Electronic structure of correlated electron systems : theory and experiment Lecture 1,2

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Rough content of 5 lectures

- Lecture 1 and 2:Electronic structure of correlated and narrow band systems.
- Lecture 2 and 3: Electronic structure and theory of transition metal oxides (orbital, charge, spin and lattice degrees of freedom)
- Importance of non uniform polarizabilities Surfaces, interfaces of strongly correlated Oxides.
- Basic electronic structure and theoretical models of Fe Pnictides

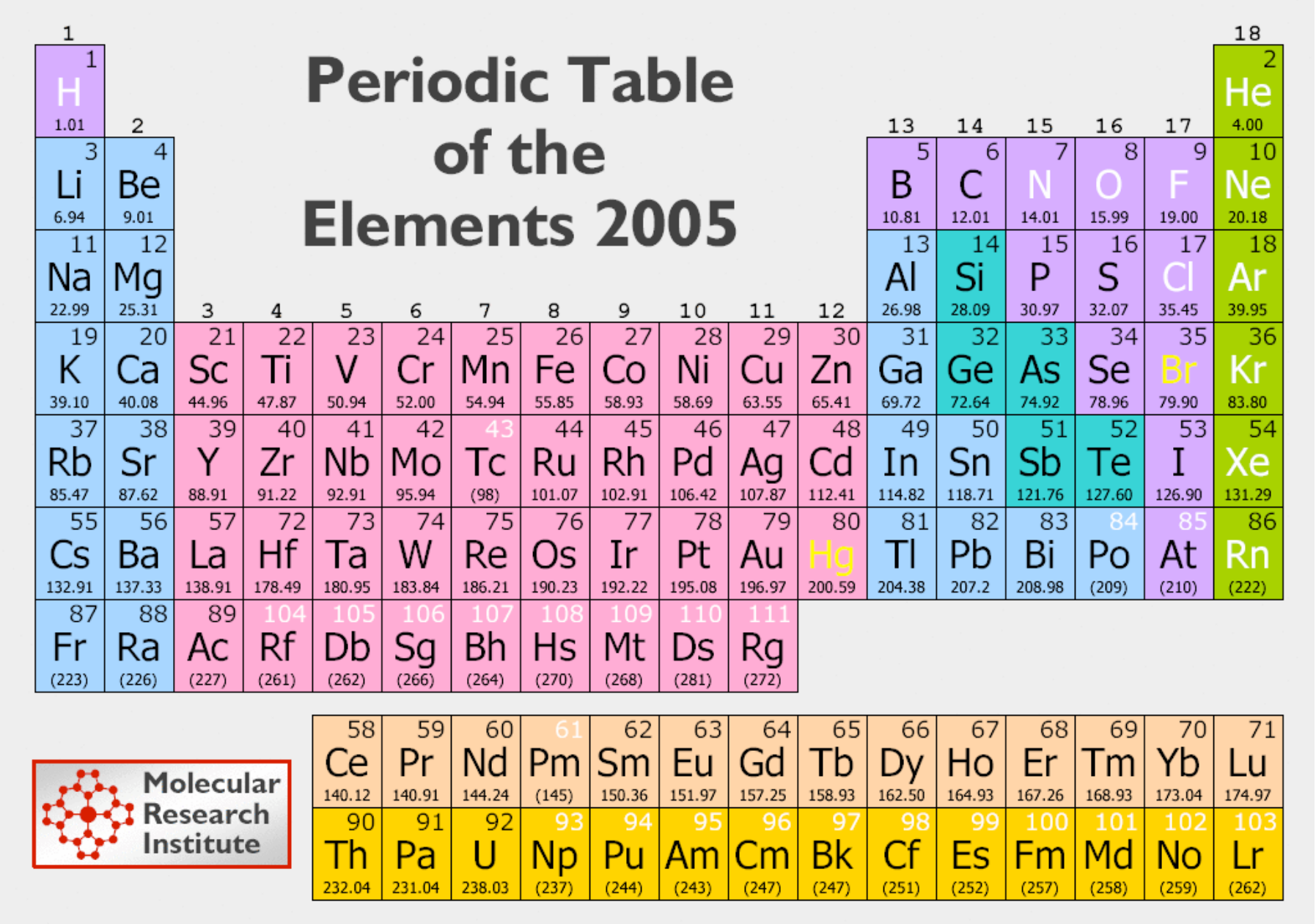
Content Lecture 1,2

- Electronic structure of correlated electron systems
  - Why are TM compounds and rare earths special
  - Quasi atomic vs band structure approaches
  - A bit about DFT, LDA+U, DMFT, Model H exact diagonalization
  - A bit about Auger and ARPES
  - Spectral weight transfer arguably the most direct evidence for strong correlation
  - Models and curiosity's

Some Old Historical milestones

- 1929-1931 Bloch Wilson theory of solids
- 1937 De Boer and Verwey (NiO-CoO breakdown of band theory
- 1937 Peierls 3d electrons avoid each other (basically the Hubbard model)
- 1950 Jonker van Zanten - Zener Pervoskites double exchange
- 1959 Anderson superexchange (U>>W)
- 1964 Hubbard model-, Hohenberg Kohn DFT-Kohn Sham, Goodenough Transition metal compounds

Everyone claiming to work on real materials should be familiar with this



Wide diversity of properties

- Metals: CrO_2, Fe_3O_4 T>120K
- Insulators: Cr_2O_3, $SrTiO_3$,CoO
- Semiconductors: Cu_2O
- Semiconductor –metal: VO_2,V_2O_3, Ti_4O_7
- Superconductors: La(Sr)$_2$CuO$_4$, $LiTiO_4$, YBCO
- Piezo and Ferroelectric: $BaTiO_3$
- Catalysts: Fe,Co,Ni Oxides
- Ferro and Ferri magnets: CrO_2, gammaFe_2O_3
- Antiferromagnets: alfa Fe_2O_3, MnO,NiO ---
- Ionic conductors (batteries) LixNi1-xO
- Oxide fuel cells use Manganites and cobaltates

Properties depend in detail on composition and structure

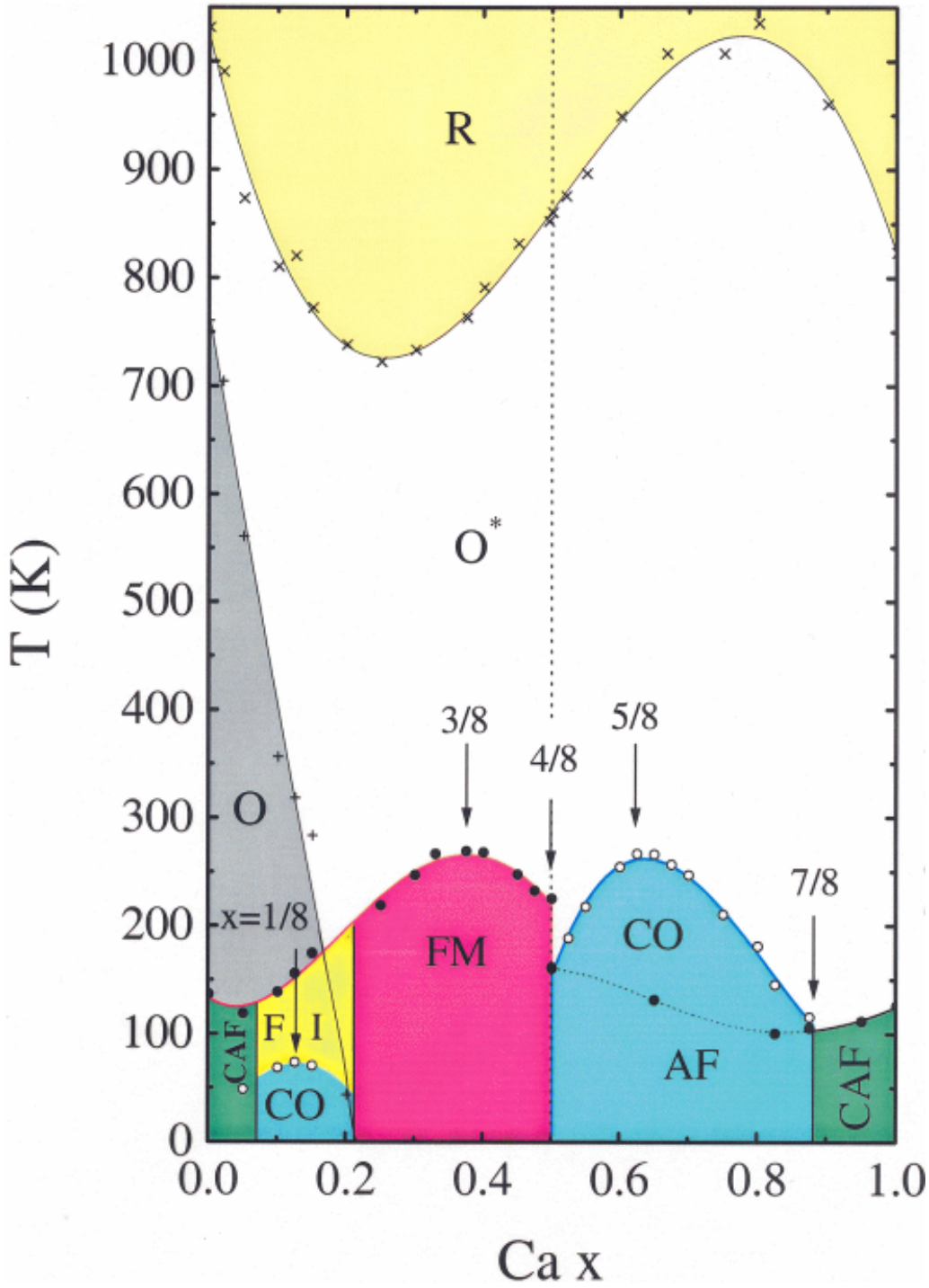
Phase Diagram of $La_{1-x}Ca_xMnO_3$

Uehara, Kim and Cheong

R: Rombohedral

O: Orthorhombic
(Jahn-Teller distorted)

O*: Orthorhombic
(Octahedron rotated)

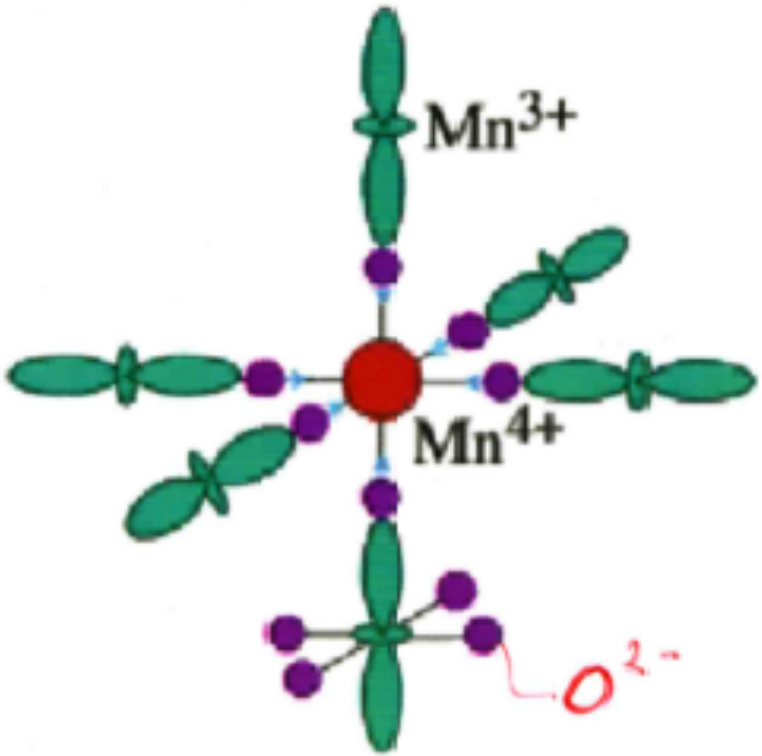


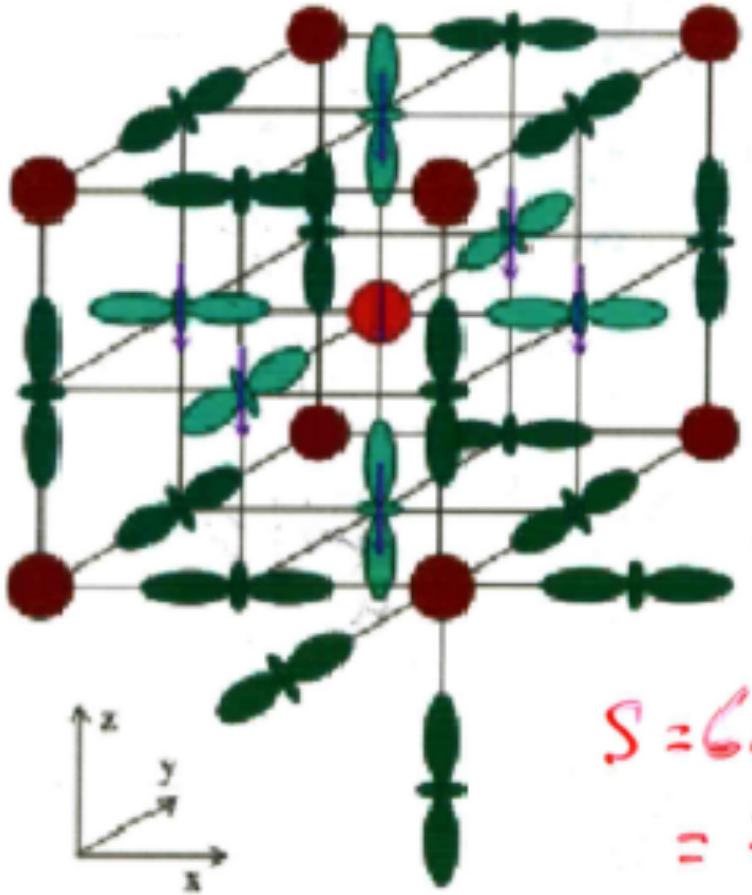
Mizokawa et al PRB 63, 024403 2001

$La_{\frac{3}{4}}Sr_{\frac{1}{4}}MnO_3$

Model for Charge, Spin and Orbital Correlations in Manganites

Mn4+ , d3, S=3/2 ,No quadrupole ; Mn3+, S=2, orbital degeneracy

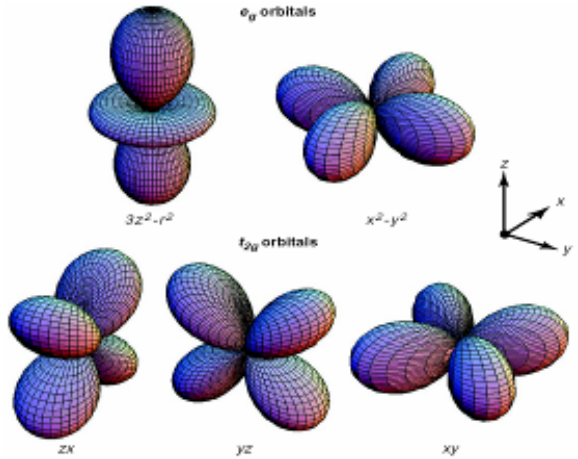




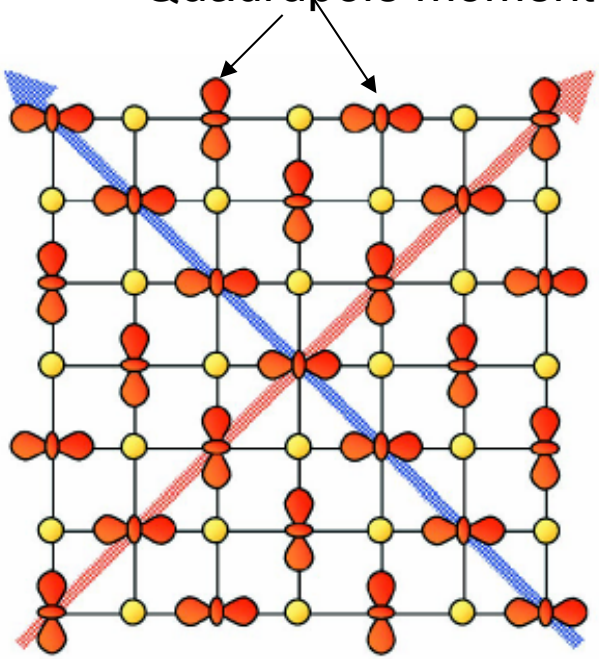
$S = 6 \times 2 + \frac{3}{2}$

$= \frac{27}{2}$

Ordering in strongly correlated systems



Quadrupole moment ordering

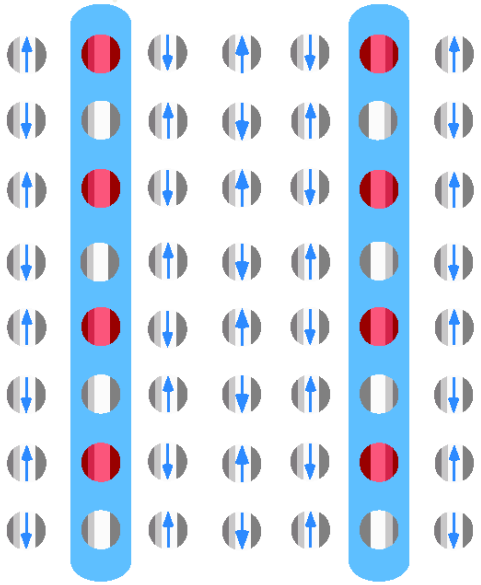


$DQ_C \sim 1\ e$
$DQ_O \sim 0$

Mn^{3+}

Mn^{4+}

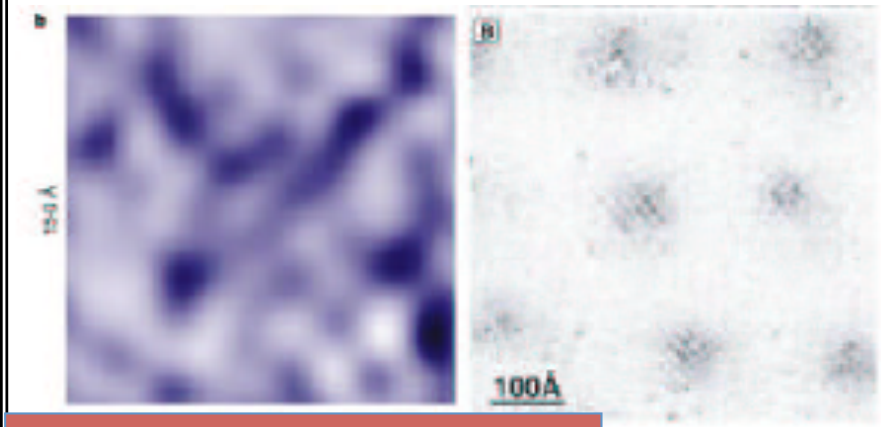
Stripes in Nd-LSCO



rivers of Charge—Antiferro/ Antiphase

$DQ < 0.5\ e$

Charge inhomogeneity in Bi2212

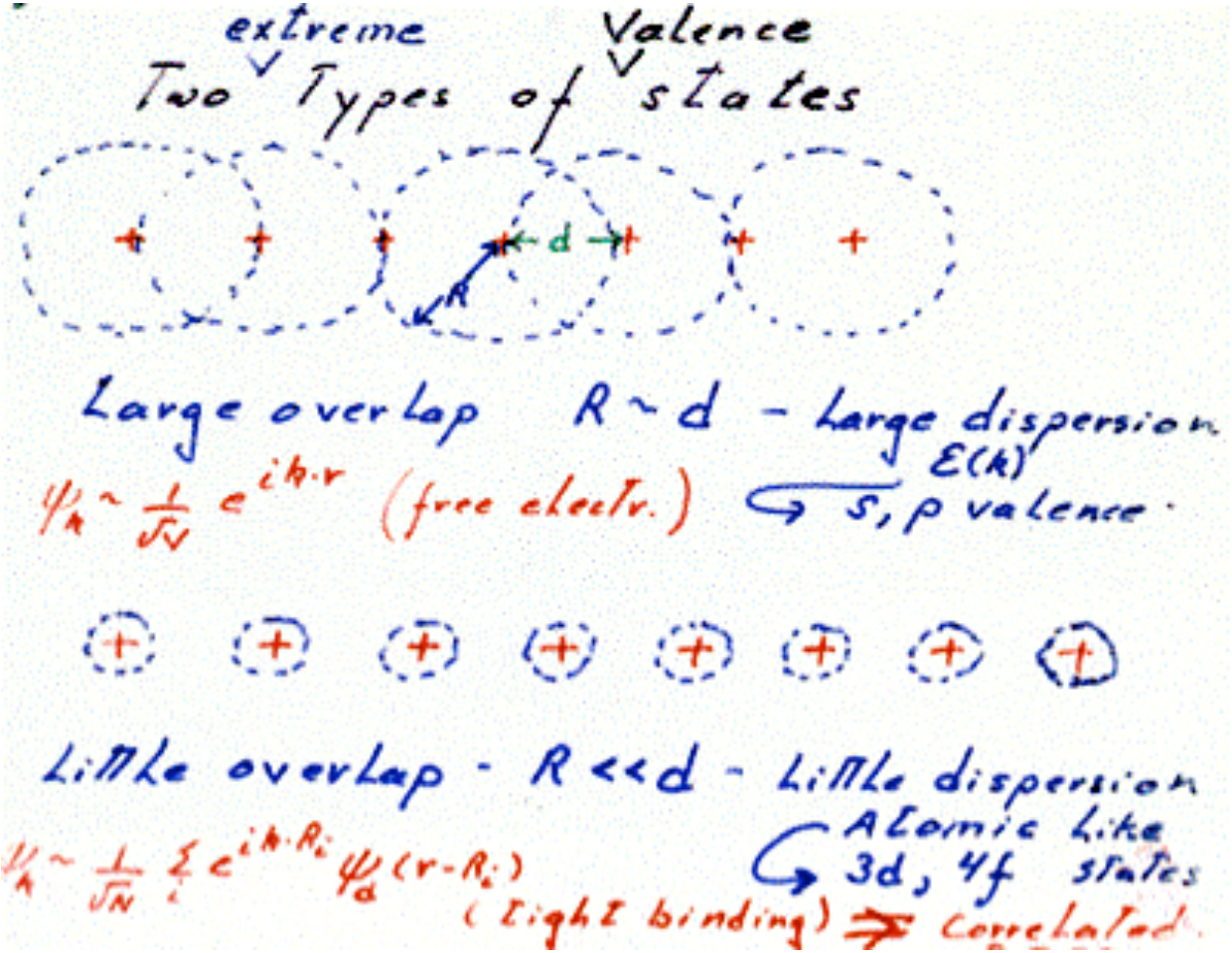


Pan, *Nature*, **413**, 282 (2001);
Hoffman, *Science*, **295**, 466 (2002)

$DQ \sim 0.1\ e$

It’s the outermost valence electron states that determine the properties ; Both the occupied and unoccupied ones

Two extremes for atomic valence states in solids



Where is the interesting physics?

Coexistance-----Hybridization

Kondo, Mixed valent, Valence fluctuation, local moments, Semicond.-metal transitions, Heavy Fermions, High Tc's, Colossal magneto resistance, Spin tronics, orbitronics

Characteristics of solids with 2 extreme valence orbitals

R>> D

- electrons lose atomic identity
- Form broad bands
- Small electron electron interactions
- Low energy scale –charge fluctuations
- Non or weakly magnetic
- Examples Al, Mg, Zn, Si

R<<D

- Valence Electrons remain atomic
- Narrow bands
- Large electron electron interactions (on site)
- Low energy scale-spin fluctuations
- Magnetic (Hunds' rule)
- Gd, CuO, SmCo3

Many solids have coexisting R>>D and R<<D valence orbitals i.e. rare earth 4f and 5d, CuO Cu 3d and O 2p, Heavy Fermions, Kondo, High Tc,s , met-insul. transitions

Why are the valence 3d and 4f orbitals in transition metal and rare earth compounds special

- Lowest principle q.n. for that l value
- Large centrifugal barrier l=2,3
- Small radial extent, no radial nodes, orthogonal to all other core orbital's via angular nodes (snuggle up to the nucleus)
- High kinetic energy (angular nodes) compensates for the strong potential energy
- Relativistic effects
- Look like core orb. But have high energy and form open shells like valence orb.

Why does $E_{n\ell}$ depend on ℓ?

Atomic - hydrogenic $\quad E_n^0 = \frac{mZ^2e^4}{2\hbar^2 n^2}$

n = principle q. n

ℓ comes in relativistic effects

$$\mathcal{E} = \sqrt{p^2c^2 + m^2c^4} \simeq mc^2 + \frac{p^2}{2m} - \frac{1}{8}\frac{(p^2)^2}{m^3c^2}$$

mass velocity

From $\langle p^2 \rangle \propto (E_n^0 + Ze^2\langle \frac{1}{r} \rangle)$

$$\Delta E = -\frac{1}{2mc^2}\left((E_n^0)^2 + 2E_n^0 Ze^2 \left\langle \frac{1}{r} \right\rangle_{n\ell} + Z^2e^4 \left\langle \frac{1}{r^2} \right\rangle \right)$$

$\left\langle \frac{1}{r} \right\rangle$ independent of ℓ $= \frac{Z}{a_0 n^2}$

$\left\langle \frac{1}{r^2} \right\rangle_{n\ell} = \frac{Z^2}{a_0^2 n^3 (\ell + 1/2)}$ $\quad a_0$ = Bohr radius

$$\Delta E_{n\ell m} = \frac{(Z\alpha)^2}{n^2}\left(\frac{n}{\ell + 1/2} - \frac{3}{4} \right) E_n^0 \qquad \left[\alpha = \frac{e^2}{\hbar c} \right]$$

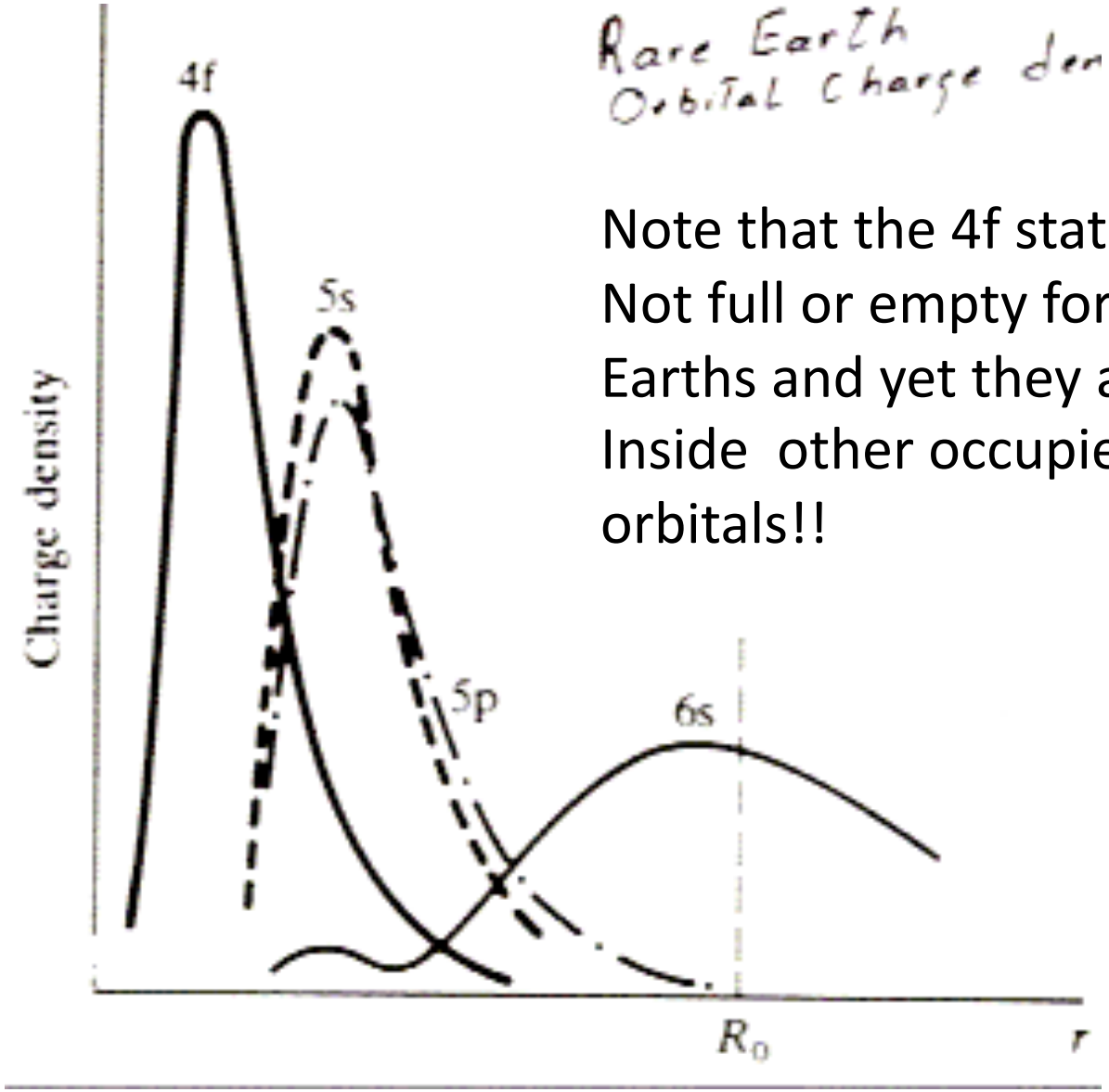
For 3d (Cu) 3S energy $\sim$ 120 eV

^3P " $\sim$ 70 eV

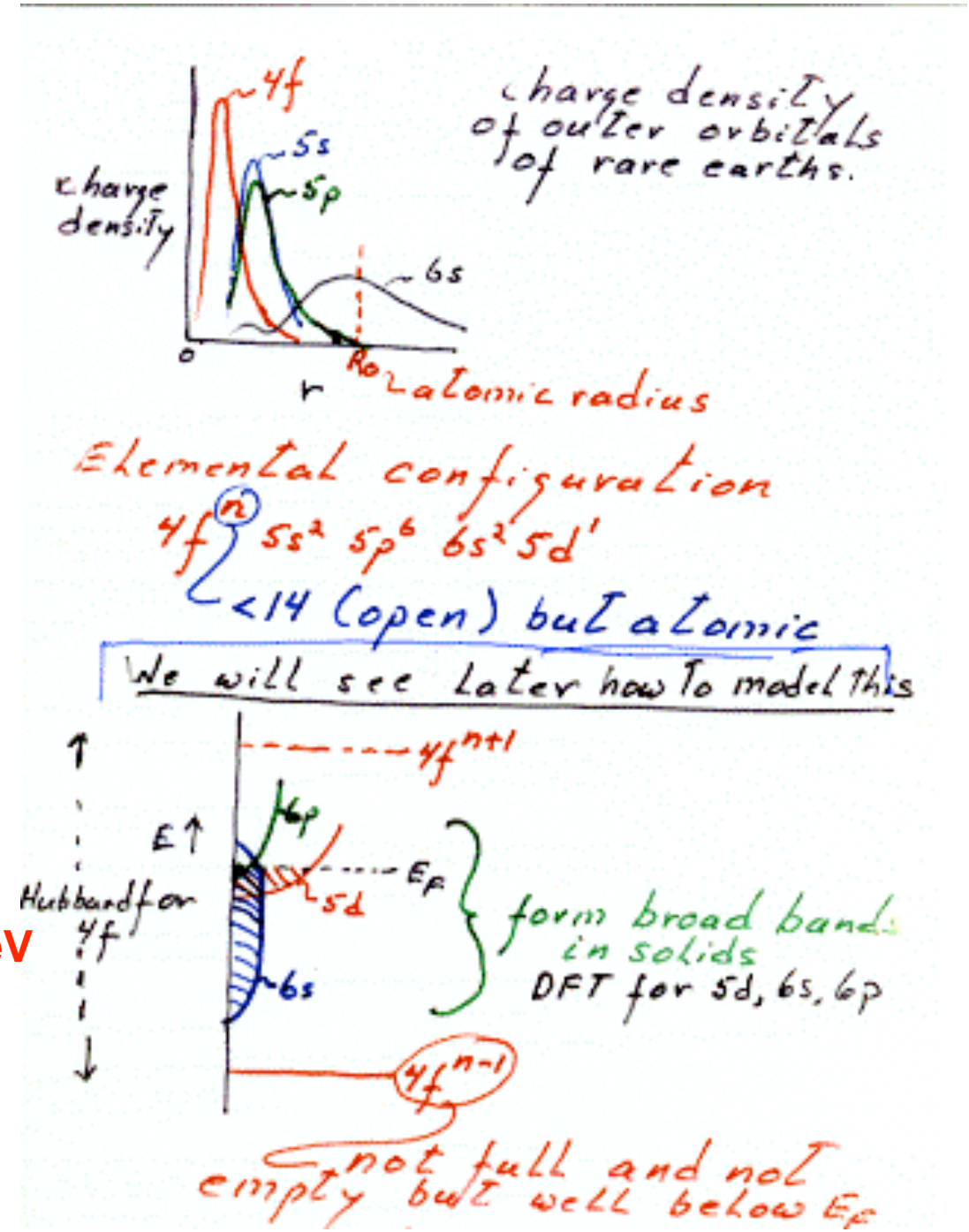
^3d " $\sim$ 10 eV

$E_{n\ell}$ can be larger than E_{n+1} if we include larger Coulomb repulsion

Special place for transition metal and rare earths



Note that the 4f states are Not full or empty for the rare Earths and yet they are well Inside other occupied orbitals!!



Hubbard For 4f U as large as 12eV

Band Structure approach vs atomic

Band structure

- Delocalized Bloch states
- Fill up states with electrons starting from the lowest energy
- No correlation in the wave function describing the system of many electrons
- Atomic physics is there only on a mean field like level
- Single Slater determinant states

Atomic

- Local atomic coulomb and exchange integrals are central
- Hunds rules for the Ground state -Maximize total spin-Maximize total angular momentum-total angular momentum J =L-S<1/2 filled shell , J=L+S for >1/2 filled shell
- Mostly magnetic ground states

Band theory - DF

$\Psi = \frac{1}{\sqrt{n!}} |\phi_{k_1} \cdots \phi_{k_n}|$ (Slater det.)

ϕ_{k_i} are one electron Bloch states

No correlation in Ψ but in $\mathcal{H}_{eff}$

$[-\frac{1}{2}\nabla^2 + W(r) + V_H(r) + V_{xc}(r)]\phi_i(r) = \epsilon_i \phi_i(r)$

↳ one particle problem

$V_H = \int d^3r' \cdot V(r-r')\rho(r')$

$V_{xc} = f(\rho(r))$

↳ $= \frac{\partial E_{xc}(\rho)}{\partial \rho}$ exchange-correlation potential

$\rho(r) = \sum_{i=1}^{n} |\phi_i(r)|^2$

↳ Hohenberg Kohn exact for $E_0 \to \rho$ (ground state)

ϕ_i & ϵ_i have no physical meaning!! math. functions to get E & ρ.

Single Slater det. Of One electron Bloch States. No correlation In the wave function

Recall that the ground State has few properties It is the excited states that Determine the response to External perturbations such as fields.

Ψ^{DF} also has no physical significance

E_j is exact $\rho_j(r)$ is exact but

$\mathcal{H}_{exact}\,\Psi^{DF} \neq E_j\,\Psi^{DF}$

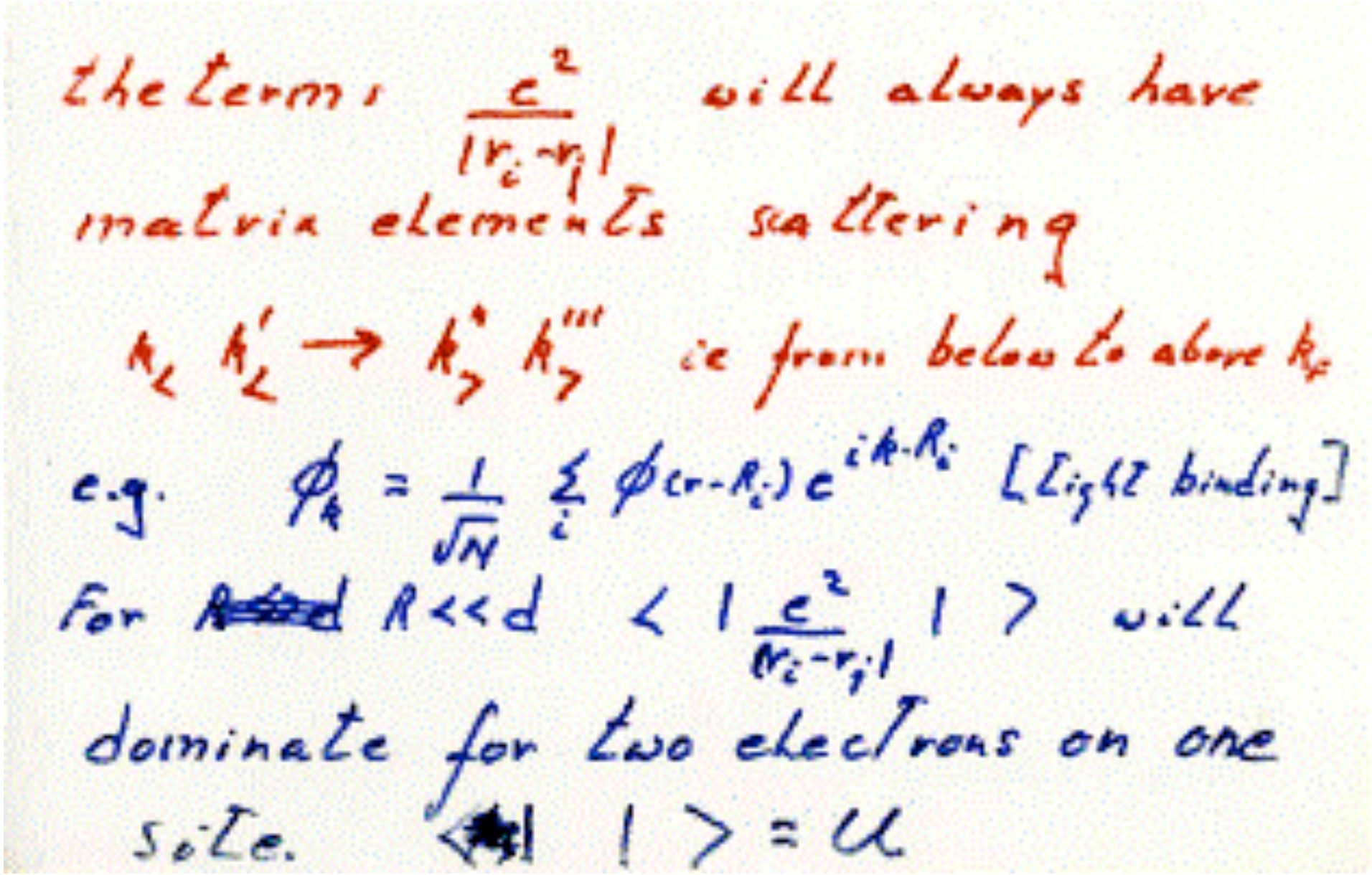
$$\mathcal{H}_{exact} = \sum_{i=1}^{n}\left[-\frac{1}{2}\nabla_i^2 + w(r_i) + \frac{1}{2}\sum_{j\neq i}\frac{e^2}{|r_i - r_j|}\right]$$

→ nuclear electron attraction

in Ψ_j ϕ_i have k as good q.n.

($\mathcal{H}_{eff}^{DF}$ has Translat. symm.)

$$\mathcal{H}_{eff}^{DF}\,\Psi_j = E_j\,\Psi_j$$



Interaction between two Bloch wave electrons = U/N ~0
So is correlation negligible?

$$\langle \Psi | \mathcal{H}_{int} | \Psi'_{\substack{k_1+k_2 \\ k_2+k_2'}} \rangle = \frac{1}{N} U \, \delta(k_1+k_2-k_1'-k_2')$$

$\to 0$ for $N \to \infty$

Small if $U \ll W$ or E_F so only few electrons are involved

For $U \gg W$ must sum over all other electrons $\to \frac{n}{N} U$ or for $n \sim N \to U$

$\therefore$ off diagonal matrix elements are large Ψ^{OF} is not an eig. fund.

For $R \ll d$ ½ filled s band if we neglect W (Transl. symm.)

$$\Psi_A = \frac{1}{\sqrt{n!}} | \phi_1 \phi_2 \cdots \phi_n |$$

one electr./atom

Surely a lattice of H atoms separated by say 1 cm would not behave like a metal

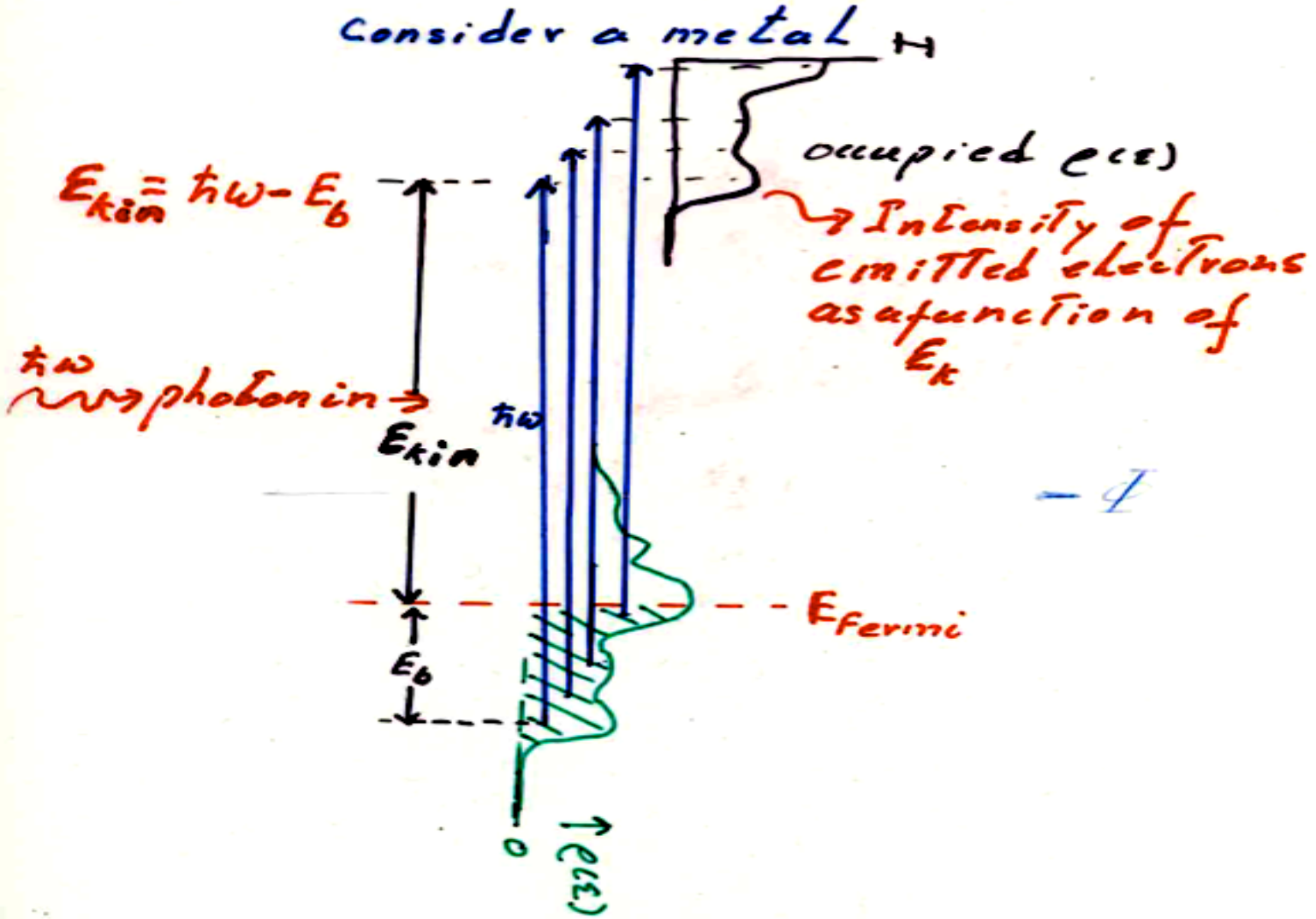
What have we forgotten ?

The electron electron repulsive interaction

Experimental evidence for atomic like behaviour in transition metal compounds and rare earths Photoemission/inverse photoemission and Auger spectrscopy

PES (Photo electron Spect.)

involves low $\hbar\omega$ → valence electrons



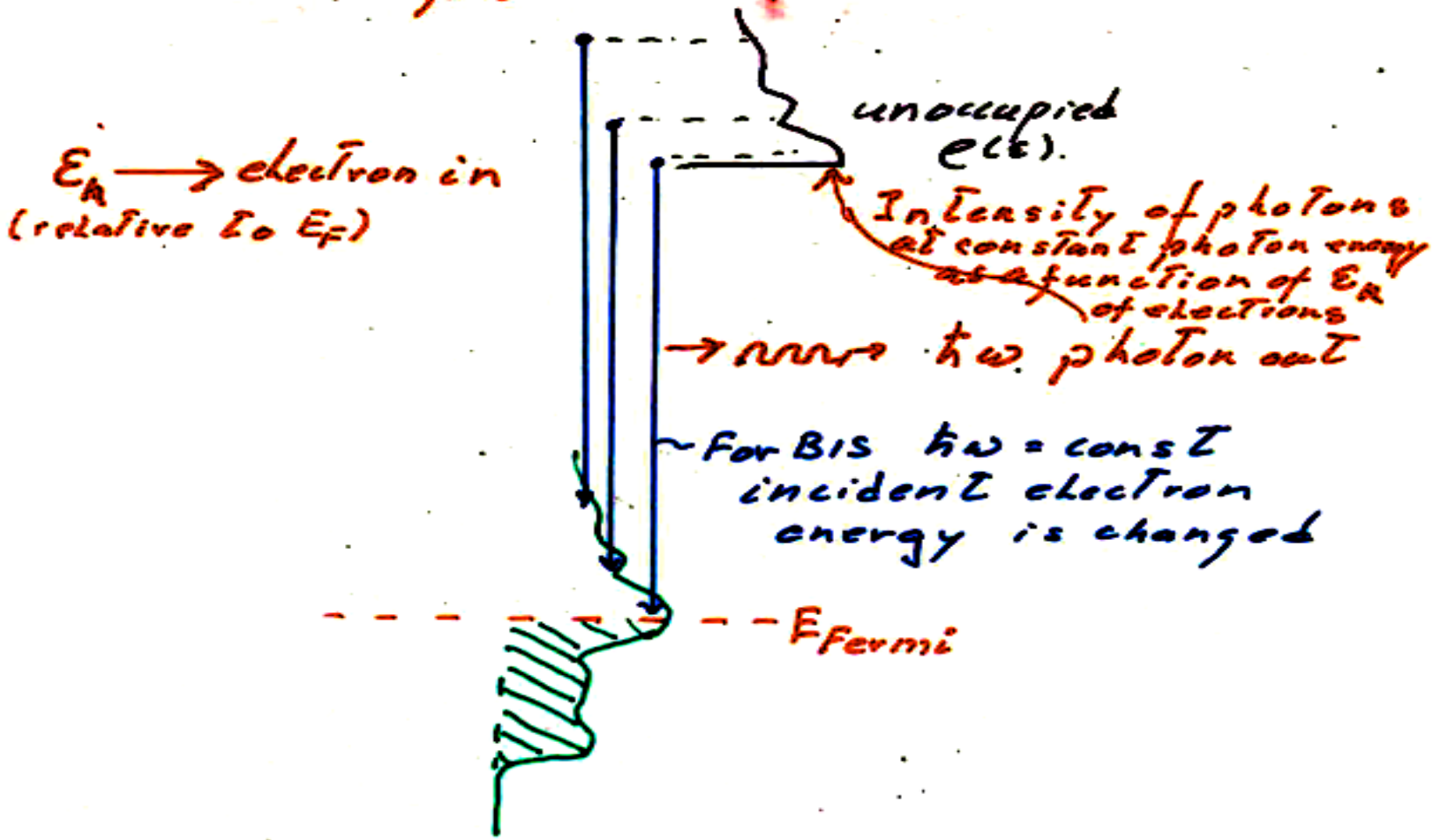
Measure density of states for electron removal × Matrix element

(Inverse PES) IPES / BIS (Bremsstrahlung isochromat spectr.)

involves conduction band states

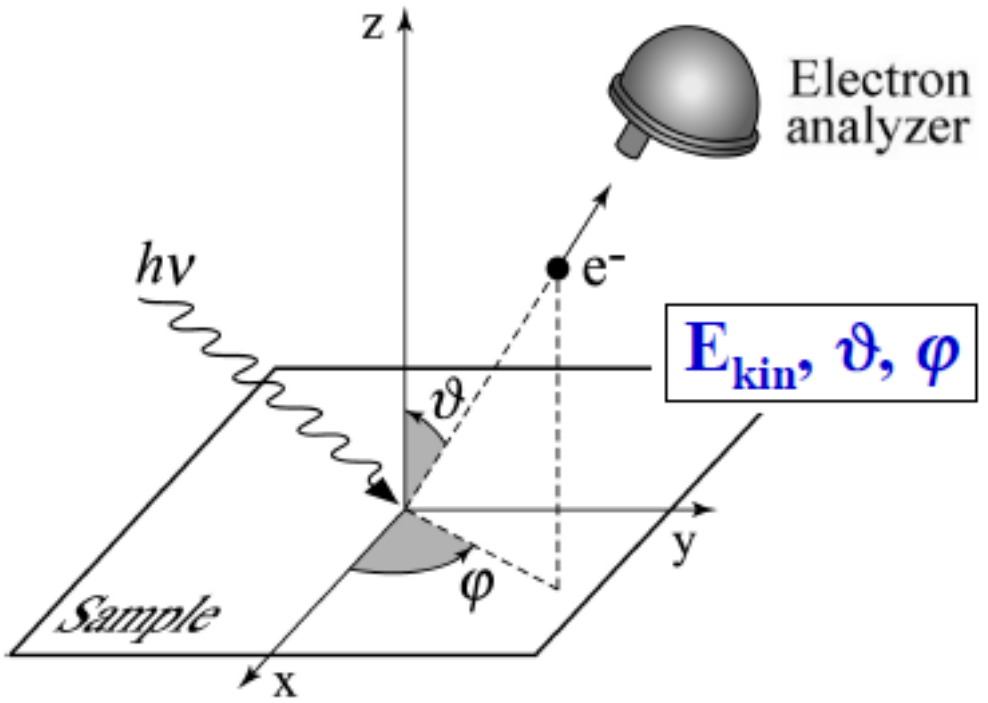
Measure $I(\hbar\omega)$ as a function of E_R

($\hbar\omega$ fixed)



Measures $\rho(E)$ for electron addition

High resolution angular resolved photoelectron spectroscopy



$$\mathbf{K} = \mathbf{p}/\hbar = \sqrt{2mE_{kin}}/\hbar$$

$$K_x = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\cos\varphi$$

$$K_y = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\sin\varphi$$

$$K_z = \frac{1}{\hbar}\sqrt{2mE_{kin}}\cos\vartheta$$

Vacuum

E_{kin}

$\mathbf{K}$

Conservation laws

$$E_f - E_i = h\nu$$

$$\mathbf{k}_f - \mathbf{k}_i = \cancel{\mathbf{k}_{h\nu}}$$

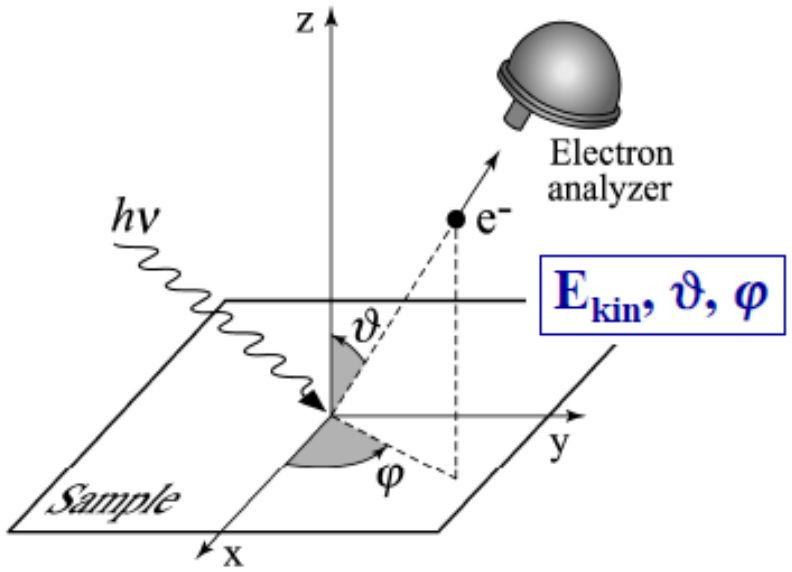
Solid

E_B

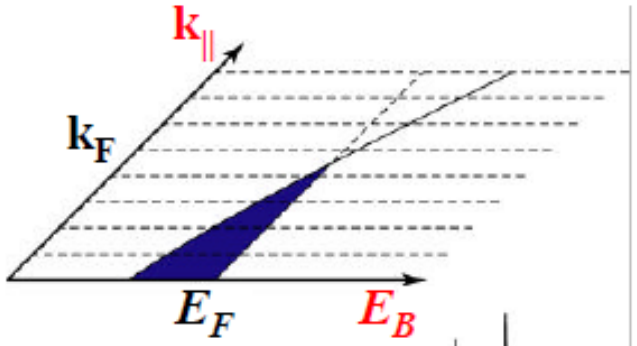
$\mathbf{k}$

Example of a simple metal in one electron theory

ARPES: Energetics and Kinematics



Electrons in Reciprocal Space

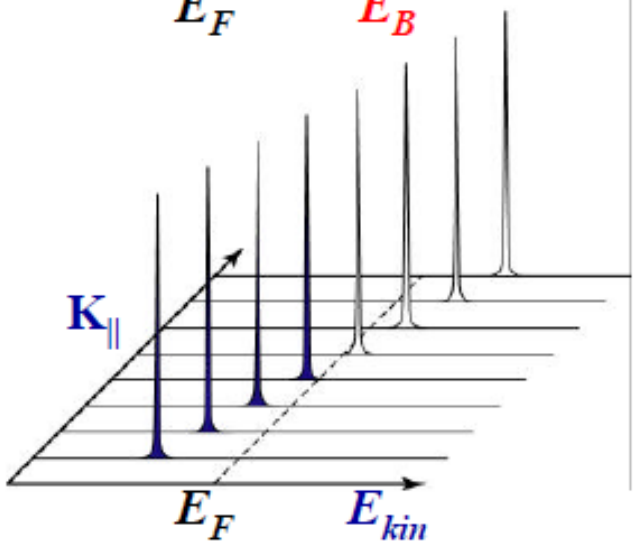


Energy Conservation

$$E_{kin} = h\nu - \phi - |E_B|$$

Momentum Conservation

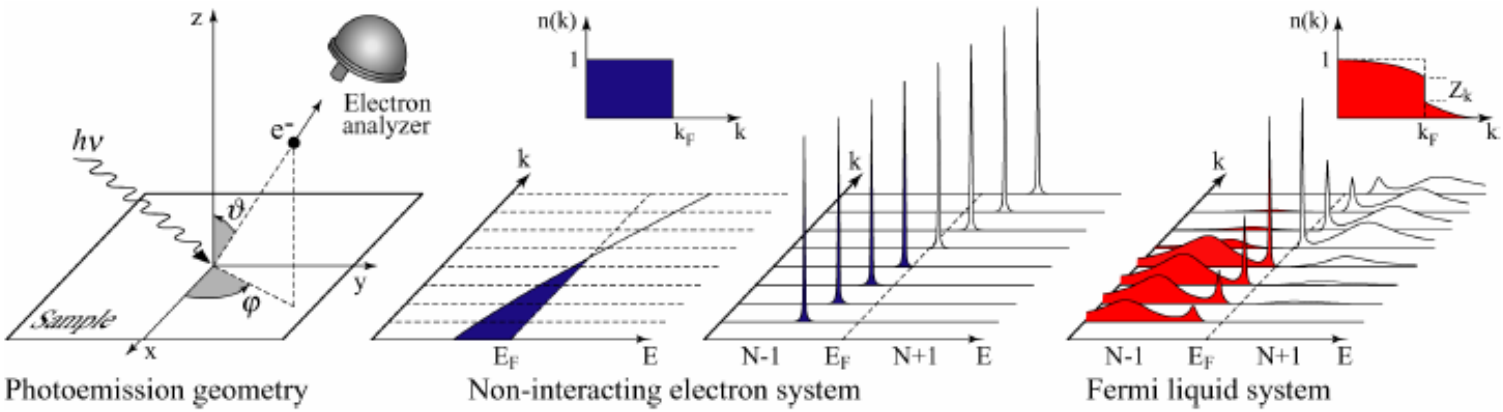
$$\hbar \mathbf{k}_{||} = \hbar \mathbf{K}_{||} = \sqrt{2mE_{kin}} \cdot \sin\vartheta$$



Example of a metal in which electrons are dressed

ARPES: The One-Particle Spectral Function

A. Damascelli, Z. Hussain, Z.-X Shen, Rev. Mod. Phys. **75**, 473 (2003)



Photoemission intensity: $I(k,\omega)=I_0\,|M(k,\omega)|^2 f(\omega)\,A(k,\omega)$

Single-particle spectral function

$$A(\mathbf{k},\omega)=-\frac{1}{\pi}\frac{\Sigma''(\mathbf{k},\omega)}{[\omega-\epsilon_{\mathbf{k}}-\Sigma'(\mathbf{k},\omega)]^2+[\Sigma''(\mathbf{k},\omega)]^2}$$

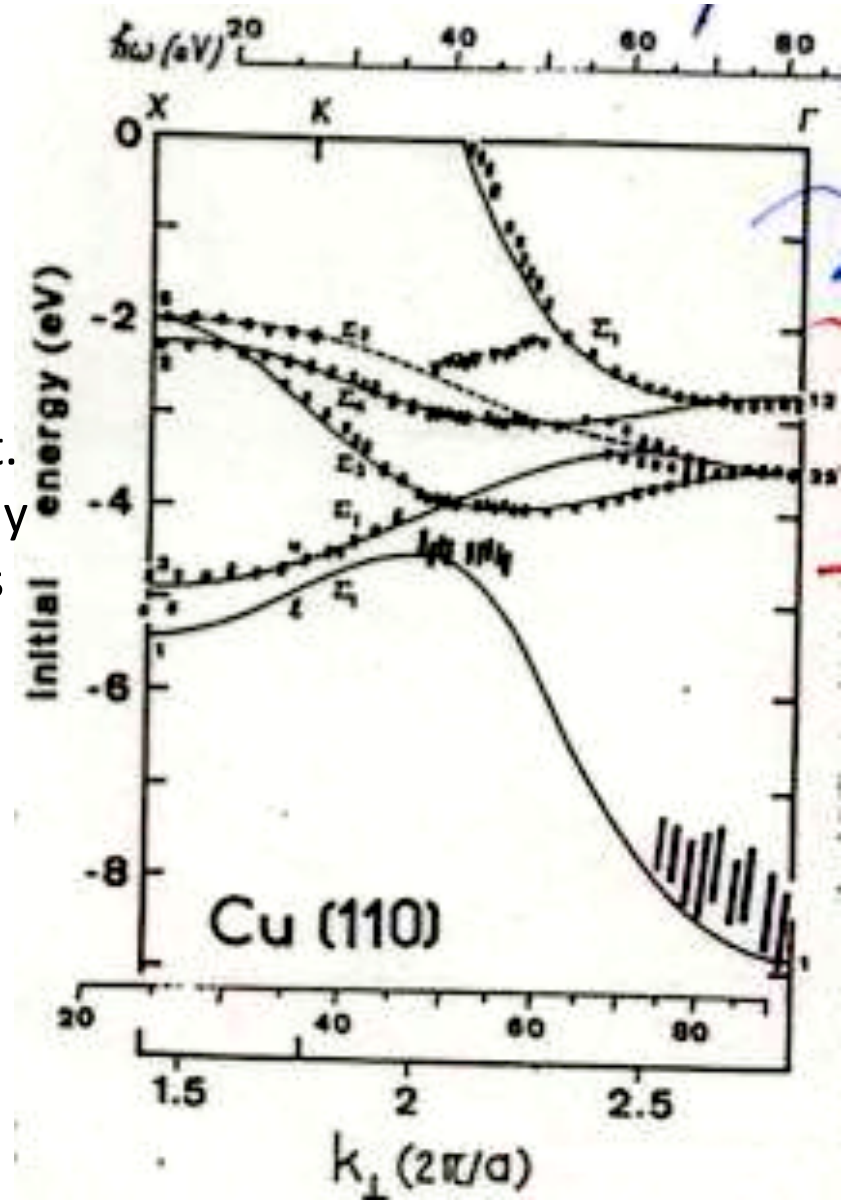
$\Sigma(k,\omega)$: the "self-energy" captures the effects of interactions

Angular resolved photoelectron spectroscopy (ARPES) of Cu metal

Thiry et al 1979

ARPES Cu

Cu is d10 so one d hole
Has no other d holes to
Correlate with so 1 part.
Theory works if the only
Important interaction is
The d-d interaction.
Great agreement with
DFT



Points –exp.
Lines - DFT

3d bands

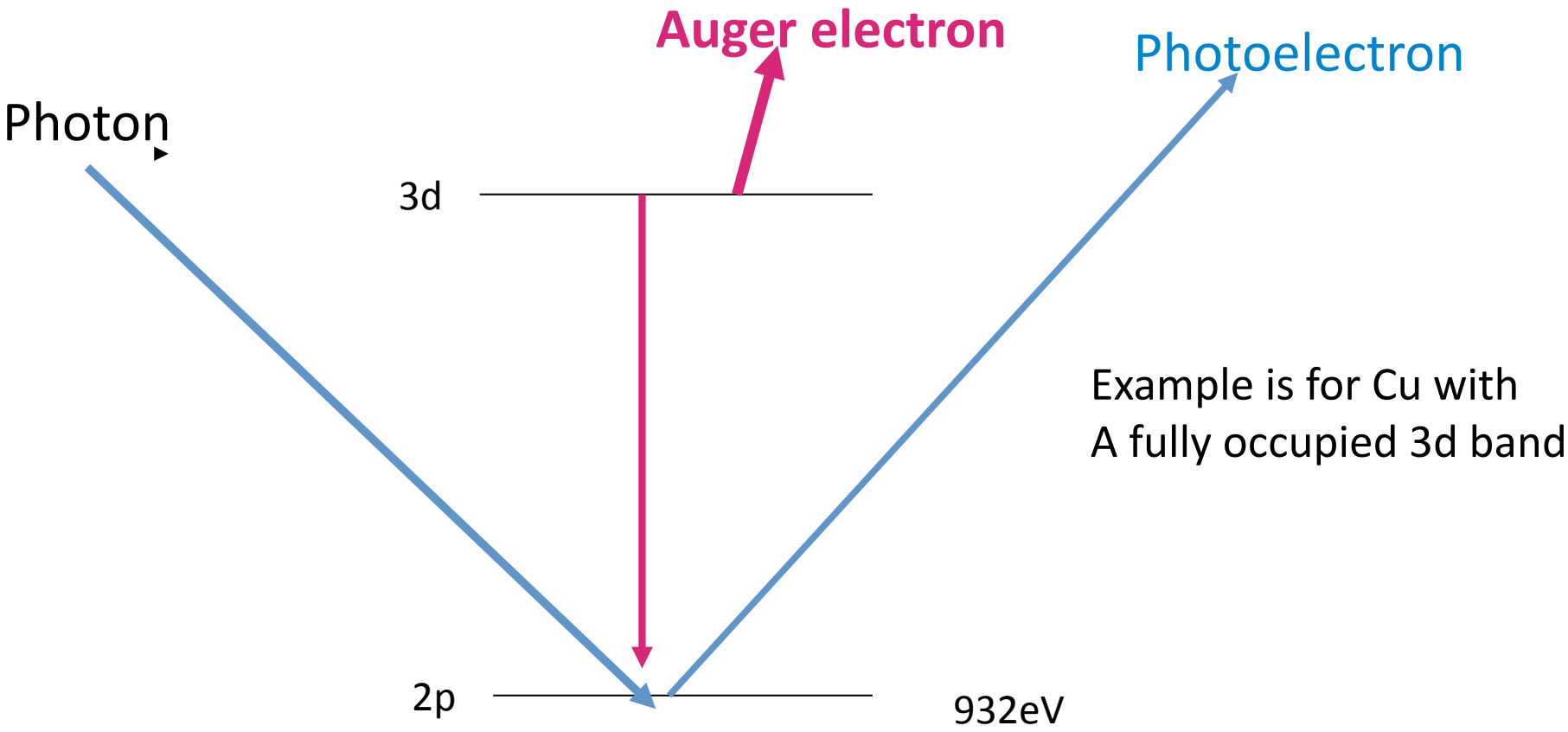
4s,4p,band

We note that for Cu metal with a full 3d band in the ground state one particle theory works well to describe the one electron removal spectrum as in photoelectron spectroscopy this is because a single d hole has no other d holes to correlated with. So even if the on site d-d coulomb repulsion is very large there is no phase space for correlation.

The strength of the d-d coulomb interaction is evident if we look at the Auger spectrum which probes the states of the system if two electrons are removed from the same atom

If the d band had not been full as in Ni metal we would have noticed the effect of d-d coulomb interaction already in the photoemission spectrum as we will see.

What if we remove 2- d electrons ?
Two hole state with Auger spectroscopy



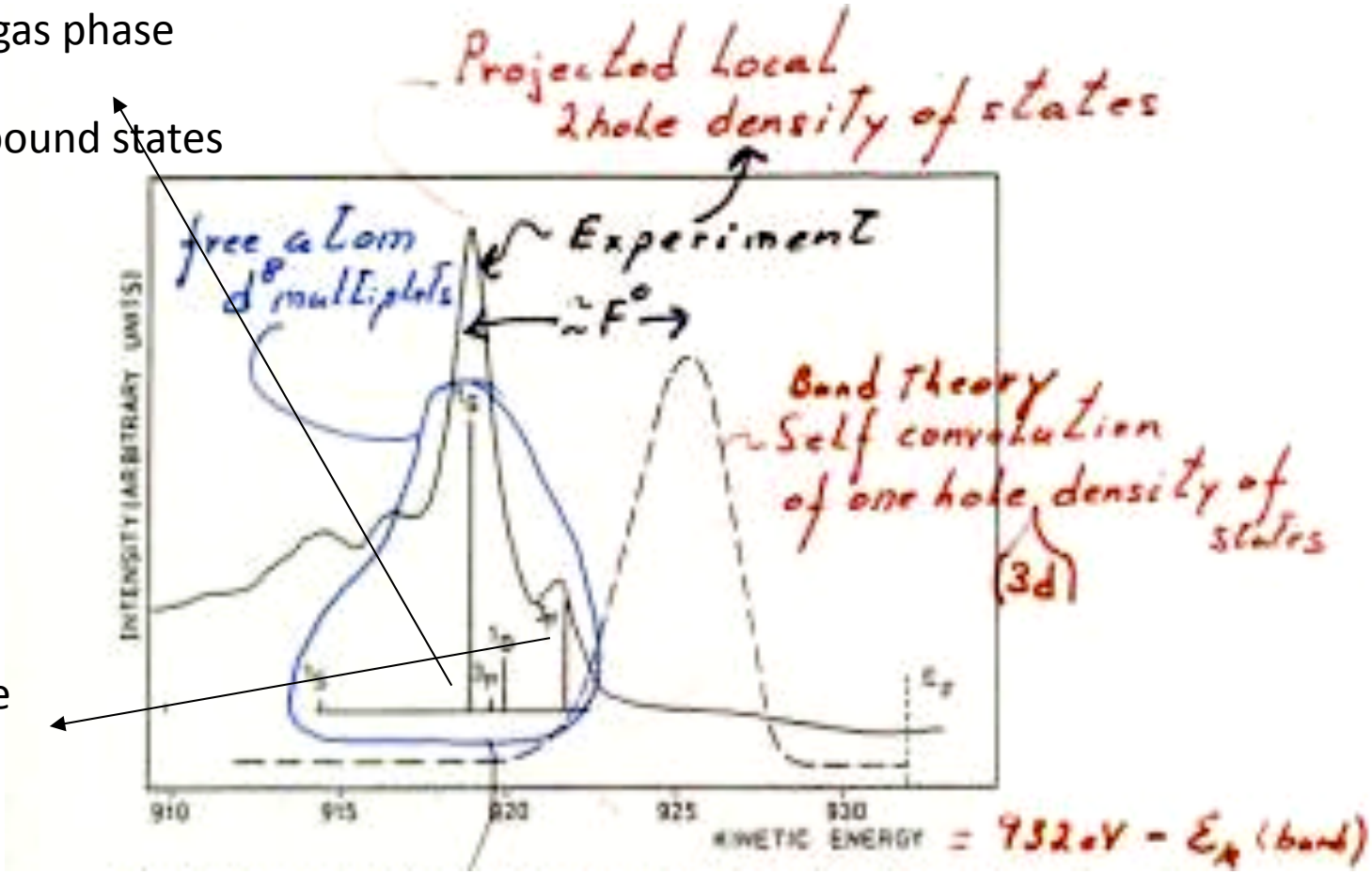
Example is for Cu with
A fully occupied 3d band

E(photon)-E(photoelectr) = E(2p) , E (2-d holes)= E(2p)-E(3d)-E(Auger)

U = E(2-d holes) -2xE(1-d hole)

Auger spectroscopy of Cu metal

Atomic multiplets
Looks like gas phase
U>W
Two hole bound states



Hund's rule
Triplet F is
Lowest

The L3M45M45 Auger spectrum of Cu metal i.e final state has 2 -3d holes on the Atom that started with a 2p hole. Solid line is the experiment. Dashed line is one Electron DFT theory, vertical bars and lables are the free atom multiplets for 8- 3d electrons on a Cu atom . Ef designates the postion of the Fermi level in the DFT .

Antonides et al 1977

Sawatzky **theory 1977**

Two particles in Hubbard (s band)

$$\mathcal{H} = t \sum_{R,s,\sigma} C^{\dagger}_{R+s,\sigma} C_{R\sigma} + U \sum_{R} C^{\dagger}_{R\uparrow} C_{R\uparrow} C^{\dagger}_{R\downarrow} C_{R\downarrow}$$

$$= \sum_{k\sigma} \varepsilon_k C^{\dagger}_{k\sigma} C_{k\sigma} + \frac{U}{N} \sum_{klq} C^{\dagger}_{l+q\uparrow} C_{l\uparrow} C^{\dagger}_{k-q\downarrow} C_{k\downarrow}$$

Momentum + Spin conservation

$[H, K] = 0 \quad [H, S] = 0$

K = Total momentum $\qquad S = 0$ or 1

For $G^{kT\,k-q\downarrow}_{q\uparrow k-q\downarrow} = \langle 0 | C_{k-k\downarrow} C_{kT}\, G(z)\, C^{\dagger}_{q\uparrow} C^{\dagger}_{k-q\downarrow} | 0 \rangle$

contains both singlet + Triplet

Triplet - soln. - self convolution of 1 part. density of states

↳ U is not active

$$G = (\delta_{kq} - \delta_{k\,k-q}) \frac{1}{2 - \varepsilon_k - \varepsilon_{k-k}}$$

Dyson $\quad G = G_0 + G_0 M_1 G \;;\; G = \frac{1}{z - H}$

$G_0 = \frac{1}{z - H_0}$ #

$$G^{k\uparrow\, k-k\downarrow}_{q\uparrow\, k-q\downarrow} = \delta_{k,q}\, \frac{1}{z - \epsilon_k - \epsilon_{k-k}} = \delta_{k,q}\, G_0(k, k-k; z)$$

$$G^{k\uparrow\, k-k\downarrow}_{q\uparrow\, k-q\downarrow} = \delta_{kq}\, G_0(k, k-q) + G_0(k, k-k)\, \frac{U}{N} \sum_{p} G^{p\uparrow\, k-p\downarrow}_{q\uparrow\, k-q\downarrow}$$

$$\sum_k \quad = G_0(q, k-q) + \sum_k G_0(k, k-k)\, \frac{U}{N} \sum_k$$

$$\sum_k G^{k\uparrow\, k-k\downarrow}_{q\uparrow\, k-q\downarrow} = \frac{G_0(q, k-q)}{1 - \frac{U}{N} \sum_k G_0(k, k-k)}$$

Ladder approximation
Is exact for only two particles

Zero's on real axis provide singlet energies

$$\mathrm{Re} \sum_k G_0(k, k-k; \omega_s) = \frac{N}{U}$$

For $U \gg W$ (bandwidth)

Two sets of poles

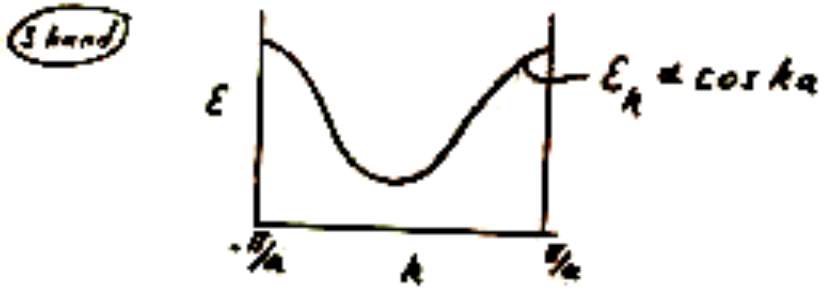
- Centered around self convolution of one particle energy's → $N(N-1)$ states
- Centered close to U with little dispersion → N states

for $W \gg U$ one electron theory

for $W \ll U$ strong correlation

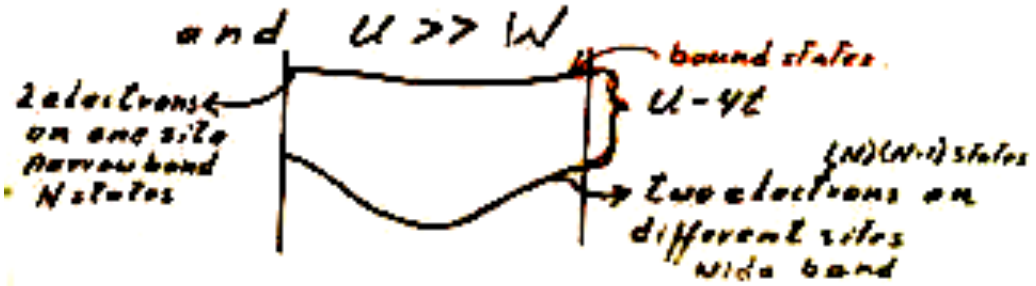
For strong correlation energy levels depend on the number of electrons

For 1 electron $M_s = 0$



For 2 spin parallel electrons same as for 1 electron

For 2 spin antiparallel electrons and $U \gg W$



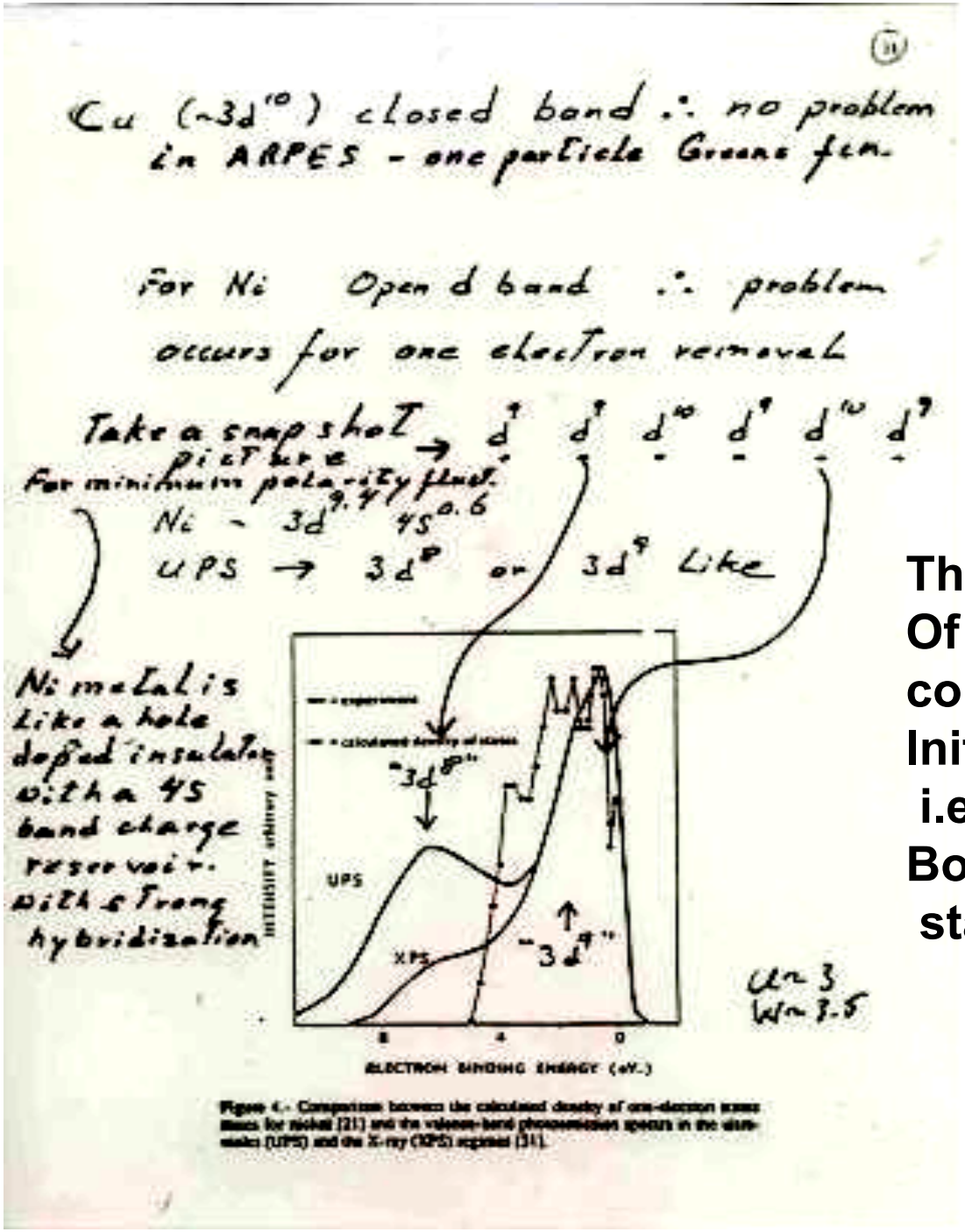
D shells are complicated by multiplet structure

- Atomic physics – d orbital is 5 fold degenerate not including the spin and neglecting the spin orbit coupling .
- Two d electrons or holes with orbital angular momentum =2 and spin of ½ can couple into total angular momentum states L with total spin 1 or 0 as follows ; singlet S, singlet G, singlet D and triplet P and triplet F
- The energy separations in the Cu Auger spectrum are from atomic coulomb integrals with triplet F as the lowest energy state for 8 d electrons as given by Hunds' rule

For U>>W and in the presence of unfilled bands the one particle removal spectrum will be very different from that of a filled band

Compare the PES of Cu metal with a full d band to that of Ni with on the average 0.6 holes in the 3d band

INTENSITY (arbunits)
Cu Pt
Cu Pd
Cu 3d
Cu
4
2
EF
BINDING ENERGY (eV)



The relative weights Of the d9 and d8 (satellite) configurations depend on Initial d occupation and i.e. mixing i.e. band width Both in the initial and final states

For a LDA/DMFT try see Lichtenstein et al PRL 067205 (2001)

In one electron theory

$$P(n) = \frac{m!}{(m-n)!\,n!}\,(1-c)^{m-n}\,c^{n}$$

= Probability that a site has n electrons

m = degeneracy c = concentration of electr. $= \frac{\langle n \rangle}{m}$

So for Ni c = 0.94 all conf.

$d^{0} \rightarrow d^{10}$ occur without energetic considerations

In atom starting point

Ni fluctuates between d^{9} a d^{10}

$d^{9}\ d^{9}\ d^{10}\ d^{9}\ d^{10}\ d^{10}$

$d^{10\downarrow}\ (d^{9})^{\uparrow}\ d^{10\downarrow}\ d^{9\uparrow}\ d^{10\downarrow}\ d^{10}$ costs U

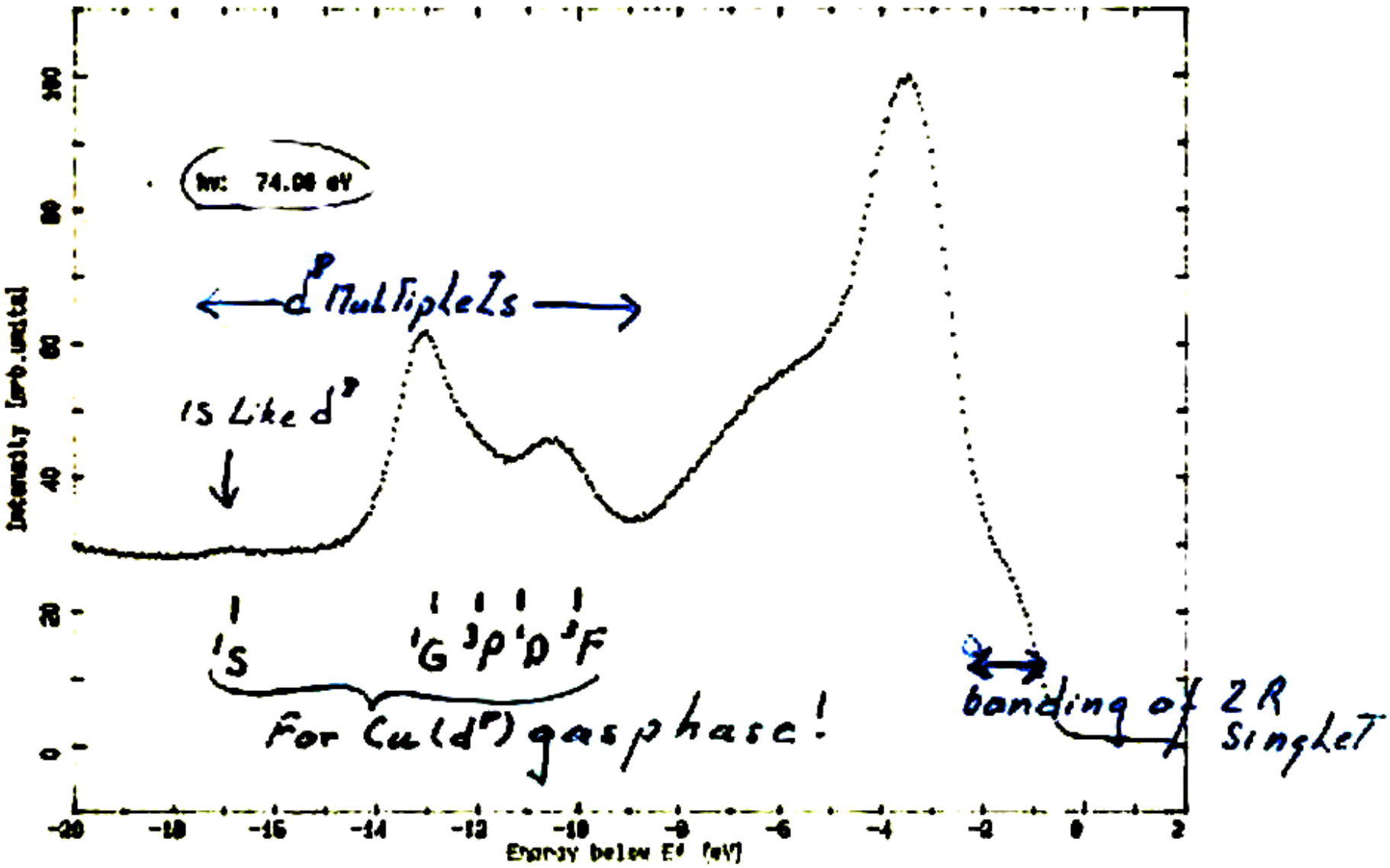
Atomic theory minimizes

polarity fluctuations

J. Ghijsen et al

Phys. Rev. B. 42, (1990) 2268.

Photoemission spectrum of CuO Cu in d9 S=1/2 state



Energy below Ef in eV

Note the atomic like multiplet structure as for the rare earths

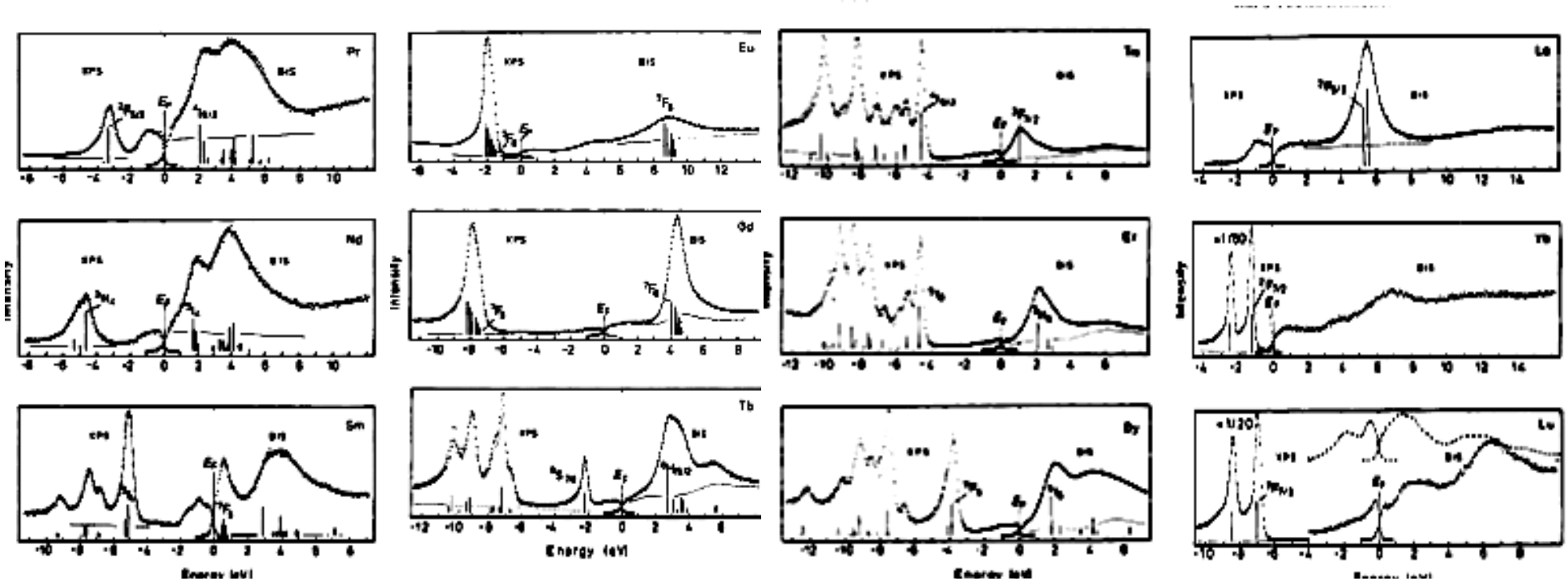
We will come back to the Photoemission and Zhang Rice singlets later.

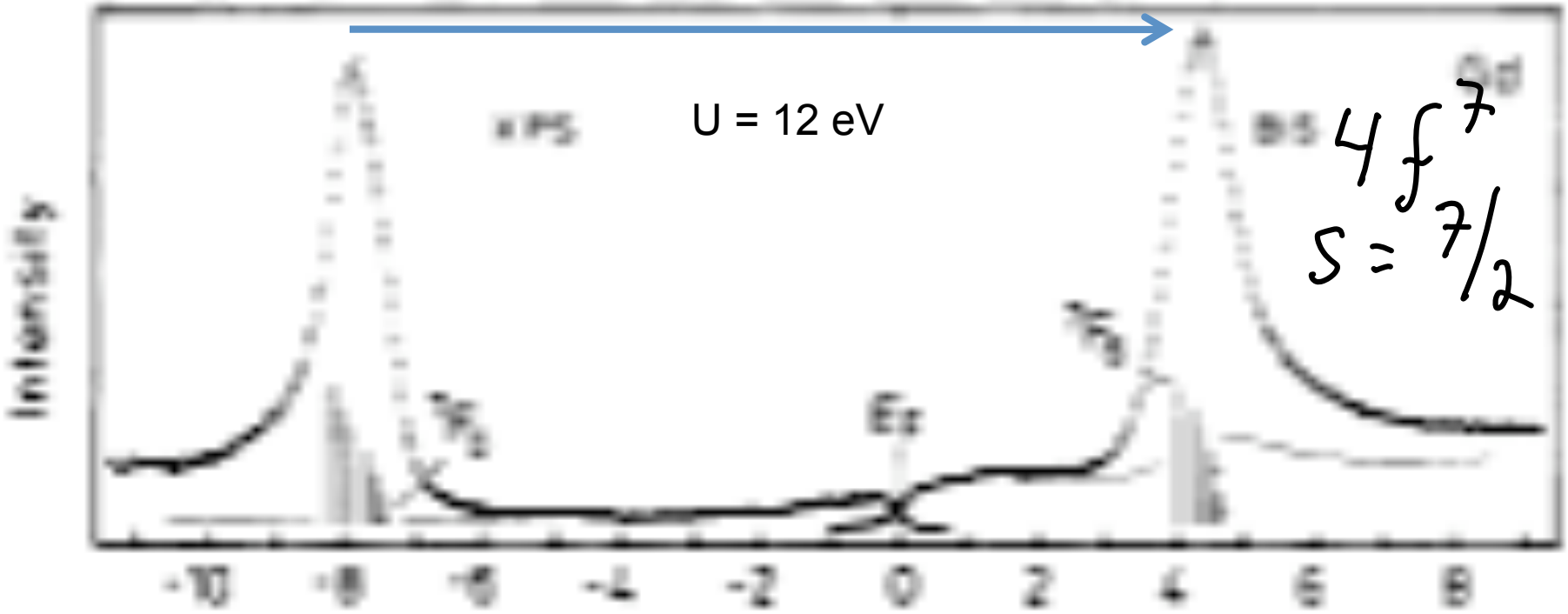
Transition metal d-d interactions

- The satellite position gives an estimate of the F0 Slater integral or U. More details below
- Important is that the multiplet spread is given by only slightly decreased gas phase atomic values i.e. F2 and F4 Slater integrals or J hund= (1/14)(F2 +F4) is reduced by at most 20% from the atomic values.
- F0 on the other hand is reduced from the atomic >20eV to about 7 eV!!!!!

Lang Baer and Cox J Phys F 11, 121 (1981)

- Photoemission and inverse photoemission of all the rare earth metals
- Demonstrates the atomic multiplets of the 4f electron removal and addition states
- Intensities given by atomic coefficients of fractional parentage starting from the Hunds' rule ground state




U = 12 eV
IPS
BIS
Gd
$4f^7$
$S = 7/2$
Intensity
Energy (eV)

MORE ON RARE EARTHS

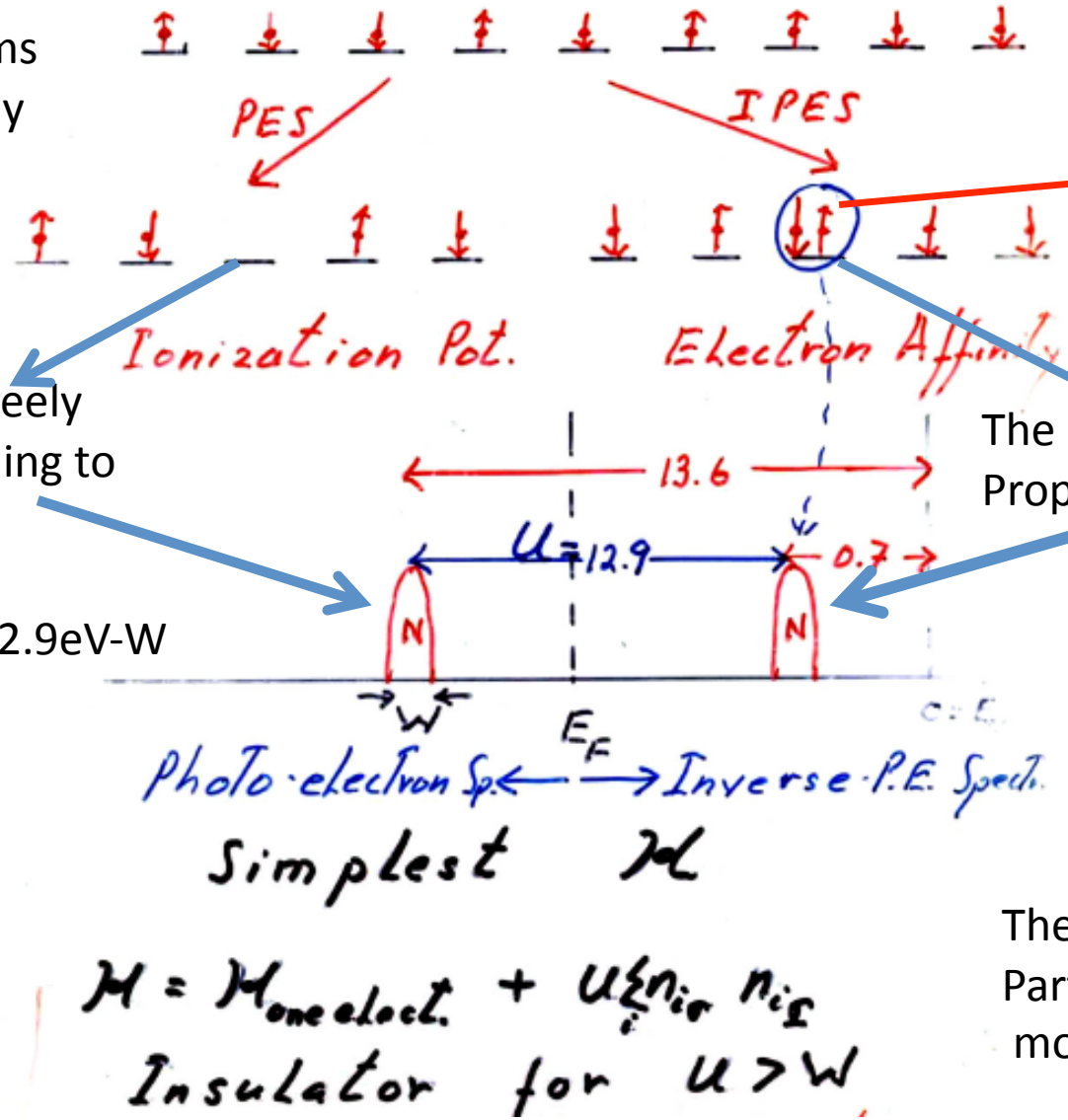
- The Hubbard U; as clearly demonstrated, its definition depends on which multiplets you take and depends strongly on the element. Convention is to either take the multiplet average or the Slater F0 integral.
- The multiplet splitting is very close to the atomic value little SCREENING OF THE HUNDS RULES INTERACTIONS I.E. SLATER F2,F4,F6 INTERACTIONS

Note the atomic physics needed to describe the rare earth 4f electron removal and addition spectrum

For the 3d transition metal compounds things are a lot more subtle. In some cases we need the atomic approaches and in others one particle theory seems to work very well

Simplest model single band Hubbard

Row of H atoms
1s orbitals only



Largest coulomb
Interaction is on site
U

The hole can freely
Propagate leading to
A width

The electron can freely
Propagate leading to a width

E gap = 12.9eV-W

The actual motion of the
Particles will turn out to be
more complicated

For large U>>W and 1 electron per site

- ----Insulator
- Low energy scale physics contains no charge fluctuations
- Spin fluctuations determine the low energy scale properties
- Can we project out the high energy scale?

$$H = \sum_{i,j} J S_i S_j \qquad J = 4t^2 / U$$

Heisenberg Spin Hamiltonian

We should be a bit careful about decoupling spin and charge degrees of freedom even in this case

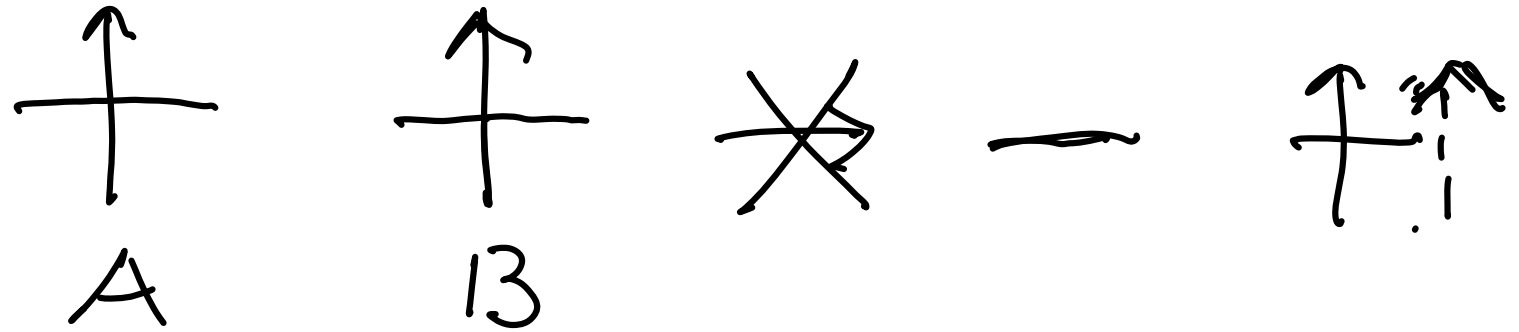
The charge distribution for the antiparrallel and parallel nn spin states are different! For the singlet there is admixture of doubly occupied sites. For triplets there is not!

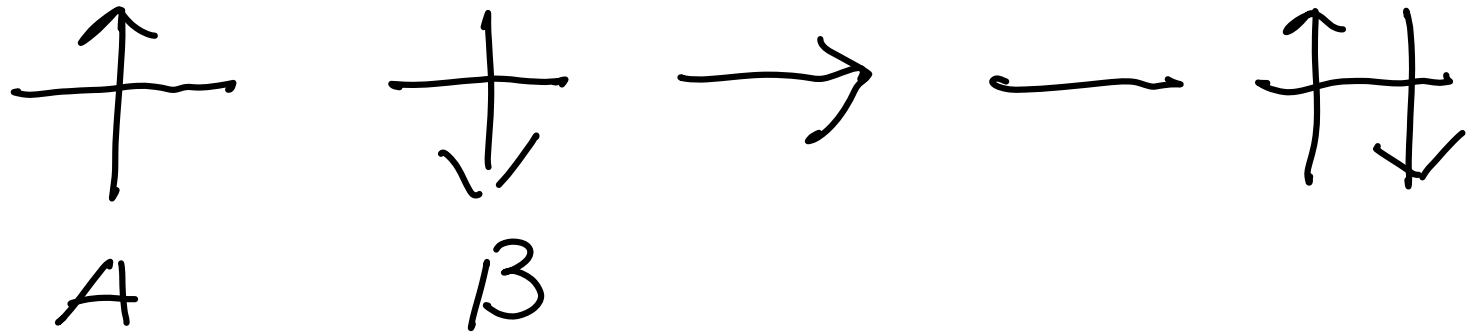
Has strong consequences!

Temperature dependent Optical conductivity

Tsvetkov et al PRB 69, 075110 (2004)

Spin order dependent Optical transitions





Before we go on lets look at a specific property of the Hubbard model which is measureable for a "doped" MH system

Seamus Davis the STS asymmetry

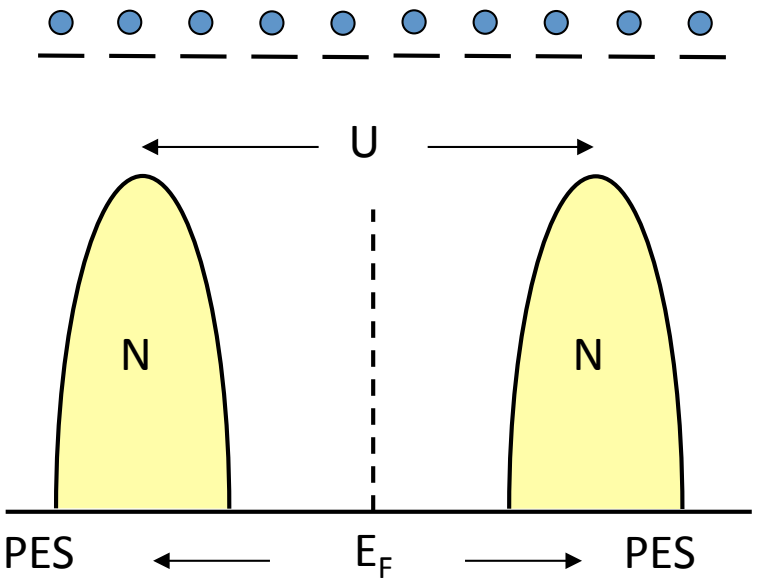
CT Shen X ray absorption in doped Cuprates

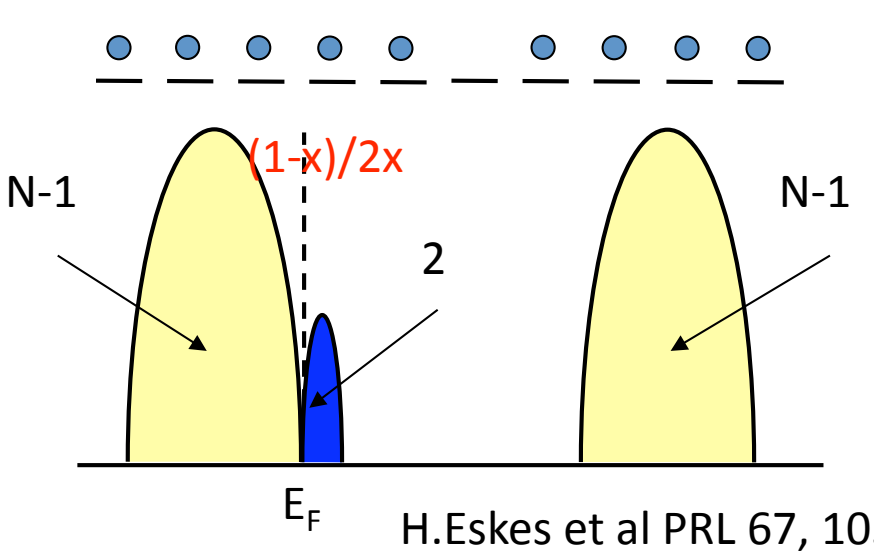
Spectral weight transfer

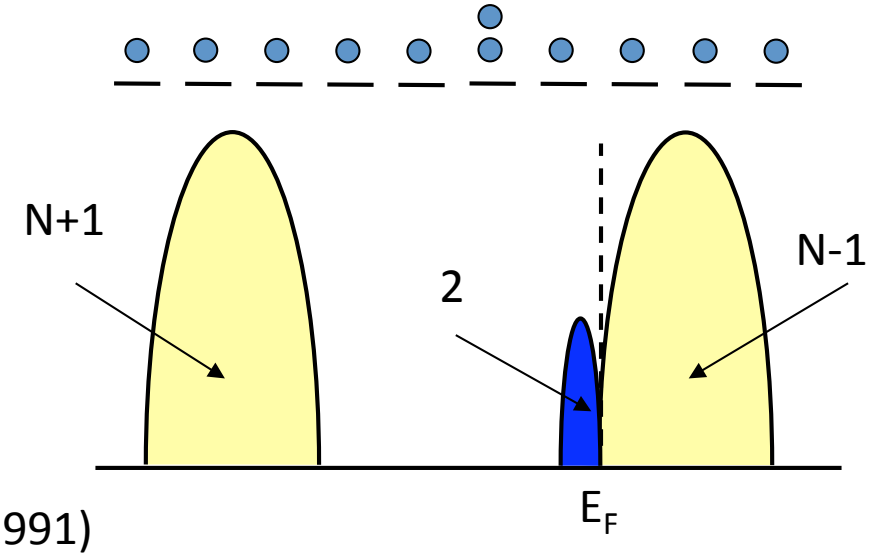
The real signature of strong correlation effects

H.Eskes et al PRL 67, 1035 (1991)
Meinders et al, PRB 48, 3916 (1993)

Doping a Mott – Hubbard system

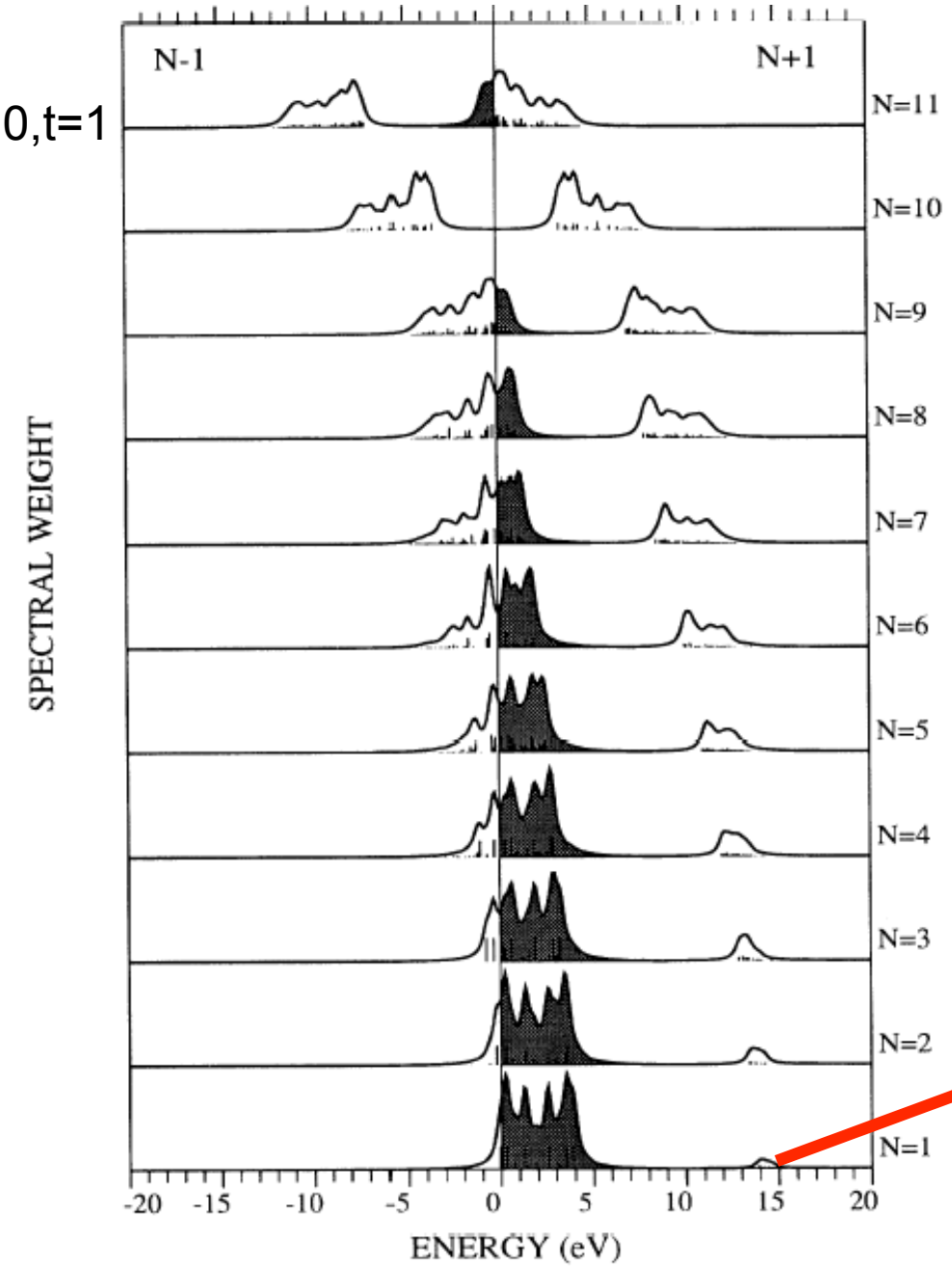






H.Eskes et al PRL 67, 1035 (1991)
Meinders et al, PRB 48, 3916 (1993

10 site Hubbard
1 D periodic U-10,t=1

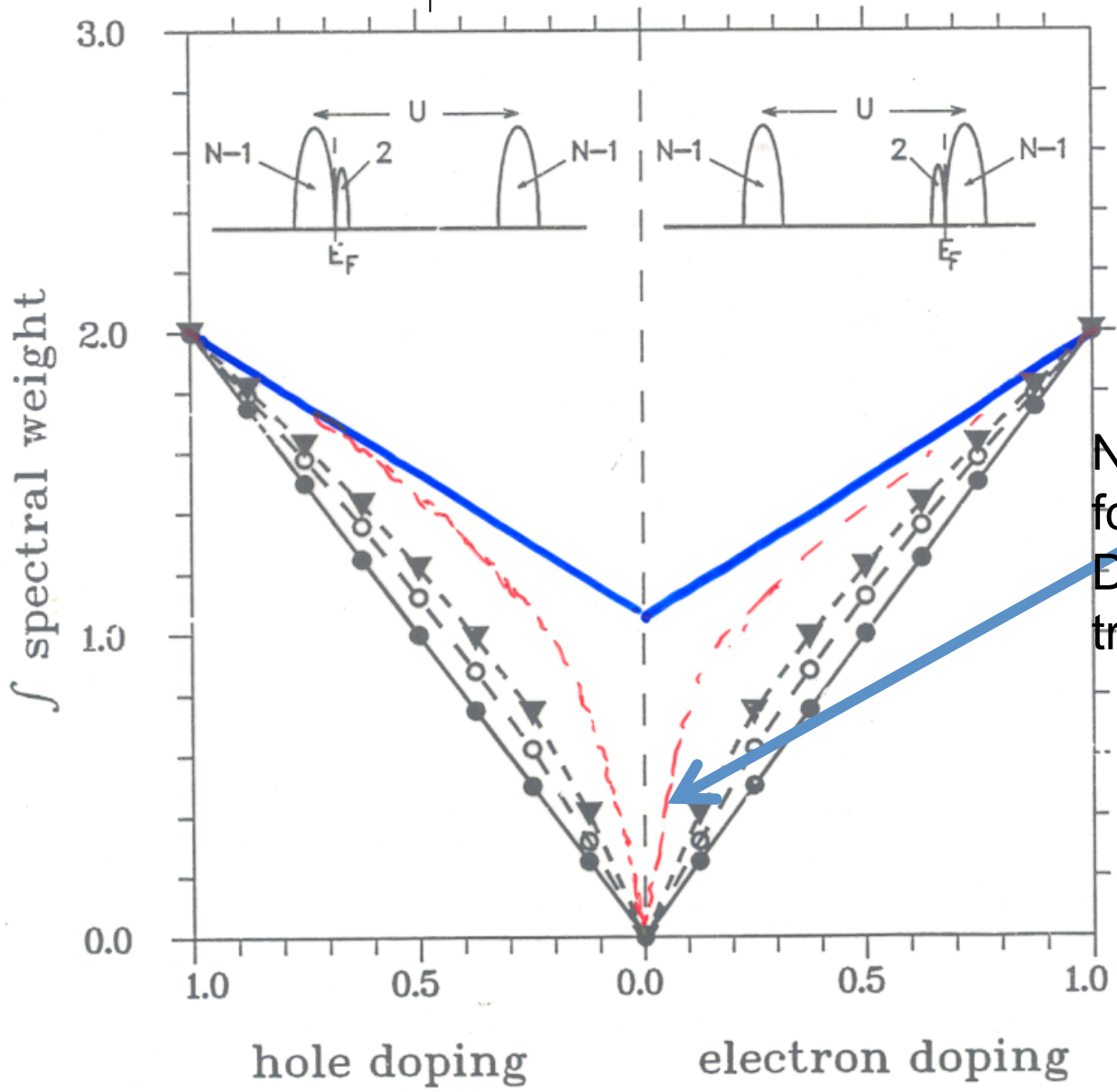


x=0.0
x=0.1
x=0.2
x=0.3
x=0.4
x=0.5
x=0.6
x=0.7
x=0.8
x=0.9

These states would be visible in a two particle addition spectral function

Meinders et al, PRB 48, 3916 (1993)

These particles block 2 or more states



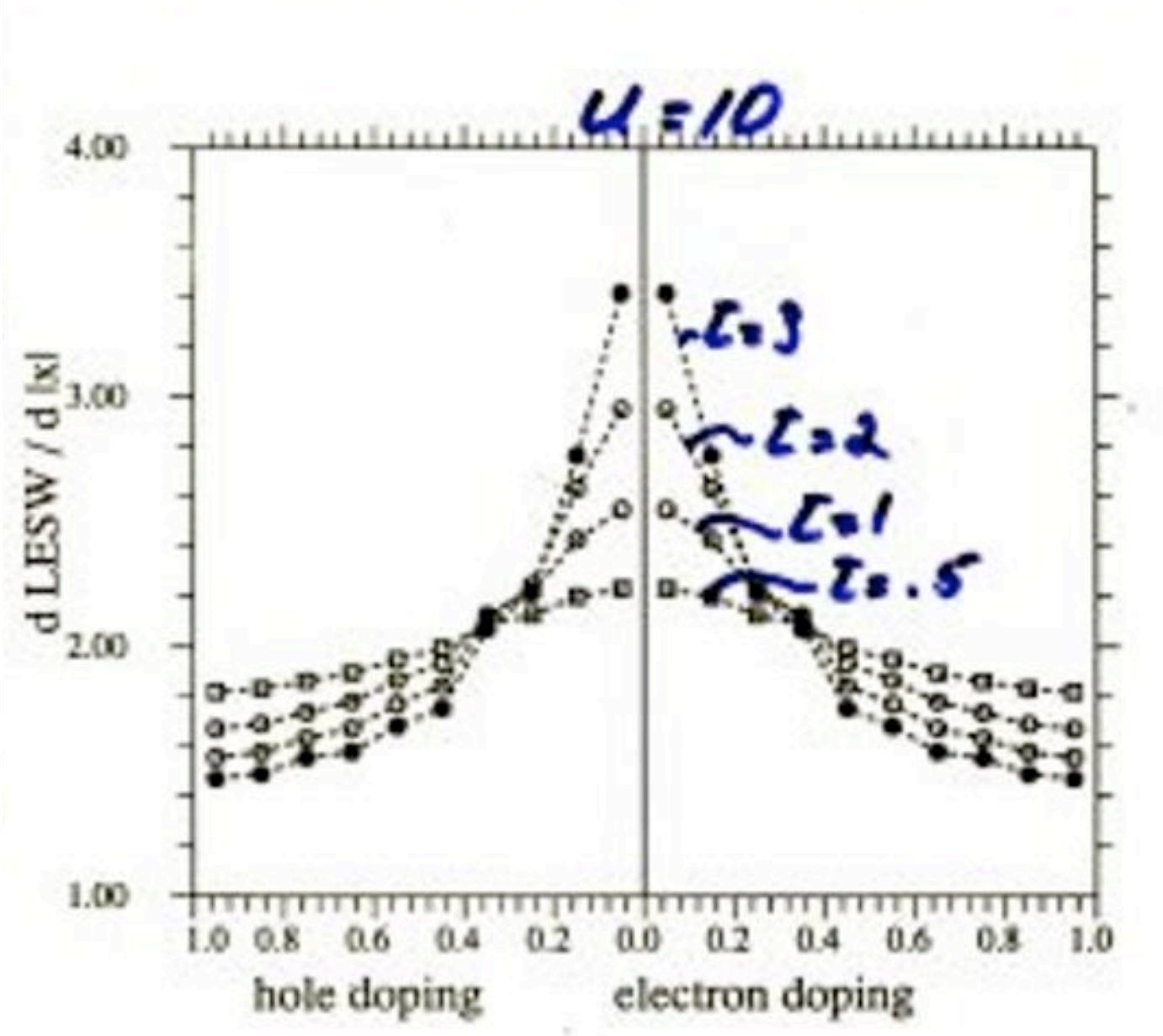
Bosons – block 0 states
Fermions – block 1 state

These –block 2 states on
The low energy scale

Note the even larger slop for finite hopping integrals Dynamic spectral weight transfer

Phillip Phillips uses this to Define “Mottness” Stanescu ,phillips PRB 69 245104 (2004)

Eskes et al PRL 67, (1991) 1035
Meinders et al PRB 48, (1993) 3916



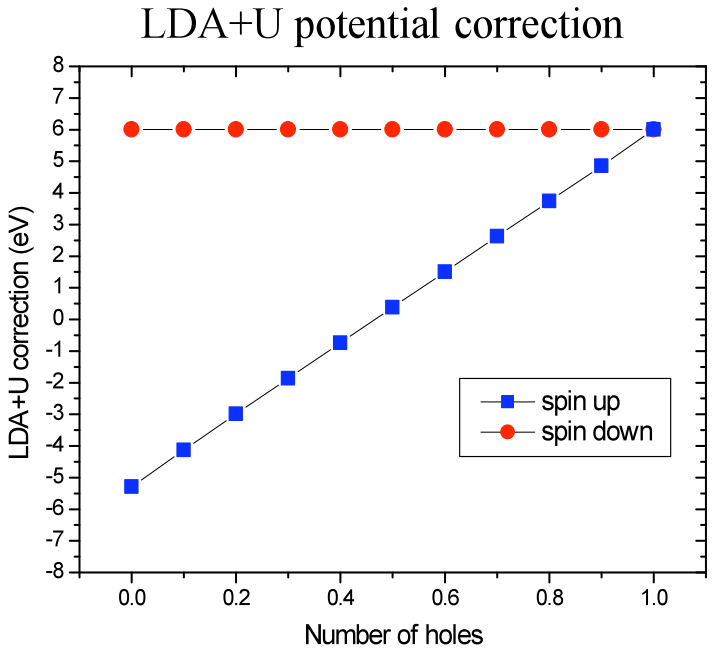
Elfimov unpublished

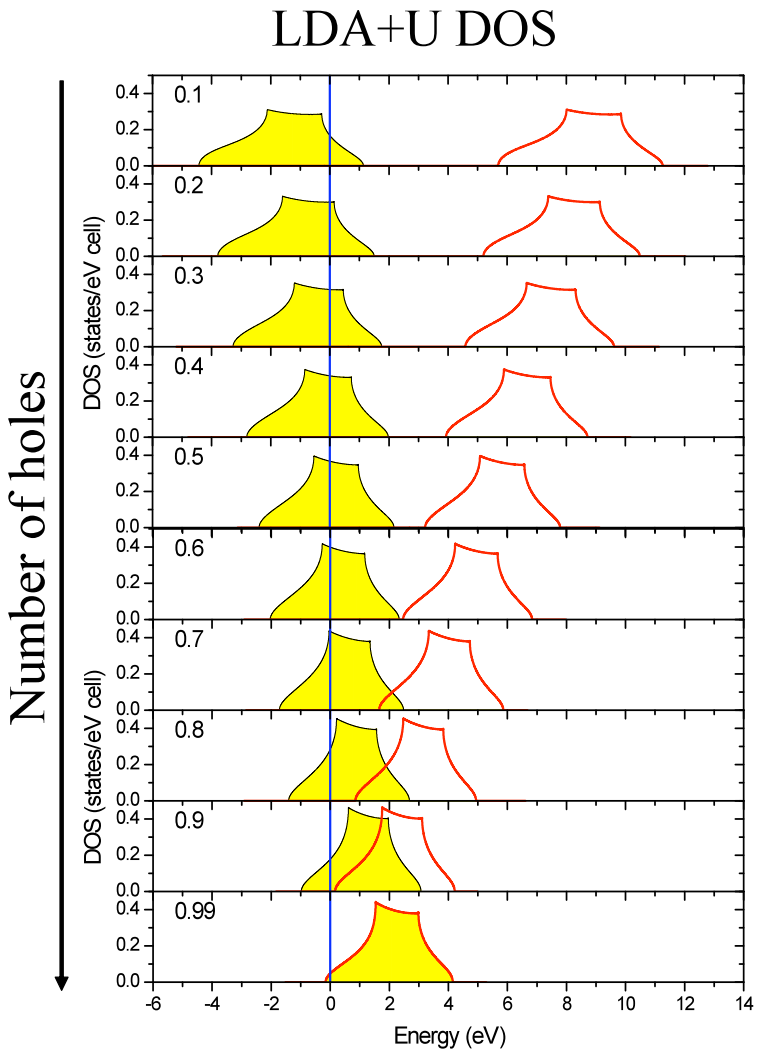
What would a mean field theory give you?

SC Hydrogen

a =2.7 Å

U=12eV





Note that there is no spectral weight transfer and a gap closing with doping From half filled . Both opposite to the real situation

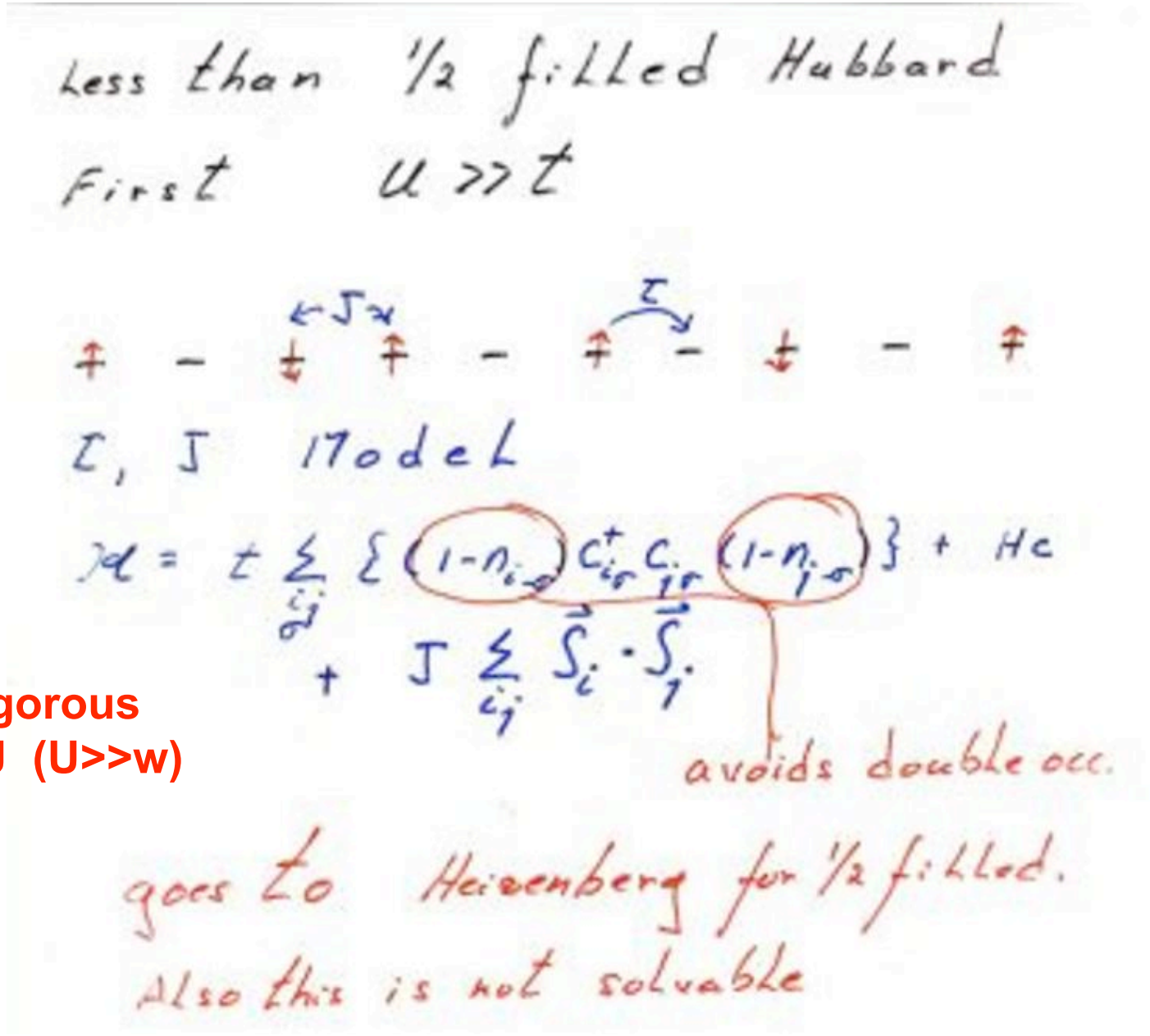
We come back to spectral weight transfer later for the transition metal compounds

Hubbard model is not exactly solvable except in 1 D but even then the spectral functions are difficult to extract

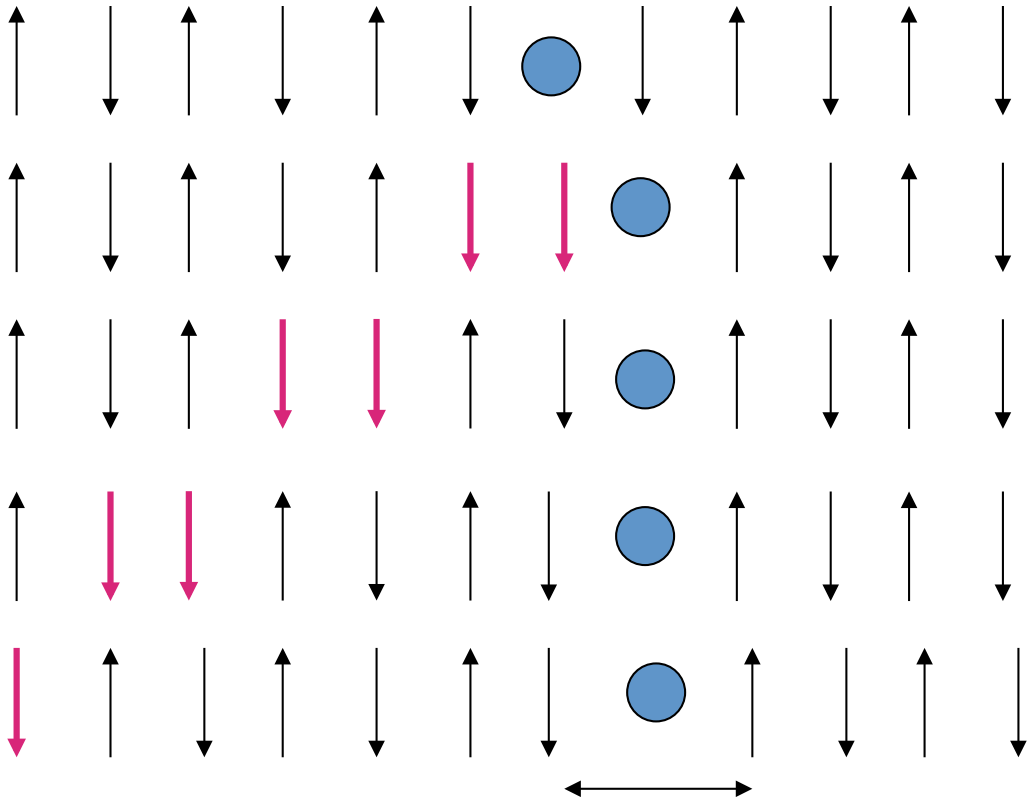
Lieb and Wu PRL 20, 1445, (1968)

A bit more about simple models and some peculiar properties in 1 and 2 dimensions of the simple models

Don't know of a rigorous
Proof of Hubb---t,J (U>>w)



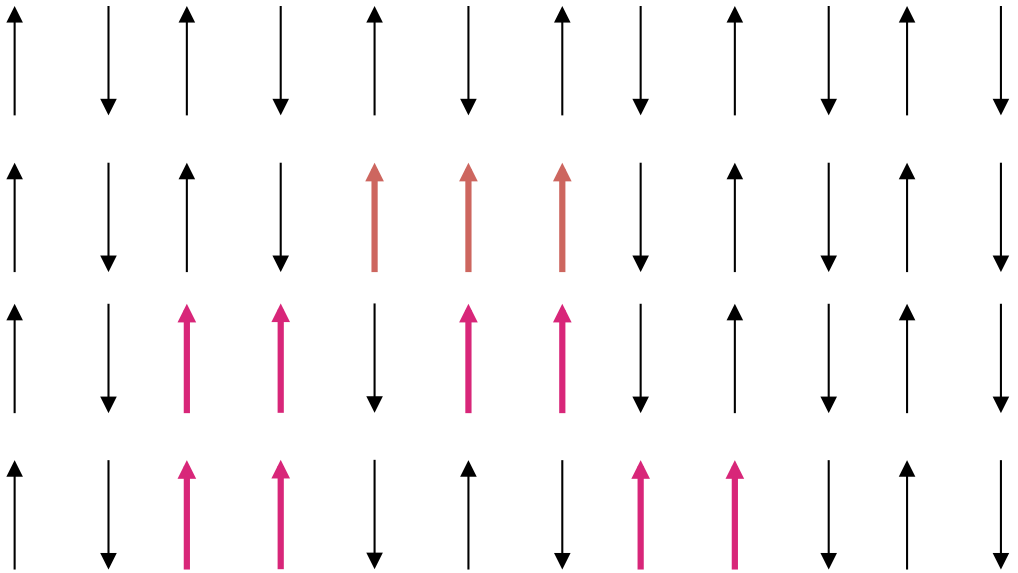
Spin charge separation in 1D



Antiphase
Domain wall

Now the charge is free to move

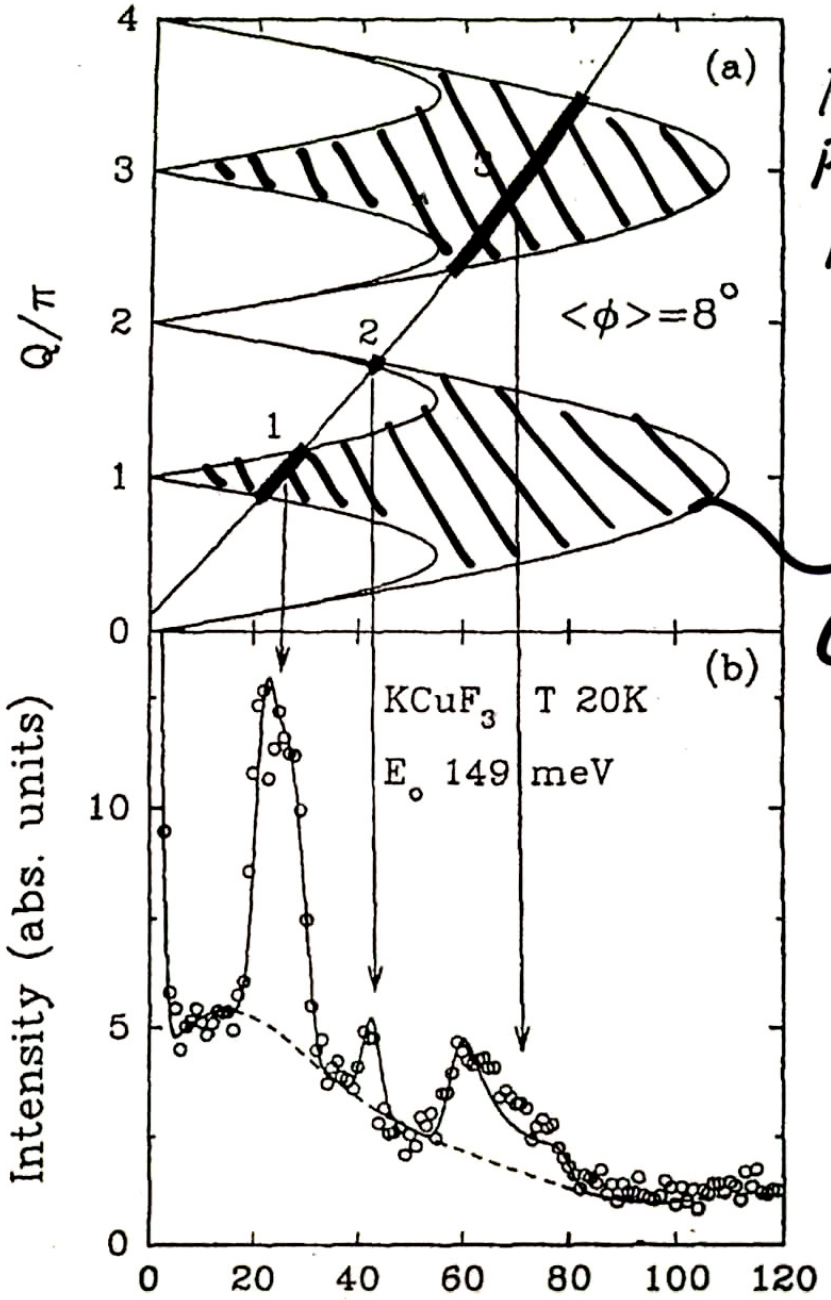
Magnons and spinons in 1D



Magnon S=1

Two spinons

Spinons propagate via $J\, S_i^+ S^-_{1+1}$



Tennant et al
Phys. Rev. B 52
13368 (1555)

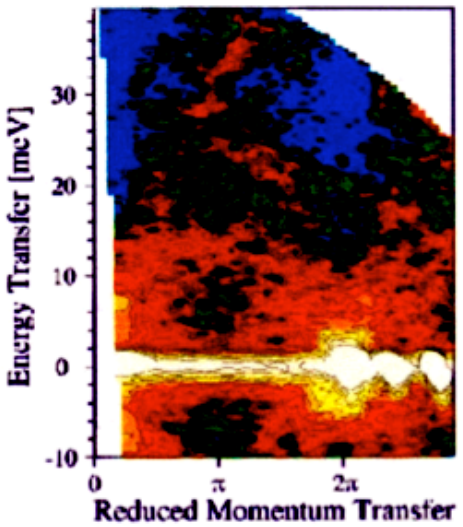
Two Spinon
Continuum.

Inelastic Neutron scattering

Figure 2.14: *Neut*
continuum in 1D.
[1891 The largest

Quantum Spin Excitations in the Spin-Peierls System CuGeO 3

M. Arai, M. Fujita, M. Motokawa, J. Akimitsu, and S. M. Bennington



T= 300K

FIG. 4(color). The dynamical structure factor at 300 K. The spin continuum persists, but with the maximum reduced from 33 to 30 meV. The lower boundary has changed completely

VOLUME 77, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1996

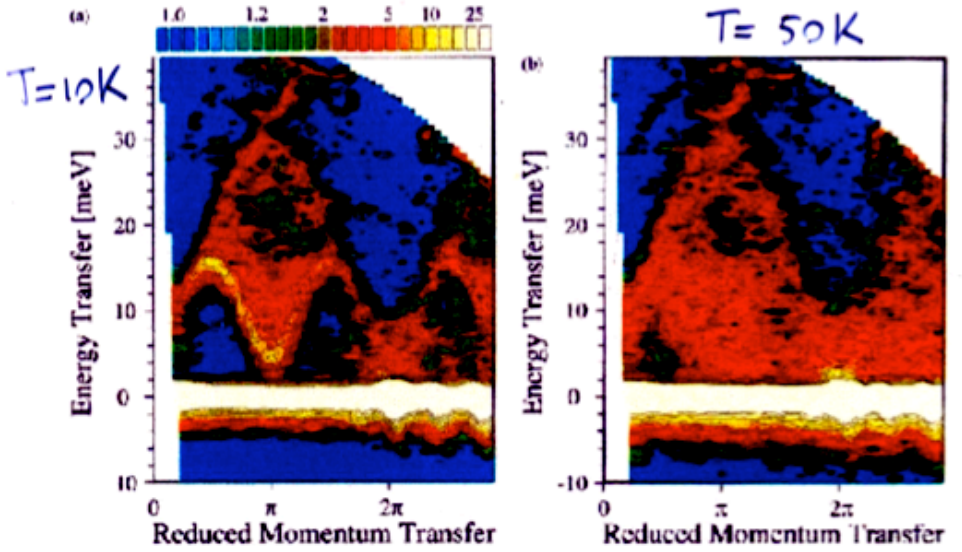
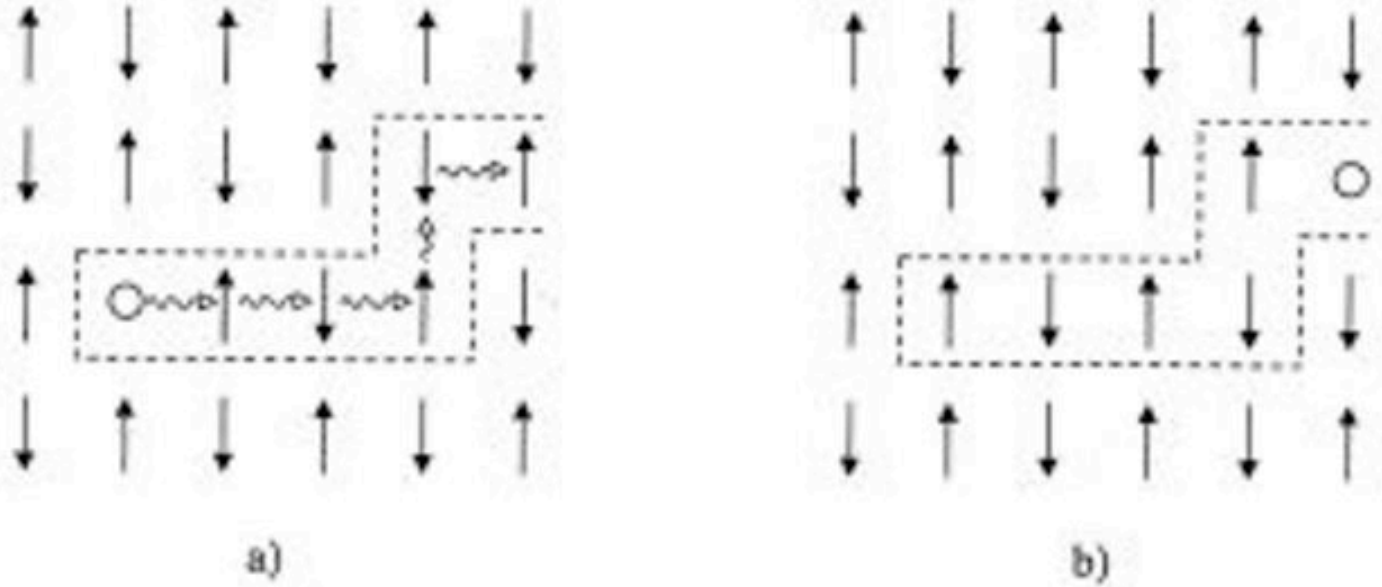


FIG. 1(color). A color contour map of the dynamical structure factor at 10 K (a) and 50 K (b).

in 2D things are much less clear!!



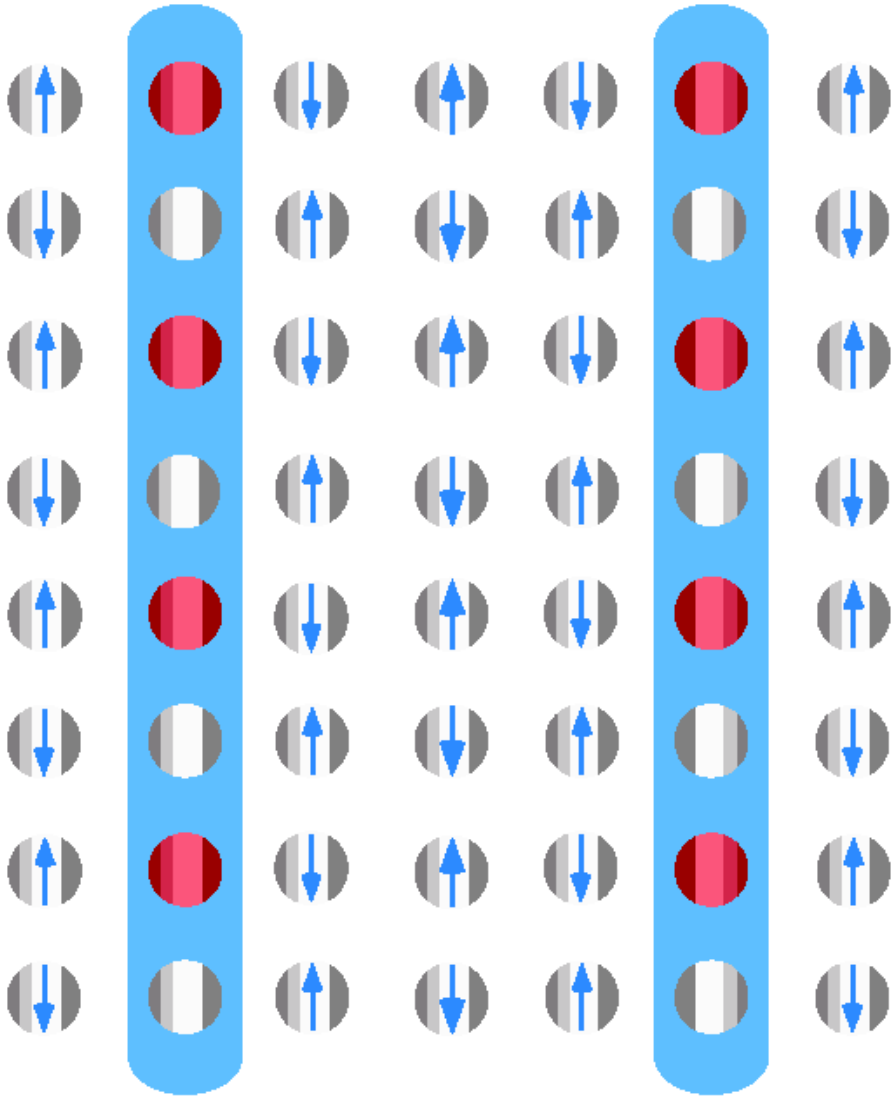
a) b)

fig. 5

Self Confinement?

Similar is some sense to the 1D case it is proposed that one has 2D rivers of charge separating anti-phase domain walls.
Charges can now fluctuate from left to right without costing J

Anisimov, Zaanen ,Andersen, Kivelson,Emery-----



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