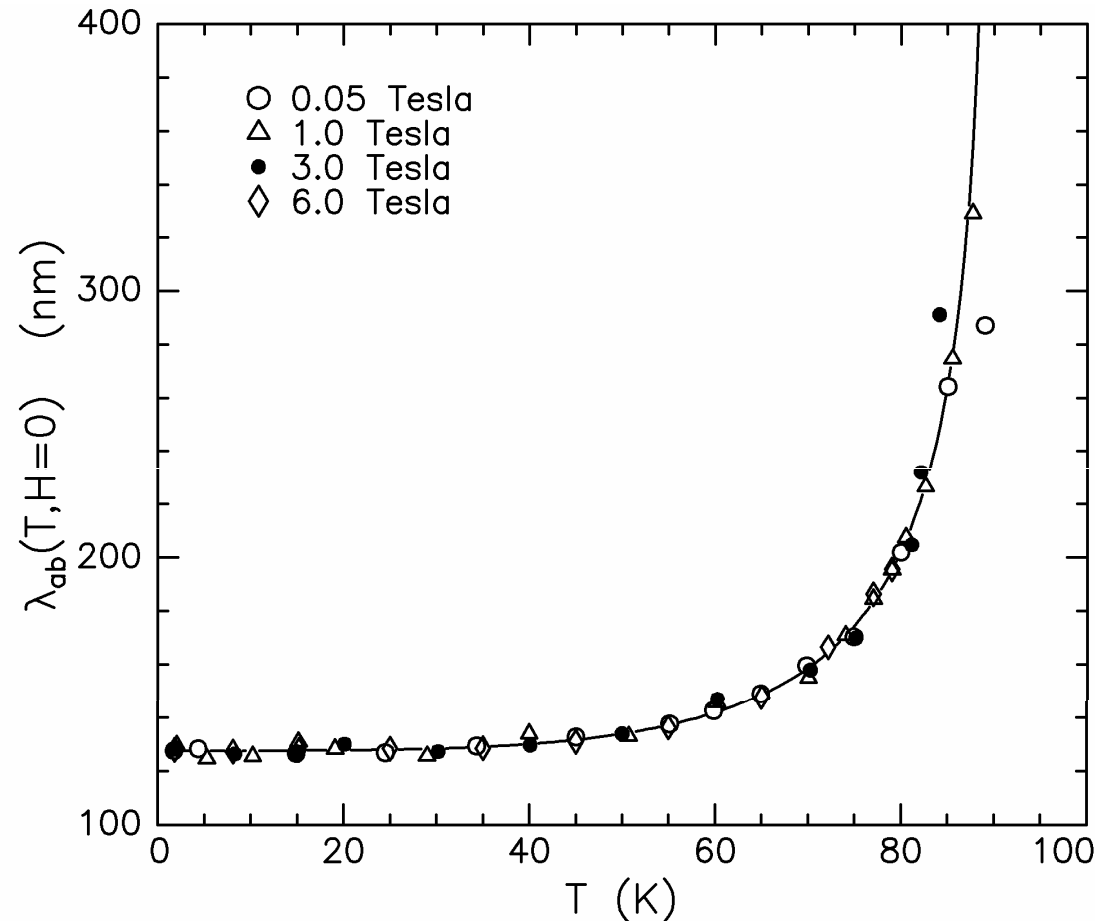
# OIE in the magnetic penetration depth and $T_c$



The OIE in the magnetic penetration depth is found to be constant, with degradation of  $T_c$  up to 50%, and thus is unrelated to the OIE in  $T_c$

## *Additional experimental information*

# Muon Spin Rotation Measurements

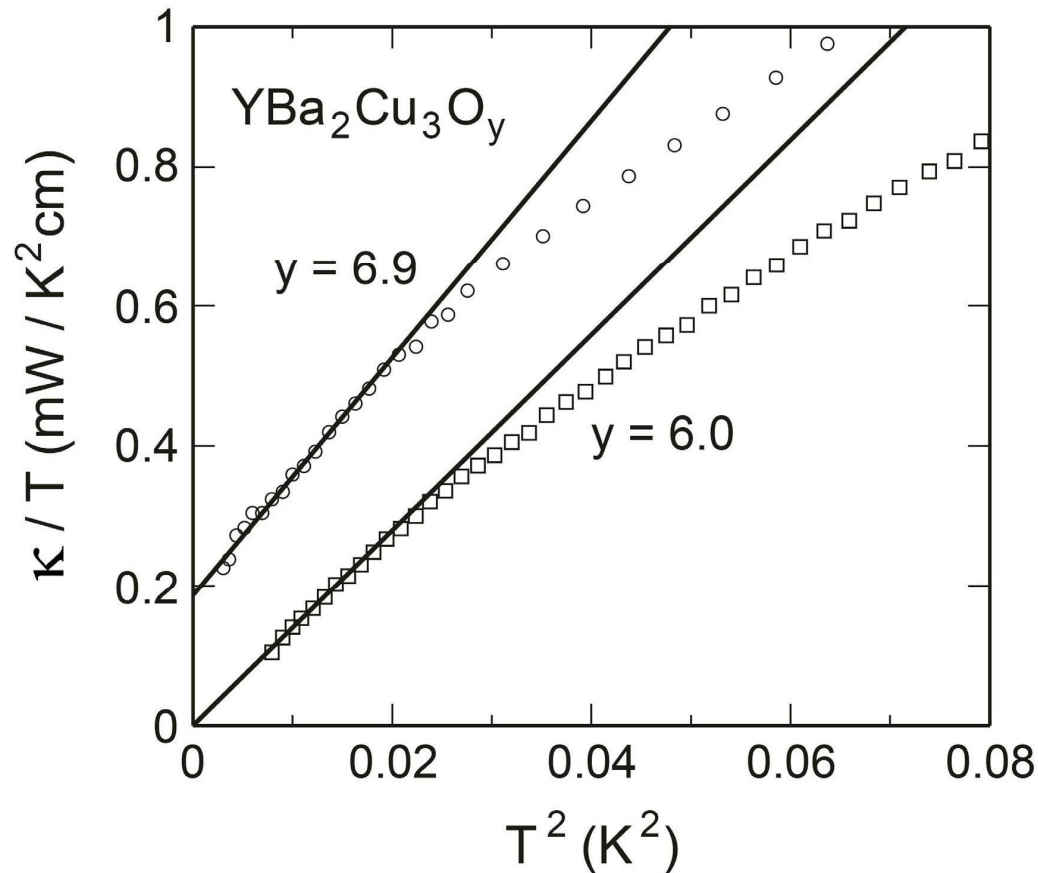


Temperature dependence of the zero-field penetration depth clearly shows that the pairing state is nodeless, best described by the two-fluid model.

Physical Review B **69**, 174505 (2004);  
Physical Review B **72**, 146502 (2005).

## *Additional experimental information*

# Specific Heat and Thermal Conductivity



Specific Heat and Thermal Conductivity  
Indicate the presence of a reservoir of  
normal excitations below  $T_C$ .

International Journal of Modern Physics Letters B **19**, 147 (2005).

# Summary and Conclusions<sup>1</sup>

- Monovalent substitution induces impurity scattering, increasing the OIE in  $T_C$  according to the standard pair breaking formula.
- Heterovalent substitution increases the OIE through an additional enhanced pair breaking which scales with the scattering rate.
- Changing the charge on BaO layer greatly depresses  $T_C$  and increases the OIE.
- Site-specific OIE data show that Pr-on-Ba-site defects induces increased electron-phonon scattering only in the  $\text{CuO}_2$  planes.
- The OIE in the magnetic penetration depth is found to be constant, with degradation of  $T_C$  up to 50%, and thus is unrelated to the OIE in  $T_C$ .
- We posit that in a perfect high- $T_C$  material, the OIE at optimum stoichiometry is identically zero (the small OIE at optimum stoichiometry arises from the imperfections inherent in the growth process).
- The pairing state is nodeless, best described by the two-fluid model.
- There exists a pool of normal electrons below  $T_C$ .
- Coulomb interactions involving holes in the BaO layers and normal electrons in the  $\text{CuO}_2$  planes (or their equivalent) govern the high- $T_C$  mechanism.

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<sup>1</sup> [Physical Review B 77, 024523 \(2008\).](#)