Ferromagnetism and the quantum critical point in $Zr_{1-x}Nb_xZn_2$

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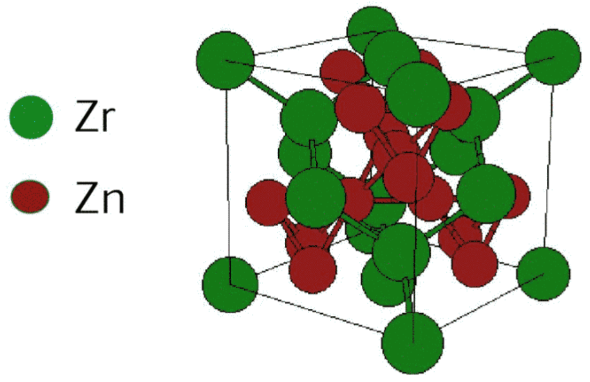
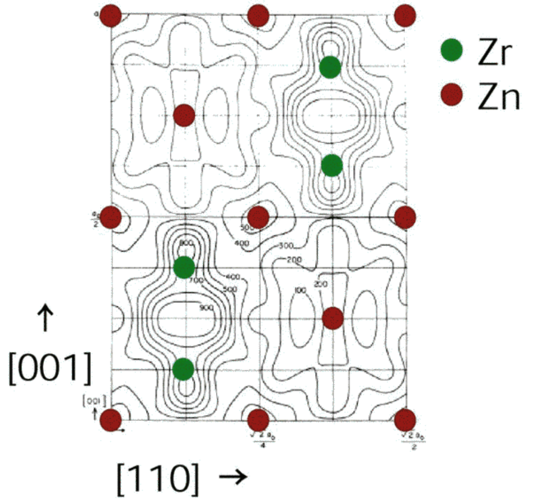
$ZrZn_2$: Itinerant Ferromagnet



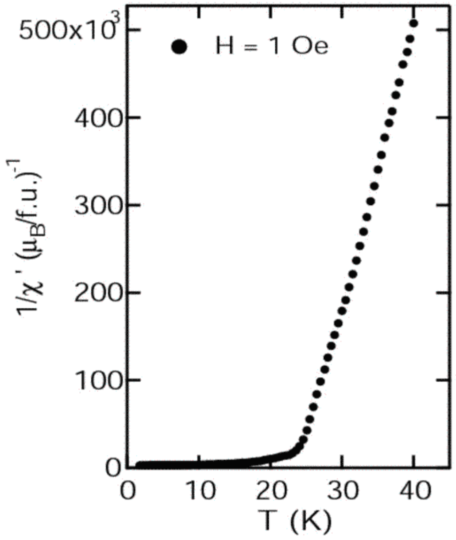
C15 Laves Phase

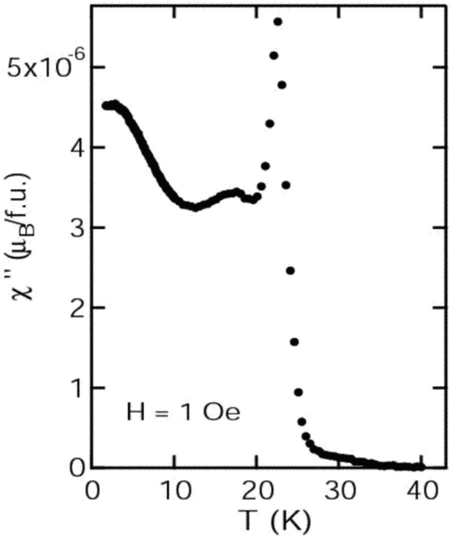
$ZrZn_2$ spin density (4.2 K)



Pickart 1964

Curie Temperature T_C: Low Field Measurements

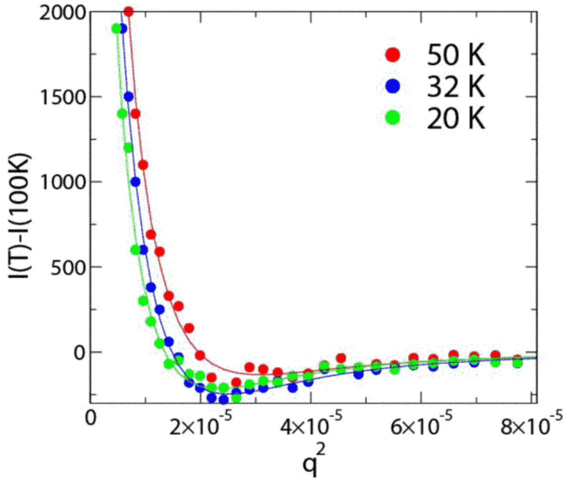




- $1/\chi$'Y0: Onset of Ferromagnetism near ~23 K
- χ": Maximum dissipation near ~23 K

Small Angle Neutron Scattering

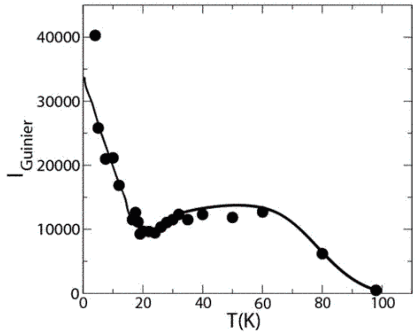
- Experiments carried out using NG3 SANS at NIST/NCNR, polycrystalline samples

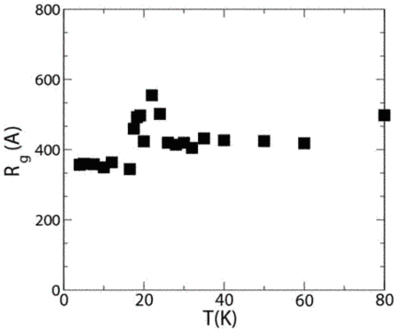


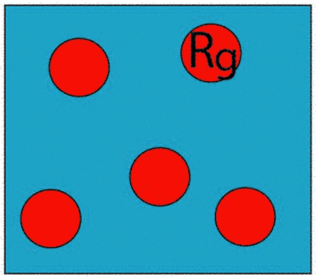
- $I(q,T)= I_{BG}(q) + I_{mag}(q,T)$ $I_{mag}(q,T) = I(q,T)-I_{100K}(q)$

  $I_{mag}(q,T) = I_{Guinier} \exp(-R_g^2q^2)$ scattering from static, magnetized regions

Magnetic Order and Correlations in $ZrZn_2$

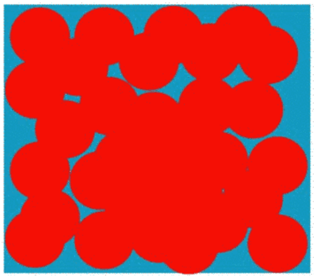






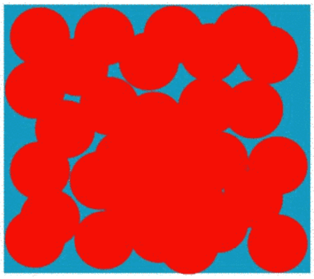
T>30 K increasing
# of magnetic regions

T_C~30 K (percolation)



15K<T<30 K
magnetic homogenization

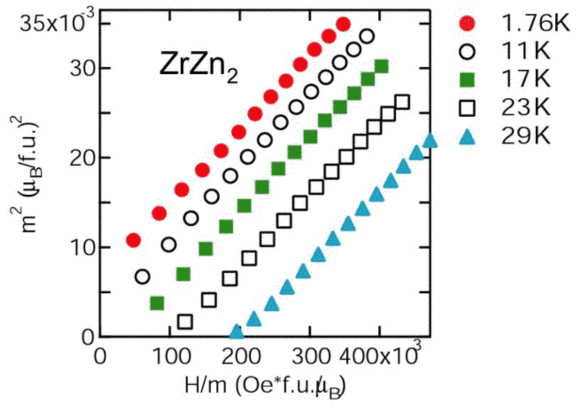
(reduced SANS)

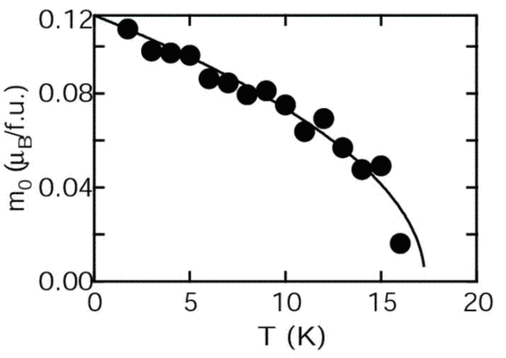


T<15 K
softening of spin waves.

(enhanced SANS)

Arrott Plots: Spontaneous Moment



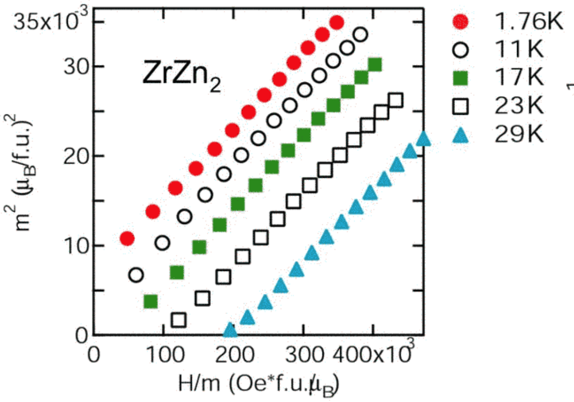


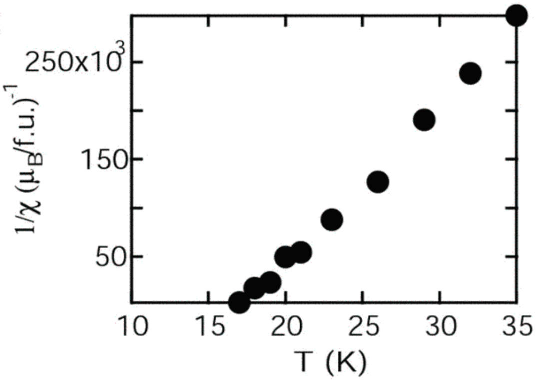
$$H=a\,(T)\,m + bm^3$$

$T<T_C$: $m(H=0,T)^2= -a/b$ $\qquad$ $m(0,T)=m(0,0)\,(1-T/T_C)^{\beta}$

$T_C=17.2$ K $\qquad$ $\beta=0.5$

Arrott Plots: Initial Susceptibility χ



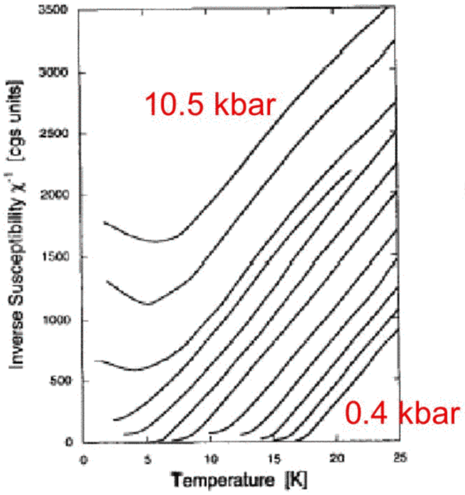


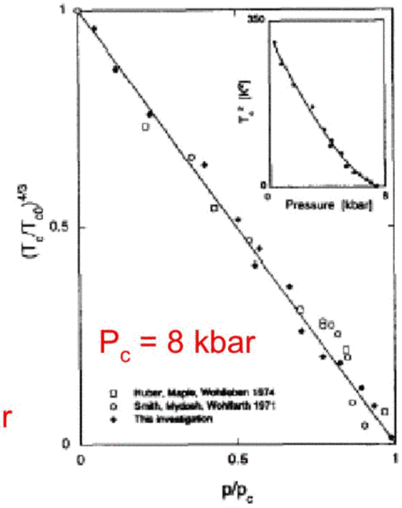
$$H=a(T)\,m + bm^3$$

$T>T_C$: $cH/cM=a(T)=1/\chi(T)$ $\chi^{-1}(T)=\chi_o^{-1}\,((T-T_C)/T_C)^{\gamma}$

$T_C=17.2K$ $\gamma=1.0$

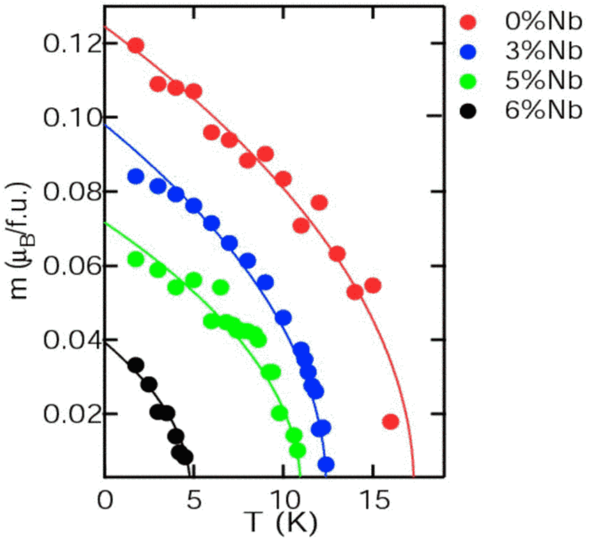
Ferromagnetic Quantum Critical Point in $ZrZn_2$: Pressure





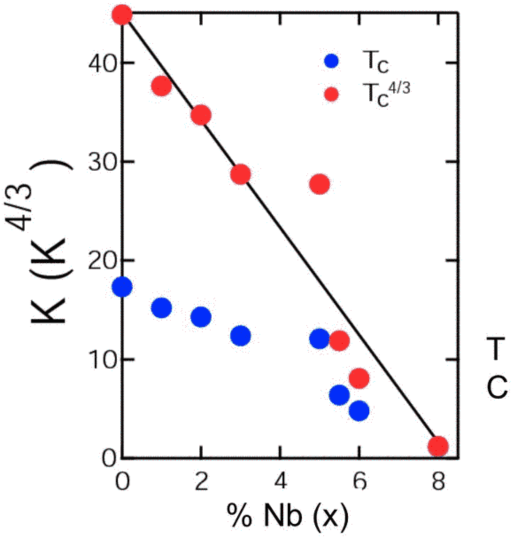
(Grosche 1995)

$Zr_{1-x}Nb_xZn_2$



- $m(H=0,T) = m_{0,0}(x)(1-T/T_C)^\beta$ $\beta=0.5$
- T_C and $m(H=0,T=0)$ are suppressed by Nb doping x

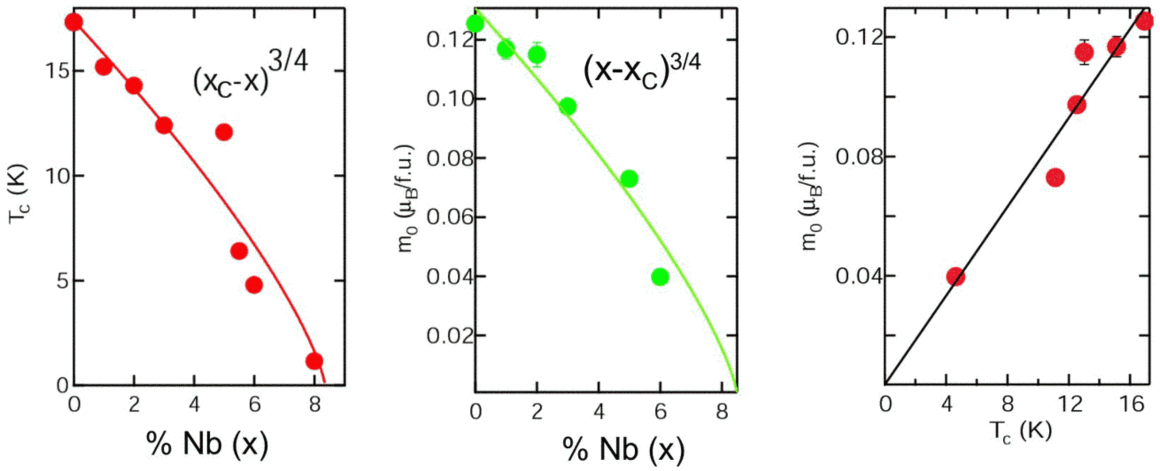
Quantum Critical Point in $Zr_{1-x}Nb_xZn_2$ ($x=x_C=0.085$)



- Three dimensional mean field quantum ferromagnet (x_C=0.085)

$T_C^{(d+n)/z}$ Q ($x-x_C$) (d=3, z=2+n=3) $T_C^{4/3}$ Q ($x-x_C$)

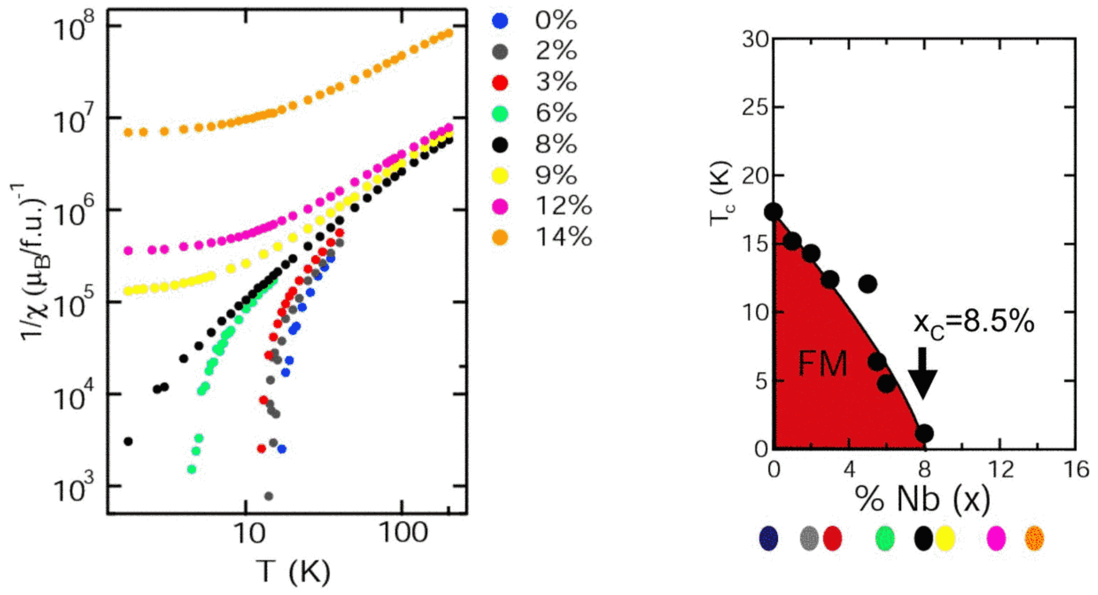
Itinerant Ferromagnetism in $Zr_{1-x}Nb_xZn_2$



- Stoner ferromagnet (+ magnetic fluctuations)

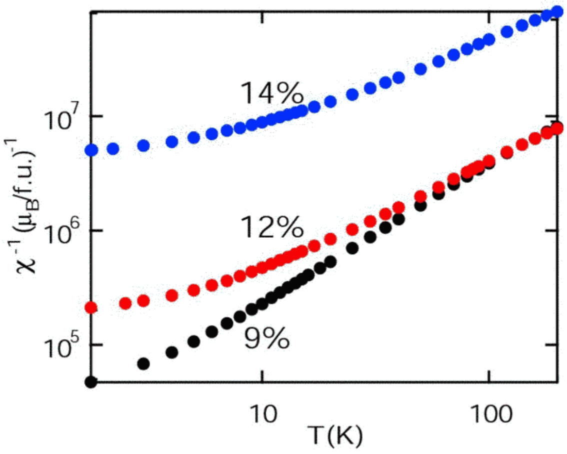
$\alpha = I\,N(E_f)$ $\quad m_0\ Q\ (\alpha-1)^{1/2}$ $\quad T_C\ Q\ (\alpha-1)^{1/2}$ $\quad m_o\ Q\ T_C$

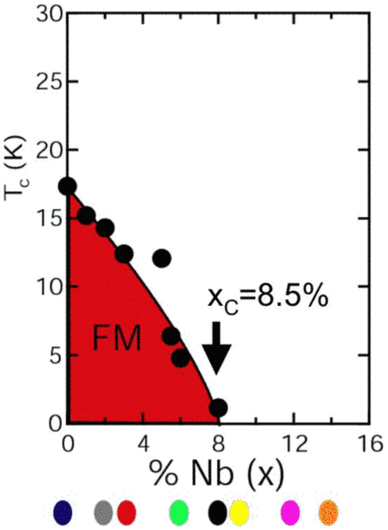
The Initial Susceptibility χ



- $x<x_C$ $\qquad \chi^{-1}=\chi_o^{-1}t^{\gamma}$ $\qquad t=(T-T_C)/T_C$
- $x>x_C$ $\qquad \chi^{-1}=\chi_o^{-1}+C^{-1}T^{\gamma}$
- $x=x_C$ $\qquad \chi^{-1}=C^{-1}T^{\gamma}$

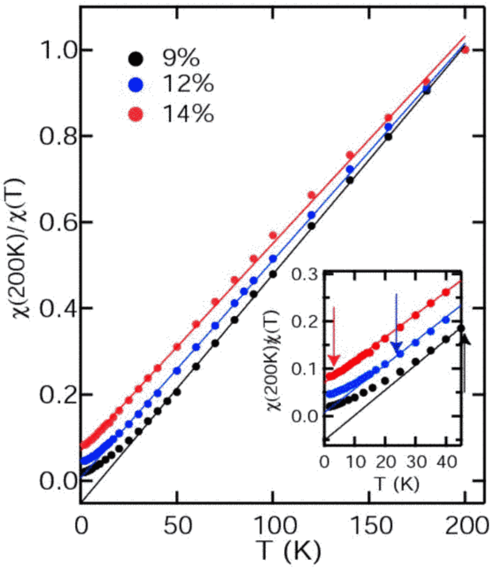
Paramagnetic Phase ($x>x_C$)

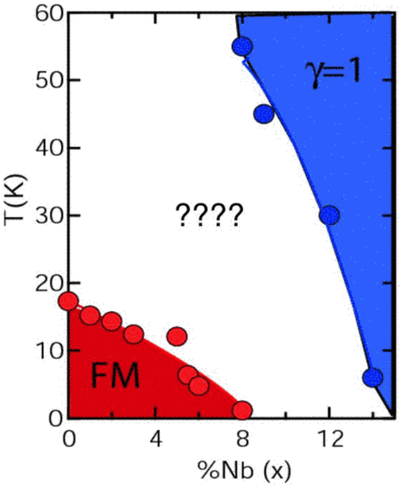




- $\chi^{-1}=\chi_o^{-1} + C^{-1}T^{\gamma} = (\theta/C)+C^{-1}T^{\gamma}$ $\chi= C/(T^{\gamma}+\theta)$
- xYx_C: $\chi_o^{-1}Y0$

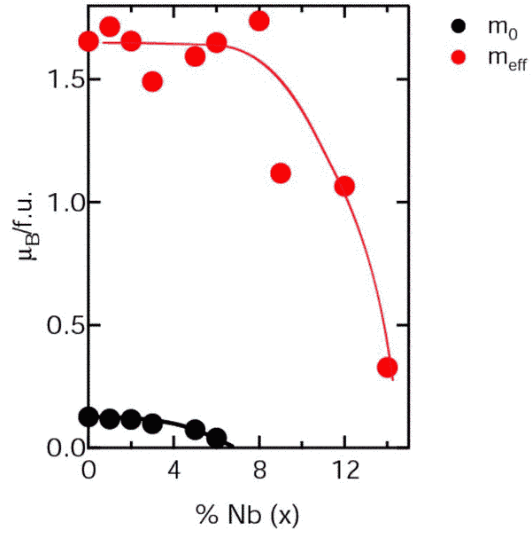
Paramagnetic Phase ($x>x_C$)

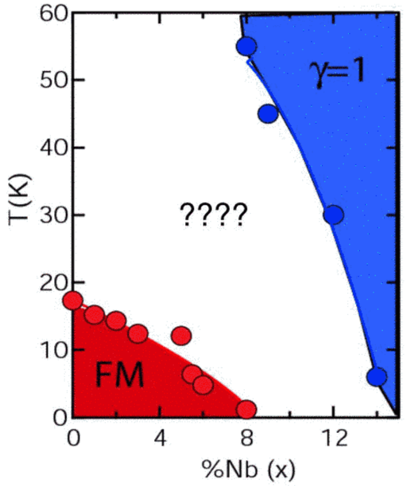




- $T>T^*$ $1/\chi = 1/\chi_o + T/C$ $\chi=C/(T+\theta)$

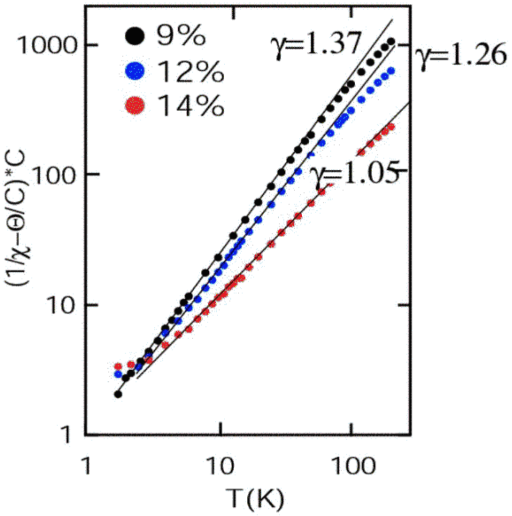
The effective Curie Constant C

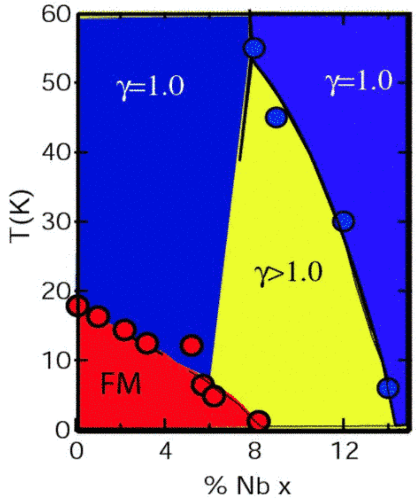




- T>T* $1/\chi = 1/\chi_o + T/C$ $\chi=C/(T+\theta)$
- $C=1/3\ N\ m_{eff}^2/k_B$

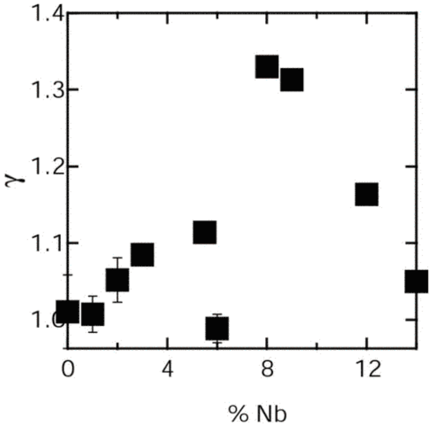
Paramagnetic Phase ($x>x_C$) : Power Law Regime

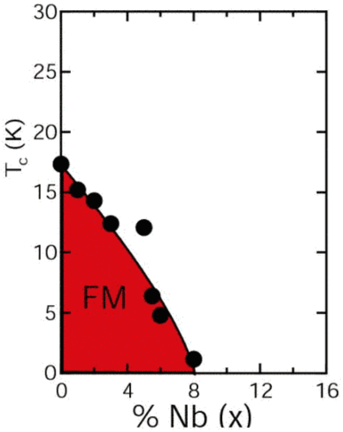




- T<T* $1/\chi=1/\chi_o + T^{\gamma}/C$ $\chi=C/(\theta+T^{\gamma})$
- $\chi(T)$ is most divergent as $\chi Y x_C$

Anomalous Exponents near the Quantum Critical Point





● $x<x_c$ $\chi(T)=\chi_o t^{-\gamma}$ $t=(T-T_C)/T_C$

● $x>x_C$ $\chi(T)=C/(T^{\gamma}+\theta)$ $(\chi_o= C/\theta)$

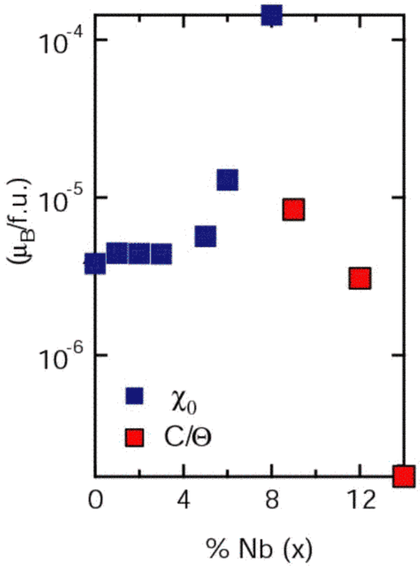
● $x=x_C$ $\chi(T)=C/T^{\gamma}$ $\gamma=d+n/z = 4/3$ (mean field 3d FM)

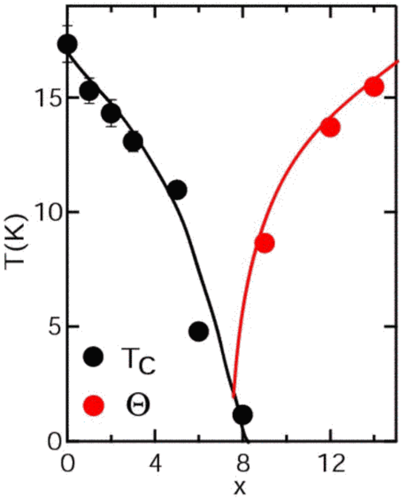
– $\gamma=1/2\nu$ $(\nu=1/d-1)$ (clean QC FM)

– $\gamma=1/\nu$ $(\nu=1/d-2)$ (dirty QC FM)

– $\gamma=1-\lambda$ (Griffiths Phase)

Generalized Curie-Weiss Law





$x<x_C$: $\chi(T)=\chi_o t^{-\gamma}$ $x>x_C$: $\chi(T)=C/(T^{\gamma}+\theta)$

$x=x_C$: T_C, θ Y 0 and C=constant

Conclusions

- $Zr_{1-x}Nb_xZn_2$: continuous quantum critical point for x=8.5%
- Mean Field Ferromagnet: $T_C(x) \sim (x-x_C)^{3/4}$ and $\chi(T, x=x_C) \sim T^{-4/3}$
- $x>x_C$: $\chi(T)=C/(T^{\gamma}+\theta)$ for $T<T^*$, $\gamma=\gamma(x)$
- $x=x_C$: $\chi(T=0)$ diverges and θY0