Isotope Effect in High-$T_{c}$ Superconductors

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Major Conclusions

- Correct identification of Pr-on-Ba-site defects as responsible for the oxygen isotope effect (OIE) in Pr-doped YBa$_2$Cu$_3$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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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*

\[(Y_{1-x}Pr_x)Ba_2Cu_3O_{7-\delta}\]

→ Assume that Pr doped **only** the Y sites

*Actual Material*

\[(Y_{1-x+y}Pr_xBa_{2-y})Cu_3O_{7-\delta}\]

→ Some \((y < 5\%)\) of the Pr actually dopes the Ba sites
**PrBa$_2$Cu$_3$O$_{7-\delta}$**

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

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

Therefore, Pr$^{+3}$ substituting for Y$^{+3}$

i.e., **monovalent** substitution

Does not affect the superconductivity

Like all rare-earth substitutions for Y

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Since Pr$^{3+}$ substituting for 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.$^1$)

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

...One would expect the opposite

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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
**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$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ data fall on the solid (enhanced OIE) line, as predicted.
Data show that as Pr-on-Ba-site defects are introduced, the OIE only occurs in the 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 CuO$_2$ layers.

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

Specific Heat and Thermal Conductivity

Indicate the presence of a reservoir of normal excitations below $T_C$.

Summary and Conclusions\textsuperscript{1}

- 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 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 CuO$_2$ planes (or their equivalent) govern the high-$T_C$ mechanism.

\textsuperscript{1} Physical Review B 77, 024523 (2008).