MAGNETIC DEFLAGRATION

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Magnetic clusters:

Mn, Mn_2, Mn_3, Mn_4, $[Mn_4]_2$, Mn_5, Mn_6, Mn_7, Mn_8, Mn_9, Mn_{10}, Mn_{11}, Mn_{12}, Mn_{13}, Mn_{16}, Mn_{18}, Mn_{21}, Mn_{24}, Mn_{26}, Mn_{30}, Mn_{84}

Fe_2, Fe_3, Fe_4, Fe_5, Fe_6, Fe_7, Fe_8, Fe_{10}, Fe_{11}, Fe_{13}, $Fe_{17/19}$, Fe_{19}

Ni_4, Ni_5, Ni_6, Ni_8, Ni_{12}, Ni_{21}, Ni_{24}

Co_4, Co_6, Co_{10}

Co_2Gd_2, Co_2Dy_2, Cr_{12}, $CrNi_6$, $CrNi_2$, $CrCo_3$, $Fe_{10}Na_2$, Fe_2Ni_3, Mn_2Dy_2, Mn_2Nd_2, V_{15}, Ho, ...

• • • • • •

S = 0, 1/2, 1, 3/2, 2, 5/2, 4, 9/2, 5, …………. 33/2

<u>Chemistry</u>: T. Liz, 1980; <u>Magnetism</u>: R. Sessolli et al., 1990s

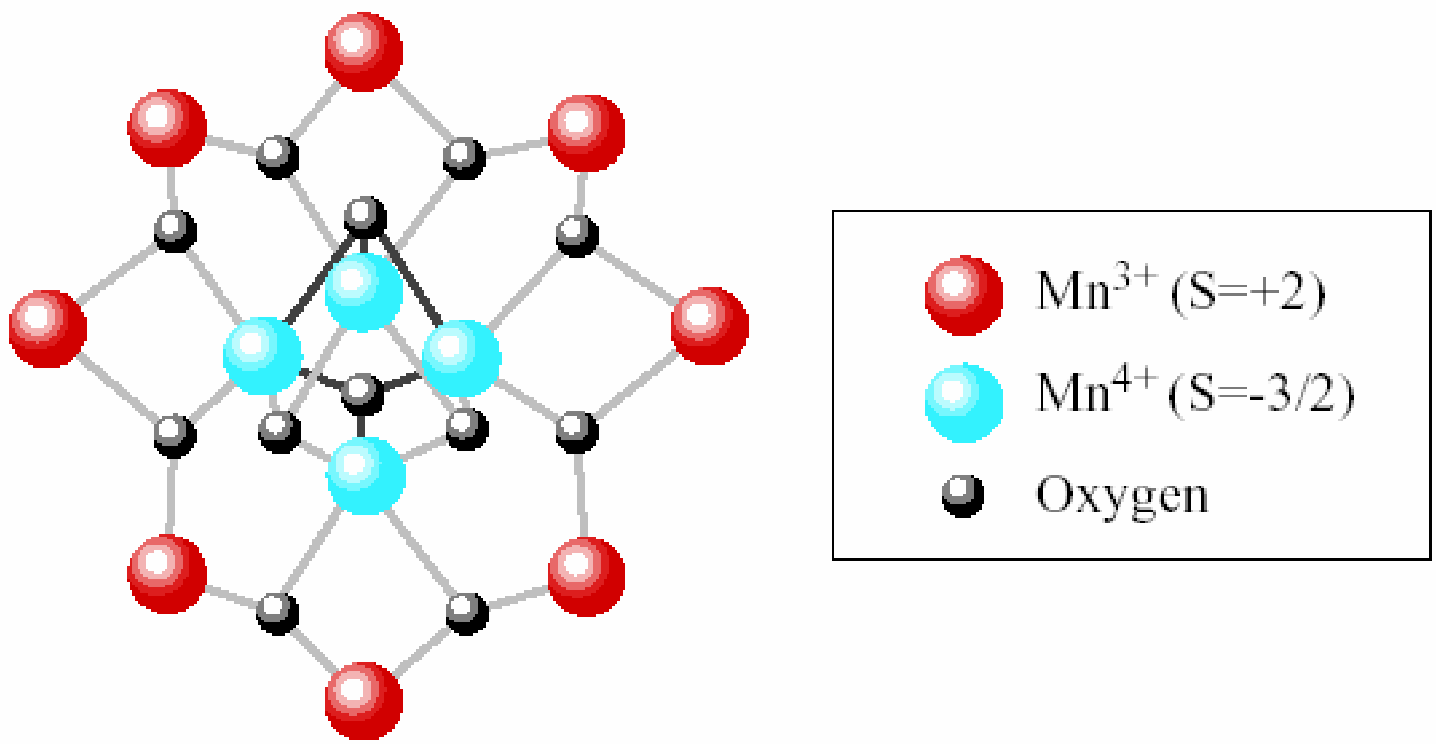
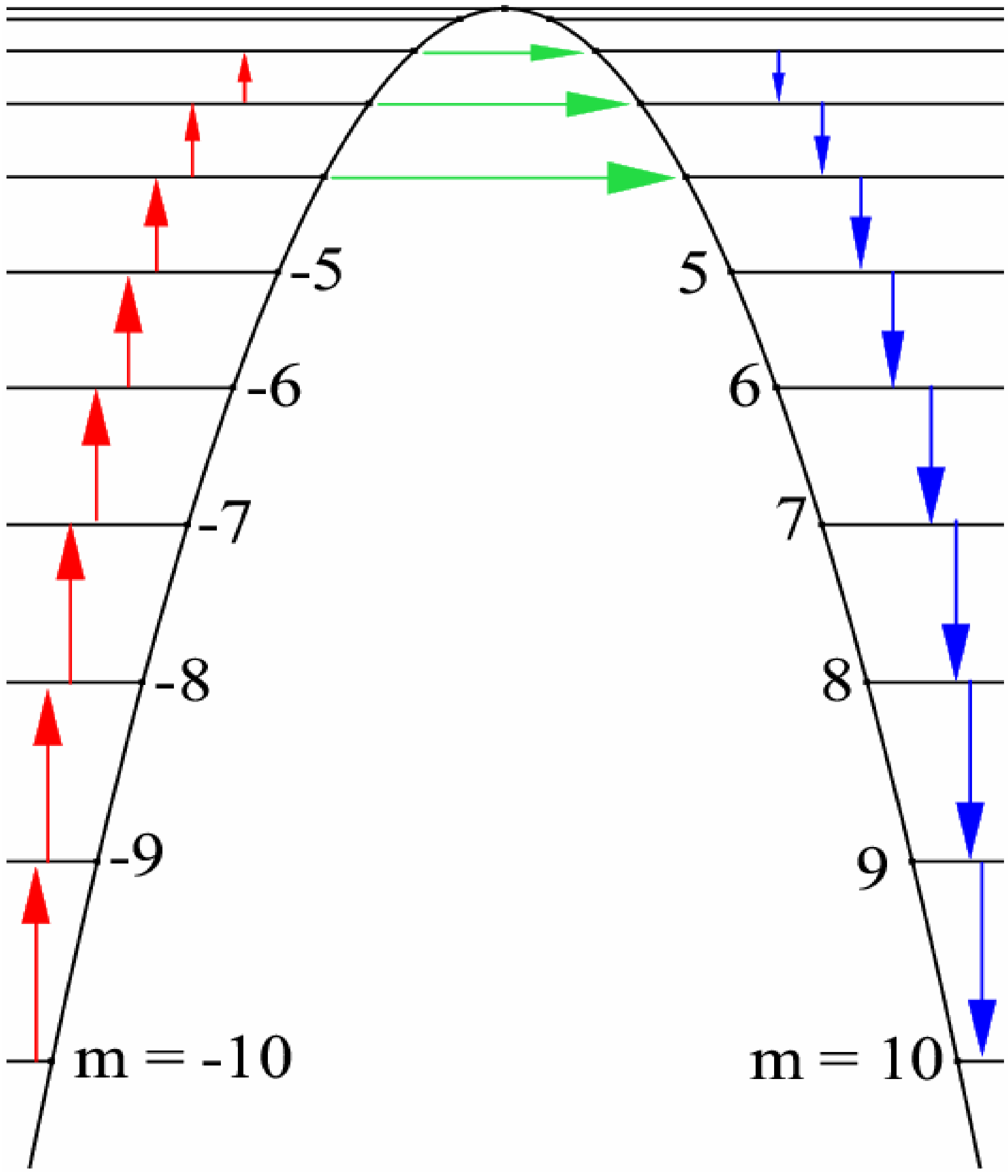


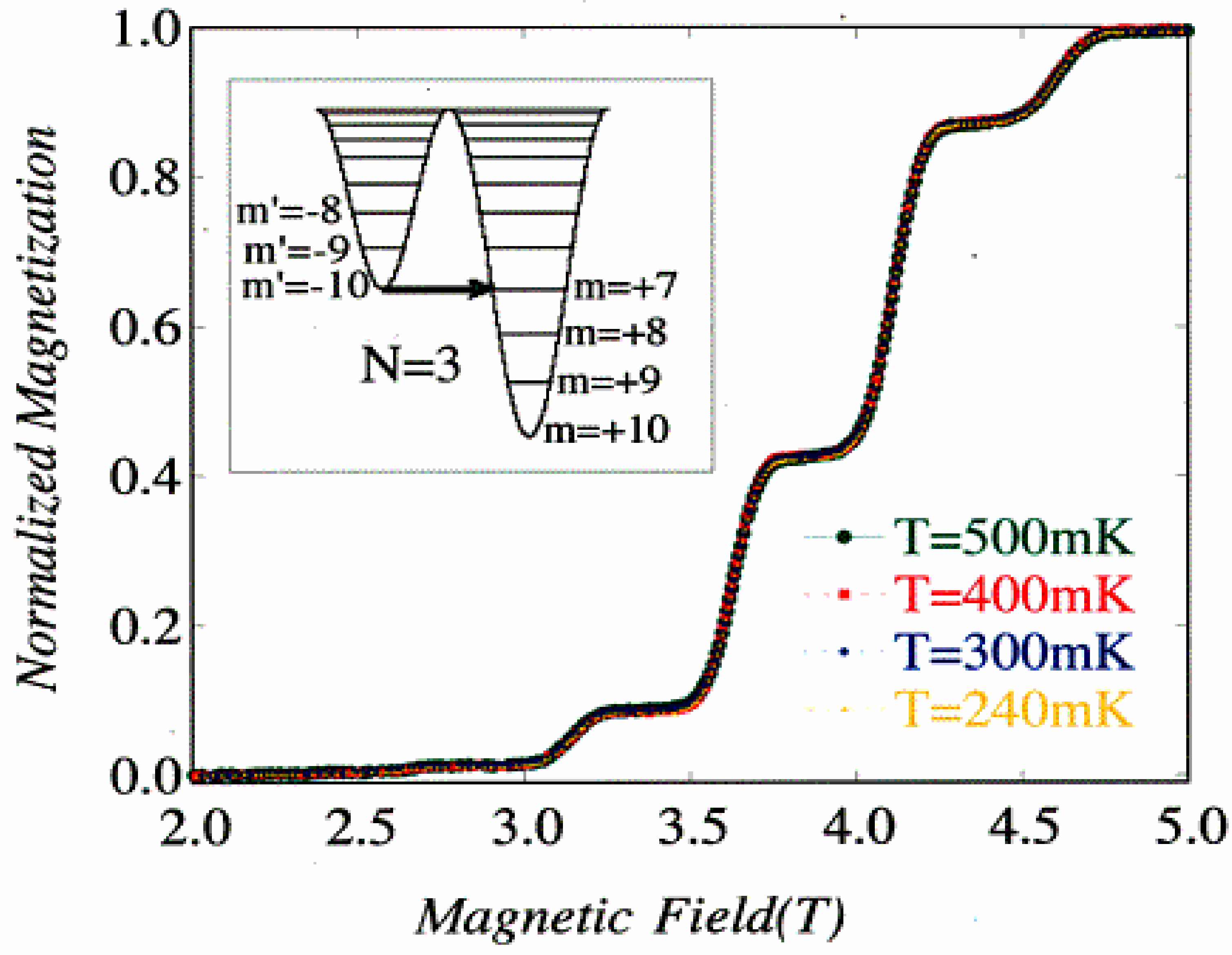
Figure 3: The magnetic core of the $S = 10$ single molecule magnet Mn_{12}-acetate. The four inner Mn ions couple anti-ferromagnetically via superexchange through oxygen bridges to the eight outer Mn ions.



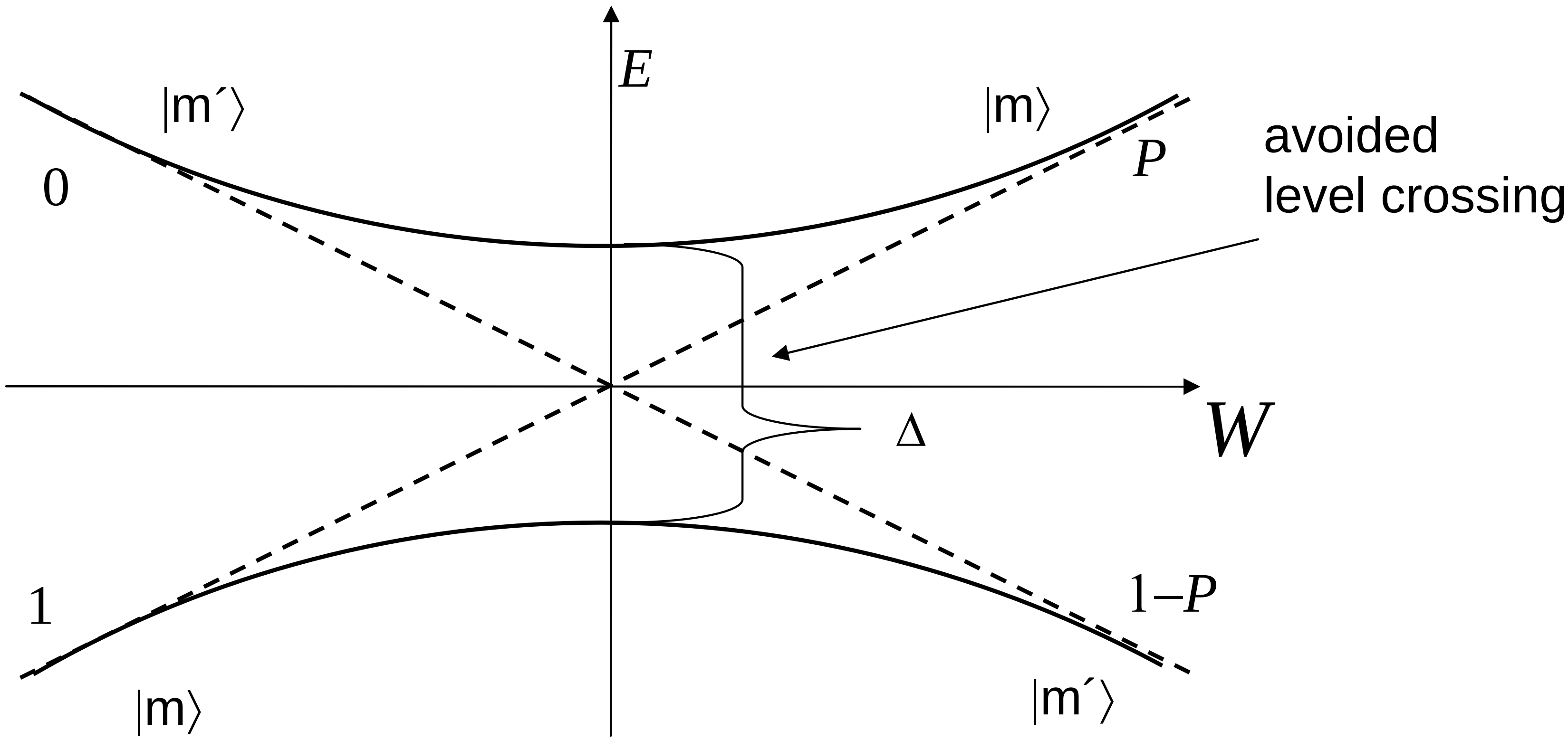
$H_Z = 0$

Quantum Magnetization Curve

J. Friedman, M. Sarachik, J. Tejada, R. Ziolo (PRL - 1996)



Landau-Zener transitions in molecular magnets



The size of the magnetization step at each crossing of spin levels is determined by the Landau - Zener probability :

$$P = \exp\left[-\frac{\pi\Delta^2}{2\eta(dE/dt)} \right]$$

AFM dimer $[Mn4]_2$, S=±9/2 , Wernsdorfer et al., Nature-2002; Hill et al., Science-2003

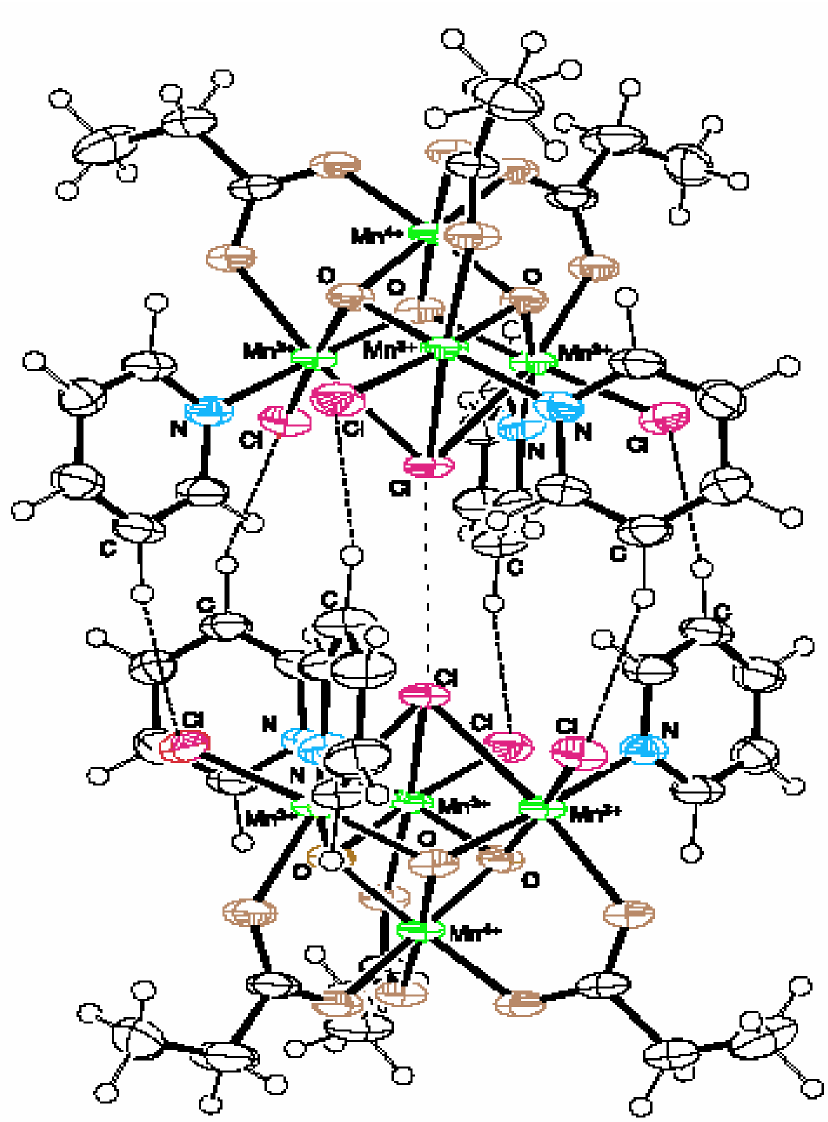


Figure 1 The structure of the $[Mn_4O_3Cl_4(O_2CEt)_3(py)_3]_2$ dimer, denoted $[Mn4]_2$. The small circles are hydrogen atoms. The dashed lines are C–H···Cl hydrogen bonds and the dotted line is the close Cl···Cl approach. Brown, oxygen; green, manganese; red, chlorine; blue, nitrogen; py, pyridine.

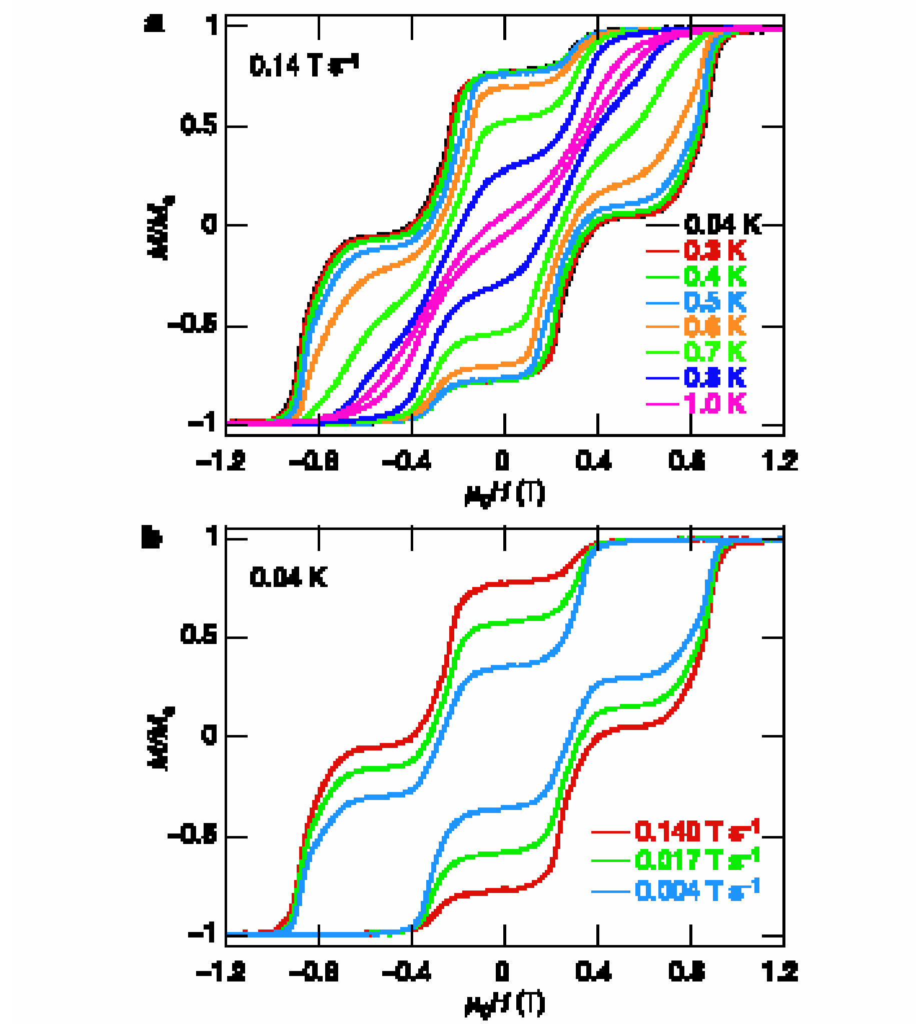
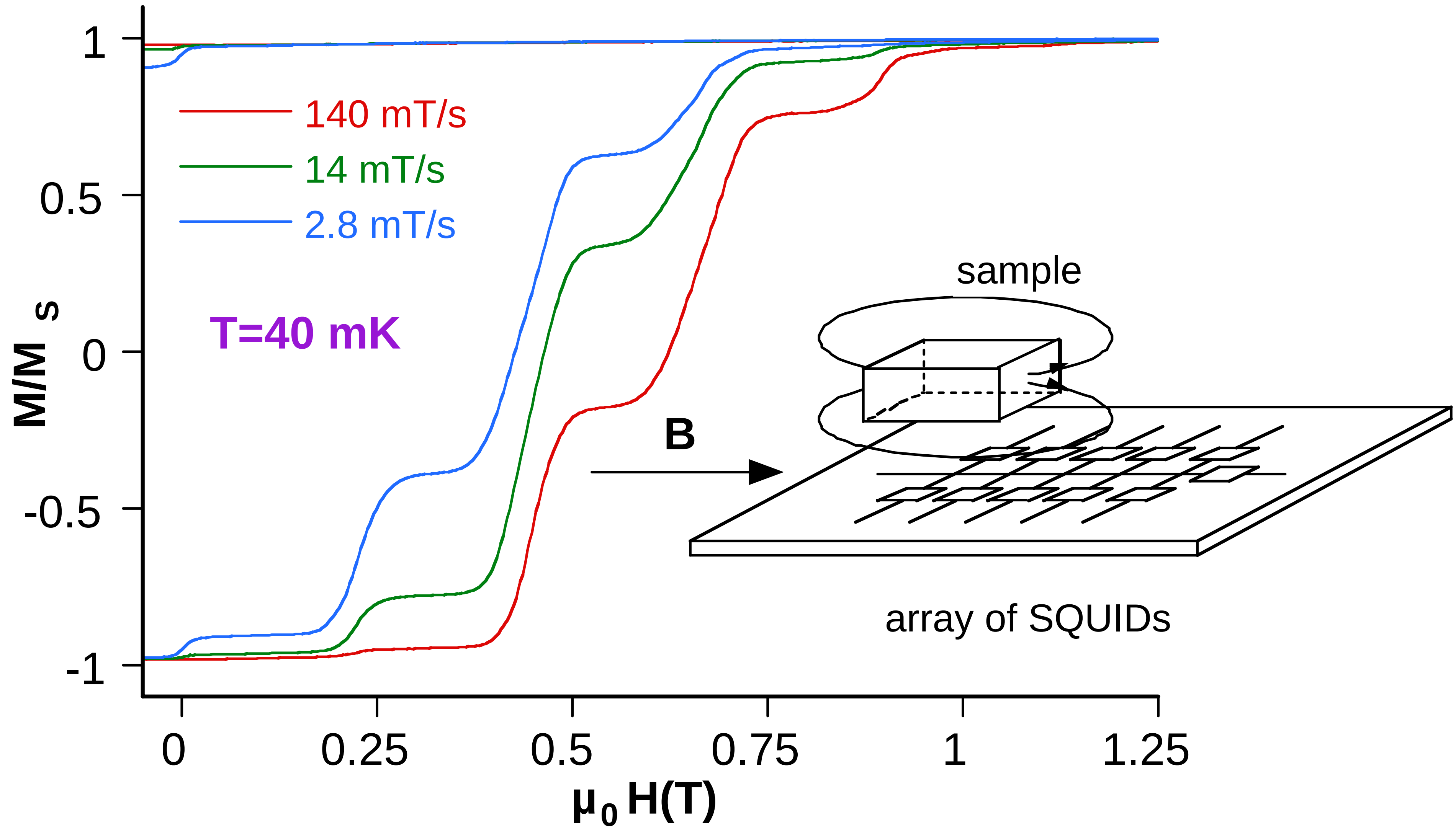


Figure 2 Magnetization (M) of $[Mn4]_2$ (plotted as fraction of maximum value M_s) versus applied magnetic field (μ_0H). **a**, **b**, The resulting hysteresis loops are shown at different temperatures (**a**) and different field sweep rates (**b**). We note that the loops become temperature-independent below about 0.3 K but are still sweep-rate-dependent owing to resonant quantum tunnelling between discrete energy states of the $[Mn4]_2$ dimer.

Magnetization curve of Fe-8 (W. Wernsdorfer)

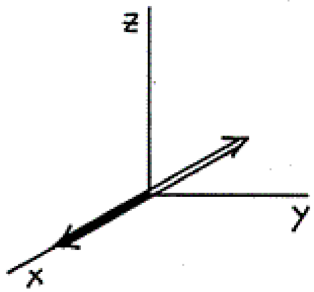


Berry Phase Effects: Interference of Tunneling Paths

Berry phase: $A \propto e^{-iS\int d\phi\,(1-\cos\theta)}$

1) $H = 0$

$\mathcal{H} = a S_z^2 - b S_x^2$



$\frac{1}{2}e^{-iS\pi} + \frac{1}{2}e^{iS\pi} = \cos(S\pi)$

[Loss, DiVincenzo, Grinstein - 1992]

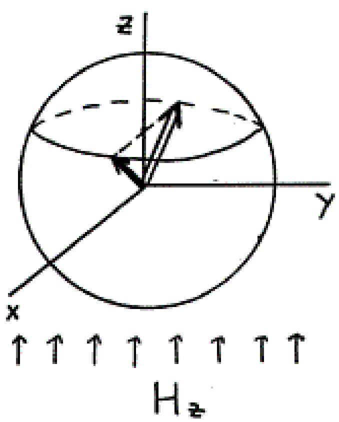
2) $H_z = 0$

$\mathcal{H} = a S_z^2 - b S_x^2 - H_z S_z$

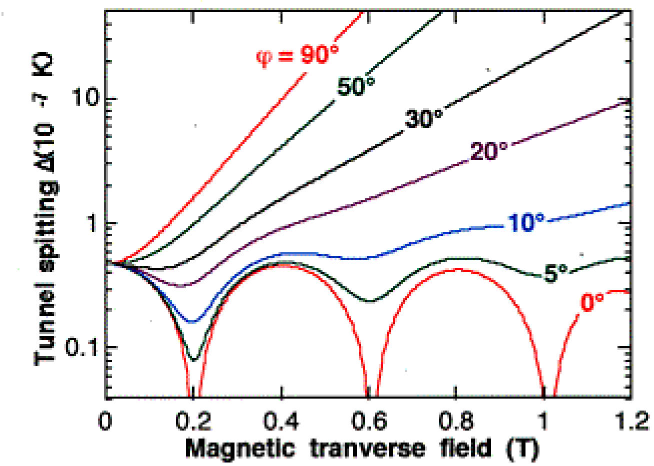
$\frac{1}{2}e^{-iS\pi\left(1-\frac{H_z}{H_c}\right)} + \frac{1}{2}e^{iS\pi\left(1-\frac{H_z}{H_c}\right)}$

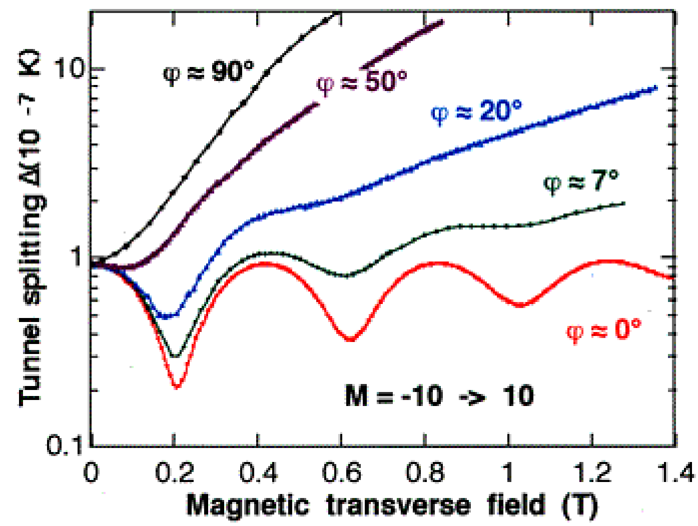
$= \cos\left[S\pi\left(1-\frac{H_z}{H_c}\right)\right]$

[Garg - 1993]



Transverse field dependence of tunnel splitting



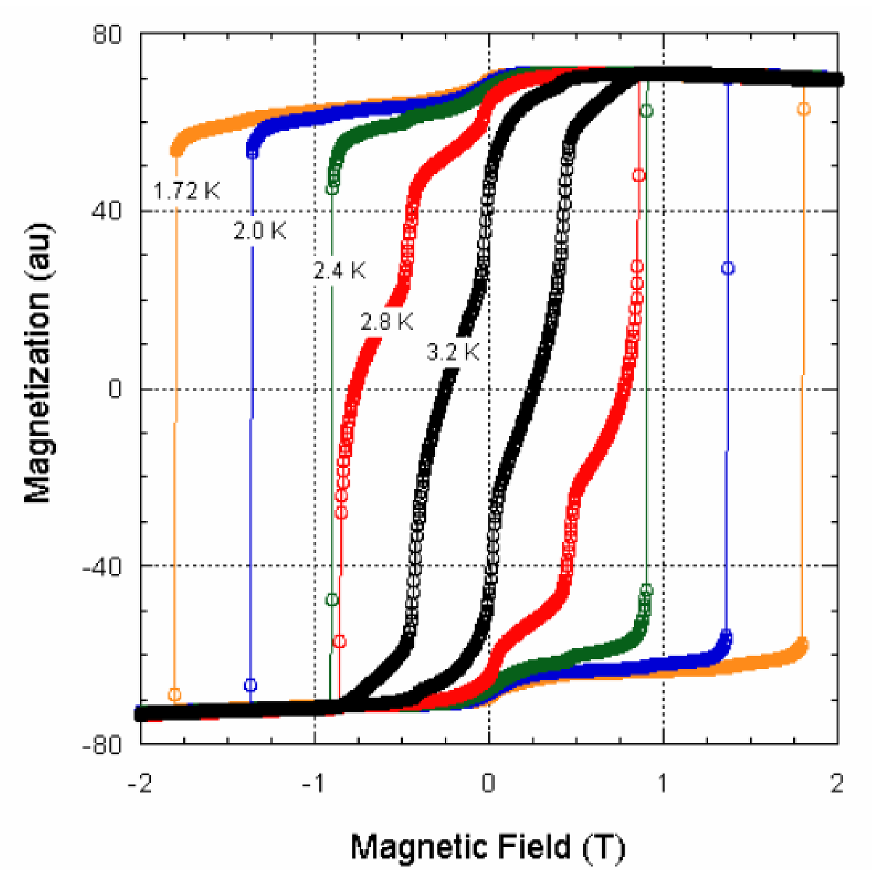


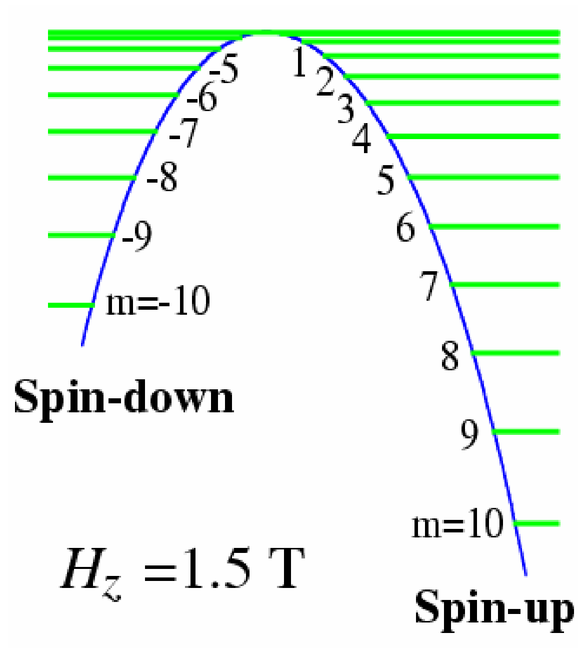
W. Wernsdorfer and R. Sessoli, *Science* 284, 133 (1999)

$H = -DS_z^2 + E\left(S_+^2 + S_-^2\right) + C\left(S_+^4 + S_-^4\right) + g\mu_B \vec{S}\vec{H}$

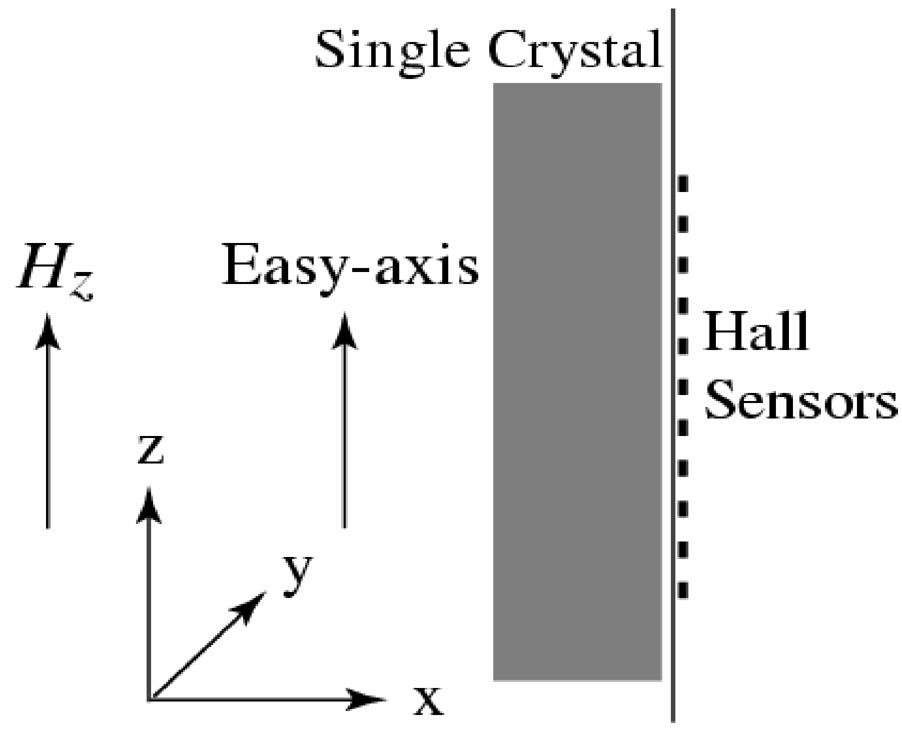
$D = 0.292\,K,\quad E = 0.046\,K,\quad C = -2.9\times10^{-5}\,K$

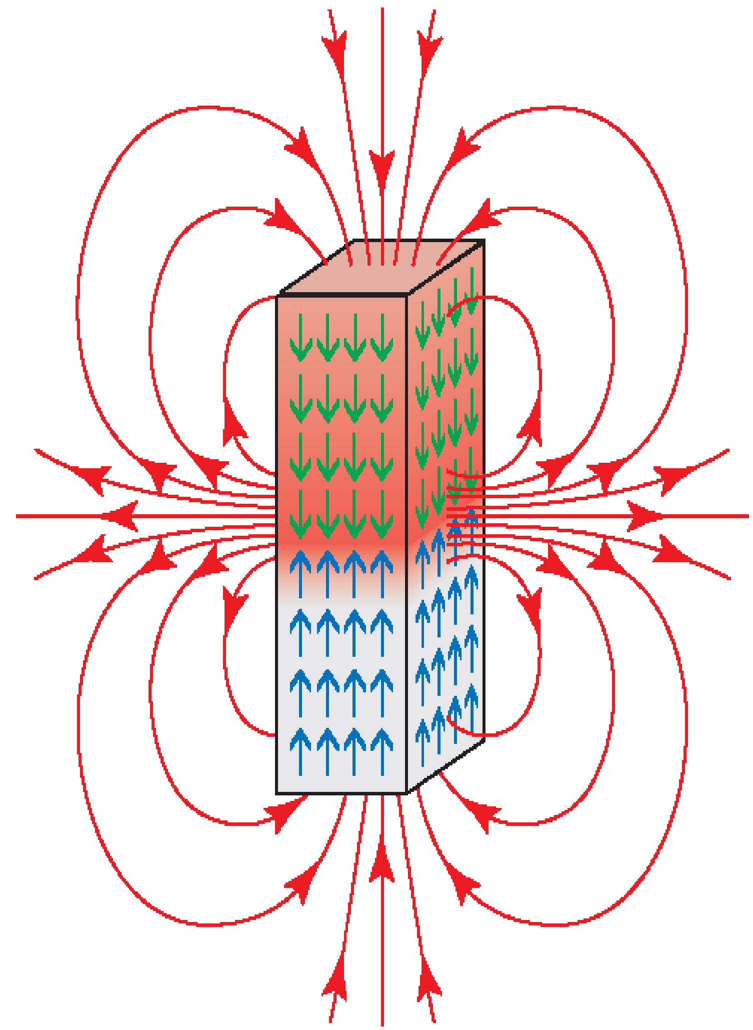
Avalanches in Mn-12 Acetate





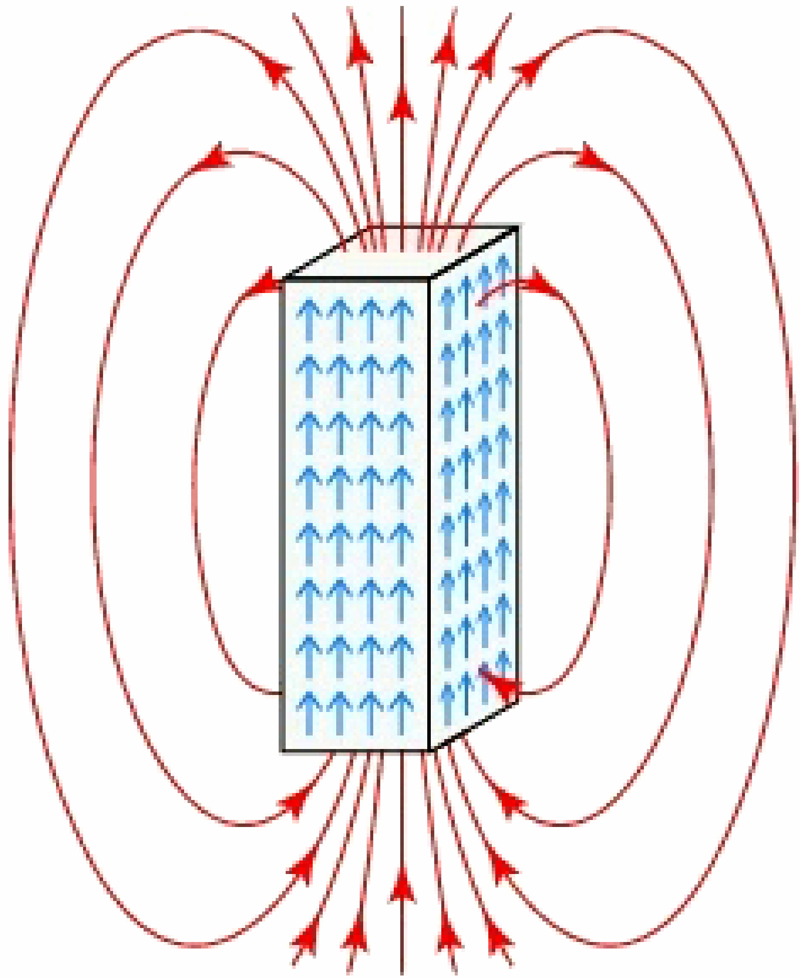
CCNY Experiment – Spring 2005, Y. Suzuki, M. Sarachik, et al.





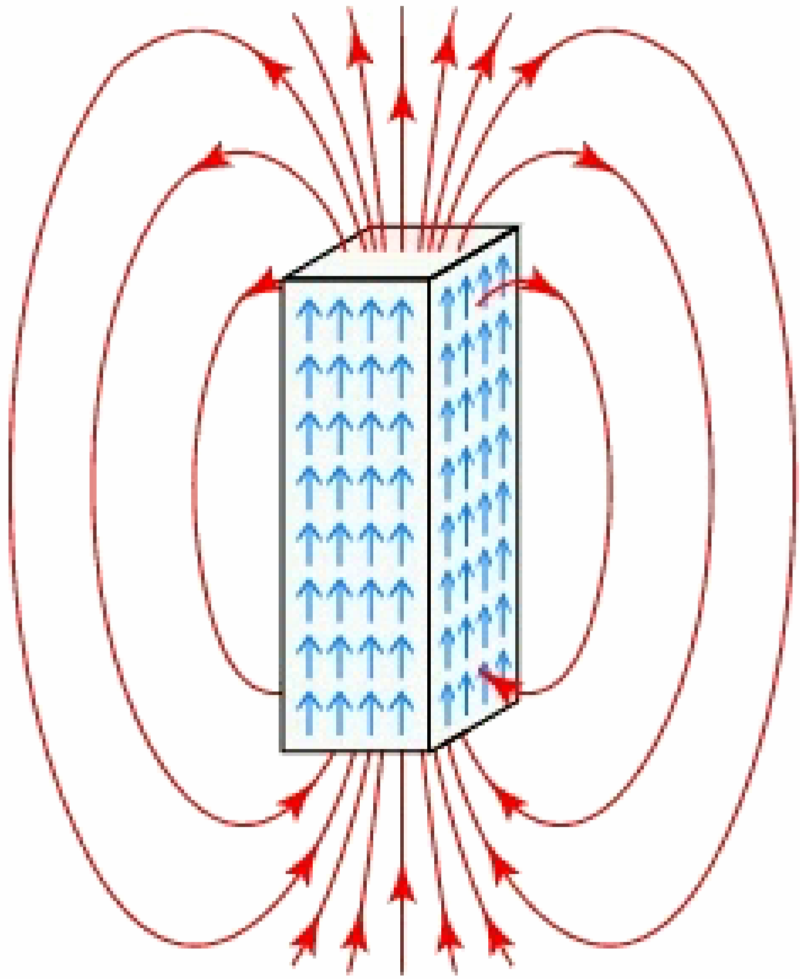
Magnetic Deflagration

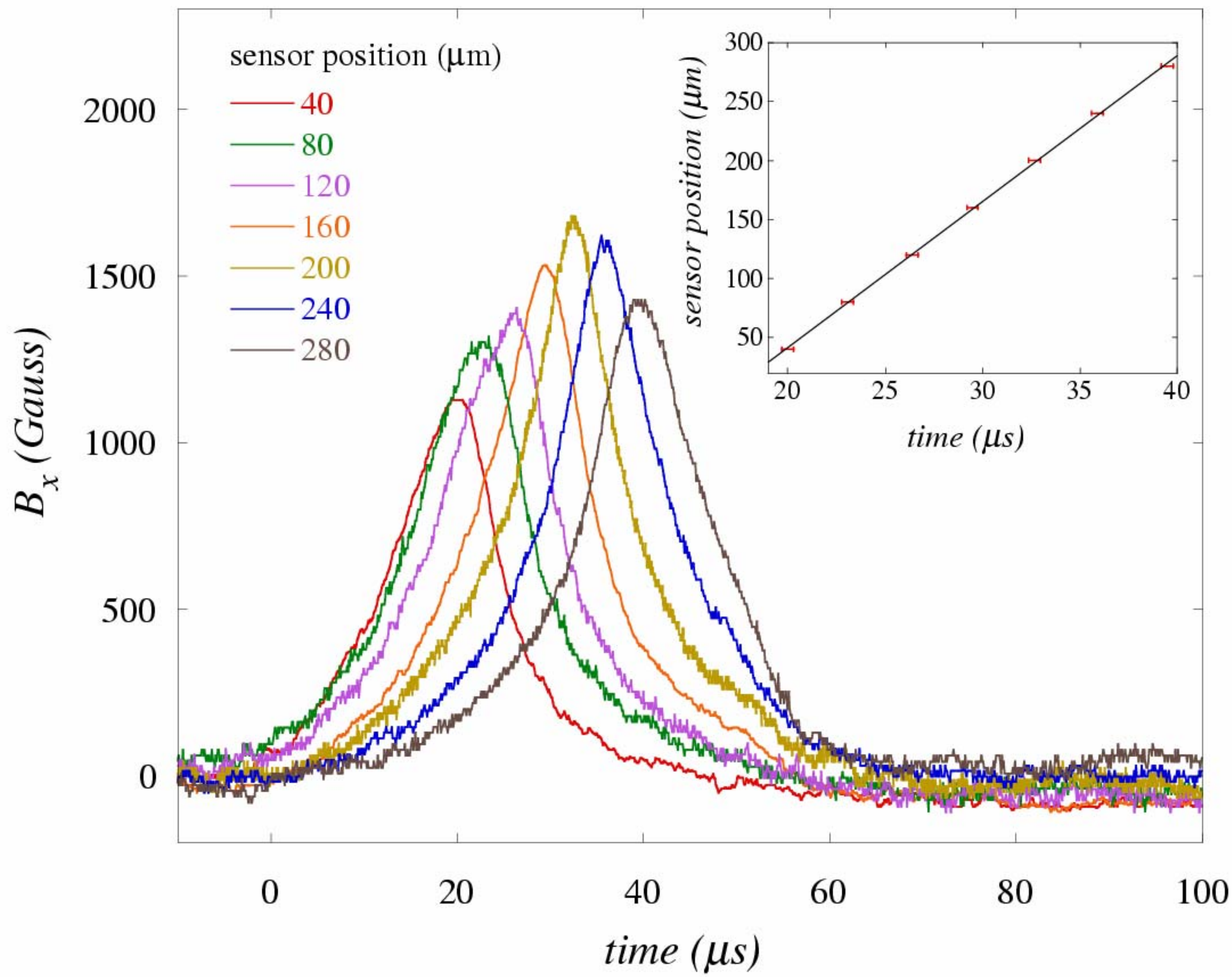
[Y. Suzuki, M. Sarachik, E. Chudnovsky, PRL – 30 Sept 2005]



Magnetic Deflagration

[Y. Suzuki, M. Sarachik, E. Chudnovsky, PRL – 30 Sept 2005]





sensor position (μm)
40
80
120
160
200
240
280
B_x (Gauss)
time (μs)
sensor position (μm)
time (μs)

Theory of Magnetic Deflagration

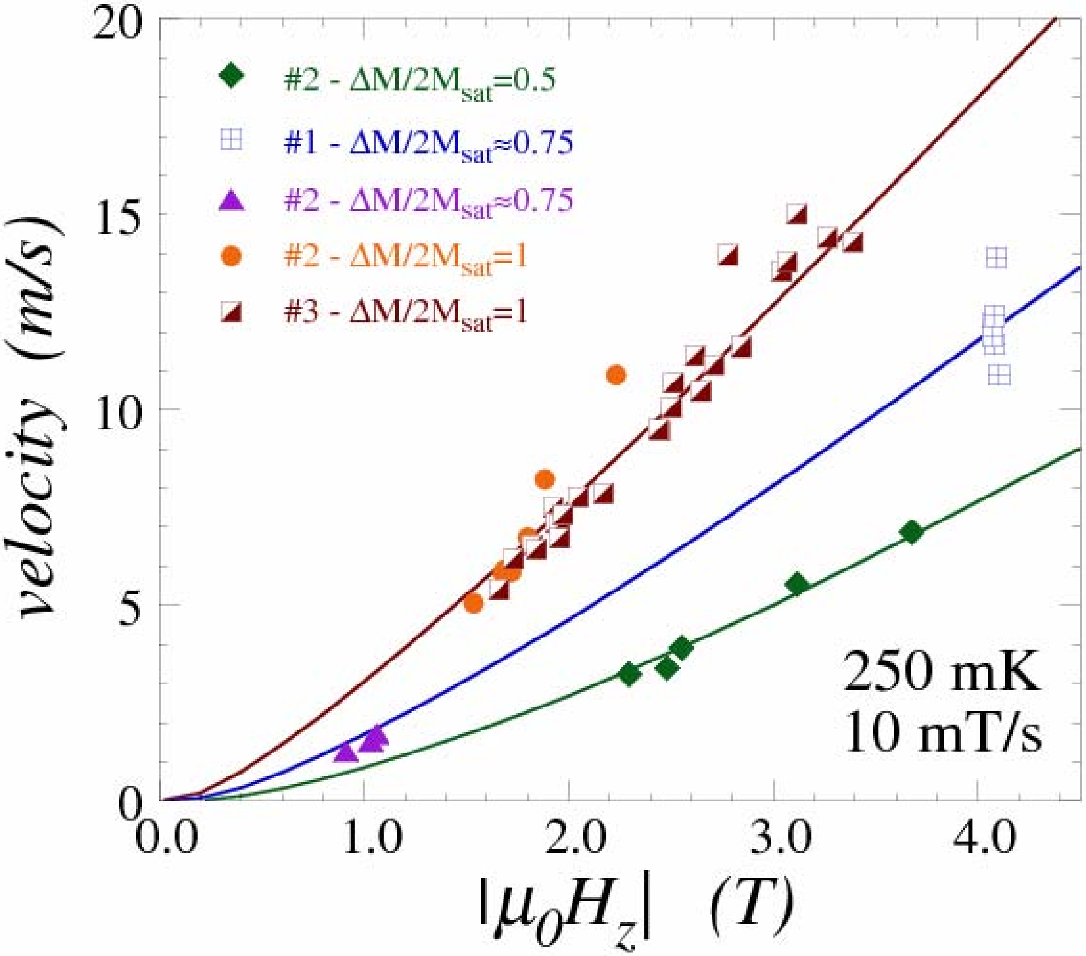
$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T, \qquad T = T(x - vt)$$

$$T = T_f \exp\left[-\frac{x - vt}{\delta}\right] \quad \text{at} \quad x > vt$$

$$\delta = \frac{\kappa}{v} \approx (\kappa\tau)^{1/2}$$

$$\tau(H) = \tau_0 \exp\left[\frac{U(H)}{k_B T}\right]$$

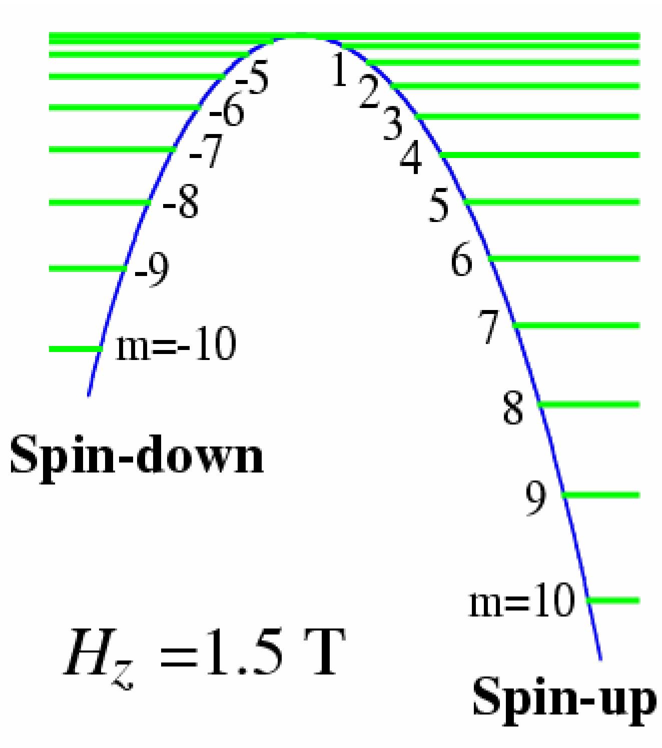
$$v \approx \left(\frac{\kappa}{\tau}\right)^{1/2} = \left(\frac{\kappa}{\tau_0}\right)^{1/2} \exp\left[-\frac{U(H)}{2k_B T}\right]$$

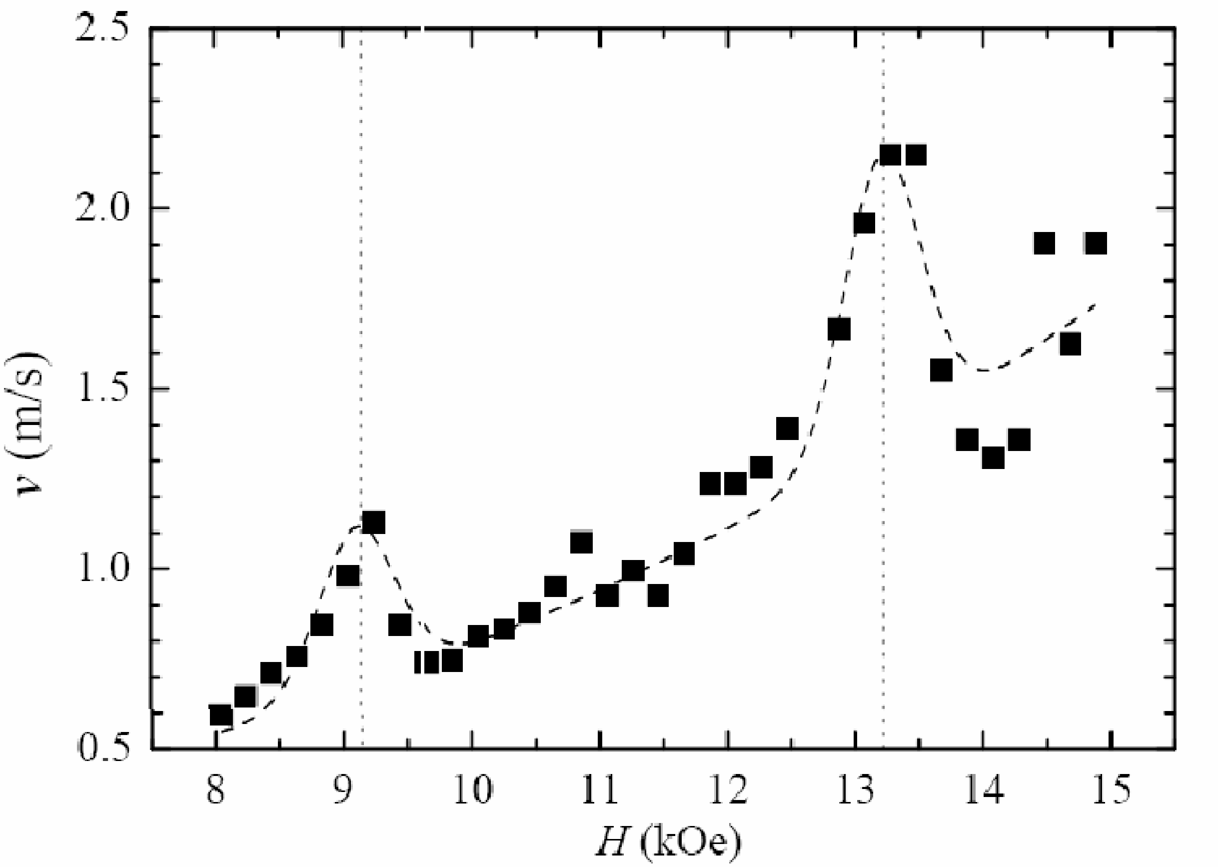


#2 - ΔM/2M$_{sat}$=0.5
#1 - ΔM/2M$_{sat}$≈0.75
#2 - ΔM/2M$_{sat}$≈0.75
#2 - ΔM/2M$_{sat}$=1
#3 - ΔM/2M$_{sat}$=1
250 mK
10 mT/s
velocity (m/s)
$|\mu_0 H_z|$ (T)
0
5
10
15
20
0.0
1.0
2.0
3.0
4.0

Quantum Magnetic Deflagration

[A. Hernandez-Minguez et al, PRL – Nov 2005, to appear]





CONCLUSIONS

Crystals of molecular nanomagnets exhibit two modes of magnetic relaxation:

- The slow relaxation mode, which is responsible for the staircase magnetization curve, is due to thermally assisted quantum tunneling (Landau-Zener transitions) between resonant spin levels.
- The fast magnetization reversal is equivalent to the deflagration in a flammable chemical substance. This observation opens ways of controllable non-destructive studies of deflagration and, possibly, detonation.