

Two-dimensional Artificial Spin Ice in a Lattice with Three-in/Three-out Ice-like Rule OR Extending Spin Ice Concepts to Another Geometries

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Geometrically Frustrated Magnets: From Spin Ice to Kagome Planes

IIP - Natal - 14/12/2011



Introduction

Some things that we know

- It is “easy” to build arrays of magnetic nanostructures of “any” desired shape in “any” desired geometry
- The shape of each island determines its basic magnetic behavior
- The systems properties depends on the island properties (internal degrees of freedom) and on the array’s geometry

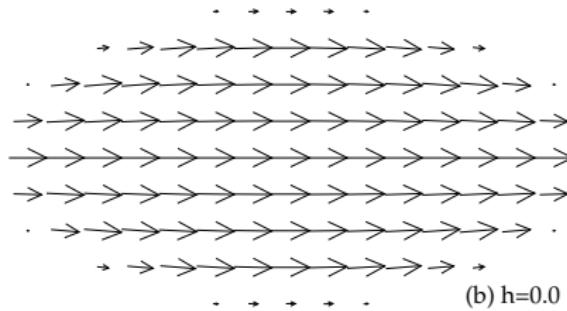
Elongated Permalloy nanoislands

- Competition between exchange and dipolar interactions favors the formation of a monodomain along the longest axis



Elongated magnetic nanoisland

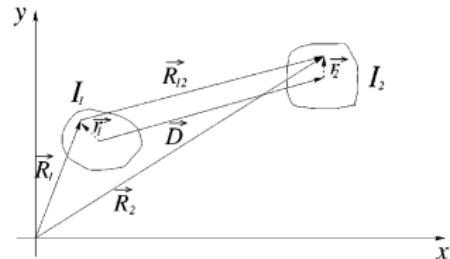
- Consider an elliptic island with major axis L_x , minor axis L_y and height L_z
- Approximation: all spins point in the same direction \rightarrow Ising variable
- Magnetic field of the island: Dipolar (Dominant term), Quadrupolar, etc.



G. Wysin, et al arXiv:1112.0913v1.

Interaction between two islands

- First approximation: Dipole-dipole interaction
- Beyond dipoles: Consider finite single domain thin particles

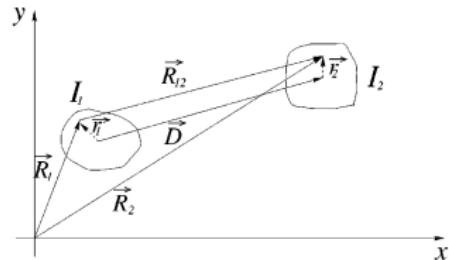


P. Politi and M.G. Pini, PRB **66**, 214414 (2002).



Interaction between two islands

- First approximation: Dipole-dipole interaction
- Beyond dipoles: Consider finite single domain thin particles



$$E \approx E^0 + E^2$$

$$E^0 = \Omega \left[\frac{\vec{S}_1 \cdot \vec{S}_2}{D^3} - 3 \frac{(\vec{S}_1 \cdot \vec{D})(\vec{S}_2 \cdot \vec{D})}{D^5} \right]$$

$$E^2 = \Omega \frac{9I_{12}}{4} \frac{\vec{S}_1^\perp \cdot \vec{S}_2^\perp}{D^5} + \Omega \frac{3I_{12}}{4} \left[\frac{\vec{S}_1^{\parallel} \cdot \vec{S}_2^{\parallel}}{D^3} - 5 \frac{(\vec{S}_1^{\parallel} \cdot \vec{D})(\vec{S}_2^{\parallel} \cdot \vec{D})}{D^5} \right]$$

where I_{12} is the semi-sum of the moment of inertia of each particle

P. Politi and M.G. Pini, PRB **66**, 214414 (2002).



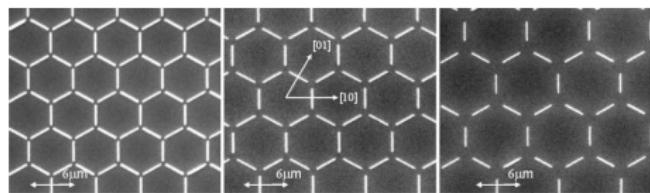
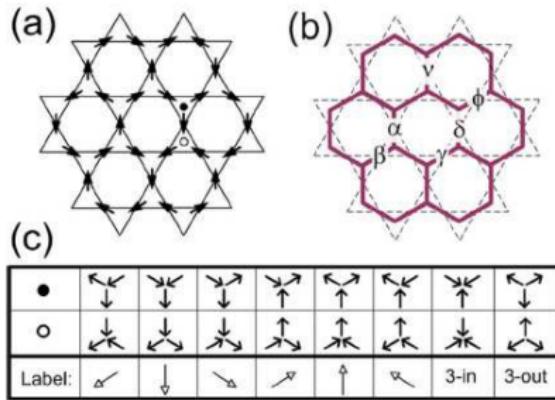
Ising-like dipoles seems to be a very good approximation!!!

A complete analysis beyond the Ising-like dipole approximation is currently in progress



Most studied systems

Artificial kagome spin ice



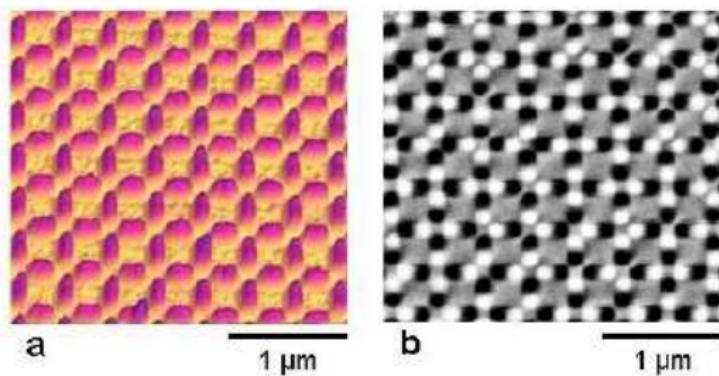
- “Frustration” and Ice-like Rule (2-in, 1-out OR 2-out, 1-in)

*Yi Qi, T. Brintlinger and J. Cumings, PRB **77** 094418 (2008)
A. Schumann, et al, APL **97**, 022509 (2010).*

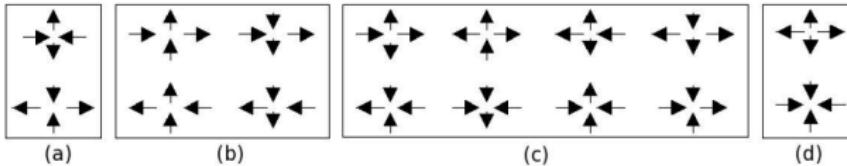


Most studied systems

Artificial square spin ice



- “Frustration” and Ice Rule (2-in, 2-out)

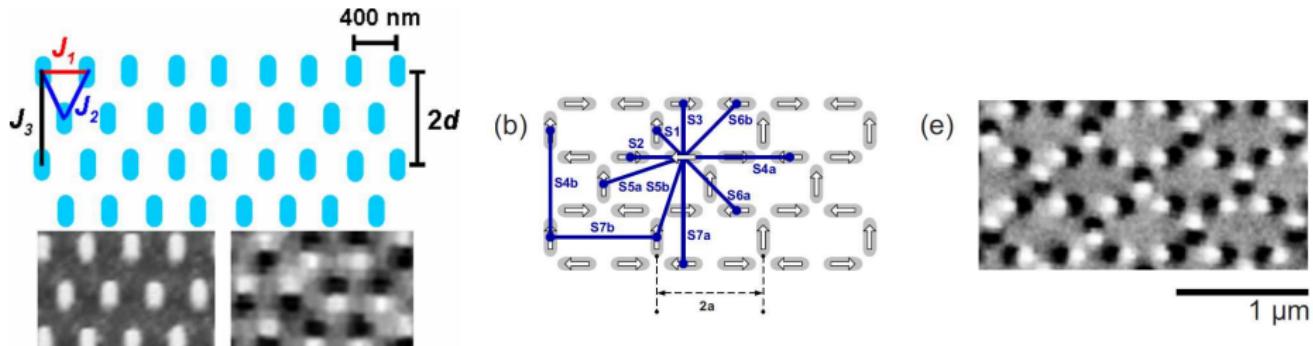


R.F. Wang, et al, *Nature (London)*, 439, 303 (2006)



Most studied systems

Triangular and brickwork lattices



- “Frustration” and Ice-like Rule (2-in, 1-out OR 2-out, 1-in)

J. Li et al, PRB **81**, 092406 (2010)

X. Ke et al, APL **93**, 252504 (2008)



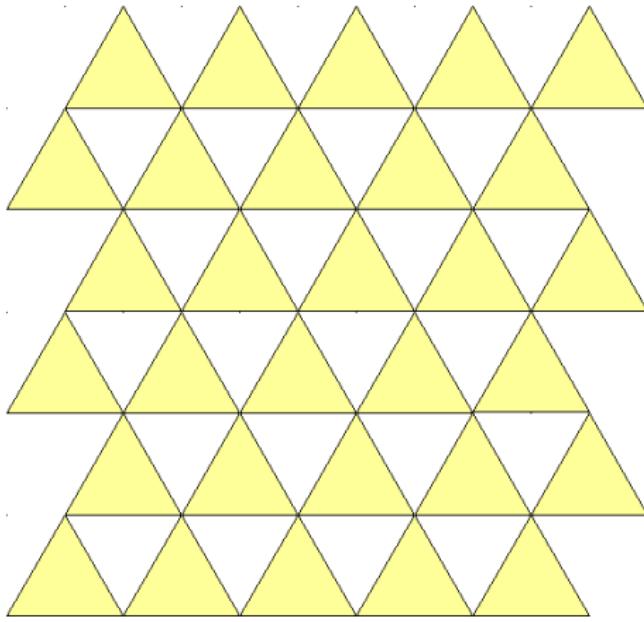
Generalizations

What happens if we have six island per vertex instead of four or three?



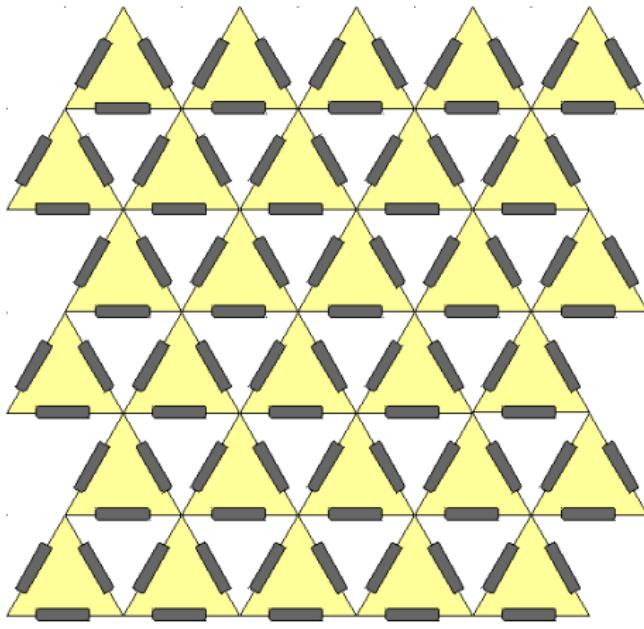
Generalizations

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Generalizations

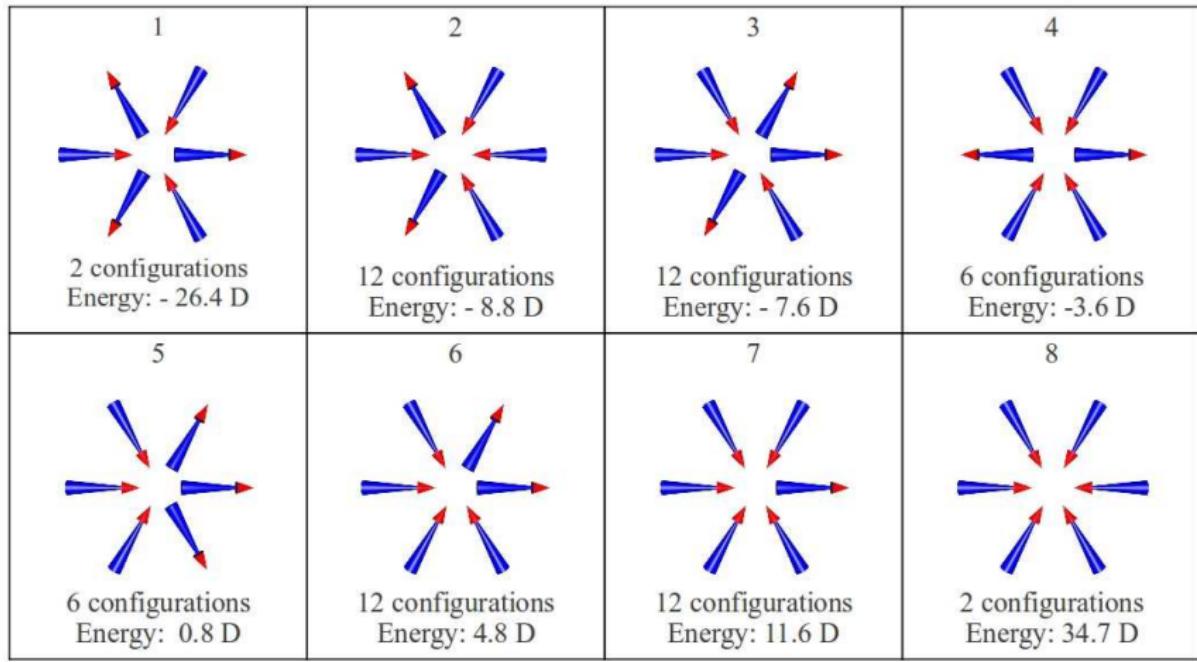
What happens if we have six island per vertex instead of four or three?



Analysis of a single vertex

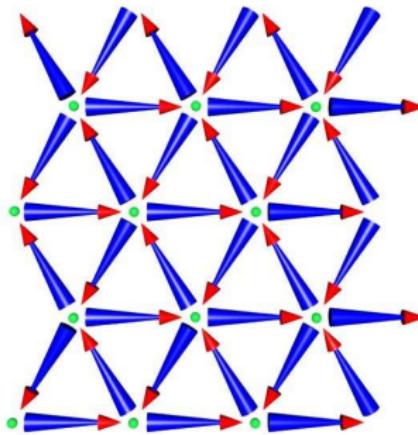
- $2^6 = 64$ configurations per vertex

Topologies



Ground-state configuration

- Simulated annealing process

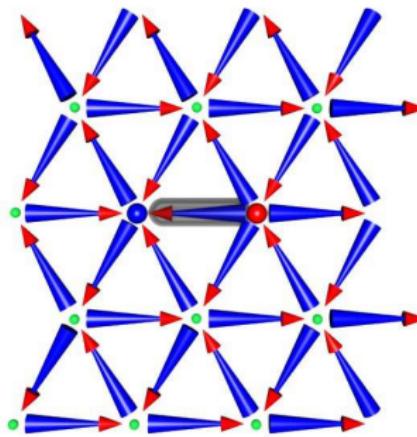


- Type I vertices only



Lowest energy excitations

- First “excited” state: Single spin flip ($\Delta E \sim 65D$)

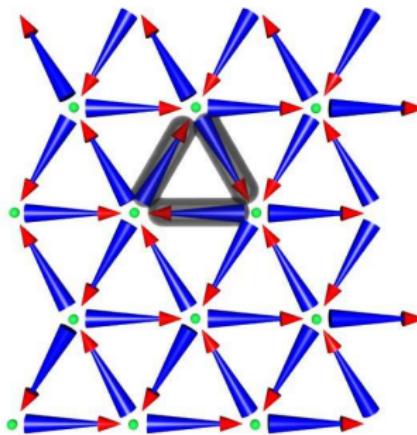


- Two type II vertices \rightarrow Magnetic monopoles



Lowest energy excitations

- Second “excited” state: “Plaquette” flip ($\Delta E \sim 76D$)

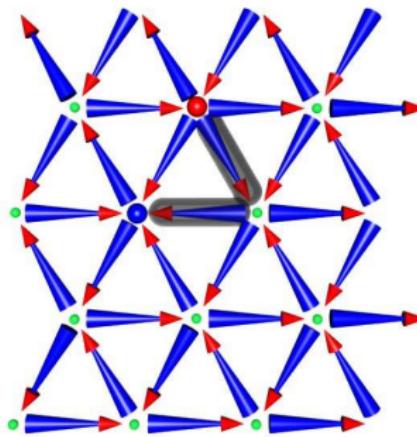


- Three type III vertices



Lowest energy excitations

- Two single spin flip (diagonal) ($\Delta E \sim 91D$)

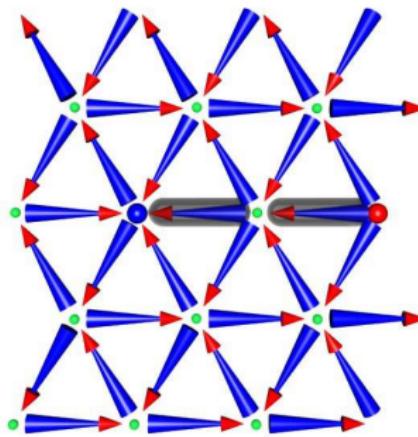


- One type III + two type II vertices



Lowest energy excitations

- Two single spin flip (linear) ($\Delta E \sim 125D$)

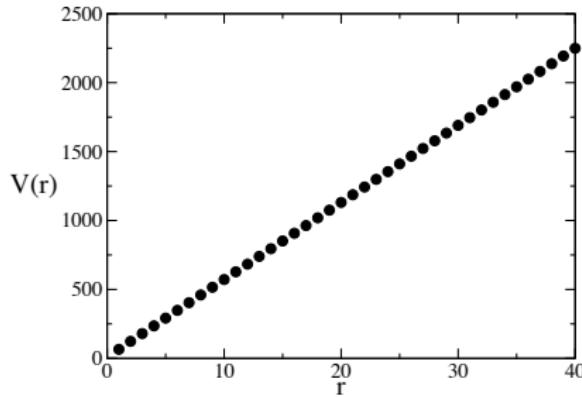


- One type V + two type II vertices



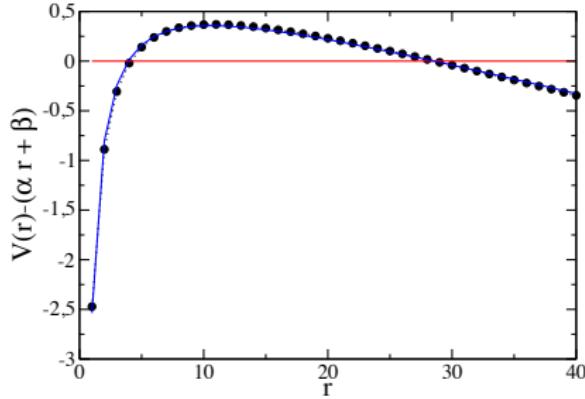
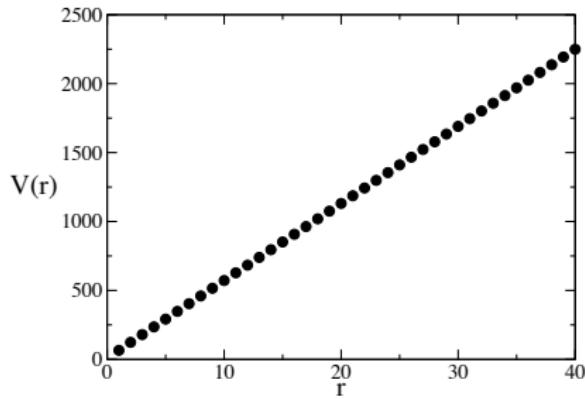
Potential between excitations

- Chain of linearly aligned spins flipped



Potential between excitations

- Chain of linearly aligned spins flipped



$$V(r) = \frac{q_t}{r} + b_t \times r + c_t$$

where $q_t = -3.5Da$, $b_t = 55.9D/a$ and $c_t = 13.1D$



Interaction between defects

	Charge (q)	Tension (b)
Square lattice ¹	$-4 \lesssim q_s \lesssim -3.9$	$b_s \sim 10$
SL height off-set ²	$-4 \lesssim q_{sh} \lesssim -3.4$	$1.0 \lesssim b_{sh} \lesssim 10$
Triangular ³	$q_t \sim -3.5$	$b_t \sim 55.9$
Kagome ⁴	$q_k \sim -3.1$	$b_k \sim 0.015$

¹ Mól et al, JAP, **106**, 063913 (2009)

² Mól et al, PRB, **82**, 054434 (2010)

³ Mól et al, arXiv:1112.0515

⁴ F. Nascimento et al. Work in progress



Thermodynamic properties

Monte Carlo procedure

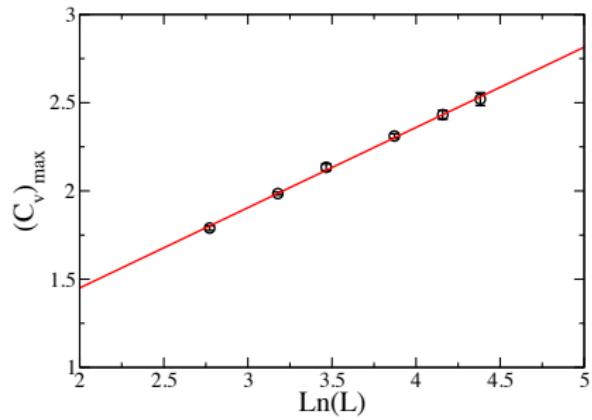
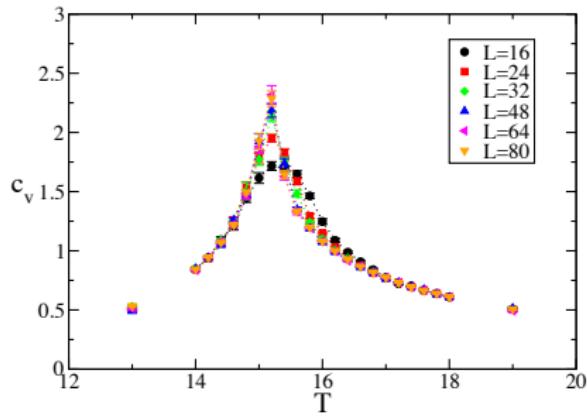
- Ising dipoles
- Dipolar interactions only
- Conventional Metropolis algorithm
- Cut-off radius in the evaluation of dipolar interactions $r_c = 5a$
- Single spin flips and loop moves

Thermodynamic properties

- Specific heat
- Density of vertices of topologies 2, 4 and 6 (single charges), 7 (double charges) and 8 (triple charges)
- Mean distance between single charges → [Assignment problem method](#)

Results

Specific heat (triangular SI)



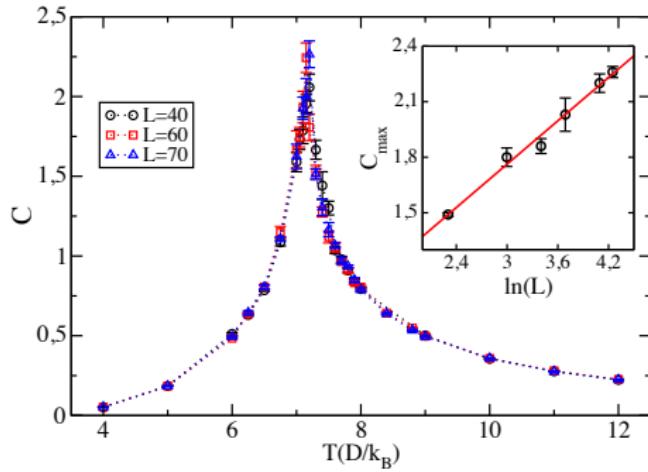
- Peak position $\sim 15D$

Mól, et al, arXiv:1112.0515



Results

Specific heat (Square SI)



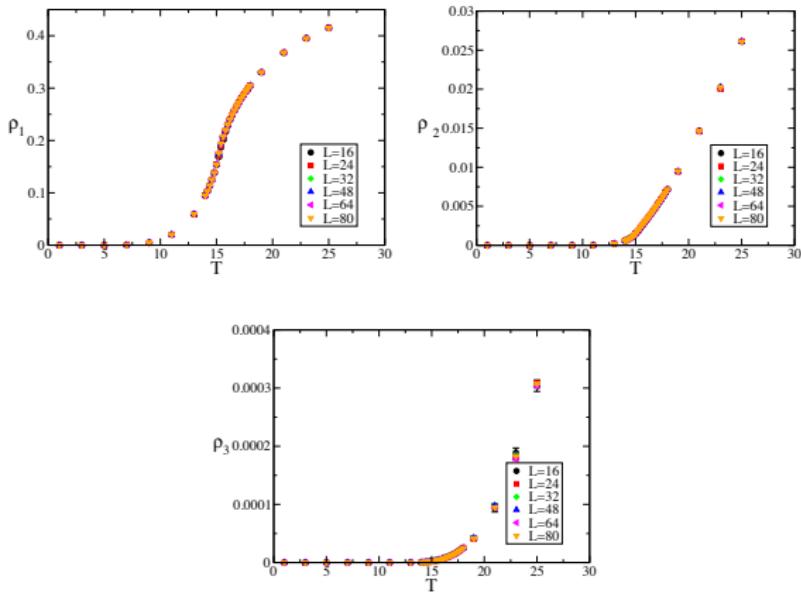
- Peak position $\sim 7D$

R. Silva, et al, arXiv:1110.2427, To appear in New Journal of Physics special issue



Results

Charges density (Triangular SI)

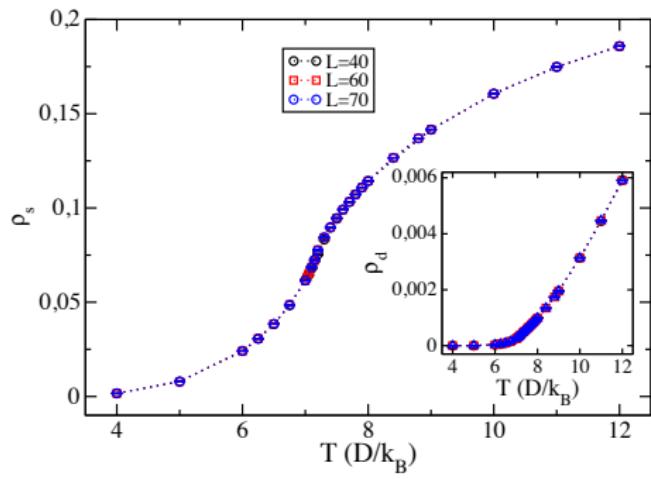


Mól, et al, arXiv:1112.0515



Results

Charges density (Square SI)

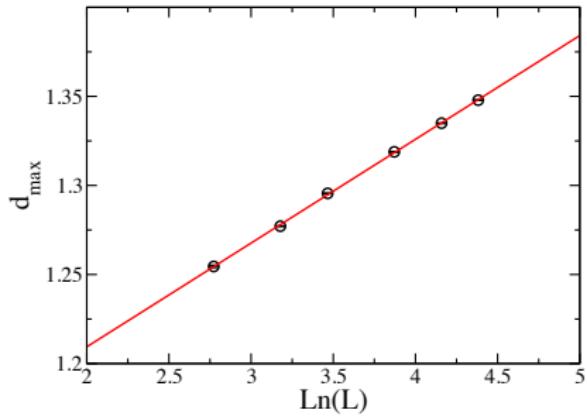
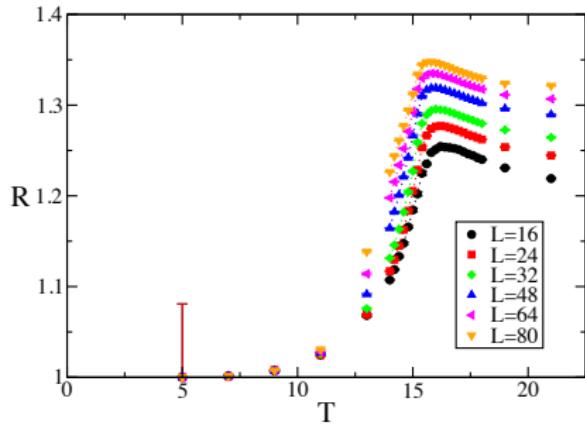


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Results

Mean distance between single charges (Triangular SI)

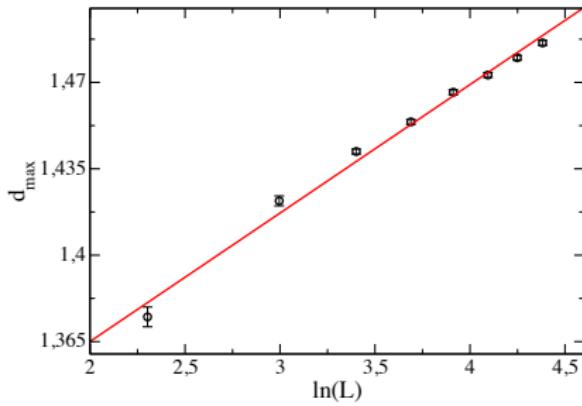
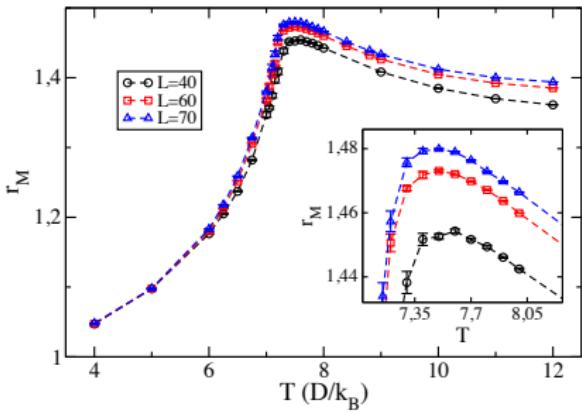


Mól, et al, arXiv:1112.0515



Results

Mean distance between single charges (Square SI)



R. Silva, et al, arXiv:1110.2427, To appear in New Journal of Physics special issue



Summary

Excitations

- It seems that there is a kind of universal behavior of the excitations in artificial 2D magnetic systems of Ising dipoles
- Magnetic charge with the same value and tunable string tension

Thermodynamics

- It seems that the square and triangular SI are in the Ising universality class
- The mean distance between single defects has a maximum in the phase transition temperature
- Low temperature → Low charge density
- High temperature → High charge density



Some expected advantages of this system

It has essentially the same properties of the square spin ice

- But there are three types of excitations instead of two

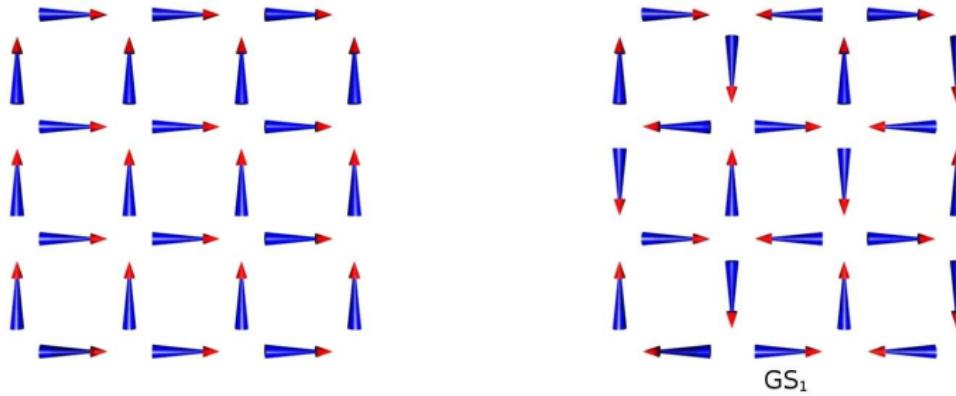
It may be easier to achieve the systems ground-state

- More islands in the same area → Stronger internal fields
- Higher critical temperature → The ground-state is more robust to thermal fluctuations
- Straight charges path → may facilitate demagnetization protocols



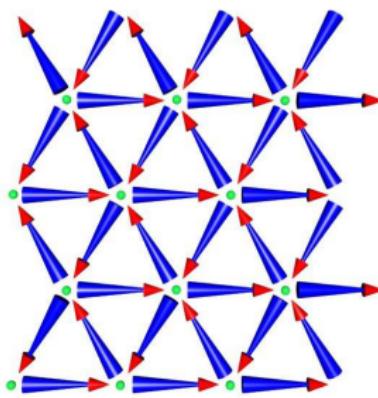
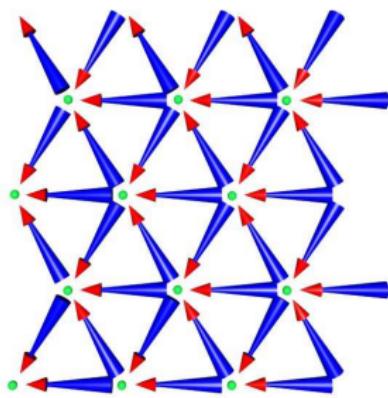
Some expected advantages of this system

Demagnetization dynamics (square lattice)



Some expected advantages of this system

Demagnetization dynamics (triangular SI)



Thank you!!!

Acknowledgments

