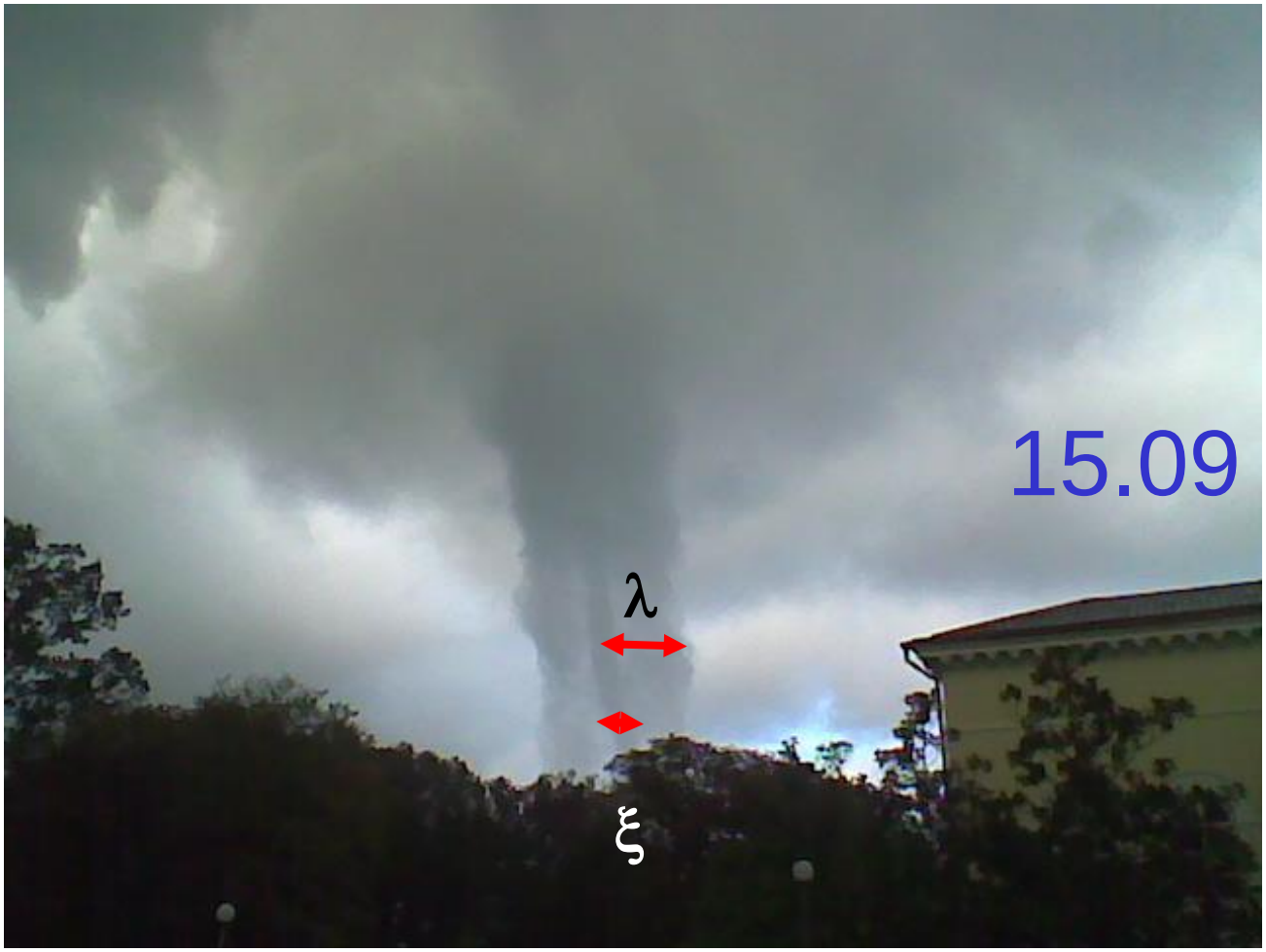
14.09 : землетрясение

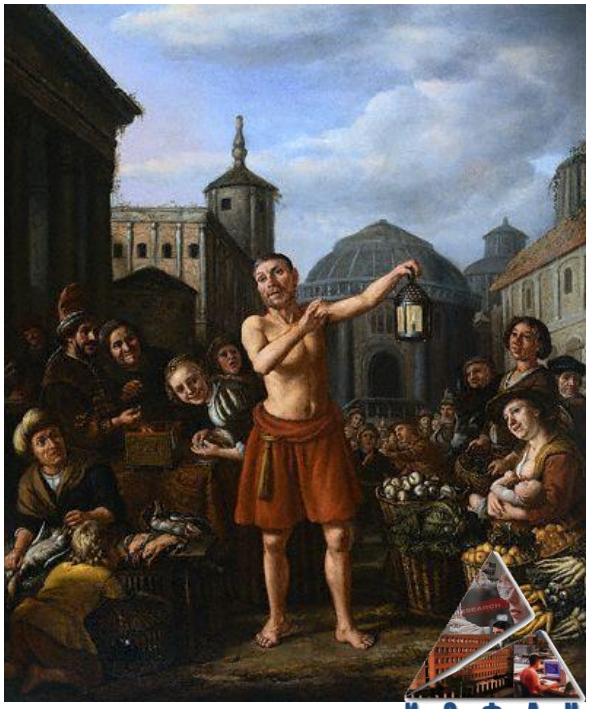


15.09 : торнадо

16.09 : ????

XI Конференция молодых ученых
"Проблемы физики твердого тела и высоких давлений"
г. Сочи, пансионат "Буревестник" 10-19 сентября 2008г

Поиски физики в нанофизике и нанофизики в физике: неупорядоченные системы, квантовые спиновые цепочки и наноматериалы на основе оксида ванадия



С.В.Демишев

Отдел низких температур и криогенной техники,
Институт общей физики им. А.М.Прохорова РАН
ул. Вавилова, 38, 119991 Москва, Россия
http://www.lt.gpi.ru

Low Temperatures and Cryogenic Engineering Department
ММII

НАНО ФИЗИКА

Наличие нанометрового масштаба в системе.

Наномасштаб играет существенную роль, определяя физические процессы.

Хорошо известные наносистемы:

КРИСТАЛЛЫ

$$\hat{H}(\vec{r}+\vec{a}) = \hat{H}(\vec{r})$$

$$a \sim 0.3 нм$$

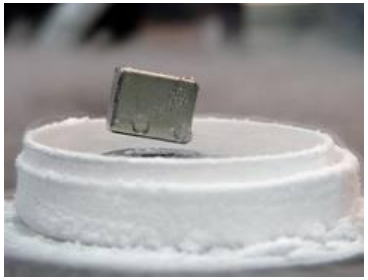
И. Кеплер
1611

СВЕРХПРОВОДНИКИ II рода с высокими H_{C2}

$$\xi = \left[\Phi_0 / 2\pi H_{c2}(0)\right]^{1/2}$$

$$H_{c2}(0) = 100 кЭ$$

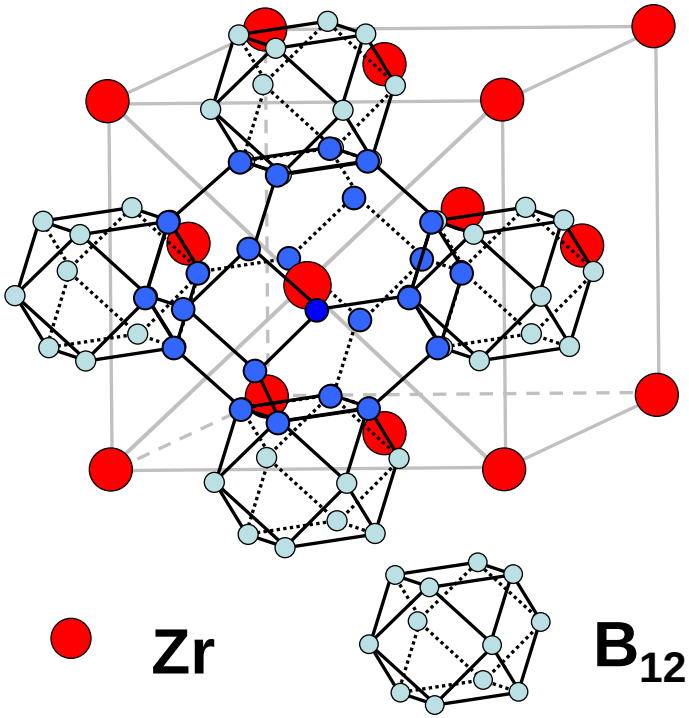
$$\xi = 5.7 нм$$



Л.В.Шубников
1937

А.А.Абрикосов
1957

НАНОФИЗИКА в КРИСТАЛЛАХ



Додекаборид циркония, ZrB_{12}: сверхпроводник с нанокластерами бора.

Переход в сверхпроводящее состояние при T_C=6.1K
B.T.Matthias et al.,
Science, 159, 530 (1968)

Каков механизм электрон-фононного взаимодействия?

Эйнштейновская (локальная) мода
R.Lortz et al.,
Phys. Rev. B, 72, 024547 (2005)

?

Широкий спектр (модель Дебая)
V.A.Gasparov et al.,
Phys. Rev. B, 73, 094510 (2006)

phys. stat. sol. (b) 243, No. 11, R72–R74 (2006) / DOI 10.1002/pssb.200642300

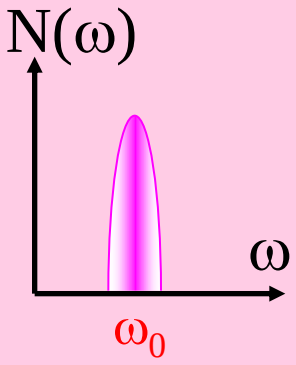
pss +++rapid research letters+++
www.pss-rapid.com

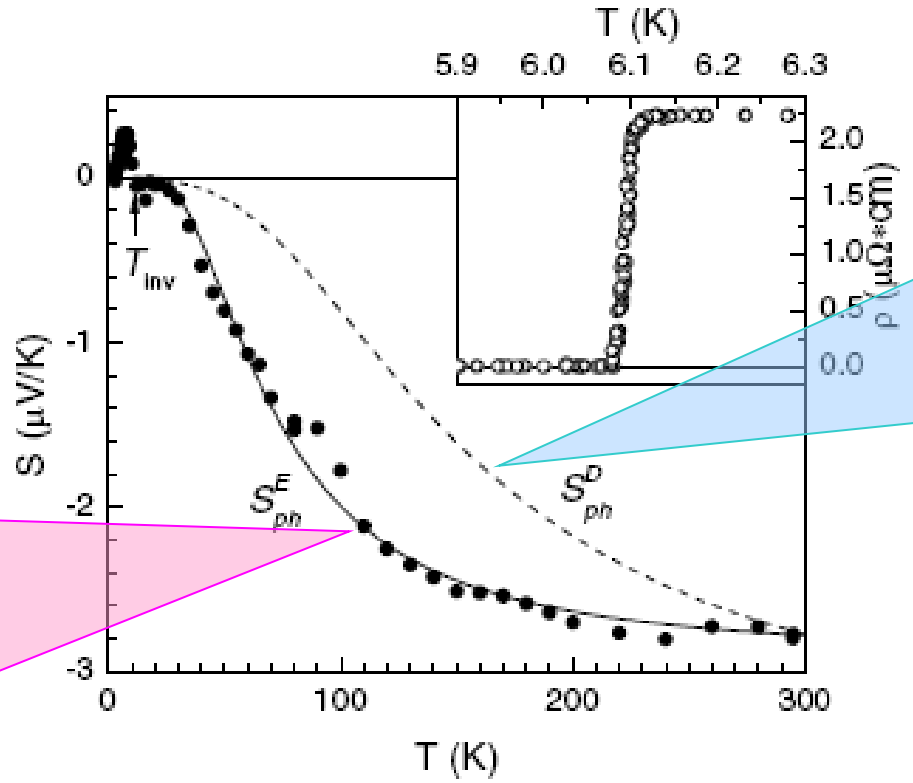
Phonon drag induced by Einstein mode in ZrB_{12}

V. Glushkov*,[1], M. Ignatov[1], S. Demishev[1], V. Filippov[2], K. Flachbart[3], T. Ishchenko[1], A. Kuznetsov[4], N. Samarin[1], N. Shitsevalova[2], and N. Sluchanko[1]

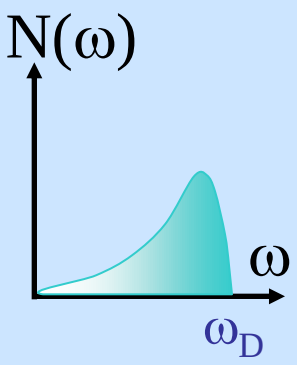
Термоэдс в ZrB_{12} определяется электрон-фононным взаимодействием (эффект фононного увлечения).

Модель Эйнштейна





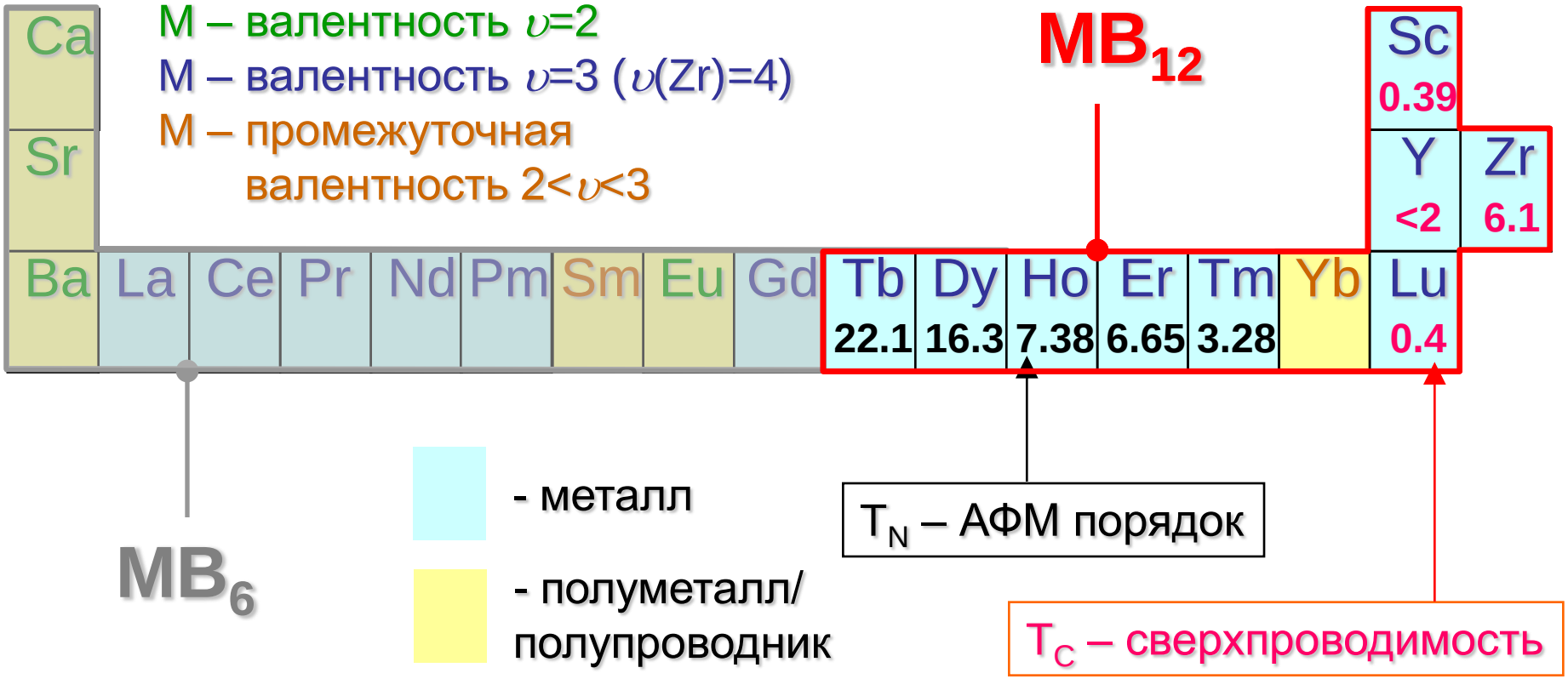
Модель Дебая



Исследование термоэлектрических эффектов в сверхпроводнике **ZrB_{12}** позволило установить, что **электрон-фононное взаимодействие и сверхпроводимость в этом соединении определяются эйнштейновской локальной модой.**

Додекабориды редкоземельных и переходных металлов

MB_6 и MB_{12} - соединения на основе каркасных структур из кластеров бора B_6 и B_{12}



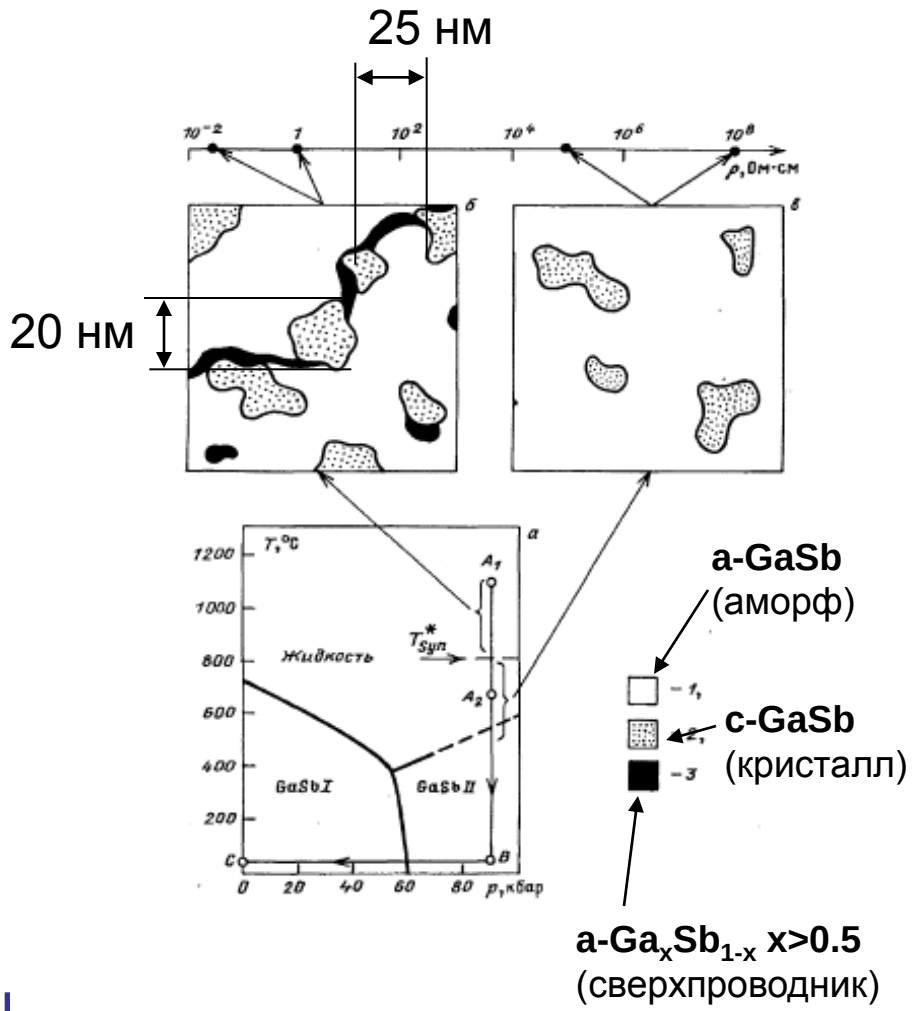
Роль локальных мод (обусловленных нанокластерами) в RB_{12}?

ЧТО ТАКОЕ НАНОФИЗИКА?

Nanophysics = very small physics

НАНОФИЗИКА В ДОИСТОРИЧЕСКИЕ ВРЕМЕНА

Аморфные полупроводники



Февраль 1994 г. *Том 164, № 2*

УСПЕХИ ФИЗИЧЕСКИХ НАУК

ОБЗОРЫ АКТУАЛЬНЫХ ПРОБЛЕМ

Аморфные полупроводники, синтезированные закалкой под давлением

С.В. Демишев, Ю.В. Косичкин, Н.Е. Случанко, А.Г. Ляпин

сложных многофазных систем. При этом включения субмикронного размера, образующиеся в процессе синтеза метастабильных фаз, как представляется, оказывают в ряде случаев определяющее воздействие не только на свойства аморфной матрицы, но также и кристаллических фаз двойных и тройных соединений.

В первом разделе обсуждаются существующие модификации схемы синтеза АПВД и используемые для описания ТФА феномено-

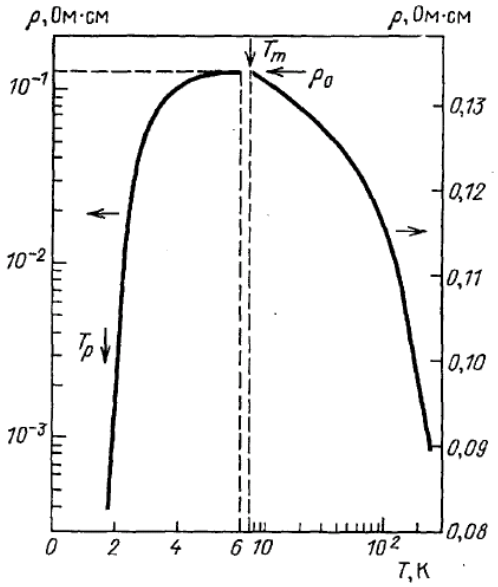
Поэтому на физически интересной нанометровой пространственной шкале в легированных полупроводниках будут доминировать квантовые эффекты [65—67], и в результате точка аномалии кинетических характеристик (порог подвижности) не будет связана с топологической особенностью при x_C [65, 66], а критический индекс для проводимости $\sigma \sim \tau^t$ составит $t \approx 0,6$ [66—67].

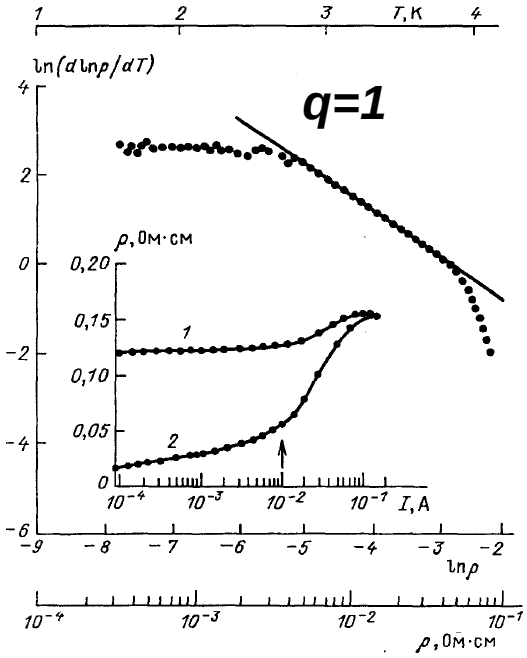
В то же время в аморфных полупроводниках дл пробега существенно меньше $l_0 \sim L_{cor} \sim 10$ Å [7, 6 рассмотренное выше ограничение снимается. Сле

Сверхпроводимость кластеров наномерового размера

Ga_xSb_{1-x} ($x > 0.5$)

$T_c = T_c(x)$

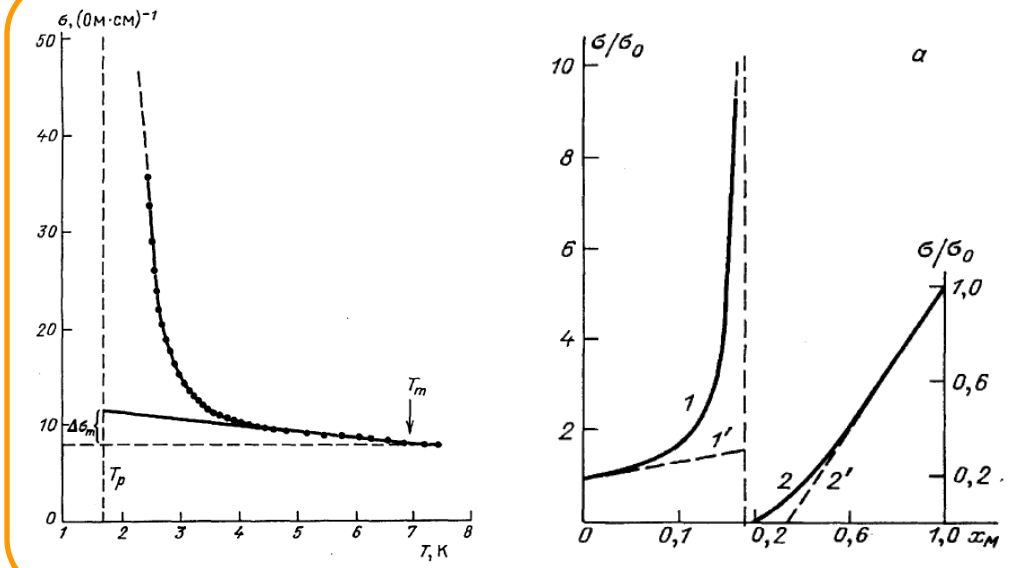




$$\sigma = \frac{\sigma_0}{[1 - (x_M/x_C)]^q} \equiv \sigma_0 \tau^{-q}$$

$$V_s(T) = \int_T^\infty \varphi(T_c)\, dT_c \qquad \frac{1}{\rho}\frac{\partial \rho}{\partial T} = q\frac{\varphi(T)}{n_c}\left(\frac{\rho}{\rho_0}\right)^{-1/q}$$

$$\ln\left(\frac{1}{\rho}\frac{\partial \rho}{\partial T}\right) = f(\ln \rho) \Rightarrow q$$



Определение критического поведения в системе со сверхпроводящими включениями

Materials Science Forum Vols. 294-296 (1999) pp 481-484
online at http://www.scientific.net

PHASE TRANSFORMATIONS

Physical Mechanisms of the Non-Equilibrium Phase Transitions in Amorphous Solids

T.V. Ischenko and S.V. Demishev

Low Temperatures Laboratory, General Physics Institute,
Vavilov street 38, RU-117942 Moscow, Russia

The idea of the non-equilibrium process driven by the special metastable states means that the processes of the crystallisation and energy transfer at the phase boundary are synchronised [4,5]. Consequently the simple analysis of the energy transfer allows to predict the possible structure of the sample which undergo the non-equilibrium phase transition. In semiconductors the characteristic time of life of the metastable state is about $\tau \sim 10^{-9}$ s and the velocity of the EC front is $v_{ex} \sim 1$ m/s. These data taken together with the equilibrium values of the thermal diffusivity $D_T^0 = 10^{-5} \div 10^{-6}$ m^2/s allow to define three characteristic spatial scales for an non-equilibrium process

$$L' = v_{ex} \cdot \tau \approx 1\,\text{nm} \qquad (1)$$

$$L'' = \left(D_T^0 \tau\right)^{1/2} \approx 10 \div 100\,\text{nm} \qquad (2)$$

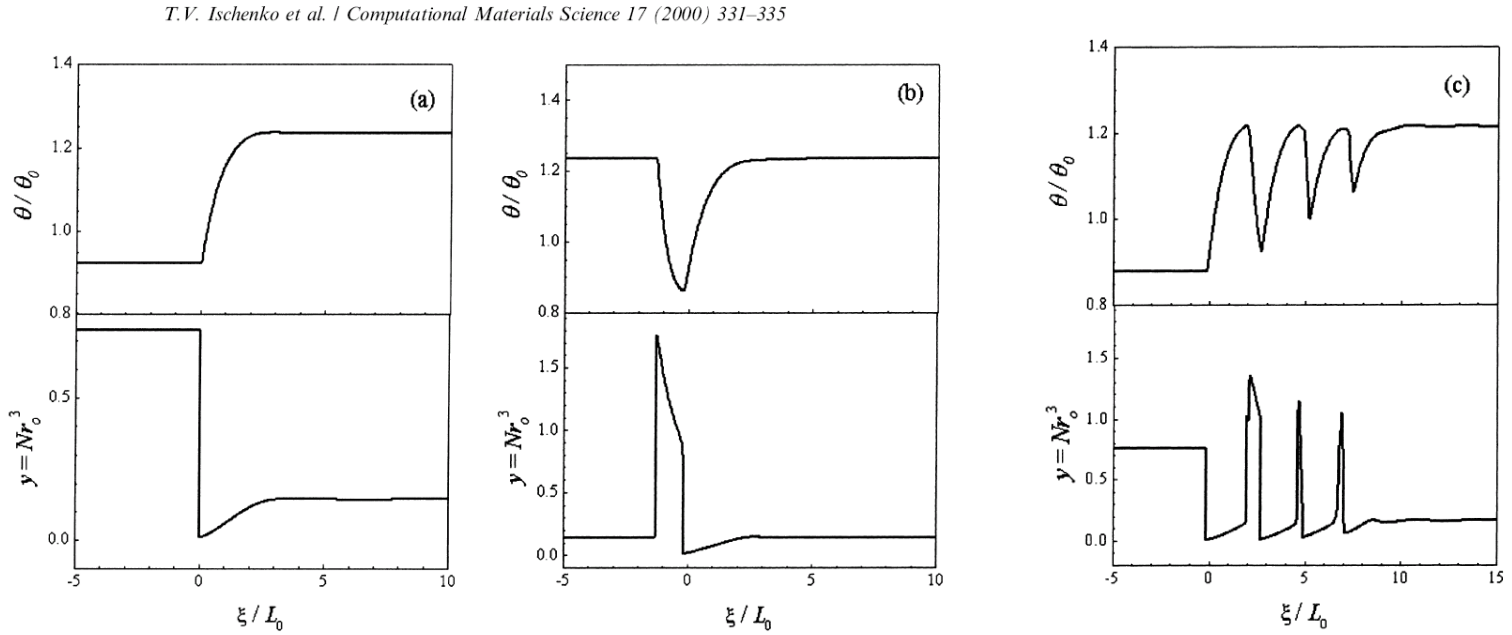
$$L''' = D_T^0 / v \approx 1 \div 10\,\mu\text{m} \qquad (3)$$

undergo EC is in agreement with the available experimental data [6]. Consequently we can conclude that for the non-equilibrium process a well-defined scales hierarchy is characteristic:

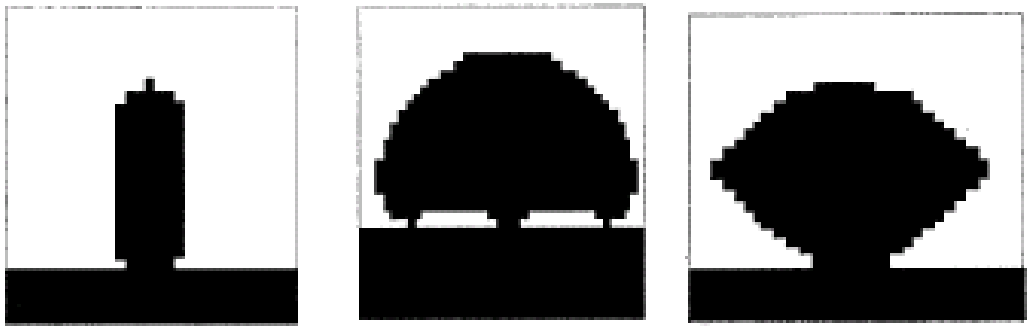
$$L' \approx L_{MRO} < L'' < L''', \qquad (4)$$

that is in contrast with the equilibrium process. Indeed, in the equilibrium diffusion controlled process of phase transition the parameter L' is about atomic distance a; the thermal field is almost homogeneous and $L'', L''' \to \infty$. As a result instead of relation (4) we get $L' \approx a << L'', L'''$ that is typical for standard process of nucleation and growth.

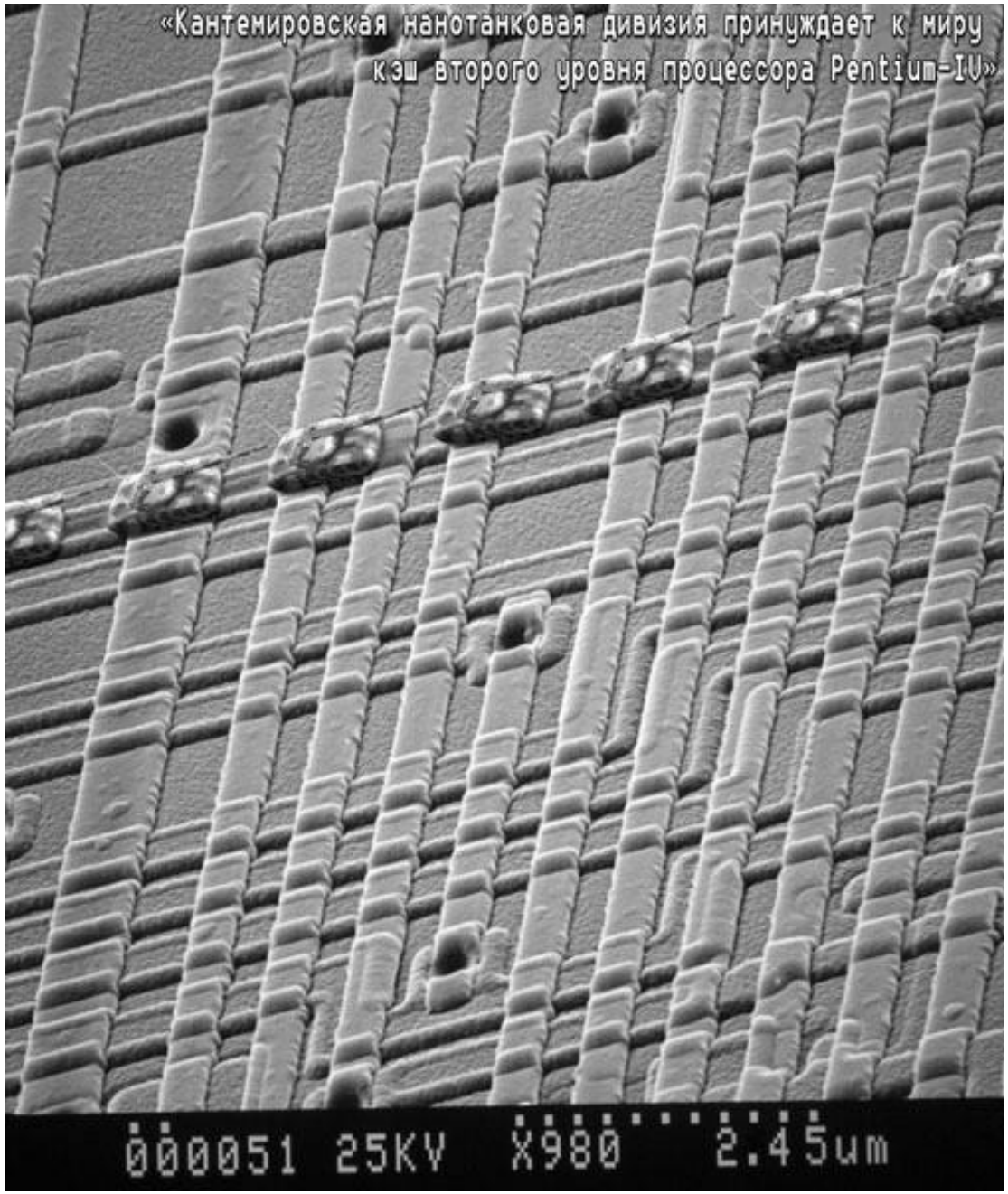
Simulated waves of non-equlibrium phase transformations



The case of solid-state amorphization

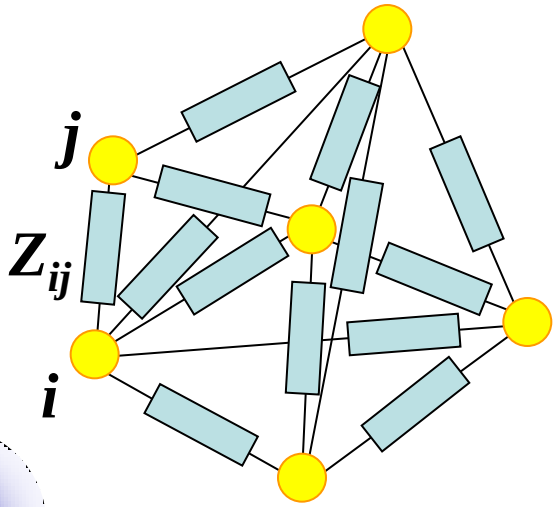


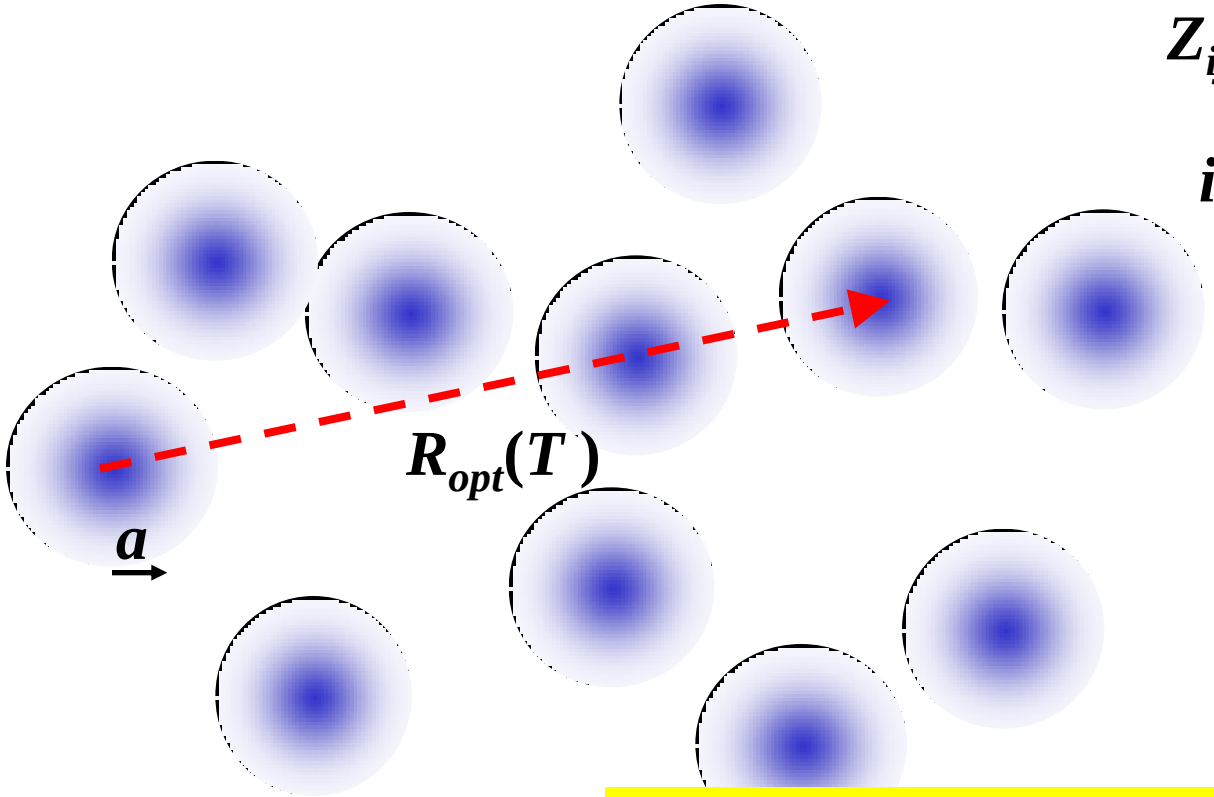
The case of explosive crystallization



НАНО ТРАНСПОРТ

Hopping conductivity- transport on a nanometer scale





$$\frac{R_{opt}}{a} \sim 3-10$$

In an amorphous material the estimate a~1 nm is expected and therefore should be R_{opt}~3-10 nm.
How about finding localization length?

$$Z_{ij} = Z_0 e^{\xi_{ij}}$$

$$\xi_{ij} = 2\frac{R_{ij}}{a} + \frac{E_{ij}}{k_B T} \le \xi_c$$

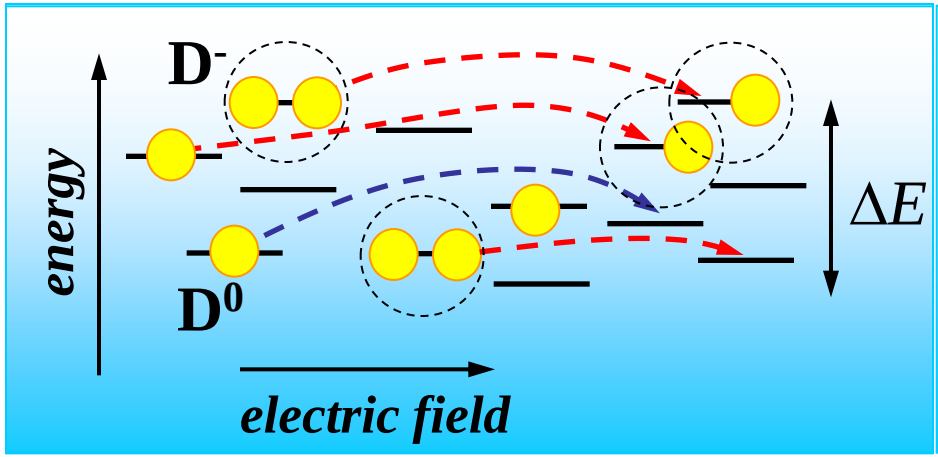
$$\rho = \rho_0 e^{\xi_c}$$

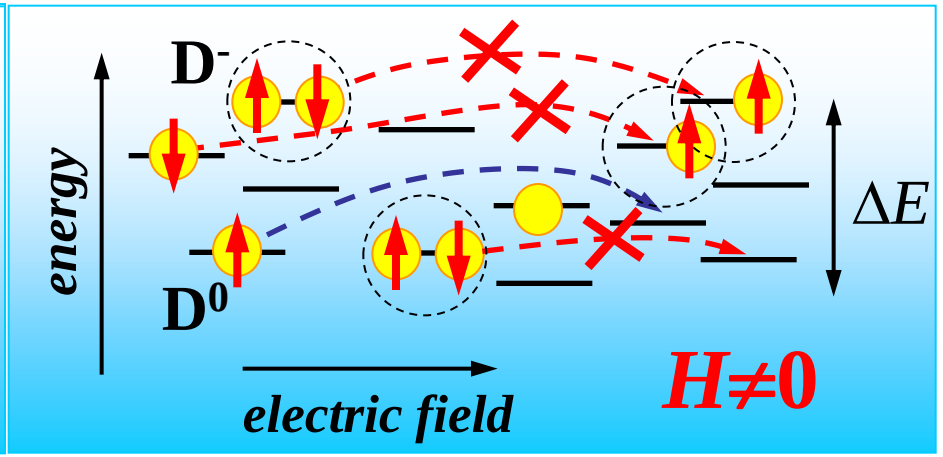
$$\xi_c = \left(\frac{T_0}{T}\right)^{\alpha}, \alpha = \frac{1}{d+1}$$

$$R_{opt} = \frac{a}{2}\xi_c, \Delta E = k_B T \xi_c$$

Spin effects in variable range hopping.

"Convenient" hopping *Hopping with D^0 and D^- states*





Magnetoresistance

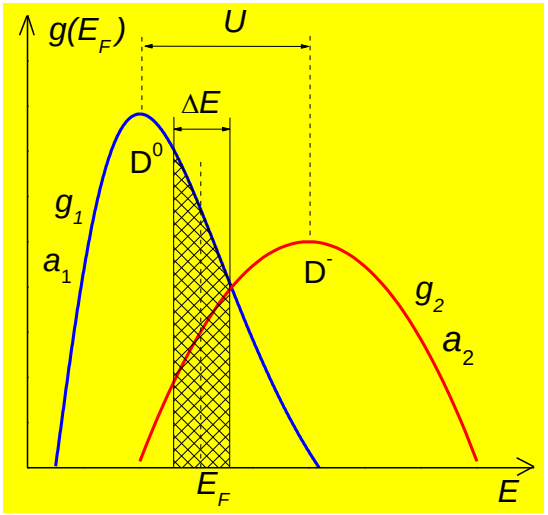
- Orbital effects (shrinkage of the wave function) — PMR
- Spin effects: Spin-polarization mechanism — *Scaling*
- Quantum interference — NMR

Spin-polarization mechanism

D^0 and D^- centers exist in the vicinity of the Fermi level and form common MA network. Polarization of the spin part of the wave function "switch" different types of transitions.

Hopping system ≡ paramagnet

Colored percolation



S.V.Demishev, A.A.Pronin, Physics of the Solid State, 2006, No 7

.

$$\sum n_i = \sum n_i(\xi, H) + n_{\uparrow\downarrow}(\xi, H) \approx$$

$$\approx a_1^{\,d} g_1 \xi^{d+1} k_B T \cdot [1 - w_{\uparrow\downarrow}(H)] + a_2^{\,d} g_2 \xi^{d+1} k_B T \cdot w_{\uparrow\downarrow}(H) = n_c$$

$$\xi_c = (T_0(H)/T)^{\alpha}; \alpha = \frac{1}{d+1}$$

Scaling

$$\ln\left[\frac{\rho(H)}{\rho(0)}\right] = \xi_0 F(x) \equiv \left(\frac{T_0}{T}\right)^{\alpha} F(x) \qquad F(x) = \left(1 - A \cdot \tanh^2(x)\right)^{-\alpha} - 1$$

$$x = \frac{\mu H}{k_B T} \qquad A = \frac{g_2 a_2^{\,d} - g_1 a_1^{\,d}}{g_2 a_2^{\,d} + g_1 a_1^{\,d}}$$

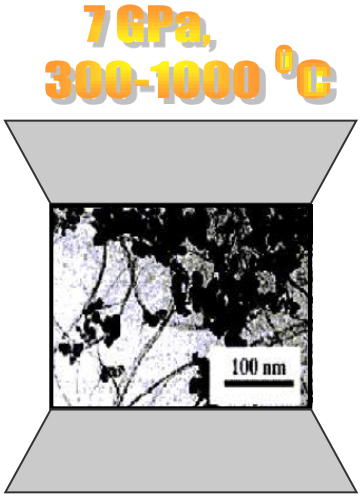
$$x \ll 1 \qquad F(x) \approx \alpha \cdot A \cdot x^2$$

Easy accounting of both spin-polarization and shrinkage mechanisms :

$$\ln\left[\frac{\rho(H)}{\rho(0)}\right] = \left(\frac{T_0}{T}\right)^{\alpha} \alpha \cdot A_{eff}(T) \cdot \left(\frac{\mu H}{k_B T}\right)^2 \qquad A_{eff} = A + (t_d e^2 a_{eff}^{\,4} k_B^{\,2} T_0^{\,2\alpha} / c^2 \hbar^2 \mu^2 \alpha) \cdot T^{2-2\alpha}$$

$$a_{eff} \sim a_2$$

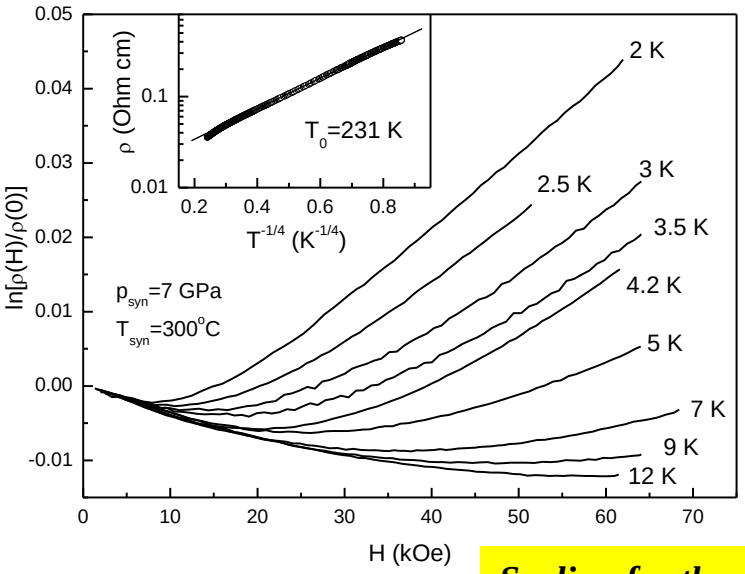
Conductivity and magnetoresistance data analysis.



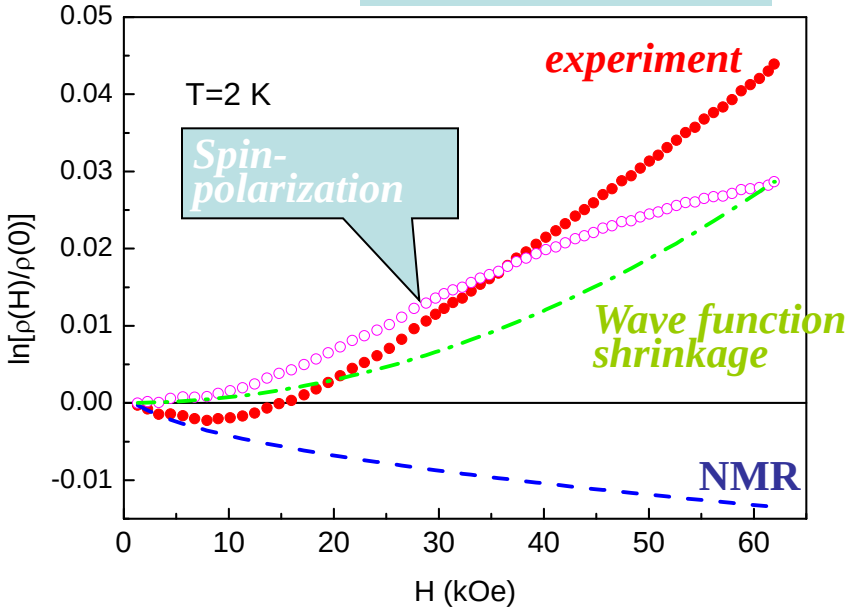
Disordered nanomaterial Obtained by modification of SWNT under high pressure and temperature.

Wide temperature range (1.8<T<60 K), where Mott law with α=1/4 and T_0=231 K is observed.

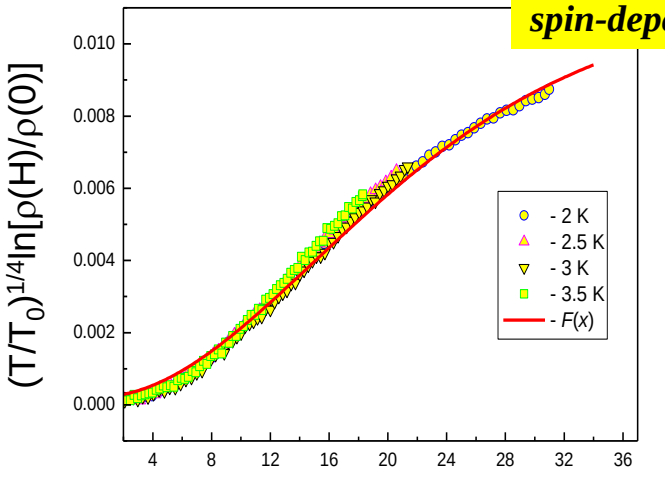
Hopping conductivity & magnetoresistance



Magnetoresistance analysis

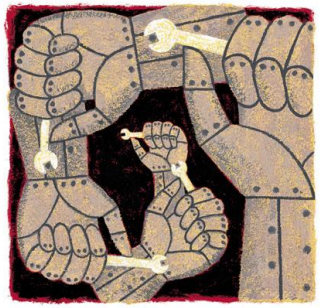


Scaling for the spin-dependent part



Shrinkage is essential and gives: a_2 ~6 nm

«НАНО», магнетизм и квантовая критичность



Richard P. Feynman,
The Nano Prophet

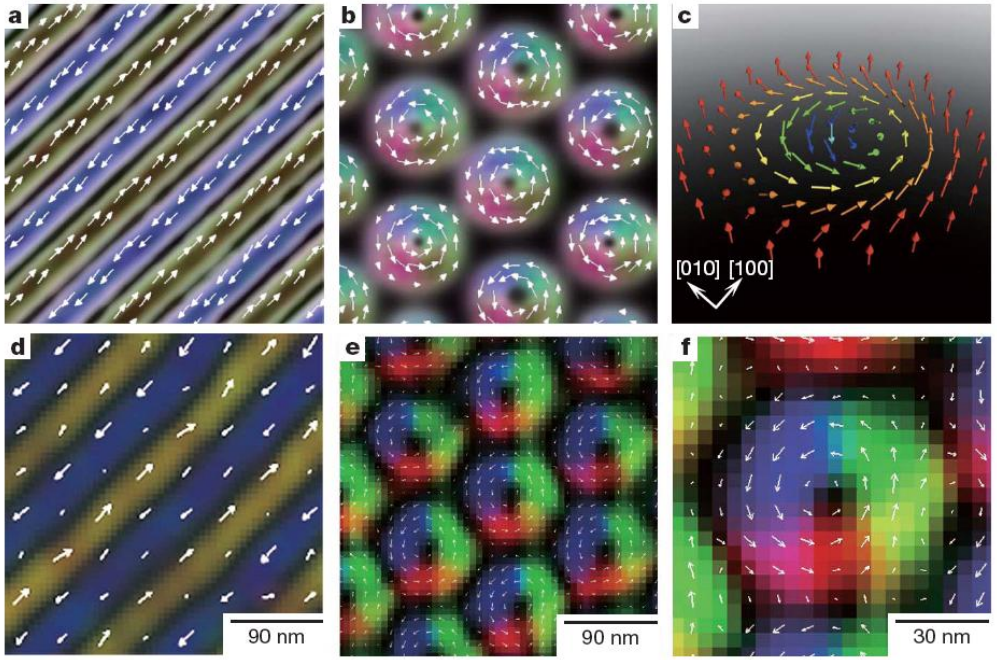
…The magnetic properties on a very small scale are not the same as on a large scale; there is the ``domain'' problem involved.
…In the year 2000, when they look back at this age, they will wonder…

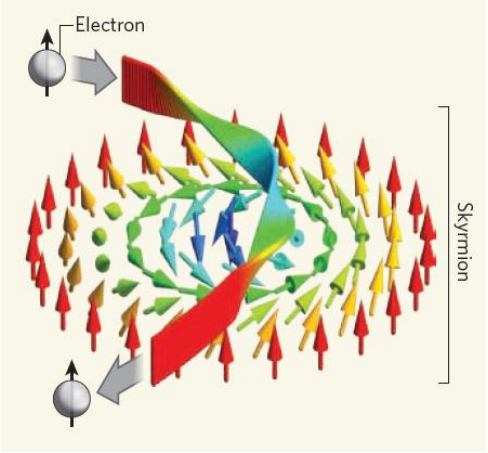
“Plenty of Room at the Bottom”
1959

Vol 465|17 June 2010|doi:10.1038/nature09124 nature

Real-space observation of a two-dimensional skyrmion crystal

X. Z. Yu[1,2], Y. Onose[2,3], N. Kanazawa[3], J. H. Park[4], J. H. Han[4], Y. Matsui[1], N. Nagaosa[3,5] & Y. Tokura[2,3,5]





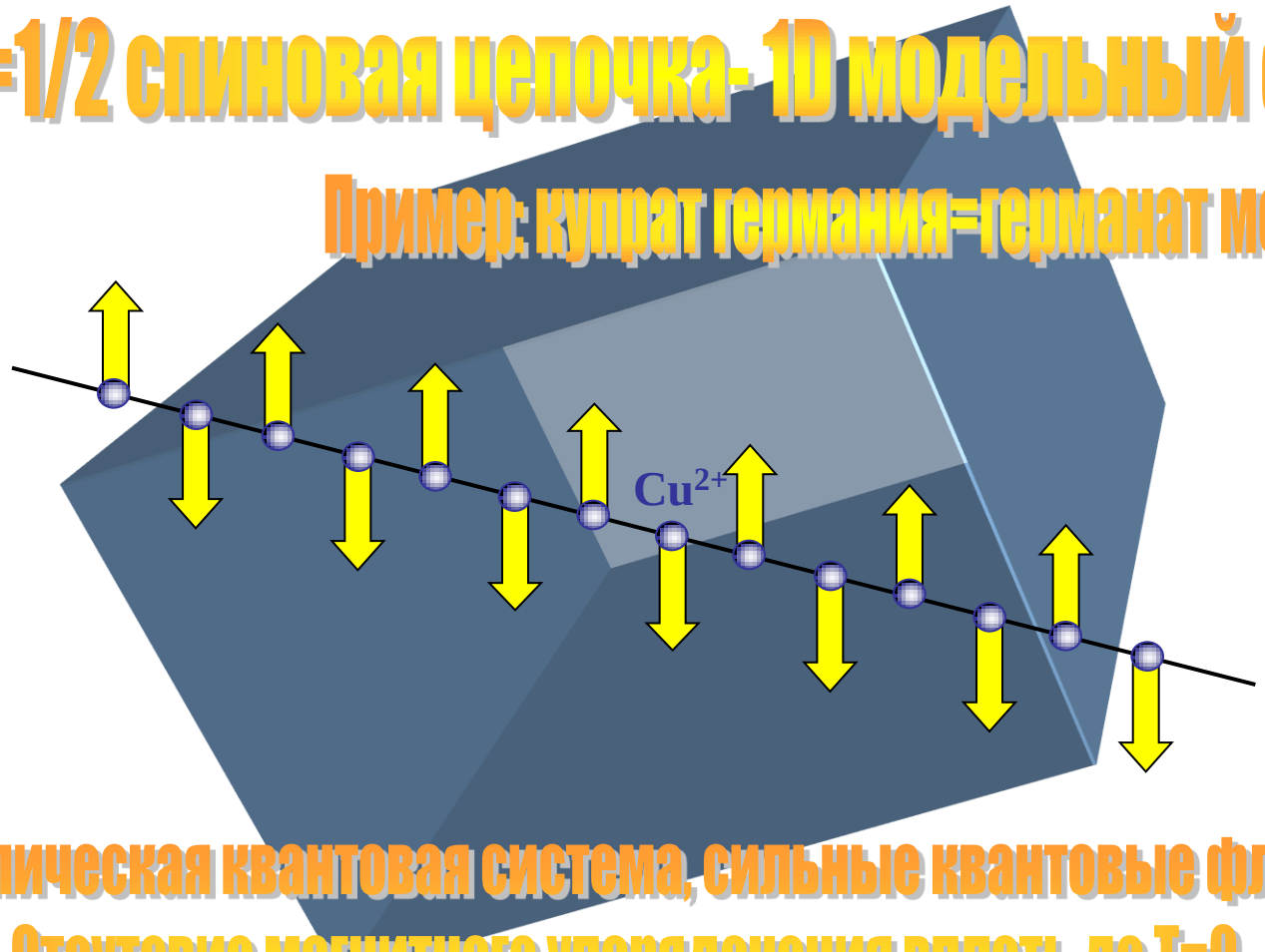
Skyrmion = Magnetic analog of an Abrikosov vortex in a type-II superconductor

Figure 1 | Topological spin textures in the helical magnet $Fe_{0.5}Co_{0.5}Si$. **a**, **b**, Helical (**a**) and skyrmion (**b**) structures predicted by Monte Carlo simulation. **c**, Schematic of the spin configuration in a skyrmion. **d**–**f**, The experimentally observed real-space images of the spin texture, represented by the lateral magnetization distribution as obtained by TIE analysis of the Lorentz TEM data: helical structure at zero magnetic field (**d**), the skyrmion crystal (SkX) structure for a weak magnetic field (50 mT) applied normal to the thin plate (**e**) and a magnified view of **e** (**f**). The colour map and white arrows represent the magnetization direction at each point.

Nanoscale magnetism can really provide new physics!

AFM S=1/2 спиновая цепочка- 1D модельный объект

Пример: купрат германия=германат меди



Макроскопическая квантовая система, сильные квантовые флуктуации.

Отсутсвие магнитного упорядочения вплоть до T=0.

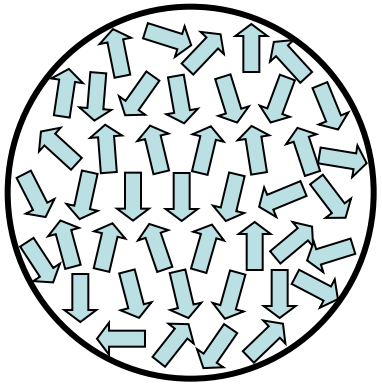
Эффекты беспорядка?

Квантовая критичность?

Пространственный масштаб ?

DISORDER DRIVEN QUANTUM CRITICAL PHENOMENA

In a disordered magnet dispersion of the exchange constants *J* exists

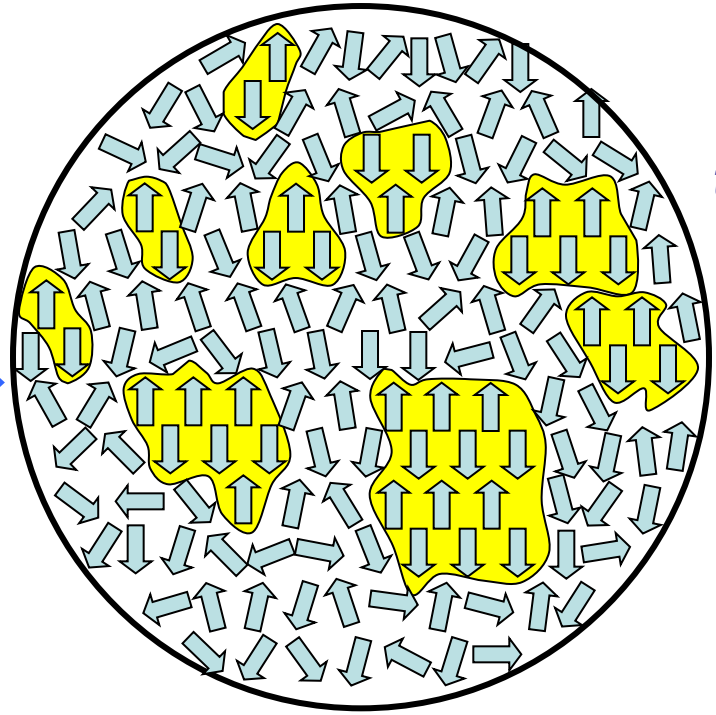


Lowering temperature

High temperatures

$$\chi = \frac{C}{T - \theta}$$

Uncorrelared spins. Curie-Weiss law for susceptibility



Low temperarures

$$\chi \sim \frac{1}{T^{\xi}}$$

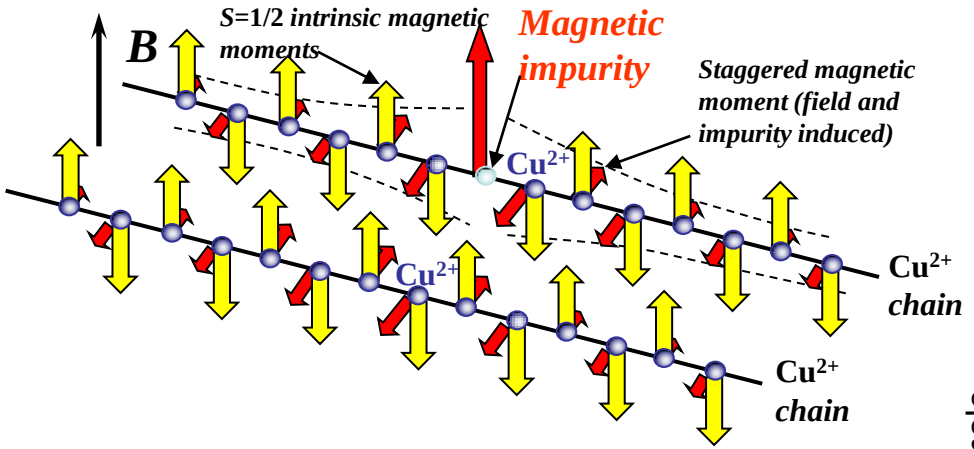
$$\xi < 1$$

Correlated spin clusters. Power law for susceptibility.

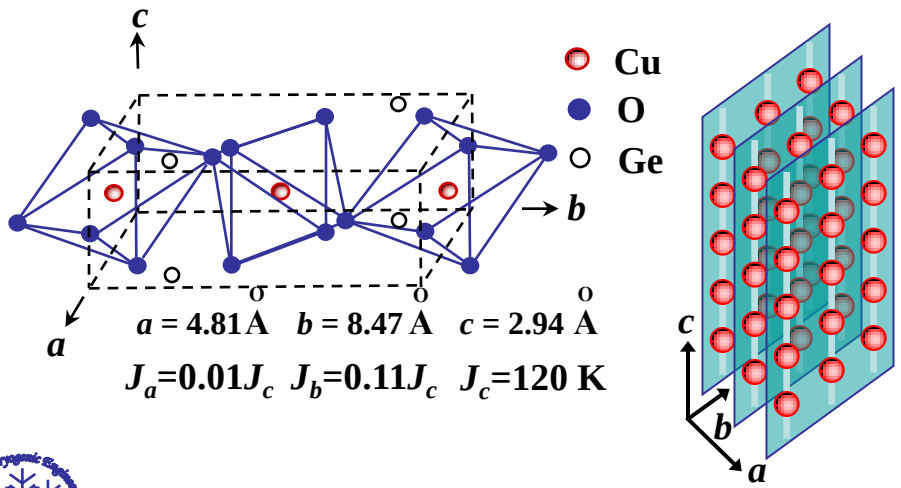
R.B.Griffiths. Phys. Rev. Lett., **23**, 17 (1969); A.J.Bray, Phys. Rev. Lett., **59**, 586 (1987)

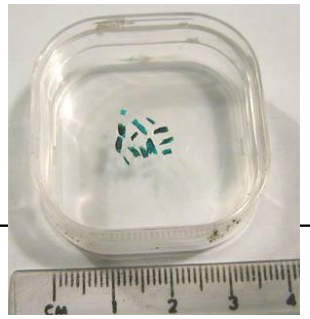
Practical realization: $CuGeO_3$ *doped with magnetic impurities.*
$Cu_{1-x}M_xGeO_3$ (x=0.02 M=Co; x=0.01 M=Fe, x=0.009 M=Mn)

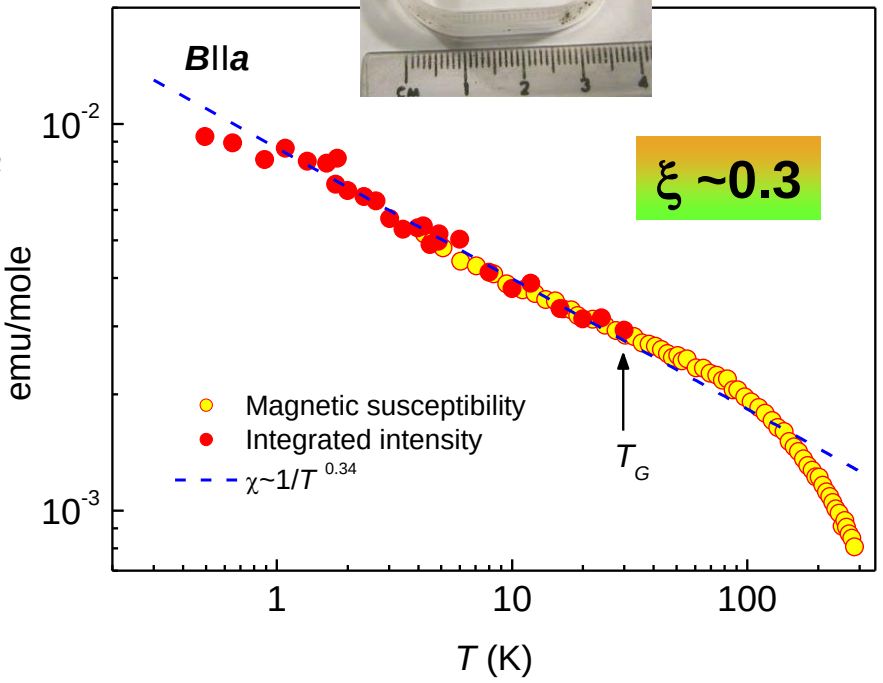
S=1/2 (Cu) AF chains



S=3/2 (Co) S=2 (Fe) S=5/2 (Mn)



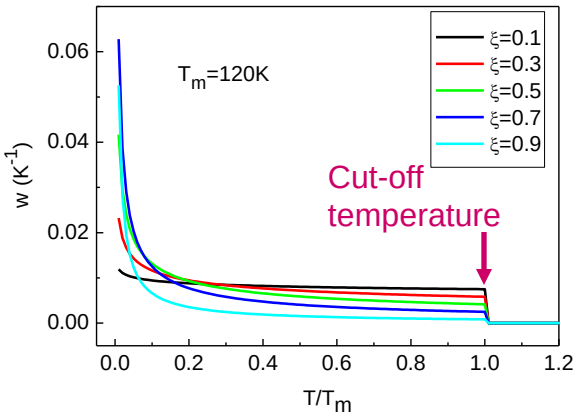


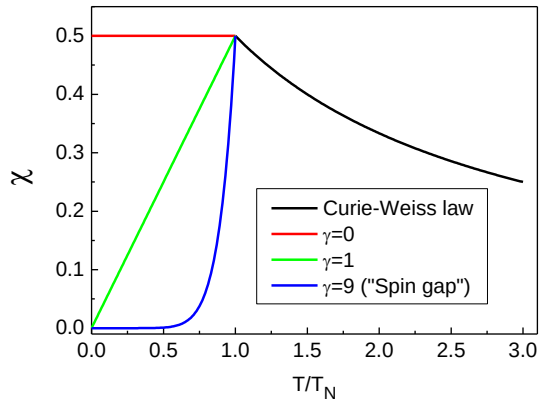


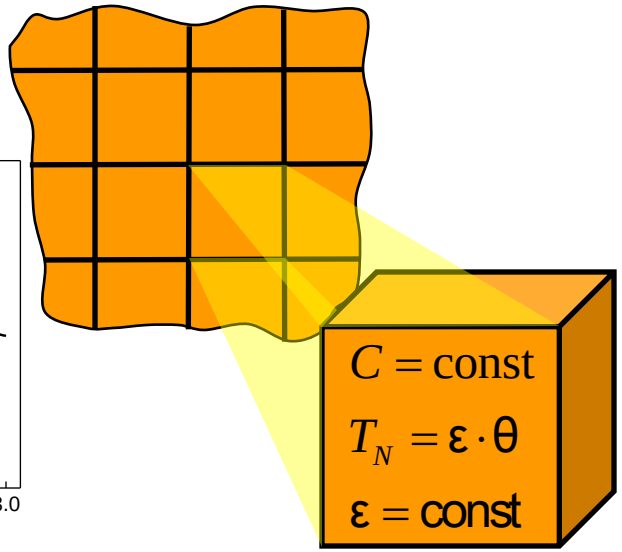
Quantum critical behavior in a wide temperature range (at least 1<*T*<T_G~30 K)!

The model:

S.V.Demishev, Phys.Sol.St., **51**(3), 514 (2009)
S.V.Demishev, Phys. Stat. Sol. B, **247**(3), 676 (2010)







Distribution of Neel temperatures in the sample:

$$w(T_N) = (1-\xi)(T_m / T_N)^{\xi} / T_m$$

Susceptibility of the cluster with T_N:

$$\chi = C/(T + \varepsilon^{-1} T_N) \qquad (T > T_N)$$

$$\chi = C(T/T_N)^{\gamma} / [T_N (1 + \varepsilon^{-1})] \qquad (T < T_N)$$

Result (susceptibility at an arbitrary temperature):

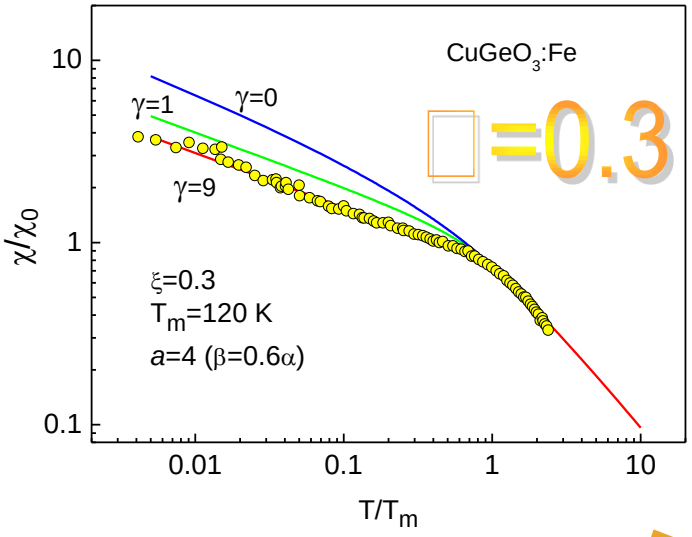
$$\chi = C/(T + \theta^*) \qquad (T > T_m)$$

$$\chi = [C/(T_m + \theta^*)](T/T_m)^{-\xi}\{1 + (1-\xi)(1+\theta^*/T_m)[1-(T/T_m)^{\gamma+\xi}]/[(1+\varepsilon^{-1})(\gamma+\xi)]\} \qquad (T < T_m)$$

$$\theta^* = T_m[\varepsilon(1-\xi) f(\varepsilon,\xi)]^{-1} - 1 \qquad f(\varepsilon,\xi) = -\xi^{-1} - \sum_{r=1}^{\infty}(-1)^r \varepsilon^r / (r+\xi) + \pi\varepsilon^{-\xi} / \sin[\pi(1-\xi)]$$

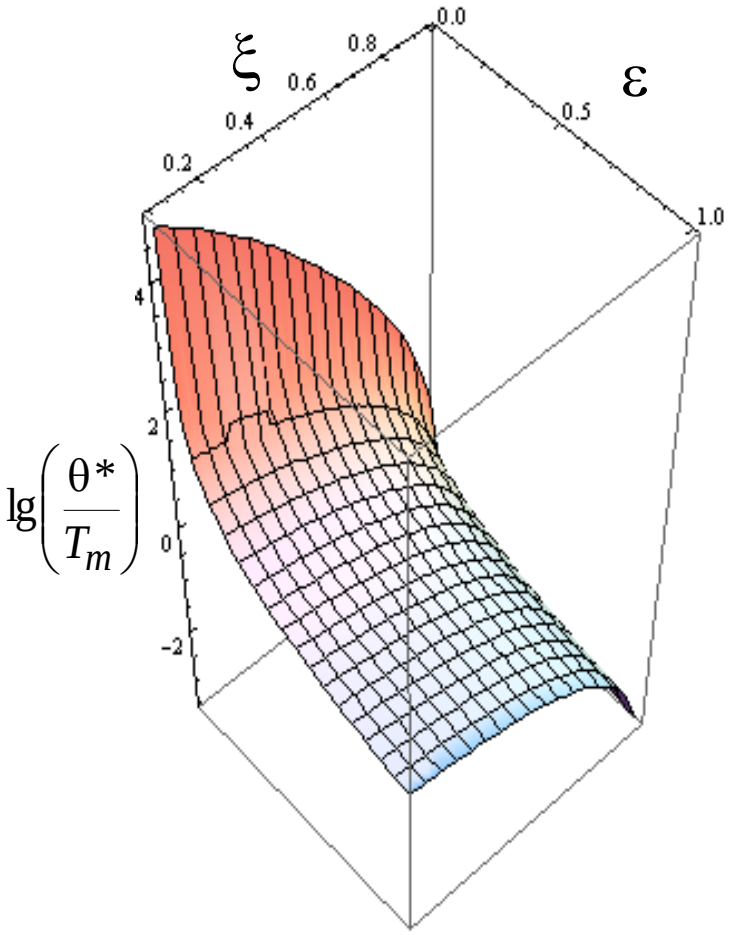
Modeling of the magnetic properties of a Griffiths phase.

S=2 (Fe)



T_m~120 K~J_c

Paramagnetic temperature in Curie-Weiss law ($T > T_m$)



Temperature vary more than two orders of magnitude in the quantum critical region.

Doping reduces *J* in spin clusters

Estimate of the characteristic cluster size

Lowering temperature results in freezing of the magnetic contribution of the spin clusters for which condition $T_N > T$ holds.

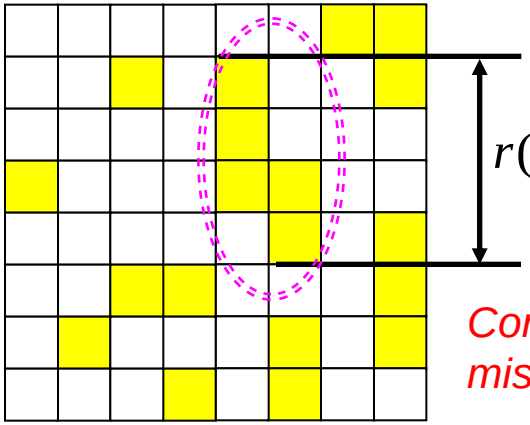
A two-phase model ("frozen" and "non-frozen clusters") may by introduced. The probability $W(T_N)$ defines "frozen" part of the sample volume.

$$v_{AF} = 1 - \left(\frac{T}{T_m}\right)^{1-\xi}$$

$$R < R_m$$

$$r = R_m / l_0$$

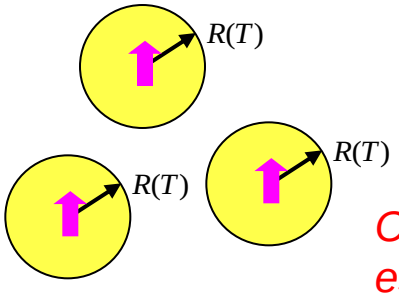
Percolation



$$r(T) \sim \frac{1}{\left|v_{AF}(T) - v_c\right|^{\eta}}$$

Correlation is missing

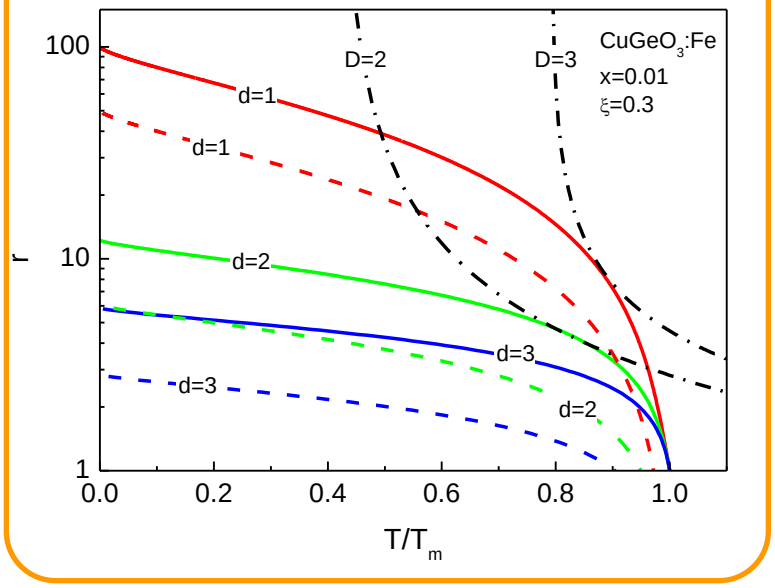
Cluster growth in vicinity of the magnetic impurity



$$\frac{T}{T_m} = \left[1 - \frac{2x}{d+1}\left(r^d - \frac{1}{r}\right)\right]^{\frac{1}{1-\xi}}$$

Correlation is essential

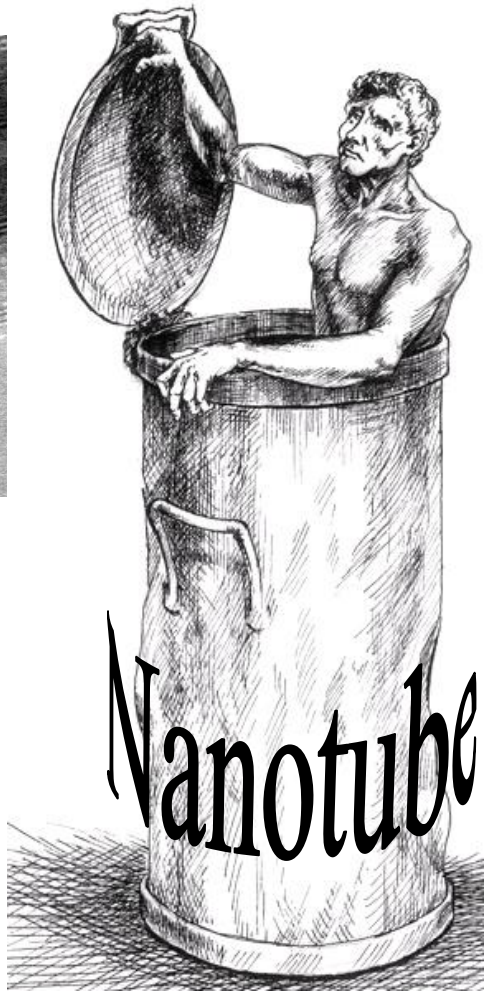
$Cu_{1-x}M_xGeO_3$ l_0~1 nm



Griffiths phase is formed by nano spin clusters!?

КВАНТОВАЯ КРИТИЧНОСТЬ И НАНОМАСШТАБ

Что будет, если рассмотреть этот вопрос в «противоположном» направлении: от «нано» к квантовой критичности ??



phys. stat. sol. (RRL) 2, No. 5, 221–223 (2008) / DOI 10.1002/pssr.200802108

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Electron spin resonance and quantum critical phenomena in VO_x multiwall nanotubes

S. V. Demishev*,[1], A. L. Chernobrovkin[1], E. A. Goodilin[2], V. V. Glushkov[1], A. V. Grigorieva[2], N. A. Samarin[1], N. E. Sluchanko[1], A. V. Semeno[1], and Yu. D. Tretyakov[2]

[1] A. M. Prokhorov General Physics Institute of RAS, 38, Vavilov street, Moscow 119991, Russia
[2] Lomonosov Moscow State University, Materials Science Department, Lenin Hills, Moscow 119991, Russia

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ФМ-АФМ кроссовер в наноматериалах на основе оксида ванадия

С. В. Демишев[1)], *А. Л. Чернобровкин*, *В. В. Глушков*, *А. В. Григорьева**, *Е. А. Гудилин**, *Н. Е. Случанко*, *Н. А. Самарин*, *А. В. Семено*

Институт общей физики им. А.М. Прохорова РАН, 119991 Москва, Россия

**Факультет наук о материалах, Московский государственный университет им. М.В. Ломоносова, 199991 Москва, Россия*

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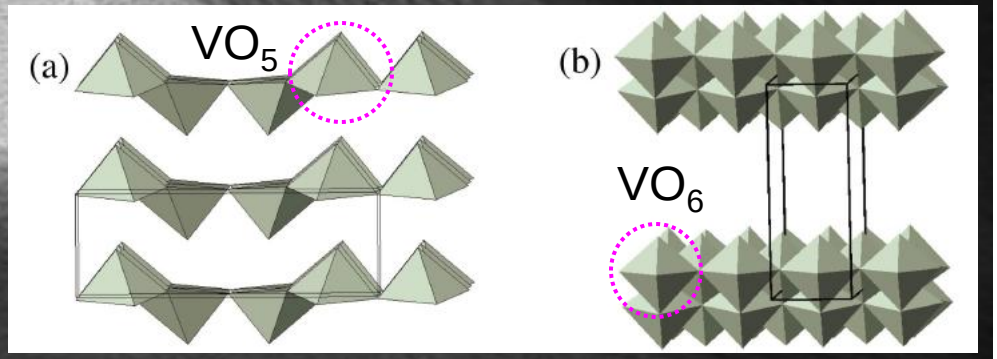
VO_x multiwall nanotubes: what for?

Applications:

- Solid-state batteries
- Chemical sensors
- Catalysts
- Non-linear optics

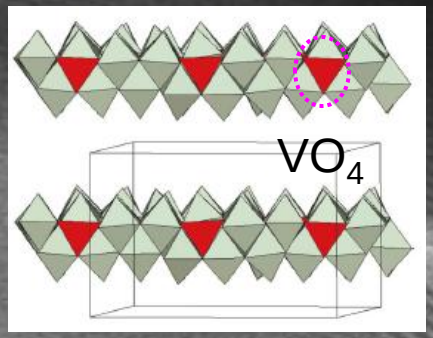
V_2O_5

$V_2O_5\,nH_2O$ gel



Different V charge states…

$Zn_4V_{21}O_{58}$

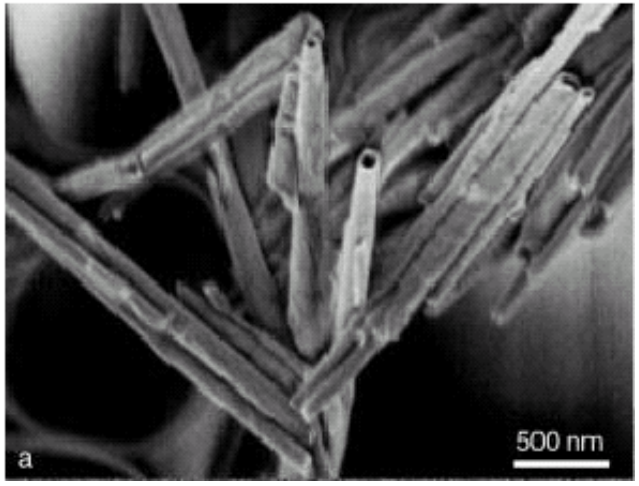


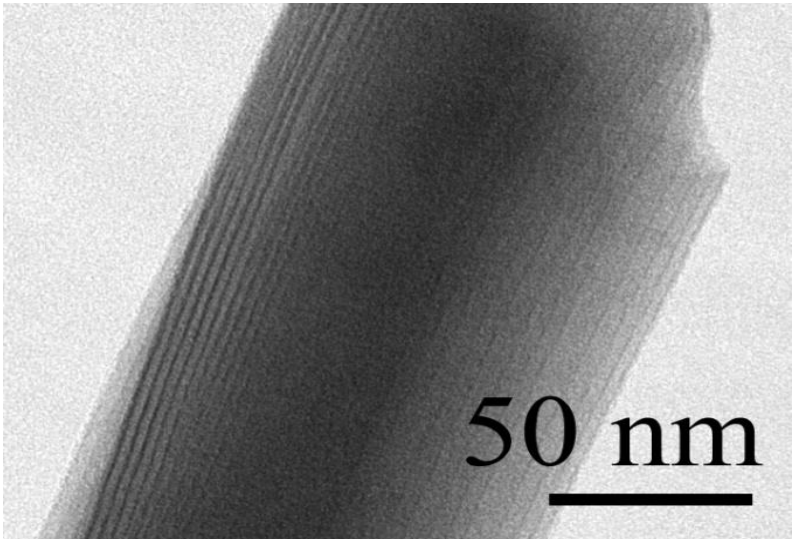
Fundamental interest:

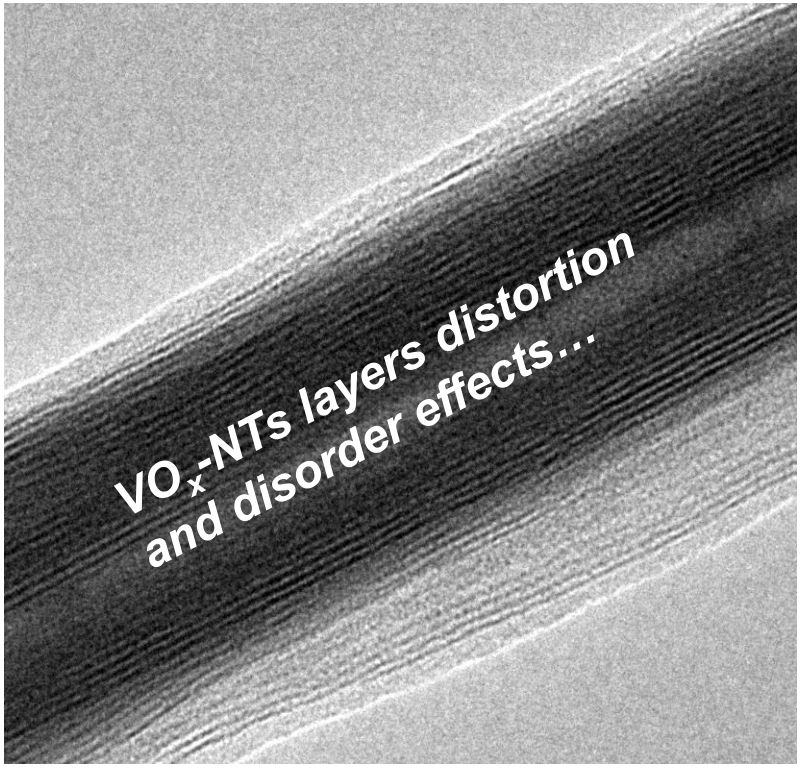
- Structural studies
- Magnetic properties (nanoscale magnets etc.)

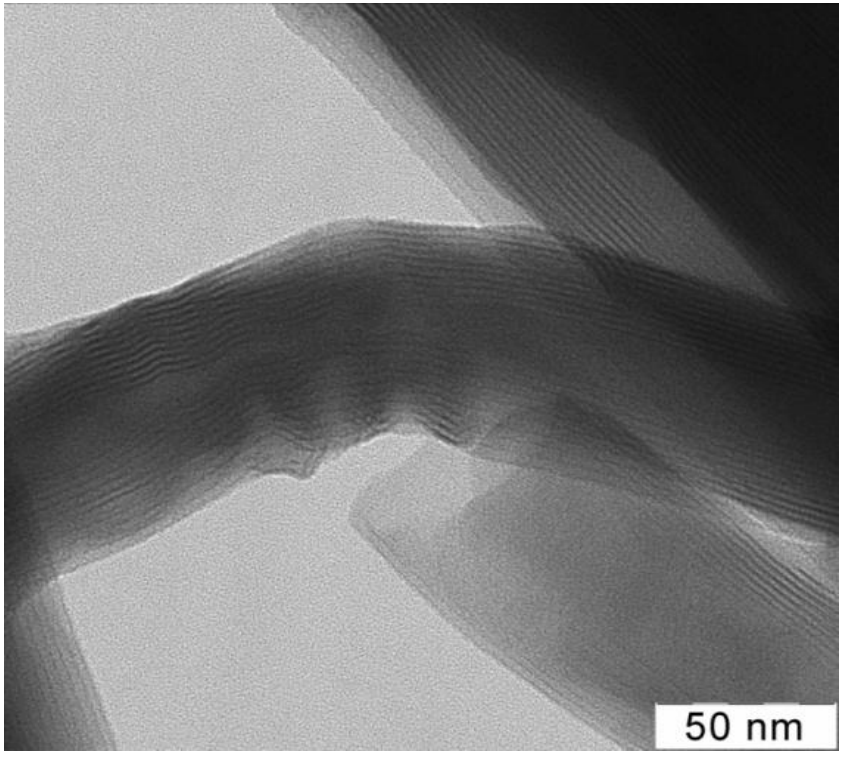
50 nm

VO_x multiwall nanotubes: TEM images









VO_x multiwall nanotubes: Structure

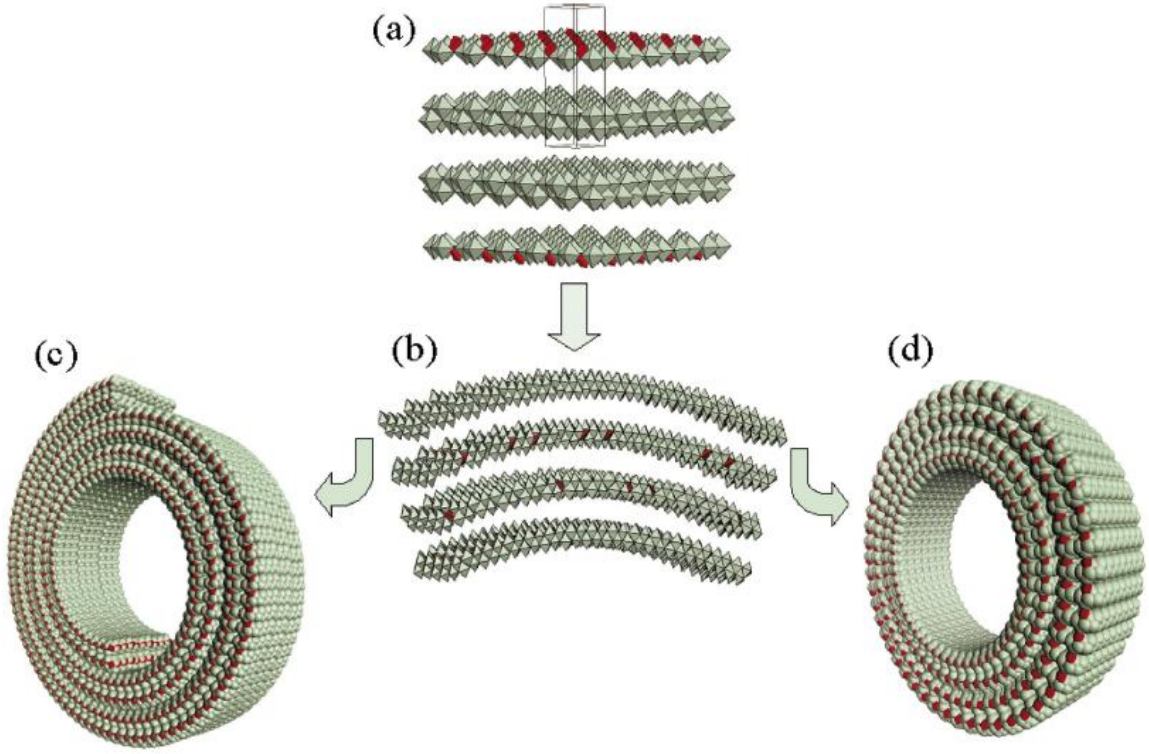
Precursor	Outer diameter, *D* (nm)	Inner diameter (nm)	Number of layers	Length, *L* (μm)
$VO(PrO^i)_3$	15 – 150	5 – 50	2 – 30	1 – 15
$VOCl_3$	50 - 100	15 - 35	10 – 20	1,5 – 5
	75 - 100	20 – 35	11 – 14	0,8 – 1,5
V_2O_5 crystal	70 - 140	20 – 35	9 – 13	2 – 12
	50 – 90	15 – 35	7 – 13	1 – 3
	70 – 100	20 – 45	6 – 11	1 – 2
	30 – 100	~ 45	3 – 10	1 – 10
	60 – 90	20 – 45	6 – 10	1 – 3
V_2O_5 gel	50 – 130	30 – 40	5 – 25	1 – 10

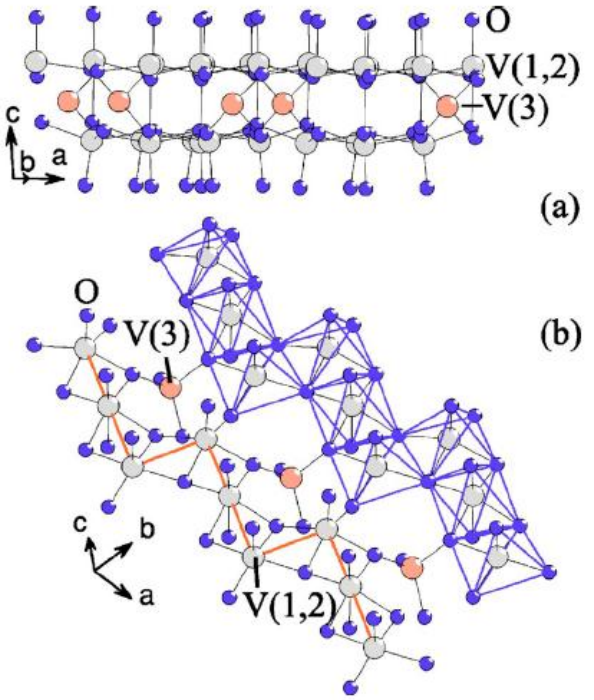
$L/D \sim 10^2$

50 nm

VO_x multiwall nanotubes: Structural models

1. **Scrolling of one or two VO_x layers ("spiral")** (Nesper et all., Advanced Materials – 2000)
2. **Scrolling of the stack of VO_x layers ("concentric")** (Serdiri et all., Materials letters – 2007)
3. **1D motive (zigzag chain…). Anisotropy in the VO_x layer, several non-equivalent V sites** (Vaviolova et al., Phys.Rev. B, 73, 144417 (2006)

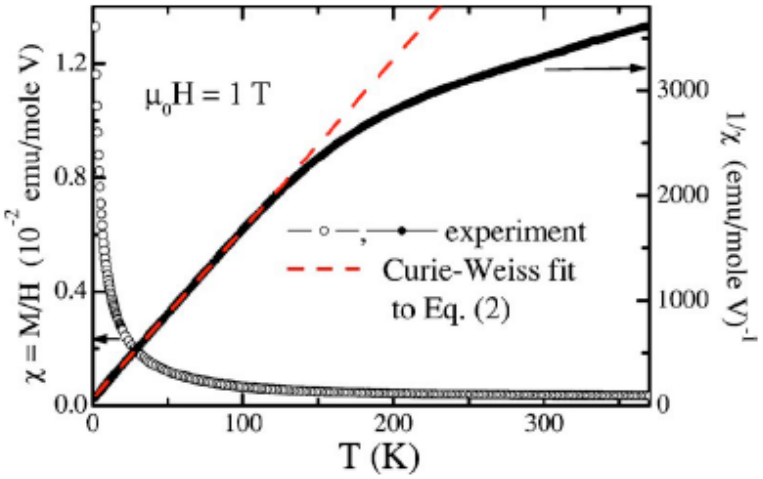




*V.Petkov et al., PRB, **69**, 085410 (2004)*

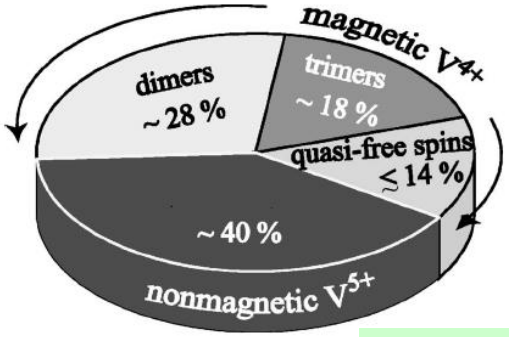
Magnetism of VO_x multiwall nanotubes: introduction

UNDOPED VO_x-NTs ARE ANTIFERROMAGNETS

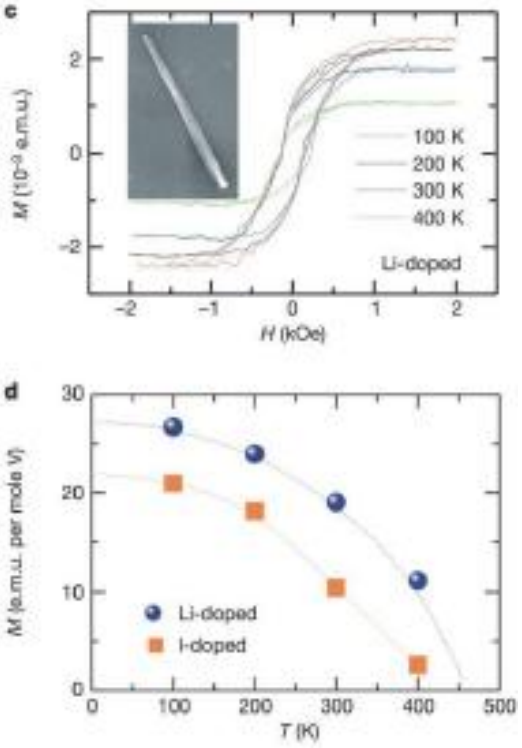


Magnetism=Free spins(AF) + AF dimers

V^{5+} S=0 – non-magnetic ion
V^{4+} S=1/2 – magnetic ion



DOPED VO_x-NTs ARE FERROMAGNETS



Ferromagnetism at room temperature In Li and I doped samples
L.Krushin-Elbaum et al.
Nature, **431**, 672 (2004)

E.Vavilova, I.Hellmann et al., Phys.Rev. B, **73**, 144417 (2006)

VO_x multiwall nanotubes: anomalous magnetism

Problems with various spin species (E.Vavilova, I.Hellmann et al., Phys.Rev. B, **73**, 144417 (2006))

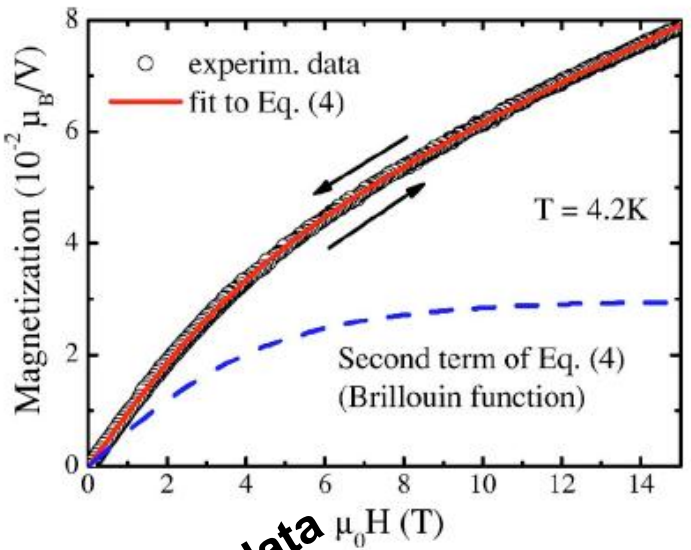
Free spins + AF dimers model

$$\chi = \chi_{CW} + \chi_D + \chi_0$$

$$\chi_{CW} = C/(T+\theta)$$

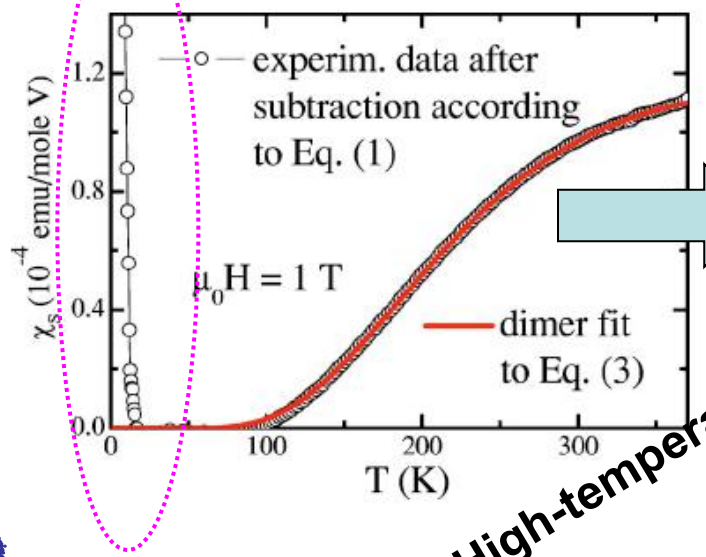
$$\chi_D = C_D/(T[3+\exp(\Delta/k_BT)])$$

$$\chi_0 = const$$



Low-temperature data

3% of V sites possess the quasi-free spins



$\Delta = 710$ K

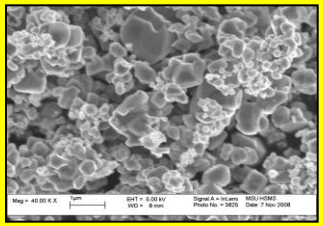
High-temperature data

17% of V sites possess the quasi-free spins

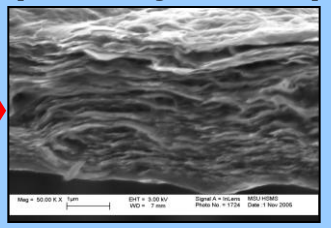
VO_x nanomaterials: synthesis

Precursor

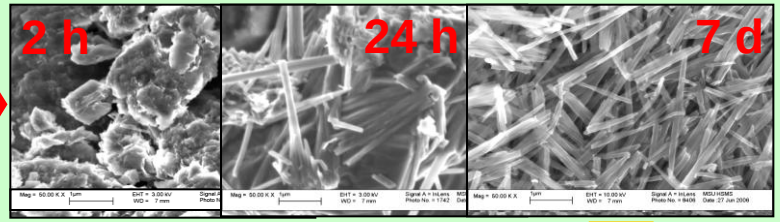
Rhombic V_2O_5



Homogenization with $C_{16}H_{33}NH_2$ (Dodecylamine)



Hydrothermal treatment (150-180 °C)



Drying of the product

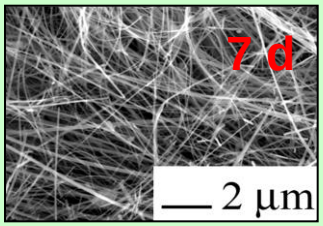
VO_x nano layers

Stacks of 4-8 disordered VO_x planes with incomplete scrolling. (pre-VOx-nanotubes)

VO_x multiwall nanotubes

Hydrothermal treatment

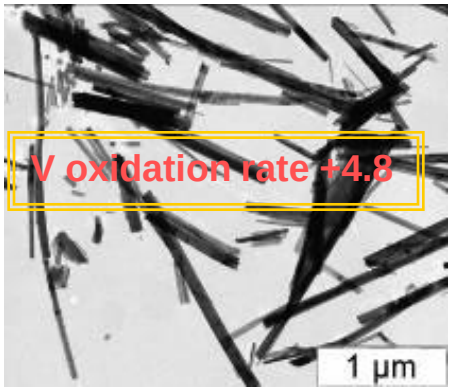
C_2H_5OH



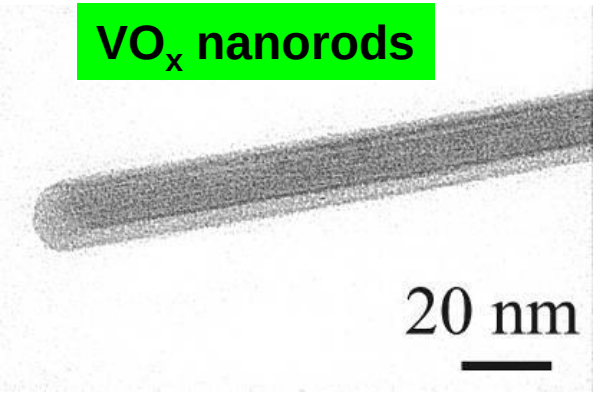
VO_x nanorods

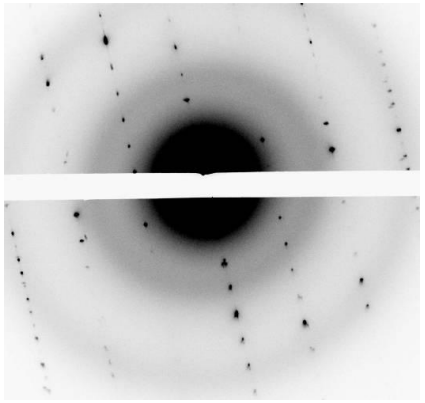
VO_x nanomaterials: different morphological forms.

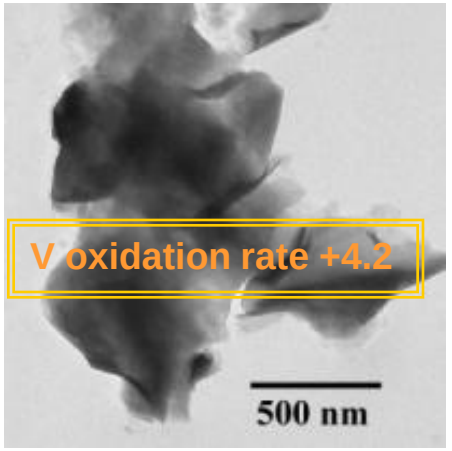
Hydrothermal treatment allows obtaining different forms of VO_x nanomaterials

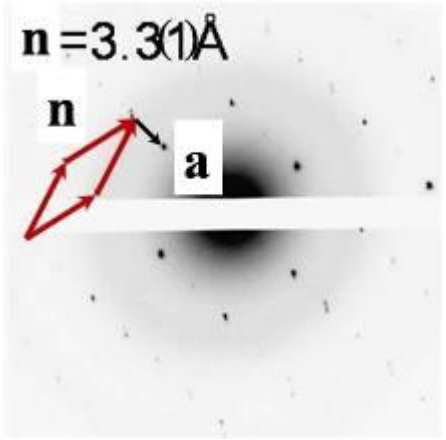


VO_x nanorods

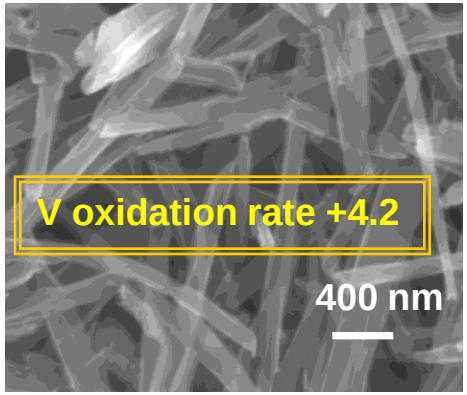




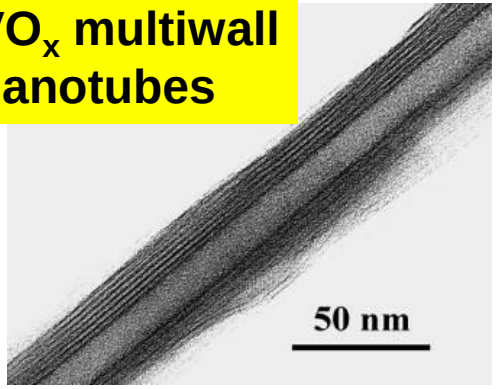


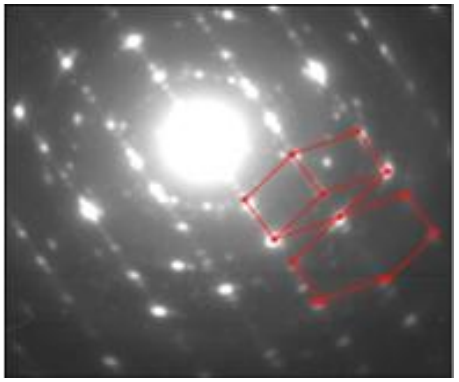


VO_x nanolayers (pre-VO_x-nanotubes)



VO_x multiwall nanotubes





VO_x nanomaterials magnetism: basic idea of research.

IDEA: Understanding of the magnetism of VO_x-NTs in wider context of different morfological forms of VO_x nanomaterials as long as synthesis schema is essentially the same.

Questions remaining from the previous research of VO_x-NTs:

Is not studied up to now

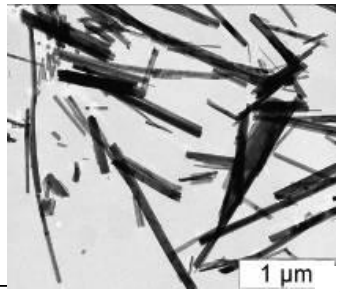
- Indirect evidence for AF dimers
- Concentration estimates
- What happens at low temperatures?

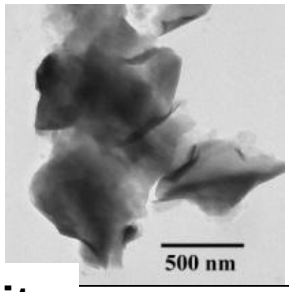
Several contributions to susceptibility, thus the ESR is an adequate tool (+ comparison with the static susceptibility data).

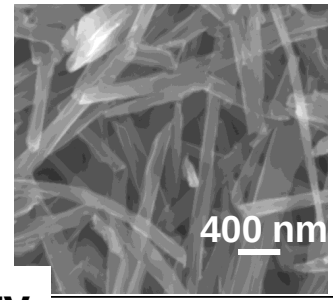
Avaliable ESR data for VO_x-NTs: X-band 77-300 K

High frequency low temperature ESR experiment is required

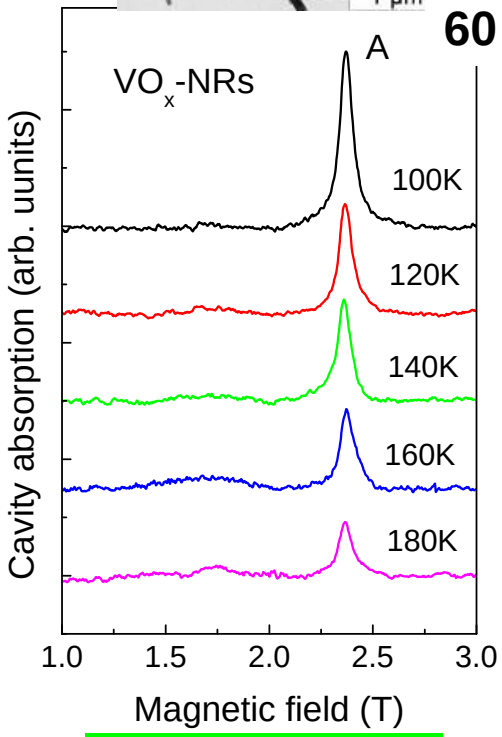
ESR in VO_x nanomaterials: spectra.







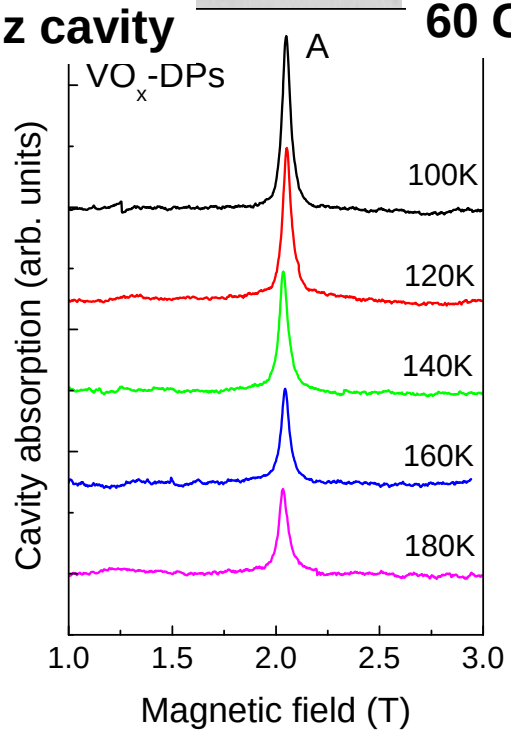
60 GHz cavity



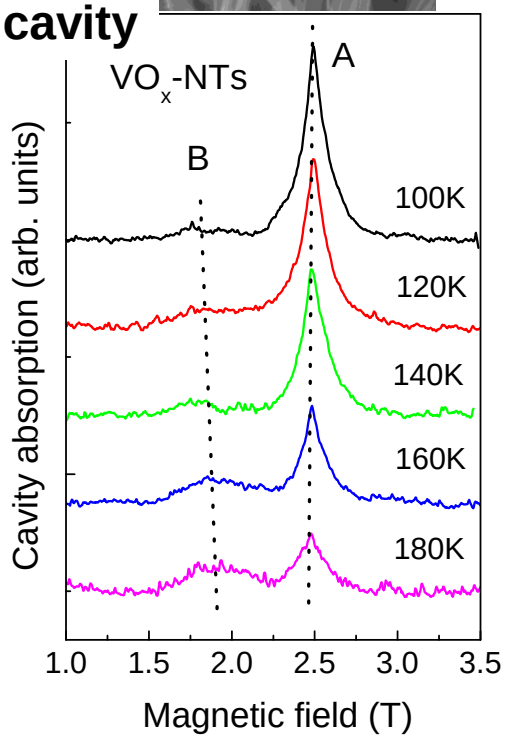
VO_x nanorods

Single ESR line

60 GHz cavity



VO_x nano layers



VO_x nanotubes

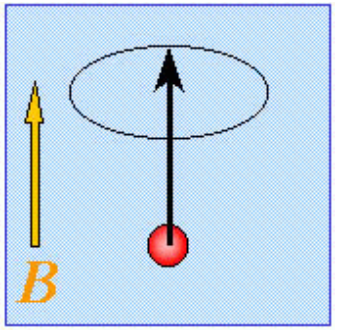
Two ESR lines

V^{5+} S=0 – non-magnetic ion

V^{4+} S=1/2 – magnetic ion

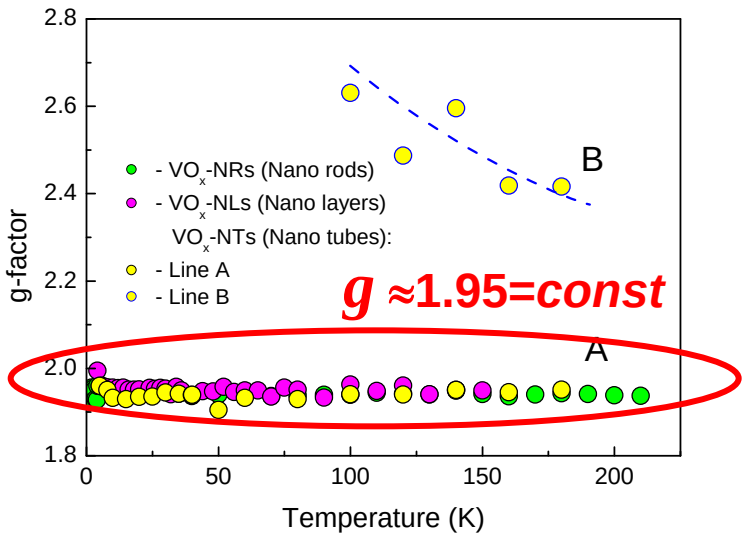
ESR in VO_x nanomaterials: spectroscopic parameters.

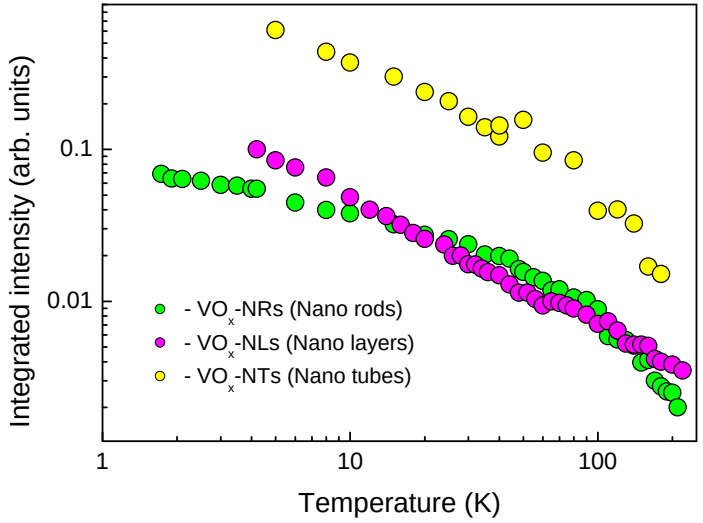
ESR in VO_x nano: Precession of the V^{4+} Magnetic moment in magnetic field



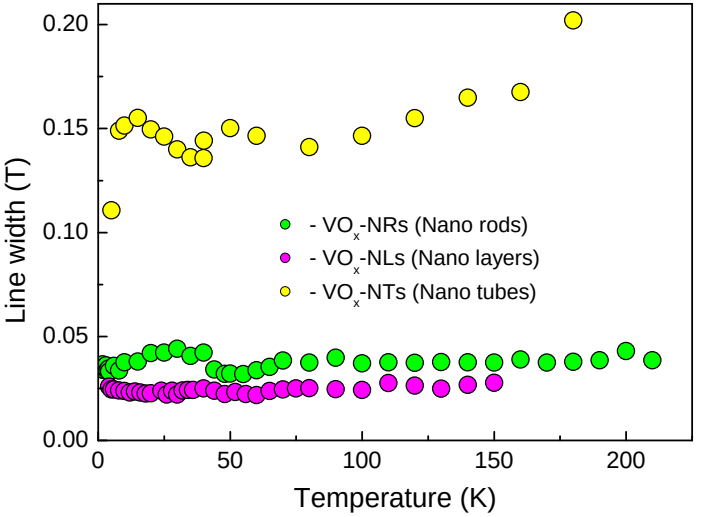
Hyromagnetic ratio, g-factor, magnituge of the oscillating magnetic dipole

$$g \sim \mu$$





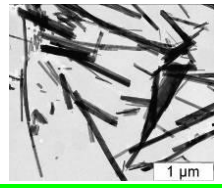
Line width, relaxation time T_2



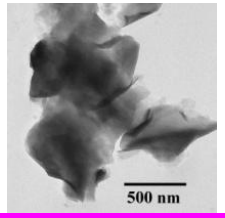
Integrated intensity, oscillating part of spin susceptibility (V^{4+} for VO_x nano)

$$I(T) \sim \chi_S(T)$$

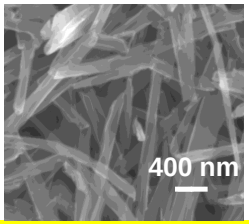
FM-AFM crossover in the VO_x nanomaterials.



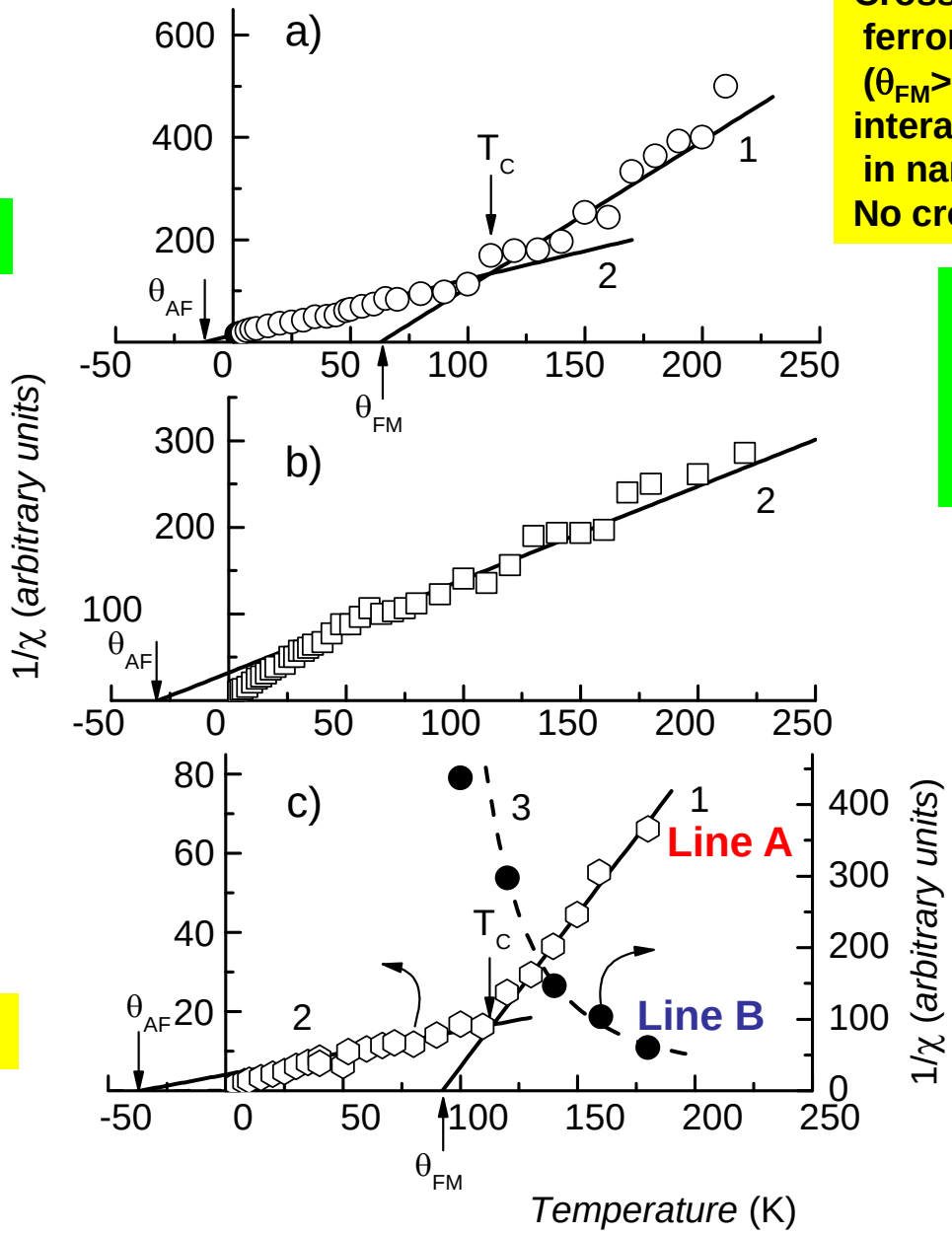
VO_x nanorods



VO_x nano layers



VO_x nanotubes



Crossover from the ferromagnetic interactions (θ_{FM}>0) to the antiferromagnetic interactions (θ_{AF}<0) at T_c~100 K in nanorods and nanotubes. No crossover in nanolayers

Crossover is accompanied by increase of the Curie-Weiss constant in the AF region (T<T_c) by 3-7 times.

As long as g=*const*, this suggests the increase of the concentration of the oscillating magnetic moments at T_c.

Line B: description within AF dimers model

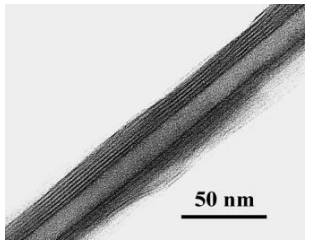
$$\chi_D = \frac{C_D}{T[3+\exp(\Delta / k_B T)]}$$

with the spin gap Δ=716 K.

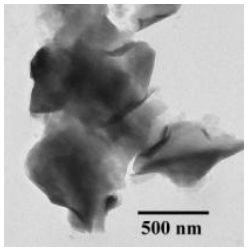
The nature of FM-AFM crossover.

Concentrations from X-ray structural analysis and oxidation rate.

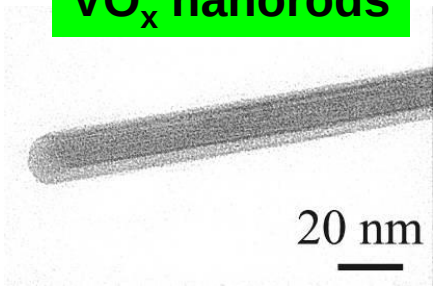
VO_x nanotubes

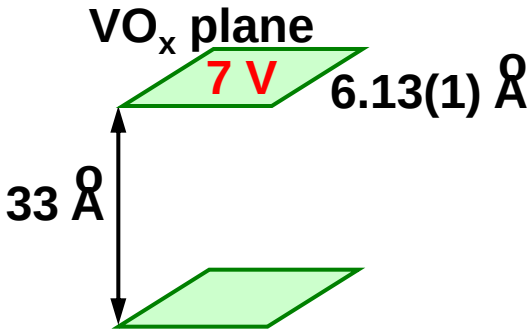


VO_x nanolayers



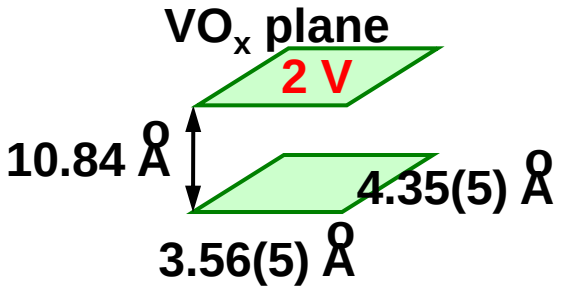
VO_x nanorods





V oxidation rate +4.2

80% V^{4+}
20% V^{5+}



V oxidation rate +4.8

20% V^{4+}
80% V^{5+}

VO_x plane: $N(V^{4+})=1.49\cdot10^{15}$ cm^{-2}

Sample volume: $N(V^{4+})=4.52\cdot10^{21}$ cm^{-3}

VO_x plane: $N(V^{4+})=2.58\cdot10^{14}$ cm^{-2}

Sample volume: $N(V^{4+})=2.27\cdot10^{21}$ cm^{-3}

The nature of FM-AFM crossover.

$$\frac{N(V^{4+})_{nanolayers}}{N(V^{4+})_{nanorods}} \sim \begin{cases} \textbf{2,} \text{ sample volume} \\ \textbf{6,} \text{ } VO_X \text{ plane} \end{cases}$$

Magnetic subsystem in VO_x nanorods is diluted with respect to magnetic subsystem in VO_x nanolayers.

FM interaction for diluted system and AFM interaction for concentrated system (agrees with the susceptibility temperature dependence for VO_x nanorods).

How about nanotubes? The V^{4+} concentration is the same as in nanolayers…

But there are dimers, which are missing in nanolayers. This make magnetic subsystem of VO_x nanotubes diluted.

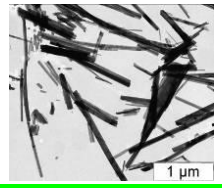
Curie-Weiss constants and g-factors give
- ***T*** **>100 K: ~ 1.3% V $^{4+}$ FM spins and ~ 98.7% V $^{4+}$ AF dimers**
- ***T*** **<100 K: ~ 8.6% V $^{4+}$ AF spins and ~ 91.4% V $^{4+}$ AF dimers**

AF dimers dominate !

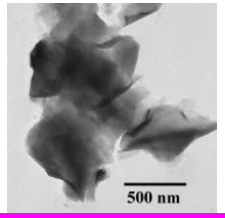
Suggested idea works!

FM-AFM crossover : e + $V^{5+} \rightarrow V^{4+}$ at T_c
A kind of electron localization effect?

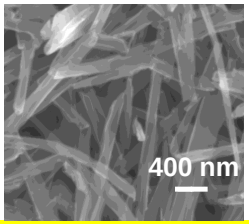
FM-AFM crossover in the VO_x nanomaterials.



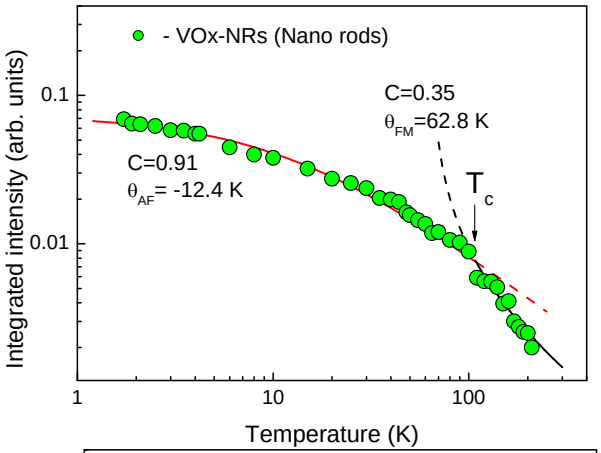
VO_x nanorods

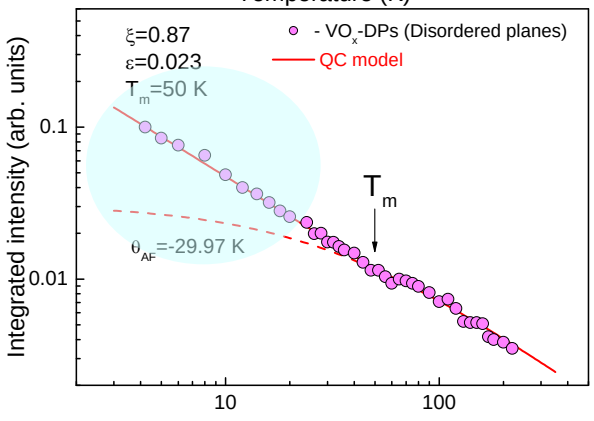


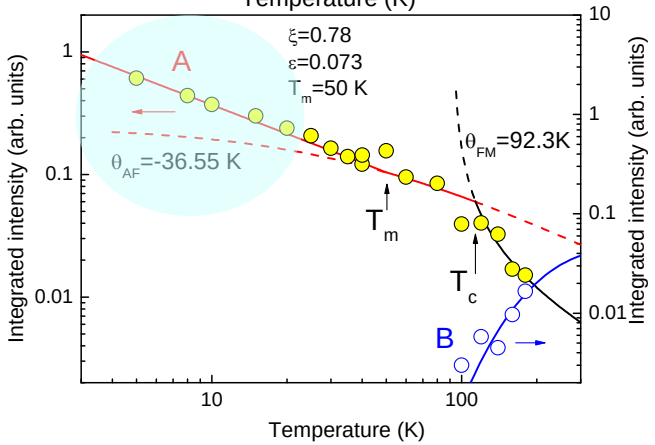
VO_x nano layers



VO_x nanotubes



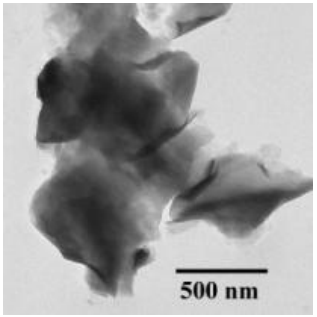




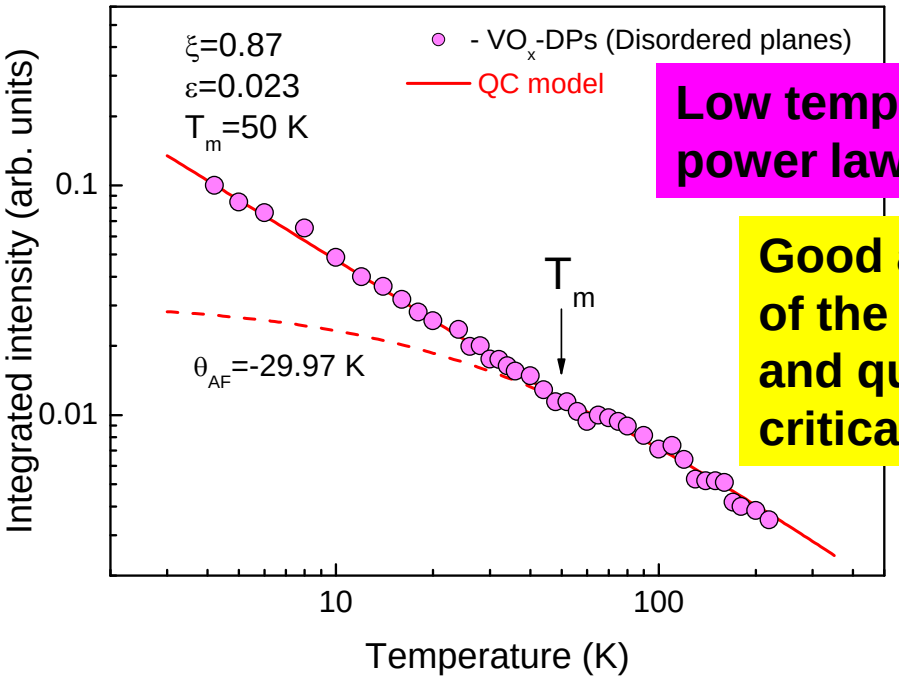
Low temperature anomaly (departures from Curie- Weiss law) at T_m~50 K

QC phenomena in VO_x nanomaterials: theory vs. experiment.

Low temperature anomaly



VO_x nanolayers



Low temperature power law with ξ=0.87

Good agreement of the experiment and quantum critical model.

The model:

Distribution of Neel temperatures in the sample:

$$w(T_N) = (1-\xi)(T_m / T_N)^{\xi} / T_m$$

Susceptibility of the cluster with T_N:

$$\chi = C/(T + \varepsilon^{-1} T_N) \qquad (T > T_N)$$

$$\chi = C(T/T_N)^{\gamma} / [T_N(1+\varepsilon^{-1})] \qquad (T < T_N)$$

Result (susceptibility at arbitrary temperature):

$$\chi = C/(T + \theta^*) \qquad (T > T_m)$$

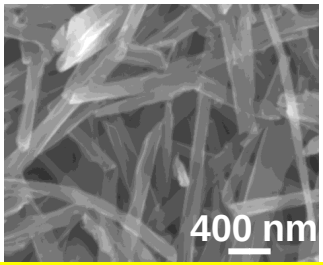
$$\chi = [C/(T_m + \theta^*)](T/T_m)^{-\xi}\{1 + (1-\xi)(1+\theta^*/T_m)[1-(T/T_m)^{\gamma+\xi}]/[(1+\varepsilon^{-1})(\gamma+\xi)]\}$$

$$(T < T_m)$$

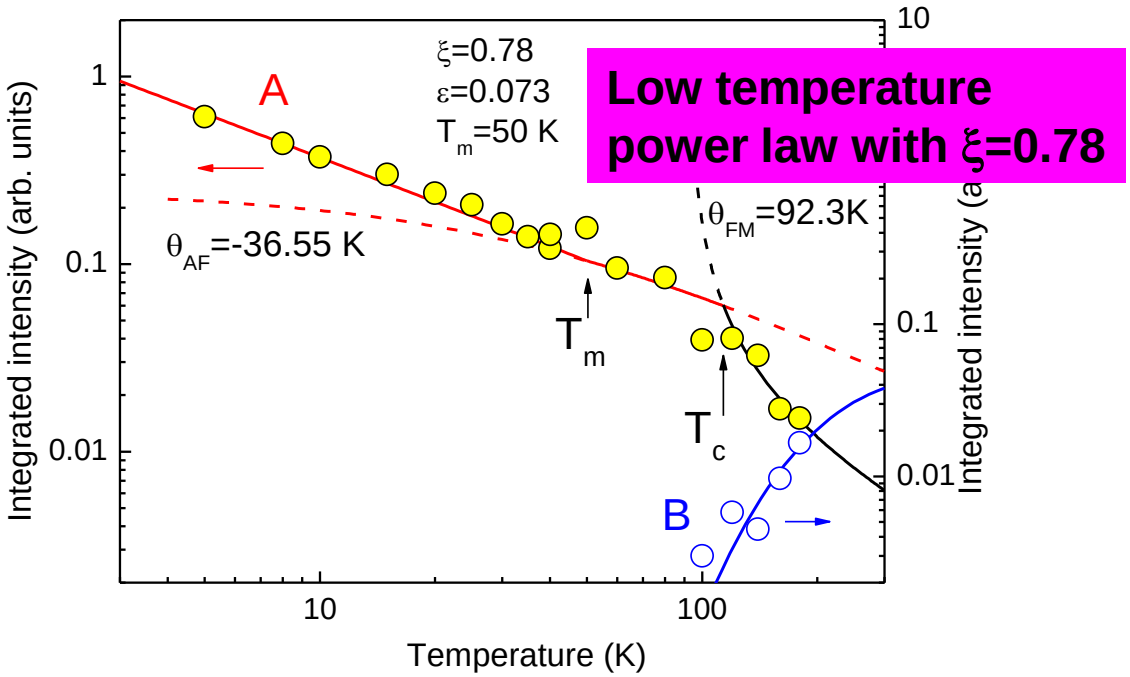
$$\theta^* = T_m[\varepsilon(1-\xi) f(\varepsilon,\xi)]^{-1} - 1 \qquad f(\varepsilon,\xi) = -\xi^{-1} - \sum_{r=1}^{\infty}(-1)^r \varepsilon^r / (r+\xi) + \pi\varepsilon^{-\xi} / \sin[\pi(1-\xi)]$$

QC phenomena in VO_x nanomaterials: theory vs. experiment.

Low temperature anomaly



VO_x nanotubes



Low temperature power law with ξ=0.78

The model:

Distribution of Neel temperatures in the sample:

$$w(T_N) = (1-\xi)(T_m / T_N)^{\xi} / T_m$$

Susceptibility of the cluster with T_N:

$$\chi = C/(T + \varepsilon^{-1} T_N) \qquad (T > T_N)$$

$$\chi = C(T/T_N)^{\gamma} / [T_N(1+\varepsilon^{-1})] \qquad (T < T_N)$$

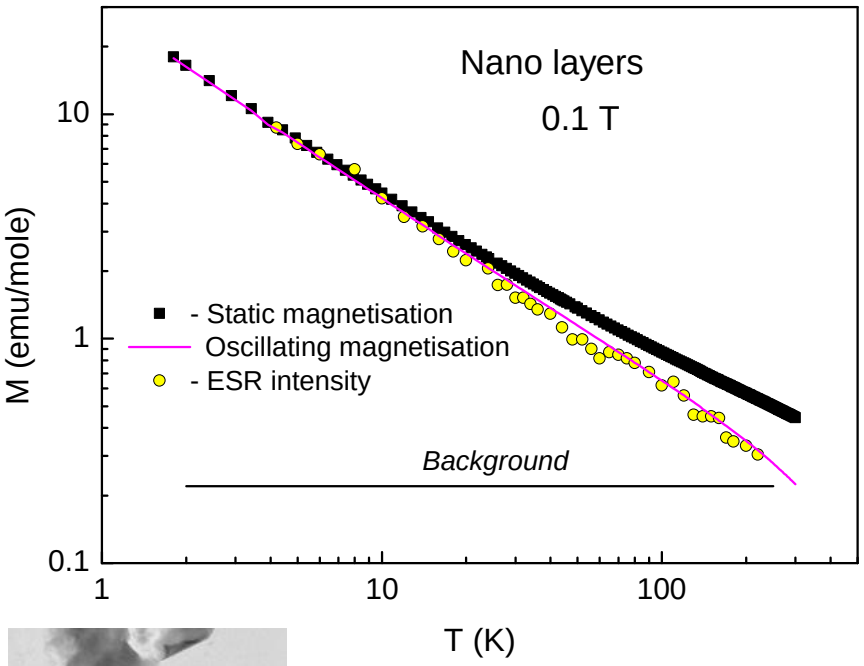
Result (susceptibility at arbitrary temperature):

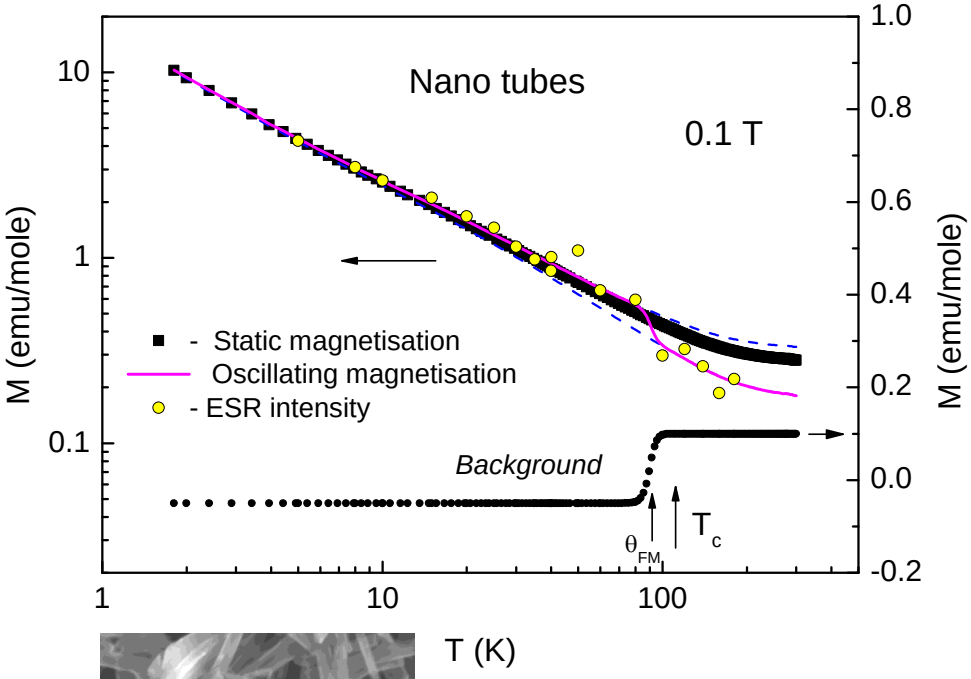
$$\chi = C/(T+\theta^*) \qquad (T > T_m)$$

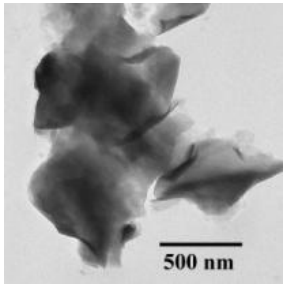
$$\chi = [C/(T_m+\theta^*)](T/T_m)^{-\xi}\{1+(1-\xi)(1+\theta^*/T_m)[1-(T/T_m)^{\gamma+\xi}]/[(1+\varepsilon^{-1})(\gamma+\xi)]\} \qquad (T < T_m)$$

$$\theta^* = T_m[\varepsilon(1-\xi) f(\varepsilon,\xi)]^{-1} - 1 \qquad f(\varepsilon,\xi) = -\xi^{-1} - \sum_{r=1}^{\infty}(-1)^r \varepsilon^r / (r+\xi) + \pi\varepsilon^{-\xi} / \sin[\pi(1-\xi)]$$

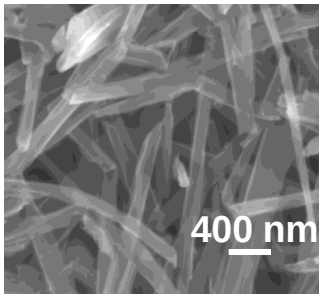
VO_x nanomaterials: static and dynamic magnetic properties.







VO_x nano layers



VO_x nanotubes

$$M = M_{osc} + M_b$$

SQUID (static)

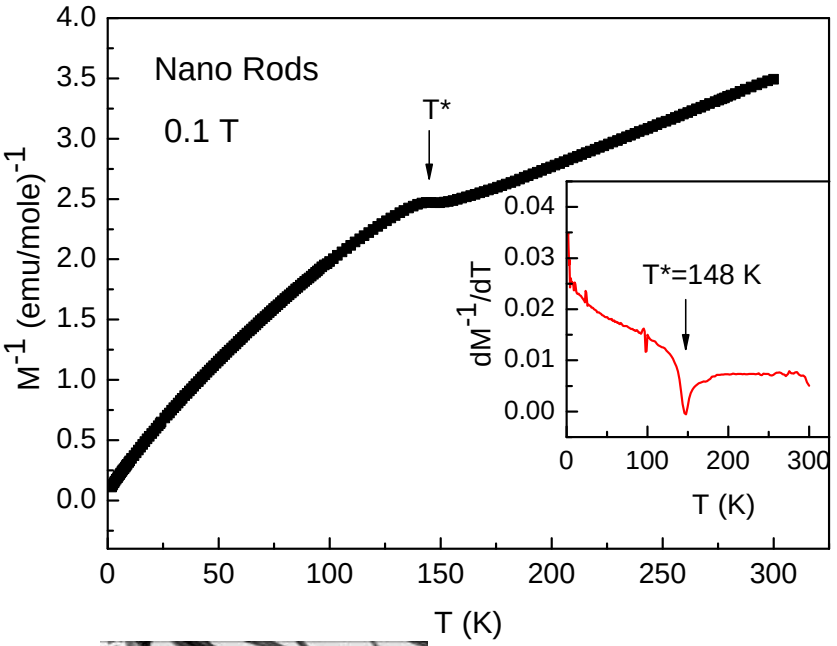
ESR (dynamic)

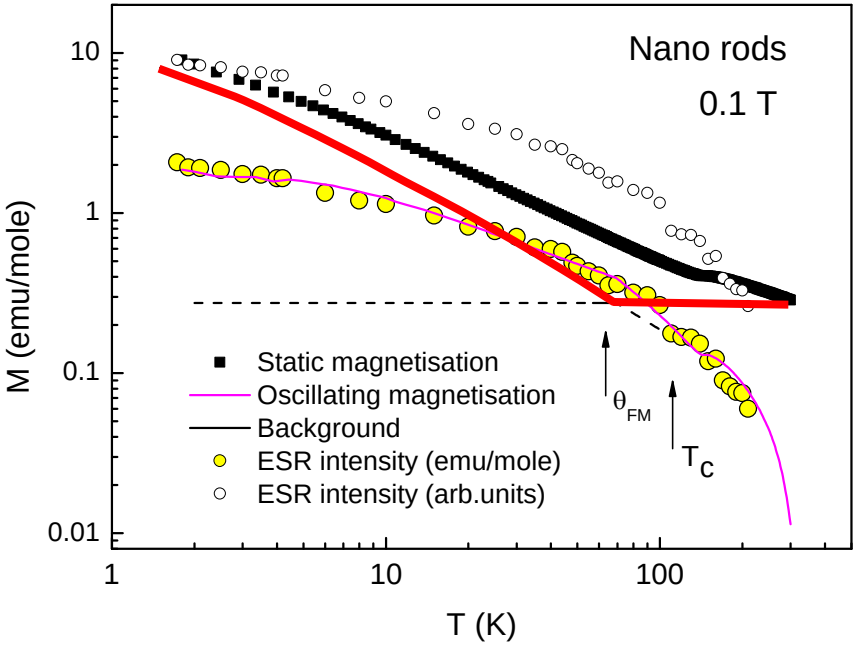
Background

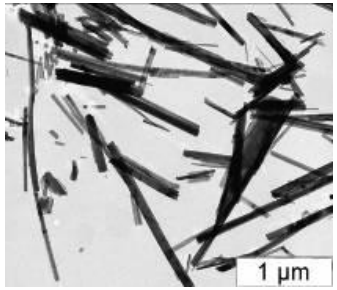
Simple Van Vleck type background structure.

Change of the background in the FM-AFM crossover region.

Mystery of the VO_x nanorods: static vs. dynamic magnetisation.







VO_x nanorods

Magnetic transition in static magnetisation at T^*~148 K > T_c (not pronounced in ESR).

Two types of V^{4+} with "high" and "low" spin fluctuation rate ?

M_b=const only for T >θ_{FM} !
Strong increase of the non-oscillating part of magnetisation in the range T >θ_{FM}.

Is this related with ferromagnetism ?

Conclusions.

Results:

Ferromagnetic – antiferromagnetic crossover in variuos VO_x nano-materials.

Type of magnetic interactions may be controlled by concentration of V^{4+} ions. FM interactions correspond to diluted case and AFM interactions correspond to concentrated case.

Observation of the disorder driven quantum critical phenomena in VO_x nano-materials, including VO_x multiwall nanotubes.

Probably the first observation of the QC behavior in nanomagnets.

Direct ESR evidence of the presence of the V^{4+} S=1/2 AF dimers in VO_x multiwall nanotubes.

Strange behavior of static magnetisation in VO_x nanorods. Effects of spin fluctuations ?

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Programme of RAS “Strongly correlated electrons” “Quantum physics of condensed matter”, the RFBR grants 07-03-00749-a, 07-03-12182-ofi, 09-03-01122-a and 09-03-00602-a.

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