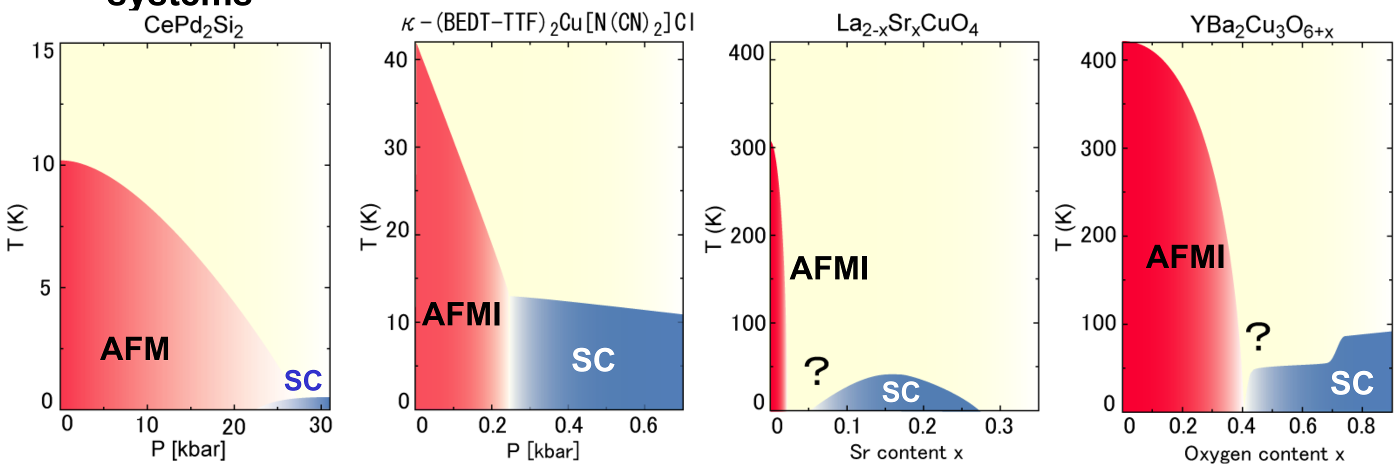
相関電子系超伝導の多様性(I)

Diversity of Correlated Superconductivity (I)

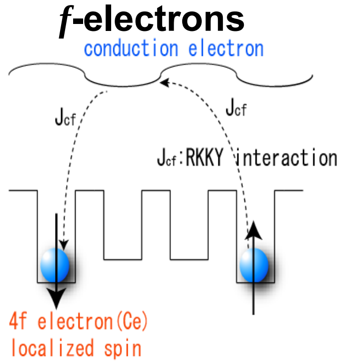
- 有機伝導系 (Organic Systems)
- 重い電子系 (Heavy-electrons systems)

Frontier of Superconducting Phenomena

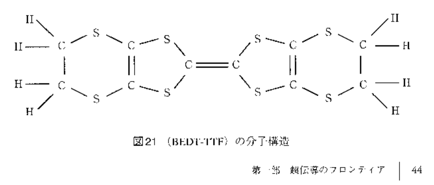
Heavy-electrons systems | **Organic conductors** | **High-T_c copper oxides**



Nearly localized *f*-electrons

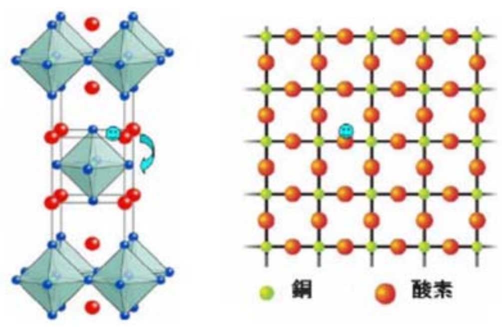


Half-field p_π bands



Strongly Correlated Electrons Systems

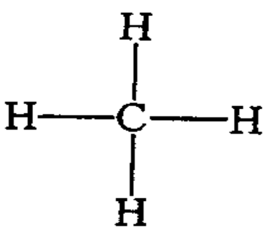
Half-filled 3*d* bands



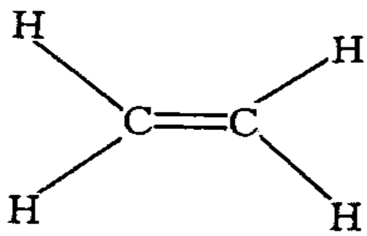
CuO_2面

分子軌道法のまとめ

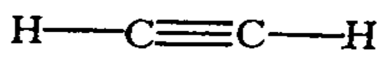
有機分子の分子軌道法とフロンティア軌道理



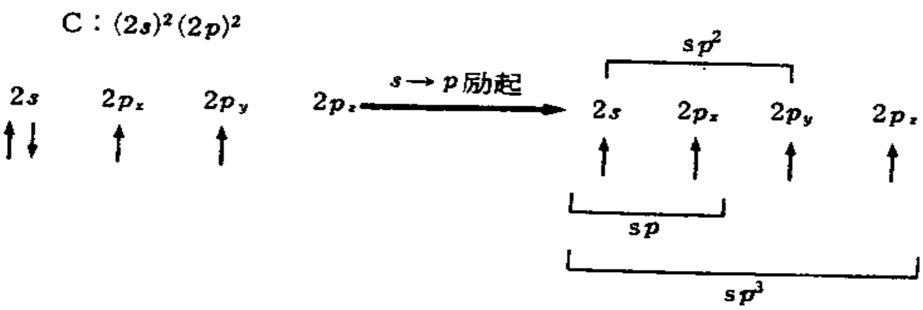
メタン



エチレン

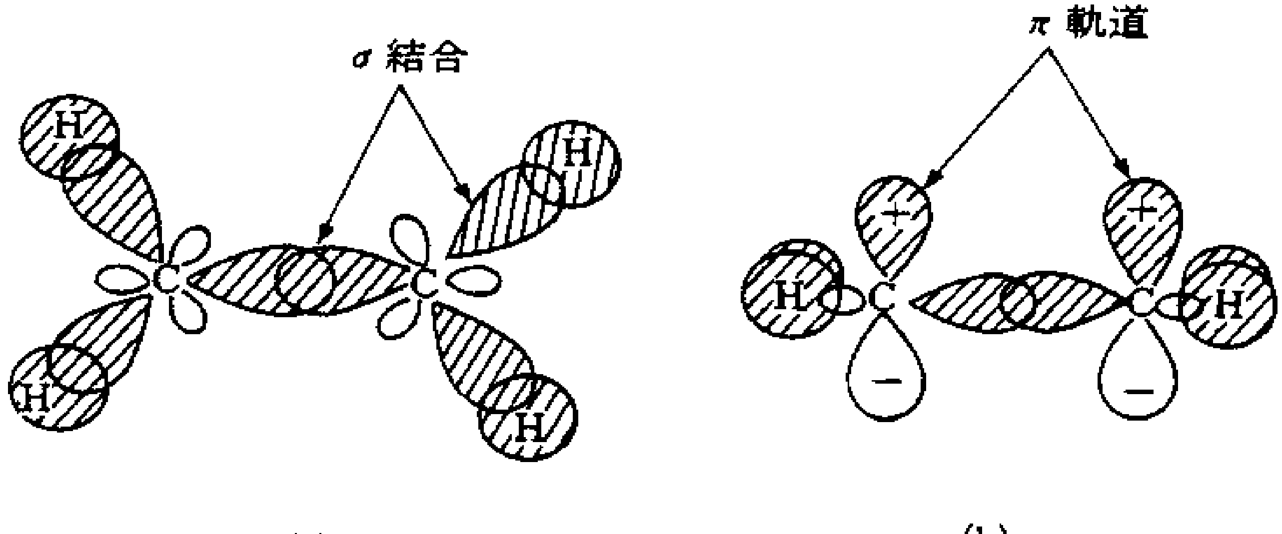


アセチレン



(a) (b)

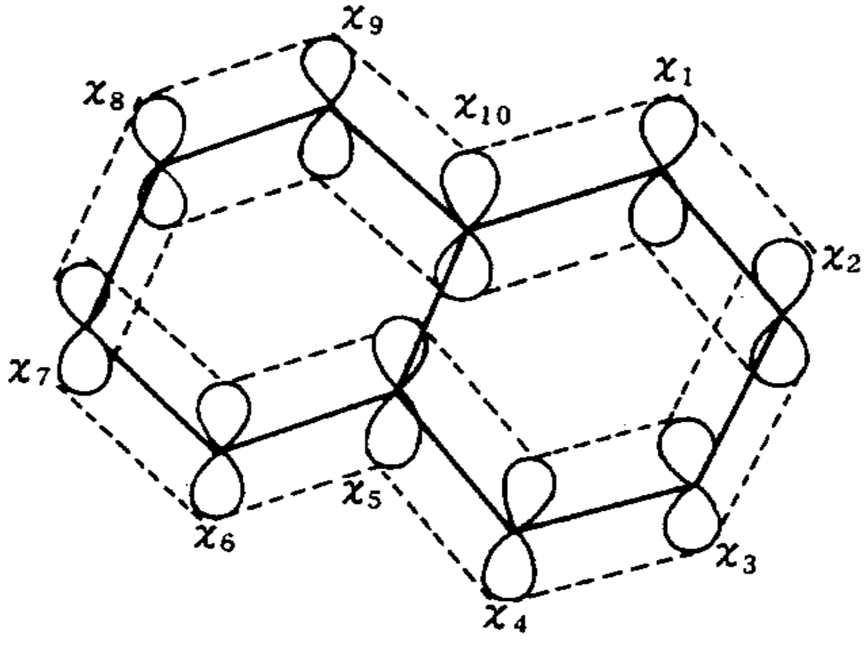
炭素原子が作る三つの混成軌道。矢印は電子スピンを表す。



(a)　　(b)

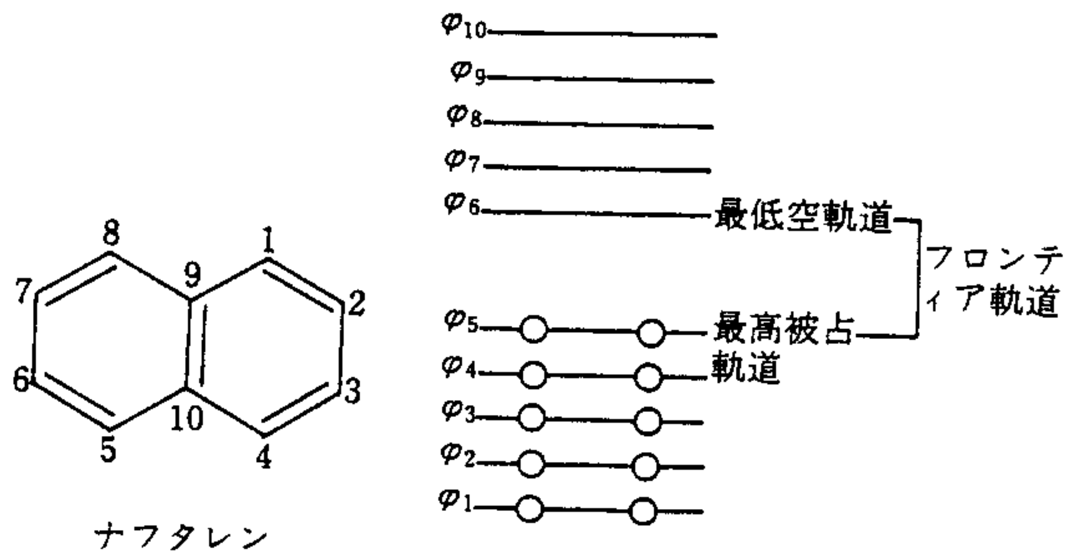
エチレンにおけるσ結合とπ軌道

フロンティア軌道理論とは何か



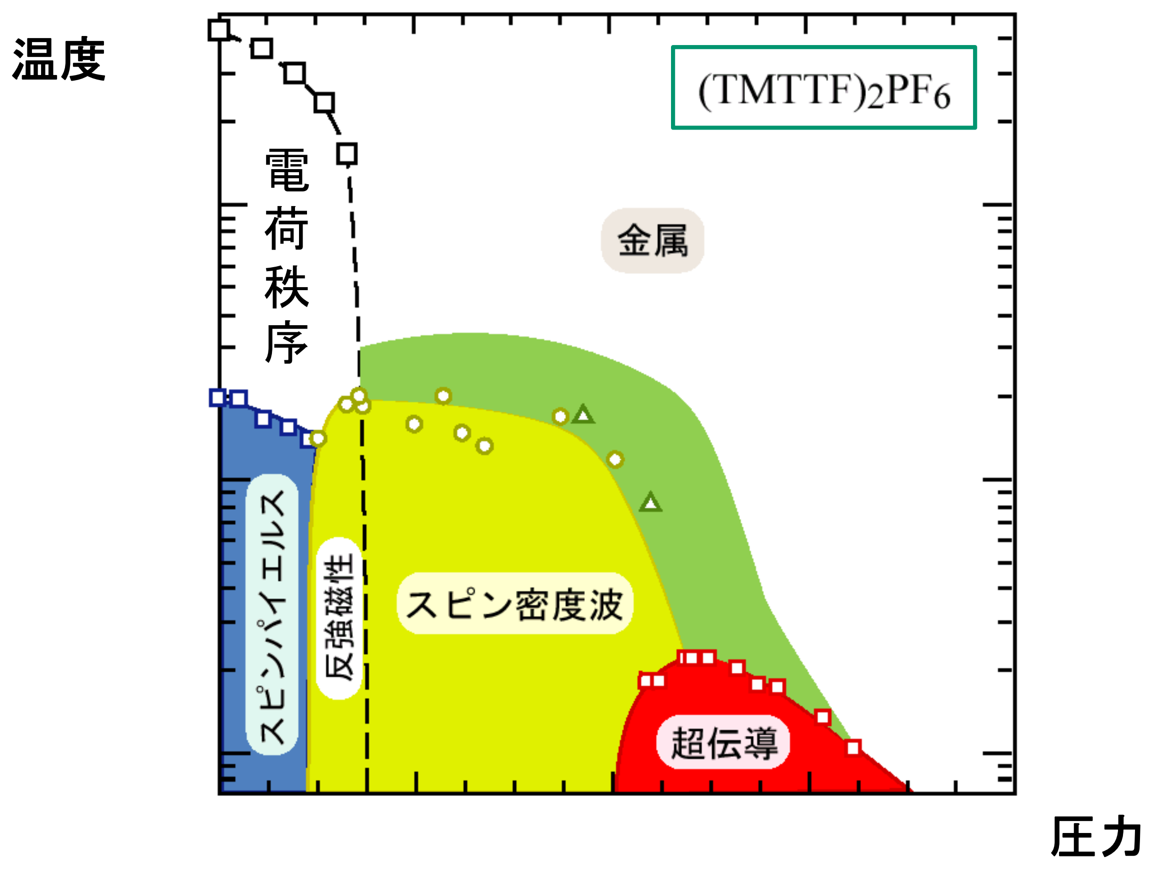
ナフタレンについて原子軌道（χ_1，χ_2，…χ_{10}）から分子軌道（$\varphi = c_1\chi_1 + c_2\chi_2 + \cdots c_{10}\chi_{10}$）ができる様子を視覚的に示したもの。

$$\varphi = C_1\chi_1 + C_2\chi_2 + \cdots\cdots C_{10}\chi_{10}$$



シュレーディンガー方程式を解いて得られたナフタレンの10個のπ電子についての分子軌道($\varphi_1, \varphi_2, \cdots \varphi_{10}$)のエネルギー値（図では数値は省略）をエネルギーの低い方から順番にならべたもの

Pressure-temperature Phase diagram for Quasi-1D Organic conductor



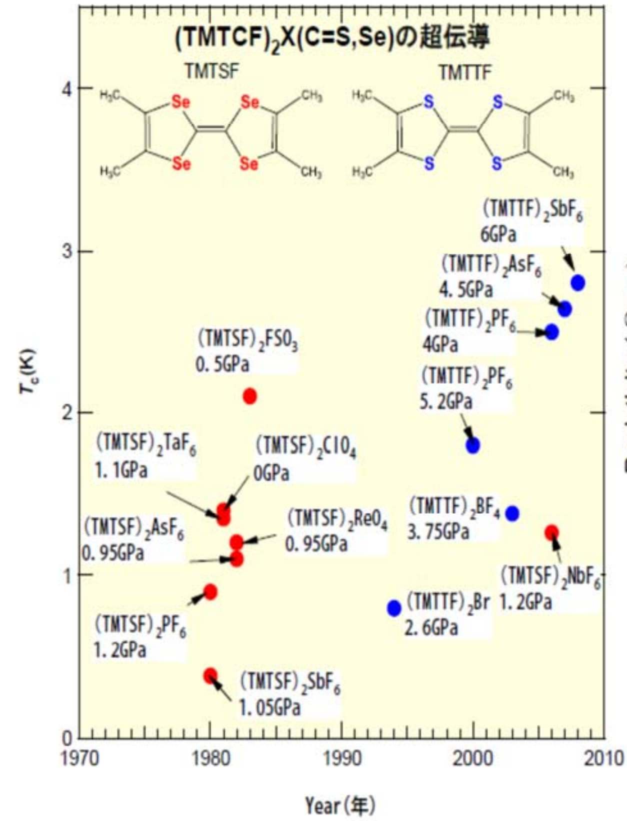


図1 (TMT*C*F)$_2$*X*の超伝導出現温度と発見年度

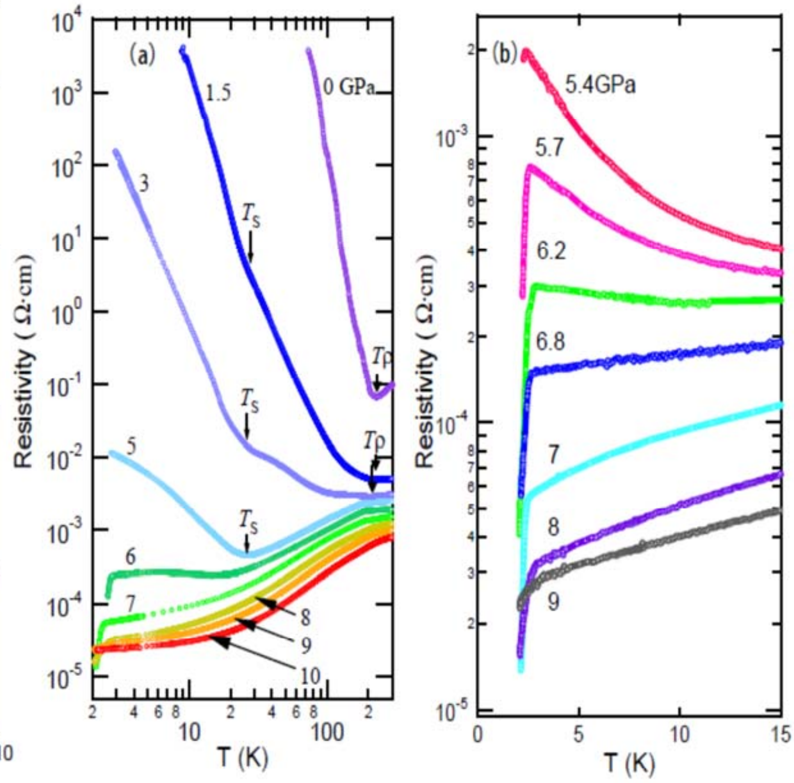


図 2 (TMTTF)$_2$SbF$_6$の圧力下における電気抵抗の挙動

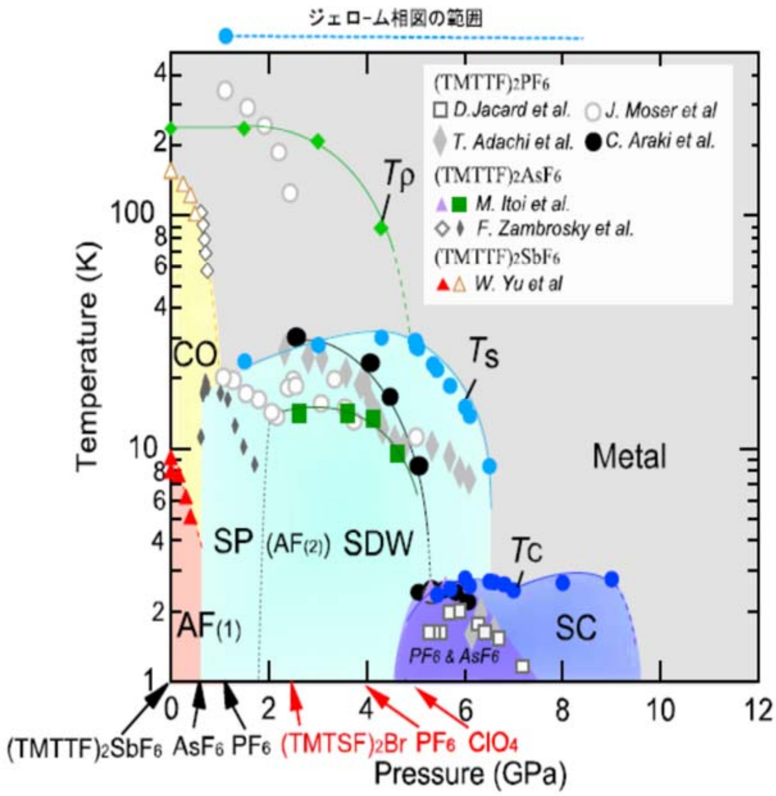
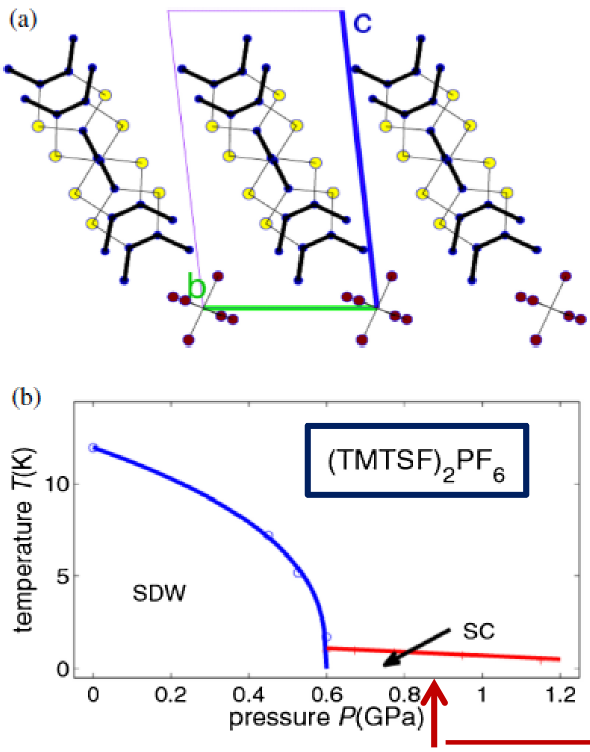
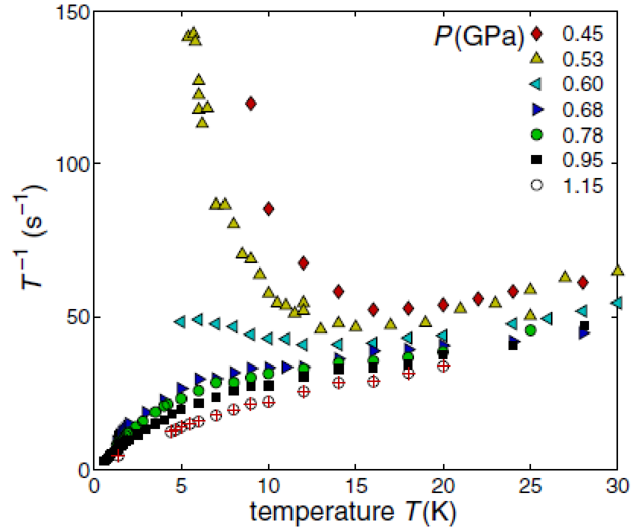


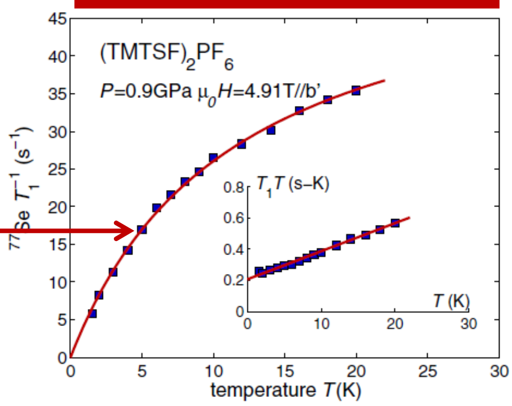
図 3 (TMTTF)$_2$SbF$_6$ を基にした新しい(TMT*C*F)$_2$*X*の電子相関図。*C*, *X*による化学圧力に対応する静水圧力を矢印で示した。CO:電荷秩序相、AF:反強磁性相、SP:スピンパイエルス相、SDW:spin density wave相、SC:超伝導相を表す。

Discovery Pressure-induced SC in Quasi One-dimensional Organic Matter



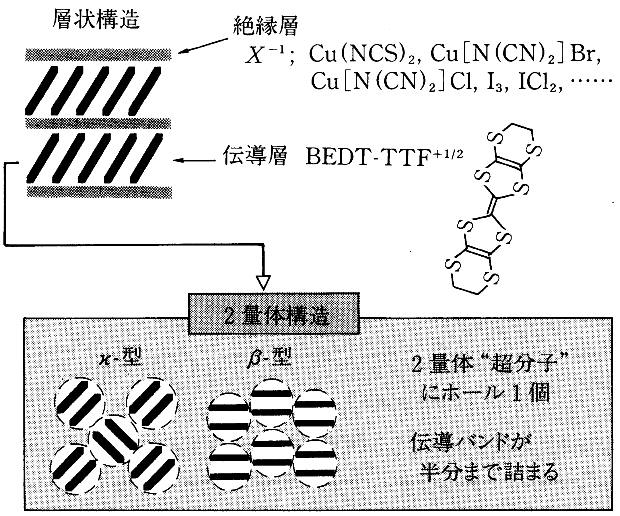


AFM spin fluctuations



Recent topics of Organic superconductors, Recent Developments in Superconductivity, J. Phys. Soc. Jpn. 81 (2012) 011004.

有機化合物超伝導体



第 1 図 (BEDT-TTF)$_2X$ の構造．BEDT-TTF 分子には両側に 4 個ずつ水素が付いている．

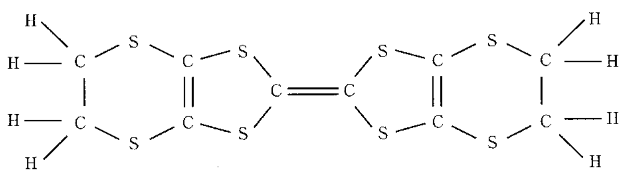
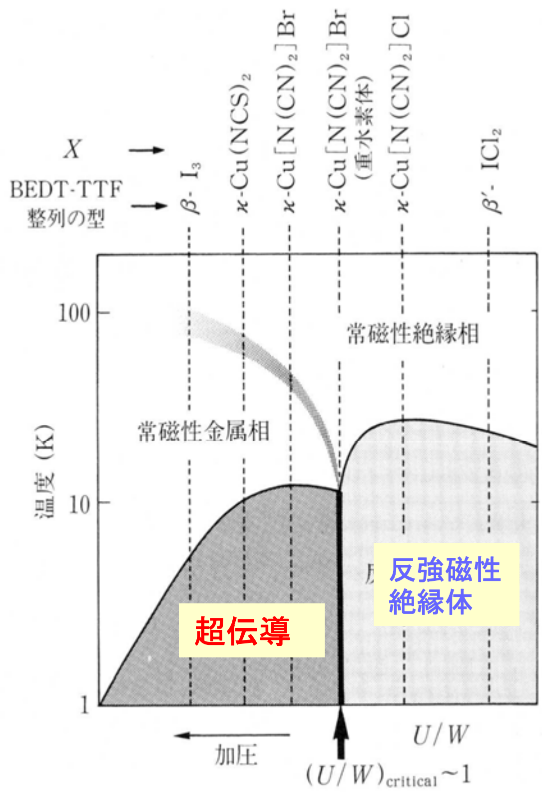


図21 (BEDT-TTF) の分子構造

超伝導ー磁性相図



第 2 図 (BEDT-TTF)$_2X$ の超伝導相，絶縁体相を説明する概念的相図．

Quasi-2D Organic Conductor

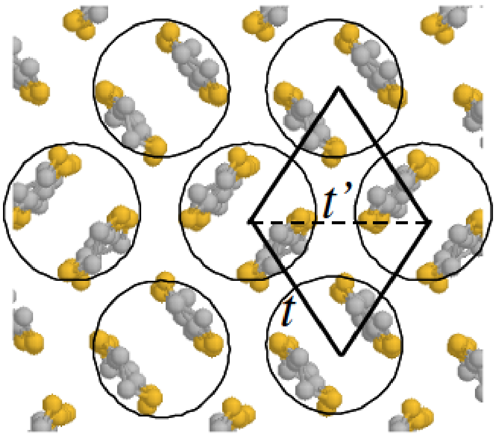
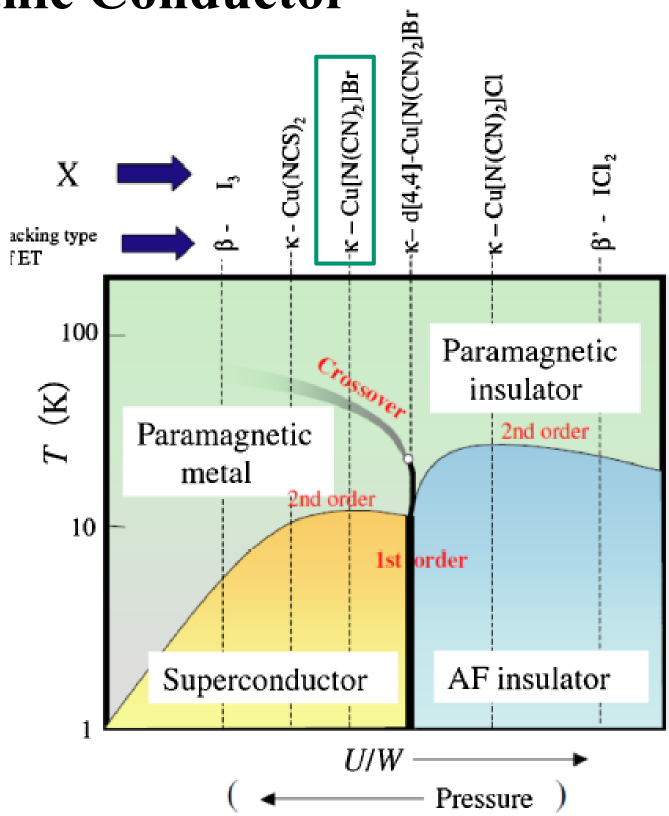


Fig. 13. (Color online) In-plane structure of BEDT-TTF layers in κ-(BEDT-TTF)$_2$X. The dimer lattice is modeled into an isosceles triangular lattice as described in §4.4. The t and t' stand for inter-dimer transfer integrals, which construct a model of anisotropic triangular lattice as depicted in Fig. 18.



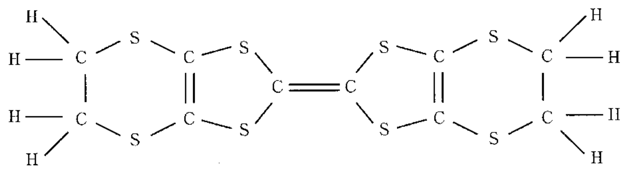
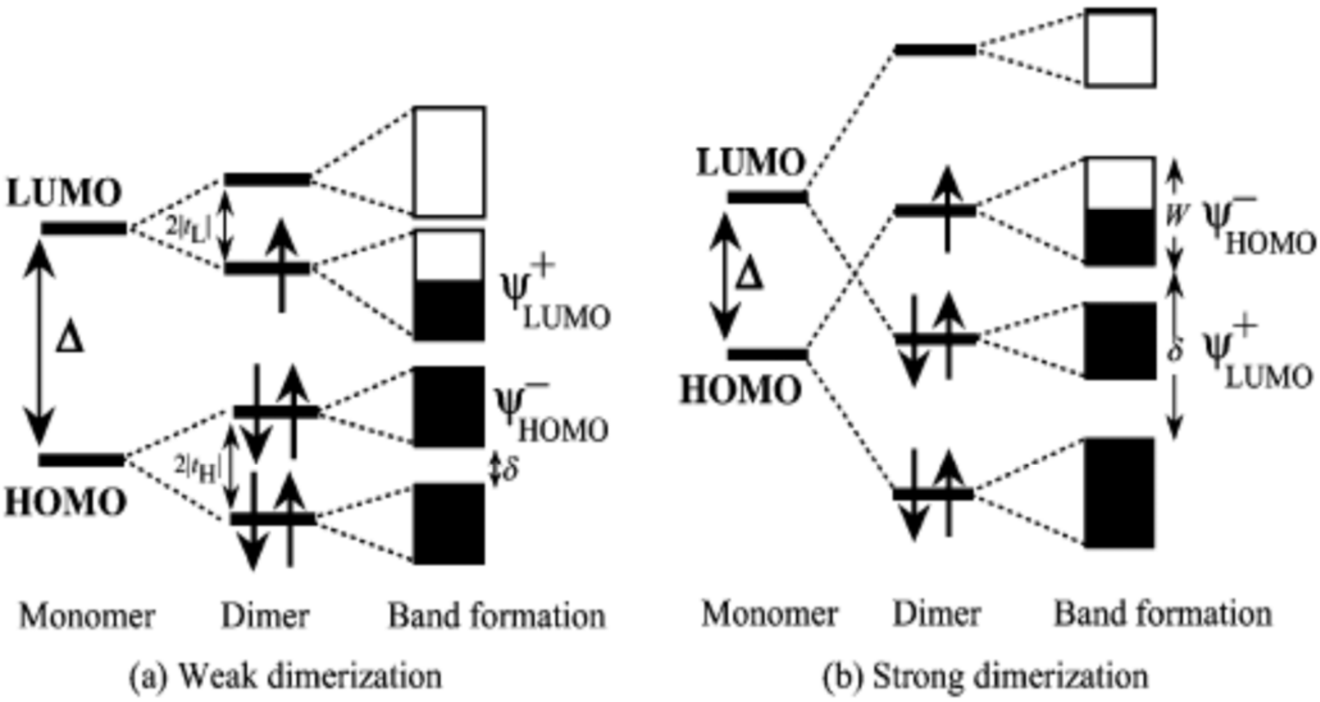


図21 (BEDT-TTF) の分子構造

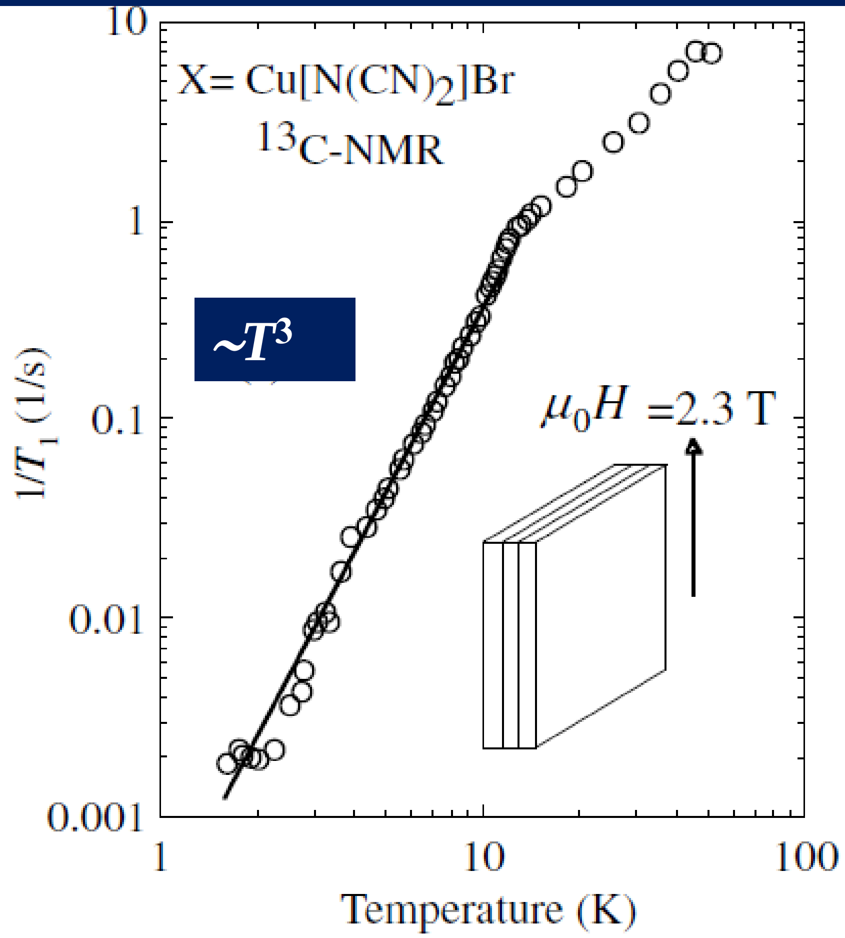
Correlated Electronic State in Dimer Organic Systems



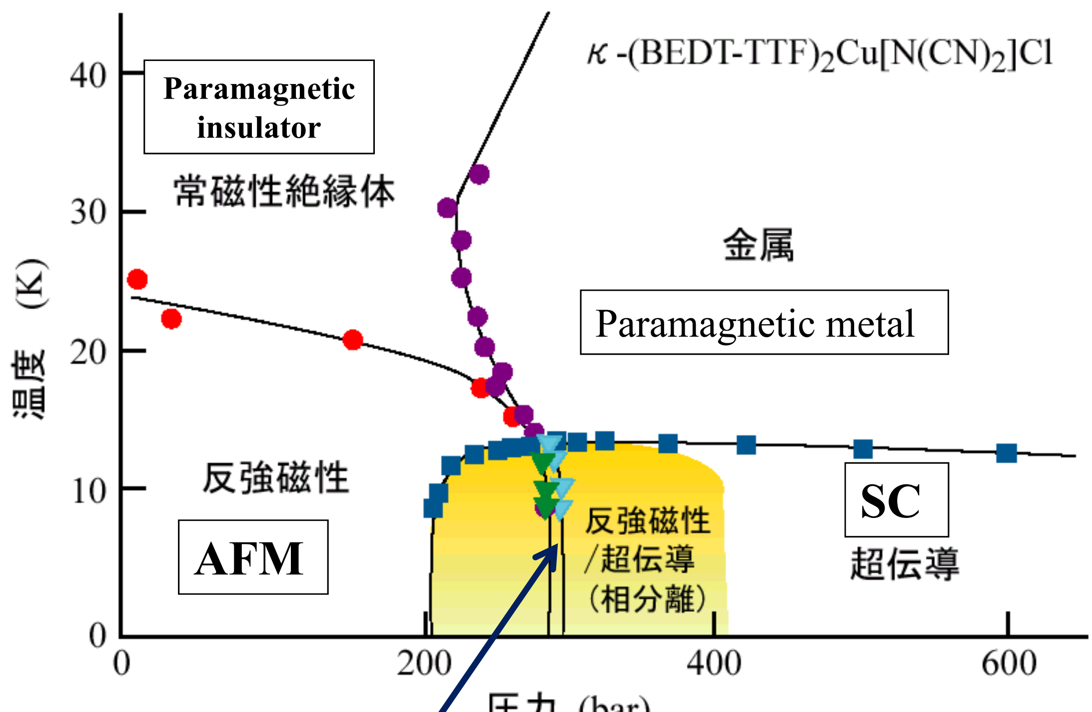
Pd(dmit)$_2$ is an electron acceptor and gives salts A[Pd(dmit)$_2$]$_2$ with monovalent cation, A^{+1}.

BEDT-TTF (ET) is an electron donor and gives salts (ET)$_2$X with monovalent anion X^{-1}.

Evidence of line-node SC gap from the T_1 measurement (Kanoda Group)



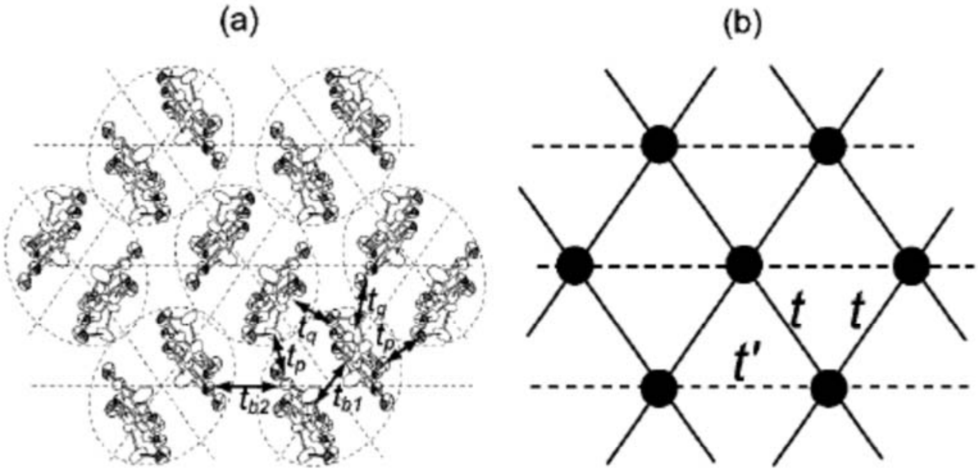
Quasi-2D Organic Conductor



Pressure tuning

AFM/SC phase separation

Spin Liquid State in an Organic Mott Insulator with a Triangular Lattice



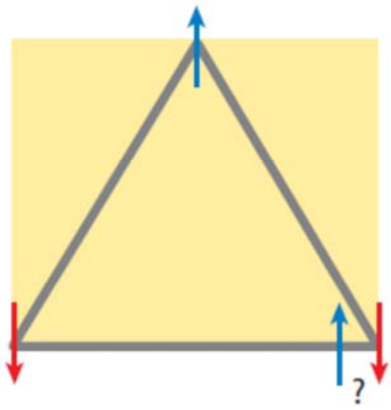
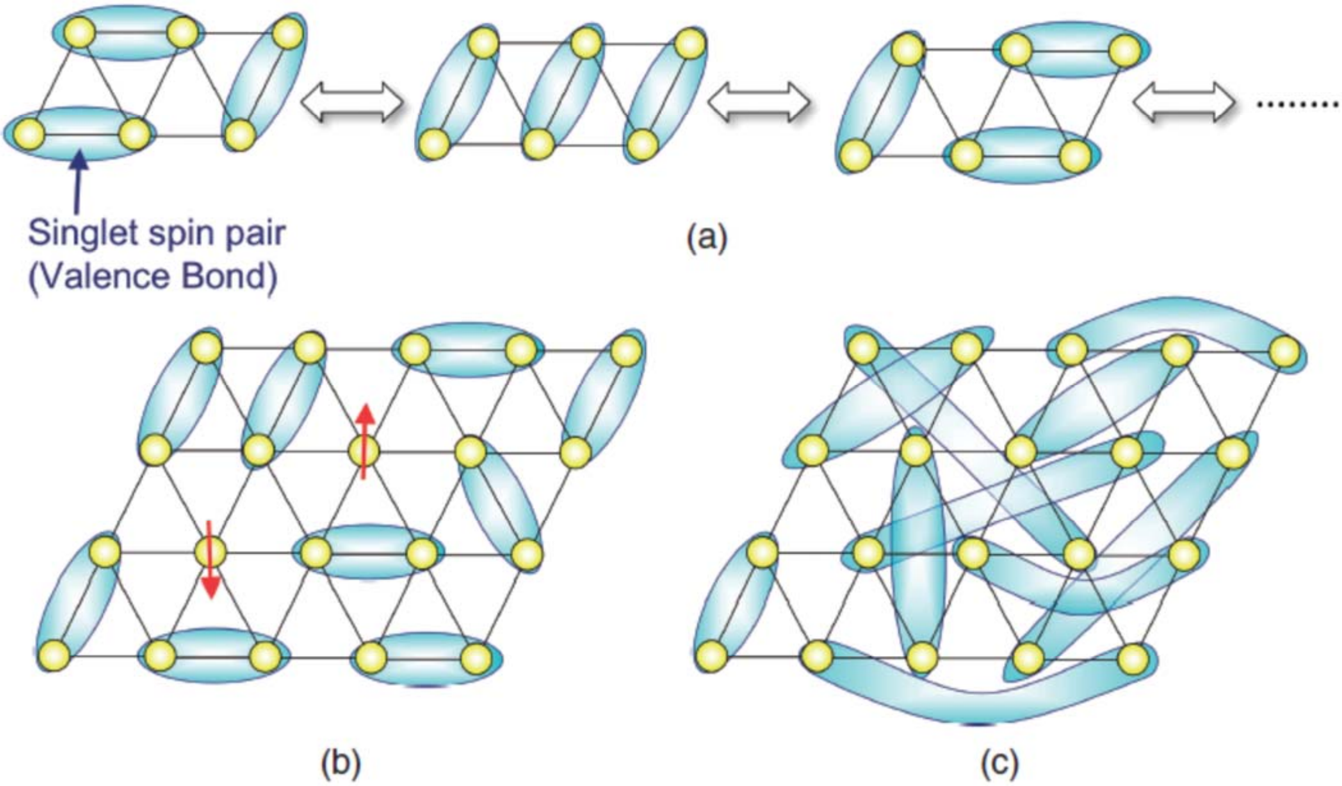


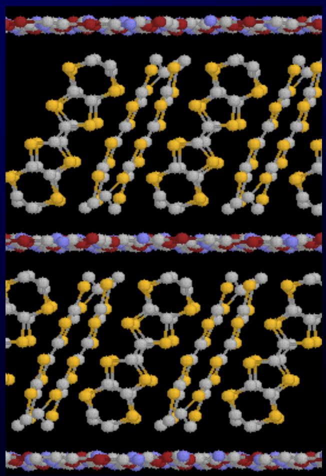
FIG. 1. (a) Crystal structure of an ET layer of κ-$(ET)_2Cu_2(CN)_3$ viewed along the long axes of ET molecules [4]. The transfer integrals between ET molecules, t_{b1}, t_{b2}, t_p, and t_q, are calculated as 224, 115, 80, and −29 meV, respec-



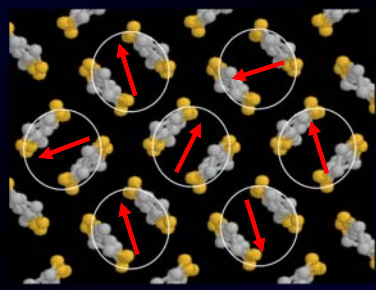
(a) Resonating valence bond in QSL. (b) Spinon.
(c) Long-range valence bonds.

擬2次元有機伝導体 κ-(ET)$_2$X; spin-1/2 on triangular lattice

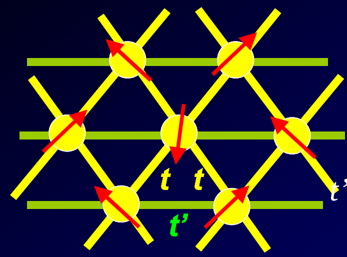
層状物質



面内構造



Kino & Fukuyama dimer model

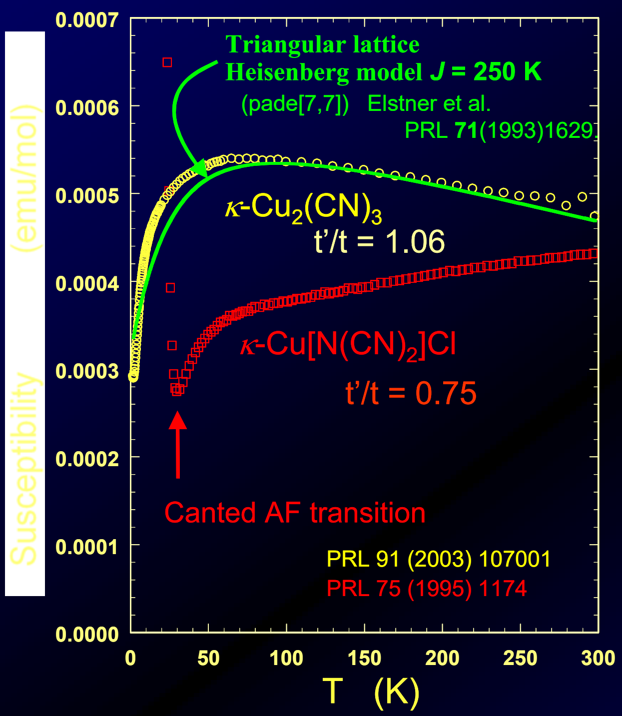


X^-	Ground State	t'/t
$Cu_2(CN)_3$	Mott insulator	1.06
$Cu[N(CN)_2]Cl$	Mott insulator	0.75

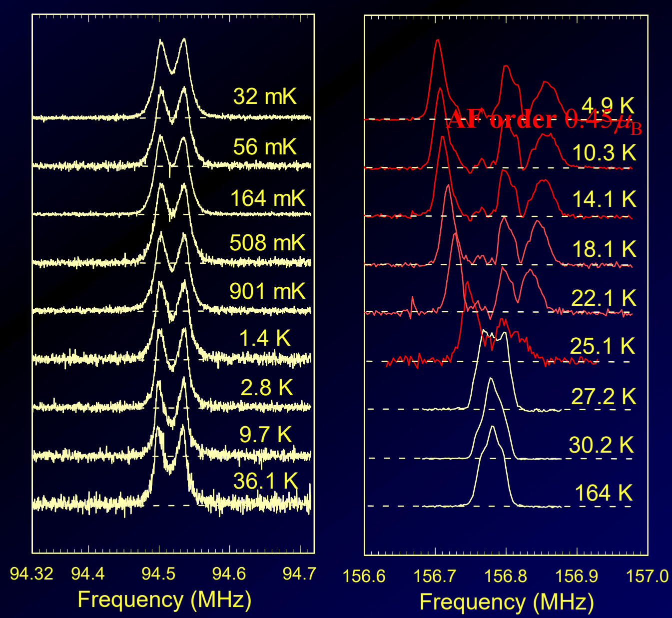
Triangular lattice
Half-filled band

30 mKまで磁気秩序は観測されない;スピン液体の発見

磁化率



^{1}H NMR スペクトル



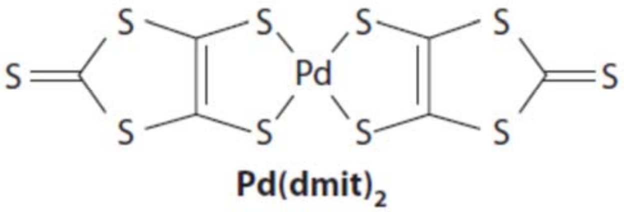
κ-(ET)$_2$Cu$_2$(CN)$_3$ | κ-(ET)$_2$Cu[N(CN)$_2$]Cl
t'/t =1.06 | t'/t =0.75

スピン液体 ⟷ 反強磁性体

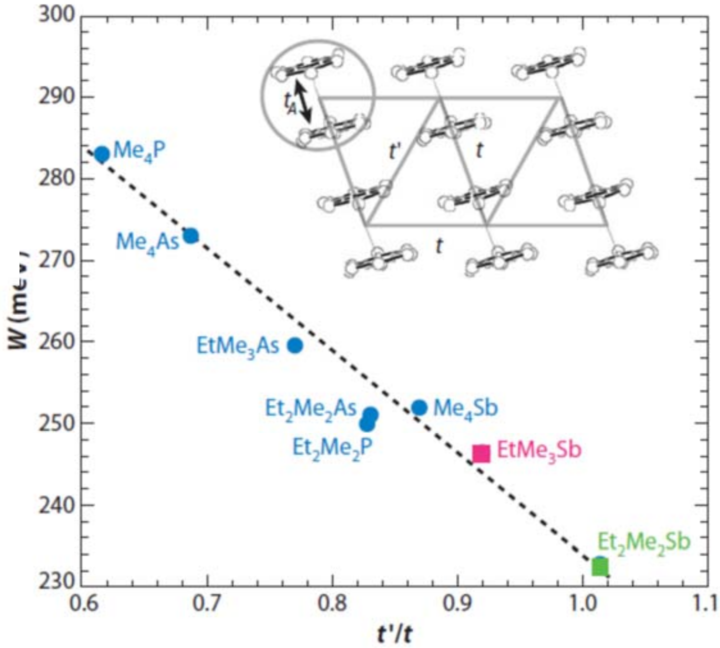
Theorist's dream came true !!

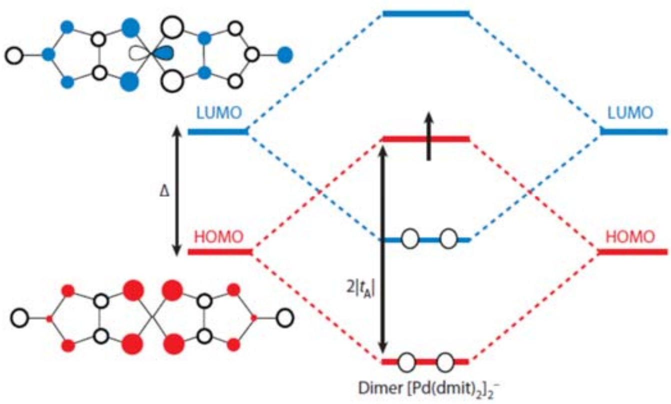
PRL 93 (2004) 127001
PRB 69 (2004) 064511
Nature 436 (2005) 534

加圧 → 金属/ 超伝導

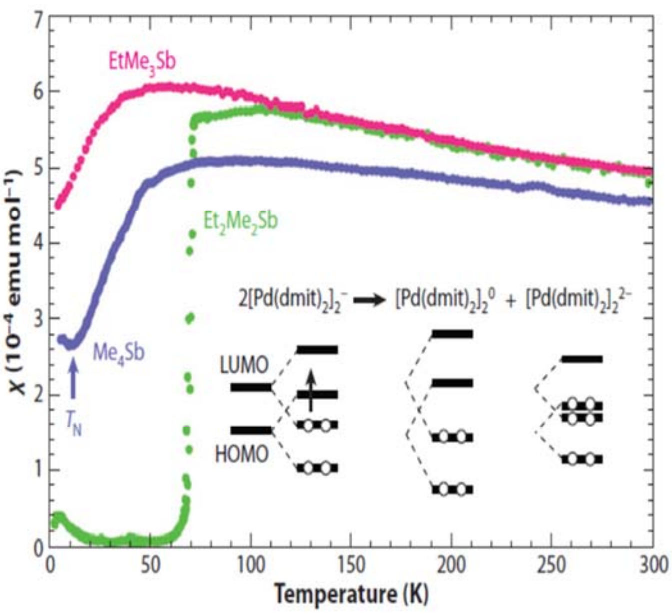


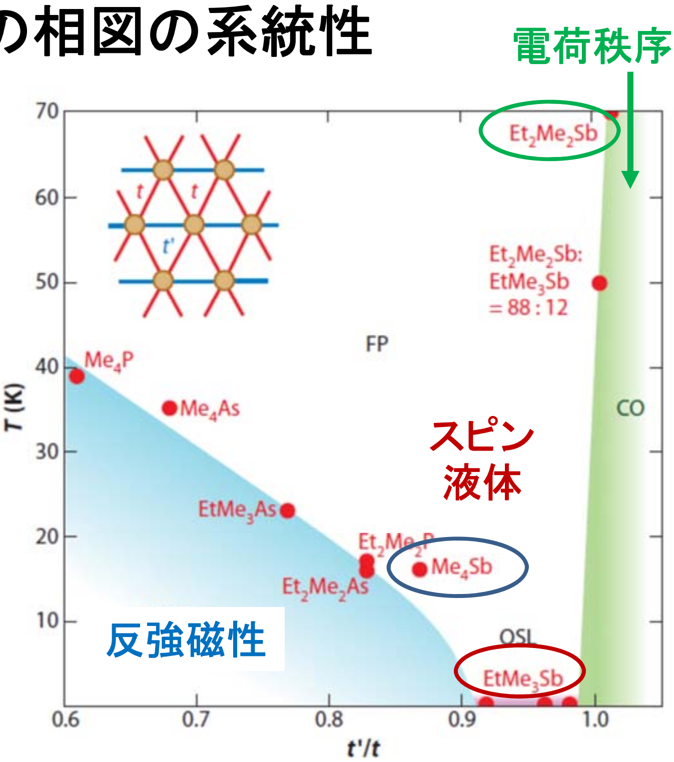
Pd(dmit)$_2$ is an electron acceptor and gives saltsA[Pd(dmit)$_2$]$_2$ with monovalent cation, A^{+1}.





有機三角格子系の相図の系統性



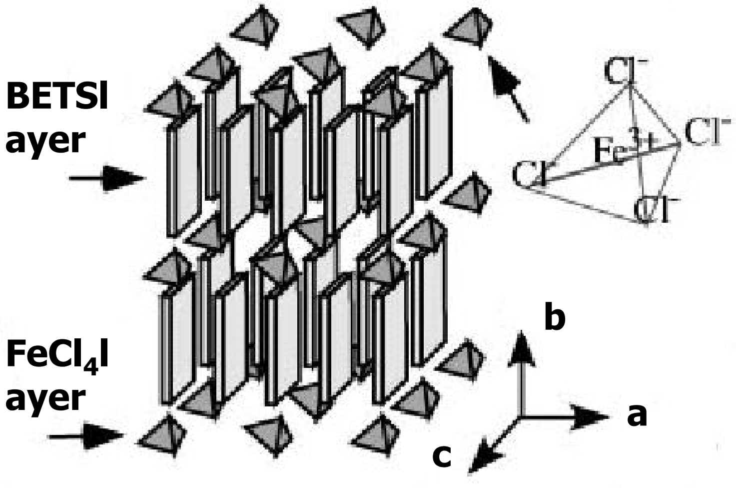


有機化合物：λ-(BETS)$_2$FeCl$_4$

BETS：伝導層

FeCl$_4$：絶縁層（磁性層）

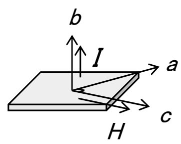
a,c方向の2次元の電気伝導性



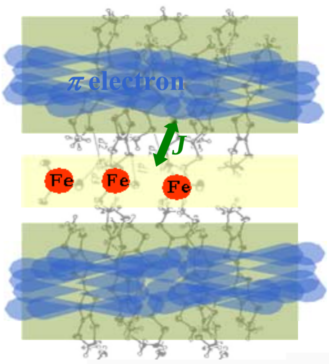
Feのd電子とBETSのπ電子（伝導電子）の負の交換相互作用が期待される

→ BETS上の内部磁場が外部磁場を打ち消す !?

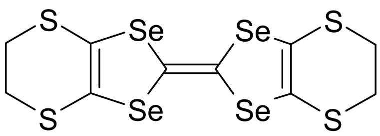
Discovery of Magnetic Field Induced SC



κ-(BETS)$_2$FeBr$_4$



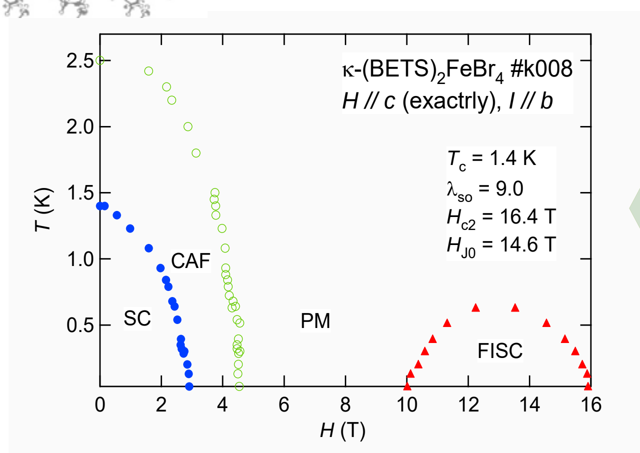
donor molecule

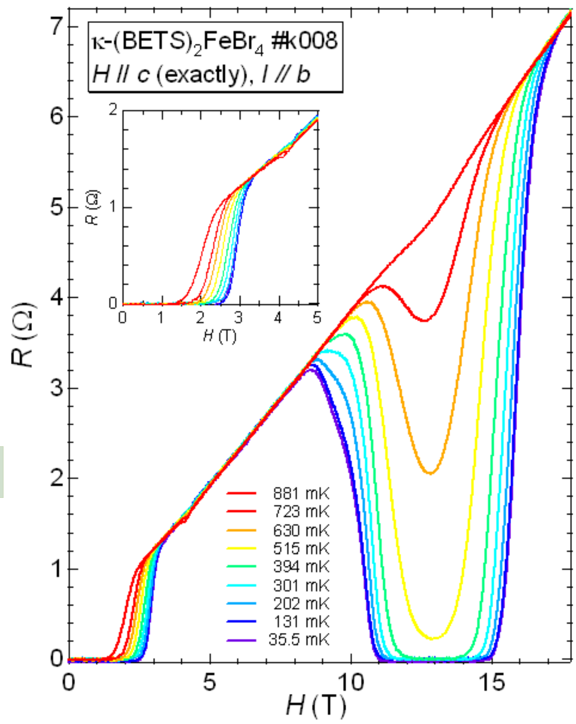


BETS

BETS=
Bis(**e**thylenedithio)**t**etra**s**elenafulvalene

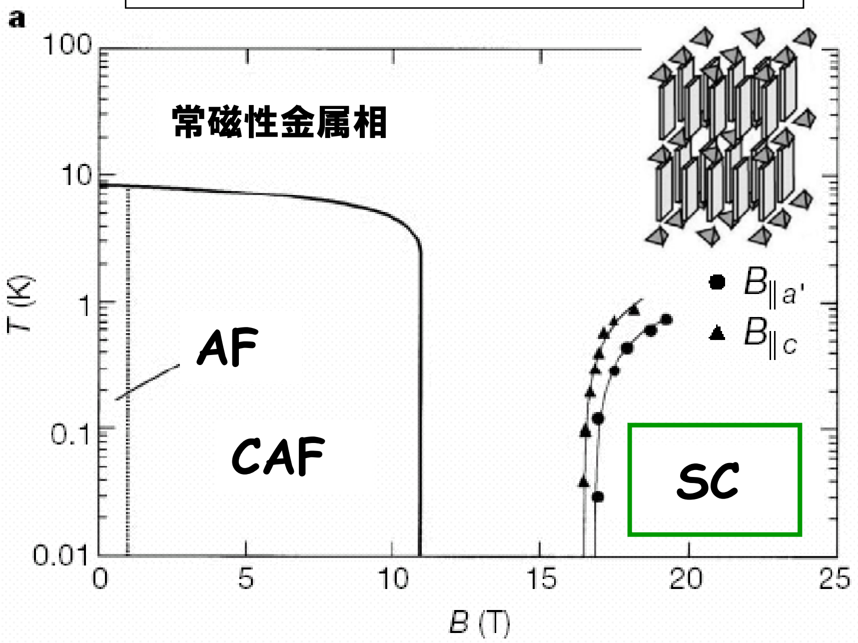
Uji et al





磁場誘起超伝導

有機化合物：λ-$(BETS)_2FeCl_4$



AF ：反強磁性絶縁相
CAF ：キャントした反強磁性相
SC ：超伝導相

S. Uji et *al*., Nature (2001)

強磁場 H>17T
磁場誘起超伝導相

磁場誘起超伝導体

λ-$(BETS)_2FeCl(Br)_4$

→ BETS上の内部磁場が外部磁場を打ち消した状態で超伝導が発現する？

有機物磁場誘起超伝導体のπ-d相互作用

加圧による磁場誘起相図は？

URhGe

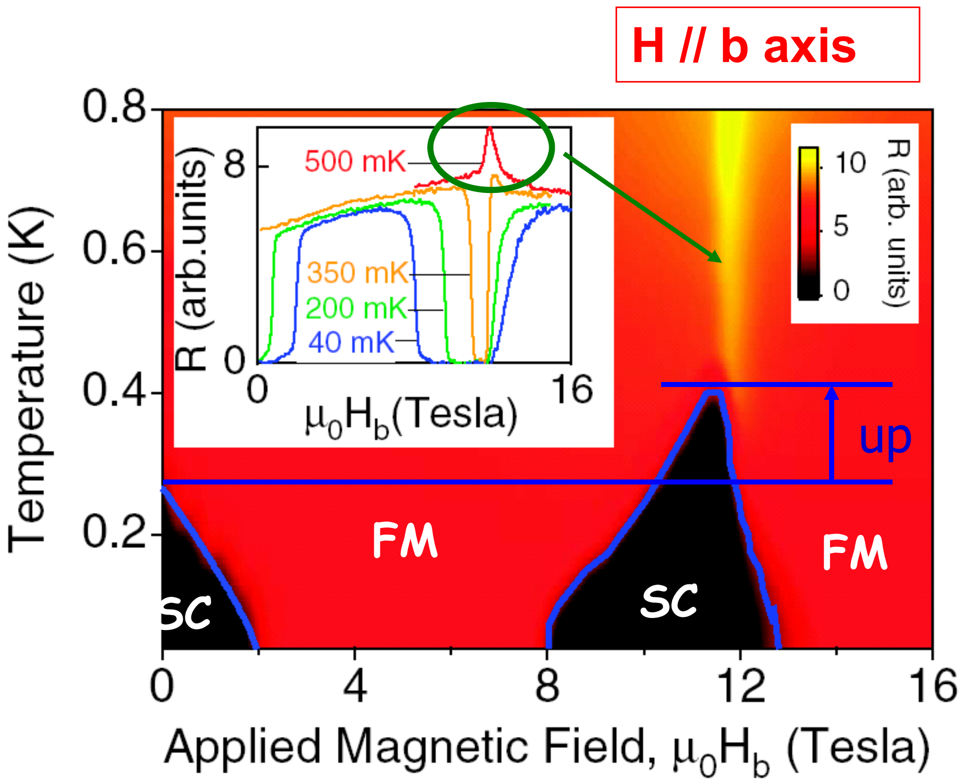
→ 自発磁化が磁場方向に傾く過程の不安定な状況でSCが誘起される。

(SCは磁気転移と関係)

（磁場方向に向いてしまうとSCは抑制）

2つの磁場誘起超伝導の発現機構は異なる?

強磁性超伝導体URhGeの磁場誘起超伝導

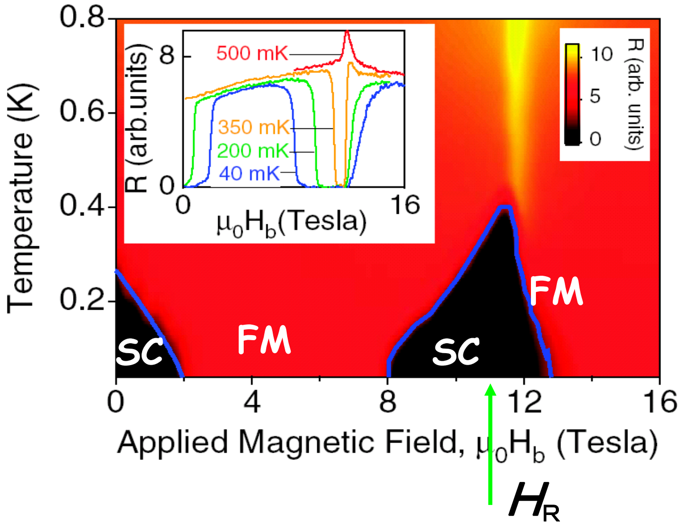


Second pocket for superconductivity (*H* : 8～12 tesla)

F. Levy *et al*., Science (2005)

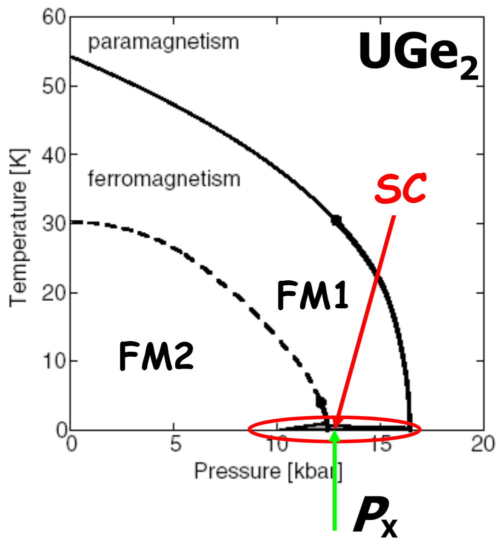
超伝導の発現は2つの強磁性状態の転移と関連

URhGe磁場誘起 SC



Change in transverse moment at H_R

圧力誘起 SC



Change in longitudinal moment at P_X

Other Topics in Superconductivity

Superconductivity in alkali-metal doped picene

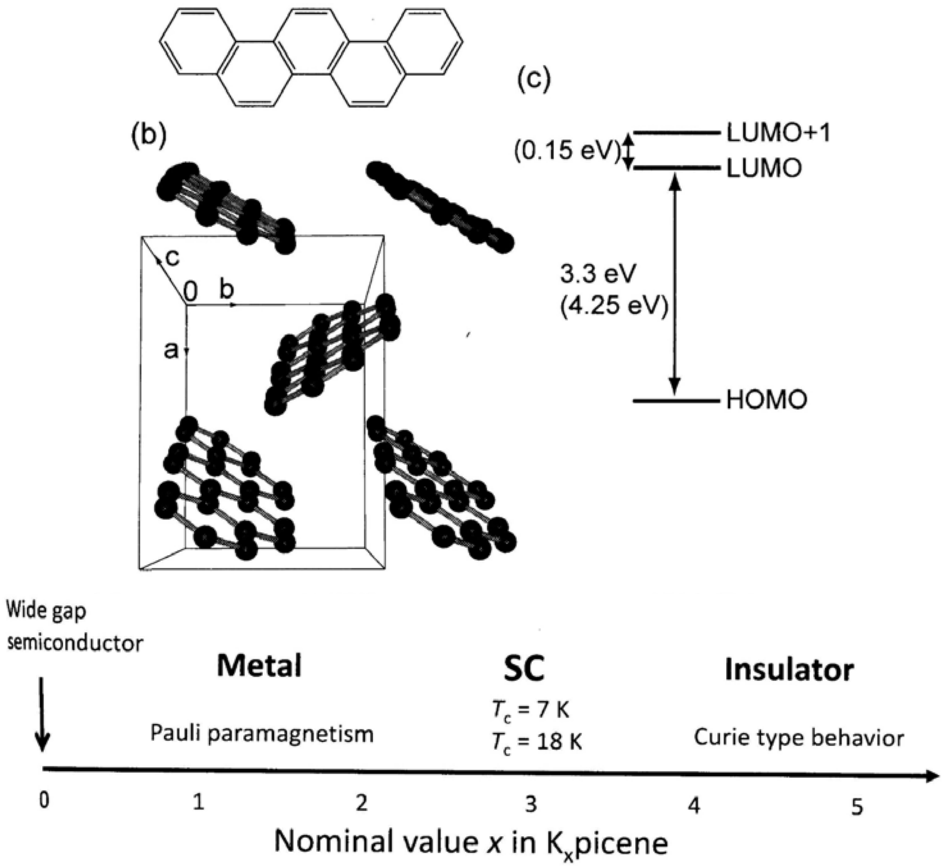
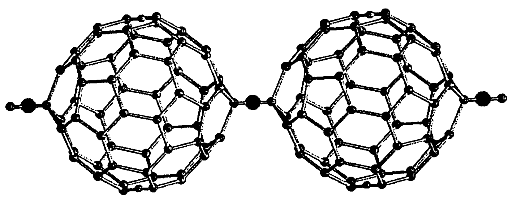
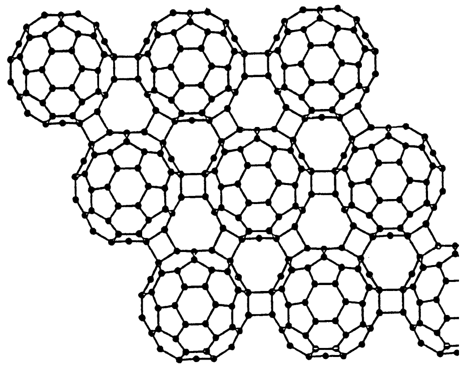


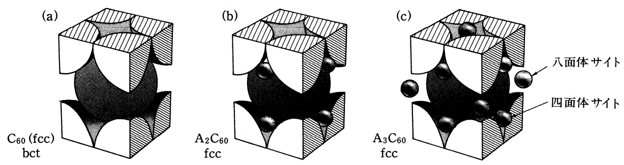
図4　カリウムをドープしたピセンにおいて，ドーピング量を変えたときの物性変化．超伝導相は，$x=3$ 付近で観測される．

Fullerene（C_{60}）polymer

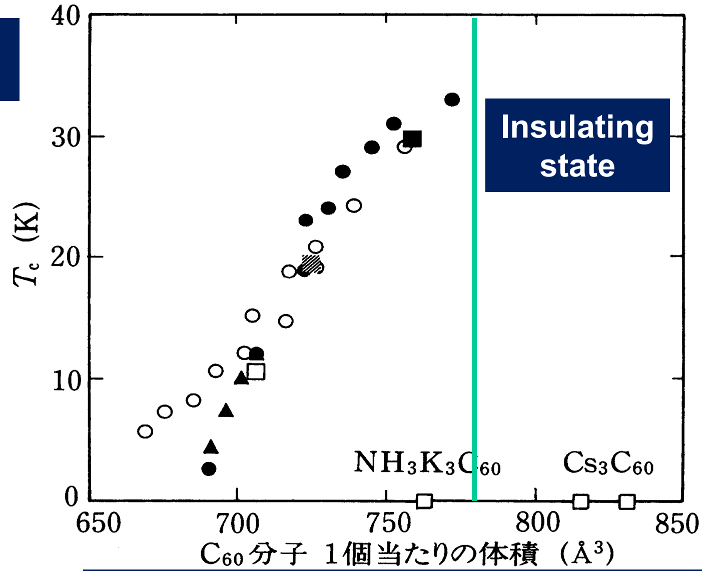




Superconductivity in alkali-metal doped fullerene crystal



T_c

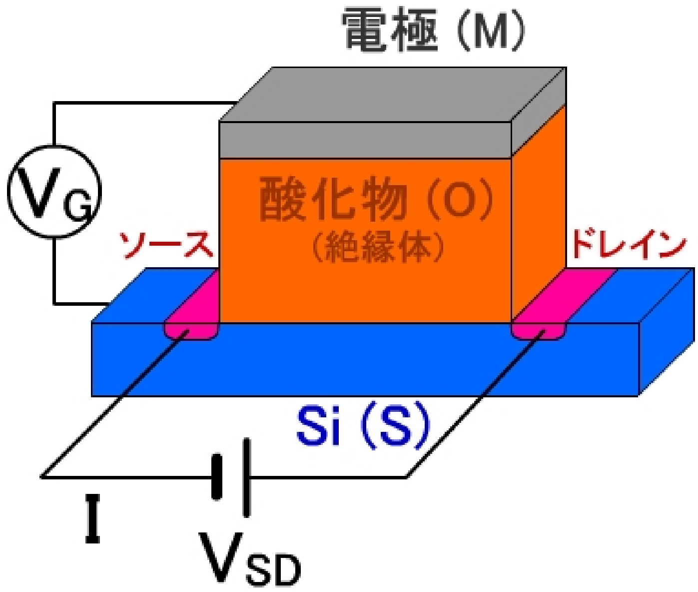


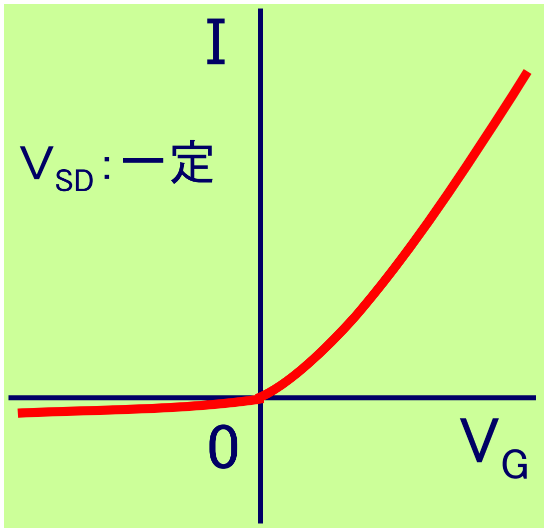
Volume per C_{60} molecule

第11図 … 当たりの体積 V との相関. ○は Zhou ら[38], ●は Tanigaki ら[39], ▲は Mizuki ら[40]による.

Electric Field effect Transistor（FET）

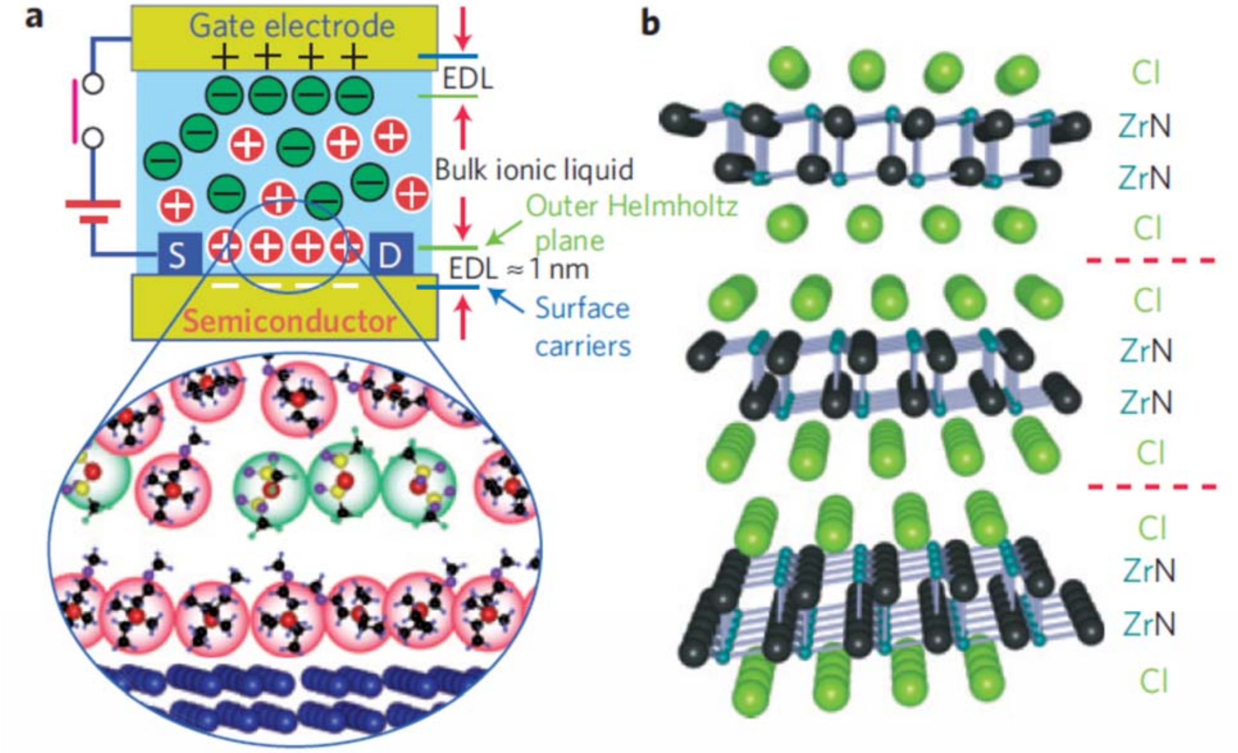
MOS device structure



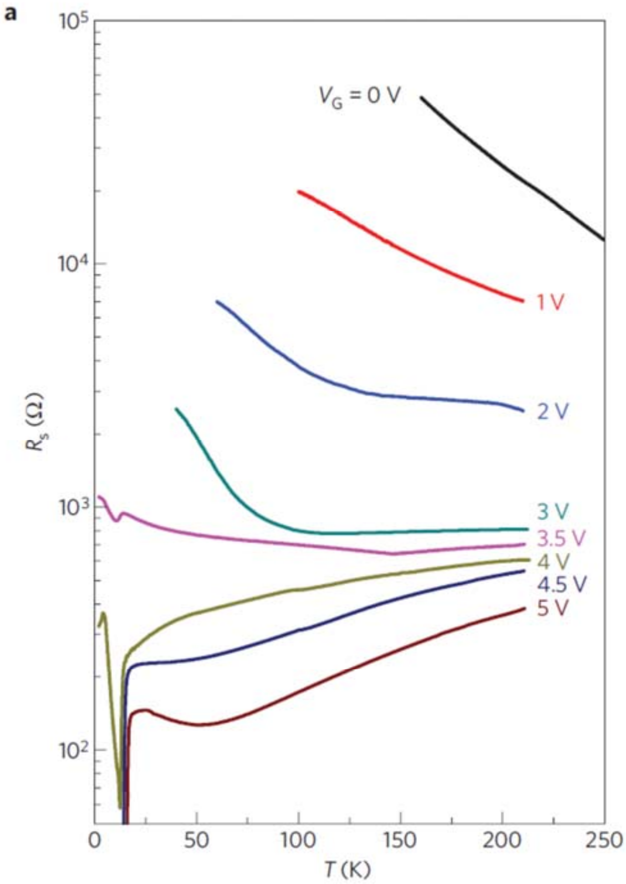


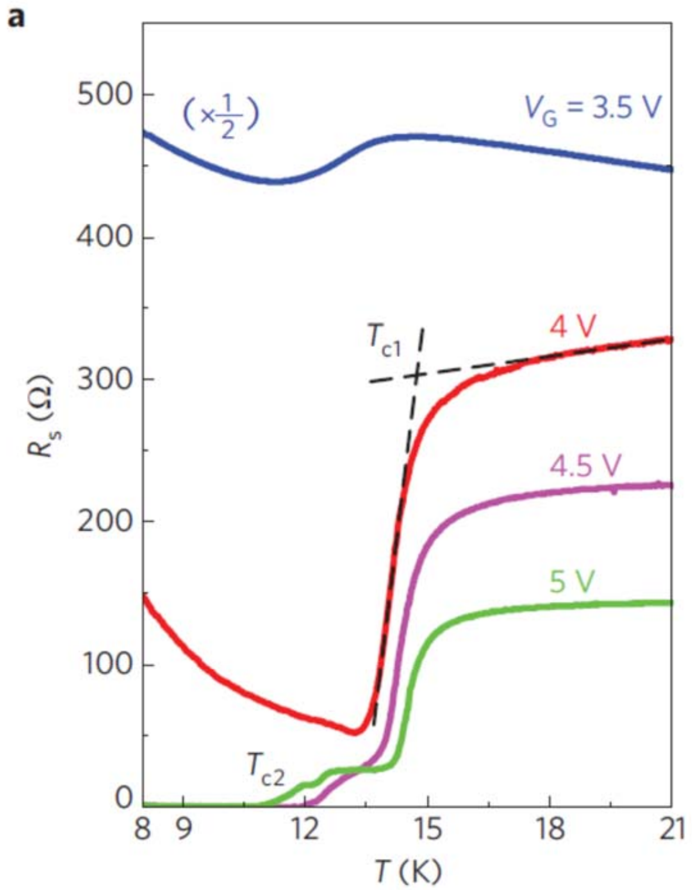
Switch function

Liquid-gated interface superconductivity on an atomically flat film



Onset of Superconductivity Driven by Electric Field





重い電子系の新奇な超伝導現象

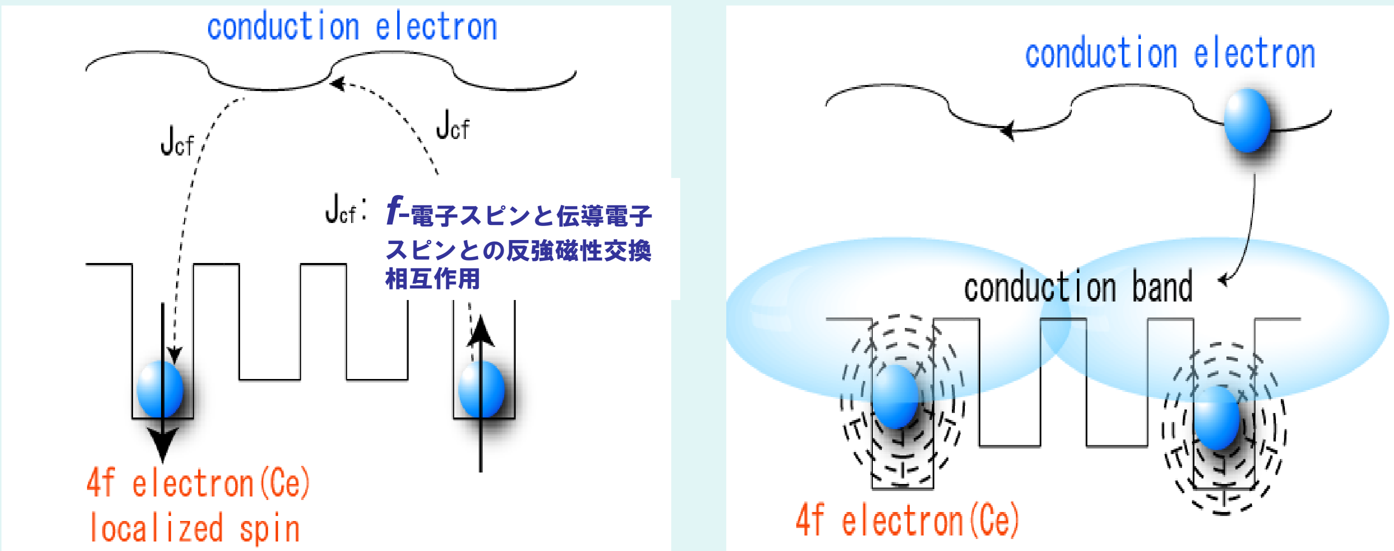
- 結晶反転対称性のない超伝導体：スピン一重項と三重項の混成
  $CePt_3Si$, $CeRhSi_3$, $CeIrSi_3$
- 電気四重極ゆらぎに起因する強結合超伝導
  $PrOs_4Sb_{12}$
- 磁気臨界ゆらぎに起因する強結合超伝導
  $CeCu_2Si_2$, $CeMIn_5$
- 強磁性と共存する時間反転対称性の破れた超伝導
  UGe_2, URhGe
- 反強磁性と超伝導の共存と競合、
  $CeIn_3$, $CeRhIn_5$（超伝導リエントラント現象？）
- 磁場誘起超伝導
  URhGe

重い電子系とは

－局在的 f －電子系の電子状態－

Rudermann-Kittel-Kasuya-Yoshida（RKKY）interaction

Spin-quenching (Kondo) effect

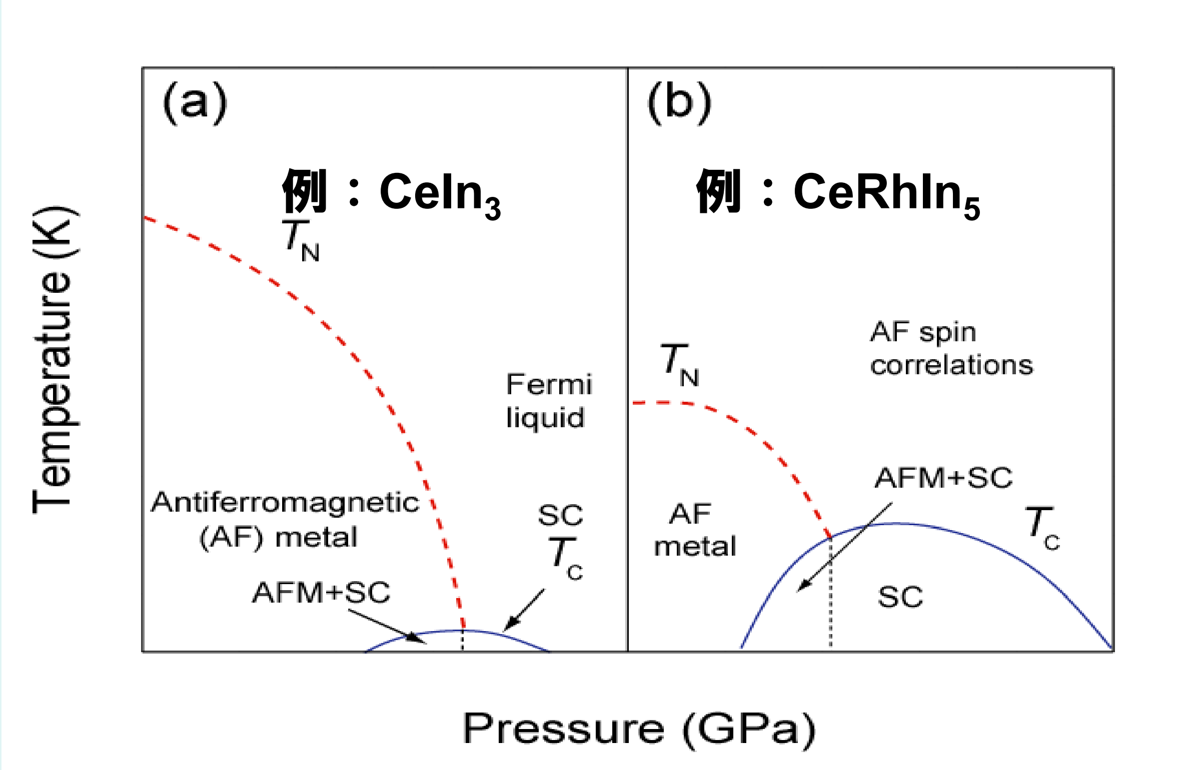


磁気秩序状態

J_{cf} の増大（加圧）

非局在的な
重い電子状態

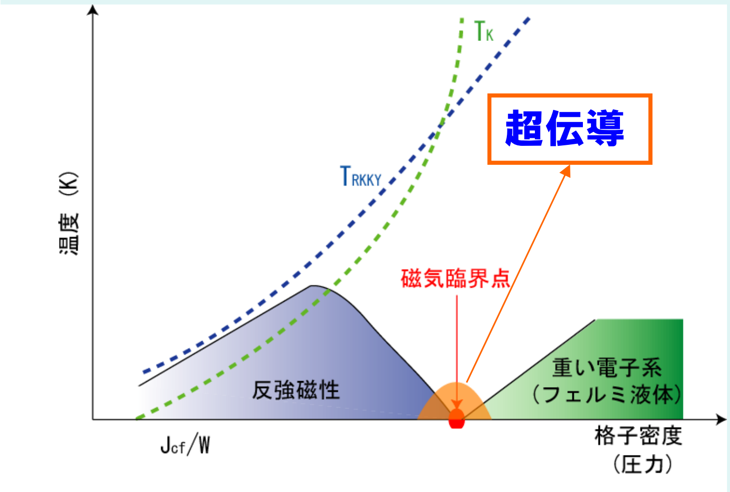
重い電子系の圧力相図



cf. $(TMTTF)_2SbF_6$の圧力相図

辺土ら

重い電子系の相図



ドニアックの相図

RKKY相互作用

$$k_B T_{RKKY} \propto \left| J_{Cf} \right|^2 D(\varepsilon_F)$$

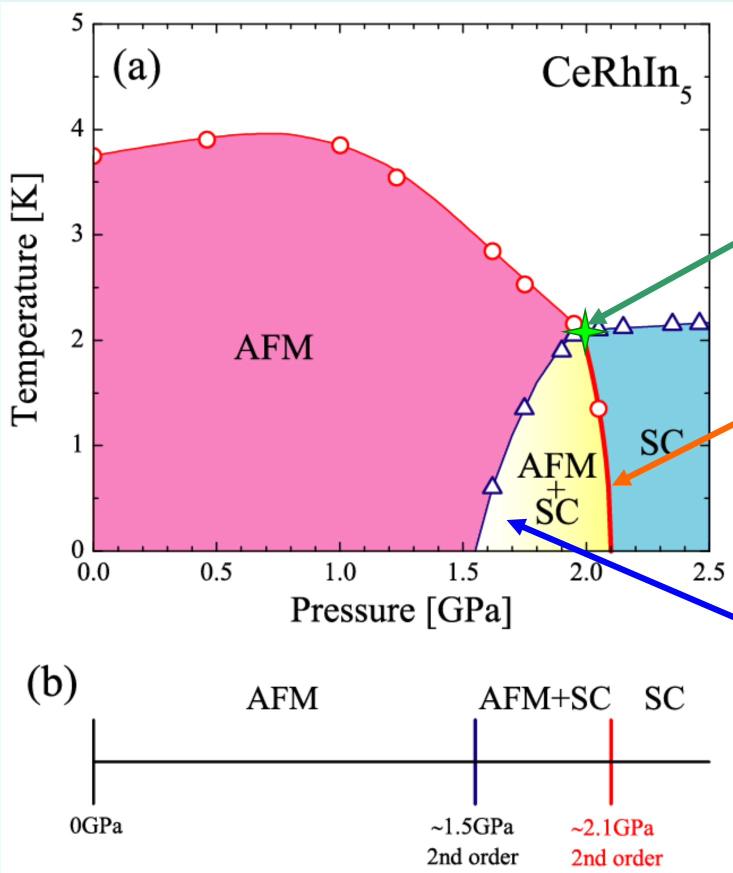
近藤効果

$$k_B T_K \propto \frac{1}{D(\varepsilon_F)} \exp\left(-1 \Big/ J_{Cf} D(\varepsilon_F)\right)$$

圧力によってJ_{cf}をコントロール

J_{cf}：伝導電子とf電子の反強磁性交換相互作用

反強磁性と超伝導の圧力ー温度相図

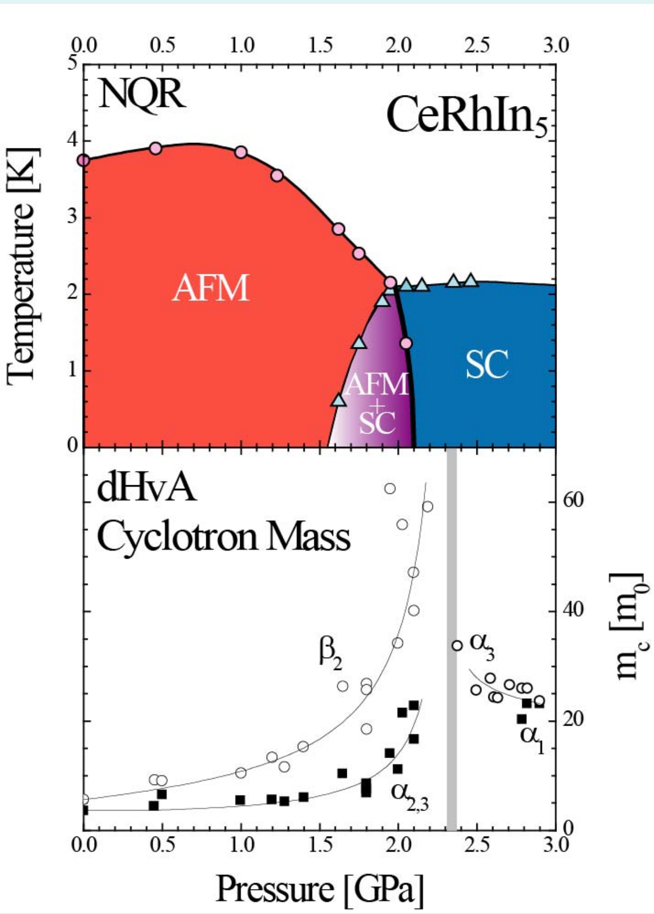


四重臨界点

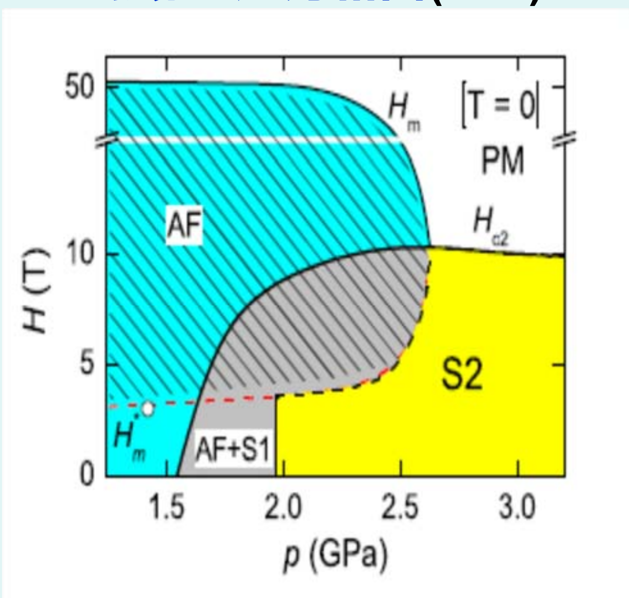
２次相転移
（AFM+SC ⇔ SC）

ギャップレスSC
（AFM+SC）

今後の研究課題



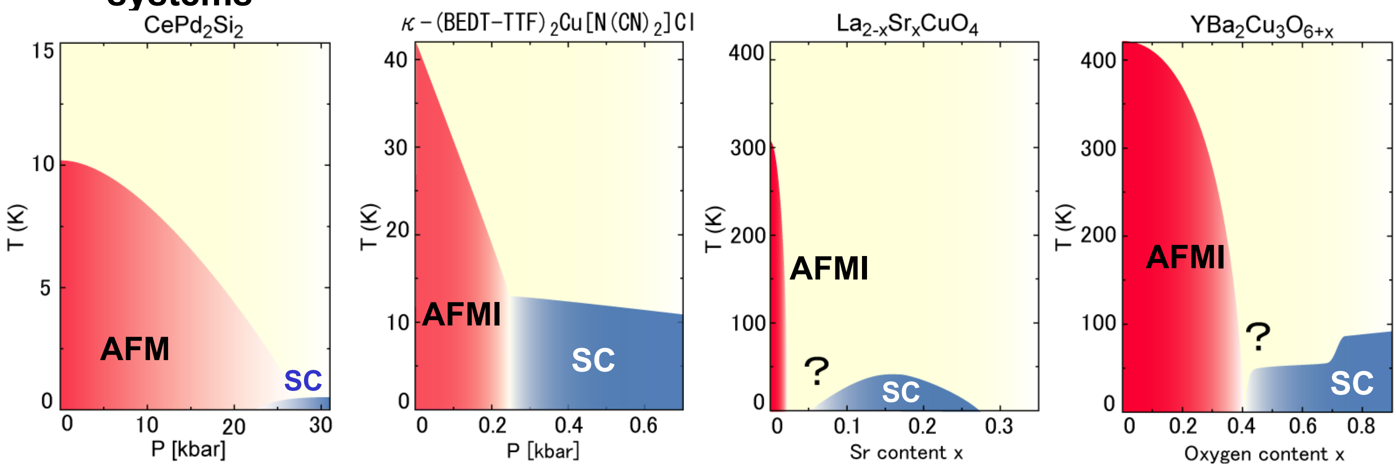
超伝導と反強磁性の
磁場ー圧力相図(T=0)



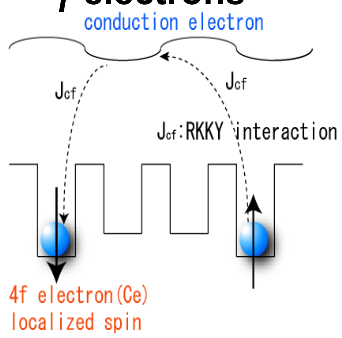
Coexistence of antiferromagnetism and superconductivity in $CeRhIn_5$ under high pressure and magnetic field
G. Knebel, D. Aoki,y D. Braithwaite, B. Salce, and J. Flouquet

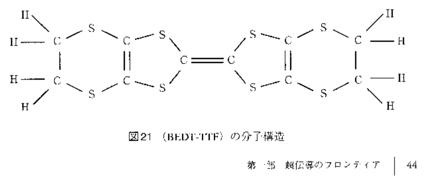
Frontier of Superconducting Phenomena

Heavy-electrons systems | **Organic conductors** | **High-T_c copper oxides**

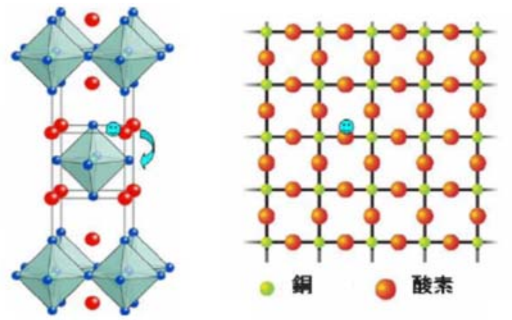


Nearly localized *f*-electrons | **Half-field p_π bands** | **Half-filled 3*d* bands**





Strongly Correlated Electrons Systems

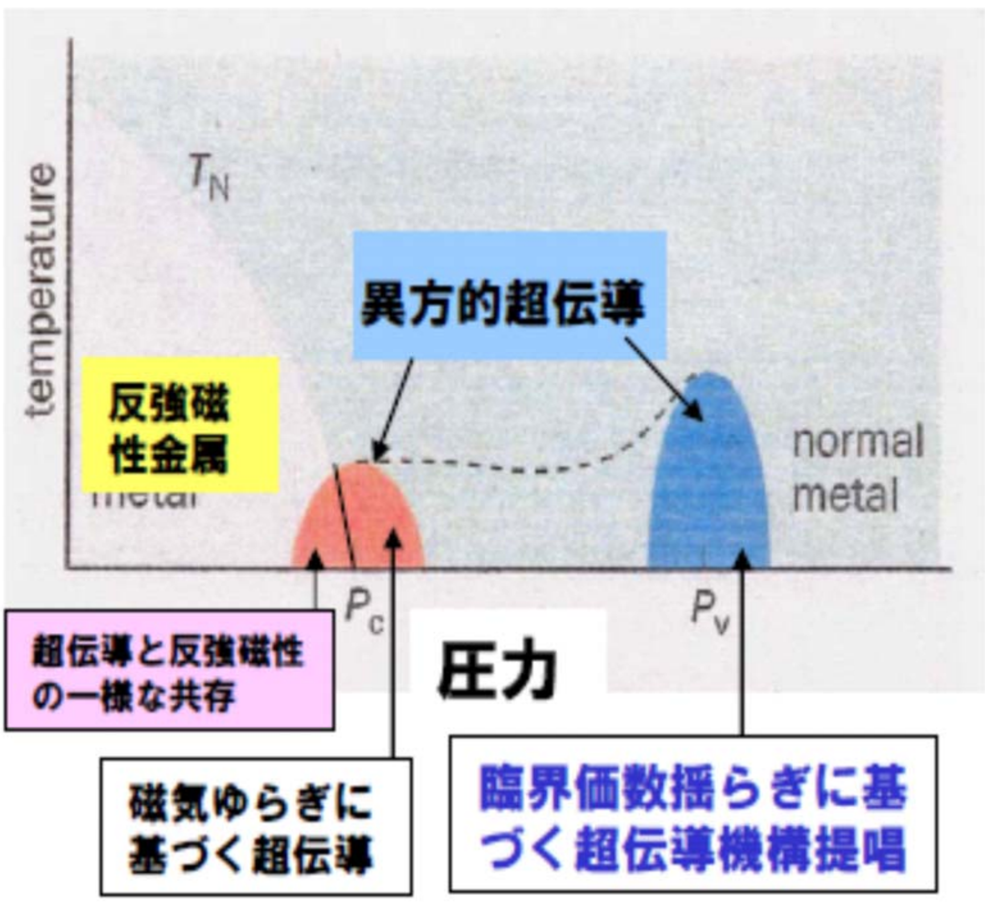


CuO_2面

$CeCu_2Si_2$

$CeNi_2Ge_2$

$CeRIn_5$



三宅ら

おわり