Ferromagnetic Phase in Correlated-electrons Matter

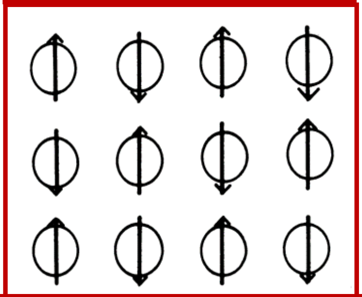
Correlation Effect in Condensed Matter

Simple Metal	Ferromagnetic (FM) Metal	Metal-Insulator transition	Antiferromagnetic Mott Insulator
$t >> U$	$t \geq U$	$t < U$	$t << U$

$$\mathcal{H} = -t\sum_{ij\sigma} c^{\dagger}_{i\sigma}c_{j\sigma} + U\sum_{i} n_{i\uparrow}n_{i\downarrow}$$

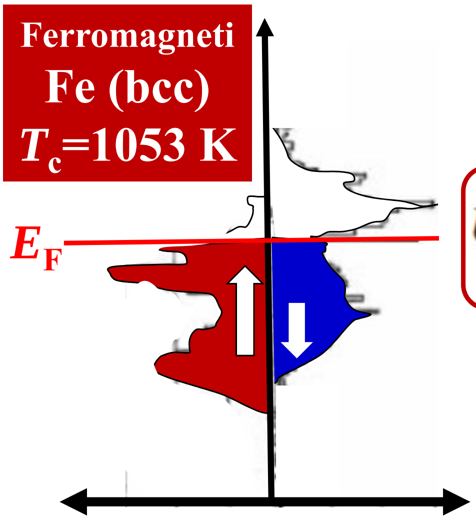
$H = 2J\,\Sigma_{ij}\,S_i \cdot S_j$

$J > 0$



Mother Compounds High-T_c Copper Oxides

Ferromagneti Fe (bcc) T_c=1053 K



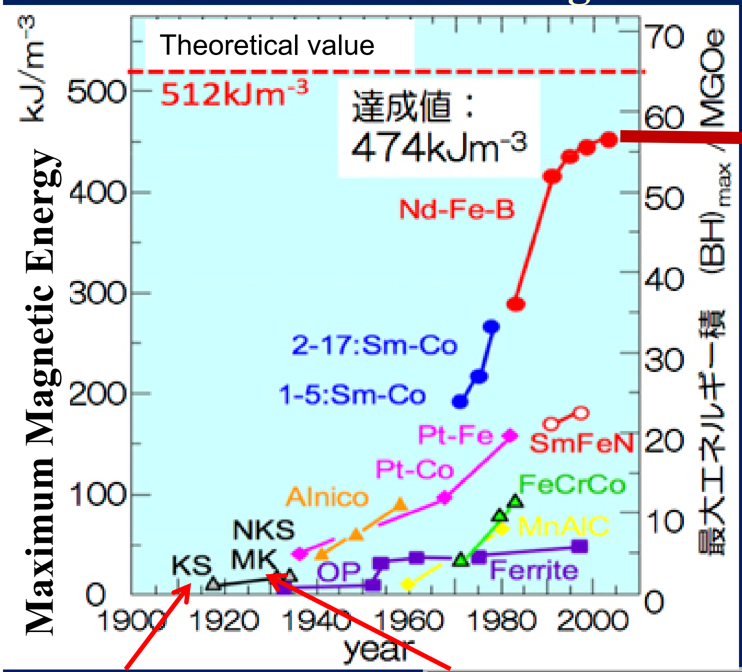
Spin Density of States

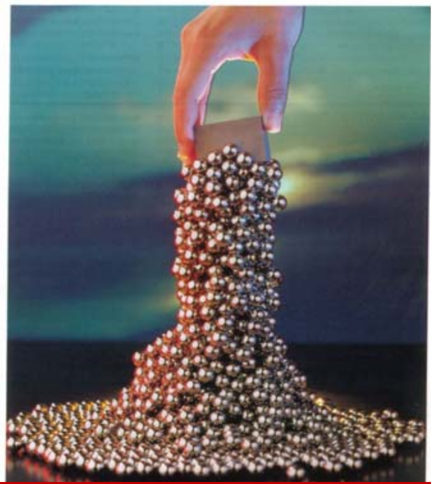
$s_{iz} = (1/2)(n_{i\uparrow} - n_{i\downarrow})$

$$U\sum_{i} n_{i,\uparrow}n_{i,\downarrow} = -2U\sum_{i} s^2_{iz}$$

On-site Repulsive Interaction U plays vital role for emergent phases

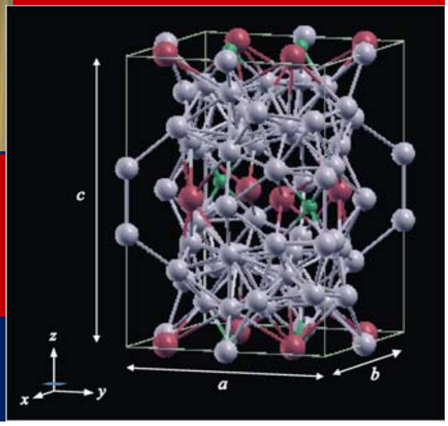
History of Research and Development of Permanent Magnets





World-record high-performance permanent magnet

Dr. M. Sagawa
（Sumitomo Special Metals Co.,Ltd）

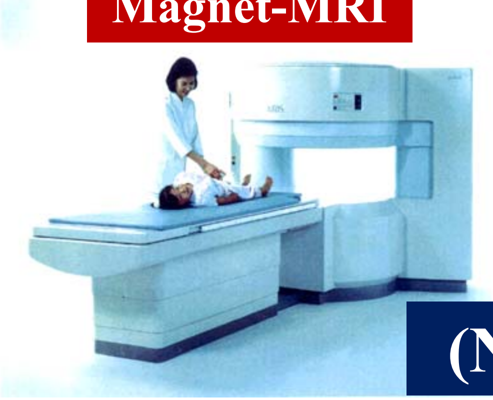


KS鋼 (1916):
Tohoku University
K. Honda

MK鋼 (1931):
Tokyo University
T. Mishima

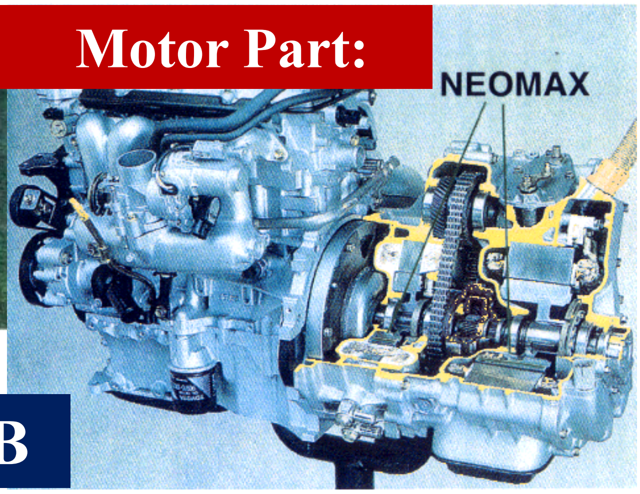
Permanent-magnet application to Technology

Permanent Magnet-MRI



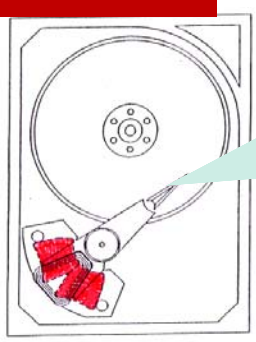
Electric Car

Motor Part:



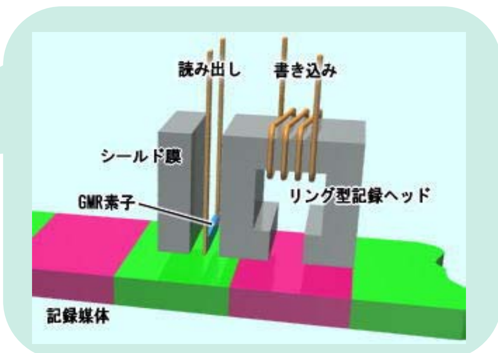
$(Nd,Dy)_2Fe_{14}B$

Magnetic-Storage Hard-Disk



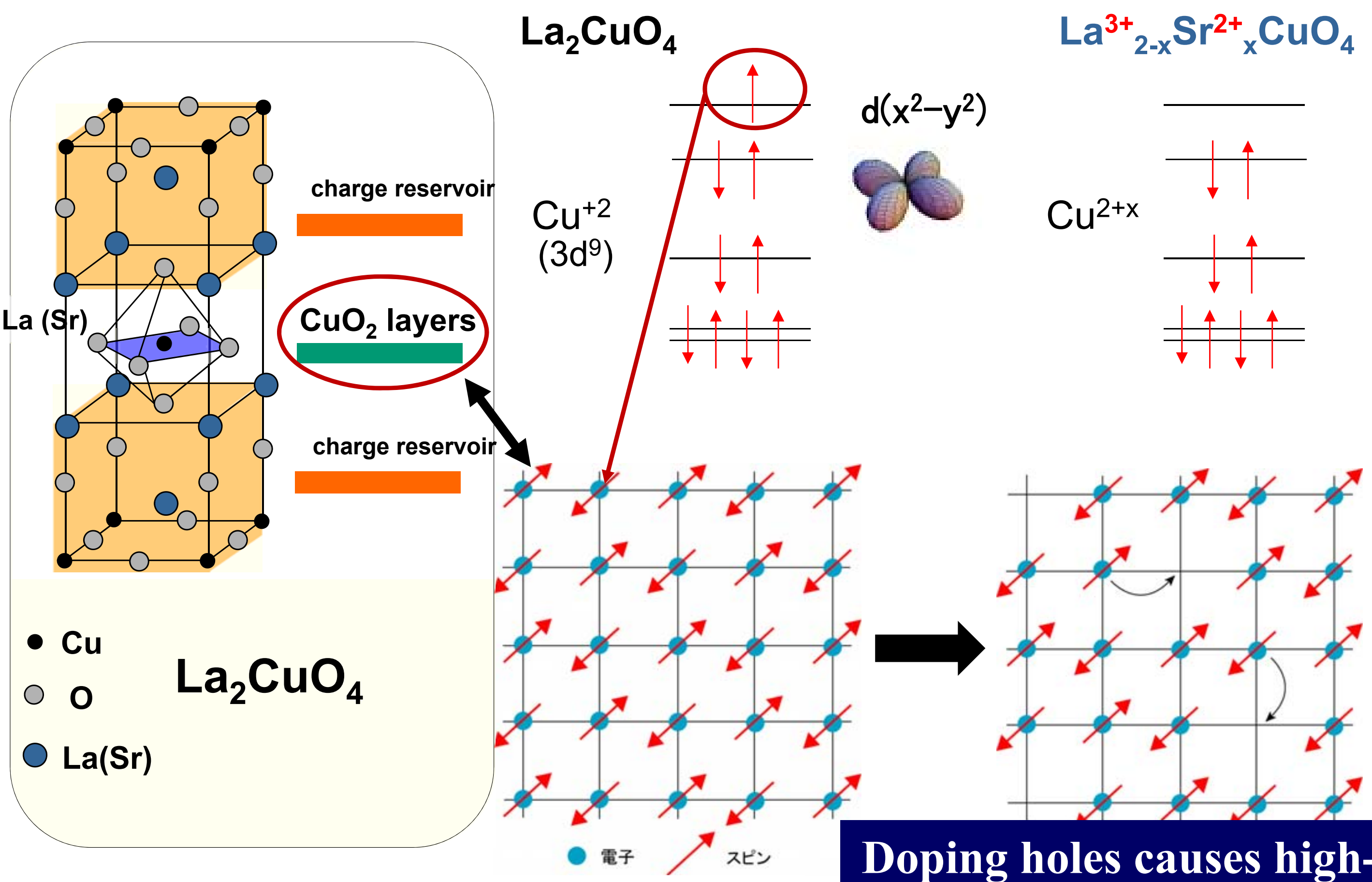
Rotary Voice Coil Motor

Readout TMR device



Towards Understanding the Mechanism of High-T_c Copper Oxides

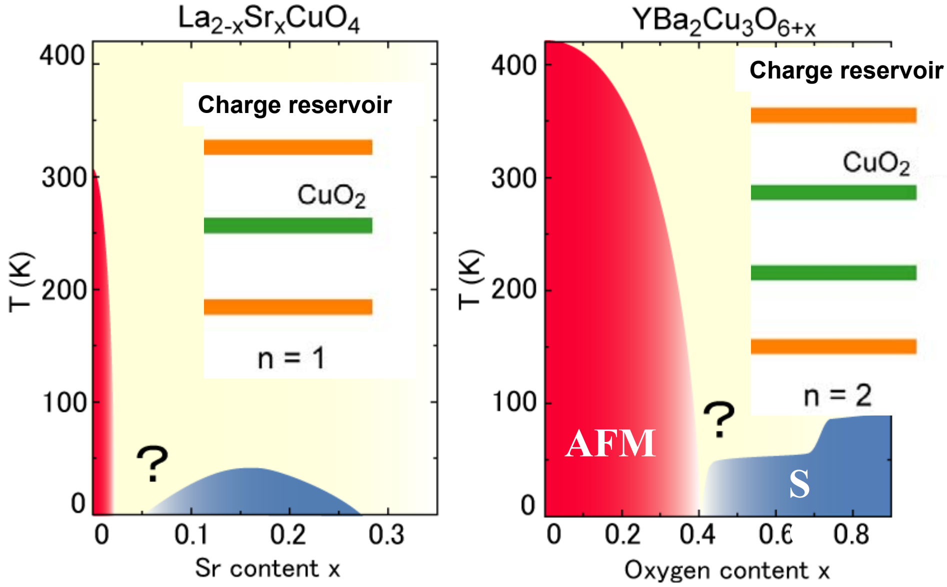
Carrier doping into Mott insulator



Antiferromagnetic Mott insulator

Doping holes causes high-T_c superconductivity

Phase Diagram of High-T_c Copper Oxides



Anomalous electronic states :
Spin glass, Stripe order , CDW , Pseudo gap, etc

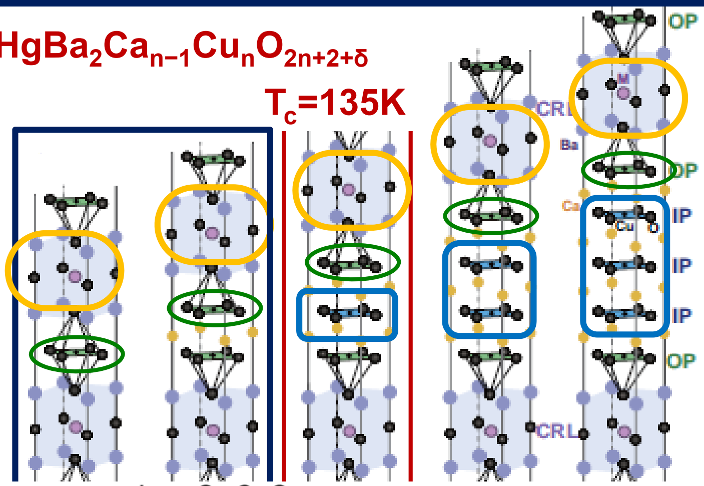
Disorder may mask intrinsic phases

A number of CuO_2 layers dependence on the phase diagram

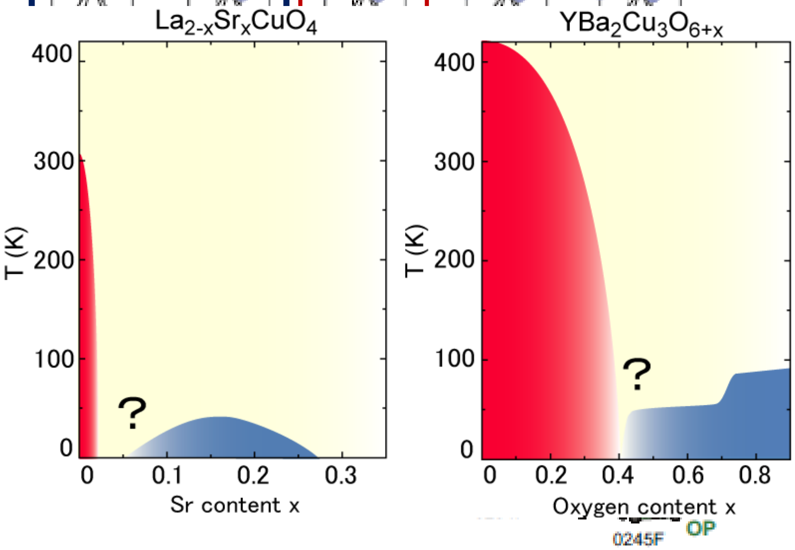
Multilayer Cuprates：Merit and Motivation

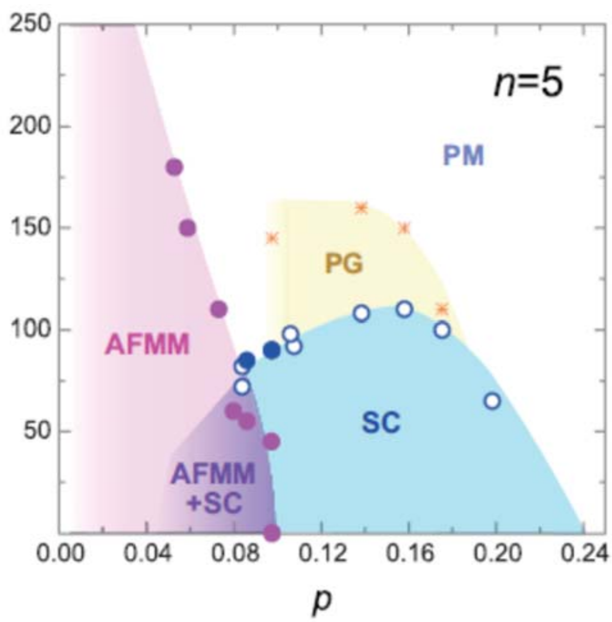
$HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$

T_c=135K



Novel Phase Diagram of Antiferromagnetic Order and Superconductivity in Multilayered Copper Oxides





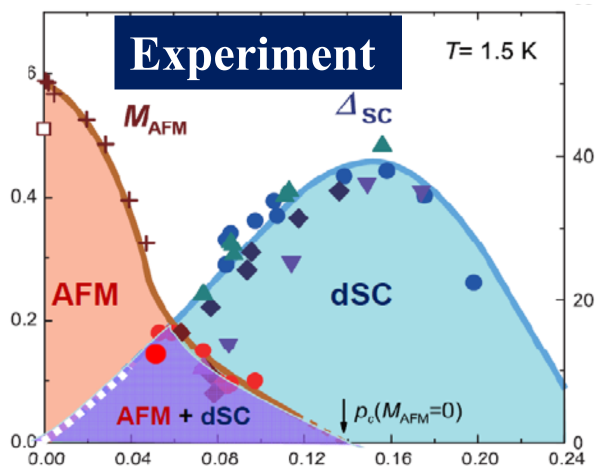
Uniform Coexistence of AFM and SC was uncovered in microscopic level

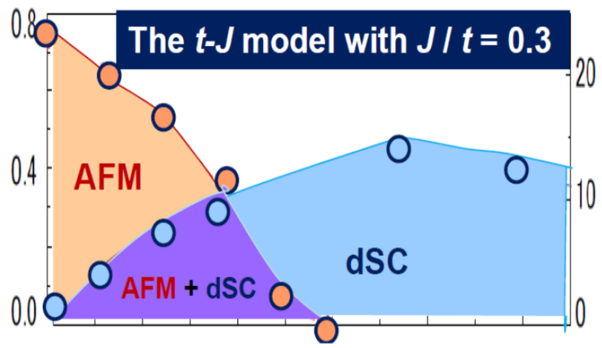
A comparison with theoretical works

Summary

	Copper Oxides
Mother compound	AFM-Mott Insulators ($T_N \sim 500$ K)
Phase diagram	Carrier doping
Electronic state	Single band
SC symmetry	d wave ($T_c = 135$ K)
Pairing interaction	AFM Super-exchange Interaction J

$$H = \sum_{\langle i,j \rangle} t_{ij} a^{\dagger}_{i\sigma} a_{j\sigma} + \sum_{i} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$





In strong coupling regime of electron correlation ($U > 8t$):

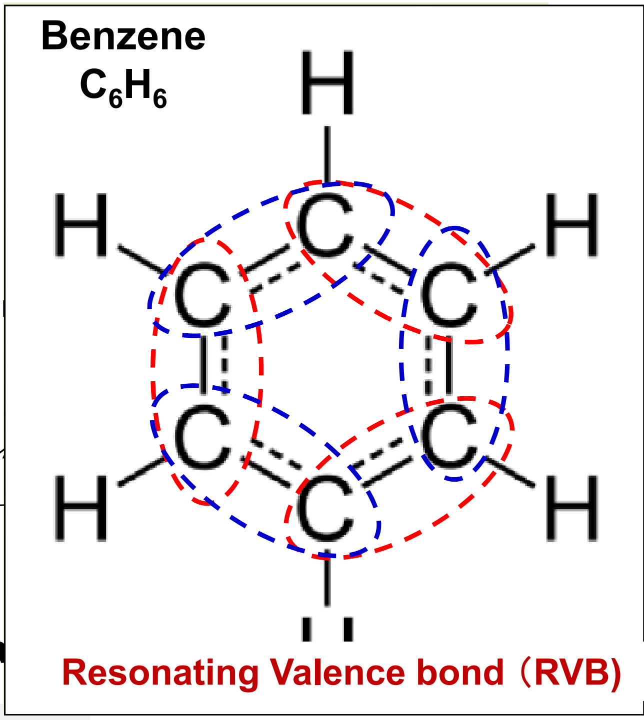
Doped Mott Insulator is the superconductor, leading to the high T_c superconductivity mediated by the AFM super-exchage interaction!!

Towards Understanding a Concept for High-T_c Copper Oxides

Origin of force in the Nature

Antiferroagnetic exchange interactio

$JS_1 \cdot S_2$



g interaction
ed by glueon

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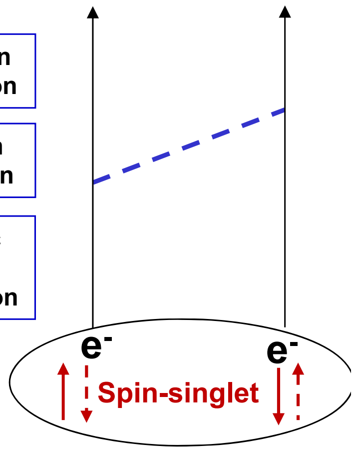
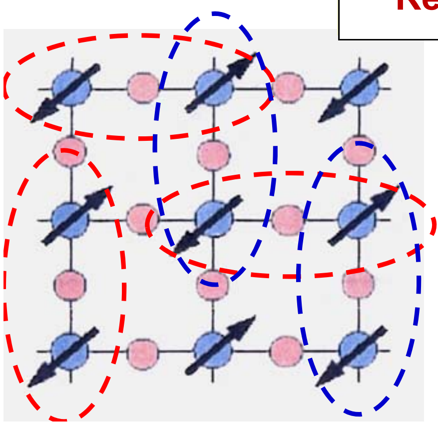
ro-magnetic
teraction
ed by photon

Formation of Copper pairs



AFM Mott Insula



BCS theory : virtual boson (phonon) exchange

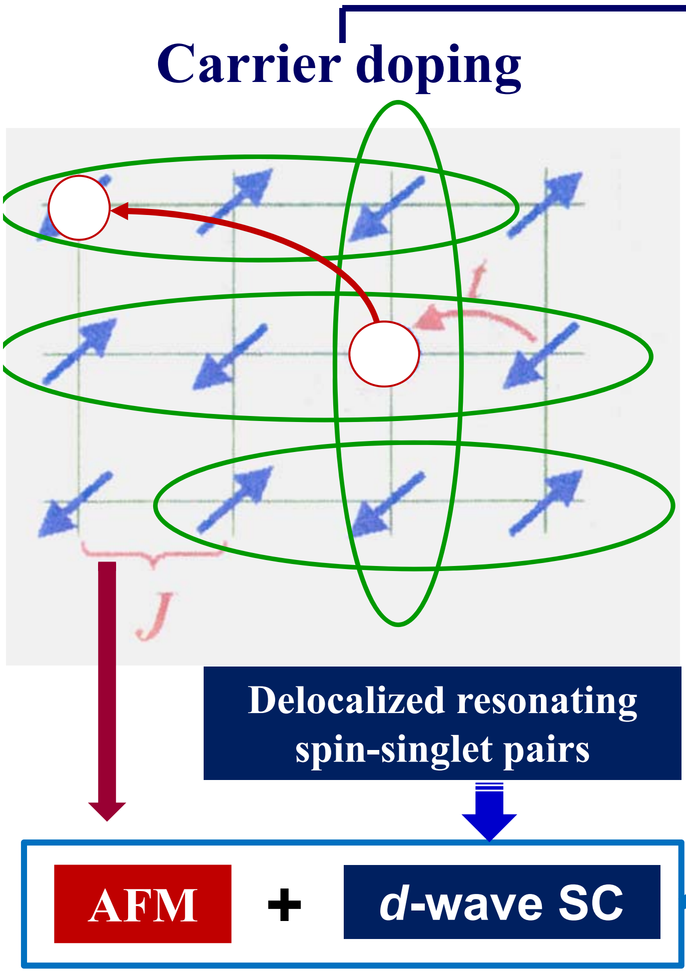
S=1/2 Heisenberg Model

$$H = \sum_{\langle i,\, j \rangle} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j,$$

AFM + Locally Resonating Spin Singlet

(M_{AF} ~ $0.6\mu_B$) ($M_{RVB} = 0\mu_B$)

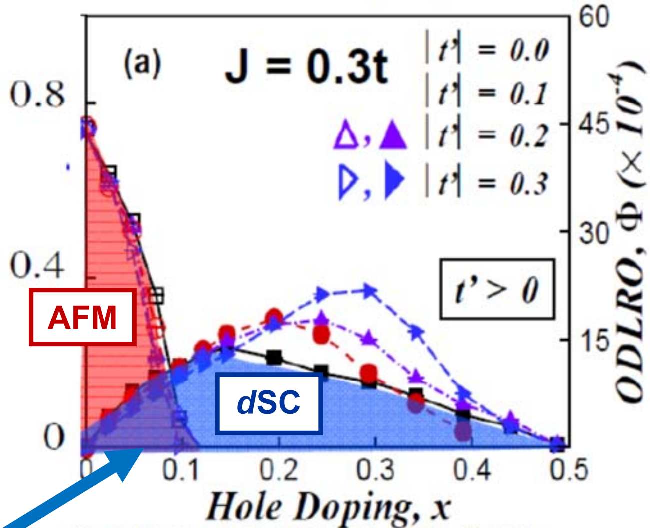
Towards understanding a concept for high-T_c cuprate



$$H = \sum_{\langle i,j \rangle} t_{ij} a_{i\sigma}^{\dagger} a_{j\sigma} + \sum_{i} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

Variational Monte Carlo on
the t – J model

S. Pathak et al., PRL 102, 027002 (2009)



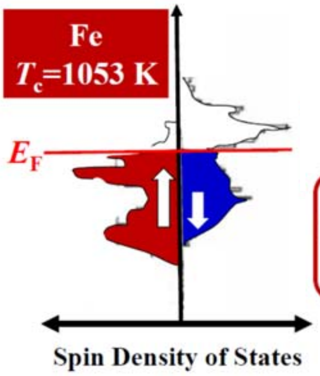
G. J. Chen et al., PRB 42, 2662 (1990).
T. Giamarchi et al., PRB 43, 12 943(1991).
A. Himeda and M. Ogata, PRB 60, R9935 (1999).
T.K. Lee and C.T. Shih, Phys. Rev. B 55 (1997) 5983.

Perspective view on

Emergent Phases of Matter under the strong electron correlation

Emergence of High-T_c SC due to Strong Electron Correlation

Ferromagnetic metal

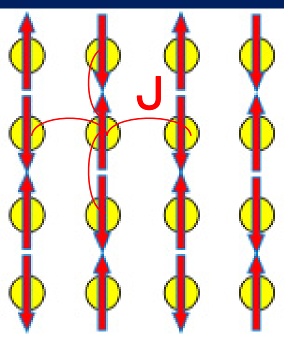


$t \geq U$

$$U\sum_i n_{i,\uparrow}n_{i,\downarrow} = -2U\sum_i s_{iz}^2$$

High-performance Permanet Magnet

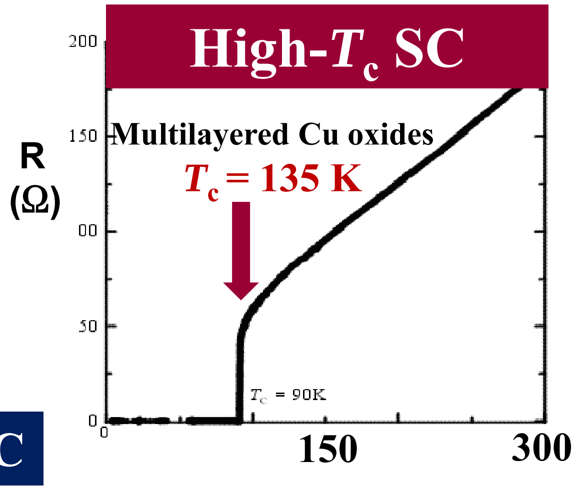
Antiferromagnetic Mott Insulator



$t << U$

All spins become anti-parallel

High-T_c SC

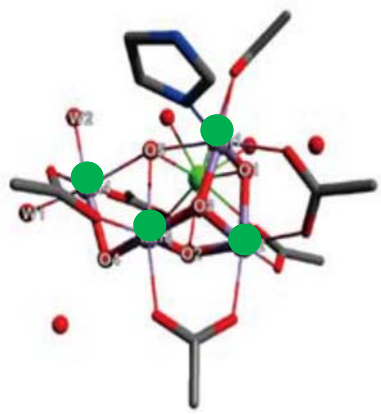


A Route to Search Room-temperature SC

Emergent Macroscopic properties generated by Local Structure in microscopic level

Plant

Photo-catalysis reaction in the Mn_4CaO_5 cluster of photosystem II

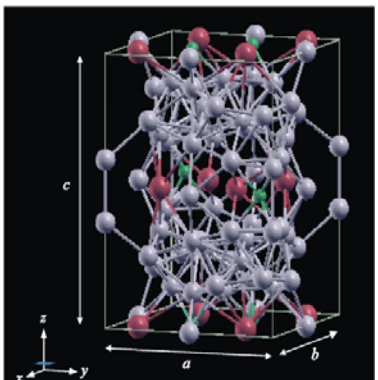


● : Mn atom (spin)

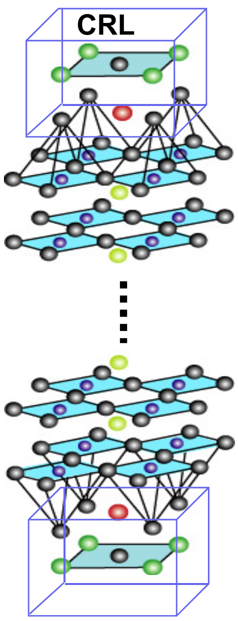
$2H_2O \rightarrow O_2 + 4e + 4H^+$

This reaction emerges through four steps change in Mn-spin states behind non-periodic complex media

Concept and Function created by Many-body State of Spins

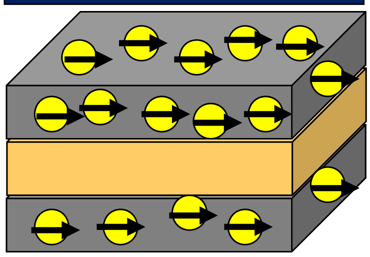


High performance Permanent Magnet $(Nd,Dy)_2Fe_{14}B$



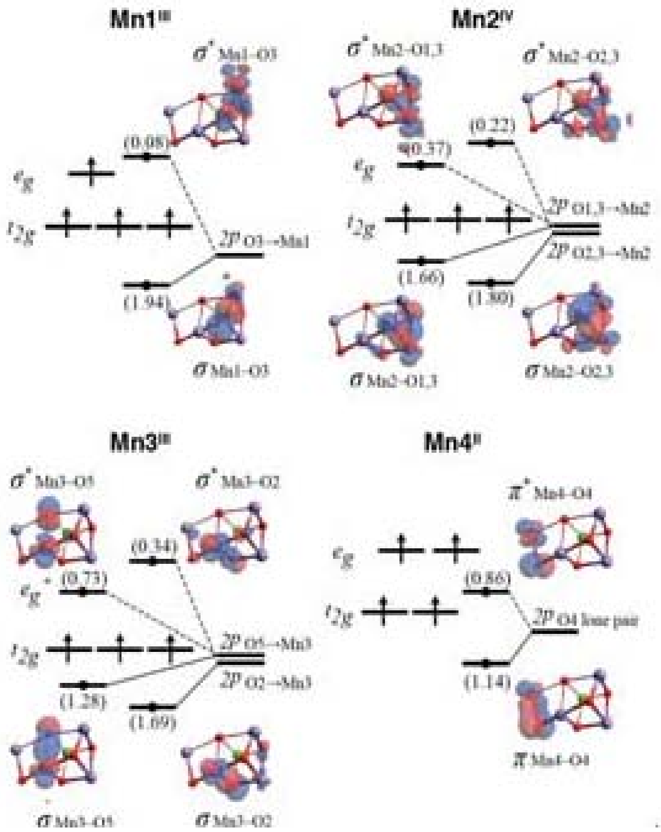
Multilayered Copper Oxides T_c = 135 K

Spintronics
TMR readout device
Spin-torque diode



Artificial Magnetic Superlattice

Reaction mechanisms of the Mn_4CaO_5 cluster of photosystem II in PLANT

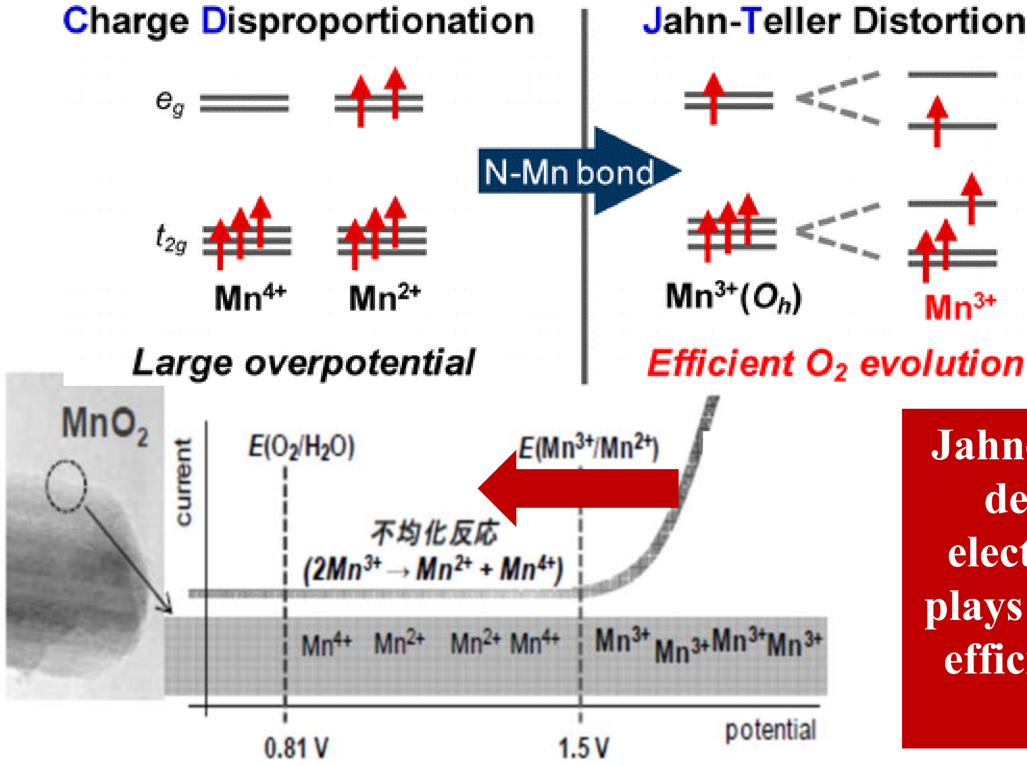


Development of efficiency or the figure of merit in the reaction process of photo-catalysis is the intensive research subject of matter science

Honda-Fujishima effect : visible light can decompose water into oxygen and hydrogen in the electrochemical cell in which TiO_2 electrode is connected with a platinum electrode.

Unfortunately, the industrial mass-product is not available yet. It is highly desired to create hydrogen as clear energy source by means of this photo-catalysis function. We may call this TiO_2 as an uncorrelated photo-catalysis matter.

The stabilization of surface-associated intermediate Mn^{3+} species is brought about by the formation of N–Mn bonds in which the inorganic Mn-oxide hybridizes with the coordination of organic amine. Then, the charge disproportionation is inhibited to lower the overpotential for water oxidation by MnO_2.



Jahn-Teller Distortion derived local 3d-electrons correlation plays a key-role for the efficient O_2 evolution from H_2O

Summary

The many-body electron correlation in condensed matter is a key-ingredient for creating the emergent phases and functional materials.

The local electron correlation may be relevant with the emergent functions in non-periodic complex systems such as metal catalyst, photo-catalysis reaction in plant and even biological matter with transition-metal elements.