TRANSICIONES de FASE CUÁNTICAS

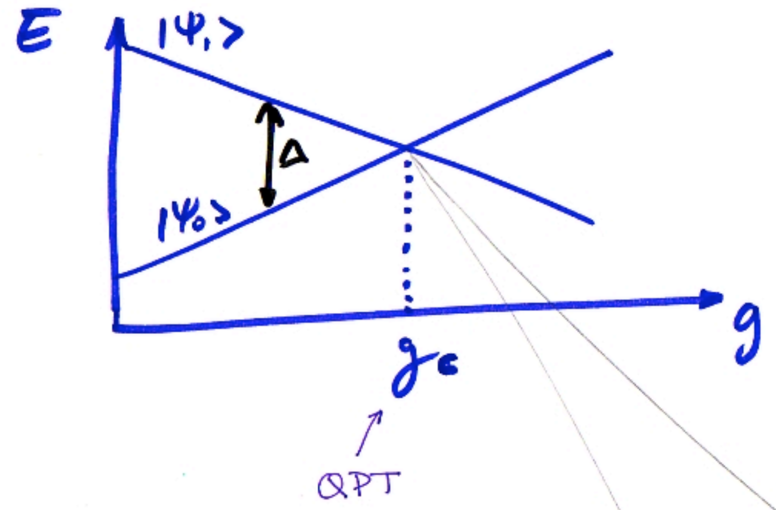
TRANSICIONES a $\boxed{T=0}$
DEBIDAS A LA VARIACIÓN DE UN PARAMETRO (H, P, x, ...)
NO- TÉRMICO

Ph. Tr.: (Classical)

- Papel esencial en la NATURALEZA
- "Cualquier" sistema físico tiene Ph. Tr. (U, H_2O ...)
  "termodinámico"
- Ocurren como variaciones de un parámetro de control
- $T \neq 0$: ORDEN MACROSCÓPICO VS. FLUCTUACIONES TÉRMICAS
- $T=0$: SÓLO $\exists$ FLUCTUACIONES CUÁNTICAS

$$\mathcal{H} = \mathcal{H}_0 + g\,\mathcal{H}_1$$

g: parámetro de control (H, P, E, x ...)



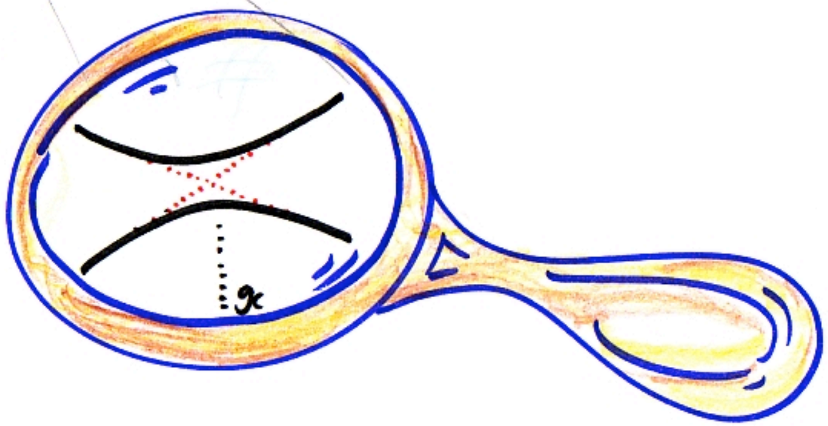
$$\mathcal{H}|\psi_i\rangle = E_i|\psi_i\rangle$$

$$\Delta \sim J\,|g-g_c|^{z\nu}$$

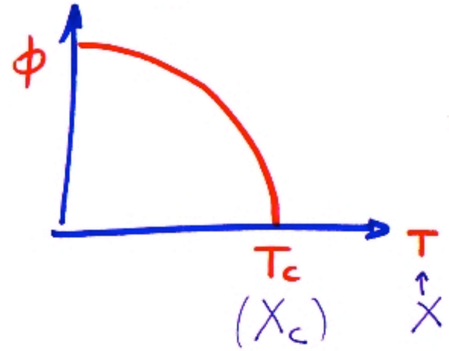
- J: Escala de Energías
- $|g-g_c|$: 0 en QPT
- $z\nu$: exponente crítico

"Avoided level crossing"

LA QPT VIENE ACOMPAÑADA DE UN CAMBIO CUALITATIVO EN LAS CORRELACIONES DEL ESTADO FUNDAMENTAL



TRANSICIONES CONTINUAS → Order parameter



- $T > T_c \Rightarrow \langle \phi \rangle_T = 0$

  pero las fluctuaciones $\delta\phi \neq 0$, en gral.

- CERCA de T_c la LONGITUD de CORRELACIÓN ξ (l. característica de las $\delta\phi$) DIVERGE:

$$\xi \propto |t|^{-\nu} \qquad t = \frac{|T-T_c|}{T_c}$$

- $\exists$ un TIEMPO DE CORRELACIÓN (τ_c) ~ Tiempo típico de relajación.

$$\tau_c \propto \xi^z \propto |t|^{-\nu z}$$

$z \equiv$ exponente crítico dinámico

Q.M. cerca del punto crítico.

2 aspectos

QM puede ser fundamental para entender la existencia de la fase ordenada (o ambas); e.g.:

- SUPERCONDUCTIVIDAD
- SUPERFLUIDEZ
- ...

¿Es la Q.M. relevante en el comportamiento crítico (asintótico)?

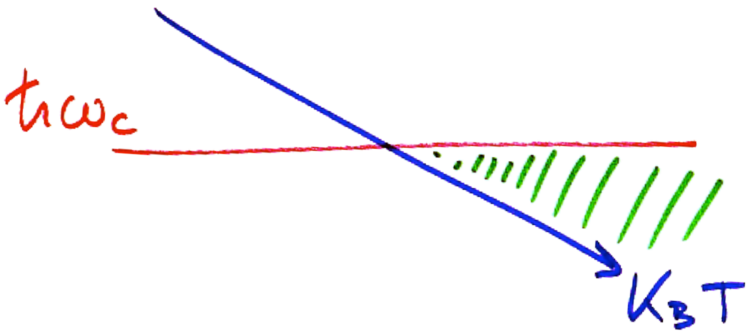
$$\tau_c \sim |t|^{-\nu z}$$

$$\hbar\omega_c \longleftrightarrow k_B T$$

$$\hbar\omega_c \sim |t|^{\nu z}$$

$\hbar\omega_c \gtrsim k_B T \longrightarrow$ QM relevante

$\hbar\omega_c \ll k_B T \longrightarrow$ Classical description.



LAS FLUCTUACIONES RELEVANTES DEL PARÁMETRO DE ORDEN PASAN A SER CUÁNTICAS

pero

$$|t| = \frac{|T - T_c|}{T_c} < T_c^{1/\nu z} \qquad \text{y} \quad \hbar\omega_c \sim |t|^{\nu z}$$

suficientemente CERCA de T_c ; $\boxed{\hbar\omega_c \ll k_B T}$ si T_c es finito

$\forall\, T_c \neq 0 \Rightarrow$ Ph.Tr. CLÁSICAS

• Si T_c es finita ...

① LAS FLUCTUACIONES CLASICAS DOMINAN LA TRANSICIÓN DE FASE, AUNQUE "SUFICIENTEMENTE CERCA" de T_c PUEDE QUERER DECIR "MUY CERCA !!" SI T_c ES MUY BAJA O LA DINAMICA LO REQUIERE ...
DA IGUAL: "ASINTOTICAMENTE", LA TR. ES CLÁSICA

② SI $T_c = 0$ $\nexists$ FLUCTUACIONES CLASICAS $\Rightarrow$ Q. P. T.

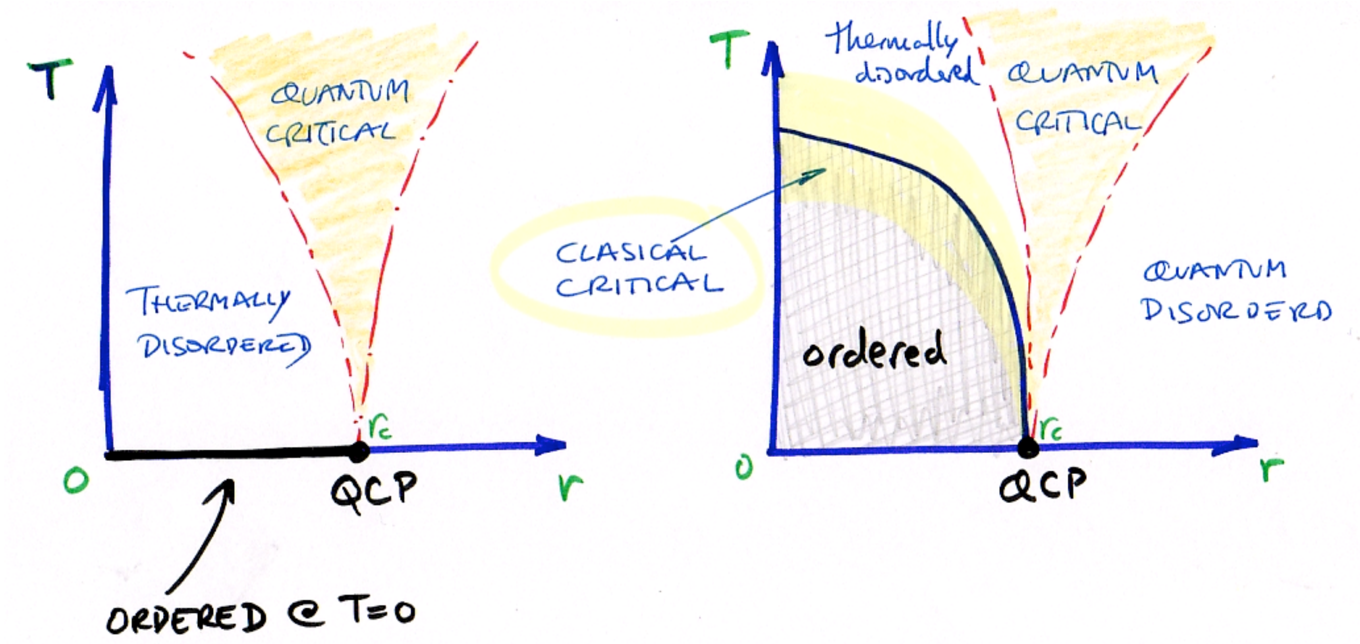
③ EL PARAMETRO DE CONTROL DEL ORDEN ES "NO-TÉRMICO"

④ DEPENDIENDO DE SI $\exists$ ORDEN A $T \neq 0$ O NO $\longrightarrow$ 2 DIAGRAMAS de FASE

1D = CADENA ISING
2D - XY $\rightarrow$ KOSTERLITZ-THOULESS

ISING - 2D
FERROMAGNETO REAL
DOPED La_2CuO_4
⋮

④ DEPENDIENDO DE SI ∃ ORDEN A $T \neq 0$ O NO → 2 DIAGRAMAS de FASE



QUÉ HAY EN LA REGIÓN CRÍTICA CUÁNTICA?

- LA FÍSICA ESTÁ CONTROLADA POR LAS EXCITACIONES TÉRMICAS DEL ESTADO FUNDAMENTAL CUÁNTICO
(las excitaciones no son las habituales,
las "leyes de potencias" no son las habituales,
comportamiento de líquido no-de-Fermi ...)

PARÁMETROS NO-TÉRMICOS EN Q.P.T.

- x ≡ "Composición" $CeCu_{6-x}Au_x$
- P ≡ PRESIÓN
- H ≡ CAMPO MAGNÉTICO

Ejemplo "típico": $LiHoF_4$ ($T_c = 1.53\,K$ @ $H=0$) model system Ising under field

σ ≡ Pauli matrices

J_{ij} ≡ exchange cte.

Γ ≡ transversal field

$$\boxed{\mathcal{H} = \sum_{i,j}^{N} J_{ij}\,\sigma_i^z \sigma_j^z - \Gamma \sum_{i}^{N} \sigma_i^x}$$

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Quantum Critical Behavior for a Model Magnet

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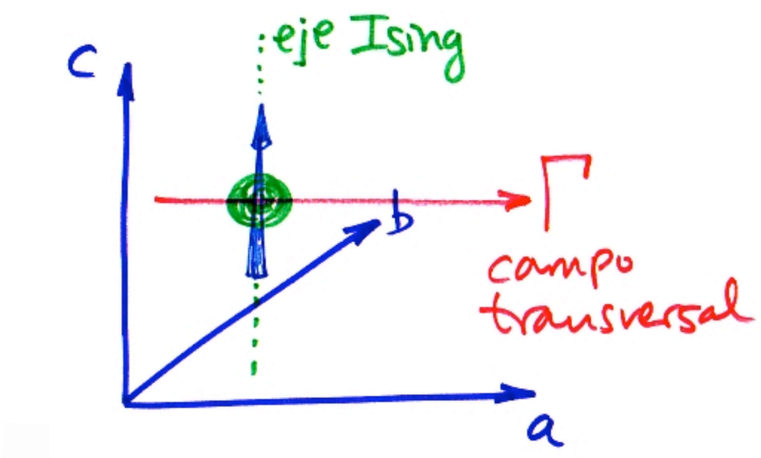
(Received 18 March 1996)

The classical, thermally driven transition in the dipolar-coupled Ising ferromagnet $LiHoF_4$ ($T_c = 1.53$ K) can be converted into a quantum transition driven by a transverse magnetic field H_t at $T = 0$. The transverse field, applied perpendicular to the Ising axis, introduces channels for quantum relaxation, thereby depressing T_c. We have determined the phase diagram in the H_t-T plane via magnetic susceptibility measurements. The critical exponent, $\gamma = 1$, has a mean-field value in both the classical and quantum limits. A solution of the full mean-field Hamiltonian using the known $LiHoF_4$ crystal-field wave functions, including nuclear hyperfine terms, accurately matches experiment. [S0031-9007(96)00753-3]



Ho^{3+} : $4f^{10}$

$S_z =$ 0 0 0 1/2 1/2 1/2 1/2 → $S=2$

$l_z =$ −3 −2 −1 0 1 2 3 → $L=6$

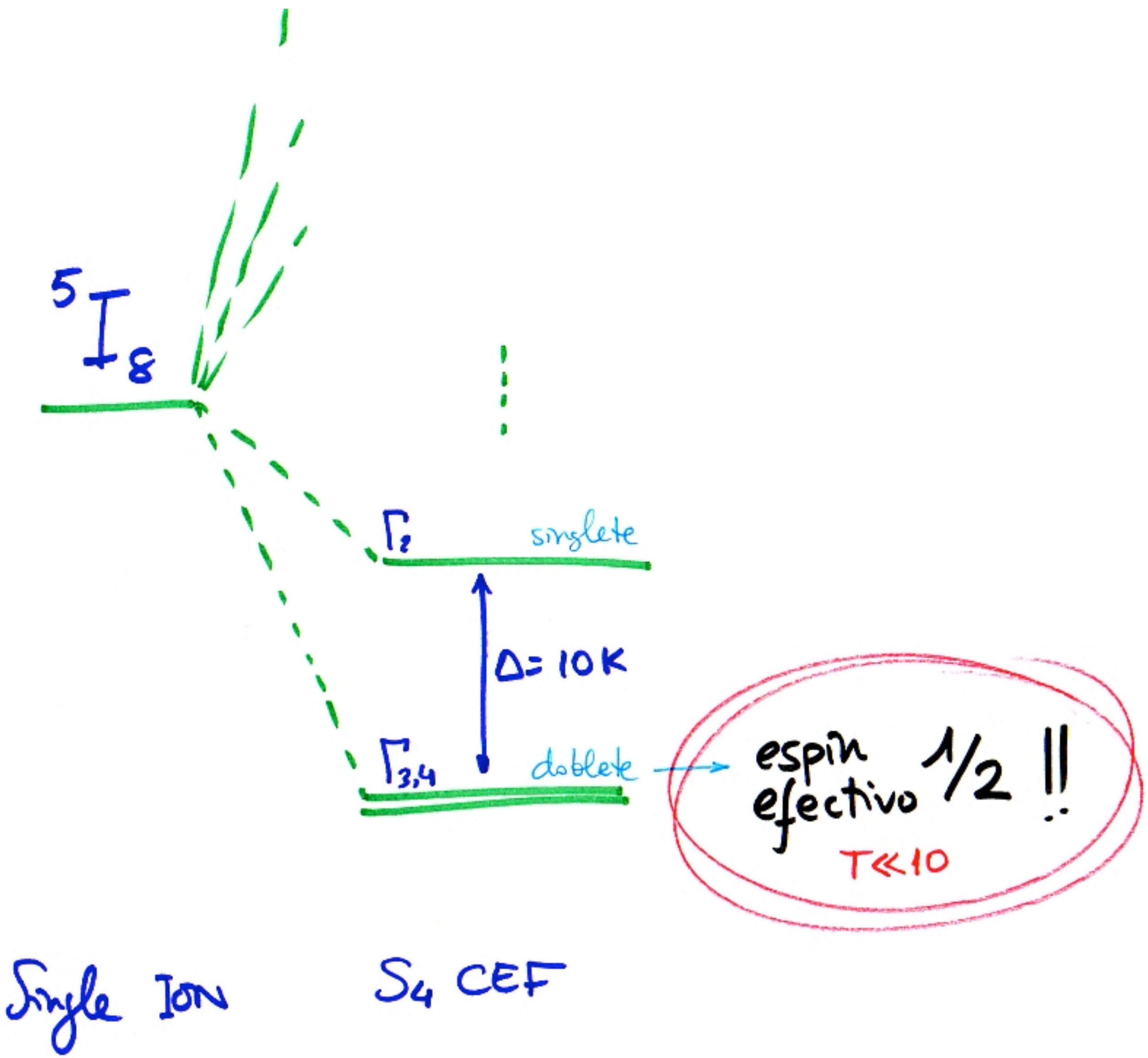
↓

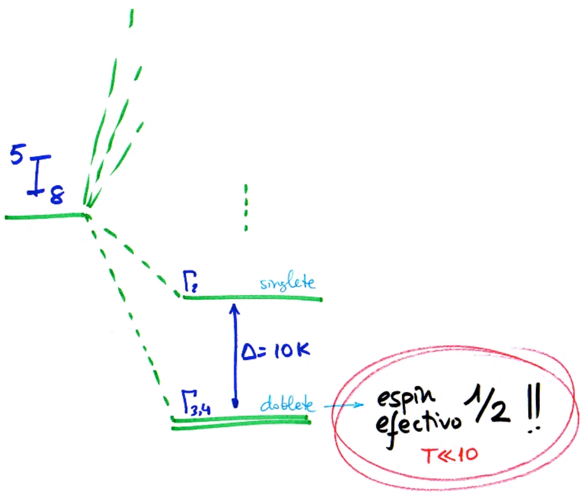
$^5I_8$

$l =$ 0, 1, 2, 3, 4, 5, 6
S P D F G H I

↳ TERMINO $^{2S+1}L_J$


$^5I_8$
single ion


$^5I_8$
Γ_2 singlete
$\Delta = 10K$
$\Gamma_{3,4}$ doblete
espin efectivo 1/2 ¡¡
T≪10
Single ION
S_4 CEF



- ISING ?? Depende del detalle "fino" del CEF

$$|\phi_i\rangle = \sum_{i=-\frac{15}{2}}^{15/2} a_i \, |6, \tfrac{3}{2}, \tfrac{15}{2}, i\rangle \quad ; \quad \sum_{i=-\frac{15}{2}}^{15/2} |a_i|^2 = 1$$

los a_i's determinan

$$\tilde{g} = \begin{bmatrix} g_{xx} & g_{xy} & g_{xz} \\ g_{yx} & g_{yy} & g_{yz} \\ g_{zx} & g_{zy} & g_{zz} \end{bmatrix}$$

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Critical behavior of the magnetic susceptibility of the uniaxial ferromagnet $LiHoF_4$

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(Received 21 February 1978).

The magnetic susceptibility of two $LiHoF_4$ single crystals has been measured in the range 1.2–4.2 K. Ferromagnetic order occurs at $T_c = 1.527$ K. Above 2.5 K, the susceptibilities parallel and perpendicular to the fourfold c axis are well interpreted by the molecular-field approximation, taking into account the ground state and the first excited state of Ho^{3+} in the crystal field of S_4 symmetry. The experimental results are consistent with $g_{\parallel} = 13.95$ and $g_{\perp} = 0$ for the ground state. The dipolar contribution to the magnetic interaction is about three times larger than the exchange one. Near T_c, the parallel susceptibility is well described by the classical law with logarithmic corrections theoretically predicted by Larkin and Khmel'mitskii for the uniaxial dipolar ferromagnet or by a power law with a critical-exponent value $\gamma = 1.05$ rather close to 1. The upper limit of the critical region is $(T_{max} - T_c)/T_c = 1.1 \times 10^{-2}$.

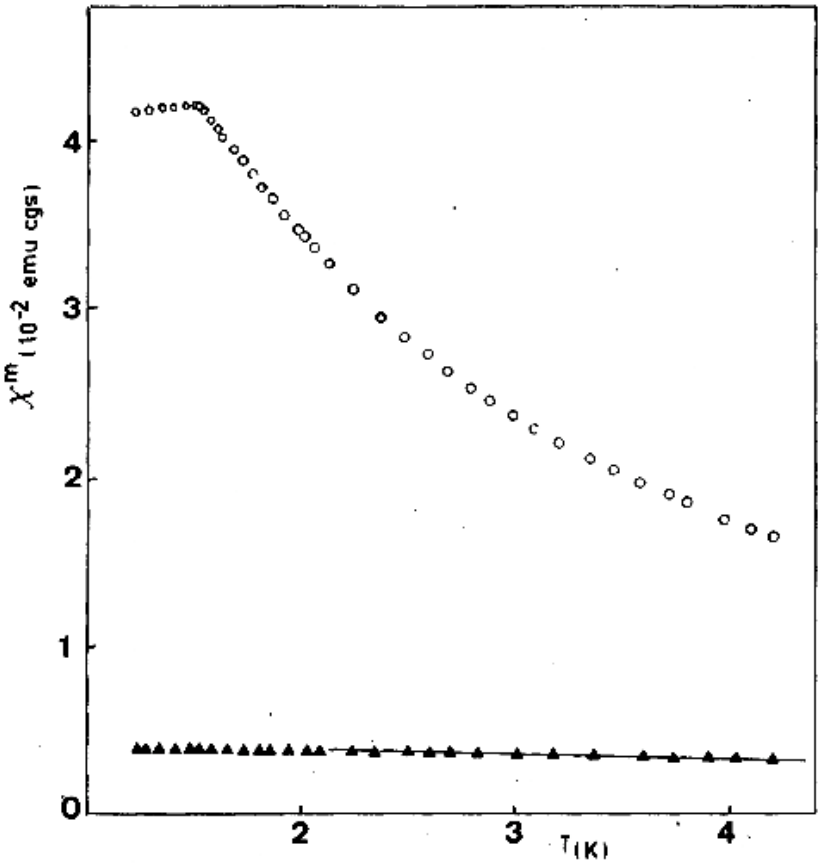


FIG. 1. Experimental parallel susceptibility per gram $\chi_{\parallel}^m$ (open circles) and perpendicular susceptibility per gram $\chi_{\perp}^m$ (black triangles) vs temperature for the spherical sample. The solid line represents the approximate theoretical law, for $e^{-E_1/kT} << 1$: $\chi_{\perp}^m = (n\mu_B^2/4k)(B + Ce^{-E_1/kT})$, with $B = 9.98$, $C = 11.3$, and $E_1/k = 10.4$ K.

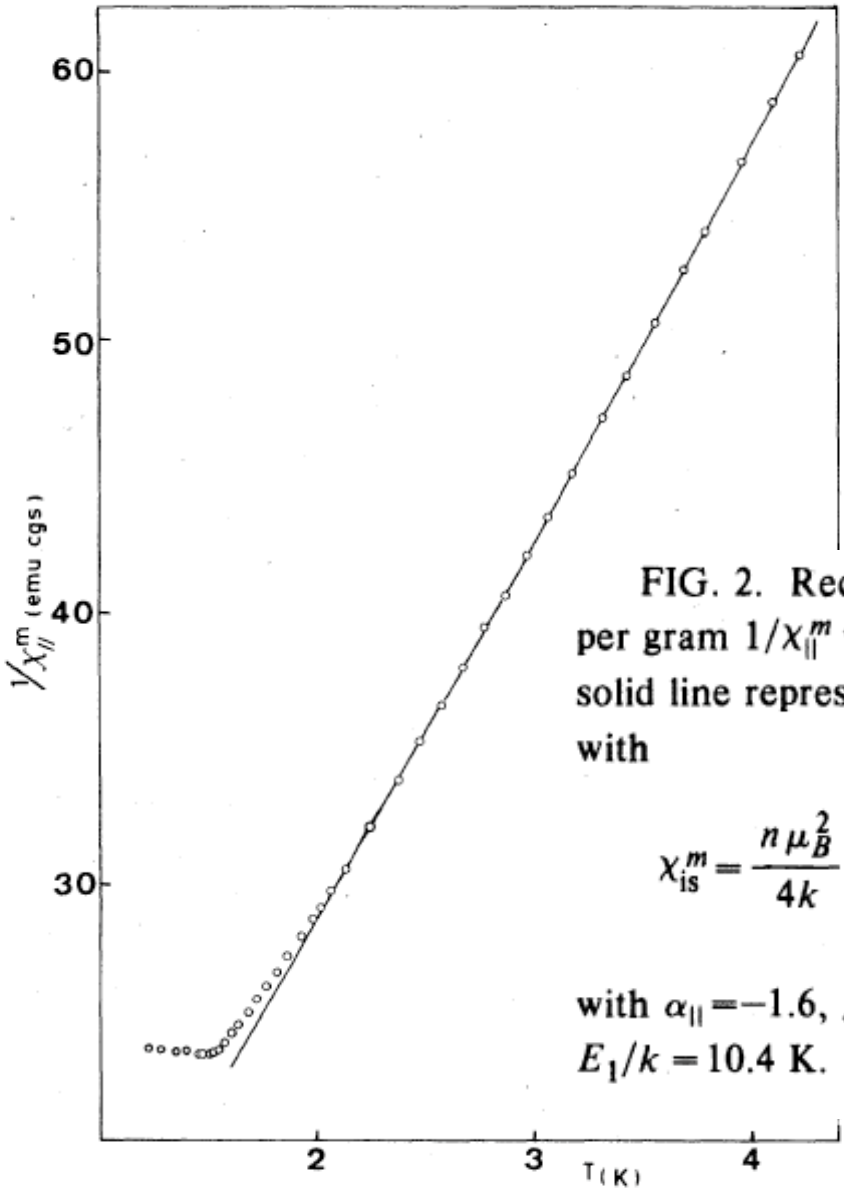


FIG. 2. Reciprocal experimental parallel susceptibility per gram $1/\chi_{\parallel}^m$ vs temperature for a spherical sample. The solid line represents the theoretical curve $1/\chi_{\parallel}^m = 1/\chi_{is}^m - \alpha_{\parallel}$ with

$$\chi_{is}^m = \frac{n\mu_B^2}{4k}\left[\frac{(g_{\parallel}^0)^2 T^{-1} + a_{\parallel}^0 + a_{\parallel}^1 e^{-E_1/kT}}{1+0.5e^{-E_1/kT}}\right]$$

with $\alpha_{\parallel} = -1.6$, $g_{\parallel}^0 = 13.95$, $a_{\parallel}^0 = 0.25$, $a_{\parallel}^1 = 3.3$, and $E_1/k = 10.4$ K.

GIROMAGNETIC RATIO

VAN VLECK

$$\chi^{m}_{isol} = \frac{n\mu_B^2}{4k_B} \cdot \frac{g_{\parallel}^{0}\, T^{-1} + a_{\parallel}^{0} + a_{\parallel}^{1}\, e^{-E_1/k_BT}}{1 + \frac{1}{2} e^{-E_1/k_BT}}$$

$$g_{\parallel}^{0} = 13.95 \quad (\chi)$$

$$g_{\parallel}^{0} = 14.1(2) \quad \text{E.P.R.}$$

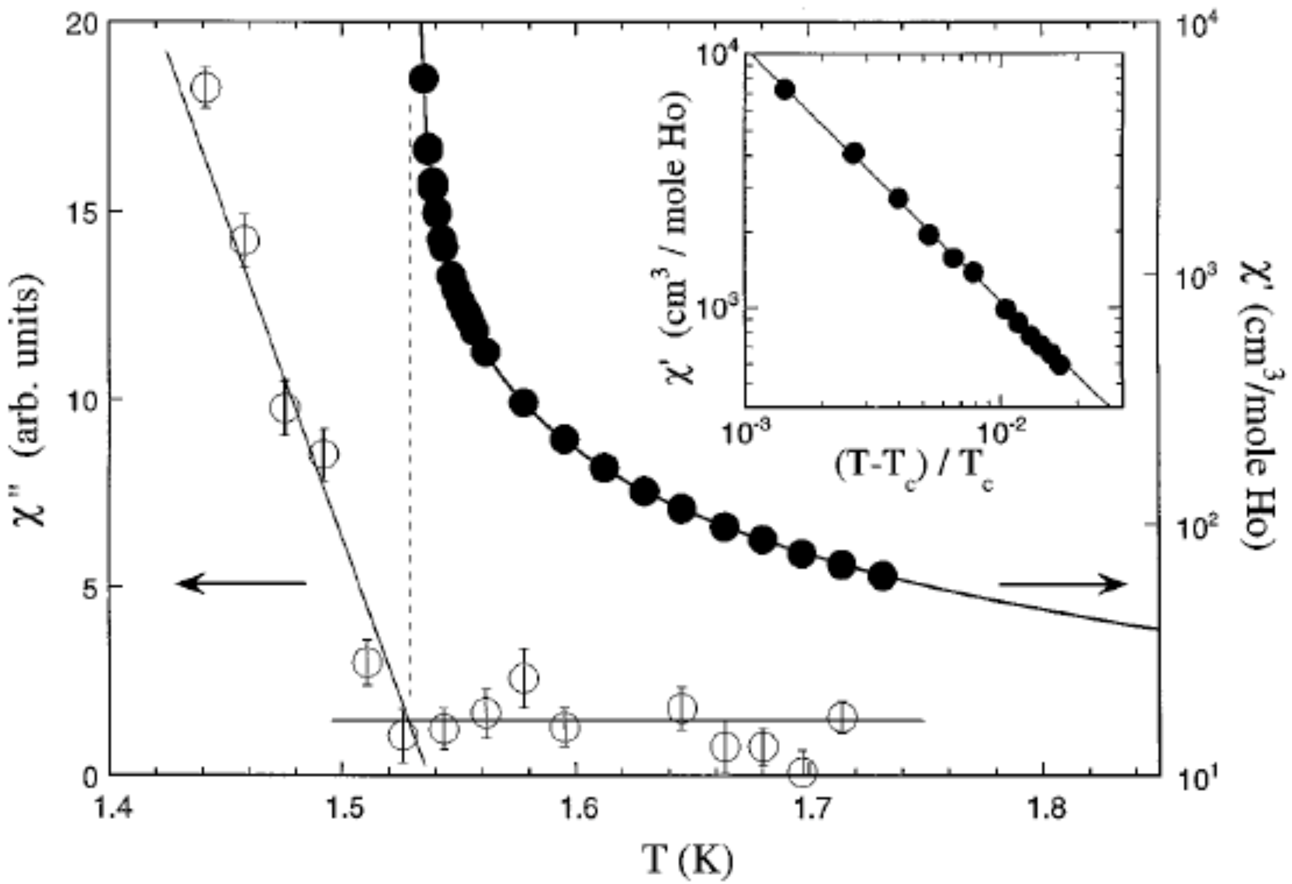
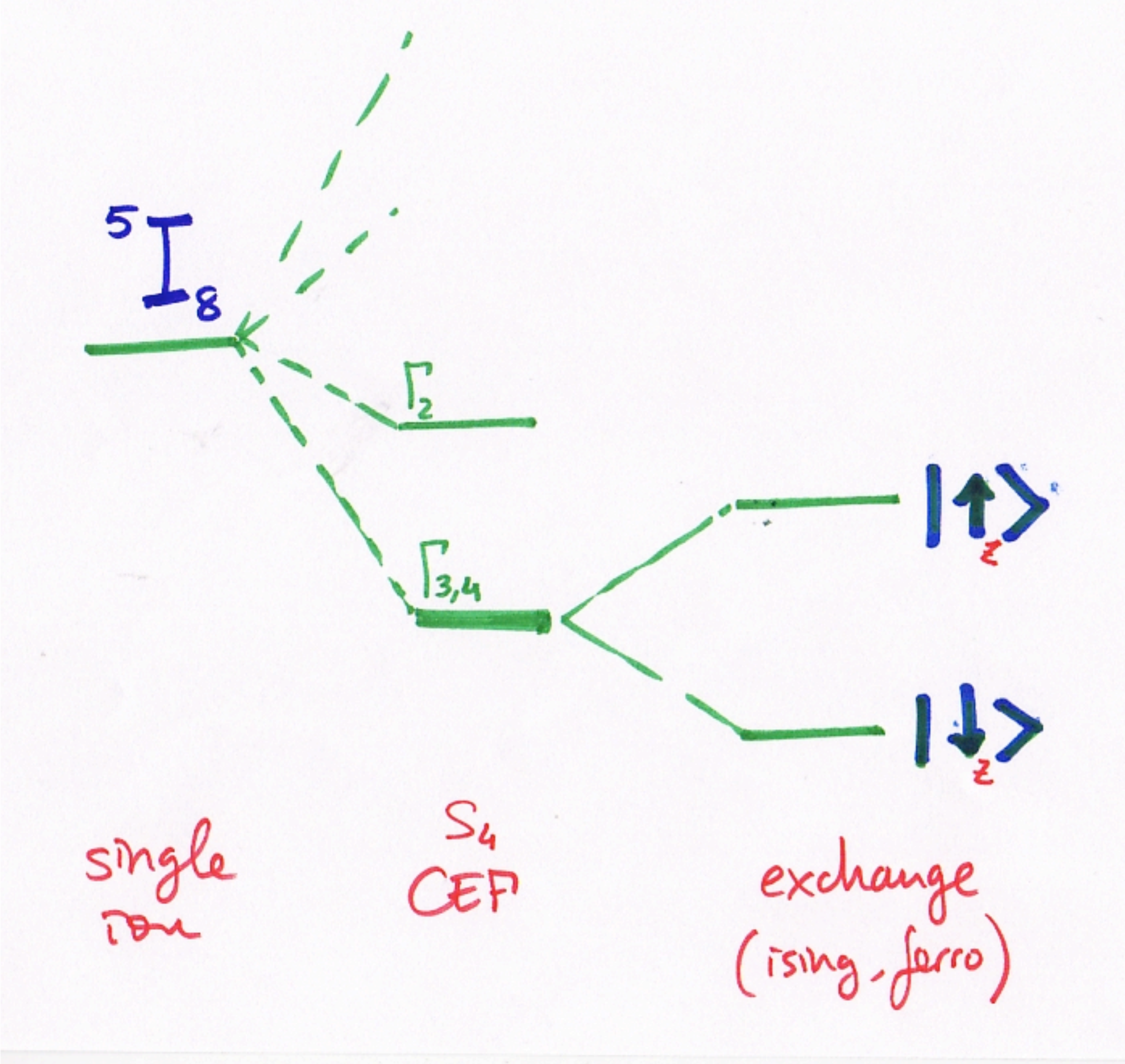
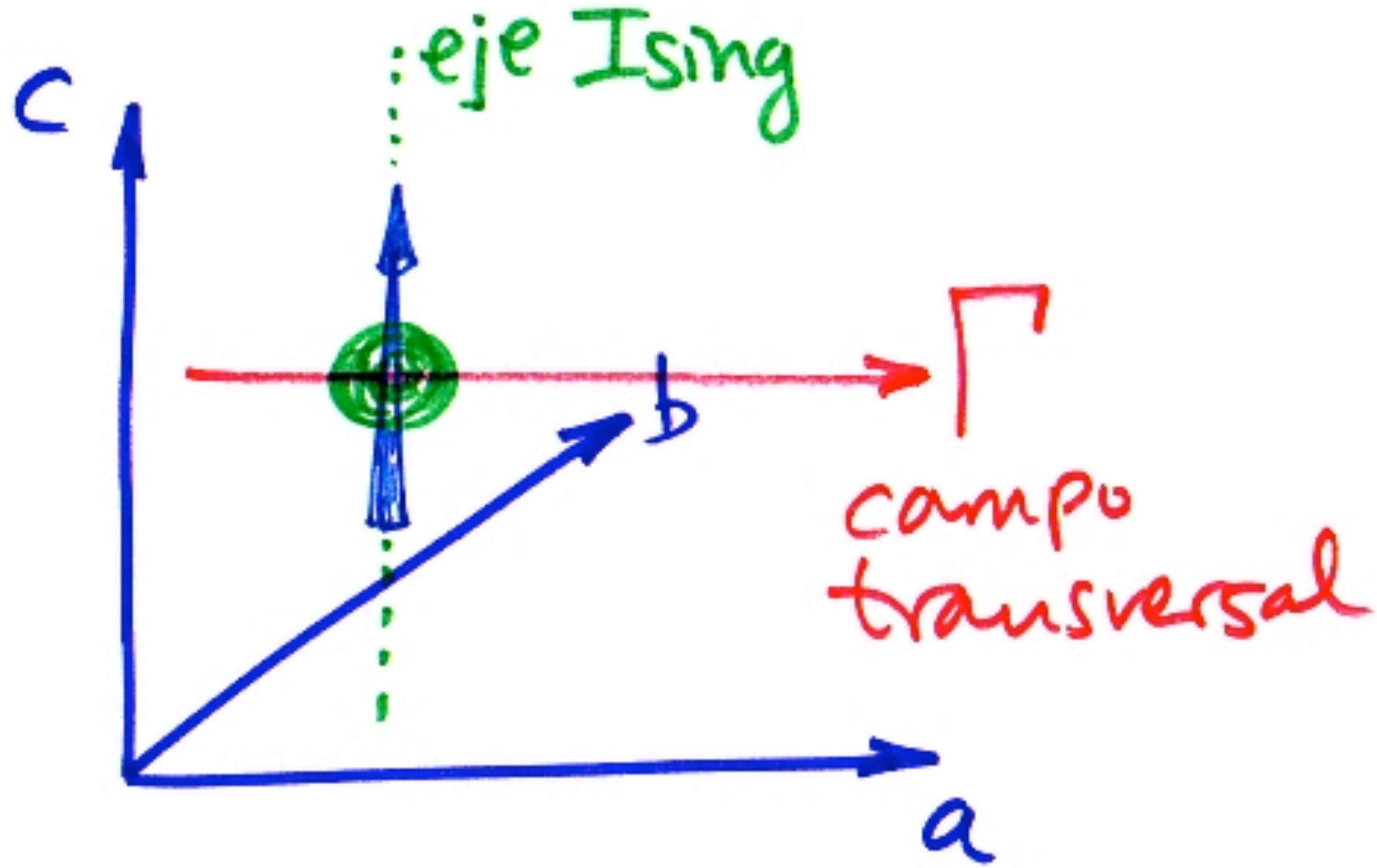
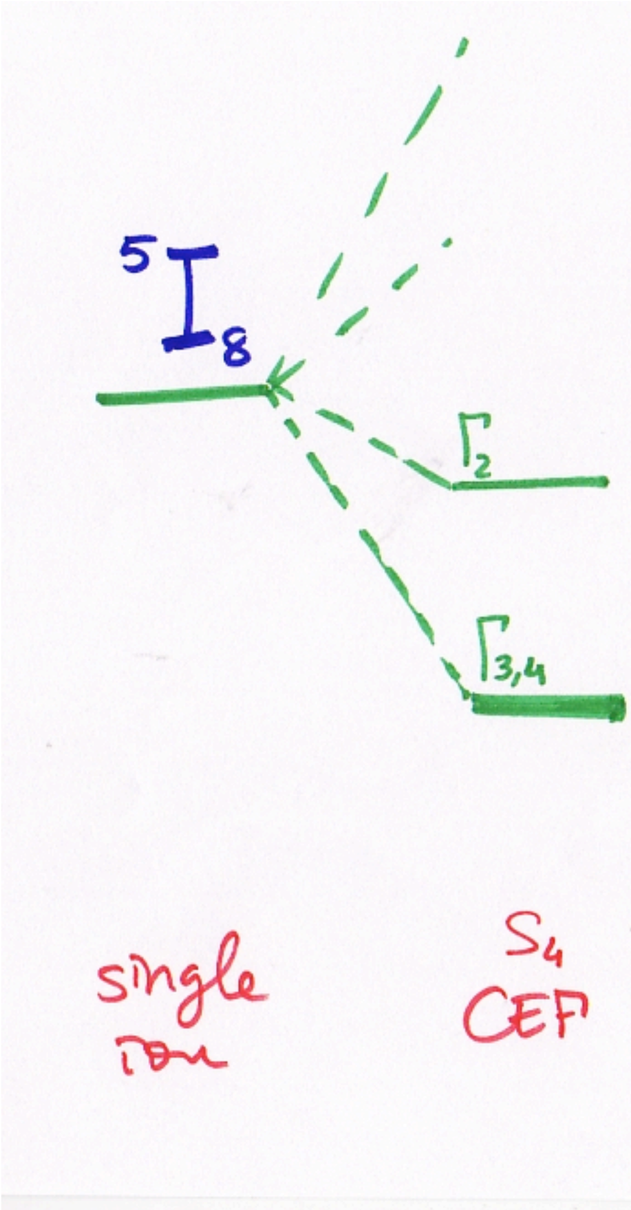


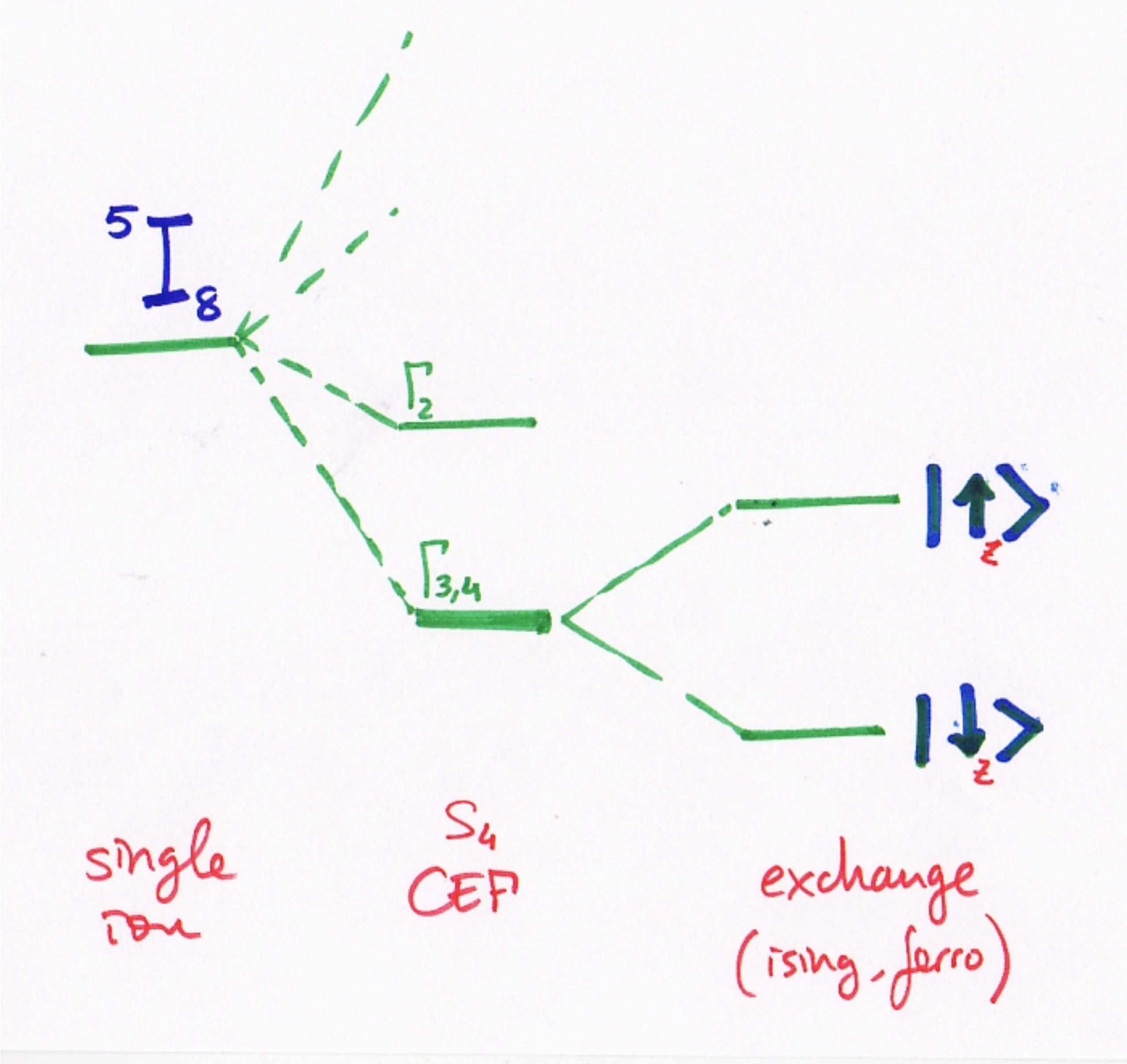
FIG. 1. Divergence of the real part of the magnetic susceptibility (filled circles) and sharp increase in the imaginary part (open circles) at the thermally driven ferromagnetic transition in $LiHoF_4$. Inset: Mean-field critical behavior with $\chi' \propto t^{-\gamma}$ and best-fit value $\gamma = 1.00 \pm 0.09$ (line).



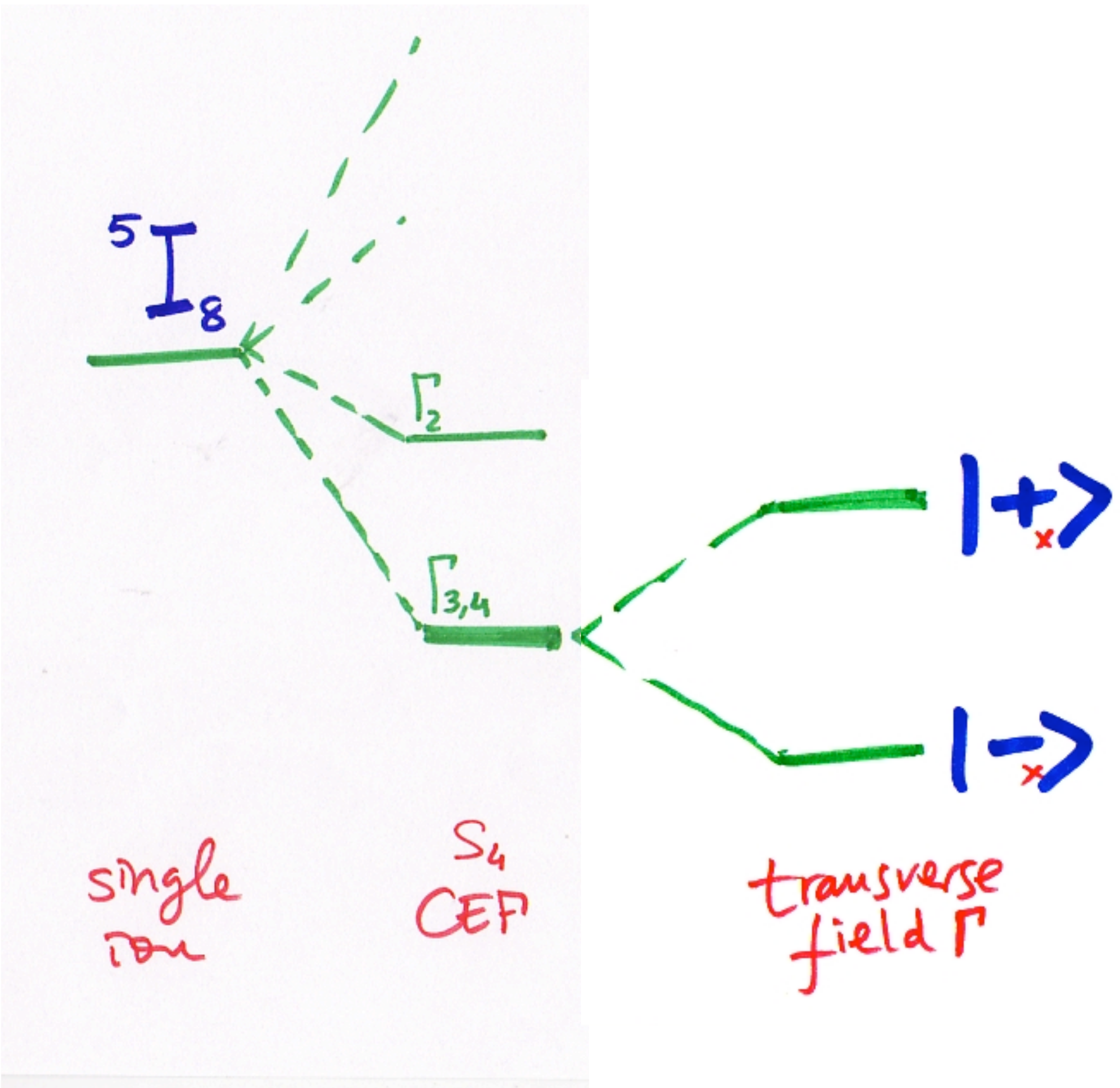
$^5I_8$
Γ_2
$\Gamma_{3,4}$
$|\uparrow_z\rangle$
$|\downarrow_z\rangle$
single ion
S_4
CEF
exchange
(ising-ferro)


eje Ising
c
b
Γ
campo
transversal
a


$^5I_8$
Γ_2
$\Gamma_{3,4}$
single ion
S_4
CEF



$^5I_8$
Γ_2
$\Gamma_{3,4}$
$|\uparrow\rangle_z$
$|\downarrow\rangle_z$
single ion
S_4
CEF
exchange
(ising-ferro)


$^5I_8$
Γ_2
$\Gamma_{3,4}$
$|+_x\rangle$
$|-_x\rangle$
single ion
S_4 CEF
transverse field Γ

$$|\pm\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow_z\rangle \pm |\downarrow_z\rangle\right)$$

Transición (*de fase cuántica*) de

Orden Clásico Ferromagnético

a Desorden Cuántico !!