On the ac magnetic susceptibility of spin-chains: solitons in one-dimensional systems

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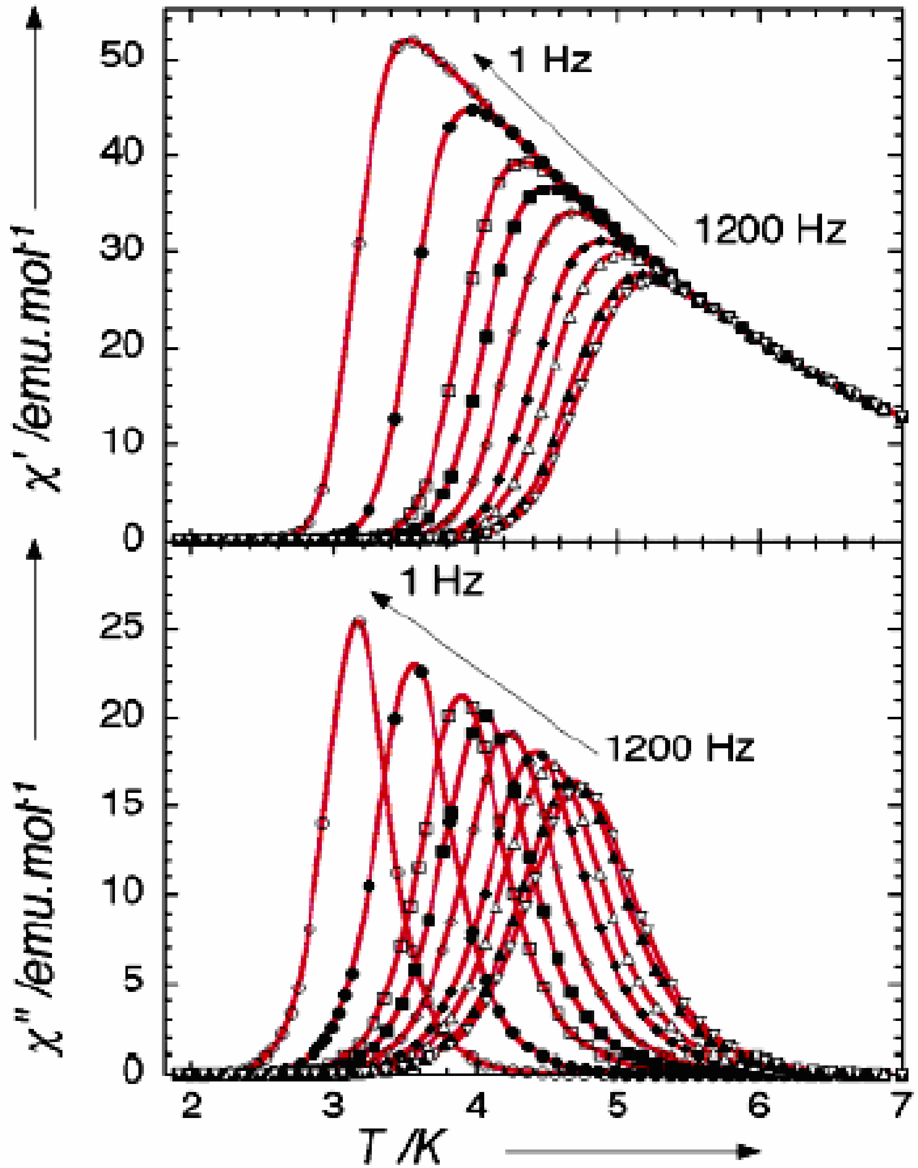
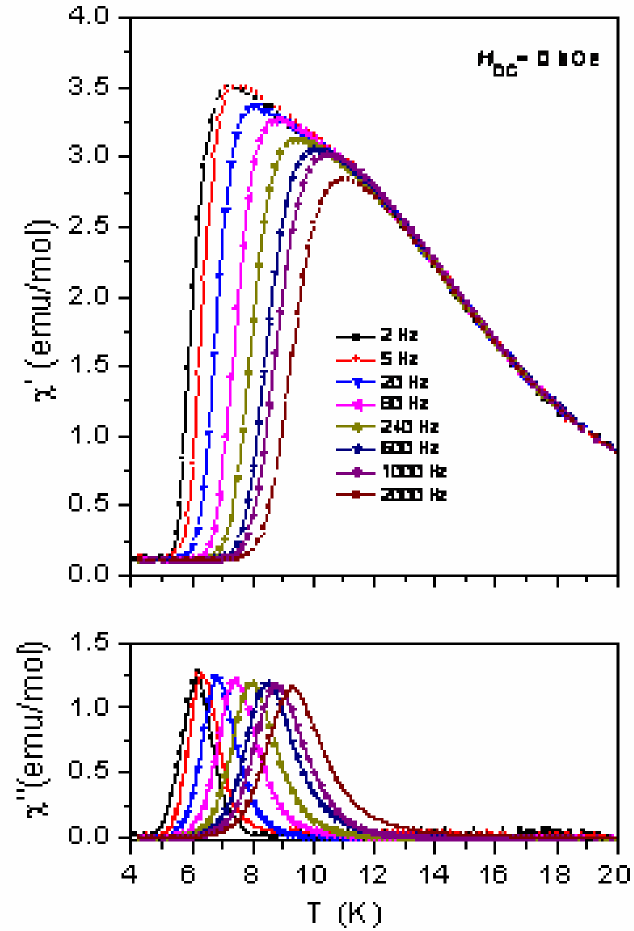
Exact solutions show that the perpendicular susceptibility at low temperatures has weak singularities in transverse H at $T = 0$ in reference to the change of J/H [S.A. Pikin and V.M. Tsukernik, Sov. Phys. JETP **23**, 914 (1966)]





[Mn2(saltmen)2Ni(pao)-(L)2](A)2

Mn(III) tetra(*ortho*-fluorophenyl)porphyrin-tetracyanoethylene

H. Miyasaka, R. Clerac, K. Mizushima et al., Inorg. Chem. **42**, 8203 (2003)

M. Balanda, M. Rams, S.K. Nayak et al., Phys. Rev. B **74**, 224421 (2006)

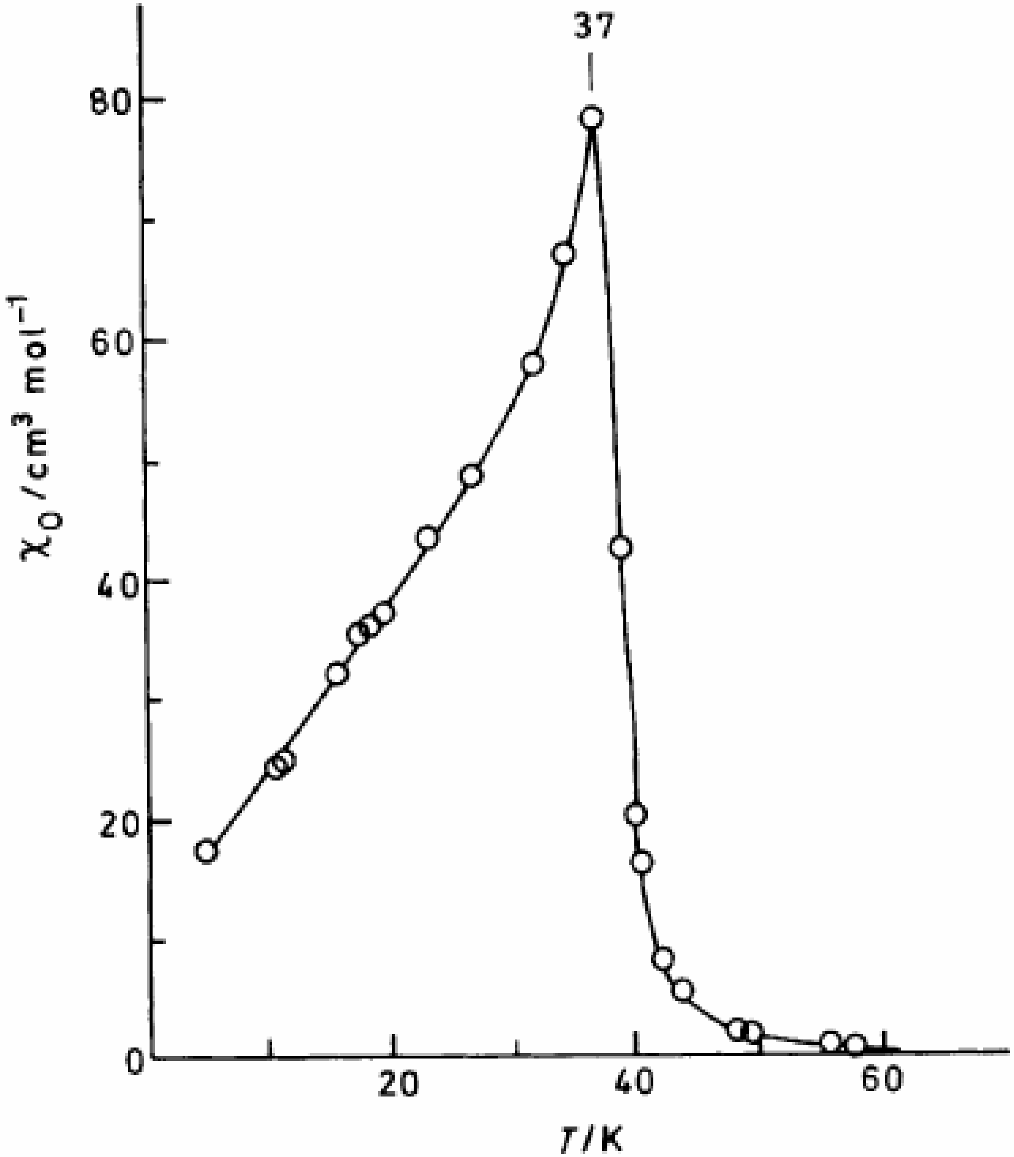


Figure 2. Initial susceptibility of $[NH_3(CH_2Ph)]_2[CrCl_4]$ from 5 to 60 K

Movement of magnetic moment under the action of alternating magnetic field

$$-MH\sin\varphi - U\sin\varphi\cos\varphi + K\frac{\partial^2\varphi}{\partial z^2} = \gamma\frac{\partial\varphi}{\partial t}$$

$$\widetilde{H} = H\cos(\omega t)$$

$$s = \frac{z}{\eta} \qquad a = \frac{d}{\eta} \qquad \eta = \sqrt{\frac{K}{U}} \qquad b = \frac{MH}{\gamma} \equiv \frac{1}{\tau_H}$$

E. Demikhov, S. Pikin, E. Pikina Phys Rev E 52 (1995) 6250

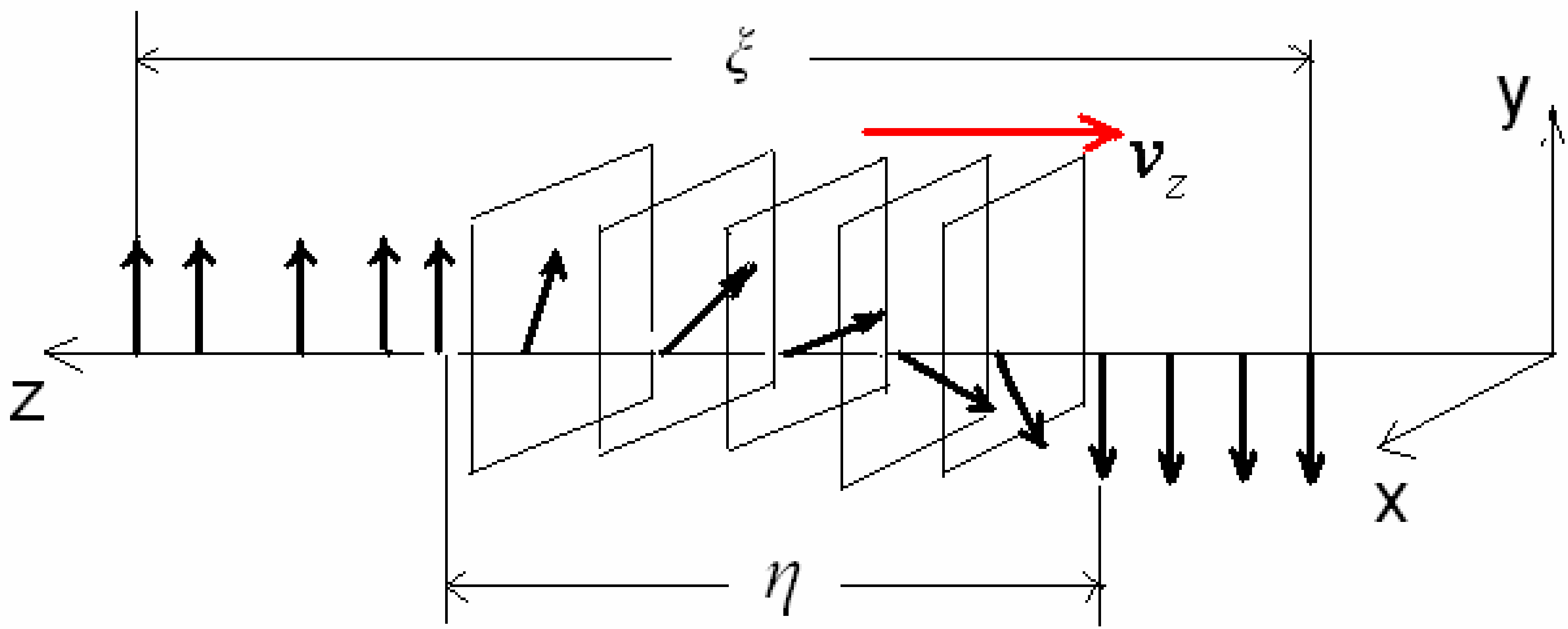
The azimuth rotation of magnetic moment in XY plane

The kink or soliton motion along Z axis

$$\varphi(s,t) = \arctan\left[\frac{1}{\sinh\left(\pm s - s_0 + \frac{b}{\omega}\sin(\omega t)\right)}\right]$$

$\varphi = 0$ and $\varphi = \pi$ at the boundaries, i.e. when value

$s - s_0 = \dfrac{z - z_0}{\eta}$ is much larger than 1



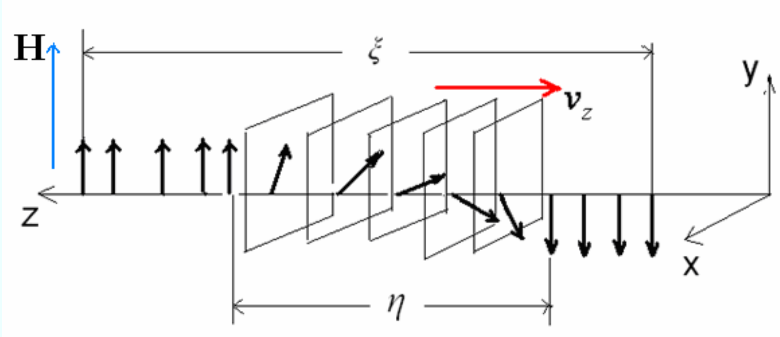
ξ
y
v z
z
x
η

The soliton velocity

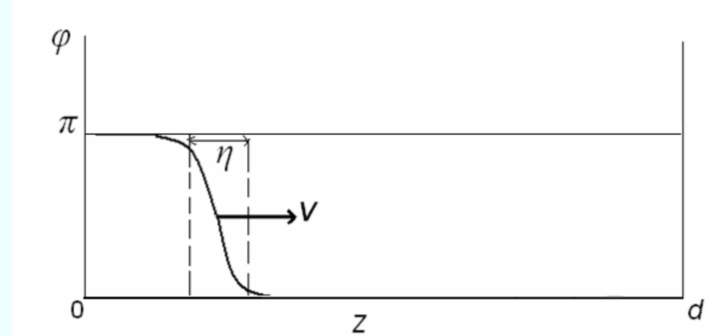
$$v_z = \mp \eta b \cos(\omega t)$$

$$\sin\varphi = \pm \frac{1}{\cosh\left(s + \frac{b}{\omega}\sin(\omega t)\right)}$$

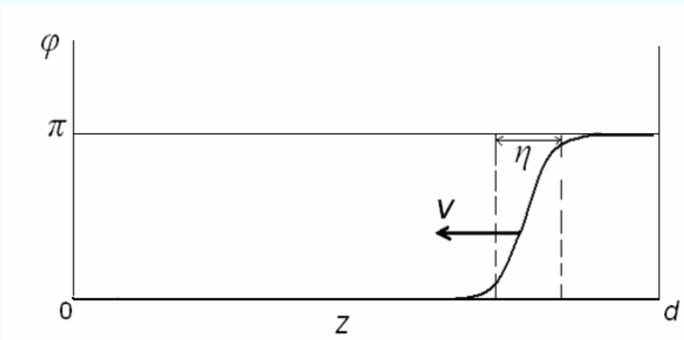
$$\cos\varphi = \tanh\left(s + \frac{b}{\omega}\sin(\omega t)\right)$$



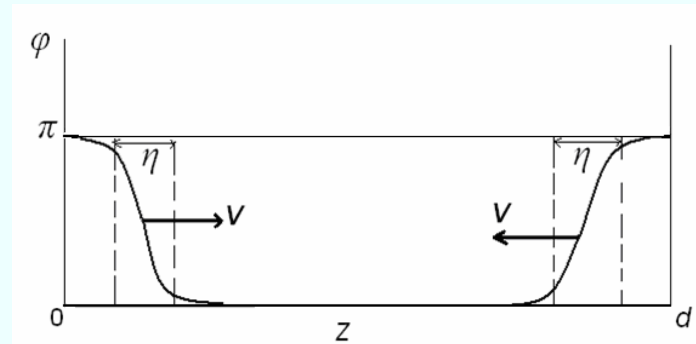
a)



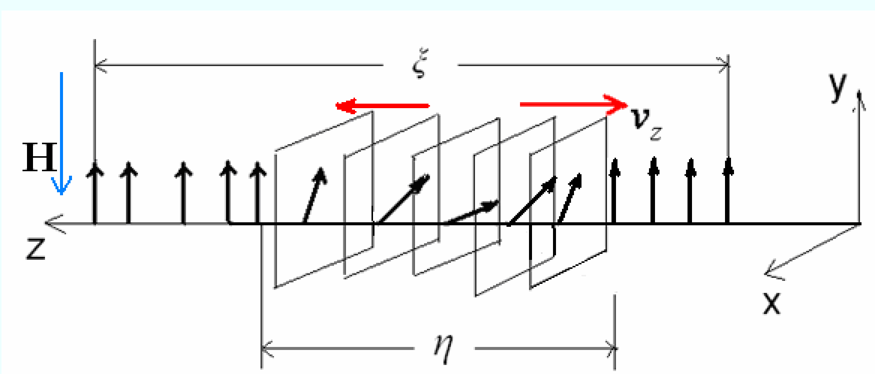
b)



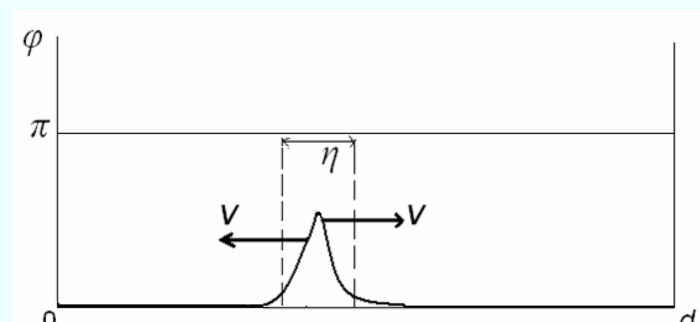
c)



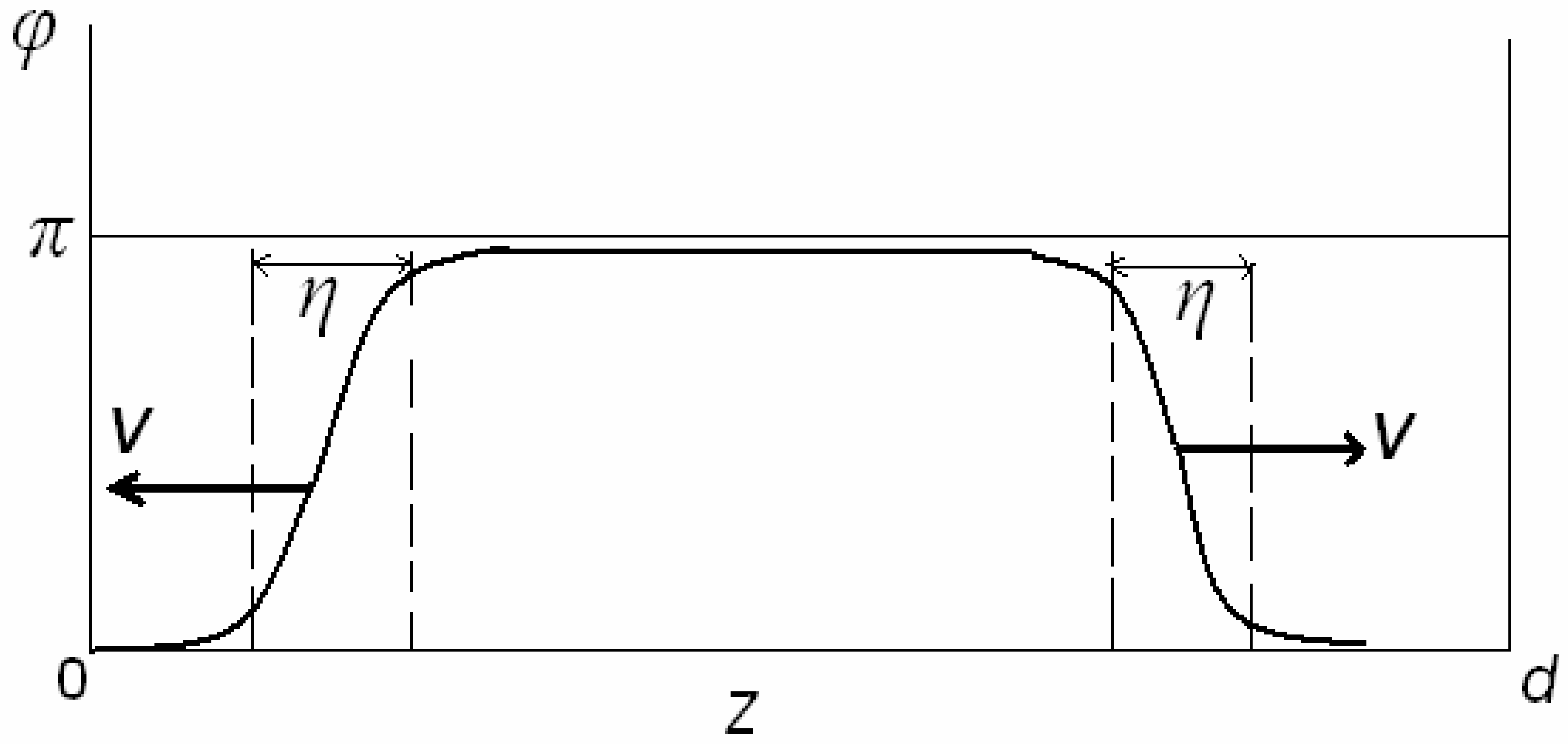
d)



e)



f)



φ
π
η
η
V
V
0
z
d

Magnetic susceptibility as the function of temperature and frequency

$$\chi(T,\omega) = \frac{M^2 N}{k_B T}\left\langle \sin^2 \varphi \right\rangle \equiv \frac{M^2 N}{2\pi k_B} f(T,\omega)$$

$$f(T,\omega) = \frac{\omega}{T}\int_0^{2\pi/\omega} dt \cdot \frac{1}{d}\int_0^d dz \cdot \sin^2 \varphi(z,t) =$$

$$= \frac{1}{aT}\int_0^{2\pi} \tanh\left[a + \frac{b}{\omega}\sin x\right] dx$$

$$x = \omega t$$

$$m_{eff} = g\sqrt{J(J+1)}\mu_B$$

The factor ${m_{eff}}^2 N / 2\pi k_B \approx$ 0.5 (*emu/mol)*K for the second substance, but for first substances, it is equal approximately 6 (*emu/mol*)K, i.e., 10 times larger as the former.

In fact, $a \sim \xi/\eta$, ξ – *correlation length*

For n defects per length ξ, the solitons can only move on distance $d = \xi/n$

The upper limit $\chi \sim nf < (2\pi n/Ta)$

Accordingly to the assumption of Glauber, the appearance of kinks has a thermo-activation character.

We shall suppose that the τ_H^{-1} value is the inverse time τ^* for of nucleus formation, $\omega_c \sim 1/\tau^*$, when frequency ω is less than $\omega_c \sim 1/\tau^*$, but $\tau_H^{-1} \sim (\tau^* \omega)^{\alpha} \omega$ when ω is larger than ω_c. The power index α can be found experimentally. At $\omega \sim \omega_c \sim 1/\tau^*$, τ_H^{-1} becomes of the order $1/\tau^*$.

What is time τ^* ?

$$\tau^* = \tau_0 \exp(E/T)$$

If the time $1/\omega$ is less than the time τ^*, then solitons (as collective motions of spins) cannot arise below a certain blocking temperature T_0.

We suppose

$$b = \frac{1}{\tau_H(\omega)} \approx \left(\frac{B\tau_0}{T}\right)\omega^{1+\alpha} \exp\left(\frac{E}{T}\right)$$

E – activation energy

When H is less than H_c and $\omega \geq \omega_c$,

Δz *interval*, were the magnetic moment sharply changes its orientation, becomes to be dependent on ω*, and it is less than* η.

$$H_c \propto \frac{K}{\mu_B} \cdot \frac{1}{\Delta z^2}$$

$$\Delta z^2(\omega) \propto \frac{D_{orient}}{\eta^2 \omega}$$ accordingly to the diffusion equation

$$H_c \propto \omega$$

When $H = \; H_c \approx \dfrac{K\eta^2\omega}{\mu_B D_{orient}}$

$$\frac{1}{\tau_{H_c}} \propto \frac{H_c^{\;2}}{\gamma T}\exp\left(\frac{E}{T}\right) \propto \frac{\omega^2}{\gamma T}\left(\frac{K\eta^2}{\mu_B D}\right)^2 \exp\left(\frac{E}{T}\right)$$

It is supposed that this dependence on ω takes place at $\omega \geq \omega_c$

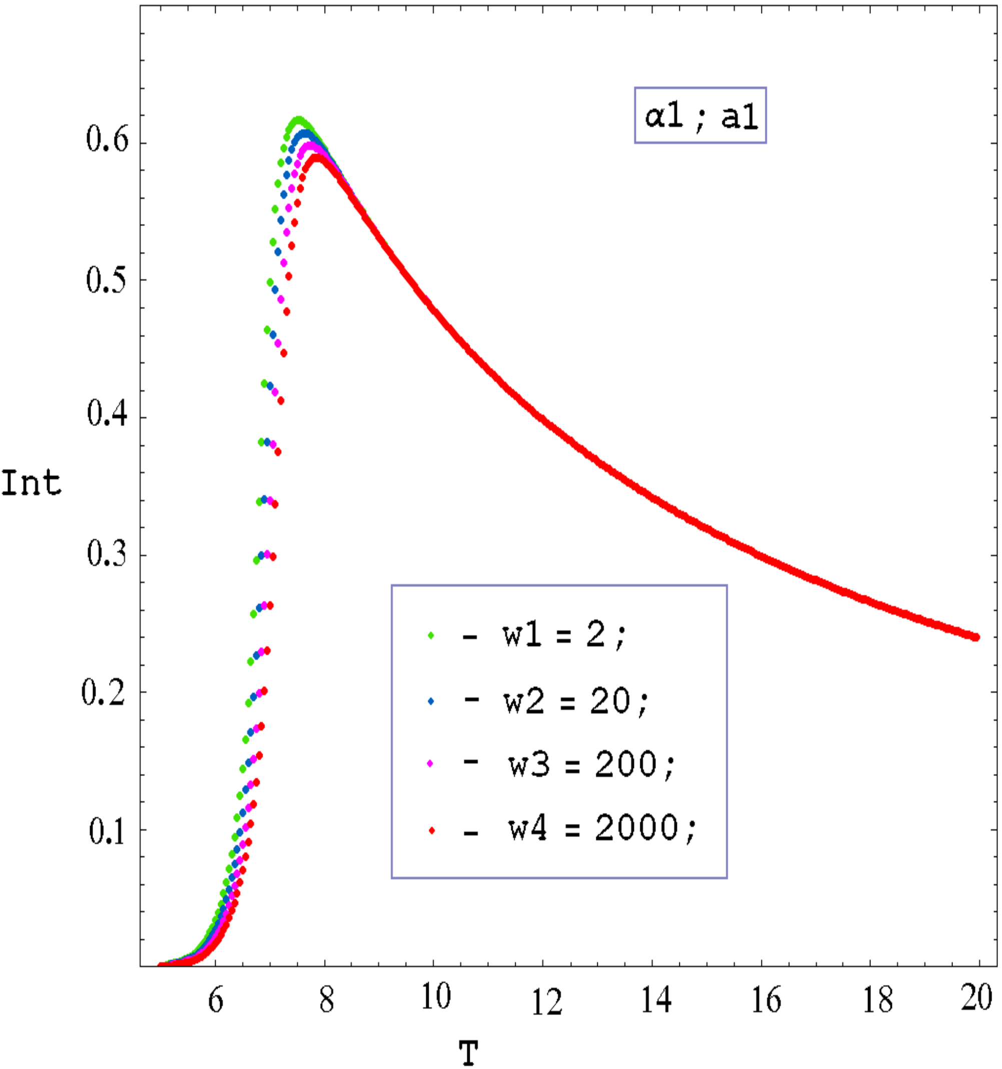
when $H \leq H_c$

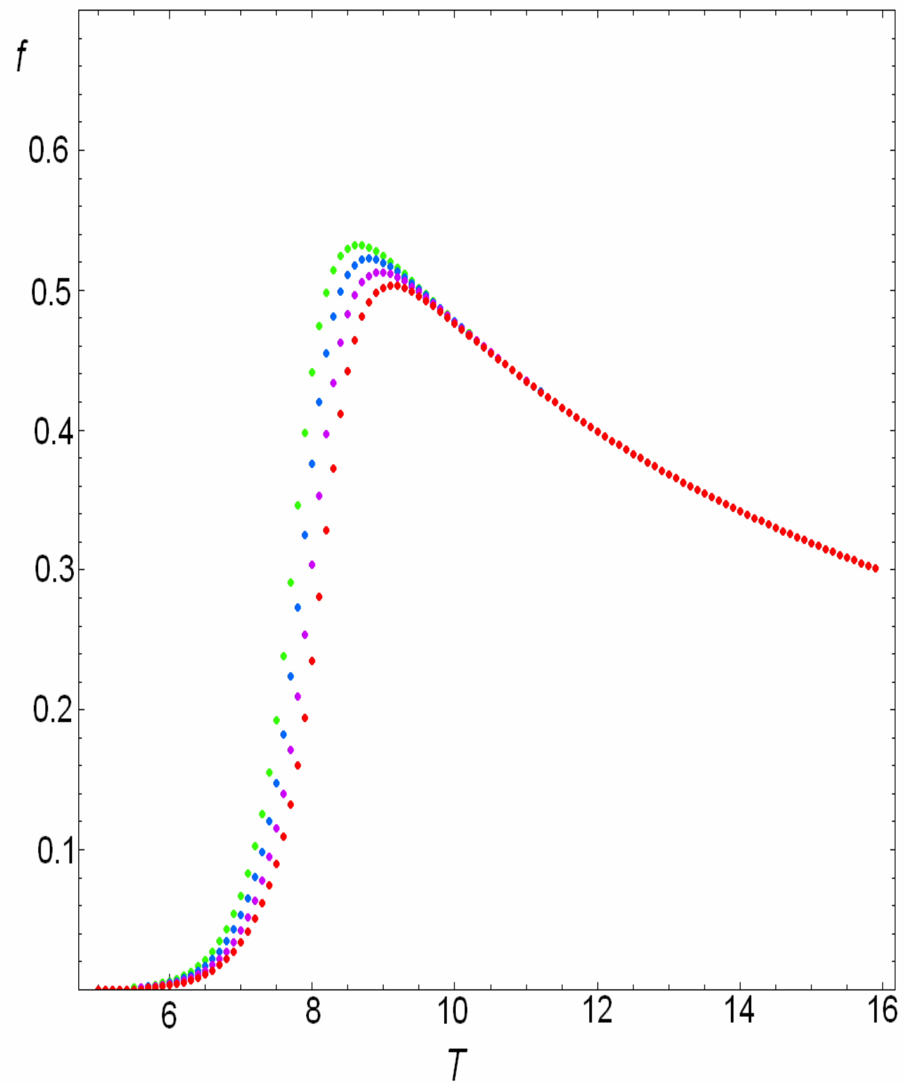
Computer simulation

$$f(T,\omega)=\frac{1}{T}\int_0^{2\pi}\tanh\left[2+\left(\frac{4310}{T}\right)\cdot\omega^{\alpha}\cdot\exp\left(-22+\frac{110}{T}\right)\sin x\right]dx$$

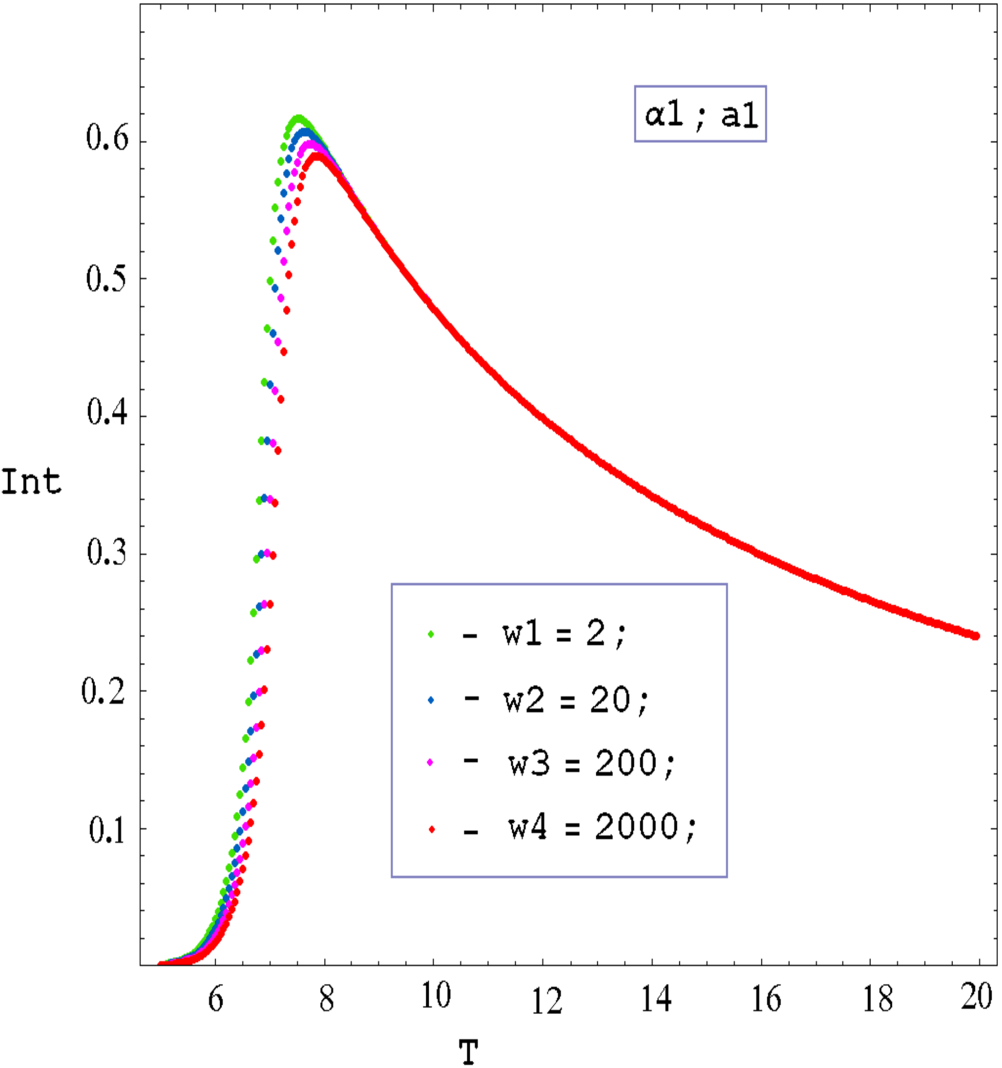
At sufficiently high temperatures, all the curves $f(T,\omega)$ turn to *one universal curve* (~ $1/T$) for different frequencies.

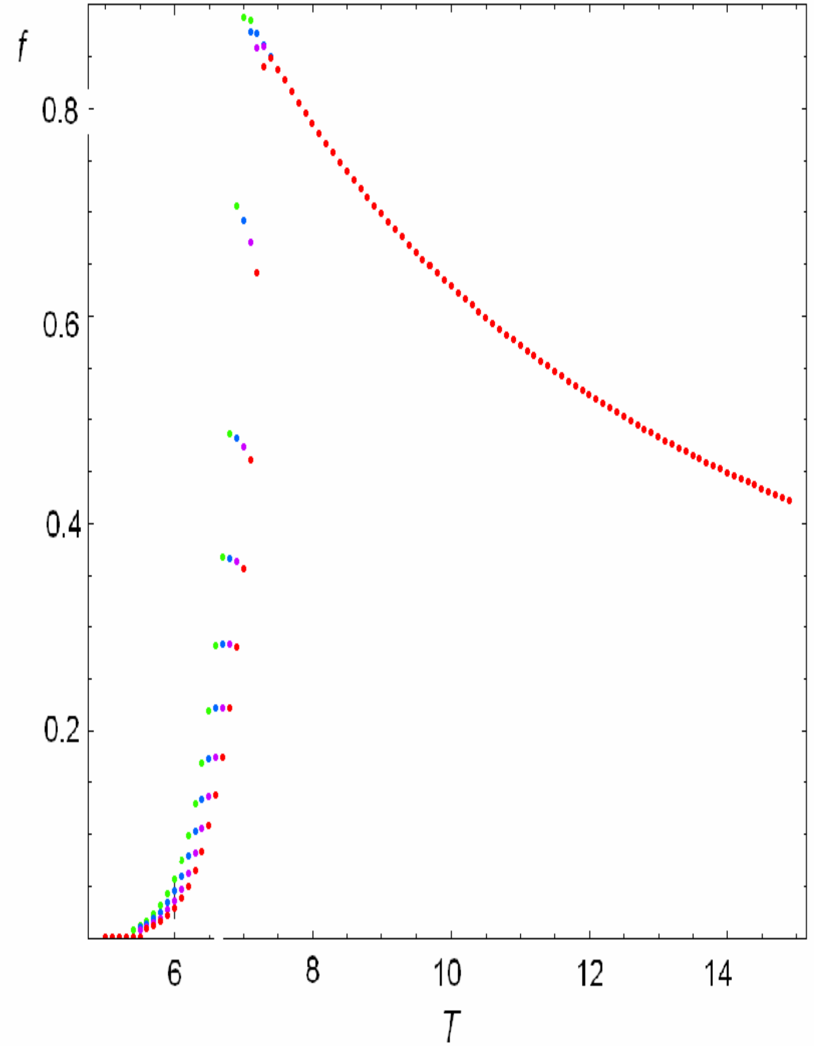
$f_{\max}(\omega)=f(T_0,\omega)$ increases with the increase in *activation energy E,* and in ratio *a*



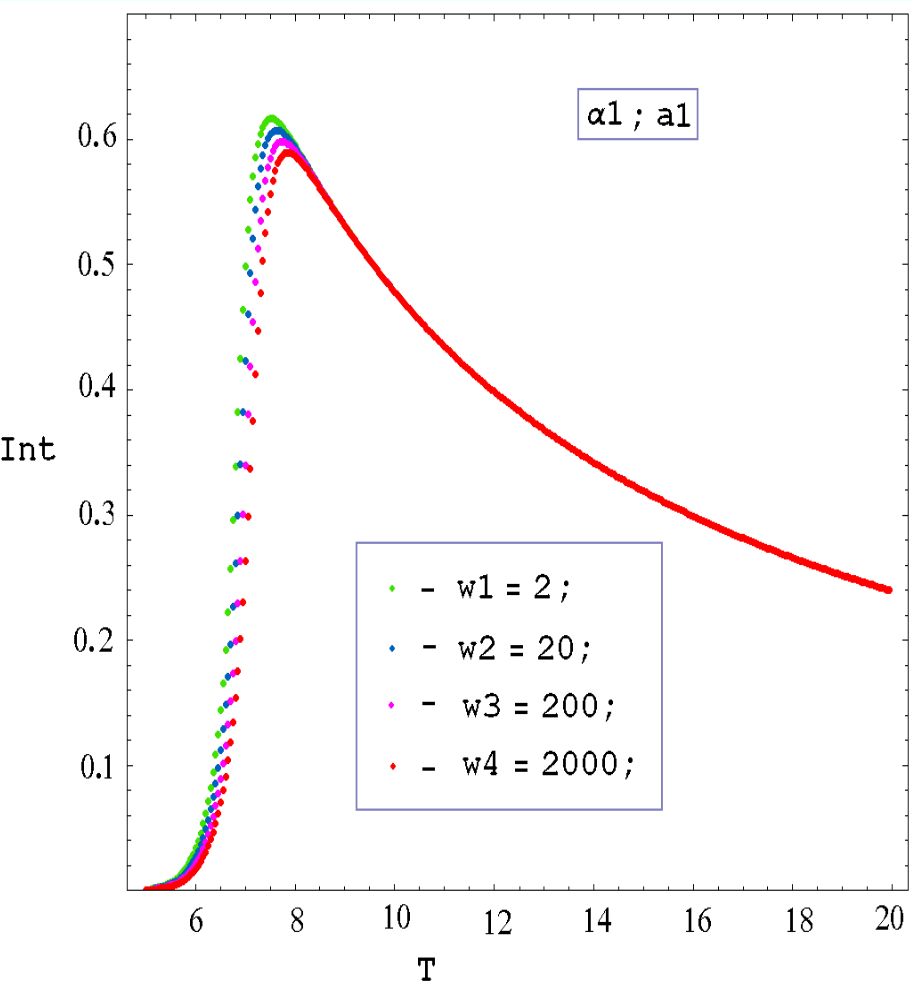


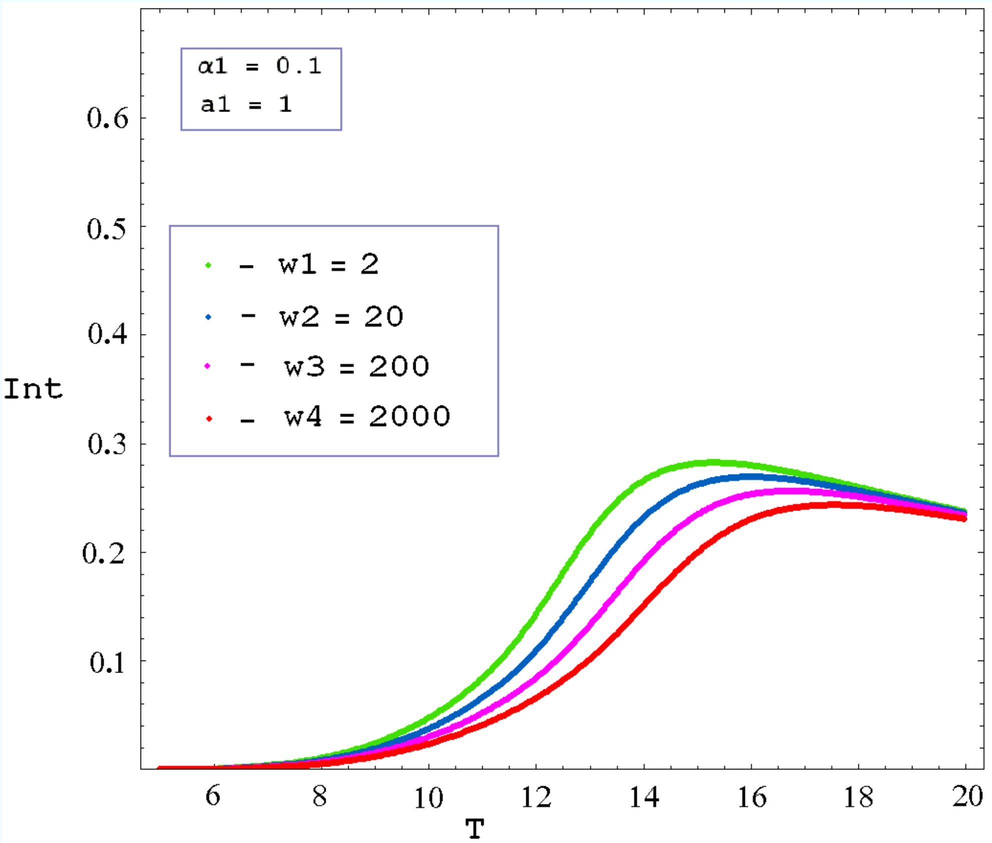
The presence of multiplier $1/T$ in "relaxation frequency" b does not show a strong effect for f, only slightly increasing f.



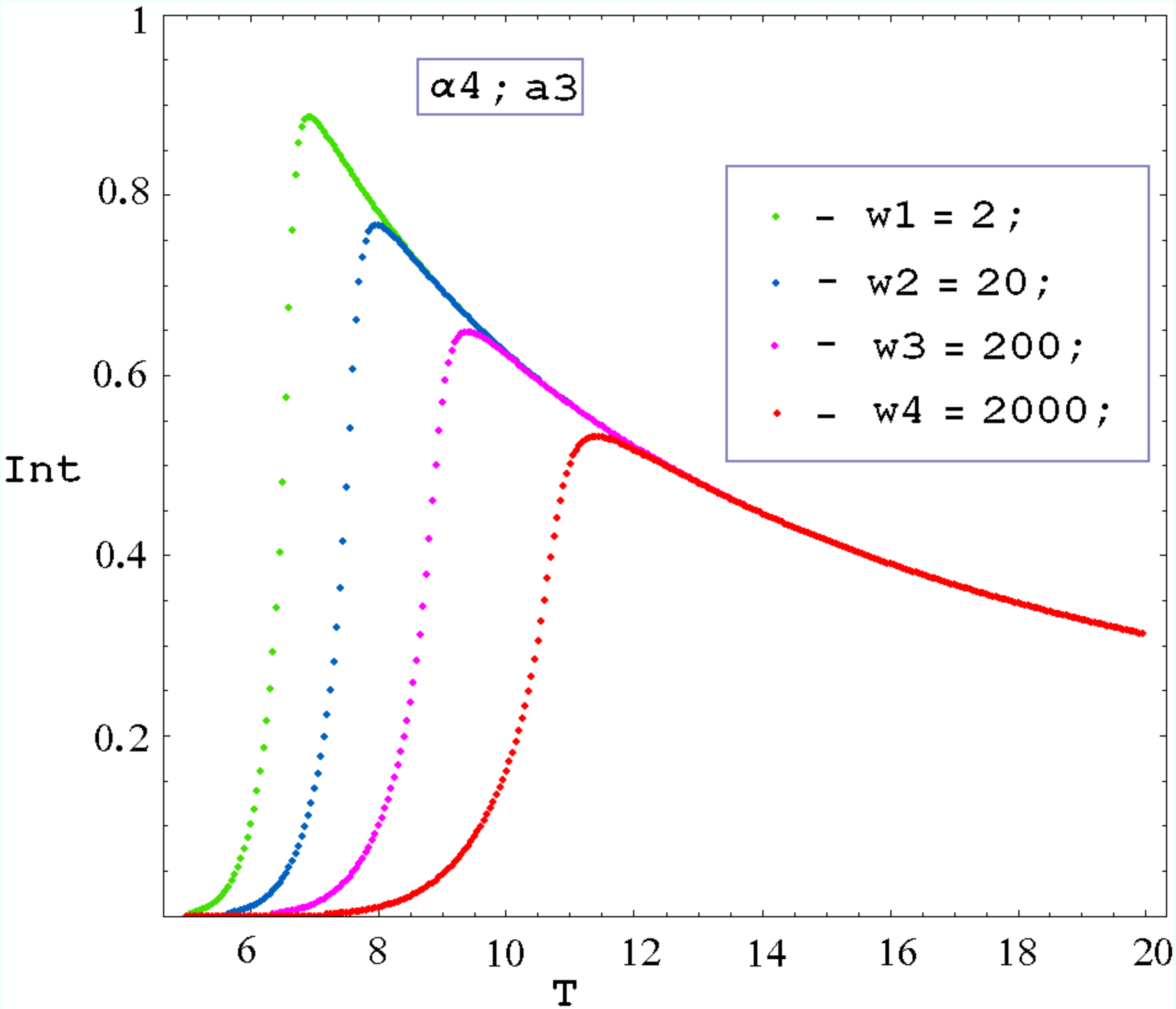


$f_{\max}(\omega) = f(T_0, \omega)$ increases with the increase in ratio a

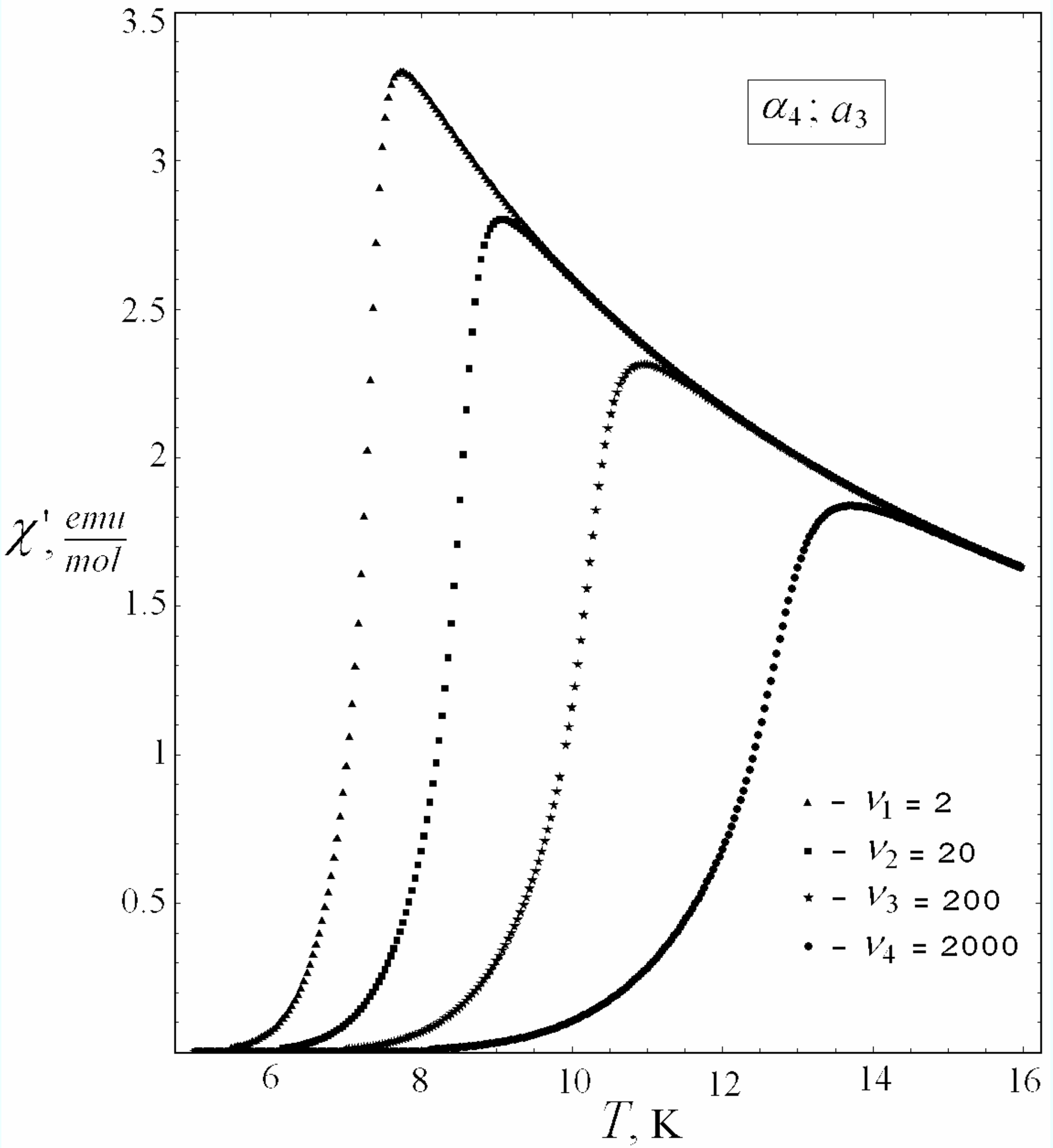




$f_{\max}(\omega) = f(T_0, \omega)$ increases with the increase in *activation energy E*



α4 ; a3
- w1 = 2;
- w2 = 20;
- w3 = 200;
- w4 = 2000;
Int
T
1
0.8
0.6
0.4
0.2
6
8
10
12
14
16
18
20



3.5
3
2.5
2
1.5
1
0.5
χ', emu/mol
6
8
10
12
14
16
T, K
α4 ; a3
– ν1 = 2
– ν2 = 20
– ν3 = 200
– ν4 = 2000

$$\chi'_{\exp erim} \approx 50\ (emu/mol)\mathrm{K},$$

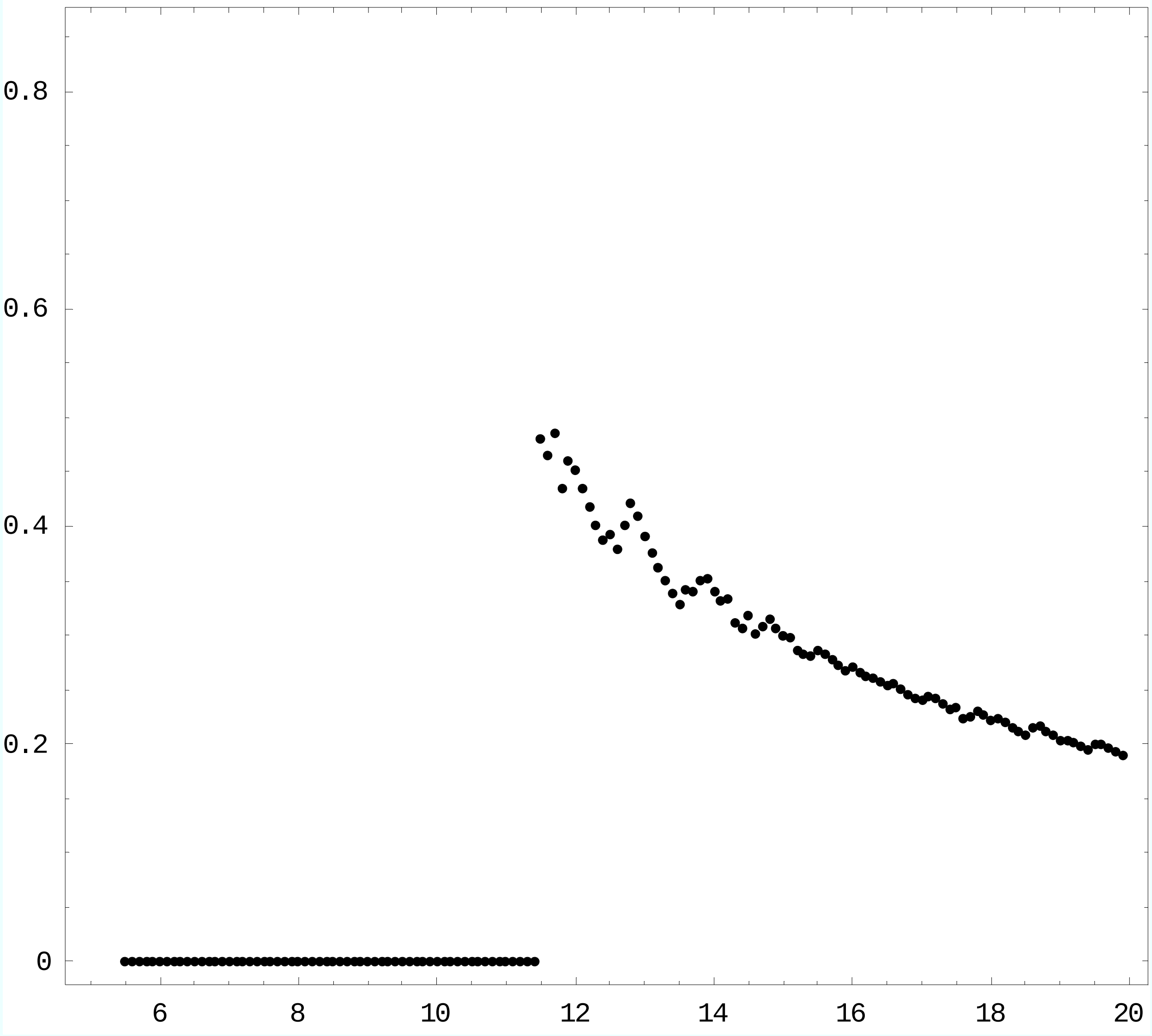
$$m_{eff}{}^2 N / 2\pi k_B \approx 6\ emu/mol, \qquad a = 3, \qquad f_{\max}(10) \approx 0.9,$$

$$\chi'_{\mathrm{exp}erim} \approx 3.5\ emu/mol,$$

$$m_{eff}{}^2 N / 2\pi k_B \approx 0.5\ (emu/mol)\mathrm{K}, \quad a = 3, \quad f_{\max}(10) \approx 0.9, \text{ i.e.,}$$

$2n$ ~ 40÷60 solitons can arise and spread simultaneously.

The kinks are sufficiently wide in the considered substances (their width η is 3 – 5 times less than length d).



0.8
0.6
0.4
0.2
0
6
8
10
12
14
16
18
20

About the temperature dependence of dc susceptibility χ_{dc}

In an one-dimensional case: some models (see for example the Kadanoff' Gaussian model and Nakamura –Sasada spin chain model) show that parallel susceptibility and correlation length have the same "critical" temperature dependence, i.e.,

$$\chi_{dc} \sim \xi \sim \exp(\Delta/T)$$

The relaxation time for solitons

$$\tau_{relax} \approx \gamma\eta^2 / K$$

i.e., $$\tau_{relax} \propto \exp(2\Delta / T)$$

when $\eta \sim \xi$.

Experimentally, $\Delta \approx 60$ K,

$$\chi_{dc} \sim \exp(60/T), \qquad \tau_{relax} \propto \exp((110 \div 120) / T)$$