Title: Composite pairing in the new “high Tc” Heavy Fermion Superconductors

Date: Apr 23, 2009 09:00 AM

URL: http://pirsa.org/09040021

Abstract: 'The discovery in 1996 of superconductivity at 0.2K near a magnetic quantum phase transition in CeIn3 opened a new dynasty of superconducting heavy electron materials, with many peculiar parallels to cuprate superconductors. In 2000, the introduction of additional layers of XIn_2, led to the discovery of the so-called "115" superconductors, with a tenfold increase in Tc[1]. By 2002, the replacement of Ce by Pu, drove the Tc up by an additional order of magnitude to 18.5K[2]. The recent discovery of a second material in this family has further deepened the mystery. In this talk I'll discuss the two newest "high temperature" heavy fermion superconductors in this series: PuCoGa5 and NpPd_2Al_5. These materials radically challenge the way we think about strongly correlated superconductivity. The way these materials directly transition from Curie paramagnets into anisotropic superconductors suggests a central role of spin as a driver for heavy electron superconductors - not just as the pairing glue - but as the basic fabric of the condensate. Motivated by these new materials, I'll discuss a model for superconductivity in the highest temperature superconductors in which the superconducting condensate involves formation of composite pairs between spins and conduction electrons[3]. Using this idea, we'll discuss how the physics of superconductivity and the Kondo effect can be combined, giving rise to a composite pairing model for the new superconductors. [1]}H. Hegger, C. Petrovic, E. G. Moshopoulou, M. F. Hundley, J. L. Sarrao, Z. Fisk, and J. D. Thompson, "Pressure-Induced Superconductivity in Quasi-2D $CeRhIn_{5}$" Phys. Rev. Lett. 84, 4986-4989 (2000). [2]J. L. Sarrao et al. , ``Plutonium-based superconductivity with a transition temperature above 18 K", Nature (London) {bf 420}, 297-299 (2002). [3] Rebecca Flint, M. Dzero, P. Coleman, "Heavy electrons and the symplectic symmetry of spin.", Nature Physics 4, 643 - 648 (2008).Nature Physics, '

Superconductivity in the newest generation of Heavy Electron Superconductors: $PuCoGa_5$ & $NpAl_2Pd_5$

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PI, Waterloo, April 2009

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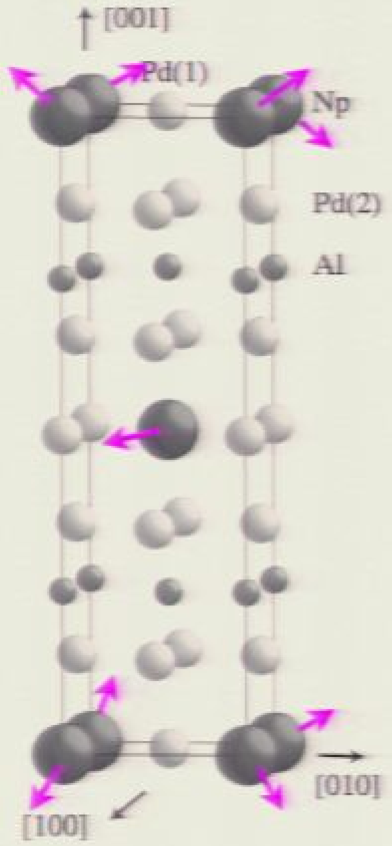

4.5K Heavy Fermion S.C
$NpAl_2Pd_5$

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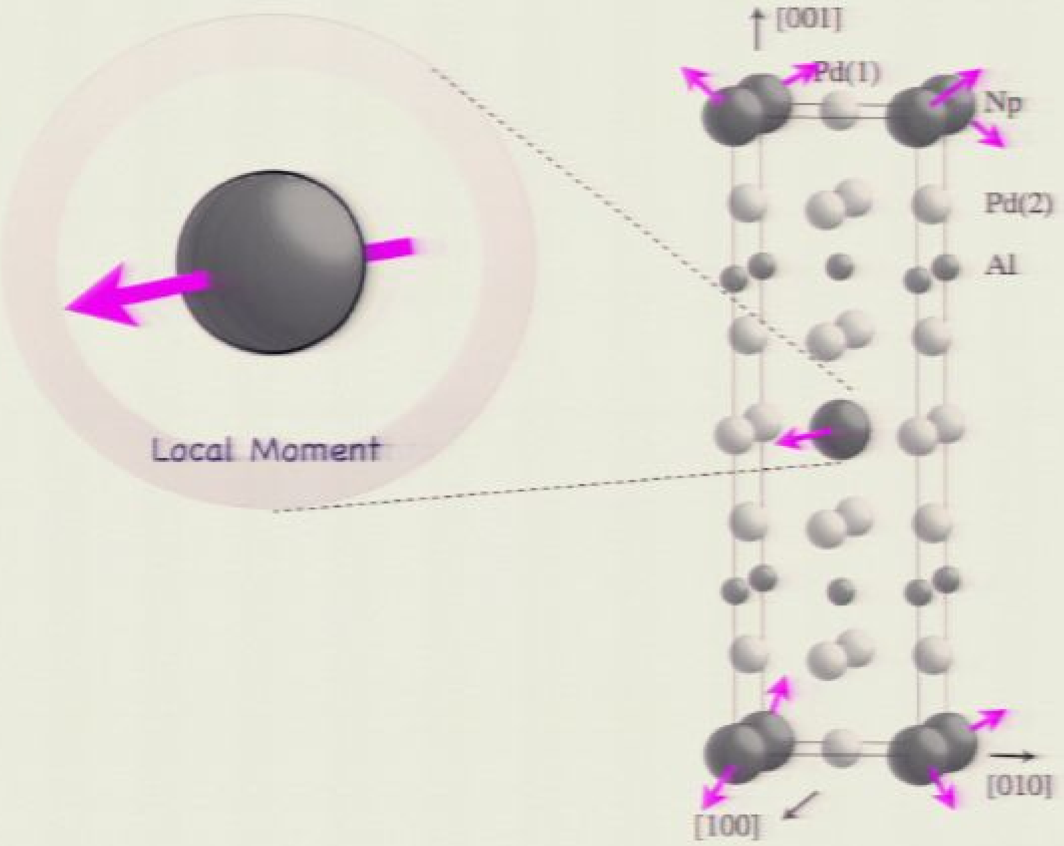

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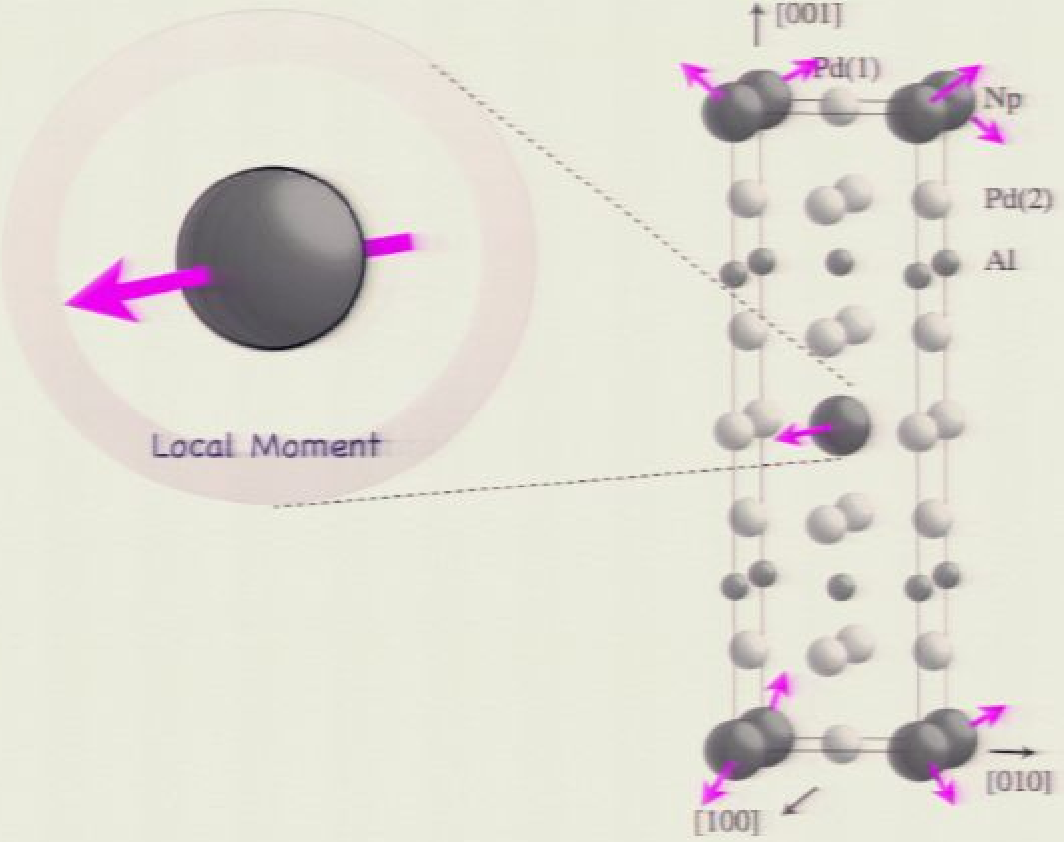

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- New Superconductors
- Composite pairs

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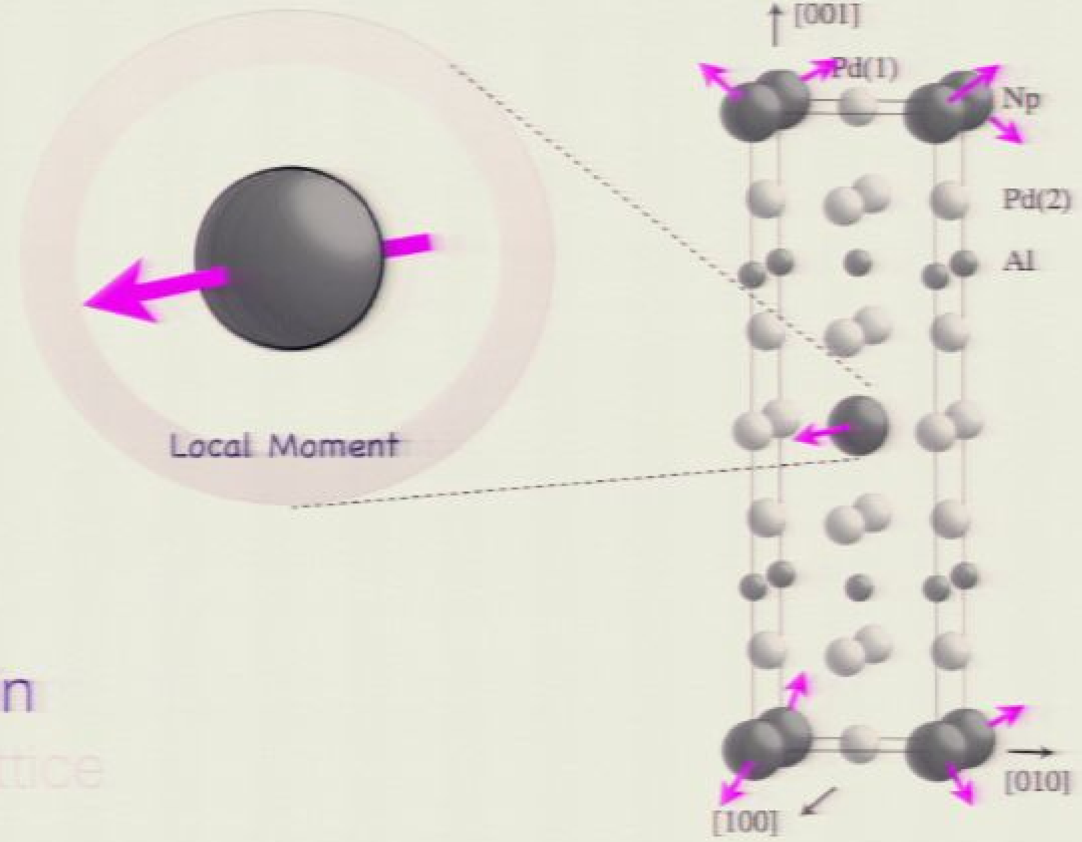

4.5K Heavy Fermion S.C
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- New Superconductors
- Composite pairs
- Symplectic symmetry of spin
- Application to the Kondo lattice

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Superconductivity in the newest generation of Heavy Electron Superconductors: PuCoGa$_5$ & NpAl$_2$Pd$_5$

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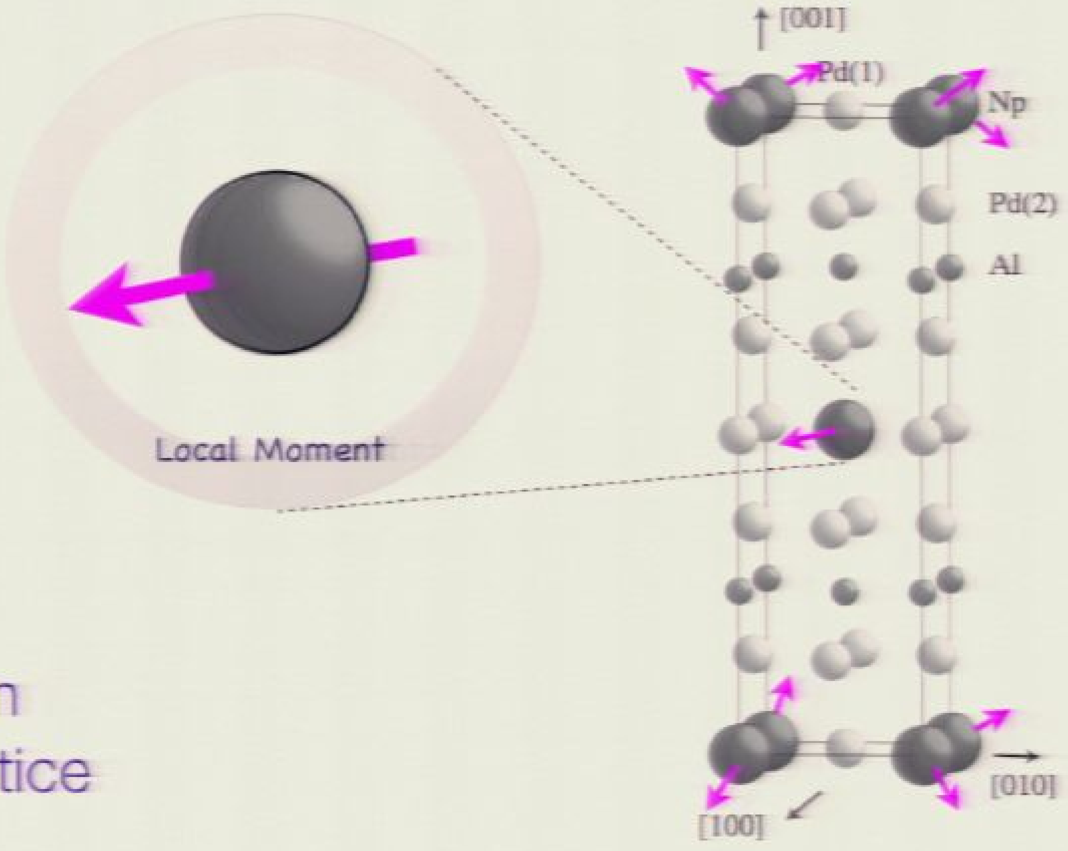

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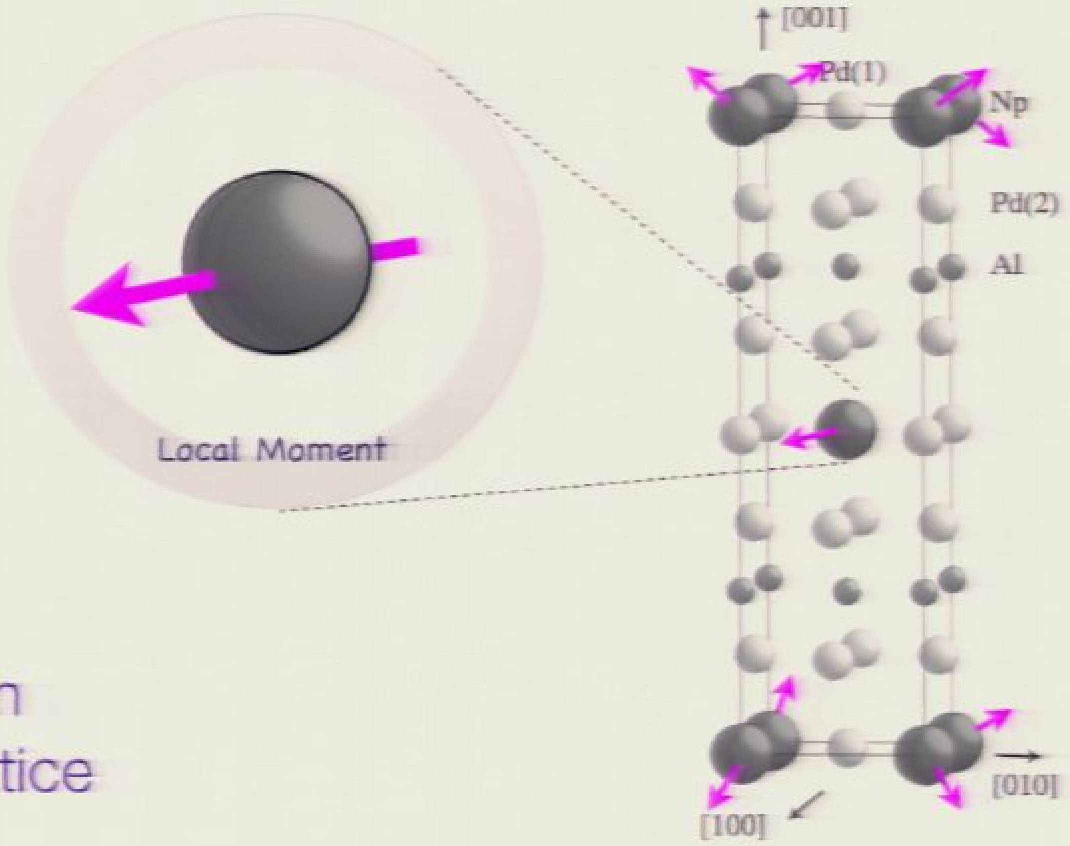

4.5K Heavy Fermion S.C
$NpAl_2Pd_5$

- New Superconductors
- Composite pairs
- Symplectic symmetry of spin
- Application to the Kondo lattice
- Predictions

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Acknowledgments:

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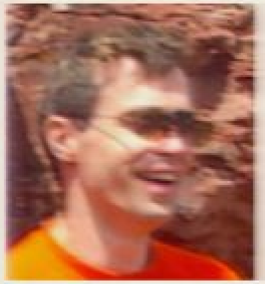
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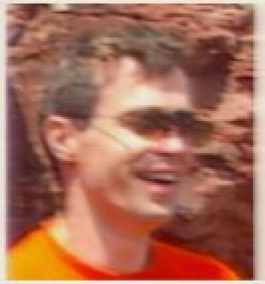
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Alexei Tsvelik (BNL)
Natan Andrei (Rutgers)
Hae Young Kee (Toronto)
PRB **60**, 3609, (1998).

Heavy Fermions:

A Collision of ideas

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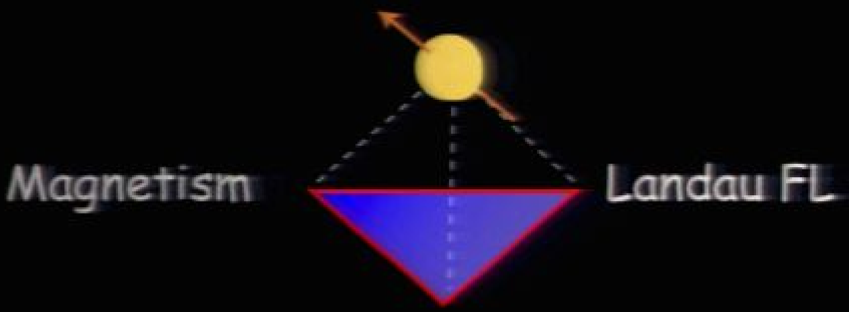

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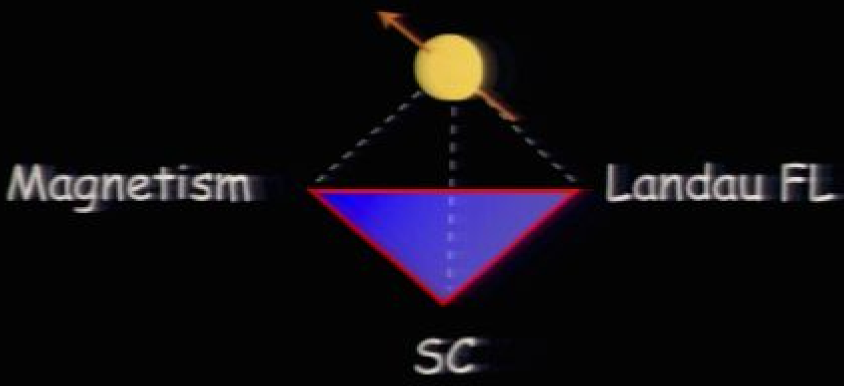

Magnetism

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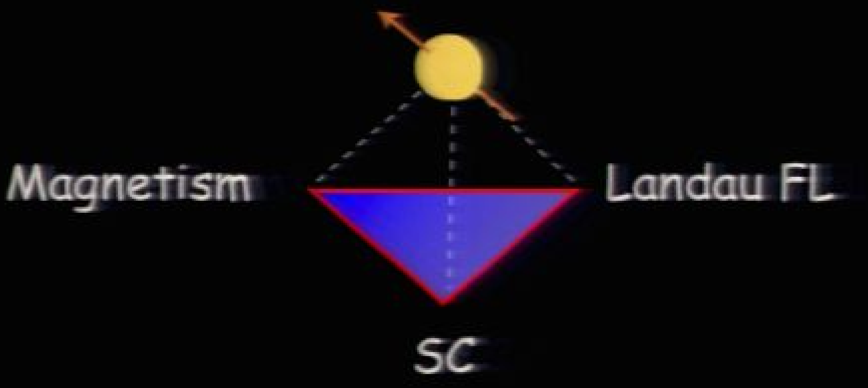

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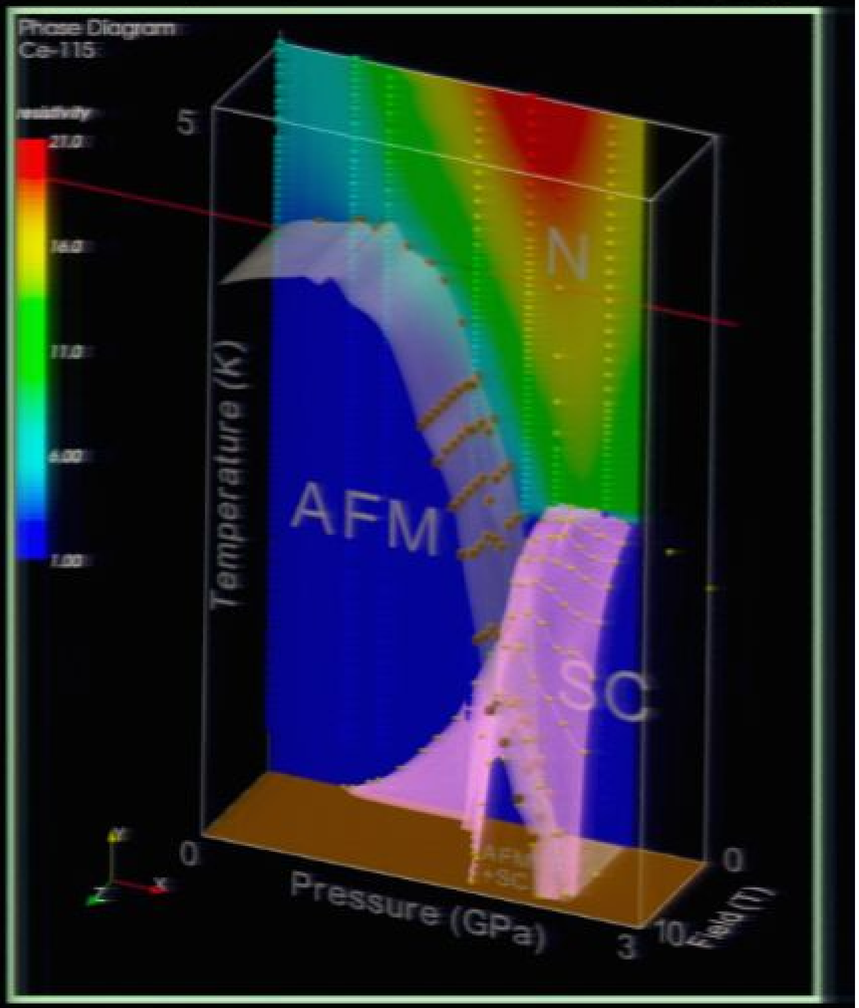
Tuson Park, (2007).

$CeRhIn_5$



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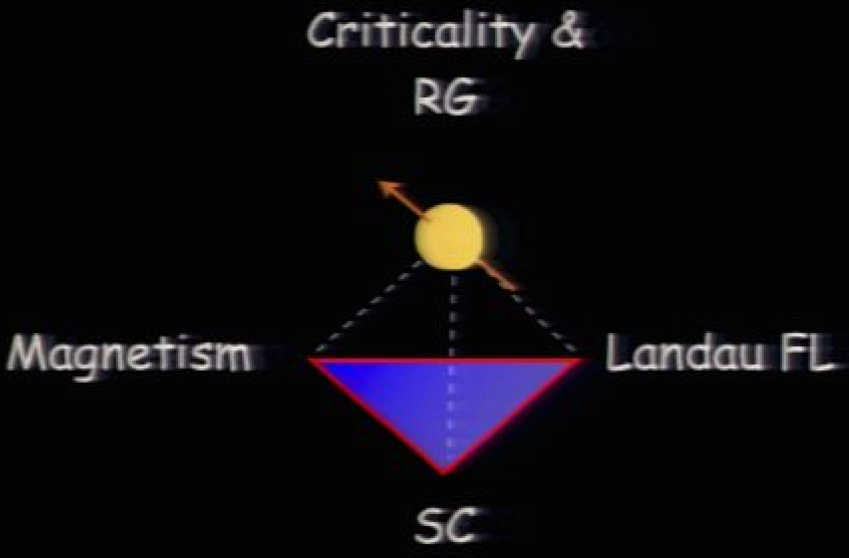

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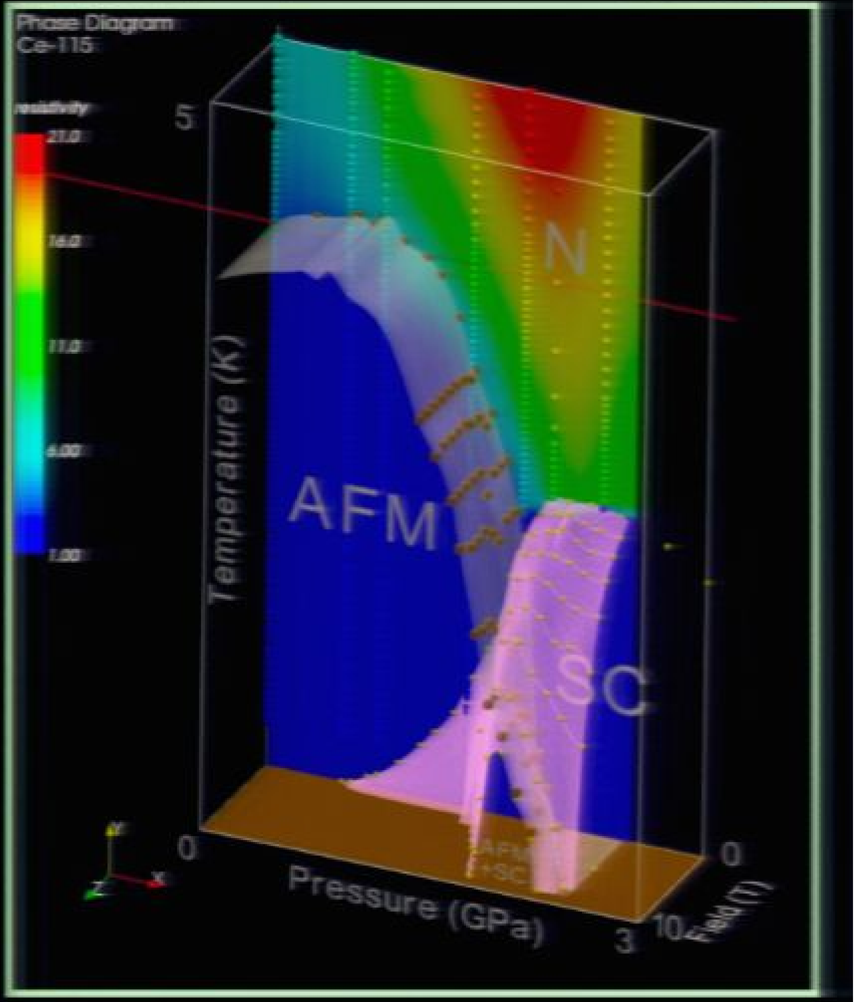

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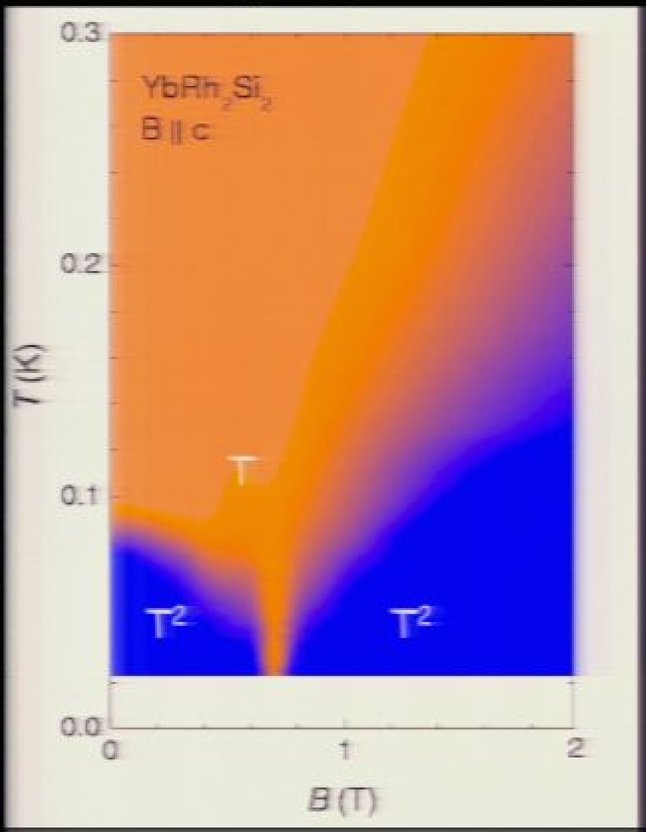
Custers et al (2003)



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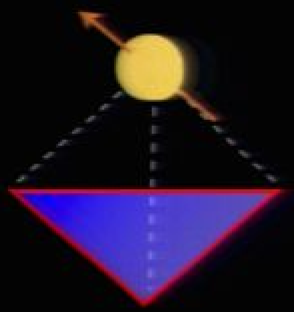

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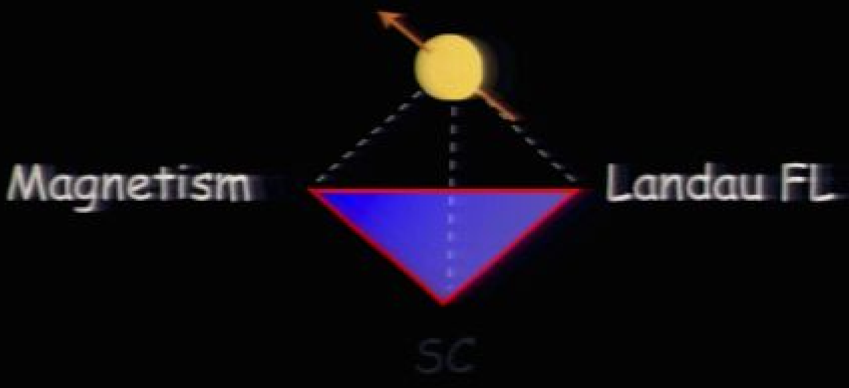

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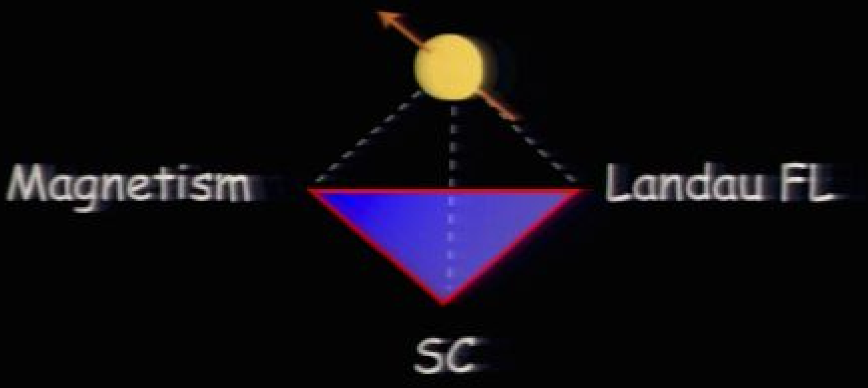

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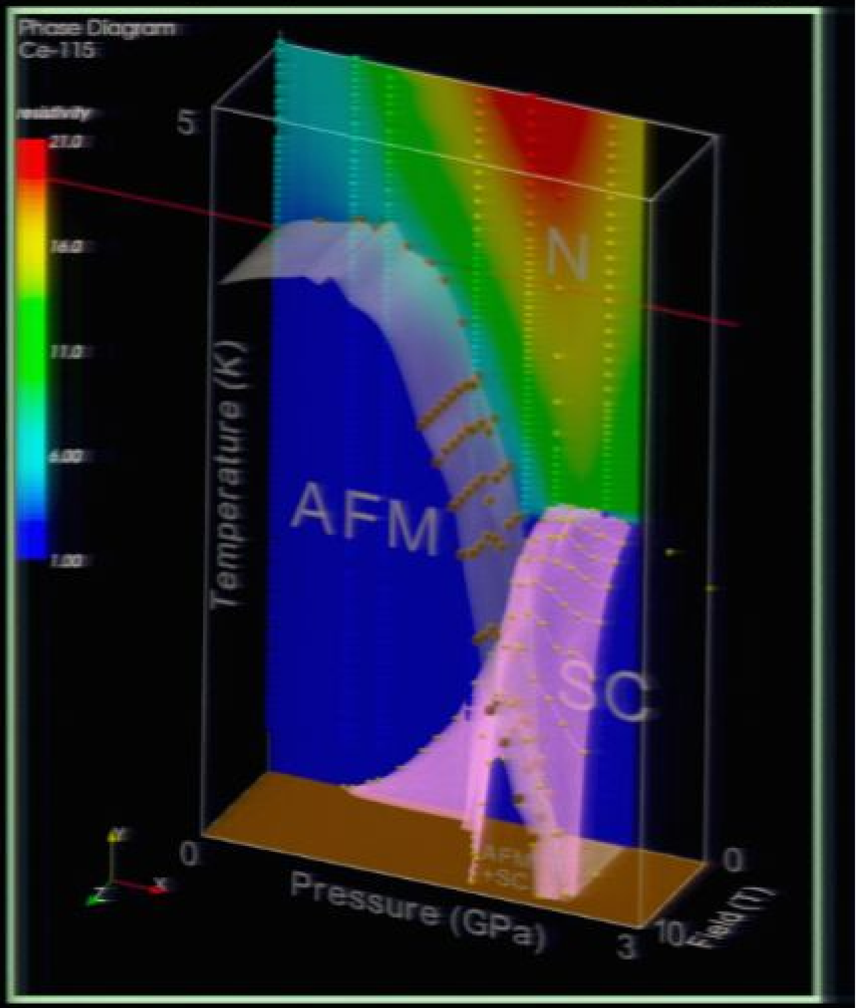

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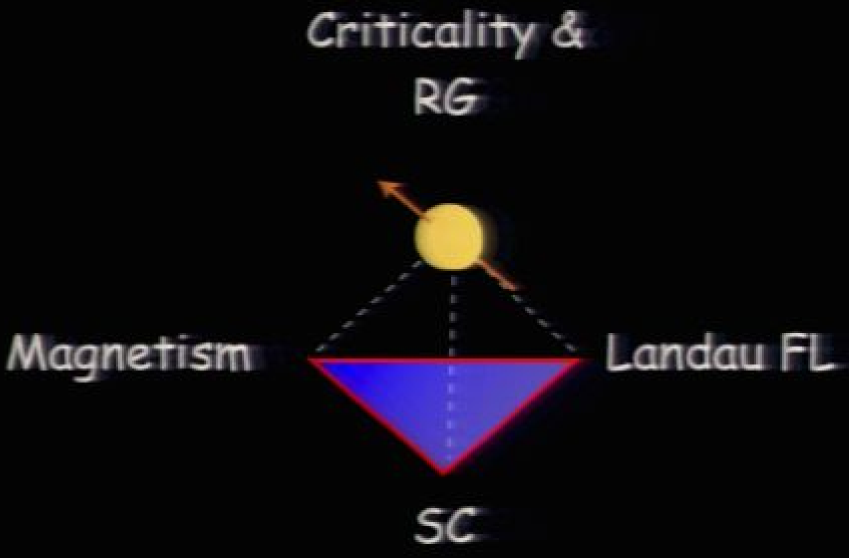

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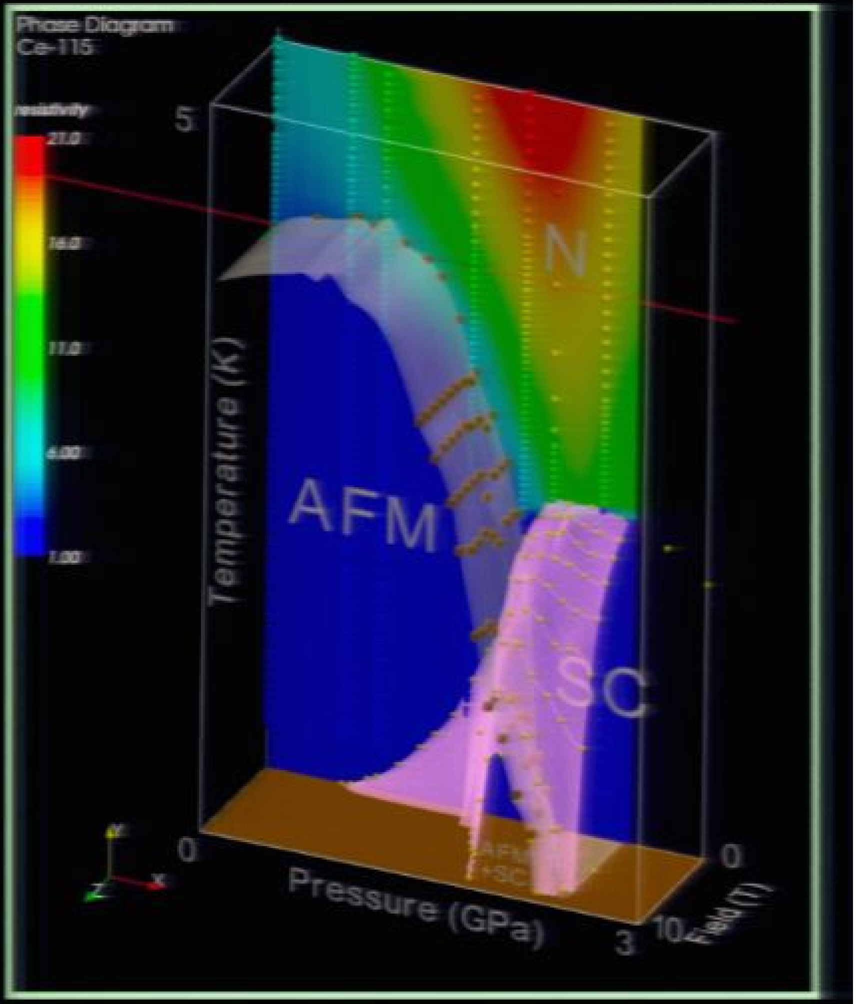

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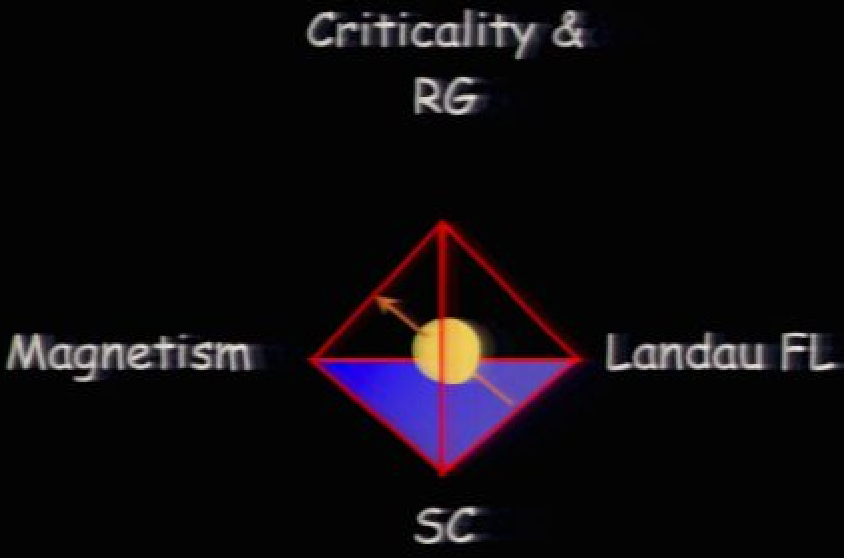

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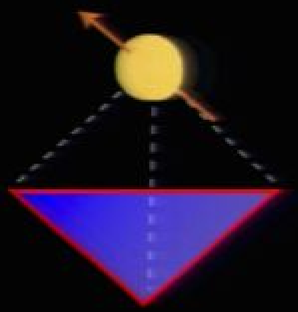

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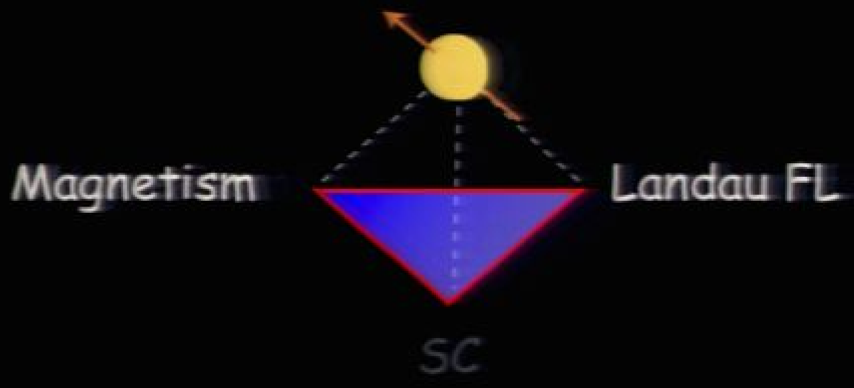

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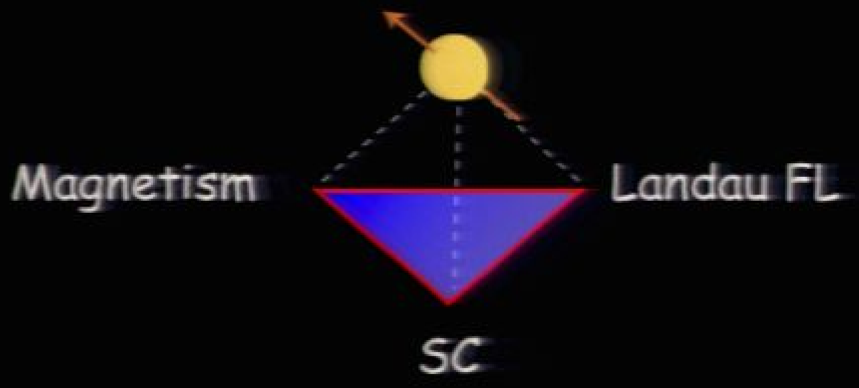

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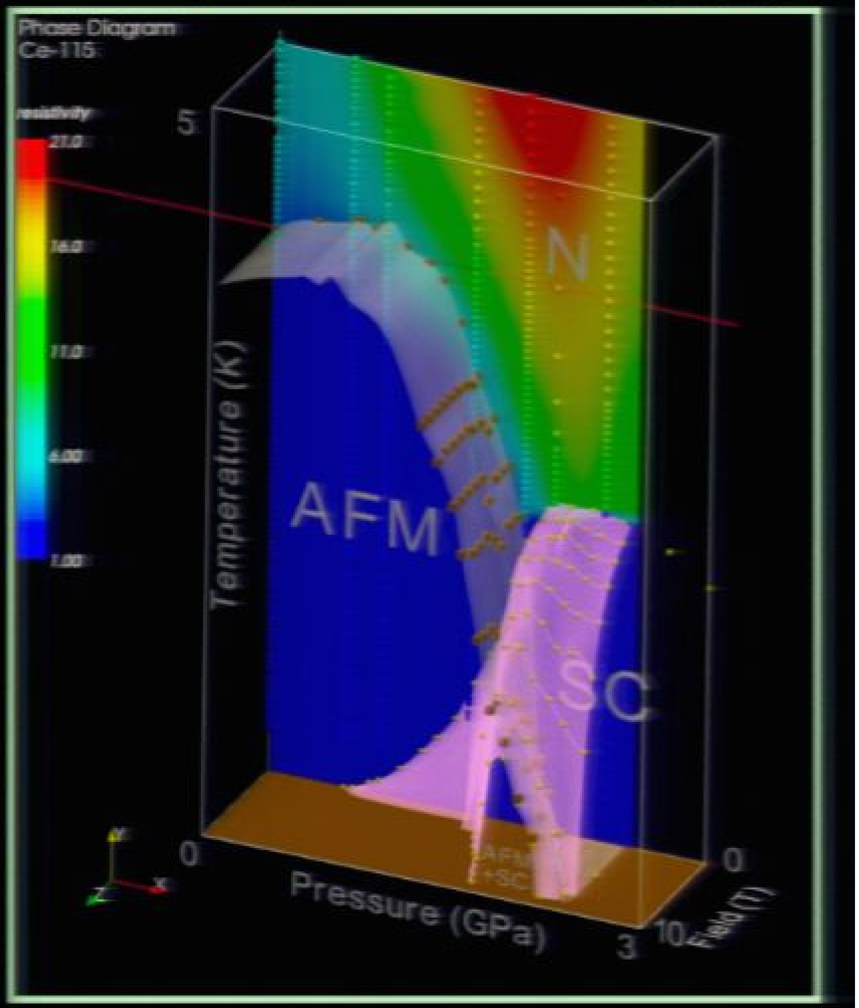

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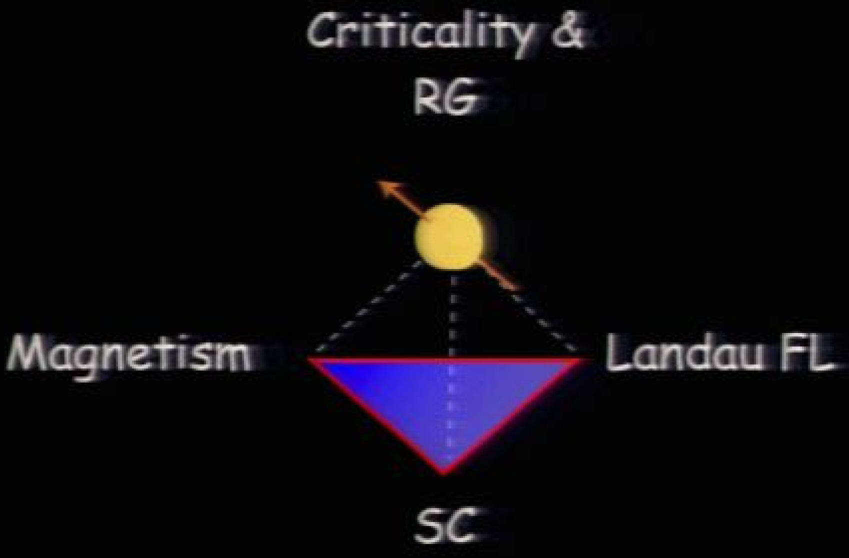

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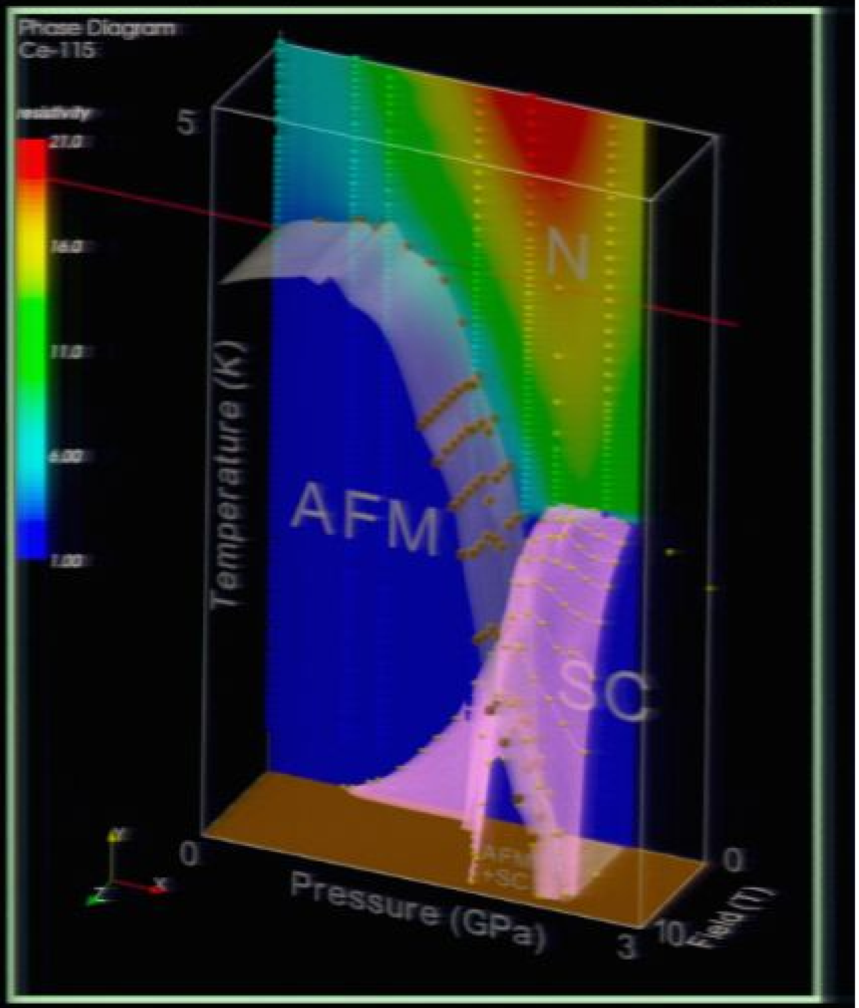

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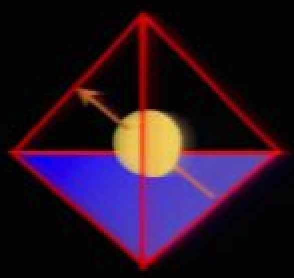

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Oxides

T_c

?

$YBa_2Cu_3O_7$ 92K

Ba2201 12K

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Oxides	T_c	T_c	Intermetallics	
?				
$YBa_2Cu_3O_7$	92K	2K	$CeCoIn_5$	'01
Ba2201	12K	0.2K	$CeIn_3$	'96

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Oxides	T_c	T_c	Intermetallics	
?		18.5K	$PuCoGa_5$	'02
$YBa_2Cu_3O_7$	92K	2K	$CeCoIn_5$	'01
Ba2201	12K	0.2K	$CeIn_3$	'96

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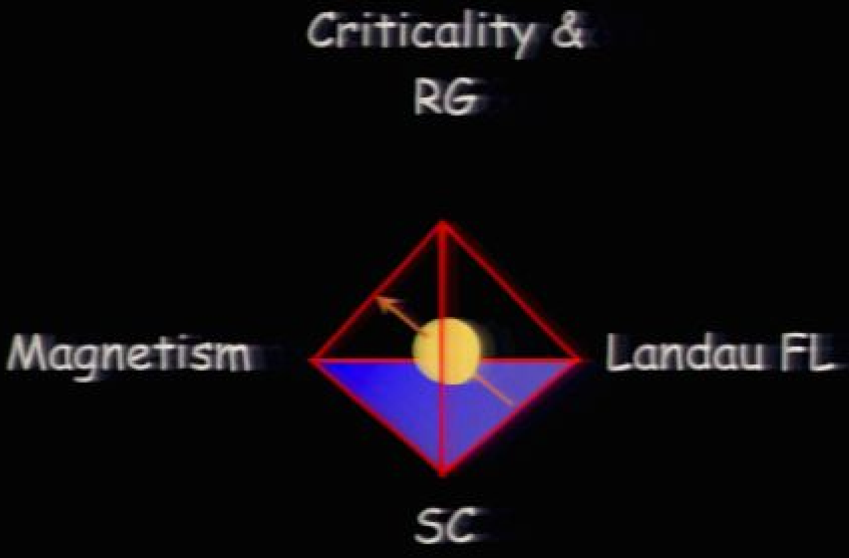

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Oxides	T_c	T_c	Intermetallics	
?		18.5K	$PuCoGa_5$	'02
$YBa_2Cu_3O_7$	92K	2K	$CeCoIn_5$	'01
Ba2201	12K	0.2K	$CeIn_3$	'96

"Fruit fly" for correlated materials

Heavy Fermions: Collision of ideas

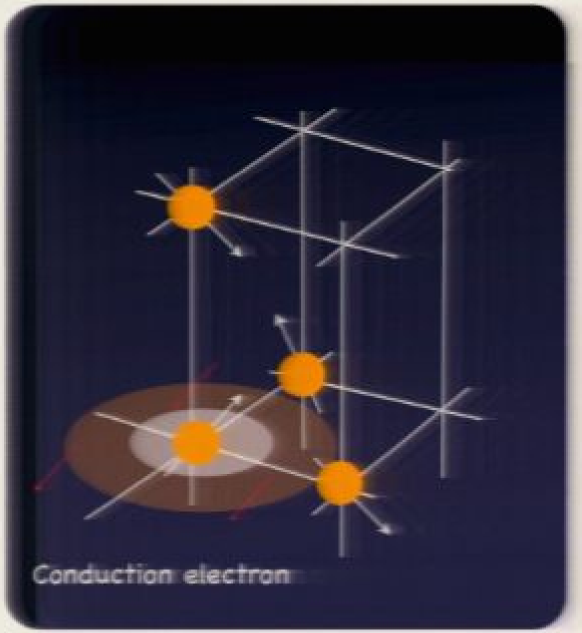
Oxides	T_c	T_c	Intermetallics	
?		18.5K	$PuCoGa_5$	'02
		4.5K	$NpAl_2Pd_5$	'07
$YBa_2Cu_3O_7$	92K	2K	$CeCoIn_5$	'01
Ba2201	12K	0.2K	$CeIn_3$	'96

"Fruit fly" for correlated materials

New superconductors

New HF Superconductors: $PuCoGa_5$ & $NpAl_2Pd_5$

J. Sarrao et al., Nature 420, (2002)



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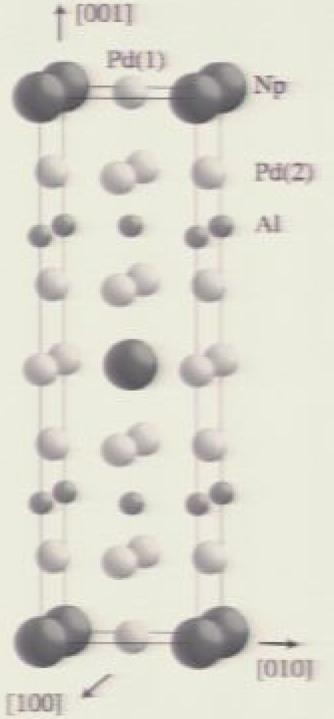

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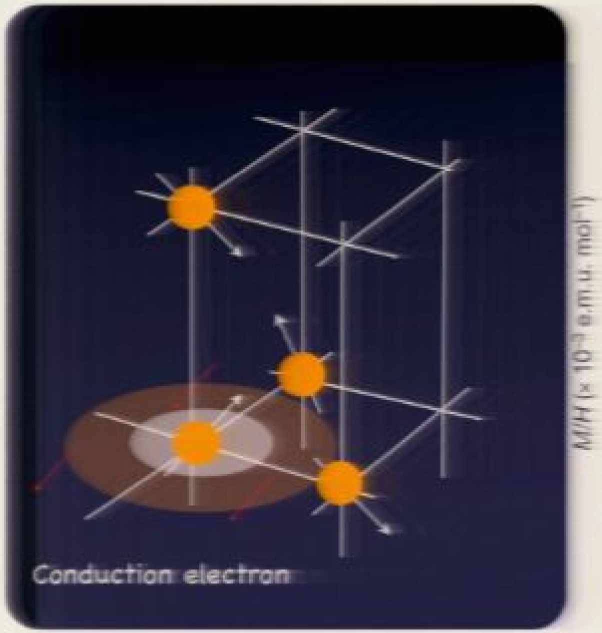

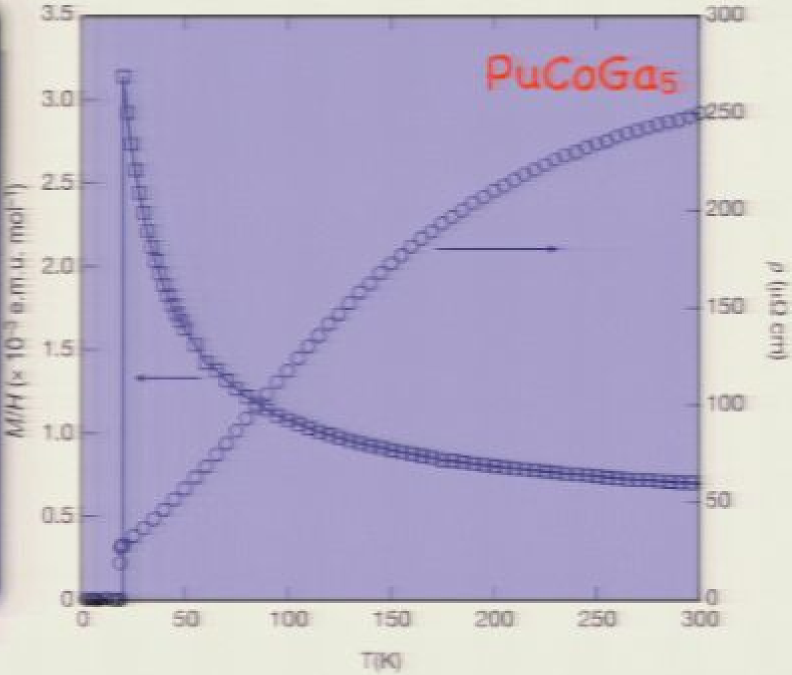

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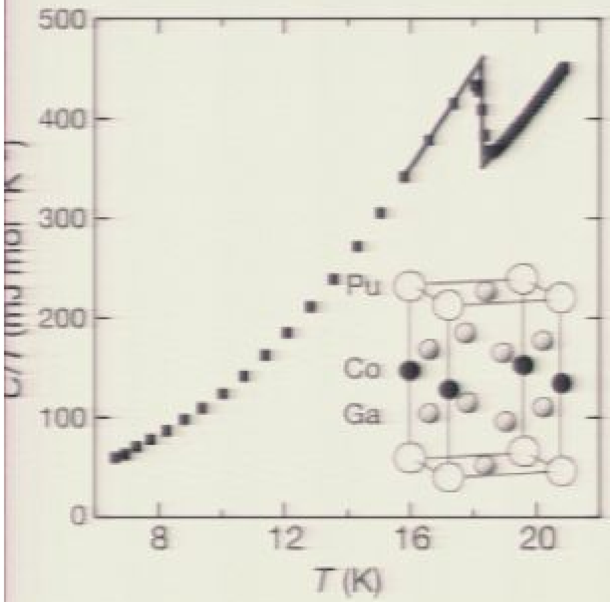

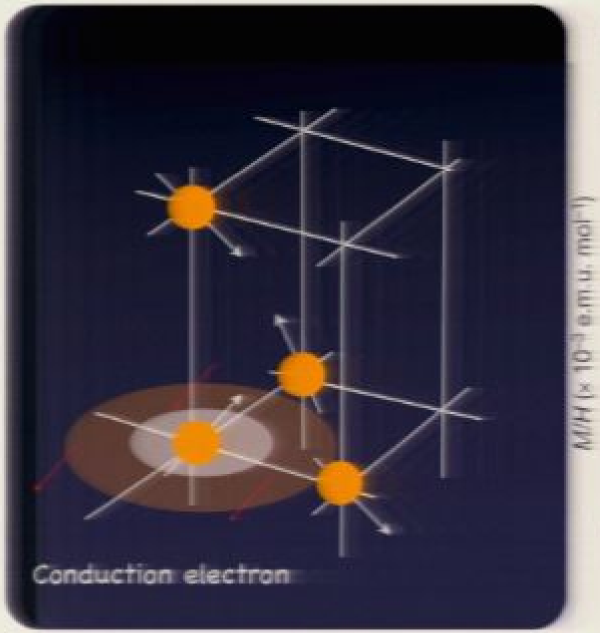

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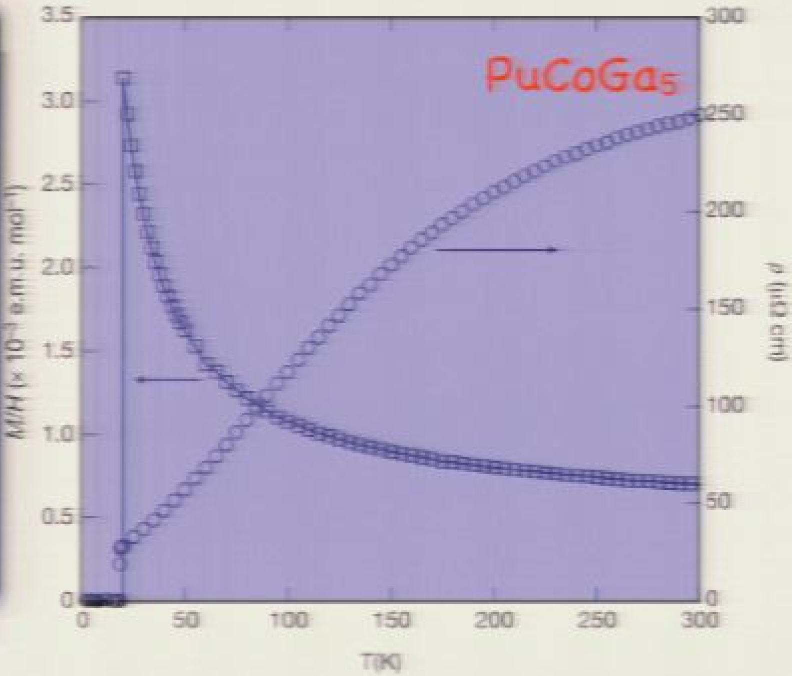

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S=0.3R ln2

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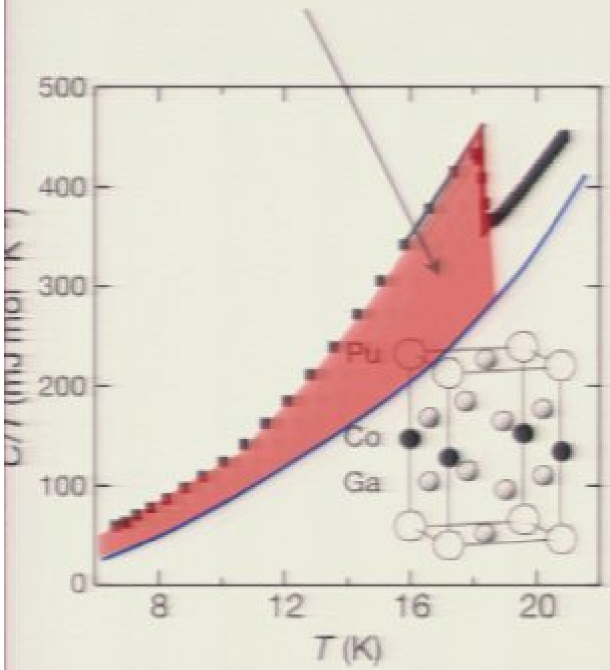

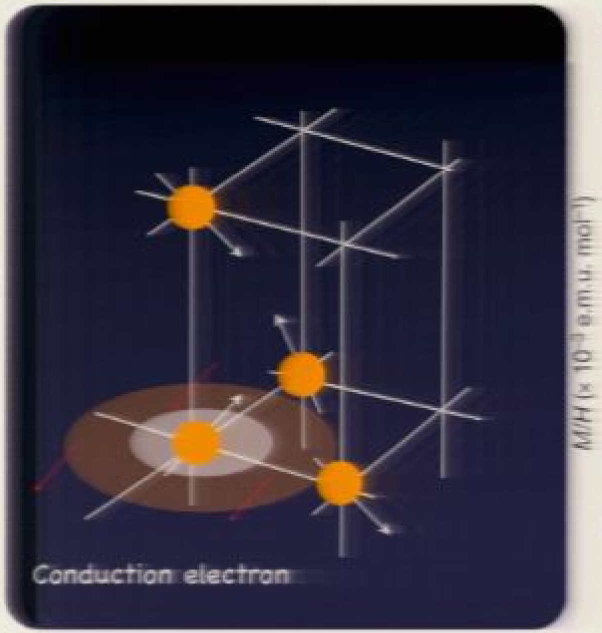

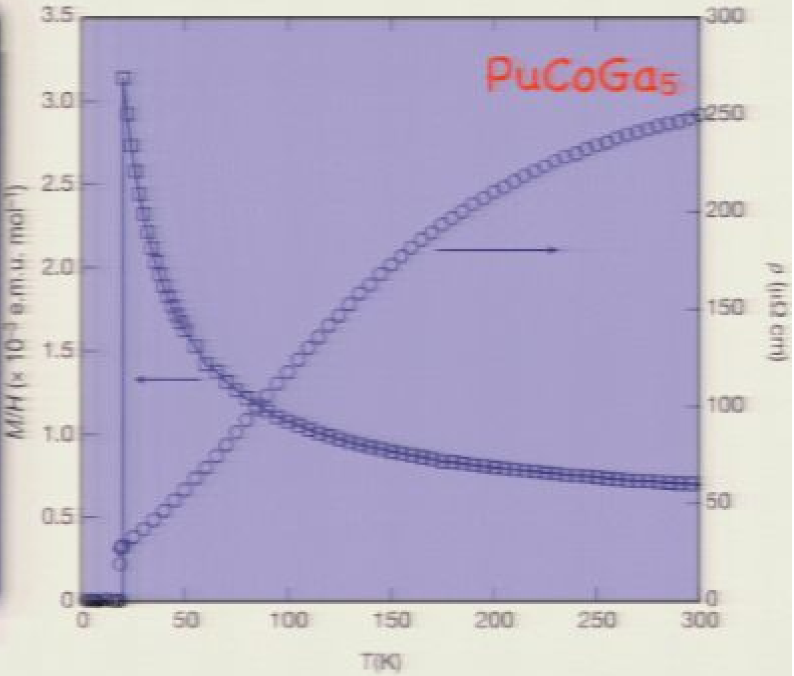

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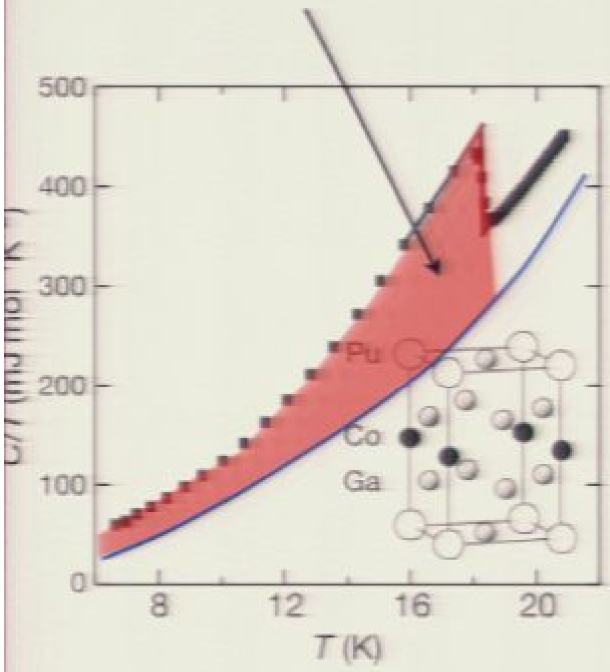

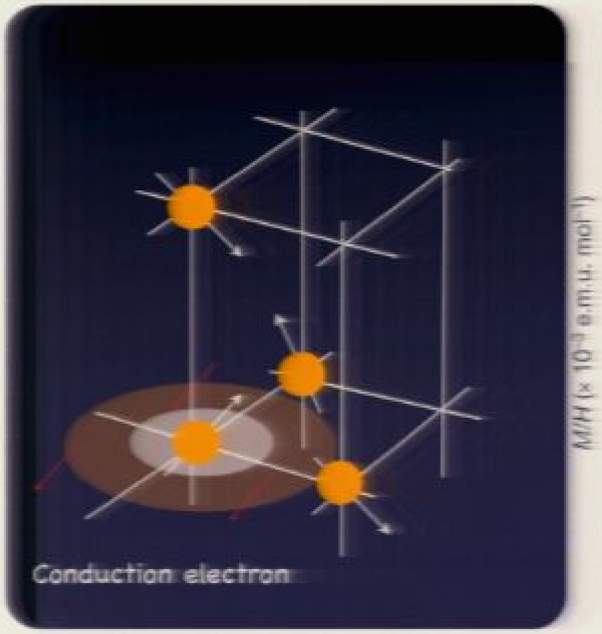

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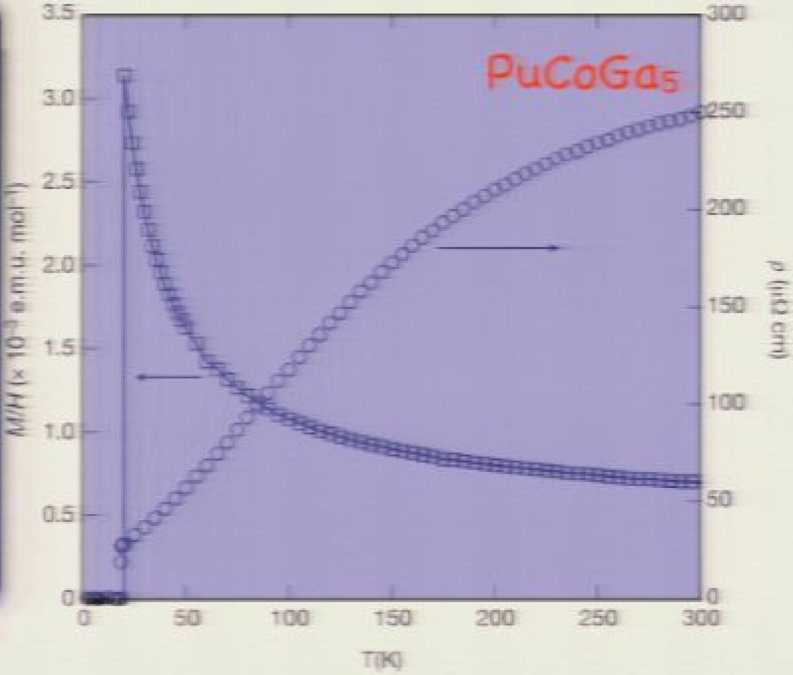
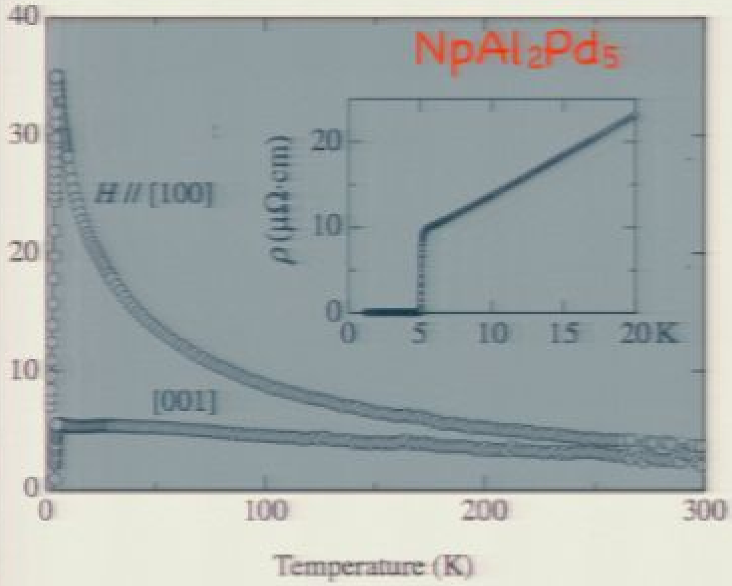


Directly Curie PM to SC

New HF Superconductors: $PuCoGa_5$ & $NpAl_2Pd_5$



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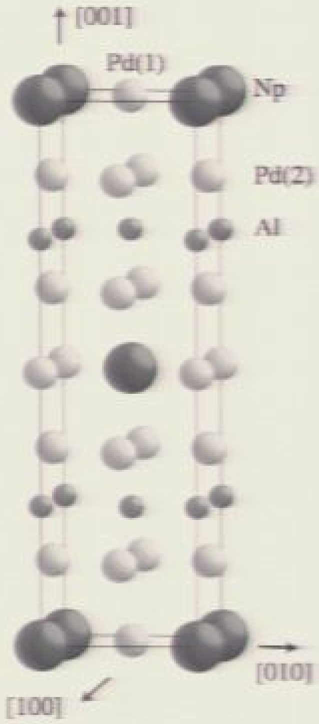

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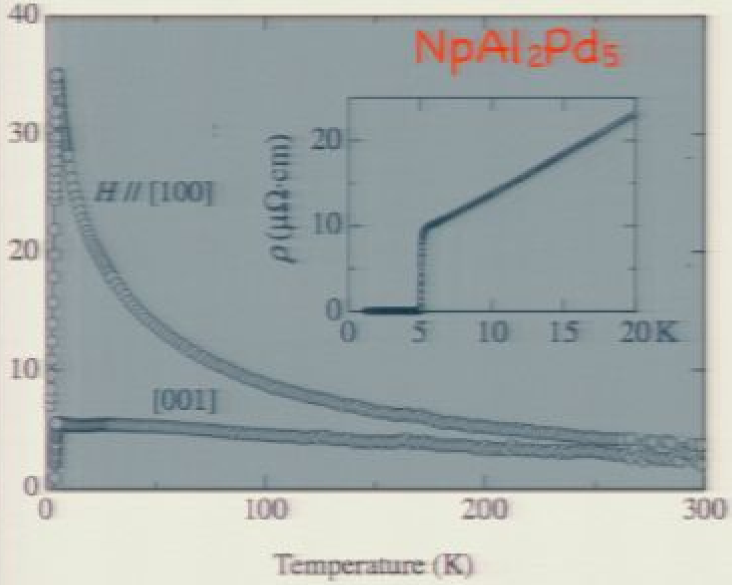
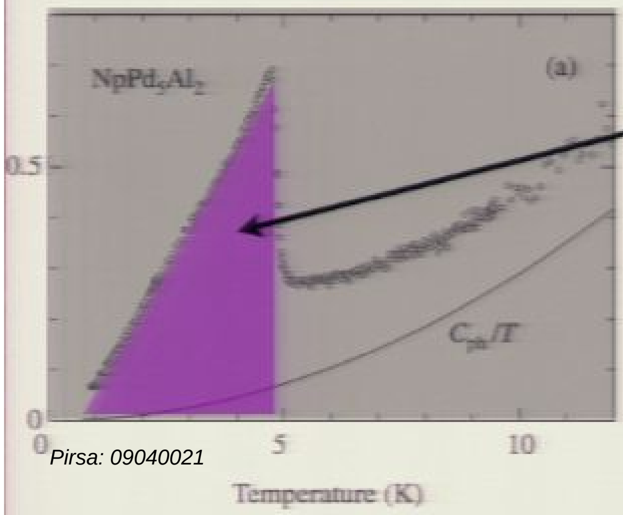
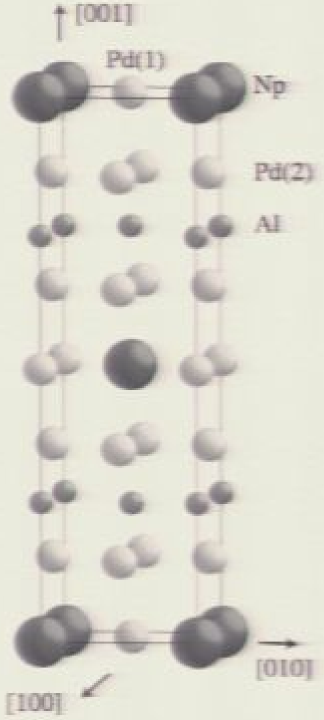


Directly Curie PM to SC



Substantial fraction of
spin entropy.
1/3 R ln 2

D. Aoki et al., JPSJ 76 (2007)



4.5K Heavy Fermion S.C
NpAl$_2$Pd$_5$

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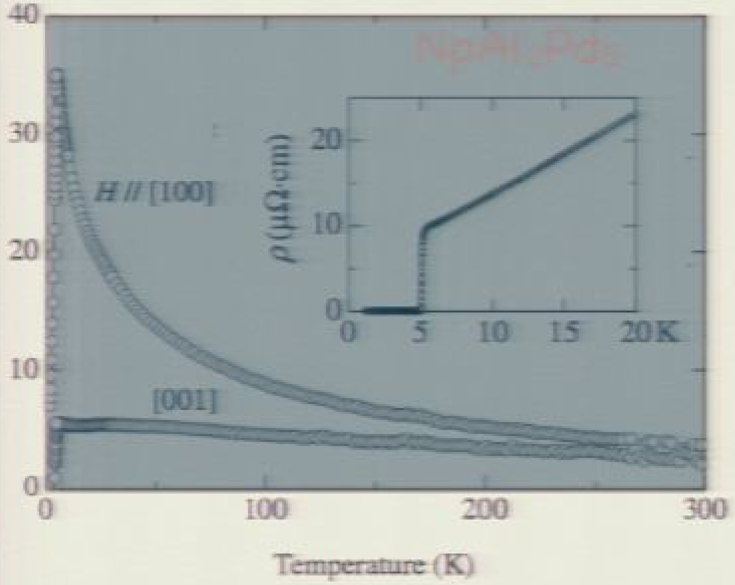

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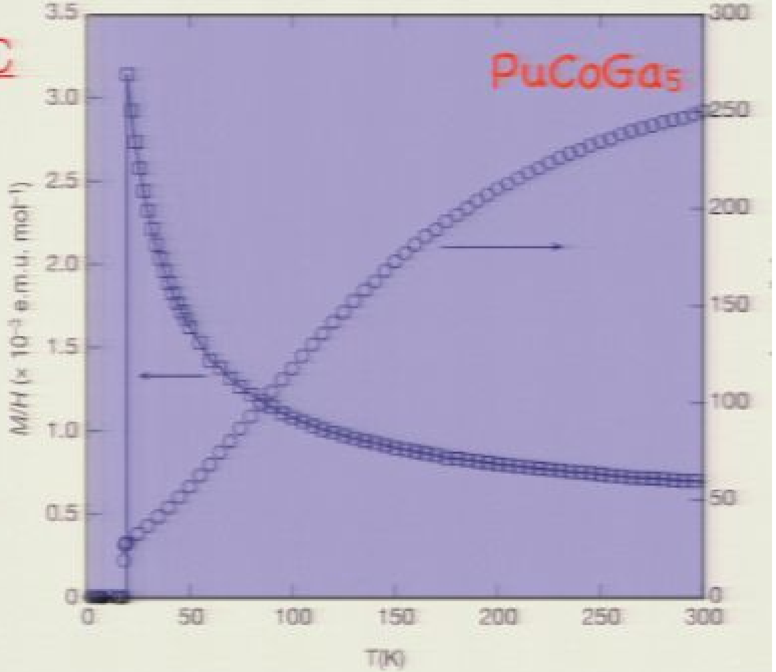

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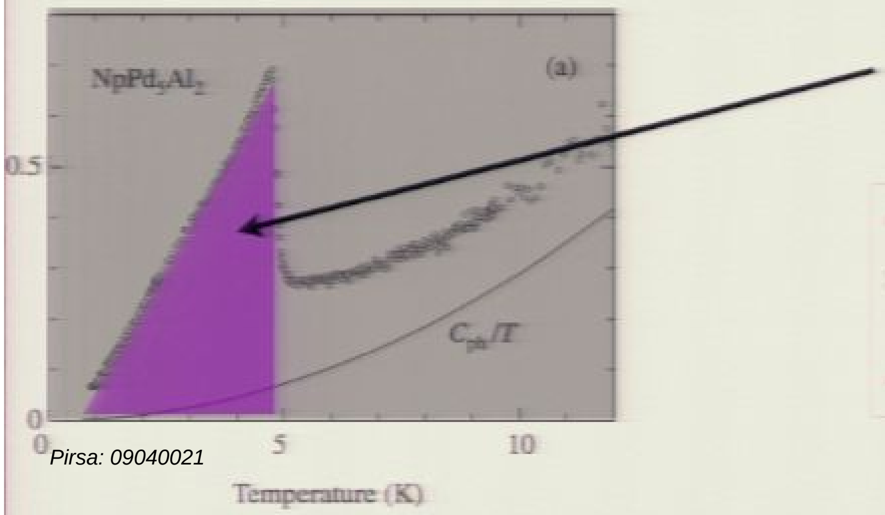
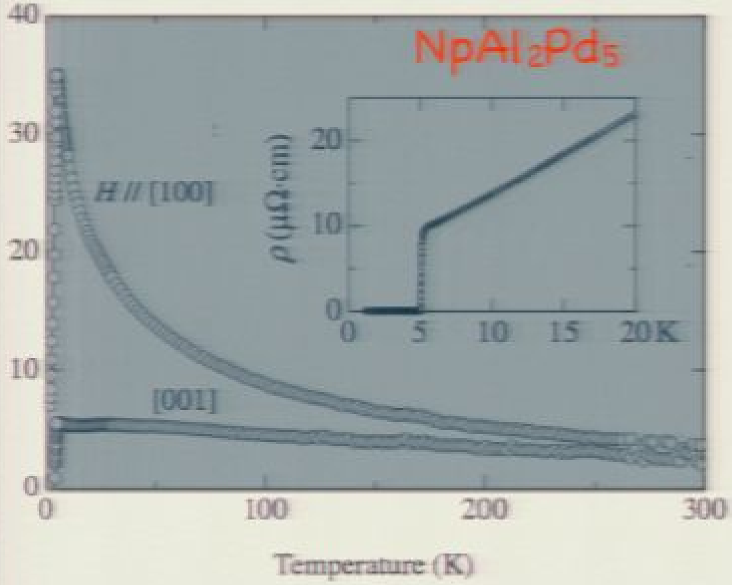


- Suggests Kondo spin quenching and superconductivity develop simultaneously.
- Spin is not the glue, but the *fabric*

New HF Superconductors: $PuCoGa_5$ & $NpAl_2Pd_5$



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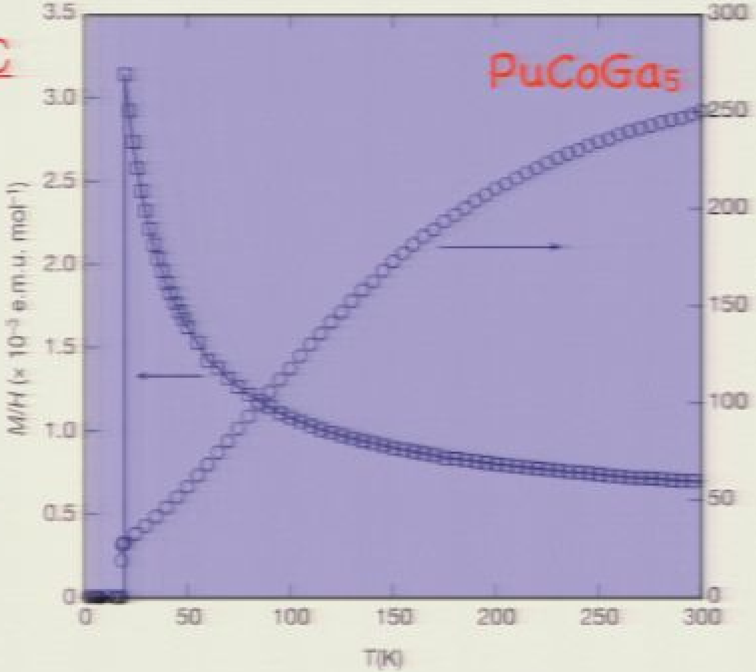

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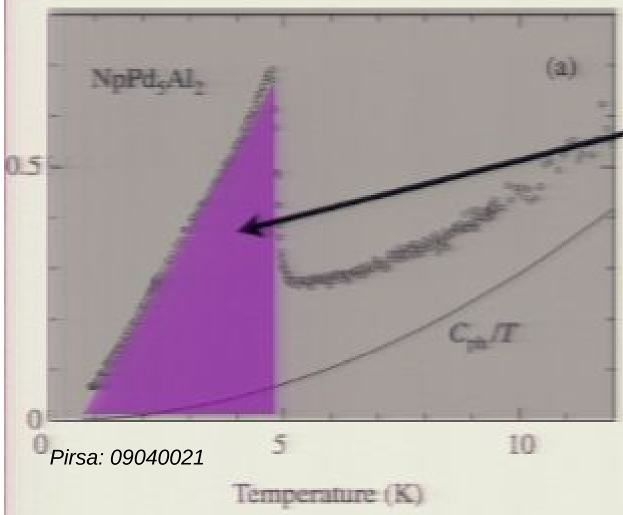

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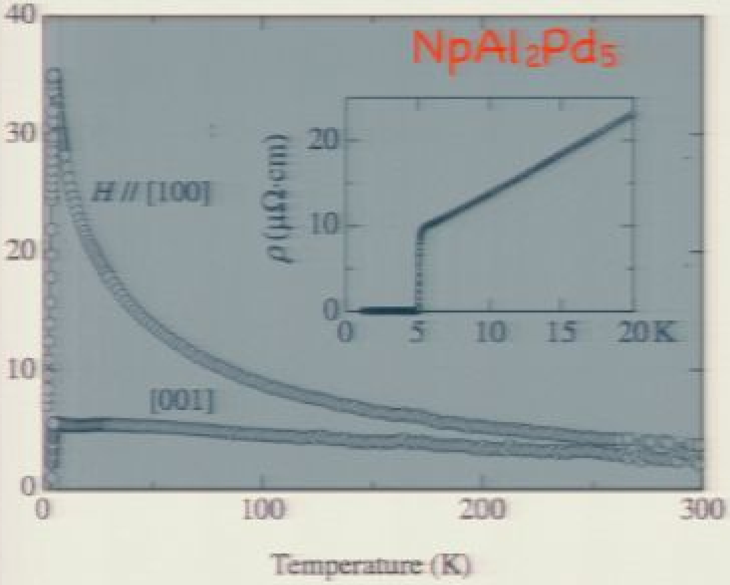

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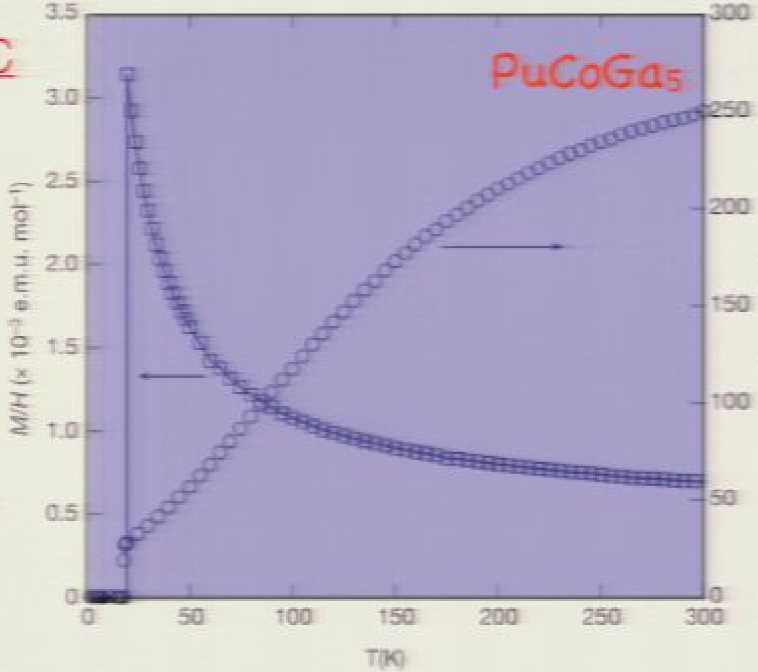

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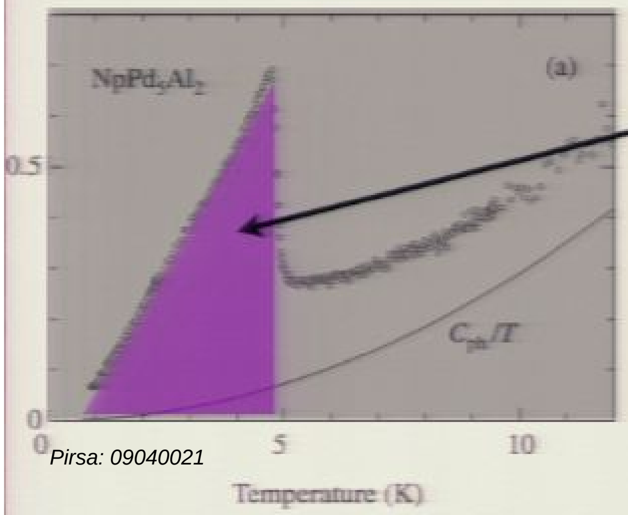

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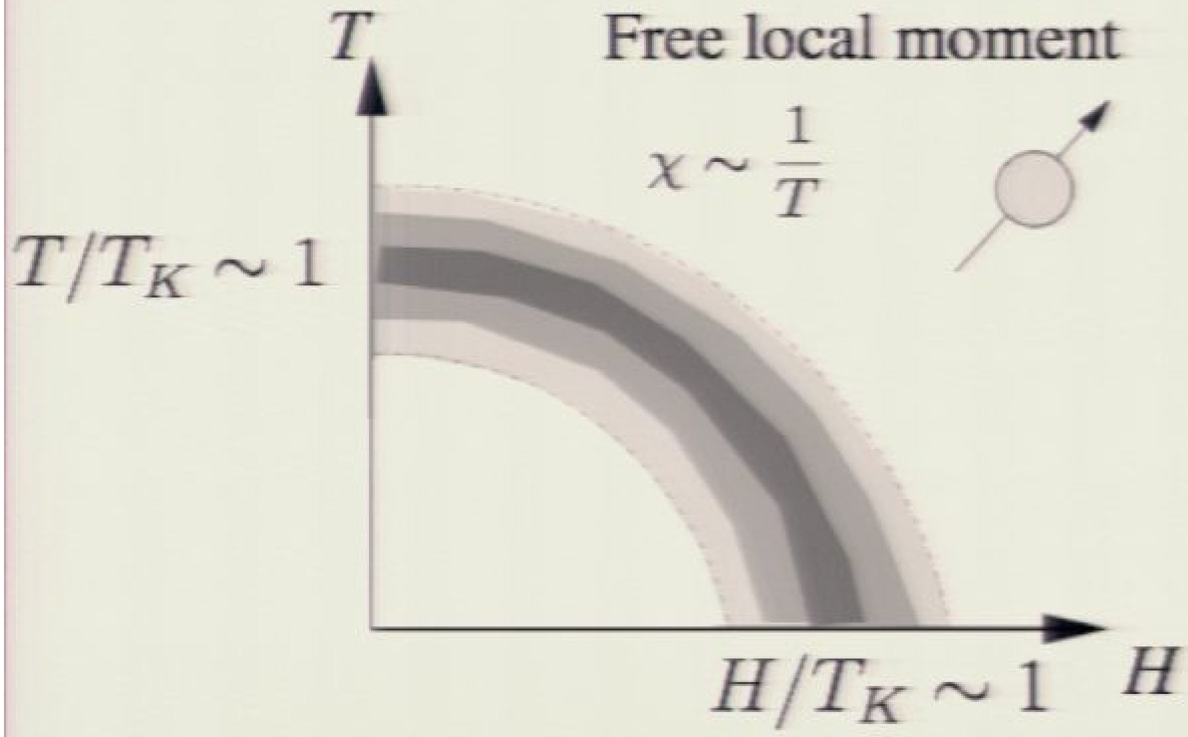
Background: Kondo effect and Heavy Fermions

Review: cond-mat/0612006



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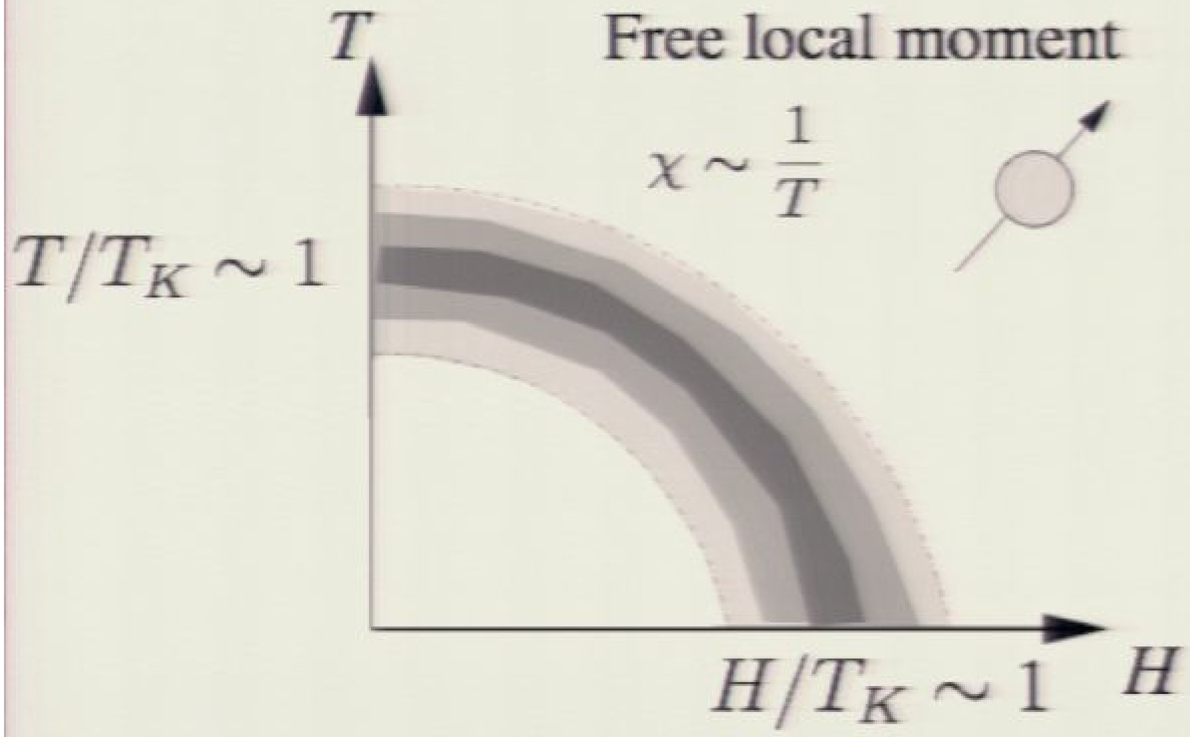

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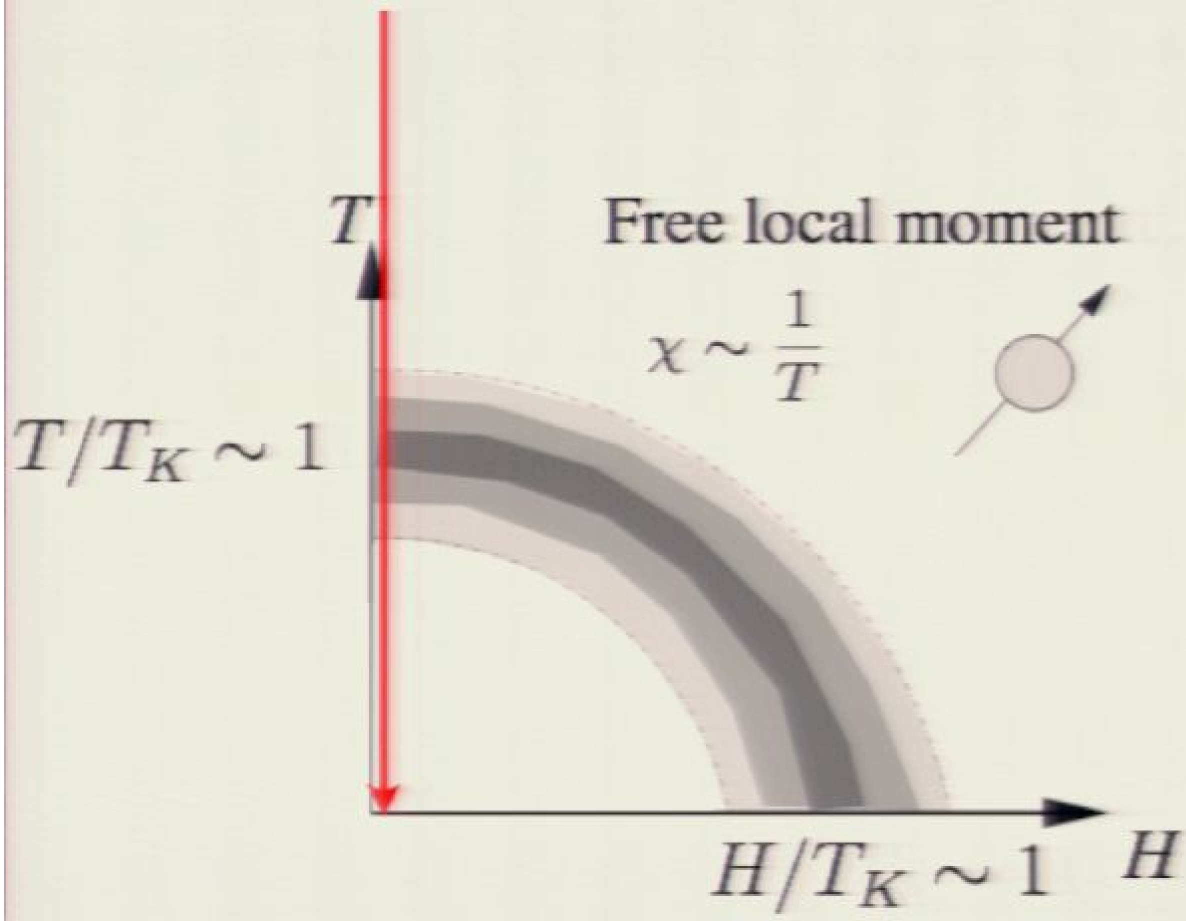
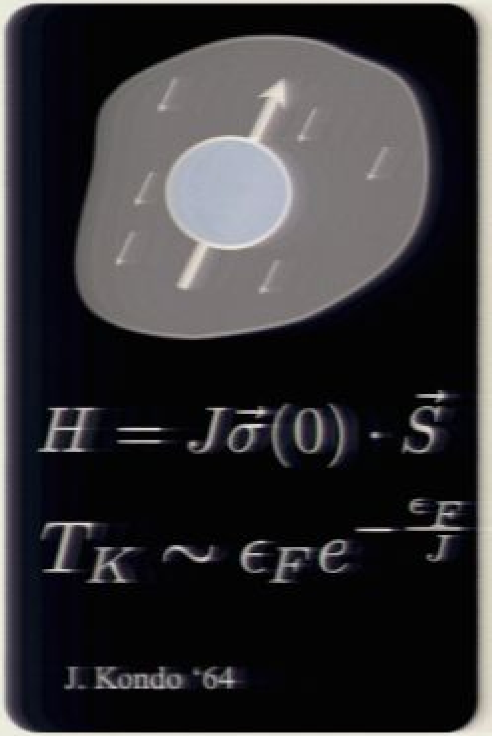




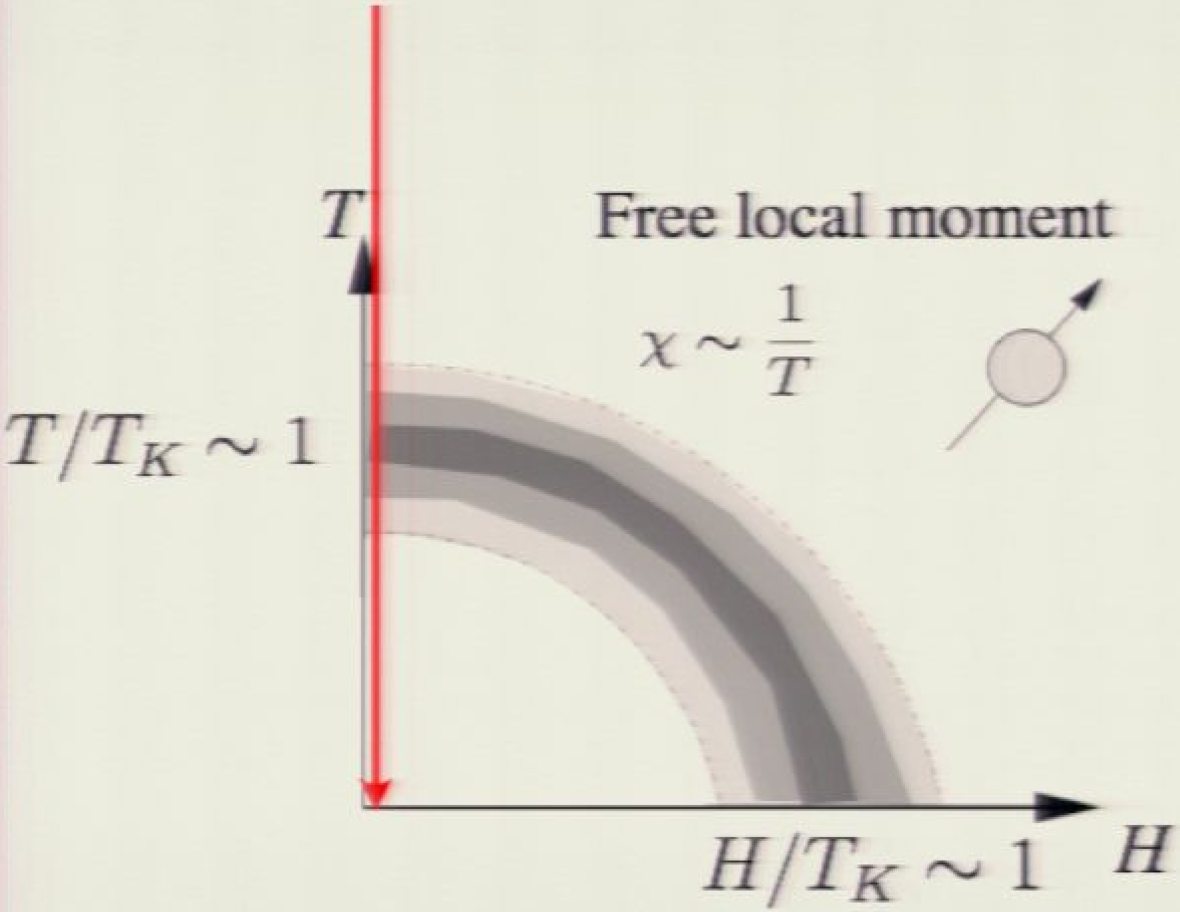
$$H = J\vec{\sigma}(0) \cdot \vec{S}$$

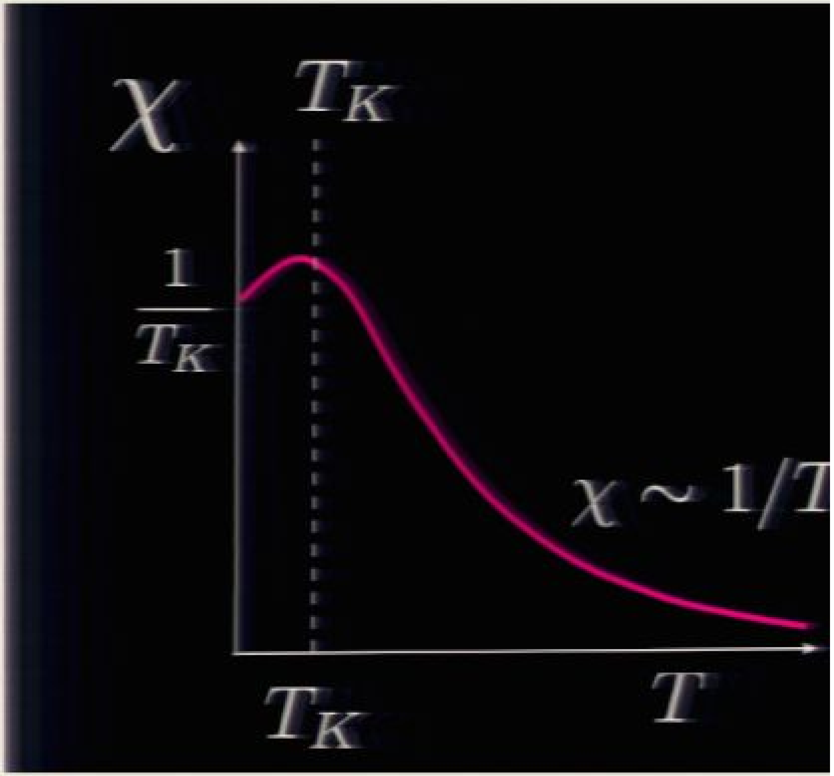
$$T_K \sim \epsilon_F e^{-\frac{\epsilon_F}{J}}$$

J. Kondo '64

Background: Kondo effect and Heavy Fermions

Review: cond-mat/0612006





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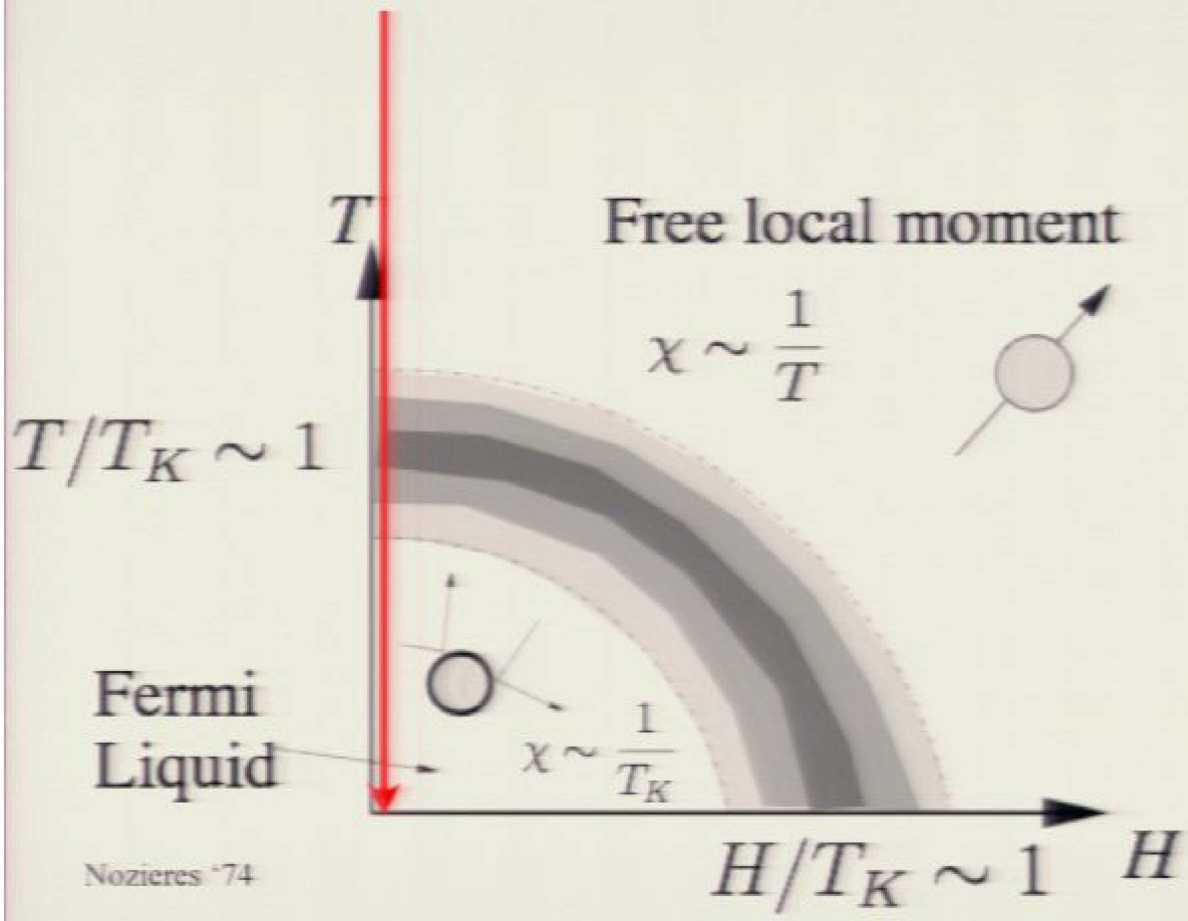
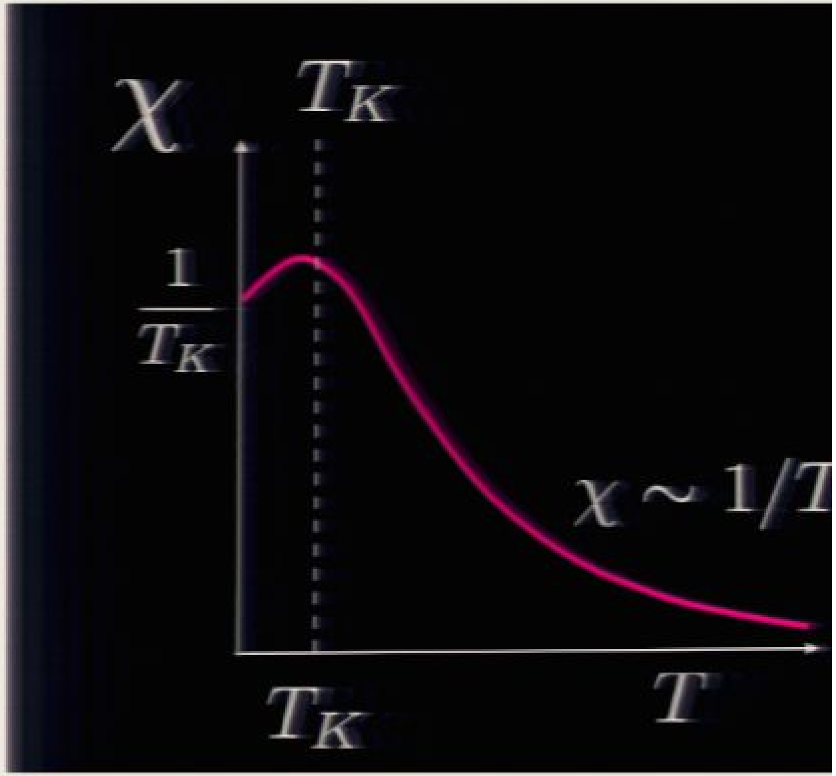


Nozieres '74



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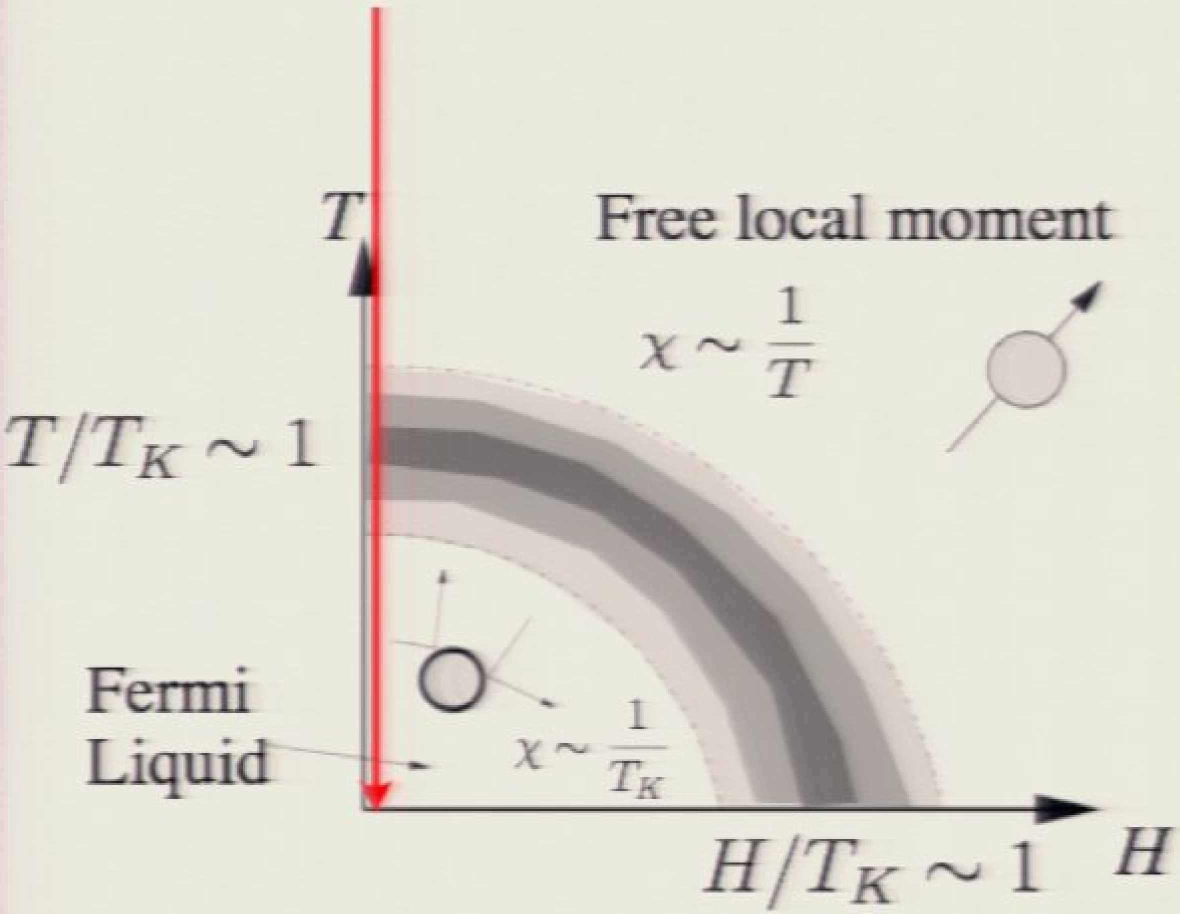

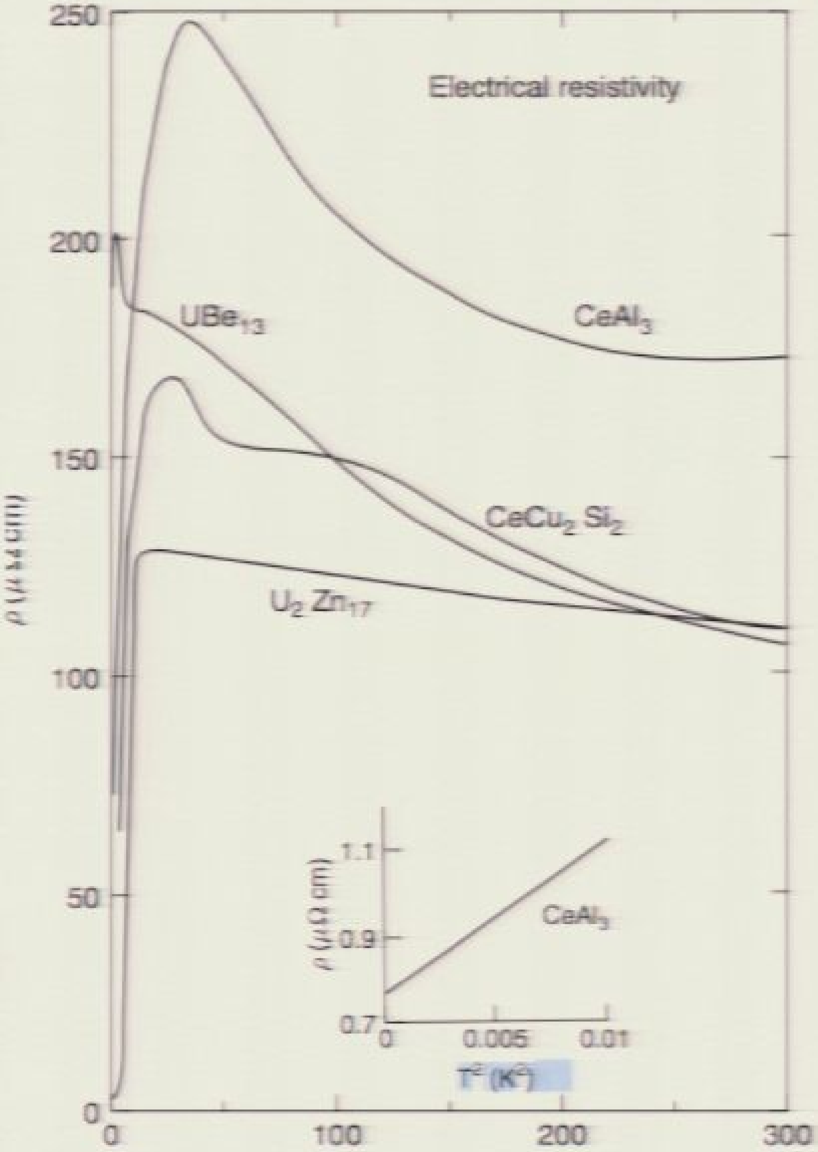

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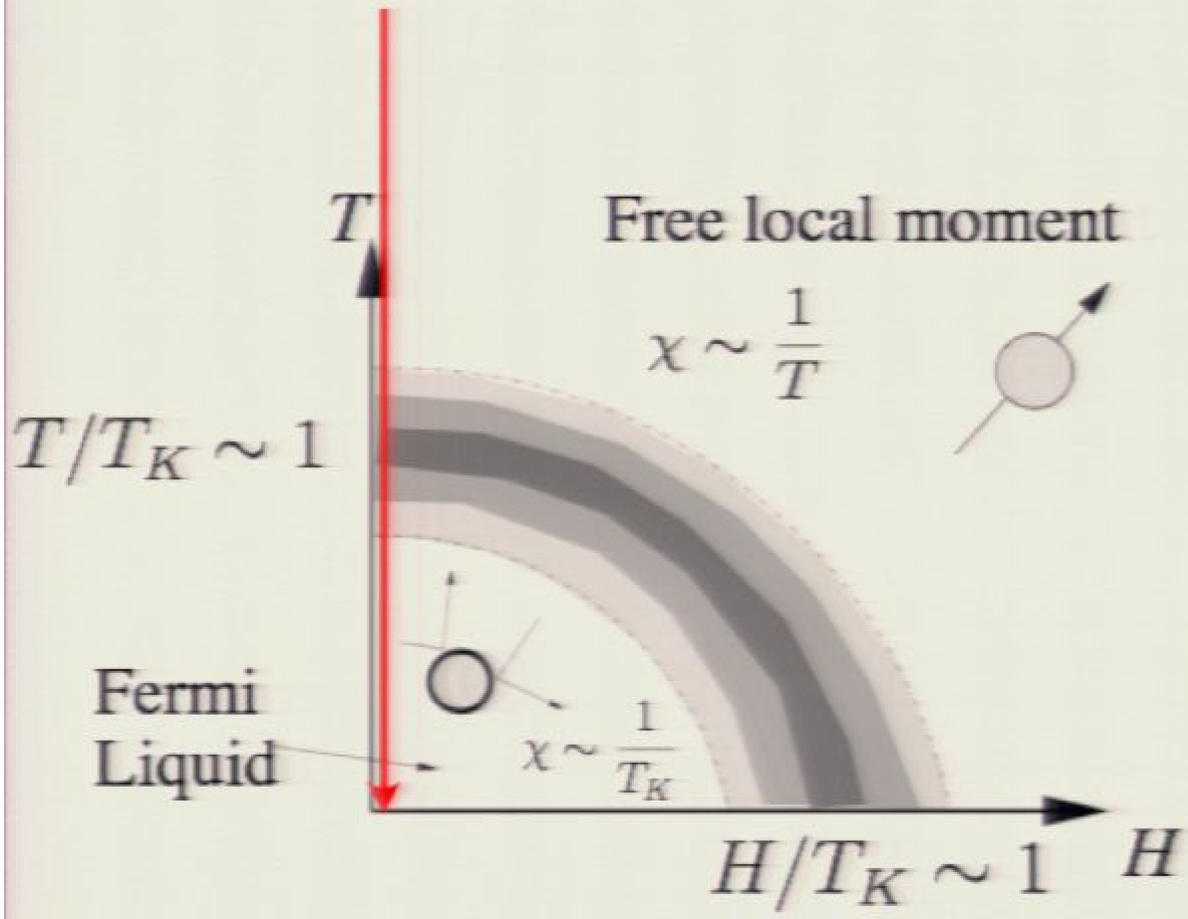

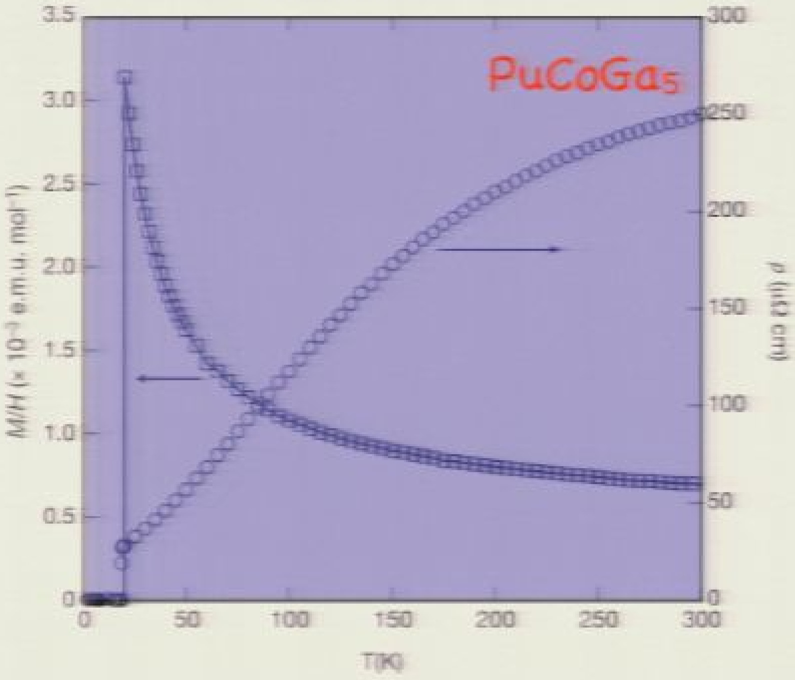

Directly Curie PM to SC

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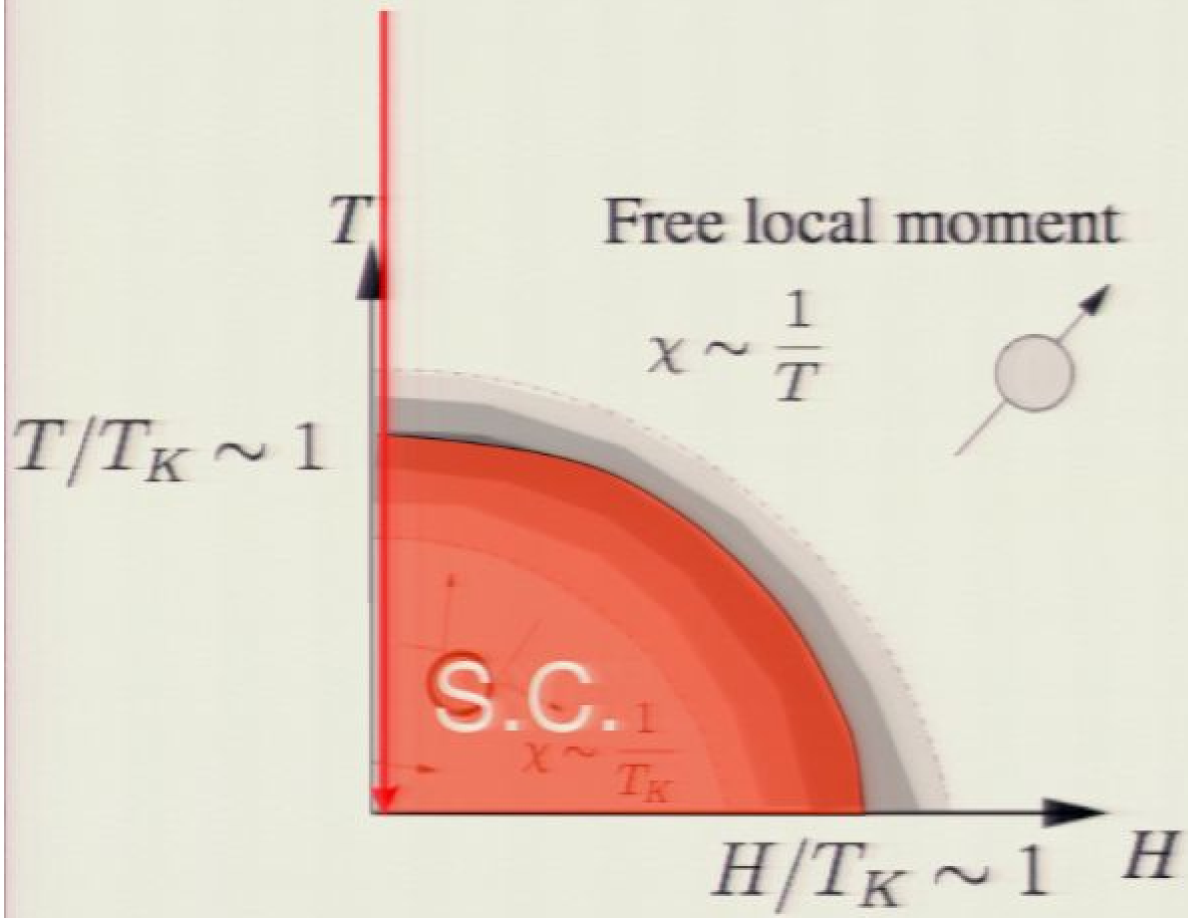
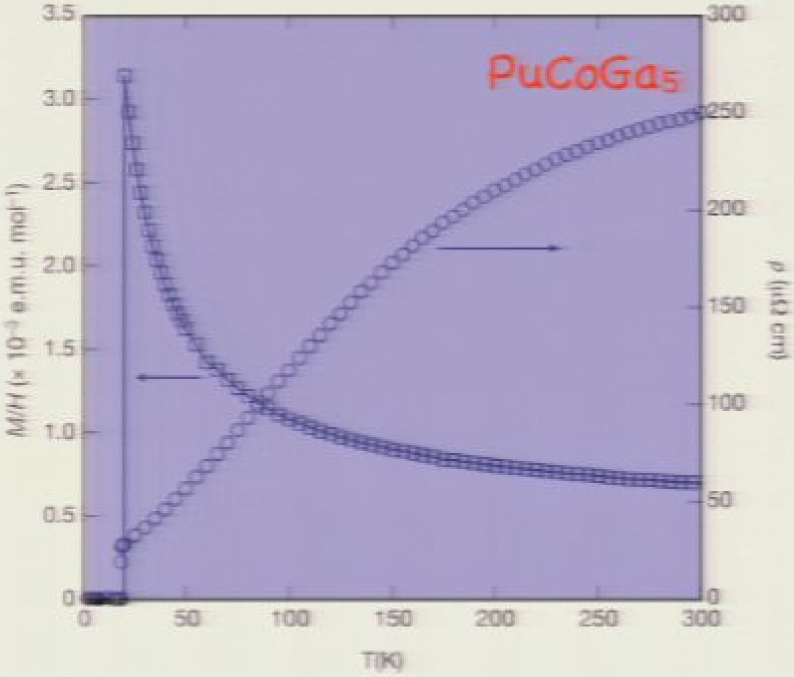
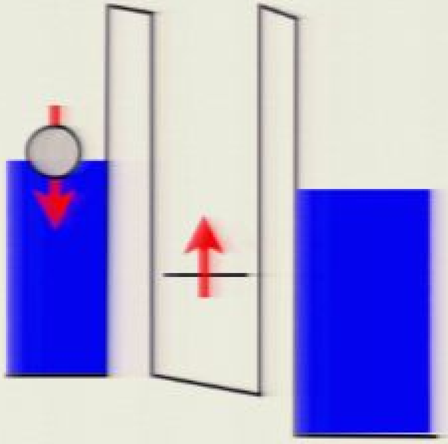




Directly Curie PM to SC

Composite pairs

Cotunneling and composite fermions



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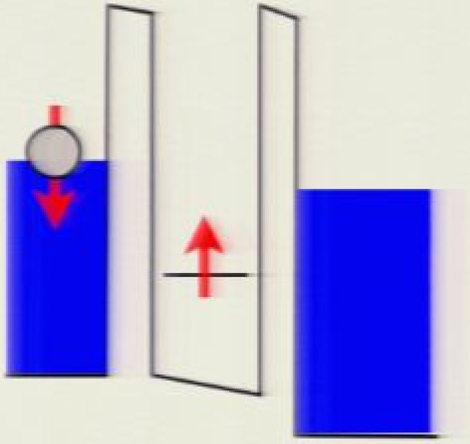
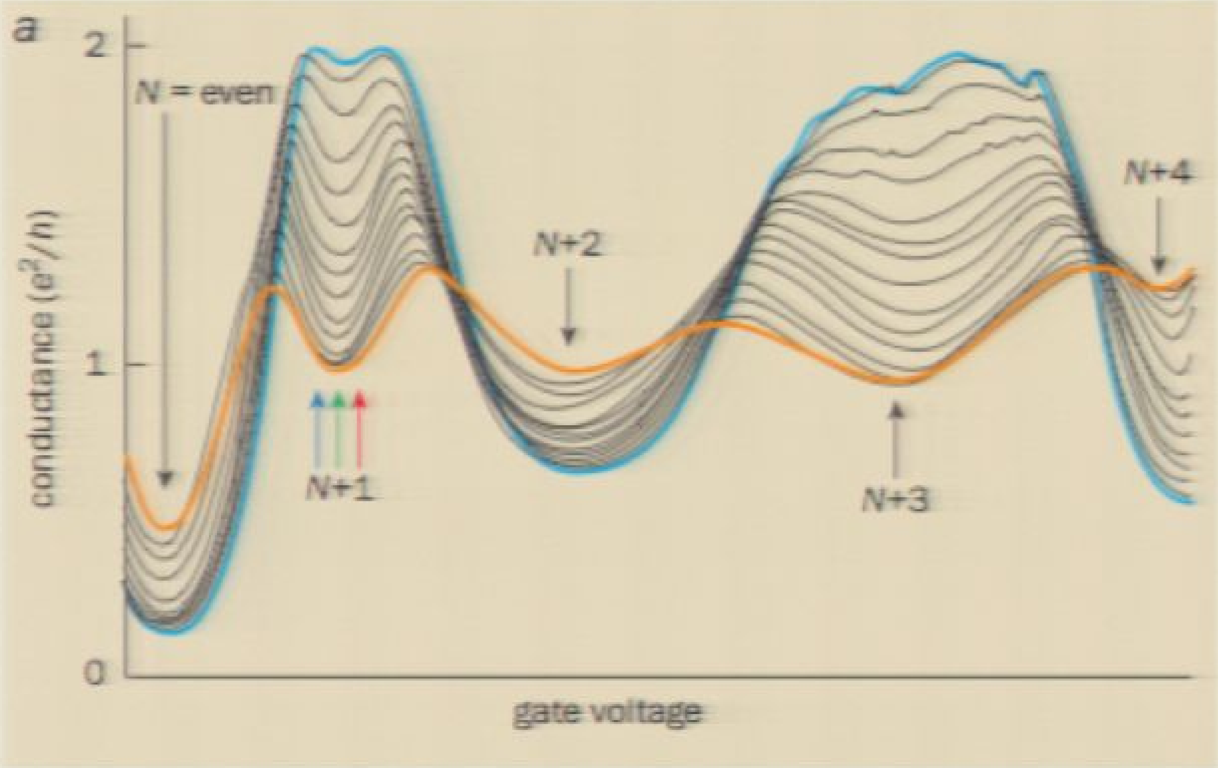


van der Wiel et al, Science (2000)



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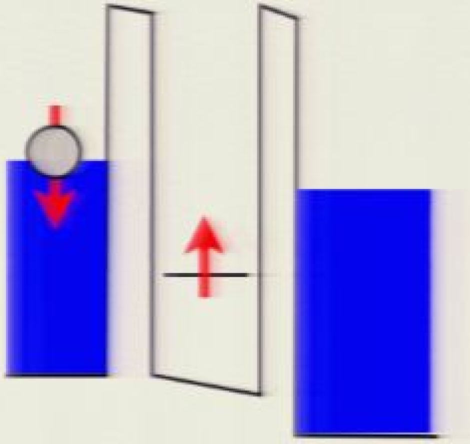

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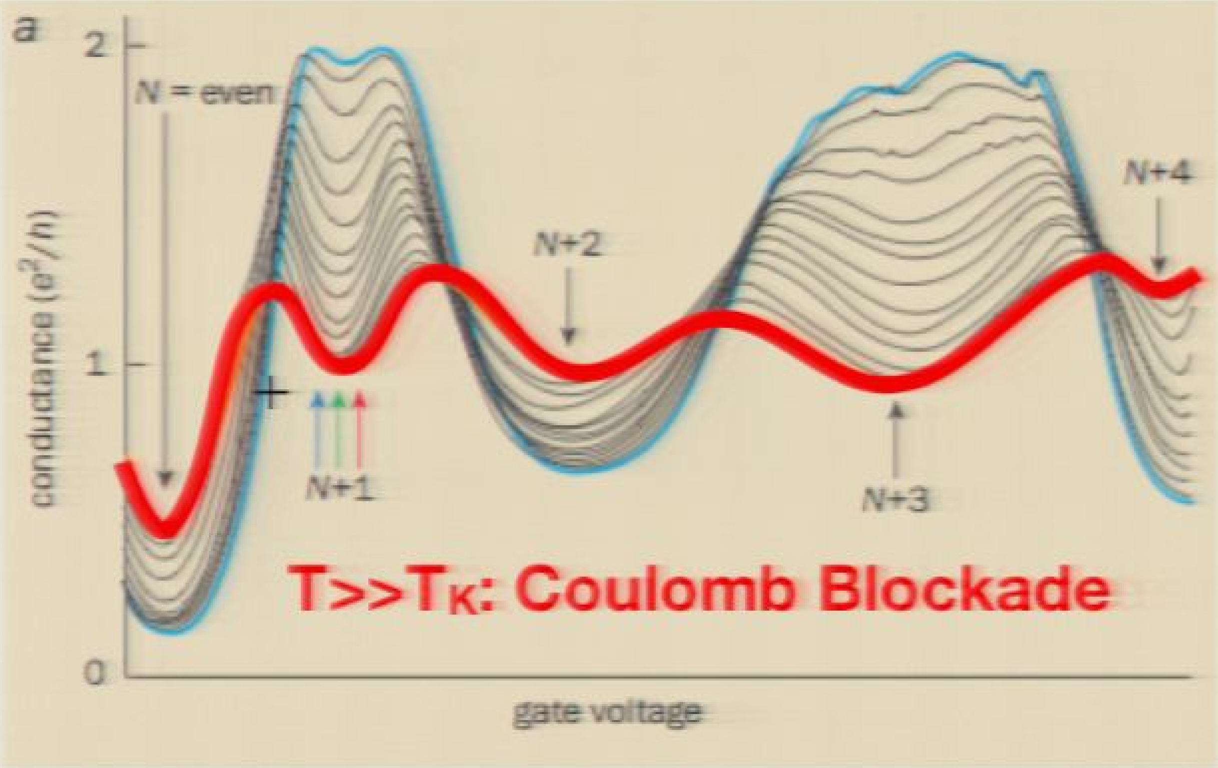
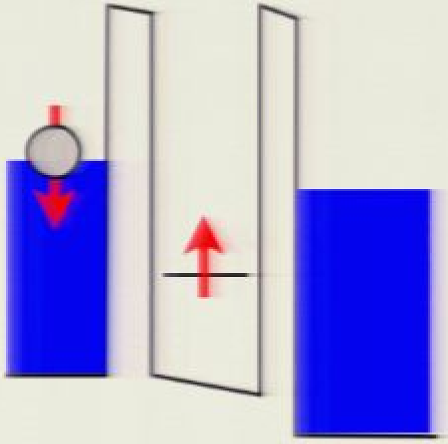
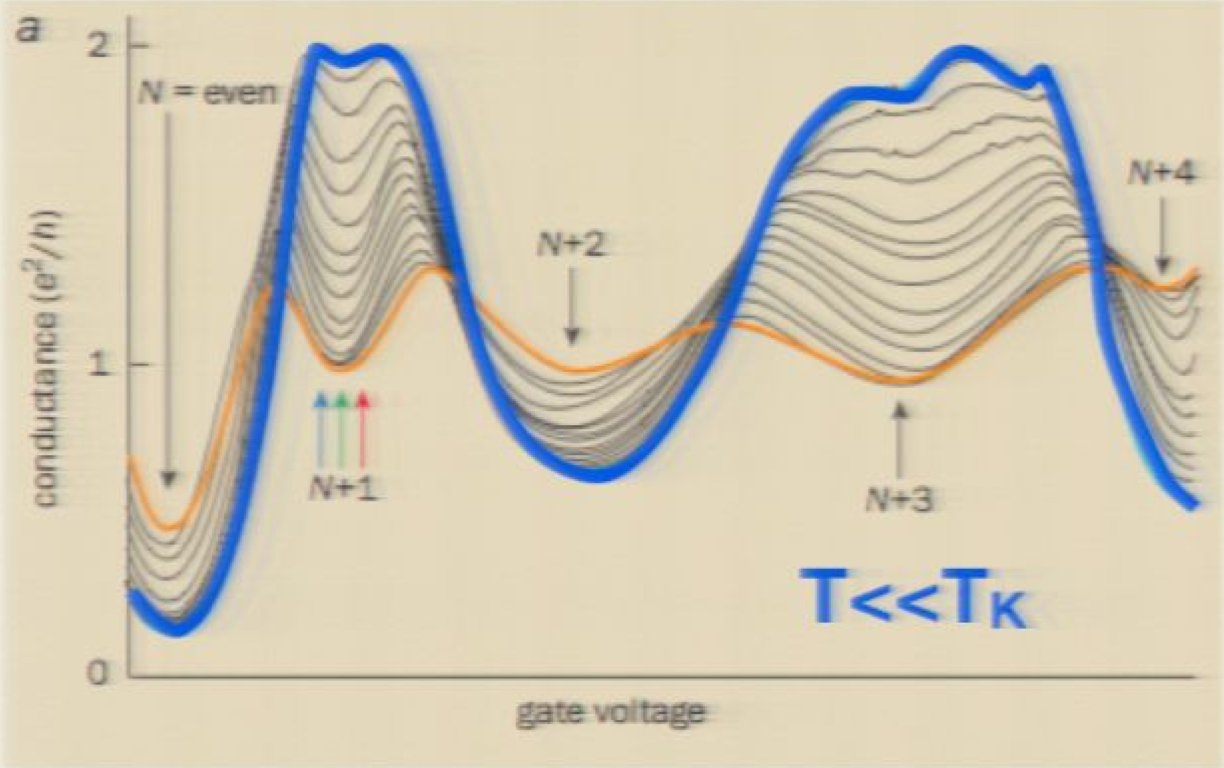


$T \gg T_K$: Coulomb Blockade

Cotunneling and composite fermions





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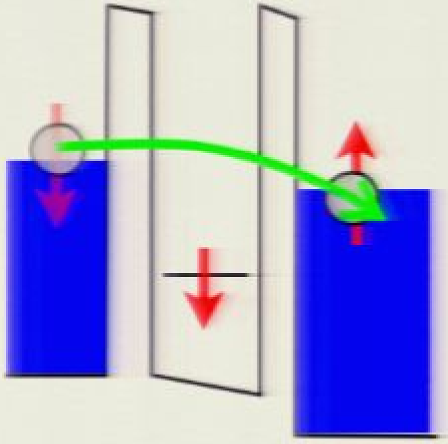
$T<<T_K$

Cotunneling and composite fermions



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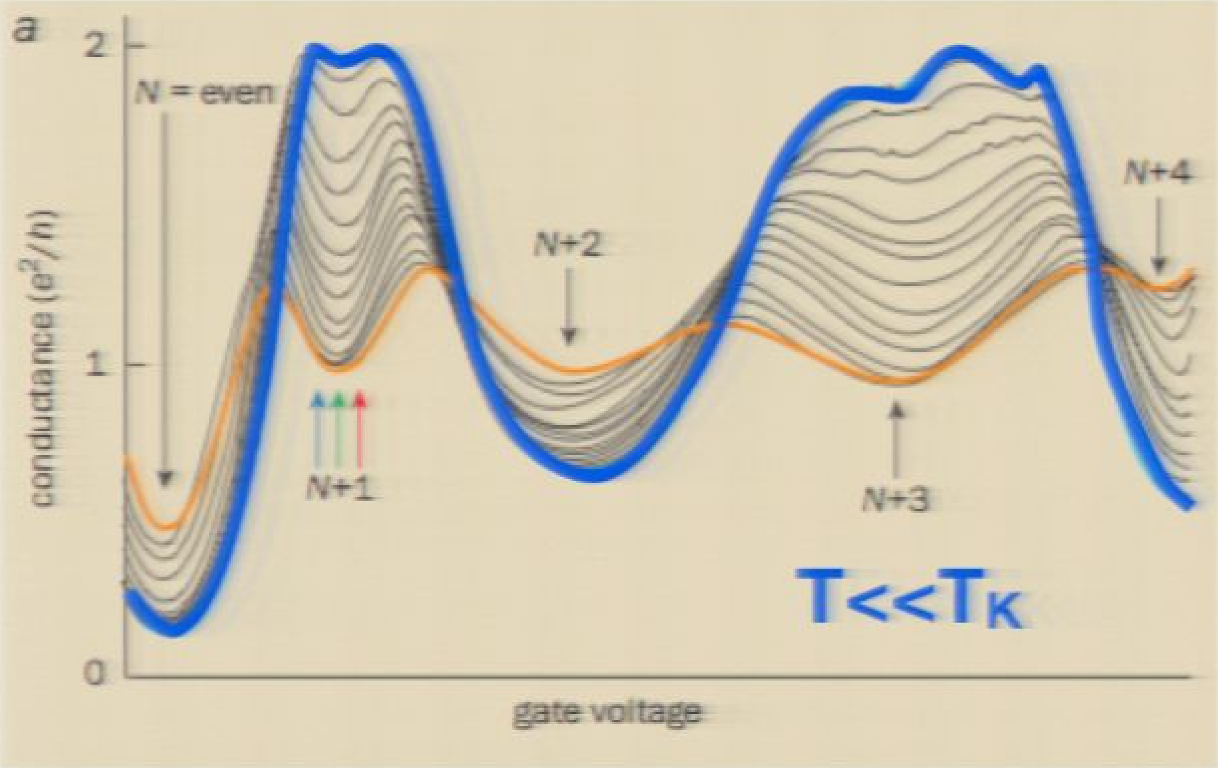

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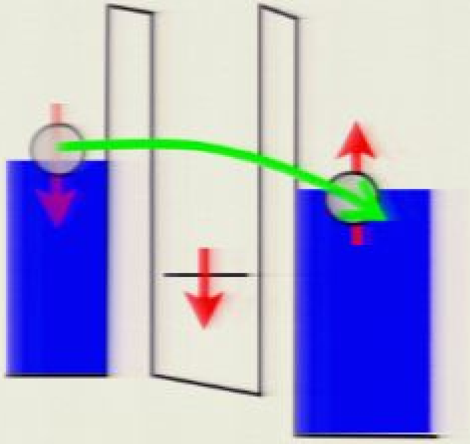

Cotunneling

(Glazman +Pustilnik)

(quantum dots)

$$f_\downarrow^\dagger = c_\uparrow^\dagger S_-$$

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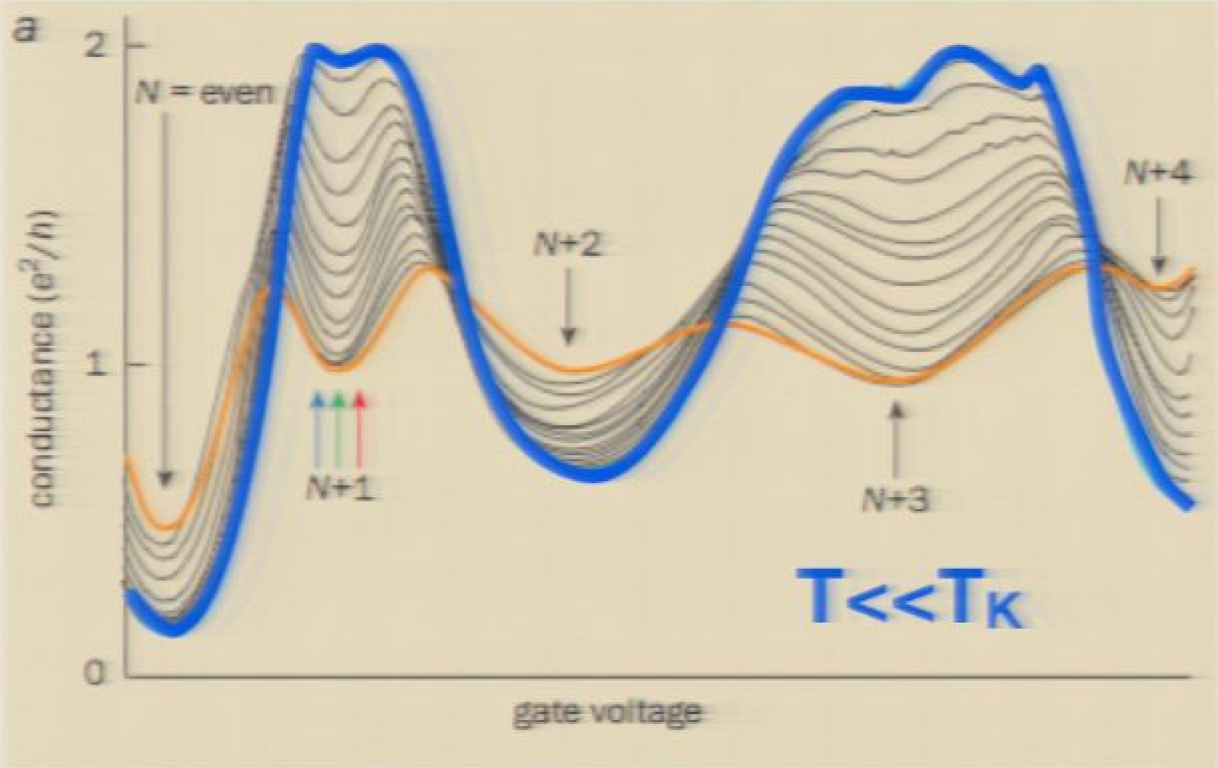

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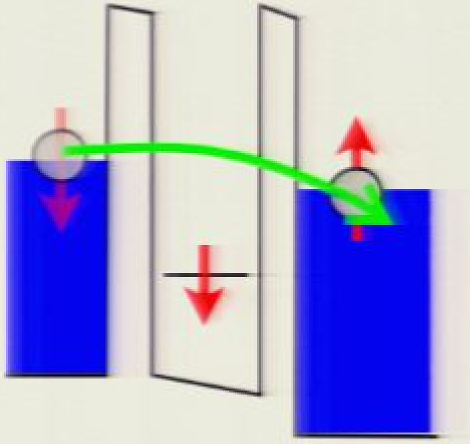

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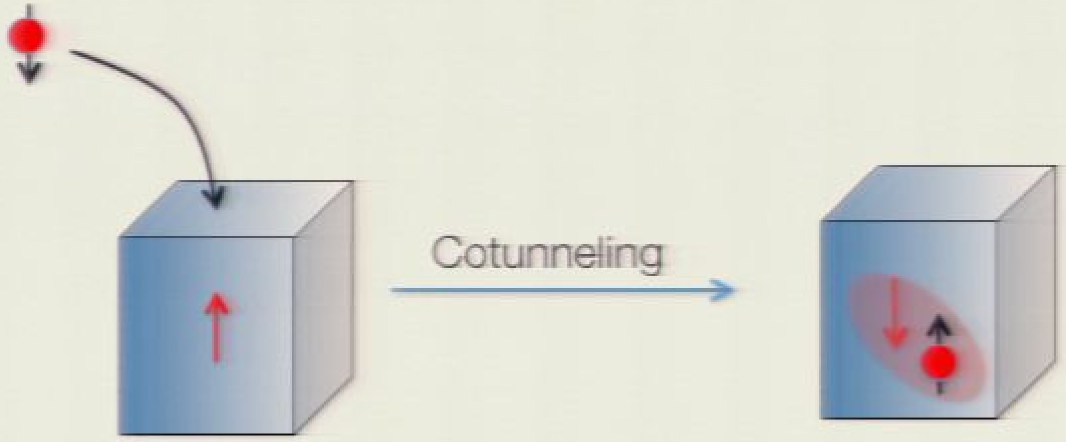
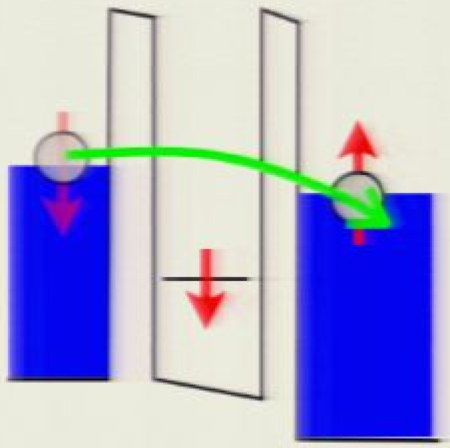


Heavy electron = (electron x spinflip)

Cotunneling and copairing:



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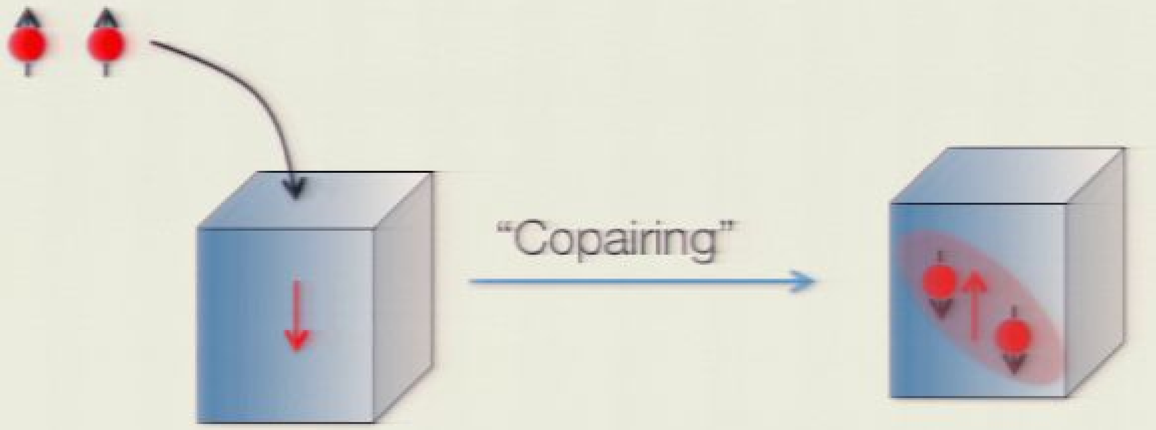

Heavy Cooper pair = (pair x spinflip)

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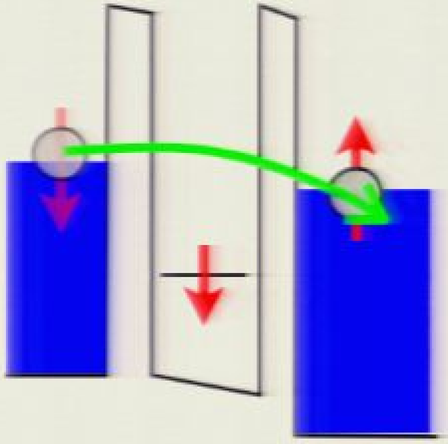

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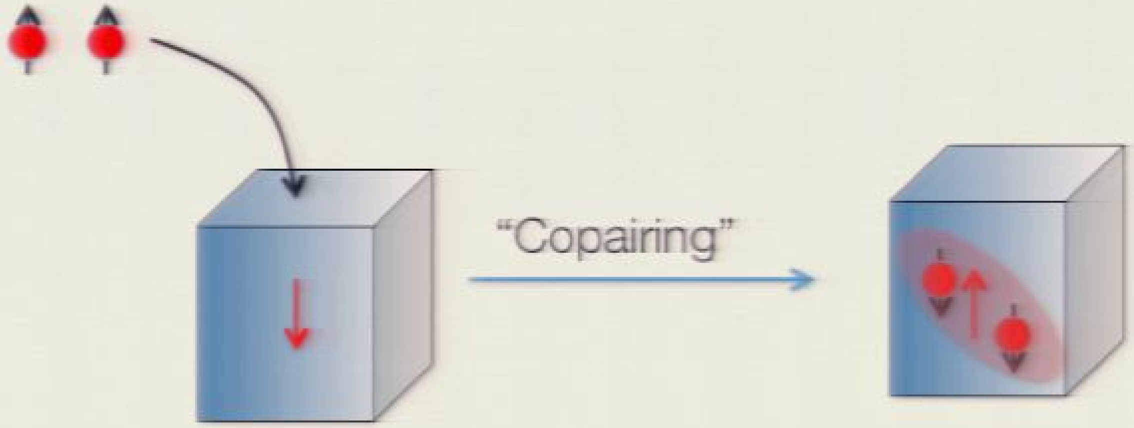
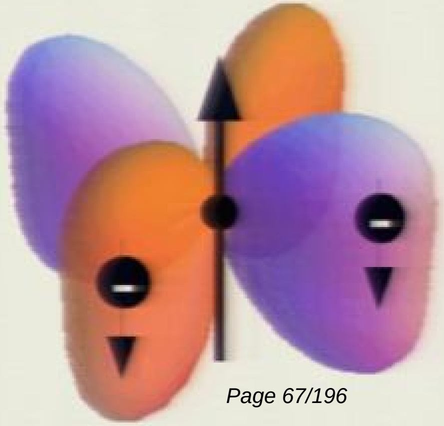


Heavy Cooper pair = (pair x spinflip)

$$\Psi^\dagger = c_{1\downarrow}^\dagger c_{2\downarrow}^\dagger S_+$$



Theoretical digression.

Strongly correlated electron physics: no small parameter

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$$Z = \sum_{\text{configs}} e^{-S[\psi]}$$

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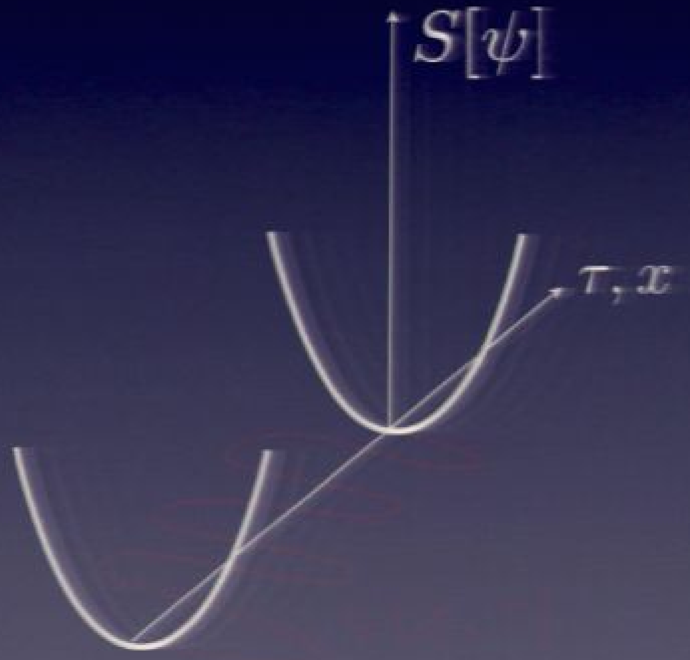

Strongly correlated electron physics: no small parameter

Large N : family of models with “N” spin components, which retain the key physics and can be solved in the large N limit.

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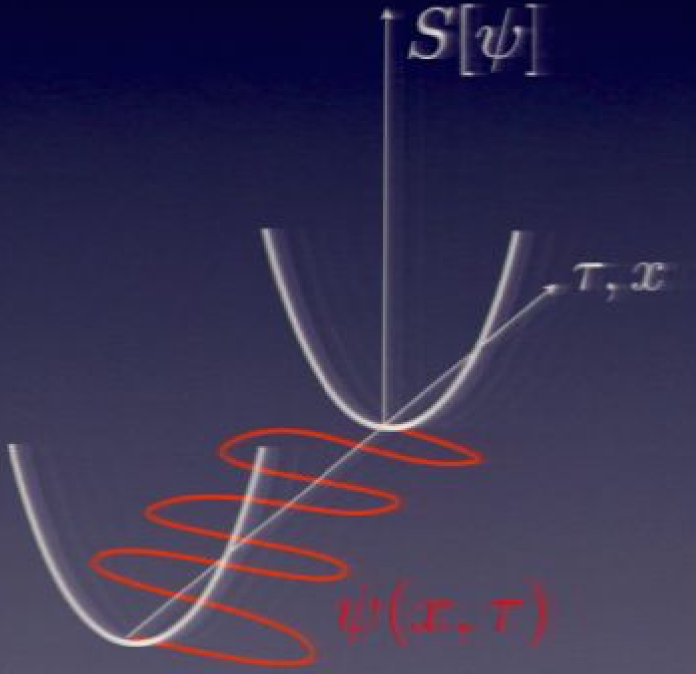

Wild quantum fluctuations!

Strongly correlated electron physics: no small parameter

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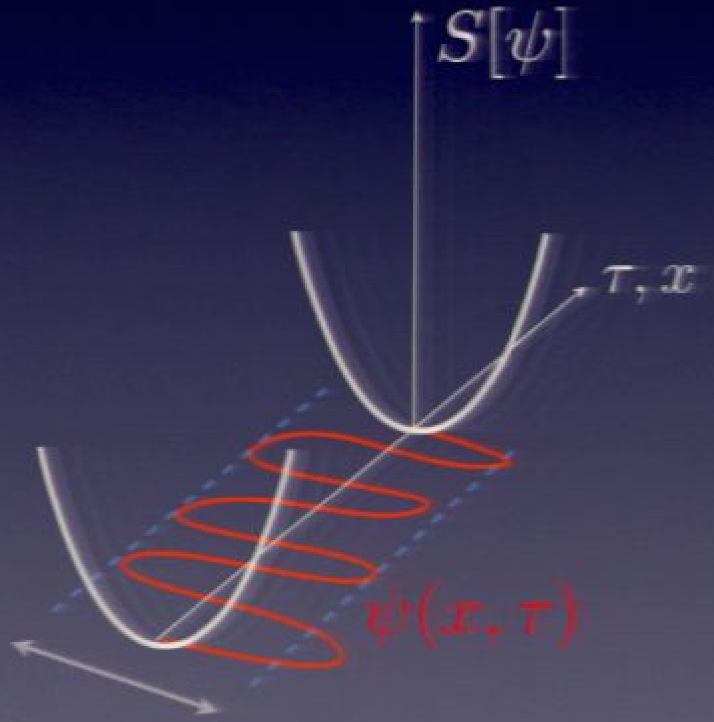
$$= \sum_{\text{configs}} e^{-S[\psi]/\frac{1}{N}}$$



$$\frac{1}{N} \sim \hbar_{eff}$$

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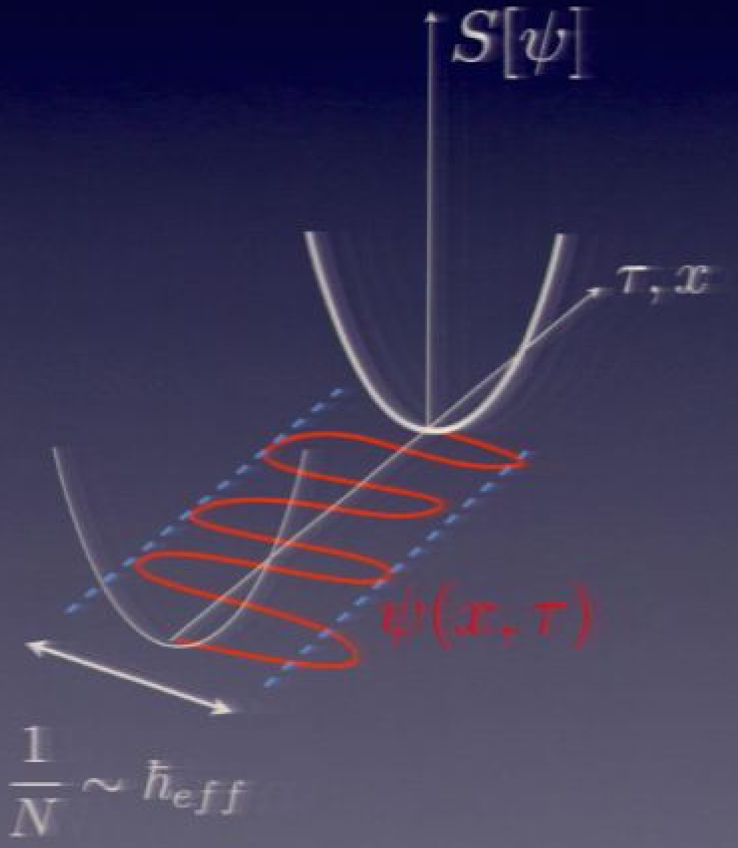
$N \to \infty$



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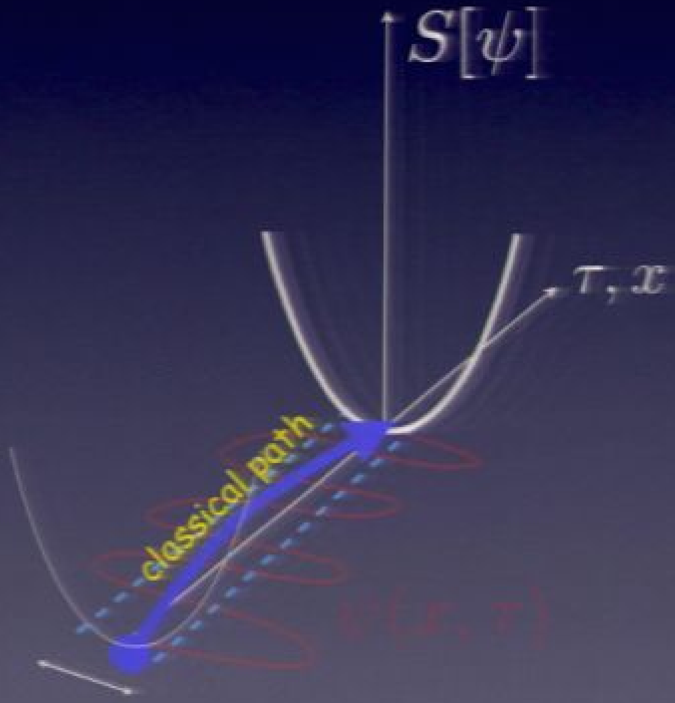

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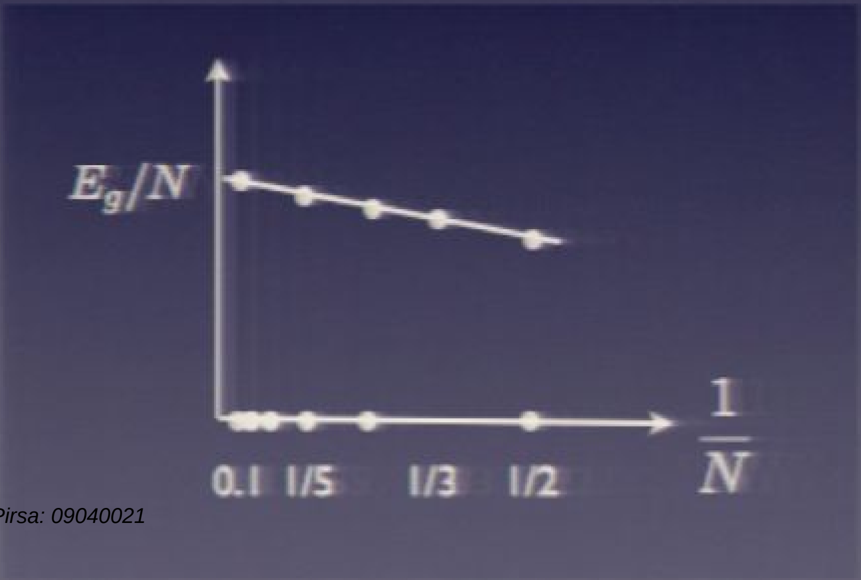

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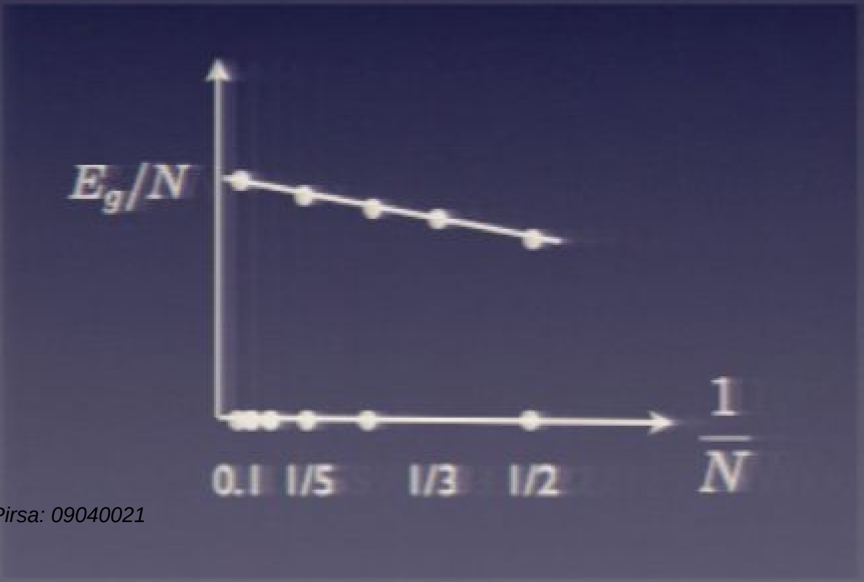

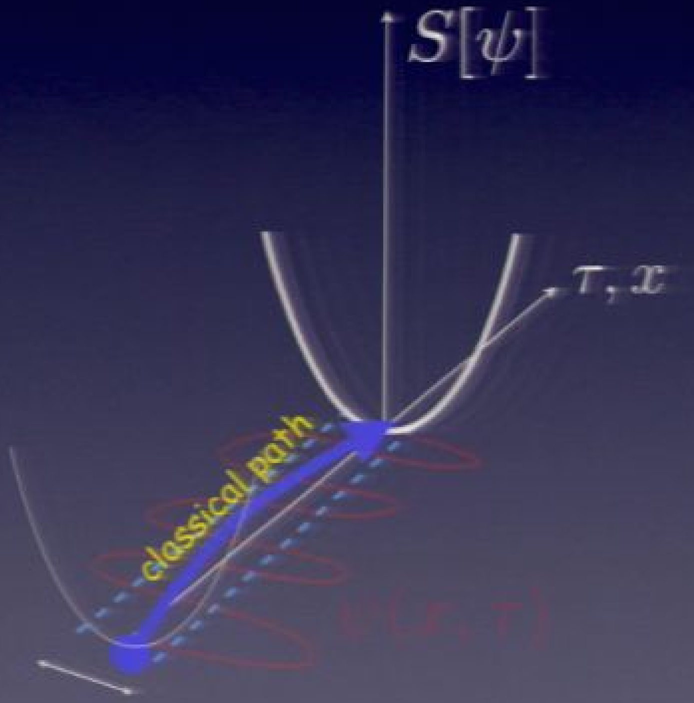

$$\frac{1}{N} \sim \hbar_{eff}$$

The magnetism and neutrality of the electron spin are manifested as two discrete parities:

odd under time reversal,
even under charge conjugation

$$S \xrightarrow{\theta} -S \quad \text{Magnetism}$$
$$S \xrightarrow{C} +S \quad \text{Neutrality}$$

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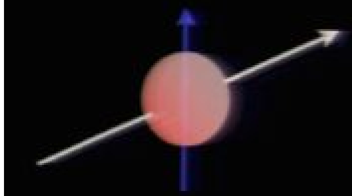

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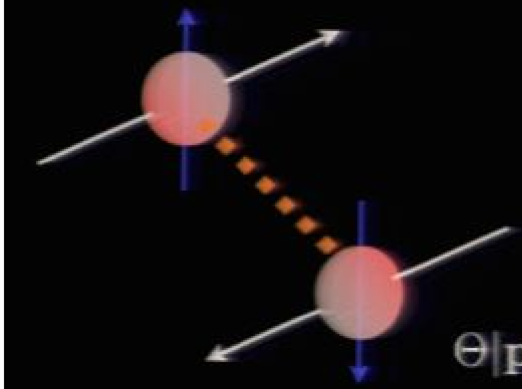

$\Theta|\mathbf{p}\uparrow\rangle = |-\mathbf{p}\downarrow\rangle$

$$S + S_{\Theta} = S - S = 0$$

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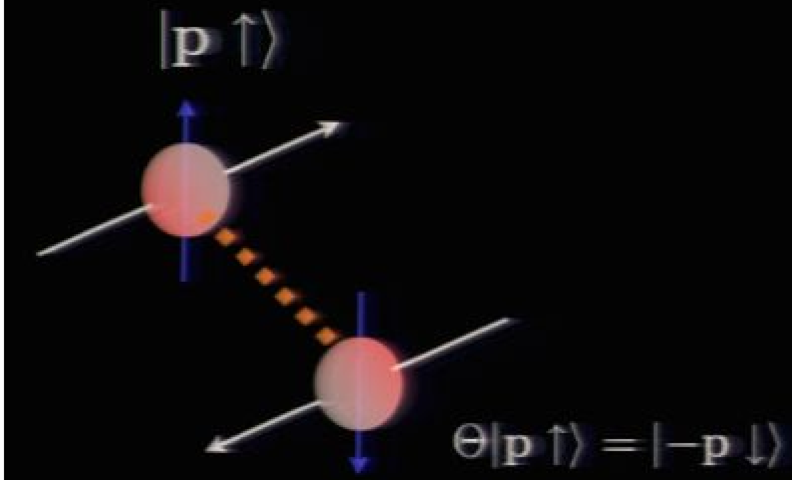

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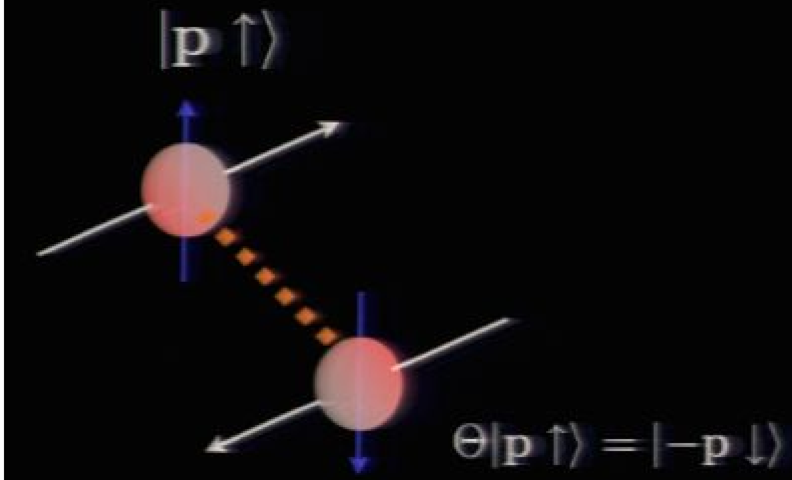

$$S + S_\Theta = S - S = 0$$

Singlet pairing is intimately related to the inversion of spins under time-reversal

The magnetism and neutrality of the electron spin are manifested as two discrete parities:

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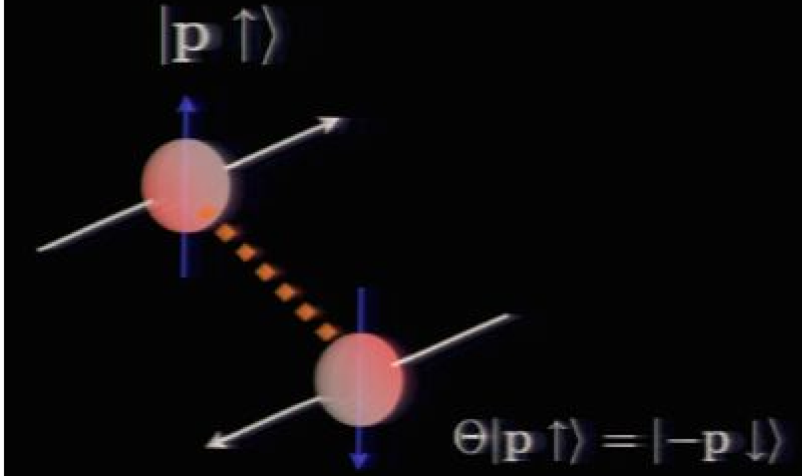
$S \xrightarrow{\theta} -S$ Magnetism
$S \xrightarrow{C} +S$ Neutrality



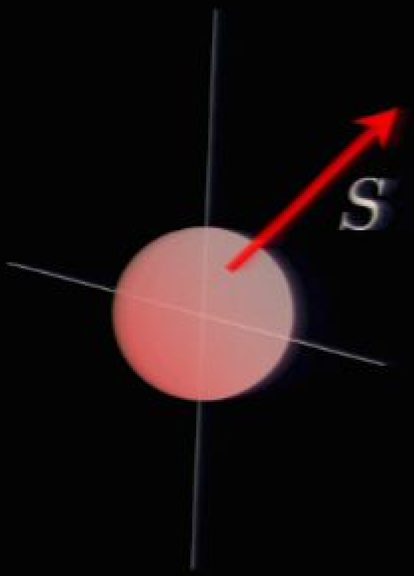
$$S + S_{\Theta} = S - S = 0$$

Singlet pairing is intimately related to the inversion of spins under time-reversal

Unfortunately, these discrete parities are lost in conventional large N expansions:
no Cooper pairs.

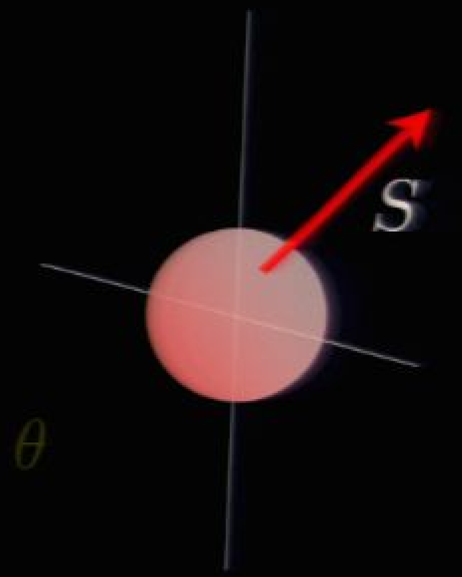
Restoring superconductivity to large N expansions requires that we understand the symmetry of time-reversal.

The Symplectic symmetry of spin



The Symplectic symmetry of spin

Rotation x time reversal



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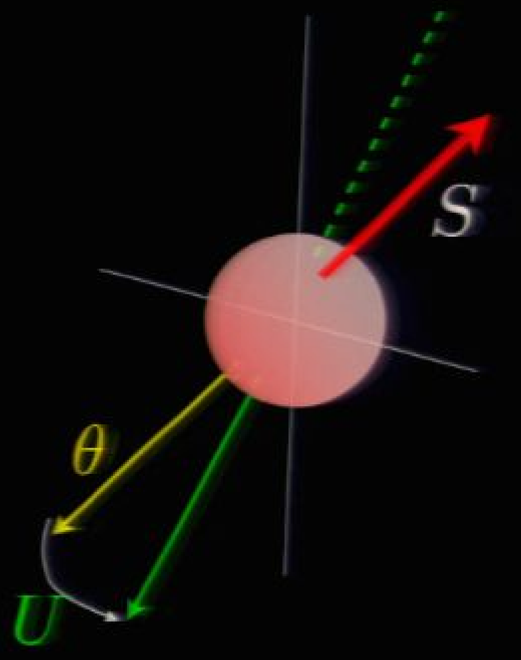

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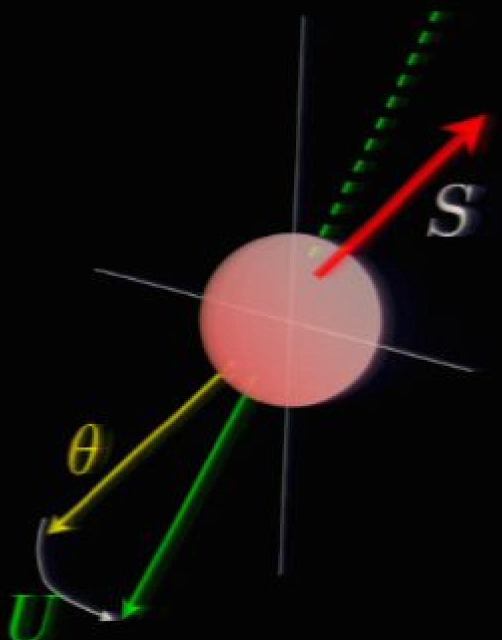
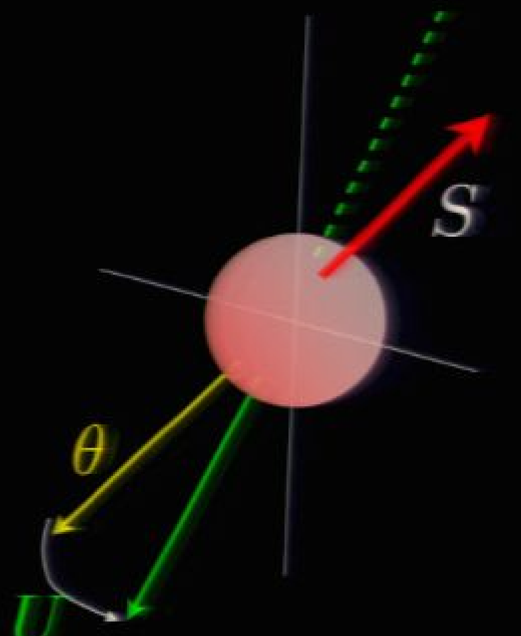


$$S \xrightarrow{U\theta} \underline{R}(-S)$$

The Symplectic symmetry of spin

Rotation x time reversal



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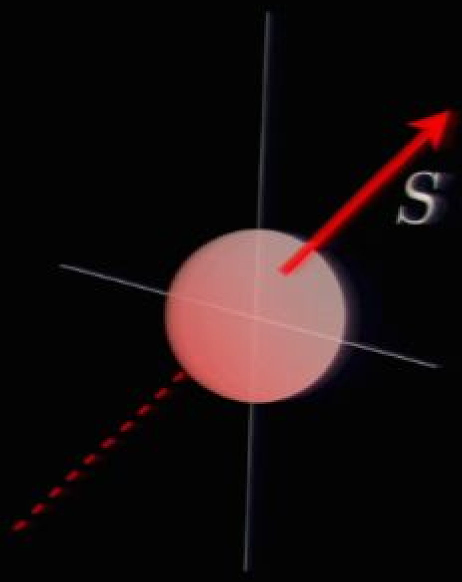
Time reversal x rotation



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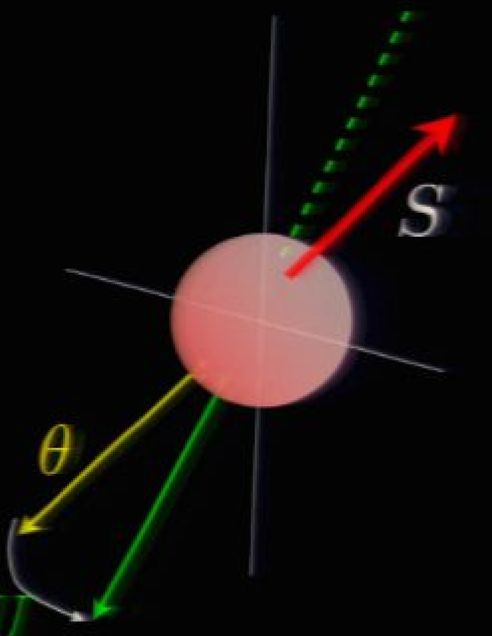
Rotation x time reversal



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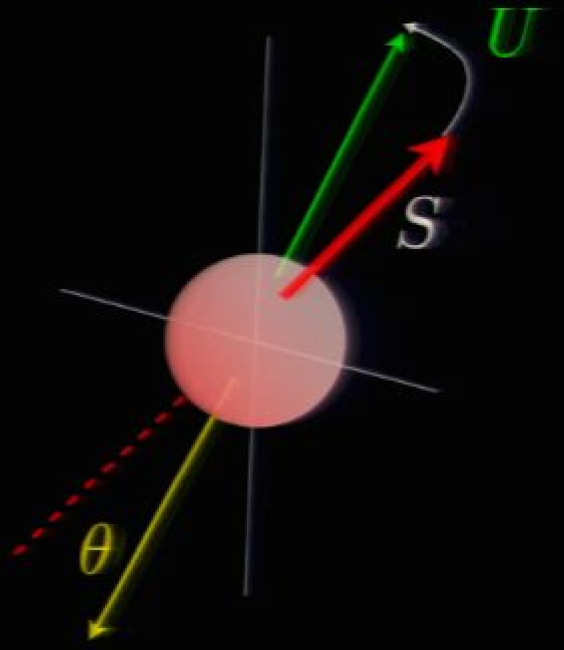
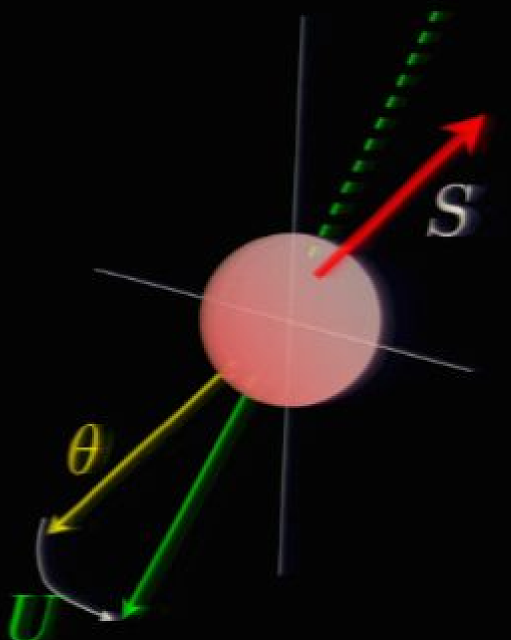


$$S \xrightarrow{\theta U} -(\underline{R}S)$$

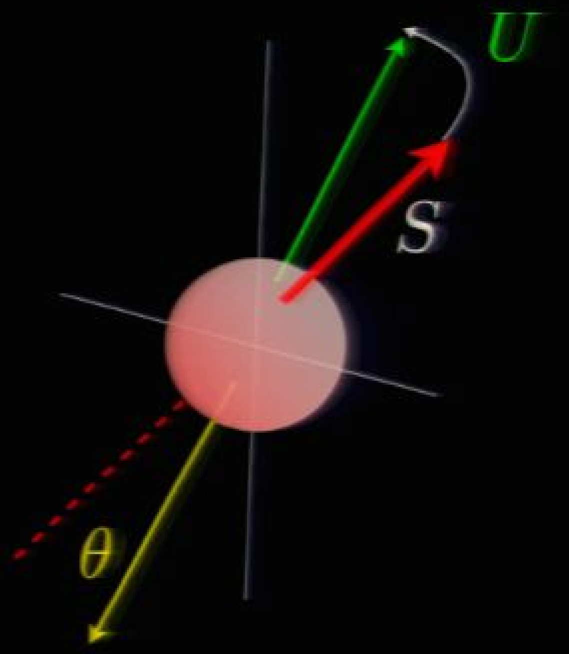
The Symplectic symmetry of spin

Rotation x time reversal = Time reversal x rotation

$$U\theta = \theta U$$



$$S \xrightarrow{U\theta} \underline{R}(-S)$$



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The Sympectic symmetry of spin

Rotation x time reversal = Time reversal x rotation

$$U\theta = \theta U$$

So that:

$$U\theta U^{\dagger} = \theta$$

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So that:

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$$\theta = i\sigma_2 \times K$$

Antiunitary operator

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So that:

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Antiunitary operator

$$\boxed{U i\sigma_2 U^T = i\sigma_2 \quad \text{SYMPLECTIC CONDITION}}$$

N-component Symplectic spin operator:
generator of SP(N)

$$\boxed{\begin{array}{l} S_{\alpha\beta} = f^\dagger_\alpha f_\beta - \tilde{\alpha}\tilde{\beta} f^\dagger_{-\beta} f_{-\alpha} \\ n_f = N/2 \end{array}}$$

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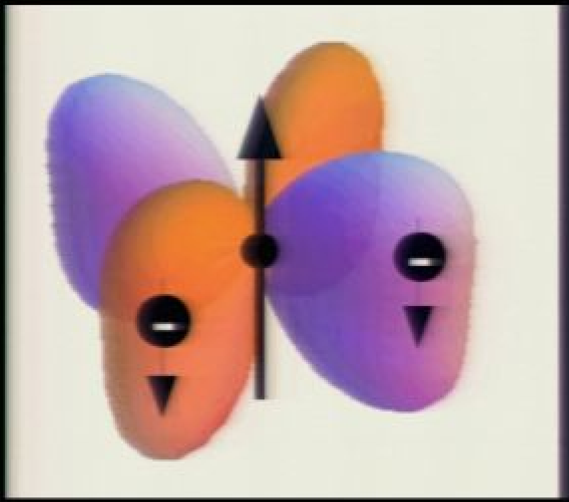
Singlet pair commutes with symplectic spin

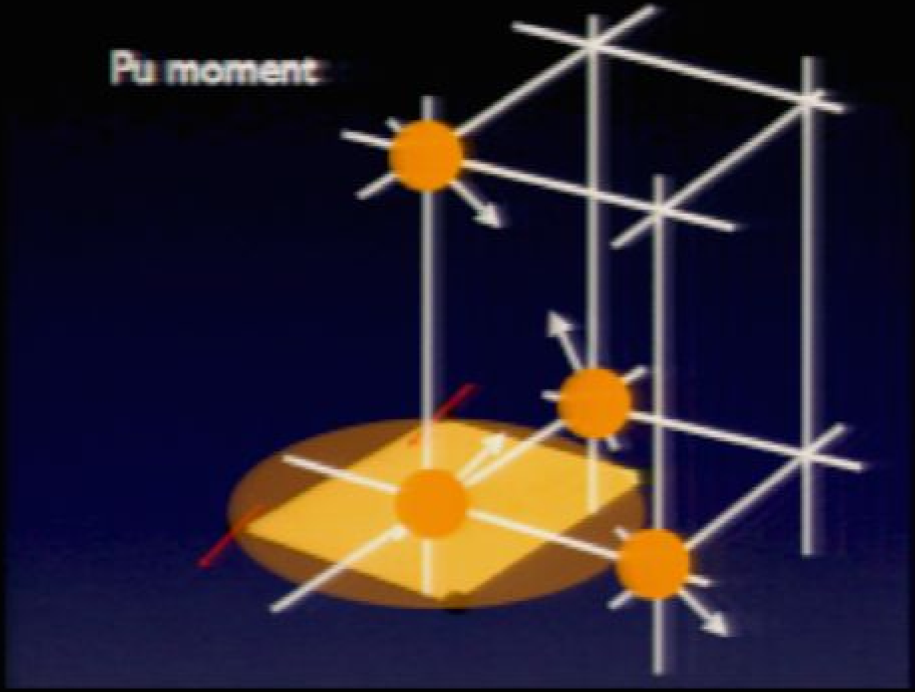
⟶ Local SU(2) gauge symmetry.

Composite pairing in the Kondo Lattice

Composite pairing in the Kondo Lattice



Model for $PuCoGa_5$ & $NpPd_2Al_5$



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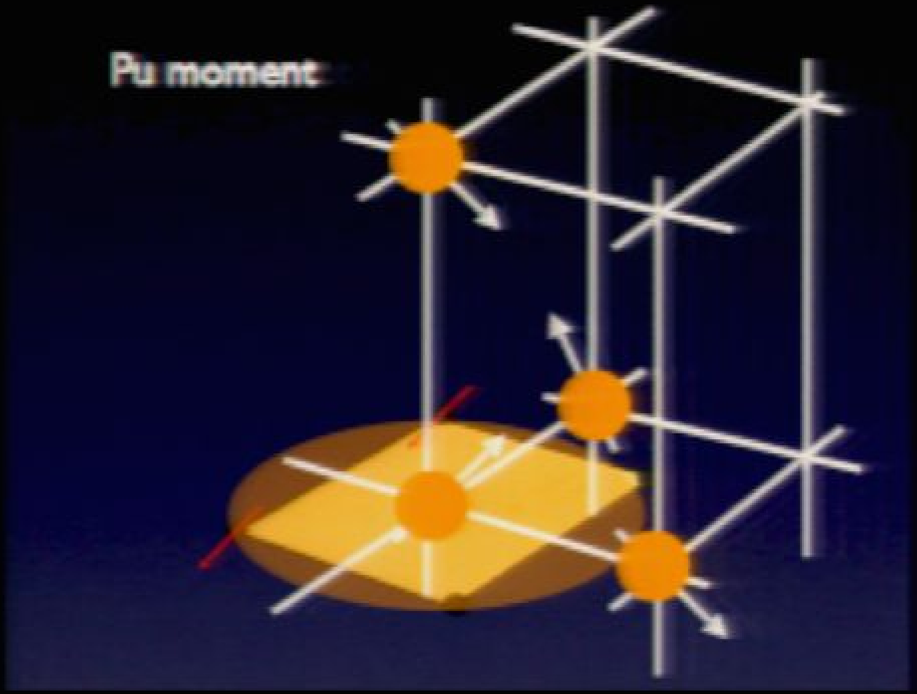

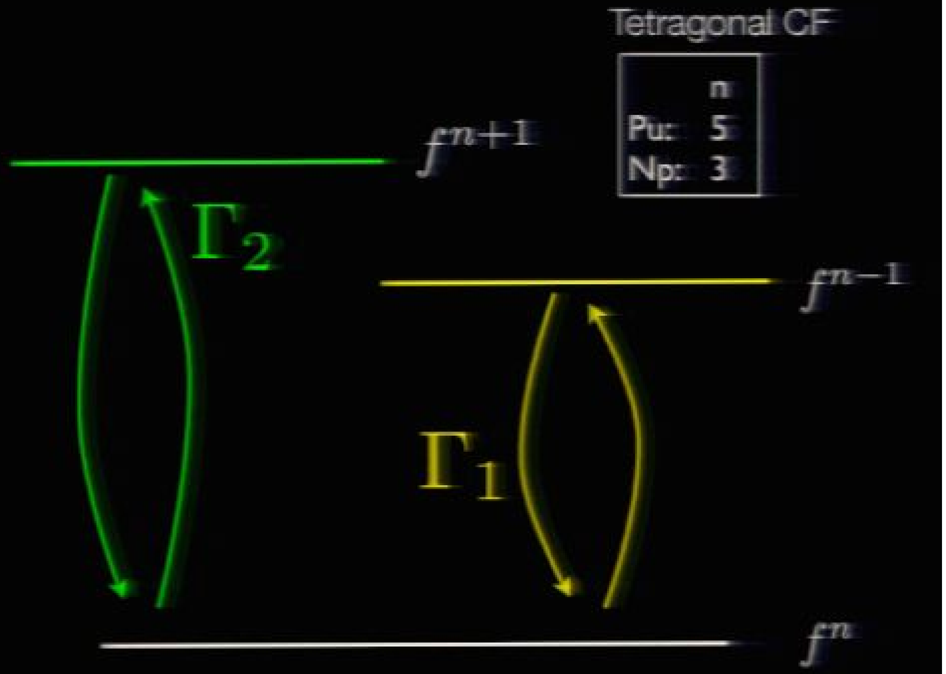

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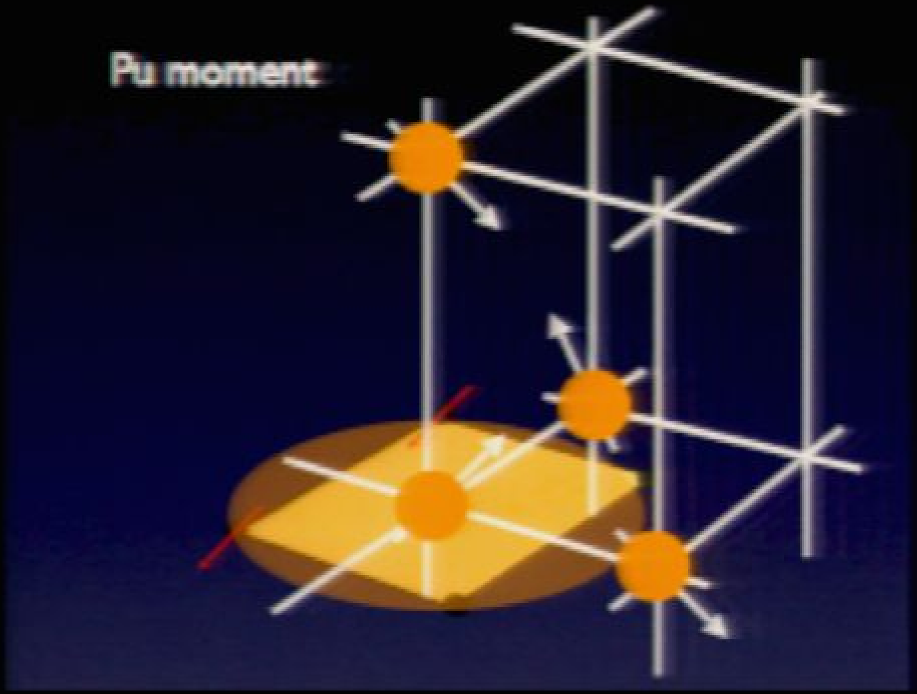

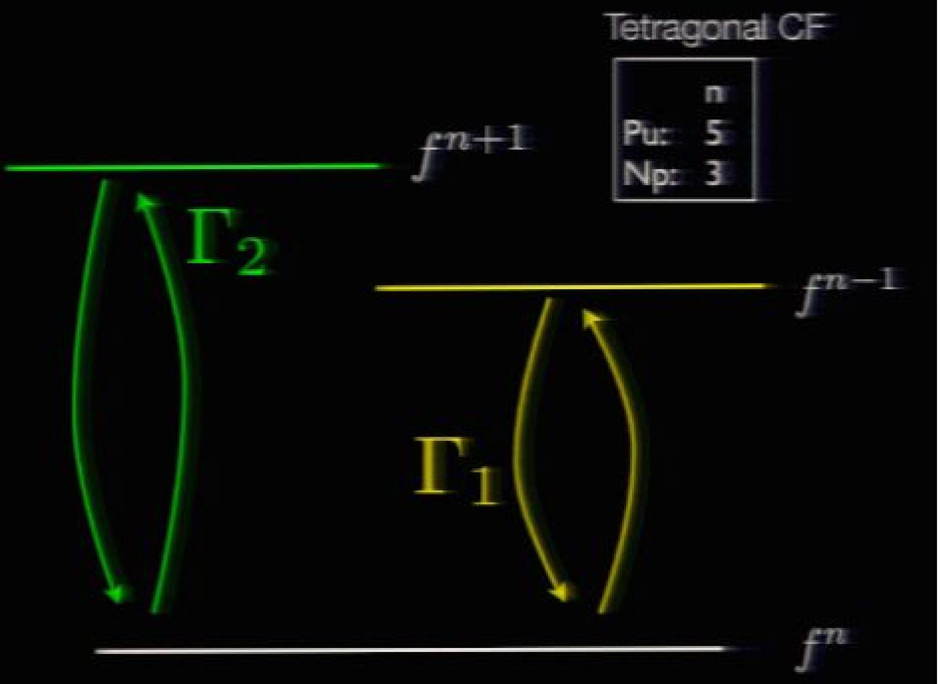

Tetragonal CF

	n
Pu:	5
Np:	3

Virtual valence fluctuations mediate Kondo-spin exchange in two channels with different symmetry (Cox, 89).

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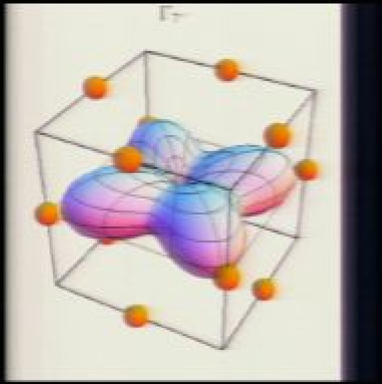
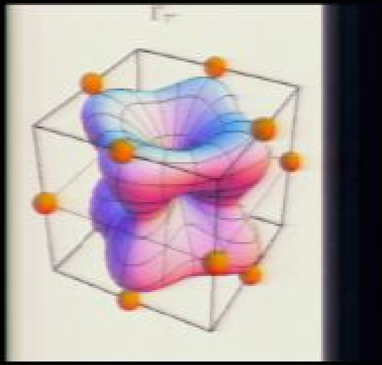


$\rangle \sim |\pm$



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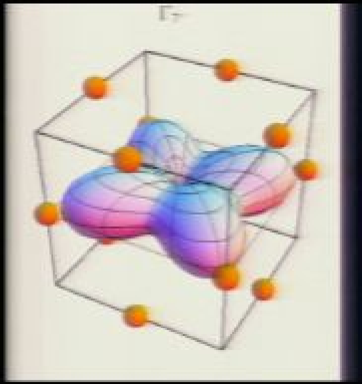
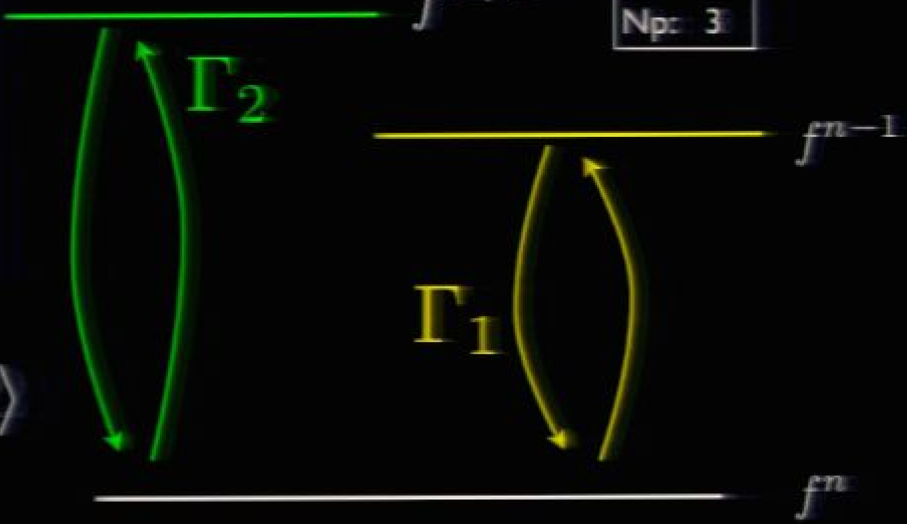


$|\Gamma_7^{+}\rangle \sim |\pm 5/2\rangle$



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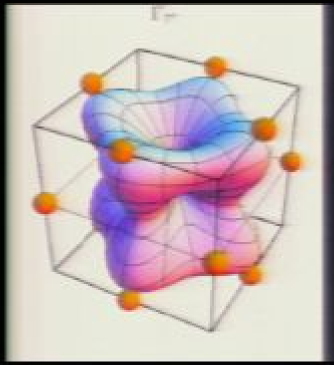

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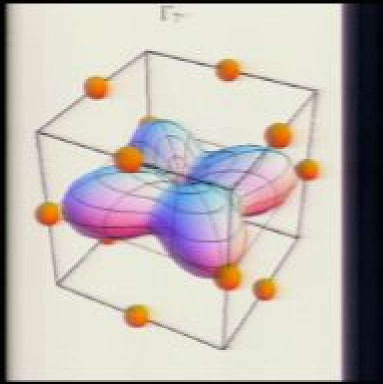
Model for PuCoGa$_5$ & NpPd$_2$Al$_5$



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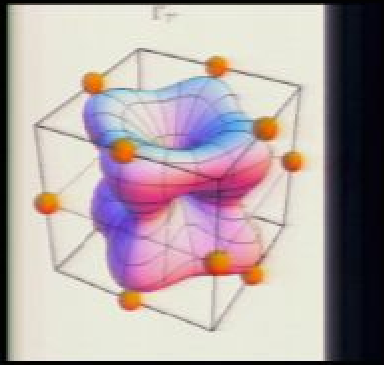

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$$H = \sum_k \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N}\sum_{\mathbf{k},\mathbf{k}'} \Big(J_1 \psi^\dagger_{1a}(j)\psi_{1b}(j) + J_2 \psi^\dagger_{2a}(j)\psi_{2b}(j) \Big) S^{ba}(j)$$

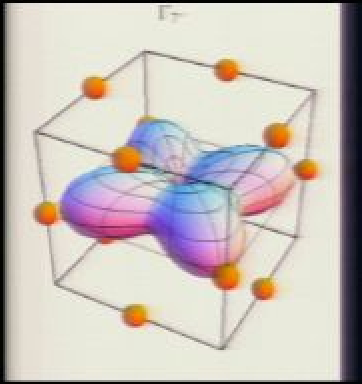
Single FS, two channels:

$$\psi_\Gamma(j) = \frac{1}{\sqrt{V}} \sum \gamma_{\Gamma\mathbf{k}} \; c_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}_j}$$

cf Cox, Pang, Jarell (96)

PC, Kee, Andrei, Tsvelik (98)

Model for PuCoGa$_5$ & NpPd$_2$Al$_5$



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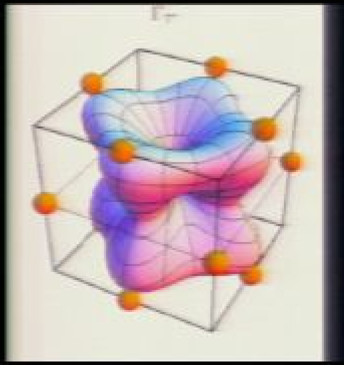

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Decoupling the interactions

$$\begin{aligned} H_I &= \frac{J_K}{N}\sum \psi_a^\dagger \psi_b \overbrace{\left(f_b^\dagger f_a - \tilde{a}\tilde{b} f^\dagger_{-a} f_{-b}\right)}^{S_{ba}} \\ &= -\frac{J_K}{N}\sum \Big[(\psi^\dagger f)(f^\dagger \psi) + (\psi^\dagger \sigma_2 f^\dagger)(f \sigma_2 \psi) \Big]. \end{aligned}$$

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$$H_I \rightarrow \left[[V f^\dagger + (\Delta f \sigma_2)]\psi + \mathrm{H.c} \right] + N\left(\frac{\bar{V}V + \bar{\Delta}\Delta}{J_K} \right).$$

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$$H_I \to \left[\underbrace{[V f^\dagger + (\Delta f \sigma_2)]}_{=\tilde f^\dagger \sqrt{|V|^2+|\Delta|^2} = \tilde f^\dagger \tilde V} \psi + \mathrm{H.c} \right] + N \left(\frac{\bar V V + \bar \Delta \Delta}{J_K} \right).$$

- “Pairing” can be gauged away for 1 channel.

Decoupling the interactions

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Decoupling the interactions

- Two channels:

Decoupling the interactions

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$$\begin{aligned} H_I \quad &\rightarrow \quad \left[[V_1 f^\dagger + (\Delta_1 f \sigma_2)]\psi_1 + \mathrm{H.c} \right] + N \left(\frac{\bar{V}_1 V_1 + \bar{\Delta}_1 \Delta_1}{J_1} \right) \\ &+ \quad \left[[V_2 f^\dagger + (\Delta_2 f \sigma_2)]\psi_2 + \mathrm{H.c} \right] + N \left(\frac{\bar{V}_2 V_2 + \bar{\Delta}_2 \Delta_2}{J_2} \right) \end{aligned}$$

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Gauge fixing does not remove the pairing

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The gauge-invariant cross term $V_1\Delta_2 - V_2\Delta_1$ describe the overscreened formation of composite pairs

$$\langle \vec{S} \cdot \psi_1 \sigma_2 \vec{\sigma} \psi_2 \rangle \sim V_1\Delta_2 - V_2\Delta_1$$

PC, Kee, Andrei & Tsvelik. (97)

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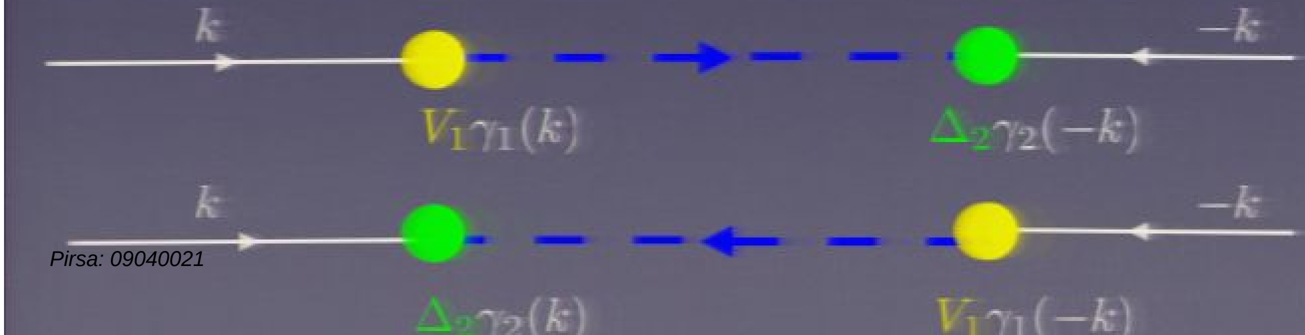
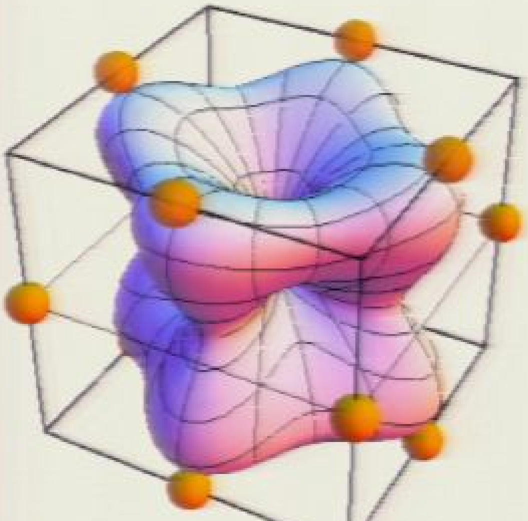
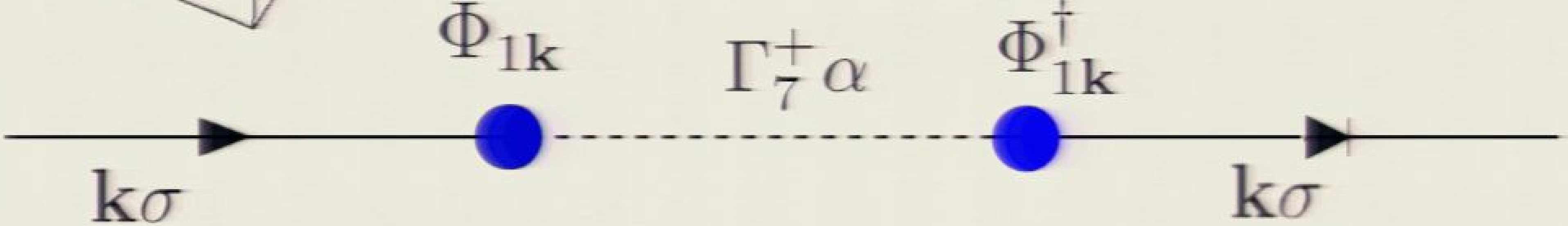


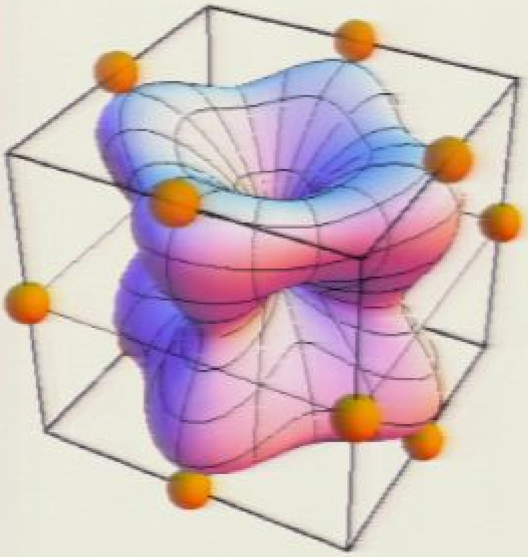
$\Delta_{eff}(k) \sim V_1\Delta_2\gamma_1(k)\gamma_2(k)$

"resonant Andreev scattering."



$= \Phi^{\dagger}_{1\mathbf{k}} . \Phi_{1\mathbf{k}}$





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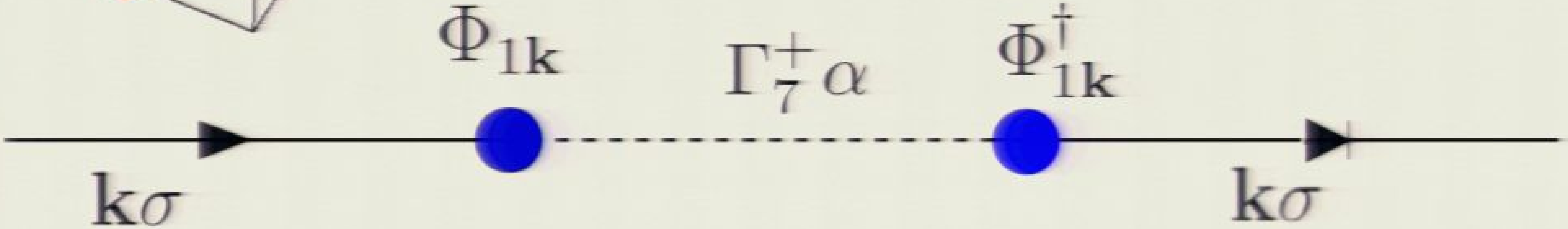

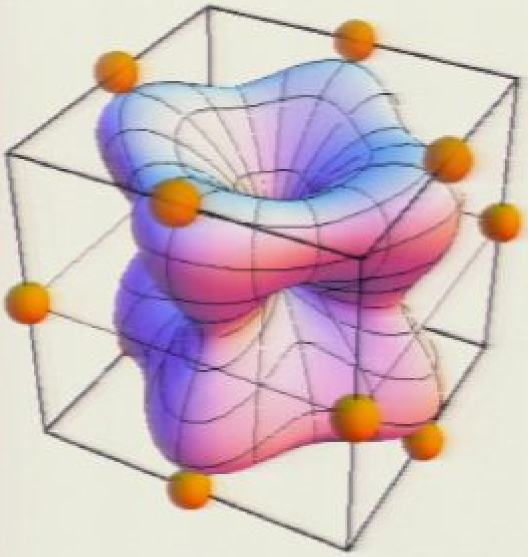

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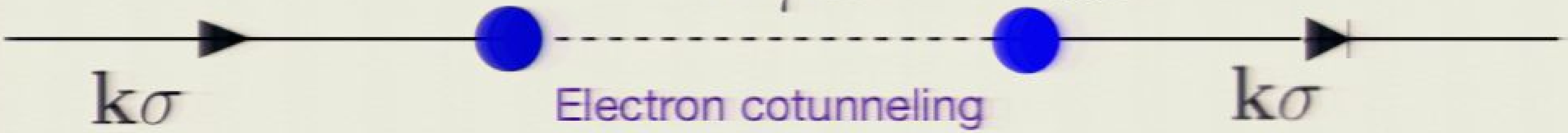
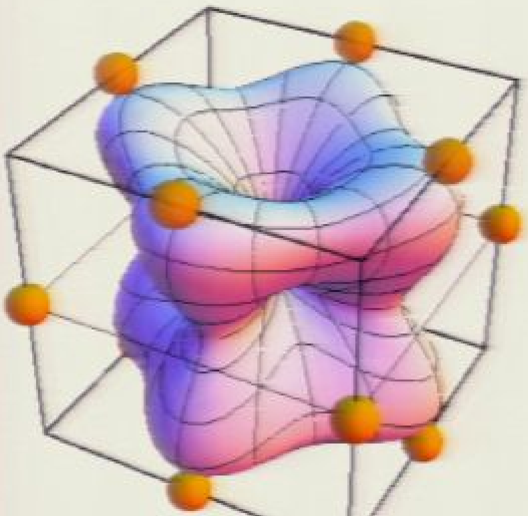
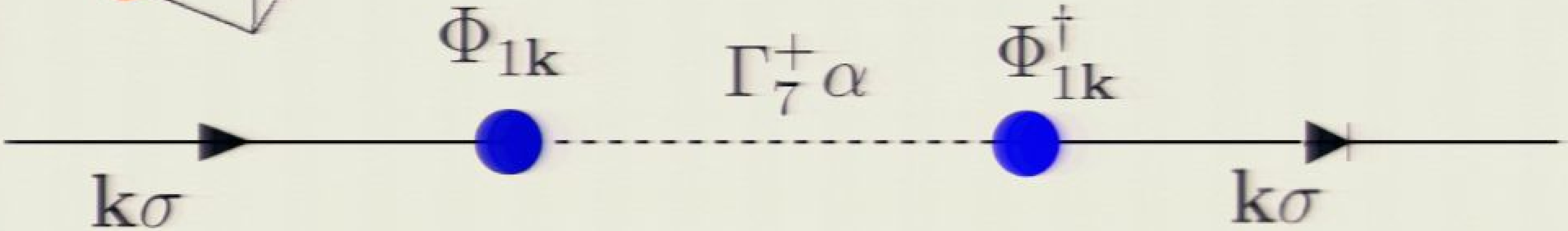
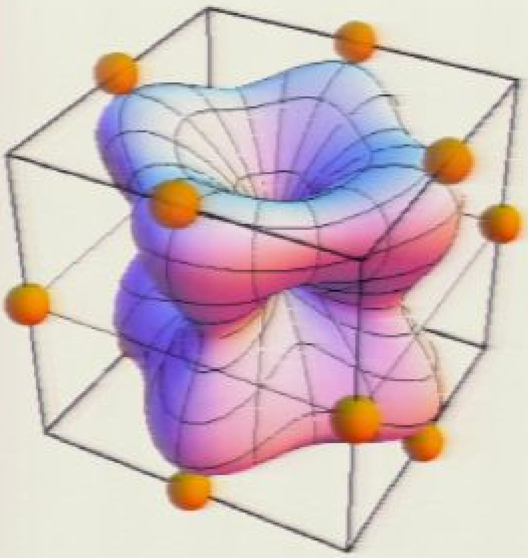
$\Phi_{1\mathbf{k}}$ $\Gamma_7^{+}\,\alpha$ $\Phi^{\dagger}_{1\mathbf{k}}$



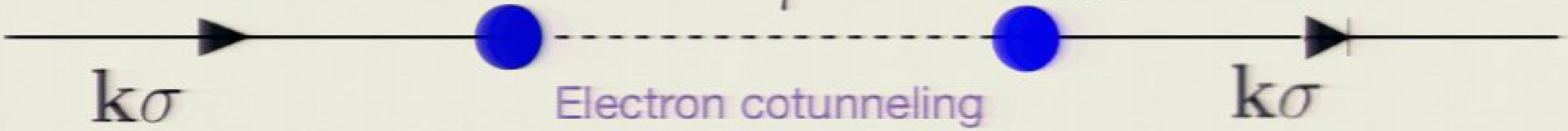


$$= \Phi^{\dagger}_{1\mathbf{k}} . \Phi_{1\mathbf{k}}$$





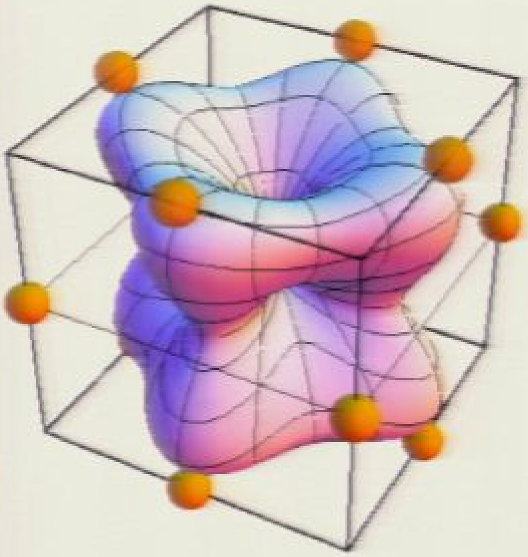
$$= \Phi^\dagger_{1\mathbf{k}} . \Phi_{1\mathbf{k}}$$



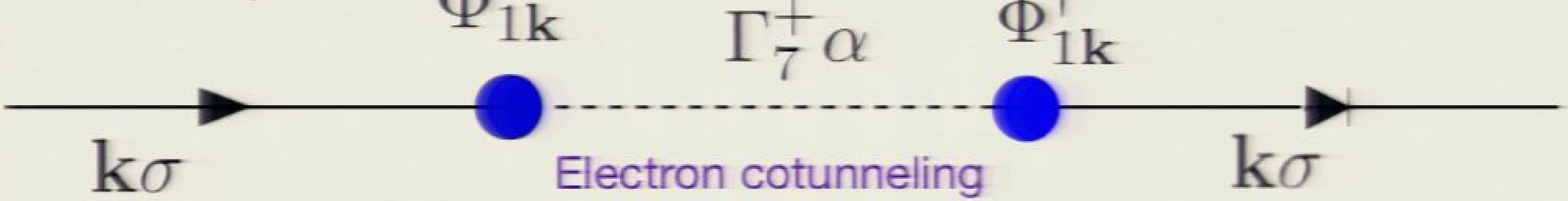
$\Phi_{1\mathbf{k}}$ $\Gamma_7^+ \alpha$ $\Phi^\dagger_{1\mathbf{k}}$

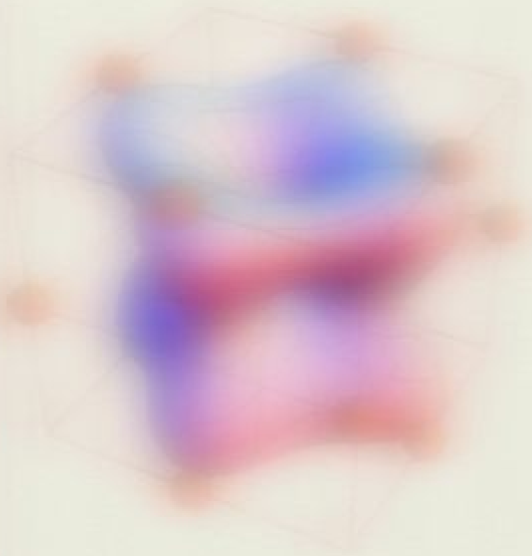
$\mathbf{k}\sigma$ $\mathbf{k}\sigma$

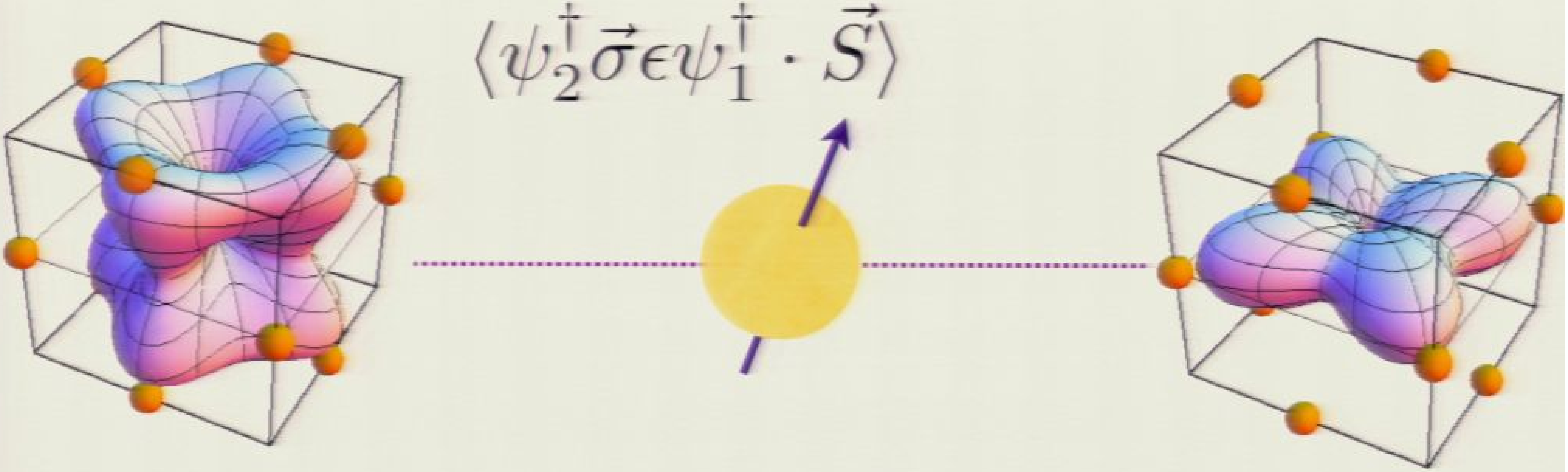
Electron cotunneling



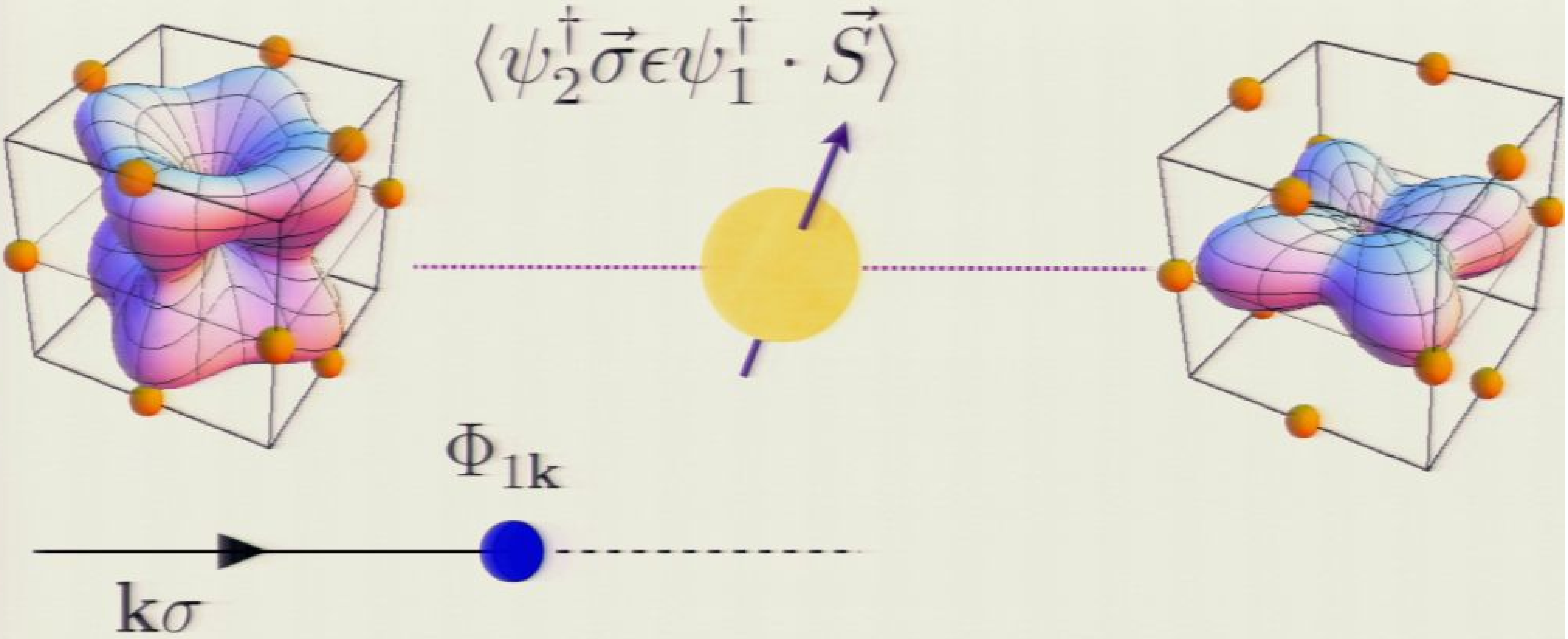
$$= \Phi^\dagger_{1\mathbf{k}} . \Phi_{1\mathbf{k}}$$



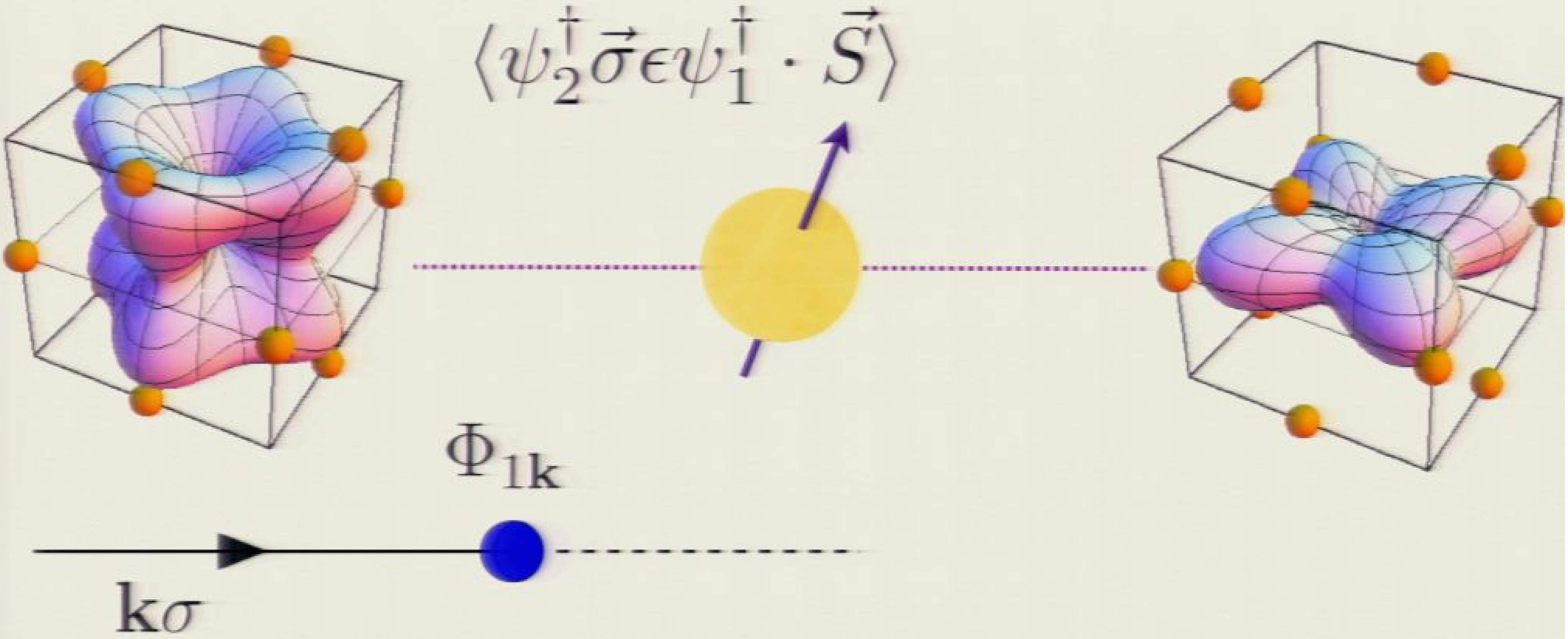




$$\langle \psi_2^\dagger \vec{\sigma} \epsilon \psi_1^\dagger \cdot \vec{S} \rangle$$



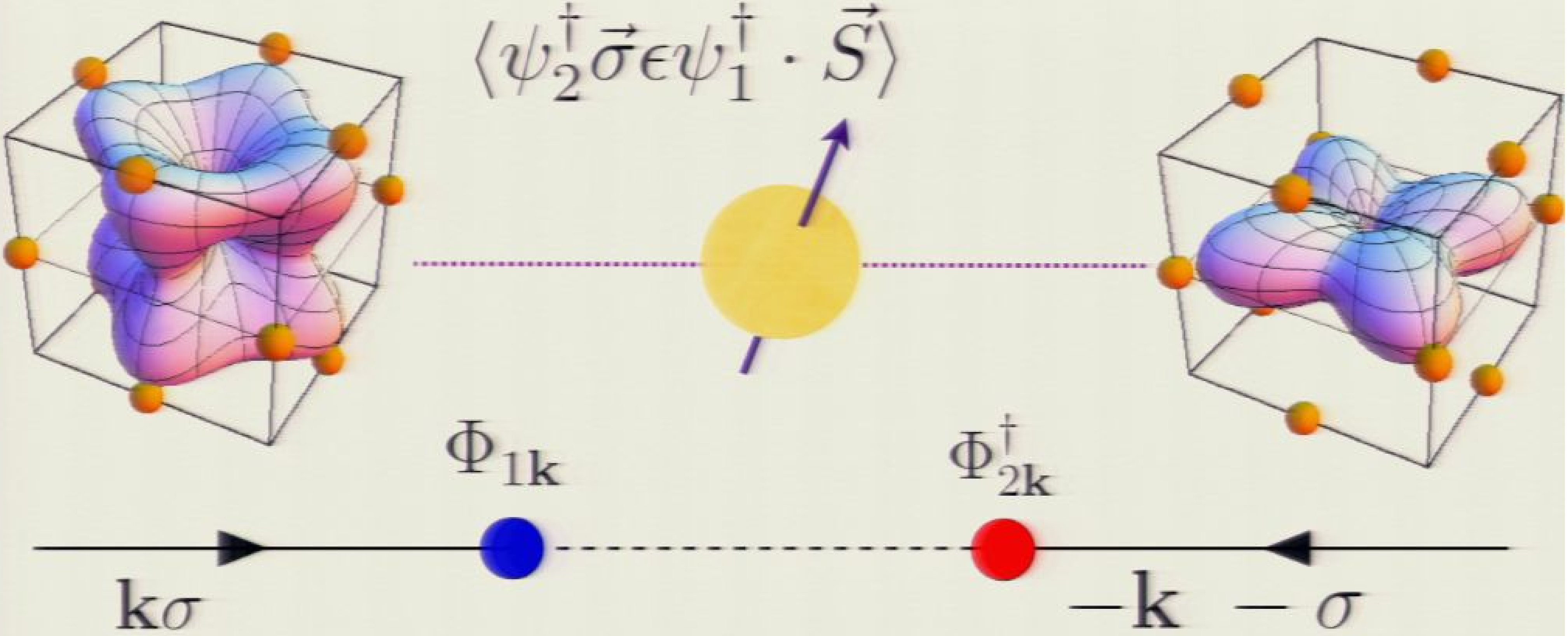
$$\langle \psi_2^\dagger \vec{\sigma} \epsilon \psi_1^\dagger \cdot \vec{S} \rangle$$



$$\langle \psi_2^\dagger \vec{\sigma} \epsilon \psi_1^\dagger \cdot \vec{S} \rangle$$

$\Phi_{1\mathbf{k}}$

$\mathbf{k}\sigma$



$$\langle \psi_2^\dagger \vec{\sigma} \epsilon \psi_1^\dagger \cdot \vec{S} \rangle$$

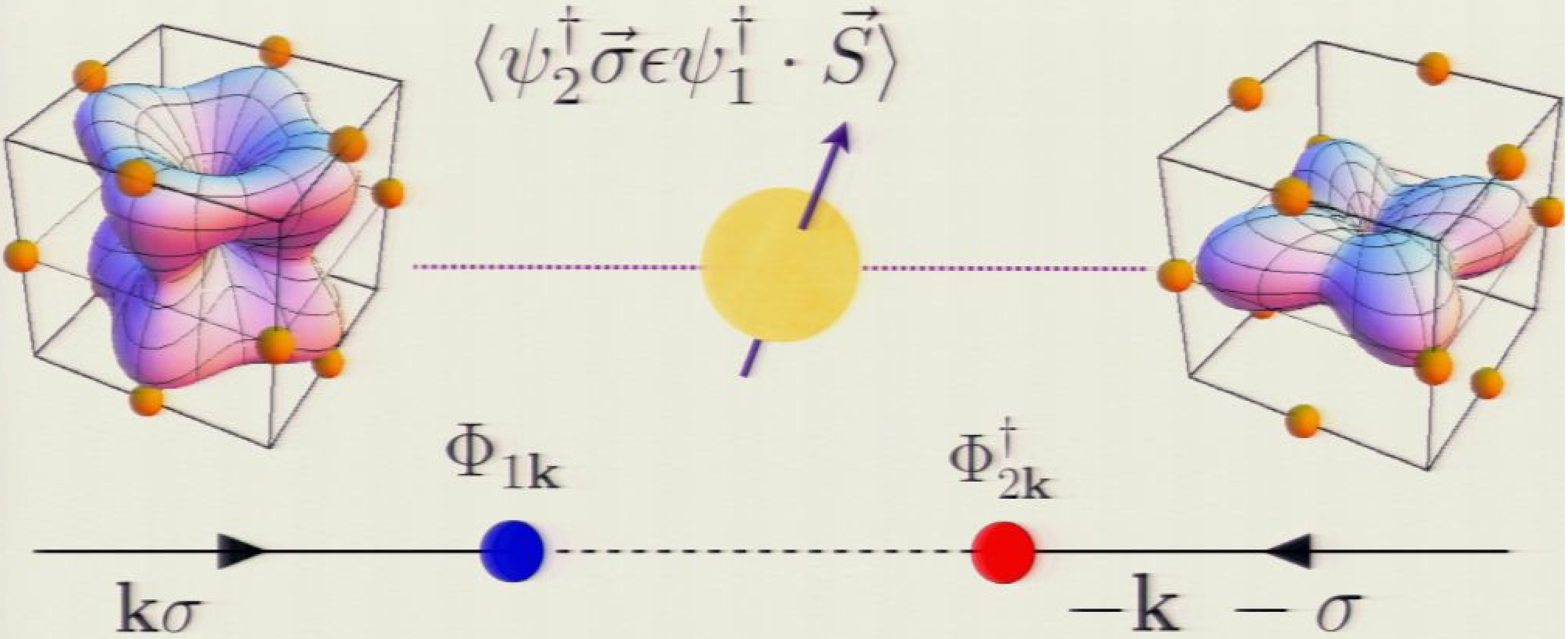
$\Phi_{1\mathbf{k}}$

$\Phi^\dagger_{2\mathbf{k}}$

$\mathbf{k}\sigma$

$-\mathbf{k} \; -\sigma$

Resonant Andreev Reflection



$\langle \psi_2^\dagger \vec{\sigma} \epsilon \psi_1^\dagger \cdot \vec{S} \rangle$

$\Phi_{1\mathbf{k}}$

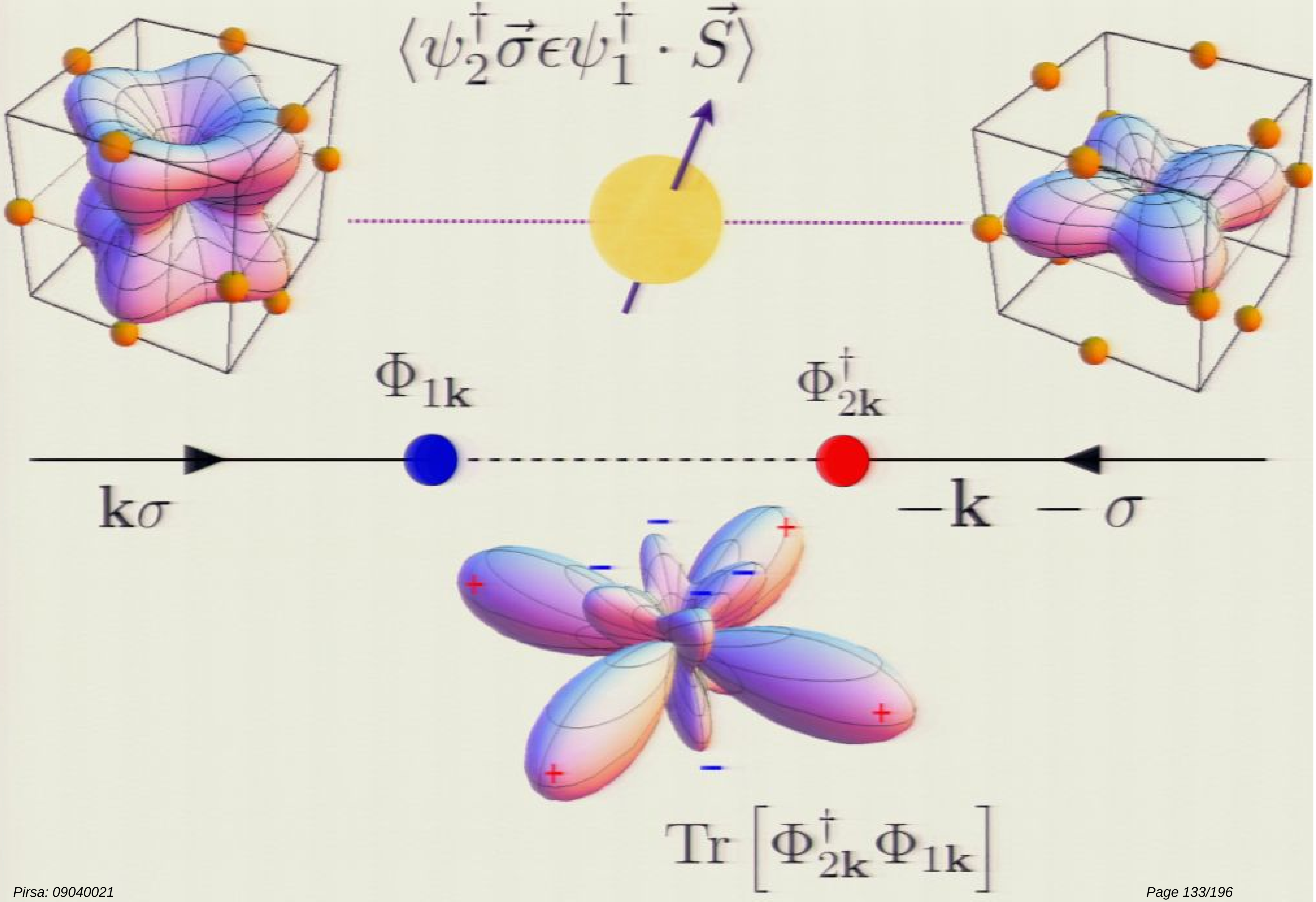
$\Phi_{2\mathbf{k}}^\dagger$

$\mathbf{k}\sigma$

$-\mathbf{k} \ -\sigma$

$$\mathrm{Tr}\left[\Phi_{2\mathbf{k}}^\dagger \Phi_{1\mathbf{k}}\right]$$

Resonant Andreev Reflection



$\langle \psi_2^\dagger \vec{\sigma} \epsilon \psi_1^\dagger \cdot \vec{S} \rangle$

$\Phi_{1\mathbf{k}}$

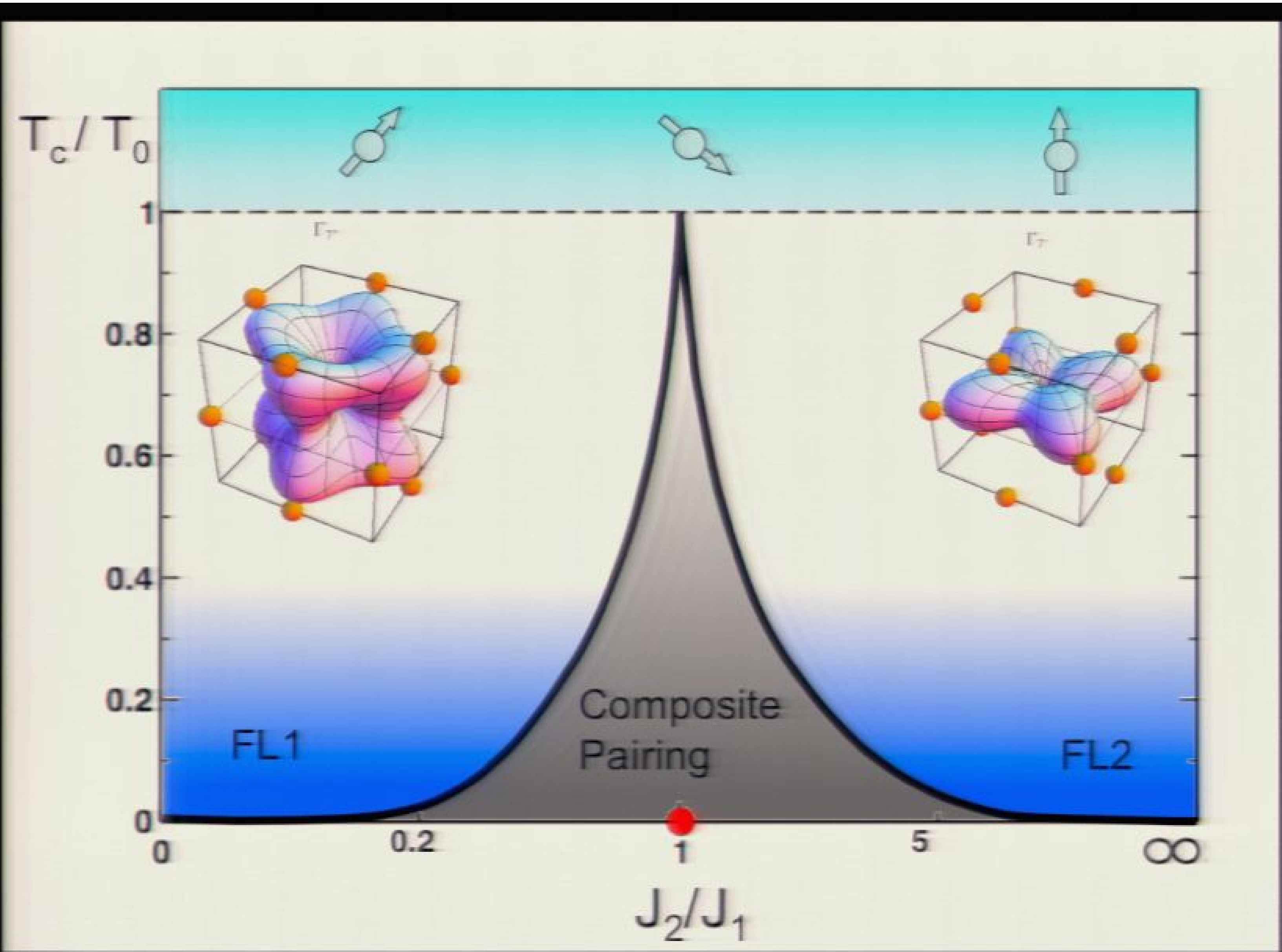
$\Phi^\dagger_{2\mathbf{k}}$

$\mathbf{k}\sigma$

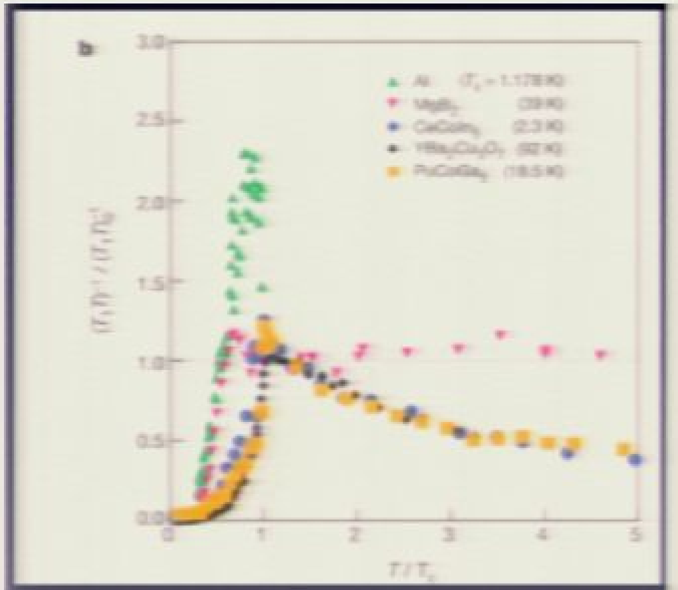
$-\mathbf{k} \;\; -\sigma$

$\mathrm{Tr}\left[\Phi^\dagger_{2\mathbf{k}} \Phi_{1\mathbf{k}}\right]$

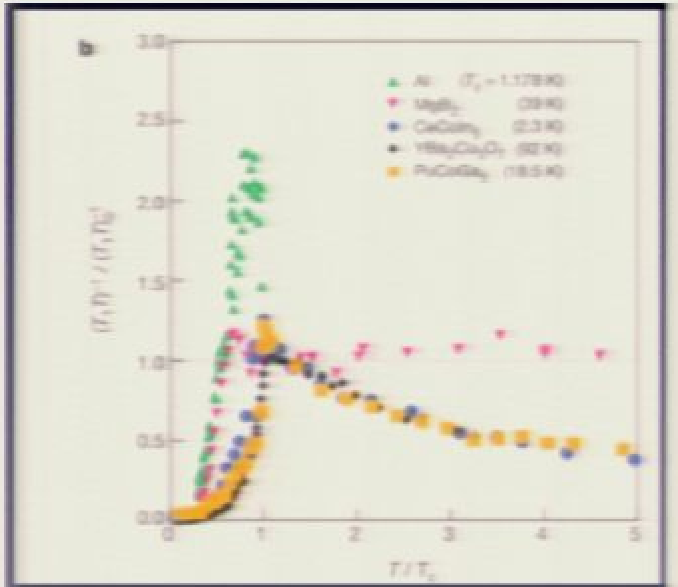
Resonant Andreev Reflection



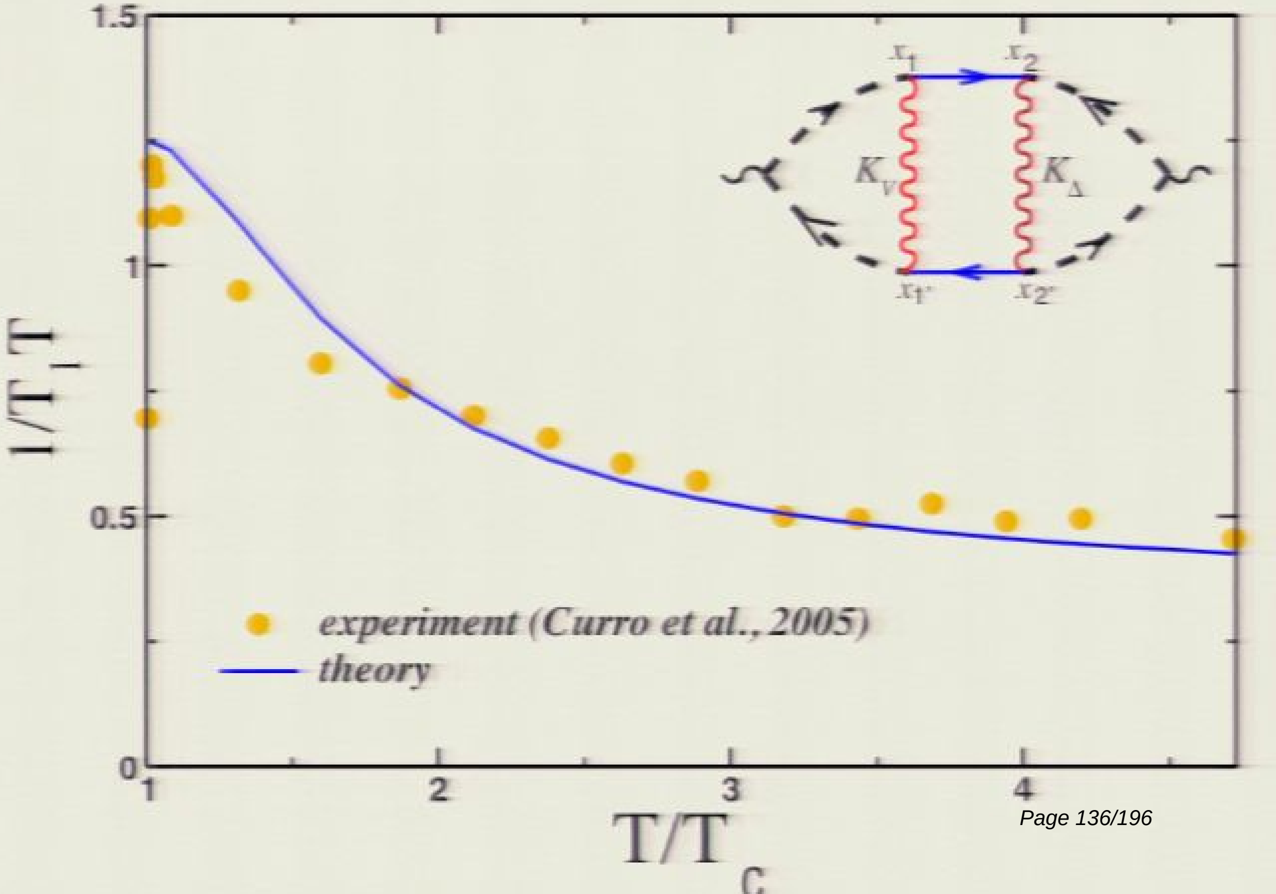
Avoided two-channel critical point gives rise to composite pairing



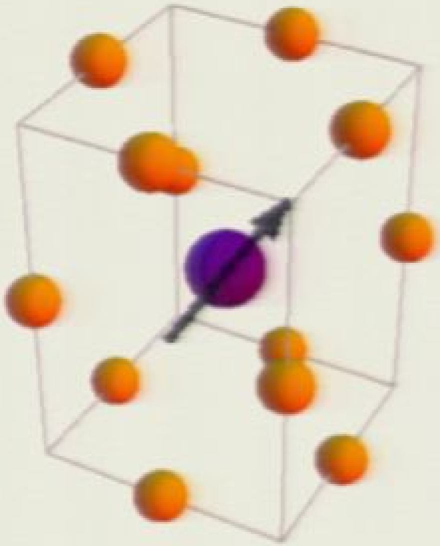
Curro et al, Nature, 434,622 (2005).

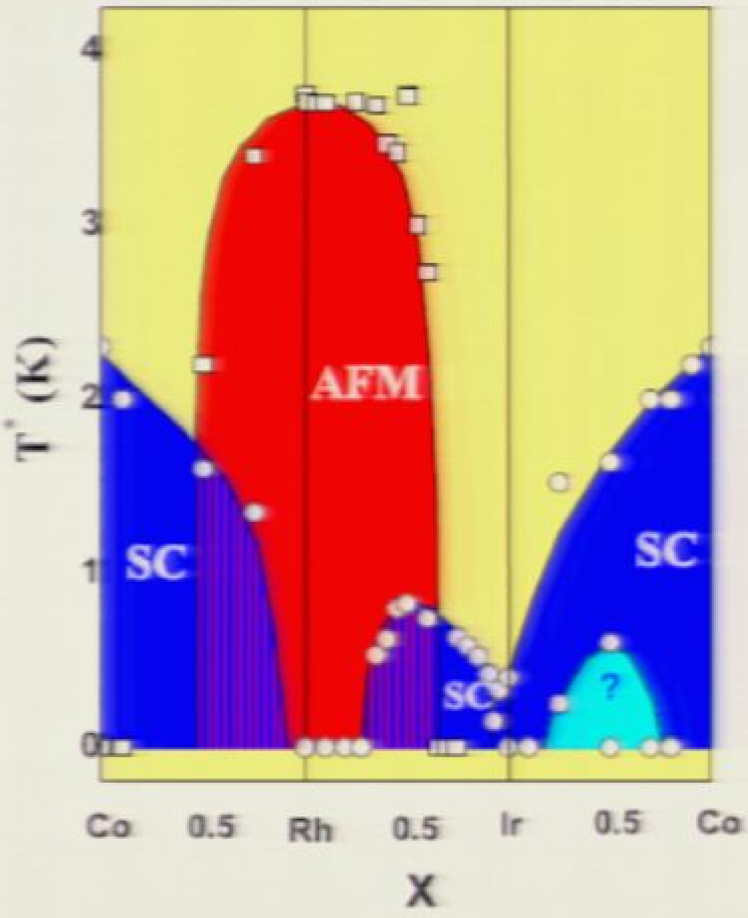


Curro et al, Nature, 434,622 (2005).



Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$





Sarrao and Thompson, JPSJ 76, 051013(2007)

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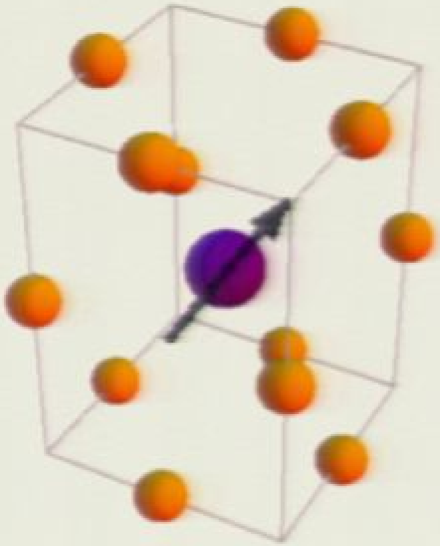
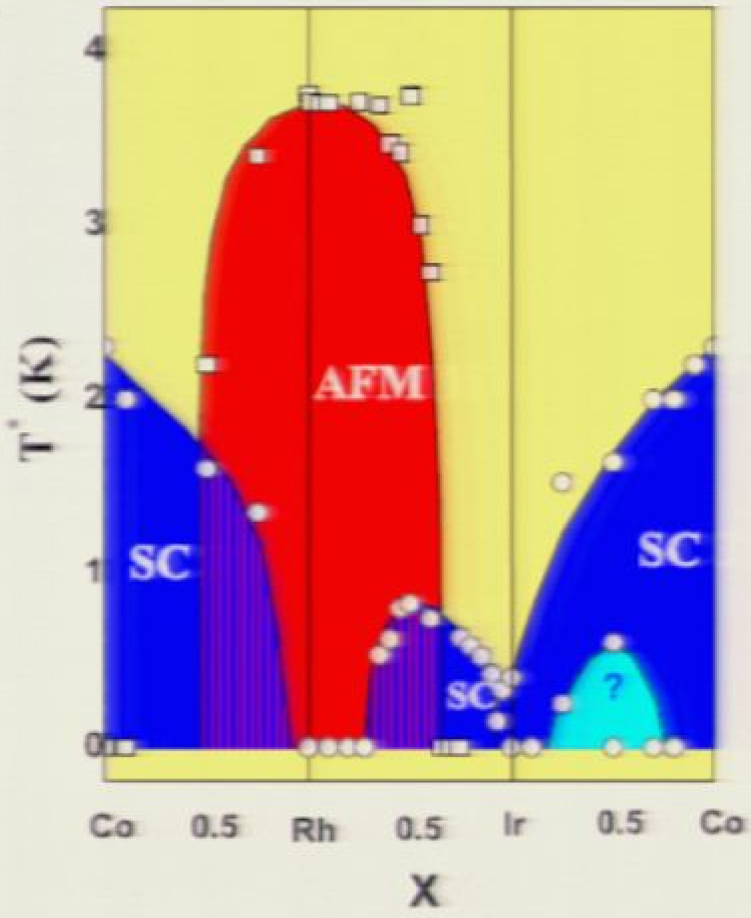
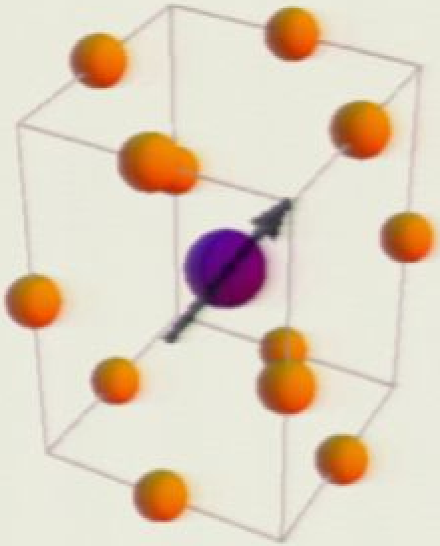


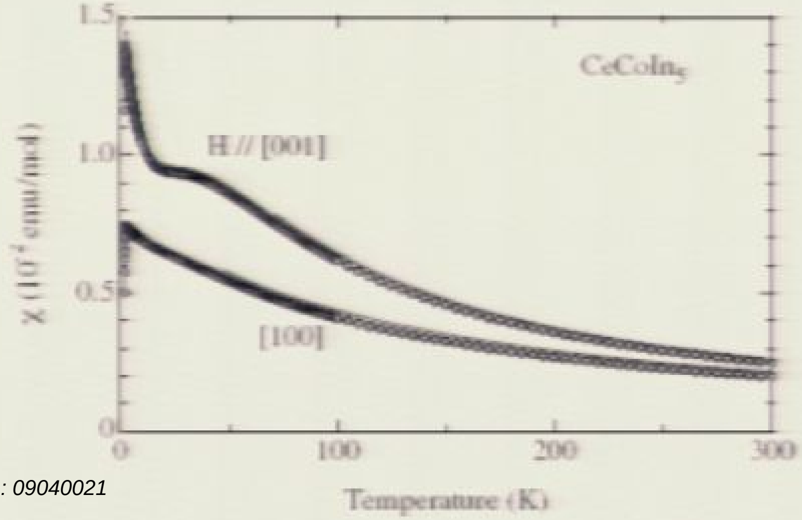
"Magnetically mediated pairing"



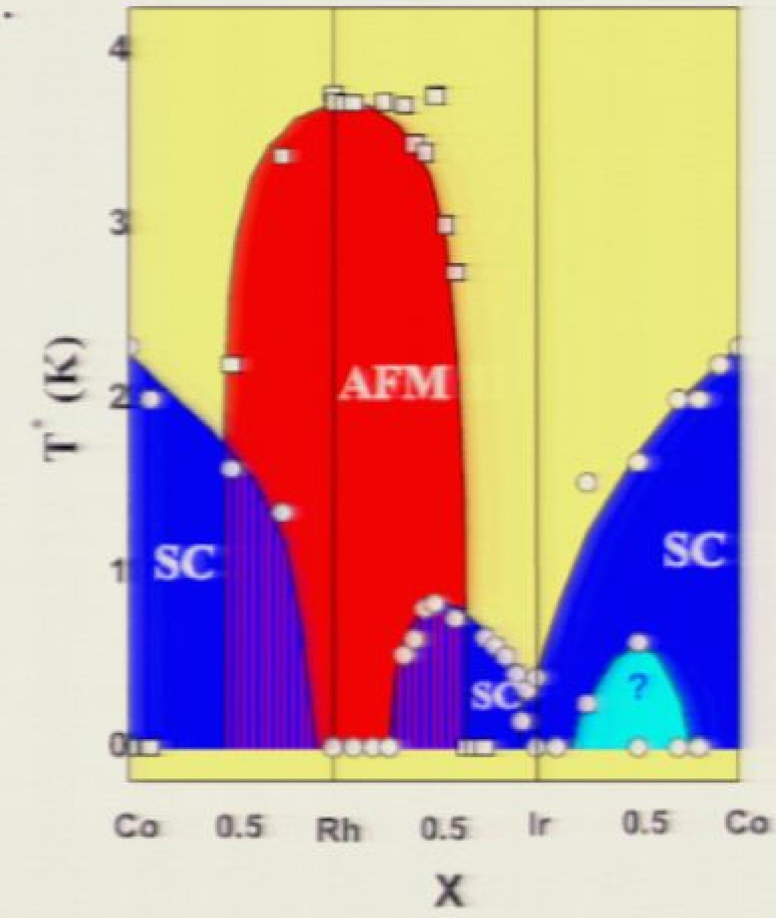
Sarrao and Thompson. JPSJ 76. 051013(2007)

Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$



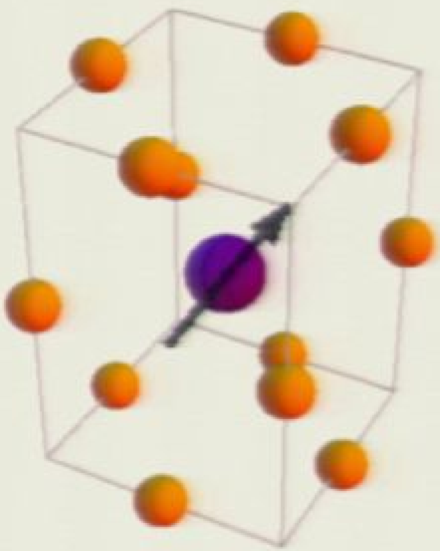


"Magnetically mediated pairing"

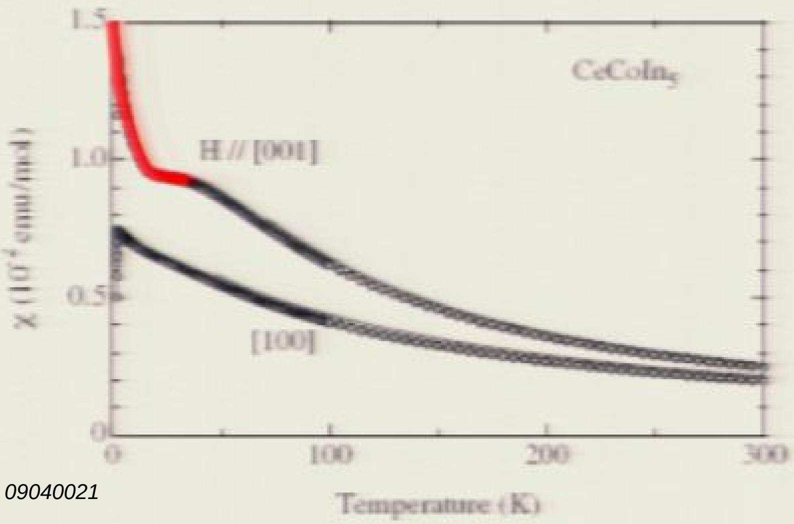


Sarrao and Thompson. JPSJ 76. 051013(2007)

Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$

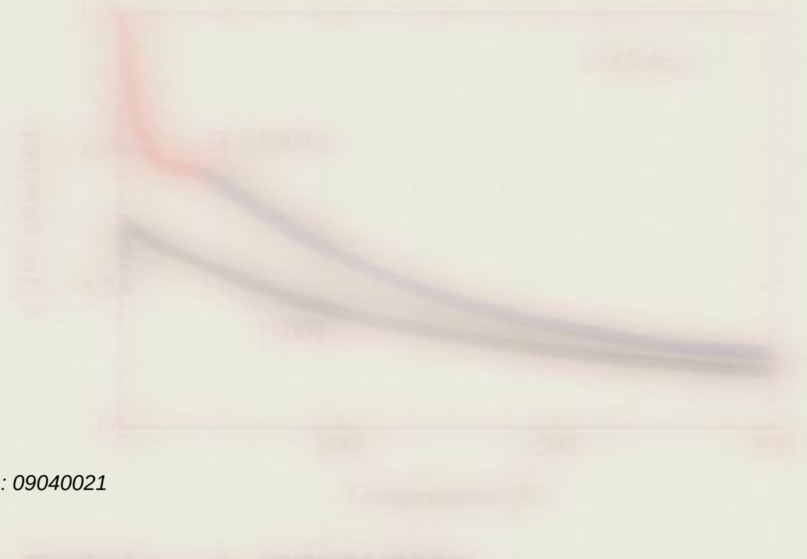


Composite pairing?

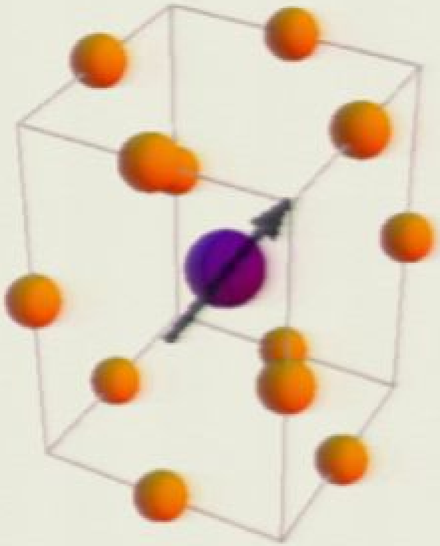


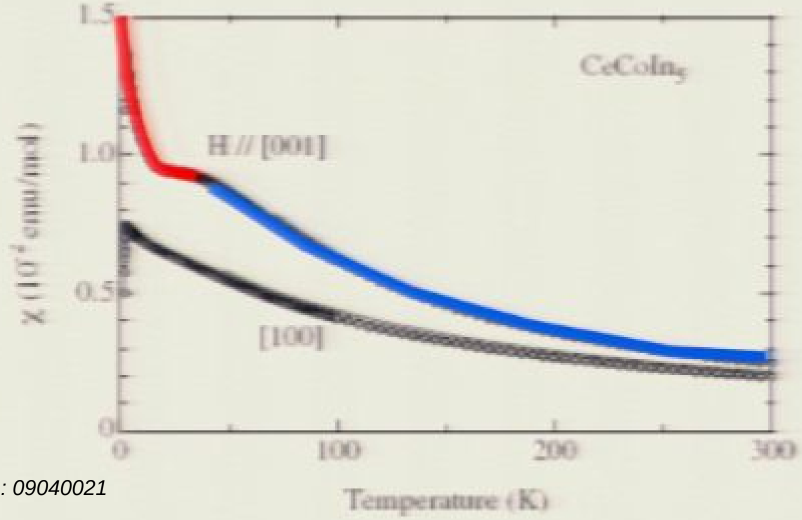
[illegible]

[illegible]



Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$





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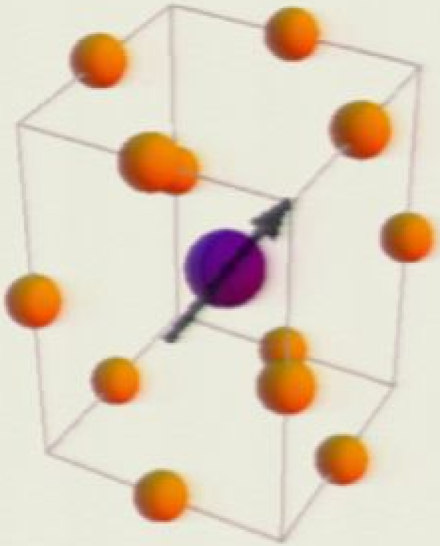
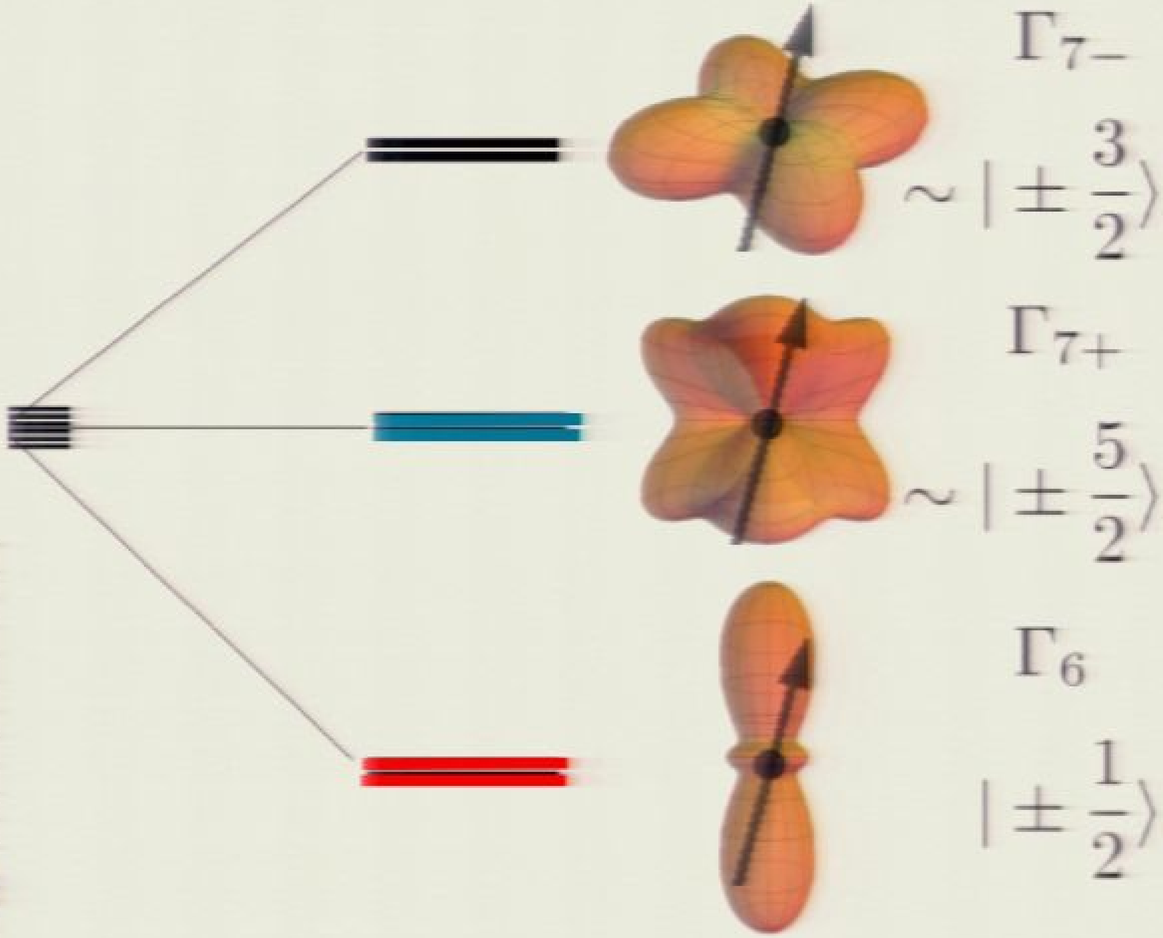
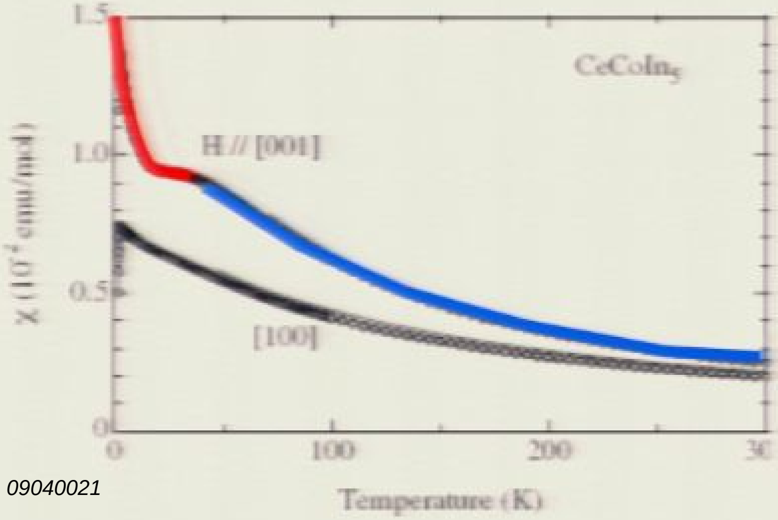




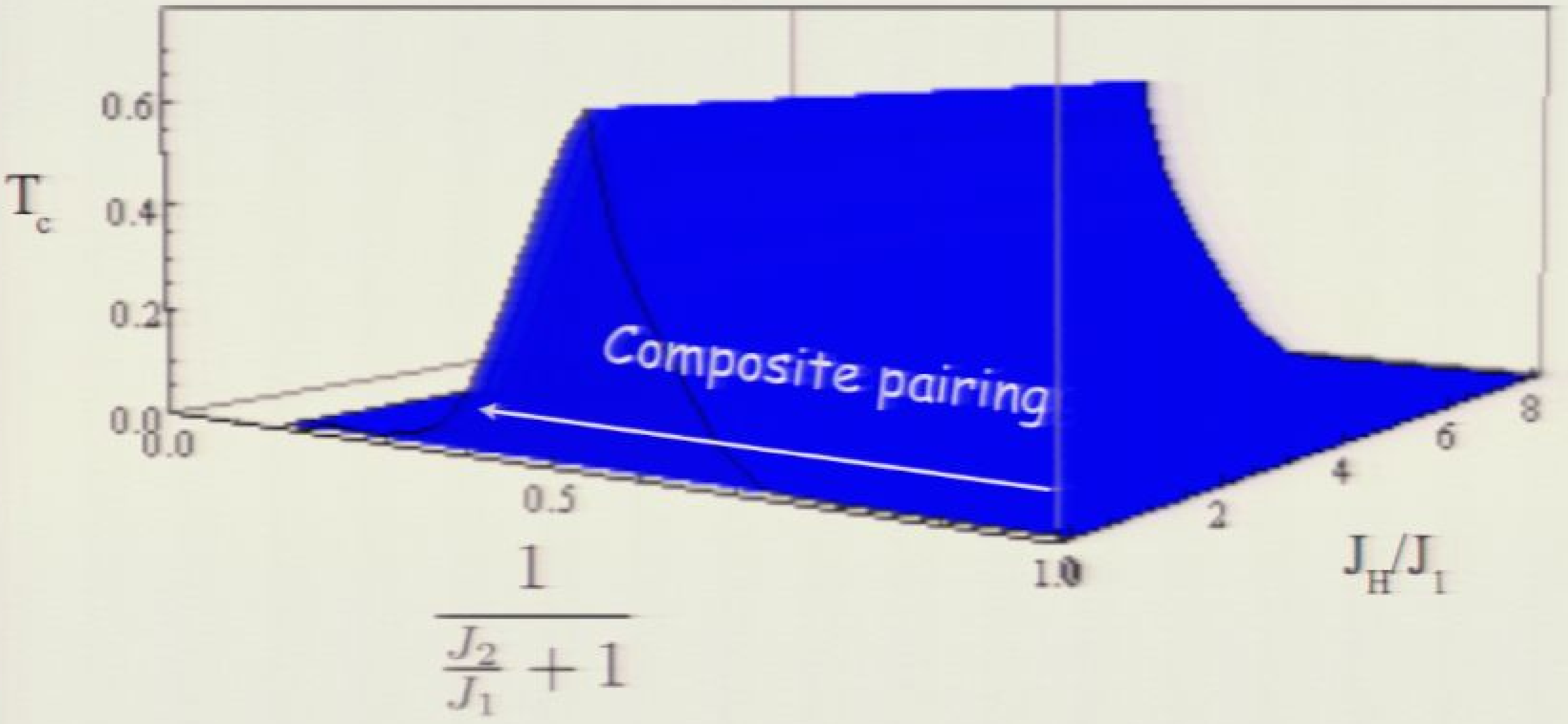


Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$

- Composite Pair Superconductivity

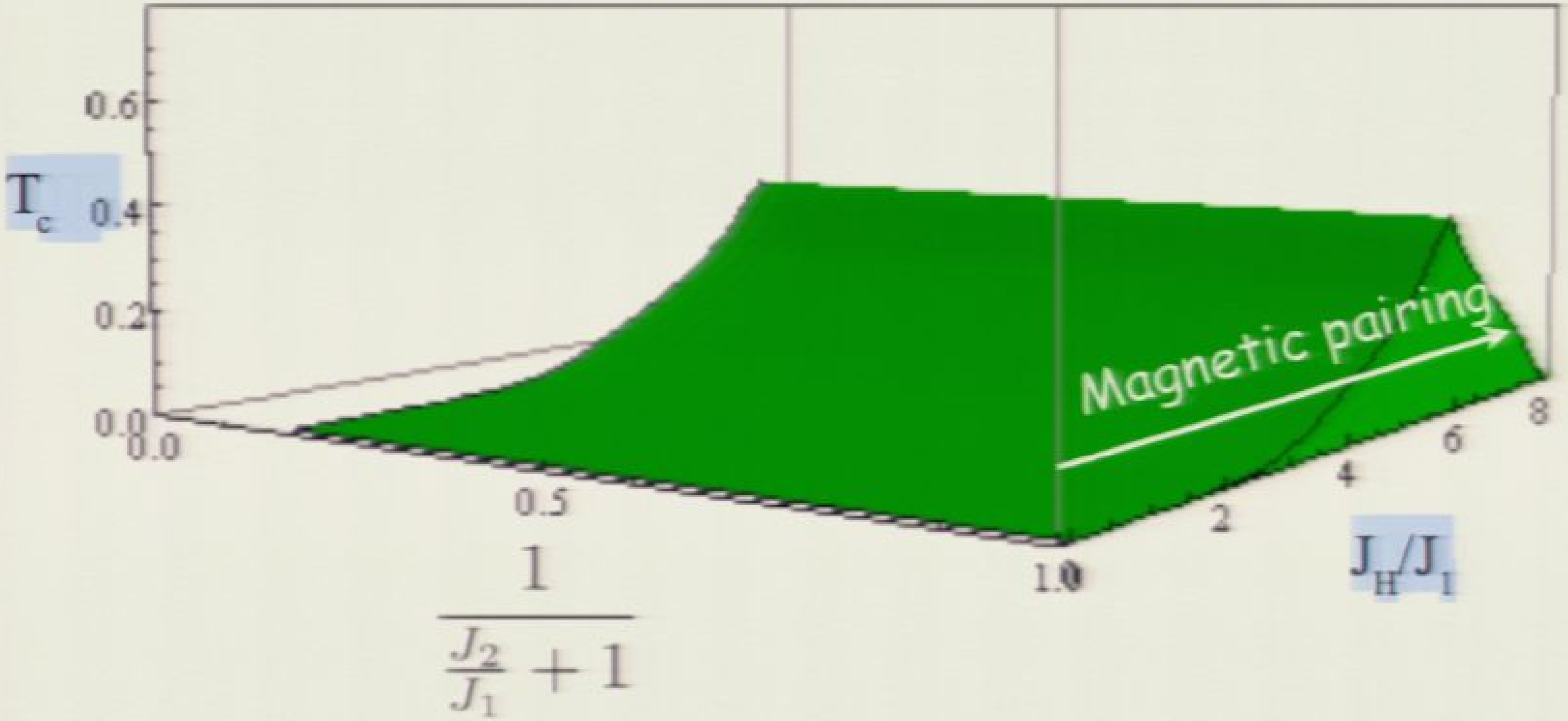
Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$

- Composite Pair Superconductivity

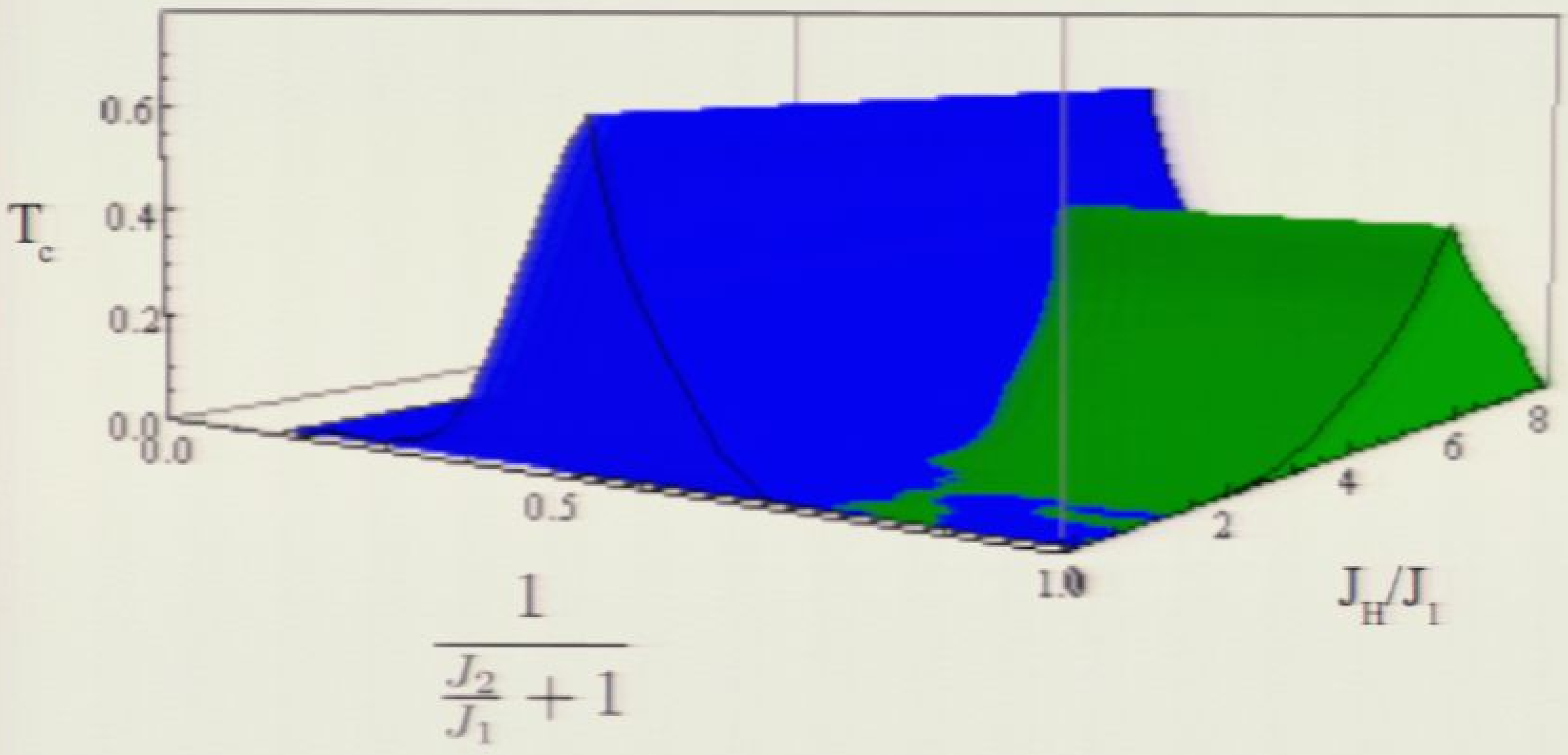


Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$

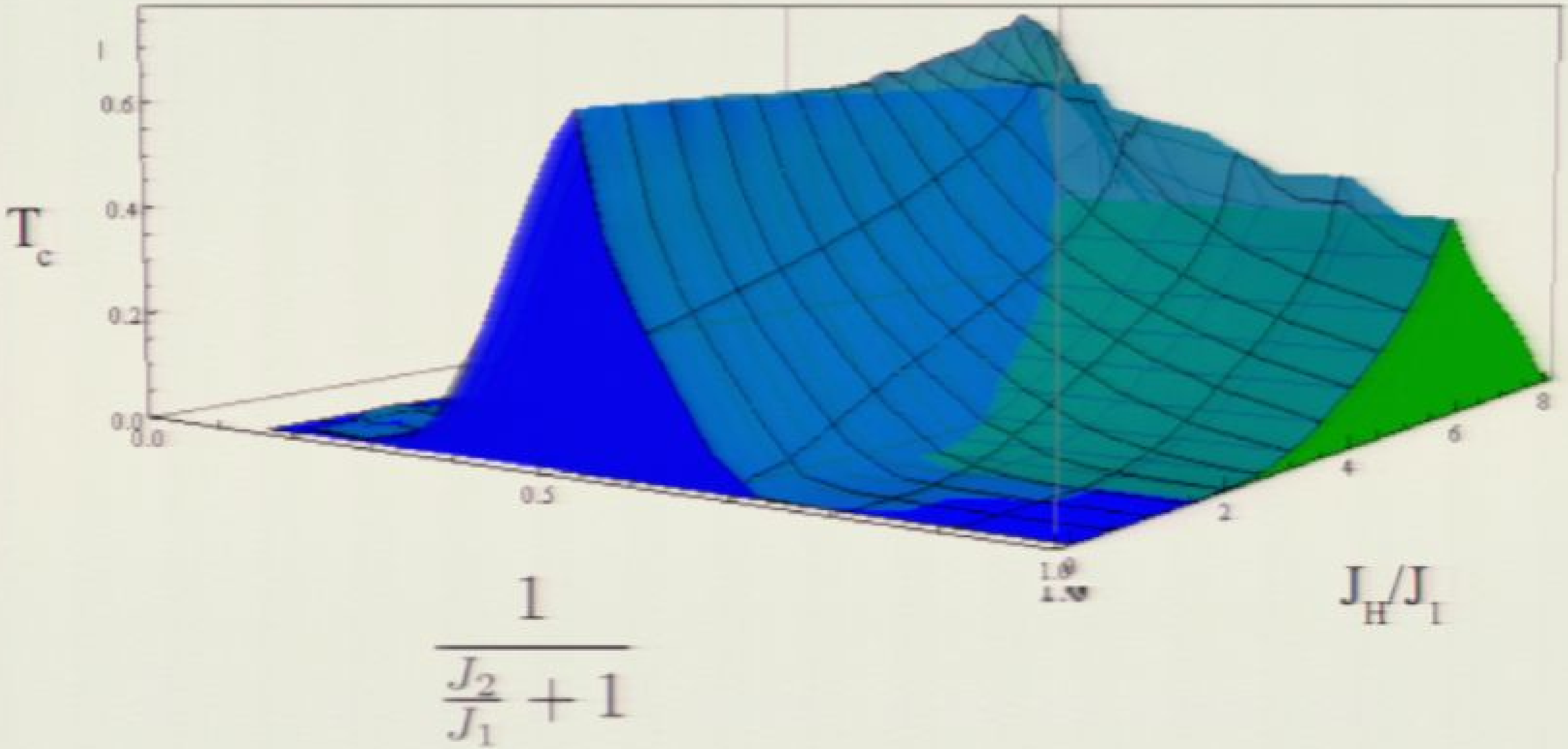
- RVB superconductivity



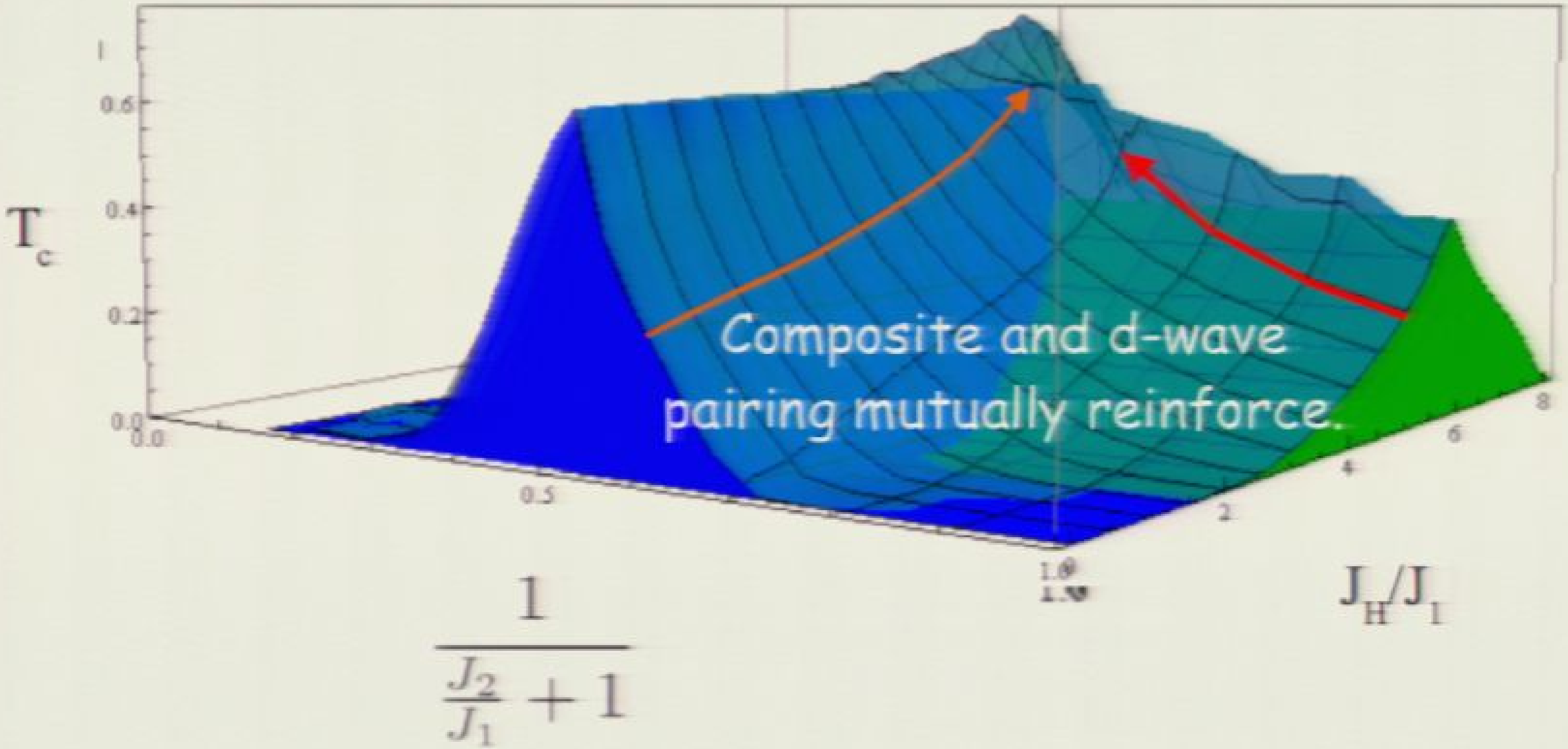
Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$



Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$

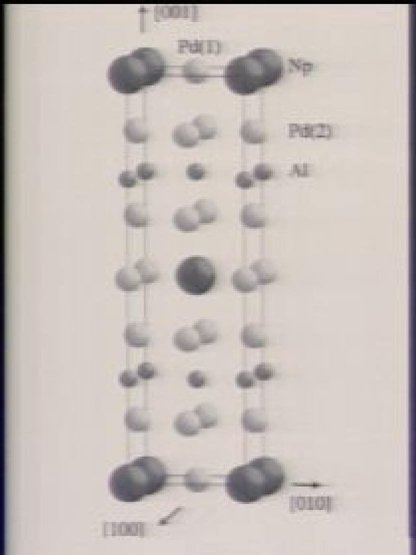


Ongoing challenge to unify magnetically mediated pairing and composite pairing: $CeCoIn_5$



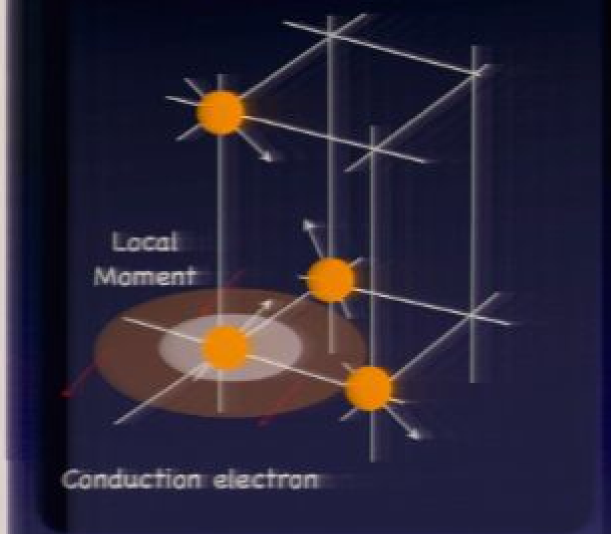
Composite and d-wave pairing mutually reinforce.

Conclusions

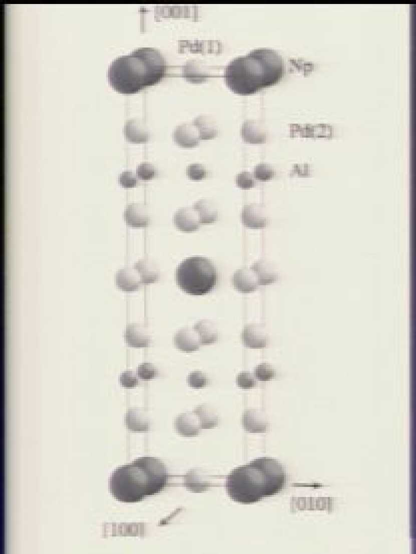


4.5K Heavy Fermion S.C $NpAl_2Pd_5$

18.5 K Heavy Fermion SC $PuCoGa_5$



Conclusions



4.5K Heavy Fermion
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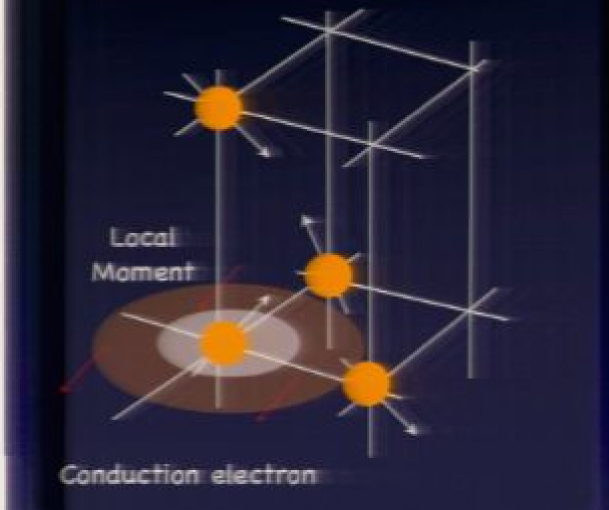
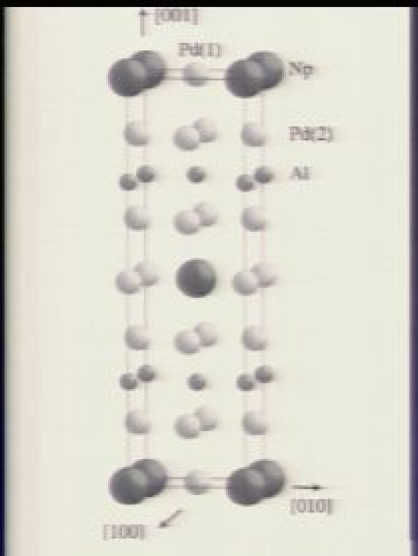


Conclusions

- Symplectic spins: 1/N expansion for heavy fermion superconductivity



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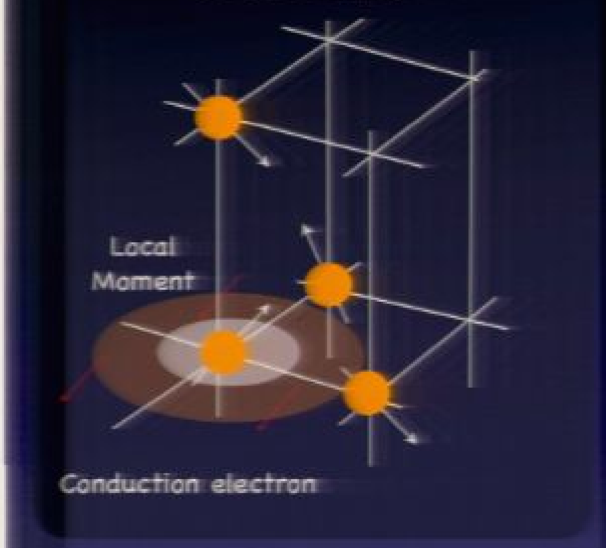
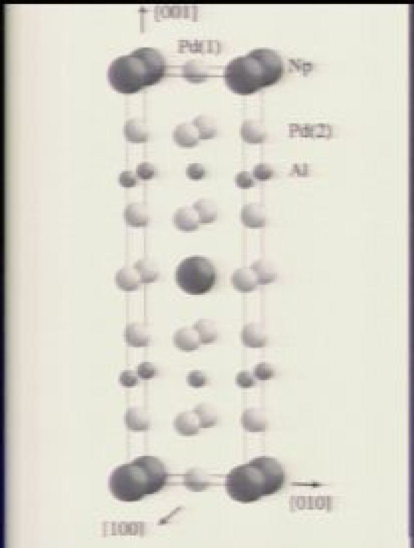


Conclusions

- Symplectic spins: 1/N expansion for heavy fermion superconductivity
- Predicts: avoided criticality.



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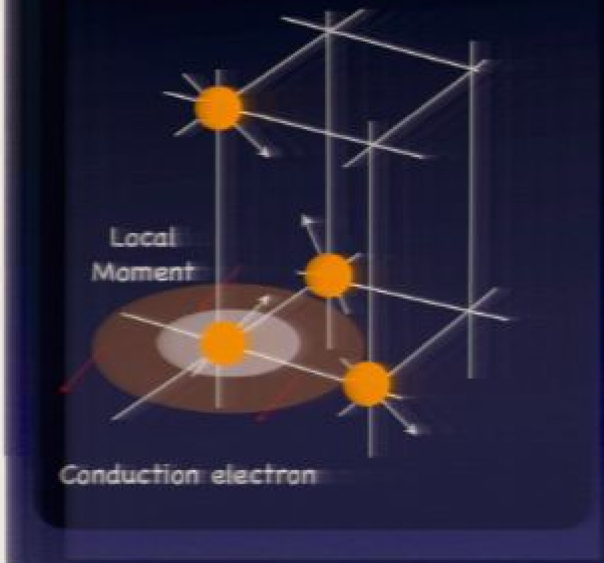

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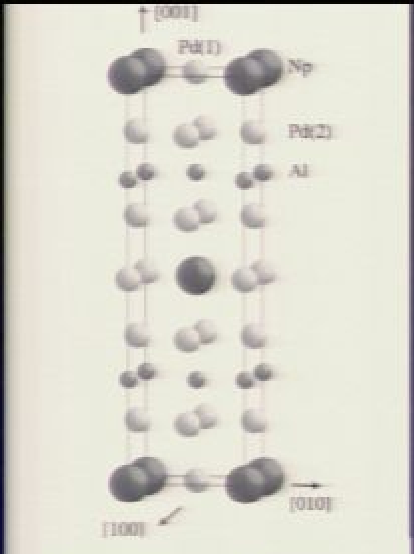

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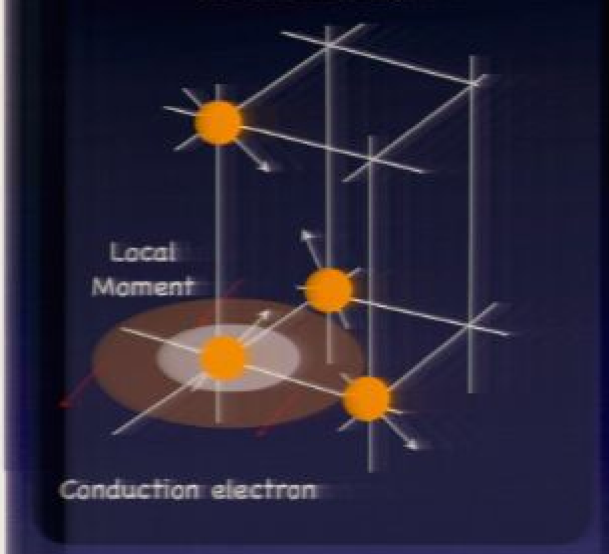
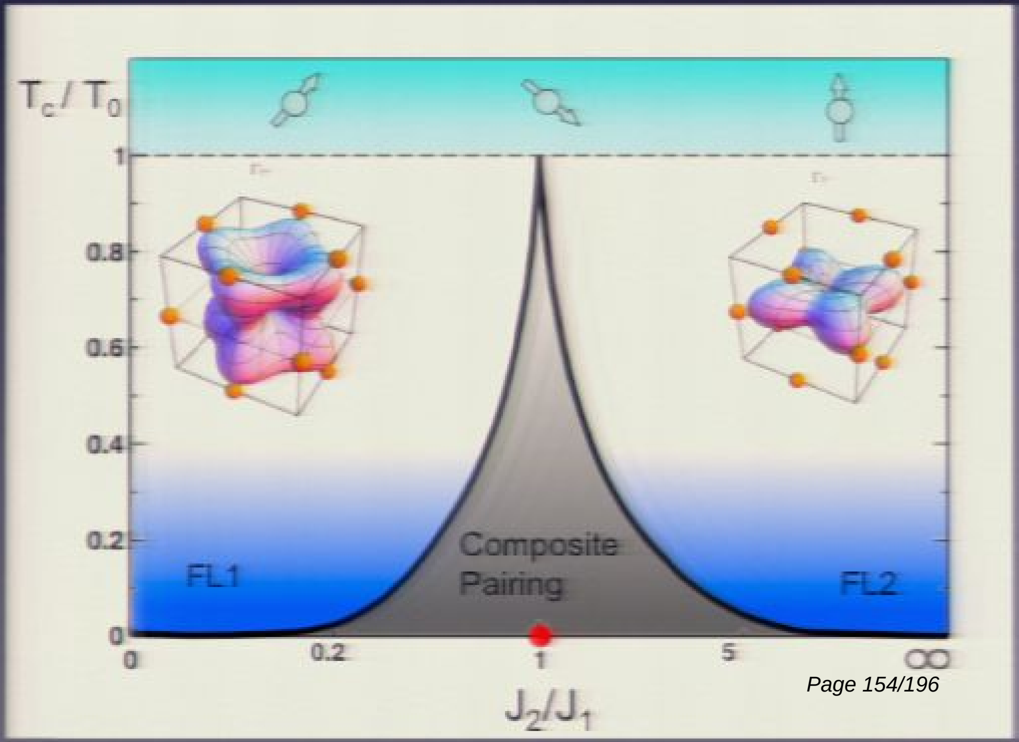
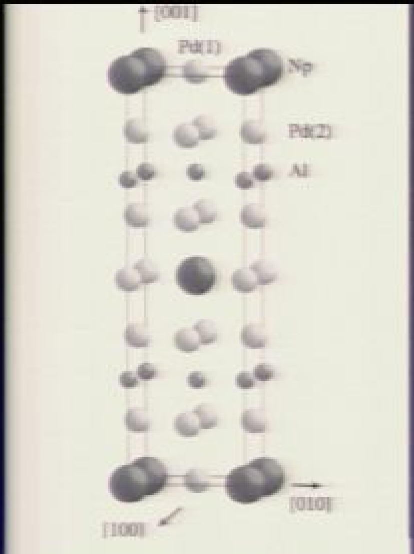




Conclusions

- Symplectic spins: 1/N expansion for heavy fermion superconductivity
- Predicts: avoided criticality.
- composite pairing and resonant Andreev scattering.



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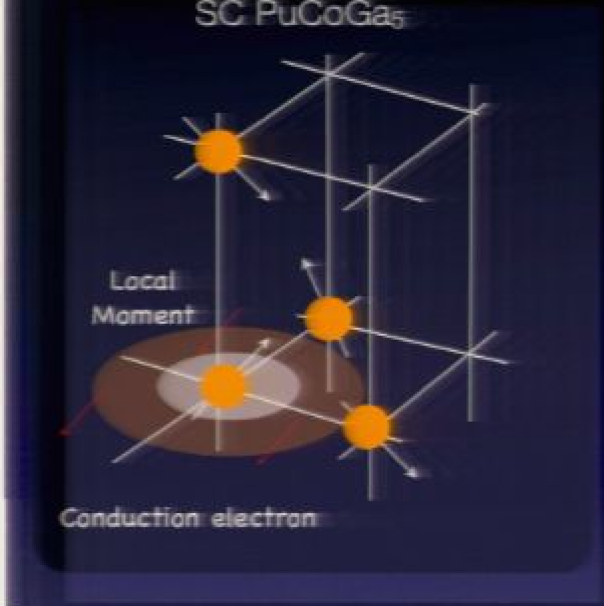

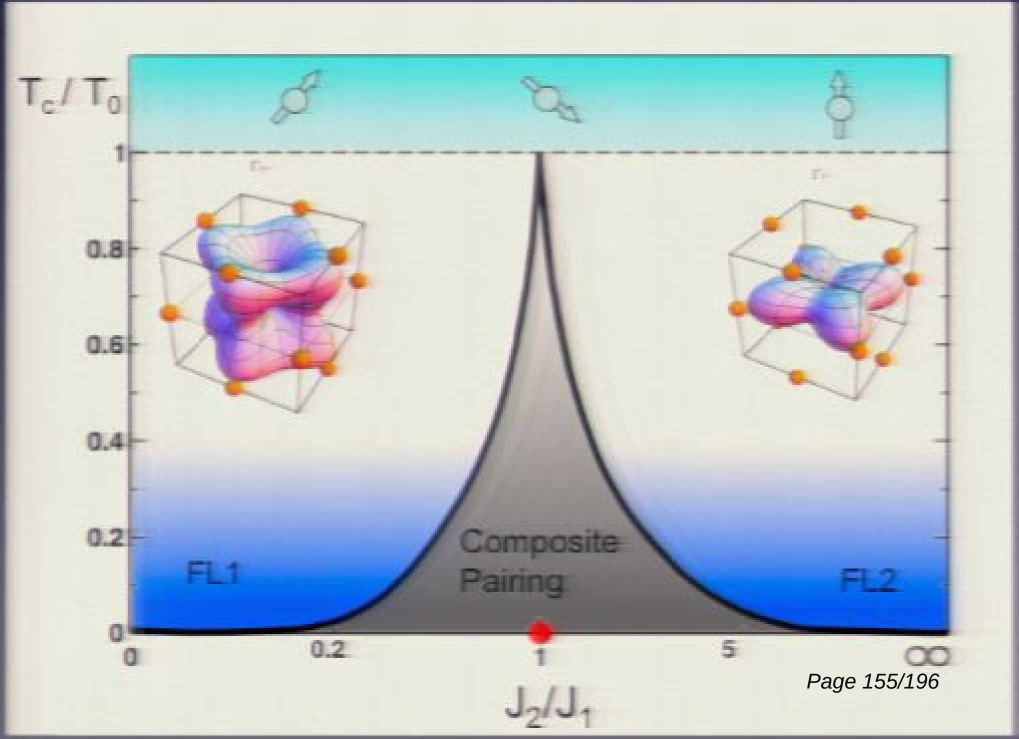

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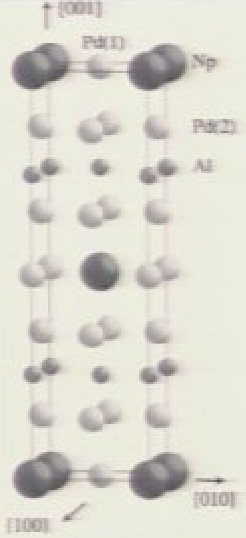

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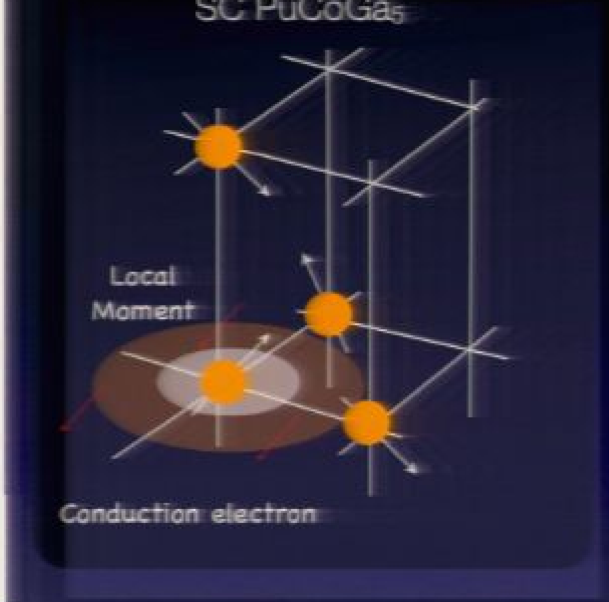
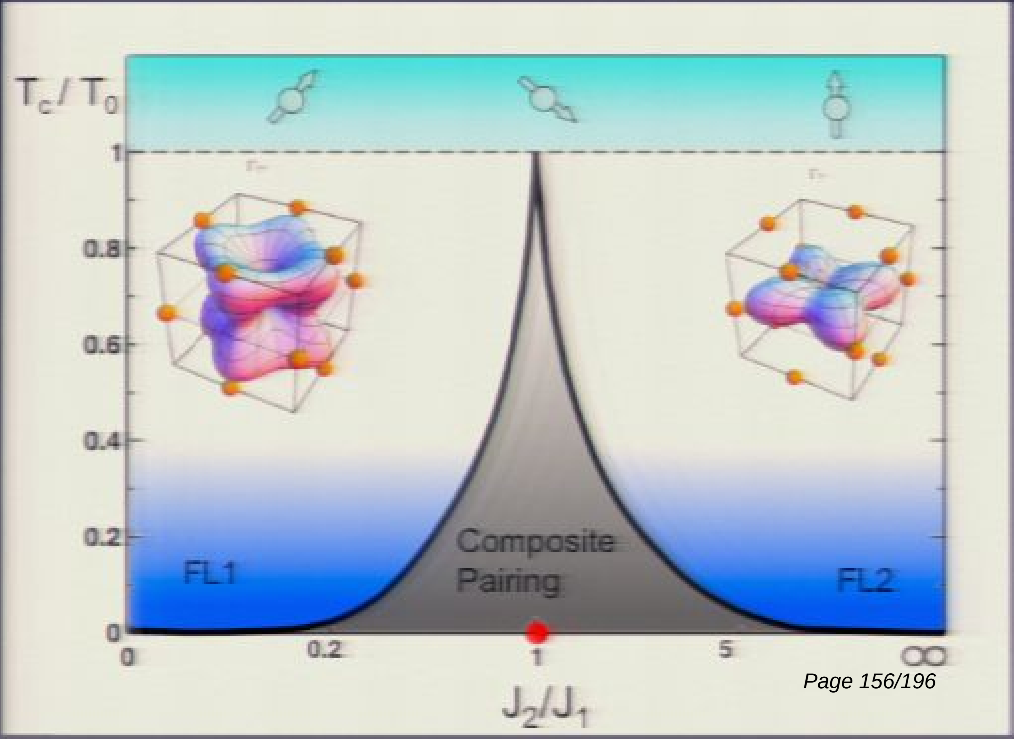
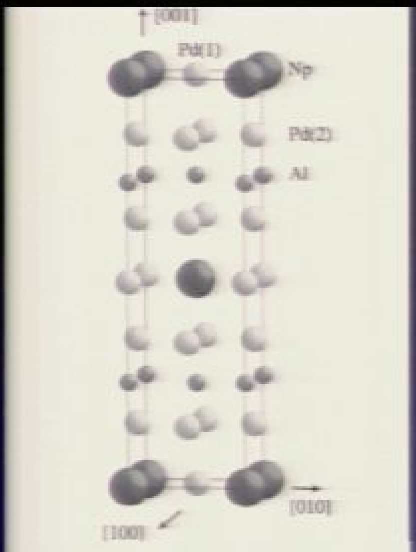




Conclusions

- Symplectic spins: 1/N expansion for heavy fermion superconductivity
- Predicts: avoided criticality.
- composite pairing and resonant Andreev scattering.
- enhancement of $1/T_1$ above Tc.



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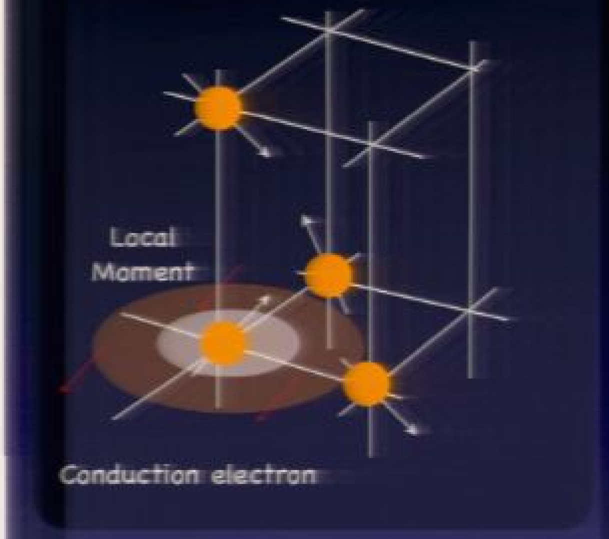
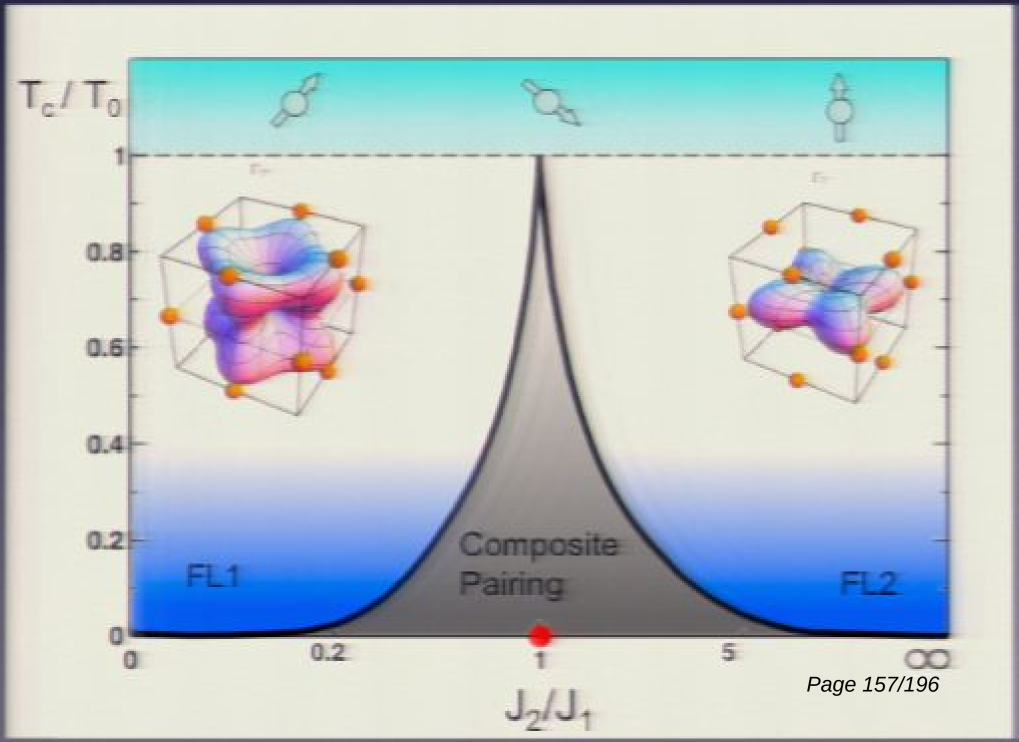
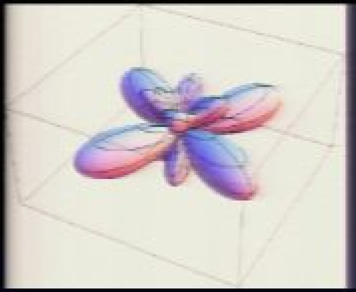
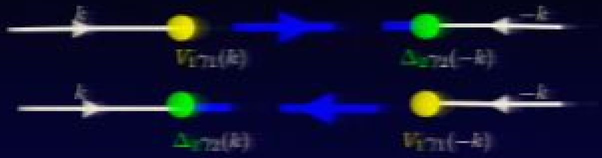


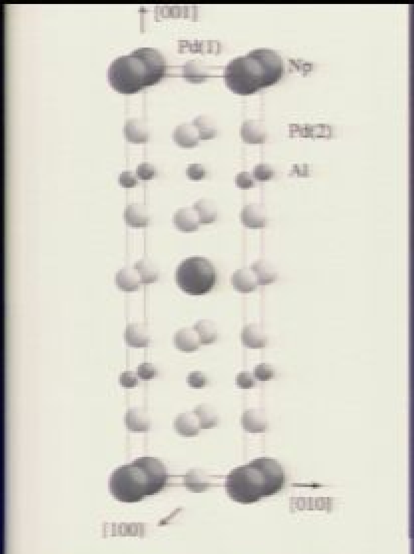


Thank You!





- Symplectic spins: 1/N expansion for heavy fermion superconductivity
- Predicts: avoided criticality.
- composite pairing and resonant Andreev scattering.
- enhancement of $1/T_1$ above Tc.
- $NpAl_2Pd_5$ and $PuCoGa_5$ have identical crystal symmetry. Possibility that Pu doping will enhance Tc in $NpAl_2Pd_5$.



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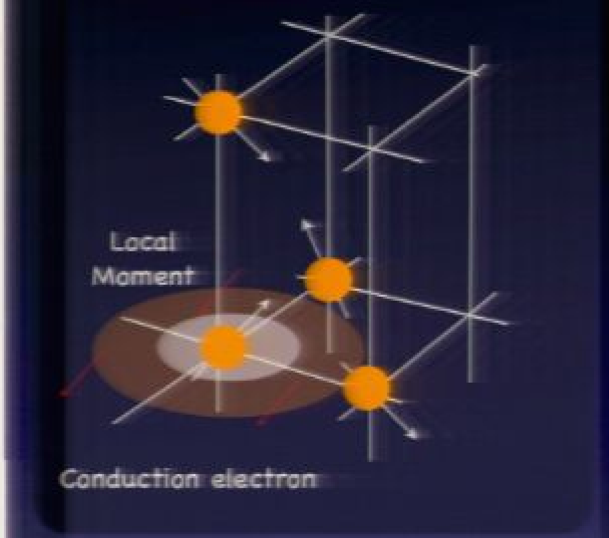

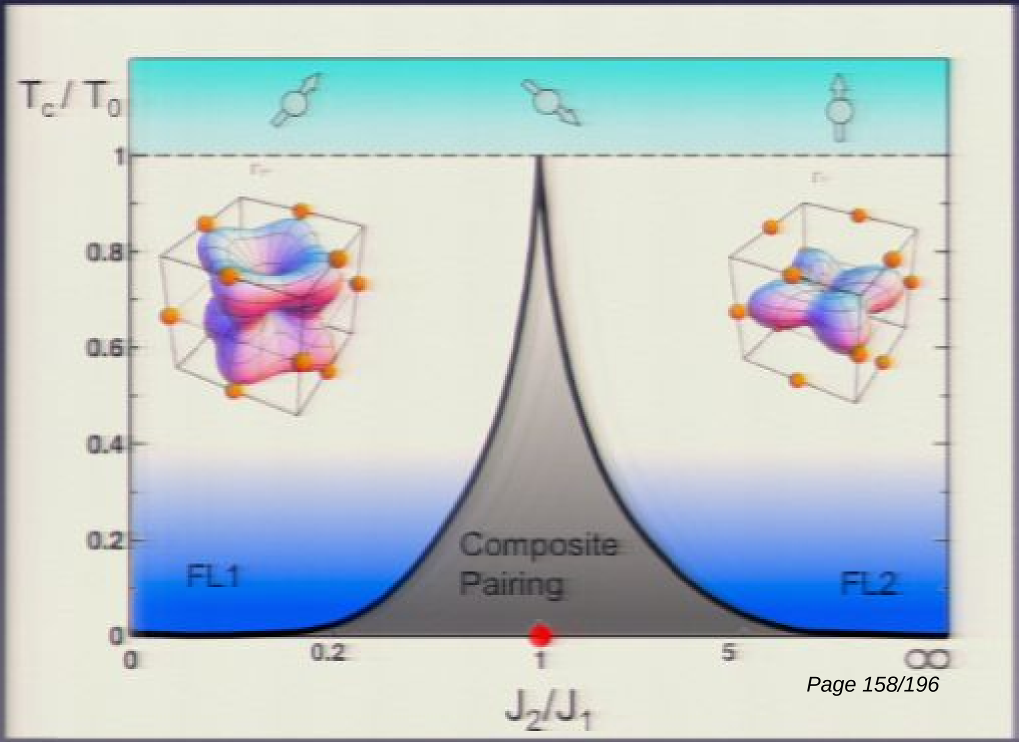

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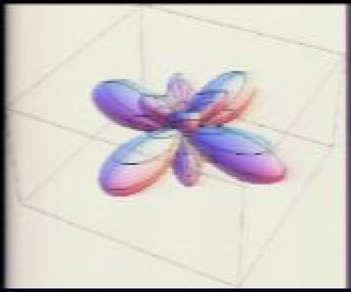

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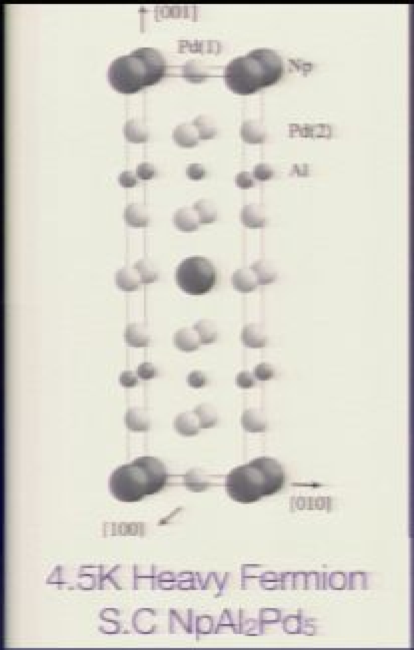

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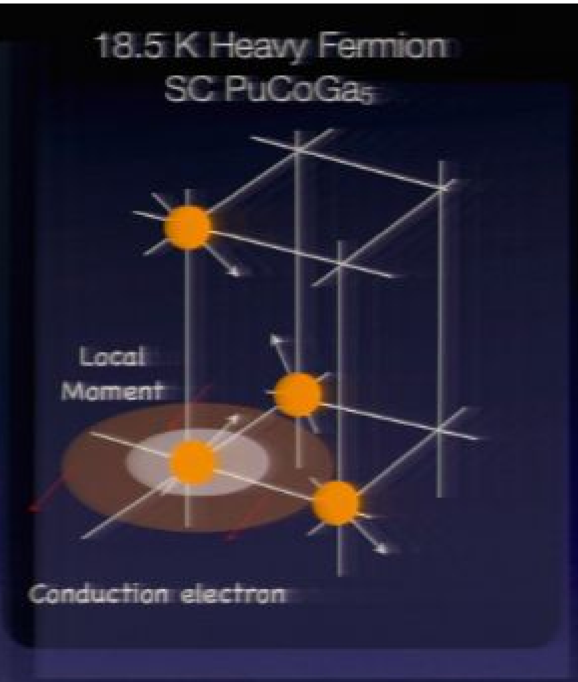

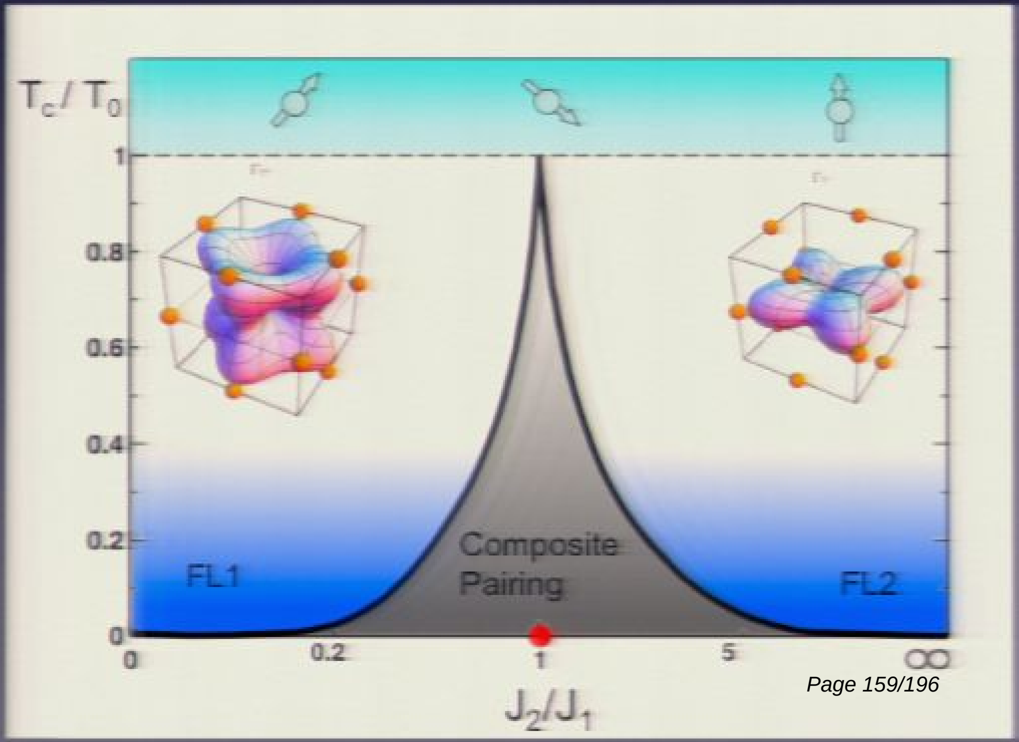

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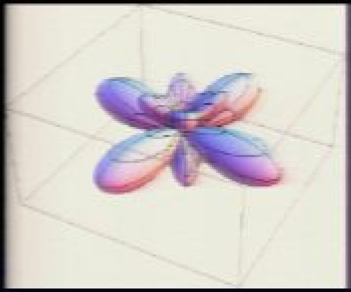

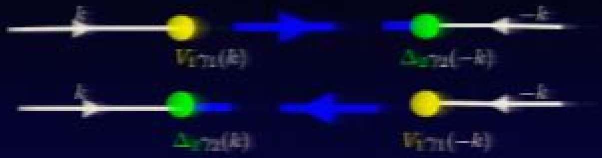

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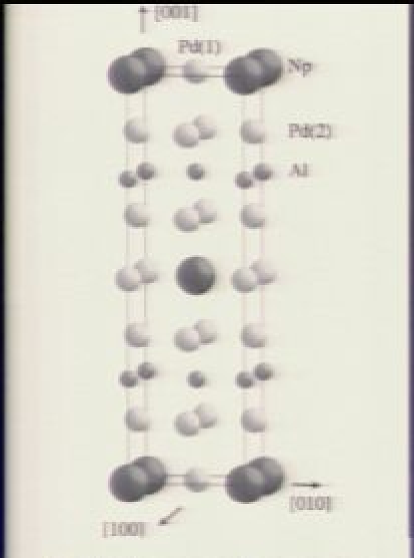

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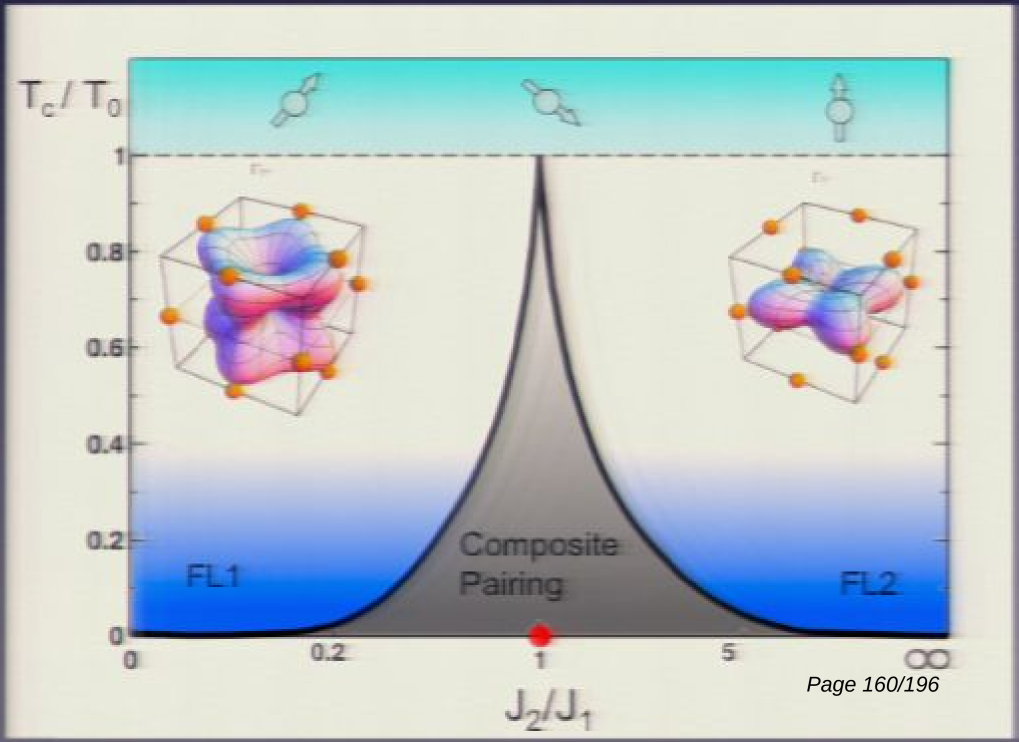

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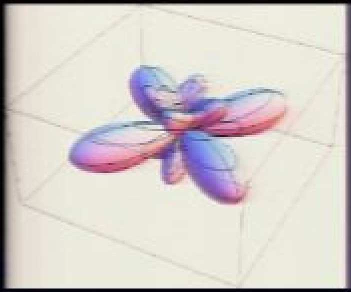

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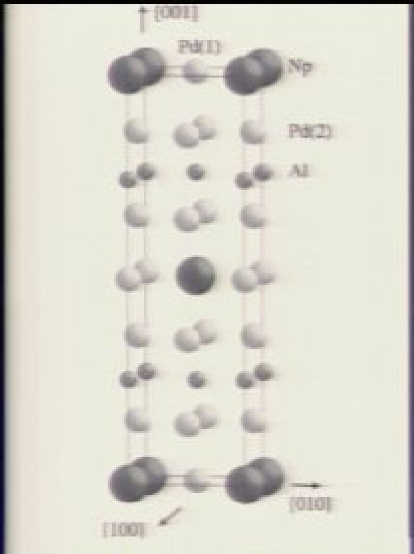

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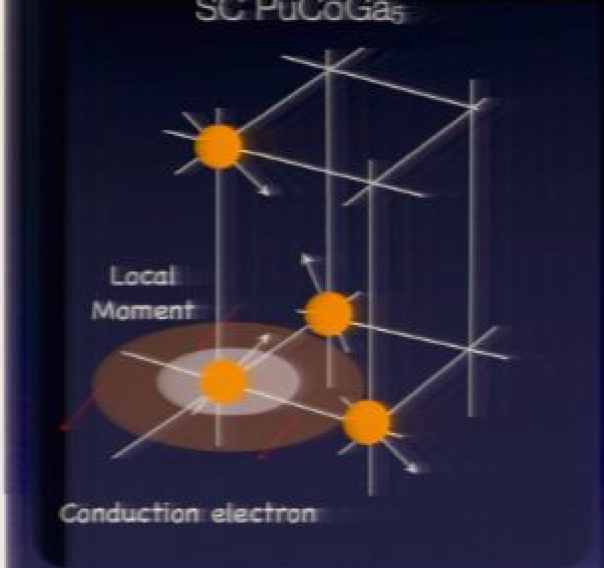

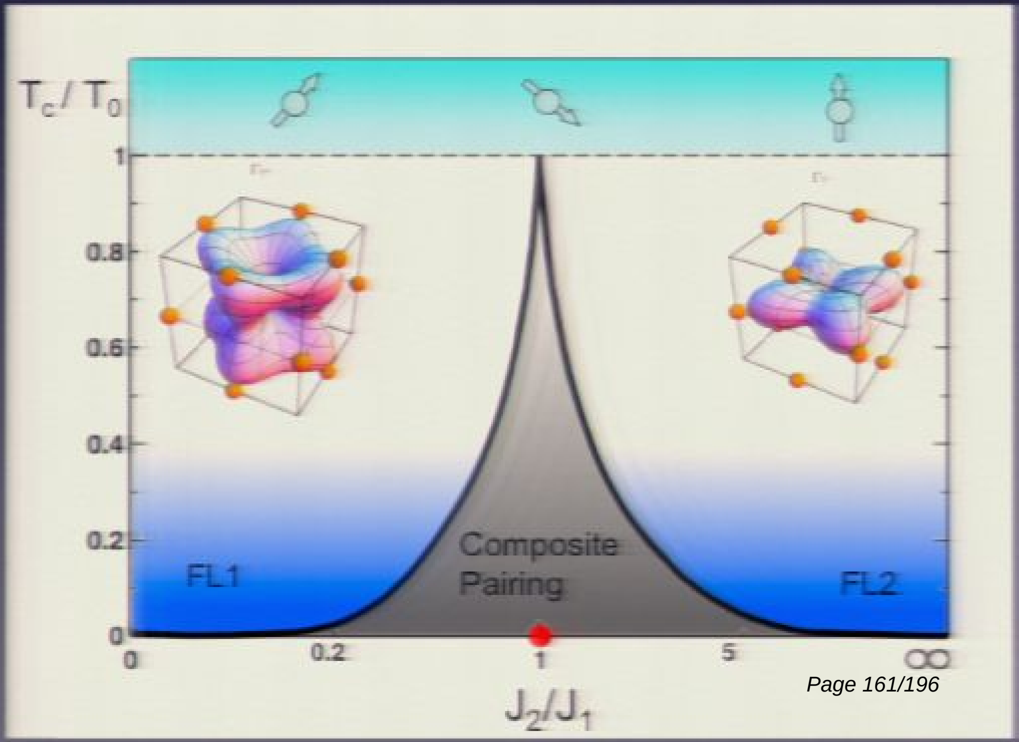

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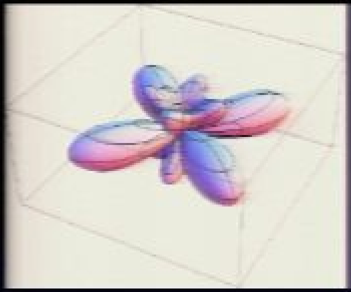

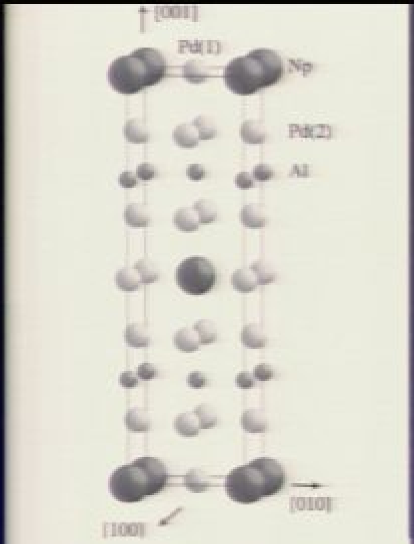

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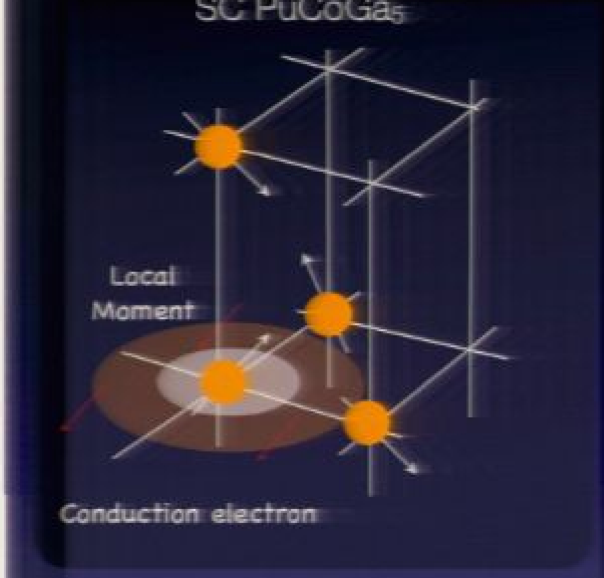

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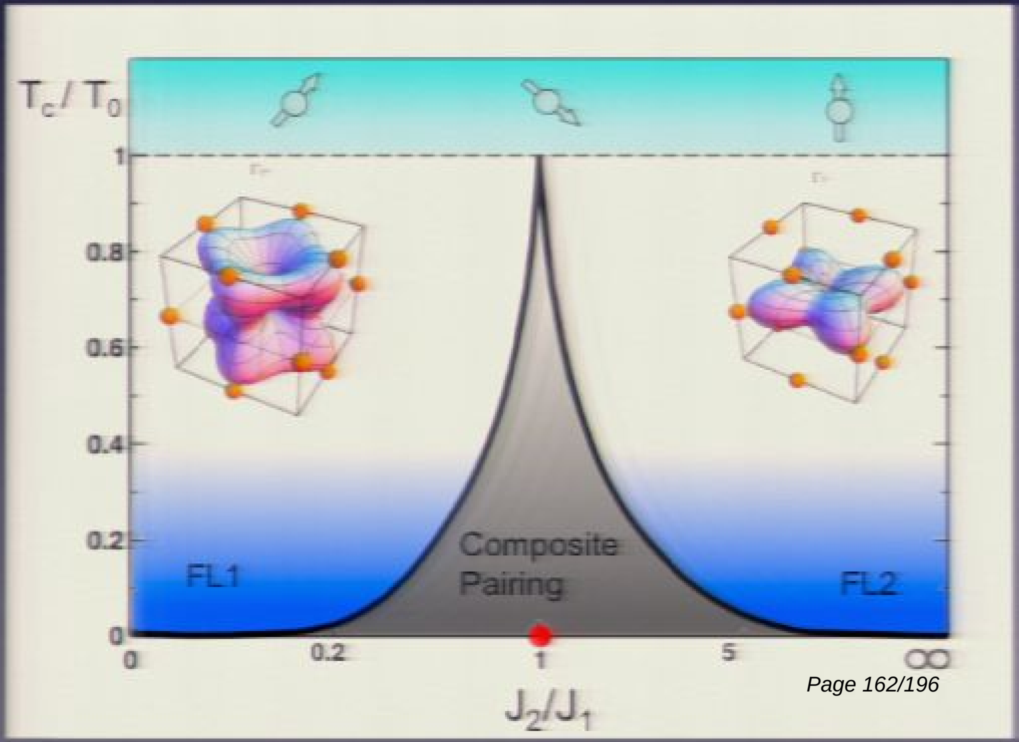

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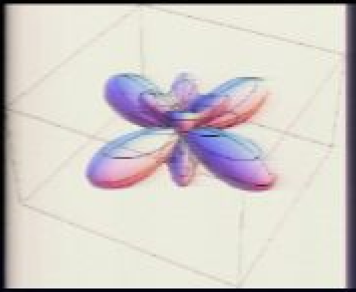

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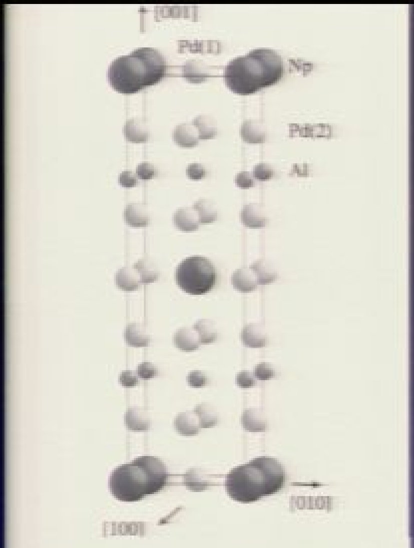

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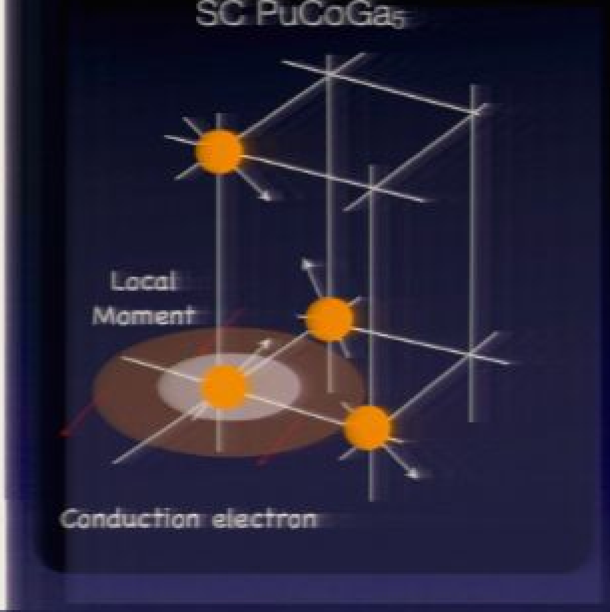

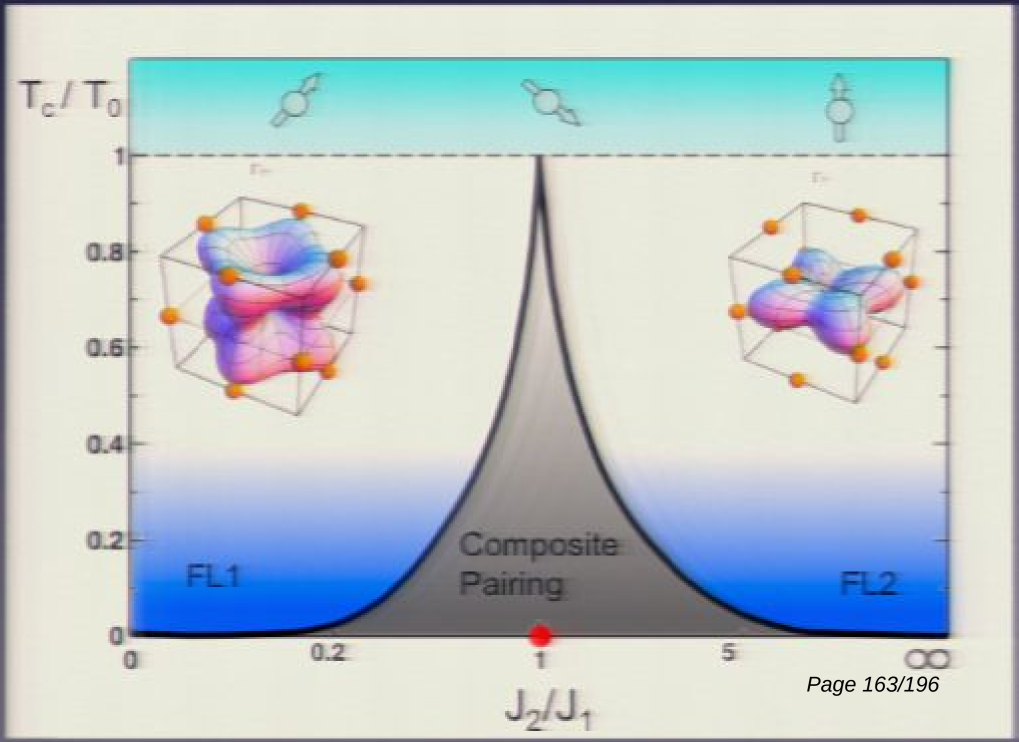

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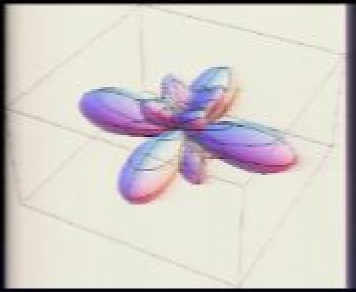

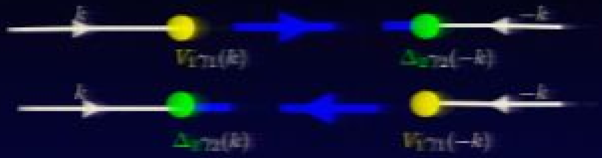

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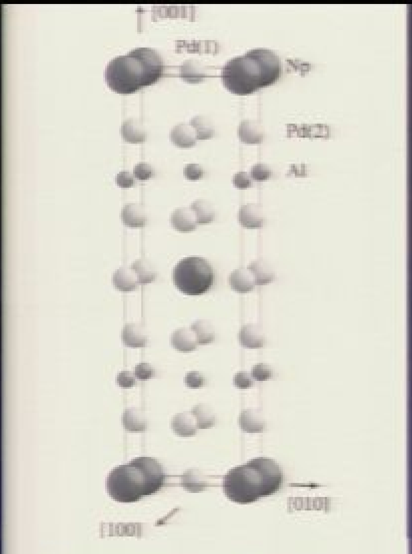

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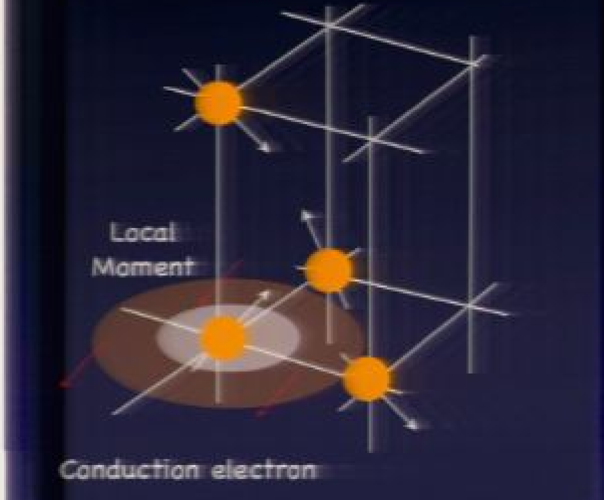

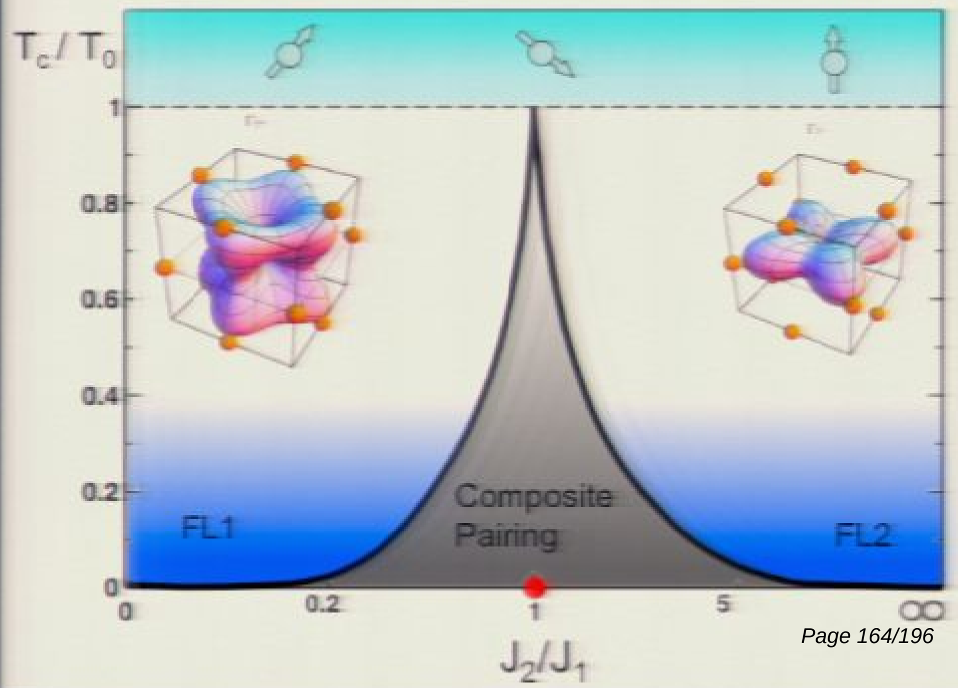

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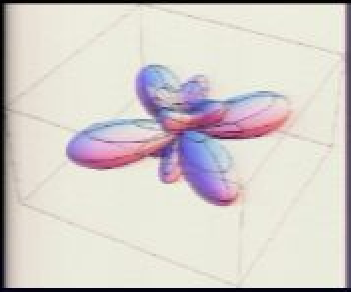

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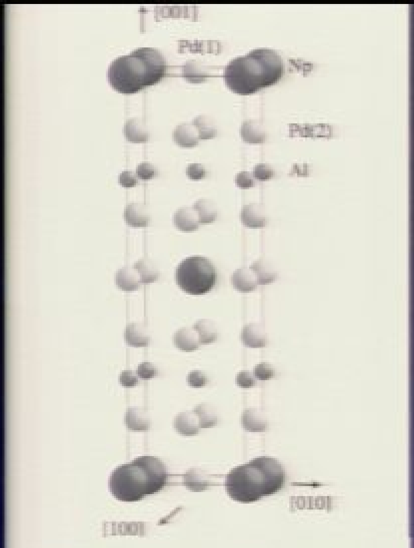

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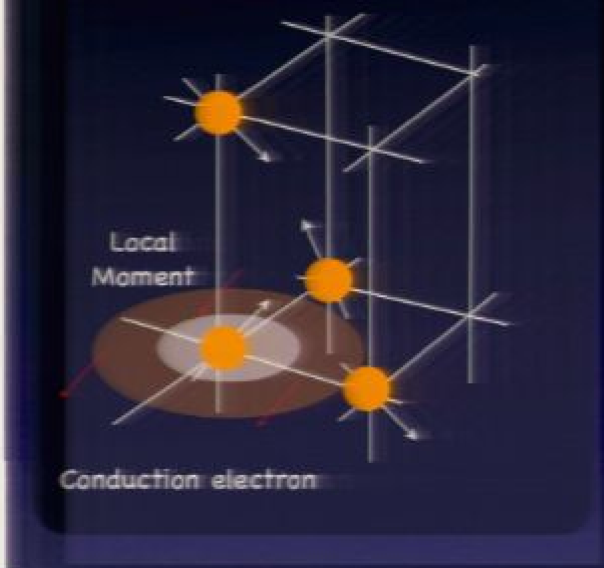

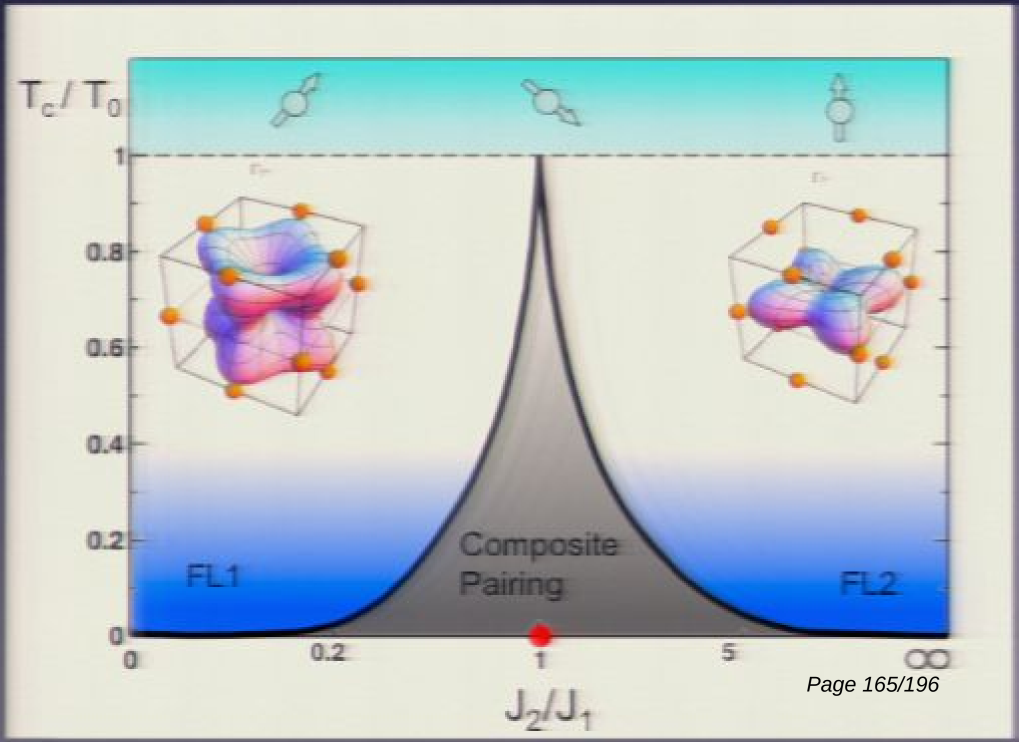

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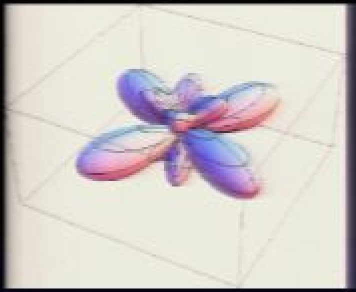

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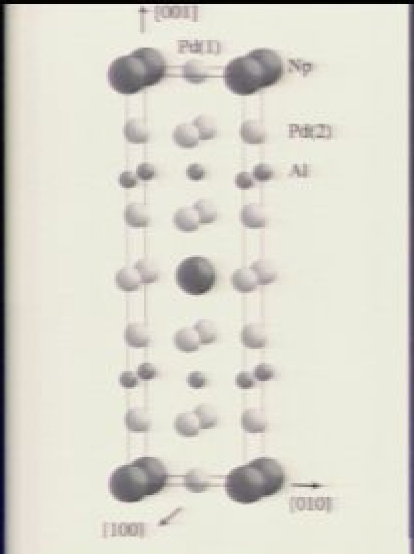

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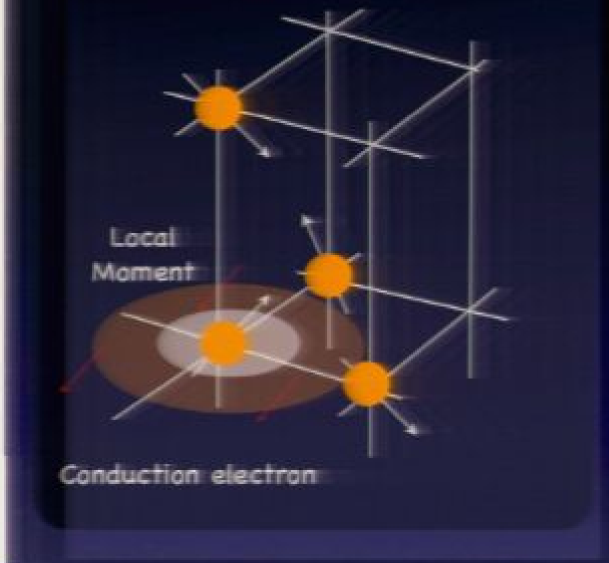

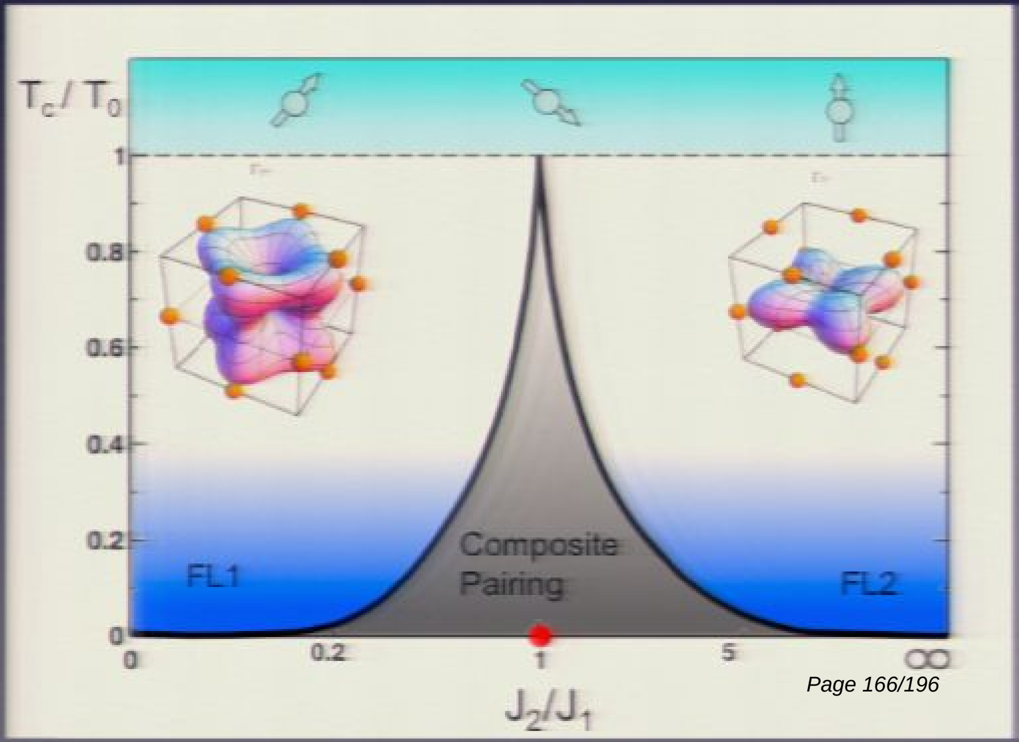

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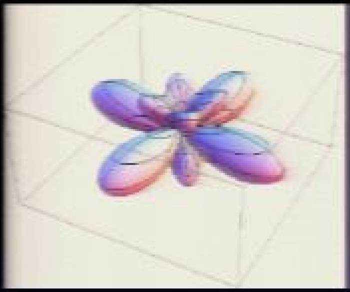

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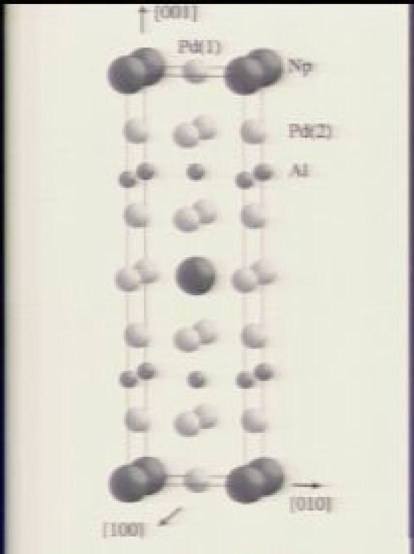

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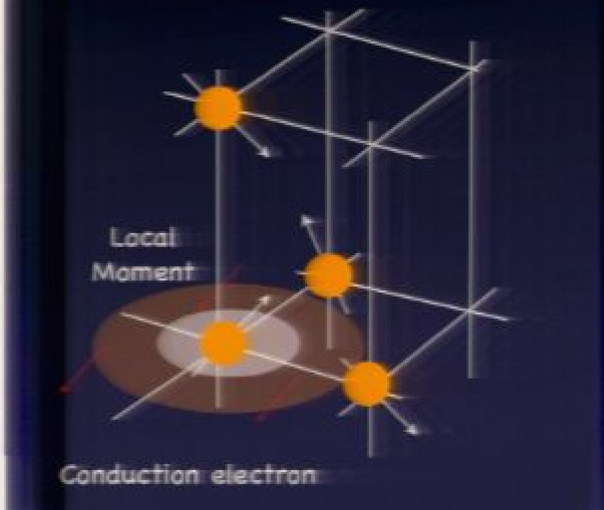

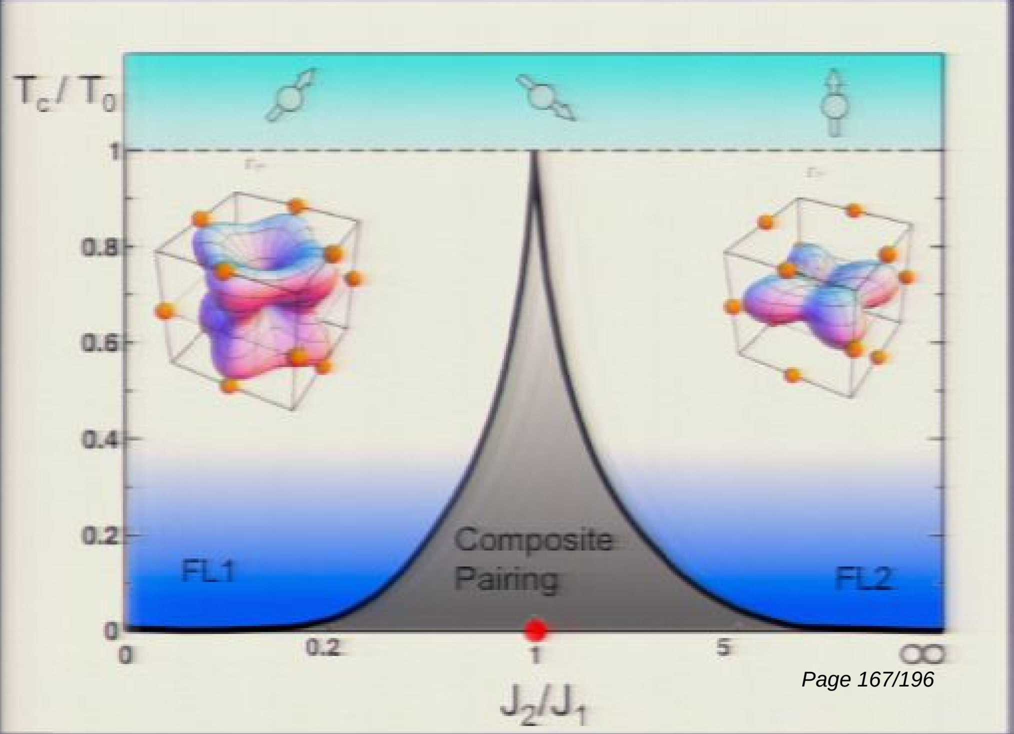

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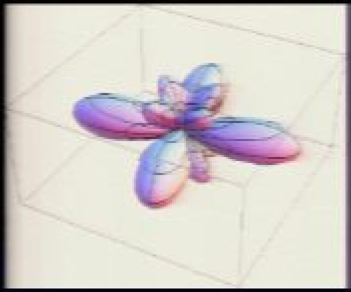

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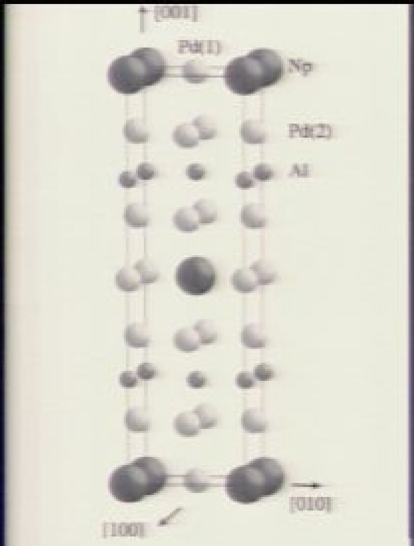

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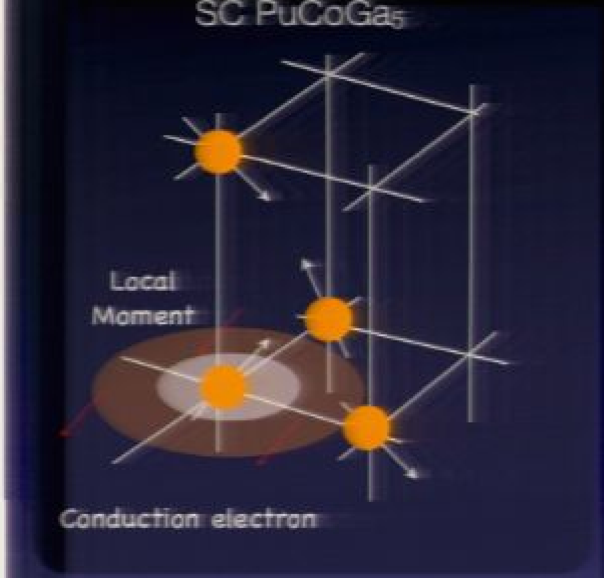

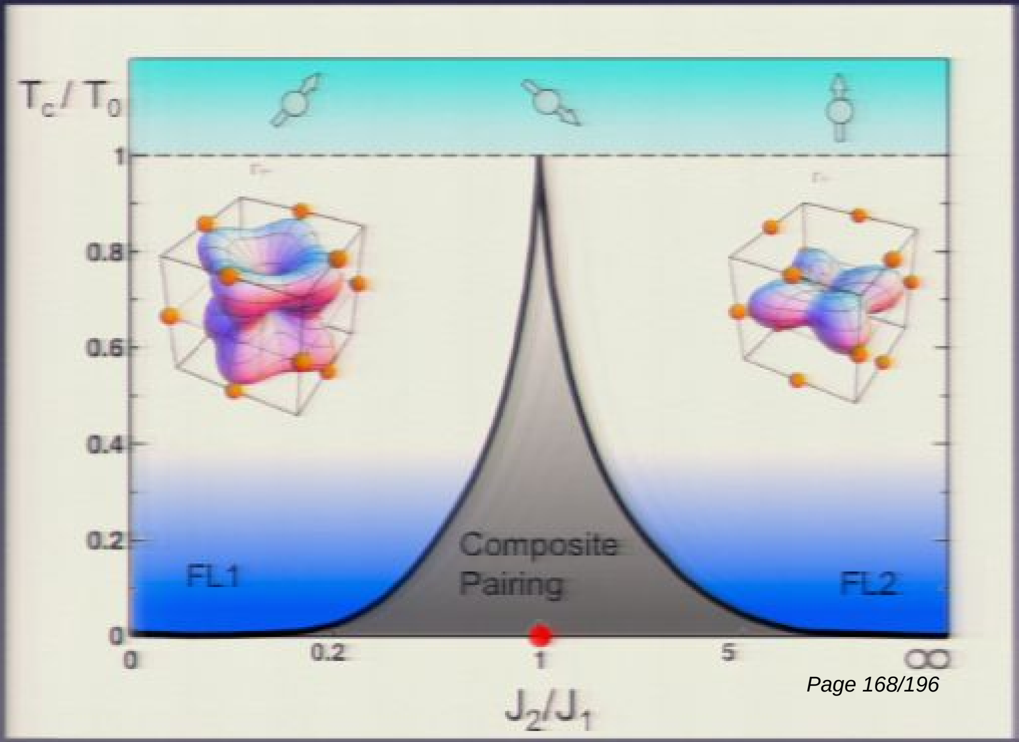

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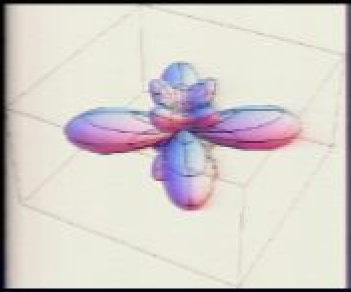

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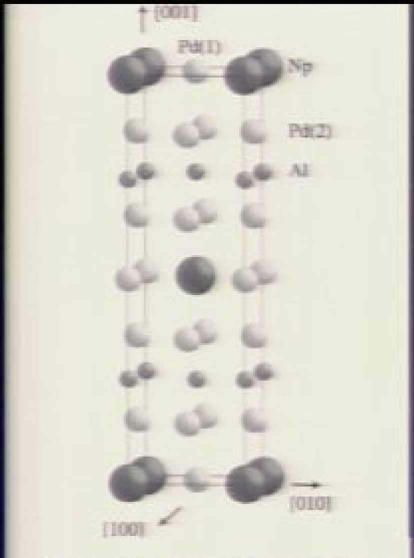

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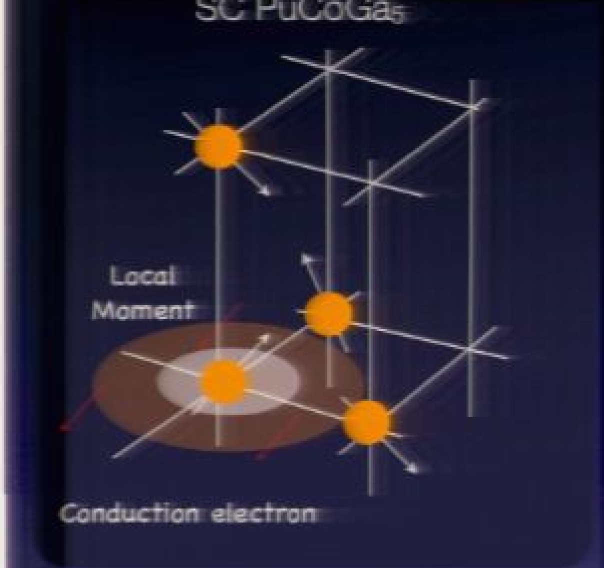

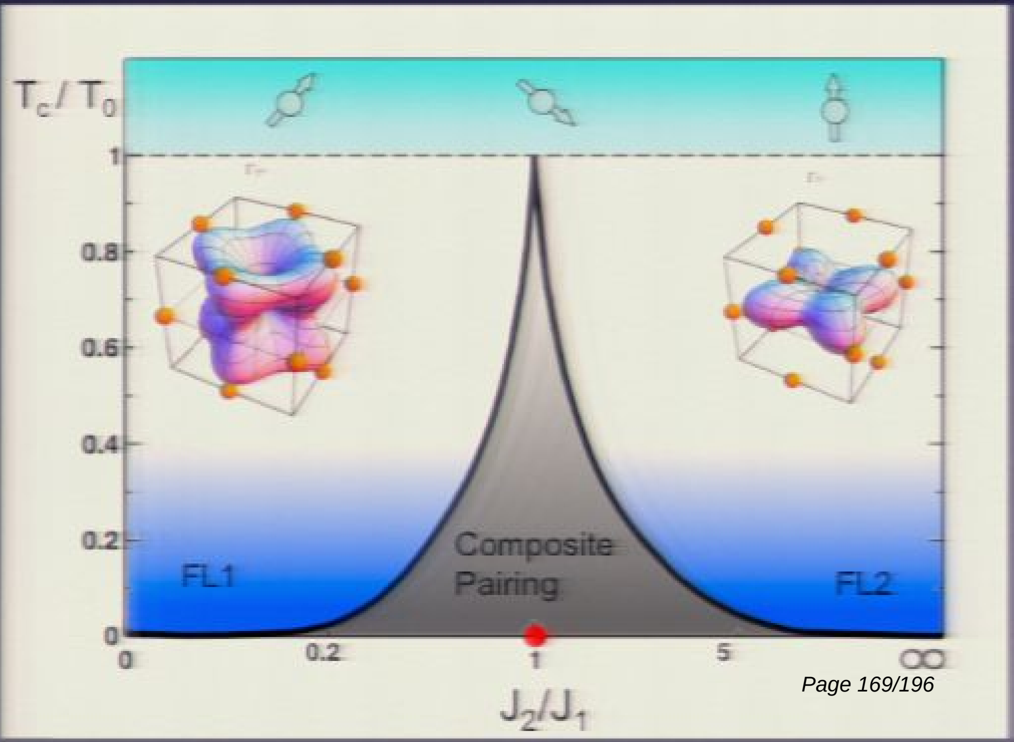

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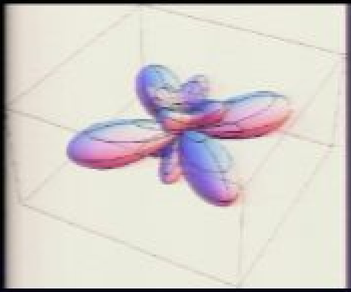

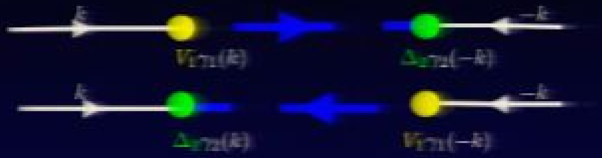

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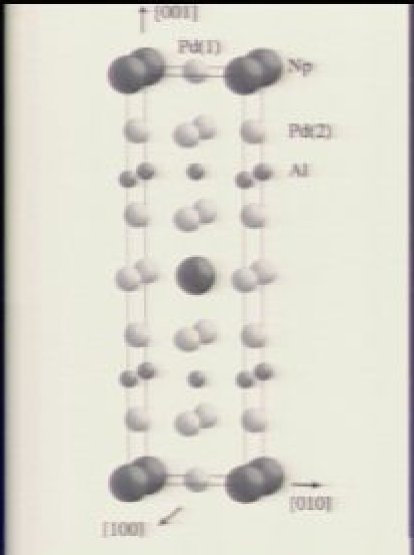

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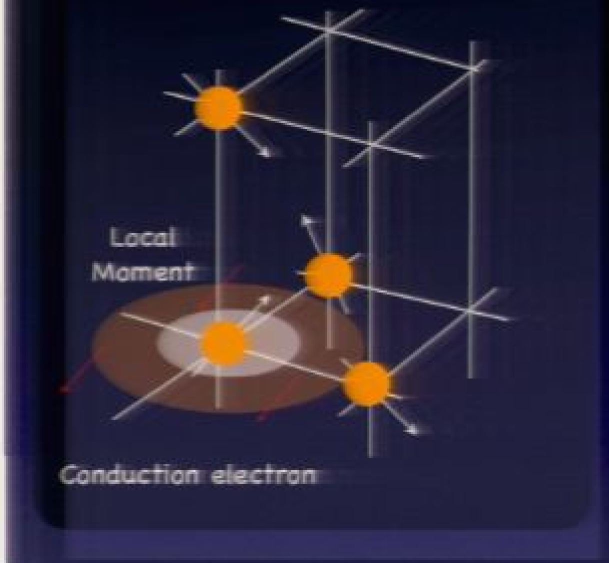

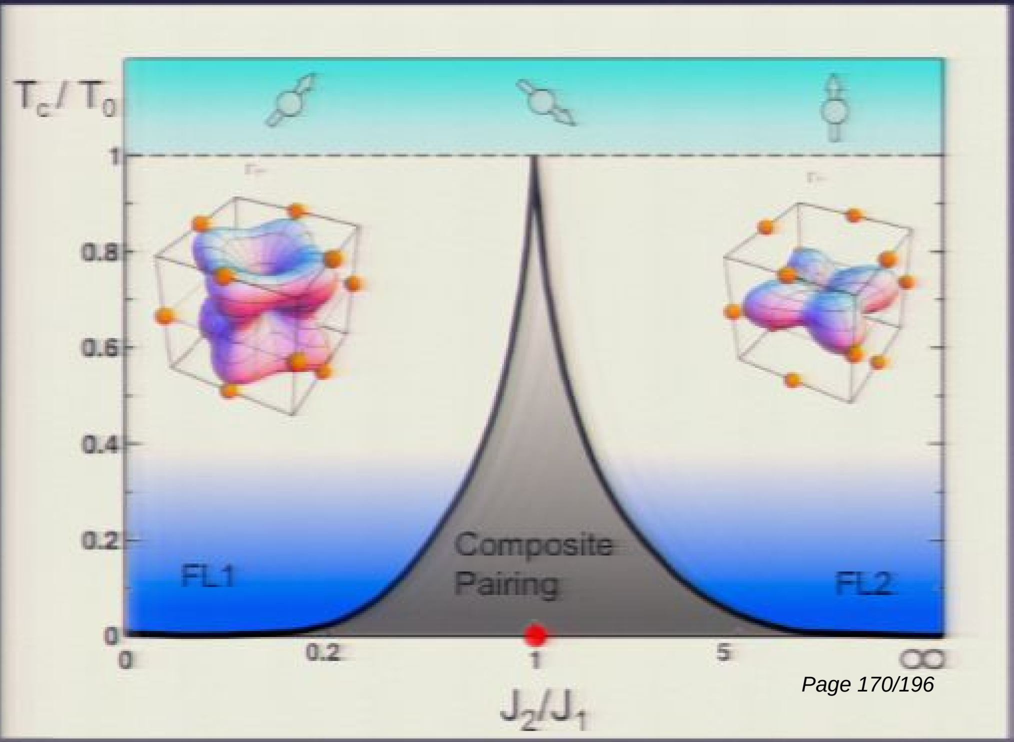

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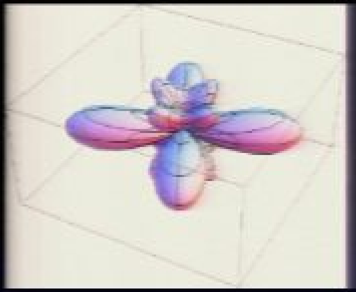

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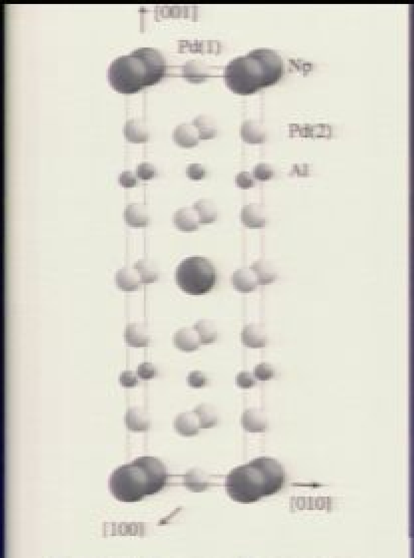

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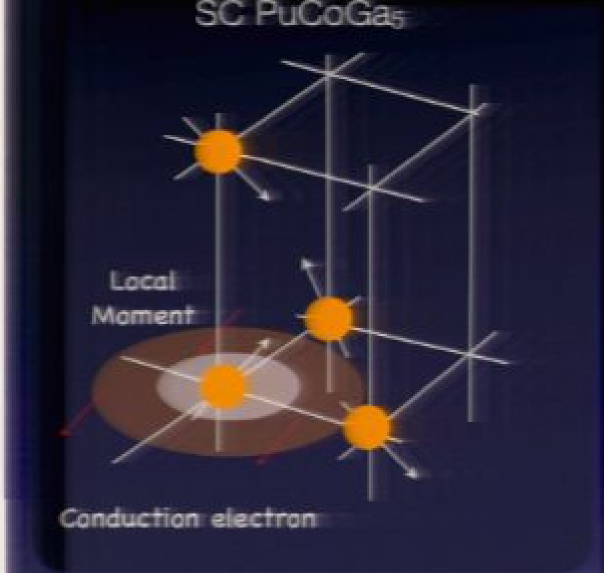

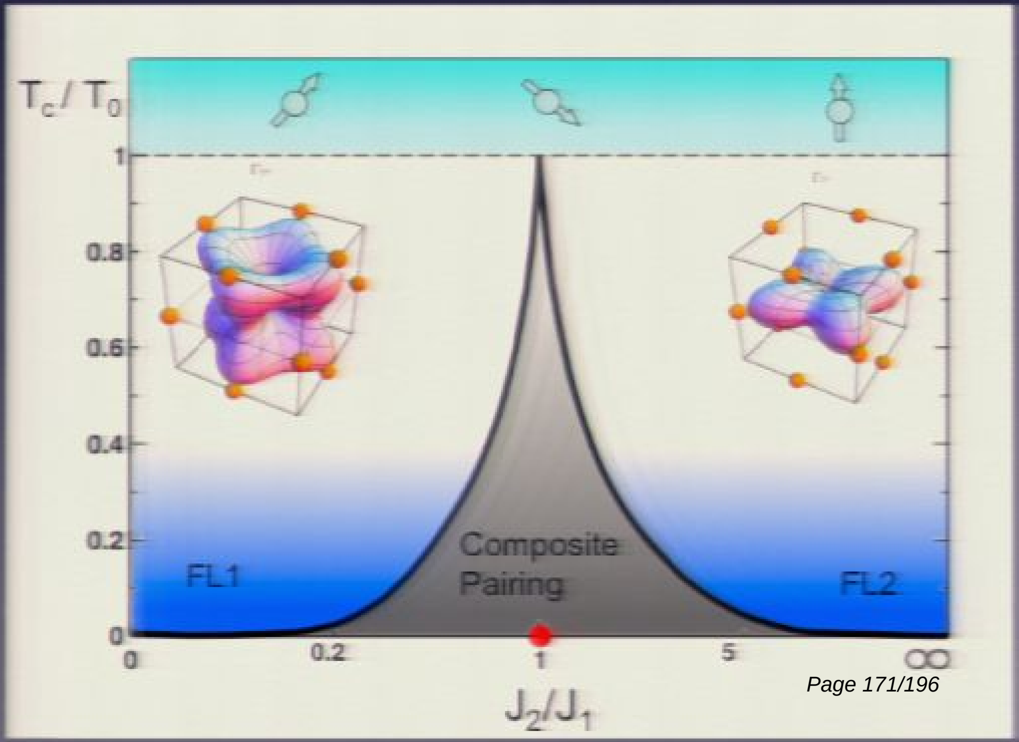

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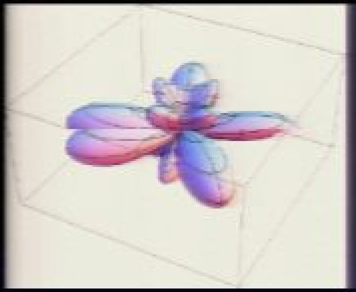

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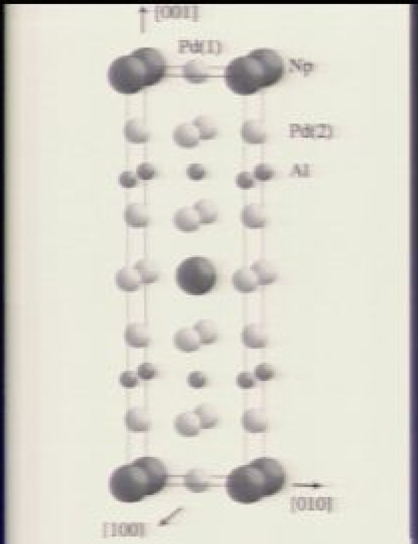

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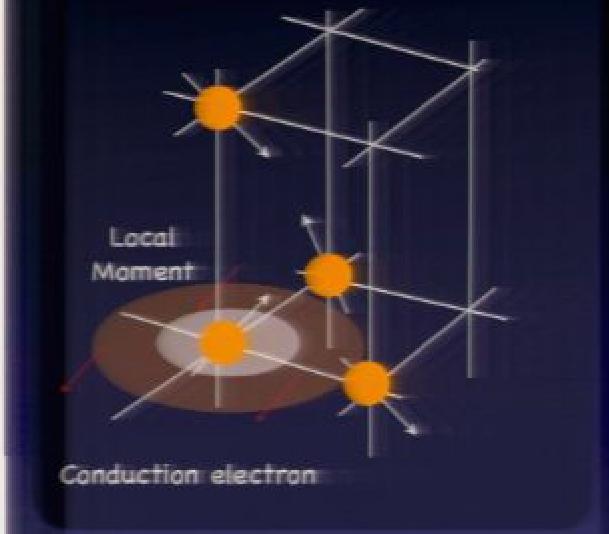

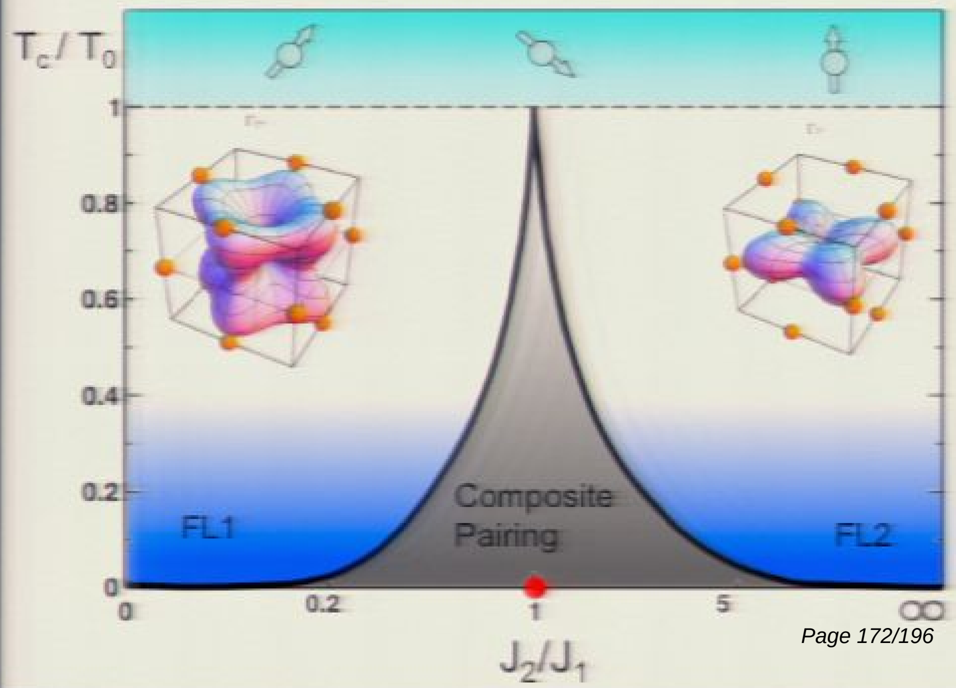

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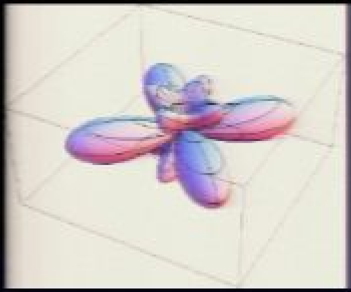

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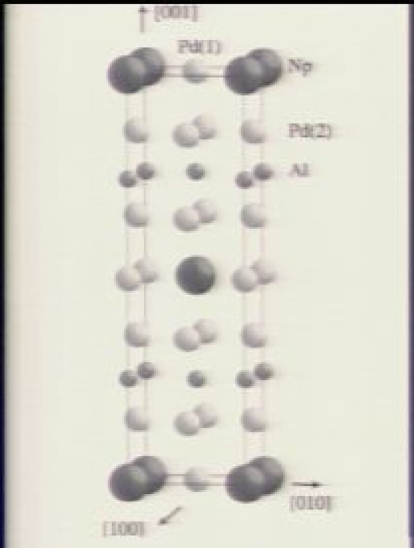

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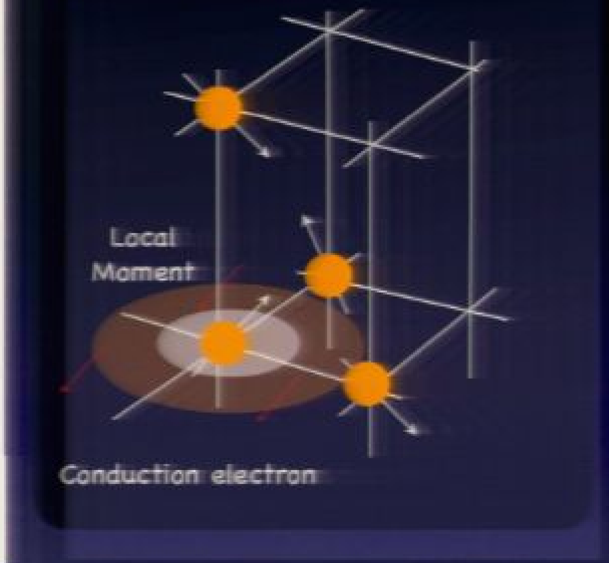

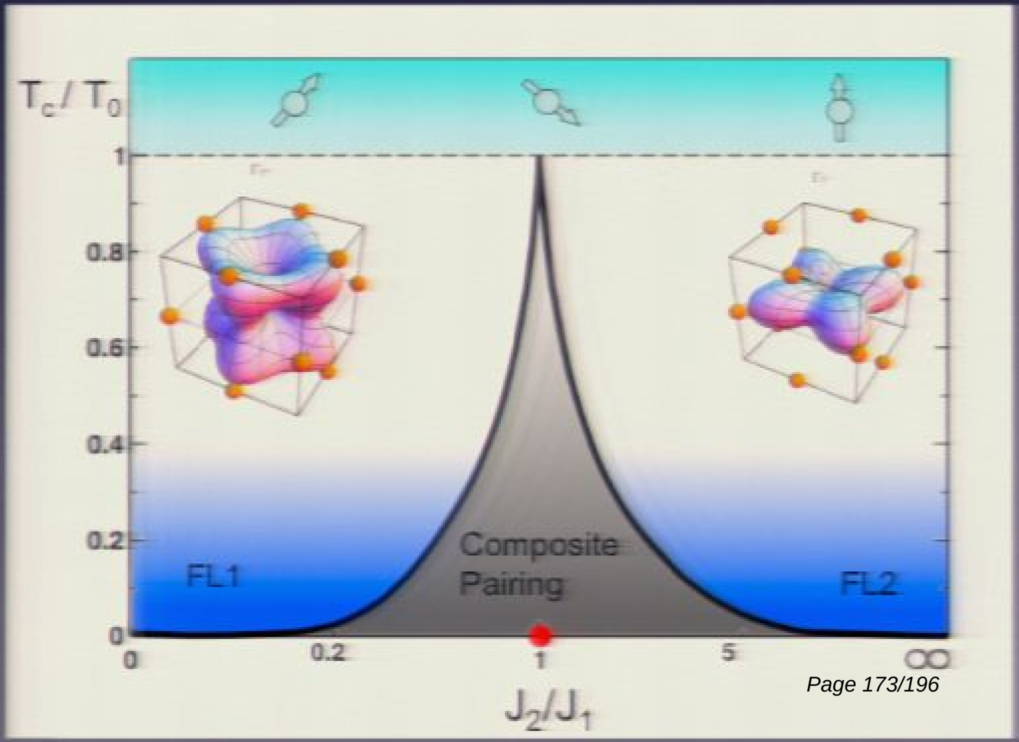

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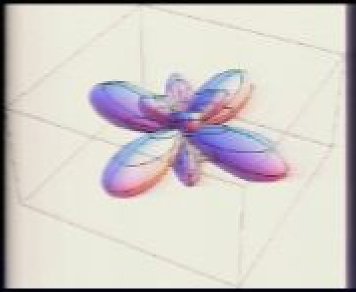

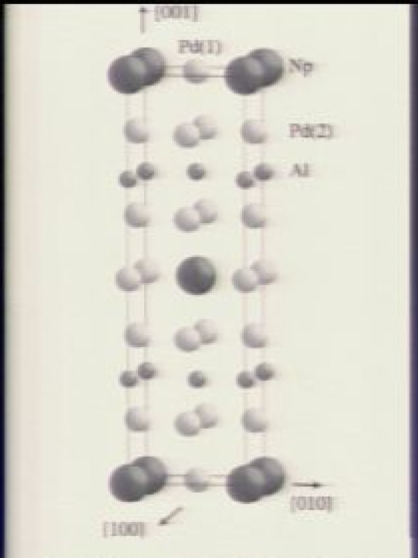

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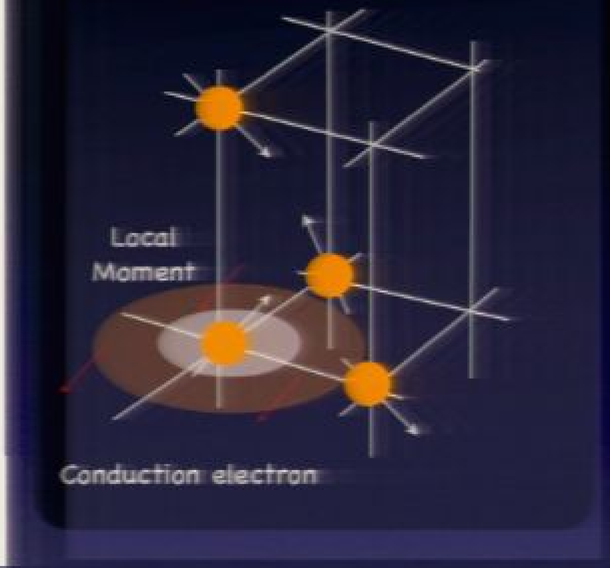

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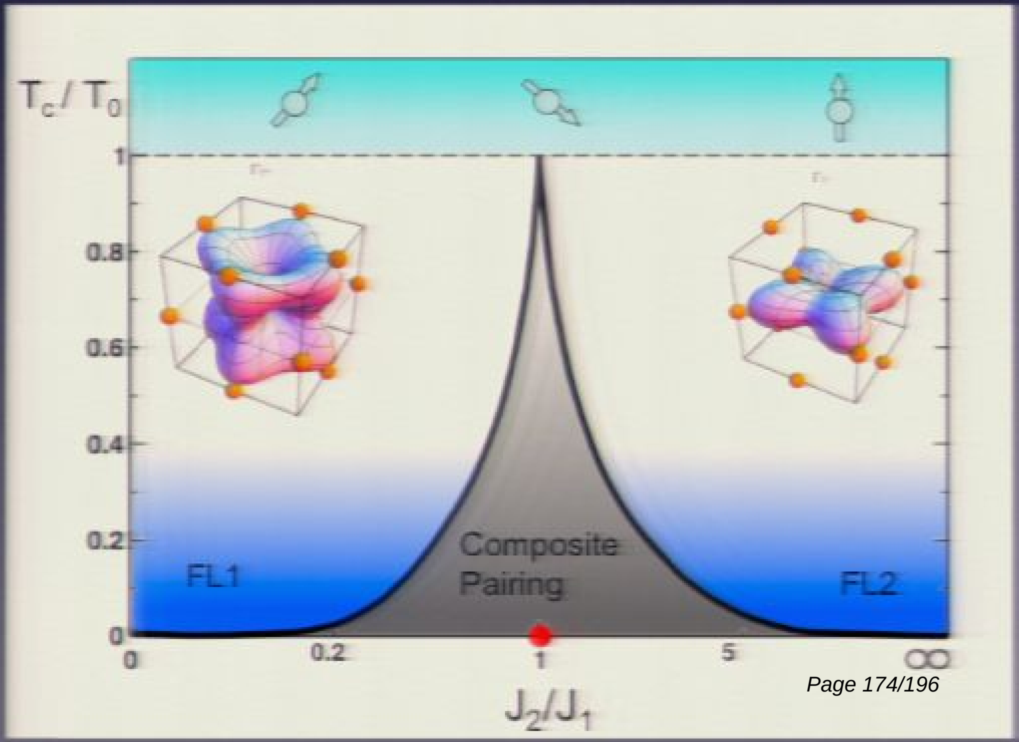

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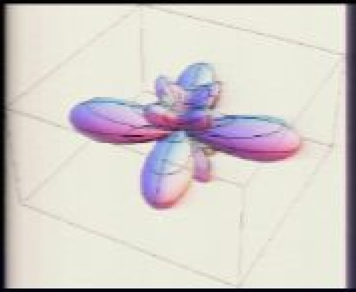

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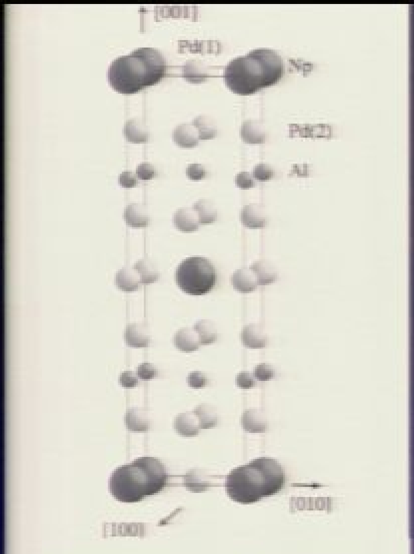

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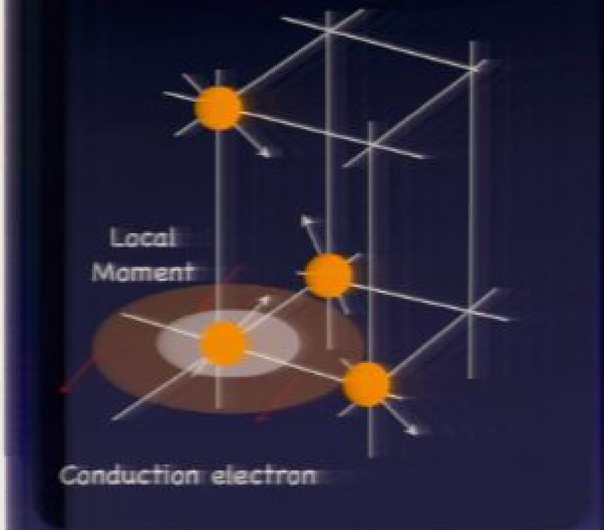

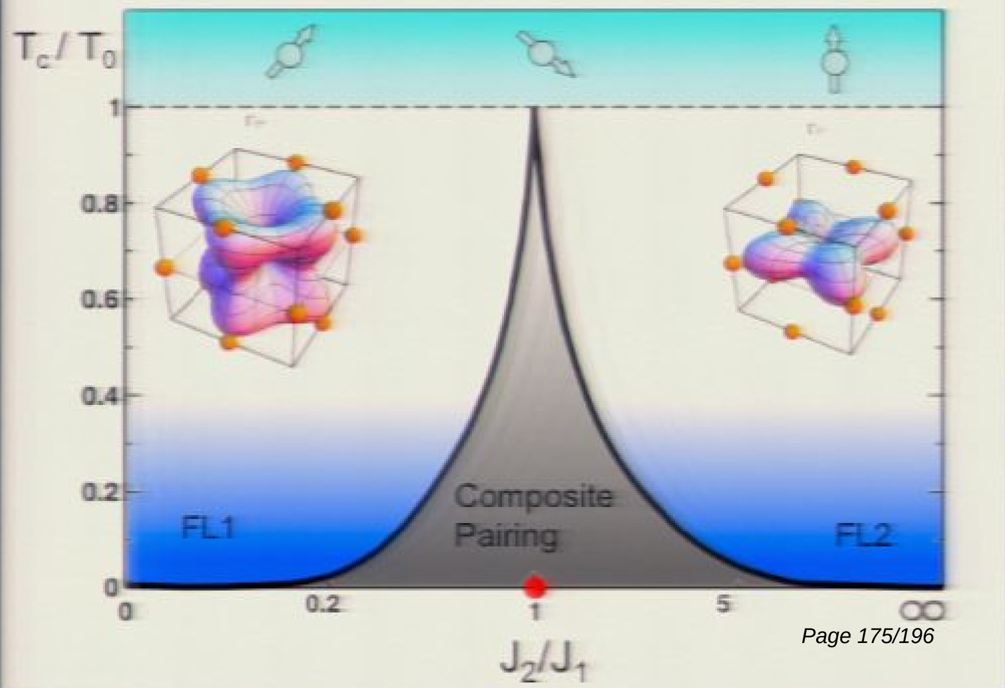

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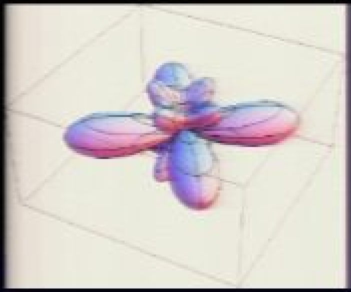

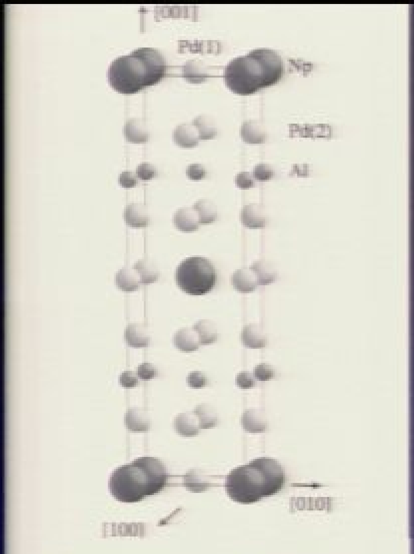

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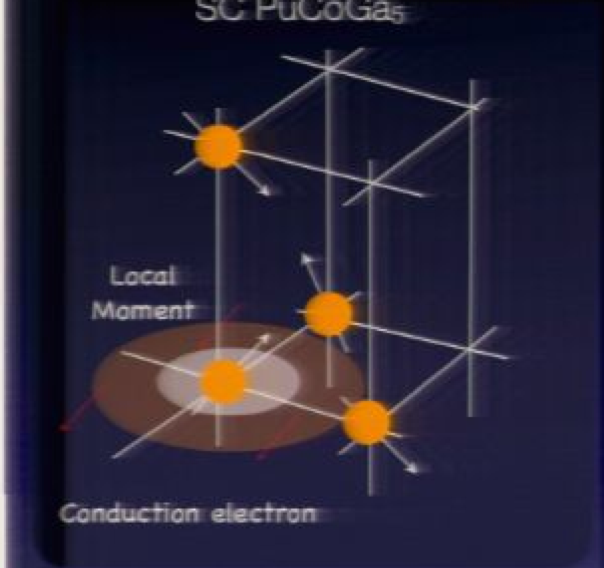

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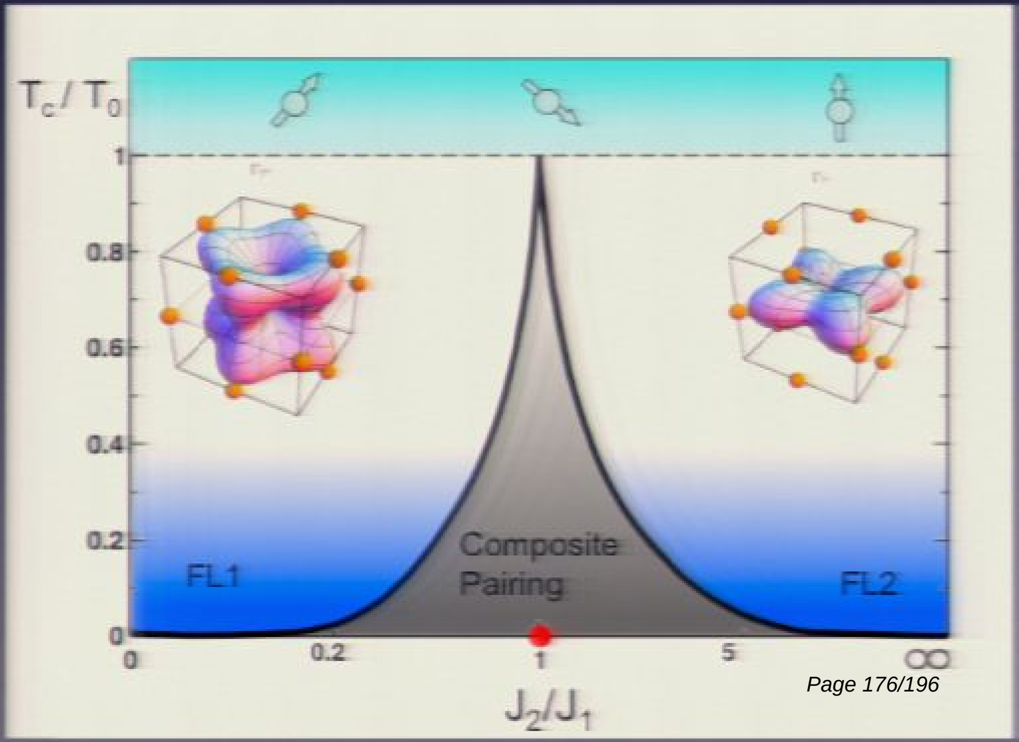

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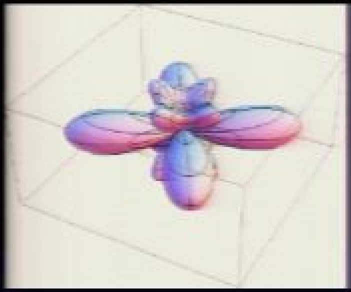

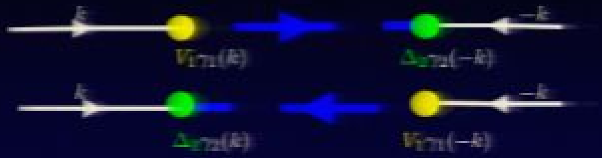

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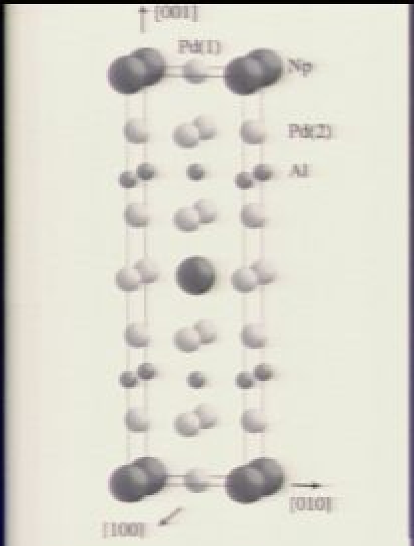

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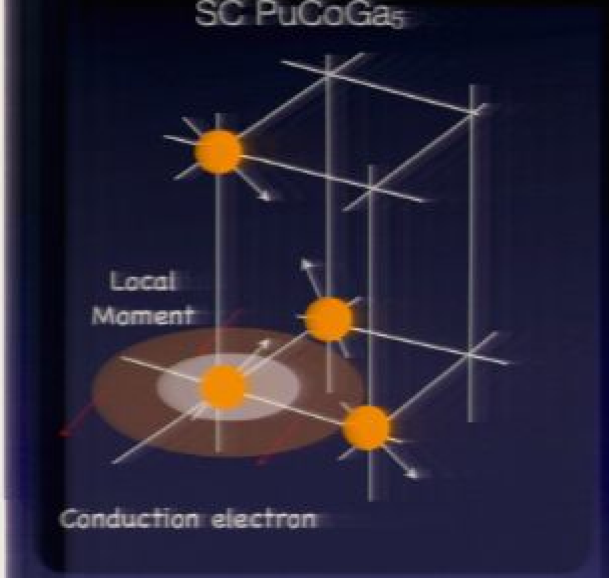

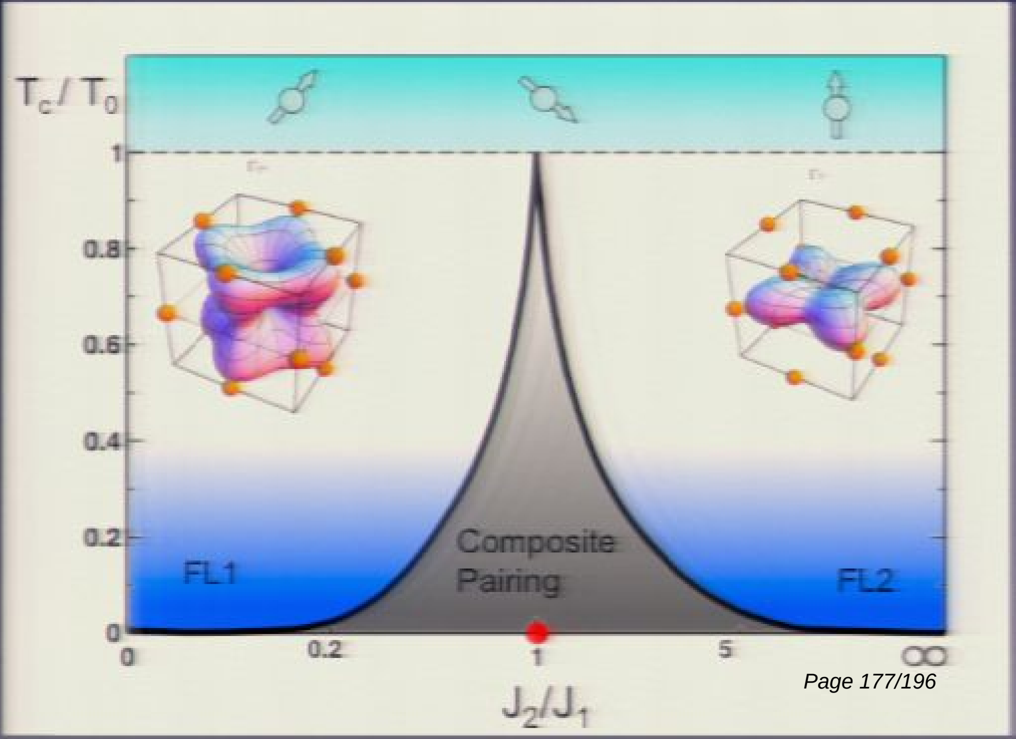

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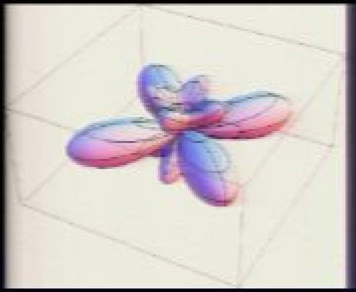

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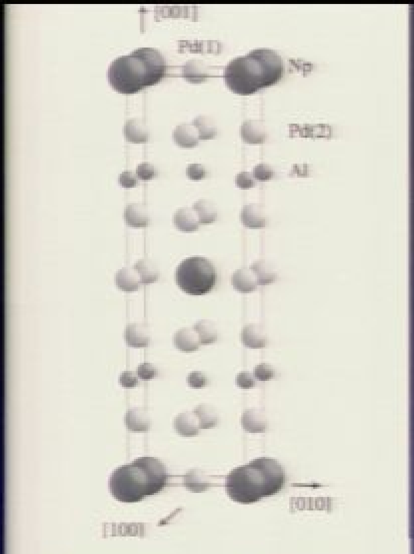

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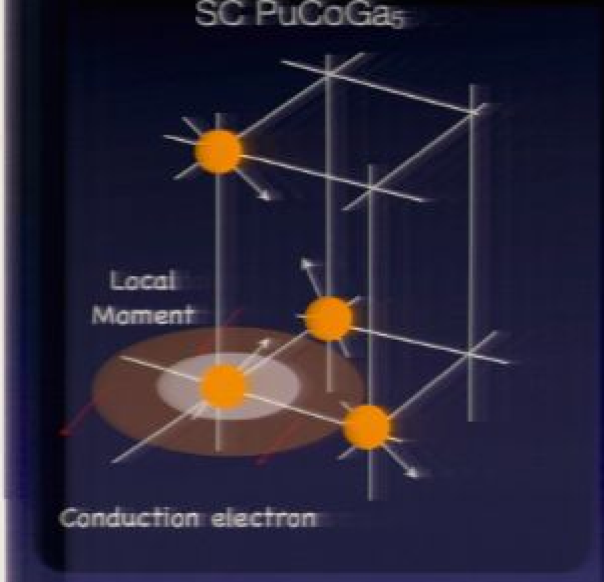

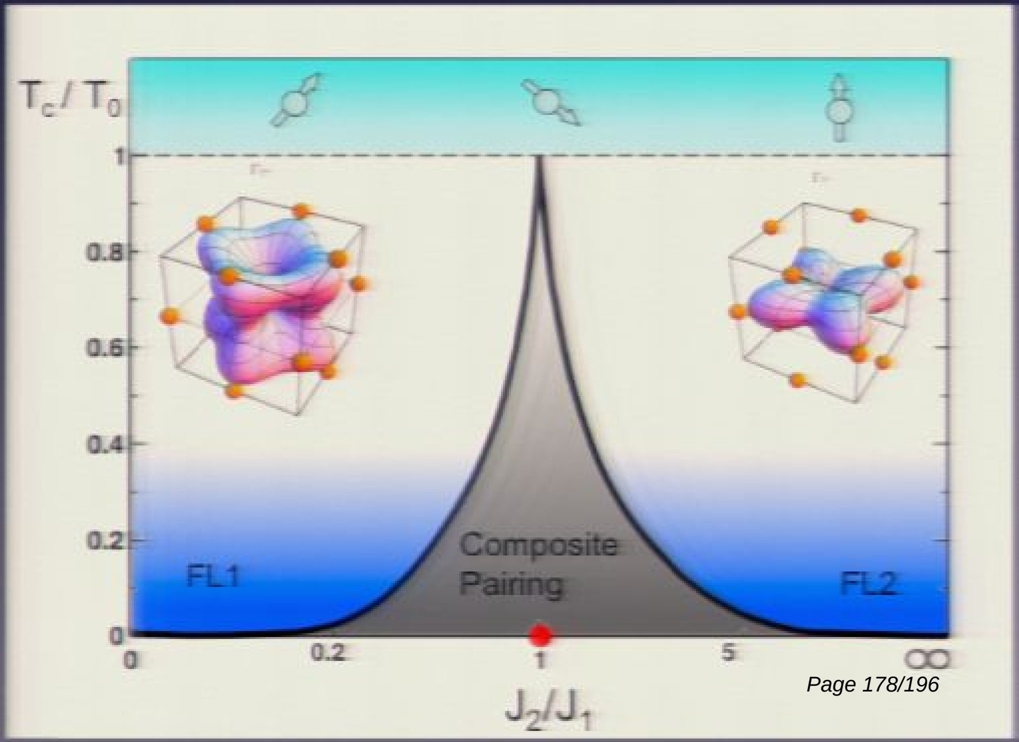

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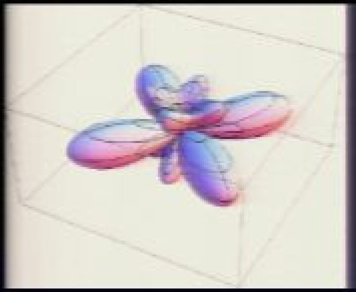

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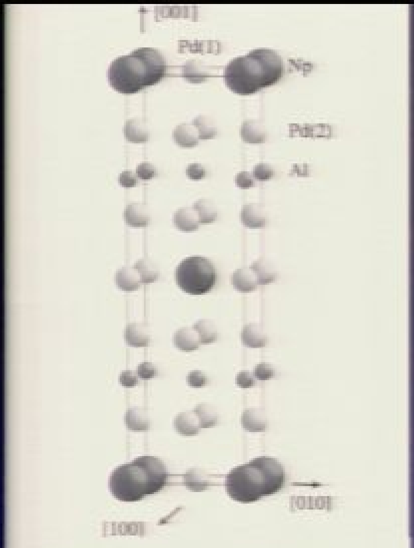

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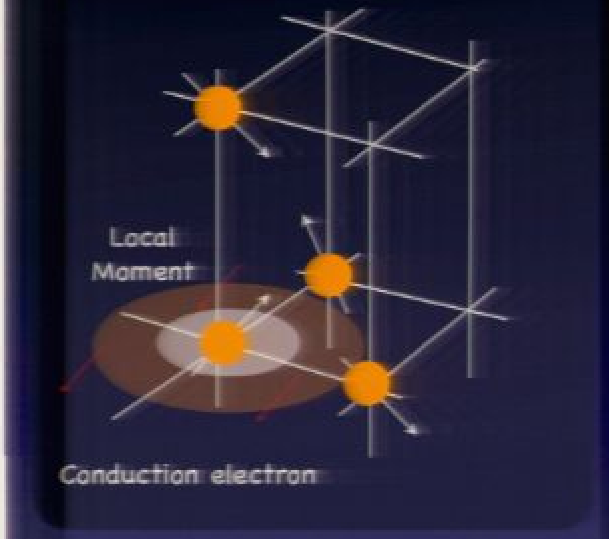

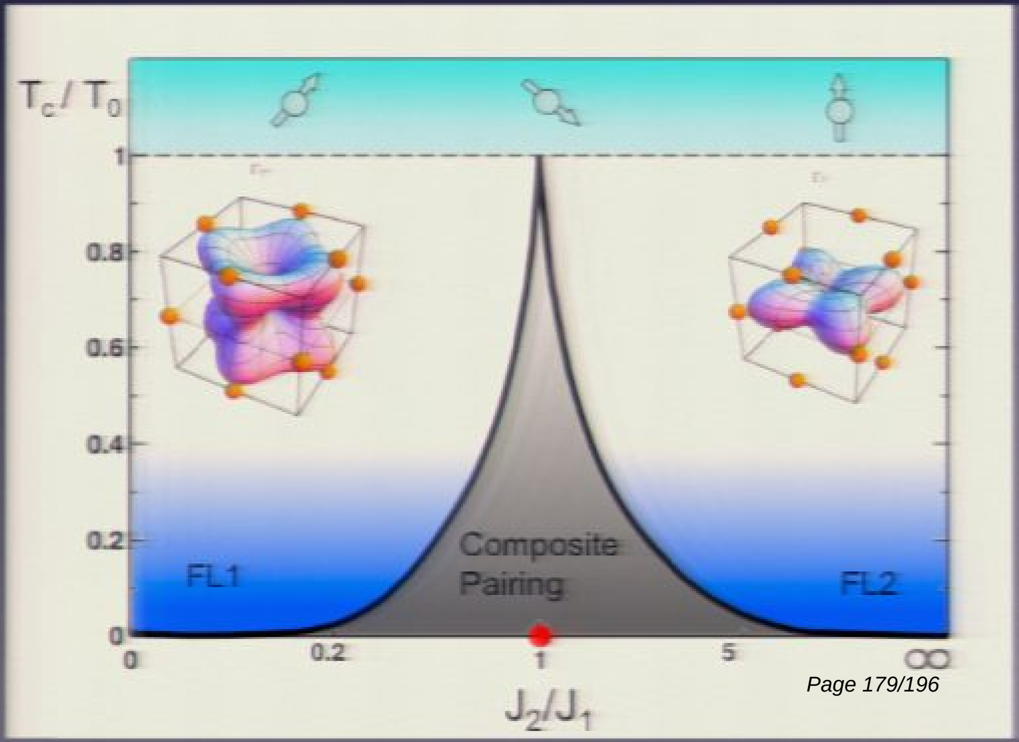

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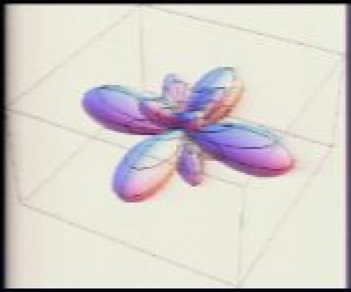

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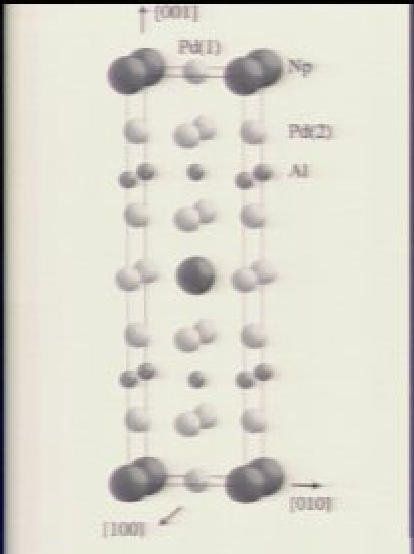

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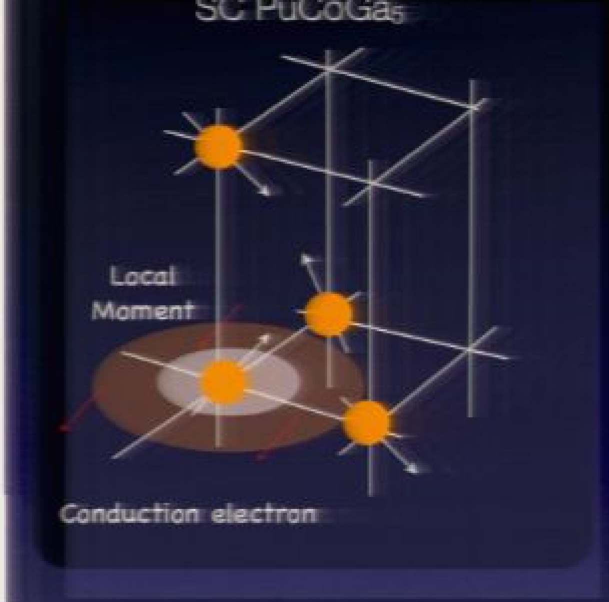

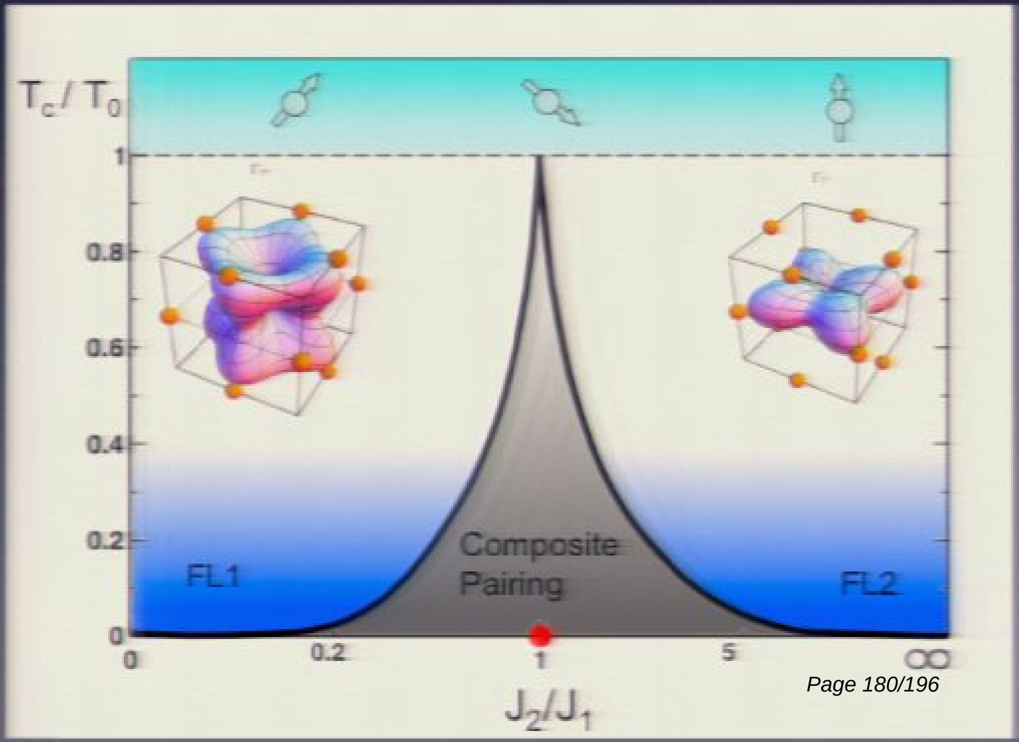

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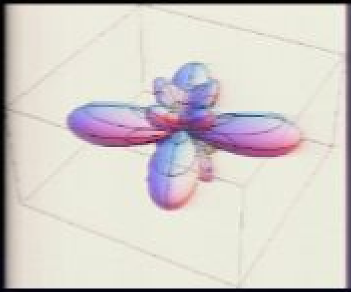

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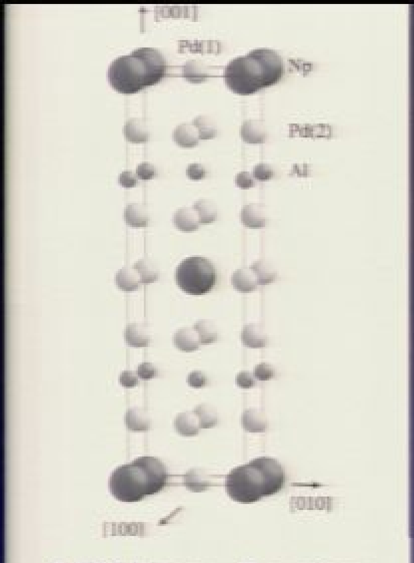

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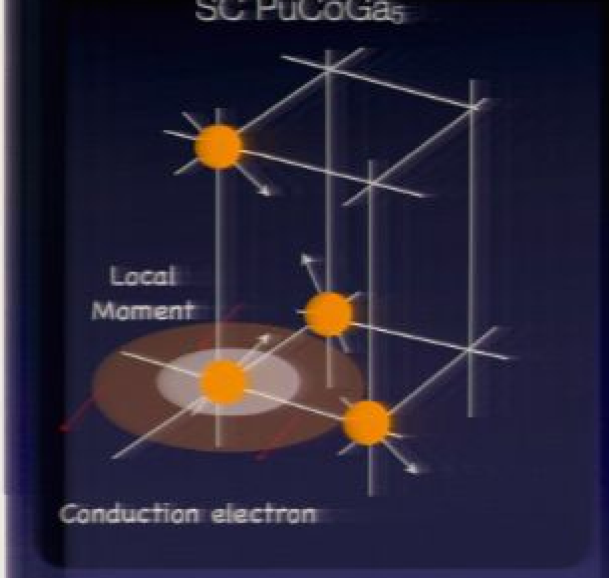

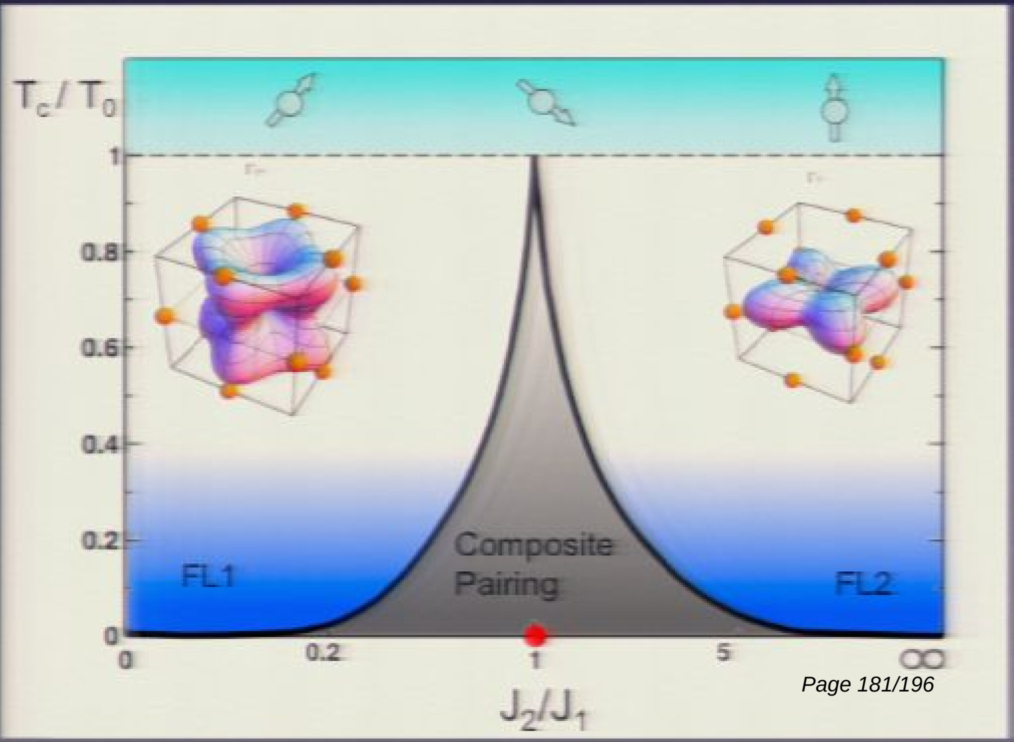

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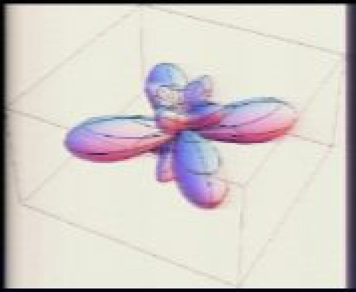

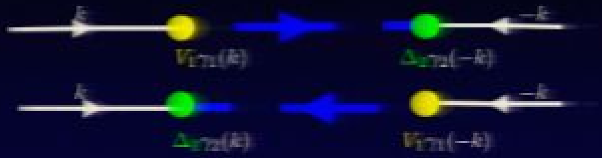

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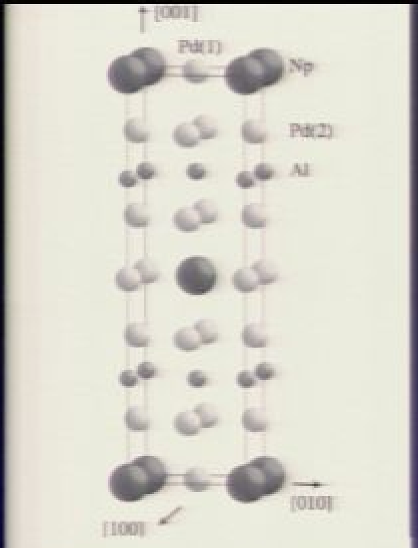

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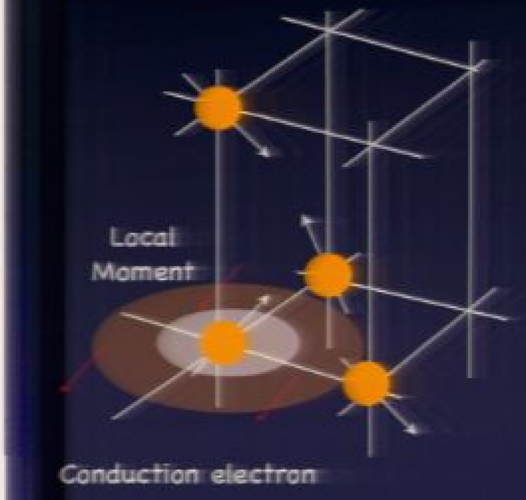

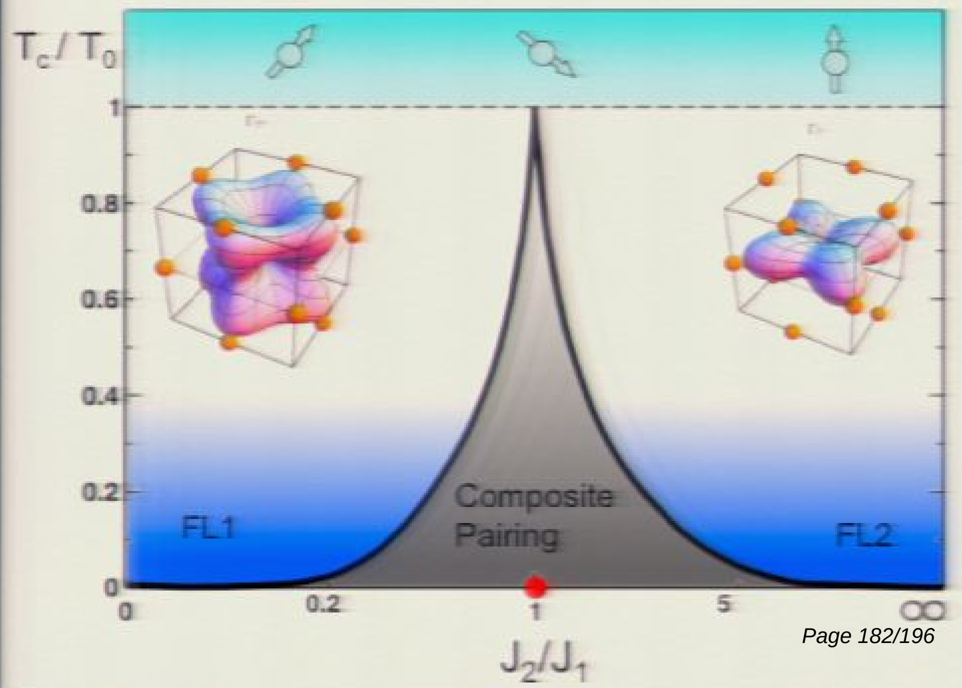

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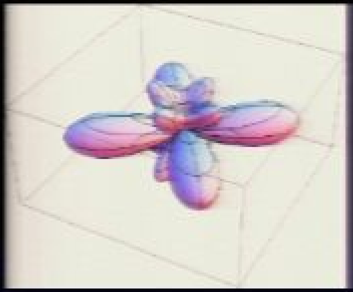

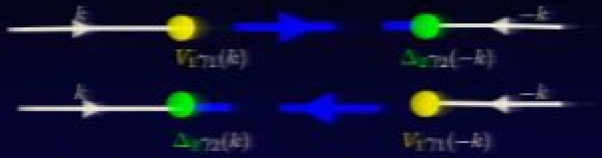

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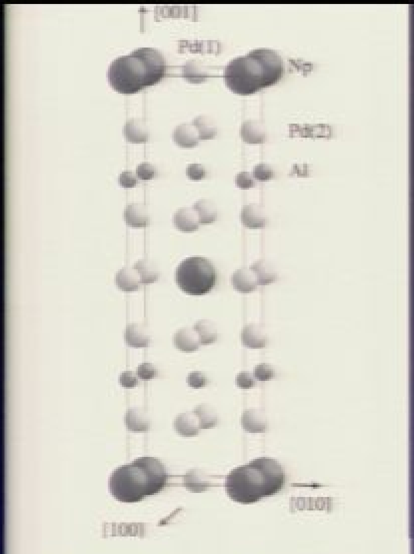

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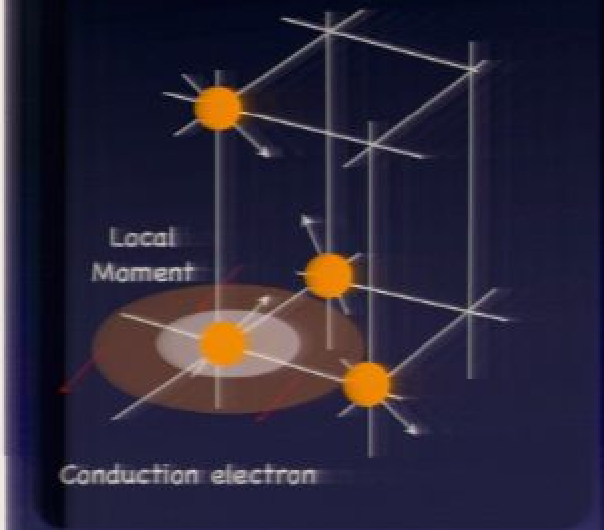

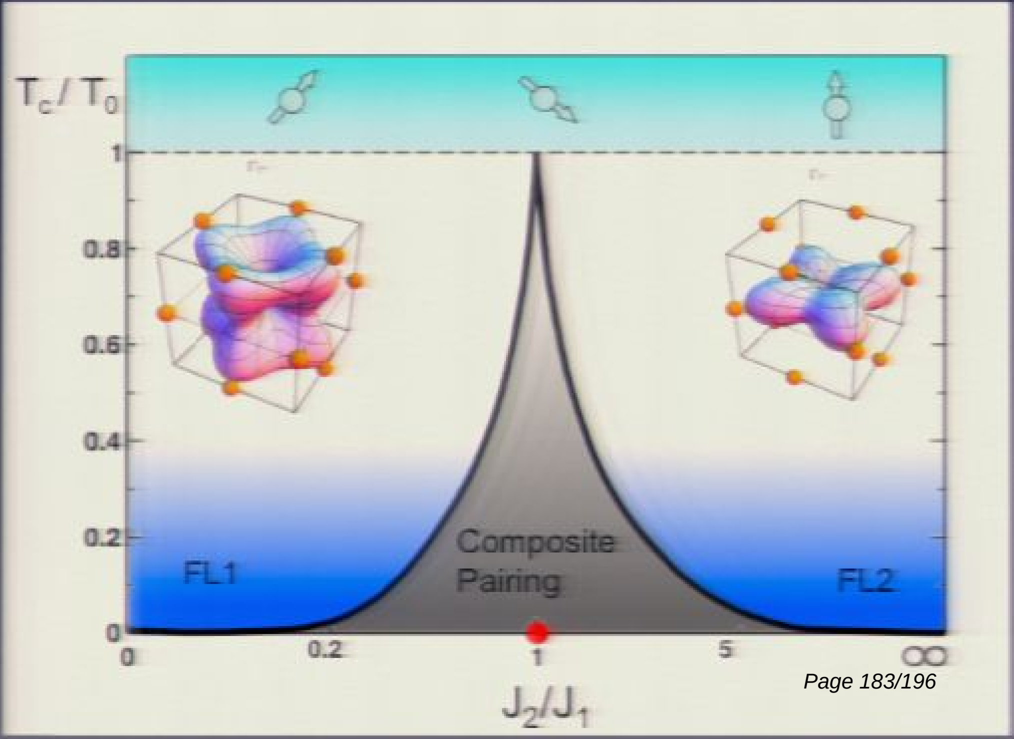

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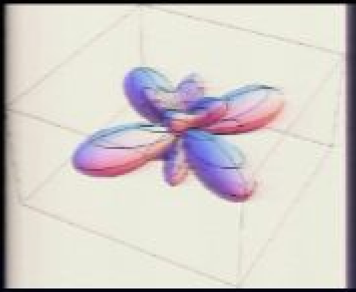

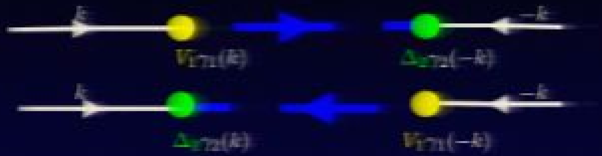

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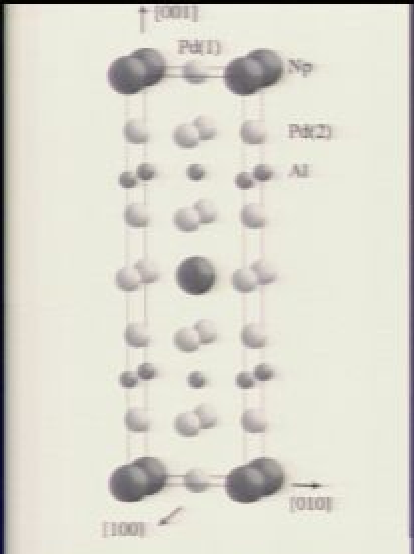

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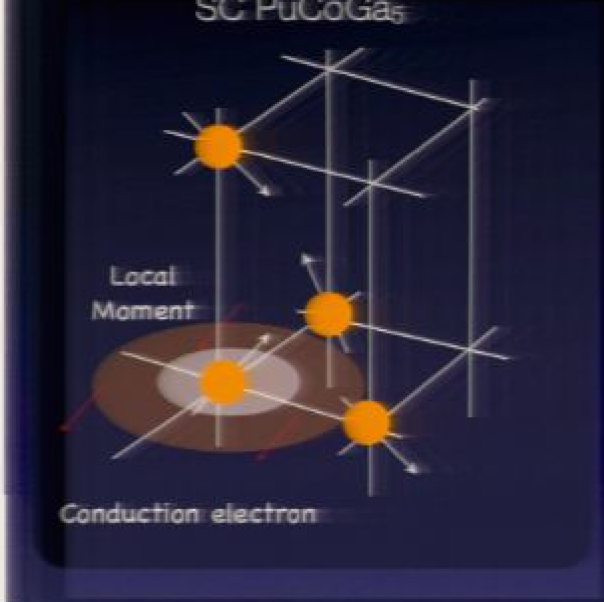

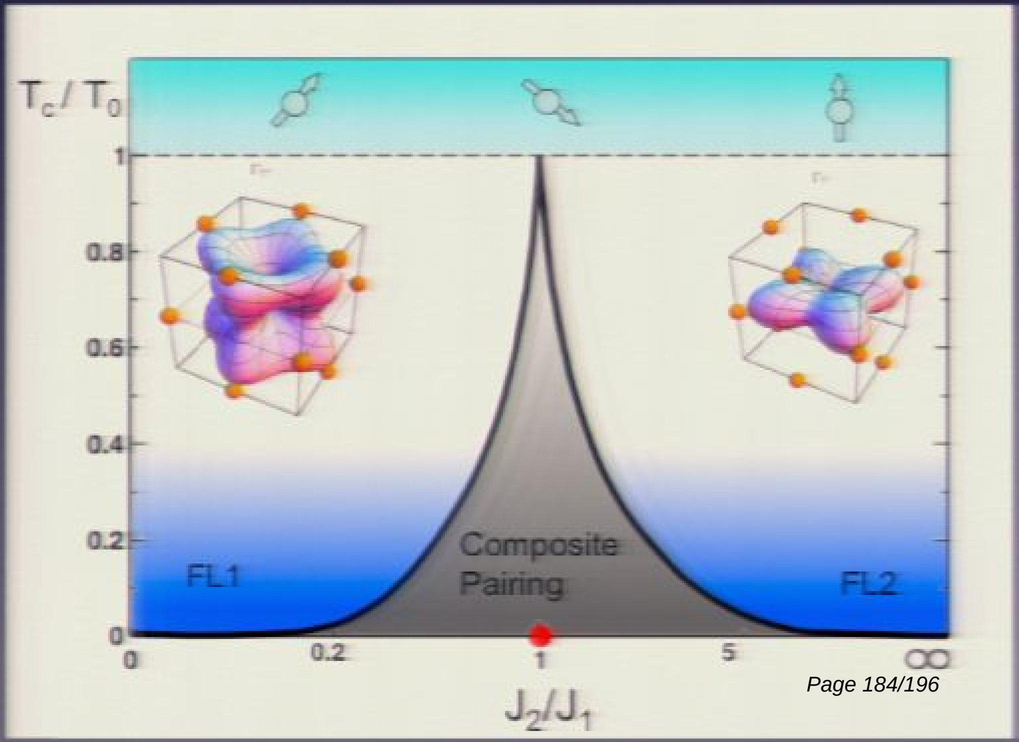

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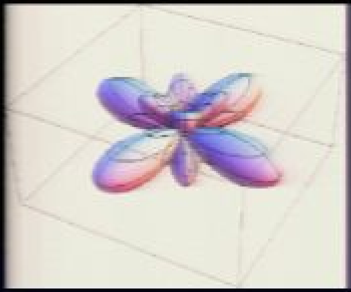

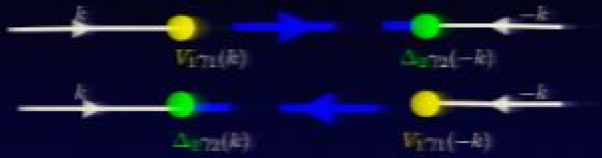

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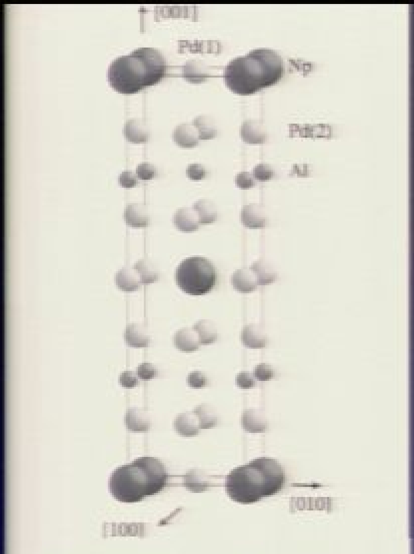

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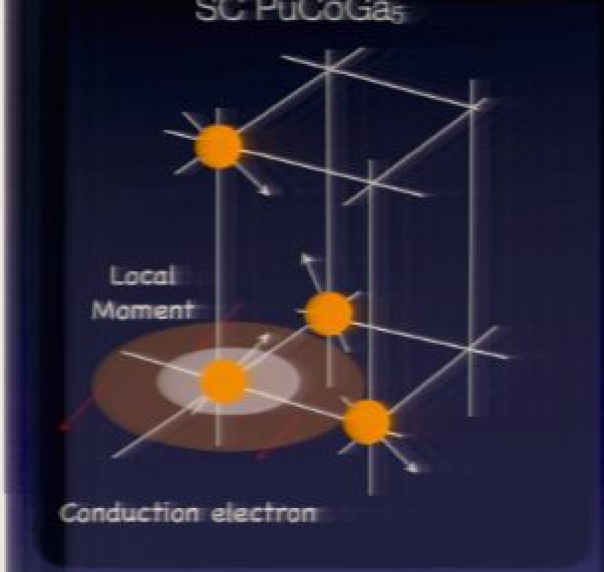

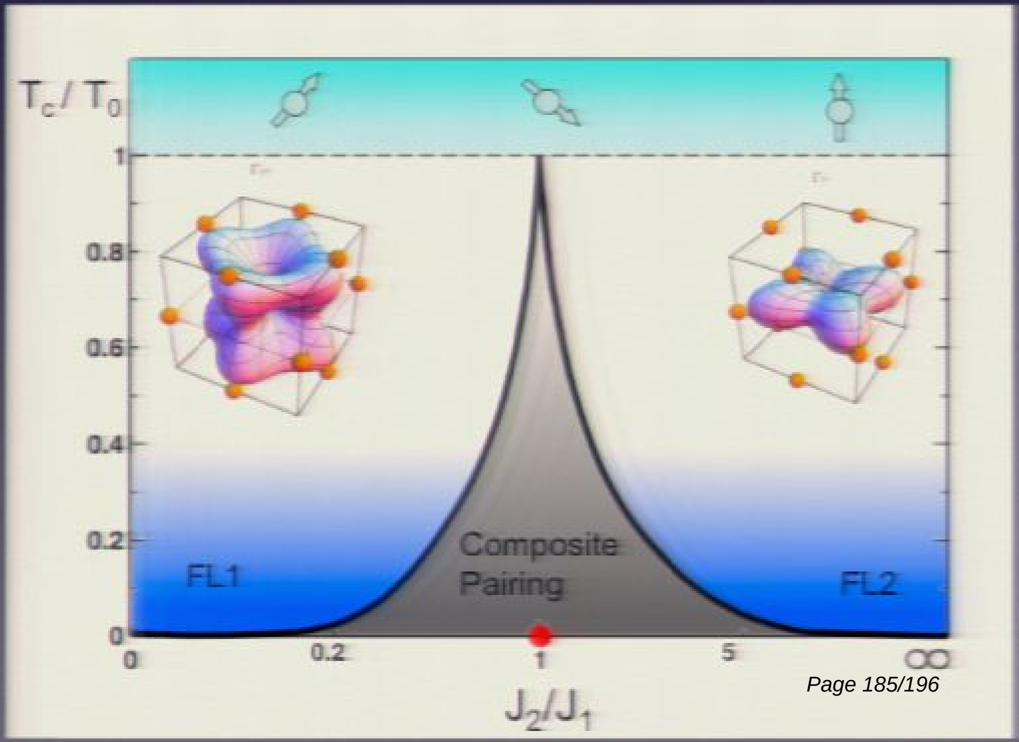

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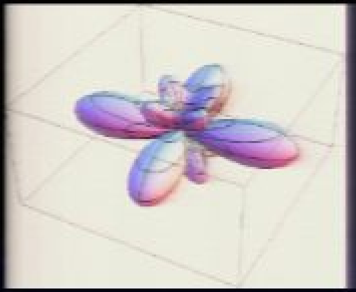

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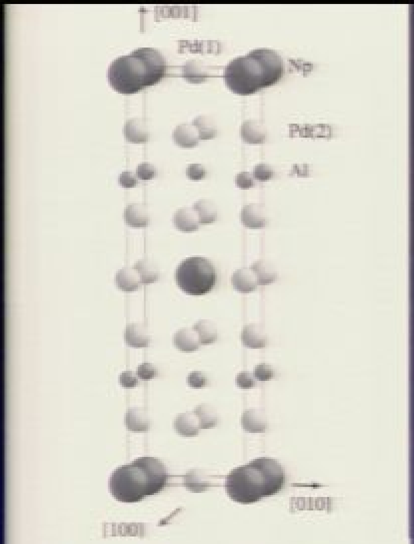

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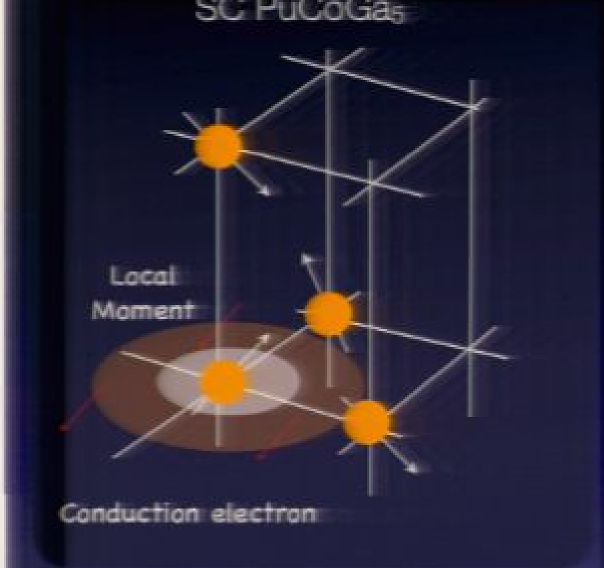

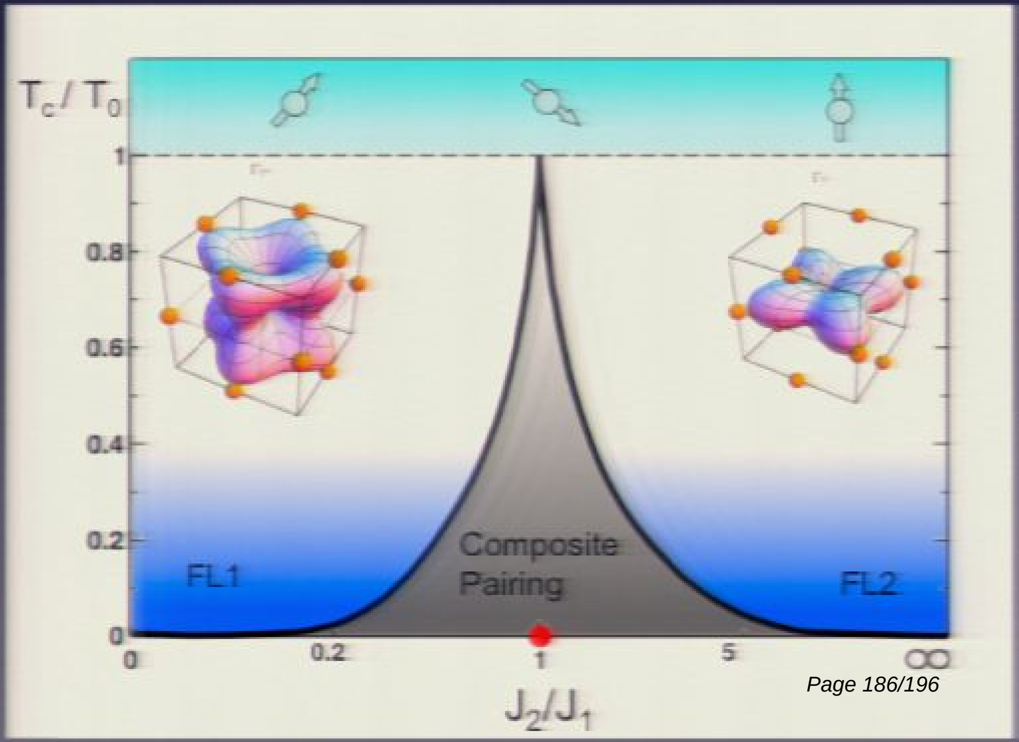

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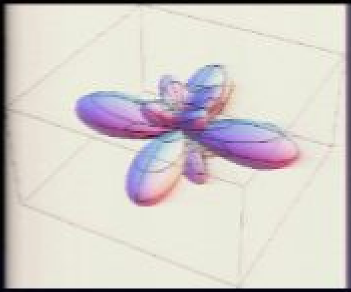

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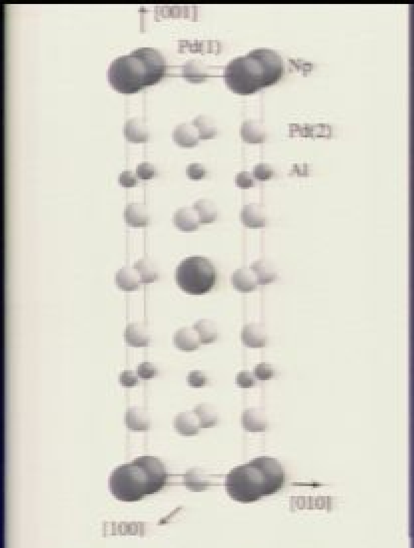

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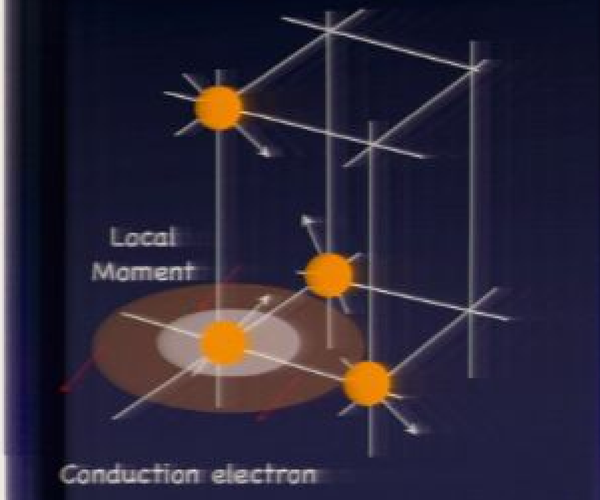

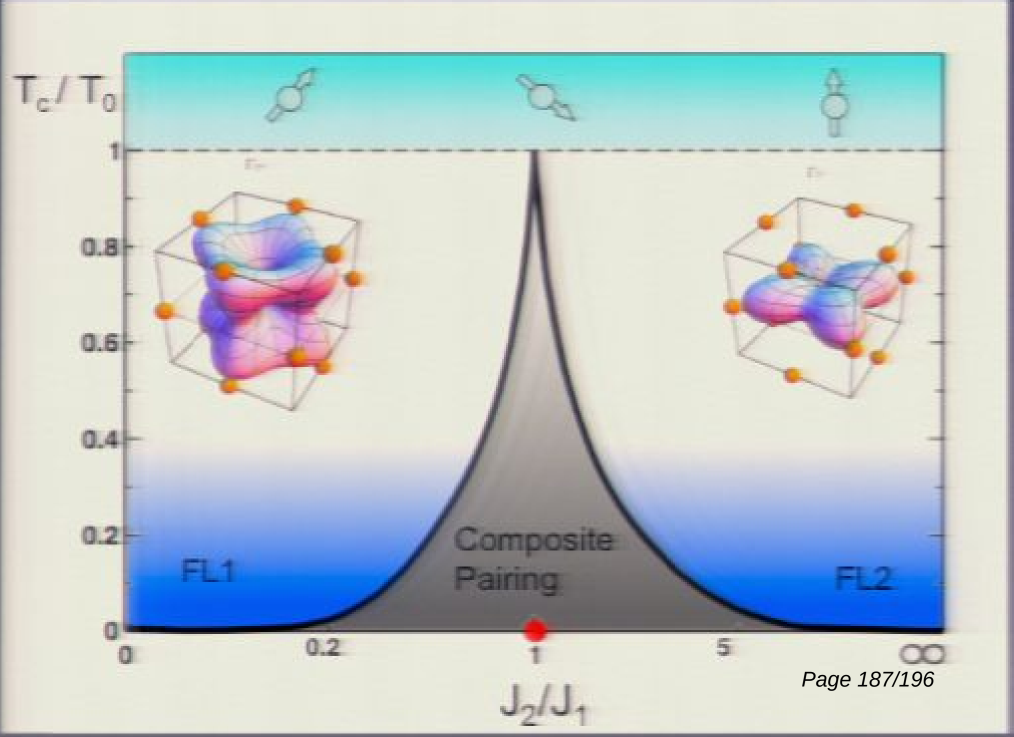

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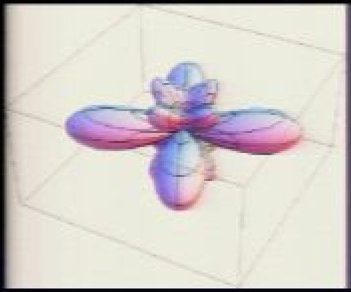

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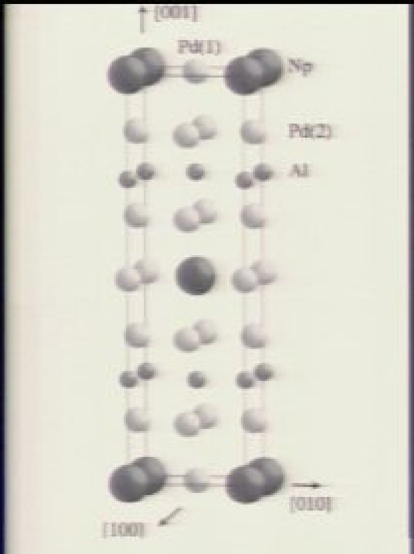

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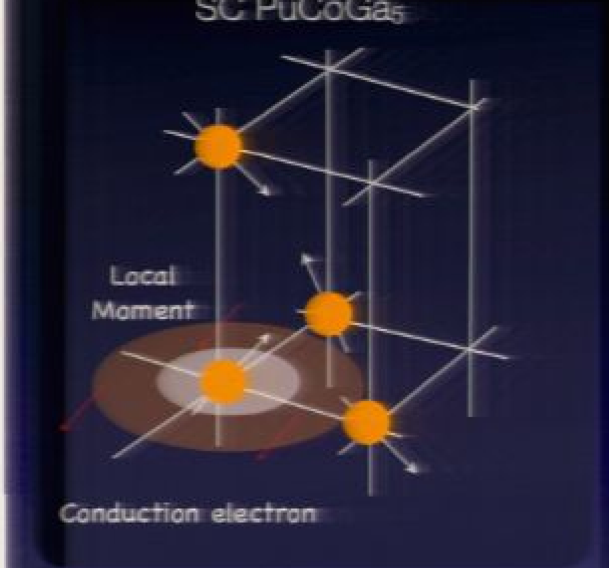

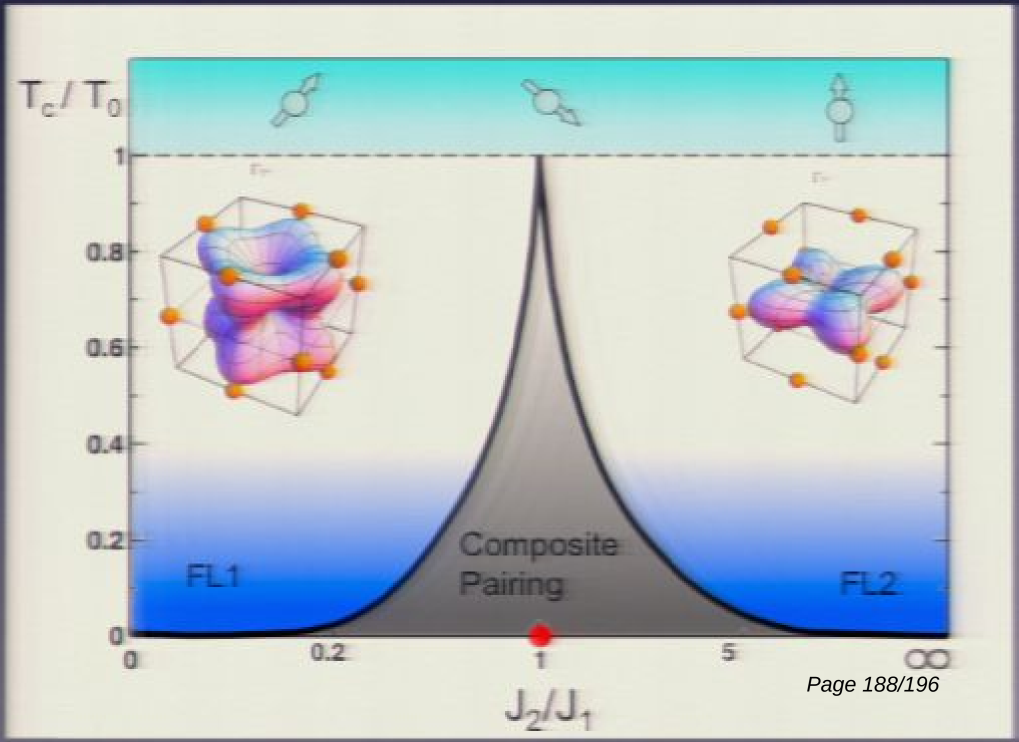

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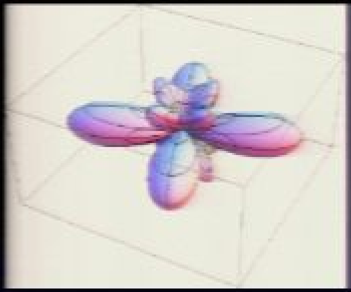

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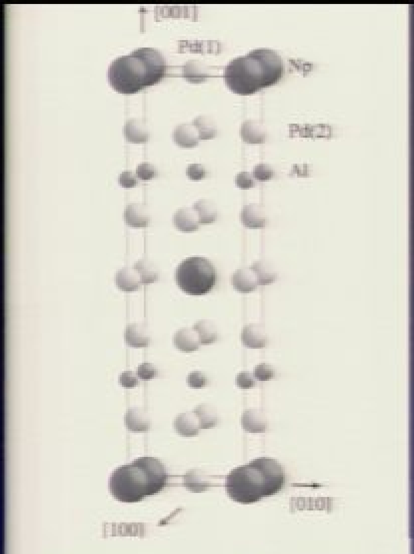

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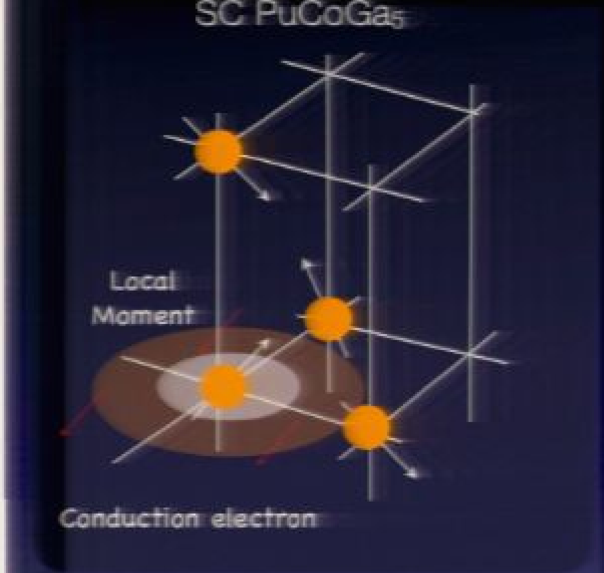

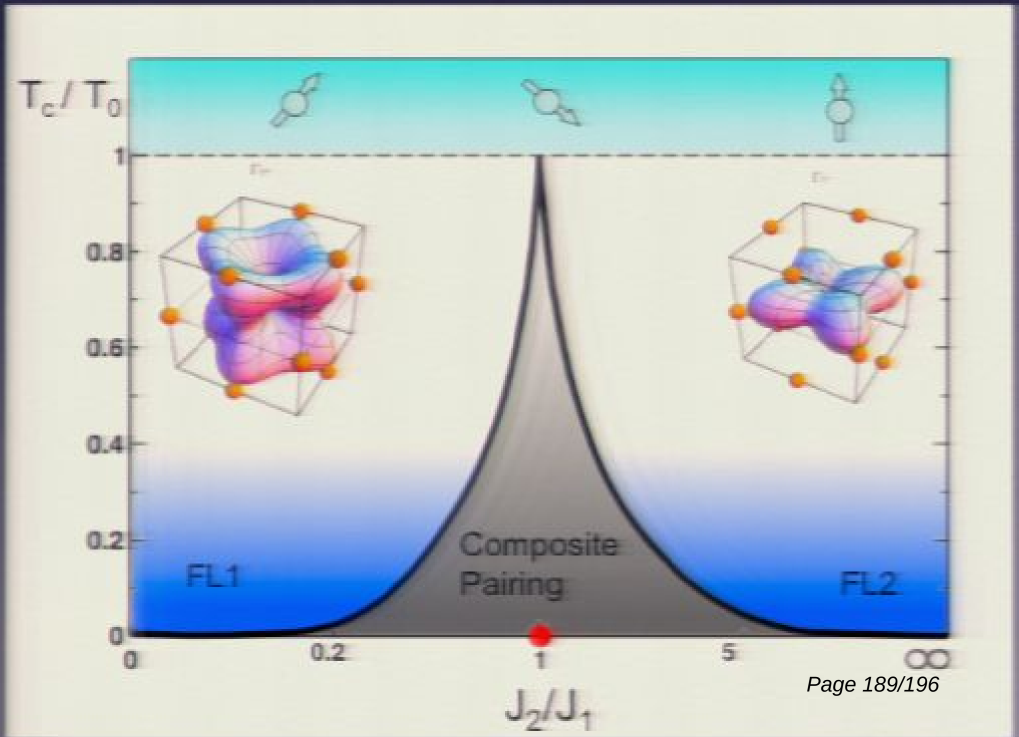

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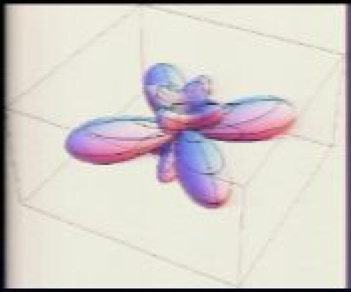

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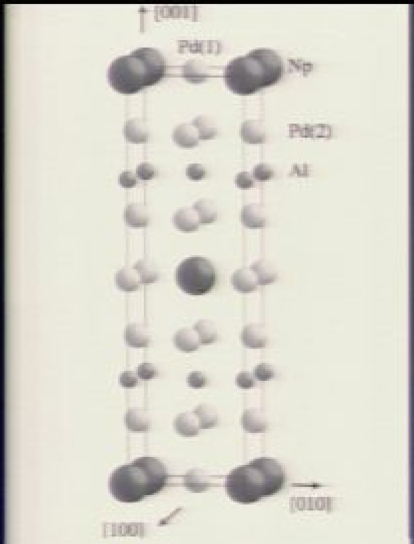

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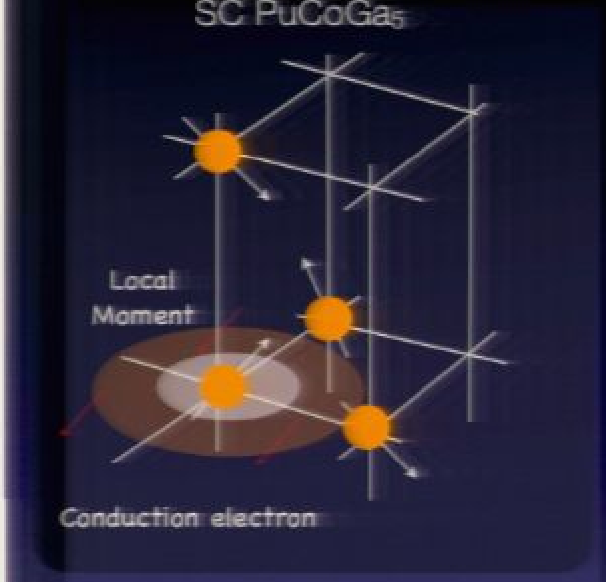

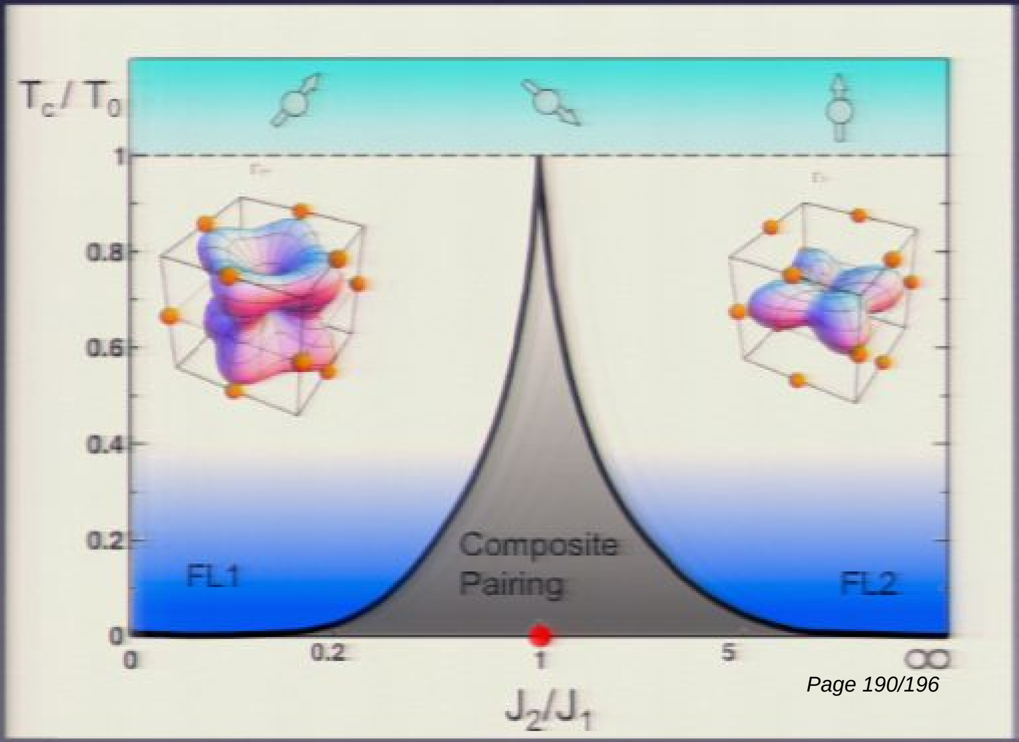

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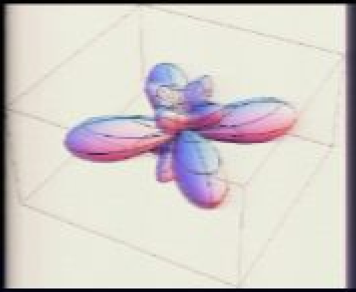

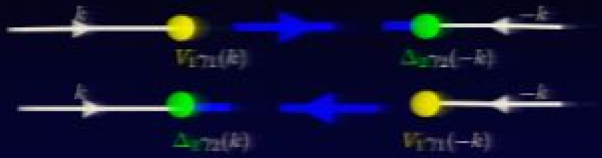

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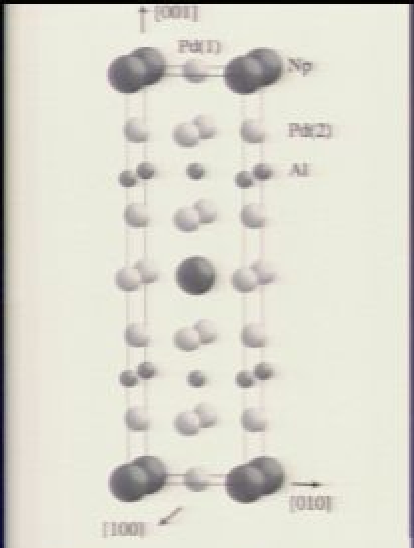

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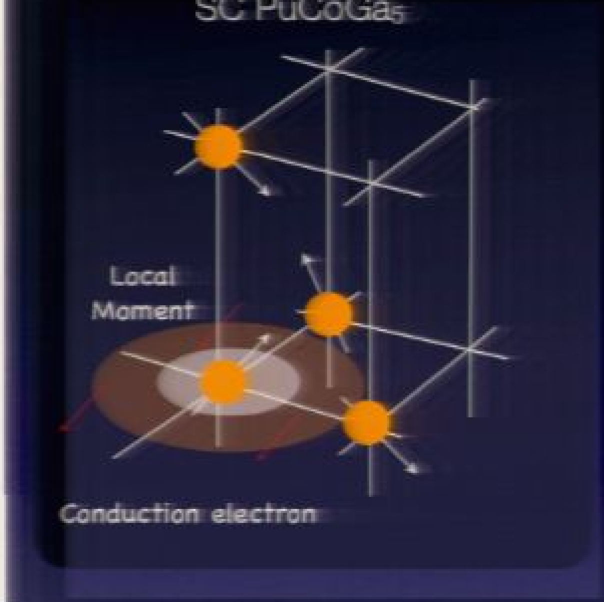

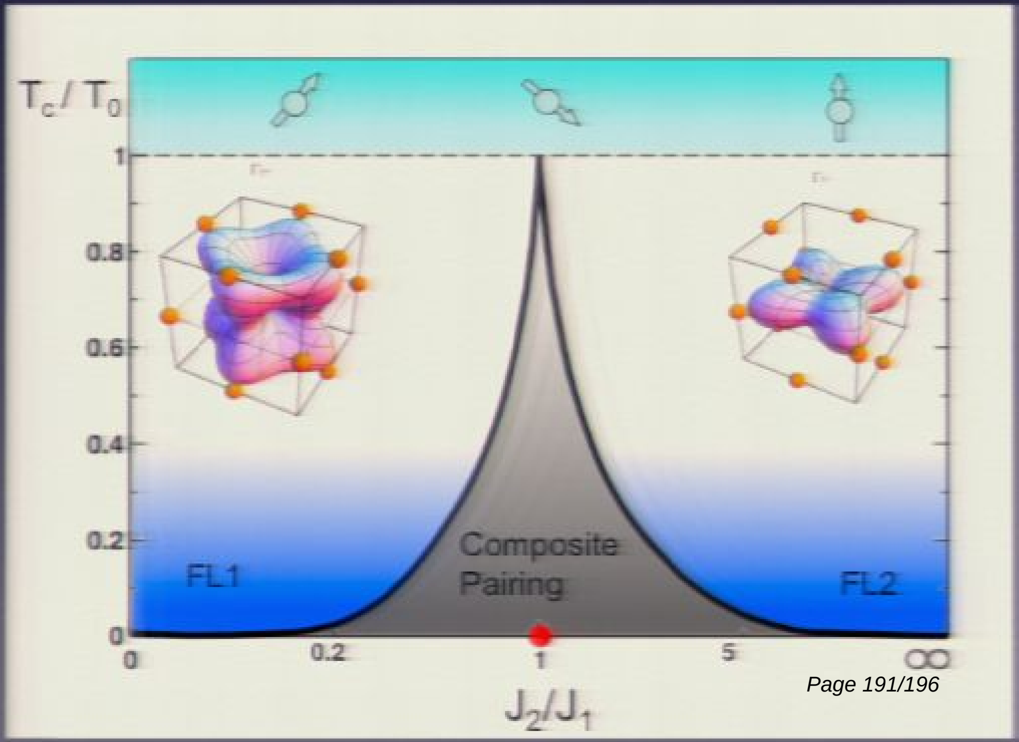

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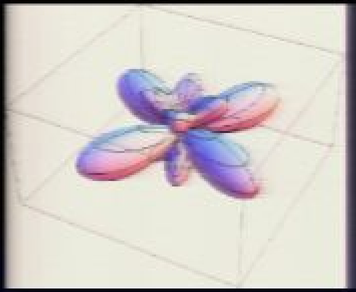

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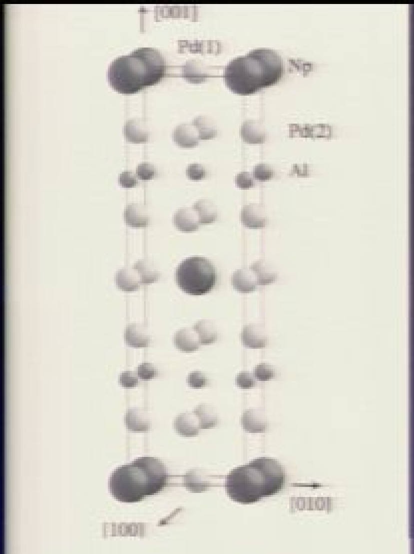

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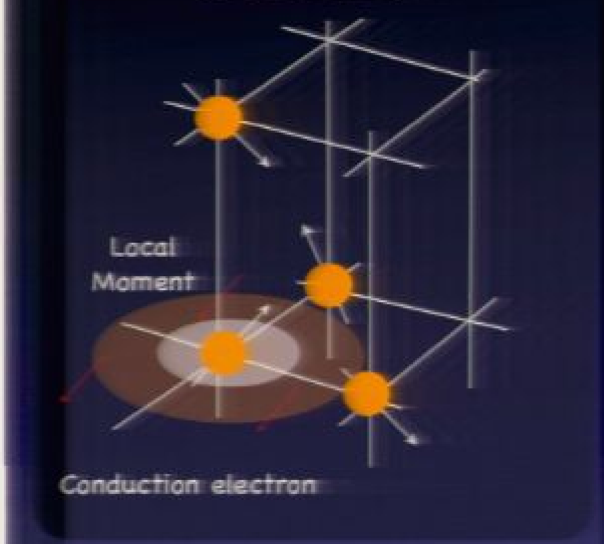

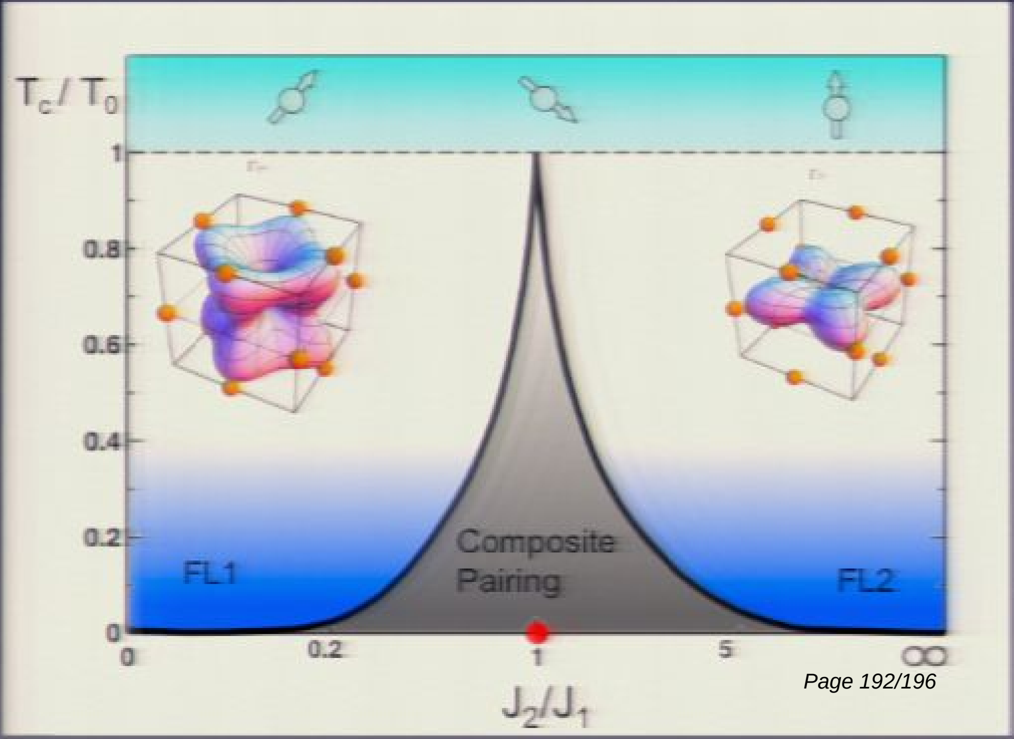

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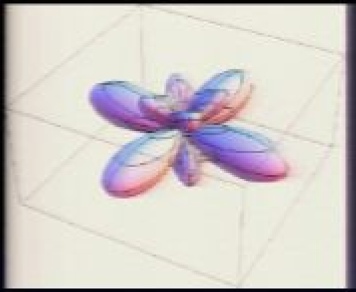

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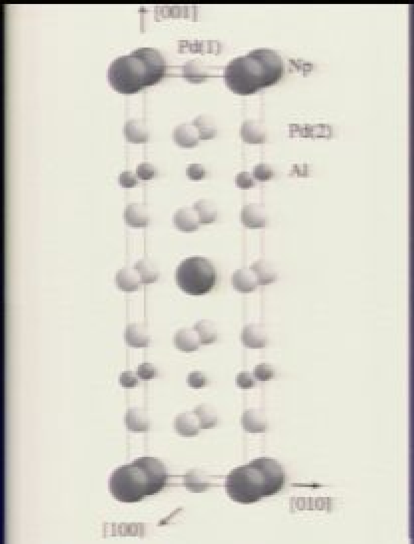

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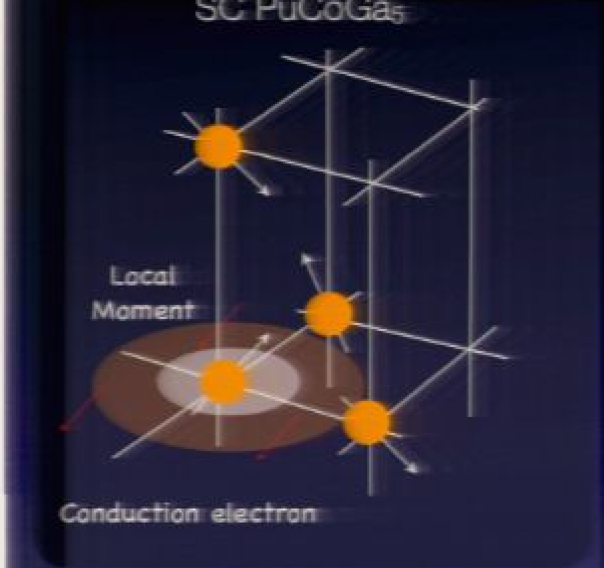

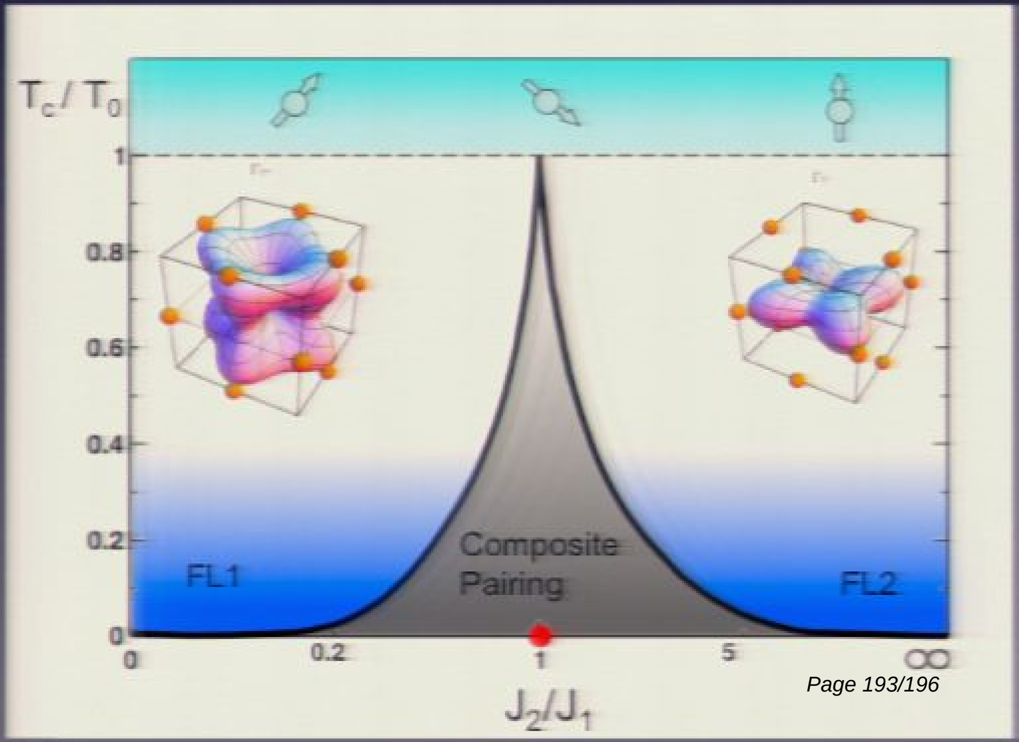

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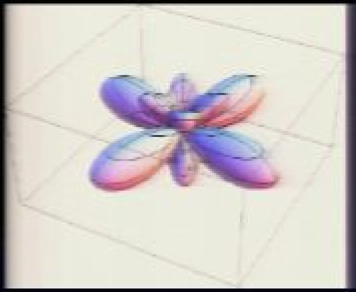

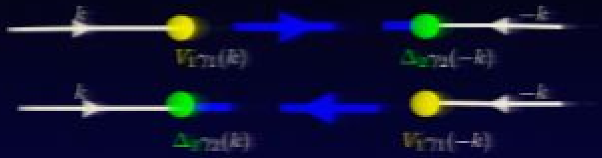

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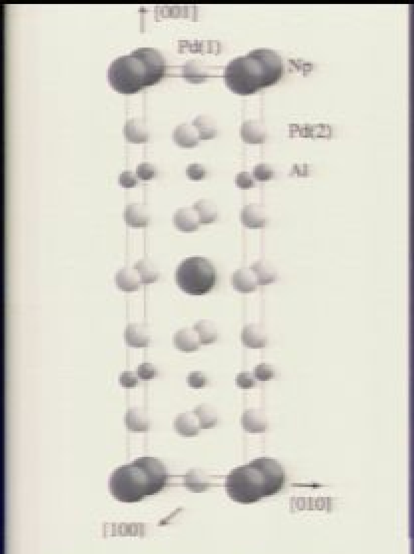

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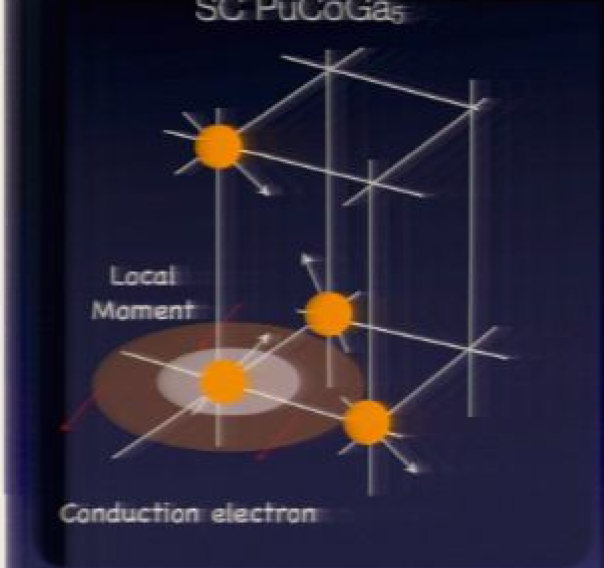

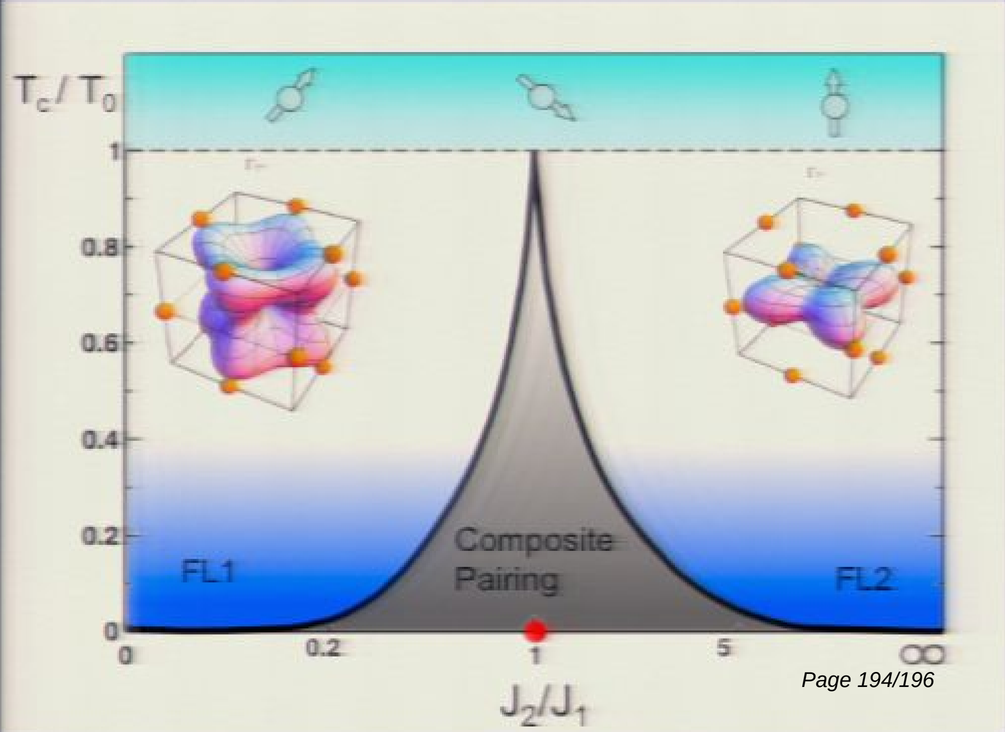

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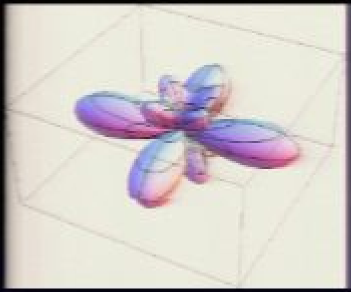

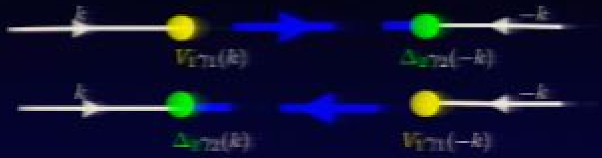

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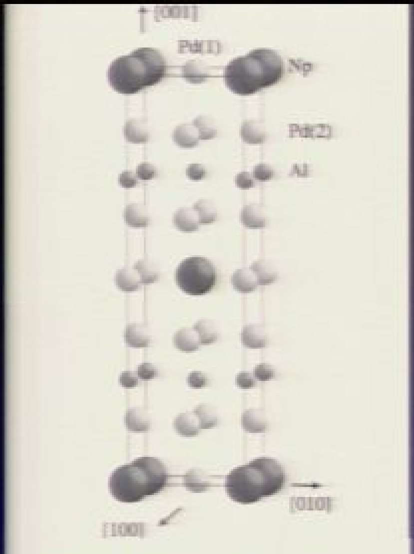

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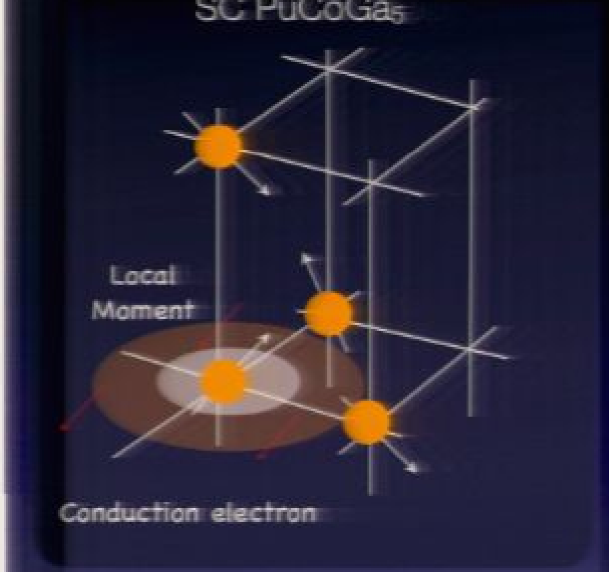

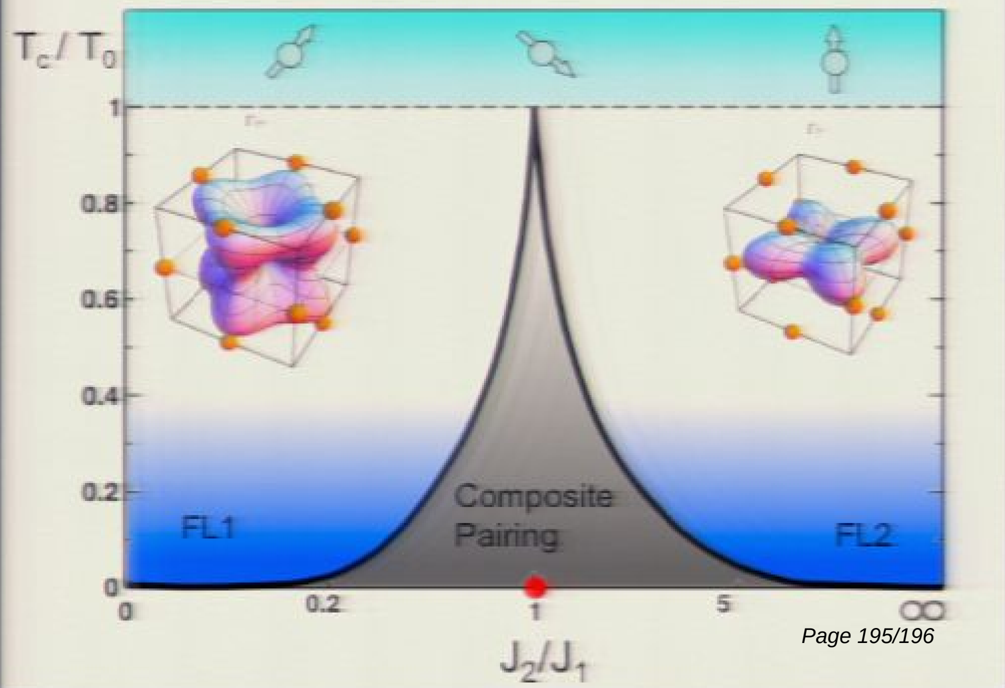

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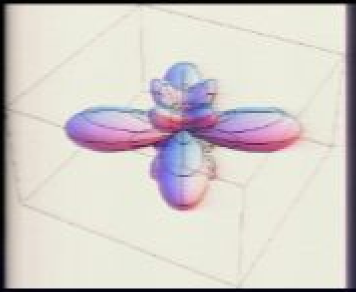

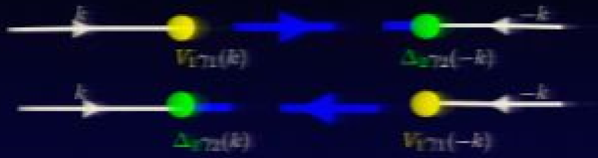

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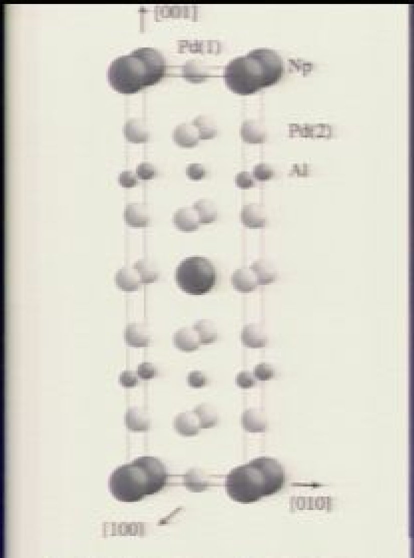

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