Magnetism and superconductivity in expanded fullerides

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Overview of the talk

Fulleride Superconductivity - A_3C_{60} superconductors

- Structural and magnetic characterization of $Rb_xCs_{3-x}C_{60}$

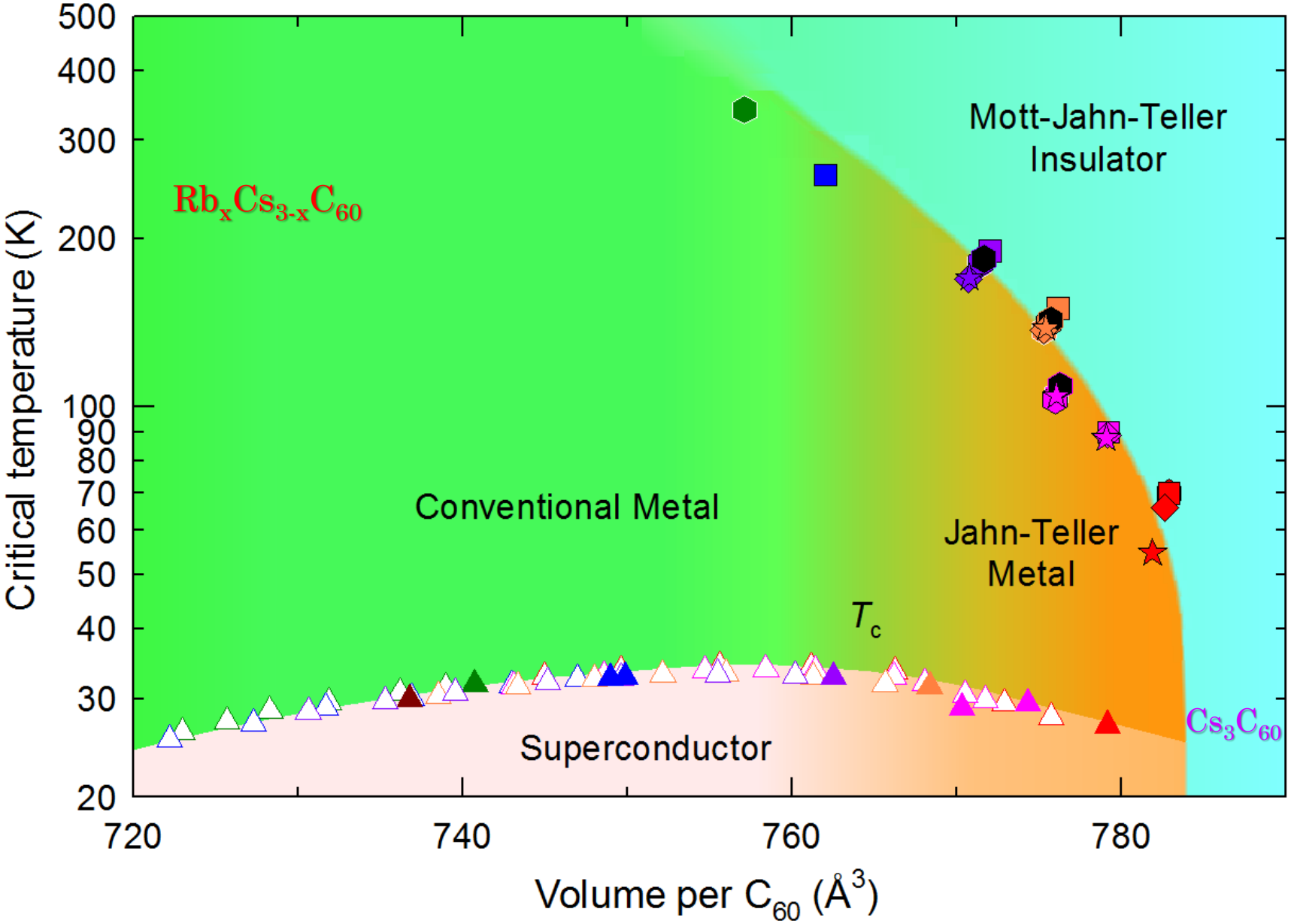
Transverse-field muon spin rotation (TF-μ^+SR) technique

- TF-μ^+SR and superconducting fullerides

Summary

- Evolution of superconducting properties of $Rb_xCs_{3-x}C_{60}$ compositions

Global phase diagram of the *fcc* A_3C_{60} fullerides

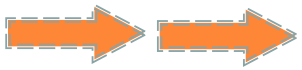


Synthesis of *fcc* $Rb_xCs_{3-x}C_{60}$ fullerides

+

+

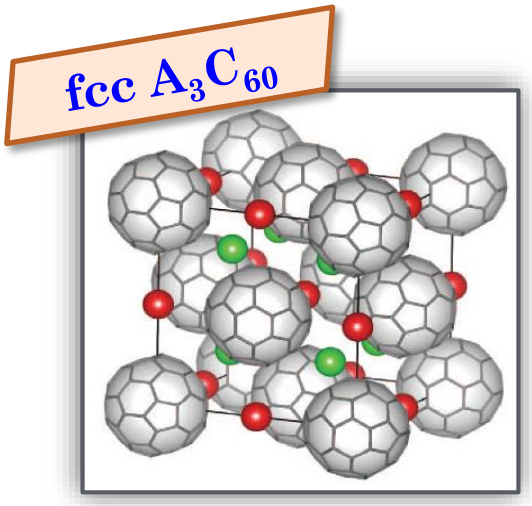
Heat treatments



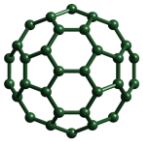
fcc $Rb_xCs_{3-x}C_{60}$

(x) (3-x)

$$0.35 \leq x \leq 2$$

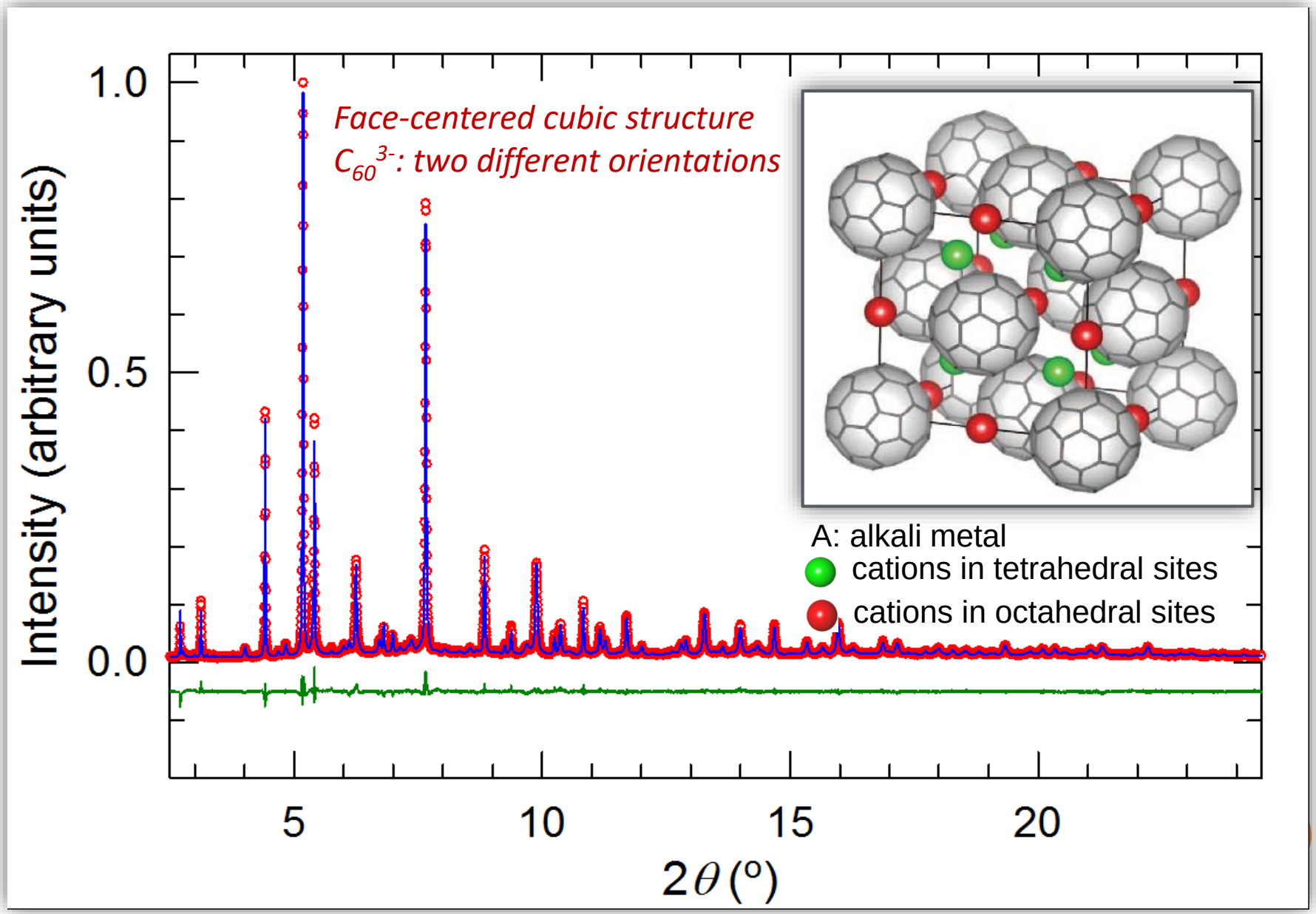


- $Rb_xCs_{3-x}C_{60}$ reproducibly synthesised using a solid state annealing route
- Phase pure samples (>1 g)
- Good stoichiometry control



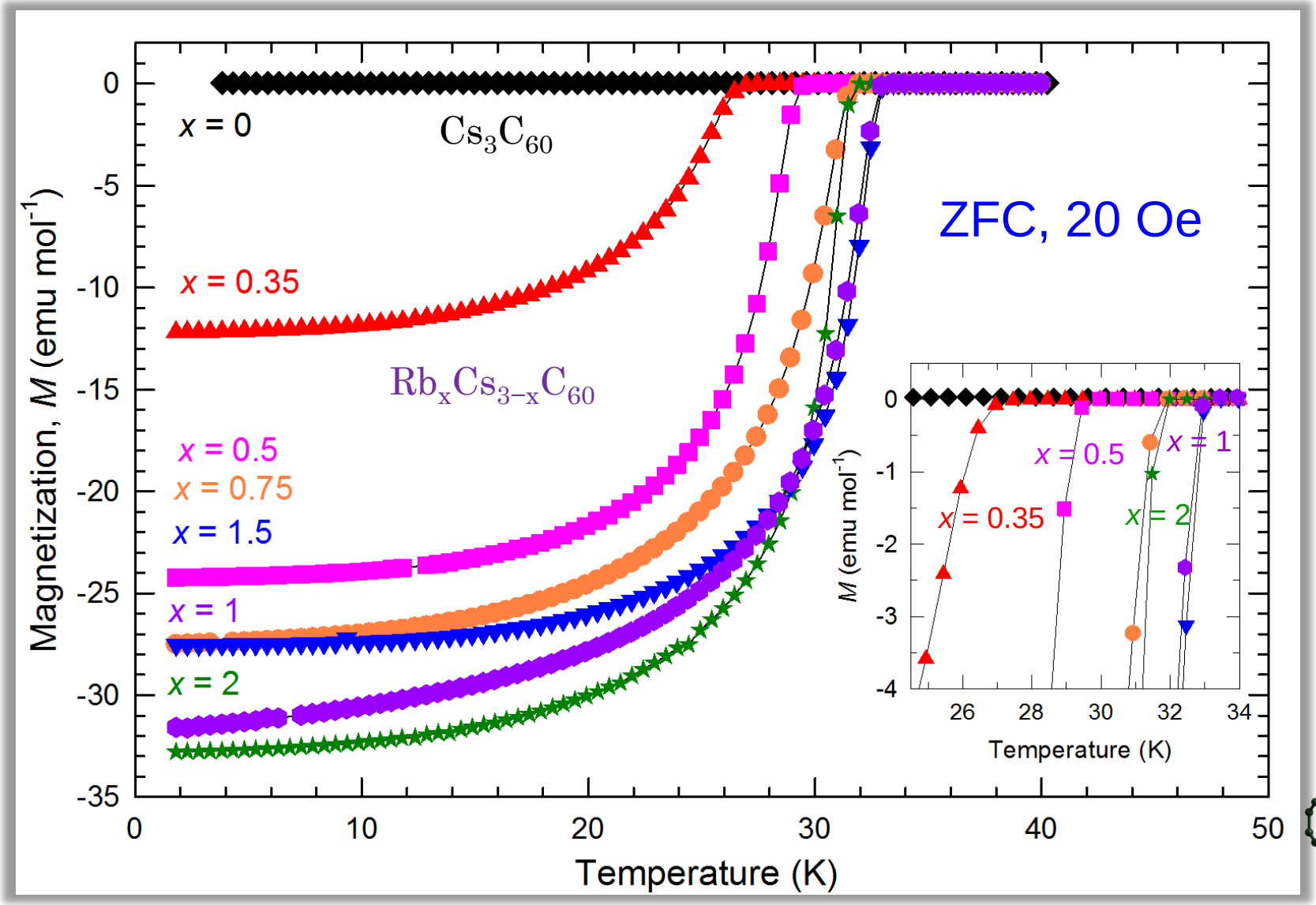
R. H. Zadik *et al.*, Science Adv. **1**, e1500059 (2015)

fcc A_3C_{60}



R. H. Zadik *et al.*, Science Adv. **1**, e1500059 (2015)

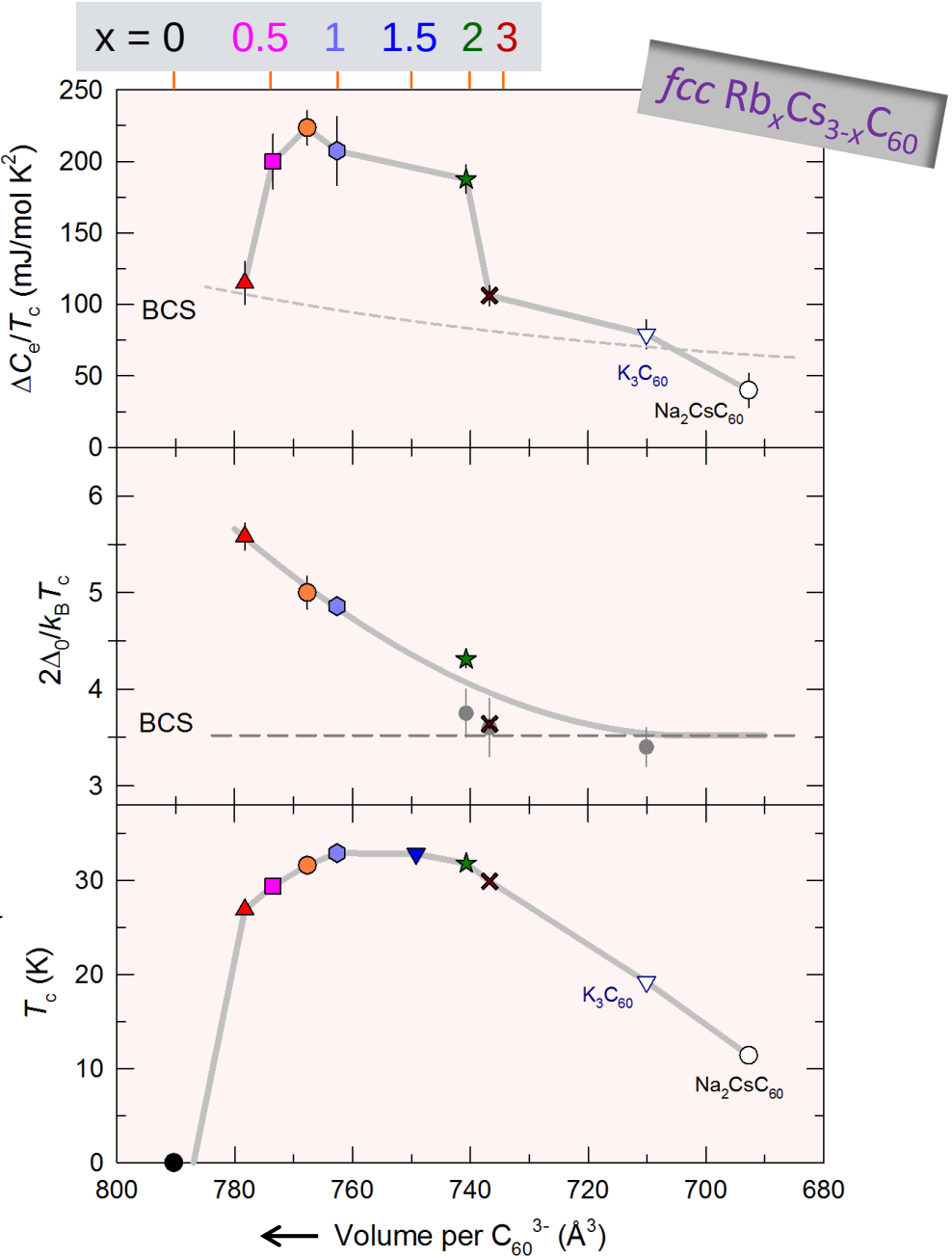
Temperature dependence of the magnetization for $Rb_xCs_{3-x}C_{60}$ compositions

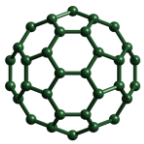


R. H. Zadik *et al.*, Science Adv. **1**, e1500059 (2015)

Superconducting properties as functions of packing density

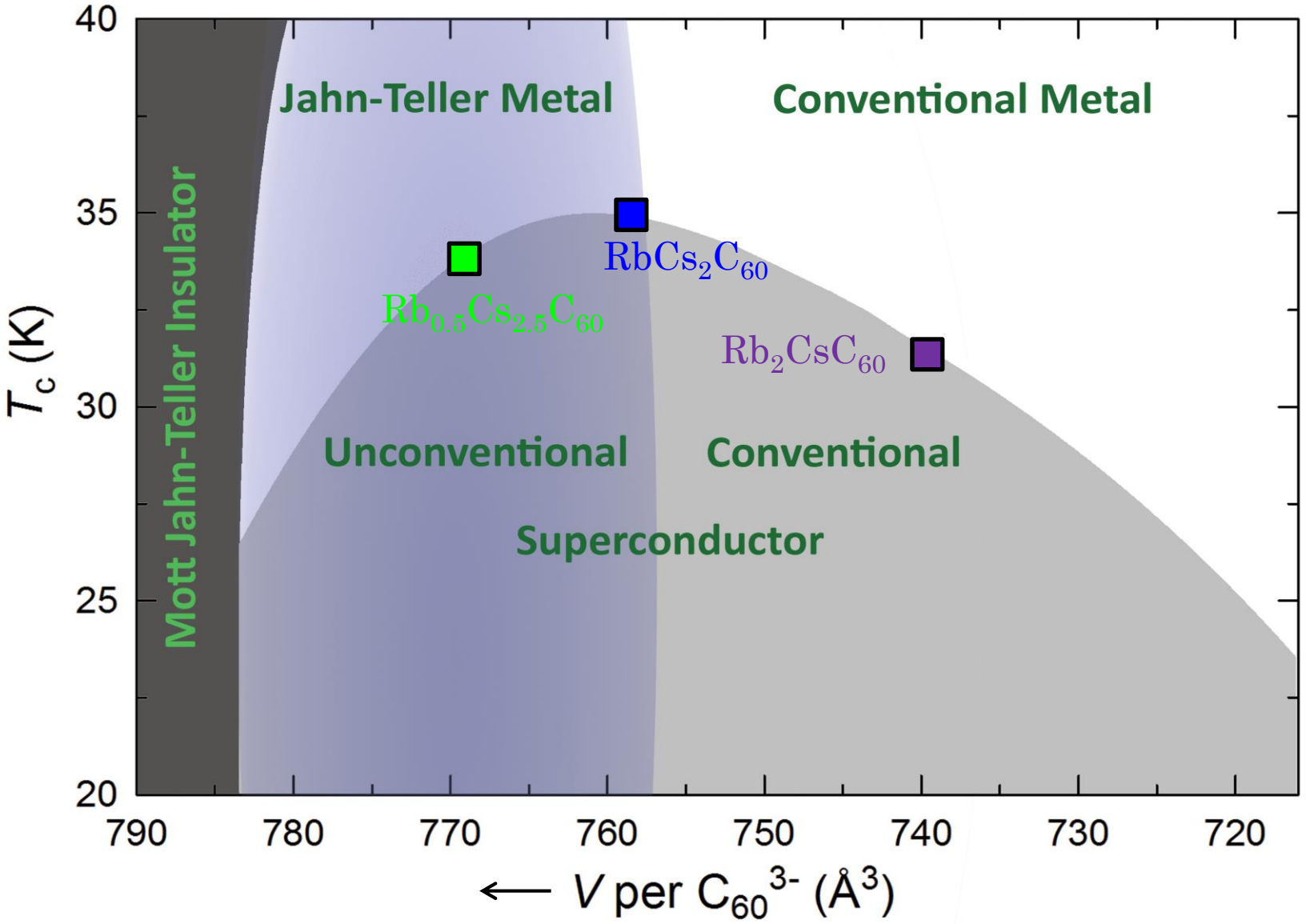
- Specific heat jump at T_c
- Superconducting gap from NMR
- Superconductivity dome





R. H. Zadik *et al.*, Science Adv. **1**, e1500059 (2015)

Electronic phase diagram of the *fcc* A_3C_{60} fullerides



Transverse-field muon spin rotation (TF-μ⁺SR) technique

Pion Decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Muon Decay

$$e^+ + \nu_e + \bar{\nu}_\mu$$

Selected properties of the muon

Mass: 207 m_e = 0.1126 m_p

Spin: ½

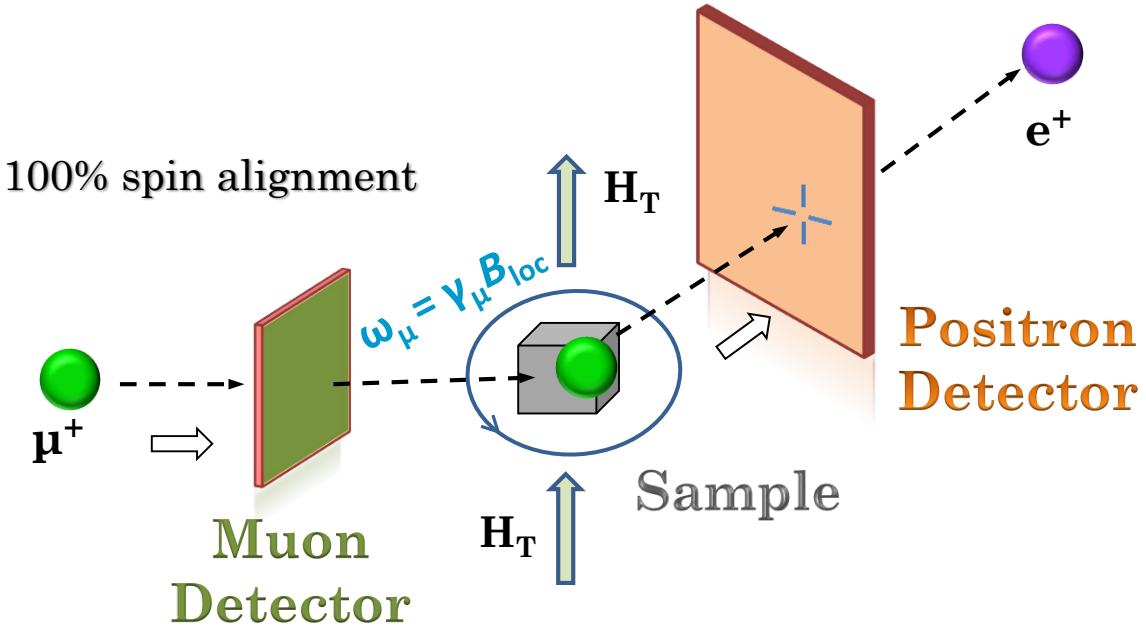
Charge: +e

Lifetime: 2.2 μs

Magnetic moment: 4.84 x 10^{-3} μ_B

Gyromagnetic ratio: (2π) x 13.554 kHz G^{-1}

Transverse-field geometry



MuSR@ISIS, UK

Why TF-μ⁺SR?

- The muon acts as a microscopic probe of the local magnetic field distribution in the vortex state and provides a direct way to measure the London penetration depth, λ

$$\frac{1}{\lambda^2} = \frac{4\pi n_s e^2}{m^* c^2} \times \frac{1}{1 + {}^{\xi}/_{\ell}}$$

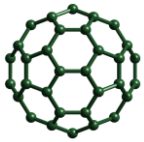
when: $\xi \ll \ell$ clean limit

$\xi \gg \ell$ dirty limit

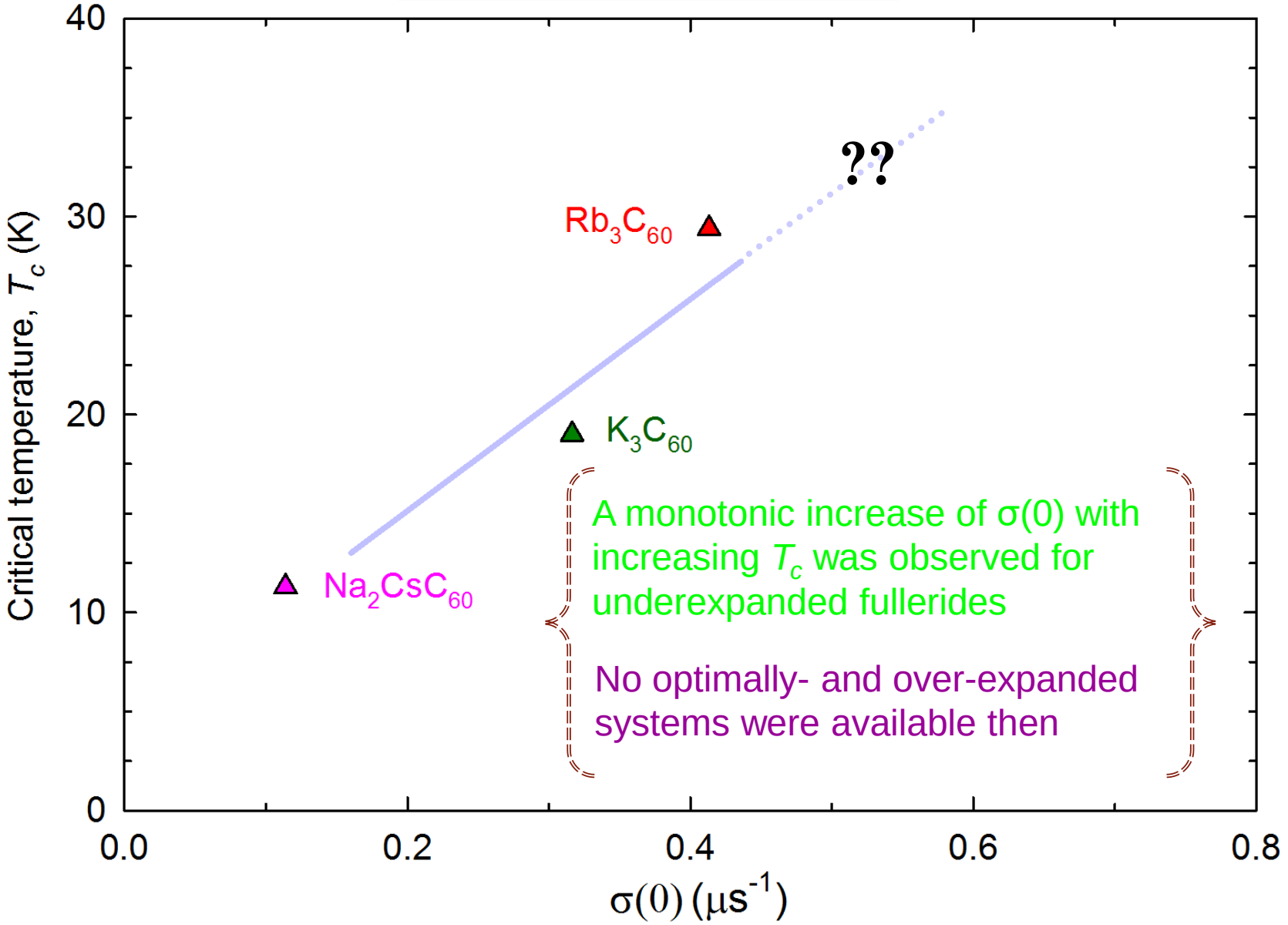
$$\sigma(0) \propto \frac{1}{\lambda^2} \propto \frac{n_s}{m^*}\left(\frac{1}{1 + {}^{\xi}/_{\ell}}\right)$$

σ : relaxation rate
n_s : superfluid density
m^* : effective mass
ξ : coherence length
ℓ : mean free path

- The temperature dependence of the relaxation rate, σ contains information on the pairing mechanism (s- or d-wave, weak/strong coupling, clean/dirty limit)



Back in 1994



Y. J. Uemura *et al.*, Physica C **235-240**, 2501 (1994)

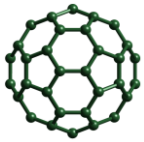
GOAL

Investigate the superconducting properties of $Rb_xCs_{3-x}C_{60}$ compositions across the superconductivity dome:

underexpanded (***x* = 2**)

optimally expanded (***x* = 1**)

overexpanded (***x* = 0.5**)

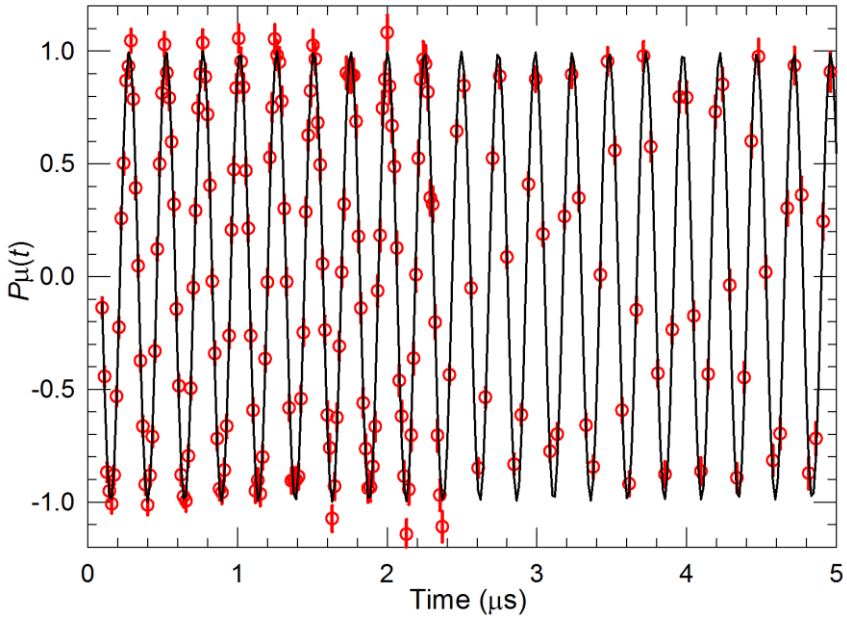


TF-μ⁺SR spectra

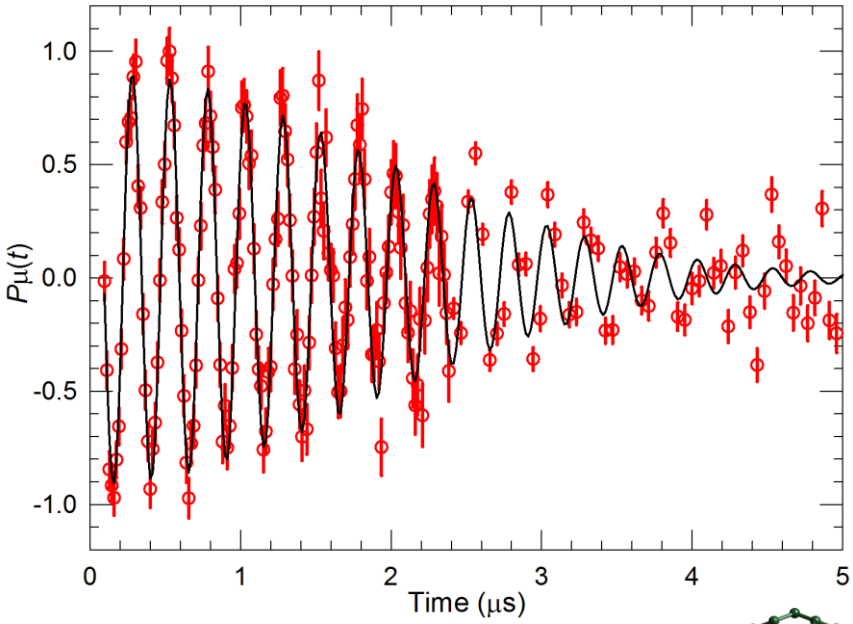
Rb_2CsC_{60}

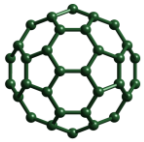
(H_{c1} = 10 mT < H_{ext} = 30 mT < H_{c2} = 68 T)

T = 50 K > T_c = 31.8 K
σ = 0.03 μs^{-1}



T = 3 K < T_c = 31.8 K
σ = 0.54 μs^{-1}





Temperature dependence of the muon spin relaxation rate

Fitting is under way

Clean Limit

$$\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = 1 + 2\int_{\Delta(T)}^{\infty}\left(\frac{\partial f}{\partial E}\right)\frac{E}{\sqrt{E^2 - \Delta(T)^2}}dE$$

Dirty Limit

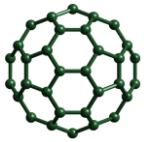
$$\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = \frac{\Delta(T)}{\Delta(0)}\tanh\left[\frac{\Delta(T)}{2k_BT}\right]$$

Fermi function: $f = [1 + exp(E/k_BT)]^{-1}$

$\lambda^{-2}(0)$: zero-temperature value of the magnetic penetration depth

s-wave symmetry

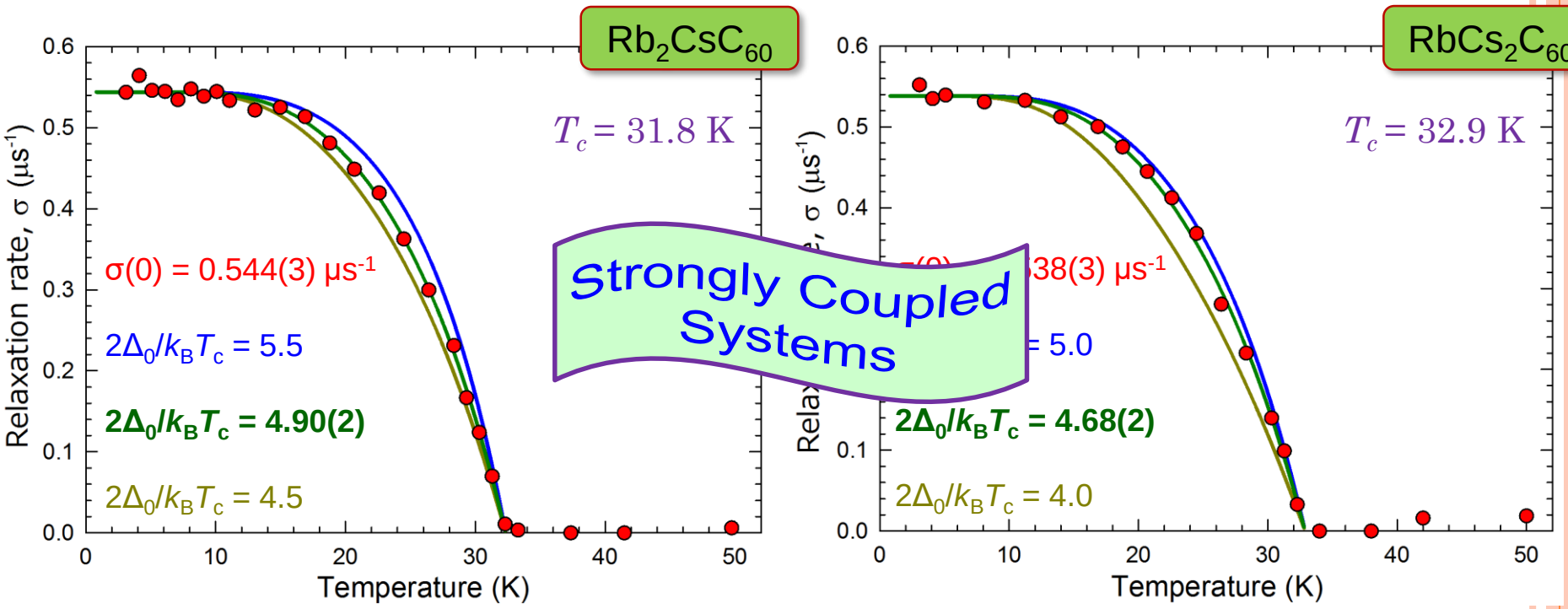
Temperature dependence of the gap: $\Delta(T) = \Delta(0)\tanh\{1.82\,[1.018(T_c/T - 1)]^{0.51}\}$



Temperature dependence of the muon spin relaxation rate

s-wave isotropic superconductors

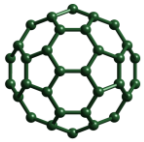
Clean Limit



Dirty Limit

$2\Delta_0/k_BT_c = 5.52(2)$

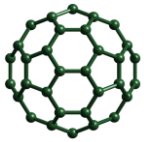
$2\Delta_0/k_BT_c = 5.31(2)$



$Rb_{0.5}Cs_{2.5}C_{60}$: different behavior, data analysis in progress

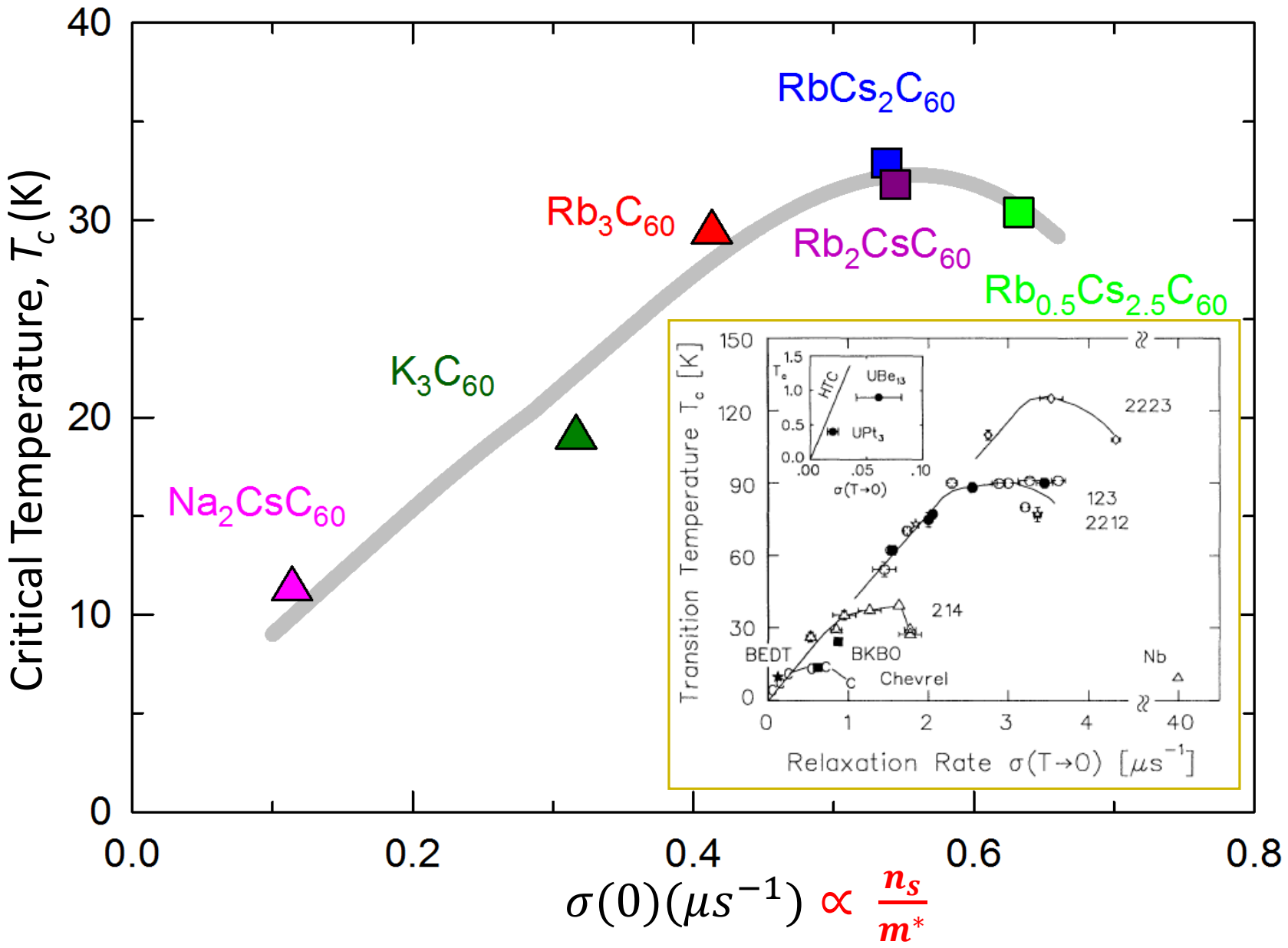
If we assume
"clean limit"

Compound	$\sigma(0)$ (μs^{-1})	$\lambda(0)$ (Å)	$n_s/(m^*/m_e)$ (cm^{-3})	T_F (K)
*Na_2CsC_{60}	0.11	8000	0.4×10^{20}	315
*K_3C_{60}	0.32	4800	1.2×10^{20}	470
*Rb_3C_{60}	0.42	4200	1.6×10^{20}	650
Rb_2CsC_{60}	0.55	3660	2.1×10^{20}	790
$RbCs_2C_{60}$	0.54	3680	2.1×10^{20}	830
$Rb_{0.5}Cs_{2.5}C_{60}$	0.63	3400	2.5×10^{20}	890



* Y. J. Uemura *et al.*, Physica C **235-240**, 2501 (1994)
Y. J. Uemura *et al.*, Nature **352**, 605 (1991)

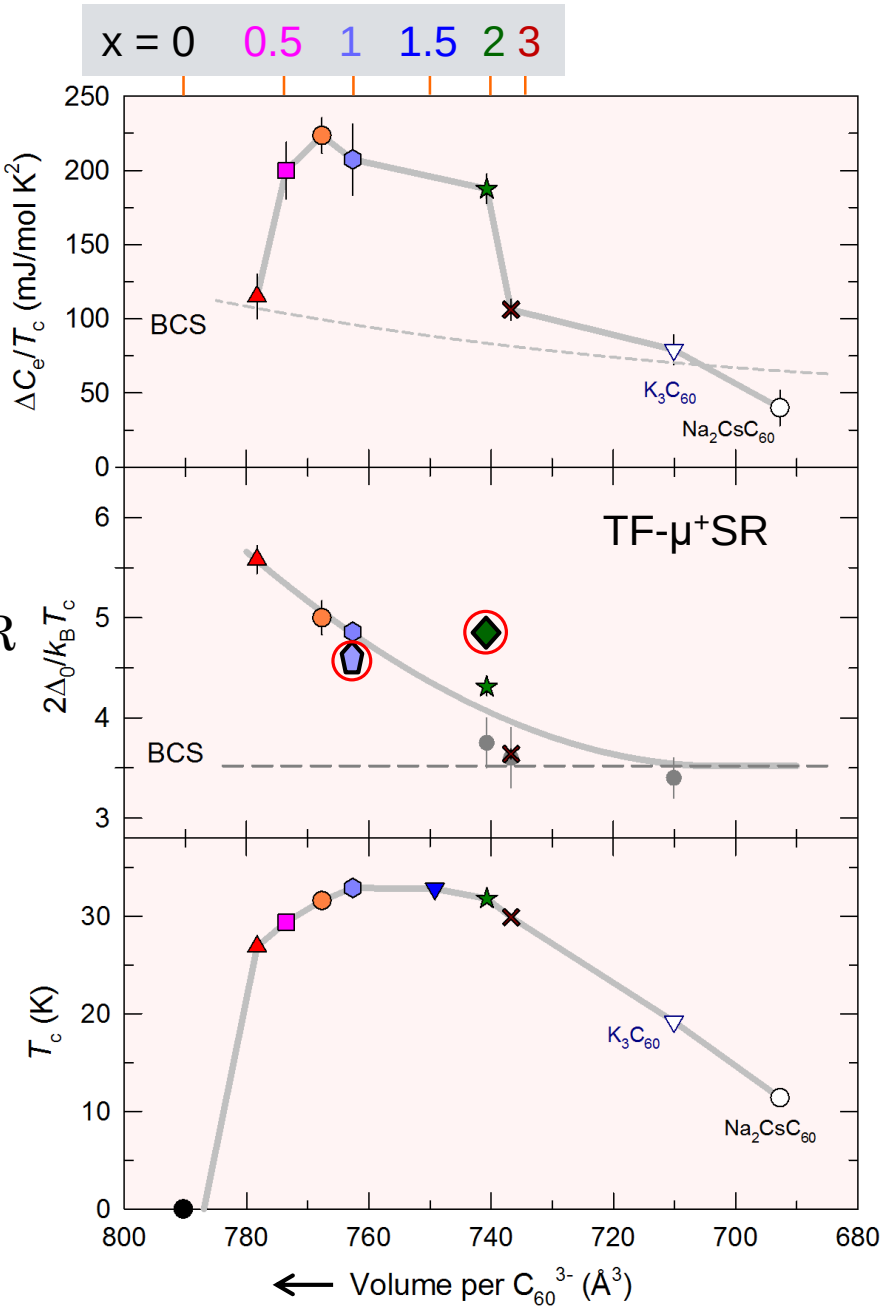
T_c *vs* σ(0) for fcc fullerides



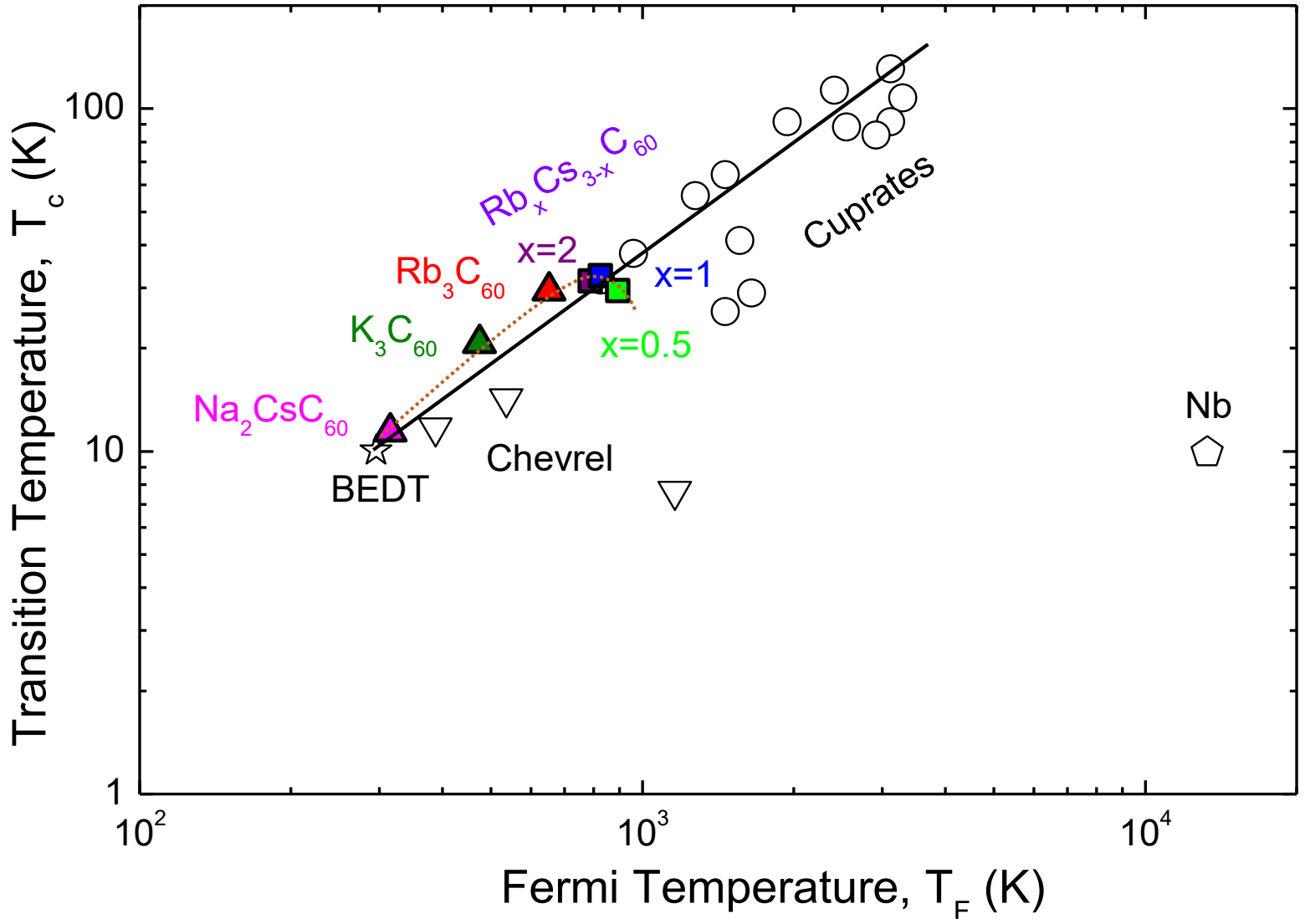
Y. J. Uemura *et al.*, Phys. Rev. Lett. **66**, 2665 (1991)

Superconducting properties in addition to TF-μ⁺SR

- Specific heat jump at T_c
- Superconducting gap from NMR + TF-μ⁺SR
- Superconductivity dome



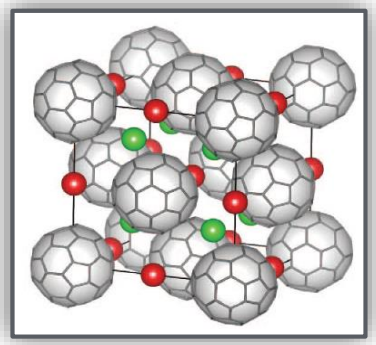
T_c *vs* effective Fermi temperature, T_F (Uemura plot)



Y. J. Uemura *et al.*, Phys. Rev. Lett. **66**, 2665 (1991)

Summary

fcc $Rb_xCs_{3-x}C_{60}$ superconductors



TF-μ^+SR

$x = 0.5$ $x = 1$ $x = 2$

- s-wave superconductors
- strongly coupled systems
- large enhancement of the gap in Rb_2CsC_{60}
- similar trend as high-T_c cuprates and other exotic superconductors

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