Magnetic behavior of materials with π-junction loops

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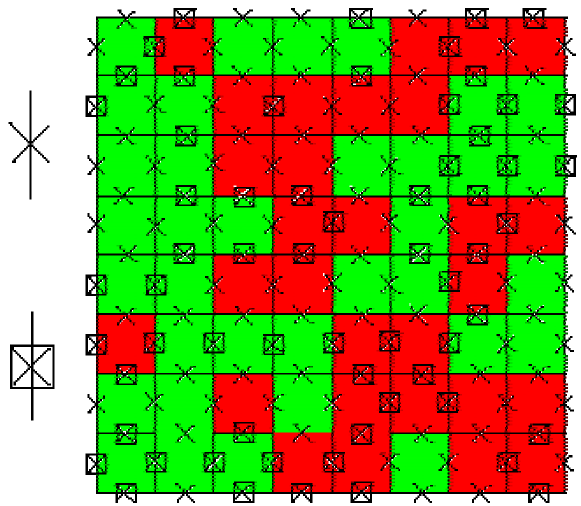
Oral Session 11-June

We are here

Gran Sasso range (2914 m) and L'Aquila

conventional Josephson junction

unconventional π-Josephson junction



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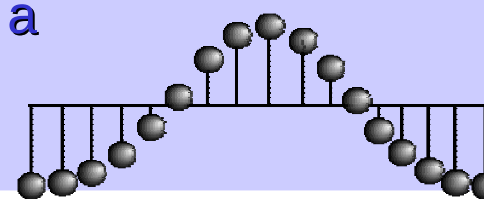

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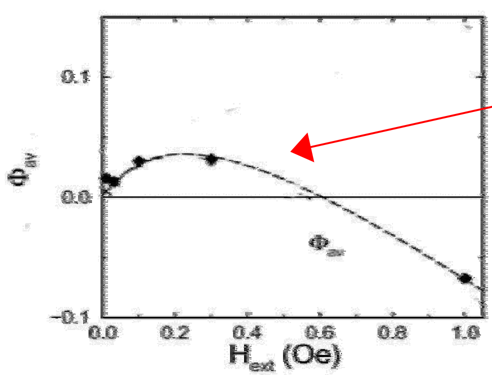
Experimental facts

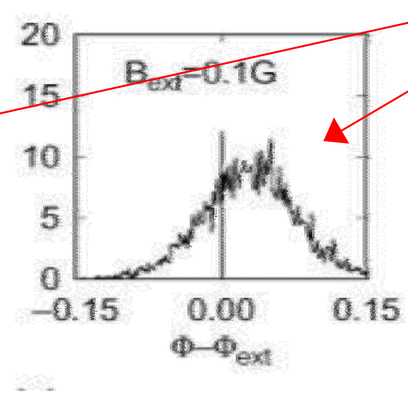
Multiply Connected Superconductors MCS:

- HTC High-Tc materials (intrinsic arrays)
- JJA Josephson Junctions Arrays (Low-Tc artificial arrays)

HTC facts

Sample is field cooled (FC) and then magnetization is measured with a susceptometer or a SSM





Paramagnetic Signal = Paramagnetic Meissner Effect (PME)

(see W.Braunisch et al., PRB **48**, 4030, 1993),
J.R.Kirtley et al., Cond.Mat. **10**, L97, 1998)

PME Theories

1) for HTC materials presence of π -junctions
M.Sigrist and T.M.Rice, J.Phys.Soc.Jpn.**61**, 4283, 1992
Confirmed with early numerical simulations by
D.Dominguez et al. PRL **72,** 2773, 1994

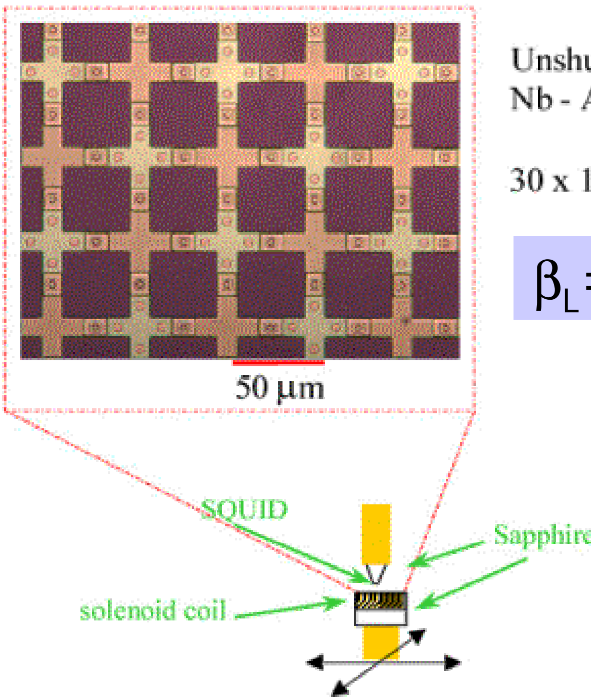
Observations of PME in Low Tc samples!!!
1) Nb Disks (see D.J.Thompson et al., PRL**75**, 529, 1995)
2) AC effect in LTC JJA (see F.M.Araùjo-Moreira et al., PRL**78**, 4625, 1997)
and more....

2) in LTC materials: a rid of hypothesis mainly based on Non-equilibrium and inhomogeneity
(see A.E.Koshelev and A.I.Larkin PRB**52,** 13559, 1995;
V.V.Moshchalkov et al., PRB**55**, 11973, 1997;
P.S.Deo et al., PRB**59**, 6039, 1999)

Experimental facts (cont')

JJA

Scanning SQUID Experiment



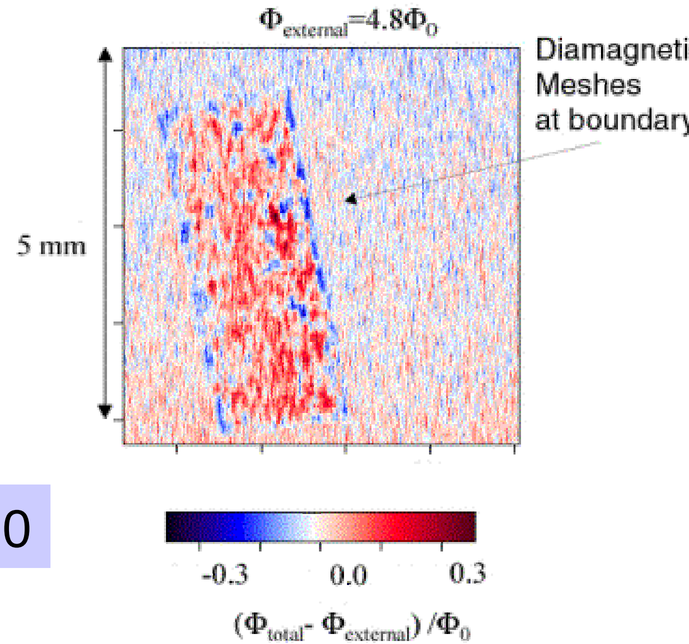
Unshunted Array
Nb - AlOx -Nb

30 x 100 junctions

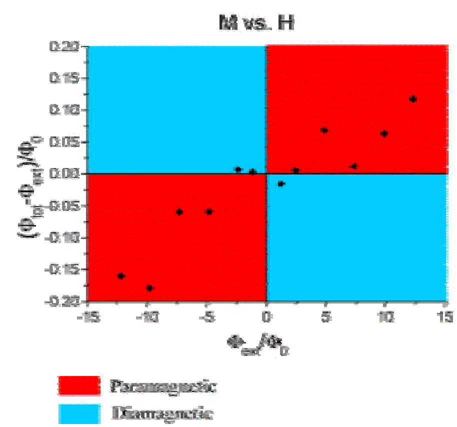
$\beta_L = 2\pi I L / \Phi_0 = 30$

Sample is field cooled
Measured with field turned on

Paramagnetic Image of JJ Array



Array Exhibits Paramagnetism
For ~~Some~~ Cooling Fields!
Almost all !!



(see A.P.Nielsen et al. PRB 62, 14380, 2000)

Three main questions

- How a paramagnetic state is generated in MCS ?
- What is the role of π-junctions ?
- It is possible for an experiment have different outputs for conventional and mixed π/conventional arrays ?

JJA Equations
(see C.De Leo et al., Phys.Rev.B64, 144518, 2001)

$$\frac{\beta_L}{2\pi}\sin\vec{\varphi} + \sqrt{\frac{\beta_L}{\beta_C}}\dot{\vec{\varphi}} + \ddot{\vec{\varphi}} = \mathbf{K}\mathbf{L}^{-1}\vec{m}$$

φ is the vector of the phases of the Josephson junction in the array
K and **L** are matrixes containing both self and mutual inductance coupling

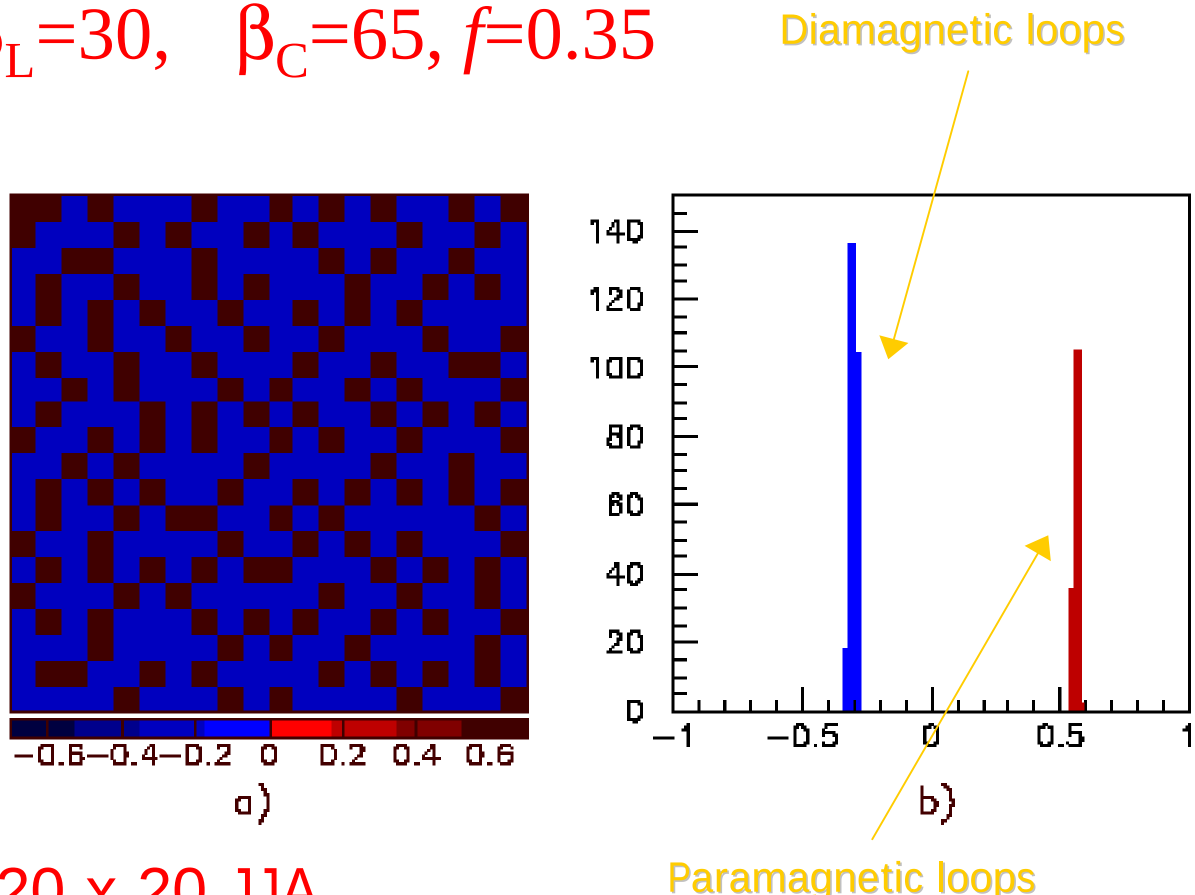
$\beta_L = 2\pi I_0 L/\Phi_0$ $\beta_C = 2\pi I_0 C R^2/\Phi_0$

$$\mathbf{m} = \frac{\vec{\phi}_{tot}}{\Phi_0} - \frac{\vec{\phi}_{ext}}{\Phi_0} = \frac{1}{2\pi}\left(\mathbf{M}\vec{\varphi} + 2\pi\vec{n} - 2\pi\vec{f}\right)$$

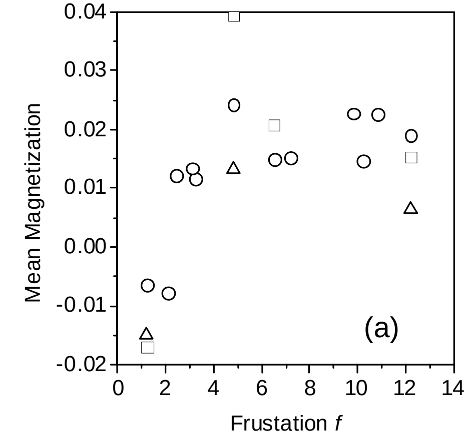
m represents the loop magnetization, **M** is a matrix
Performing the oriented sum of the phases on a loop

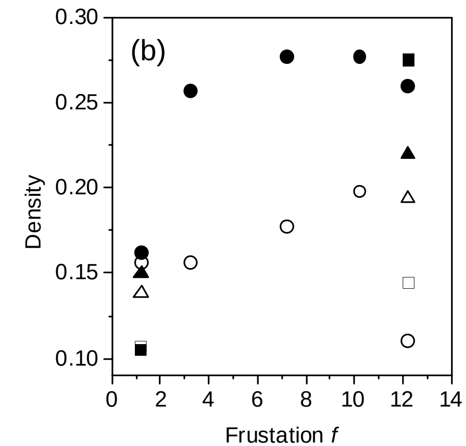
Simulations (conventional)

$\beta_L=30, \quad \beta_C=65, f=0.35$



20 x 20 JJA





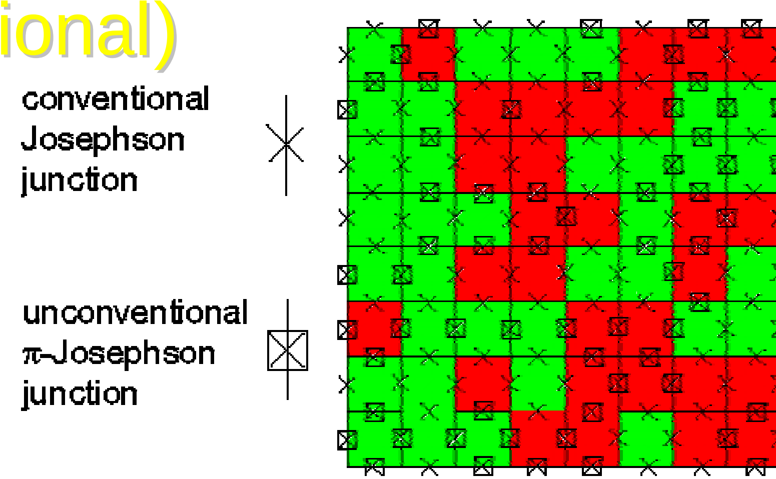
Squares 20x20 array
Triangles 10x10
Circlea 10x40

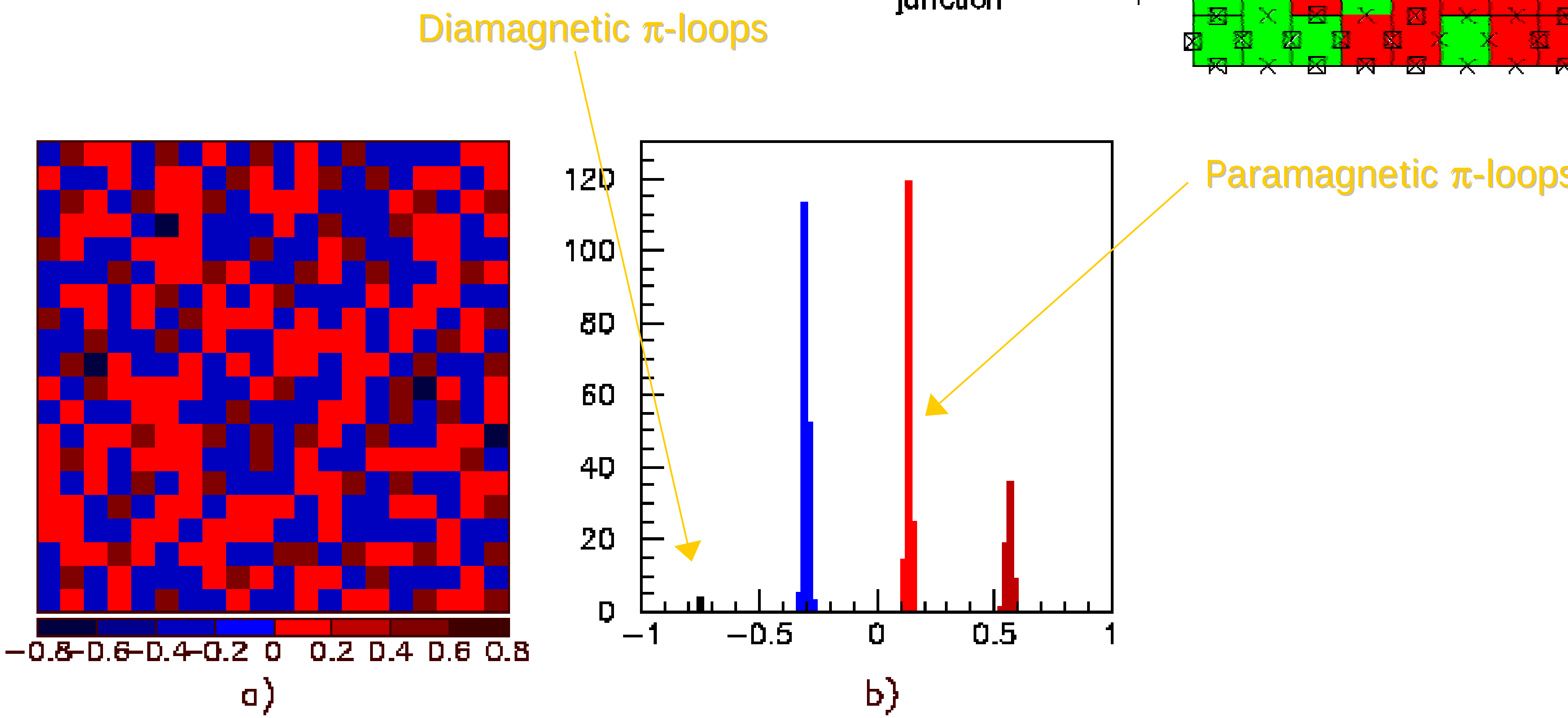
(see A.P.Nielsen et al., Phys.Rev.B62, 14380, 2000 and C.De Leo et al., Phys.Rev.B64, 144518, 2001)

Simulations (mixed π/conventional)

Important: to avoid MC effects we study the first period 0<f<1

$\beta_L=30,\ \beta_C=65,\ f=0.35$



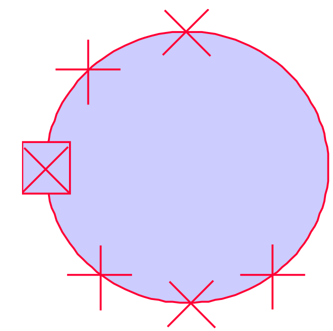


(see C.De Leo and G.Rotoli, cond-mat/0205434)

Single loop states

For a loop of p equal Josephson conventional/π junctions
The current states are given by the solutions of:

$$\gamma_n = \sin\left(\frac{1}{p}\left(2\pi n - \pi k - 2\pi f - \beta\gamma_n\right)\right)$$



A 5+1π loop
p=6, k=1

If β is large lowest energy solutions are given by

$$\gamma_\mathrm{n} = -\mathrm{A}_\mathrm{n} f + \mathrm{B}_\mathrm{n}$$

$$A_n = \frac{2\pi/p}{1+\beta/p}$$

$$B_n = n\frac{2\pi/p}{1+\beta/p} \qquad (k=0)$$

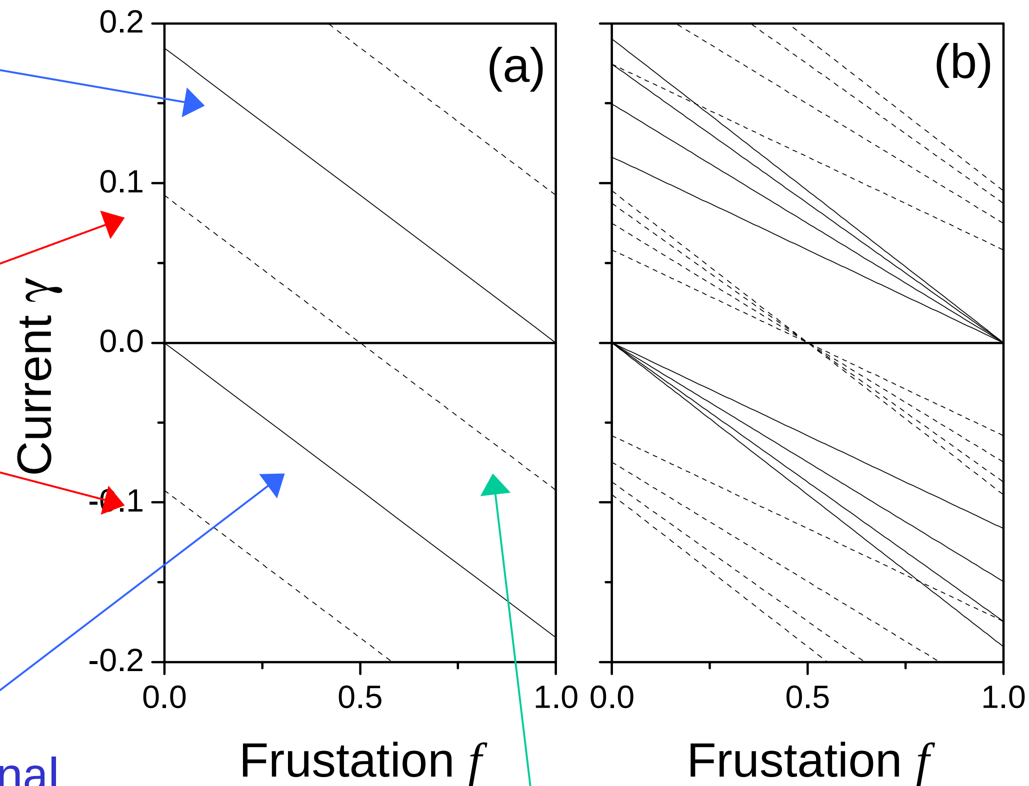
$$B_n = (-1)^n \frac{\pi/p}{1+\beta/p} \qquad (k=1)$$

Single loop states (cont')

para conventional loop

Spontaneus currents

dia conventional loop



π-loop

p=4, k=0 and p=4, k=1 magnetization states

p=3,3+1π,6,5+1π,12,11+1π 24,23+1π magnetization states

Energy approach

Writing the total energy as

$$E = N_0 E_0 + N_1 E_1 + E_I$$

Where E_I is the interaction energy

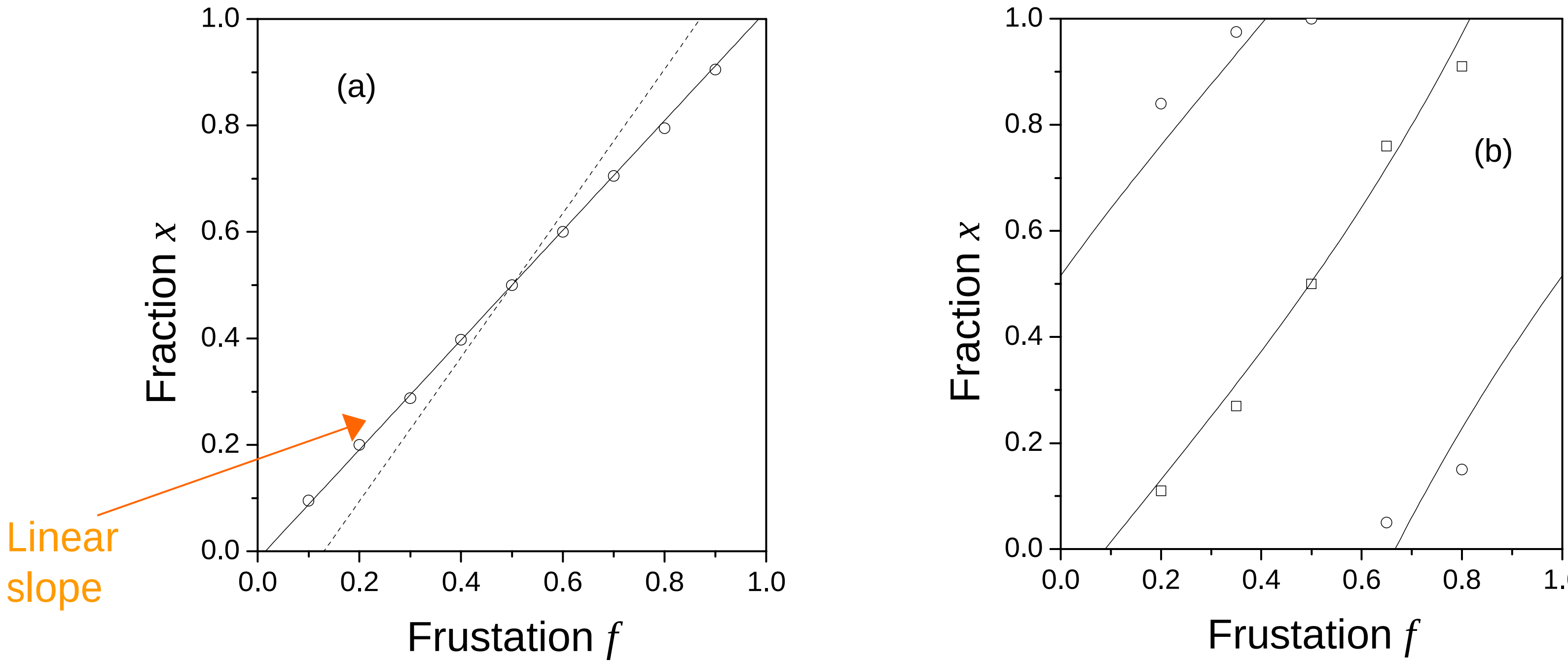
$$E_I = -\zeta N_0 N_1 m_0 m_1$$

Using $m_n = (1/2\pi)\beta\gamma_n$ is possible to minimize the total energy and find the concentration of paramagnetic loop $x = N_p / N$ as function of frustation f.

This method can be extended also to more complex situations for example to a mixed π/conventional array simply minimizing with respect to both concentration of conventional and π loops and increasing the number of free parameters ζ.

Energy approach (cont')

Results of the fitting to the energy minimum



We find ζ=–0.116 for the conventional array and ζ=–0.022, ζ_m=–0.002 for the mixed array (two parameters).

Note the minus sign and the large values.

(see submitted to SUST special ICEM2002 at...web->)

Conclusions

- How a paramagnetic state is generated in MCS ?

  Diamagnetic currents at boundary favors paramagnetic loops into the array
- What is the role of π-junctions ?

  π-junctions simply increase the number of magnetization states making the system have a more complex energy surface
- It is possible for a FC experiment have different outputs for conventional and mixed π/conventional arrays ?

  Yes (in our opinion), if the search is made for special values of frustation (f=0.5) and carefully compared with f=0 experiments needs however high resolution and a near zero distance from the array (this means that MO may be better than SSM;

  see C. De Leo and G. Rotoli SUST 14, 111, 2001)

Acknowledgements

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ADDITIONAL REFERENCES

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