Oxygen Isotope Effects in Novel Superconductors

Alexander Shengelaya

Tbilisi State University, Georgia

5th Georgian-German Workshop in Basic Science August 2012

Discovery of the isotope effect in mercury

Isotope Effect in the Superconductivity of Mercury*

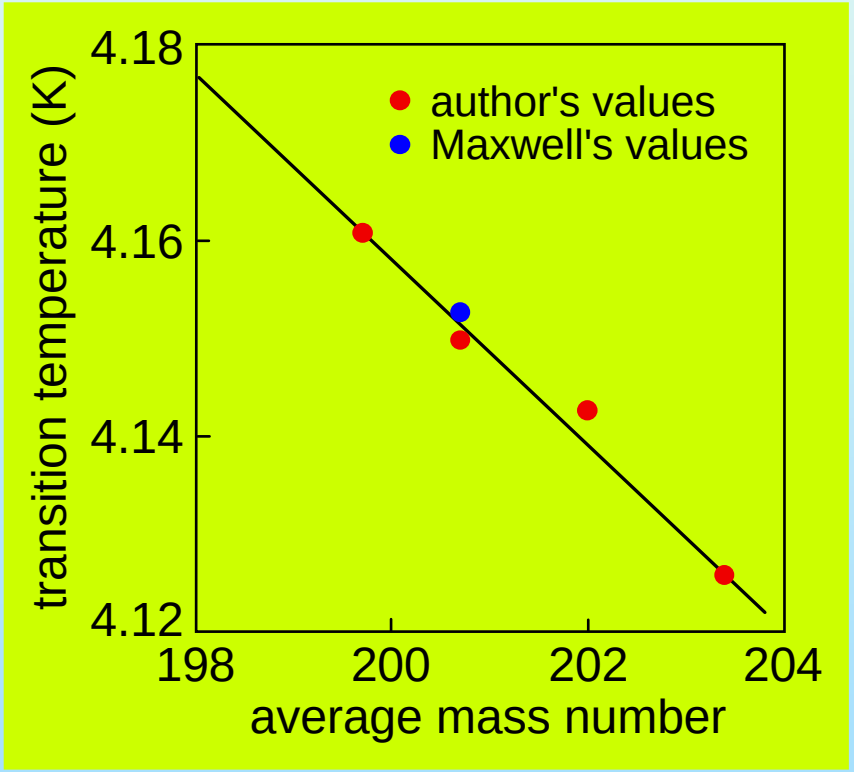
EMANUEL MAXWELL
National Bureau of Standards, Washington, D. C.
March 24, 1950

Phys. Rev. **78**, 477 (1950)

Superconductivity of Isotopes of Mercury*

C. A. REYNOLDS, B. SERIN, W. H. WRIGHT, AND L. B. NESBITT
Rutgers University, New Brunswick, New Jersey
March 24, 1950

Phys. Rev. **78**, 487 (1950)



$$T_c \propto M^{-\alpha} \quad \Rightarrow \quad \alpha = 0.43(6)$$

The Nobel Prize in Physics 1972

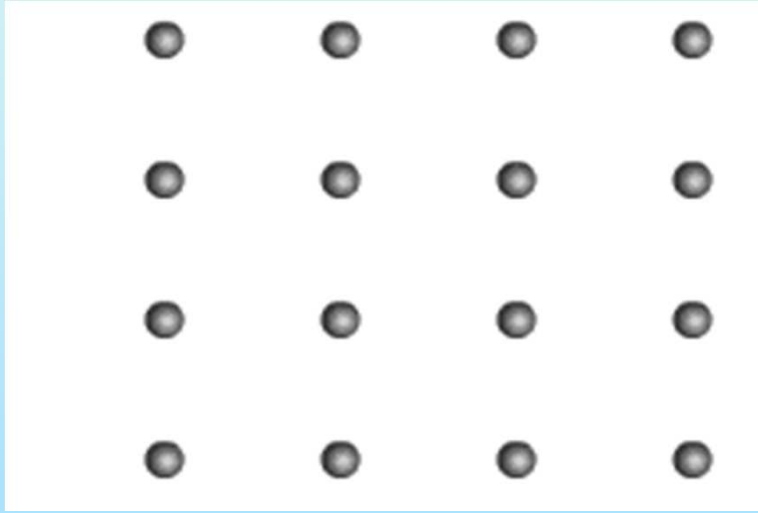
"for their jointly developed theory of superconductivity, usually called the BCS-theory"

John Bardeen

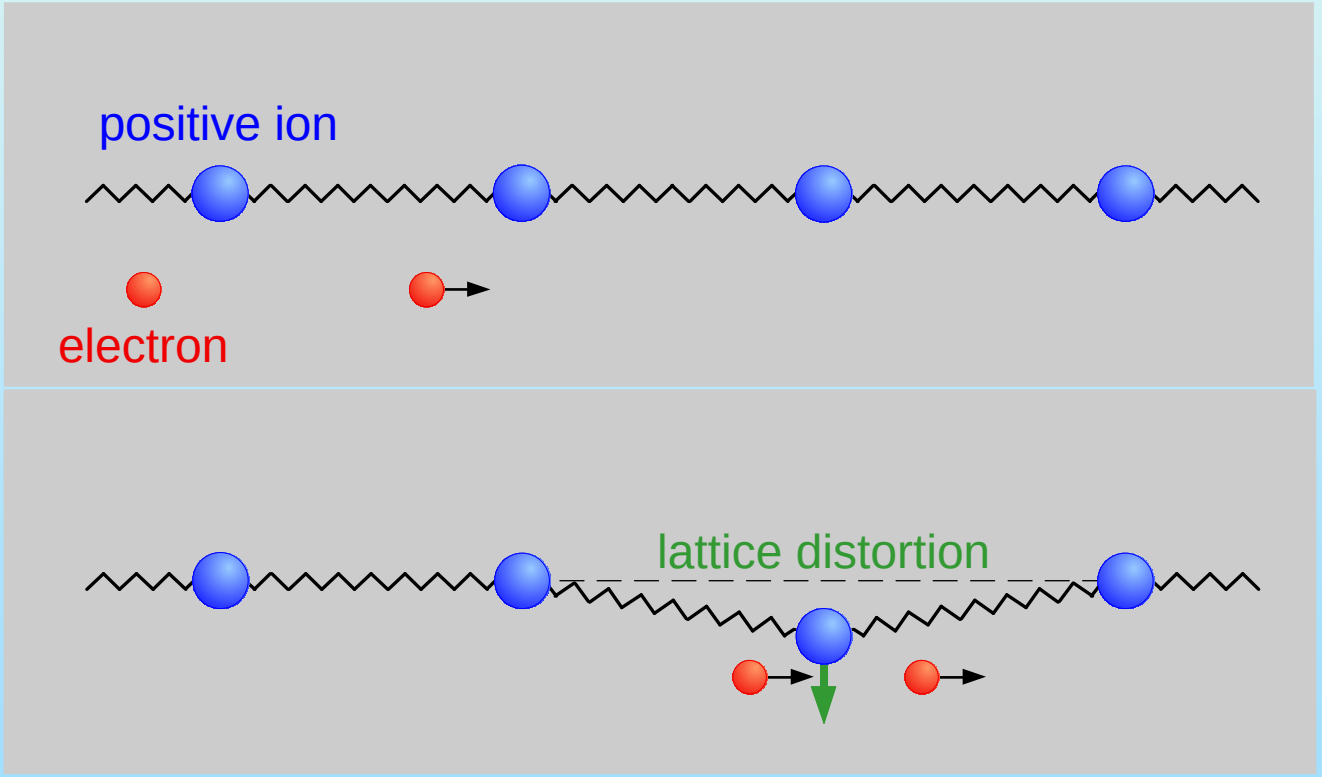
Leon Neil Cooper

John Robert Schrieffer

ზეგამტარობის მექანიზმი : ელექტრონების დაწყვილება - კუპერის წყვილები



phonons



Isotope effect

BCS theory (1957)

$$T_c \propto \omega_D \exp(-1/\lambda)$$

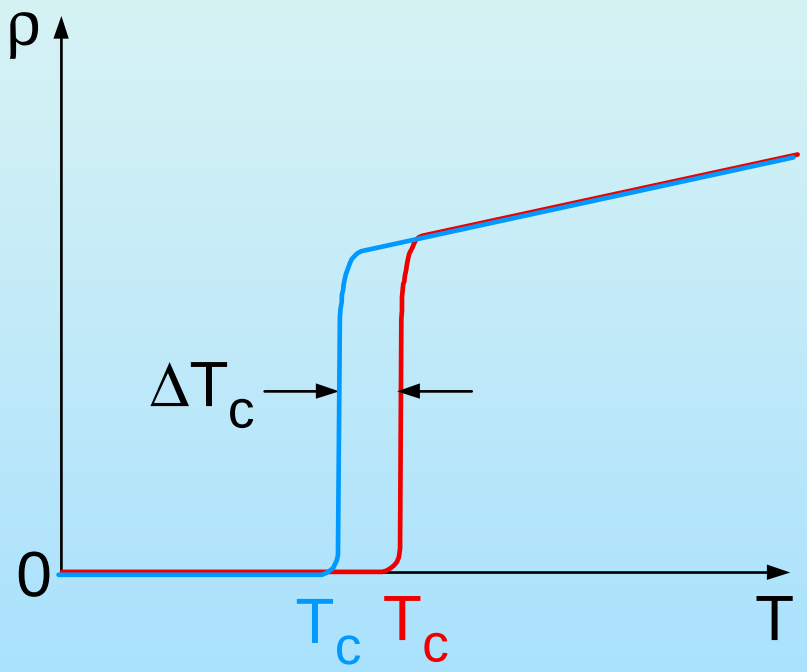
$$T_c \propto M^{-\alpha} \qquad \alpha = -d\ln T_c / d\ln M$$

$$\alpha_{BCS} = 1/2$$

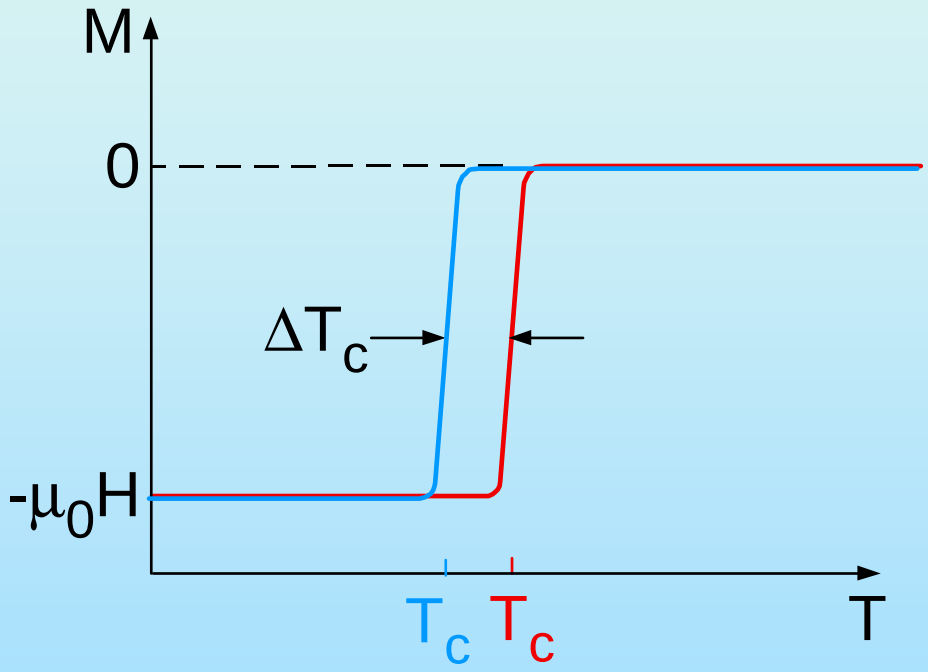
ω_D : typical phonon frequency (Debye frequency)
λ : electron-phonon coupling constant

Isotope effect on T_c

resistivity ρ



magnetization M



M > M

$T_c \propto M^{-\alpha}$ $\alpha = d\ln T_c / d\ln M$

Isotope effect

Experimental results for “simple” metals

Material	Symbol	T_c	α
Cadmium	Cd	0.5	0.5
Carbon (fullerene)		30	0.25
Lead	Pb	7.2	0.48
Mercury	Hg	4.1	0.5
Molybdenum	Mo	0.9	0.37
Osmium	Os	0.7	0.20
Rhenium	Re	1.7	0.23
Ruthenium	Ru	0.5	0±0.05
Thallium	Tl	2.4	0.50
Tin	Sn	3.7	0.47
Zinc	Zn	0.9	0.45
Zirconium	Zr	0.6	0±0.05

Theoretical models

exchange of virtual bosons in a polarizeable medium

pairing $\Leftrightarrow$ attractive interaction between electrons

$$k_B T_c \approx E_0 \exp(-1/\lambda)$$

E_0: energy scale of the interaction
λ : coupling constant (weak coupling)

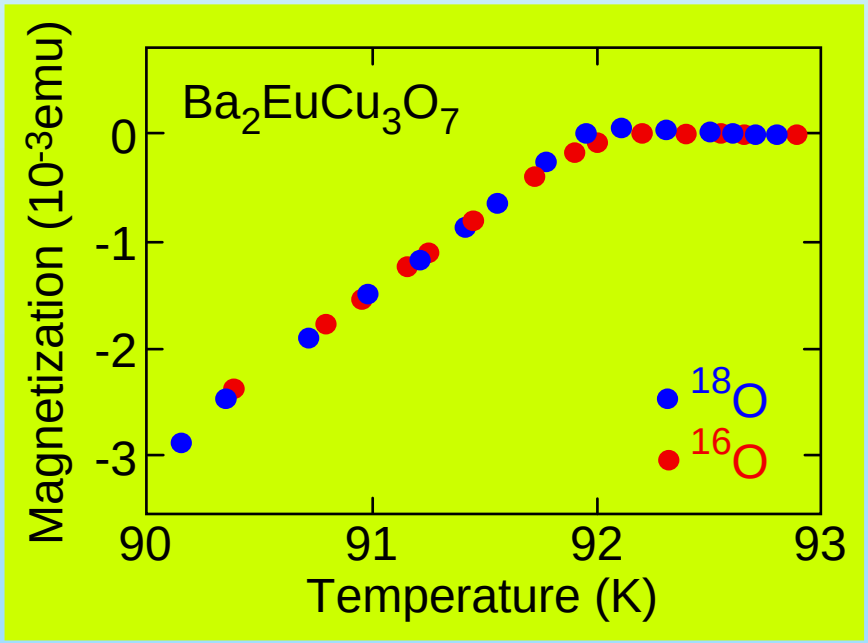
Theoretical models of superconductivity

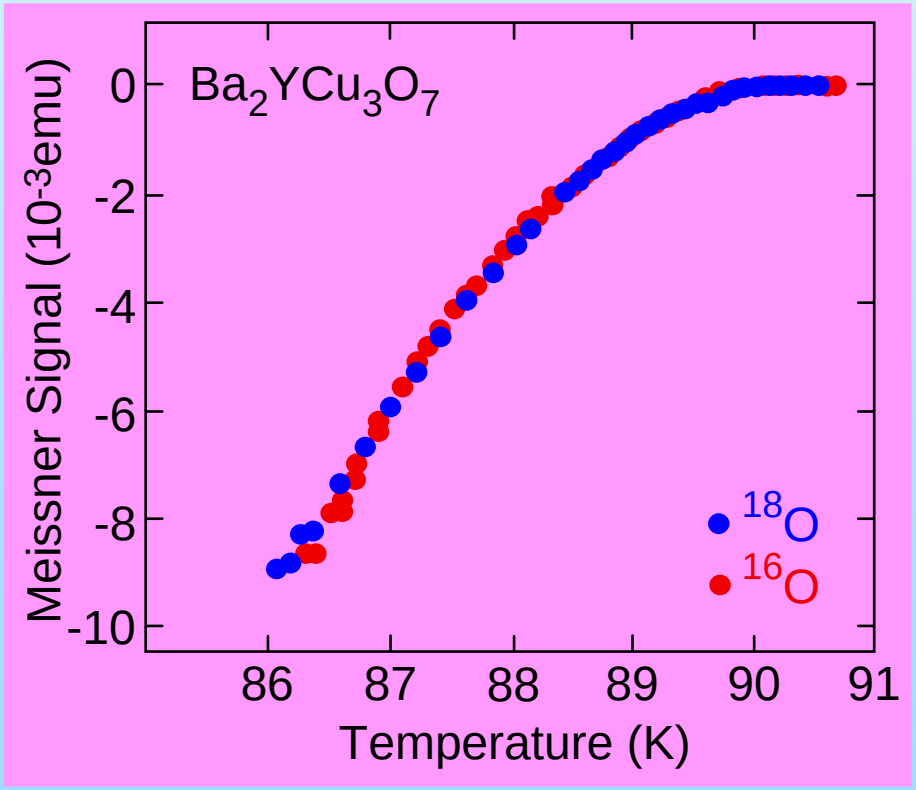
polarizeable medium	excitation (virtual boson)	type of carrier
crystal lattice	phonon	electron/ defect electron
	phonon	polaron (electron + lattice deformation)
electron system	plasmon	electron
	exziton	electron
spin system	spin fluctuations (magnon)	electron

VOLUME 58, NUMBER 22 PHYSICAL REVIEW LETTERS 1 JUNE 1987

Isotope Effect in the High-T_c Superconductors $Ba_2YCu_3O_7$ and $Ba_2EuCu_3O_7$

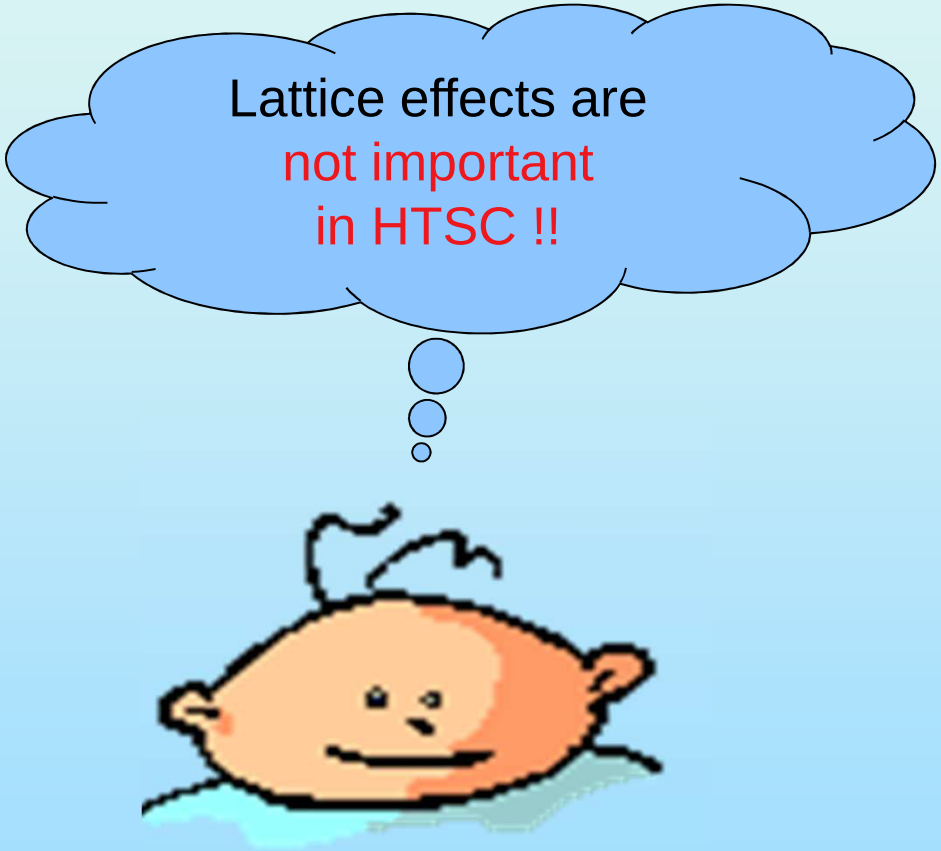
B.Batlogg, R.J.Cava, A.Jayaraman, R.B.van Dover, G.A.Kourouklis, [a]S.Sunshine, D.W.Murphy, L.W.Rupp, H.S.Chen, A.White, K.T.Short, A.M.Mujsce, and E.A.Rietman
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 24 April 1987)





Oxygen-isotope effect on T_C in $YBa_2Cu_3O_7$: Early results

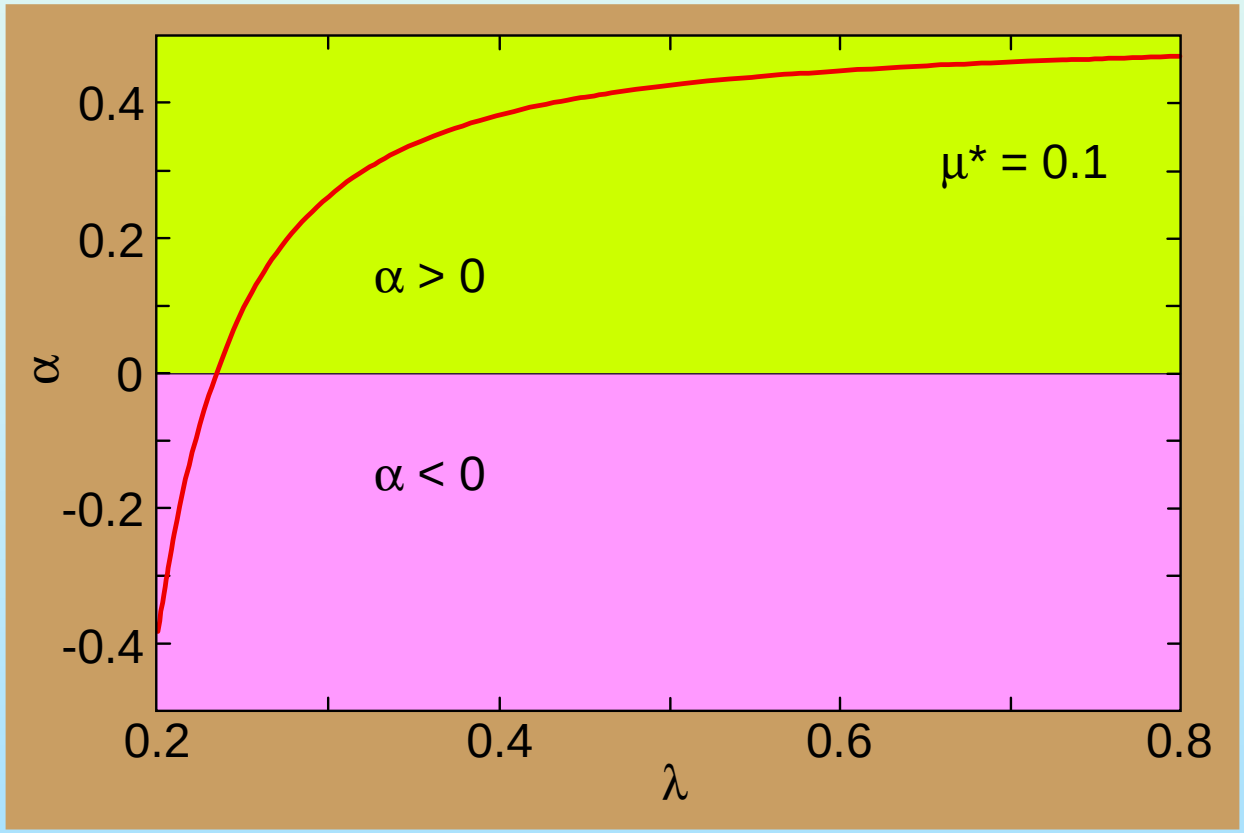
System	T_C (K)	^{18}O (%)	ΔT_C (K)	α_O	Reference
$YBa_2Cu_3O_7$	92.1	75	< 0.1	0 ± 0.02	Batlogg et al. (1987)
$EuBa_2Cu_3O_7$	92.15	75	< 0.1	0 ± 0.02	Batlogg et al. (1987)
$YBa_2Cu_3O_7$	90.0	(90)	<0.3	0 ± 0.027	Bourne et al. (1987)
$YBa_2Cu_3O_7$	92.1 91.4 91.5	90 75 73	0.5 0.3 0.4	0.05 0.04 0.05	Leary et al. (1987)



Is this correct?

- Isotope effect is small ⇒ electron-phonon interaction is not important
- Isotope effect is large ⇒ electron-phonon interaction is very important
- Need reliable experiments and adequate theory to answer this question!

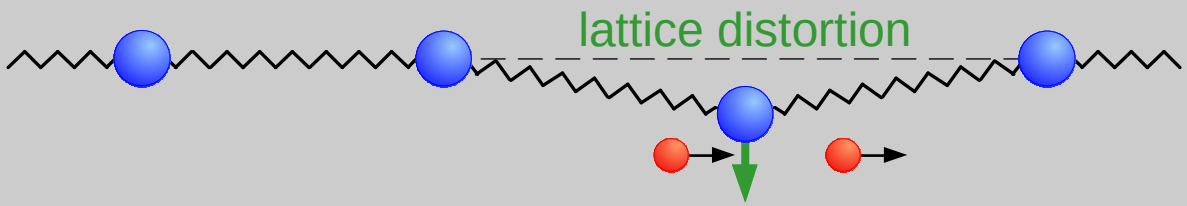
Isotope effect exponent α



$$\alpha = \frac{1}{2}\left(1 - \frac{(1+\lambda)\,(1+0.62\lambda)\,\mu^{*2}}{[\lambda-\mu^{*}\,(1+0.62\lambda)]^{2}}\right)$$

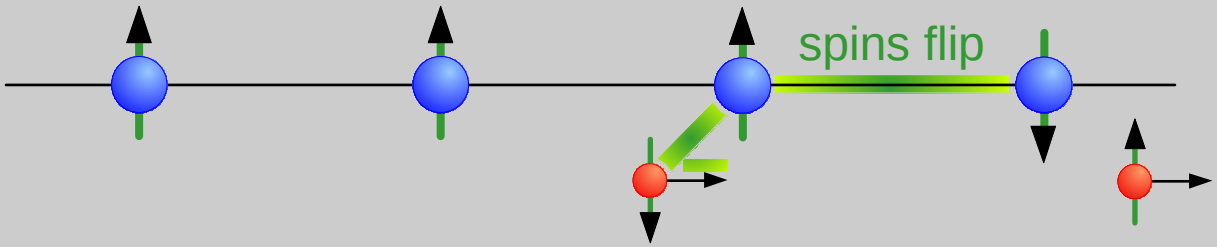
Mc Millan, Phys. Rev. **167**, 331 (1968)

phonons

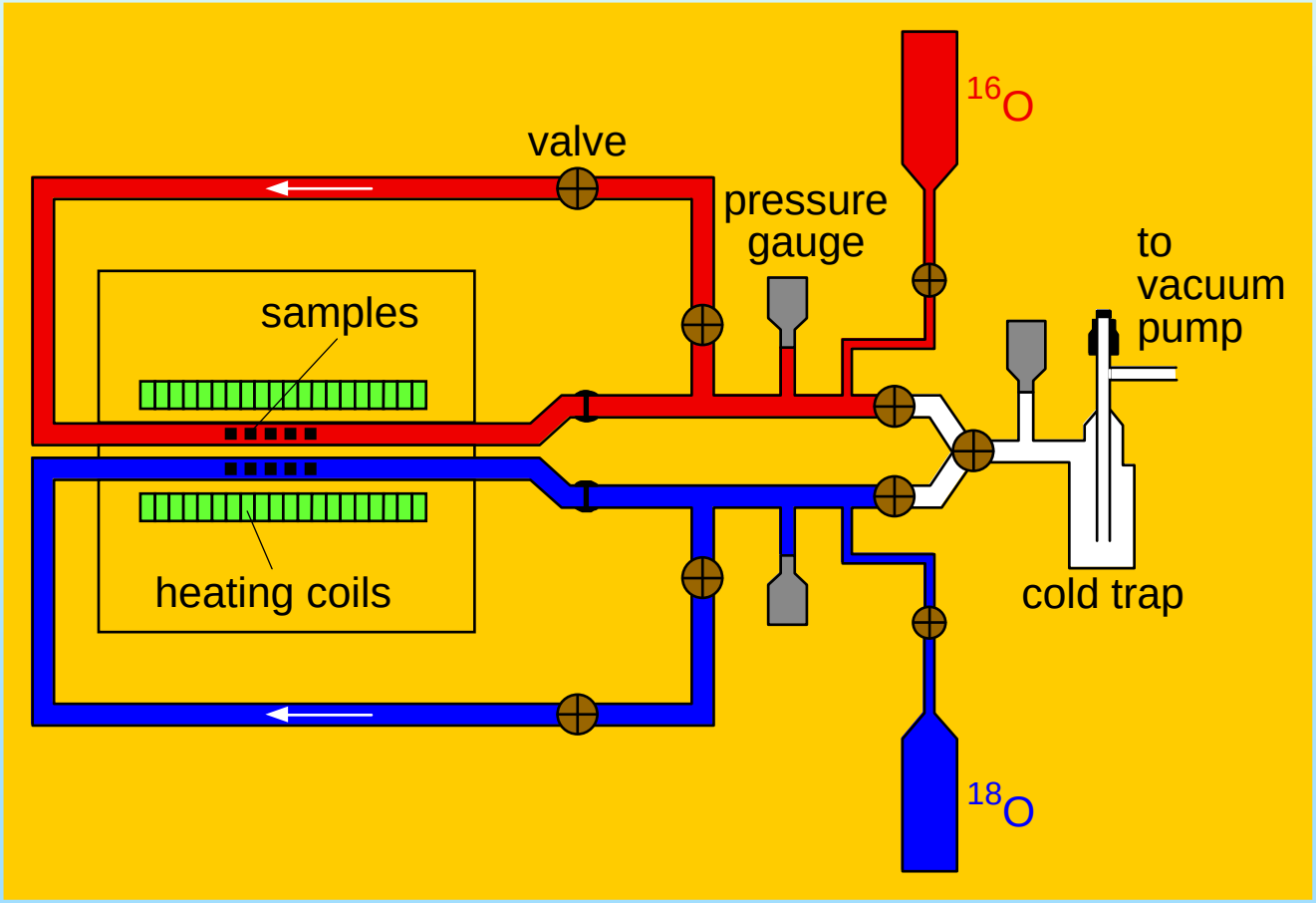


and/or ?

magnetic spin fluctuations



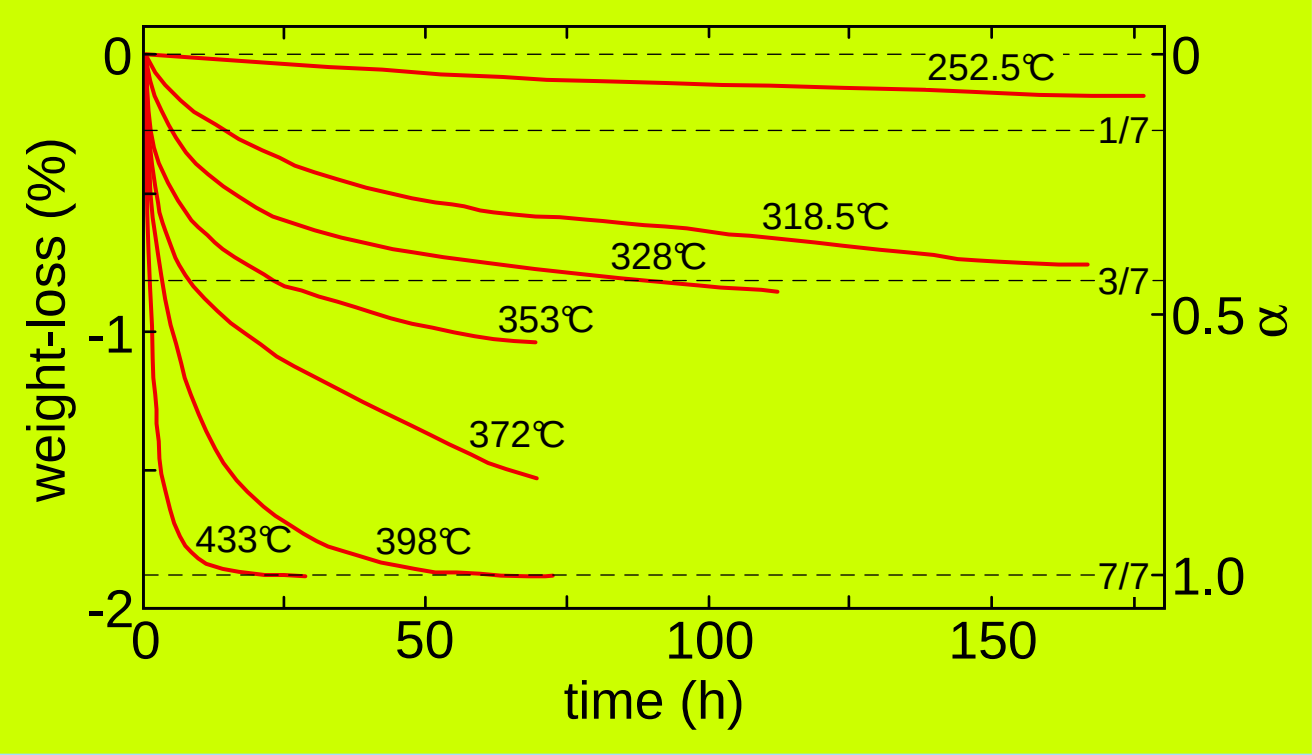
Experimental set-up for the preparation of $^{16}O/^{18}O$ samples



K. Conder, Materials Science and Engineering **R32**, 41 (2001)

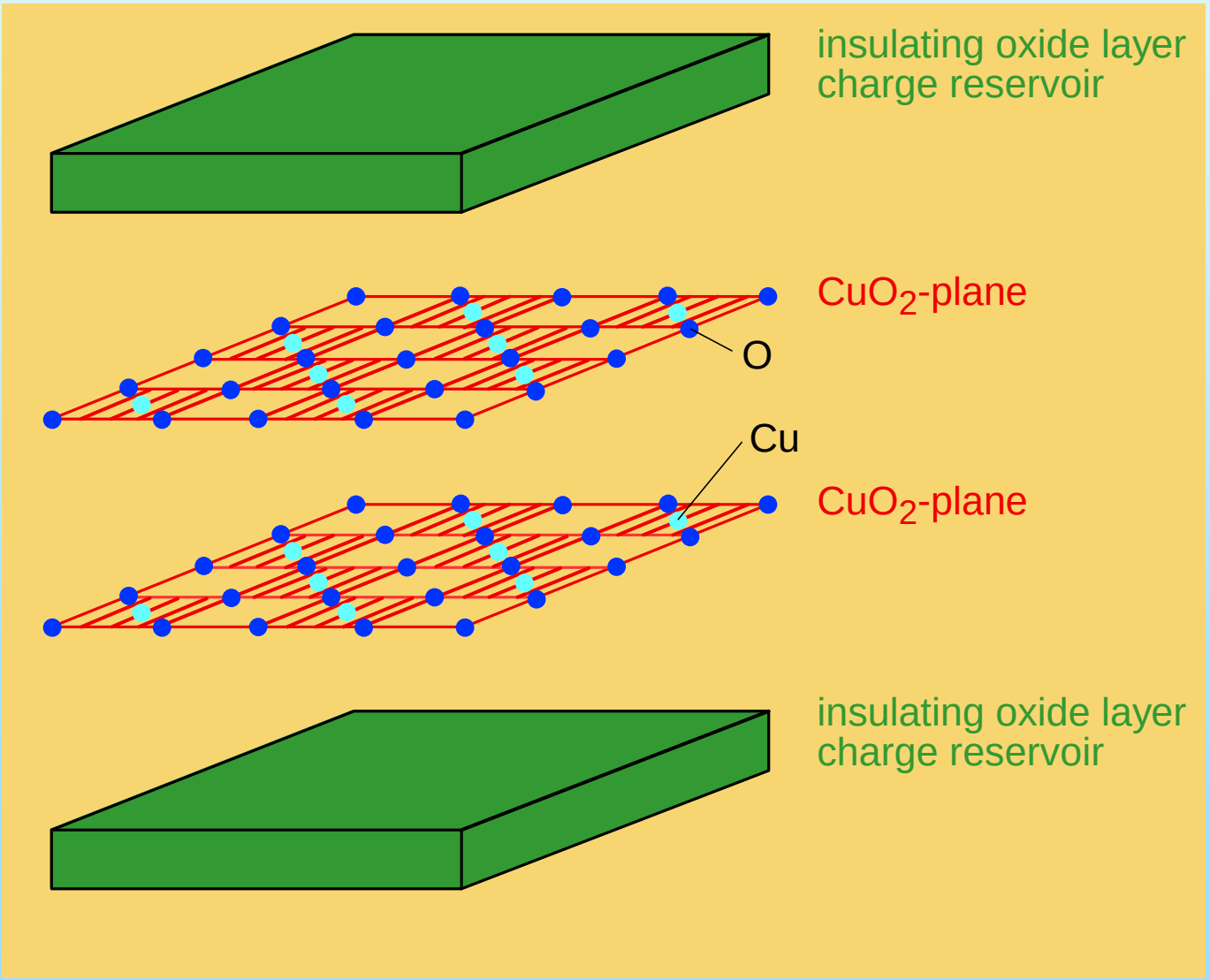
Experimental set-up for the preparation of $^{16}O/^{18}O$ samples

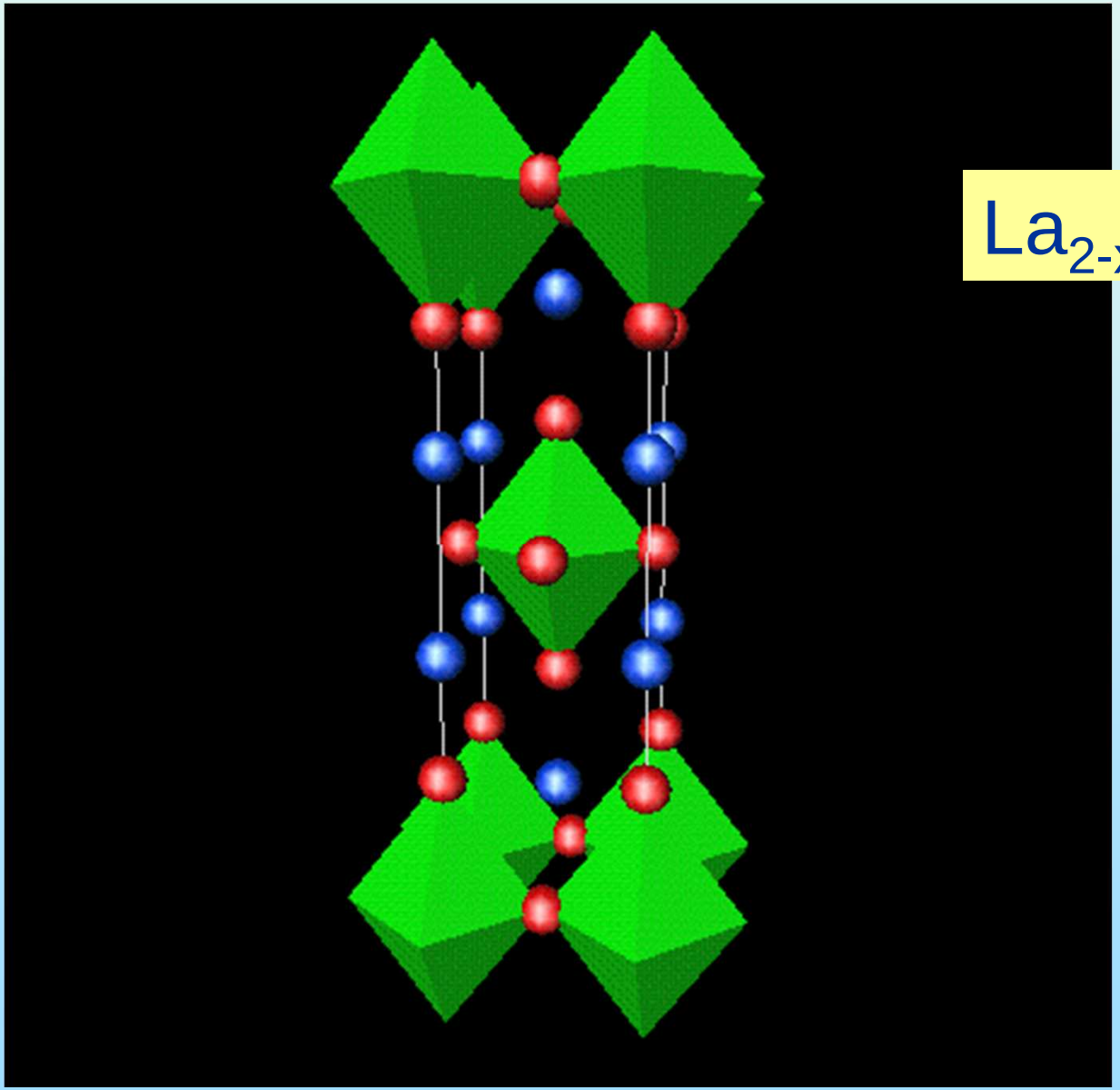
Thermogravimetric curves during isothermal oxyen exchange in Y123 substituted with ^{18}O



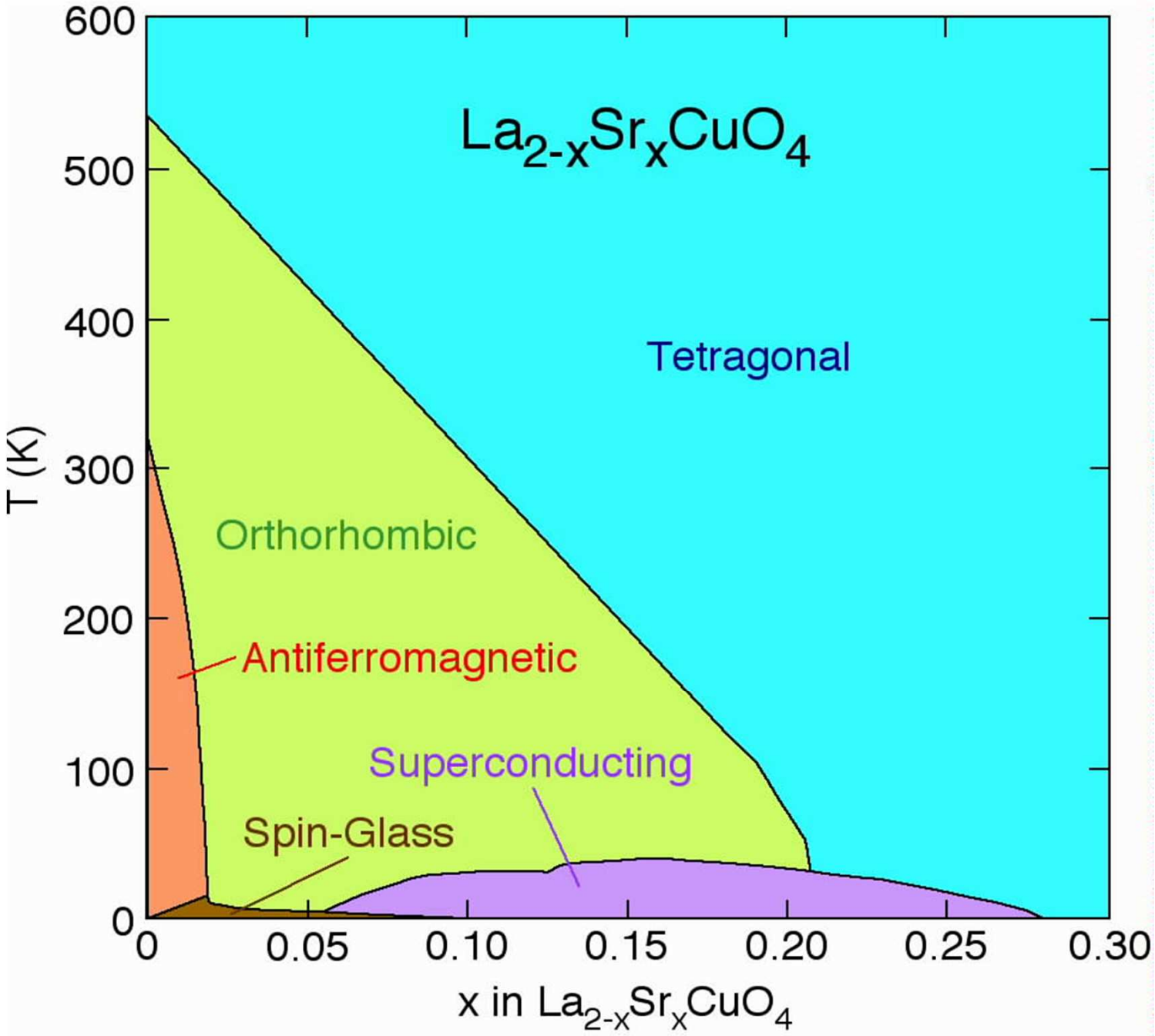
K. Conder, Materials Science and Engineering **R32**, 41 (2001)

Schematic structure of cuprate superconductors

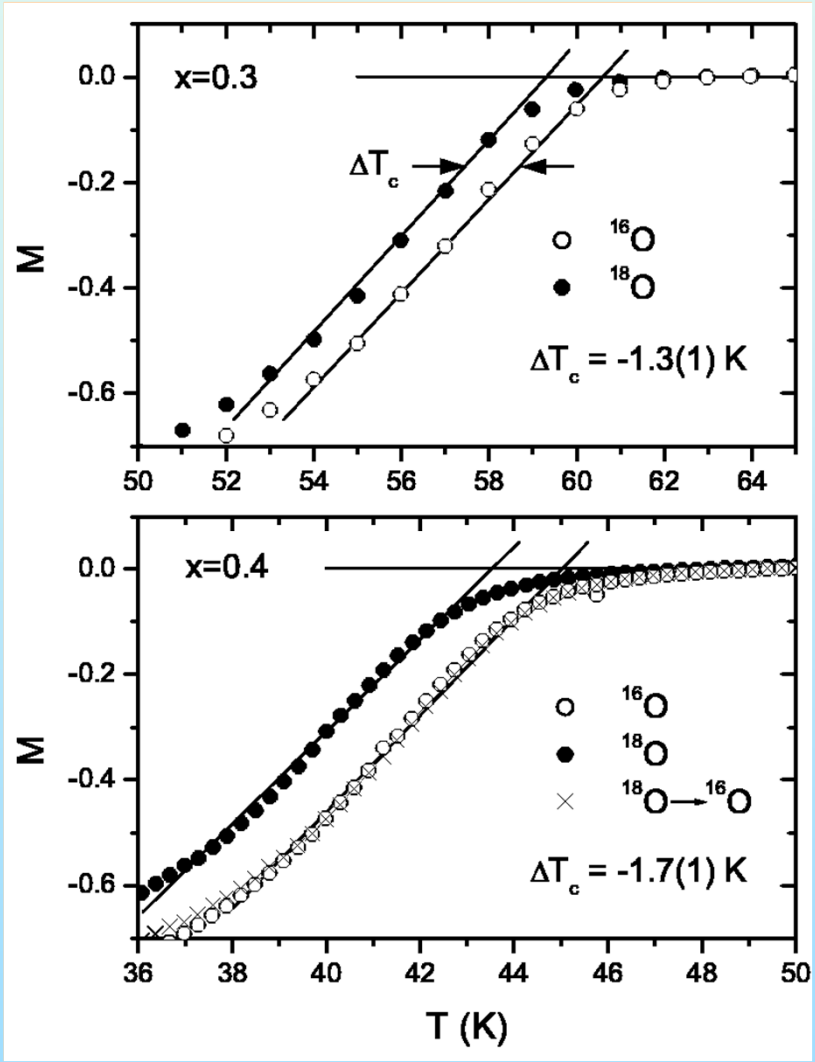




$La_{2-x}Sr_xCuO_4$


La2-xSrxCuO4
Tetragonal
Orthorhombic
Antiferromagnetic
Superconducting
Spin-Glass
T (K)
600
500
400
300
200
100
0
0
0.05
0.10
0.15
0.20
0.25
0.30
x in La2-xSrxCuO4

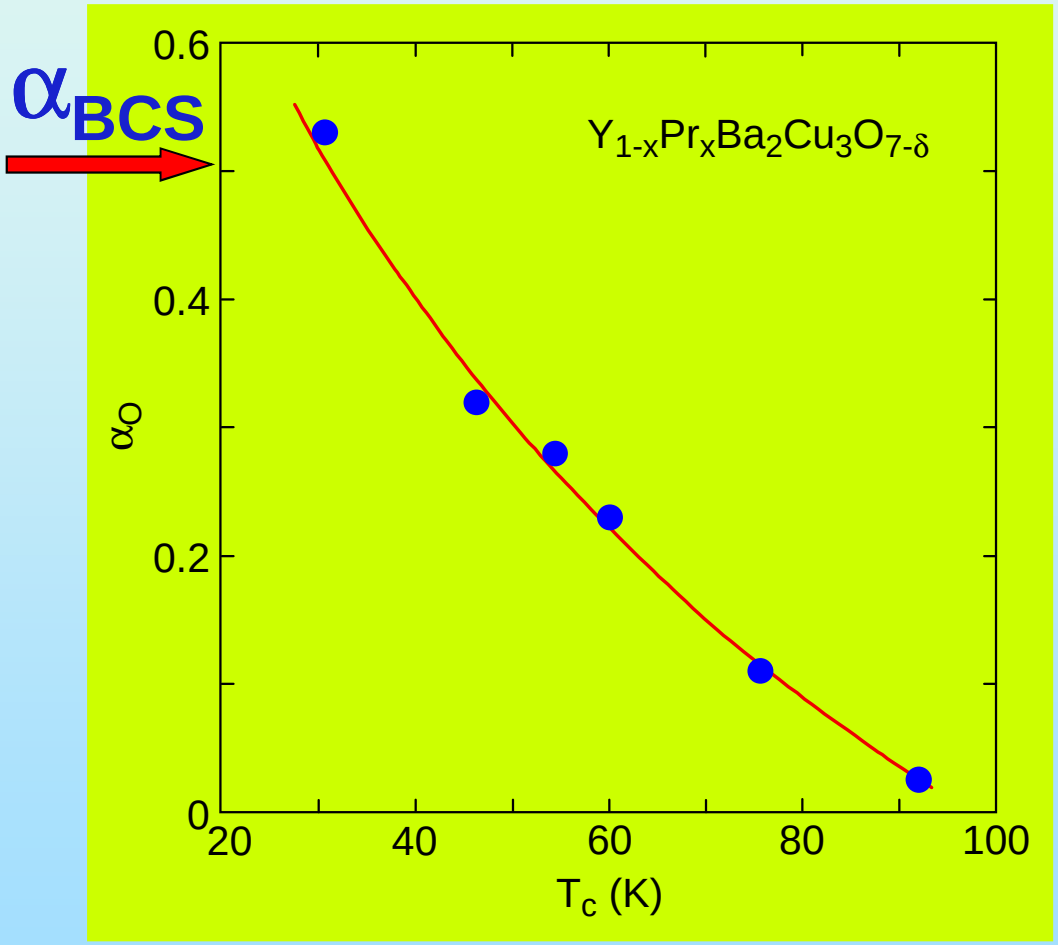
$Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$



Normalized magnetization curves:
1 mT, field cooled

Khasanov *et al*., cond-mat / 0201165

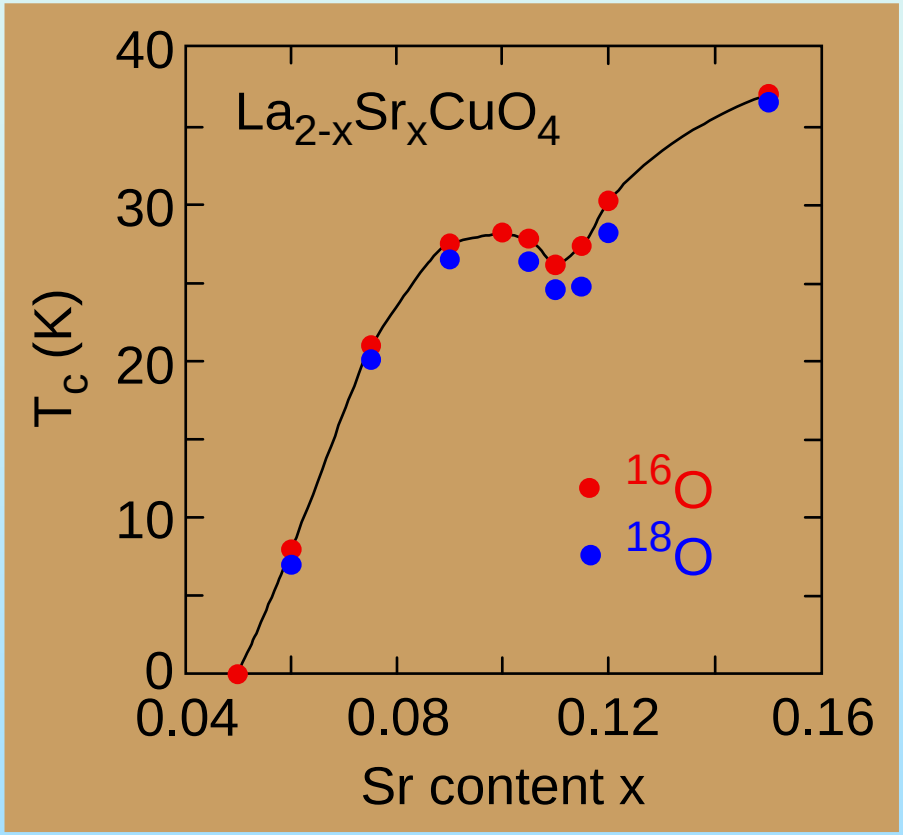
Oxygen-Isotope Effect on T_c

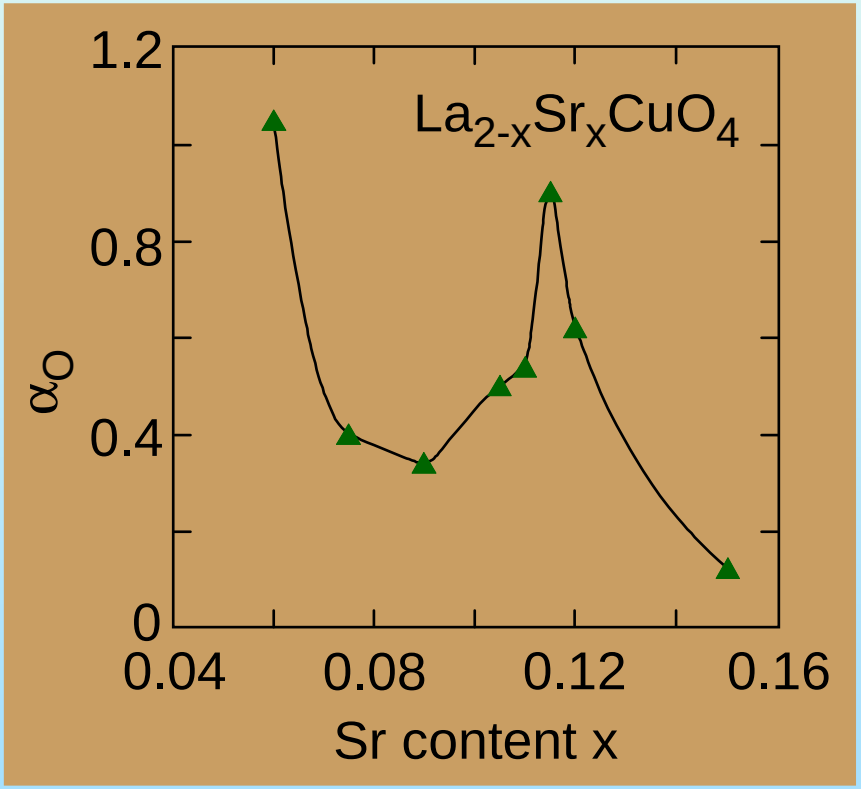


$$\alpha_O = - \frac{\Delta T_c / T_c}{\Delta M_O / M_O}$$

Franck *et al*., Phys.Rev. B **44**, 5318 (1991)

OIE on T_c in $La_{2-x}Sr_xCuO_4$

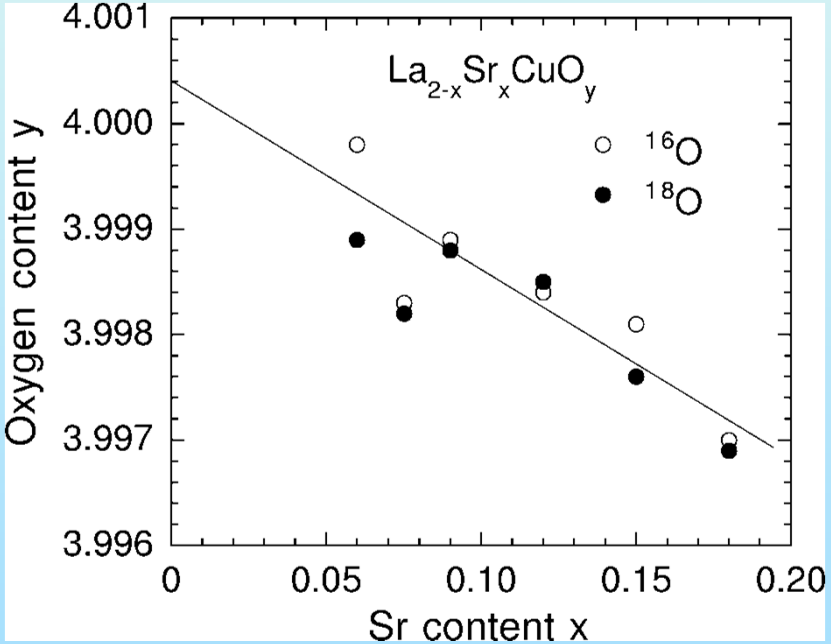




Zhao *et al.*, Nature **385**, 236 (1997)
Zhao *et al.*, J. Phys.: Condens. Matter **10**, 9055 (1998)

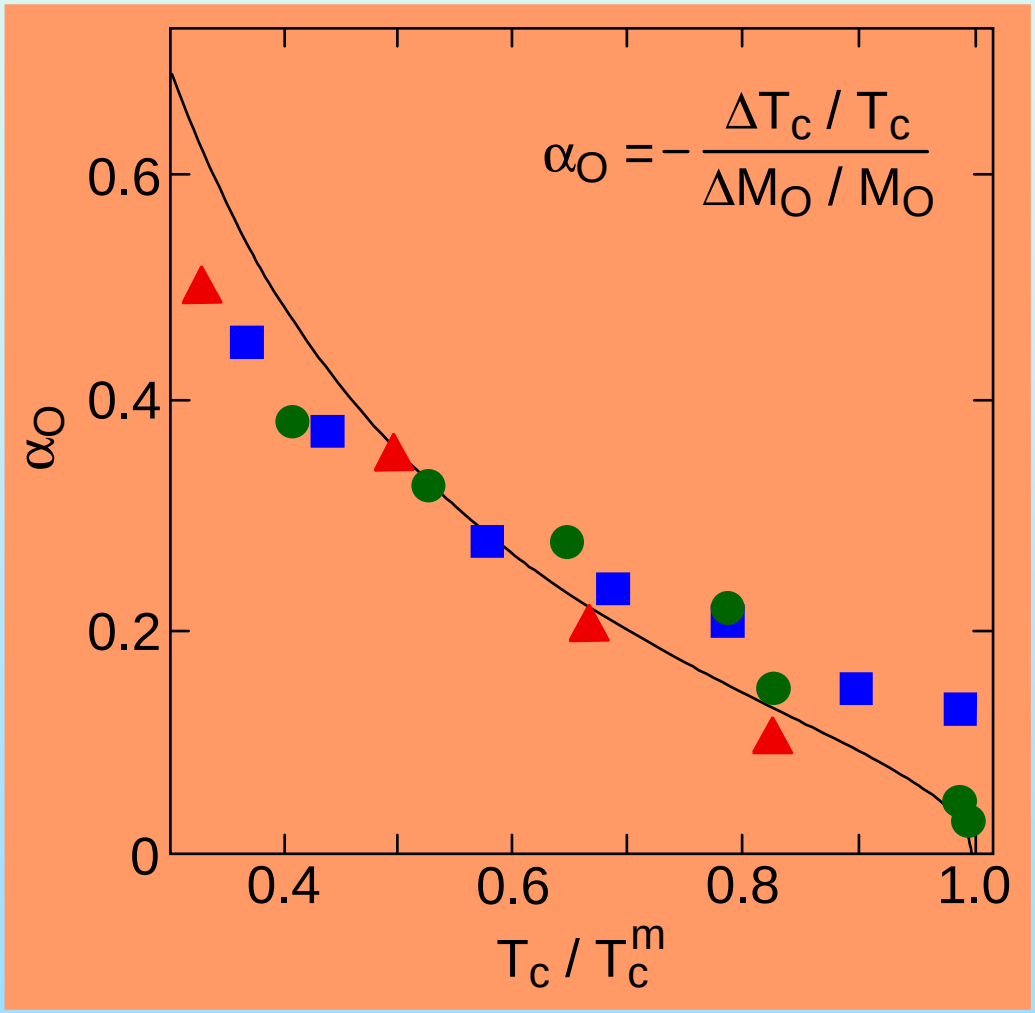
Precise volumetric analysis of the oxygen content in $La_{2-x}Sr_xCuO_y$

- Very accurate determination of the oxygen content usig a precise volumetric analysis
- Oxygen contents of sample pairs ($^{16}O/^{18}O$) with identical x are the same within +/- 0.0002 per Cu site
- $\Rightarrow$ difference in hole densities of the ^{16}O and ^{18}O samples is negligible
- $\Rightarrow$ large observed OIE are intrinsic



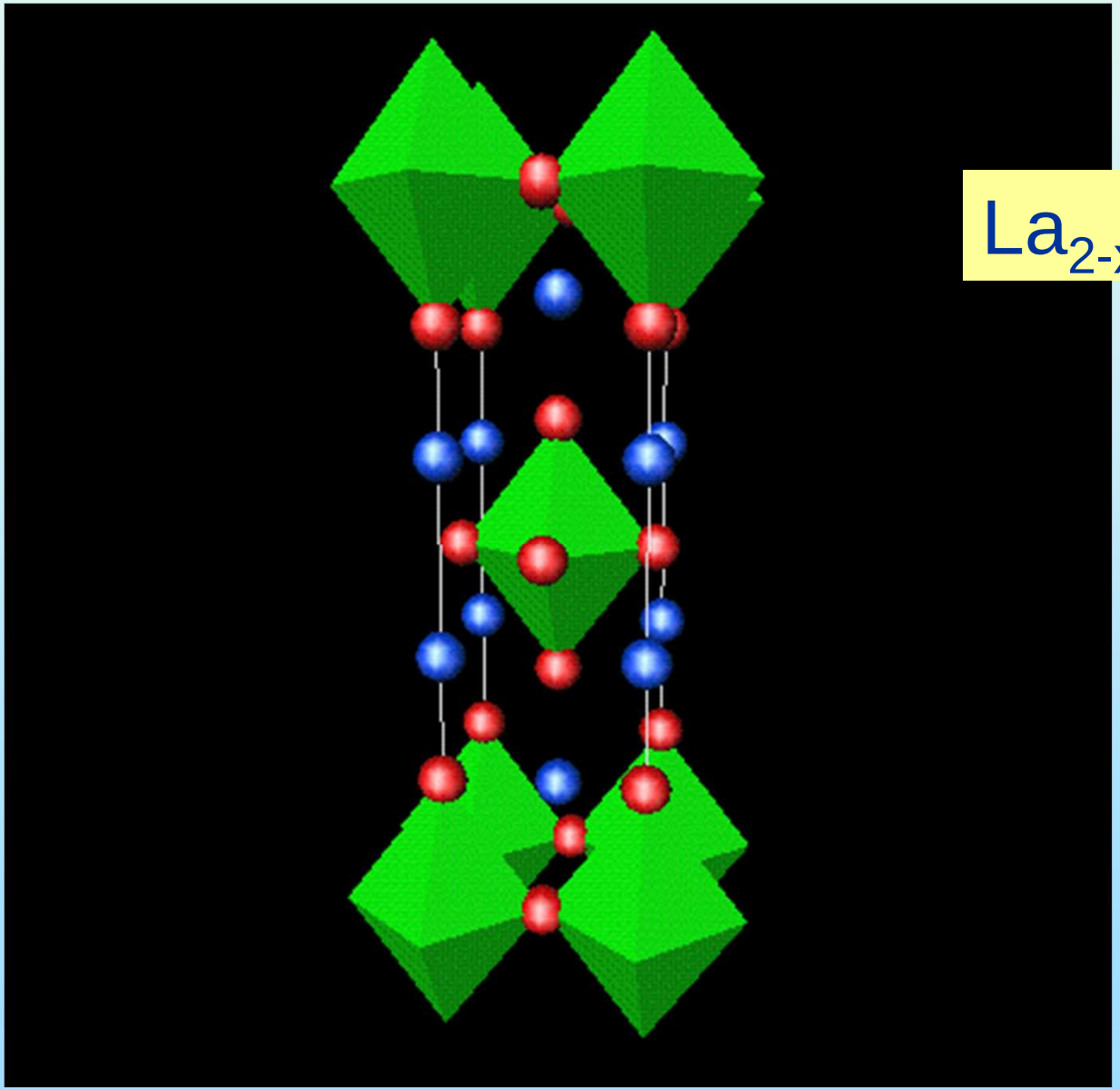
Zhao, Keller & Conder, J. Phys.: Condens. Matter **13**, R569 (2001)

Oxygen-isotope effect on T_c



- $La_{1.85}Sr_{0.15}Cu_{1-x}Ni_xO_4$
- $YBa_{2-x}La_xCu_3O_z$
- $Y_{1-x}Pr_xCa_yBa_2Cu_3O_7$

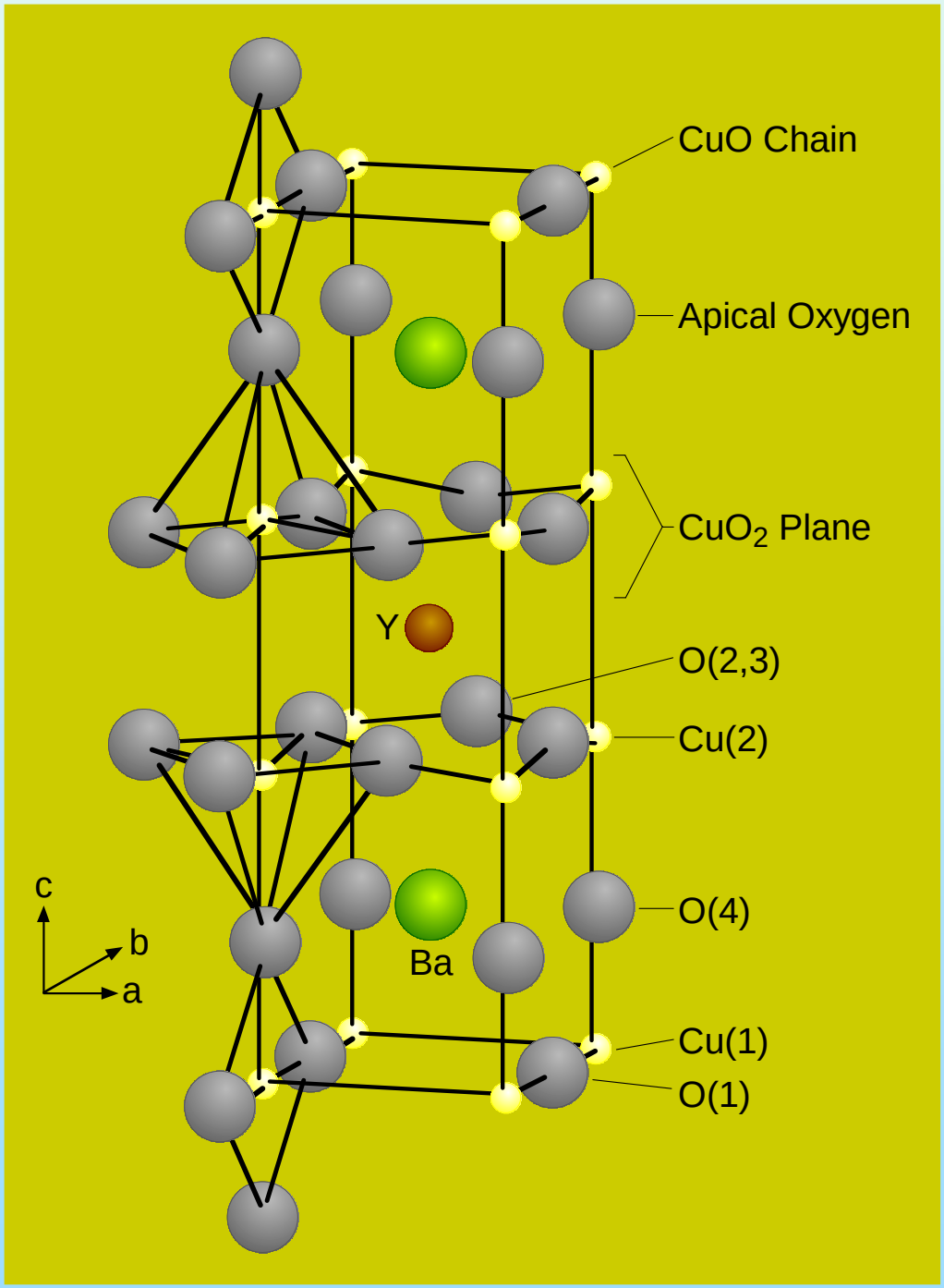
Schneider and Keller, PRL. **69**, 3374 (1992)



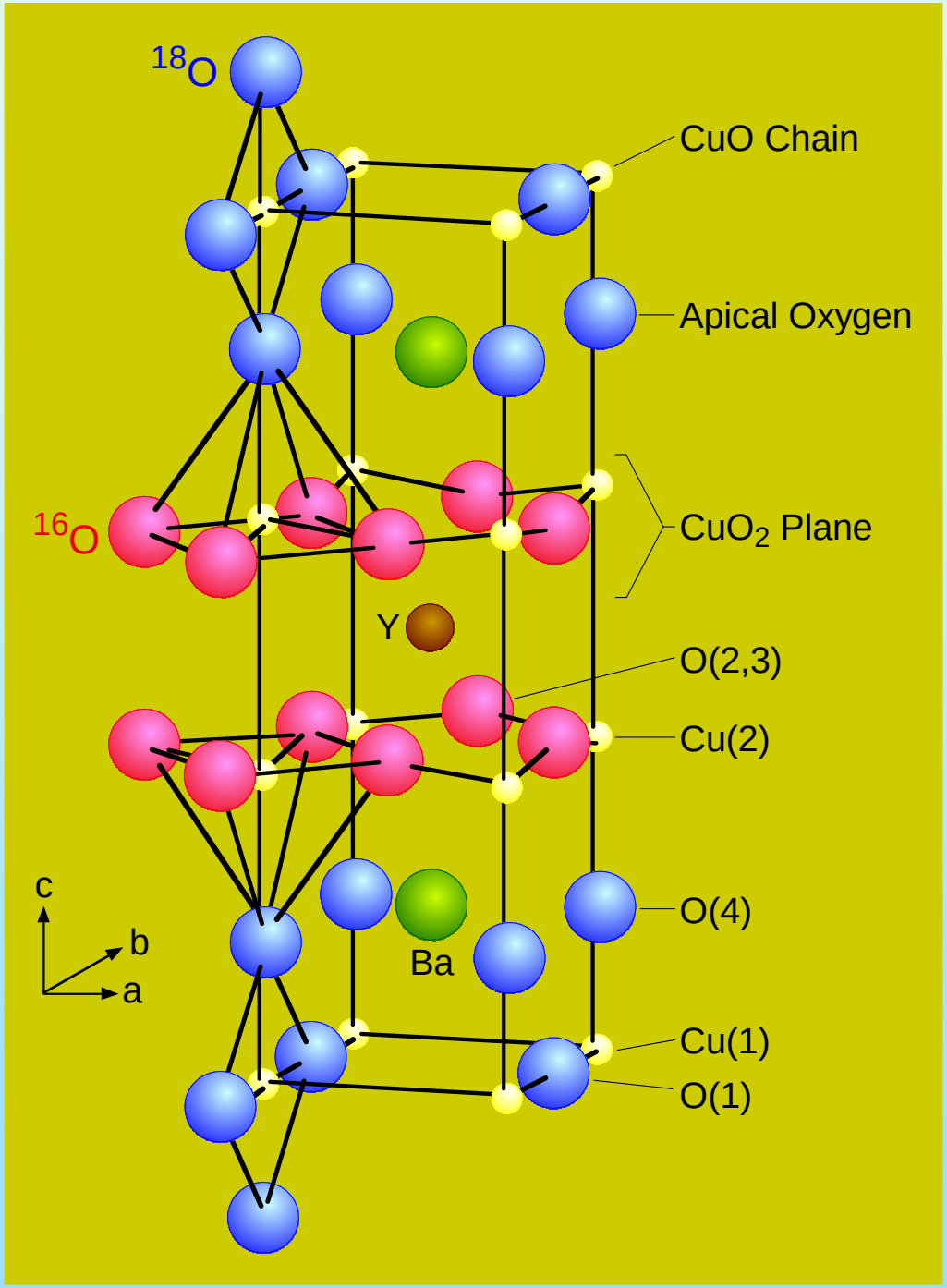
$La_{2-x}Sr_xCuO_4$

Site-selective oxygen-isotope effect experiment ?

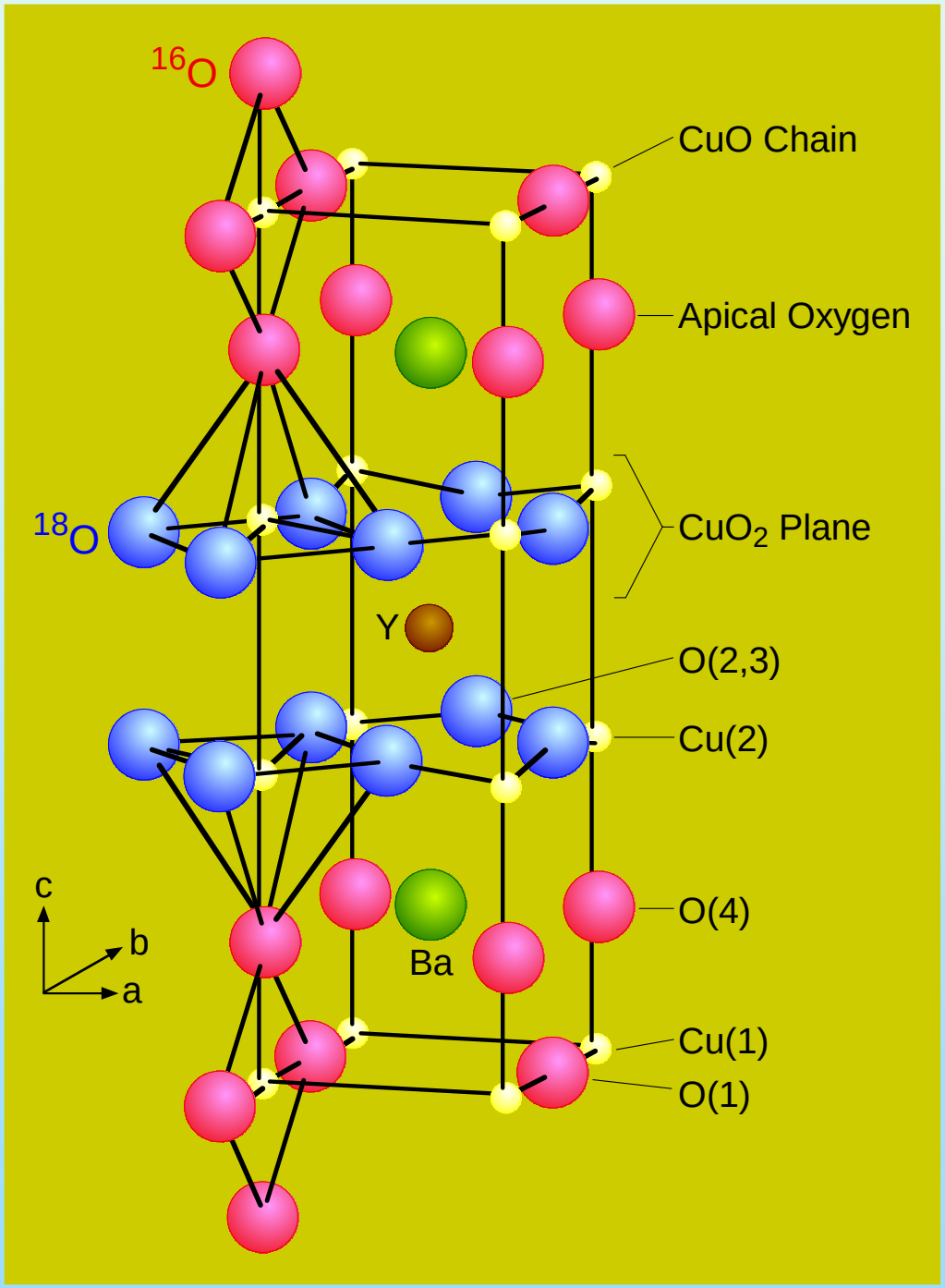
Structure of $YBa_2Cu_3O_x$

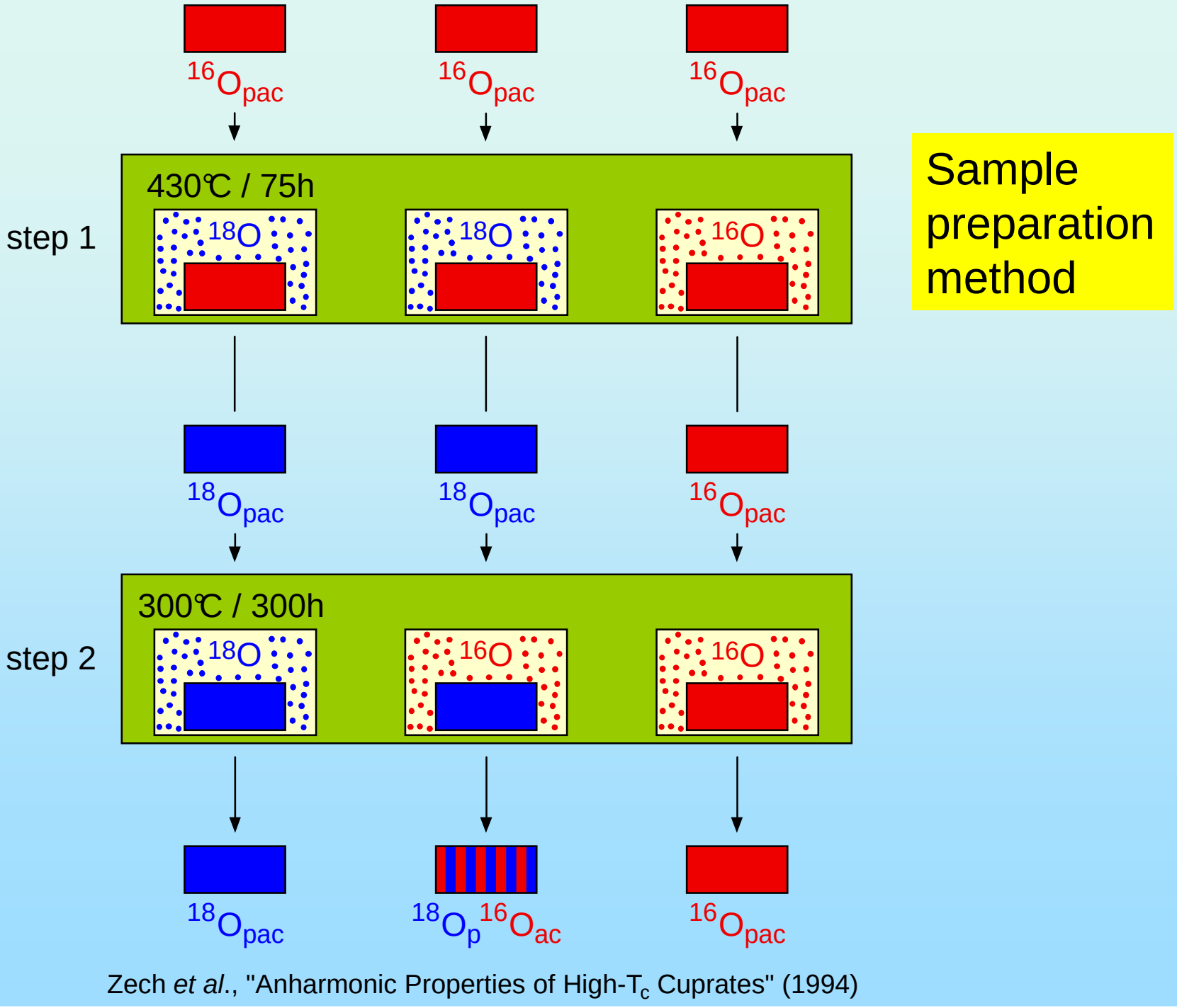


Structure of $YBa_2Cu_3O_x$



Structure of $YBa_2Cu_3O_x$



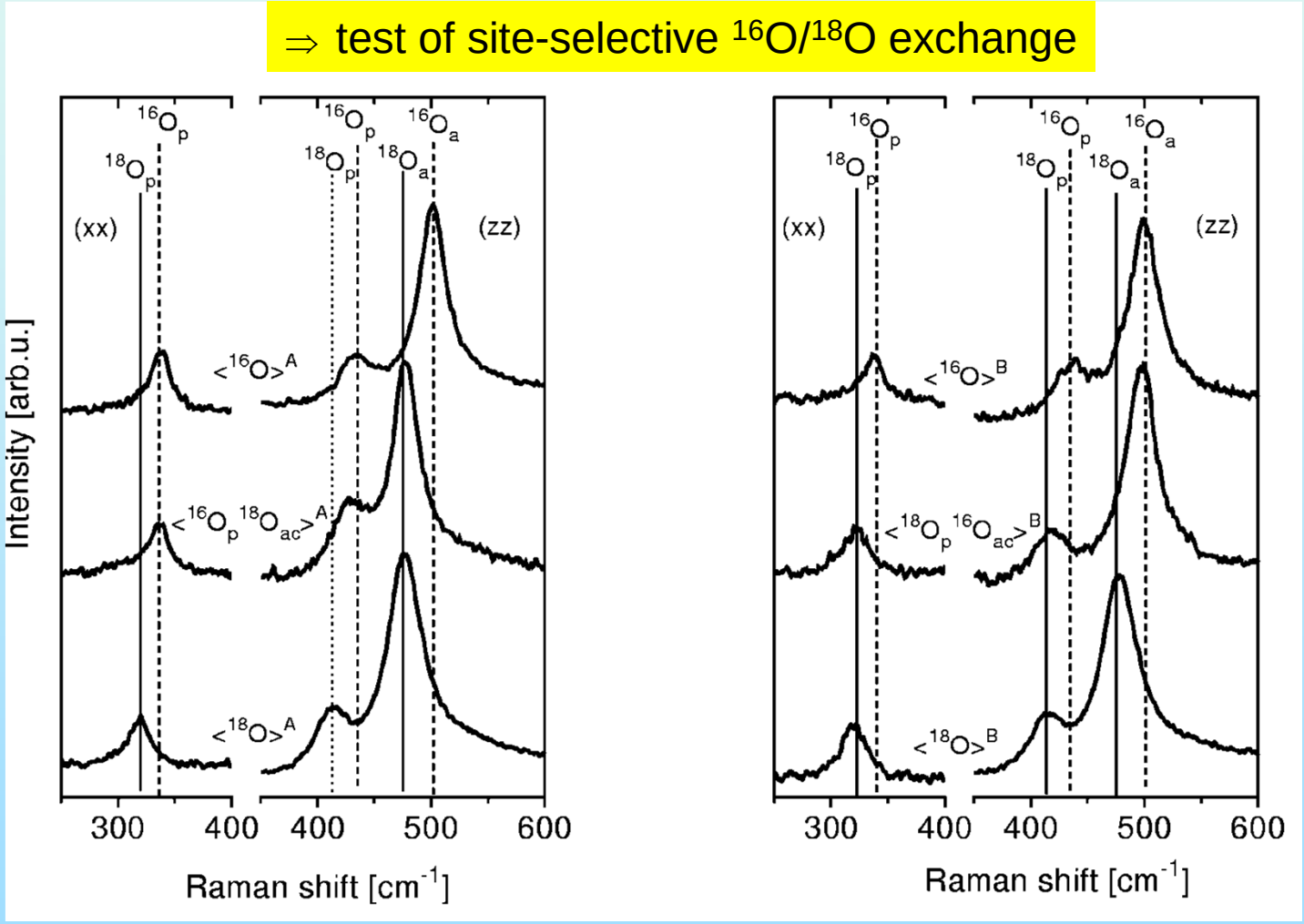


Sample preparation method

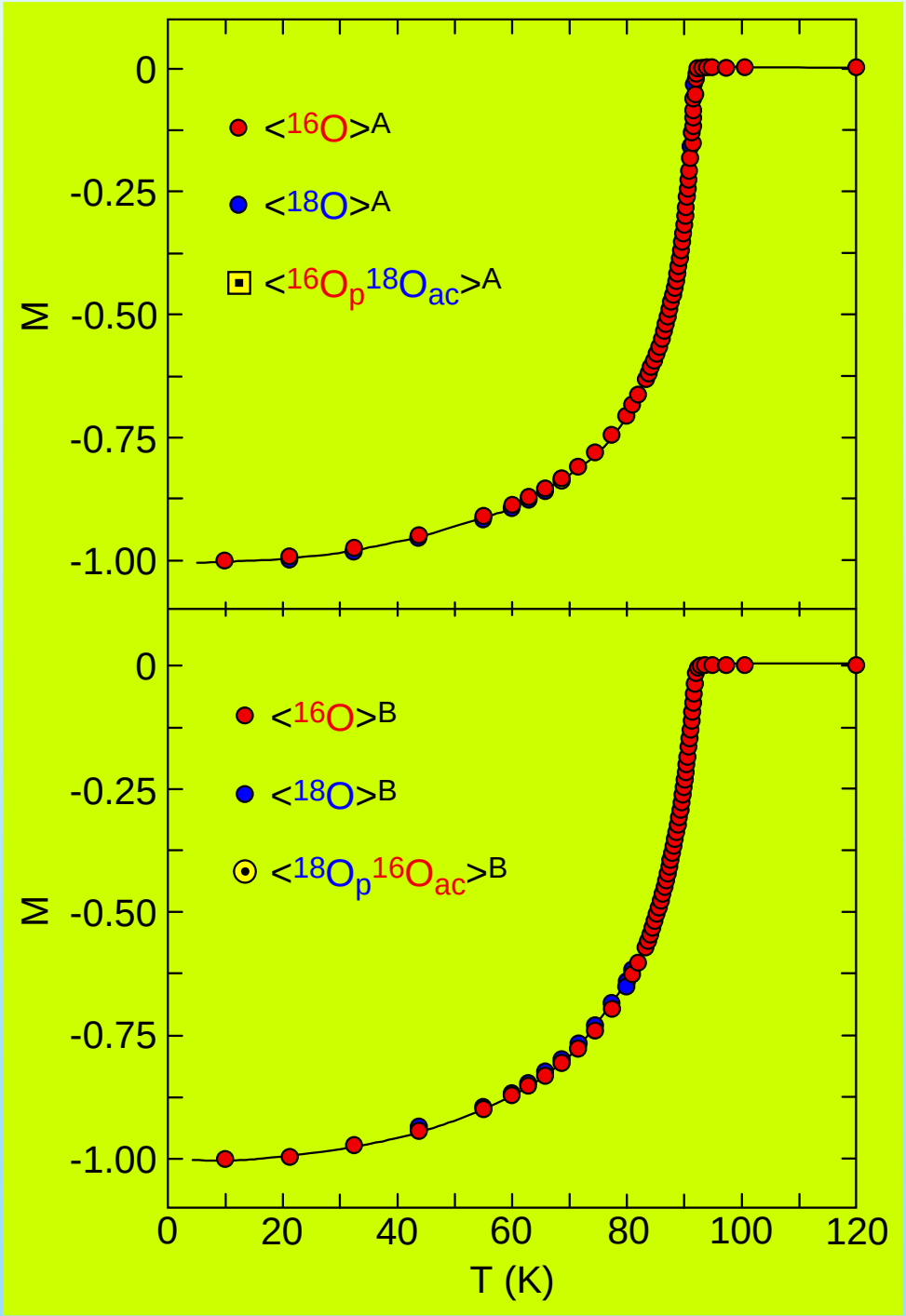
Zech *et al.*, "Anharmonic Properties of High-T_c Cuprates" (1994)

Raman spectra of $YBa_2Cu_3O_x$

⇒ test of site-selective $^{16}O/^{18}O$ exchange

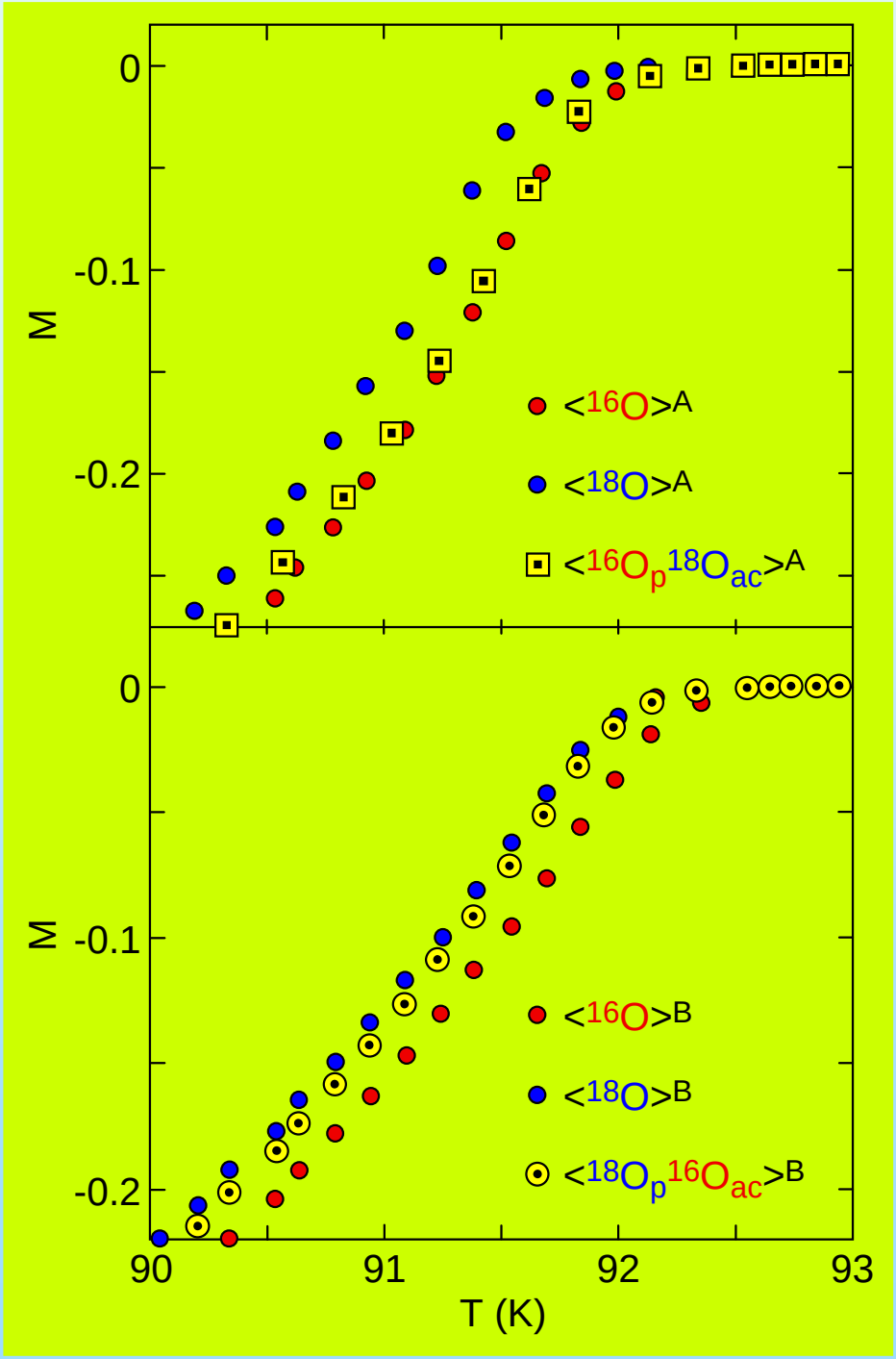


Zech *et al.,* Nature **371**, 681 (1994)



Site-selective oxygen isotope effect in optimally doped $YBa_2Cu_3O_{6+x}$

Zech *et al*., Nature **371**, 681 (1994)

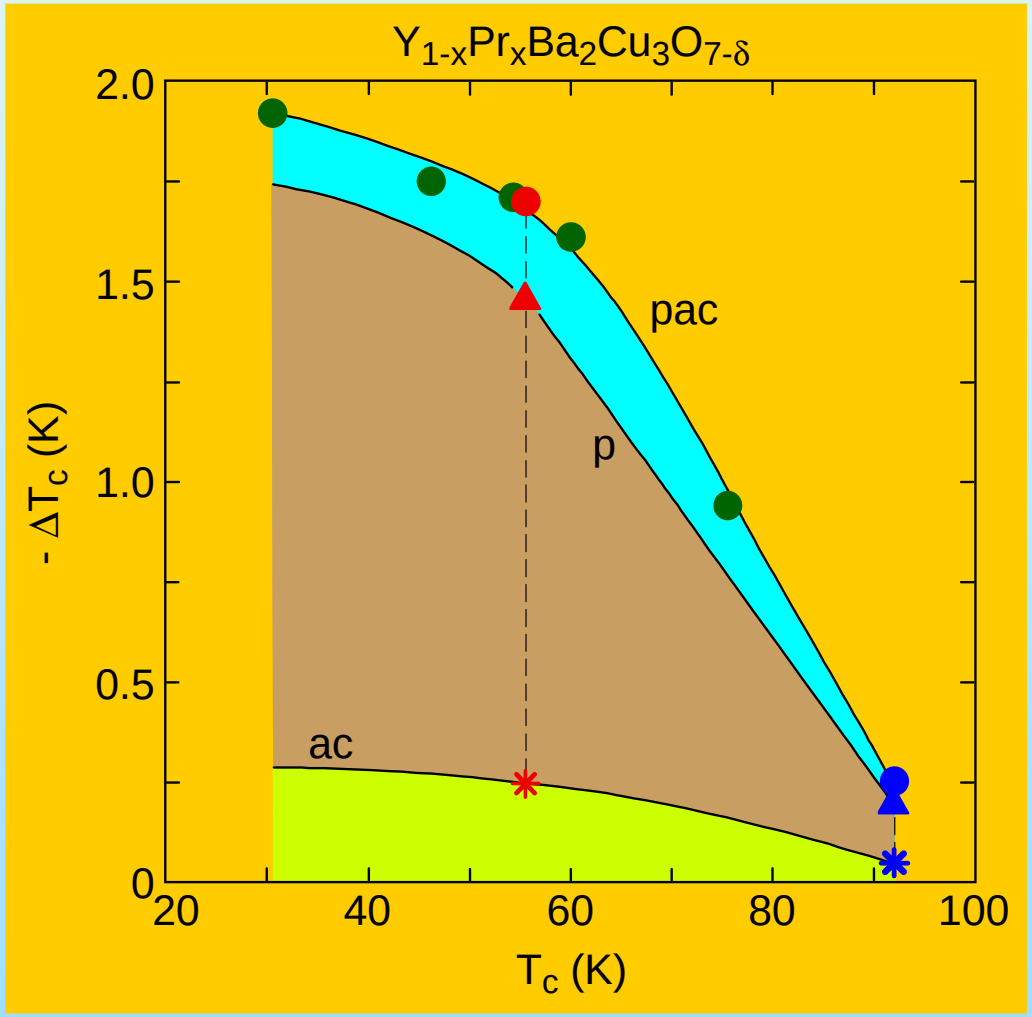


Site-selective oxygen isotope effect in optimally doped $YBa_2Cu_3O_{6+x}$

$\Rightarrow$ planar oxygen atoms mainly (> 80 %) contribute to the total OIS

Zech *et al*., Nature **371**, 681 (1994)

Oxygen-Isotope Effect on T_c



ac : apical and chain oxygen
p : plane oxygen
pac : plane, apical and chain oxygen

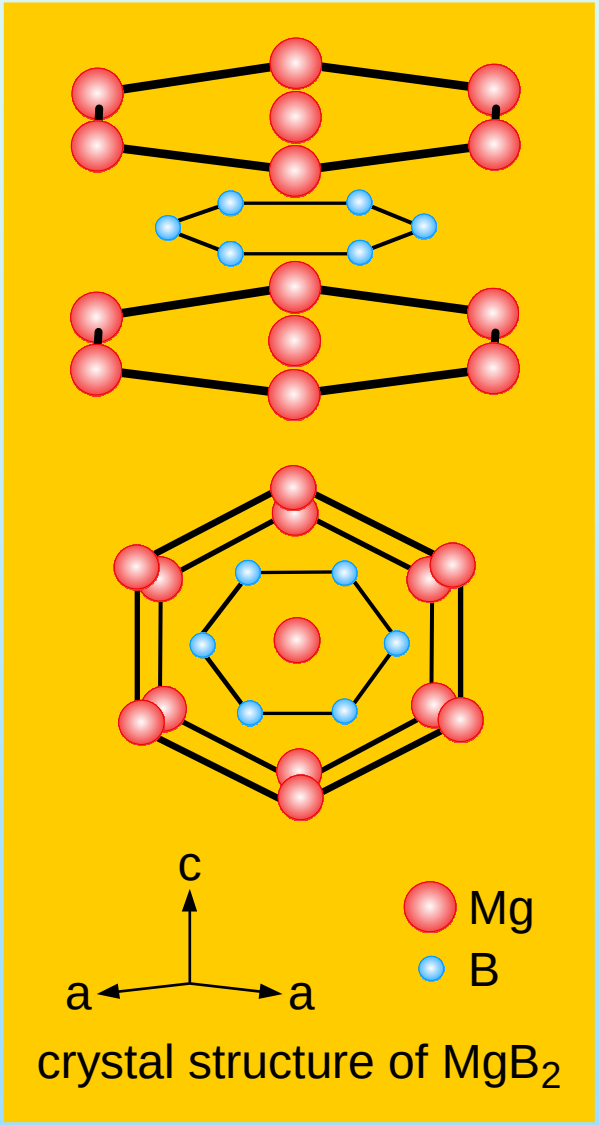
● Franck *et al.*, Phys.Rev. B **44**, 5318 (1991)

● ▲ ✱ Zech *et al.*, Nature **371**, 681 (1994)

● ▲ ✱ Zhao *et al.*, Phys.Rev. B **54**, 14982 (1996)

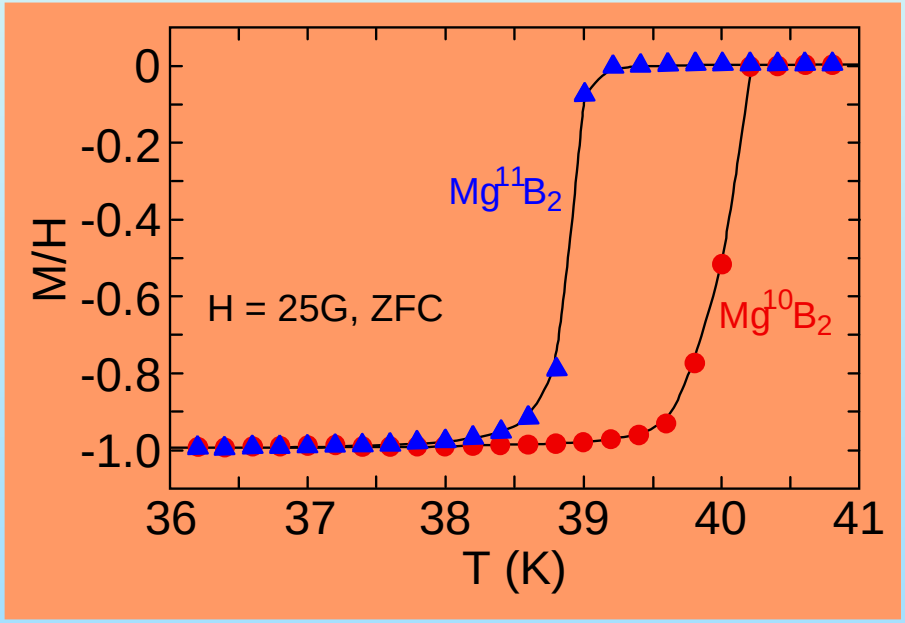
Zhao, Keller & Conder, J. Phys.: Condens. Matter **13**, R569 (2001)

Boron isotope effect in superconducting MgB_2



crystal structure of MgB_2

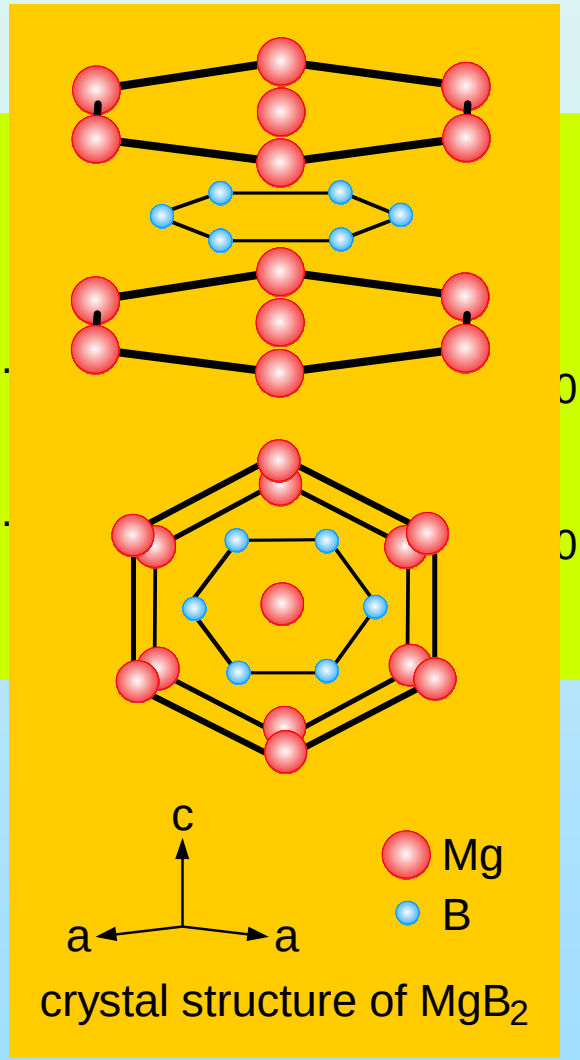
MgB_2 is a phonon-mediated layered high-temperature superconductor



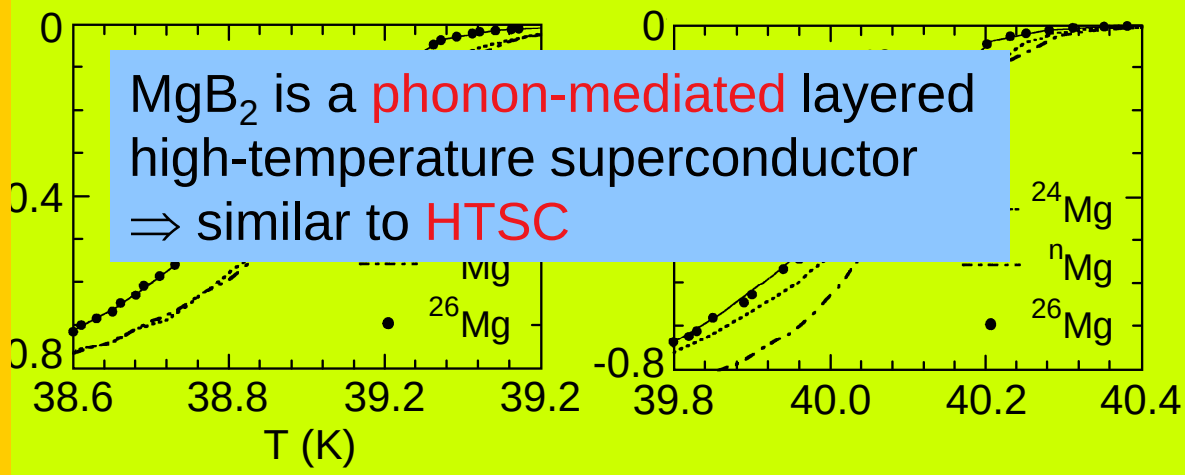
$\alpha_B = 0.26(3)$

Bud'ko *et al.*, PRL **86,** 1877 (2001)

Mg and B isotope effect in superconducting MgB_2



crystal structure of MgB_2



MgB_2 is a phonon-mediated layered high-temperature superconductor
$\Rightarrow$ similar to HTSC

$\alpha_B = 0.30(1)$
$\alpha_{Mg} = 0.02(1)$

Hinks, Claus & Jorgensen, Nature **411**, 457 (2001)

Question 1

What is the isotope effect in superconductors ?
How isotope exponent is defined ?

Question 2

Why by heating the sample in $^{18}O_2$ atmosphere isotope exchange can be made ?

Question 3

How oxygen isotope effect exponent depends on doping in cuprate high-T_c superconductors ?