RTS Workshop
Loen, Norway,17-23 June 2007

High-T_c superconducting elements under very high pressures

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outline

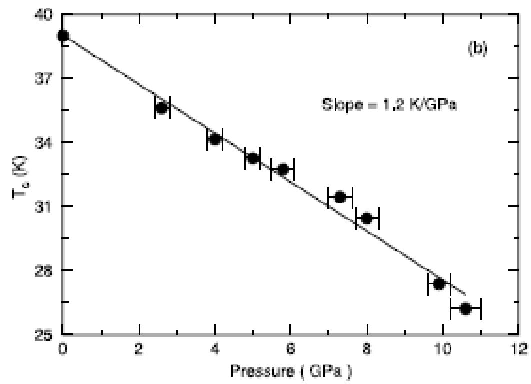
- Superconductivity on the table
- How high can we push it up?
  - History
  - Tc at Mbar pressure
- Sc from insulator
  - Halogen, Chalcogen
- Sc from metal
  - Alkaline, Heavy alkaline
- Summary and future challenge

High-T_c superconductors under pressure

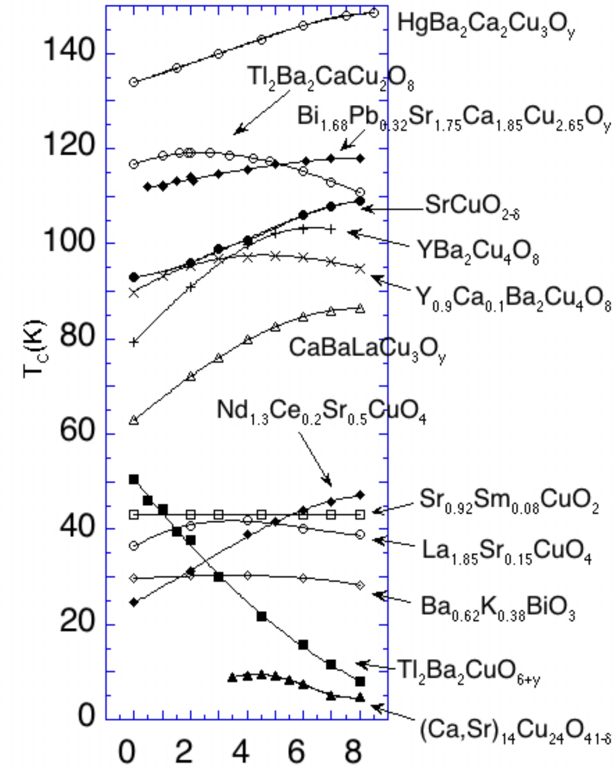
- HgBa$_2$Ca$_2$Cu$_3$O$_y$ ～138 K
  ～164 K (WR)

L. Gao et al., Phys. Rev. B 50, 4360 (1993).

- MgB$_2$ 39 K

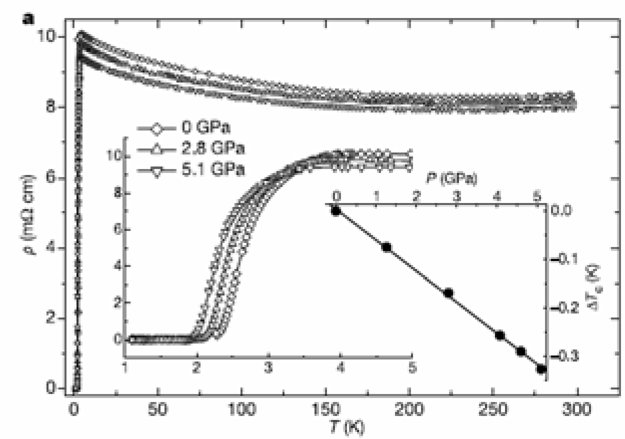


J. Nagamatsu et al., Nature 410 (2001) 63.
F. S. Razavi et al., Physica C 366 (2002) 73.



courtesy; Prof. H. Takahashi

- B-doped diamond ～11 K



E. A. Ekimov al., Nature 428(2004)542.

- Li, Y, Ca ～20 K （30～50 GPa）

K. S et al., Nature 419 (2002) 597.

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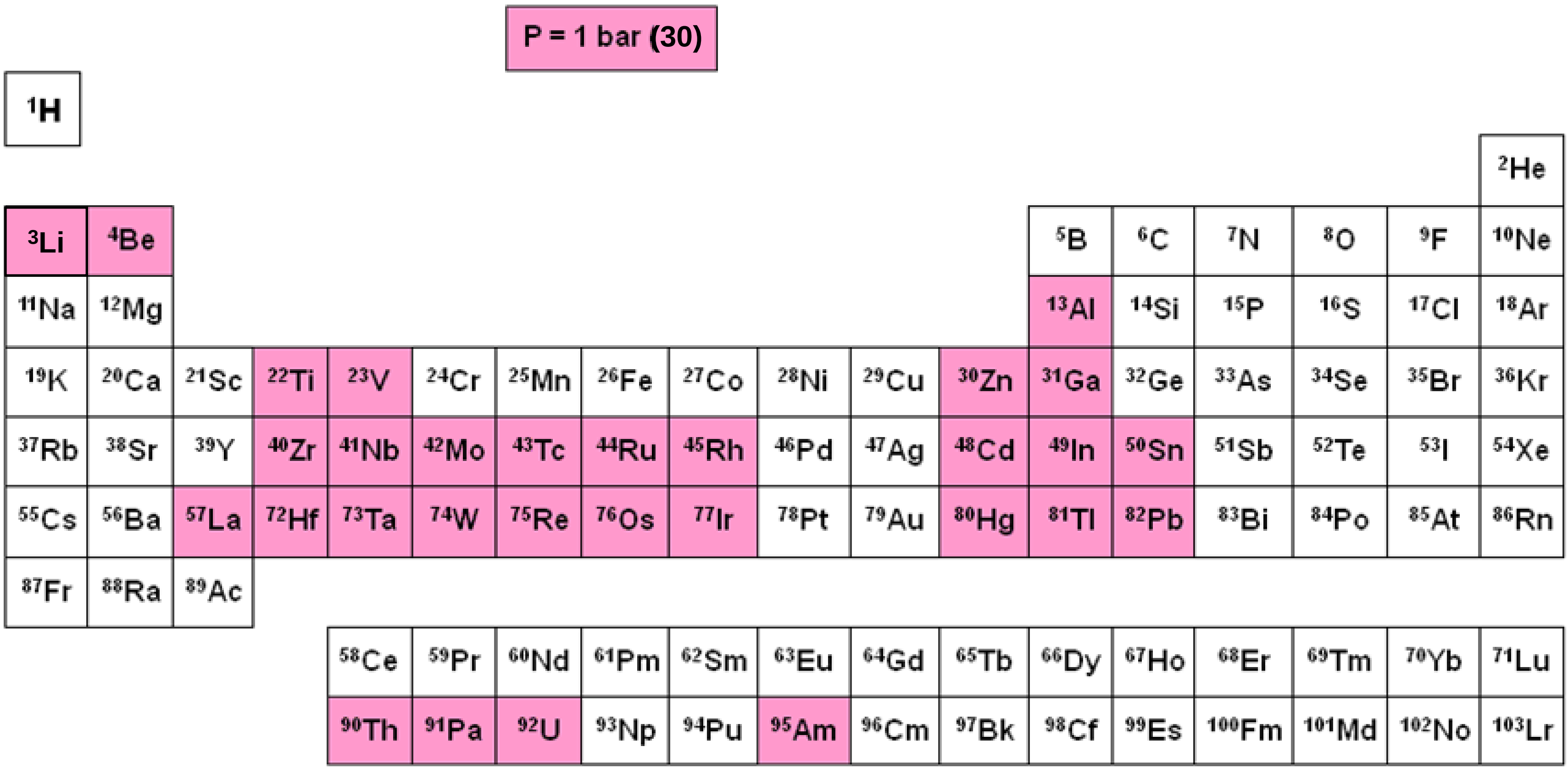
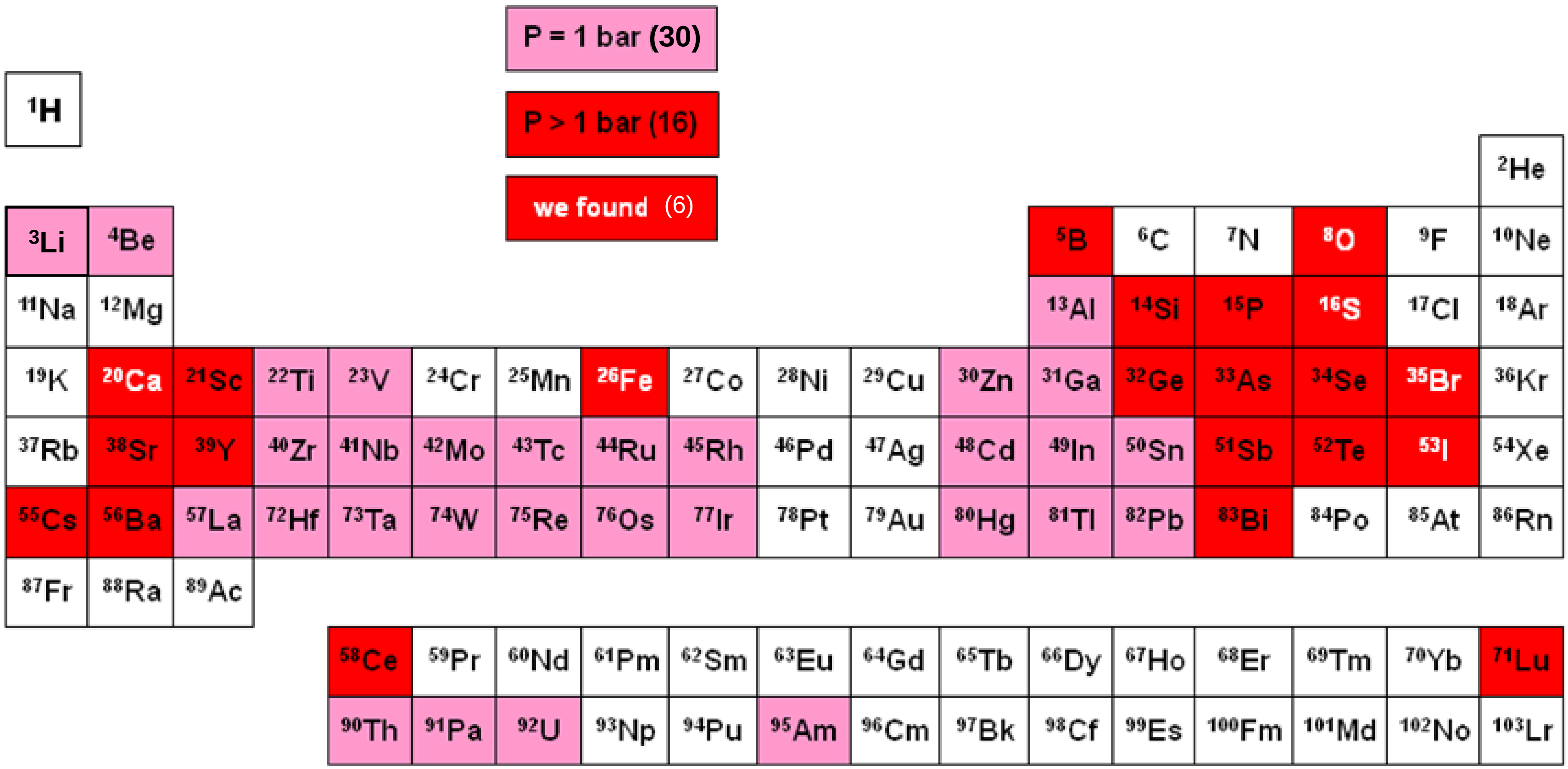
RPS; room pressure superconductors

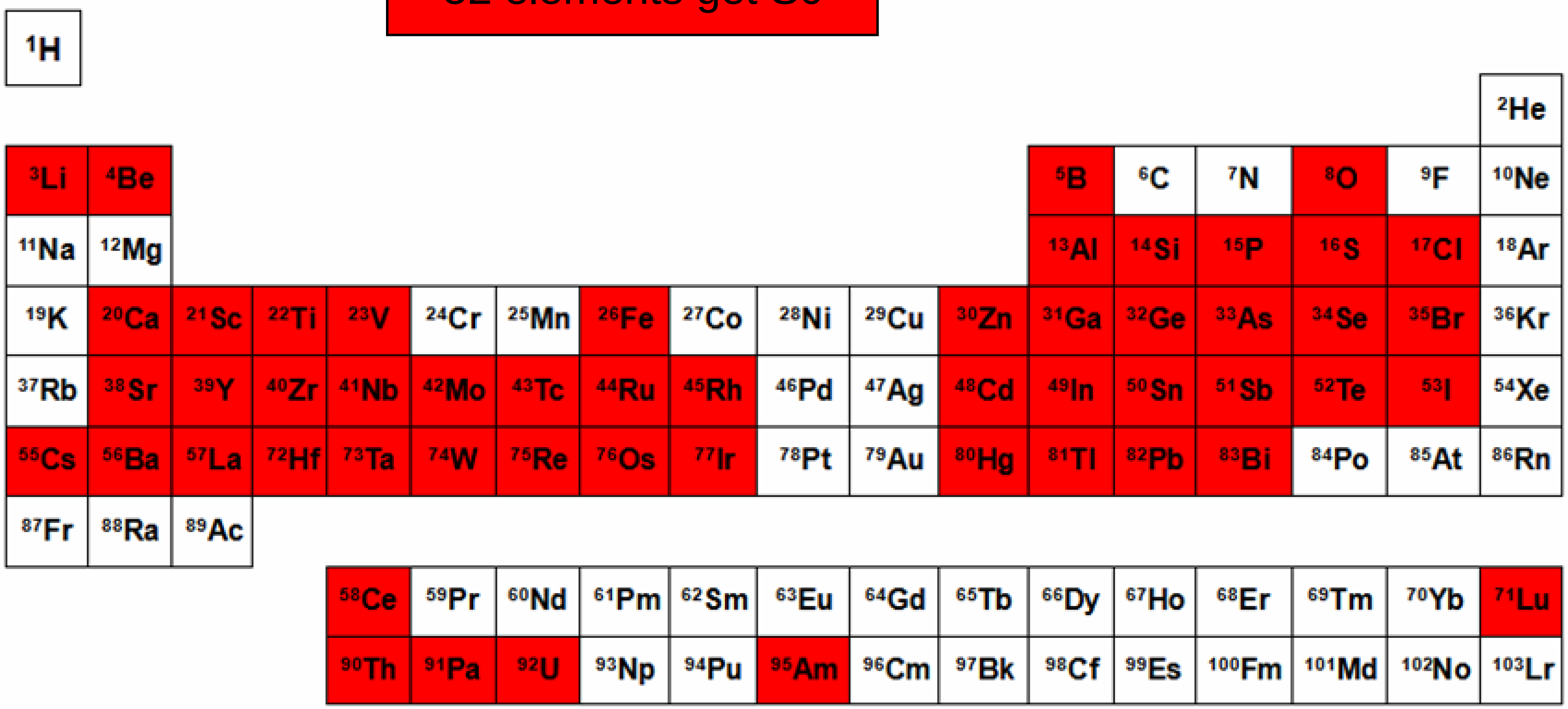


Superconducting Elements 2007



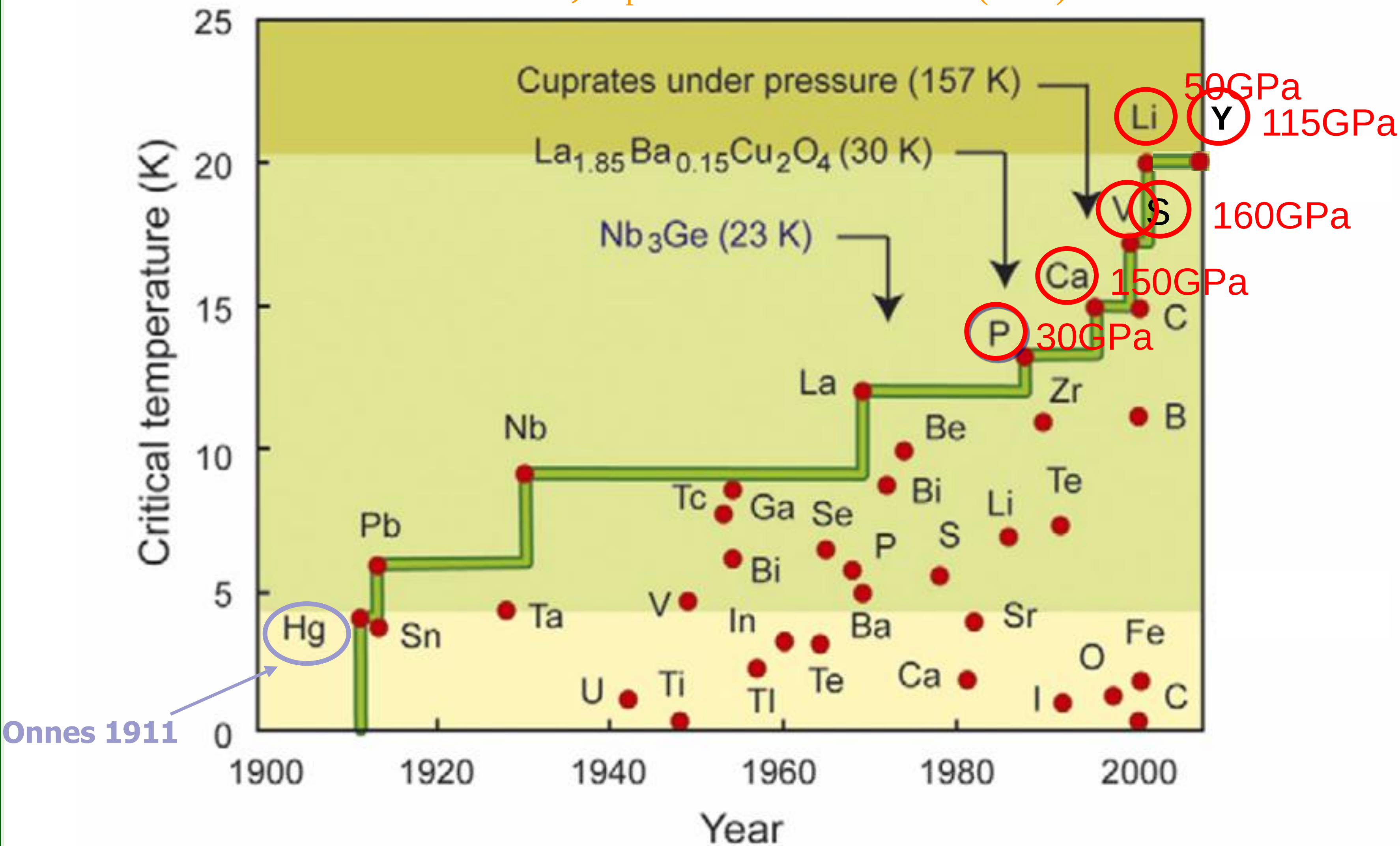
forgetting about “pressure”

52 elements get Sc



The history in elements…

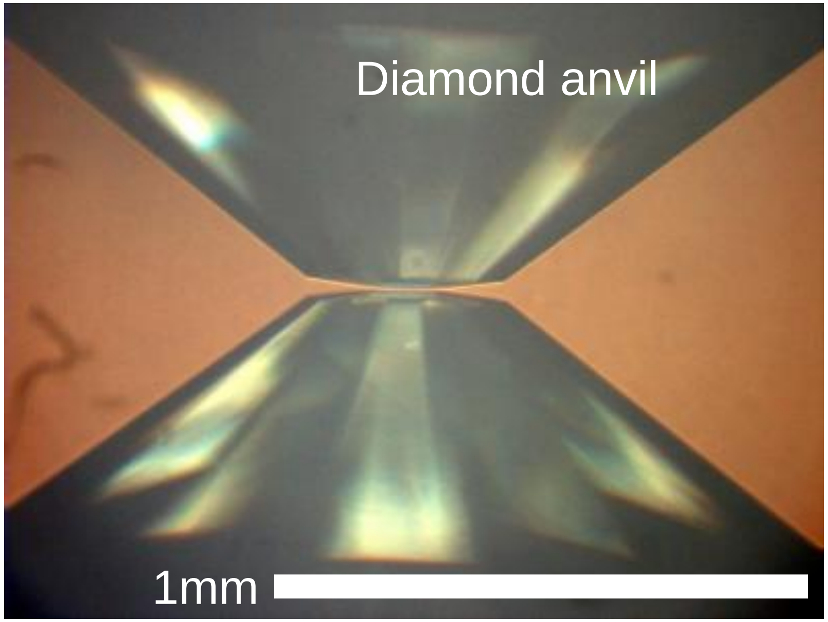
C. Buzea & K. Robbie, Supercond. Sci. Technol. **18** (2005) R1–R8

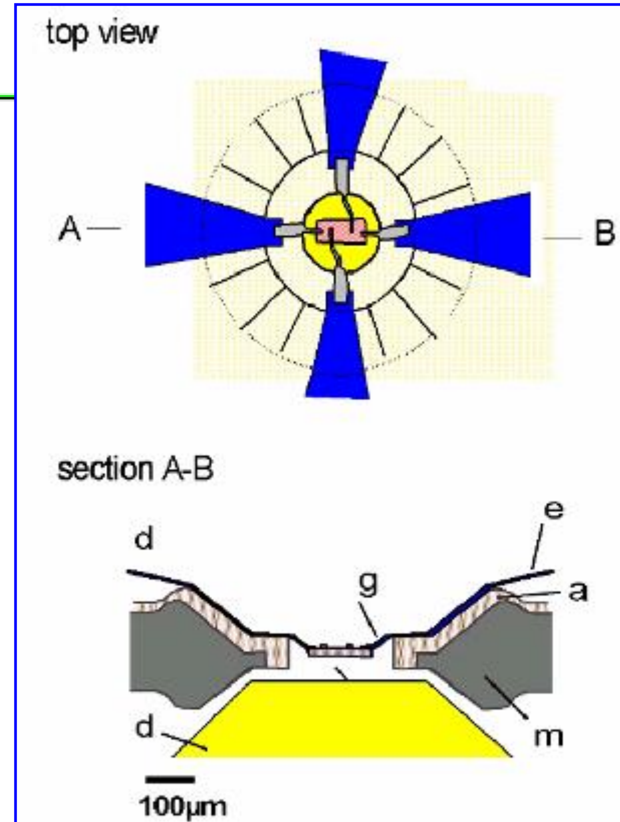


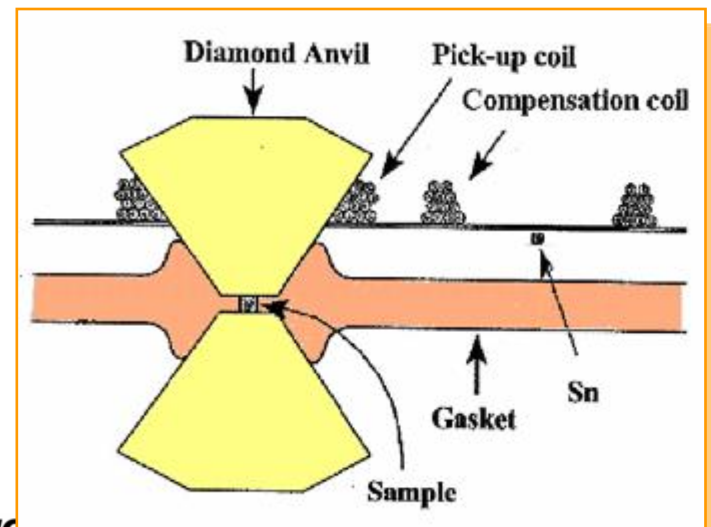
K. J. Dunn and F. P. Bundy: Phys. Rev. B **25** (1982) 194.

S. Okada *et al.*, J. Phys. Soc. Jpn. 65 (1996) 1924.

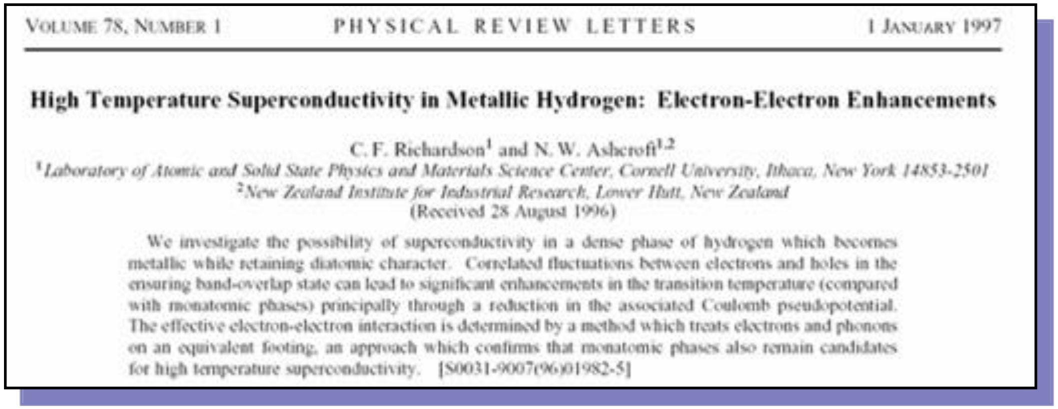
Experimental tools







Halogen, Chalcogen, Nitrogen,…, Hydrogen,…



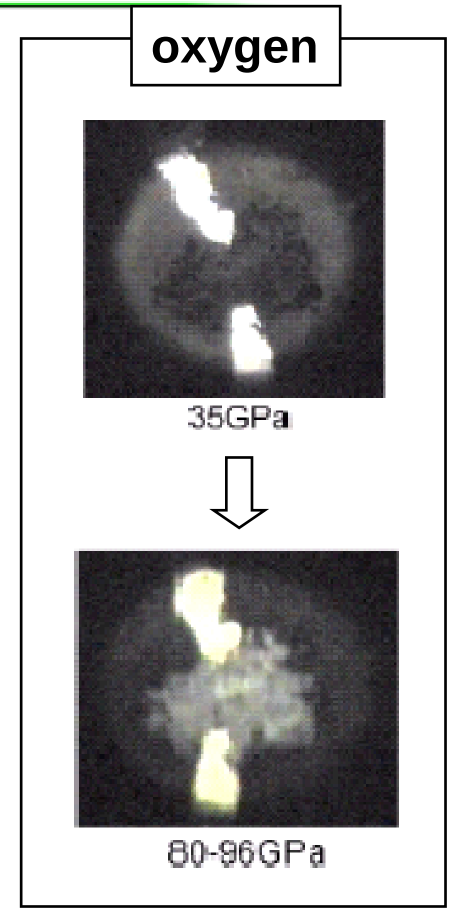
VOLUME 78, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 1997

High Temperature Superconductivity in Metallic Hydrogen: Electron-Electron Enhancements

C. F. Richardson[1] and N. W. Ashcroft[1,2]

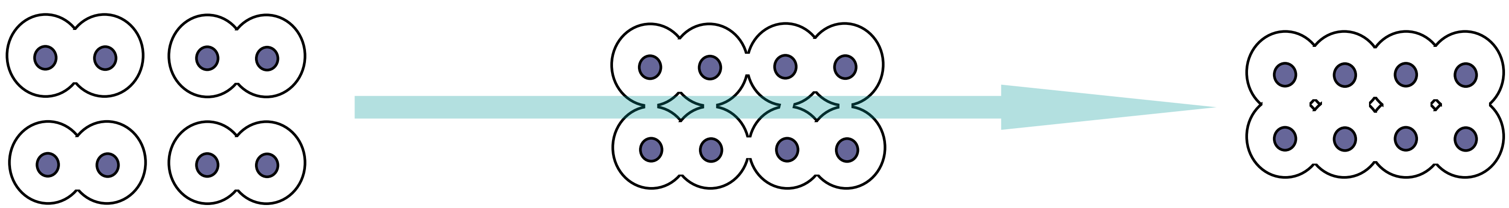
[1]*Laboratory of Atomic and Solid State Physics and Materials Science Center, Cornell University, Ithaca, New York 14853-2501*
[2]*New Zealand Institute for Industrial Research, Lower Hutt, New Zealand*
(Received 28 August 1996)

We investigate the possibility of superconductivity in a dense phase of hydrogen which becomes metallic while retaining diatomic character. Correlated fluctuations between electrons and holes in the ensuring band-overlap state can lead to significant enhancements in the transition temperature (compared with monatomic phases) principally through a reduction in the associated Coulomb pseudopotential. The effective electron-electron interaction is determined by a method which treats electrons and phonons on an equivalent footing, an approach which confirms that monatomic phases also remain candidates for high temperature superconductivity. [S0031-9007(96)01982-5]



X_2 molecule

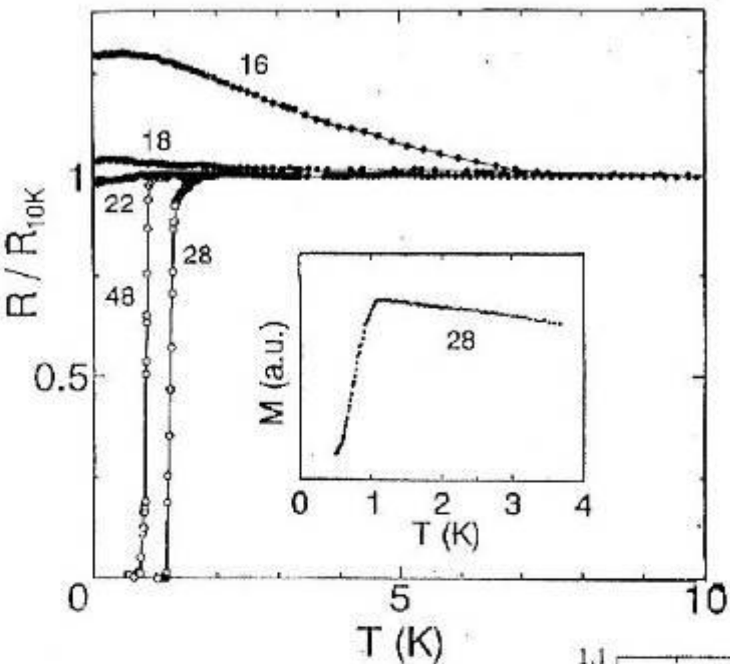
H_2、 O_2、 N_2、 F_2、 Cl_2、 Br_2、 I_2



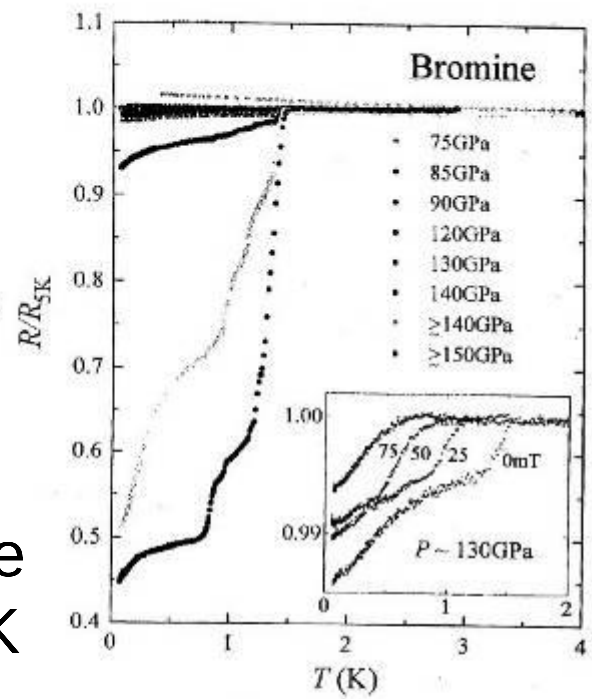
Molecular insulator

Molecular metal

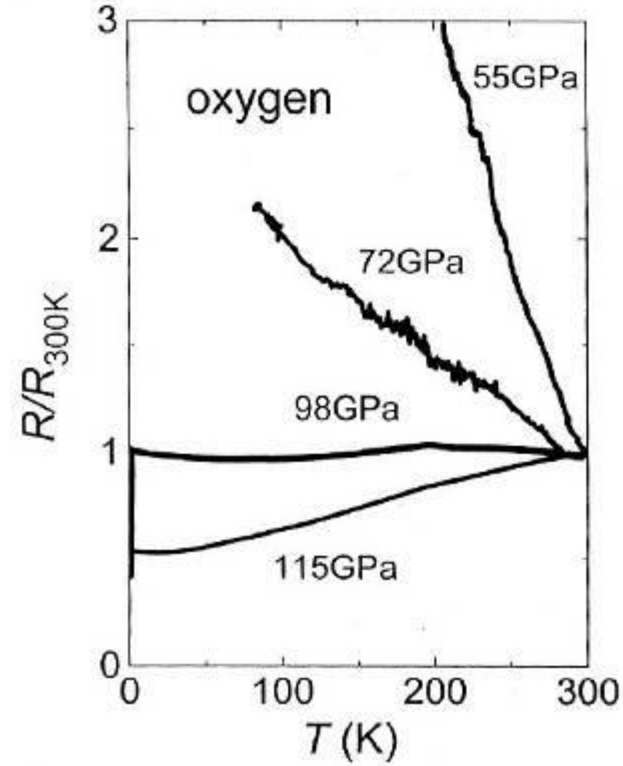
Monatomic metal



Iodine
Tc~1.5K

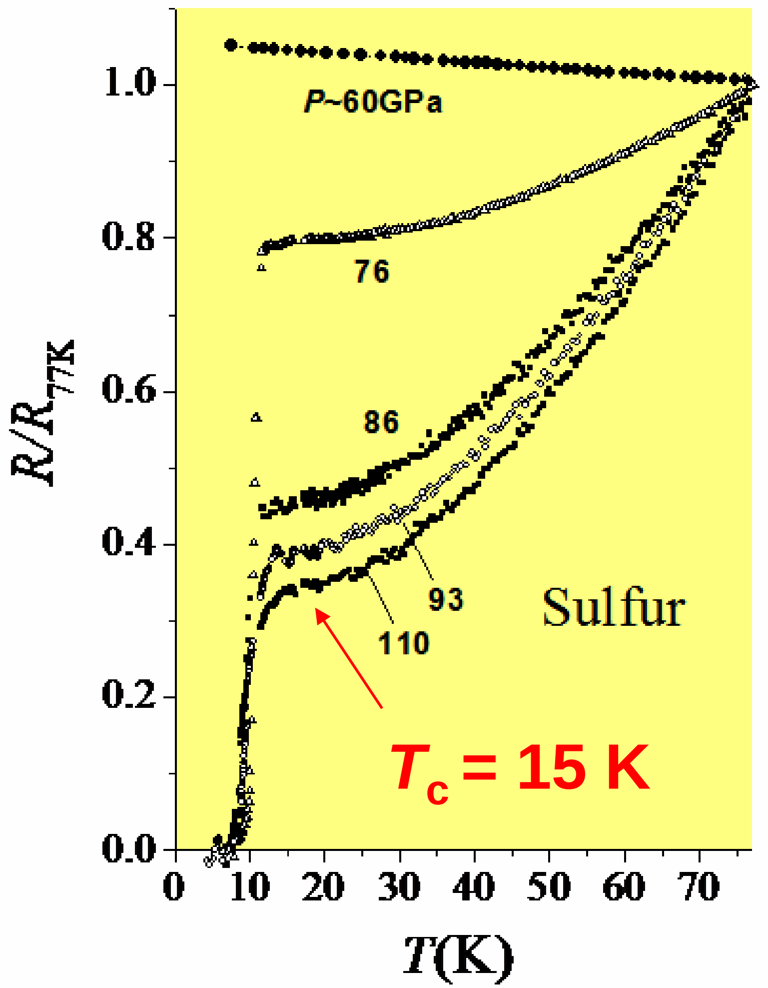


Bromine
Tc~1.5K



Oxygen
Tc~0.5K

Superconductor from insulator



Insulator

↓

Semiconductor

↓

Metal

↓

Superconductor

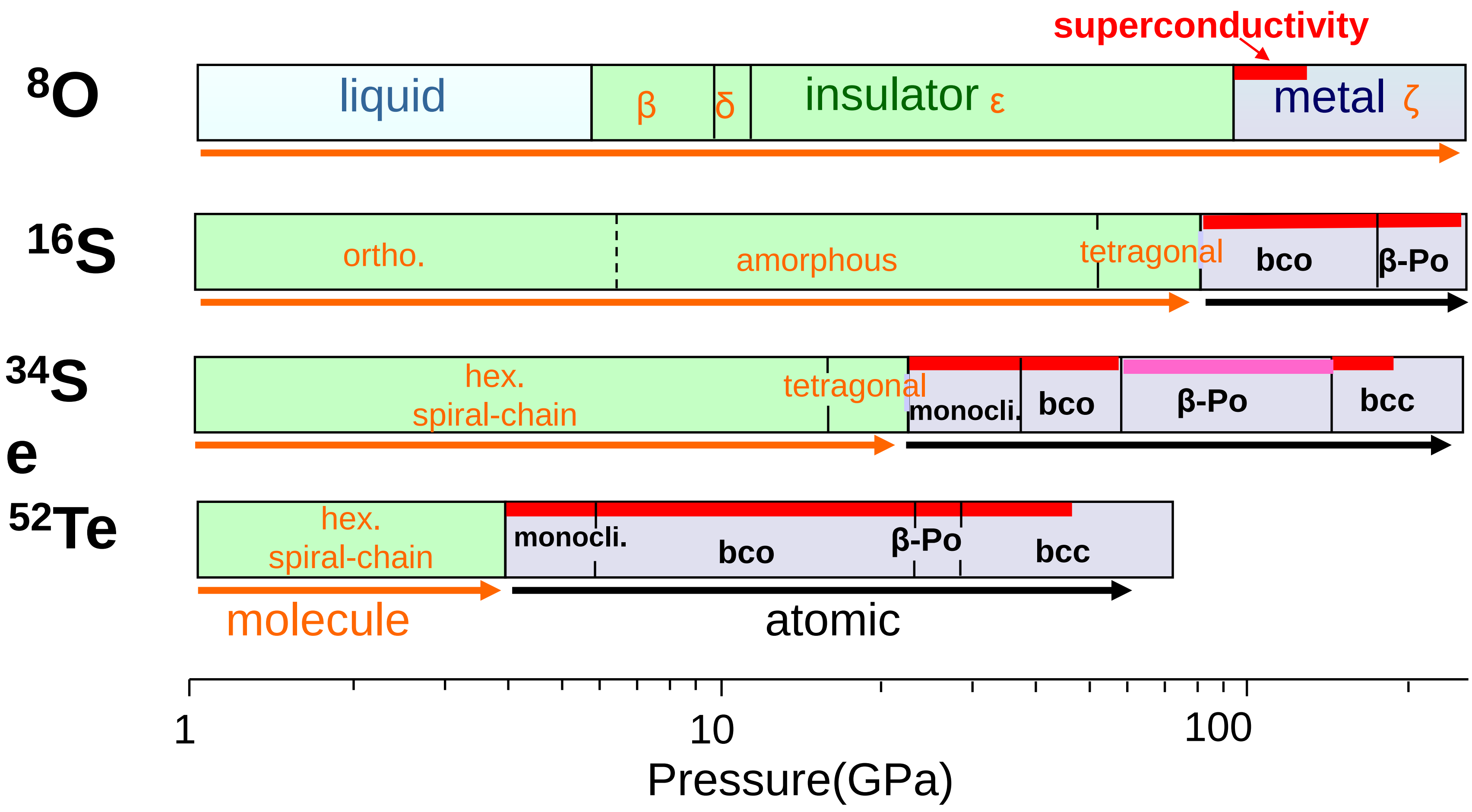
Press, Dense (red arrow) | **Cool, down** (blue arrow)

S. Kometani *et al*,. J. Phys. Soc. Jpn., 66 (1997) 2564.

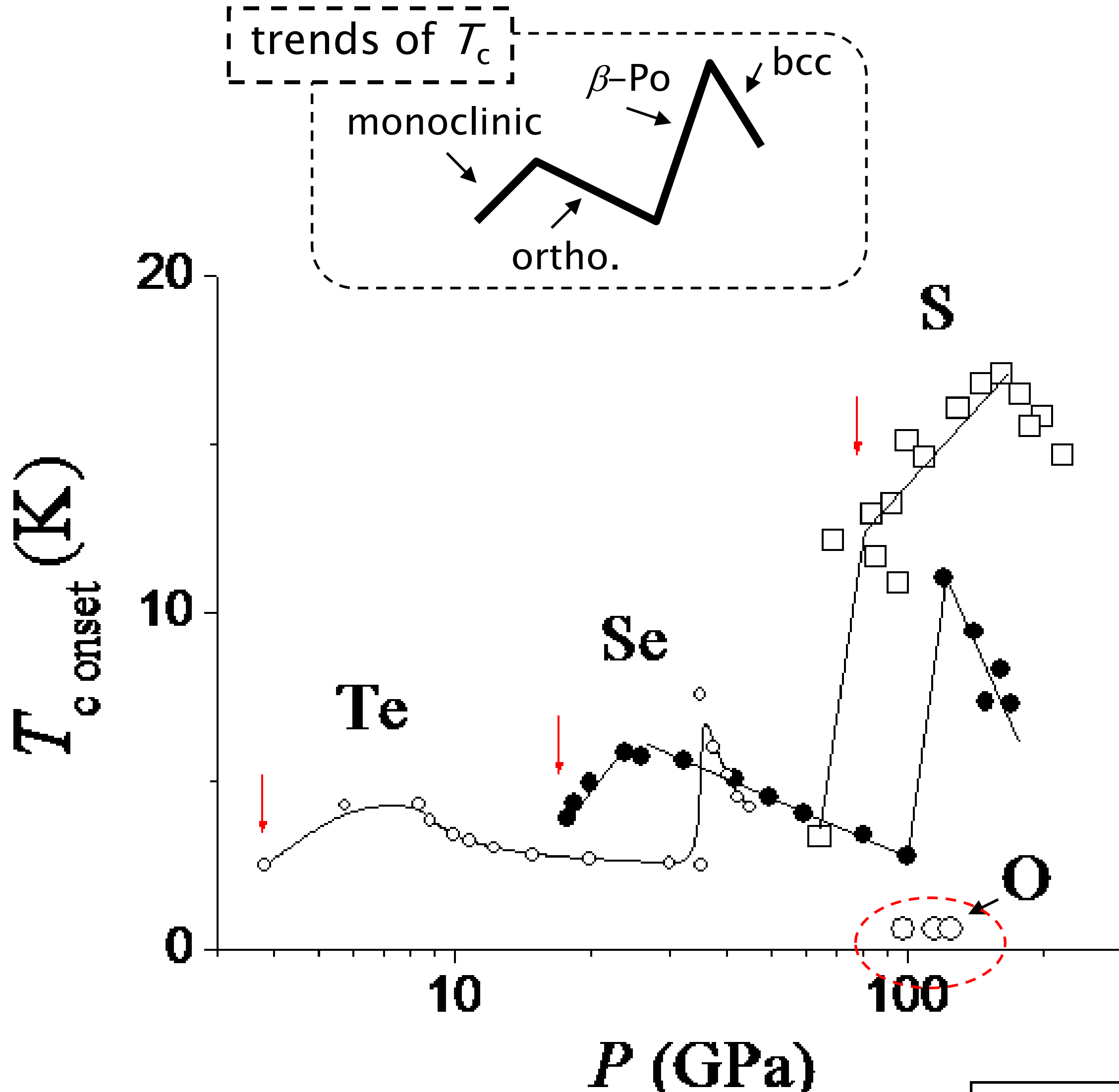
^{16}S 17 K at 200 GPa

^{34}Se 8 K at 150 GPa

^{56}Te 7.4 K at 35 GPa



Lighter elements; higher T_c at higher P

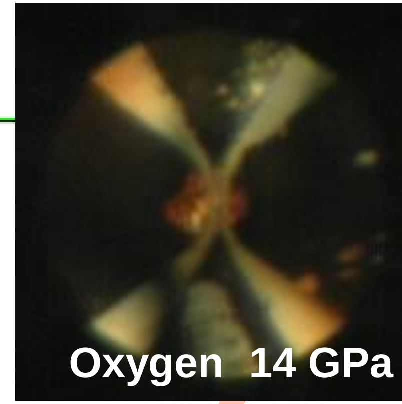


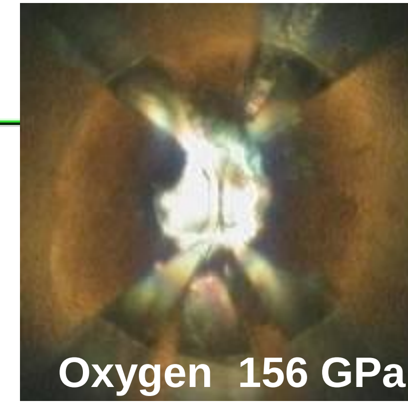
	VIb	
^{7}N	^{8}O	^{9}F
^{15}P	^{16}S	^{17}Cl
^{33}As	^{34}Se	^{35}Br
^{51}Sb	^{52}Te	^{53}I
^{83}Bi	^{84}Po	^{85}At

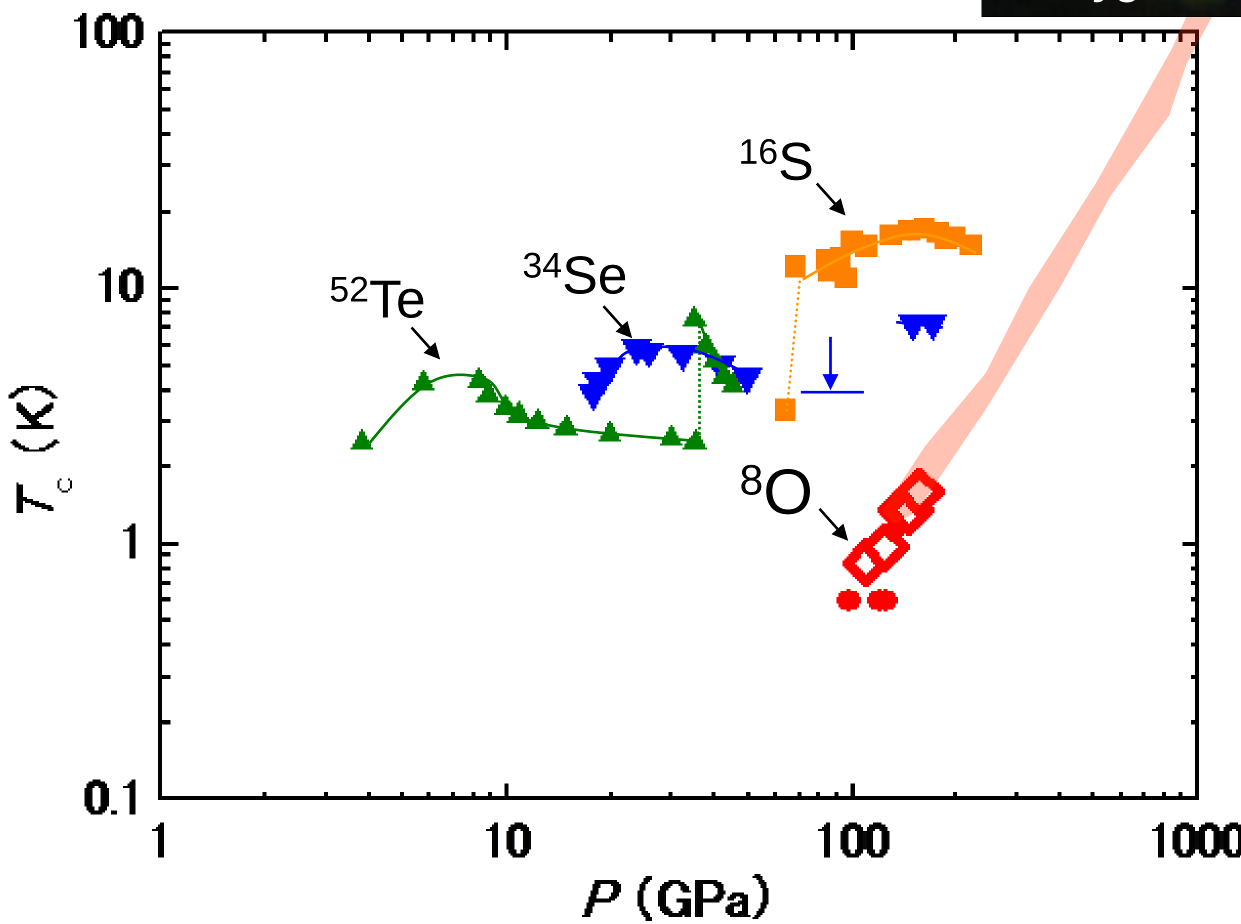
Oxygen may need much higher pressure

↓ Molecular dissociation, (=metallization)

New data for metallic oxygen







^{8}O 1.6 K at 156 GPa

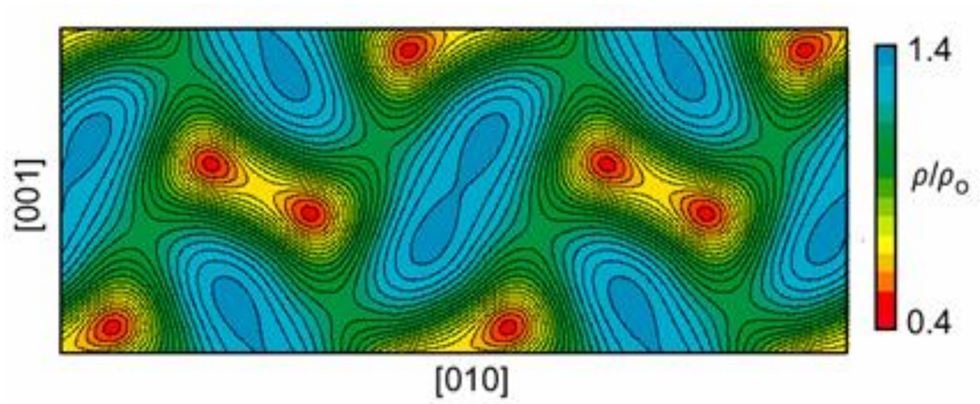
^{16}S 17 K at 200 GPa

^{34}Se 8 K at 150 GPa

^{56}Te 7.4 K at 35 GPa

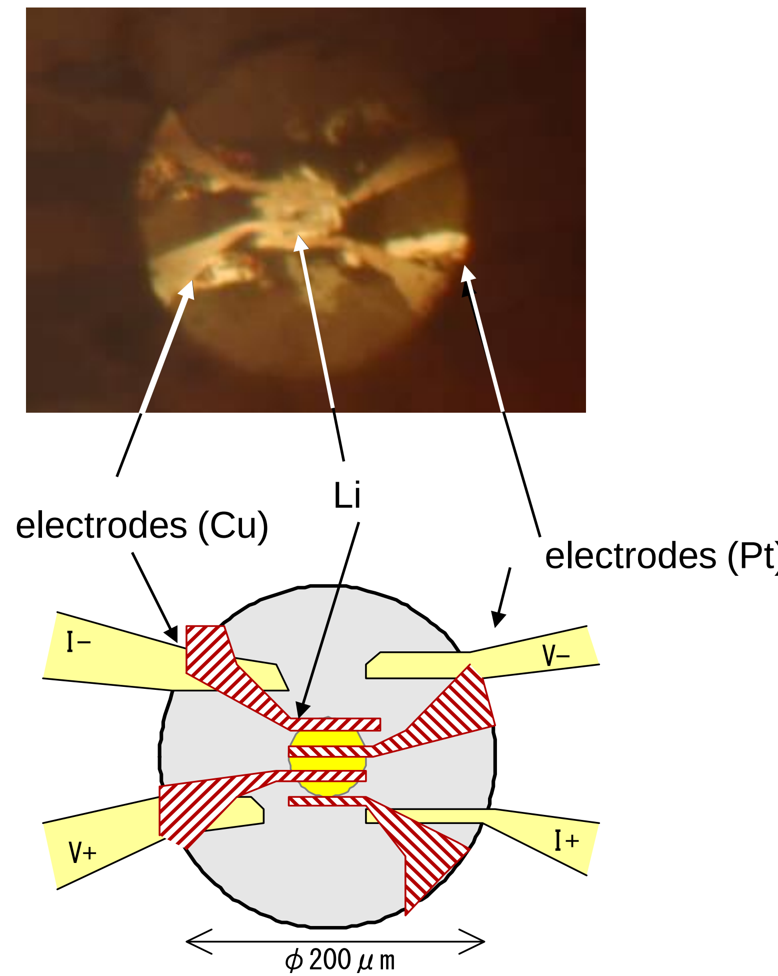
Mizobata

Li: metal-hydrogen-like metal?



LDA 2s charge density in Cmca structure

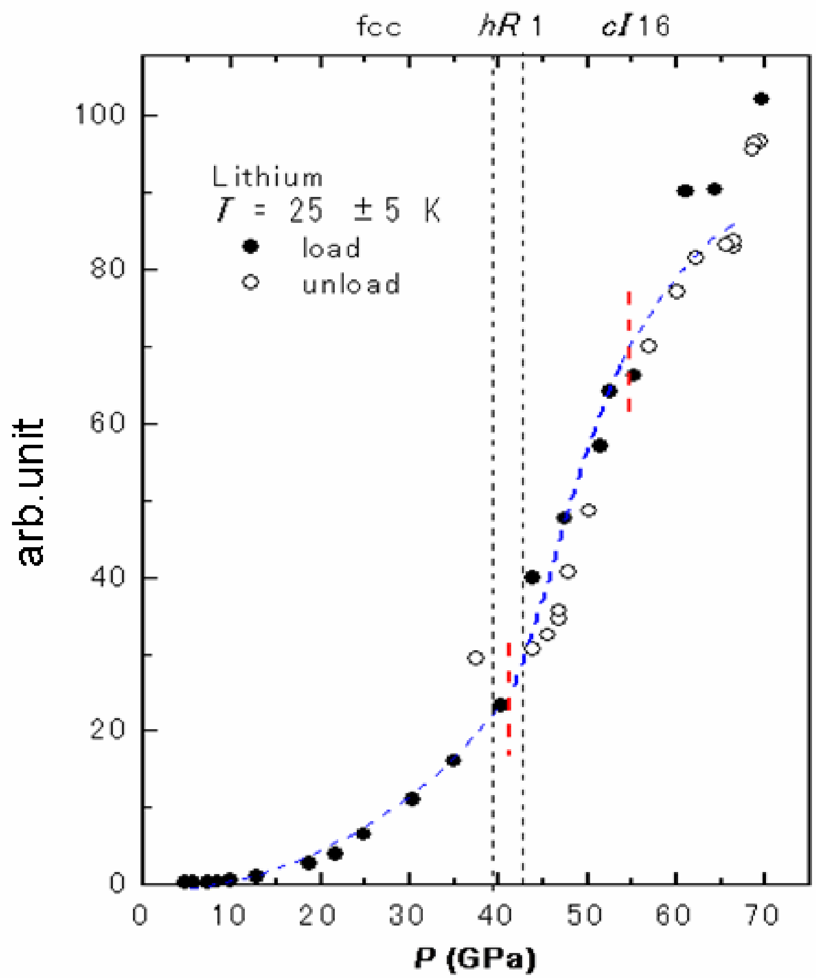
J.B.Neaton and Ashcroft, Nature 400, 141 (1999)

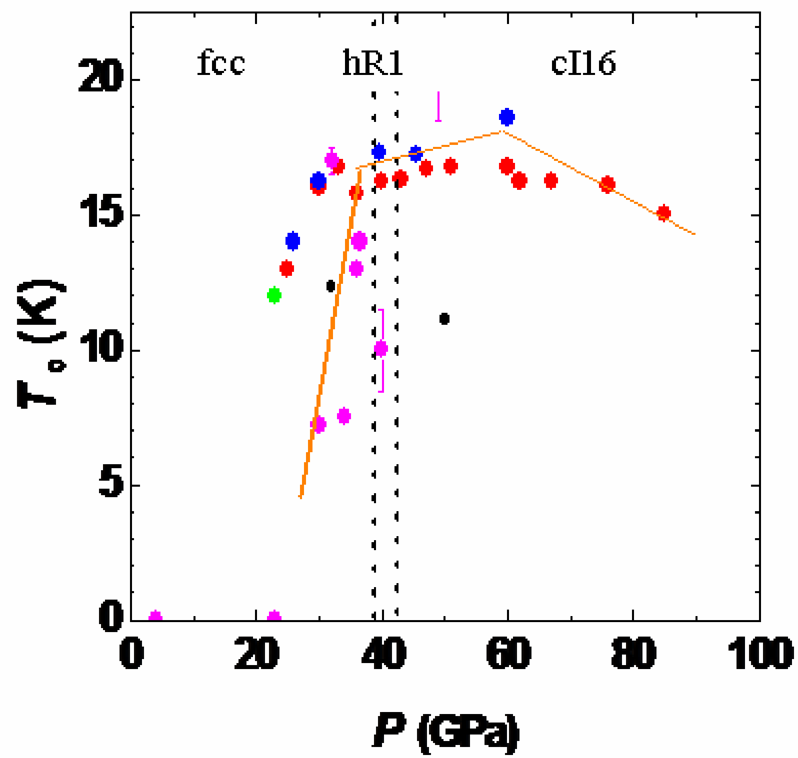


High chemical activity

Fine deposited electrodes enables true 4-probe method.

Lower symmetry, lower conductivity



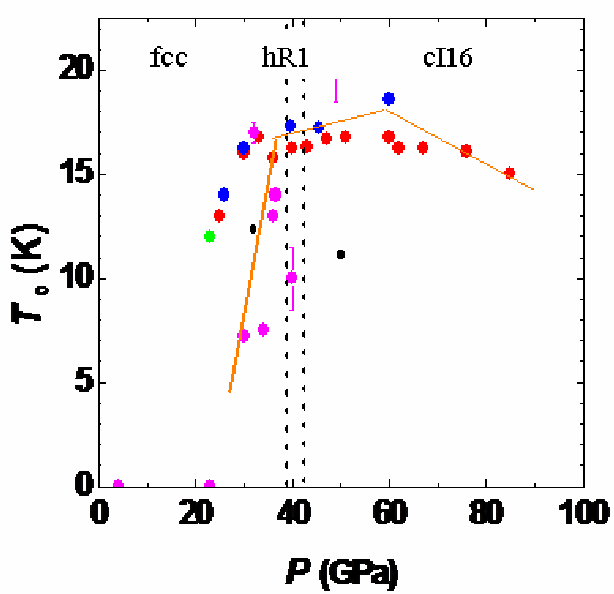


K. Shimizu *et al.*, Nature 419 (2002) 597.

The significant increase of ρ.

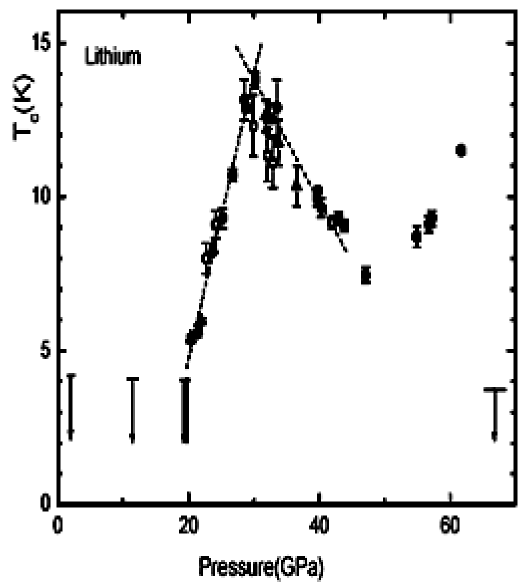
Lithium: T_c-P

Resistance measurement
non-hydrostatic (no pressure medium)



K. Shimizu *et al.*, Nature 419 (2002) 597.

Magnetization measurement
hydrostatic (Helium pressure medium)

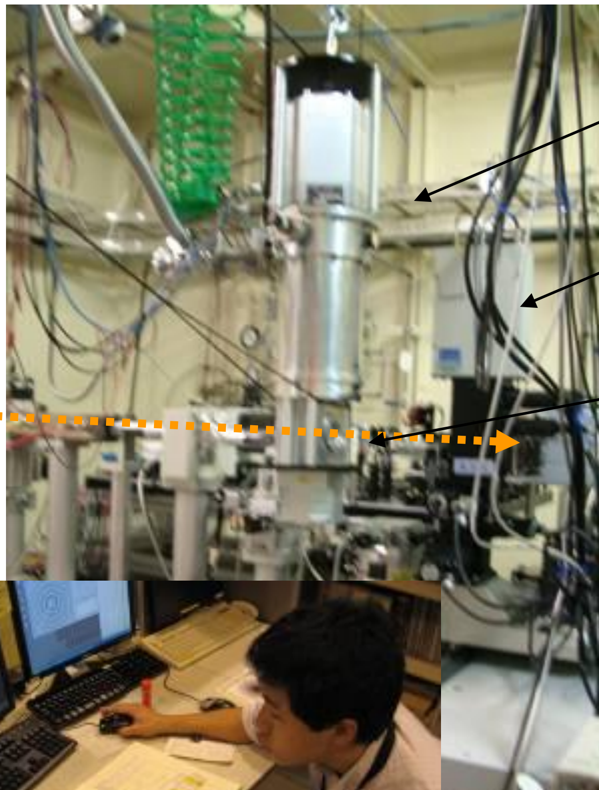


S. Deemyad and J. S. Schilling

Hydrostaticity, Structural effect, Further transition at high pressure

x-ray diffraction + resistance measurement @ SP8

SPring-8 BL10XU



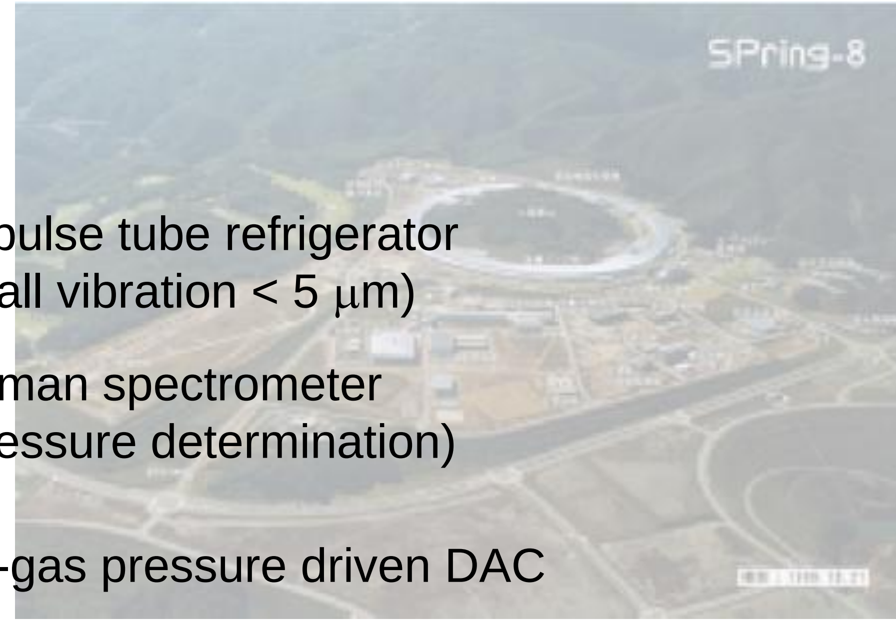
x-ray

15μmϕ

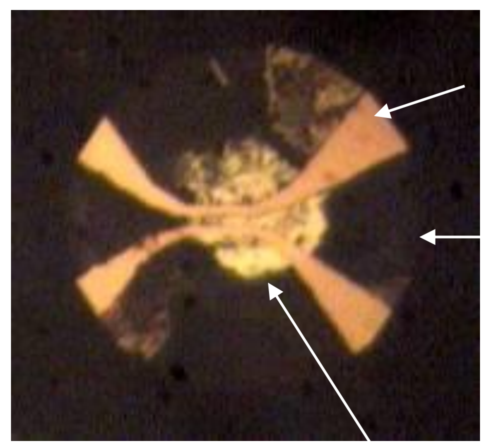
4K-pulse tube refrigerator
(small vibration < 5 μm)

Raman spectrometer
(pressure determination)

He-gas pressure driven DAC



Matsuoka

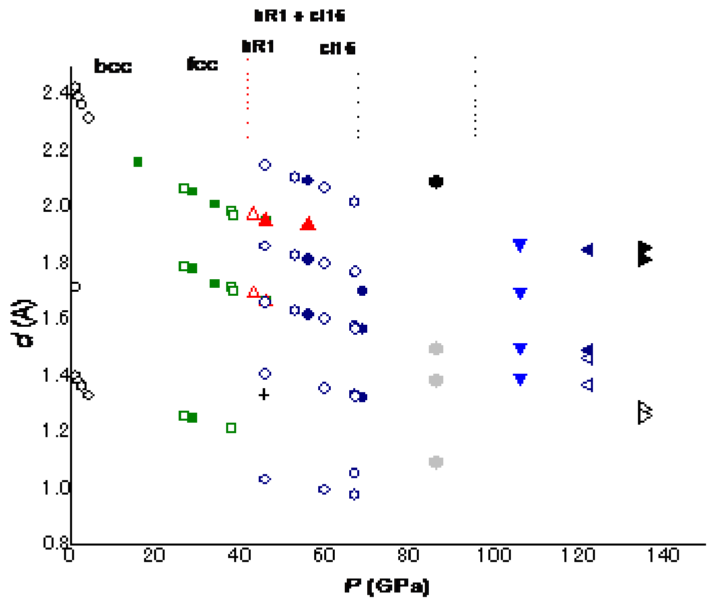


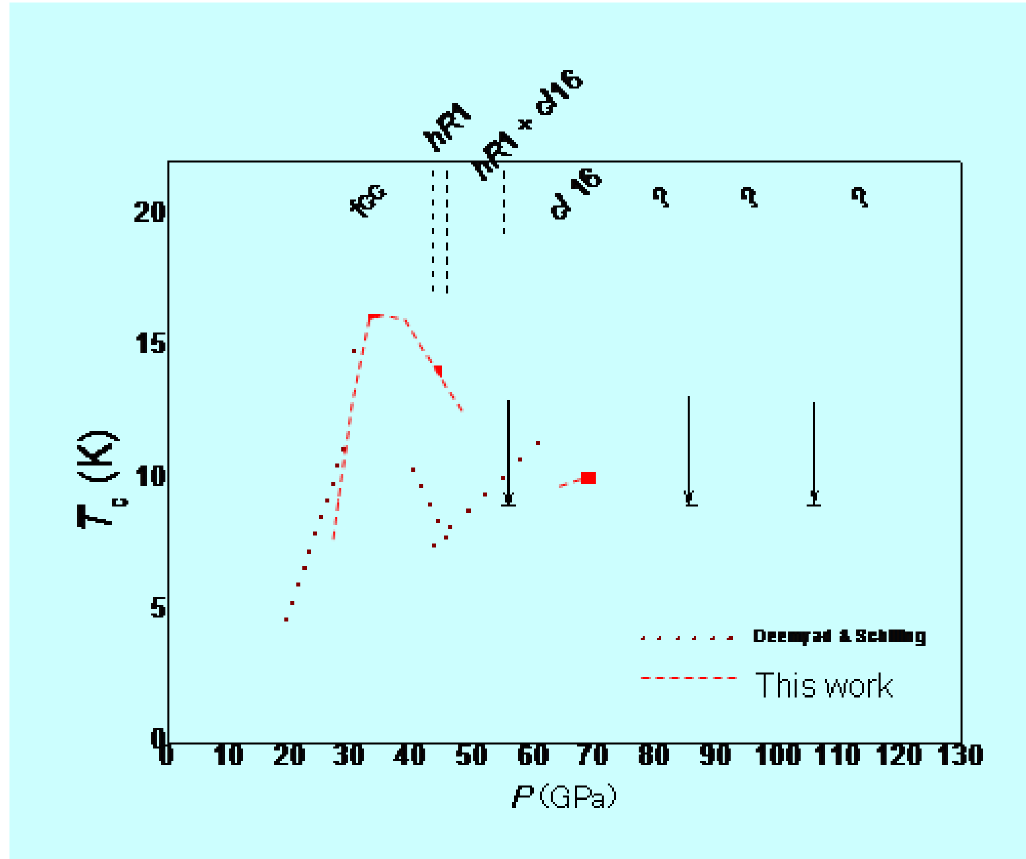
Deposited electrodes
(Cu)

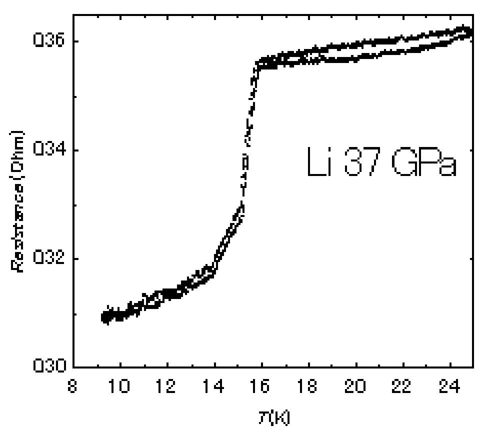
Beveled anvil
(φ100 -300μm)

Sample (Li) φ30 μm x 20 μm ^{t}

T_c vs. Pressure and structural sequences







structure	fcc	*hR*1	*cI*16	?	?	?
T_c	↗	↘	↗	? < 9K	? < 9K	? < 9K

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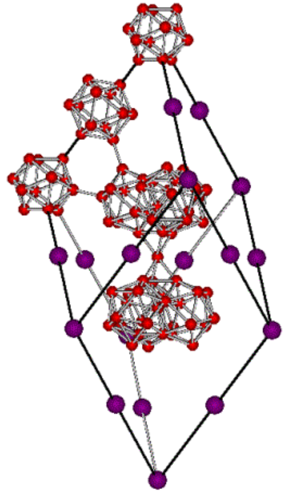
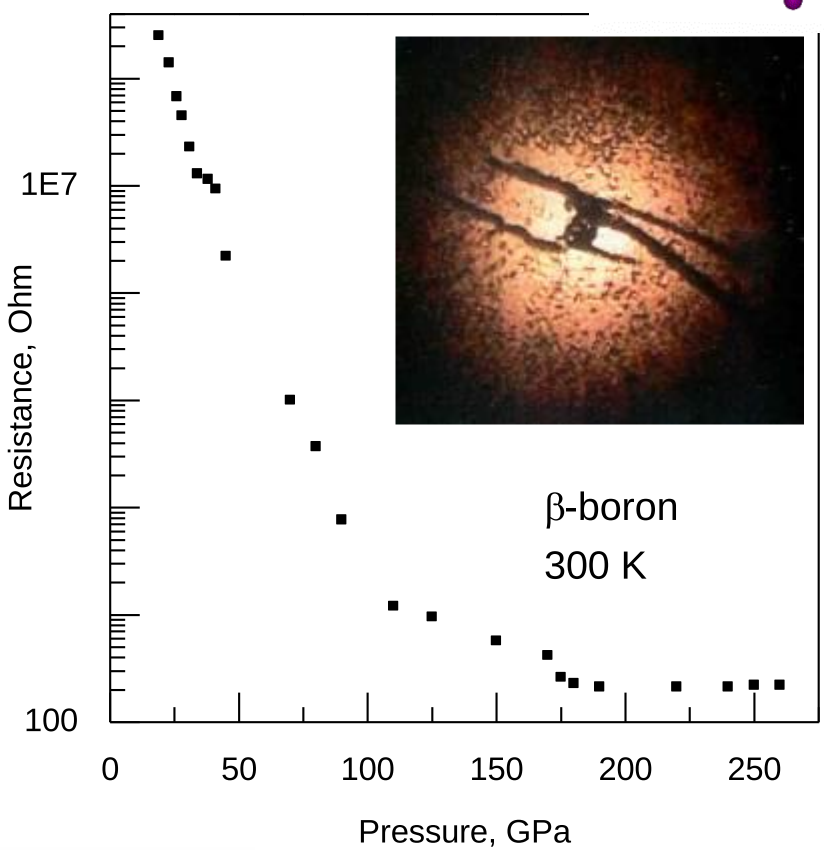
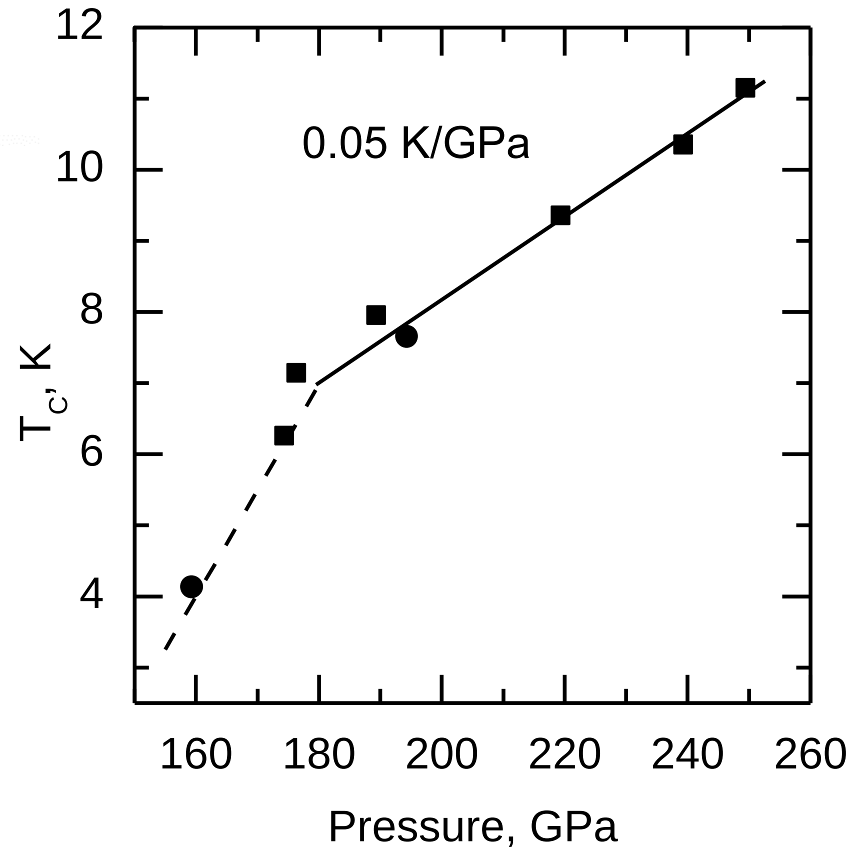
Boron, β-boron

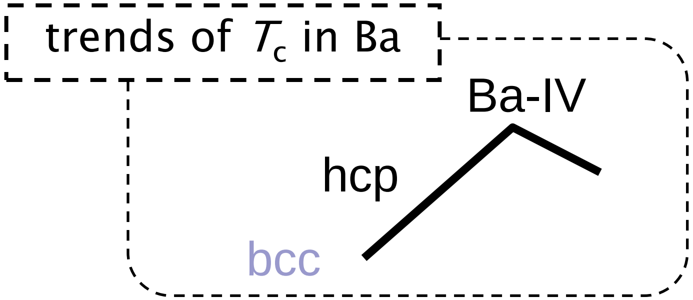


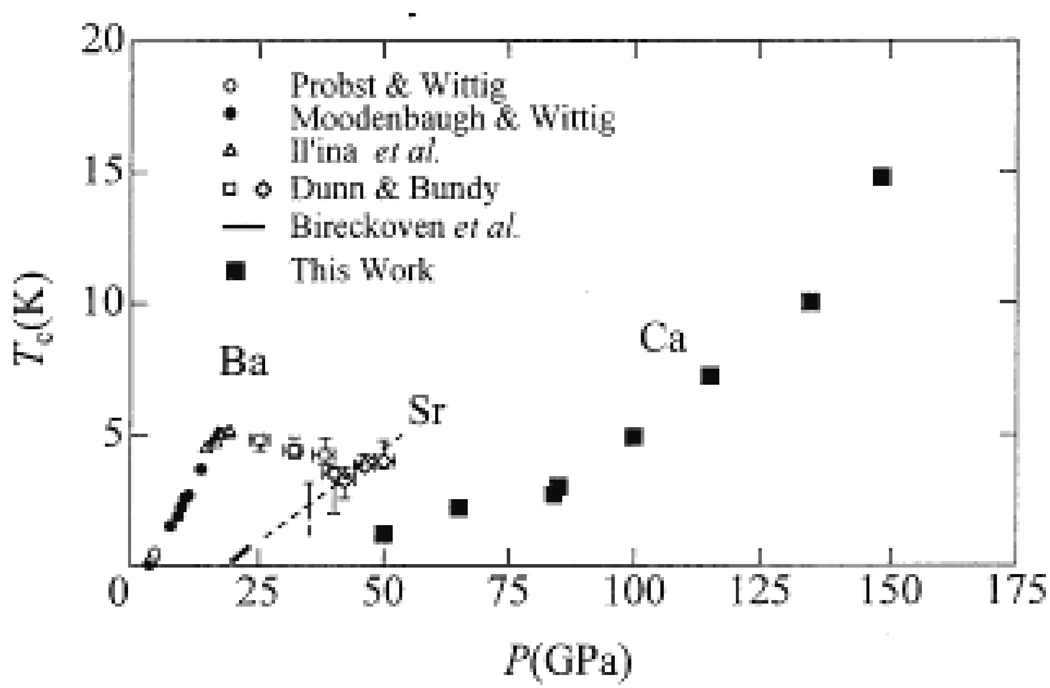


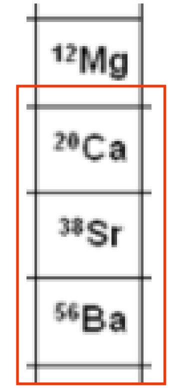


M. I. Eremets *et al*. Science **293** (2001) 272.

Superconductivity in heavy alkaline (IIa) metals

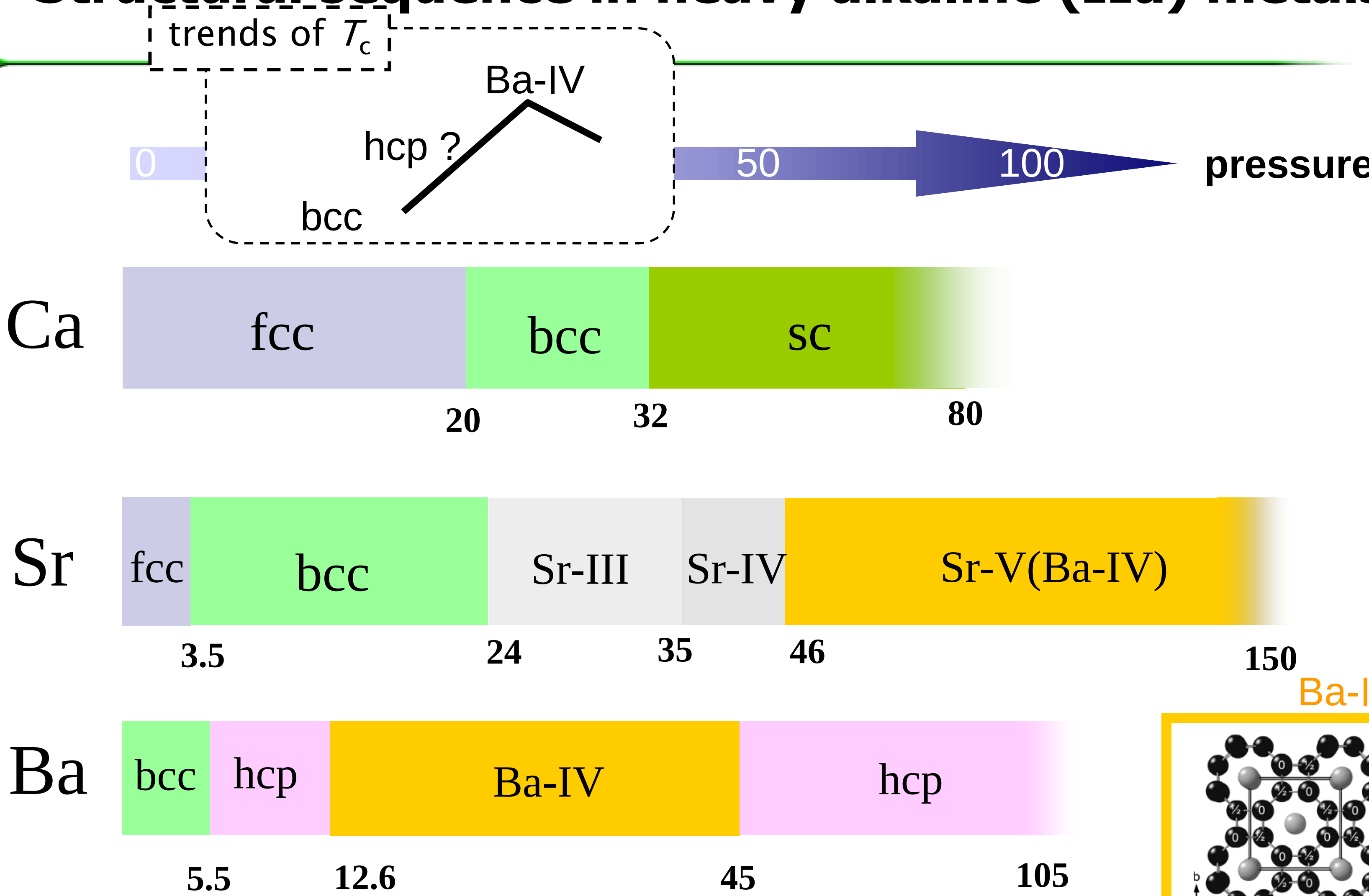




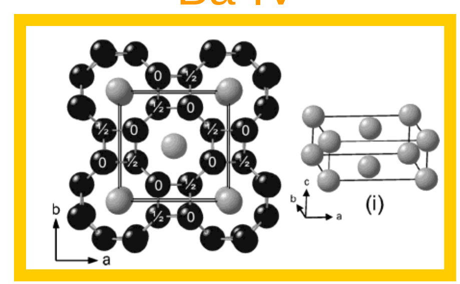


S. Okada *et al.*, J. Phys. Soc. Jpn. 65 (1996) 1924.

Structural sequence in heavy alkaline (IIa) metals



Ba-IV

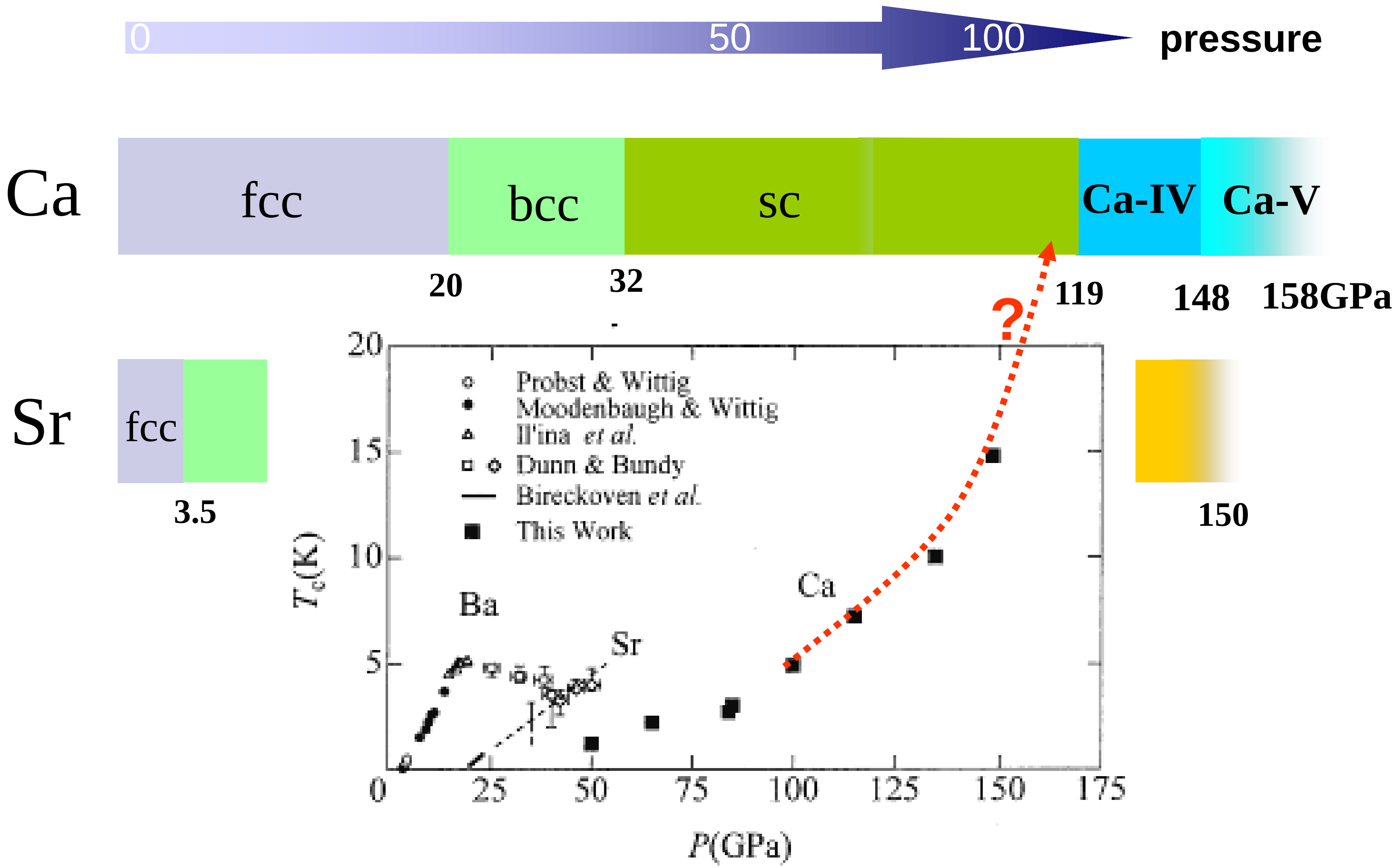


- Max. T_c in Ba-IV type structure
- *s*-*d* electronic transfer

M.Winzenick and W. B. Holzapfel, High Pressure Science & Technology, p384-p386 (1995).

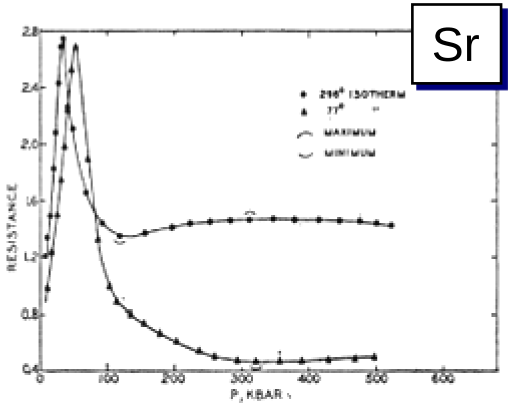
M. I. Mcmahon *et al.*, Phys. Rev. B **61**, 3135 (2000).

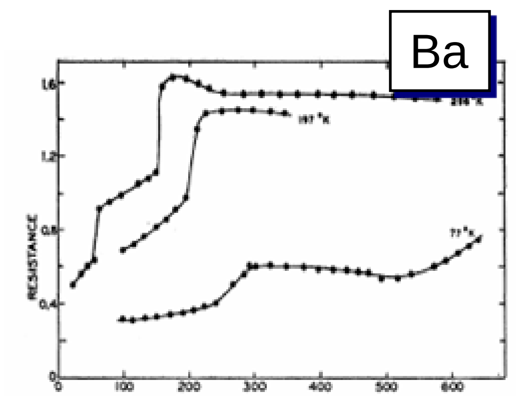
New structure in calcium at megabar pressure

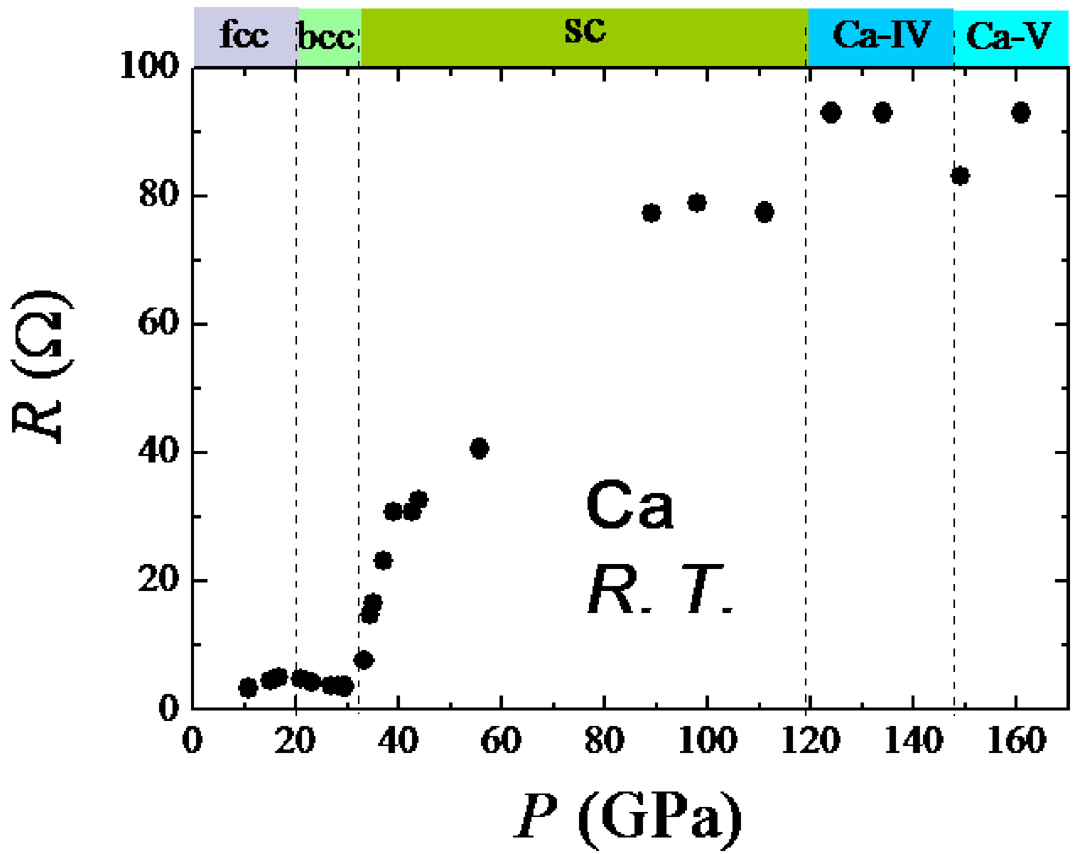


T. Yabuuchi *et al.*, J. Phys. Soc. Jpn. 74 2391 (2005).

Resistance at room temperature

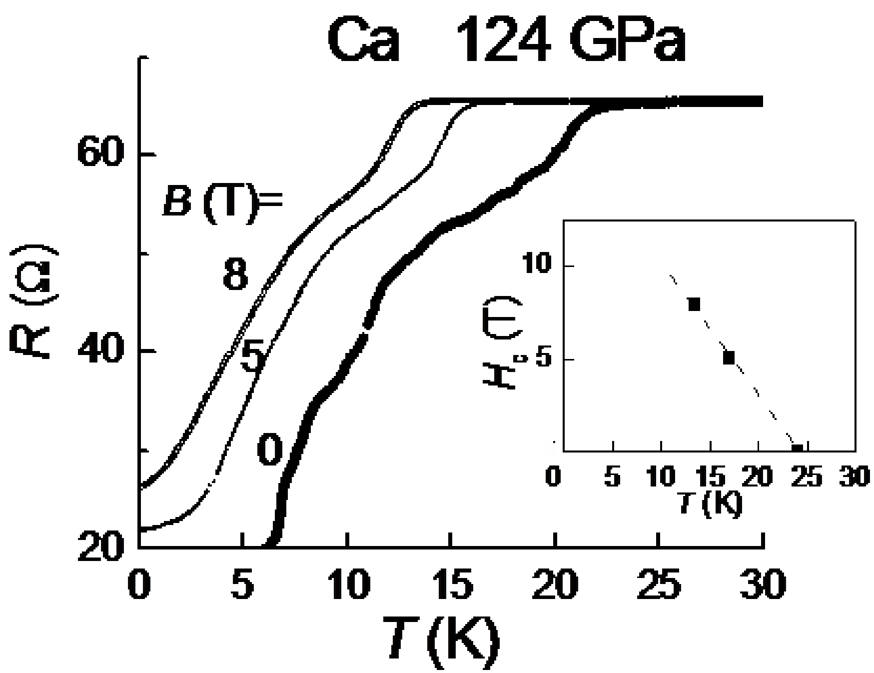


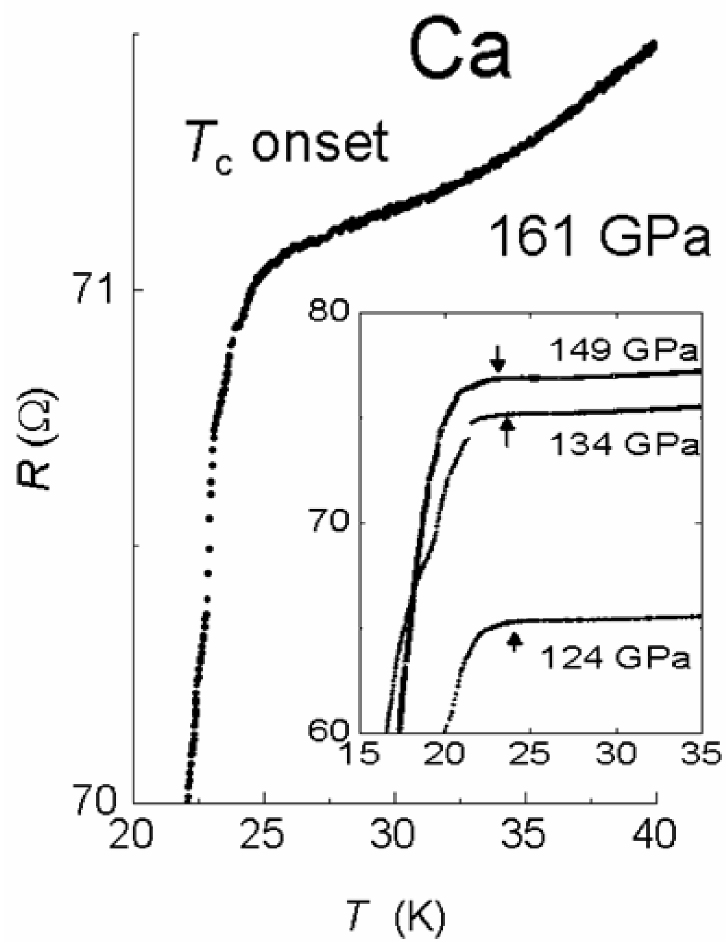




R. A. Stager and H. G. Drickamer, Phys. Rev. 131, 2524 (1963).

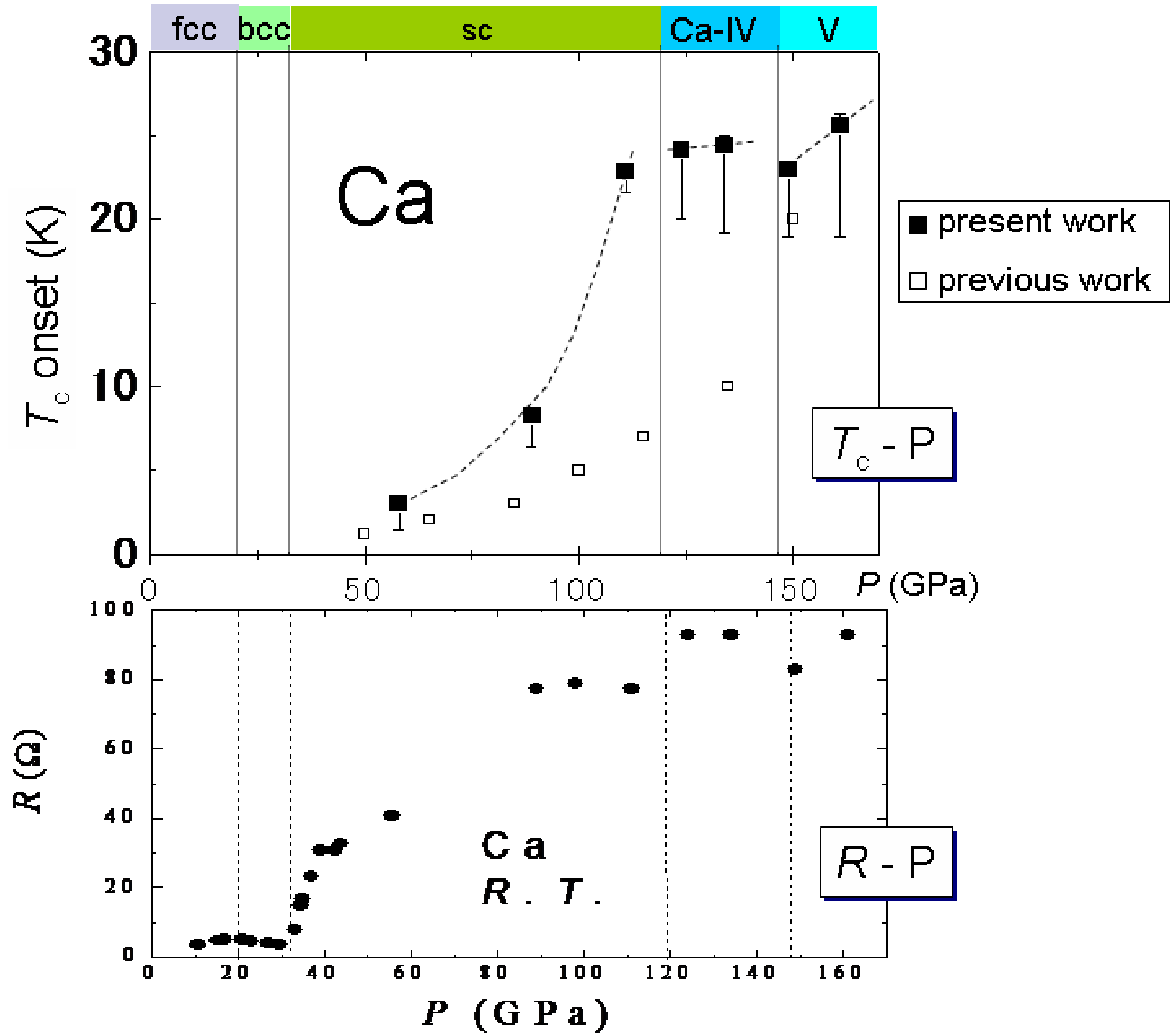
Superconductivity in Ca





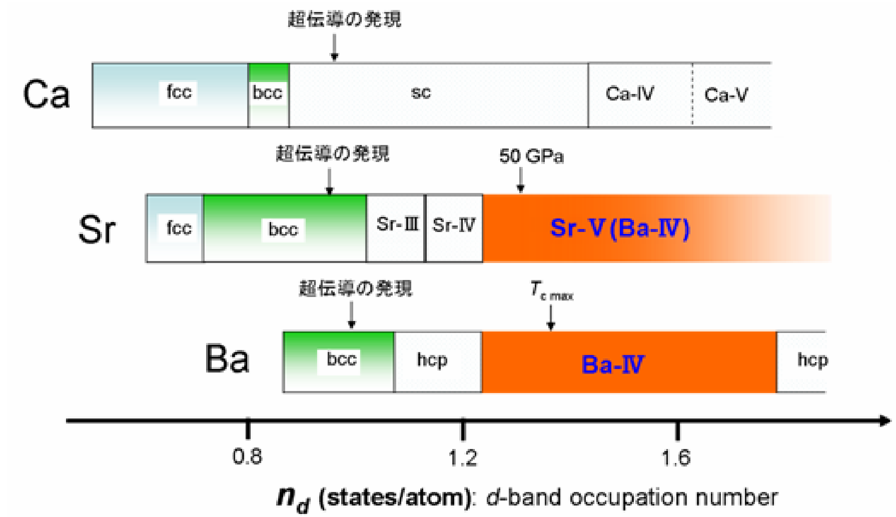
T. Yabuuchi et al., J. Phys. Soc. Jpn. 75 (2006).

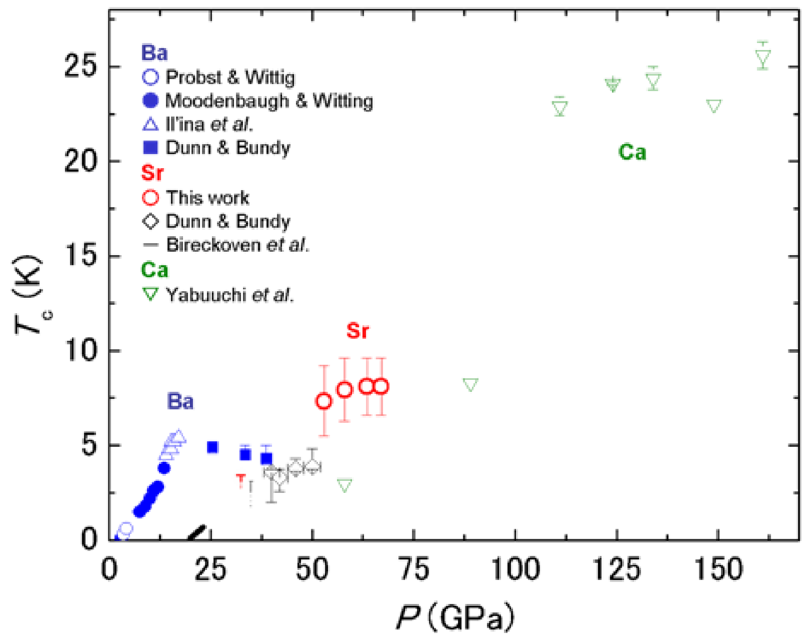
Pressure dependence of T_c

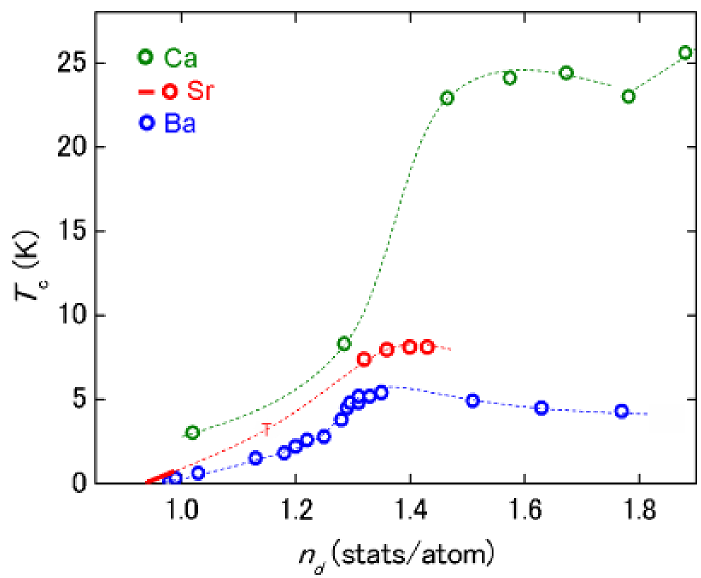


heavy alkaline

Mizobata

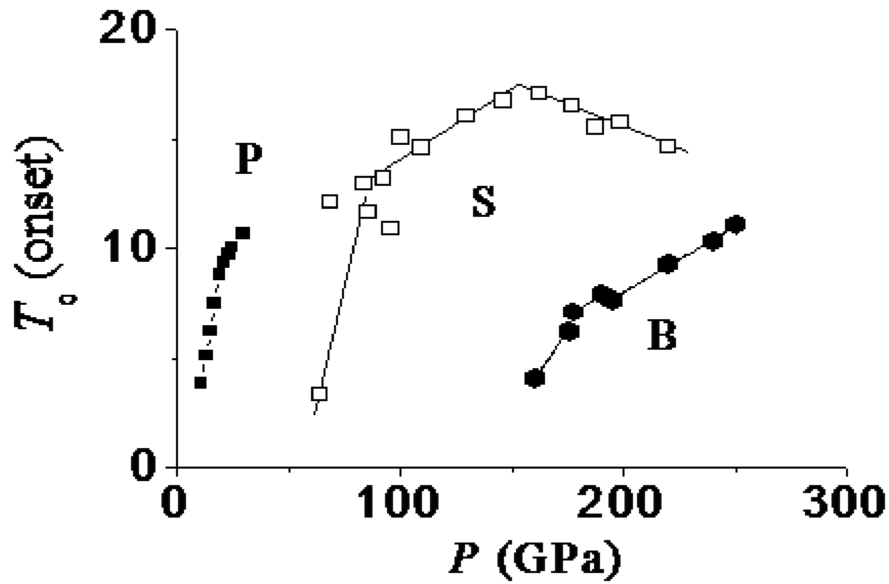




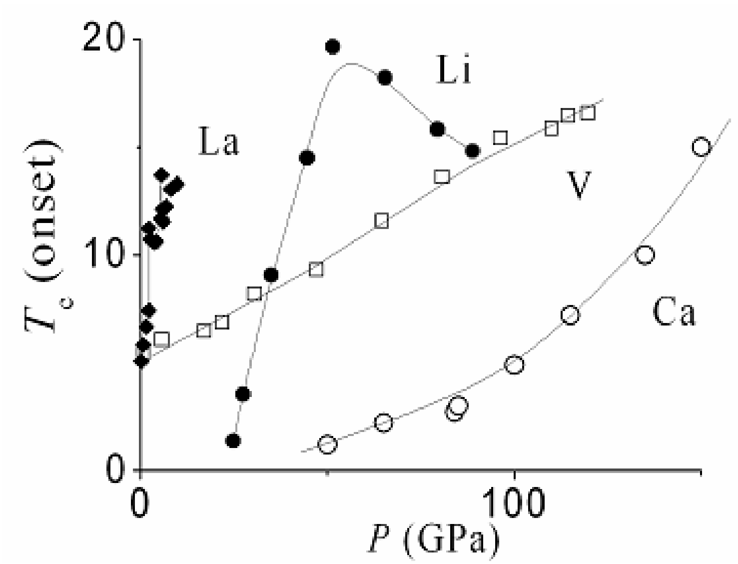


High T_c elements ($\equiv T_c$ > 10 K) at P > 100 GPa

from insulator



from metal



[P] **I. Shirotani** *et al*., Phys. Rev. B 50 (1994) 16274.
[S] **S. Kometani** *et al*., J. Phys. Soc. Jpn. 66 (1997) 2564.
[B] **M. I. Eremets** *et al*., Science 293 (2001) 272.

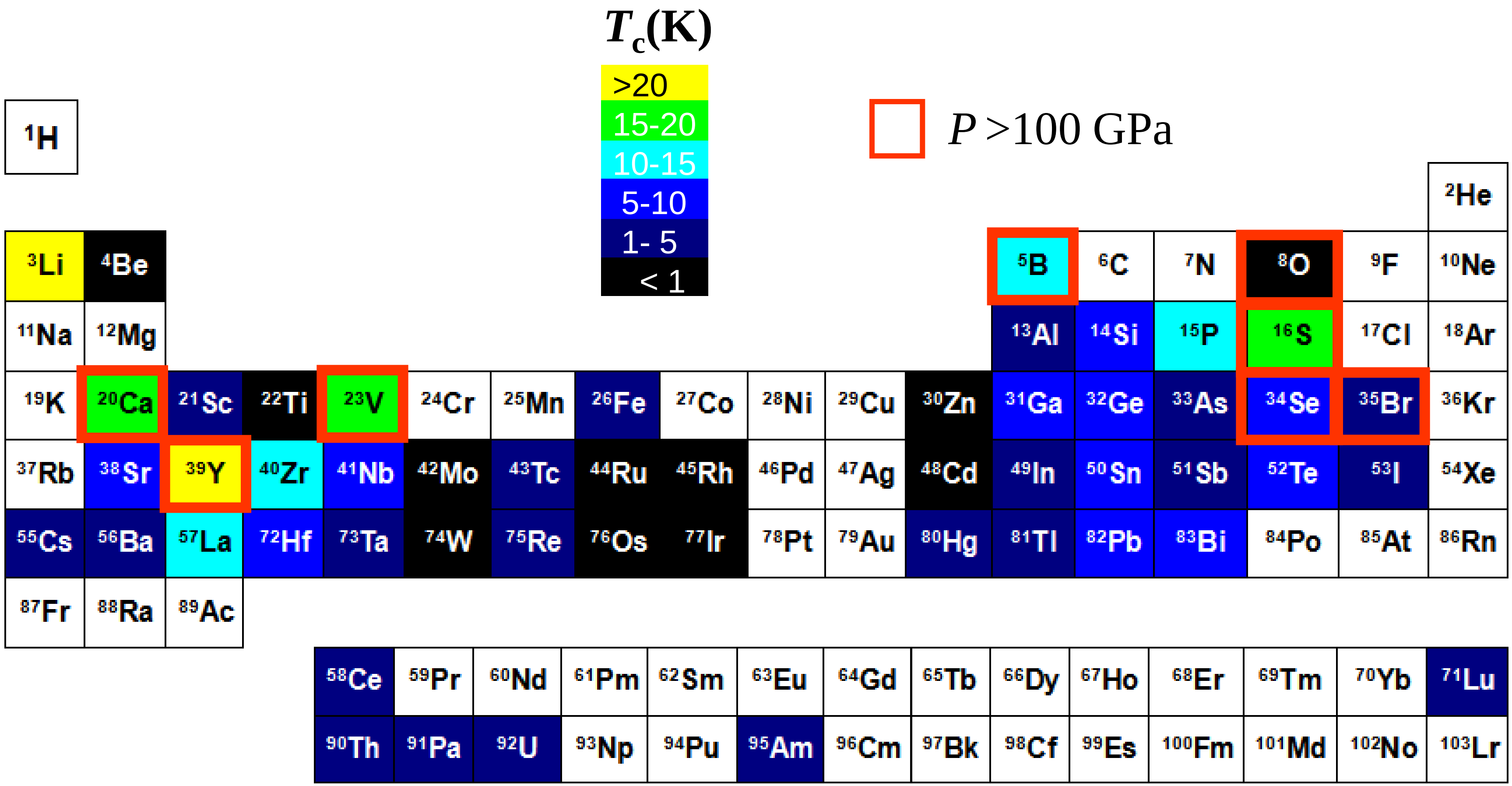
[La] **V. G. Tissen**, Phys. Rev. B 53 (1996) 8238.
[Li] **K. Shimizu** *et al*., Nature 419 (2002) 597.
[V] **M. Ishizuka** *et al*., Phys. Rev. B 61 (2000) R3823.
[Ca] **S. Okada** *et al*., J. Phys. Soc. Jpn. 65 (1996) 1924.

forgetting about “pressure”

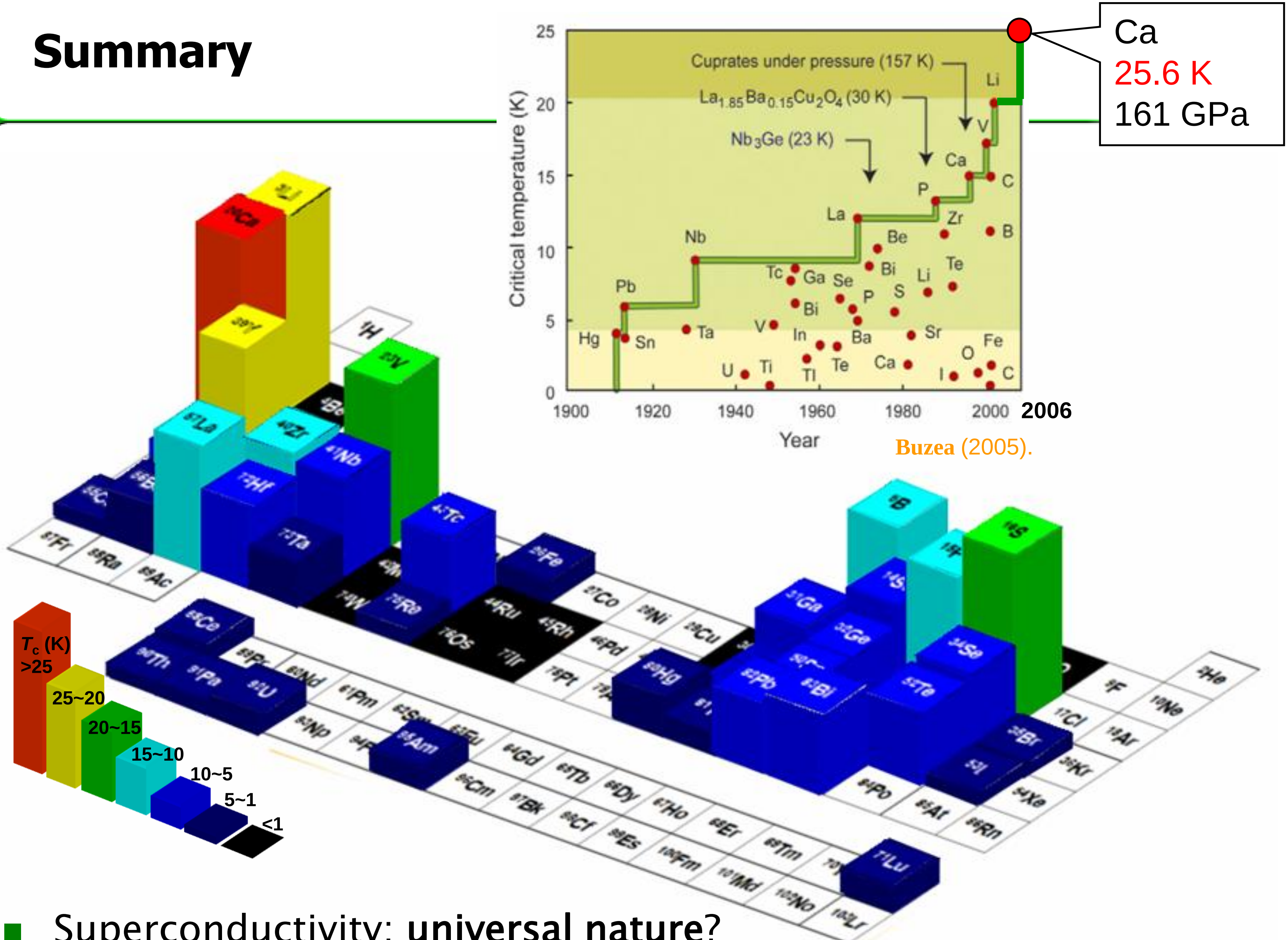
52 elements get Sc

^{1}H																	^{2}He
^{3}Li	^{4}Be											^{5}B	^{6}C	^{7}N	^{8}O	^{9}F	^{10}Ne
^{11}Na	^{12}Mg											^{13}Al	^{14}Si	^{15}P	^{16}S	^{17}Cl	^{18}Ar
^{19}K	^{20}Ca	^{21}Sc	^{22}Ti	^{23}V	^{24}Cr	^{25}Mn	^{26}Fe	^{27}Co	^{28}Ni	^{29}Cu	^{30}Zn	^{31}Ga	^{32}Ge	^{33}As	^{34}Se	^{35}Br	^{36}Kr
^{37}Rb	^{38}Sr	^{39}Y	^{40}Zr	^{41}Nb	^{42}Mo	^{43}Tc	^{44}Ru	^{45}Rh	^{46}Pd	^{47}Ag	^{48}Cd	^{49}In	^{50}Sn	^{51}Sb	^{52}Te	^{53}I	^{54}Xe
^{55}Cs	^{56}Ba	^{57}La	^{72}Hf	^{73}Ta	^{74}W	^{75}Re	^{76}Os	^{77}Ir	^{78}Pt	^{79}Au	^{80}Hg	^{81}Tl	^{82}Pb	^{83}Bi	^{84}Po	^{85}At	^{86}Rn
^{87}Fr	^{88}Ra	^{89}Ac															
			^{58}Ce	^{59}Pr	^{60}Nd	^{61}Pm	^{62}Sm	^{63}Eu	^{64}Gd	^{65}Tb	^{66}Dy	^{67}Ho	^{68}Er	^{69}Tm	^{70}Yb	^{71}Lu	
			^{90}Th	^{91}Pa	^{92}U	^{93}Np	^{94}Pu	^{95}Am	^{96}Cm	^{97}Bk	^{98}Cf	^{99}Es	^{100}Fm	^{101}Md	^{102}No	^{103}Lr	

Observed the highest T_c



Summary



- Superconductivity: **universal nature**?
- Bad metals become good superconductors.

and future

- Challenging subjects
  - Hydrostaticity ⇔ uniaxial compression
  - Higher P (>300 GPa)
  - *In situ* & precise measurements (SC , +X-ray , Heat Capacity , + Thermal expansion, ･･･)