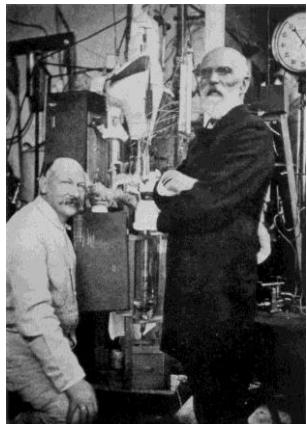
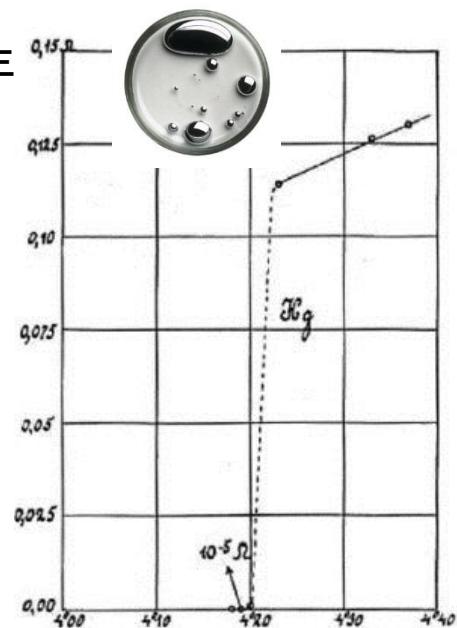


超伝導・超流動入門

□ 水銀: 1911年

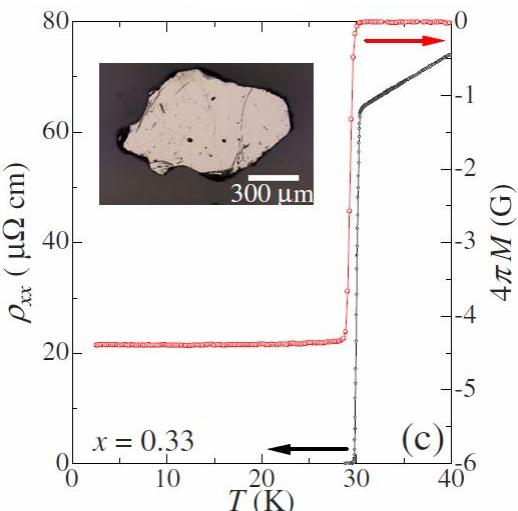


Heike Kamerlingh
Onnes & Johannes
Diderik van der Waals
(r.), in Leiden, 1908



Historic graph showing the superconducting transition of mercury, measured in Leiden in 1911 by H. Kamerlingh Onnes

□ 鉄系超伝導体
 $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$

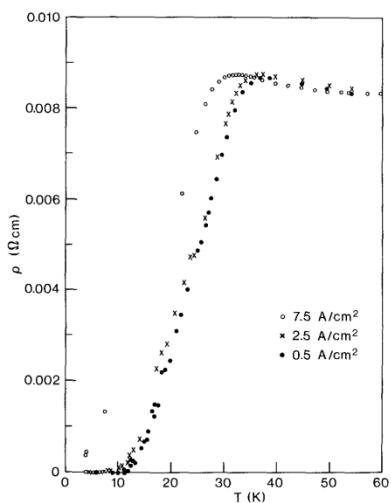


Kasahara (2010) PRB 81, 184519

□ 銅酸化物高温超伝導: 1986年



写真はYBCO



Z. Phys. B Condensed Matter
64, 189-193 (1986)

The Nobel Prize in Physics
1987



J. Georg Bednorz
Prize share: 1/2



K. Alexander Müller
Prize share: 1/2

The Nobel Prize in Physics 1987 was awarded jointly to J. Georg Bednorz and K. Alexander Müller "for their important breakthrough in the discovery of superconductivity in ceramic materials"

- 電気抵抗 0
- 完全反磁性

超伝導・超流動入門

□ 従来型超伝導体

水銀($T_c = 4.2$ K)、アルミニ($T_c = 1.2$ K)、Nb ($T_c = 9.2$ K)

□ 銅酸化物超伝導体

(La_{1-x}Ba_x)₂CuO₄, YBa₂Cu₃O₇, Bi₂Sr₂CuO₆,..,

□ 有機物

κ -(BEDT-TTF)₂Cu(NCS)₂

..

□ 鉄系超伝導体

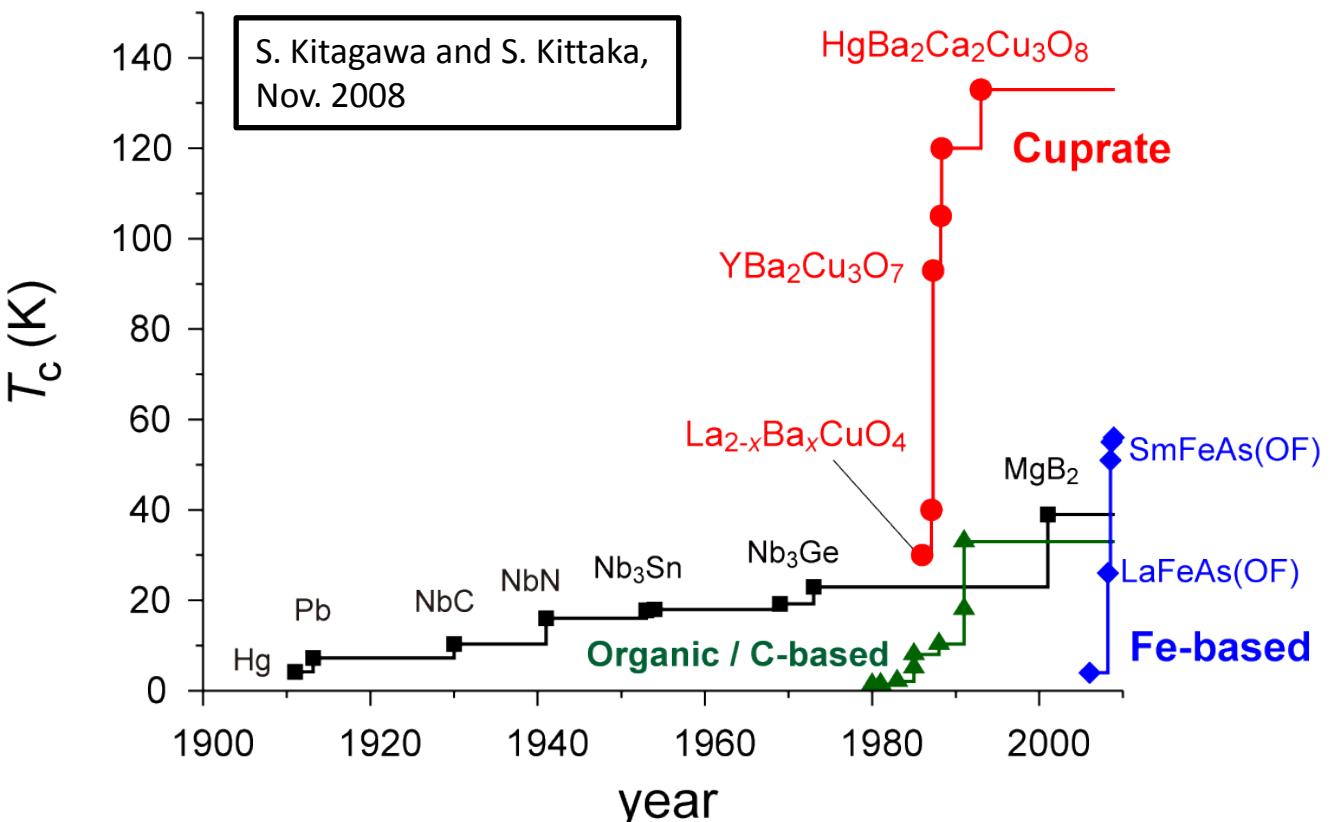
BaFe₂(As,P)2, FeSe,..,

□ 現在の最高のT_cは 153 K HgBa₂Ca₂Cu₃O_{8+y} @15 GPa

J. Phys. Soc. Jpn. 82 (2013) 023711

□ 最低のT_c (?)

Rh 0.32 mK



超伝導・超流動入門

$\Delta(T)/\Delta(0)$

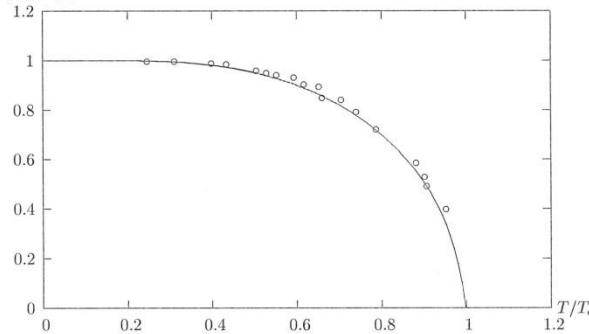
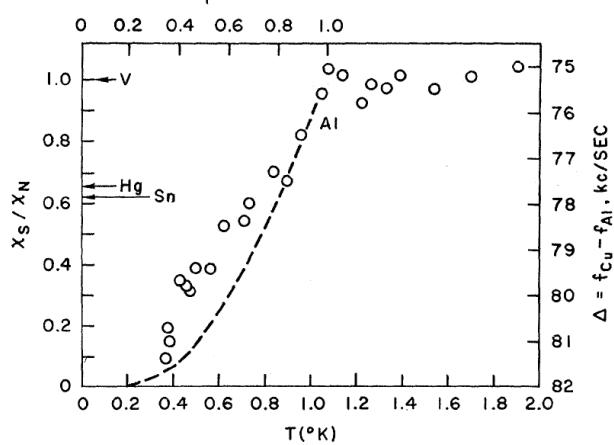


図 7.5: ギャップ関数の温度依存性

白丸はアルミニウム試料で行われたトンネル実験から得られた実験値。

Knight shift of Al R. H. Hammond and G. M. Kelly
Phys. Rev. Lett. 18, 156 (1967)

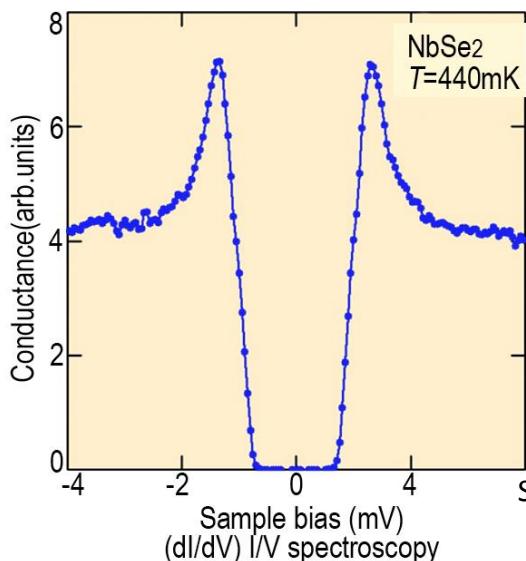
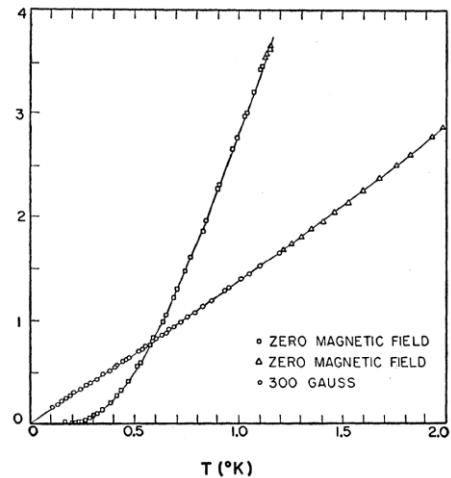


物質名	T_c [K]	Θ_D [K]	$\frac{\Delta(0)}{k_B T_c}$	$\frac{\Delta C_V(T_c)}{C_V^N(T_c)}$	$H_c(0)$ [Oe]	$\frac{H_c^2(0)}{C_V^N(T_c) T_c}$
BCS	(7.114)	—	$\frac{\pi}{\exp(C)} \approx 1.76$	$\frac{12}{7\zeta(3)} \approx 1.43$	(7.155)	$\frac{6\pi}{\exp(2C)} \approx 5.942$
Cd	0.56	209	1.72	1.32	30	5.65
Hg	4.154	71.9	1.98	2.37	411	7.46
Sn	3.722	199	1.79	1.60	305.5	6.13
Pb	7.193	105	1.98	2.71	803	7.45
Nb	9.23	275	1.83	1.87	1980	6.37
Al	1.196	428	1.77	1.29	99	5.85
Zn	0.852	327	1.72	1.30	53	5.65

表 7.1: BCS 理論と代表的な超伝導体の実験値との比較(出典: 理科年表・丸善より)

$\Theta_D = \hbar\omega_D/k_B$ は Debye 温度である。

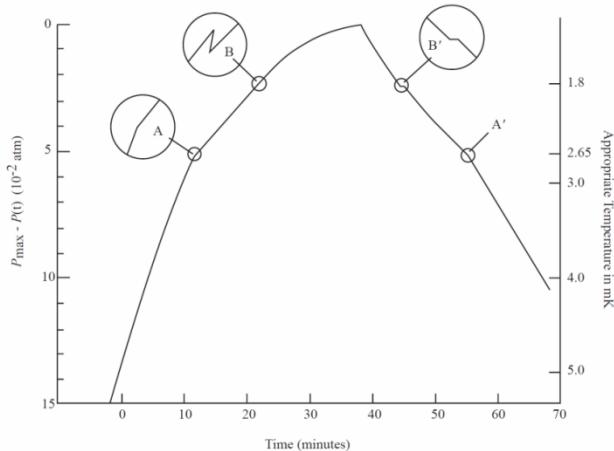
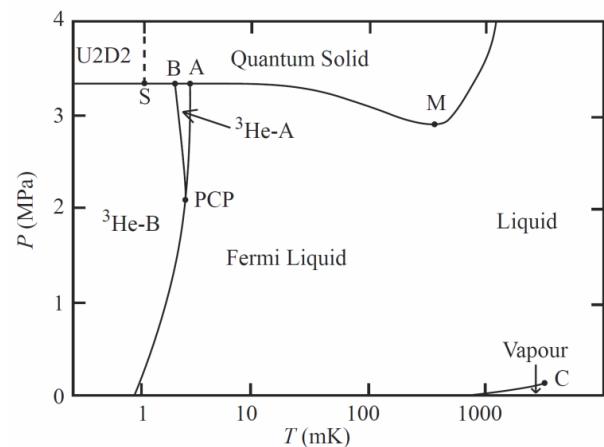
Heat capacity of Al
Philips PhysRev.114.676 (1959)



Density of states
Fermi面を壊すことによる運動エネルギーの損と引力によるエネルギー利得が釣り合うまで
ギャップが開く

STM © Hanaguri, Riken

超伝導・超流動入門



固液共存相で実験していたから固体 ${}^3\text{He}$ のスピンの相転移なのか液体の相転移なのかわからなかった。

The Nobel Prize in Physics 1996



David M. Lee



Douglas D. Osheroff



Robert C. Richardson

Prize share: 1/3

Prize share: 1/3

Prize share: 1/3

The Nobel Prize in Physics 1996 was awarded jointly to David M. Lee, Douglas D. Osheroff and Robert C. Richardson "for their discovery of superfluidity in helium-3".

Photos: Copyright © The Nobel Foundation

Phys. Rev. Lett. 28, 885 (1972)

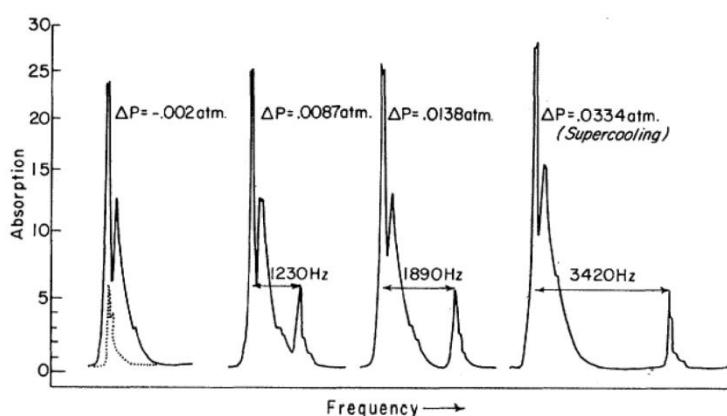
Evidence for a New Phase of Solid ${}^3\text{He}$ [†]

D. D. Osheroff, R. C. Richardson, and D. M. Lee

Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850

(Received 10 February 1972)

Measurements of the melting pressure of a sample of ${}^3\text{He}$ containing less than 40-ppm ${}^4\text{He}$ impurities, self-cooled to below 2 mK in a Pomeranchuk compression cell, indicate the existence of a new phase in solid ${}^3\text{He}$ below 2.7 mK of a fundamentally different nature than the anticipated antiferromagnetically ordered state. At lower temperatures, evidence of possibly a further transition is observed. We discuss these pressure measurements and supporting temperature measurements.



T_c 以下で液体のNMR信号がシフトすることが判明

D. D. Osheroff et al., PRL 29, 920 (1972)

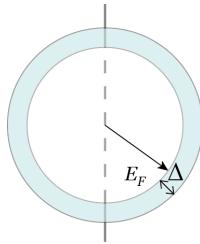
固体ヘリウム3の核スピンの整列は超流動転移(2.48 mK)よりも少し低い温度(0.93 mK)だった。

超伝導・超流動入門

$$\Psi = \psi_{orbital} \times \chi_{spin}$$

□ 普通の超伝導体(Hg, Al, etc.)

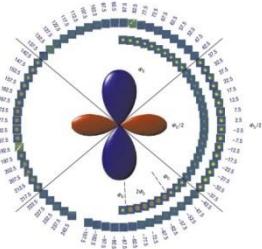
s-wave, singlet



$$\Psi_s = \Delta_0 e^{i\phi}$$

□ 高温超伝導体(YBCO, BSCO)

d-wave, singlet



$$\Psi_{d_{x^2}-d_{y^2}} = \Delta_0(k_{x^2} - k_{y^2}) e^{i\phi}$$

Nature Phys. 2, 190 (2006)

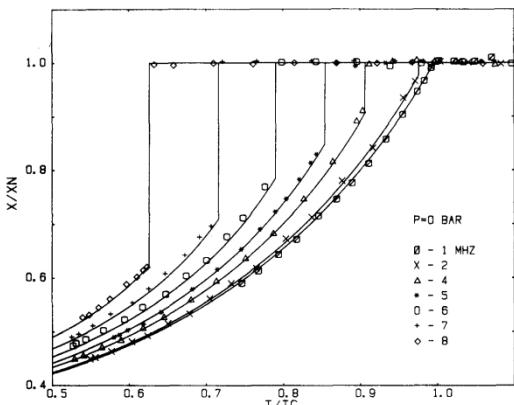
□ Triplet超伝導体 (Sr_2RuO_4 , UPt_3 , ??)

(p, f)-wave, triplet

超伝導対称性は未確定

超流動ヘリウム3の磁化率測定

Dobbs, Helium three



□ ${}^3\text{He}$ の超流動

p-wave, tripletであることが確立している唯一の例。

$$G = \underline{\text{SO}(3)_S} \times \underline{\text{SO}(3)_L} \times \underline{\text{U}(1)_\phi}$$

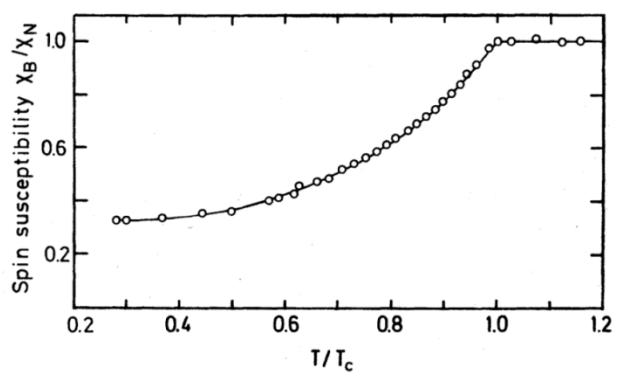
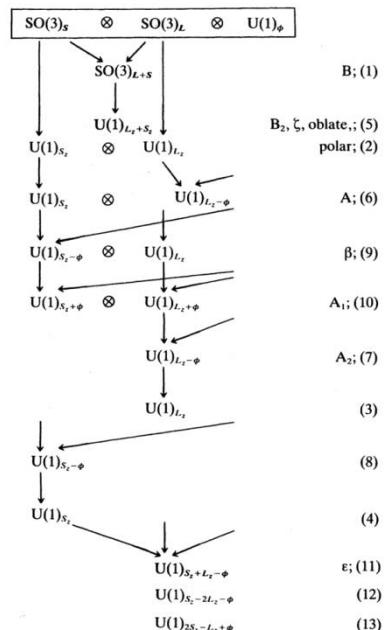
スピン

軌道

位相

群論的にいろんな破り方が可能。

実際には一番エネルギーの低い状態が実現。



超伝導・超流動入門

- Singlet superconductor
スピン空間の自由度は無い

$$\Delta_{k\alpha\beta} = \begin{pmatrix} 0 & \Delta \\ -\Delta & 0 \end{pmatrix} = \Delta i\sigma_2$$

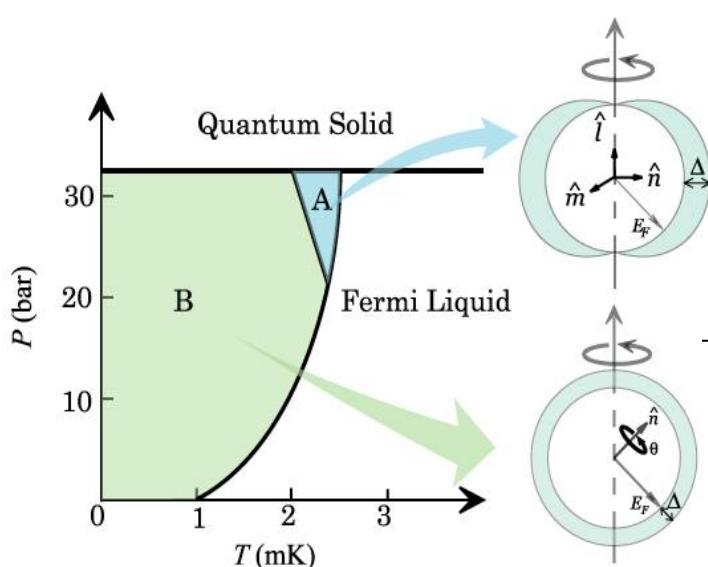
- Triplet superconductor:
スピン空間の自由度を d
ベクトルで表現

$$\begin{aligned} \Delta_{k\alpha\beta} &= \begin{pmatrix} \Delta_{\uparrow\uparrow} & \Delta_{\uparrow\downarrow} \\ \Delta_{\downarrow\uparrow} & \Delta_{\downarrow\downarrow} \end{pmatrix} = \begin{pmatrix} -d_x + id_y & d_z \\ d_z & d_x + id_y \end{pmatrix} \\ &= (d(\mathbf{k}) \cdot \boldsymbol{\sigma}) i\sigma_2 \end{aligned}$$

さらにP波($|l|=1$)の3つの球面調和関数 $(p_x, p_y, p_z) = Y_{1,\pm 1}, Y_{1,0}$ で展開

$$\Delta_{k\alpha\beta} = \left(\sum_{\mu k} d_{\mu k} \hat{p}_k \sigma_\mu \right) i\sigma_2$$

- Order parameter of 3He



[ABM state]

Anderson-Morel (PRL 1960)

Anderson-Brinkmann (PRL 1973)

$$\begin{aligned} d_{\mu j} &= \Delta_{ABM} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & i \\ 0 & 0 & 0 \end{pmatrix} \\ &\rightarrow \Delta(T) \times \underbrace{\hat{d}_\mu}_{\text{Spin}} \times (\hat{m}_j + i\hat{n}_j) \underbrace{\hat{d}_\mu}_{\text{Orbital}} \end{aligned}$$

[BW state]

Balian-Werthamer (PR 1963)

$$\begin{aligned} d_{\mu j} &= \Delta_{BW} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ &\rightarrow \Delta(T) \times R_{\mu j}(\hat{n}, \theta) \times e^{i\phi} \end{aligned}$$

回転行列

位相