PAUL SCHERRER INSTITUT

Case study: elemental superconductors

Rustem Khasanov, PSI, Switzerland

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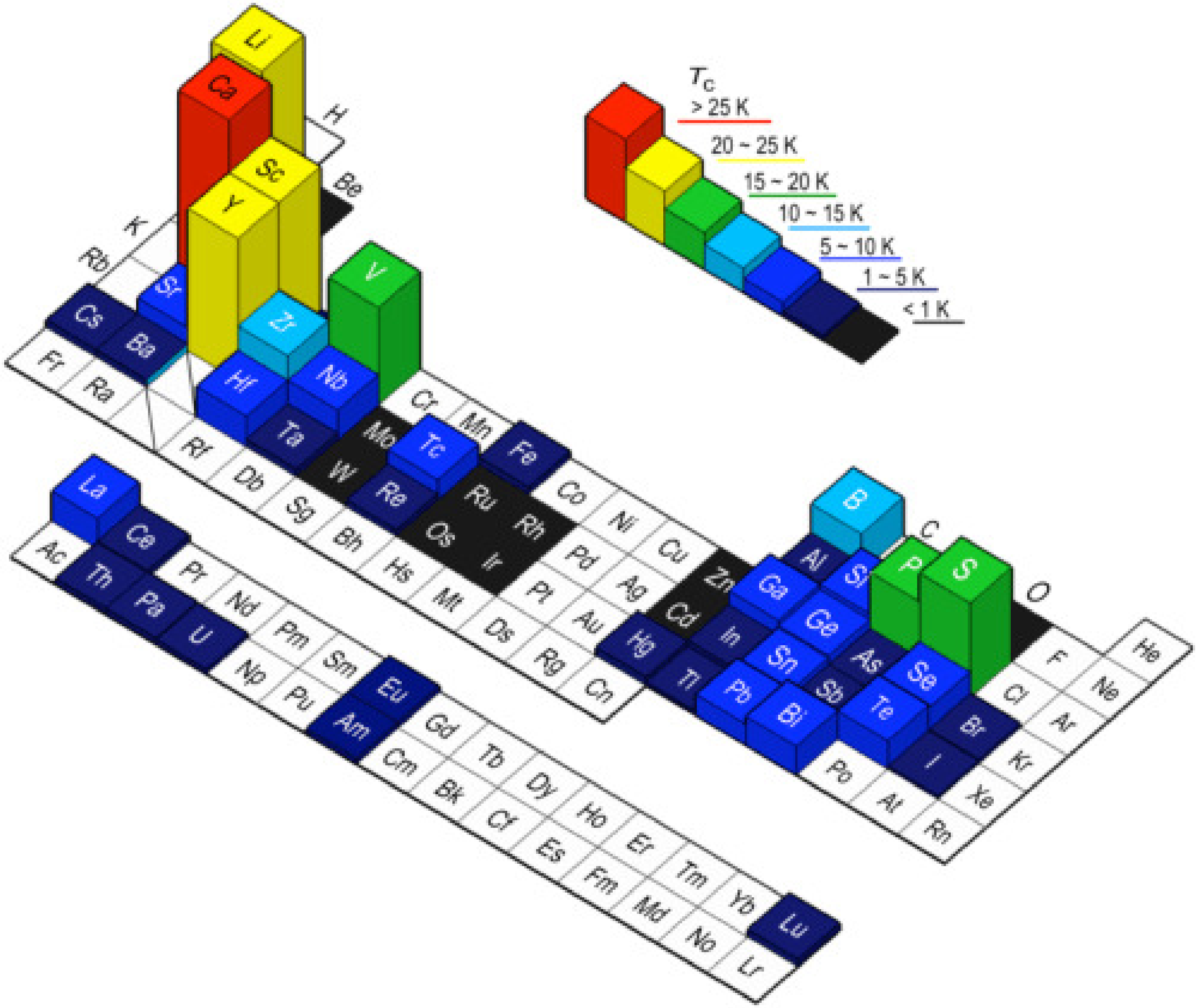
Outline

- Elemental superconductors
- μSR in studies of type-I superconductivity
  - Sn
  - Bi-II
  - Ga-II
- Universal relations for type-I superconductors

Elemental superconductors



Most of elemental superconductors are of a type-I

For some elemental superconductors the type of superconductivity is still not known!

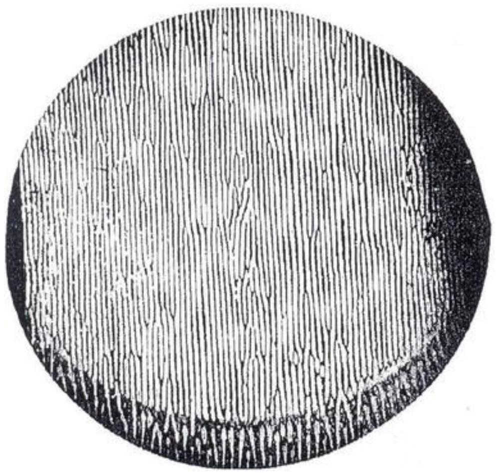
Superconductivity

Superconducting elements

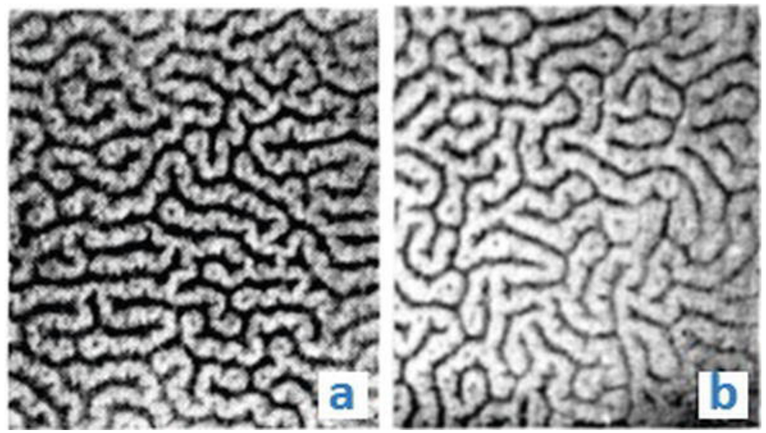
	T [K]		T [K]
Al	1.19	Ru	0.49
Cd	0.56	Sn	3.72
Ga	1.09	Ta	4.48
Hg	4.00	**Tc**	**8.22**
In	3.40	Th	1.37
Ir	0.14	Ti	0.39
La	5.00	Tl	2.39
Mo	0.92	U	0.68
Nb	**9.13**	V	5.30
Os	0.65	Zn	0.87
Pb	**7.19**	Zr	0.55
Re	1.70		

Intermediate state of type-I superconductors

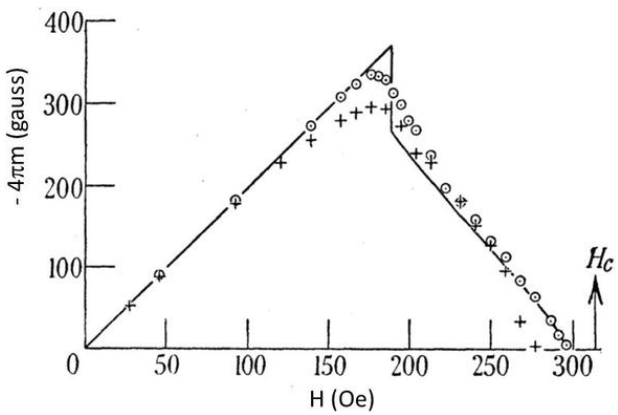
Intermediate state of type-I superconductor



Sharvin et al., ZhETPh, 33, 1341, 1957



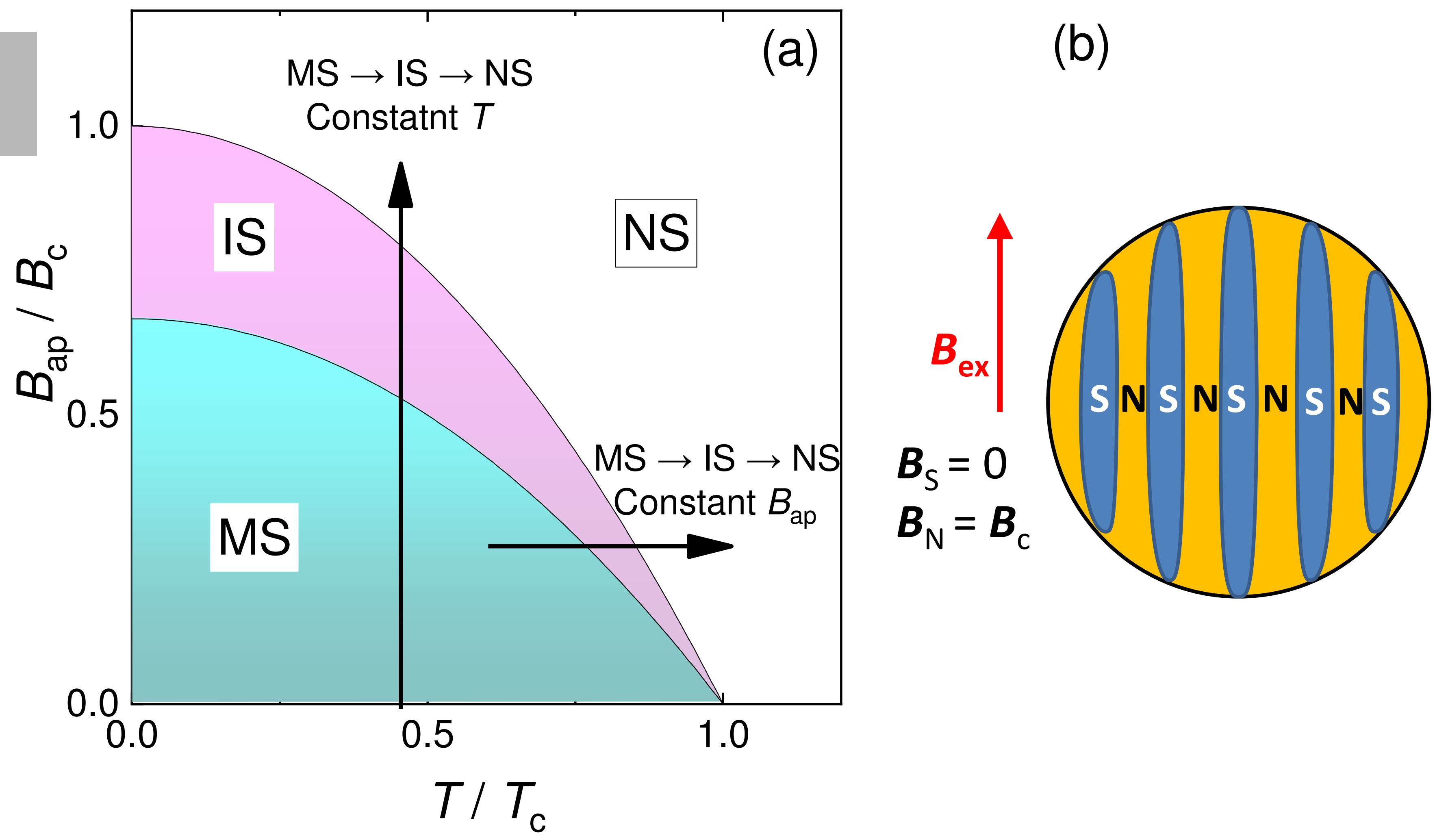
Faber, Proc.Roy.Soc., A248, 460 (1958)



Magnetization curve of cylindrical mercury specimen measured at increasing (⊙) and decreasing (+) fields. H_c is thermodynamic critical field measured in parallel field.

Desirant and Shoenberg, Proc. Roy. Soc. 194, 63 (1948)

Intermediate state of the sphere

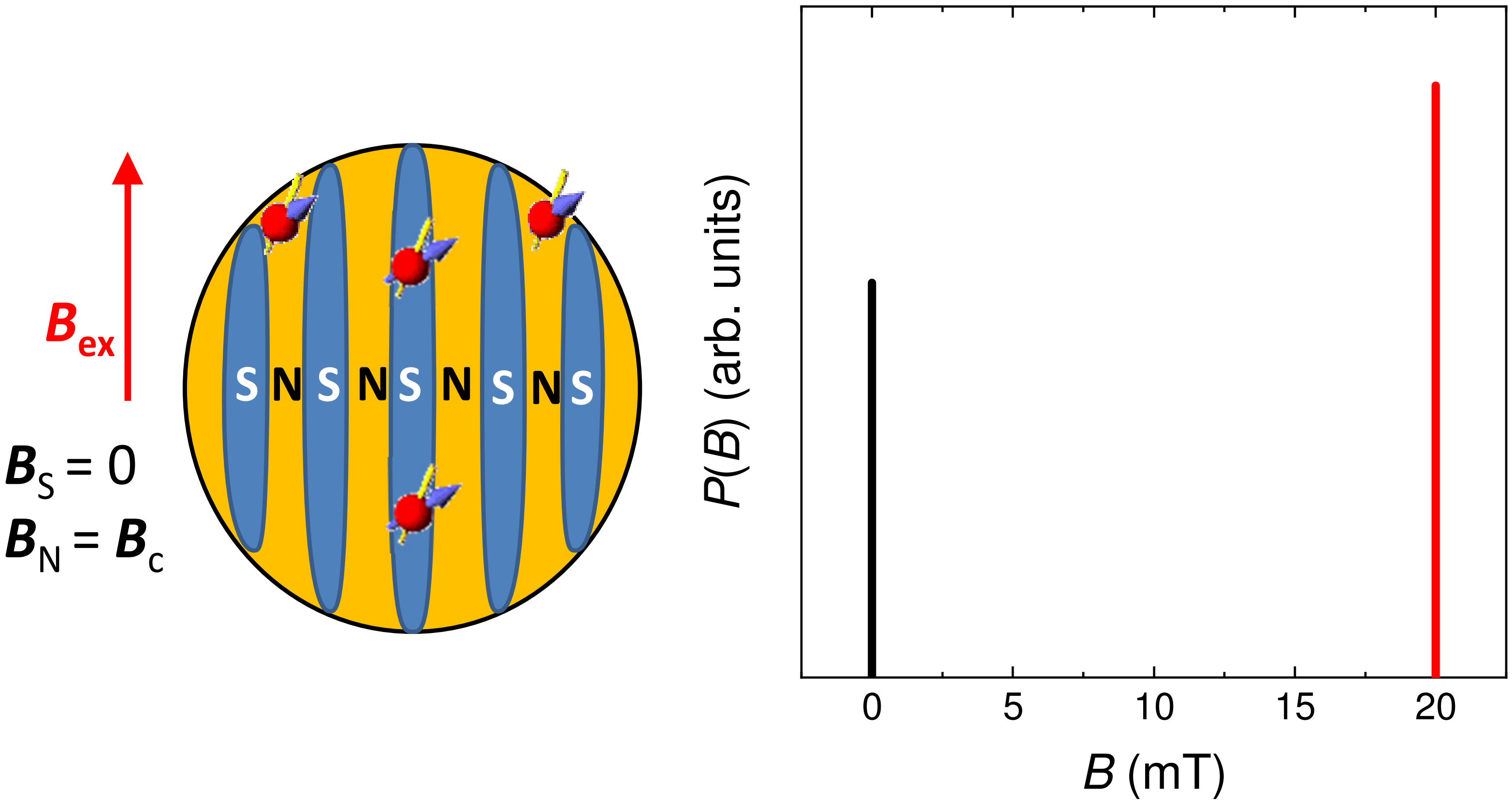


μSR on type-I superconductors

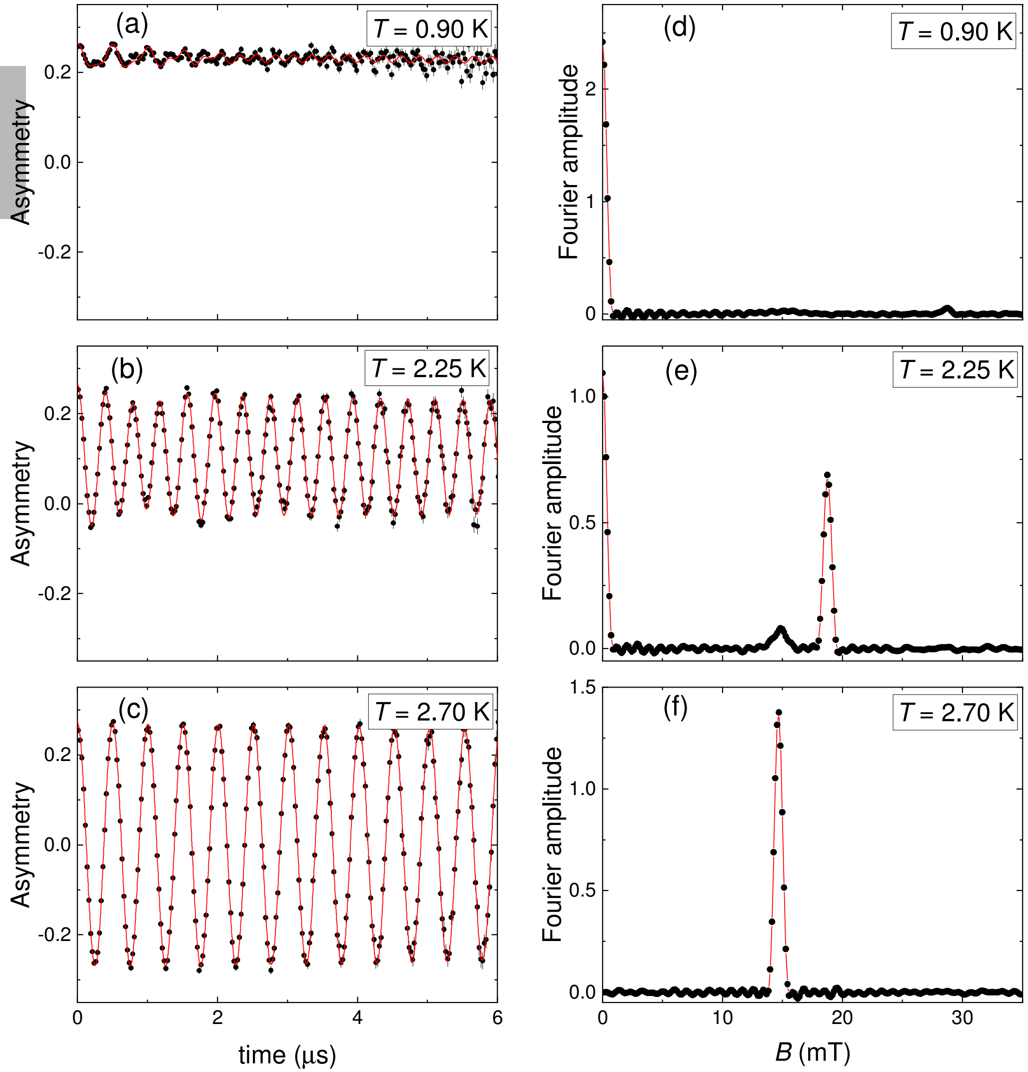
µSR on type-I superconductors

1. M. Gladisch, D. Herlach, H. Metz, H. Orth, G. zu Putlitz, A. Seeger, H. Teichler, W. Wahl, and W. Wigand, Hyperfine Interact. **6**, 109 (1979).
2. V. G. Grebinnik, I. I. Gurevich, V. A. Zhukov, A. I. Klimov, L. A. Levina, V. N. Maiorov, A. P. Manych, E. V. Mel'nikov, B. A. Nikol'skii, A. V. Pirogov, A. N. Ponomarev, V. S. Roganov, V. I. Selivanov, and V. A. Suetin, Sov. Phys. JETP **52**, 261 (1980).
3. V. S. Egorov, G. Solt, C. Baines, D. Herlach, and U. Zimmermann, Phys. Rev. B **64**, 024524 (2001).
4. V. S. Egorov, G. Solt, C. Baines, D. Herlach, and U. Zimmermann, Physica B **289-290**, 393 (2000).
5. V. Kozhevnikov, A. Suter, T. Prokscha, and C. Van Haesendonck, arXiv:1802.08299.
6. D. Singh, A. D. Hillier, and R. P. Singh, Phys. Rev. B **99**, 134509 (2019).
7. J. Beare, M. Nugent, M. N. Wilson, Y. Cai, T. J. S. Munsie, A. Amon, A. Leithe-Jasper, Z. Gong, S. L. Guo, Z. Guguchia, Y. Grin, Y. J. Uemura, E. Svanidze, and G. M. Luke, Phys. Rev. B **99**, 134510 (2019).
8. R. Khasanov, M. M. Radonji´c, H. Luetkens, E. Morenzoni, G. Simutis, S. Schönecker, W. H. Appelt, A. Östlin, L. Chioncel, and A. Amato, Phys. Rev. B **99**, 174506 (2019)
9. R. Karl, F. Burri, A. Amato, M. Donegà, S. Gvasaliya, H. Luetkens, E. Morenzoni, and R. Khasanov, Phys. Rev. B 99, 184515 (2019).
10. R. Khasanov, H. Luetkens, and E. Morenzoni, arxiv:1906.12253.

μSR in type-I superconductors



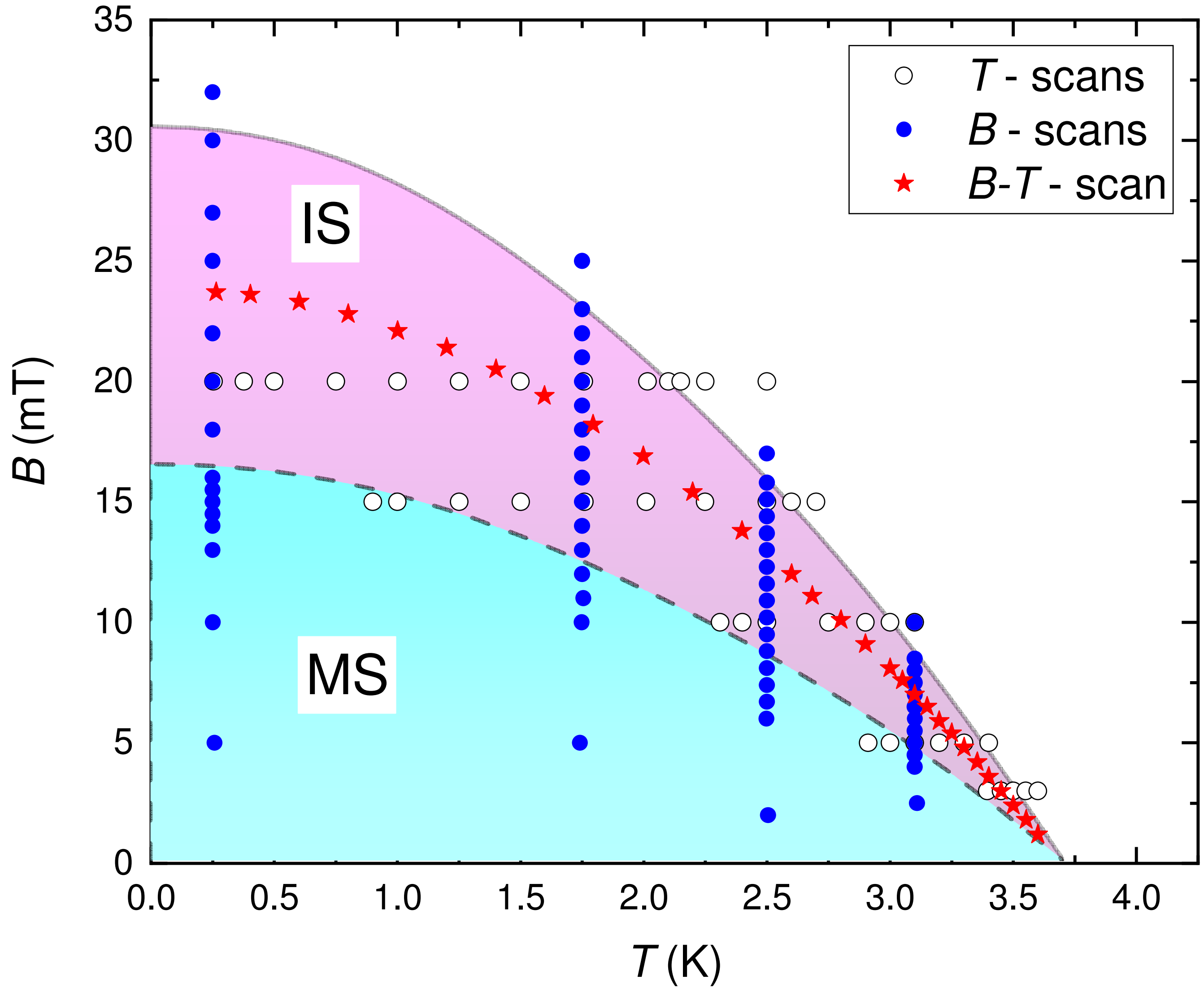
Raw data: elemental Sn



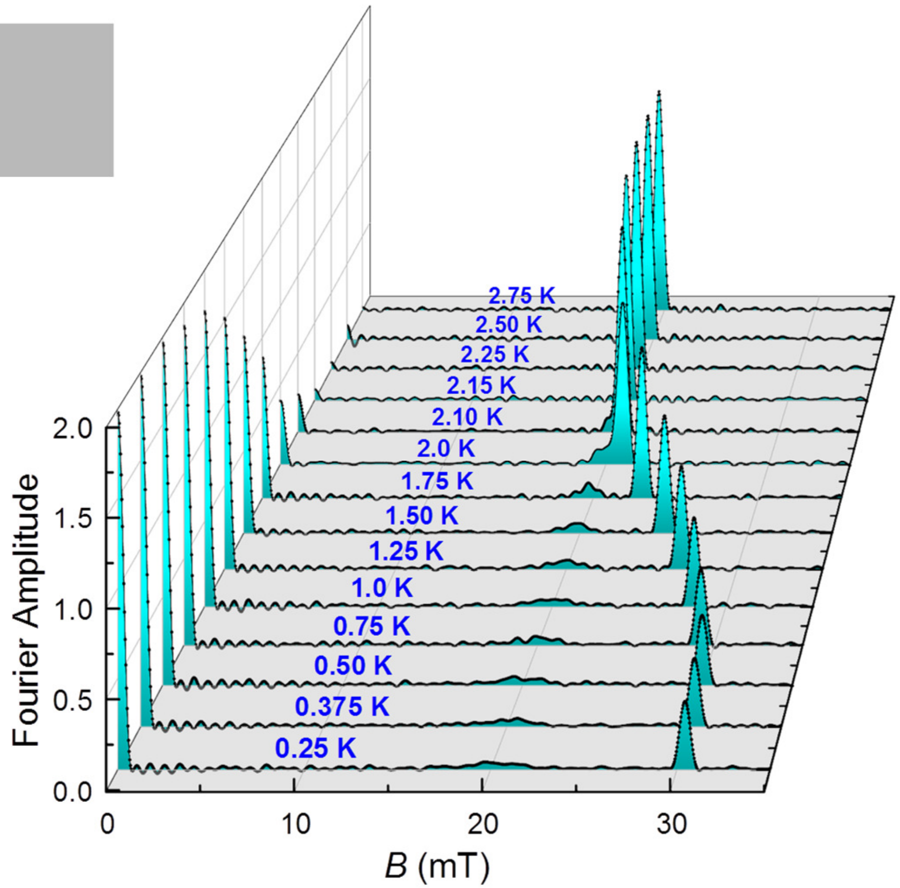
Raw data taken at B_{ap} = 15 mT at
T = 0.90 K [panels (a) and (d)],
2.25 K [panels (b) and (e)], and
2.70 K [panels (c) and (f)].

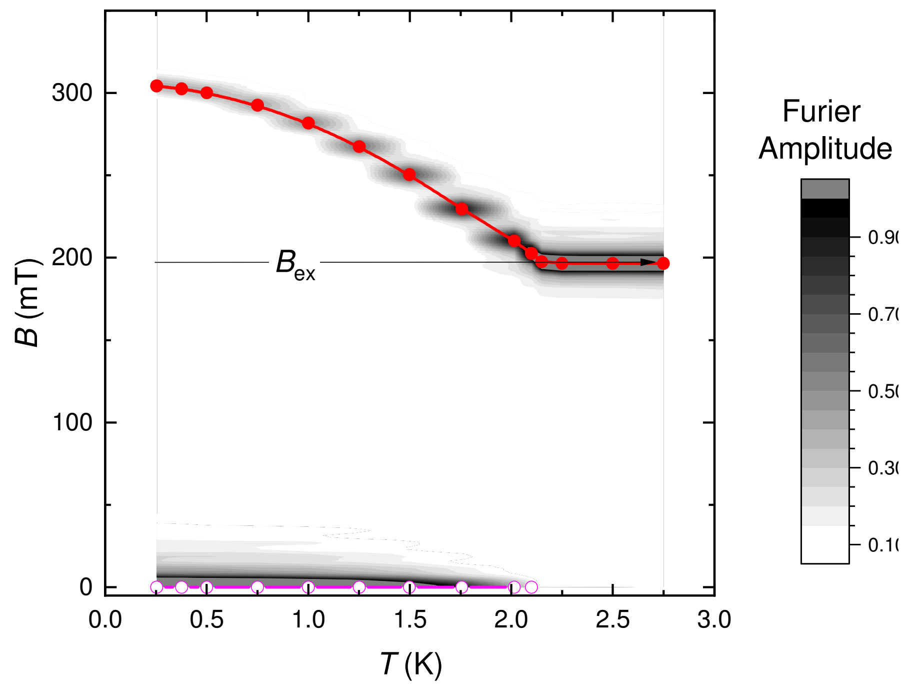
μSR on β-Sn

Way to measure: elemental Sn

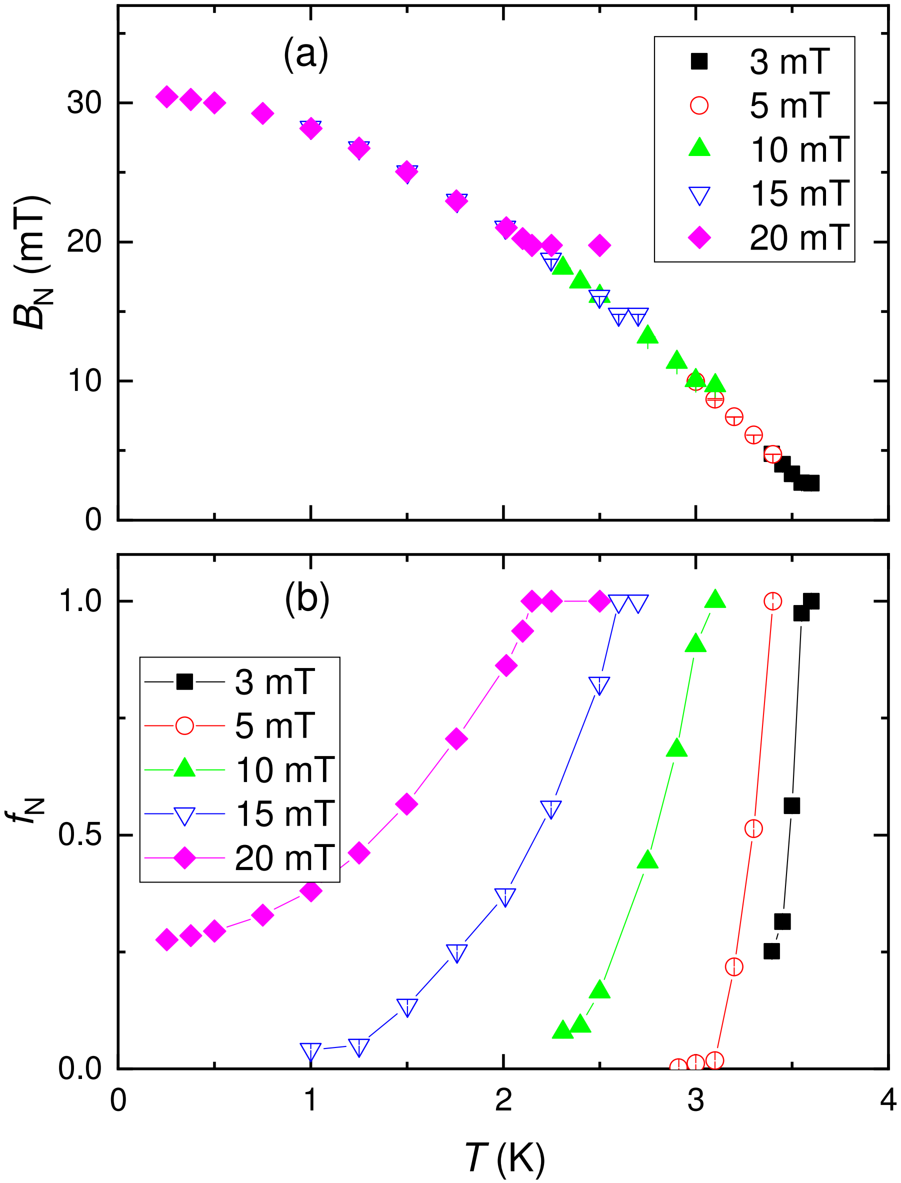


Temperature scans

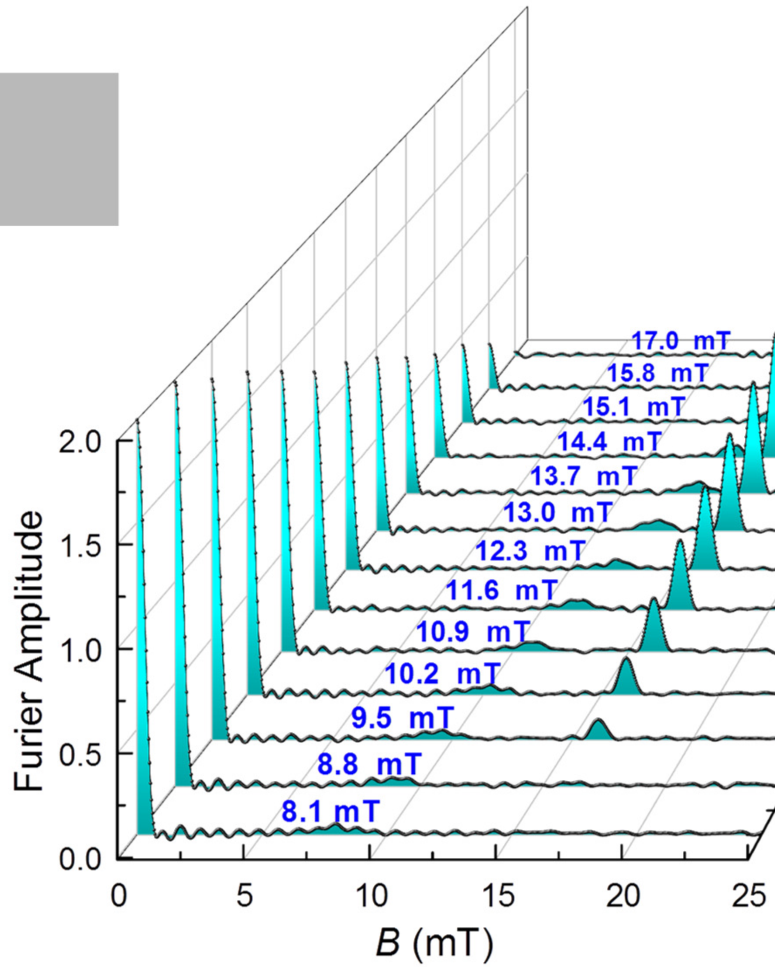


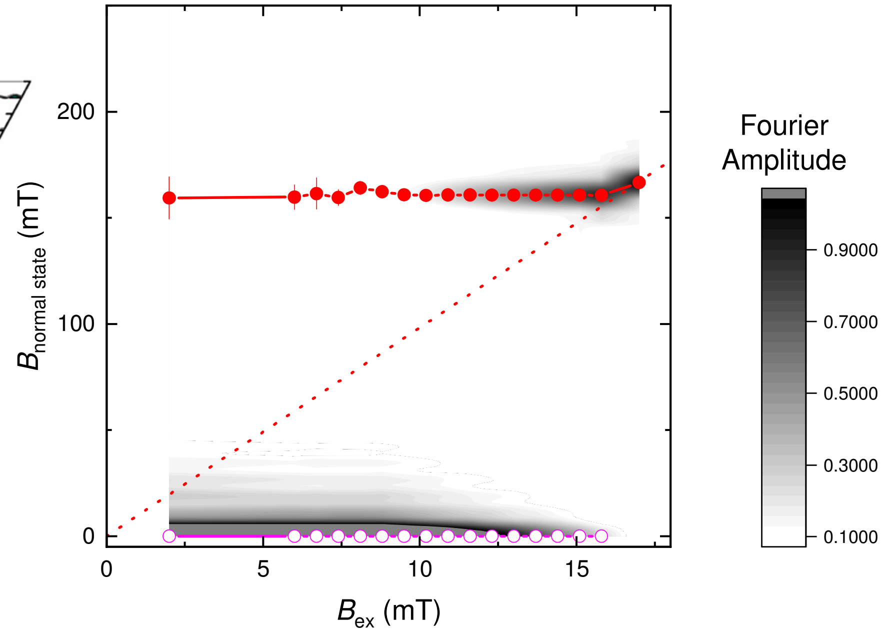


Temperature scans

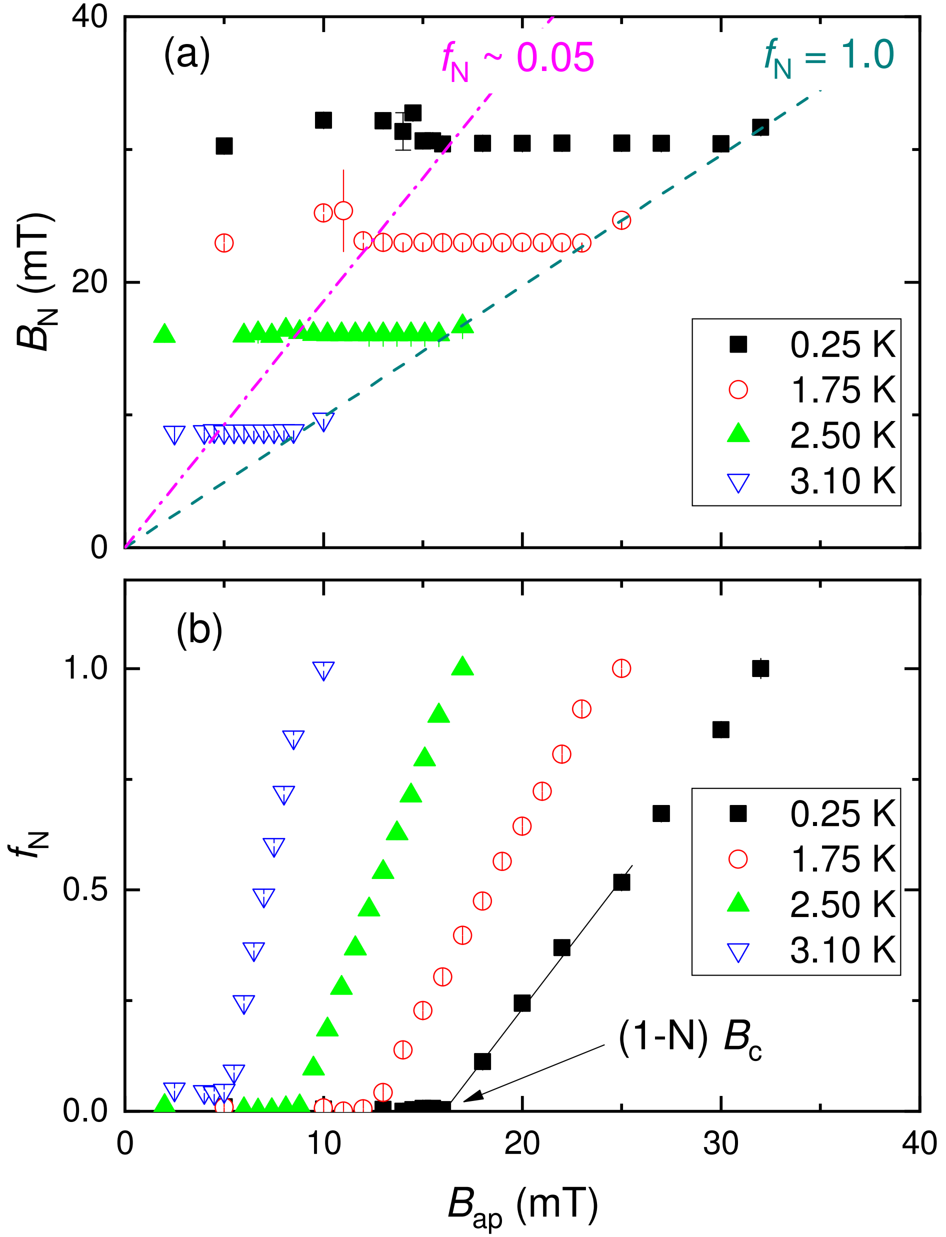


Field scan at T=2.50 K

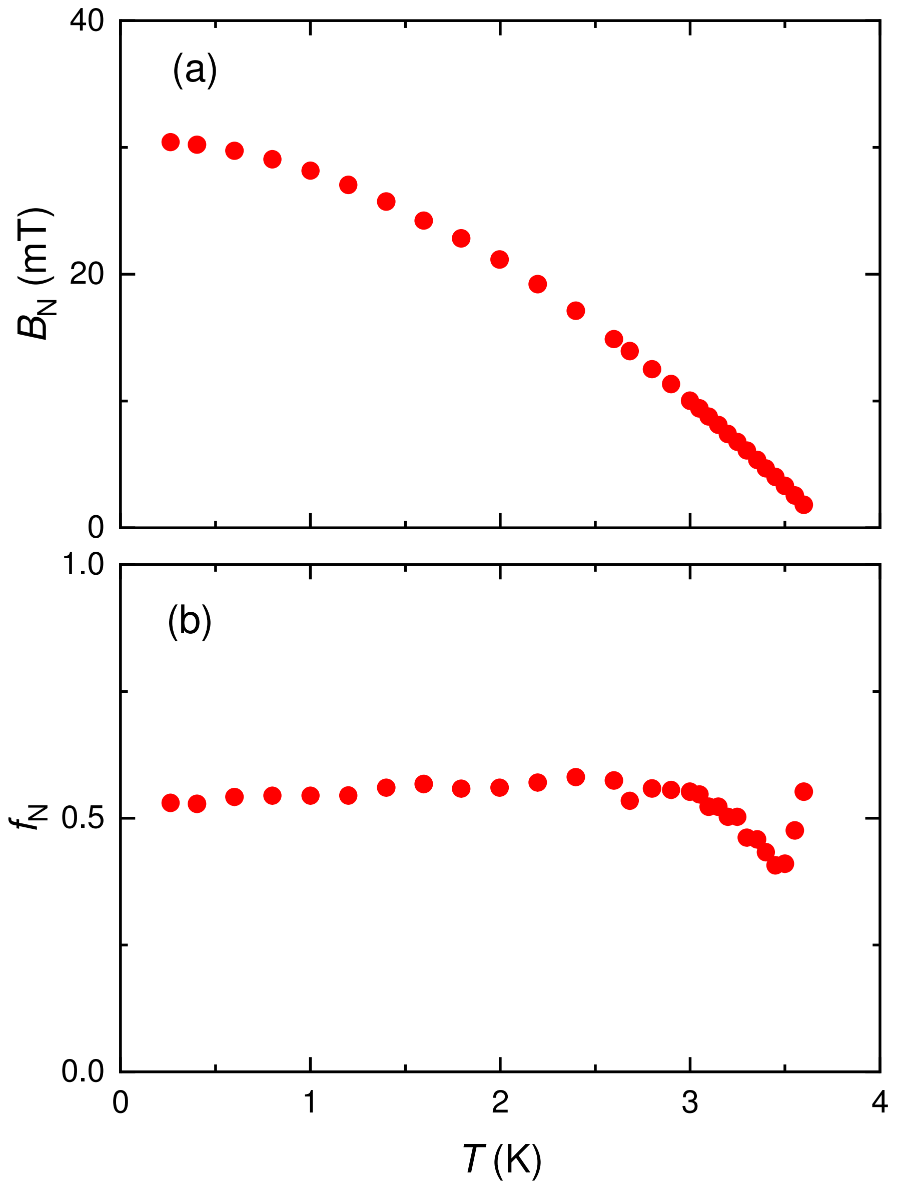




Field scans

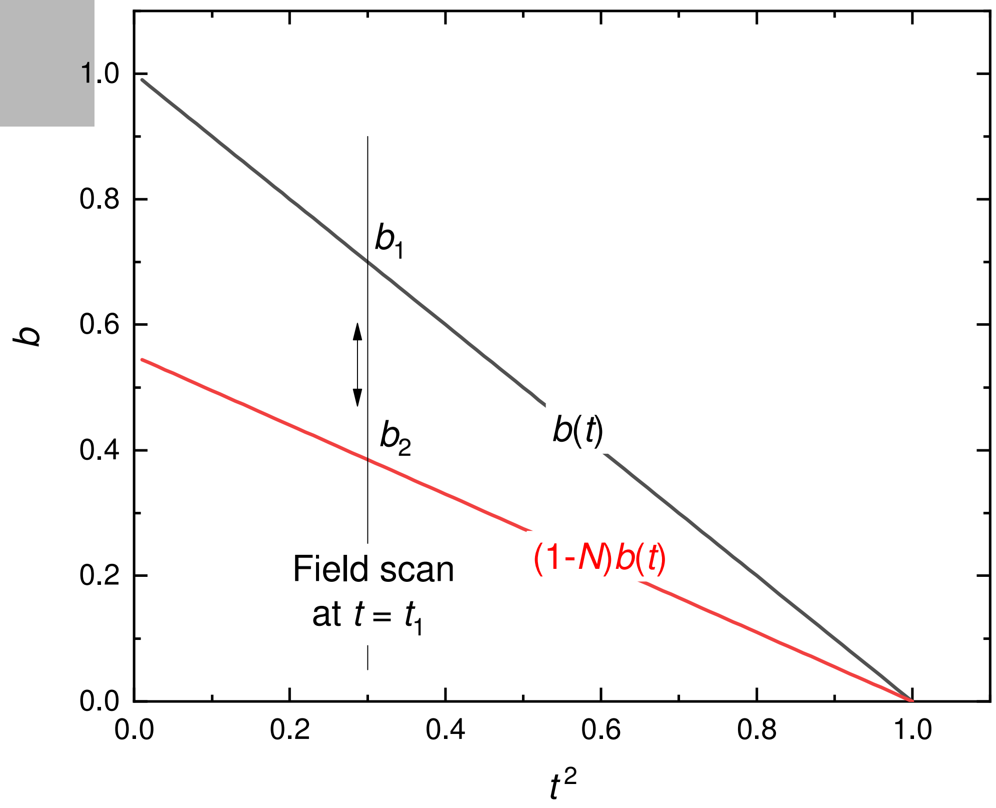


B-T scans



Information obtained from μSR on type-I sc's

Demagnetization: scaling of $f(T)$ and $f(B)$



***B*-scans**

$$f(b_1, t_1) = 1$$
$$f(b_2, t_1) = 0$$
$$b_2 = (1 - N) b_1$$

$$f(b, t_1) = \frac{b}{b_1}\frac{1}{N} - \frac{1 - N}{N}$$

$f(B)$ curves should scale with $1/B_c$ at corresponding T

Demagnetization: scaling of $f(T)$ and $f(B)$

T-scans

$$f(T) = \frac{T^2 - T_c{}^2}{T_c(B)^2 - T_c{}^2}\frac{N-1}{N} + \frac{1}{N}$$

f(*T*) curves scale with

$1/(1-t_c^2)$ at corresponding *B*

B-scans

$$f(b_1, t_1) = 1$$
$$f(b_2, t_1) = 0$$
$$b_2 = (1-N)b_1$$

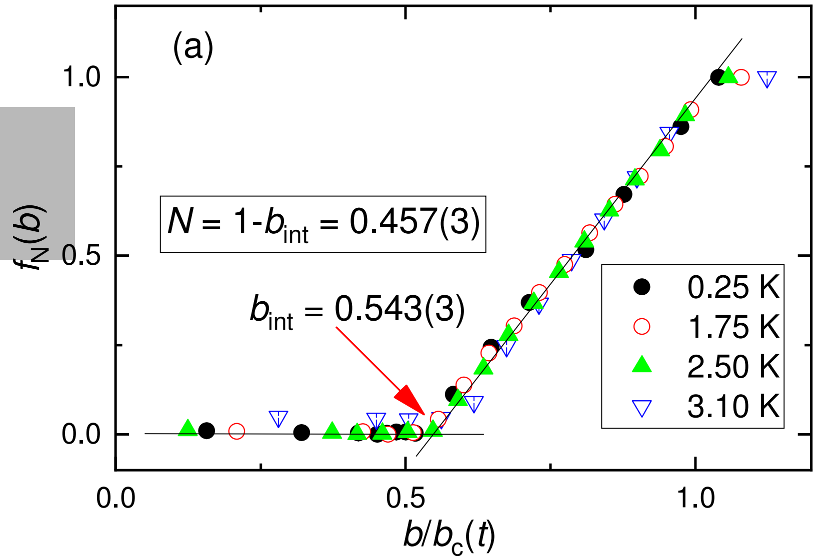
$$f(b, t_1) = \frac{b}{b_1}\frac{1}{N} - \frac{1-N}{N}$$

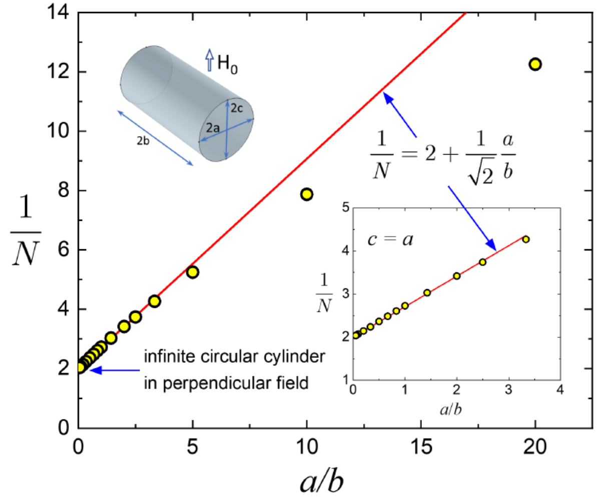
$$f(B) = \frac{B}{B_c(T)}\frac{1}{N} - \frac{1-N}{N}$$

f(*B*) curves should scale with

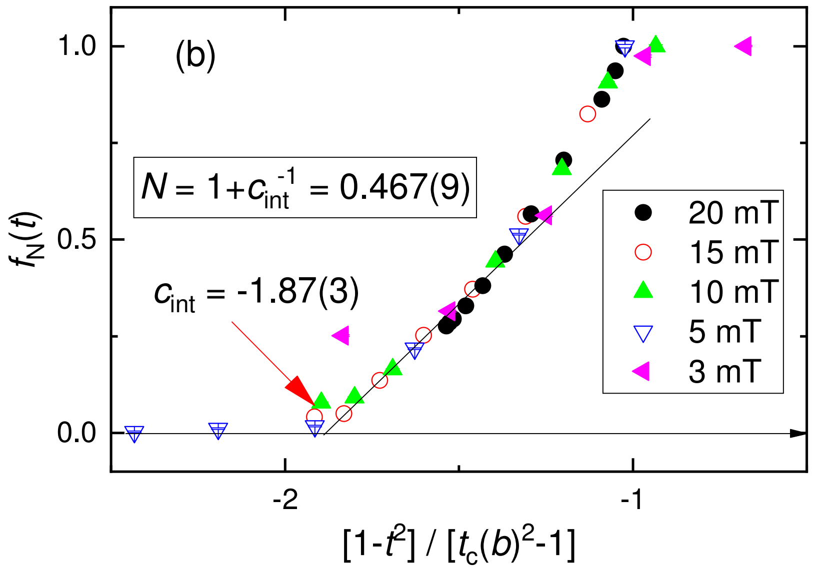
$1/B_c$ at corresponding *T*

Demagnetization: scaling of $f(T)$ and $f(B)$





Prozorov and Kogan, Phys. Rev. Applied **10**, 014030 (2018)



Sample dimensions: ø = 20.0 mm, h = 100 mm

$N_{theor} = 0.467$. $N_{exp} = 0.457 – 0.467$

α-model [Johnston, *SST* **26**, 115001 (2013)]

The single-band -model of superconductivity was first developed by Padamsee *et al* [J. Low Temp. Phys. **12** 387 (1973)]. It is adapted from the single-band Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity to allow fits to electronic heat capacity versus *T* data that deviate from the BCS prediction. The model was further reconsidered by Johnston [SST **26**, 115001 (2013)].

The model assumes that the normalized superconducting order parameter $\Delta(T)/=\Delta(0)$ is the same as in BCS theory, calculated using the weak-coupled BCS value $\alpha_{BCS} = \Delta(0) / k_B T_c = 1.764$. On the other hand, to calculate the electronic free energy, entropy, heat capacity and thermodynamic critical field versus *T*, the -model takes α to be an adjustable parameter.

α-model. Gap equations

$$\int_0^{k_B\Theta_D} \frac{d\epsilon}{E} \tanh\left(\frac{E}{2k_BT}\right) = \frac{1}{N(0)V},$$

where

$$E = \sqrt{\epsilon^2 + \Delta^2}$$

$$\int_0^{k_B\Theta_D} \frac{d\epsilon}{E} \tanh\left(\frac{E}{2k_BT}\right) = \ln\left(\frac{2\Theta_D}{\alpha_{BCS}T_c}\right).$$

$$\int_0^{k_B\Theta_D} \frac{d\epsilon}{E} \tanh\left(\frac{E}{2k_BT}\right) = \ln\left[\frac{2k_B\Theta_D}{\Delta(0)}\right].$$

$$\int_0^{\frac{k_B\Theta_D}{\Delta(0)}} \frac{d\tilde{\epsilon}}{\tilde{E}} \tanh\left(\frac{\alpha_{BCS}\tilde{E}}{2t}\right) = \ln\left[\frac{2k_B\Theta_D}{\Delta(0)}\right],$$

$$\tilde{\Delta} = \frac{\Delta}{\Delta(0)}, \qquad \tilde{\epsilon} = \frac{\epsilon}{\Delta(0)}, \qquad t = \frac{T}{T_c}.$$

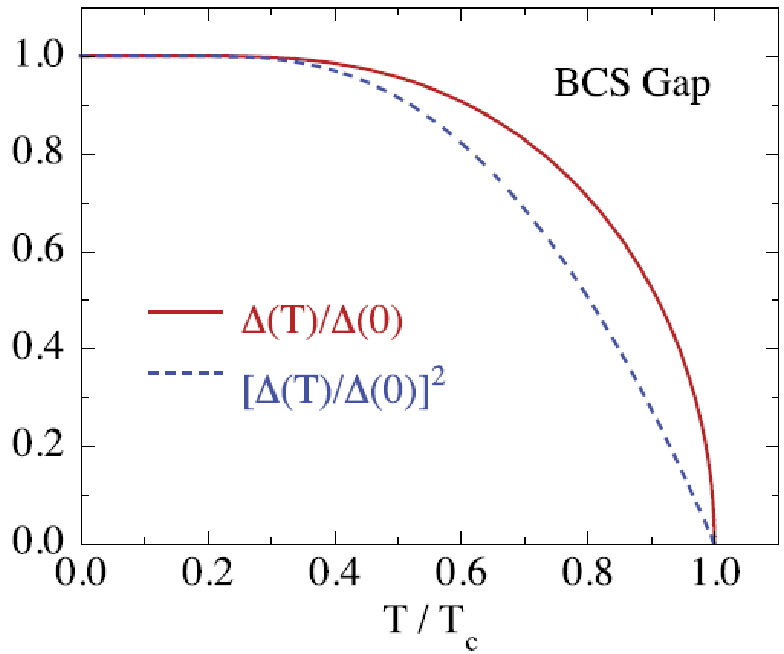


Figure 1. Normalized BCS energy gap $\Delta(T)/\Delta(0)$ and its square versus reduced temperature T/T_c as obtained by numerically solving equation (11) in the weak-coupling limit (1).

α-model. The Entropy, Heat capacity and Free energy

$$\frac{S_{\rm es}(t)}{\gamma_{\rm n}T_{\rm c}} = \frac{6\alpha_{\rm BCS}^2}{\pi^2 t}\int_0^\infty f(\alpha_{\rm BCS},\tilde{E},t)\left(\tilde{E}+\frac{\tilde{\epsilon}^2}{\tilde{E}}\right)\mathrm{d}\tilde{\epsilon},$$

$$\frac{C_{\rm es}(t)}{\gamma_{\rm n}T_{\rm c}} = \frac{6\alpha_{\rm BCS}^3}{\pi^2 t}\int_0^\infty f(1-f)\left(\frac{\tilde{E}^2}{t}-\frac{1}{2}\frac{\mathrm{d}\tilde{\Delta}^2}{\mathrm{d}t}\right)\mathrm{d}\tilde{\epsilon},$$

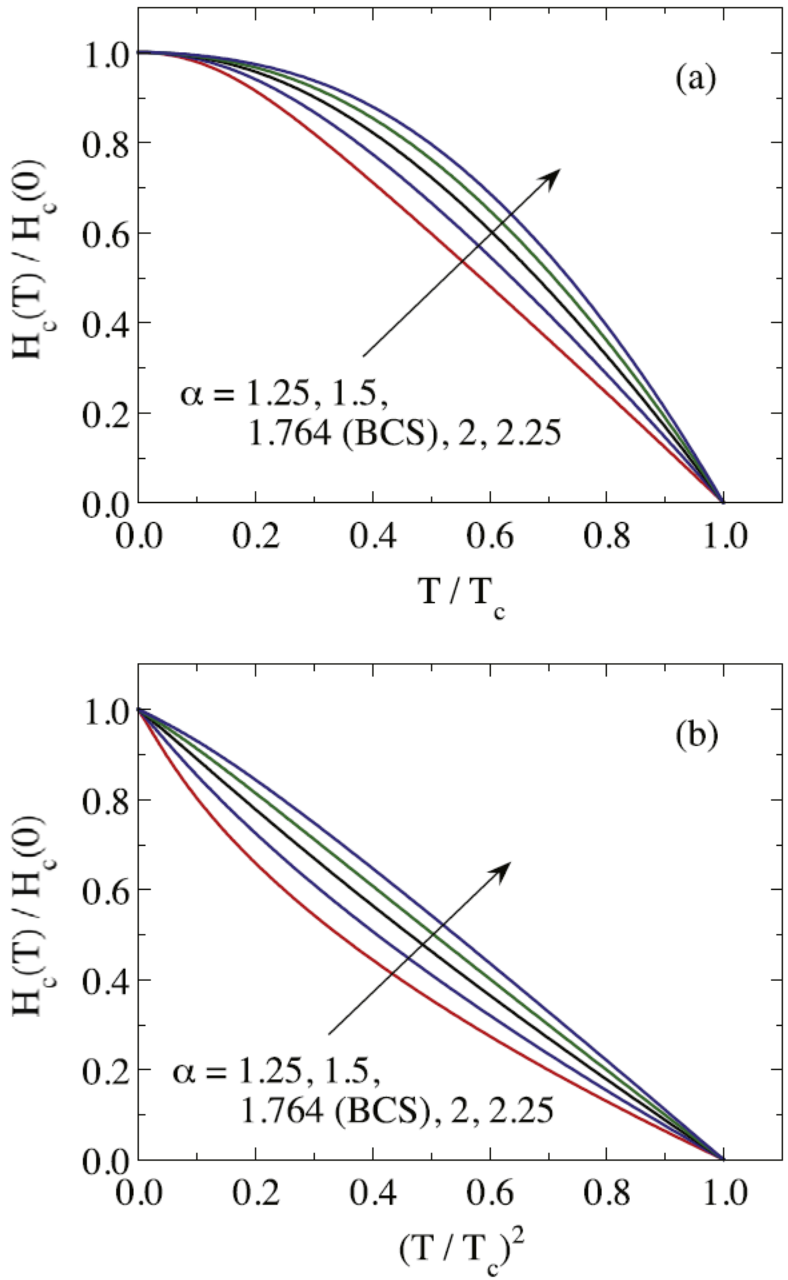
$$\frac{F_{\rm es}(t)}{\gamma_{\rm n}T_{\rm c}^2} = -\frac{3\alpha_{\rm BCS}^2}{4\pi^2} \times\left[\tilde{\Delta}^2+4\int_0^\infty f(\alpha_{\rm BCS},\tilde{E},t)\left(\frac{2\tilde{\epsilon}^2+\tilde{\Delta}^2}{\tilde{E}}\right)\mathrm{d}\tilde{\epsilon}\right].$$

$$f \equiv f(\alpha_{\rm BCS},\tilde{E},t) = \frac{1}{\mathrm{e}^{\alpha_{\rm BCS}\tilde{E}/t}+1}$$

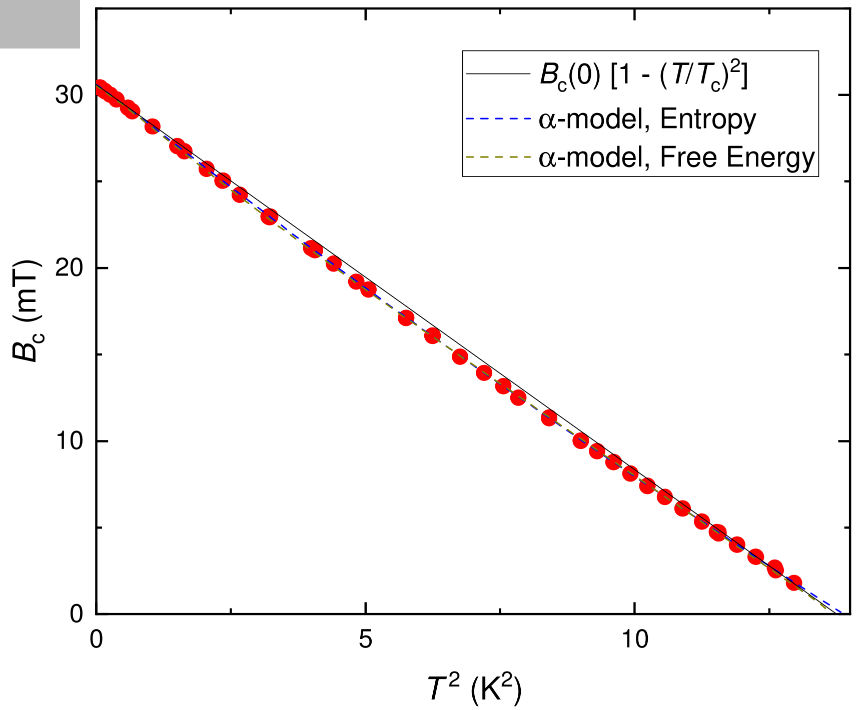
$$\text{with } \frac{E}{k_{\rm B}T} = \frac{\alpha_{\rm BCS}\tilde{E}}{t}.$$

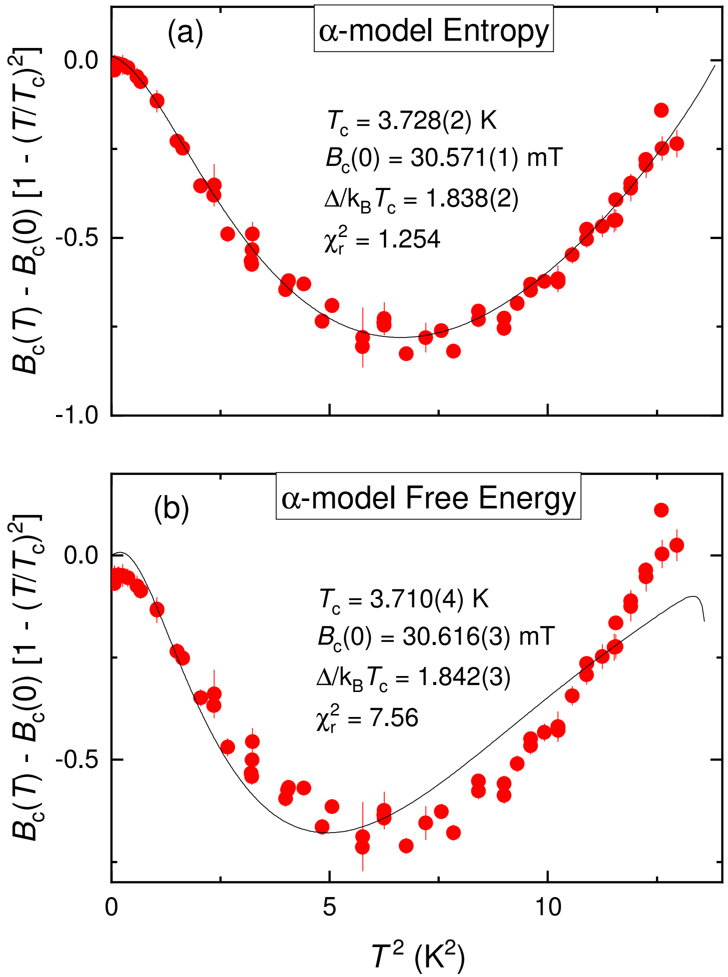
$$\frac{B_{\rm c}^2(t)}{8\pi} = F_N(t) - F_{\rm S}(t),$$

$$\frac{B_{\rm c}^2(t)}{8\pi} = T_{\rm c}\int_t^1 [S_{\rm N}(t') - S_{\rm S}(t')]dt'$$



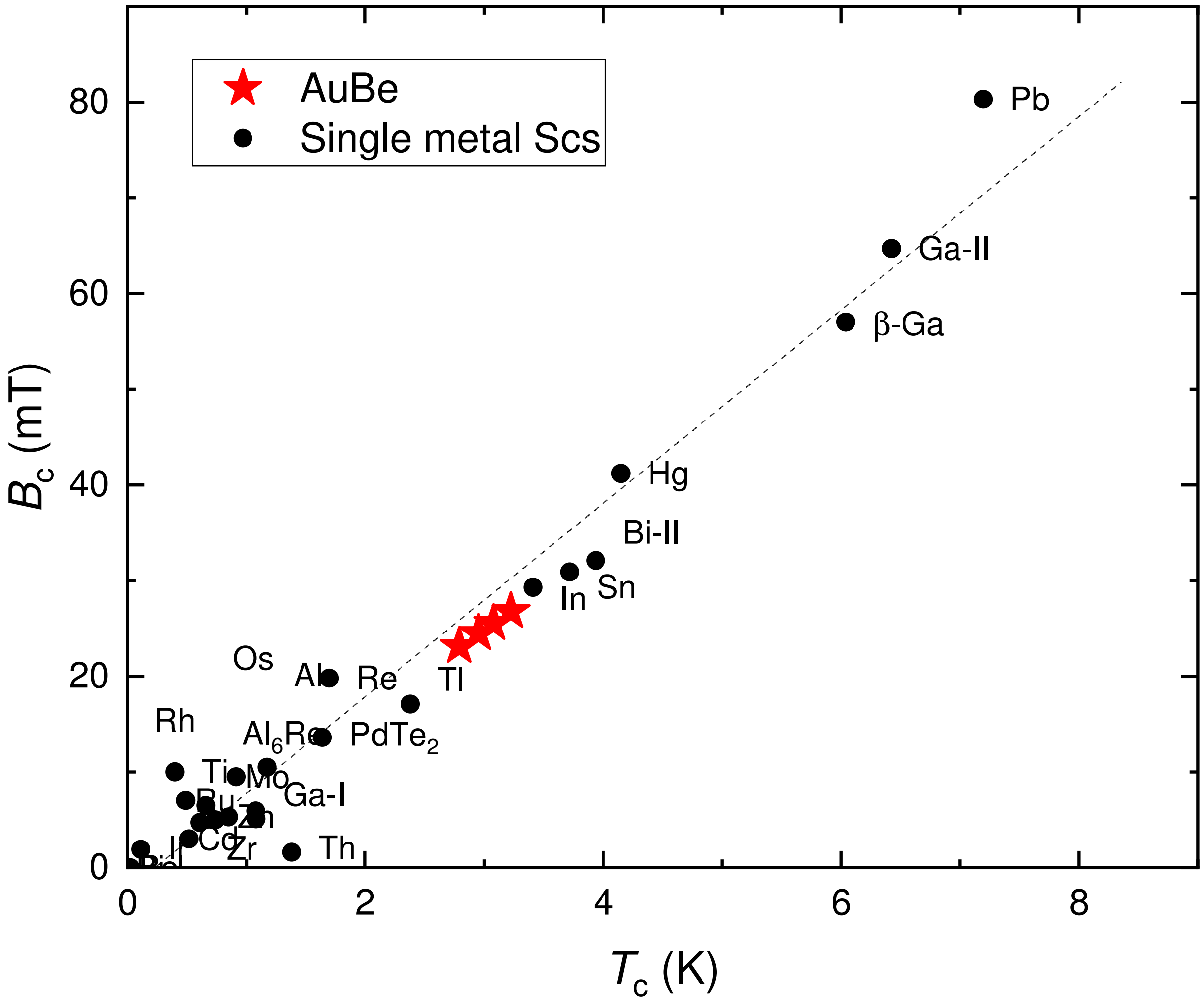
T-dependence of the thermodynamic critical field





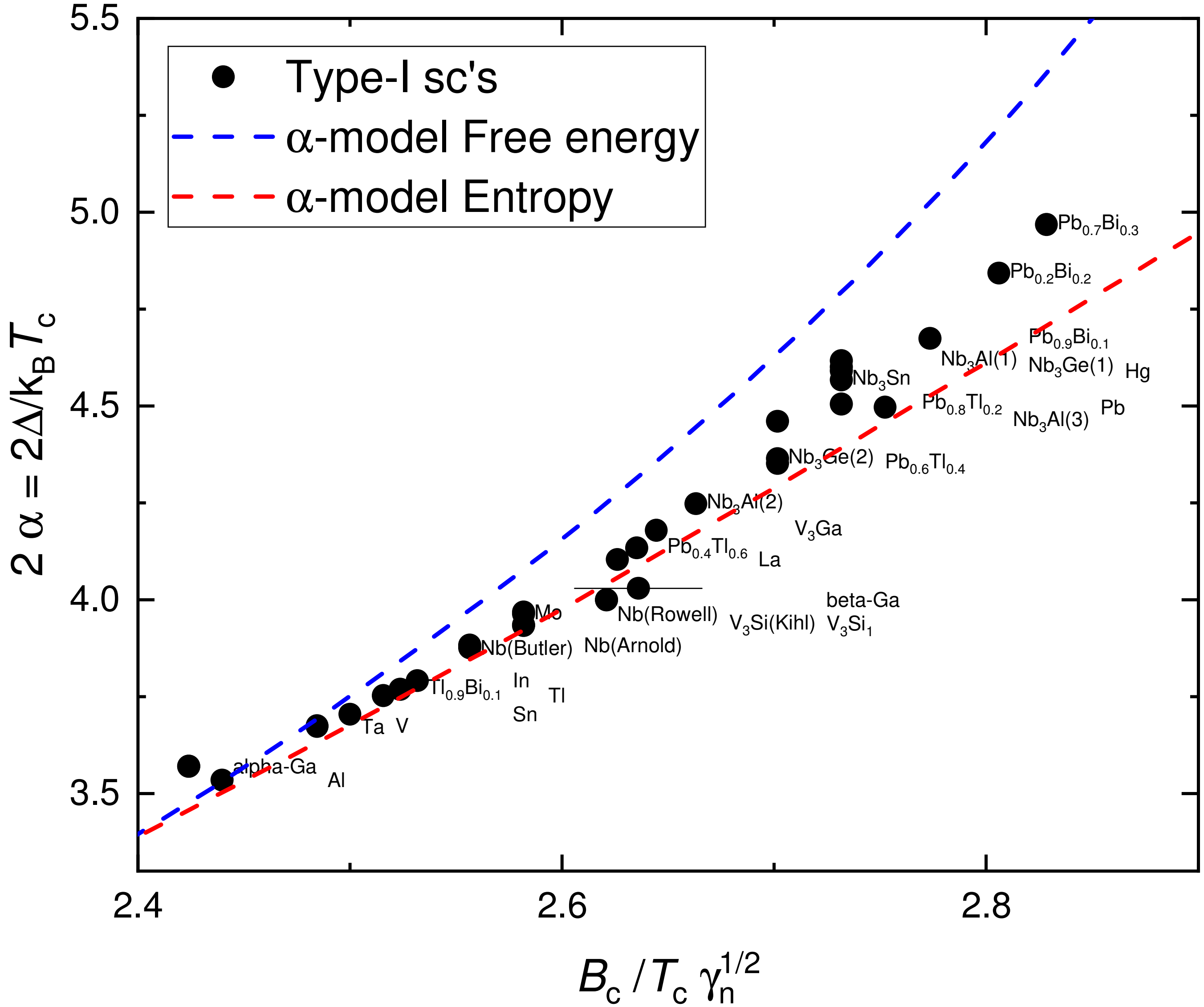
Universal relations for type-I superconductors

Universal relations for type-I superconductors



Kind of a "Uemura line" for conventional type-I superconductors!

Universal relations for type-I superconductors



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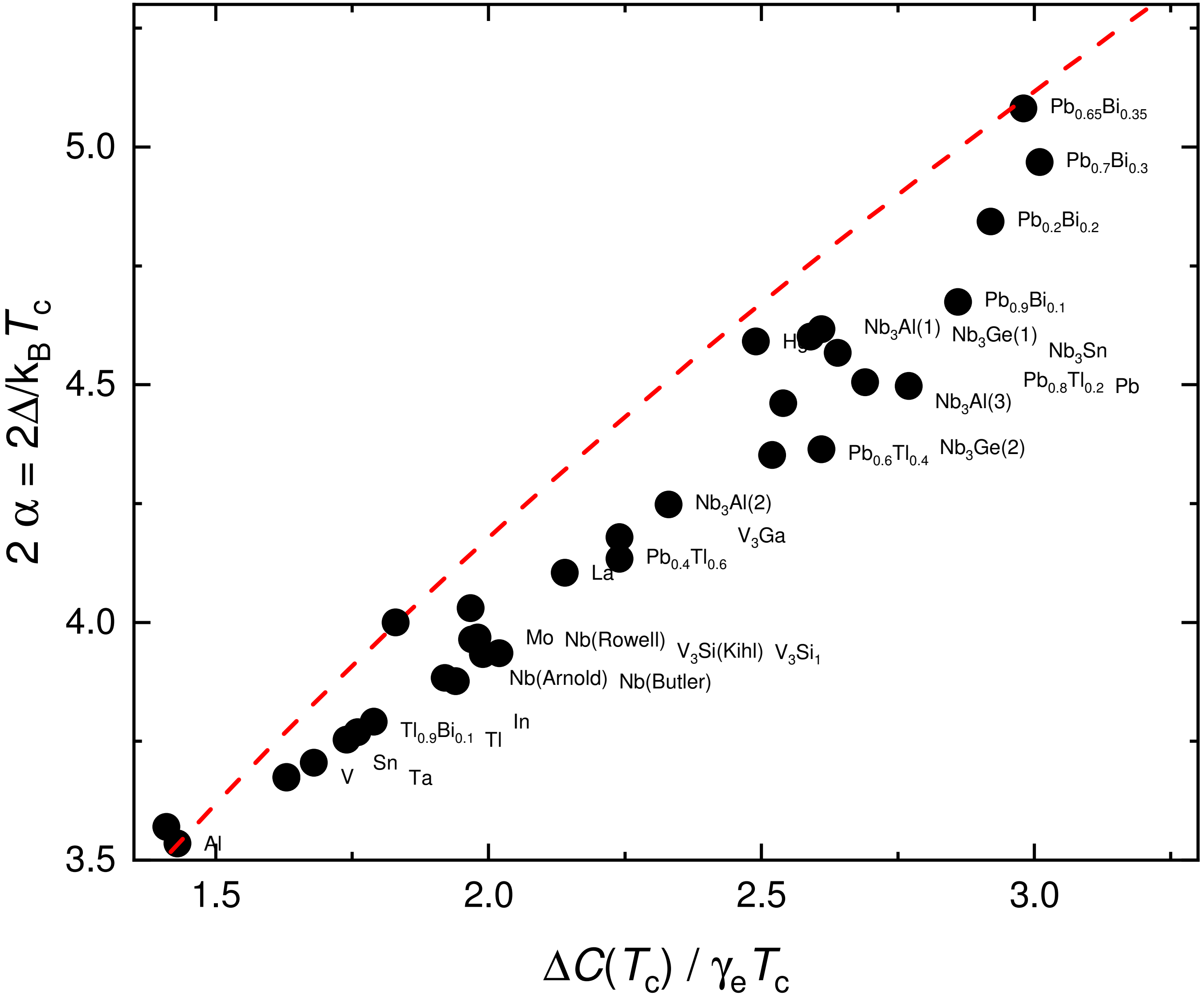
Species	Free electron value for γ in $mJmol^{-1}K^{-2}$	Experimental value for γ in $mJmol^{-1}K^{-2}$
Li	0.749	1.63
Be	0.500	0.17
Na	1.094	1.38
Mg	0.992	1.3
Al	0.912	1.35
K	1.668	2.08
Ca	1.511	2.9
Mn	170	5.2
Fe	4.98	10
Co	4.98	10.3
Cu	0.505	0.695
Zn	0.753	0.64
Ga	1.025	0.596
Rb	1.911	2.41
Sr	1.790	3.6
Ag	0.645	0.646
Cd	0.948	0.688
In	1.233	1.69
Sn	1.410	1.78
Cs	2.238	3.20
Ba	1.937	2.7
Au	0.642	0.729
Hg	0.952	1.79
Ti	1.29	1.47
Pb	1.509	2.98

In single-element superconductors γ is spread between 1 and 3!

Universal relations for type-I superconductors



Conclusion

Single element superconductors are still very interesting objects to be studied!

The universal trends for type-I superconductors become a consequence of a strong coupled BCS approach!

Thanks

M. Elender, H. Luetkens, A. Amato, E. Morenzoni, R Gupta, D. Das

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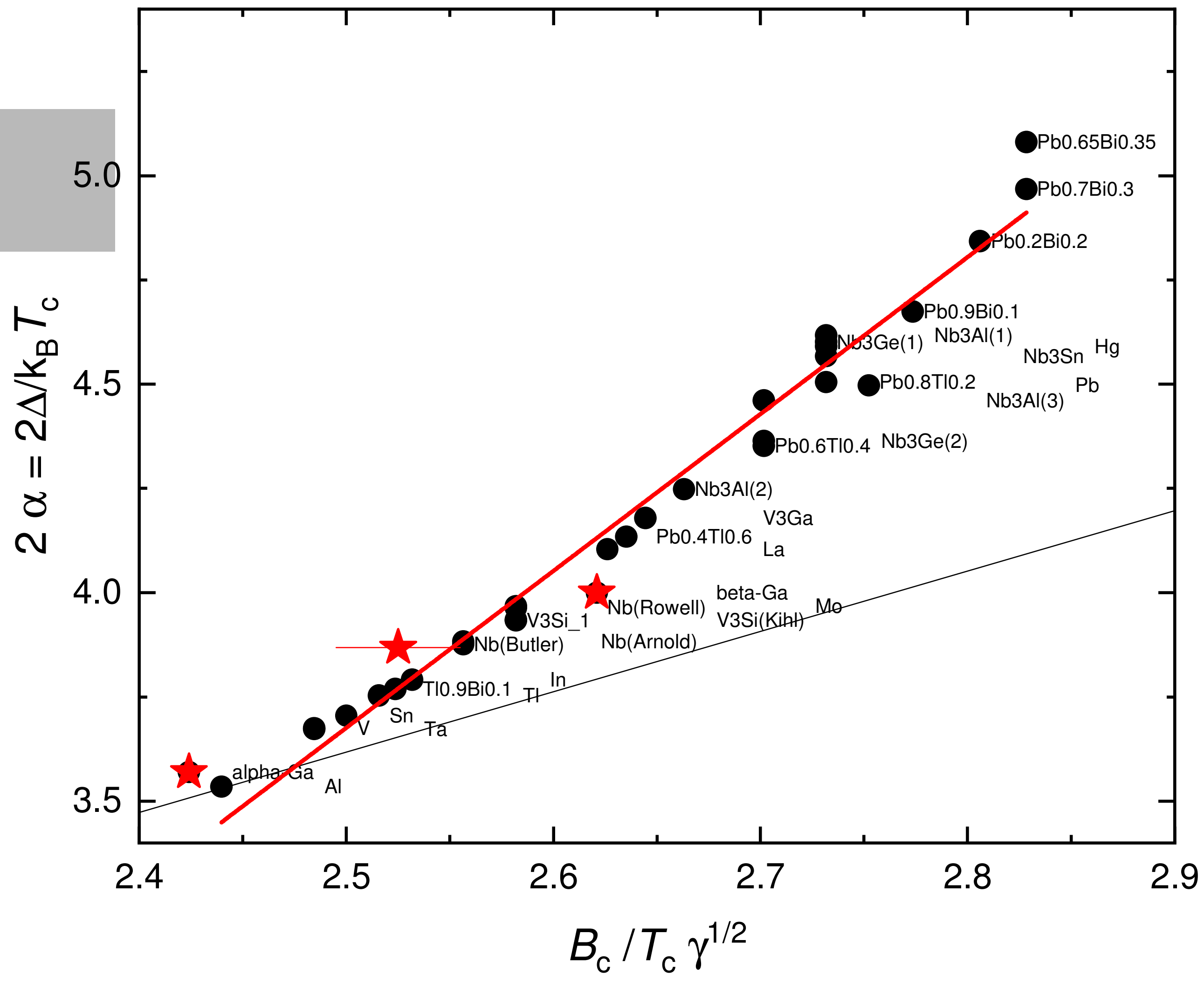

α-model with free α

$$\frac{H_c(0)}{(\gamma_n T_c^2)^{1/2}} = \sqrt{\frac{6}{\pi}}\,\alpha \approx 1.382\alpha.$$

Black points from Carbotte RMP **62**, 1027 (1990)