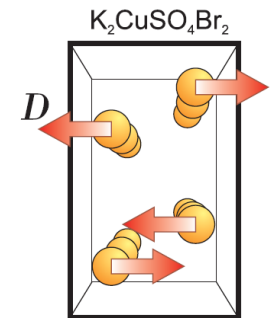
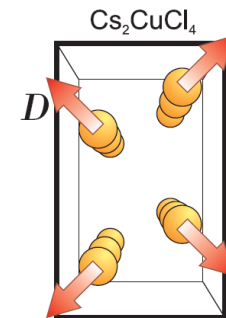
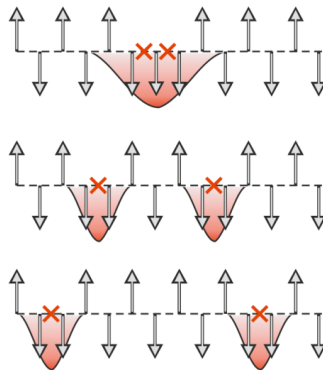
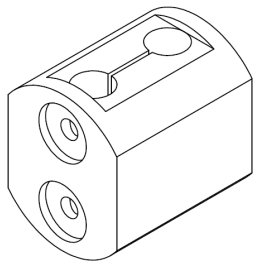


Магнитный резонанс спинов и магнонов в квантовых магнетиках

А.И.Смирнов



Институт физических проблем им. П. Л. Капицы РАН



СПЕКТРИНА 2016 Гатчина

Кооперация



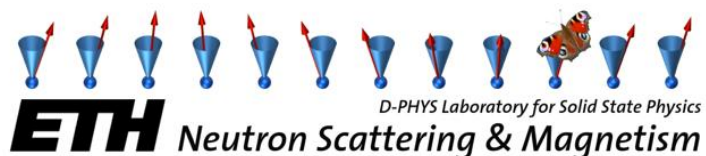
ИФП РАН им П.Л. Капицы
*К.Ю. Поваров, Т.А. Солдатов,
С.В. Петров*



О.А. Старых



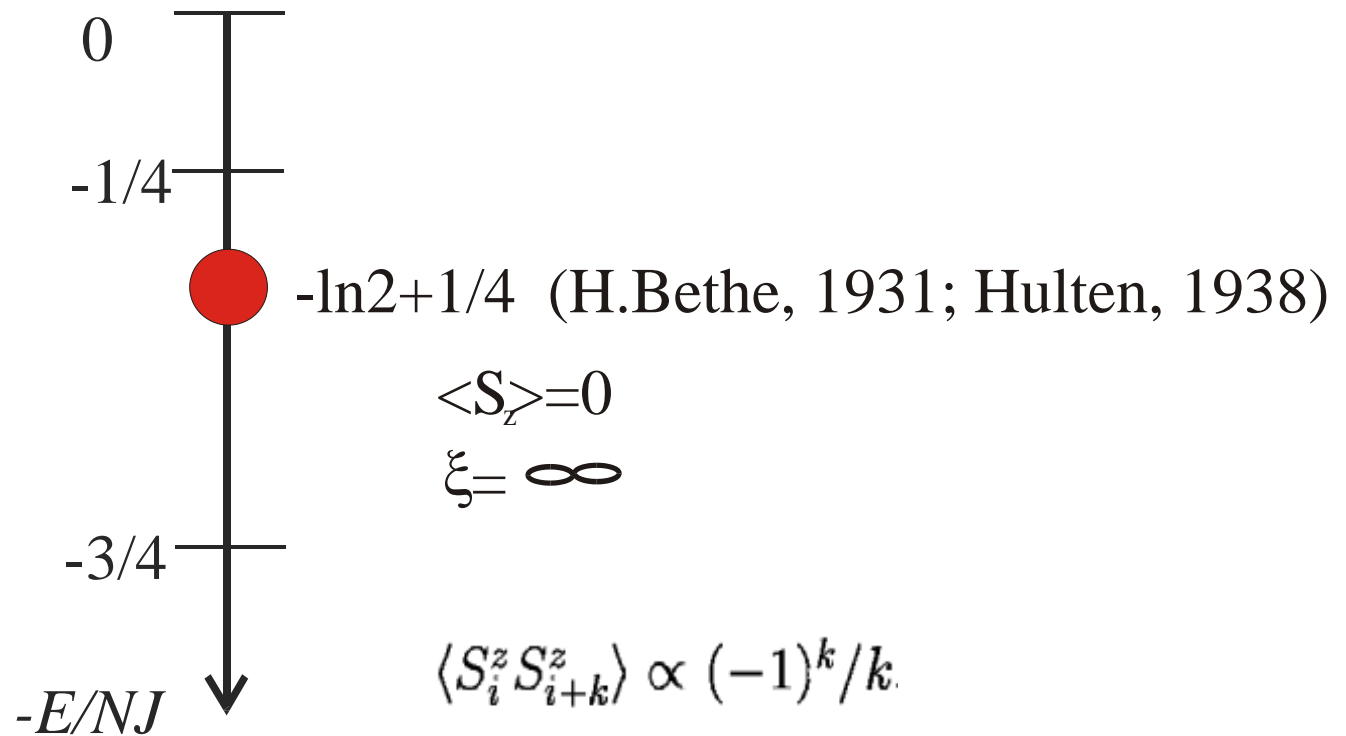
А.Я. Шапиро



M. H'alg, W. E. A. Lorenz, and A. Zheludev

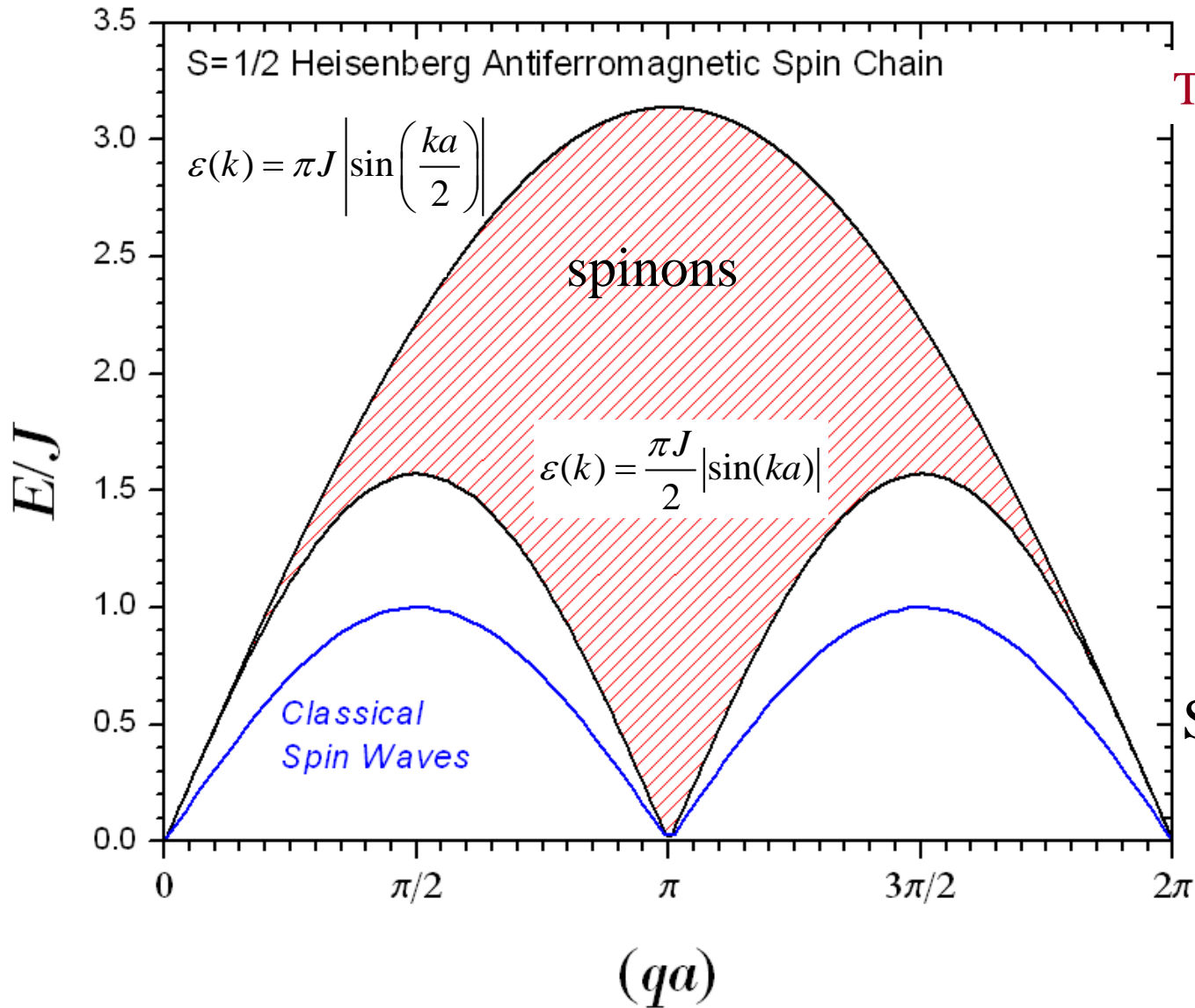
В гейзенберговской $S=1/2$ спиновой цепочке нет неелевского порядка даже при $T=0$

Ground state of $S=1/2$ chain

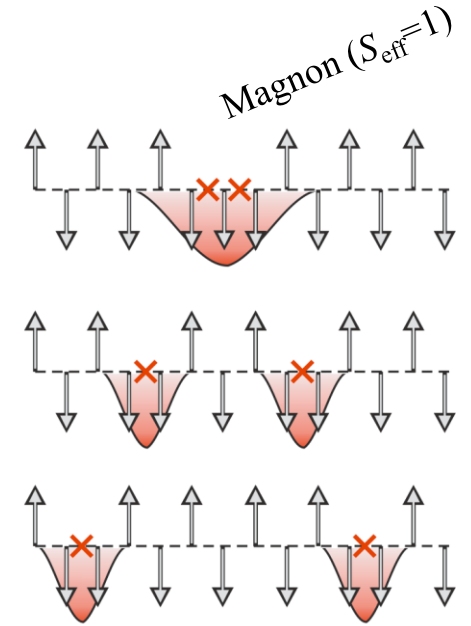


$T=0$ is the critical point

Спектр возбуждений в $S=1/2$ АФМ цепочке



Two-spinon continuum



Spinons carry $S=1/2$

¹ L. D. Faddeev and L. A. Takhtajan, "What is the spin of a spin wave?" Phys. Lett. A, 85, 375 (1981).

Multispinon Continua at Zero and Finite Temperature in a Near-Ideal Heisenberg Chain

B. Lake,^{1,2,*} D. A. Tennant,^{1,2} J.-S. Caux,³ T. Barthel,⁴ U. Schollwöck,⁴ S. E. Nagler,⁵ and C. D. Frost⁶

KCuF₃

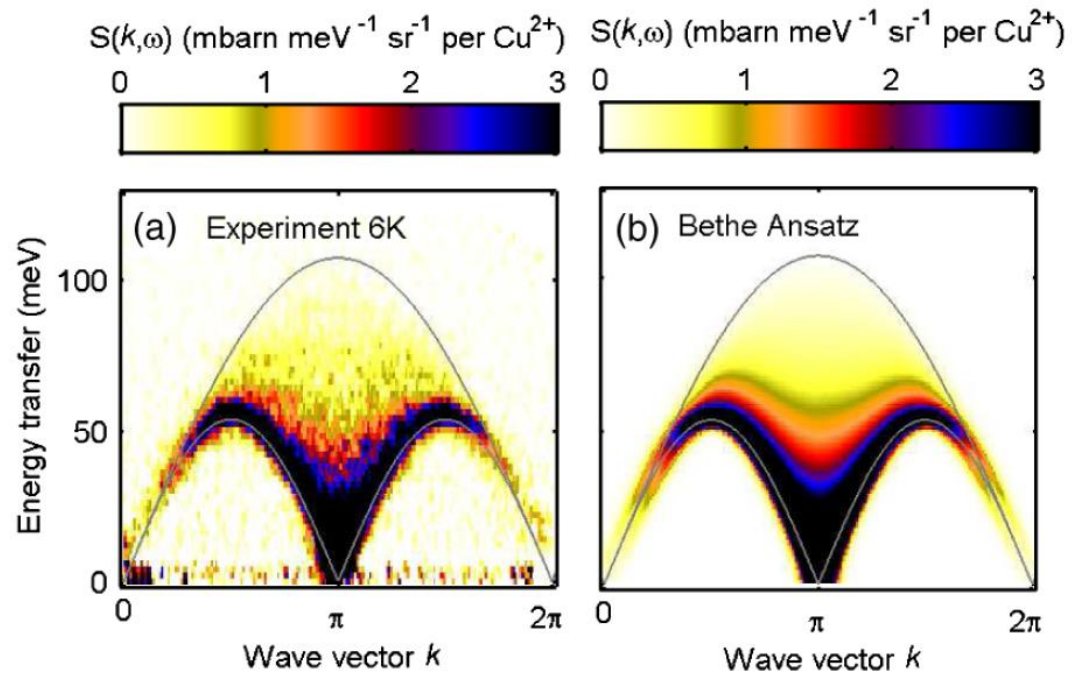
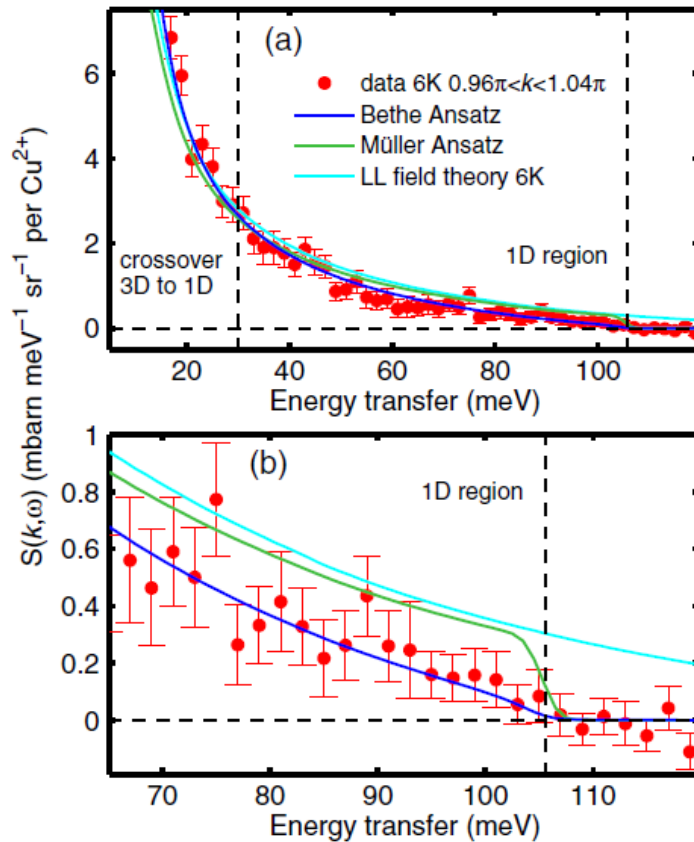


FIG. 1 (color online). INS data compared to theory. (a) The data show the multispinon continuum lying predominantly between the upper ($\omega_u(k)$) and lower ($\omega_l(k)$) boundaries for 2-spinon processes (gray lines). (b) The dynamical structure factor computed via the algebraic Bethe ansatz.

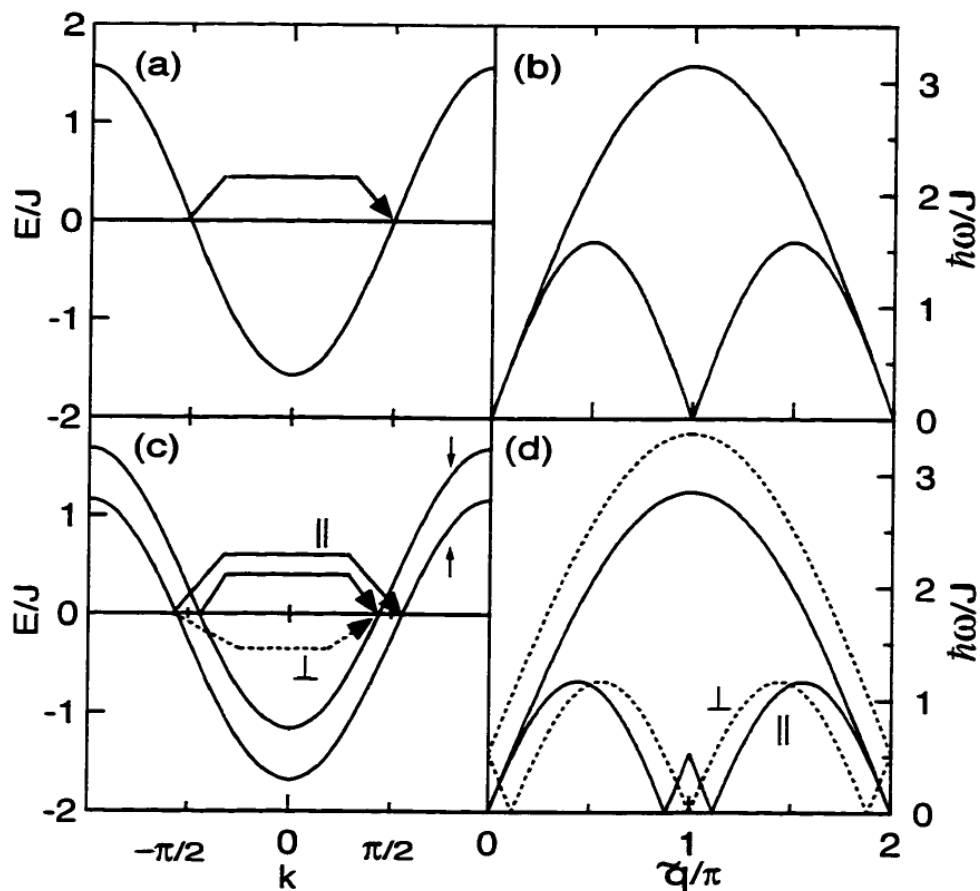


B.Lake et al PRL 2013

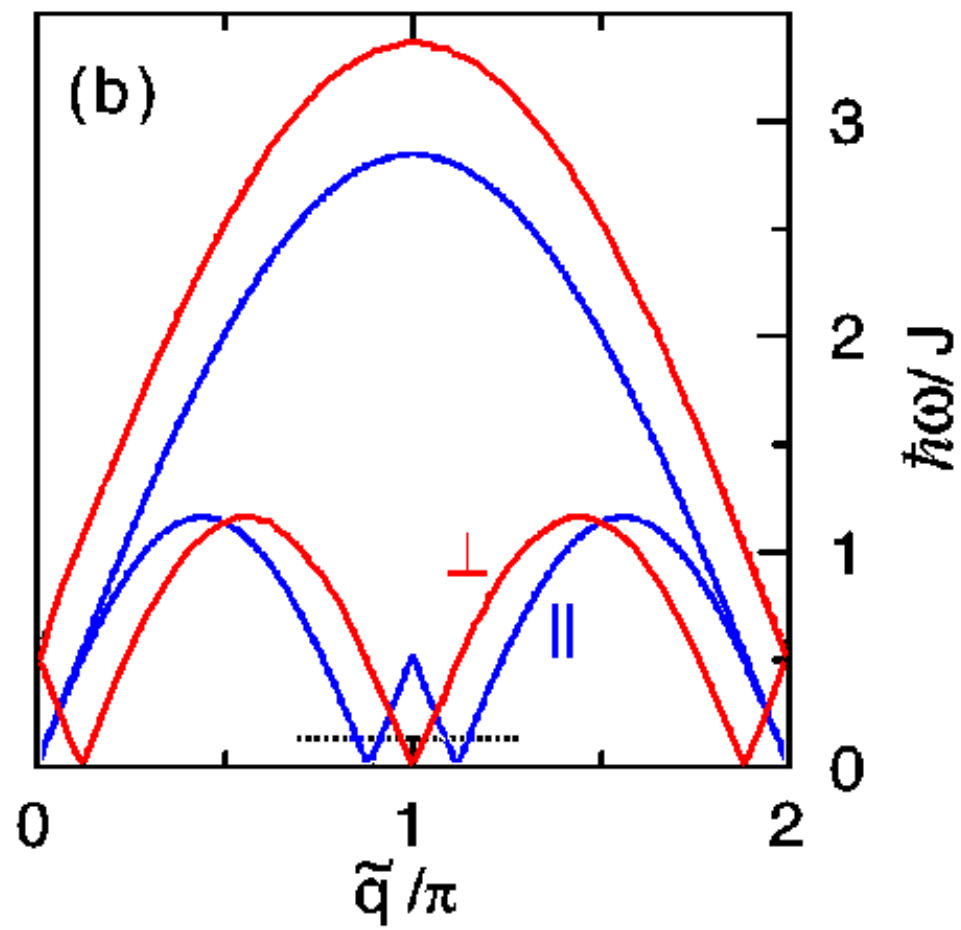
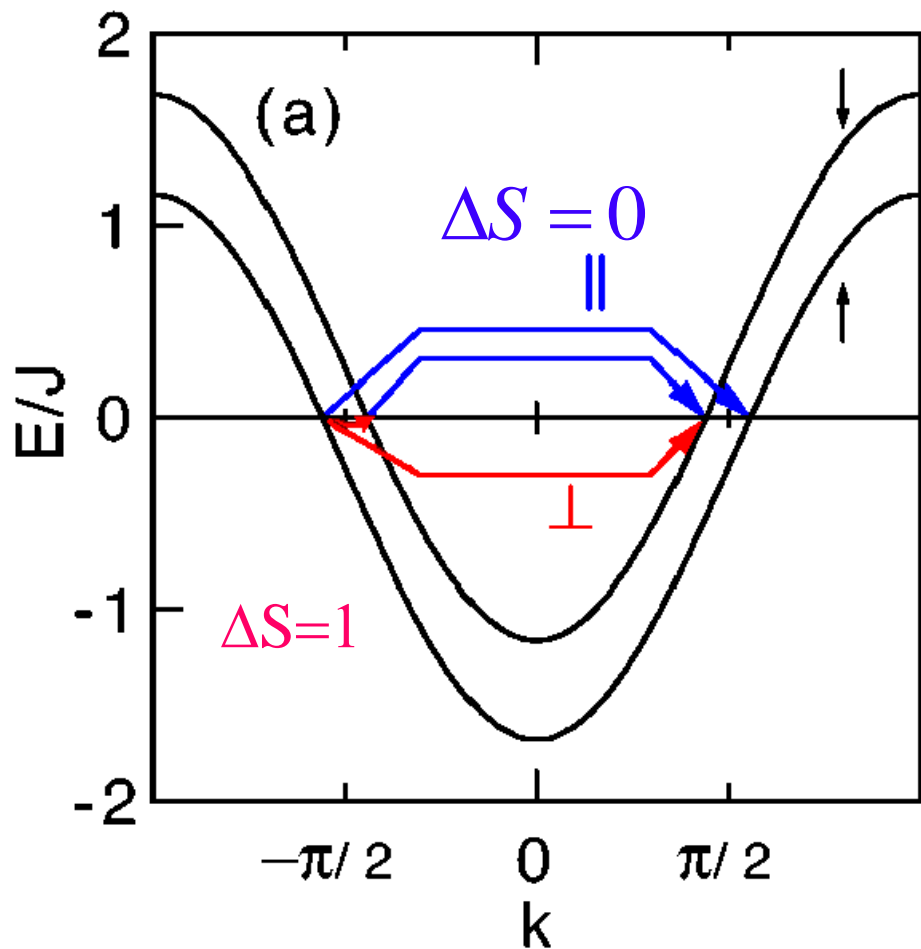
FIG. 2 (color online). Comparison of the INS data at $k = \pi$ and $T = 6$ K, with the theoretical approaches. (a) The data agree approximately with the Luttinger liquid, Müller ansatz, and algebraic Bethe ansatz. (b) Differences between the theories increase at higher energies and the Luttinger liquid and Müller ansatz show strong discrepancies with the data near the 2-spinon upper threshold.

Континум двухспиновых возбуждений описывается на основе фермионного представления гейзенберговского и зеемановского гамильтонианов.

$$\mathcal{H}_{MF} = \sum_{\alpha q} \left[-J\gamma \cos q - \frac{1}{2}g\mu_B H(\delta_{\alpha\uparrow} - \delta_{\alpha\downarrow}) \right] c_{\alpha q}^+ c_{\alpha q},$$



Spinons: fermions



Fermions confirmed by neutron scattering: soft modes near $q=\pi$

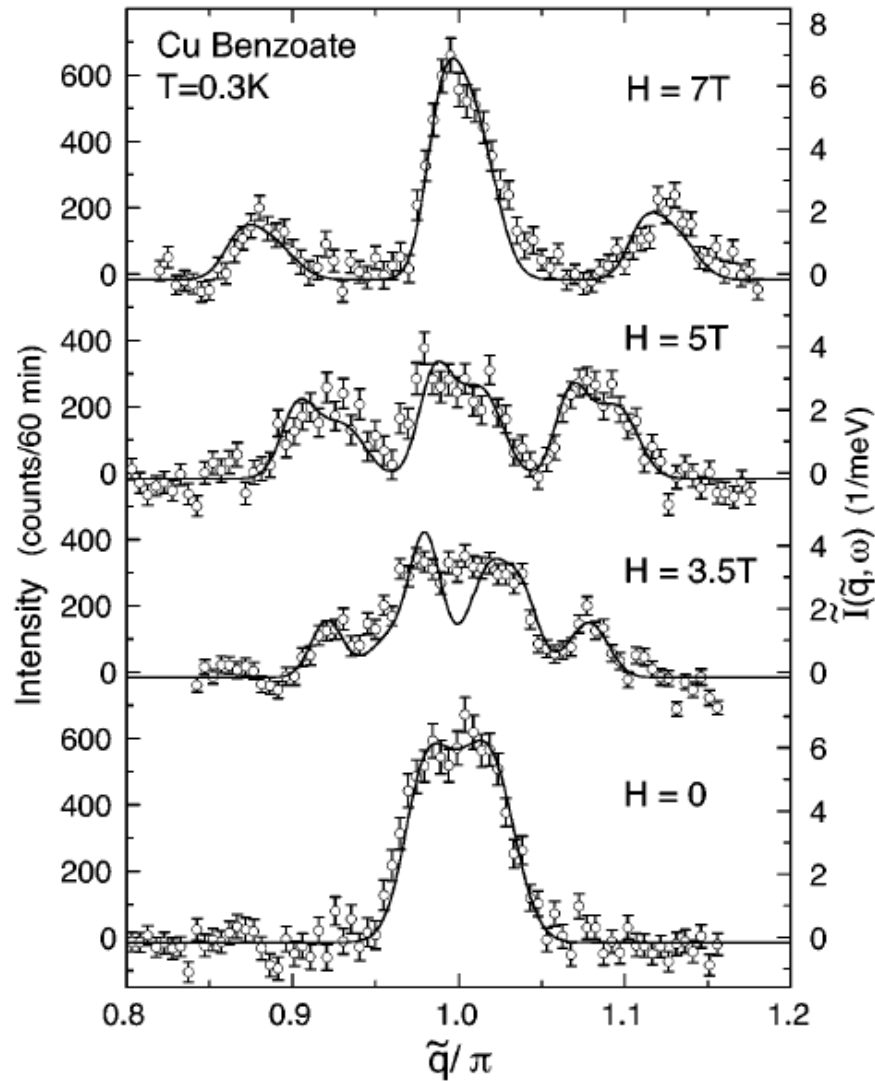
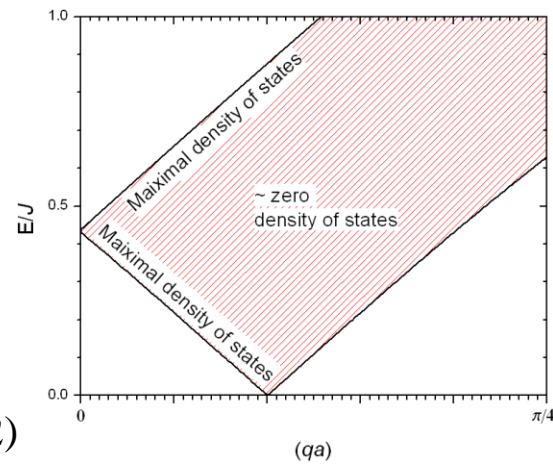
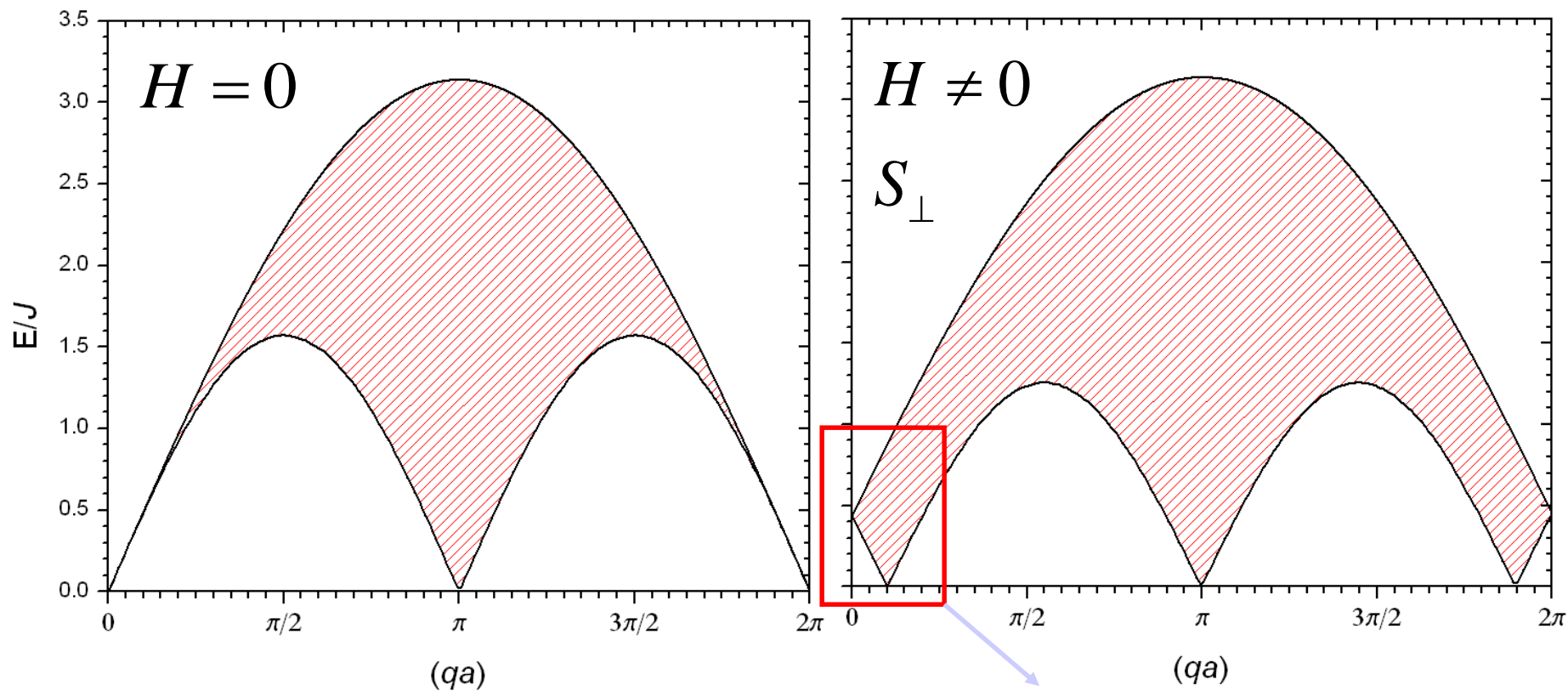


FIG. 2. Magnetic scattering at $\hbar\omega = 0.21$ meV along the $(0.3, 0, l)$ direction for four values of magnetic field H at $T =$

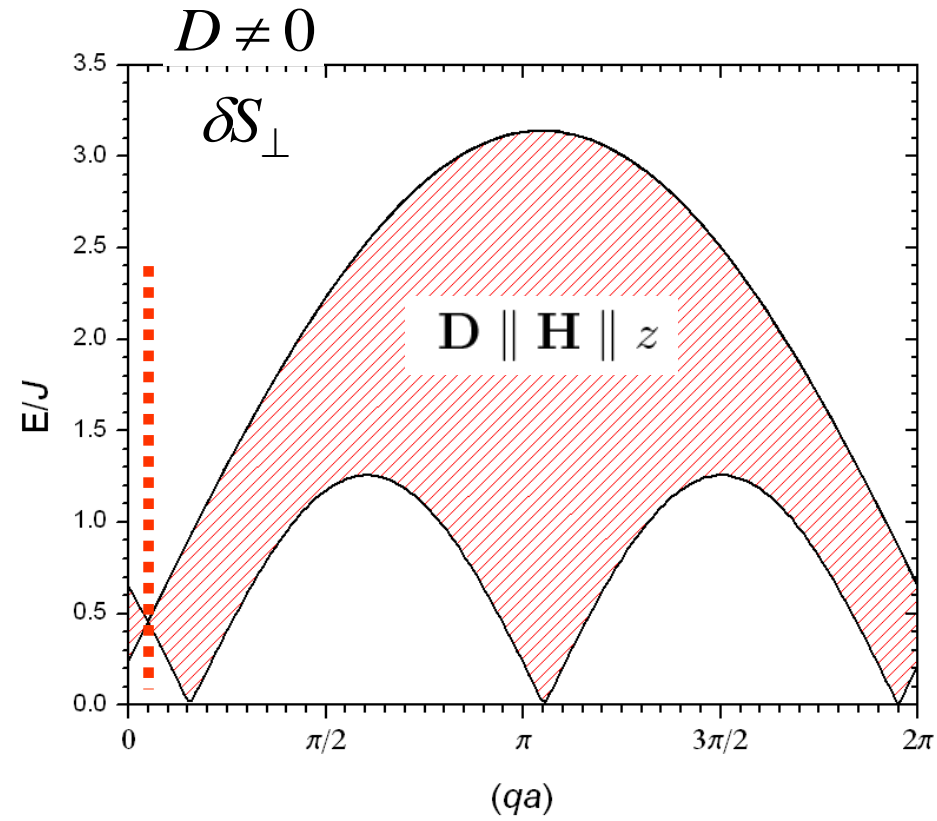
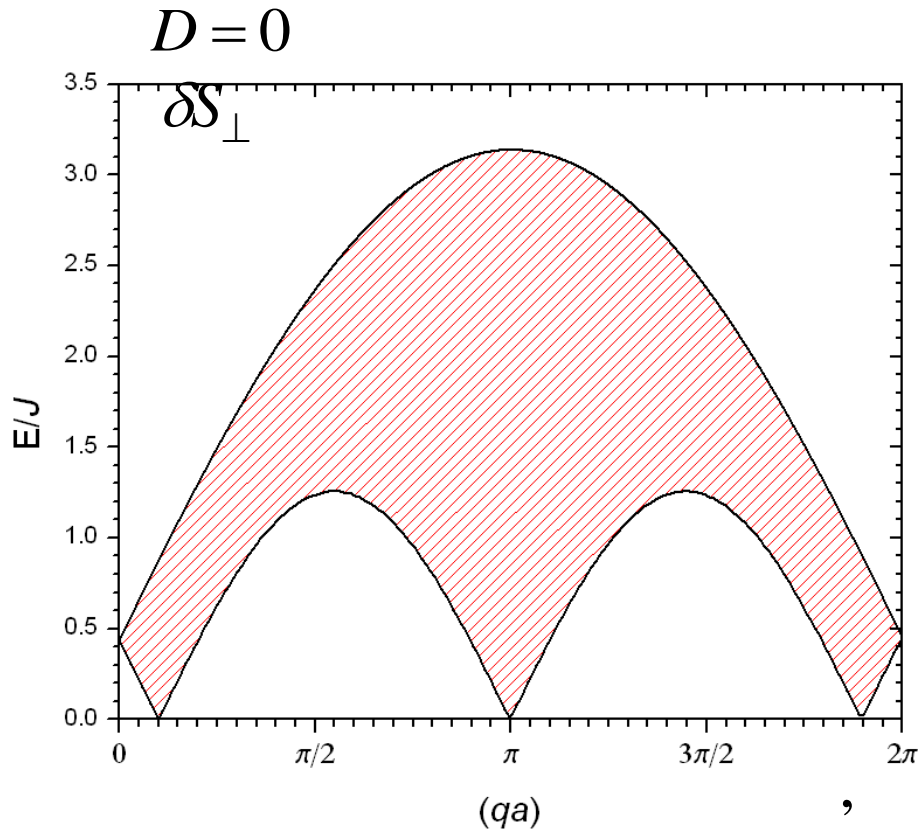
Континуум в магнитном поле (для поперечных флуктуаций)



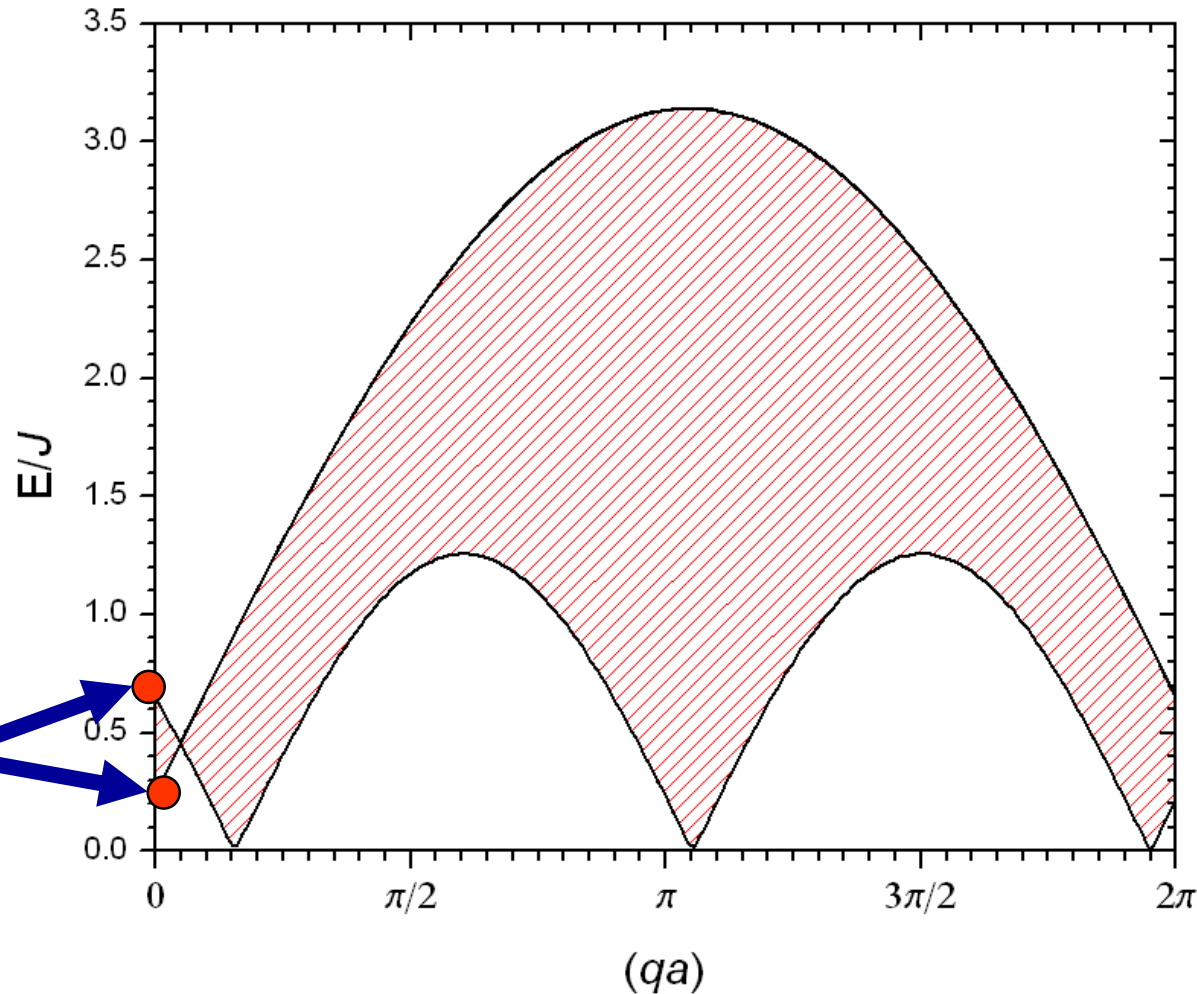
$$\mathcal{H} = \sum_n J(\mathbf{S}_n \cdot \mathbf{S}_{n+1}) + (\mathbf{D} \cdot [\mathbf{S}_n \times \mathbf{S}_{n+1}]) - \mu_B g(\mathbf{H} \cdot \mathbf{S}_n)$$

Преобразование $S_n^+ = \tilde{S}_n^+ e^{i\alpha n}$, $\alpha = -D/J$ зануляет (в главном порядке) действие ВДМ

Однако порождает сдвиг $\delta q = DJ/a$



Спинонный дублет при $q=0$ для $H//D$



$$H \neq 0$$

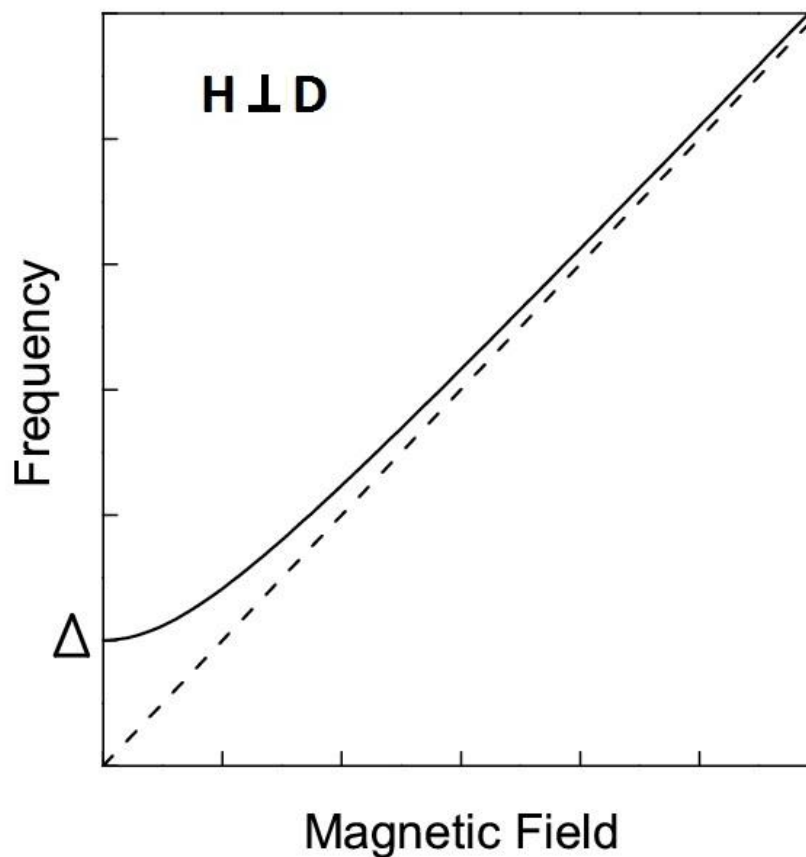
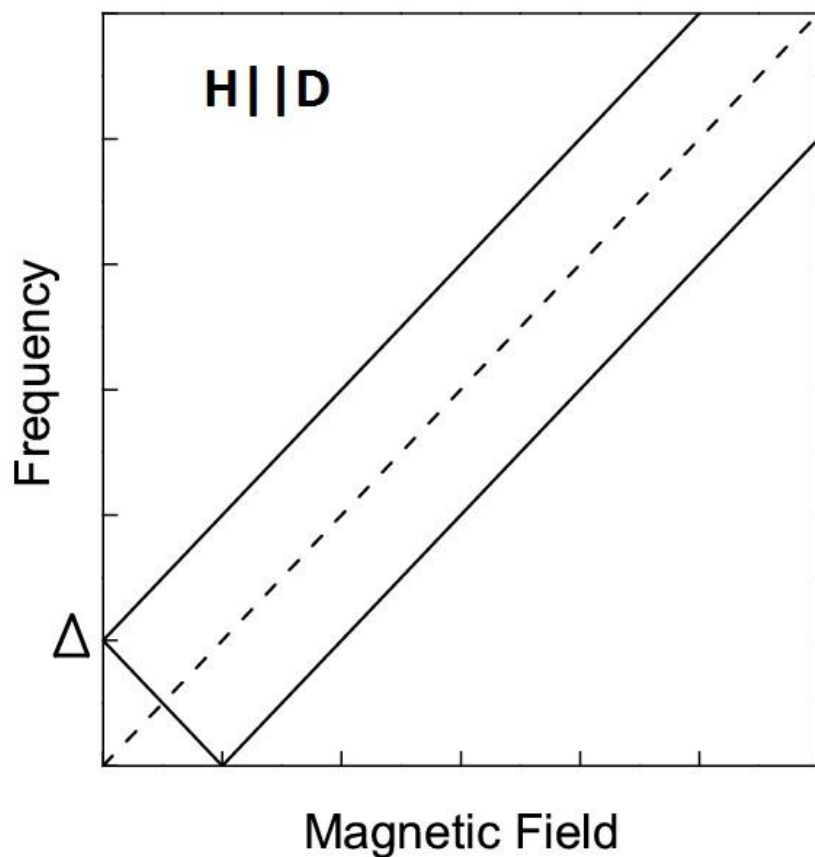
$$S_{\perp}$$

$$D \parallel H \parallel z$$

Resonant
frequencies

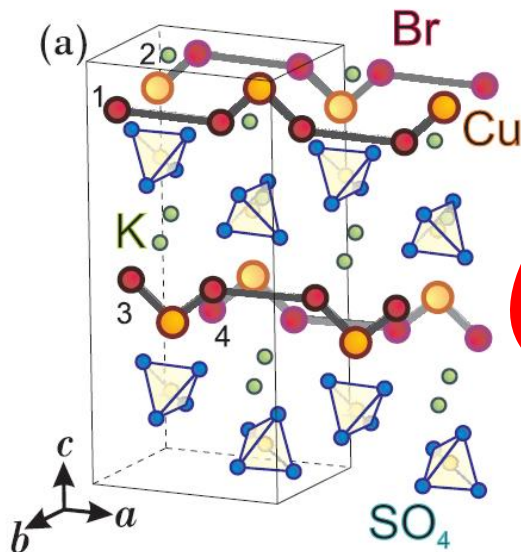
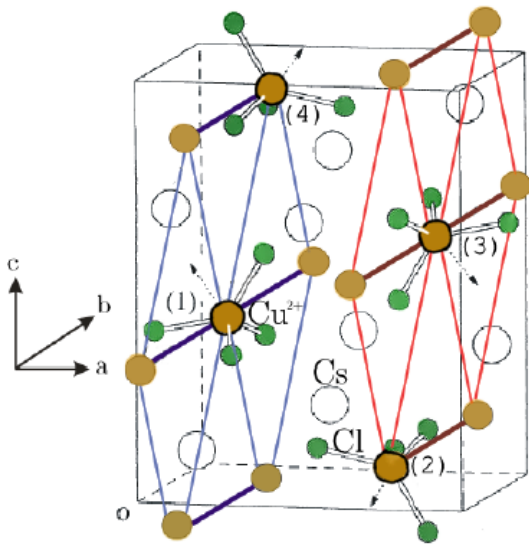
Дублет является следствием континуума (фермионных возбуждений) и **однородного** взаимодействия Дзялошинского-Мории

Частотно-полевые зависимости для магнитного резонанса спинов в цепочке с *однородным* взаимодействием Дзялошинского-Мории



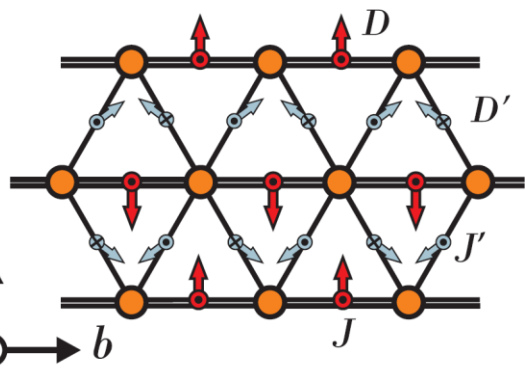
$$H \parallel D, \nu = g\mu_B H \pm \frac{\pi}{2} D$$

$$H \perp D, \nu = \sqrt{(g\mu_B H)^2 + \frac{\pi^2}{4} D^2}$$

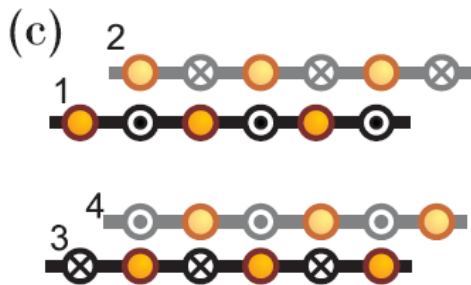
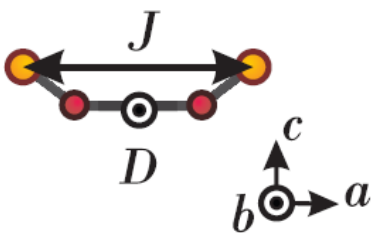


Пока известно только два
цепочечных АФМ
с однородным ВДМ

Cu^{2+} ($S=1/2$)

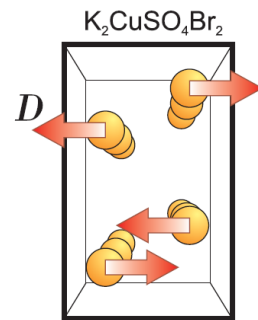
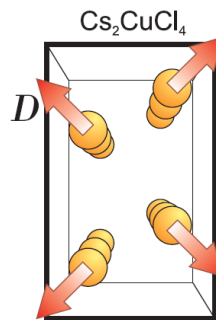


$J/J'=3$. J' is frustrated
 $J= 4 \text{ K}$ $T_N=0.6 \text{ K}$

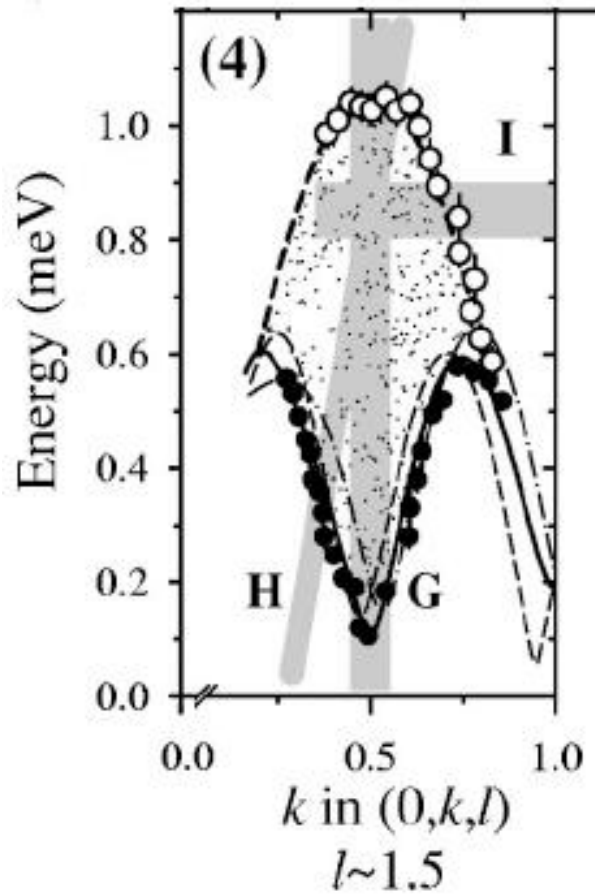


$J/J'=600$

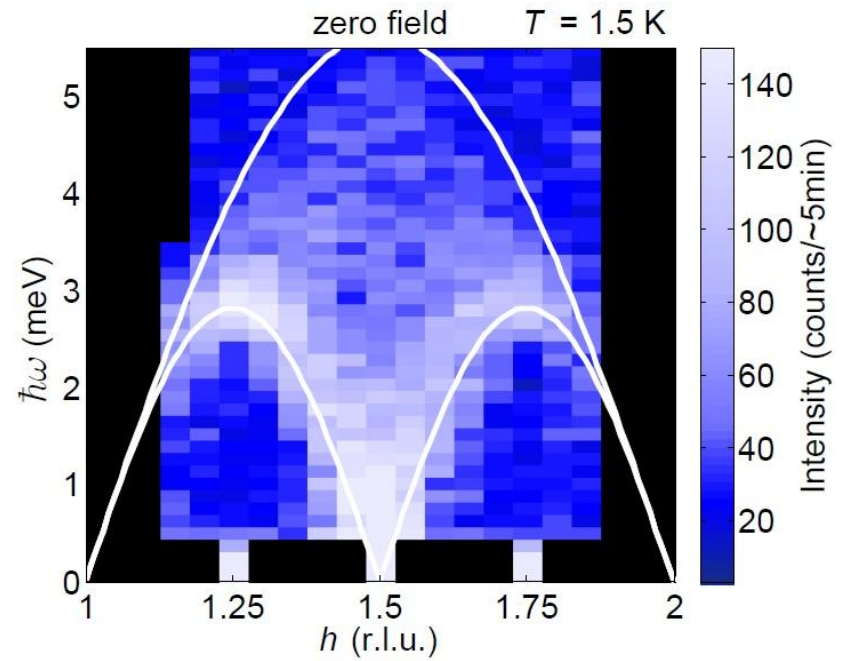
$J= 20 \text{ K}$
 $T_N \sim 0.07 \text{ K}$



$$\mathcal{H} = \sum_n J(\mathbf{S}_n \cdot \mathbf{S}_{n+1}) + (\mathbf{D} \cdot [\mathbf{S}_n \times \mathbf{S}_{n+1}]) - \mu_B g(\mathbf{H} \cdot \mathbf{S}_n)$$

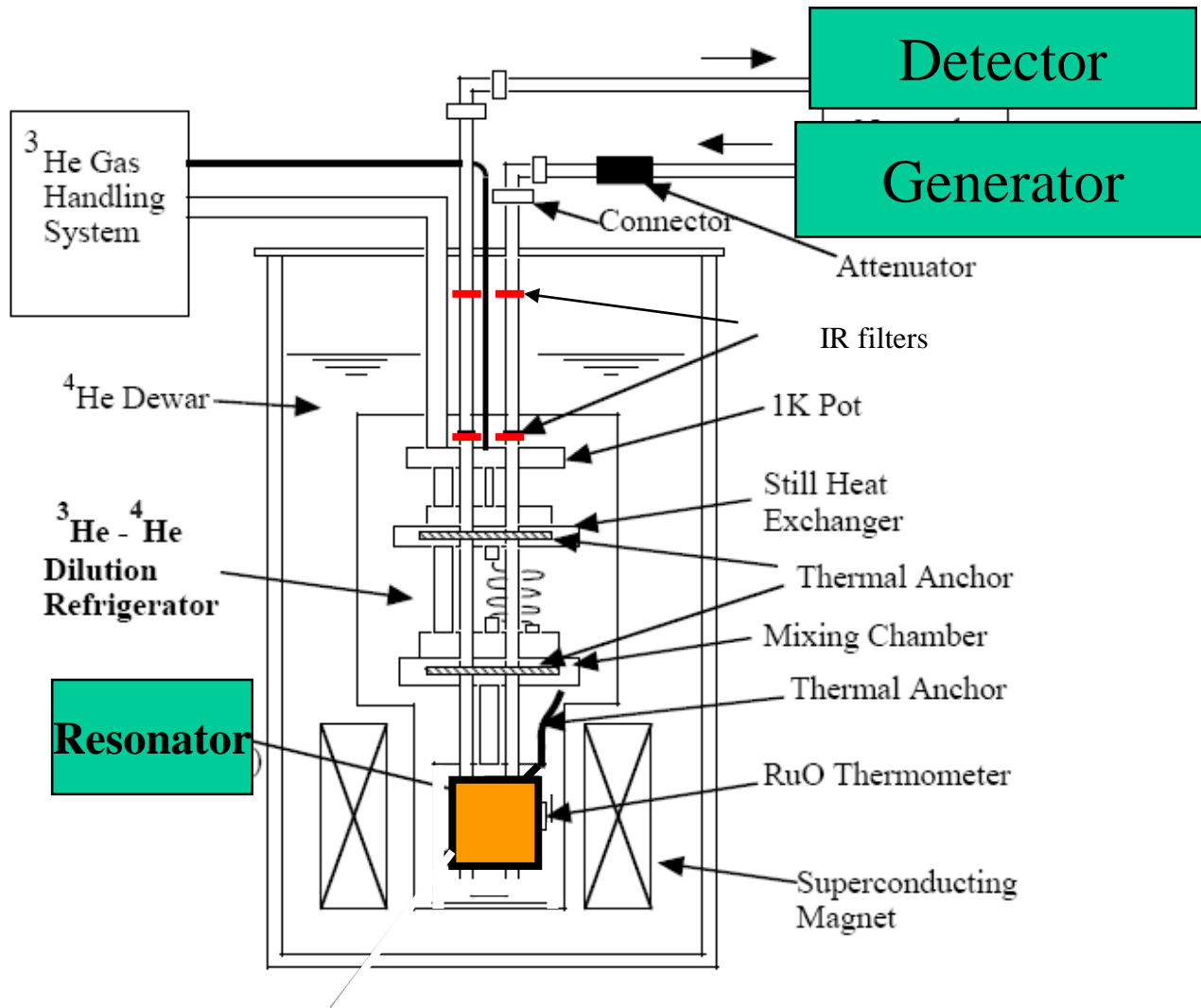


R. Coldea et al, PRB **68** 134424 (2003)



M. Hälg et al, PRB (2014)

Микроволновый спектрометр в криостате растворения



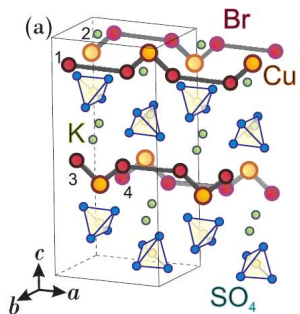
$T = 0.05-20\text{ K}$

$B = 14\text{ T}$

Freq. range 1-300 GHz

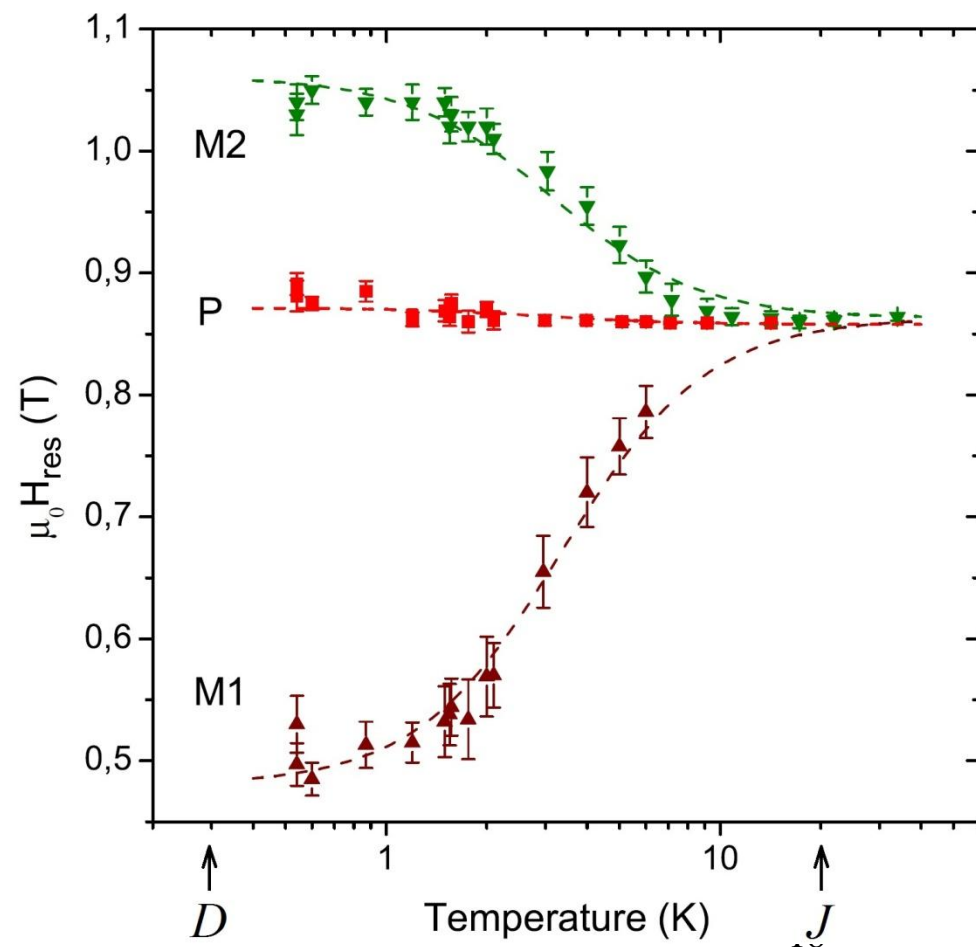
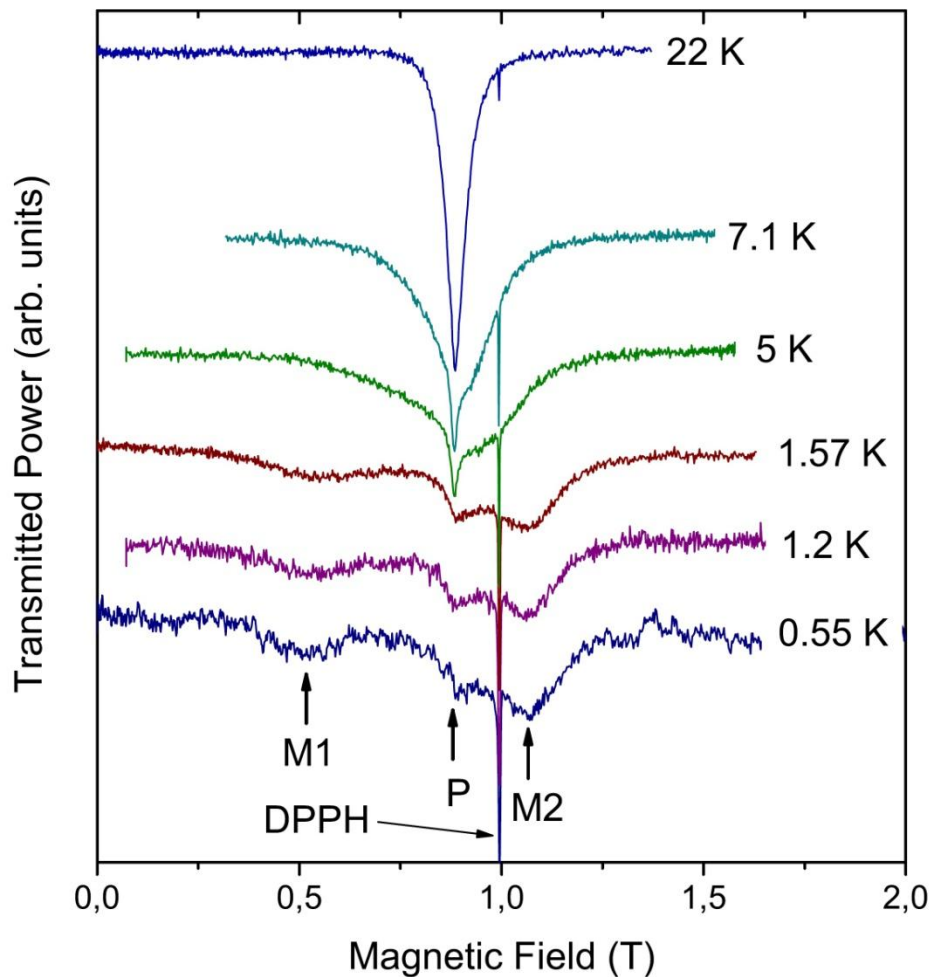
After Sakon et al JPSJ 72 (2003)





$\mathbf{H} \parallel \mathbf{D}$: при охлаждении появляется дублет линий

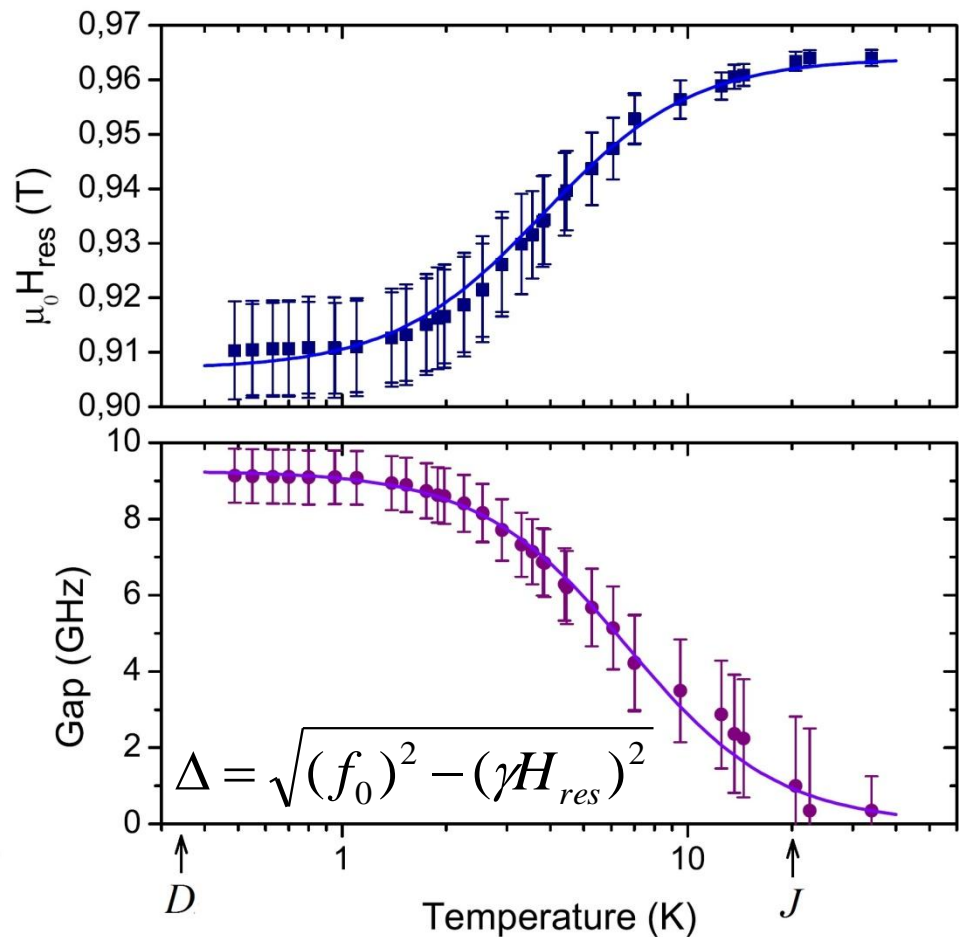
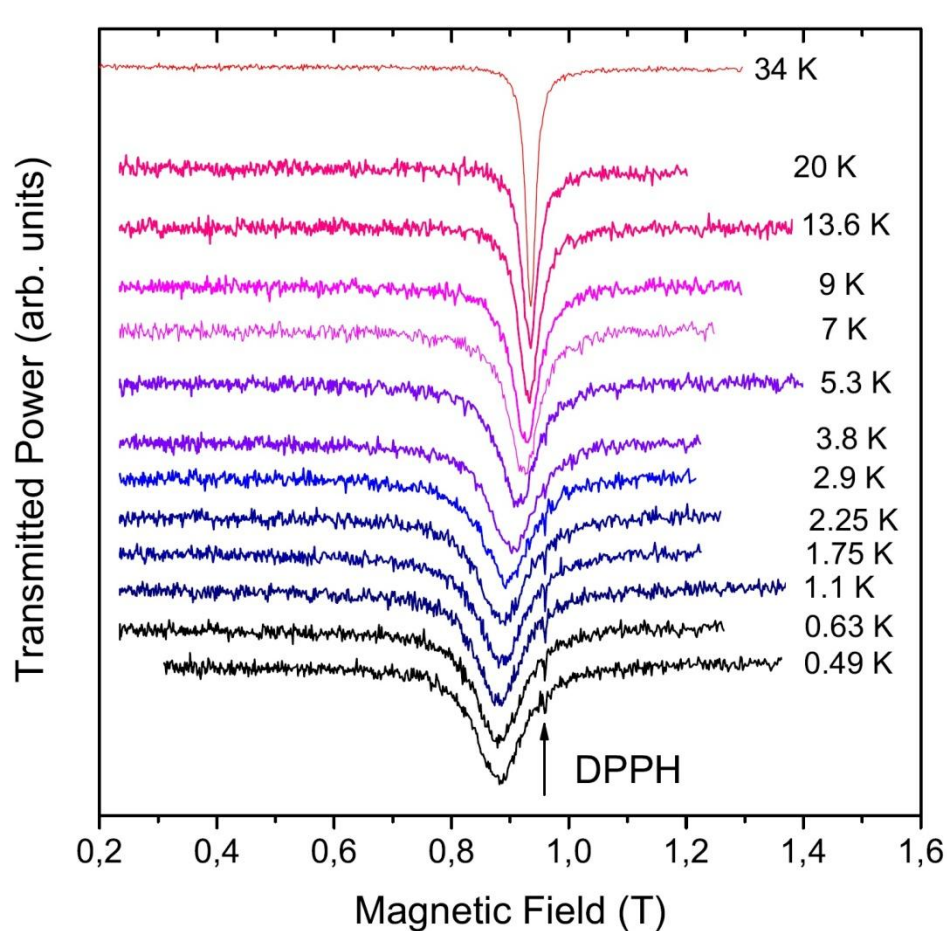
$\mathbf{H} \parallel b$ Частота 27.8 ГГц



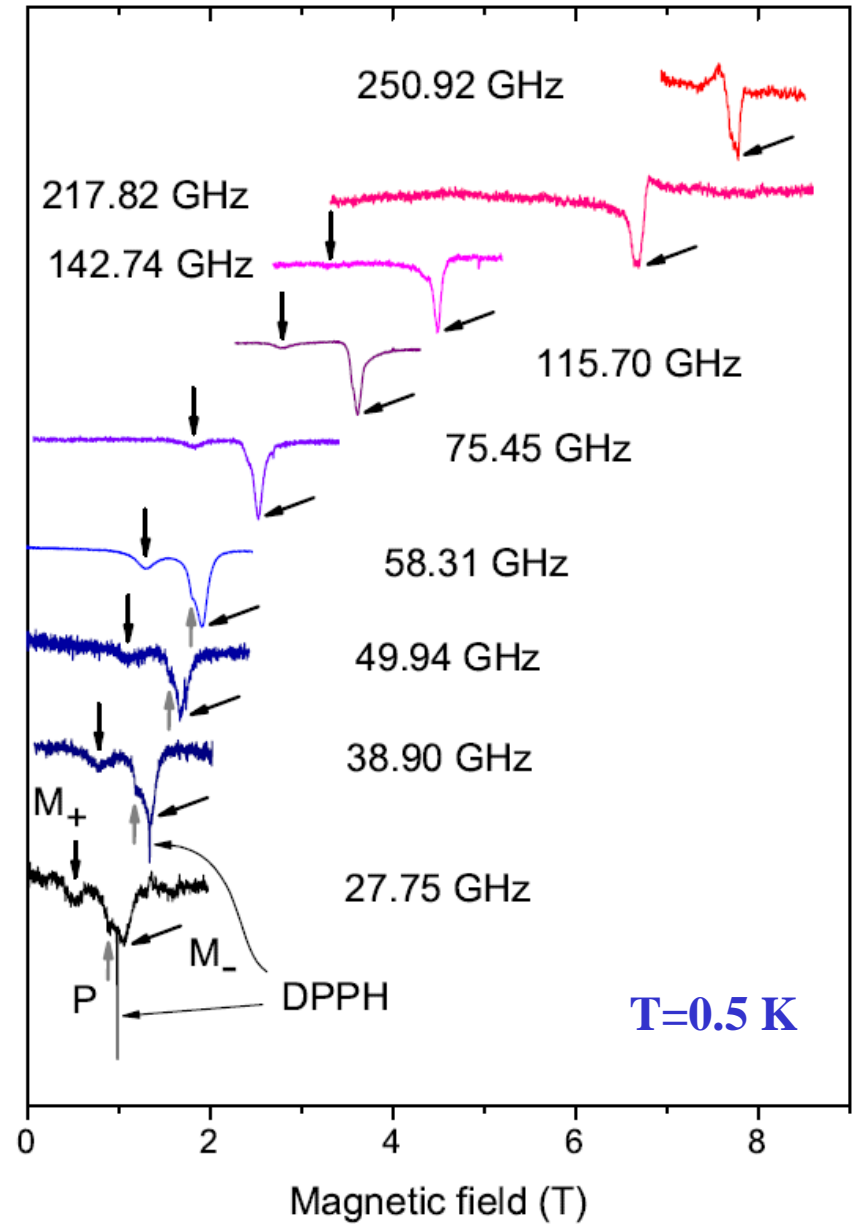
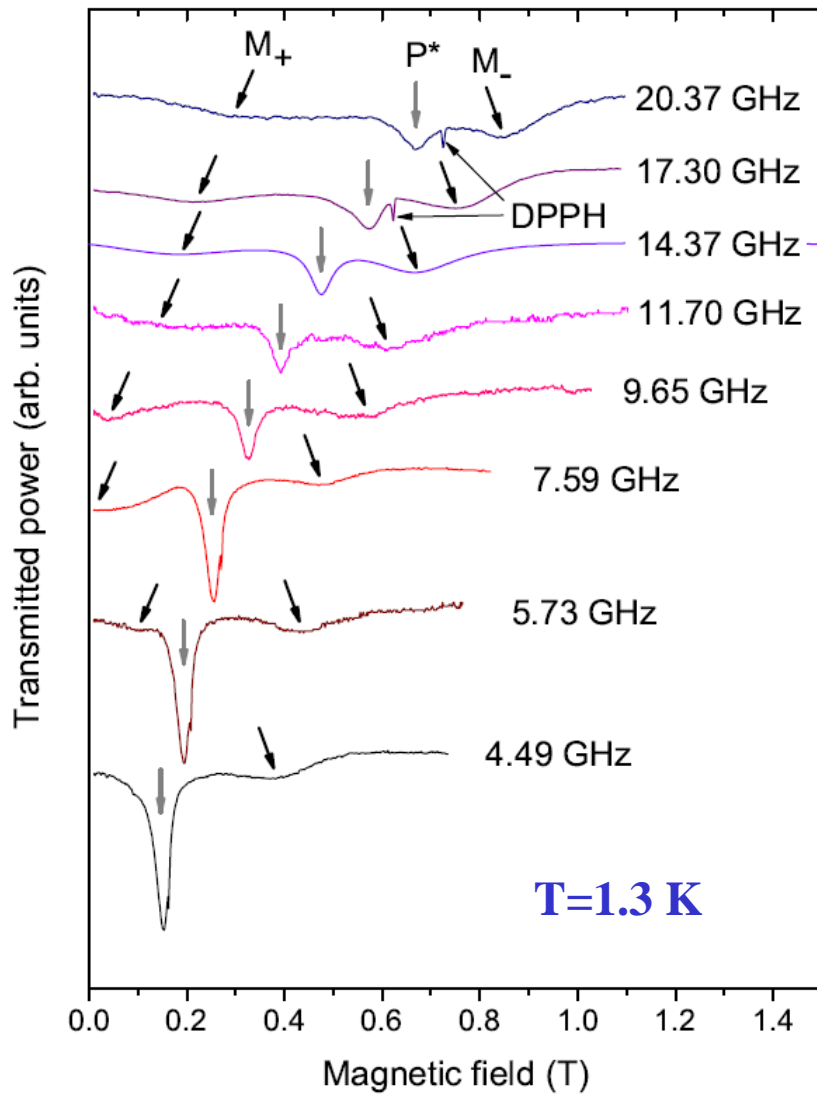
H \perp **D**: При охлаждении открывается щель $\Delta = 9$ GHz ($D=0.27$ K)

$$f = \sqrt{\Delta^2 + (\gamma H)^2}, \quad \gamma = \frac{g\mu_B}{2\pi\hbar}$$

H \parallel *a*, $f_0 = 27.8$ GHz



Линии магнитного резонанса на разных частотах для $\text{H}\parallel\text{D}$



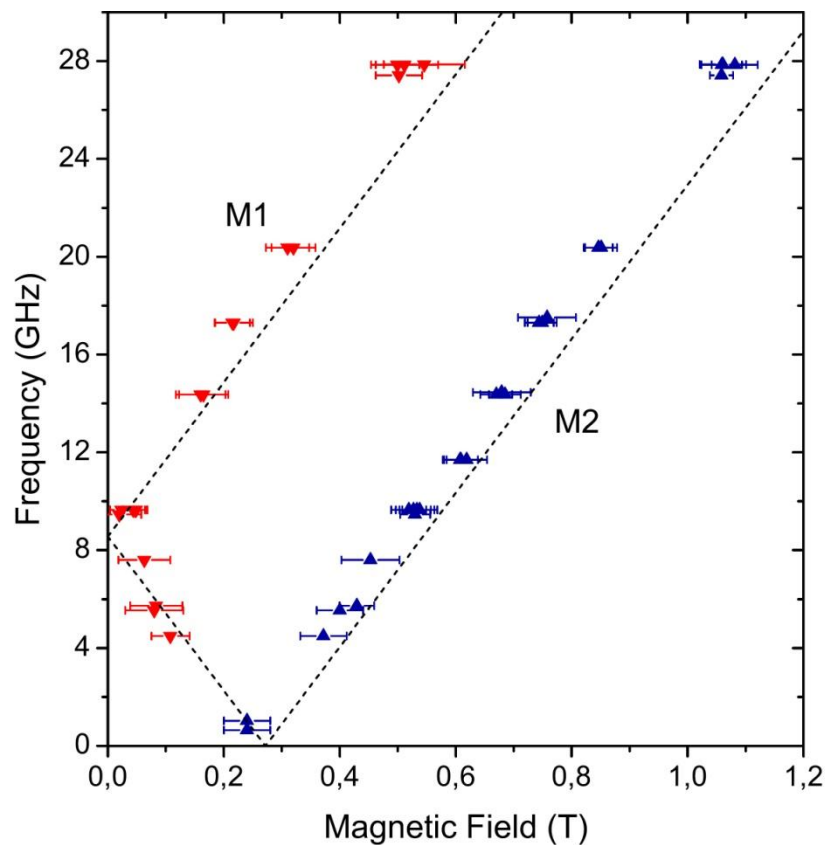
$H//D$

Спиновый дублет исчезает

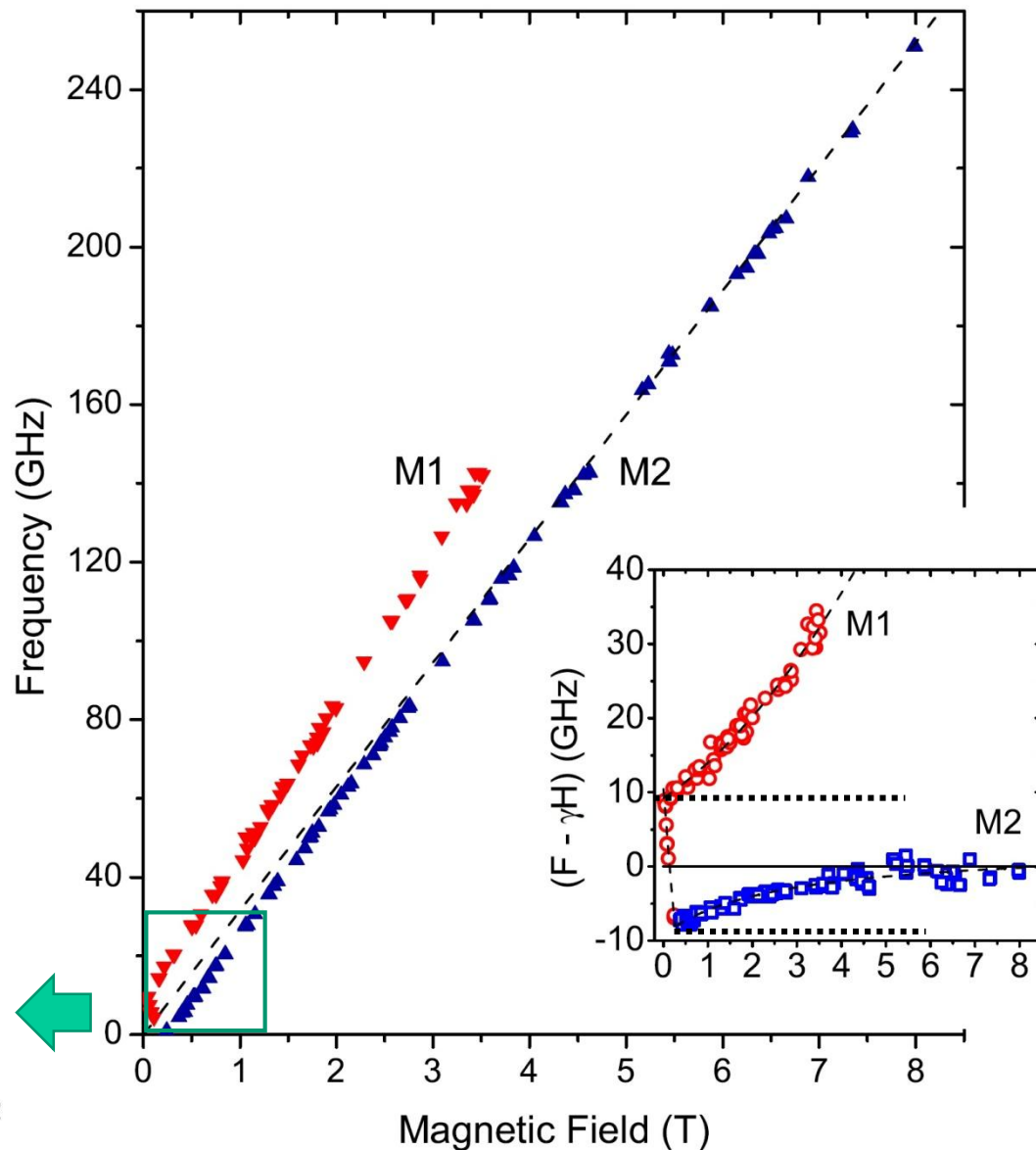
в поле $H_{col} \approx 3.5$ T

Пунктирные линии – теория при

$D = 0.27$ K



Здесь нет подгоночных параметров



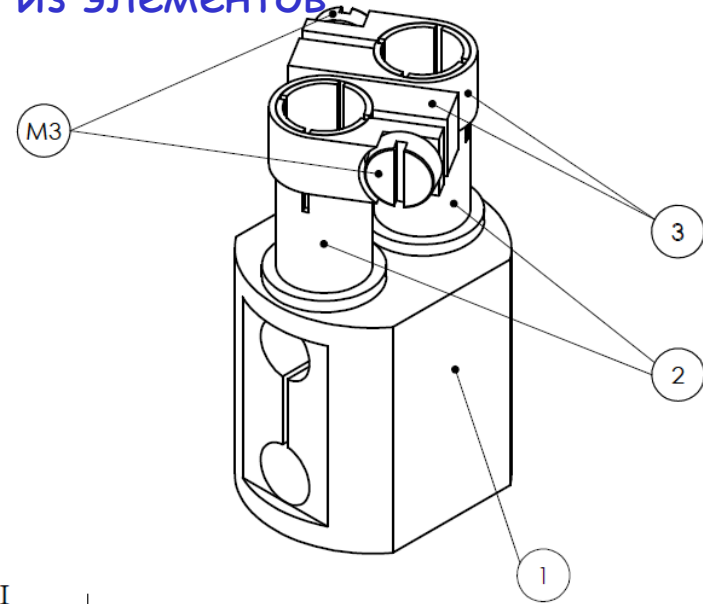
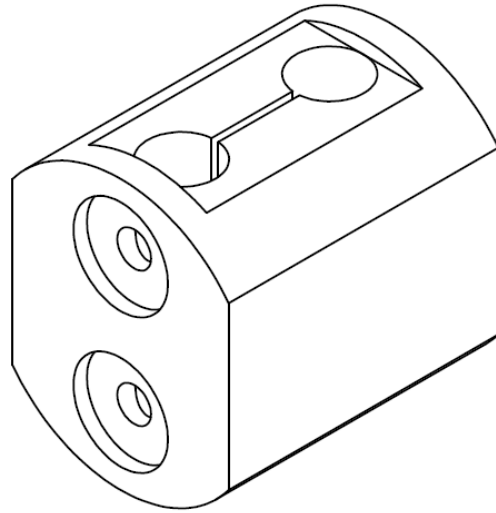
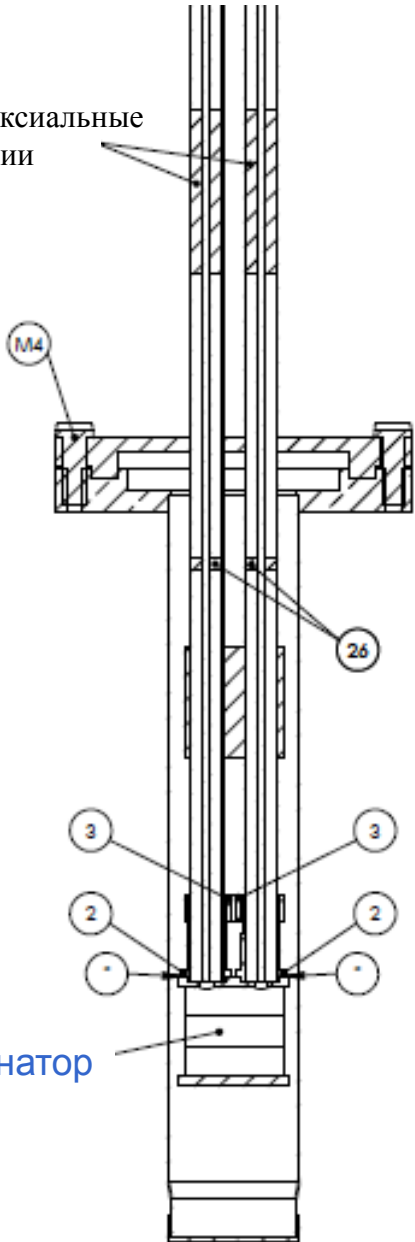
$T=1.3$ K

21

Smirnov et al PRB 2015

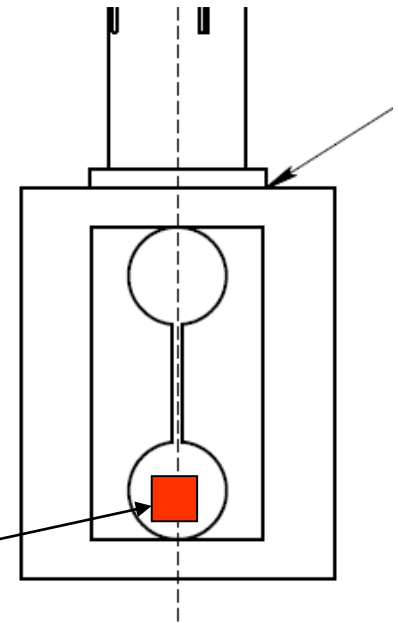
Квазиторoidalный резонатор на 4 ГГц. - один из элементов многочастотного спектрометра ЭСР

Коаксиальные
линии



$$4 \text{ ГГц} \approx 0.2 \text{ К} \approx 0.02 \text{ meV}$$

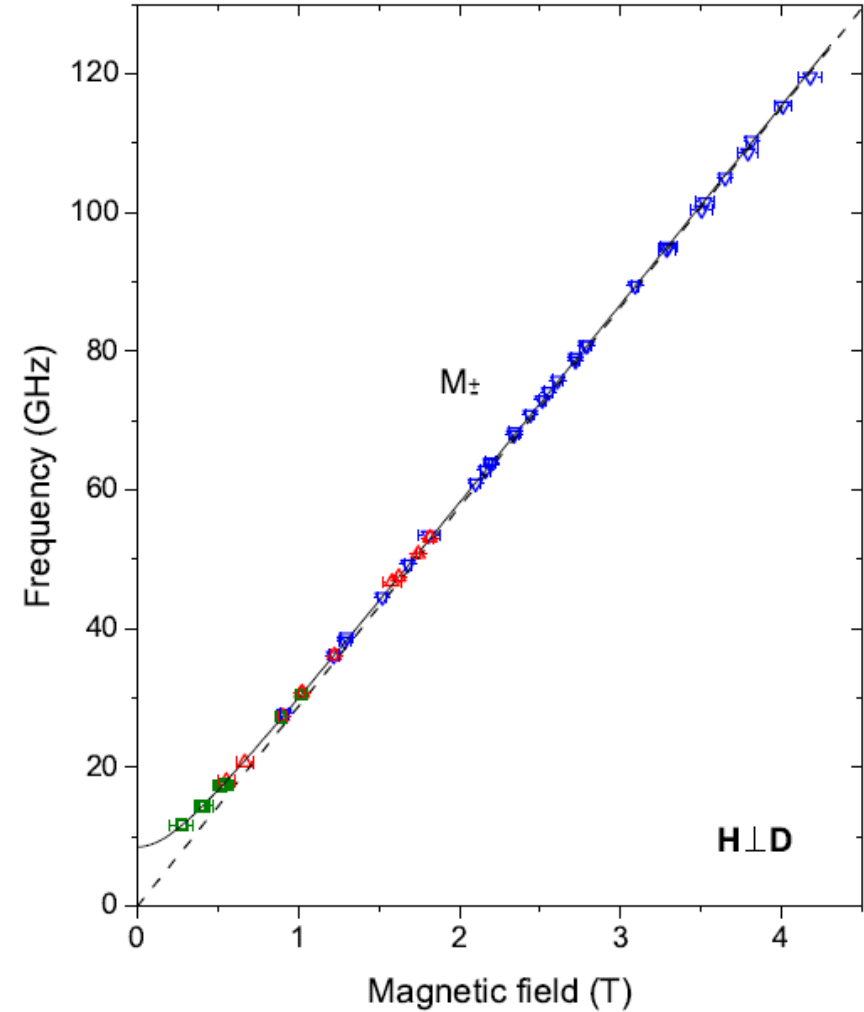
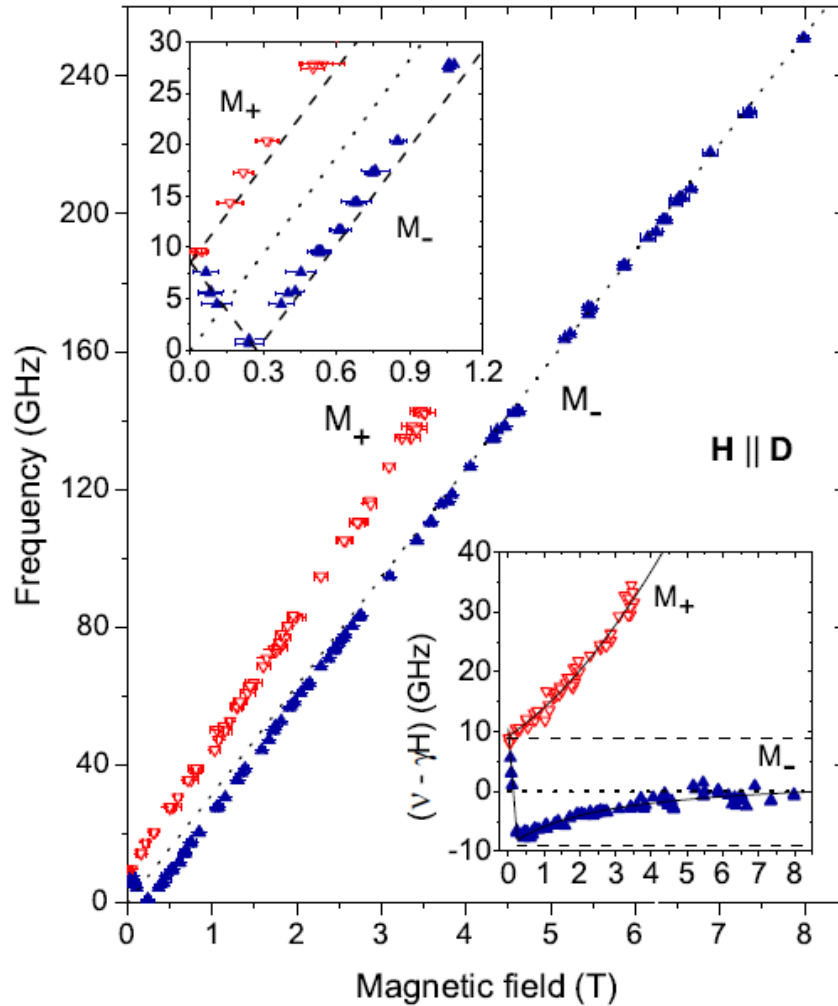
образец



Частотно-полевые зависимости магнитного резонанса для двух ориентаций магнитного поля при $T=0.5$ К

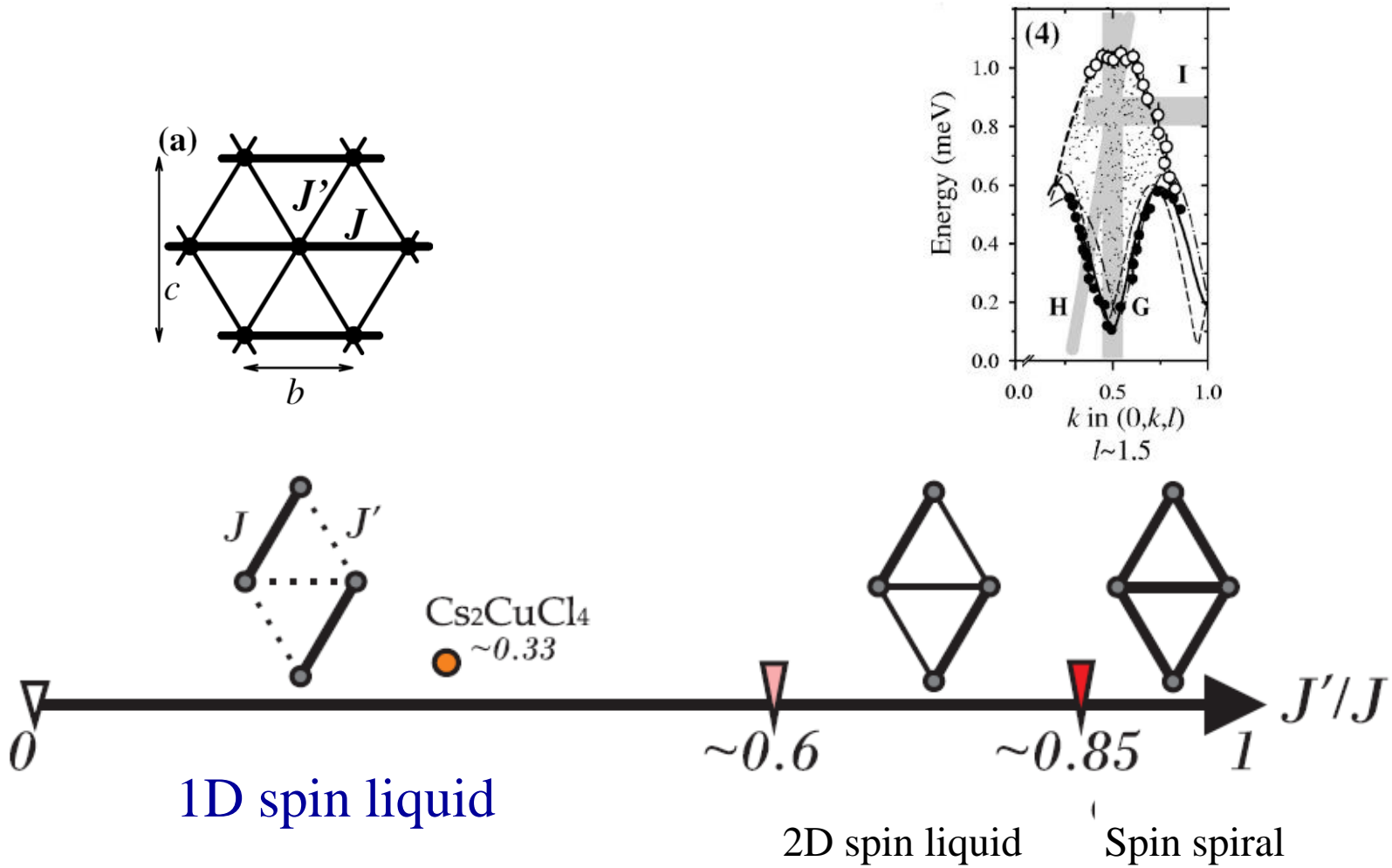
$$\Delta = \frac{\pi D}{2},$$

$$\Delta = 9 \text{ GHz} \Rightarrow D = 5.7 \text{ GHz} = 0.27 \text{ K}$$

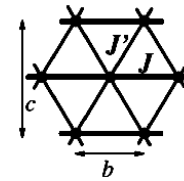


Спиноны в треугольном АФМ.

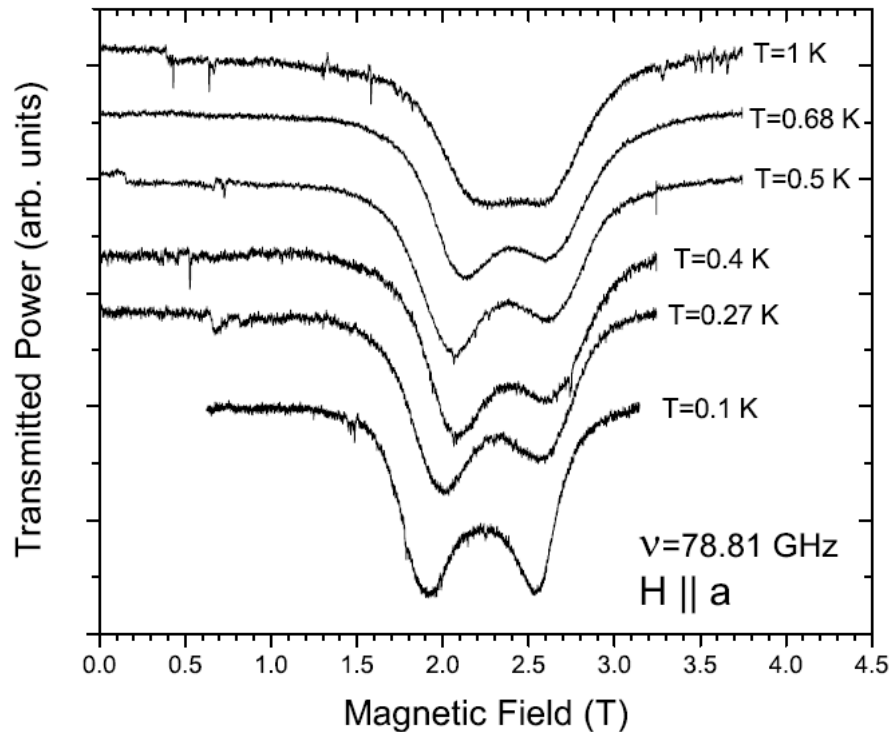
Почему цепочечный спектр (континуум) в треугольном АФМ?
 Фрустрация обменов J' приводит к расцеплению цепочек в Cs_2CuCl_4



ESR в спин-жидкостной фазе Cs_2CuCl_4

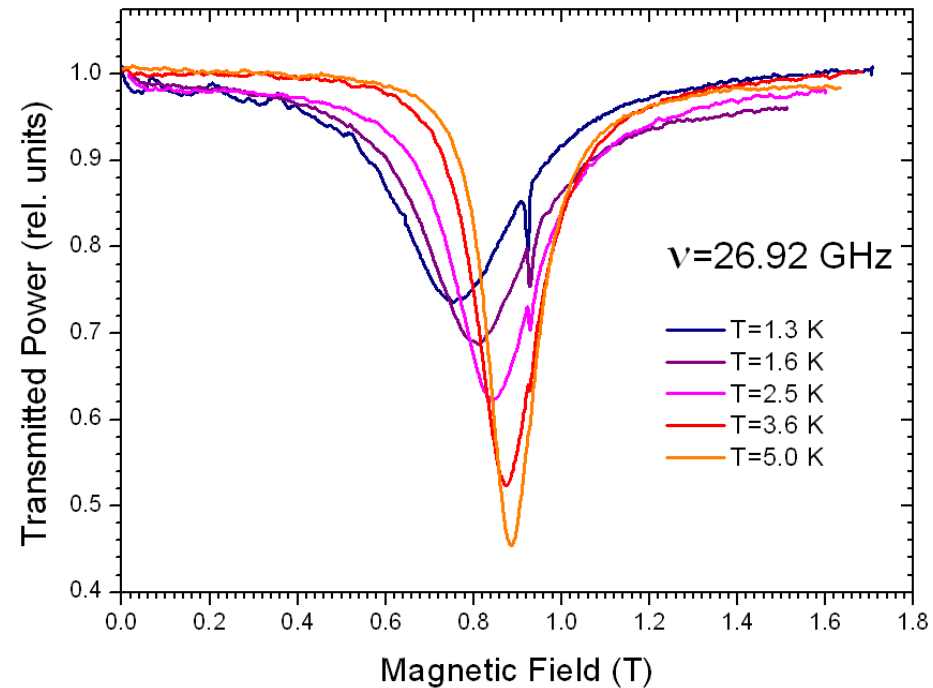


Дублет при $\mathbf{H} \parallel \mathbf{D}$



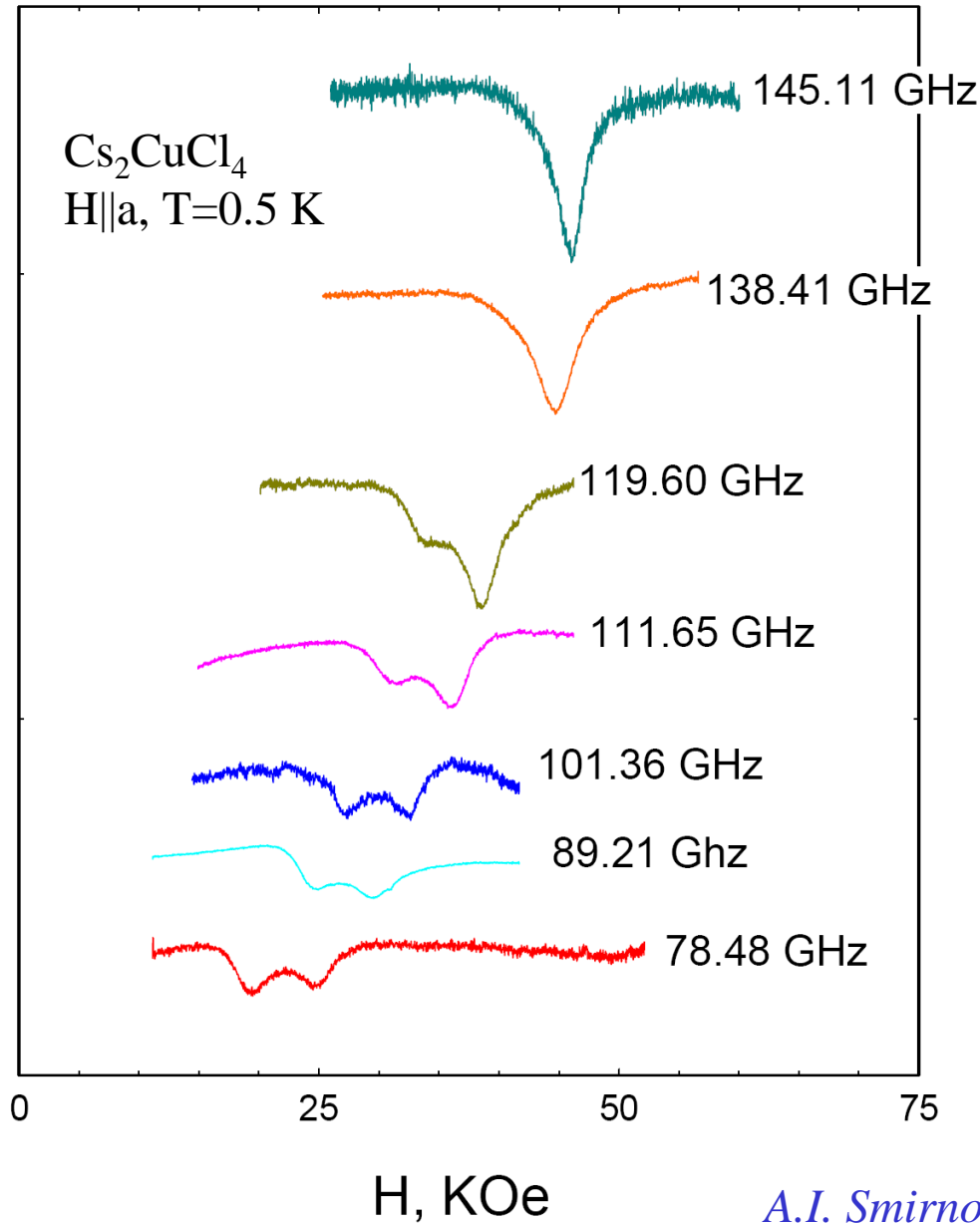
Smirnov et al. PRB 2012

Одиночная линия и сдвиг при $\mathbf{H} \perp \mathbf{D}$



Povarov et al. PRL 2011

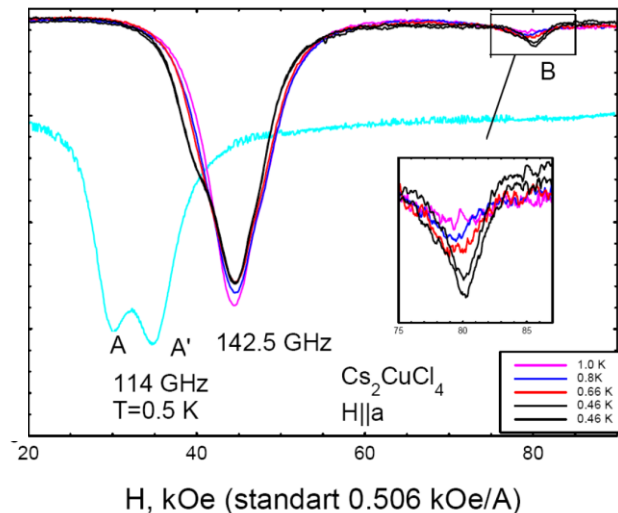
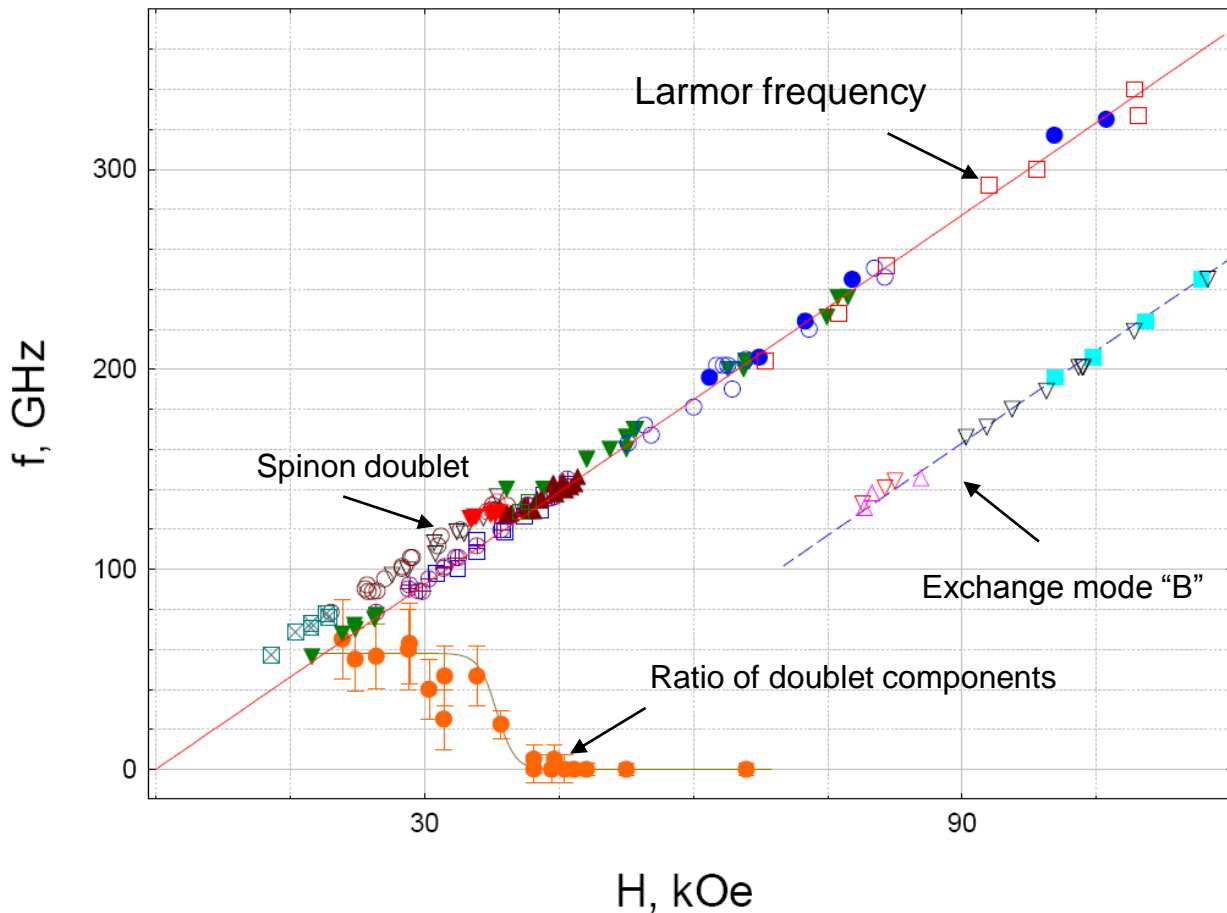
Коллапс дублета в сильном поле $H \parallel a$, $T=0.5$ K



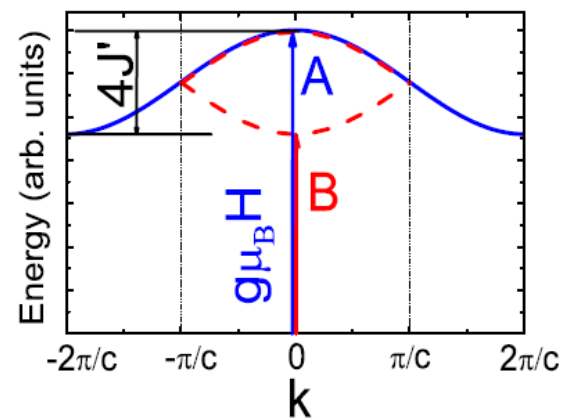
Кроссовер от спионов к магнонов при переходе в насыщенную фазу

$H \parallel a$ Cs_2CuCl_4

$T=0.5$ K

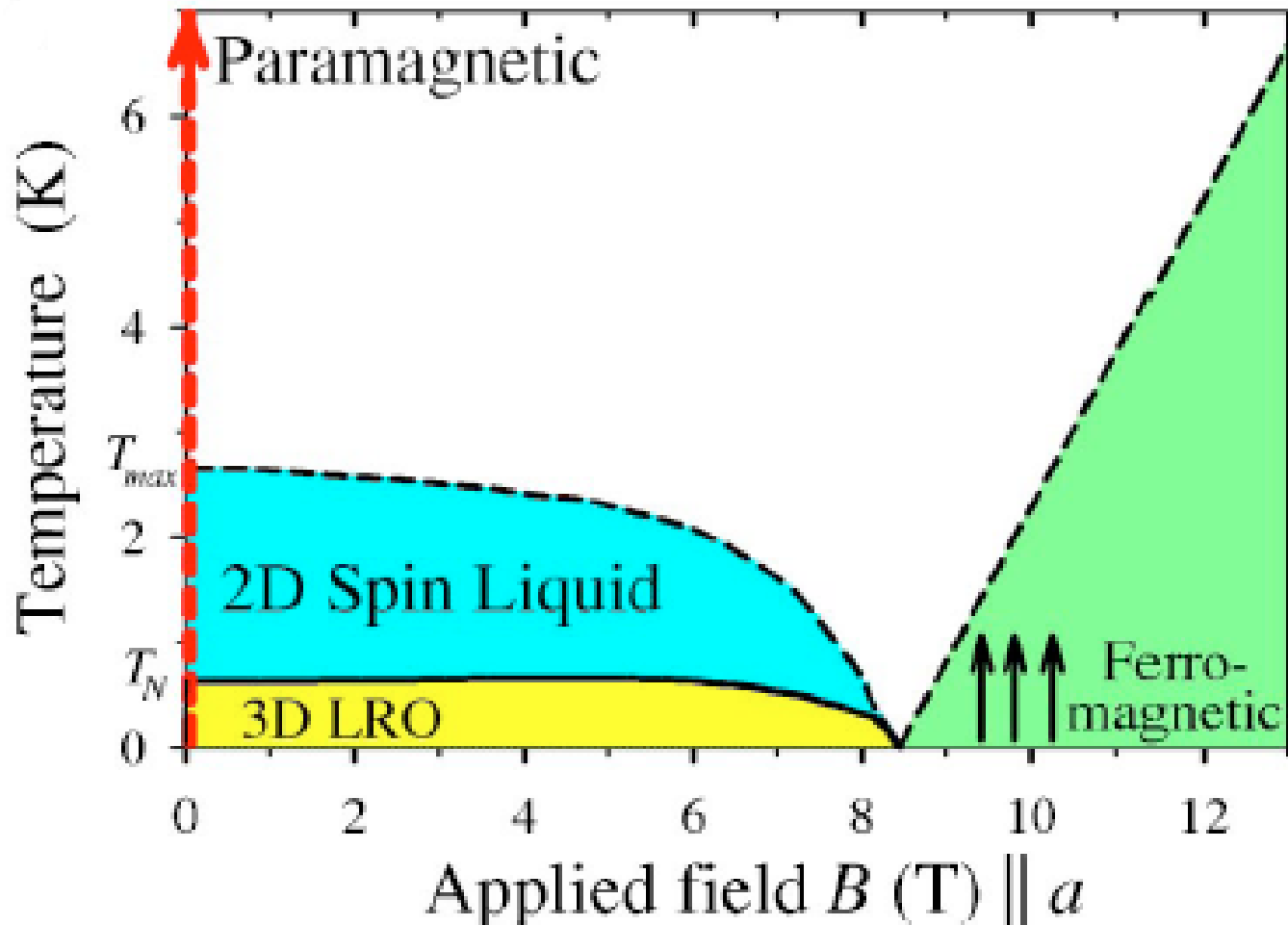


(b)



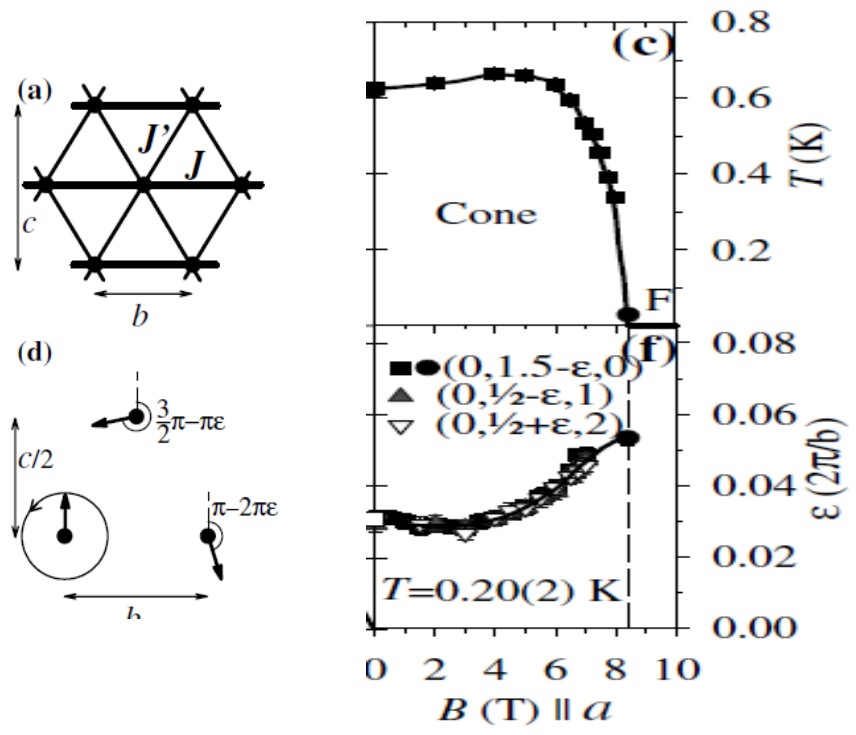
В упорядоченной фазе - сильная редукция параметра порядка:
 $\Delta S/S=0.25$ (Coldea et al PRL 2001)

Каким будет спектр возбуждений – спектром упорядоченных или флуктуирующих спинов?



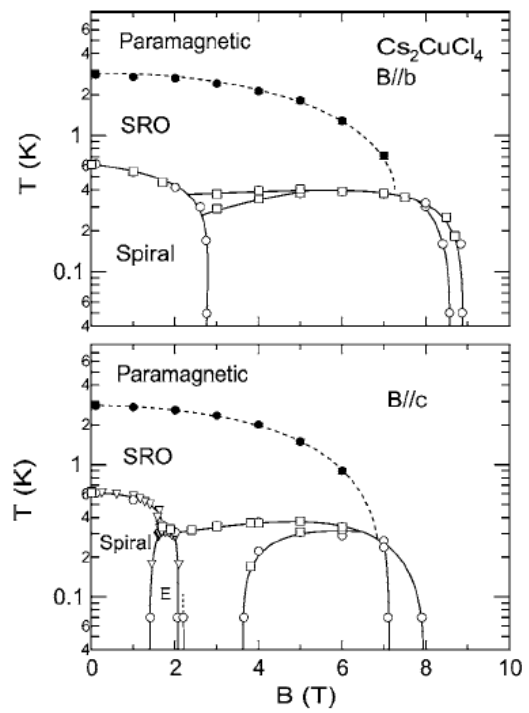
Low-temperature ordering in Cs_2CuCl_4 at $T_N=0.62 \text{ K} = 0.14 \text{ J}$

Coldea et al PRL 2001

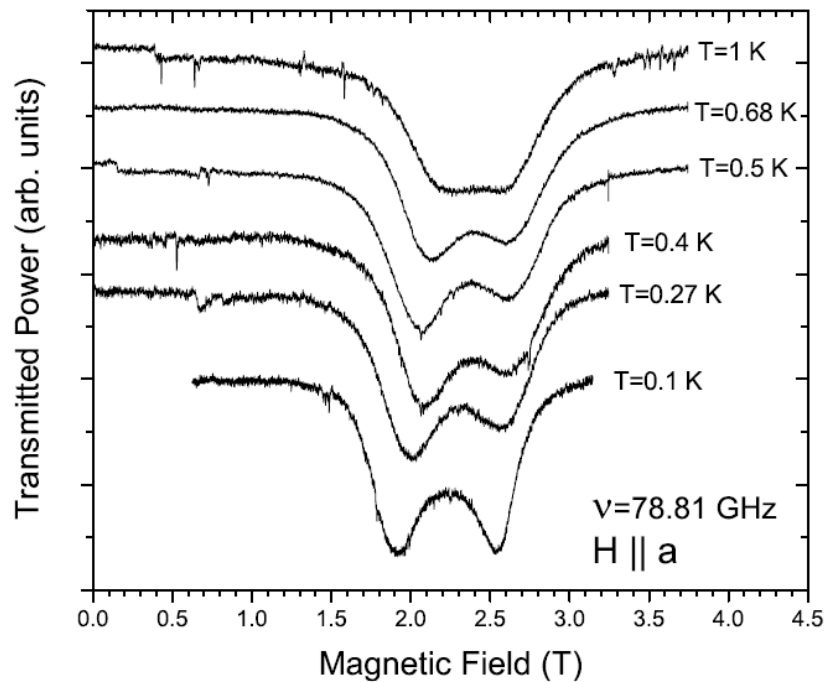
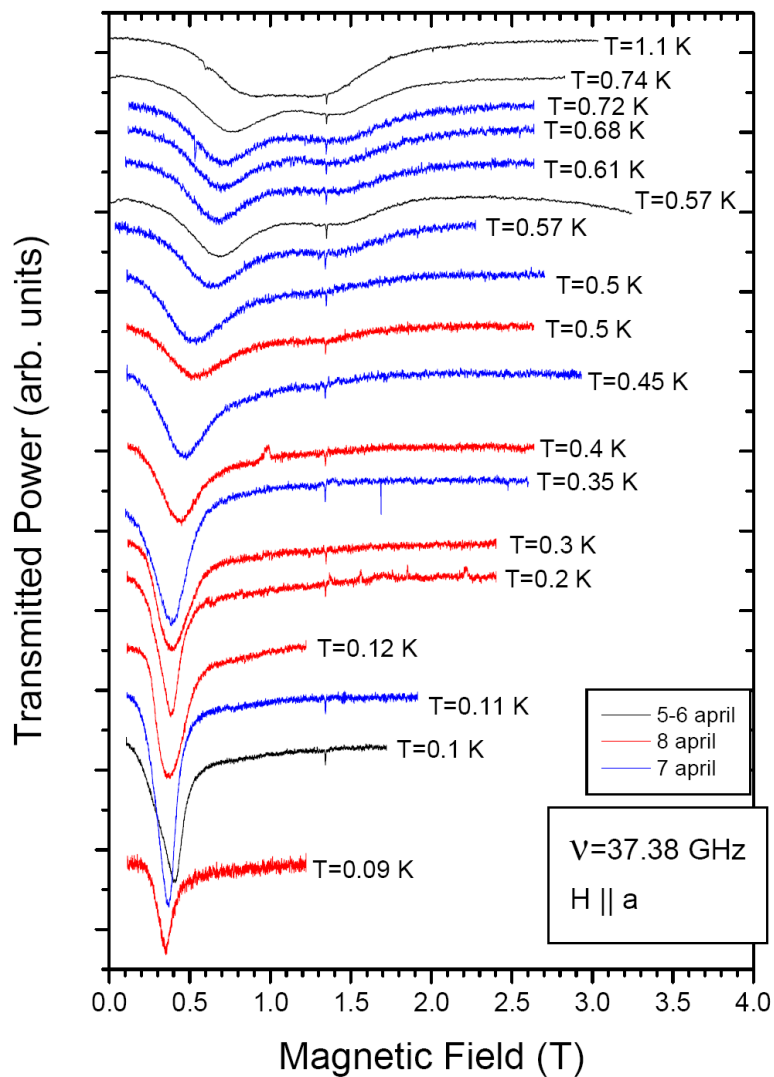


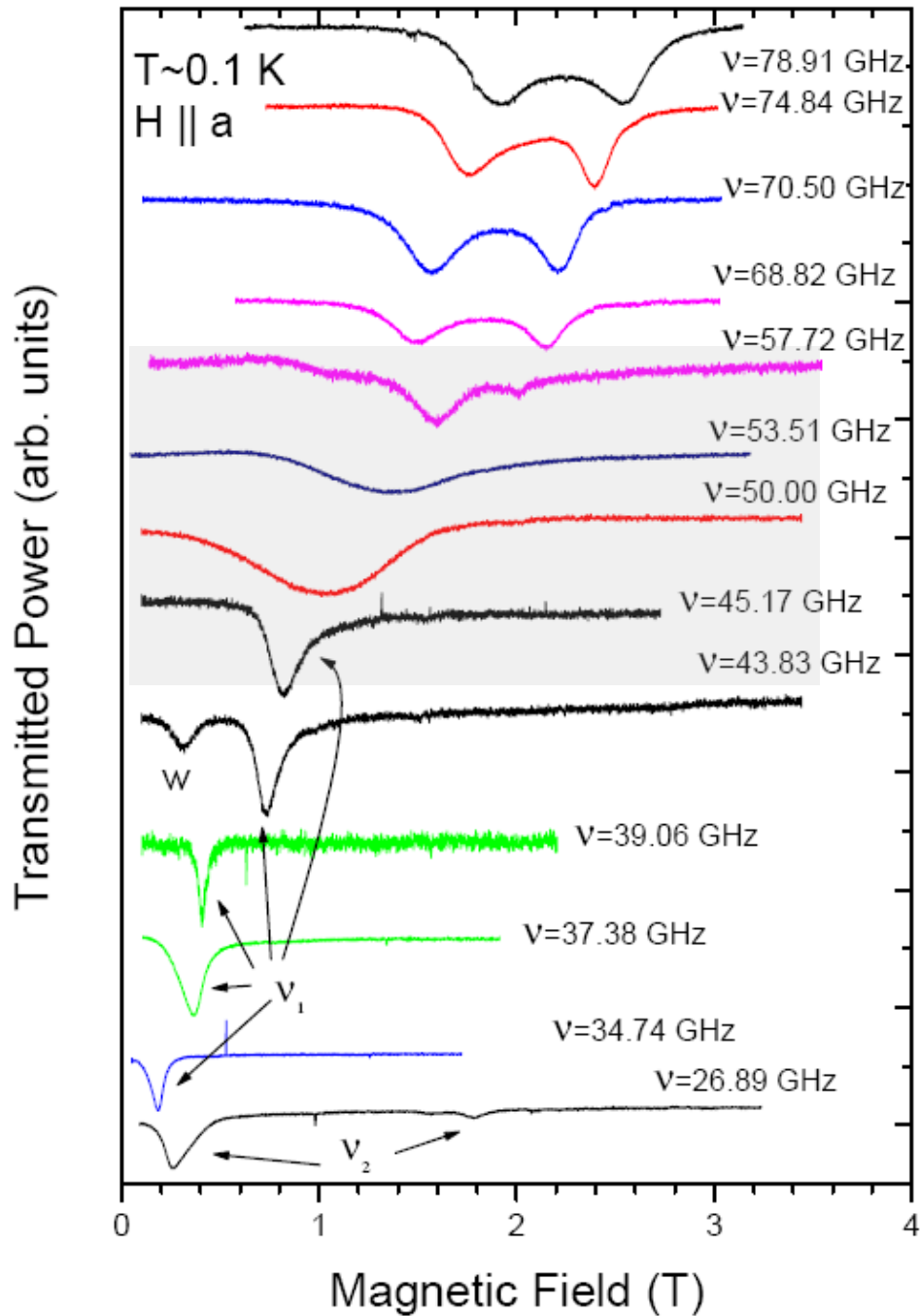
Tokiwa et al.

PHYSICAL REVIEW B 73, 134414 (2006)

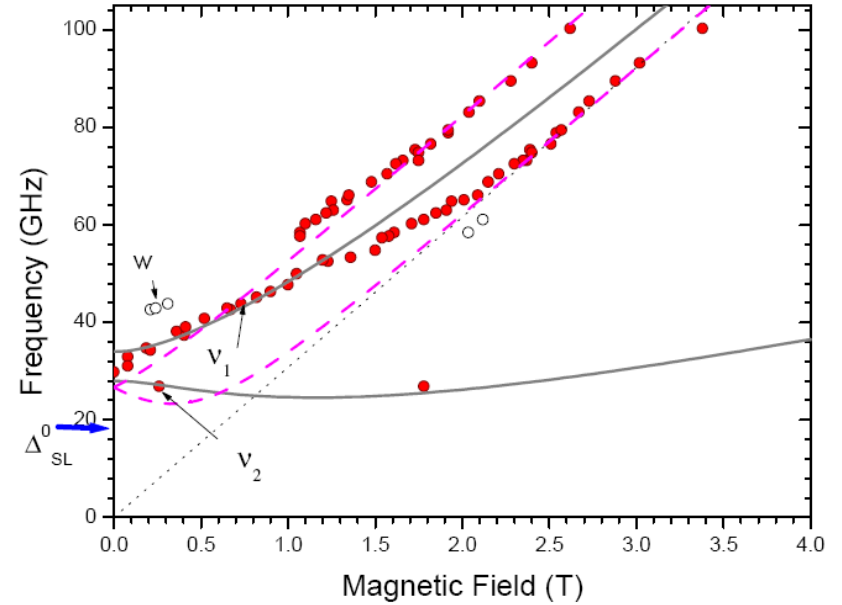


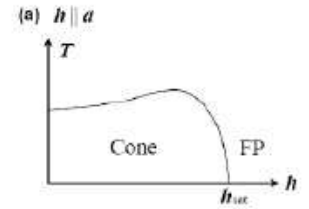
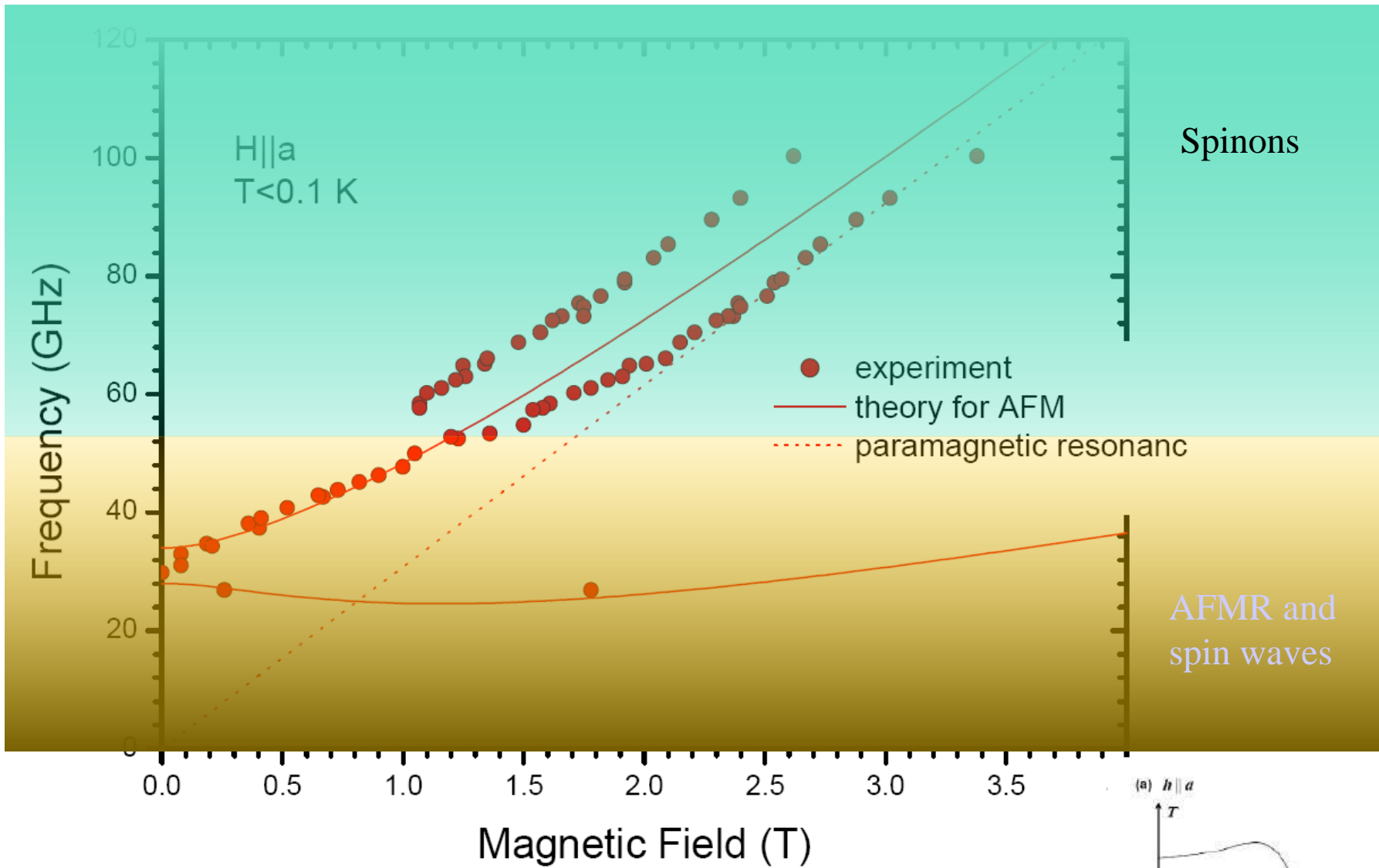
Different evolution for low and high frequencies:



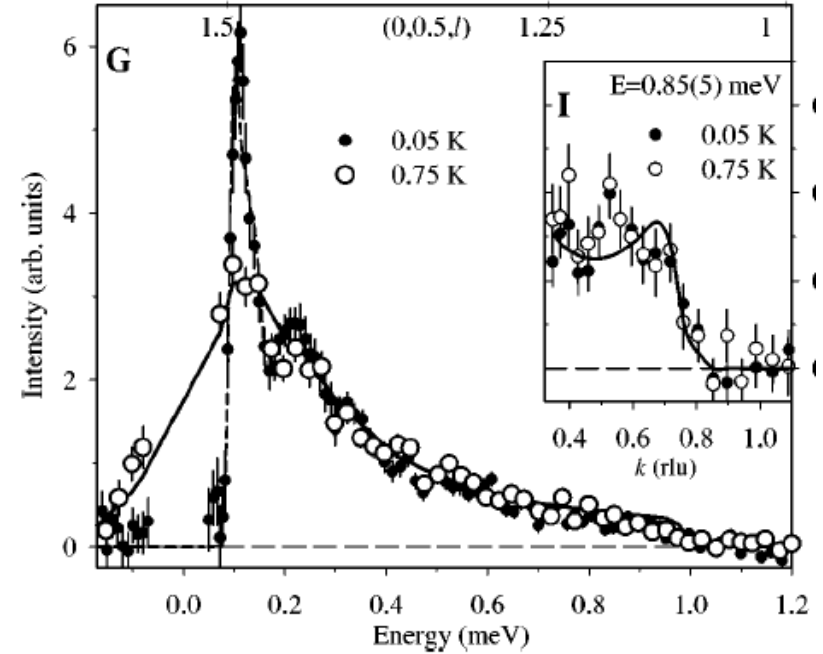
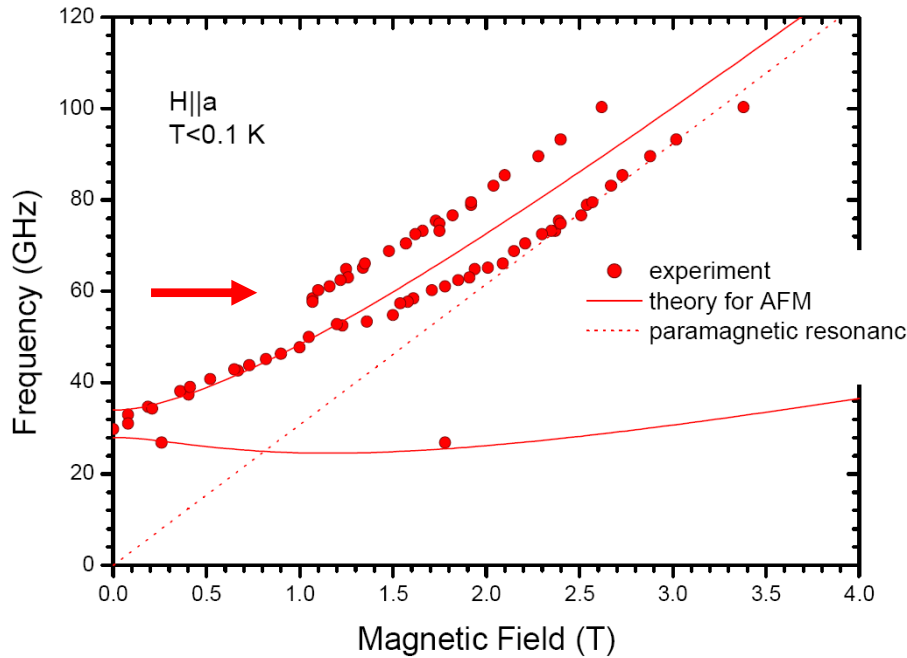


Crossover from antiferromagnetic resonance to spinons





Crossover energy from neutrons (H=0) and ESR (H=0-3 T)



60 GHz

A. Smirnov et al PRB 2012

ESR : $k=0$, small splitting

R. Coldea et al, PRB 2003

Neutrons: k , ε -dependence

Выводы:

Спинонный дублет, возникает из континуума благодаря однородному взаимодействию Дзялошинского-Мории.

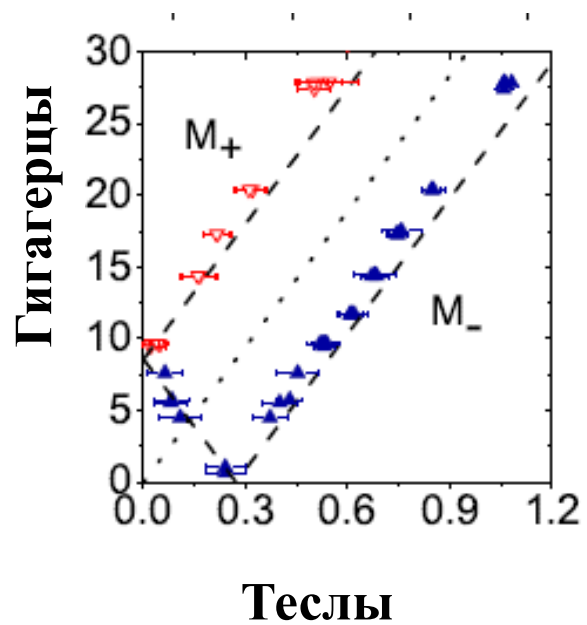
Кроссовер от спинонного резонанса к магنونному вблизи обменной частоты.

Коллапс дублета в сильном поле и обратный кроссовер от спинонов к магнонам в сильном поле.

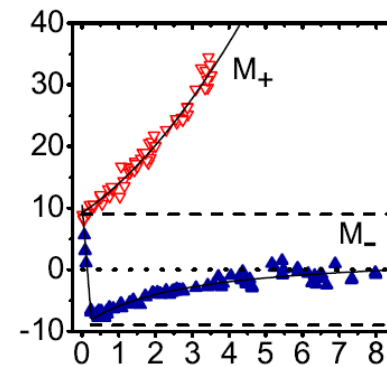
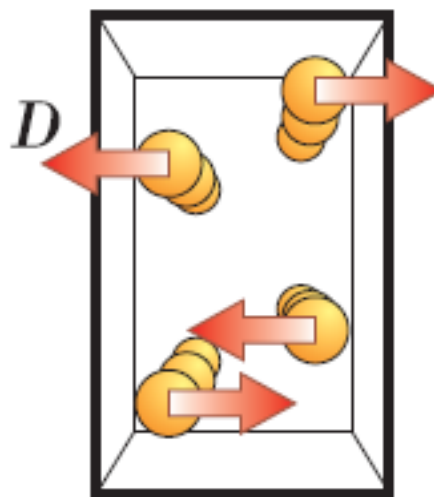
Спасибо за внимание

СПЕКТРИНА 2016

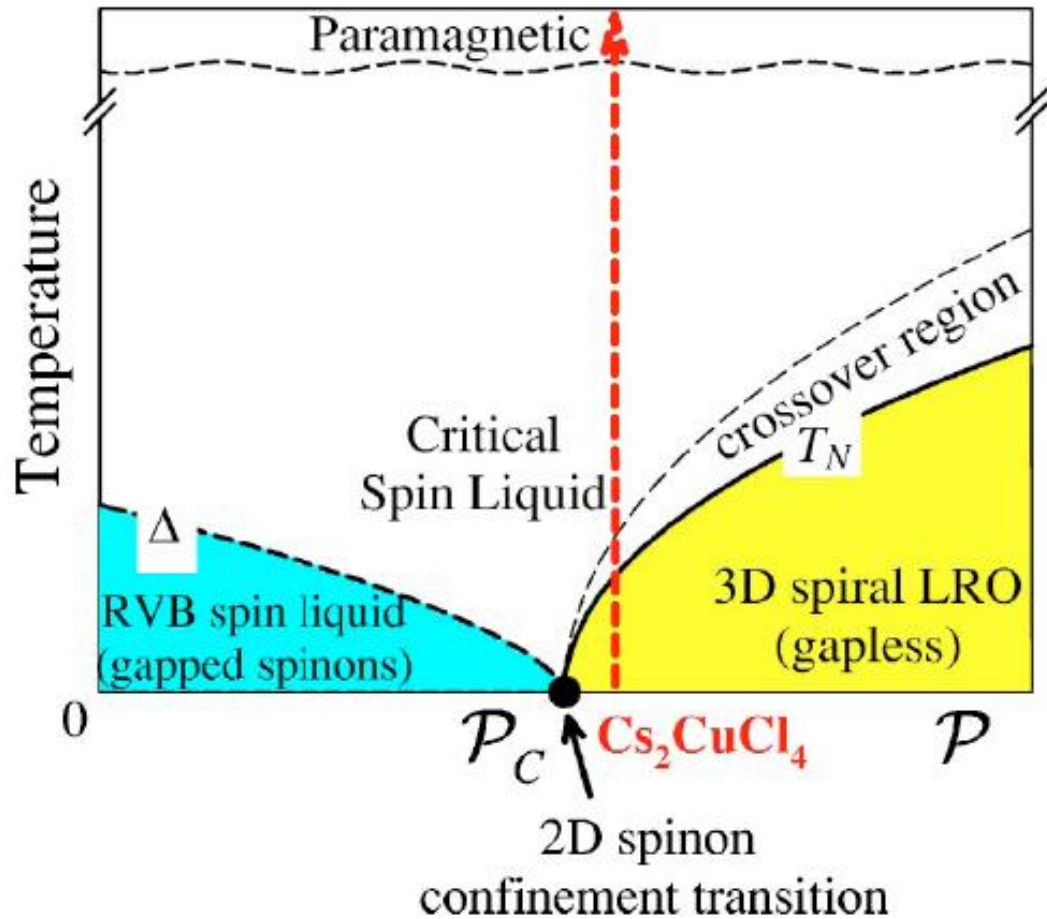
Спасибо за внимание



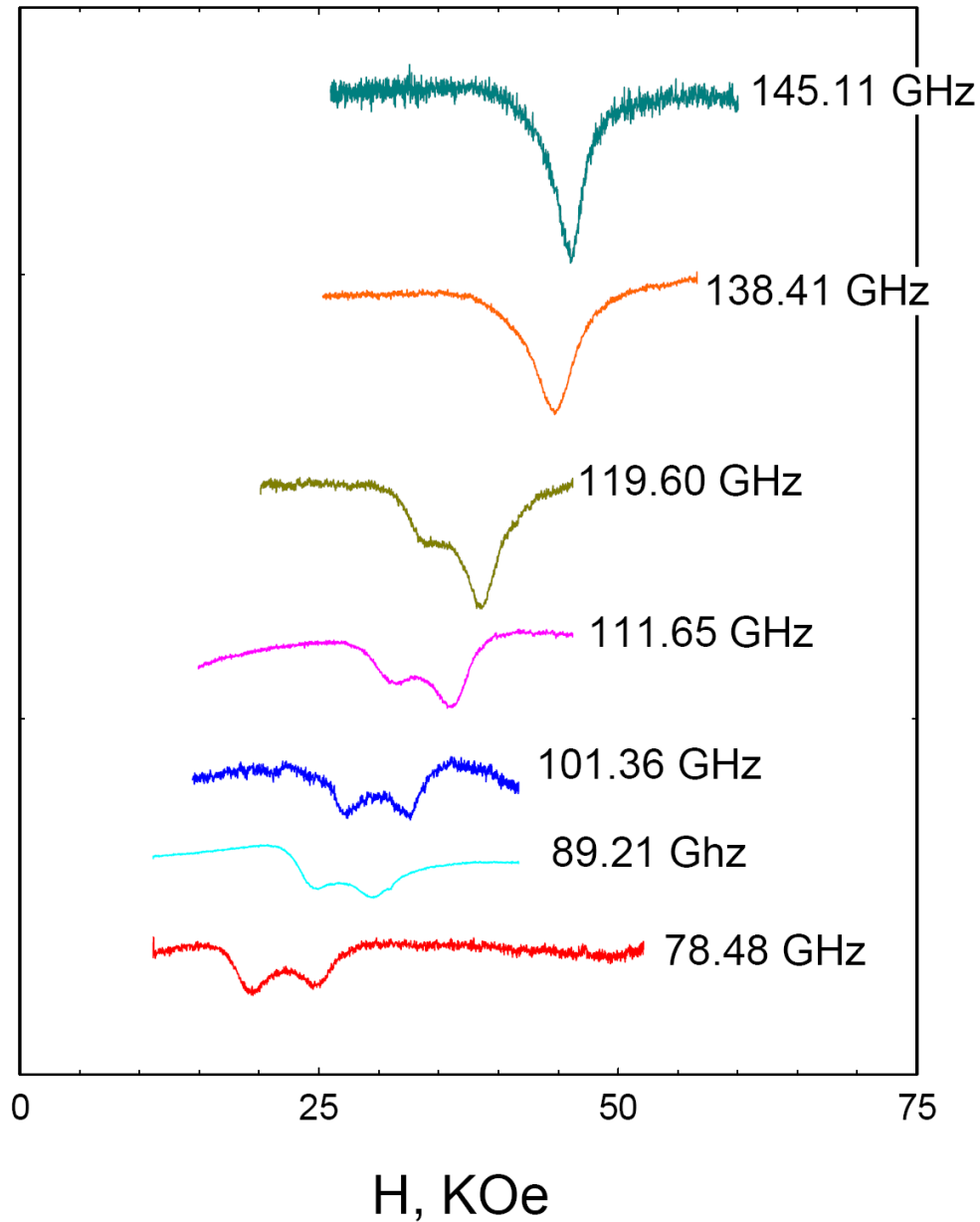
Купорос



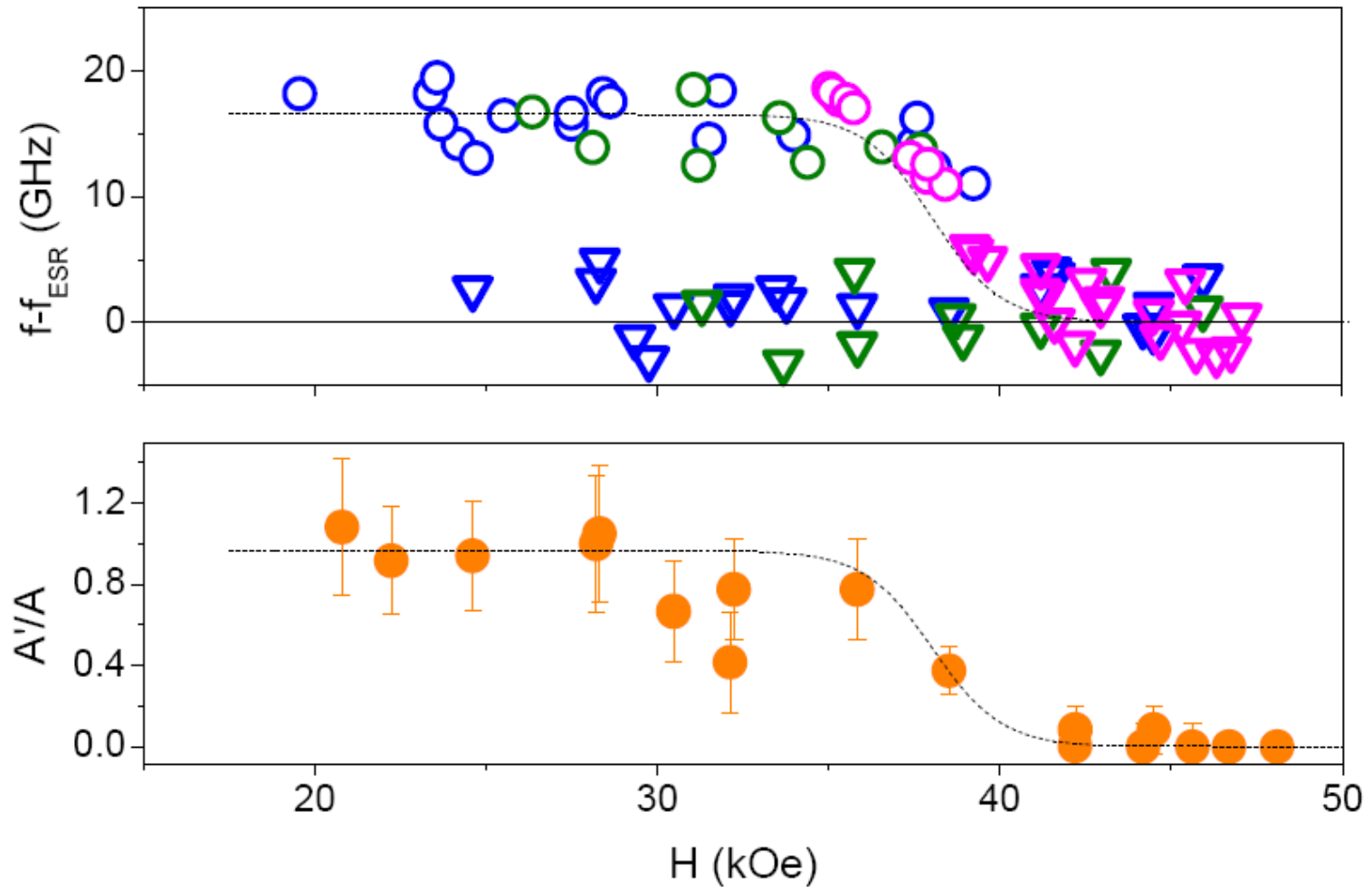
Quantum criticality



Suppression of continuum by a magnetic field:
collapse of the doublet in a strong field $H \parallel a$, $T=0.5$ K

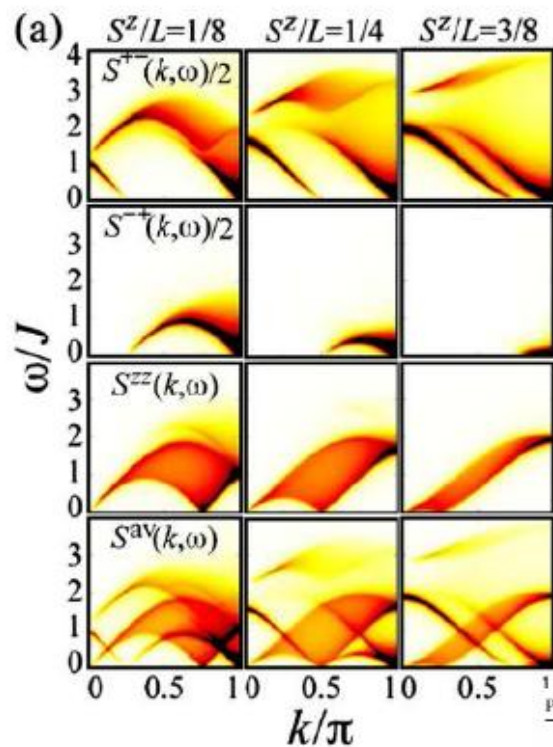


Collapse of the doublet: resonance frequencies and ratio of components



Theory for the continuum intensity in a field

PRL **102**, 037203 (2009)



PRL **102**, 037203 (2009)

PHYSICAL REVIEW LETTERS

week ending
23 JANUARY 2009

Dynamically Dominant Excitations of String Solutions in the Spin-1/2 Antiferromagnetic Heisenberg Chain in a Magnetic Field

Masanori Kohno

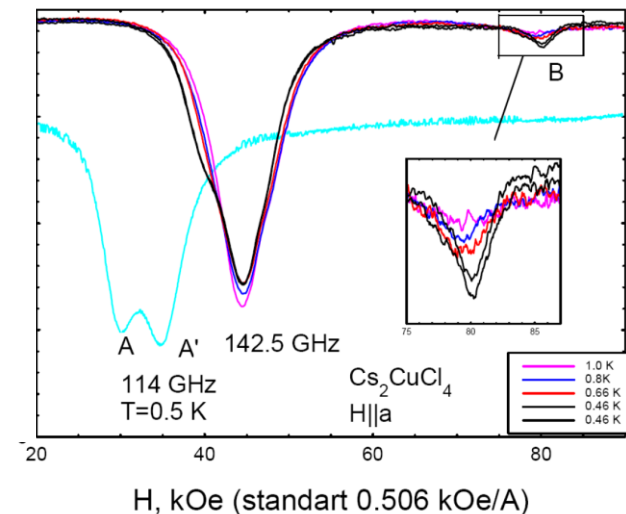
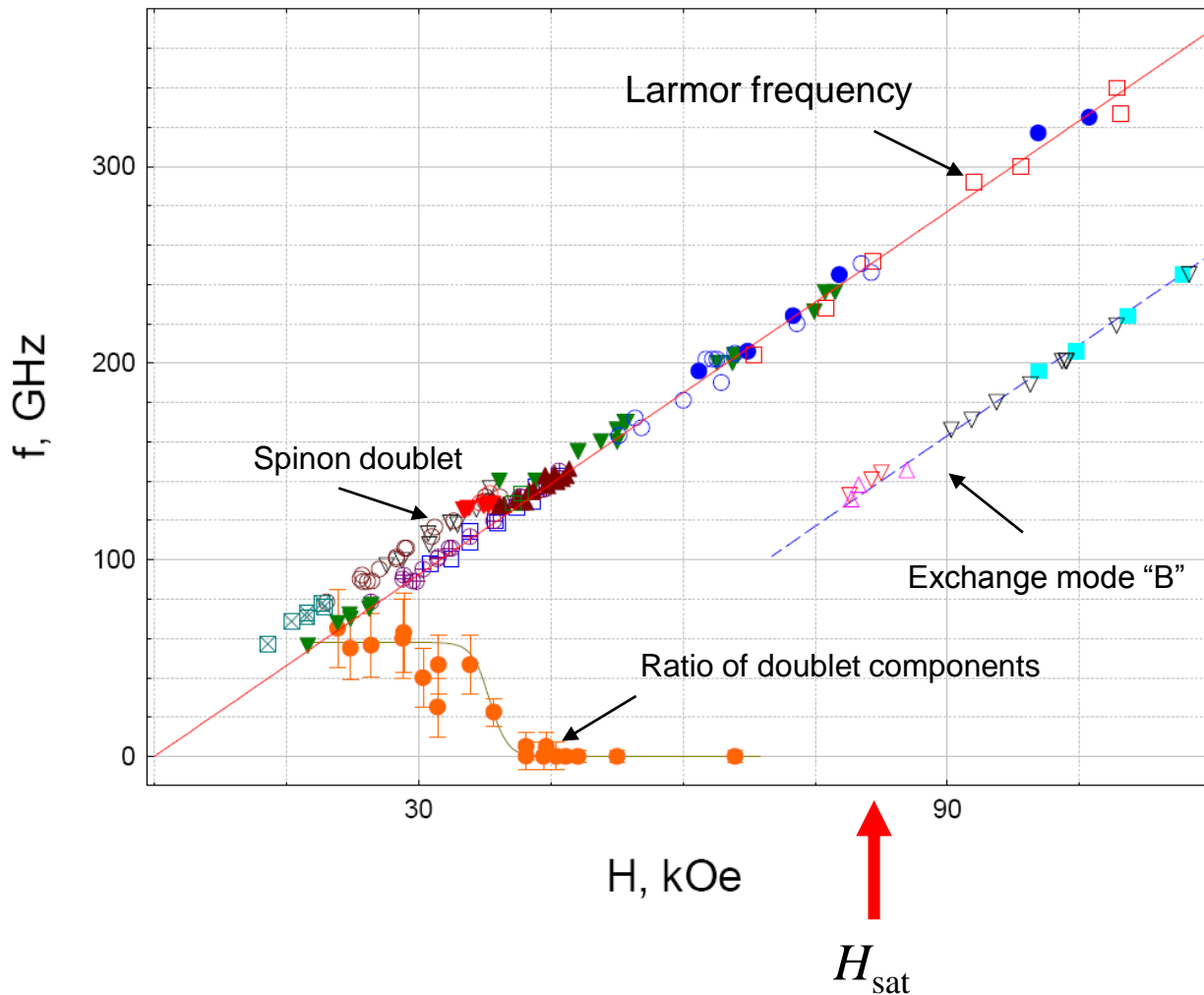
WPI Center for Materials Nanoarchitectonics, National Institute for Materials Science, Tsukuba 305-0047, Japan
(Received 22 August 2008; revised manuscript received 10 December 2008; published 22 January 2009)

Using Bethe-ansatz solutions, this Letter uncovers a well-defined continuum in dynamical structure factor $S^{+-}(k, \omega)$ of the spin-1/2 antiferromagnetic Heisenberg chain in magnetic fields. It comes from string solutions that continuously connect the mode of the lowest-energy excitations in the zero-field limit and that of bound states of overturned spins from the ferromagnetic state near the saturation field. The relevance to real materials is confirmed through comparisons with experimental results.

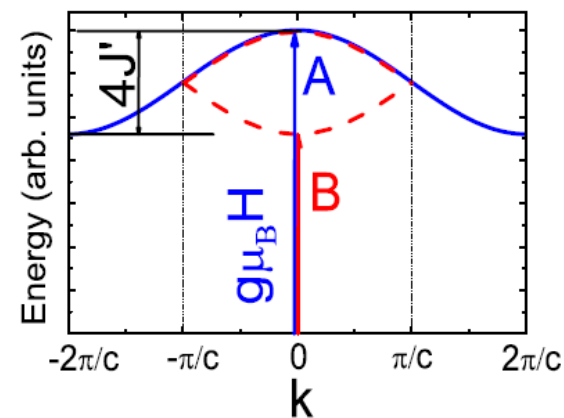
Crossover to spin waves above the saturation

T=0.5 K

H||a Cs₂CuCl₄



(b)



Выводы:

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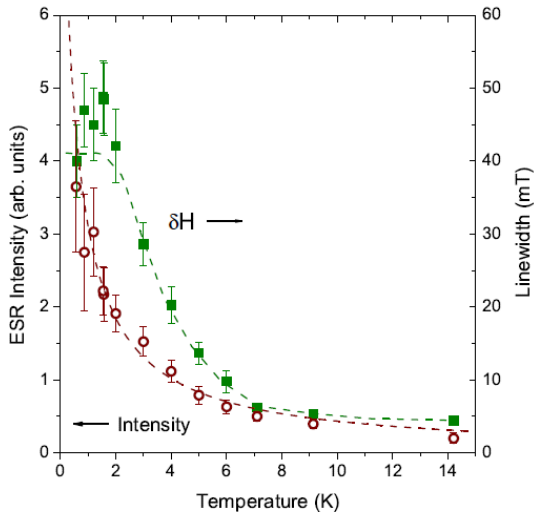
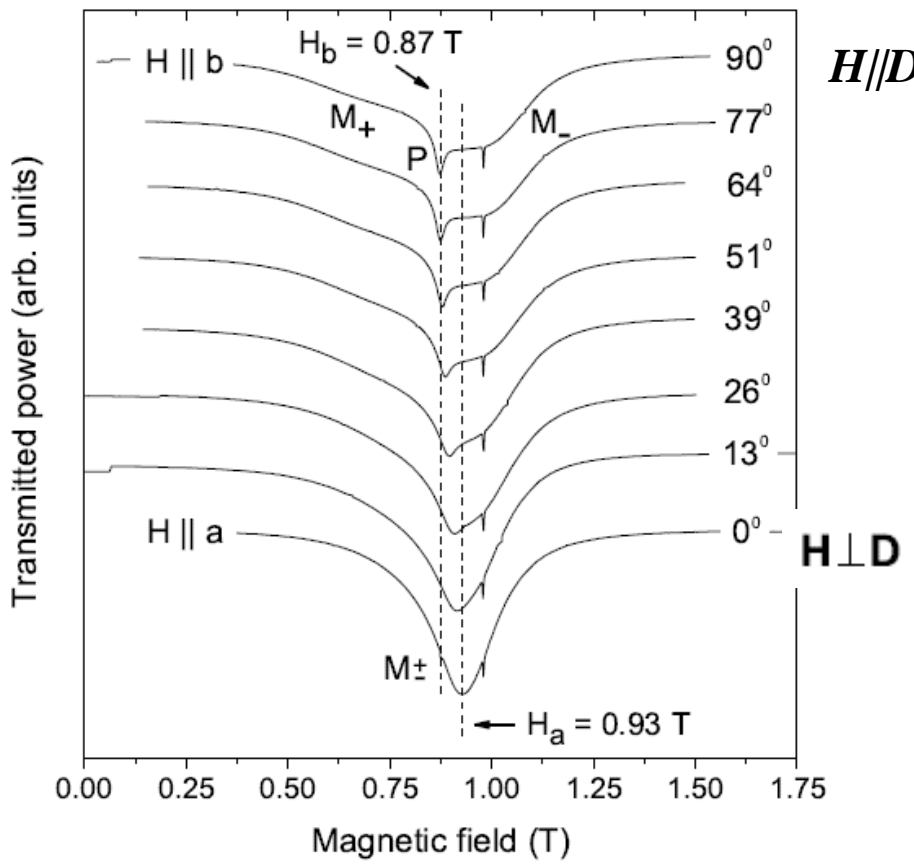
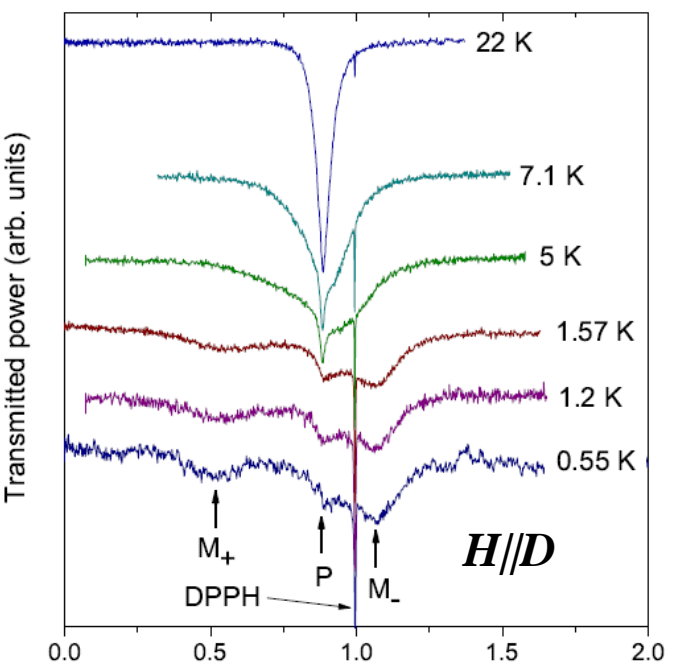
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Спасибо за внимание

СПЕКТРИНА 2016

Взаимодействие парамагнитных дефектов и спинов. Обменное сужение линии



Уширение линии дефектов в режиме медленного обмена ($\delta\nu \gg J^$) при удалении линий друг от друга*

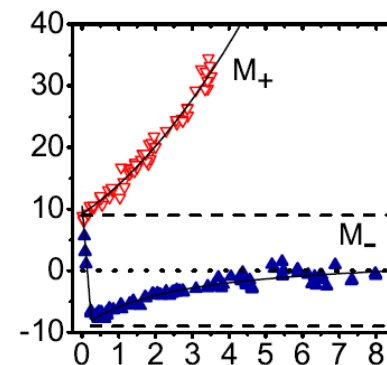
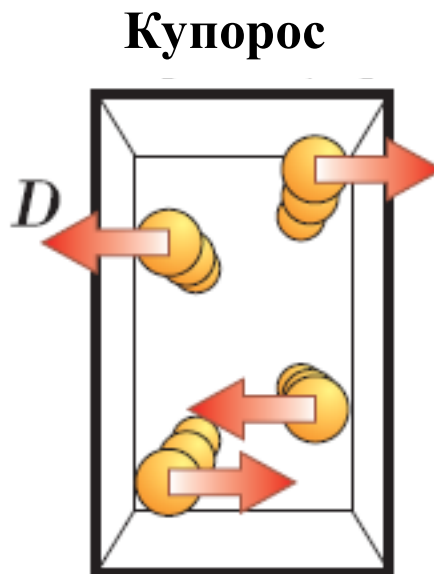
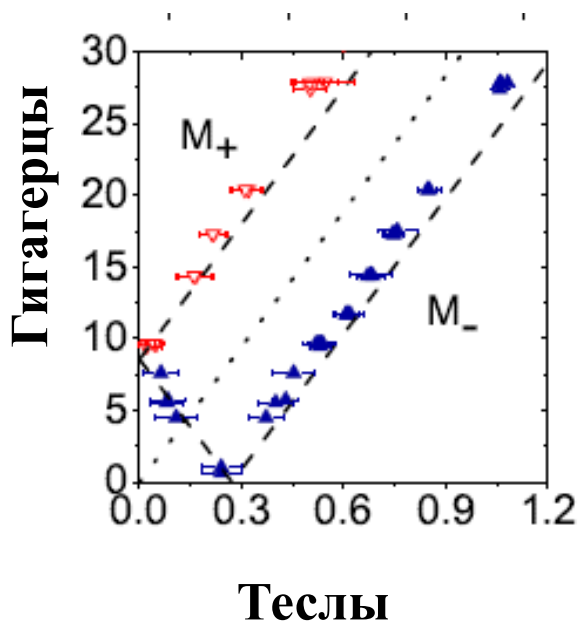
Слияние линий дефектов и спинов при переходе в режим быстрого обмена ($\delta\nu < J^$) при сближении линий*

Оценка для $J^* \sim 0.25 \text{ K} \ll J$

Вывод №3

Взаимодействие парамагнитных дефектов и делокализованных возбуждений с эффективным обменным параметром $J^* \sim 0.01 \text{ J}$

Спасибо за внимание

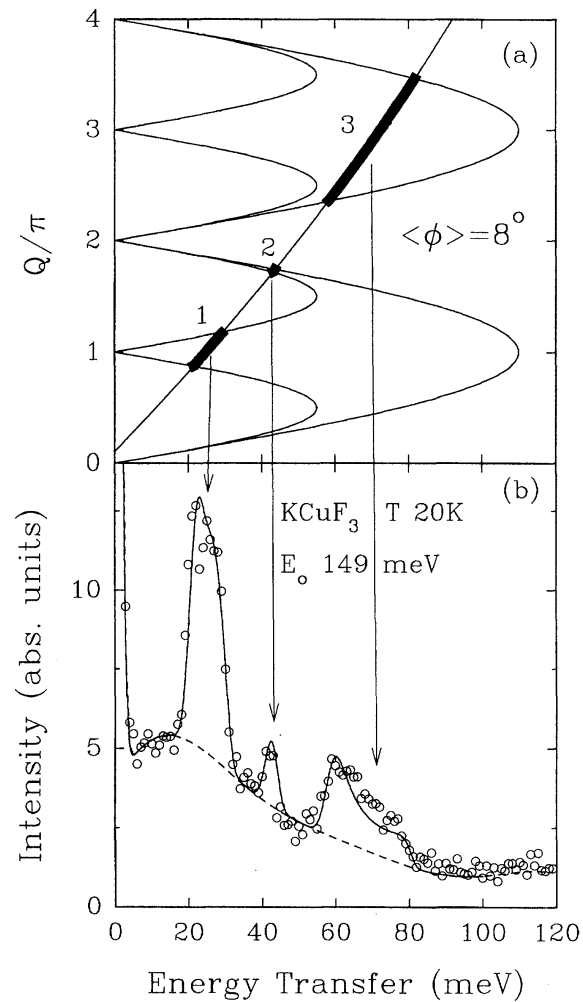


Measurement of the spin-excitation continuum in one-dimensional KCuF_3 using neutron scattering

D. Alan Tennant and Roger A. Cowley
Oxford Physics, Clarendon Laboratory, Oxford University, Parks Road, Oxford OX1 3PU, United Kingdom

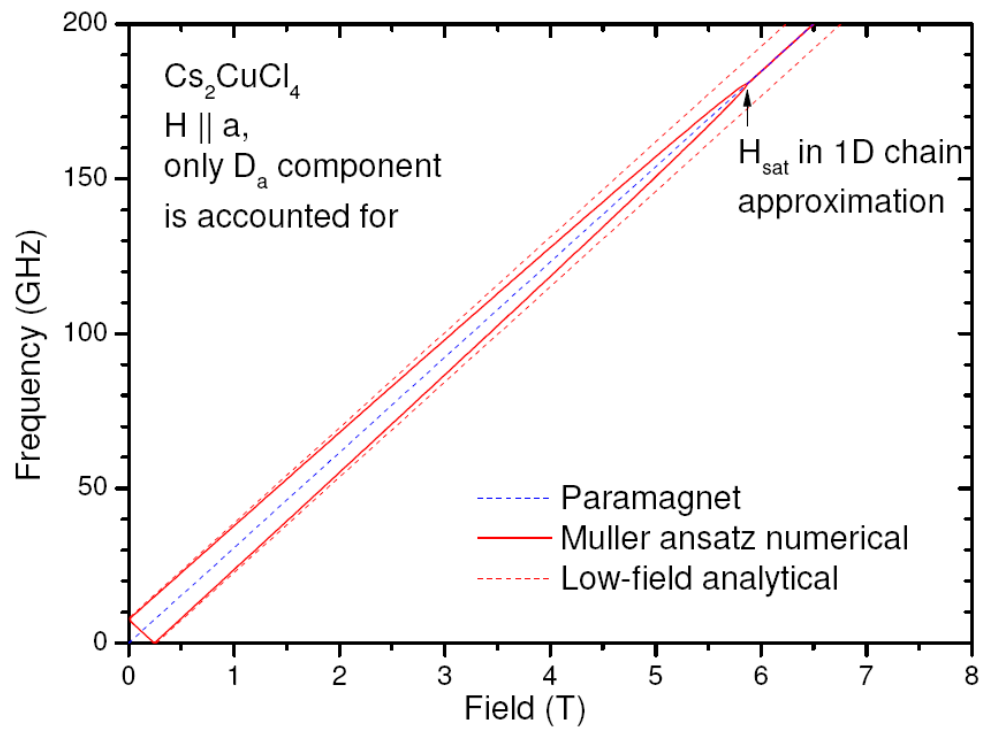
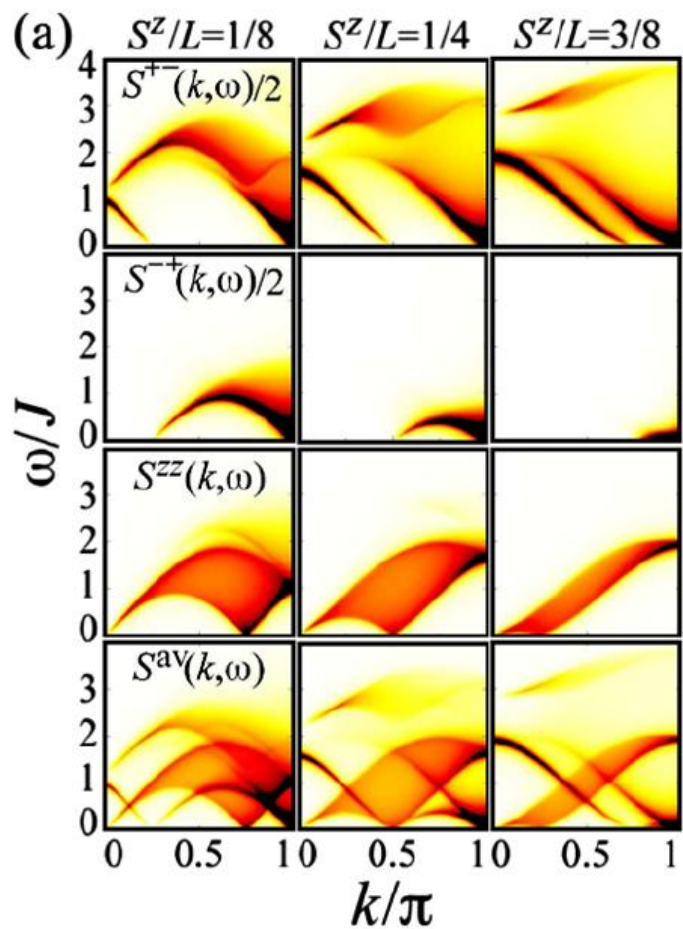
Stephen E. Nagler
Department of Physics, University of Florida, Gainesville, Florida 32611

Alexei M. Tsvelik
Oxford Physics, Department of Theoretical Physics, Oxford University, Keble Road, Oxford OX1 3PU, United Kingdom



**Experimental check of
continuum**

Theory for the continuum: collapse of the doublet is expected in a magnetic field



PRL 102, 037203 (2009) PHYSICAL REVIEW LETTERS week ending 23 JANUARY 2009

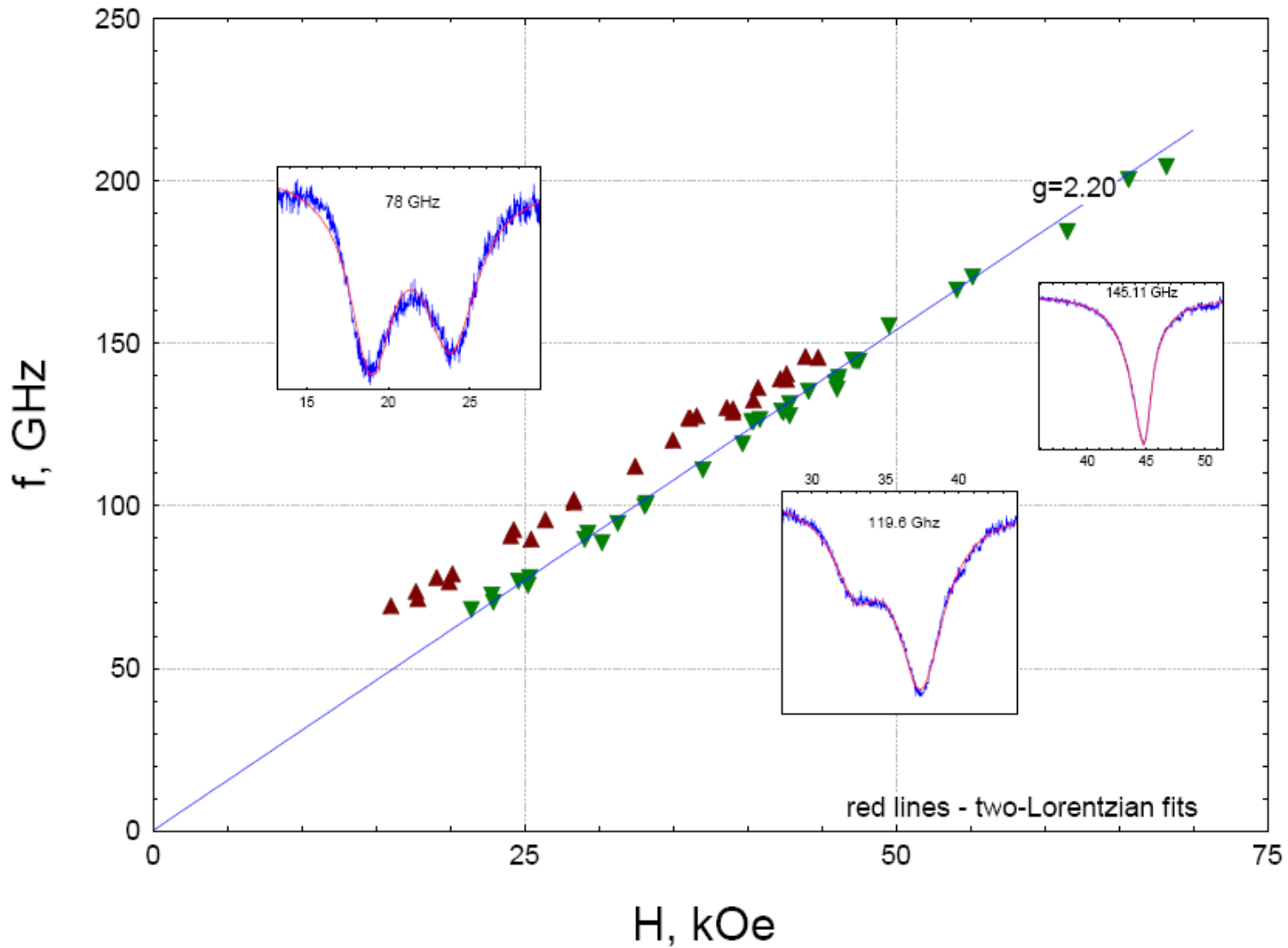
Dynamically Dominant Excitations of String Solutions in the Spin-1/2 Antiferromagnetic Heisenberg Chain in a Magnetic Field

Masanori Kohno

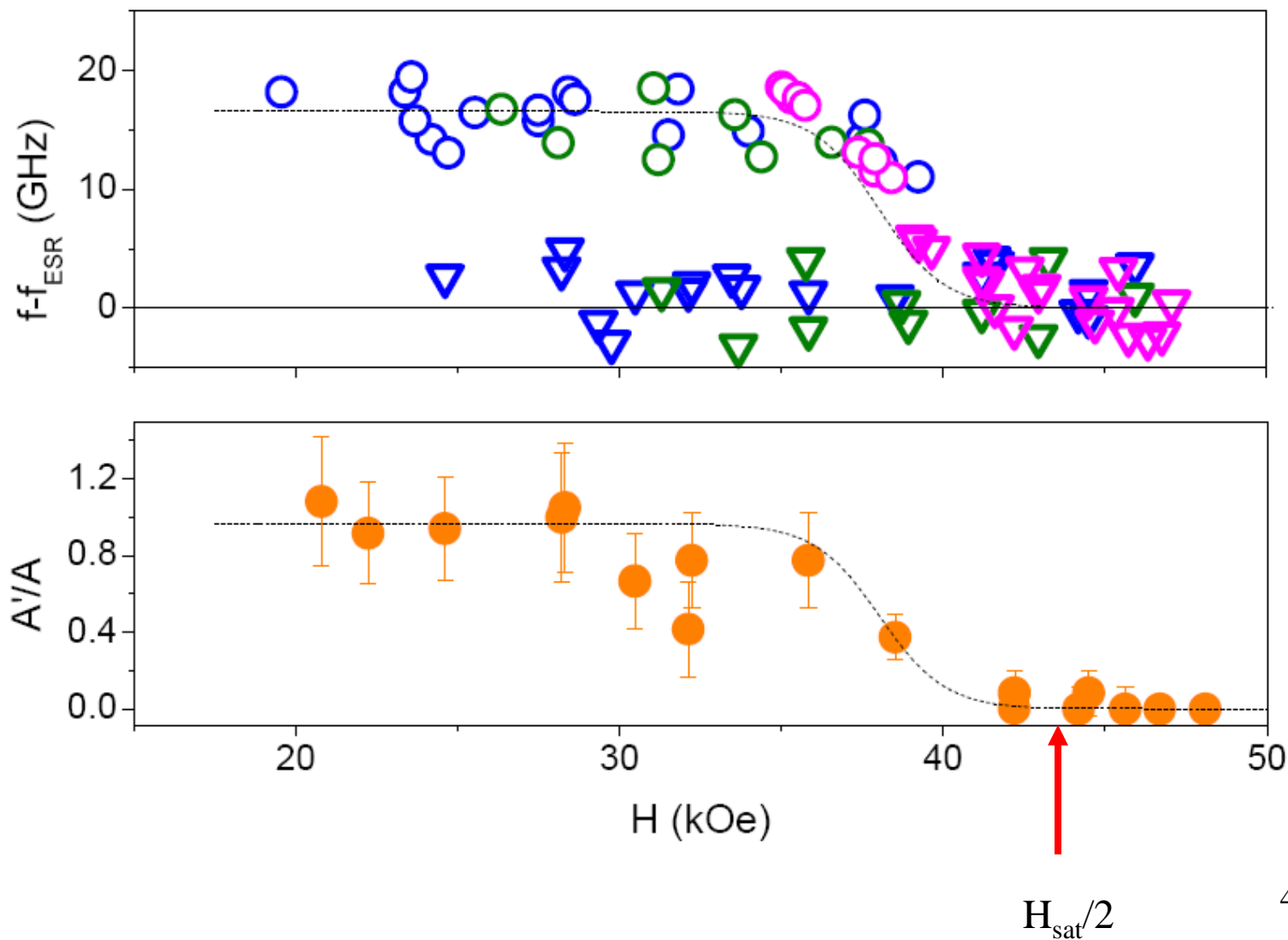
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T = 0.5 K Collapse of the doublet in a field H||a Cs₂CuCl₄

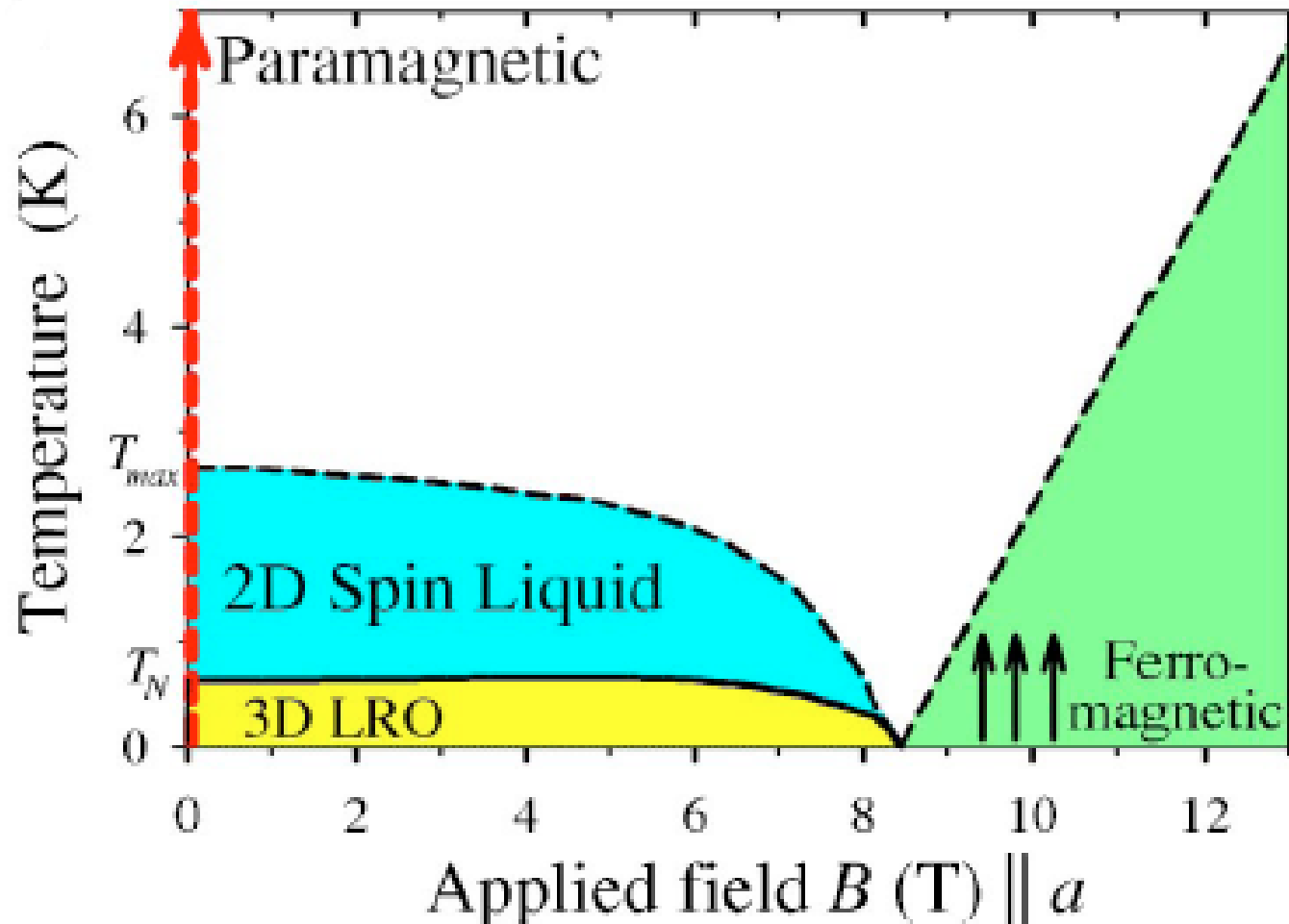


Collapse of the doublet: resonance frequencies and ratio of components

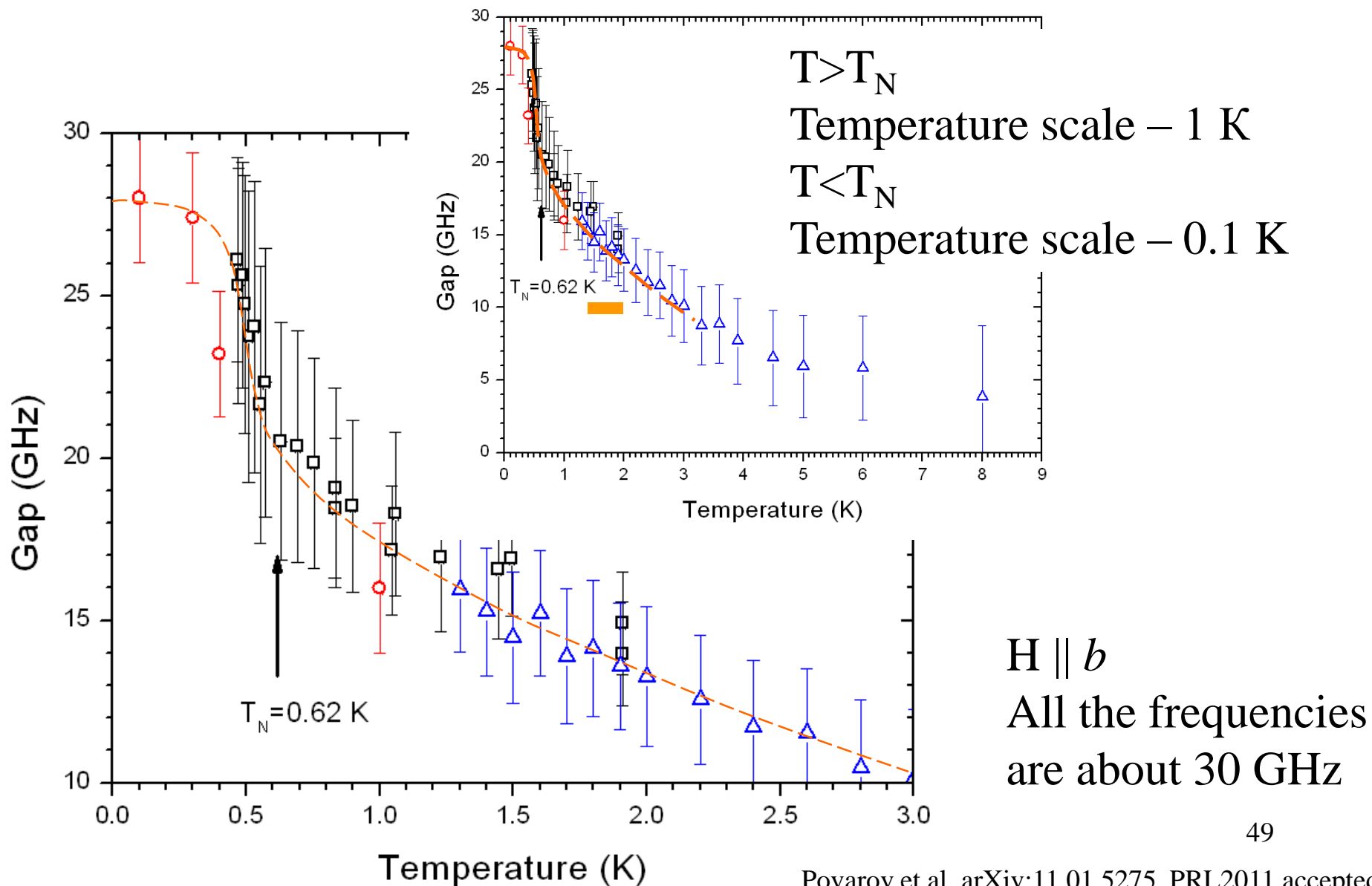


Below T_N a strong reduction of the order parameter by quantum fluctuations exists : $\Delta S/S=0.25$ (Coldea et al PRL 2001)

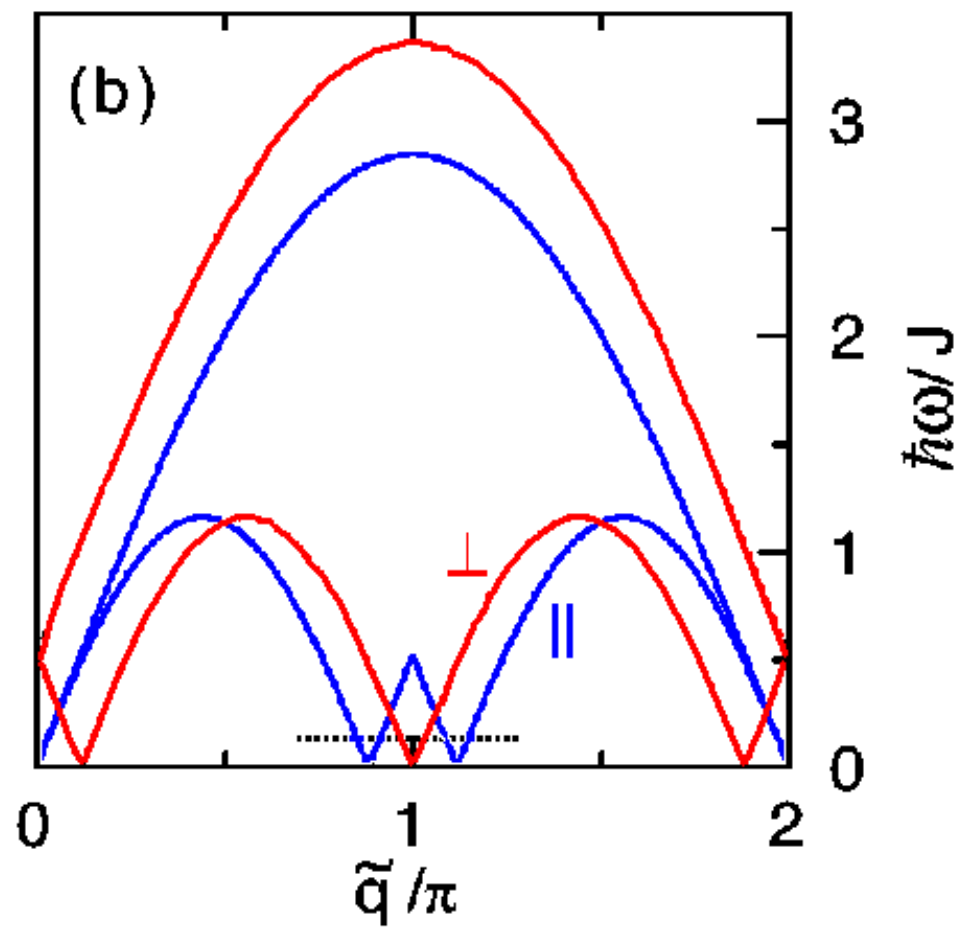
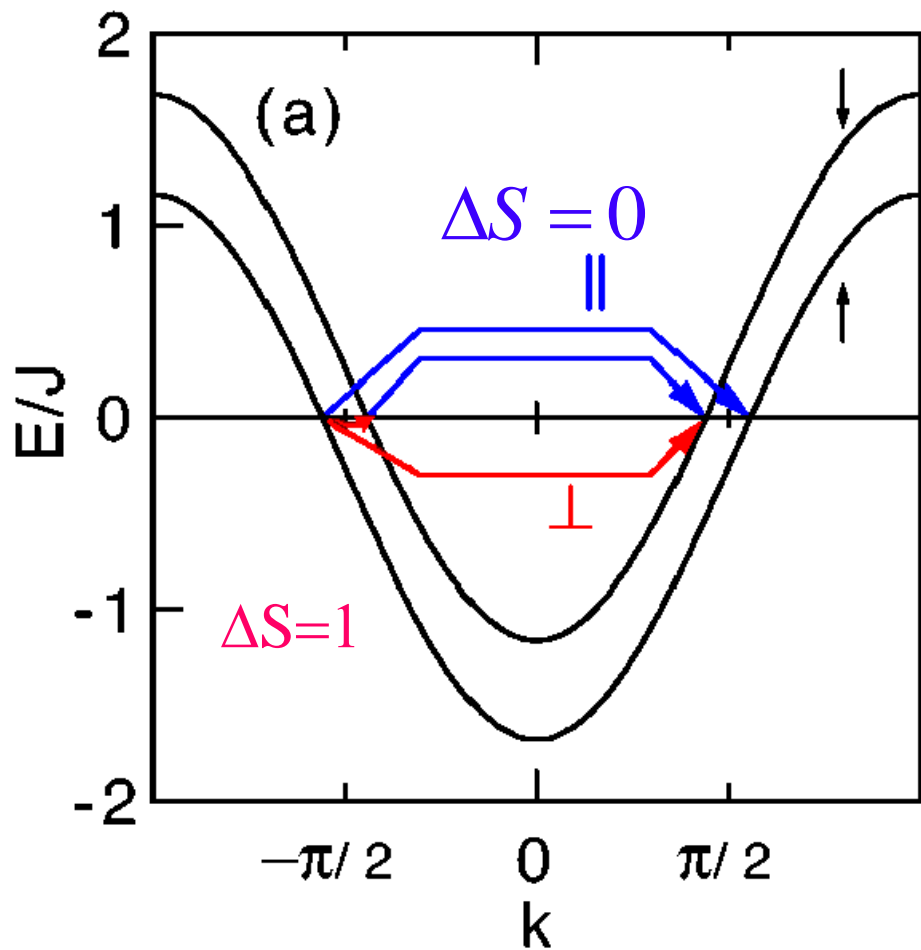
What excitation spectrum will appear – that of frozen or fluctuating spins?



T-dependence near the transition to the ordered phase



Spinons: fermions



Fermions confirmed by neutron scattering: soft modes near $q=\pi$

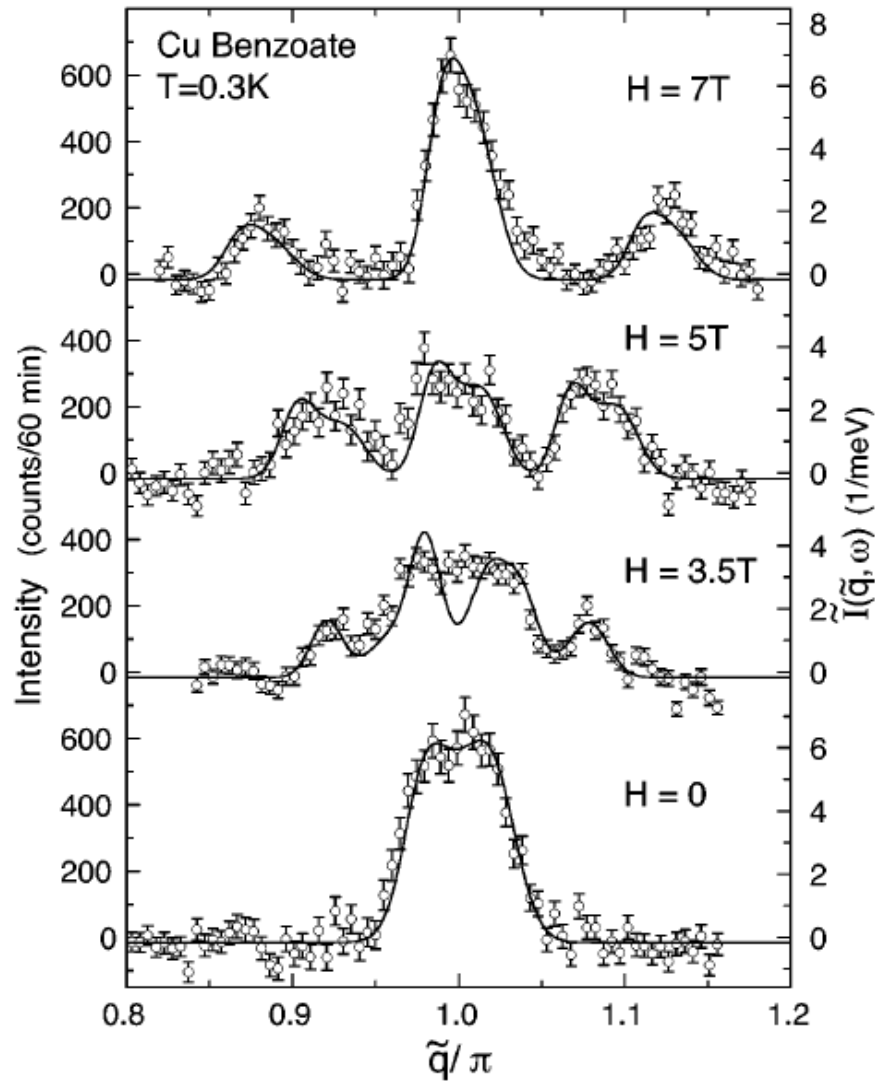
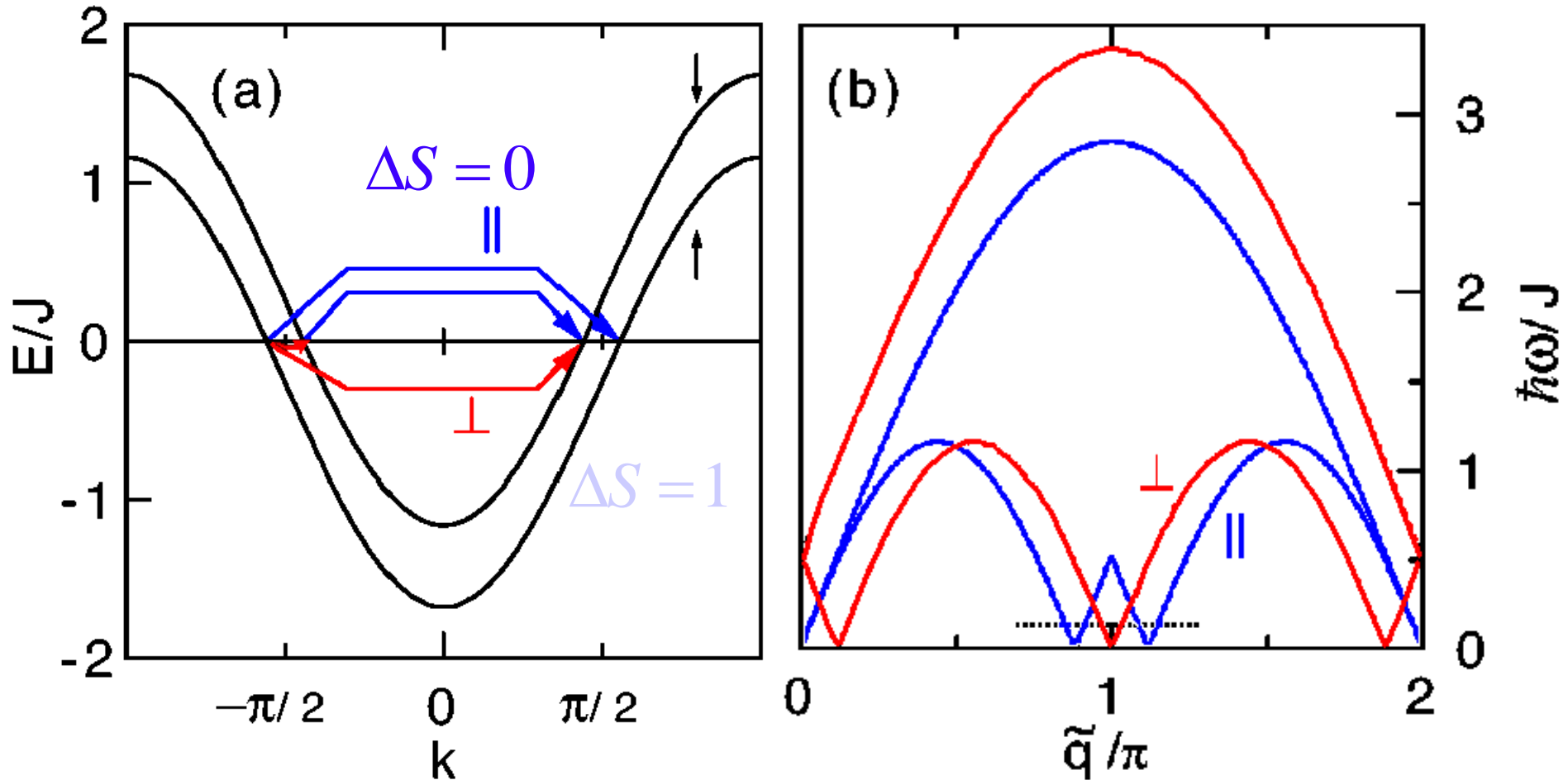


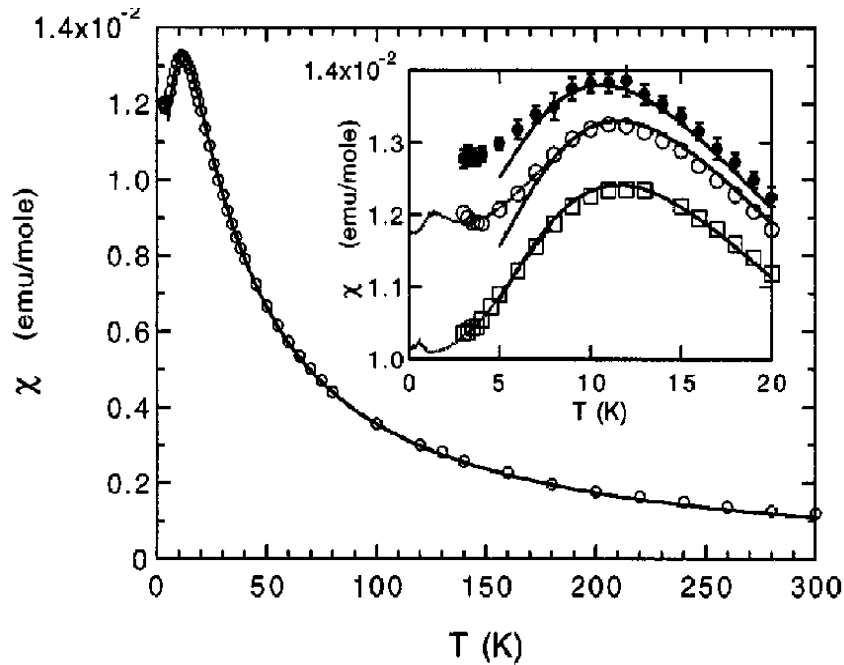
FIG. 2. Magnetic scattering at $\hbar\omega = 0.21$ meV along the $(0.3, 0, l)$ direction for four values of magnetic field H at $T =$

Continuum boundaries in the magnetic field

Spinons: fermions

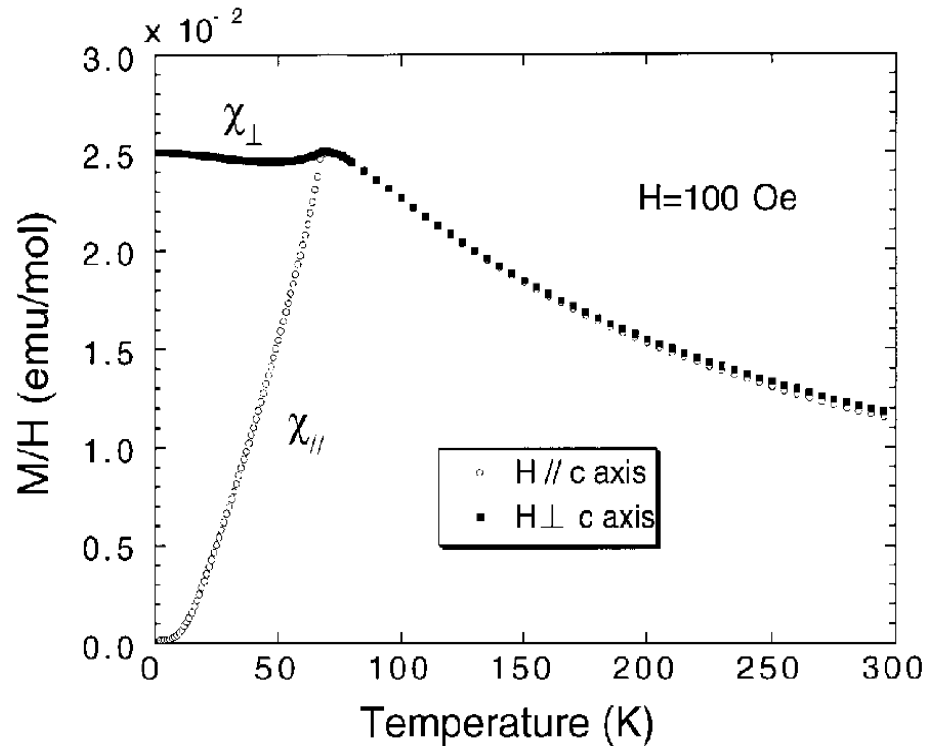


Susceptibility of a quantum $S=1/2$ chain and of an antiferromagnet



$S=1/2$ chains in copper benzoate

Dender et al PRB 1996



AFM MnF_2

After Katsumata JPCM 2000