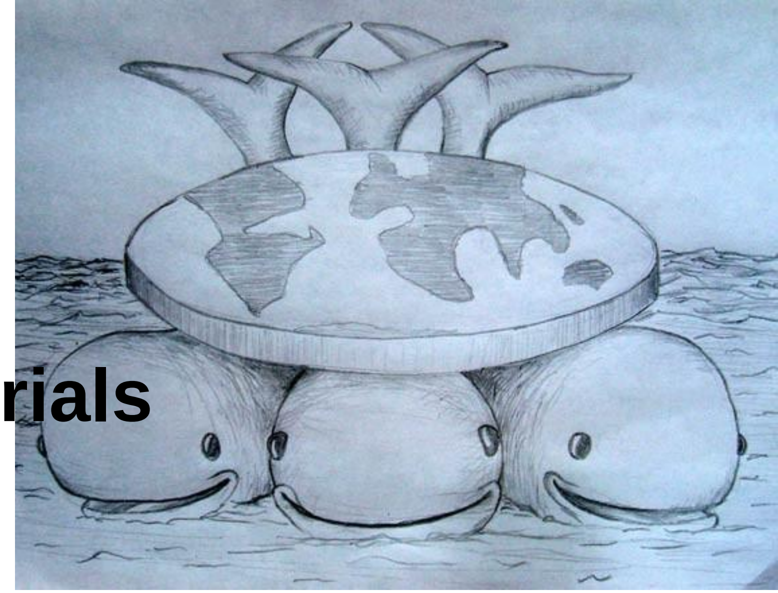
Co-proposers of SC

- Michel Kenzelmann, Uwe Filges, PSI
- Yixi Su, Jörg Voigt, JCNS
- Andrew Sazonov, Aahen Tech
- University
- Beatrice Gillon, Isabelle Mirebeau, Alexandre Bataille, Philippe Bourges, LLB
- Fabienne Duc, Paul Frings, LNCMI-Toulouse
- Virginie Simonet , Institut Neel
- Josep Nogués Sanmiquel, Univ. Aut. Barcelona
- Igor Golosovsky, PNPI

OUTLINE



- **Functional magnetic materials**
  - Epitaxial single crystals
  - Non-collinear Magnetism
  - Molecular Magnetism
  - Photo-crystallography
- **Emergent Phenomena and Topological States**
  - Frustrated magnets
  - Multipolar interactions
- **The challenges of superconductivity**
- **High field magnetism**
- **Electromagnon and hybrid excitations**

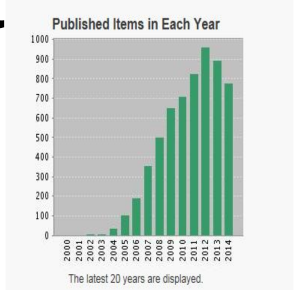
OUTLINE

- Emergent Phenomena and Topological States
- Functional magnetic materials
- Non-collinear Magnetism
- The challenges of superconductivity
- Frustrated magnets
- Molecular Magnetism
- Epitaxial single crystals
- High field magnetism
- Electromagnon and hybrid excitations

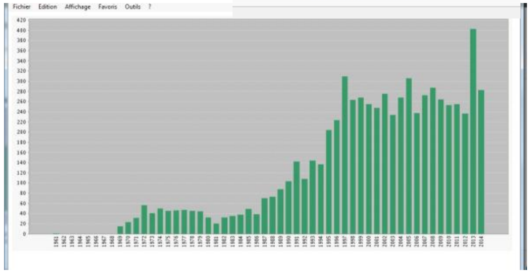
- **Functional magnetic materials**
  - **Permanent Magnets, Magneto-caloric, Magnetostrictive**
  - **Magnetic shape memory**
  - **Multiferroics (Magnetoelectrics)**
  - **Epitaxial magnets**
  - **Molecular magnets**
  - **Nano magnets**

Functional magnetic materials

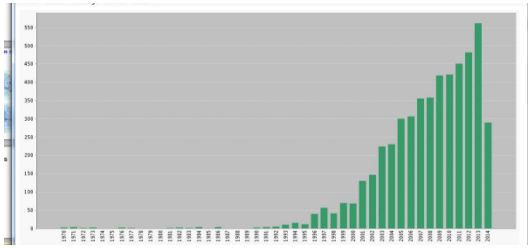
- Multiferroics (Magnetoelectrics)



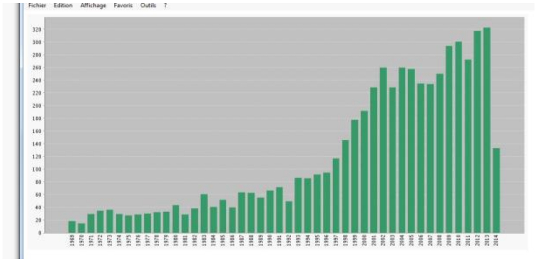
- Epitaxial magnetic (crystal)



- Nano magnetic (crystal)

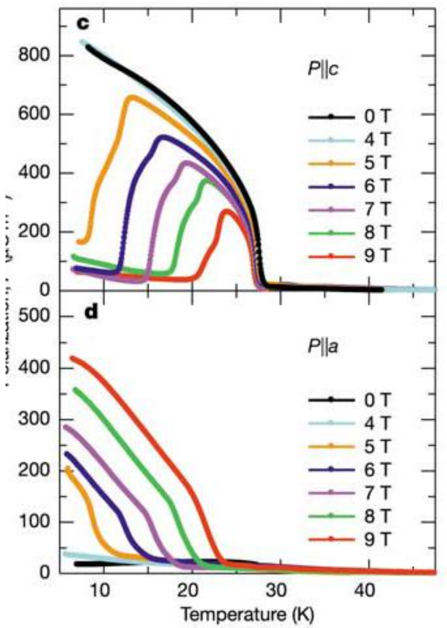


- Molecular magnetic (crystal)



● Multiferroics (Magnetoelectrics)

● TbMnO3



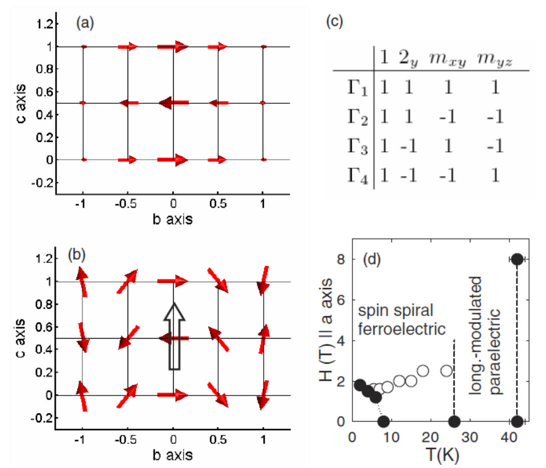
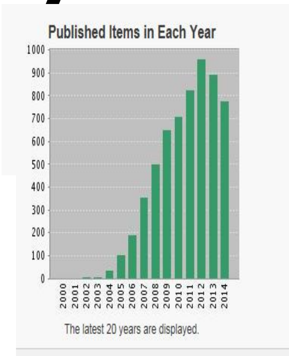


FIG. 4 (color online). Schematic of the magnetic structure at (a) $T = 35$ K and (b) $T = 15$ K, projected onto the b-c plane.



T. Kimura et al. *Nature* 426, 55, 2003

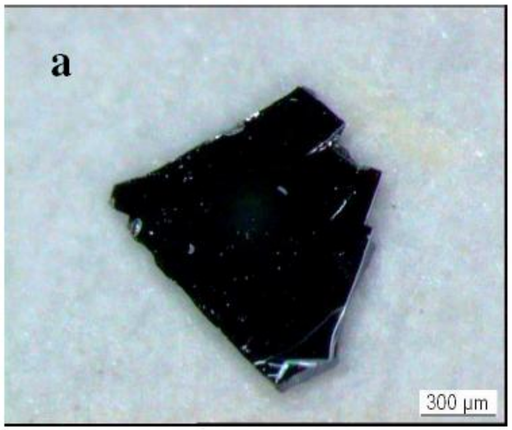
M. Kenzelmann et al.,PRL 95, 087206,2005

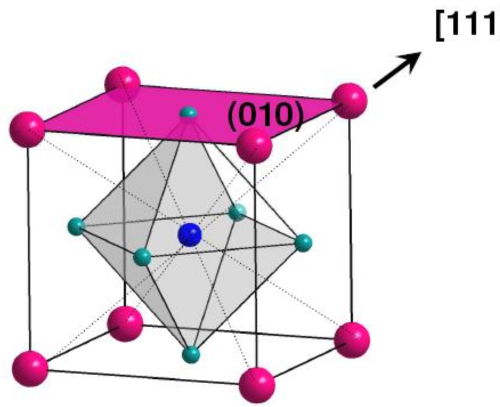
- **Proper FE** ***Polarization*** **due to Structural instability -**
- **Imroper FE** ***Polarization*** **due to some other ordering**

PRL **100,** 227602 (2008) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2008

Electric-Field-Induced Spin Flop in $BiFeO_3$ Single Crystals at Room Temperature

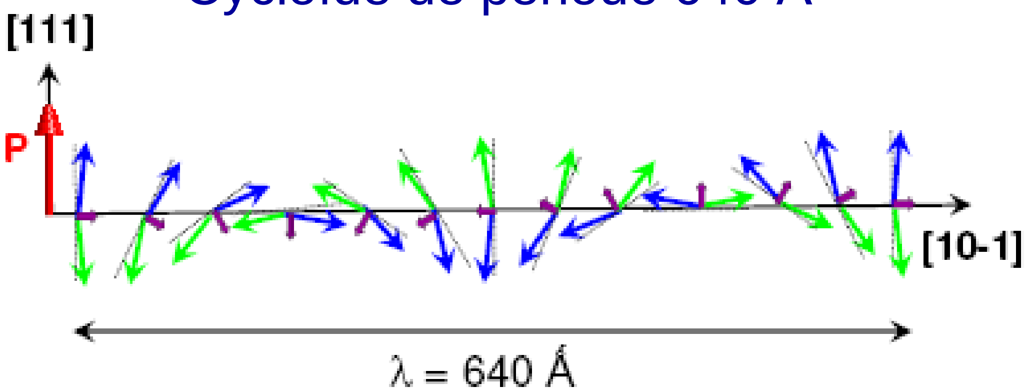
D. Lebeugle,[1] D. Colson,[1] A. Forget,[1] M. Viret,[1] A. M. Bataille,[2] and A. Gukasov[2]
...tat Condensé, DSM/IRAMIS, CEA Saclay, F-91191 Gif-Sur-Yvette, France
...rillouin, DSM/IRAMIS, CEA Saclay, F-91191 Gif-Sur-Yvette, France
...eceived 24 January 2008; published 2 June 2008)

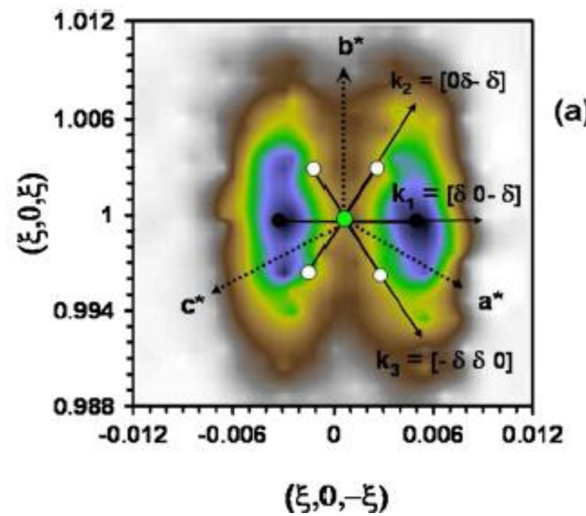


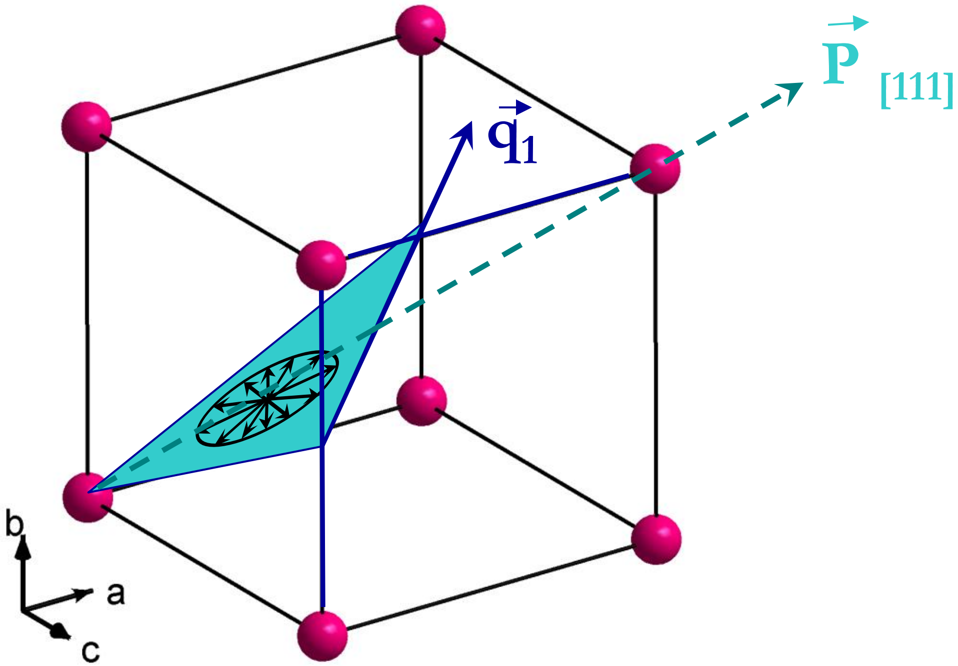


Etat vierge

$BiFeO_3$, 900x800x40 µm^3
Cycloïde de période 640 Å

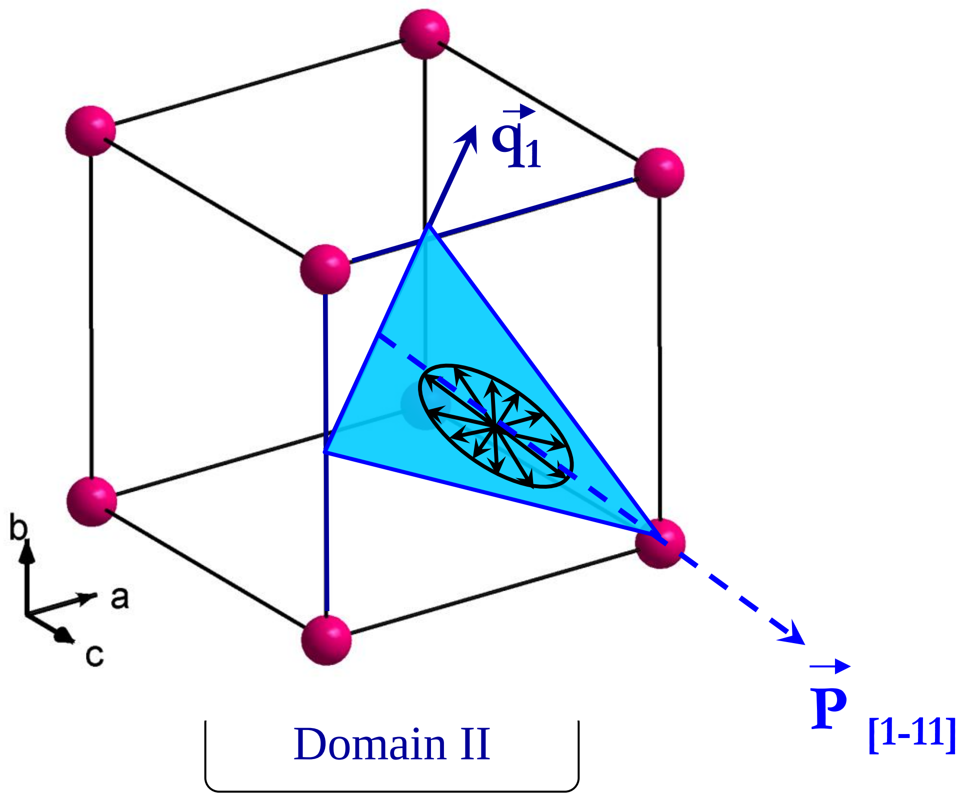






Domain I

Rotation plane : (-12-1) = $P_{[111]} \times q_1$



Rotation plane : (121) = $P'_{[1\text{-}11]} \times q_1$

PRL 100, 227602 (2008) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2008

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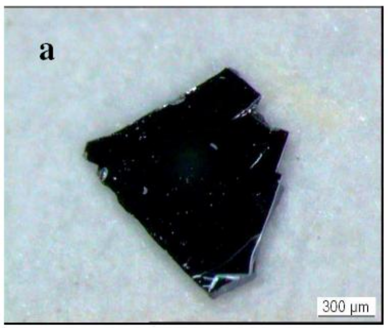
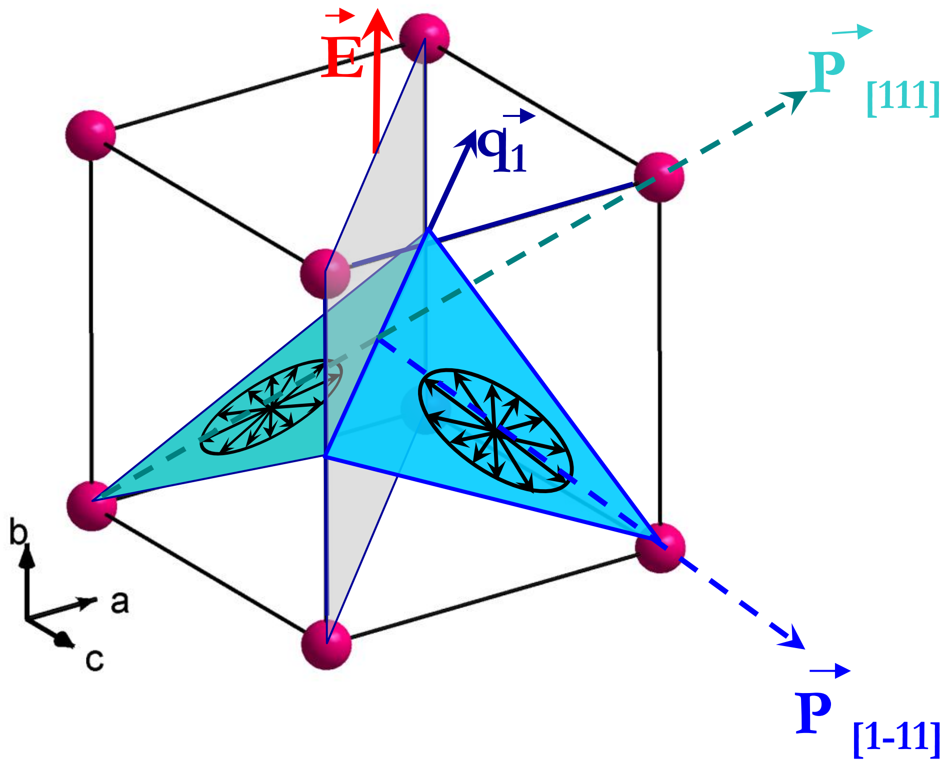
[1]Service de Physique de l'Etat Condensé, DSM/IRAMIS, CEA Saclay, F-91191 Gif-Sur-Yvette, France
[2]Laboratoire Leon Brillouin, DSM/IRAMIS, CEA Saclay, F-91191 Gif-Sur-Yvette, France
(Received 24 January 2008; published 2 June 2008)





Electric-Field-Induced Spin Flop in $BiFeO_3$ Single Crystals at Room Temperature

nature materials

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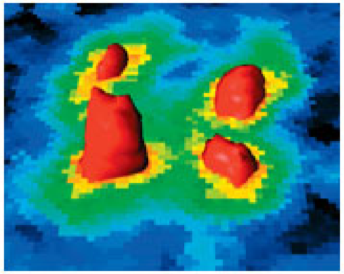
Research Highlights

Nature Materials **7**, 517 (2008)
doi:10.1038/nmat2217

Looking, seeing, sensing

A COUPLING, INDEED top

Phys. Rev. Lett. **100**, 227602 (2008)



MICHEL VIRET

One of the most intensively studied multiferroic materials is $BiFeO_3$, mostly because it shows room-temperature multiferroic coupling with a large spontaneous electric polarization. Although the material has been known to be magnetoelectric since the 1960s, actual evidence of multiferroic coupling in bulk material has been missing, mainly owing to the lack of suitable high-quality crystals. Having achieved the growth of high-quality $BiFeO_3$ crystals, Delphine Lebeugle and co-workers now report on a neutron diffraction study into the coupling between magnetic and ferroelectric properties of $BiFeO_3$. They find that although the material has no linear magnetoelectric effect, the antiferromagnetic moments form a low-pitch spiral that creates an efficient multiferroic coupling. However, a more efficient switching of magnetic properties can be achieved not through a direct multiferroic coupling but if the antiferromagnetic moments of $BiFeO_3$ are used to switch the magnetic moments of a ferromagnet through the exchange interaction at the interface between the two materials. Therefore, an electric field applied to $BiFeO_3$ indirectly switches the ferromagnetic state of the adjacent layer, as has been demonstrated recently.

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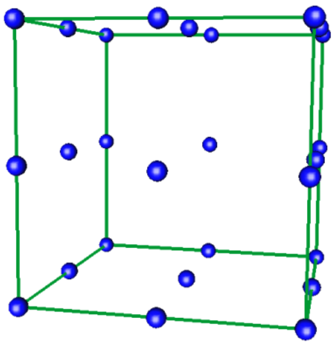
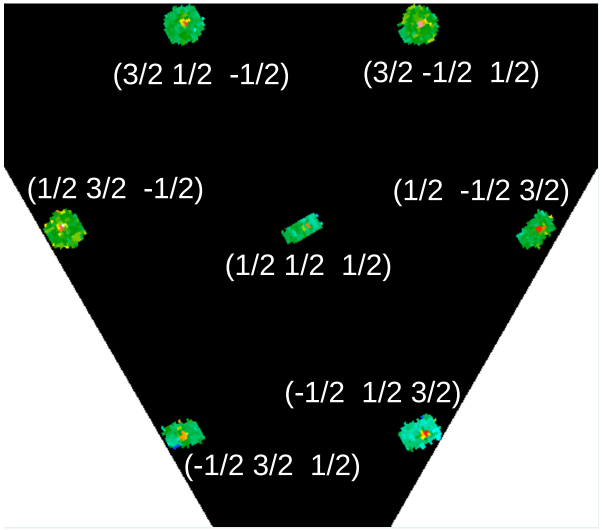
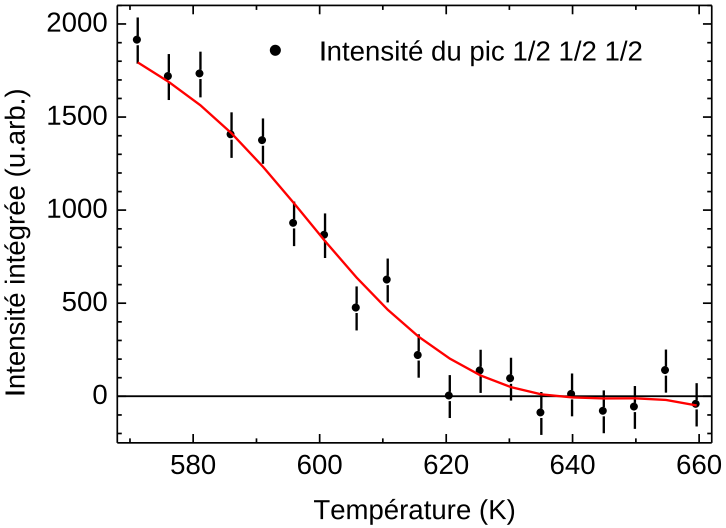
- Seeing the matrix
- Look very carefully
- A coupling, indeed

● Epitaxial crystals

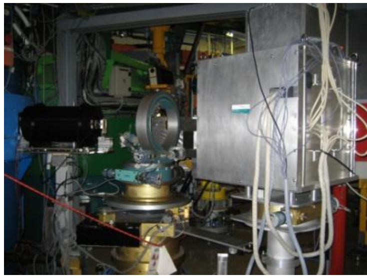
BiFeO3 90 nm x 1 cm² **V= 0,009 mm³**





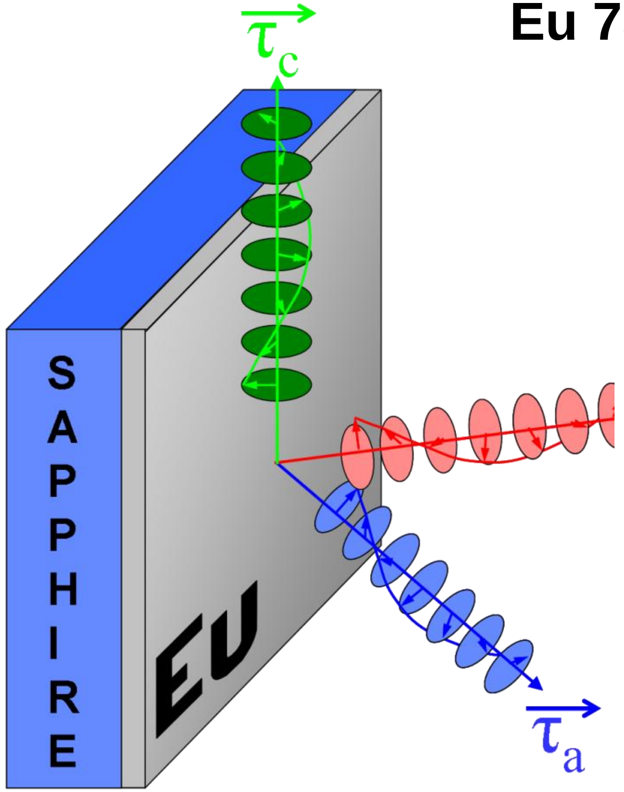


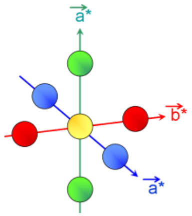
H. Béa *et al.*, *Phil. Mag. Lett.* **87** 165 (2007)
D. Sando *et al.*, *Nature Mat.* **12** 641 (2013)

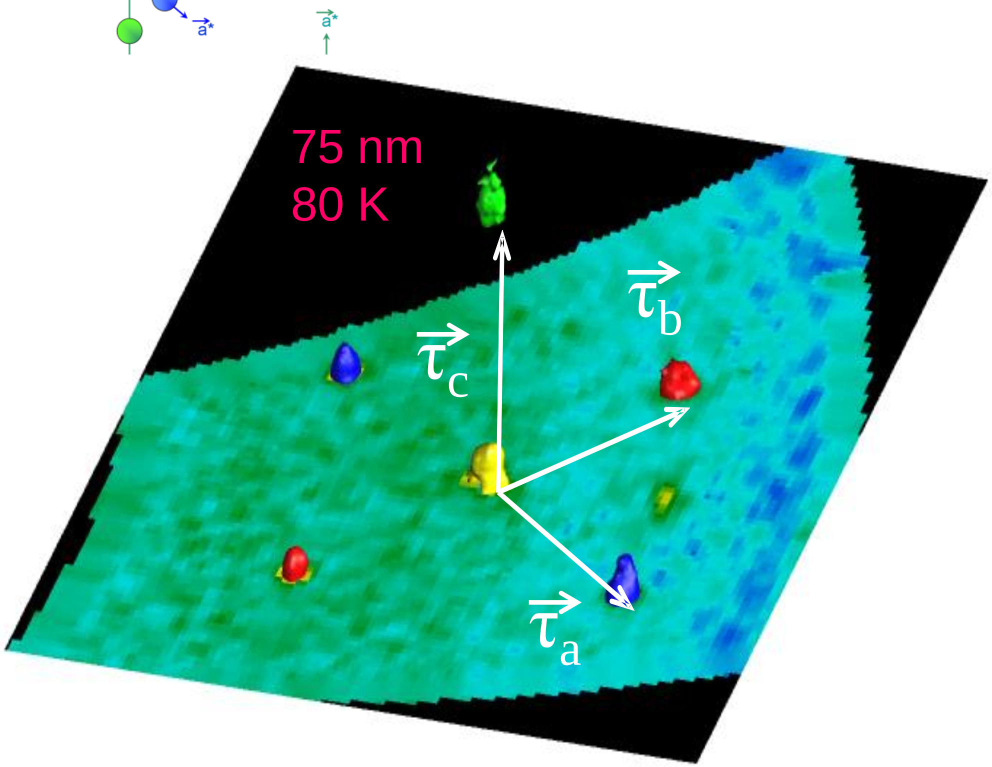


• Epitaxial crystals

Eu 75 nm x 1 cm^2 **V= 0,0075 mm^{23}**



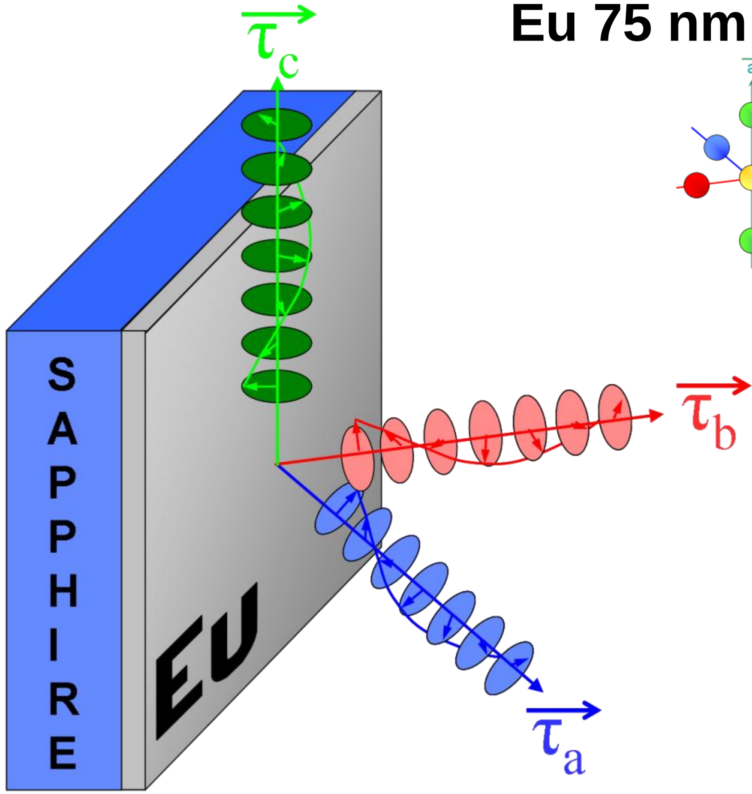


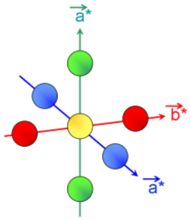


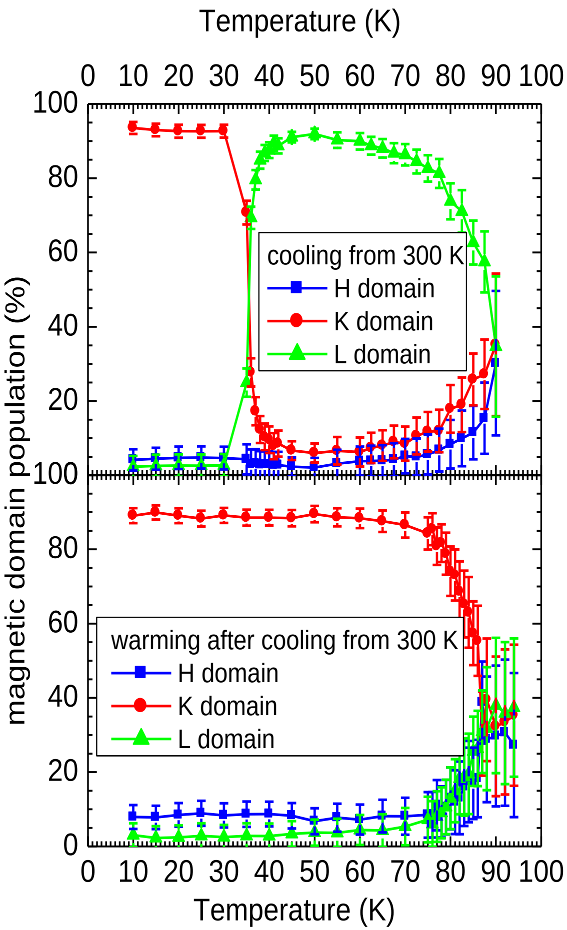
A. Bataille et al. *J. Appl. Phys. 105, 07A928, 2009*

● Epitaxial crystals

Eu 75 nm x 1 cm^2 **V= 0,0075 mm^3**







A. Bataille et al. *J. Appl. Phys. 105, 07A928, 2009*

SCIENTIFIC REPORTS

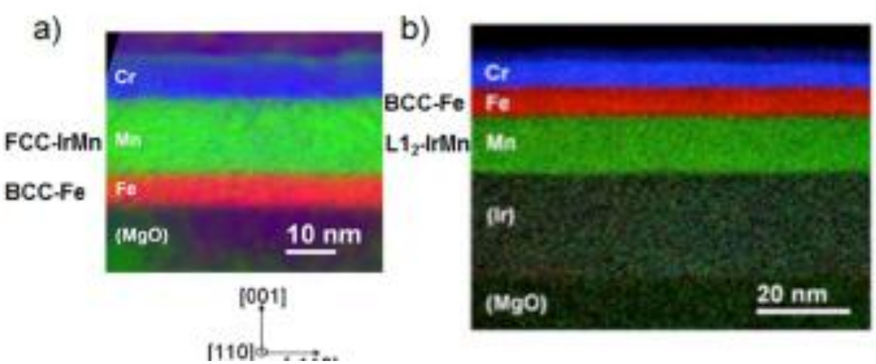
● Epitaxial crystals

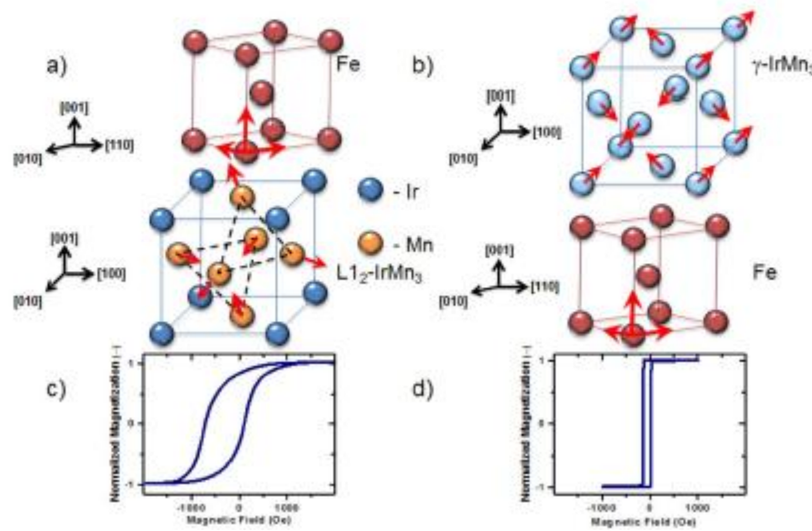
OPEN

The antiferromagnetic structures of $IrMn_3$ and their influence on exchange-bias

SUBJECT AREAS:
TRANSMISSION ELECTRON MICROSCOPY

A. Kohn[1,2], A. Kovács[3], R. Fan[4], G. J. McIntyre[5], R. C. C. Ward[6] & J. P. Goff[7]





● Epitaxial crystals

SCIENTIFIC REPORTS

OPEN

The antiferromagnetic structures of IrMn and their influence on exchange-bias

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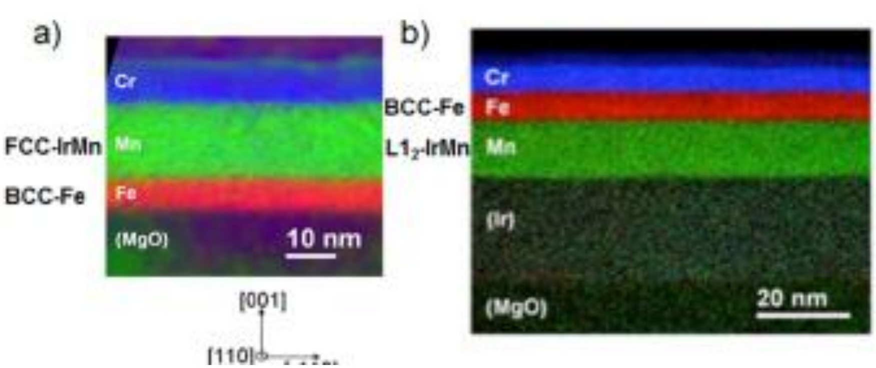
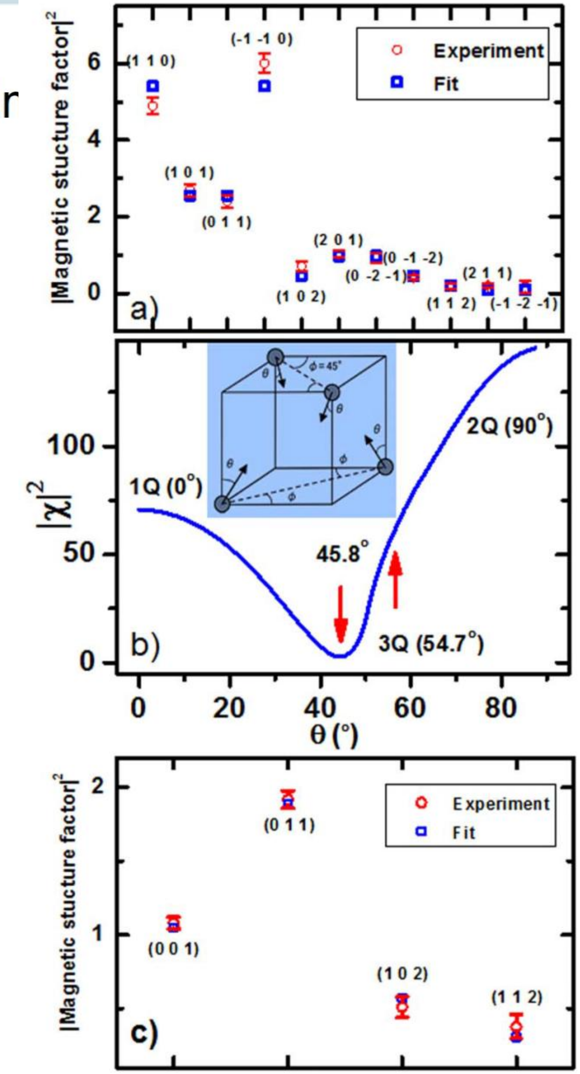




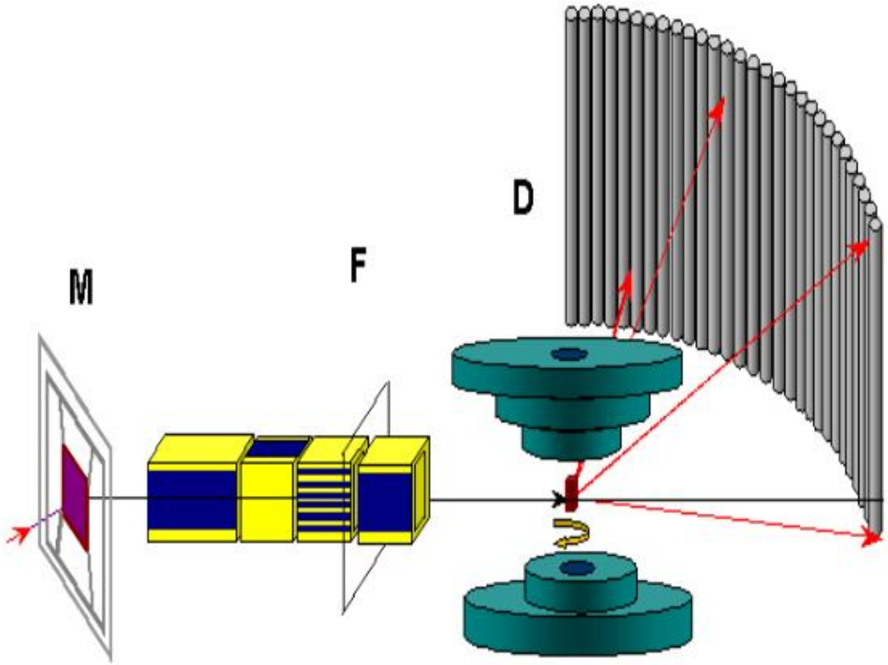
- **Epitaxial crystals**

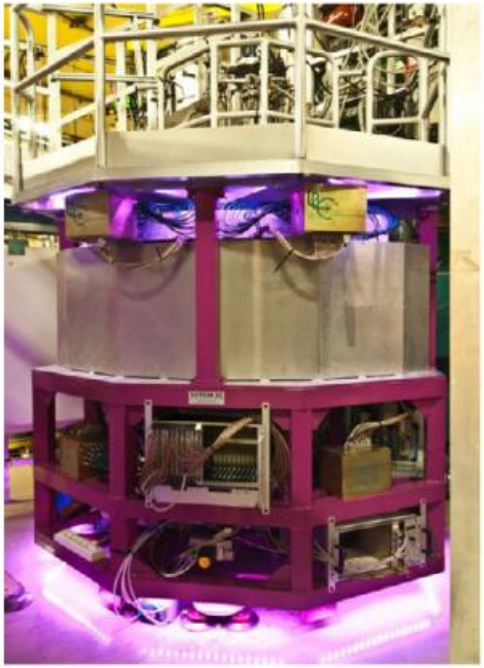
Eu 75 nm x 1 cm^2 V= 0,0075 mm^3

Practical volume now > 0.01 mm3 only CN

2-3 orders of magnitude smaller needed HN

VIP Neutron DIFFRACTOMETER (5C1) LLB



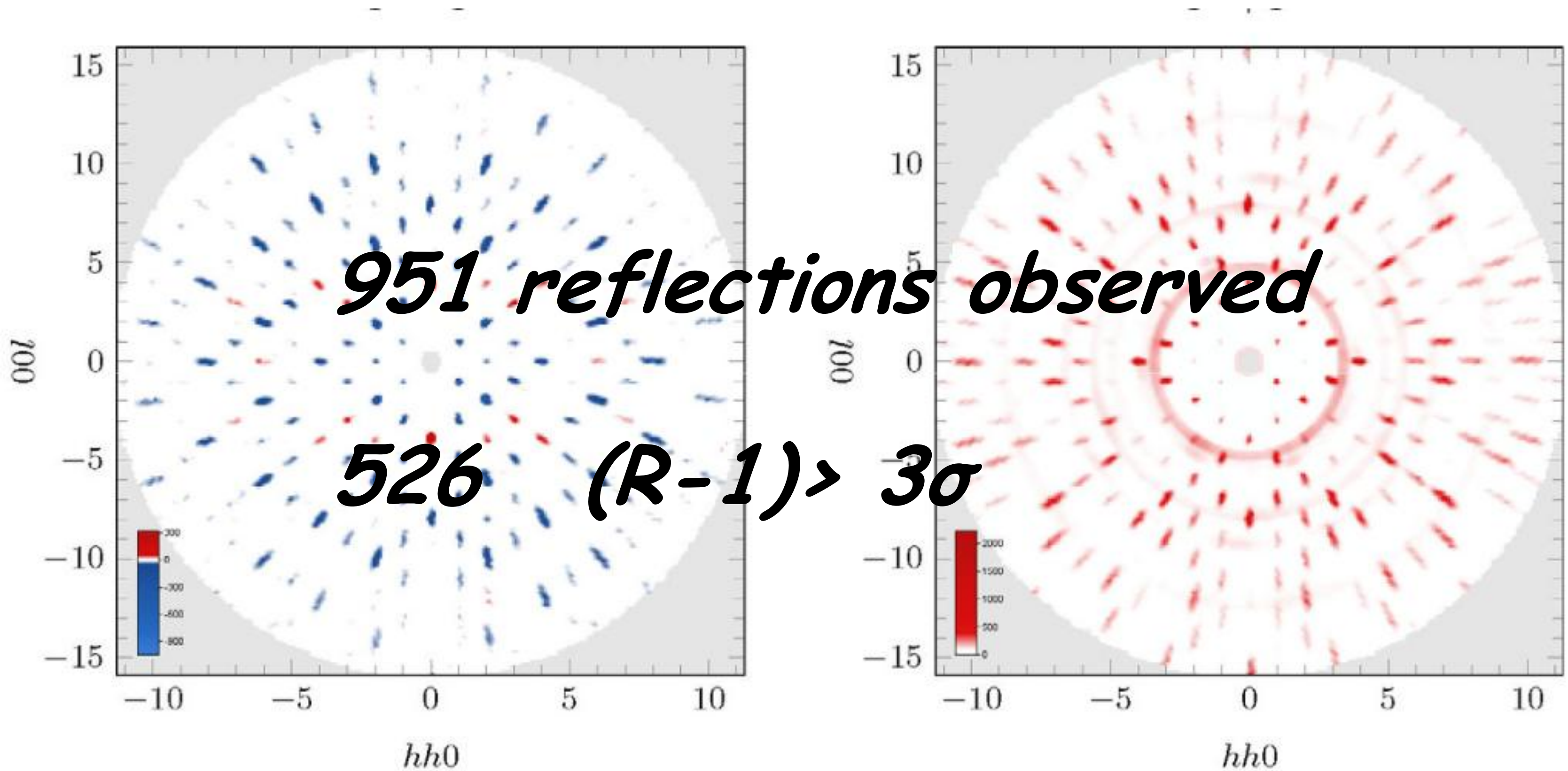


80°x25°,   λ=0.84 Å

VIP Neutron DIFFRACTOMETER (5C1) LLB

Yb2Ti2O7   2 K, 1T
V~60mm3

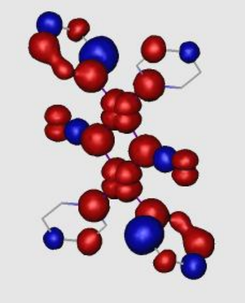
3500 steps of 0.1
Exposition 4 sec/frame



951 reflections observed

526   (R-1)> 3σ

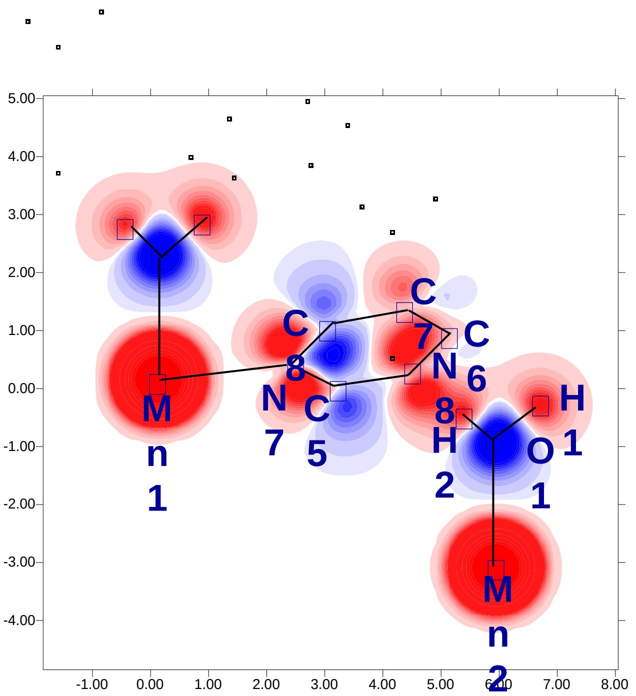
Fig. 3. Two dimensional cuts in the reciprocal space measured on VIP from $Yb_2Ti_2O_7$ (about 100 mm^3) during 5 hours. Left panel: The difference $I^+ - I^-$. Right panel: The sum $I^+ + I^-$.

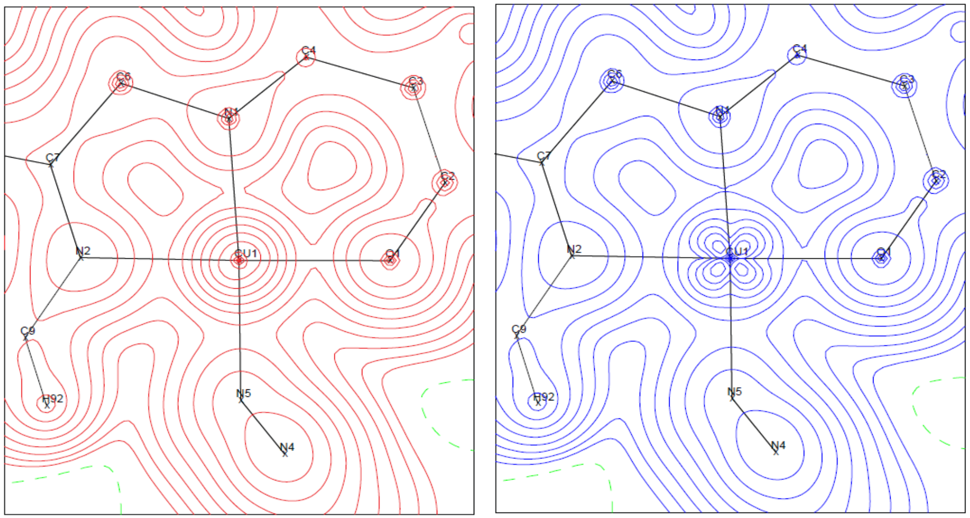


Molecular Magnetism

SPIN DENSITY

JOINT X-PND REFINEMENT





Spin up **Spin down**

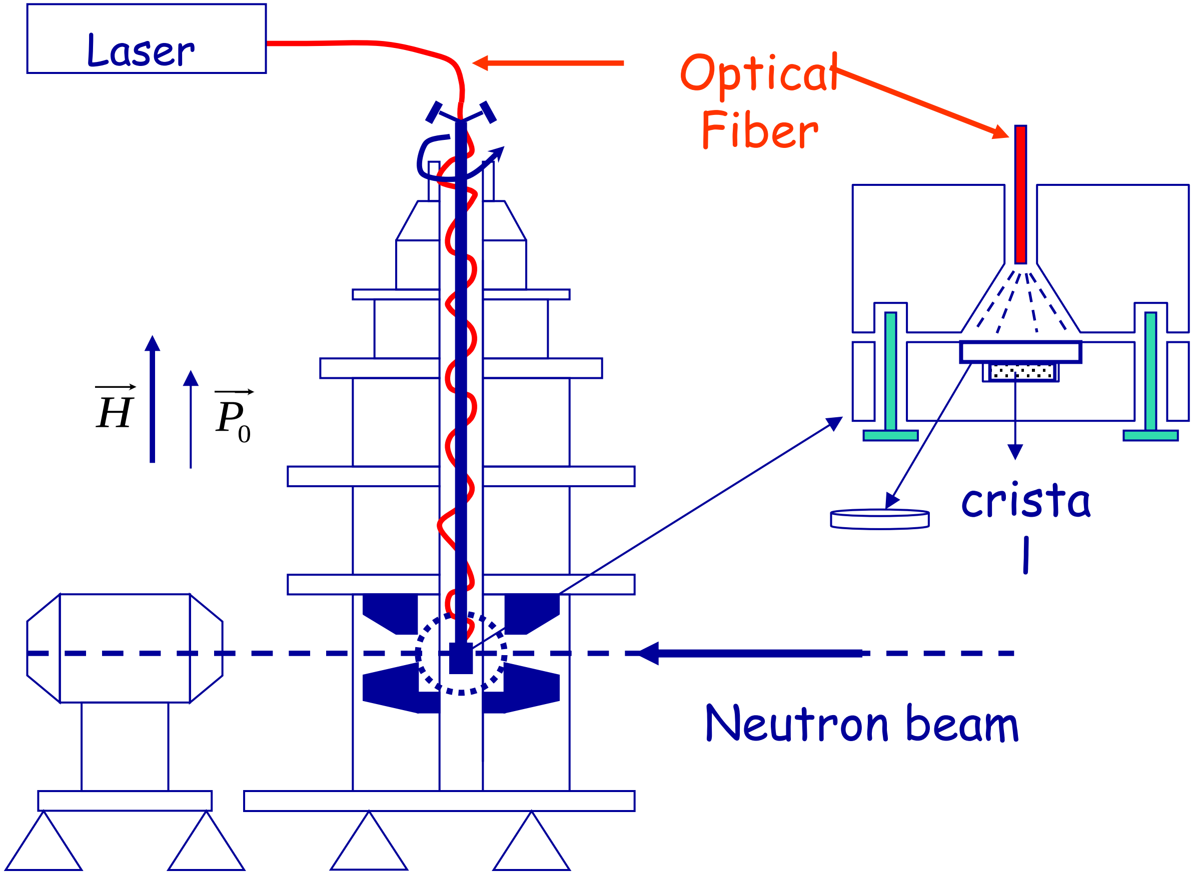
N2(CH)4 (pirimidine)h

B. Gillon et al.

M. Deutch et al.

● Molecular Magnetism

Photocrystallography



A. Goujon, B. Gillon A Gukasov, J Jeftic, and F Varret Phys. Rev. B 67, 2003

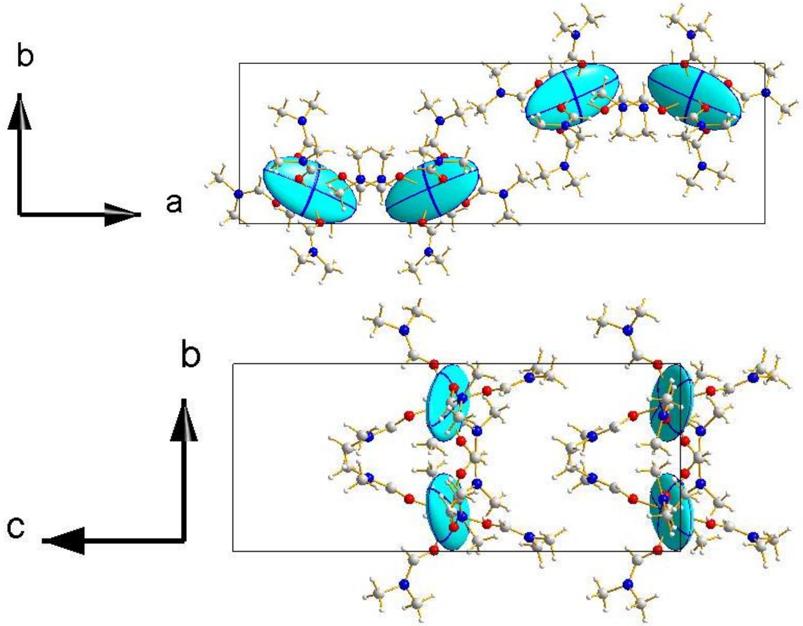
Molecular Magnetism

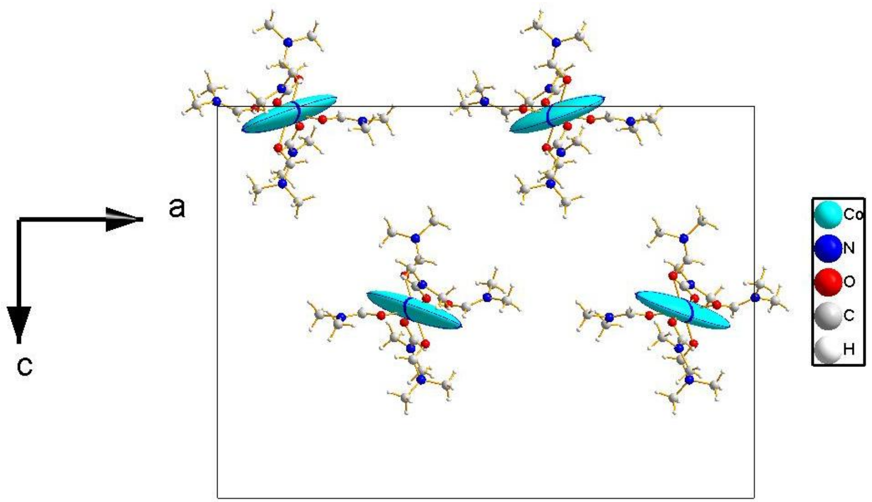
Practical volume now > 10 mm3 HN (CN)

3 orders of magnitude smaller needed HN

A. Goujon, B. Gillon A Gukasov, J Jeftic, and F Varret Phys. Rev. B 67, 2003

- **Local Anisotropy in the complex [$Co2^{+}$(DMF)6]**





$$\vec{m} = \overline{\overline{\chi}}\vec{H}$$

$$\vec{F}_M(\vec{Q}) = \sum_{k}^{atoms} \overline{\overline{\chi_k}}\vec{H} f_k(\vec{Q}) \exp\left(i\vec{Q}\cdot\vec{r}_k\right)$$

A Gukasov[1] and P J Brown[2] J. Phys.: Condens. Matter 14 (2002) 8831–883

Institute of Physics Publishing · Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter **14** (2002) 8831–8839 · PII: S0953-8984(02)37675-6

Determination of atomic site susceptibility tensors from polarized neutron diffraction data

A Gukasov[1] and P J Brown[2]

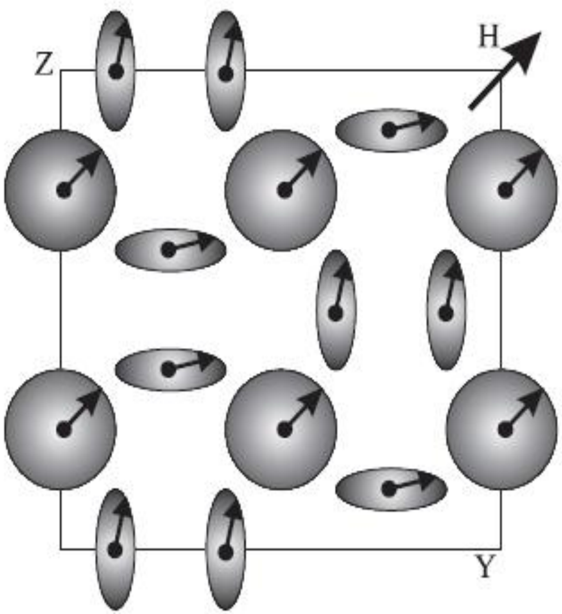


Figure 4. The [100] projection of the unit cell of $Nd_{3-x}S_4$ s
for $H \parallel [011]$.

Institute of Physics Publishing · Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter **14** (2002) 8841–8851 · PII: S0953-8984(02)37676-8

Site susceptibility tensors and magnetic structure of $U_3Al_2Si_3$: a polarized neutron diffraction study

A G Gukasov[1], P Rogl[2], P J Brown[3], M Mihalik[4] and A Menovsky[5]

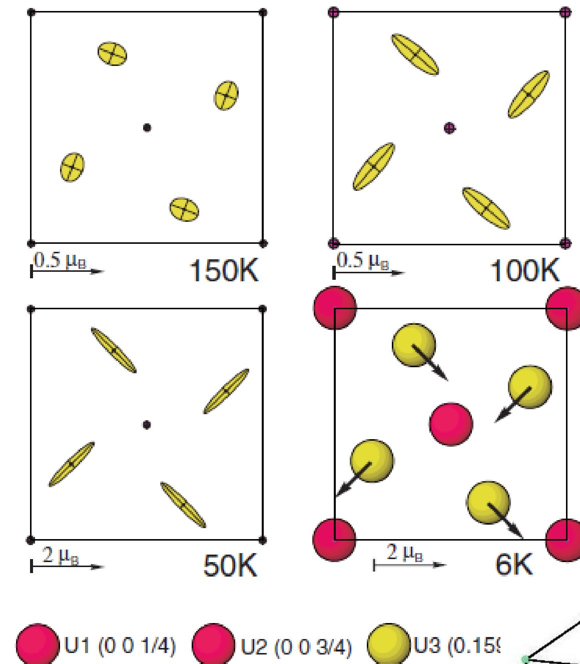
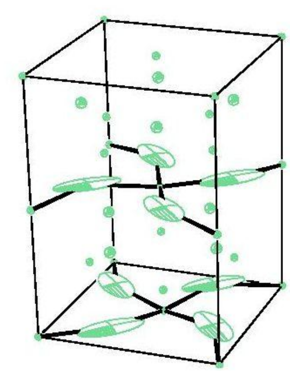
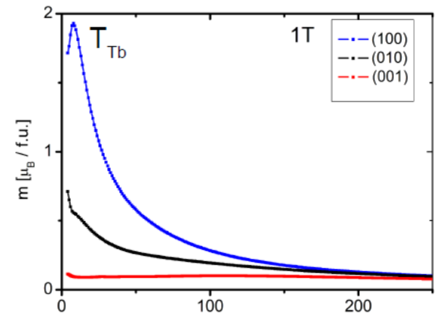


Figure 3. Evolution with temperature of the magnetic anisotropy



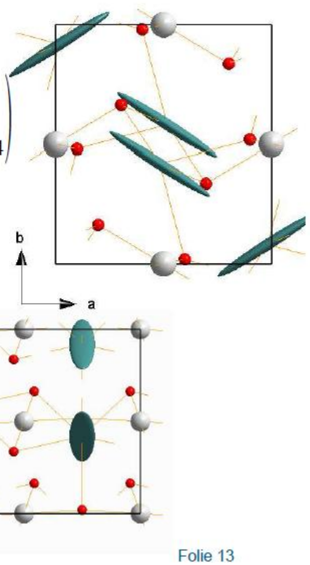
Multiferroics

- **TbMnO3**



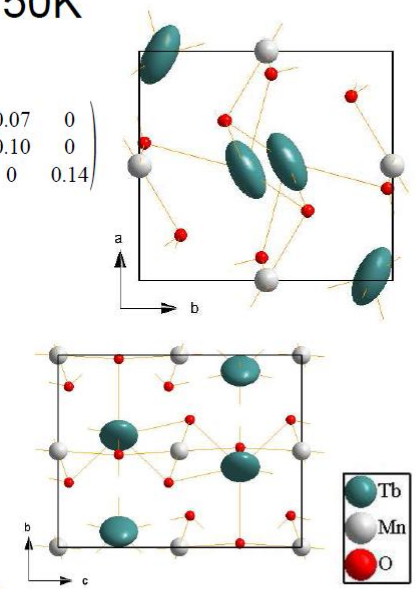
T=50K

$$\underline{\underline{\chi}}^{50K}=\begin{pmatrix}0.65 & 0.41 & 0\\ 0.41 & 0.25 & 0\\ 0 & 0 & 0.04\end{pmatrix}$$



T=150K

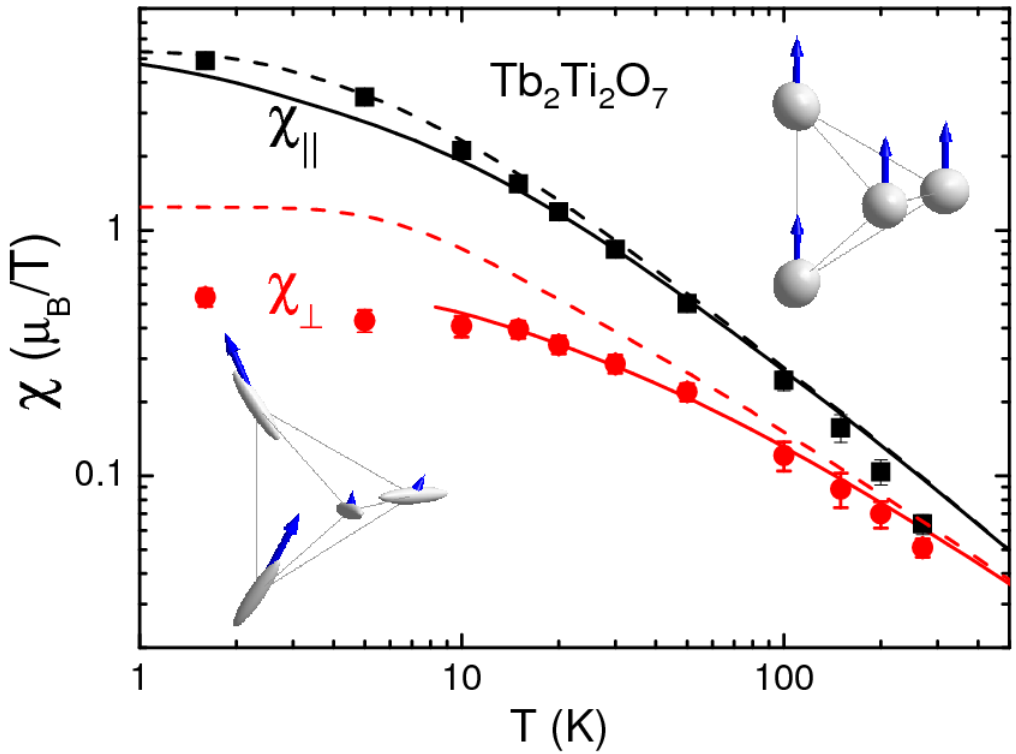
$$\underline{\underline{\chi}}^{150K}=\begin{pmatrix}0.19 & 0.07 & 0\\ 0.07 & 0.10 & 0\\ 0 & 0 & 0.14\end{pmatrix}$$

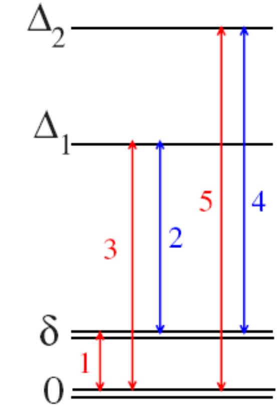


J. De Groot et al. unpublished

Soft-Ising (Spin Liquid Tb2Ti207)

Lines shows fit using CF parameters from inelastic neutrons for Tb2Ti2O7.
I. Mirebeau, M. Hennion and P. Bonville . Phys Rev. B 184436, 2007



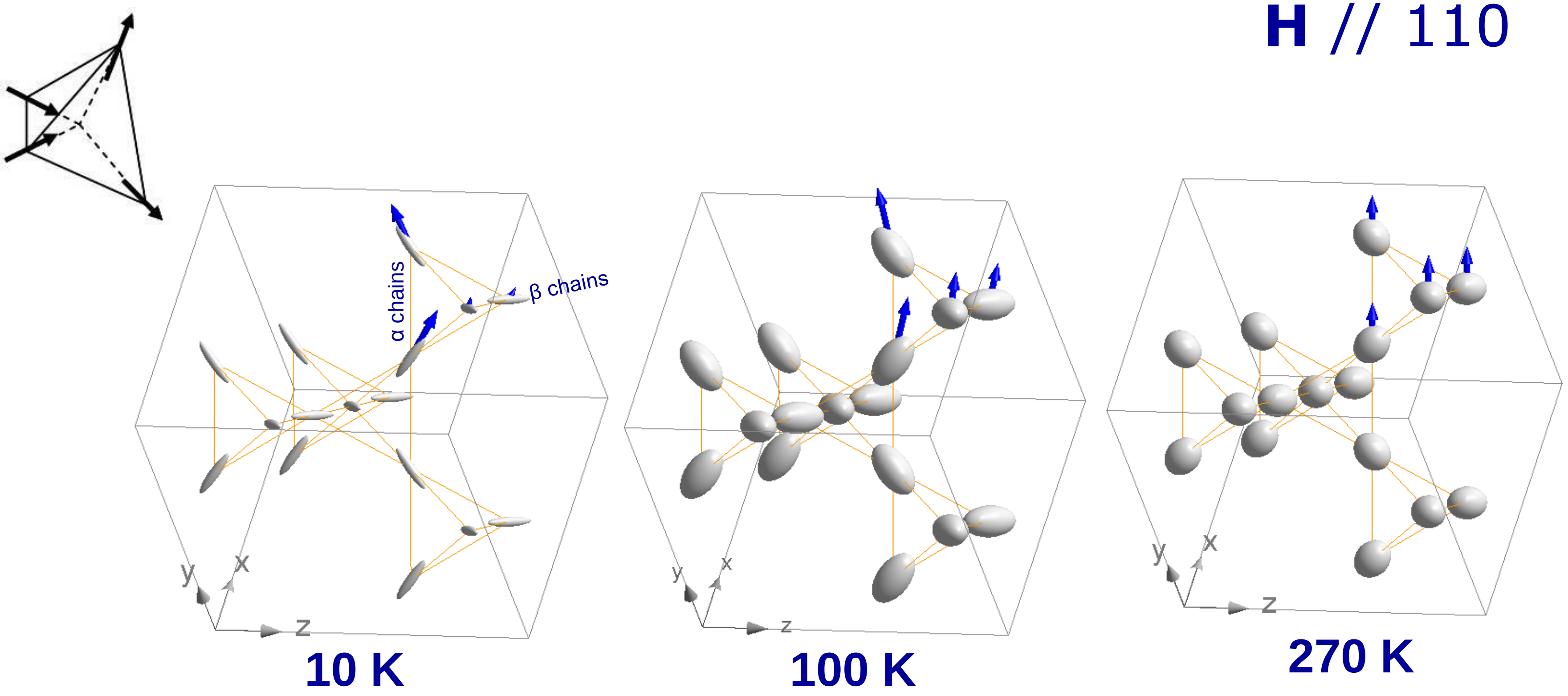


$\delta \approx 15$ K

$$M_i = \chi_{ij} H_j + \lambda \langle M_j \rangle$$

FROM HEISENBERG TO ISING BEHAVIOR

H // 110



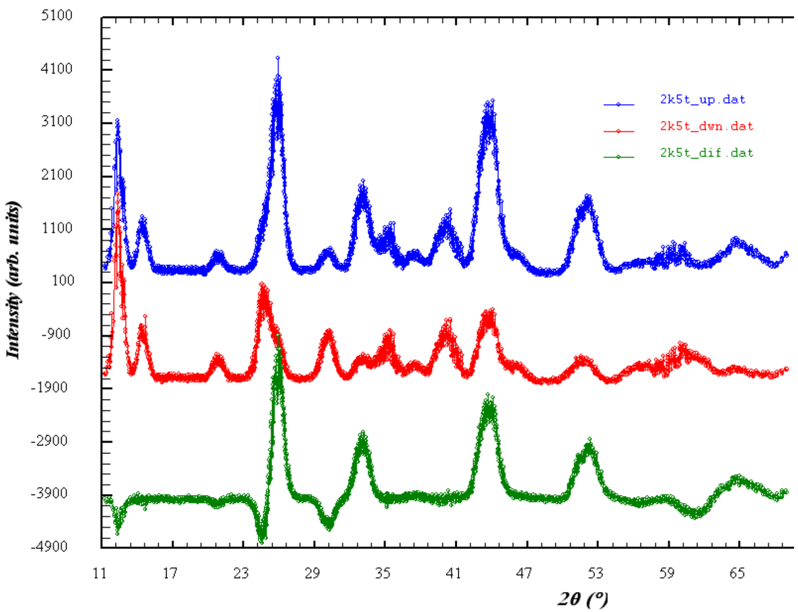
Ellipsoids are multiplied by T to compensate Curie-Weiss behavior

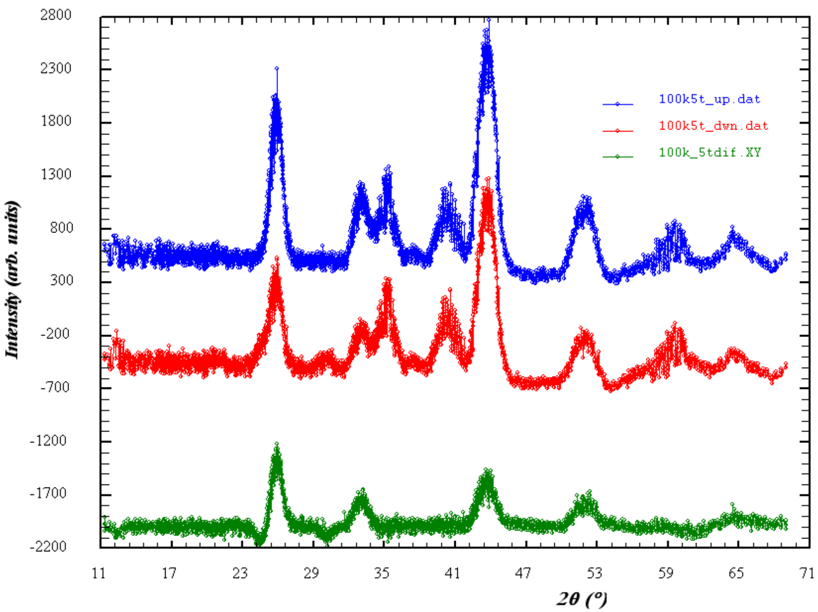
ASPs on Powder

Tb2Sn2O7

2k 5T

100k 5T

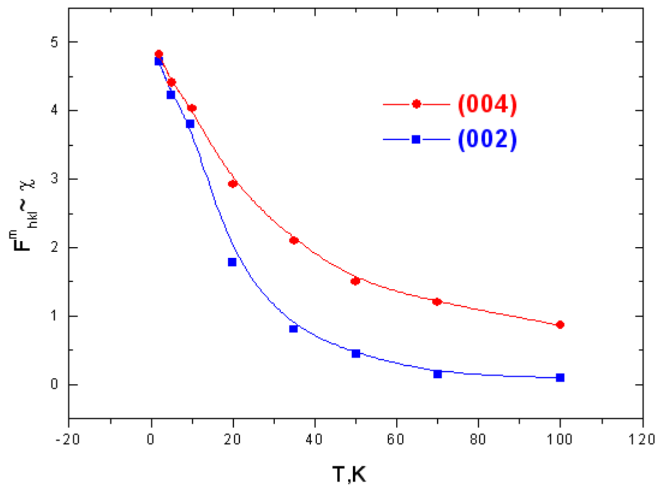


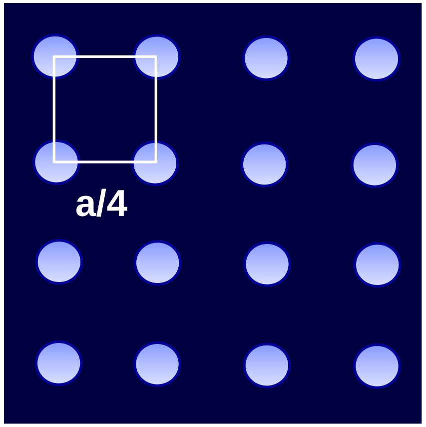


ASPs using Unpolarized Neutrons

Extinction rules for pyrochlore impose (00h)=4n

Fd-3m

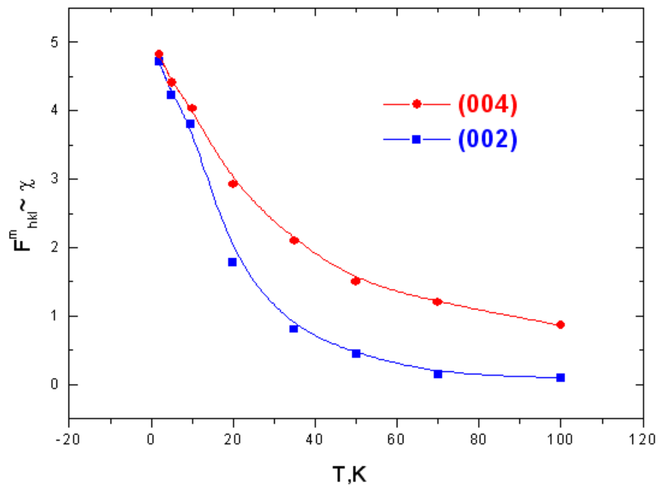


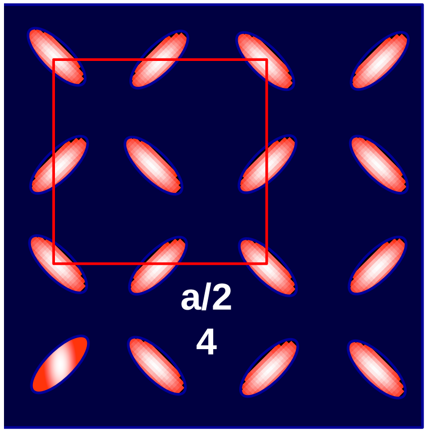


$I_m(400) \sim \chi_{11}$ Heisenberg behavior

ASPs using Unpolarized Neutrons

Lattice is doubled under magnetic field (200) appears





$I_m(400) \sim \chi_{11}$ Heisenberg behavior

I_m $(200) \sim \chi_{12}$ Ising or XY behavior

IOP FTC
IOP Publishing — Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter **22** (2010) 502201 (5pp) doi:10.1088/0953-8984/22/50/502201

FAST TRACK COMMUNICATION

Determination of atomic site susceptibility tensors from neutron diffraction data on polycrystalline samples

A Gukasov[1] and P J Brown[2]

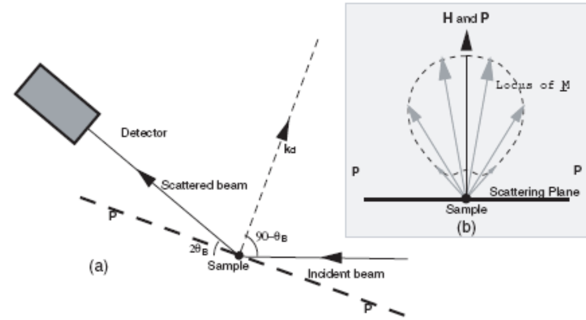
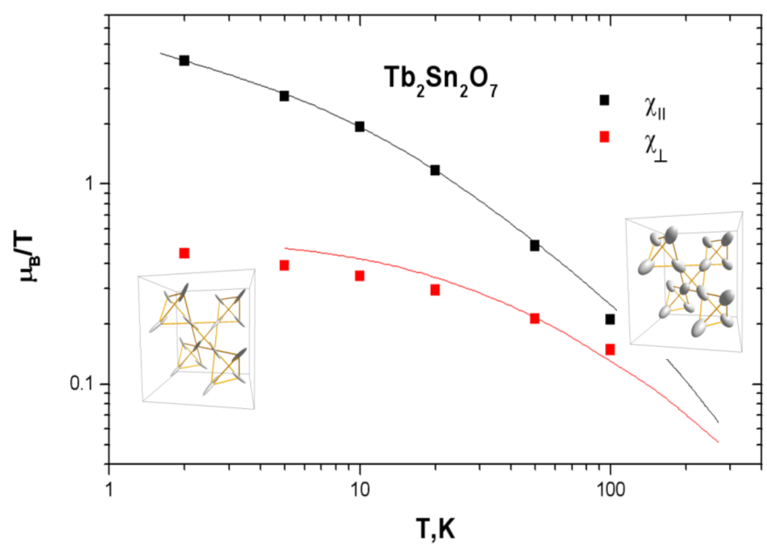


Figure 1: (a) Section in the scattering plane perpendicular to the polarisation and magnetic field direction showing the geometry for scattering by a polycrystalline sample. (b) The shaded inset shows the plane perpendicular to the scattering vector $\mathbf{k}_d$ of a reflection and indicates the locus of the magnetic interaction vectors of different contributing grains

$$
\begin{aligned}
\langle|\mathrm{M}_\perp(\mathbf{k})|^2\rangle &= \frac{H^2}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} |\mathrm{M}_\perp(\mathbf{k})|^2 d\psi \\
&= \frac{H^2}{\pi}\left[\left(\frac{\Xi_{11}^2+\Xi_{22}^2}{2}+\Xi_{12}^2\right)\psi + \left(\frac{\Xi_{12}(\Xi_{11}+\Xi_{22})}{2}\right)\cos 2\psi\right]_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \\
&= H^2\left(\frac{\Xi_{11}^2+\Xi_{22}^2}{2}+\Xi_{12}^2\right) \qquad (7)
\end{aligned}
$$

and the mean value of $\mathrm{M}_\perp(\mathbf{k})\cdot\mathbf{P}$ is

$$
\begin{aligned}
\langle \mathrm{M}_\perp(\mathbf{k})\cdot\mathbf{P}\rangle &= \frac{PH}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\left(\Xi_{11}\cos^2\psi + 2\Xi_{12}\sin\psi\cos\psi + \Xi_{22}\sin^2\psi\right) d\psi \\
&= \frac{PH}{\pi}\left[\left(\frac{\Xi_{11}+\Xi_{22}}{2}\right)\psi + \Xi_{12}\cos 2\psi\right]_{-\frac{\pi}{2}}^{\frac{\pi}{2}}
\end{aligned}
$$



CHILSQ program in CCSL (P J Brown)

WAITING FOR FULLPROF

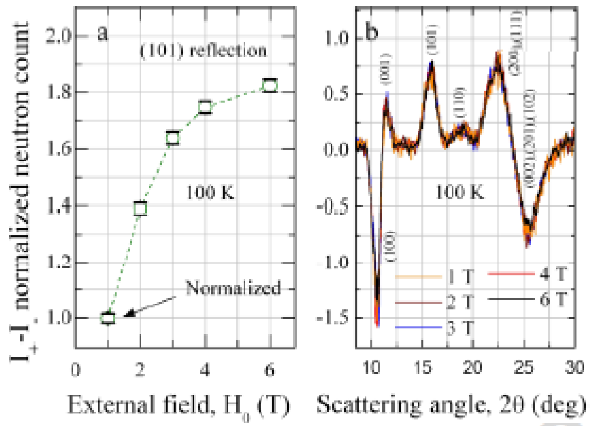
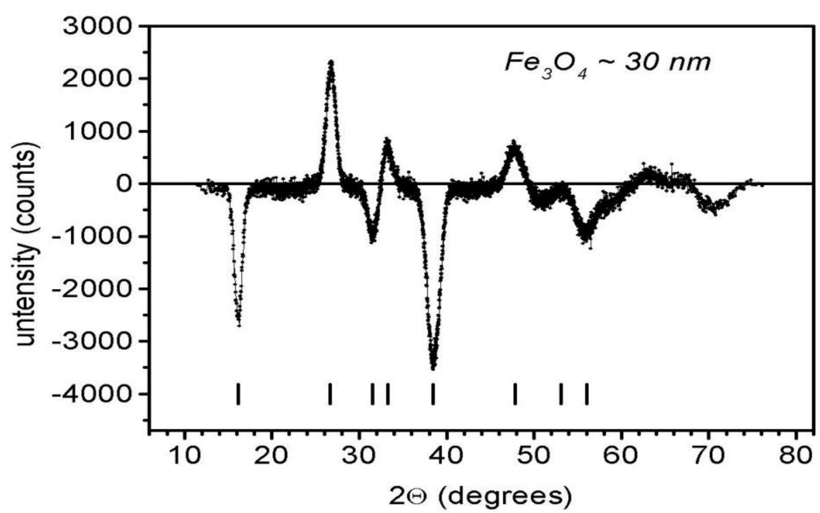


Fig. 6. This figure is reconstructed from data collected in a study of $TbCo_2Ni_3$ [13]. The 100 K observed (a) (101) reflection's integrated count $\mathbf{H}_0$ dependence, normalized to that observed at $\mathbf{H}_0 = 1$ T (the dashed line is a guide to the eye) and (b) the flipping difference, $I_+ - I_-$, profile, normalized to the (101) reflection's integrated count, under the influence of different magnitude external magnetic fields, (1 T – orange, 2 T – brown, 3 T – blue, 4 T – red and 6 T – black). (The colors are visible in the online version of the article; http://dx.doi.org/10.3233/JNR-140015.)



Local Anisotropy

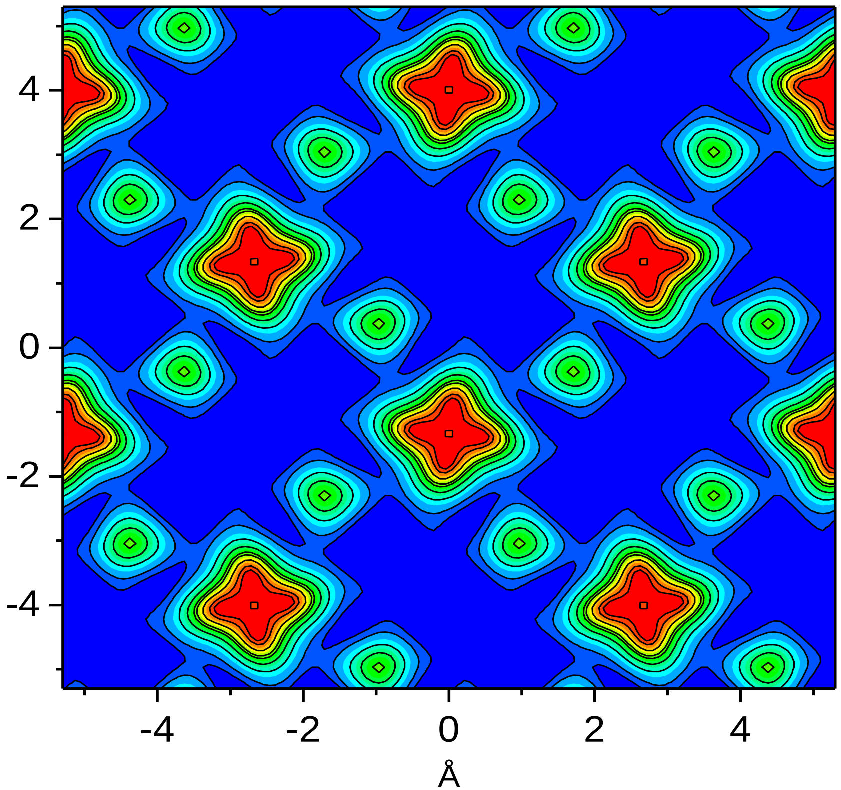
Practical volume now > 10 mm3 HN (CN)

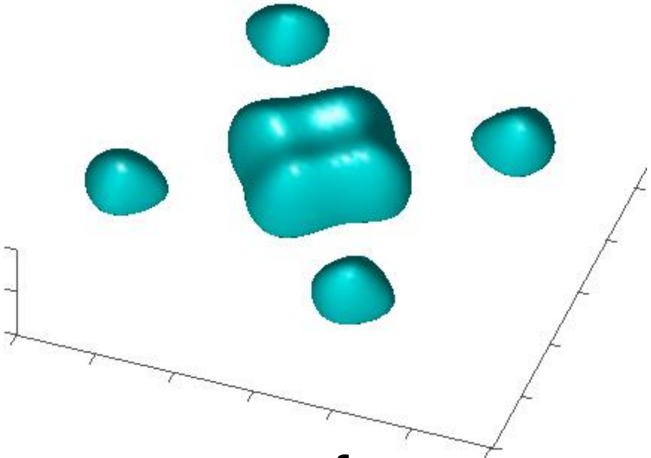
3 days for full temperature dependence

Should be not more than several hours to work as a local (site) Magnetometer

Superconductivity

$Ca_{1.5}Sr_{0.5}RuO_4$





Large amount of magnetization on Oxygen

0.35 μ_B Ruthenium
0.08 μ_B Oxygen (in-plane)
0.01 μ_B Oxygen (apical)

A. Gukasov , M Braden, R J Papoular, S Nakatsuji and Y Maeno . PRL89, 87202

Superconductivity

PHYSICAL REVIEW B **88**, 184413 (2013)

Magnetization distribution and orbital moment in the nonsuperconducting chalcogenide compound $K_{0.8}Fe_{1.6}Se_2$

S. Nandi,[1,2,*] Y. Xiao,[1] Y. Su,[2] L. C. Chapon,[3] T. Chatterji,[3] W. T. Jin,[1,2] S. Price,[1] T. Wolf,[4] P. J. Brown,[5,3] and Th. Brückel[1,2]

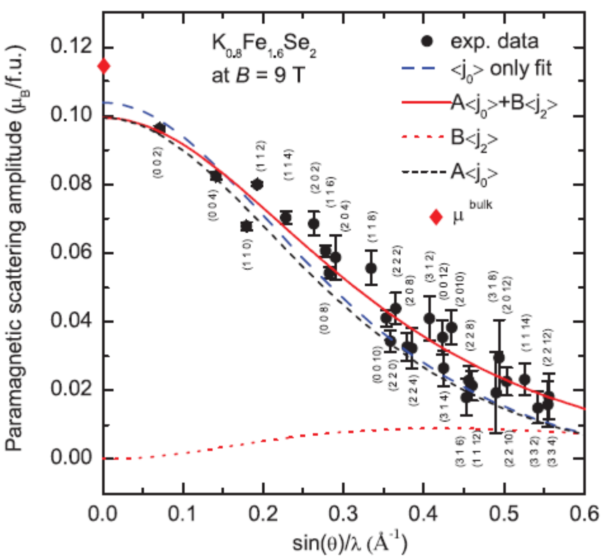


FIG. 2. (Color online) Paramagnetic scattering amplitudes of Fe at $T = 600$ K. The large-dashed curve (blue) shows fitting using the $\langle j_0 \rangle$ form factor for Fe^{2+}, Ref. 27. The solid (red) curve shows fitting with $\langle j_0 \rangle$ and $\langle j_2 \rangle$ form factors with individual contributions are indicated by short-dashed (black) and dotted (red) lines, respectively.[28] A and B are fitting parameters.

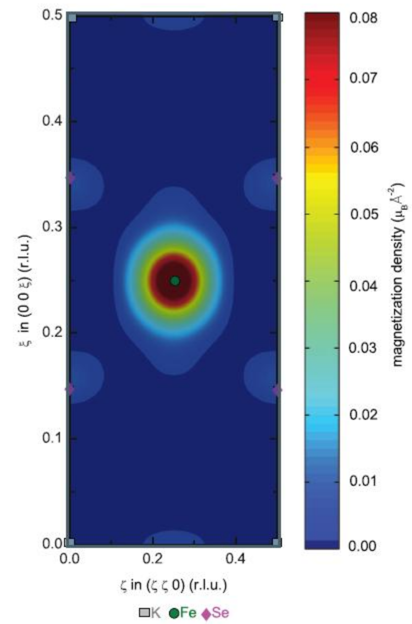
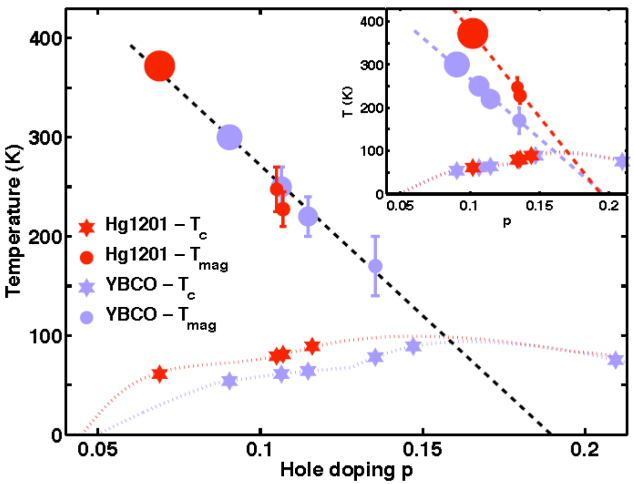


FIG. 3. (Color online) Maximum-entropy reconstruction of the magnetization distribution in tetragonal $K_{0.8}Fe_{1.6}Se_2$ at 600 K projected down to [1 1 0].

3d t_{2g} type; 66% in *xz/yz* symmetry

Superconductivity



Varma loops

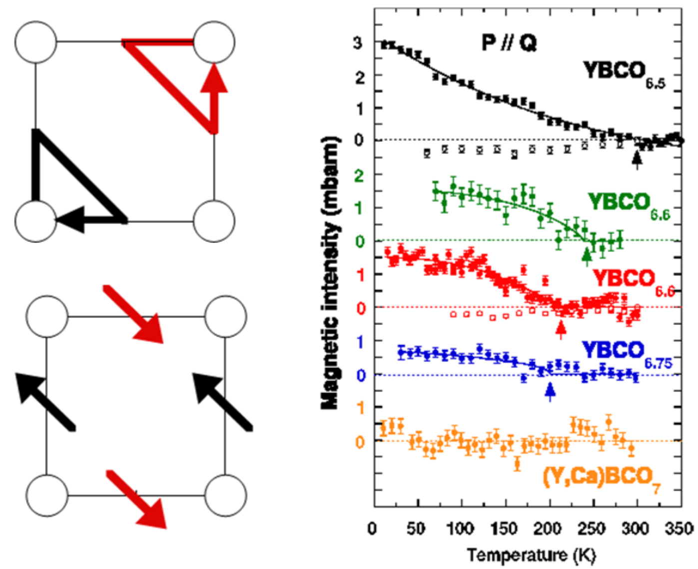


Figure 1 (from [Fau06]): right side) Magnetic intensity measured from the polarized neutron experiment on 4F1 (LLB) on 5 different YBCO samples corresponding to 5 increasing doping from underdoped (YBCO6.5) to overdoped (Y,Ca)BCO7. The behavior matches the evolution of the pseudogap determined by resistivity data. left side) CuO2 plaquette where only the Cu atoms are represented showing two intra-unit cell magnetic orders. The upper panel shows the loop current model proposed by Varma [Var06]. The lower panel shows a magnetic model with moments (spin or orbital) at the oxygen sites. Both models can account for the experimental data.

V. Balédent, et al. *Phys. Rev. Lett.* **105,** 027004 (2010).

- **Superconductivity**

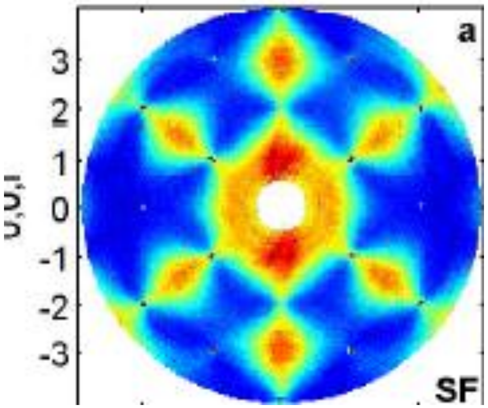
Practical volume now > 100 mm3 CN

For non superconducting samples

2-3 orders needed HN

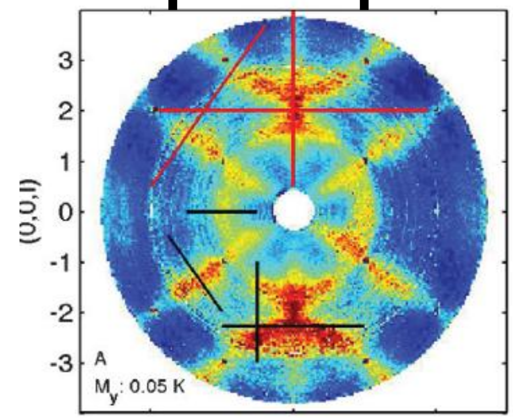
● Frustrated Magnets

Spin Ice



D7 NPA

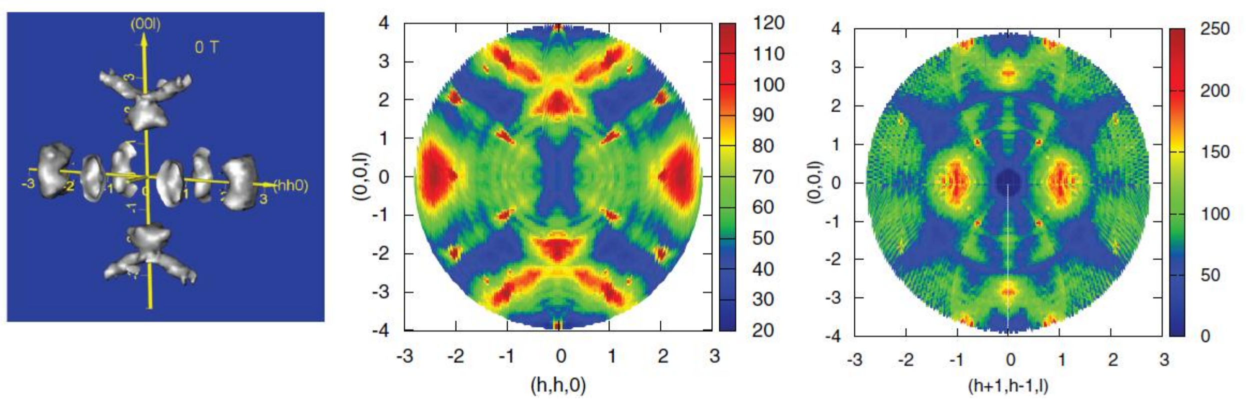
Spin Liquid



6T2 PSD

Spin Liquid

P. BONVILLE, A. GUKASOV, I. MIREBEAU, AND S. PETIT — PHYSICAL REVIEW B **89**, 085115 (2014)



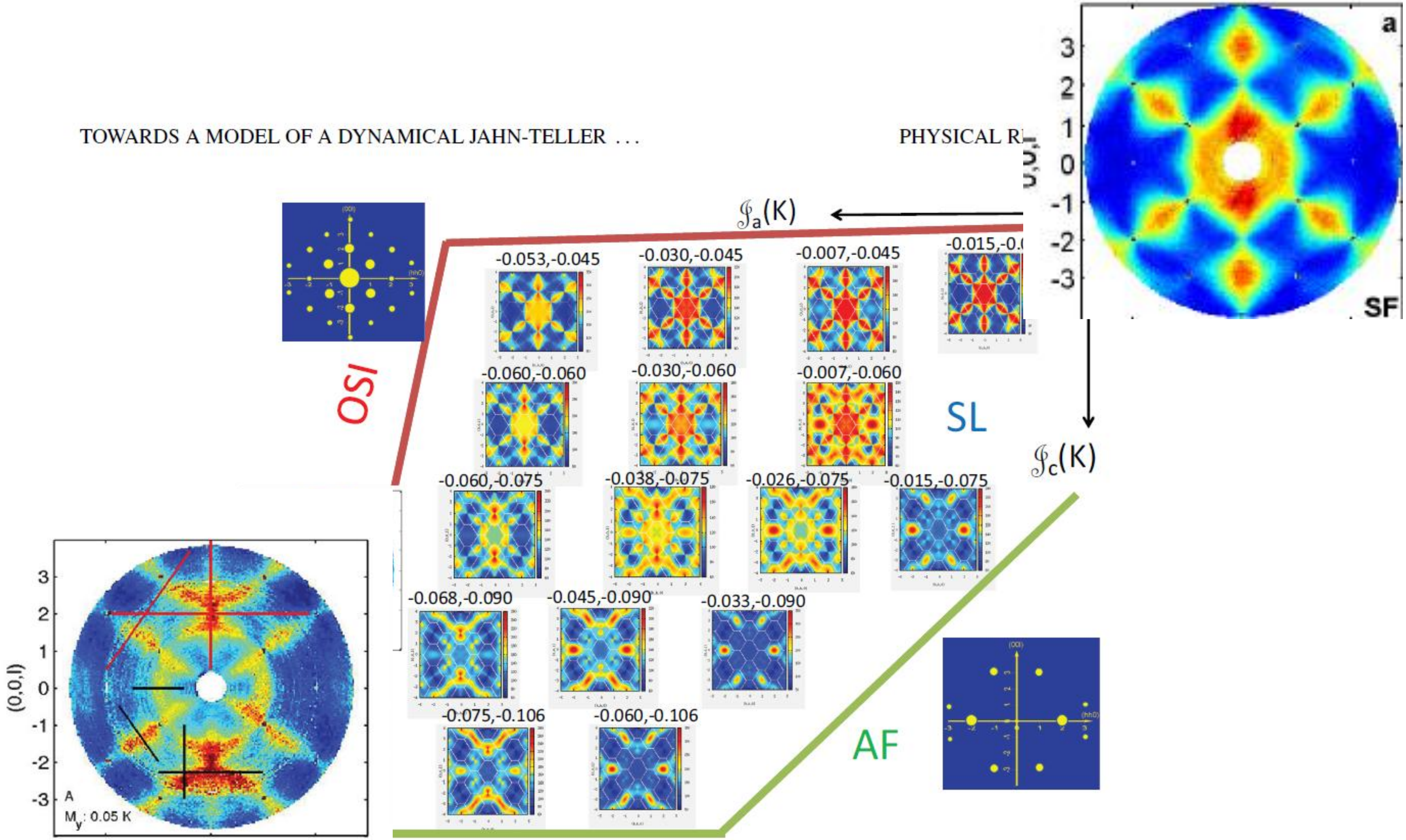


FIG. 4. (Color online) Calculated diffuse scattering maps in the (hhl) plane of the reciprocal space for the spin-flip channel at 0.05 K, according to the geometrical setup of Ref. [20]. The **q** maps are represented in the spin liquid (SL) phase of our model (see Ref. [39]), which stands as a wedge between the antiferromagnetic (AF) phase and the ordered spin ice (OSI) phase. The figure is a sketch of a cut in the exchange

- **Frustrated magnets Diffuse Scattering**

Practical volume now > 400 mm3 CN

2-3 orders and 3D q access needed CN

Frustrated Magnets in field

PHYSICAL REVIEW B **88**, 184428 (2013)

Magnetic structure in the spin liquid $Tb_2Ti_2O_7$ induced by a [111] magnetic field: Search for a magnetization plateau

A. P. Sazonov,[1,2,3,*] A. Gukasov,[3] H. B. Cao,[4,3] P. Bonville,[5] E. Ressouche,[6] C. Decorse,[7] and I. Mirebeau[3]

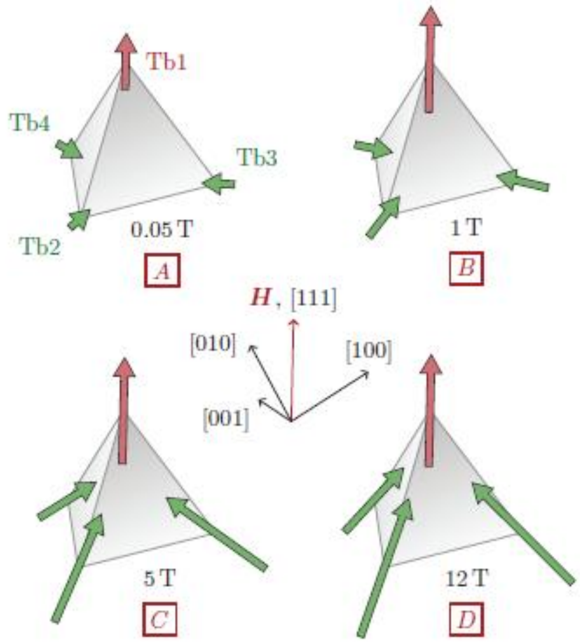


FIG. 4. (Color online) Field dependence of the Tb magnetic moments of $Tb_2Ti_2O_7$ at 300 mK under $\boldsymbol{H} \parallel [111]$, for typical field values (cases A to D in Fig. 3). Only a single tetrahedron is shown for simplicity.

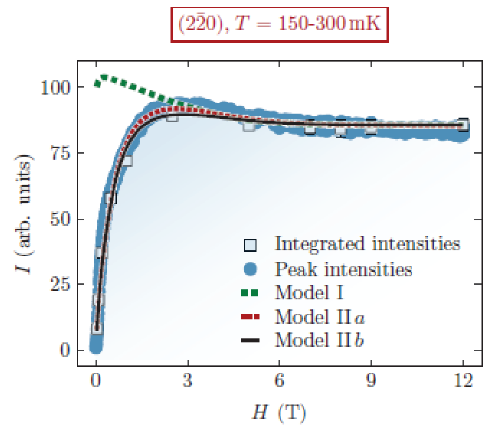


FIG. 10. (Color online) Field dependence of the $(2\bar{2}0)$ Bragg reflection under $\boldsymbol{H} \parallel [111]$. The blue open squares correspond to the integrated intensities obtained with the data collections at 300 mK, and the blue closed circles are peak intensities measured during the field scans at 150–200 mK. Error bars are smaller than the symbol size if not given. The lines are mean-field calculations described in Sec. V. The green dashed line corresponds to Model I (no symmetry breaking). The red dotted and black solid lines are Model II a (quantum mixing with static Jahn-Teller effect) and Model II b (quantum mixing with dynamic Jahn-Teller effect), respectively. The two variants of the Model II yield the same result within less than 5% for all calculated Bragg peaks.

- # Frustrated magnets

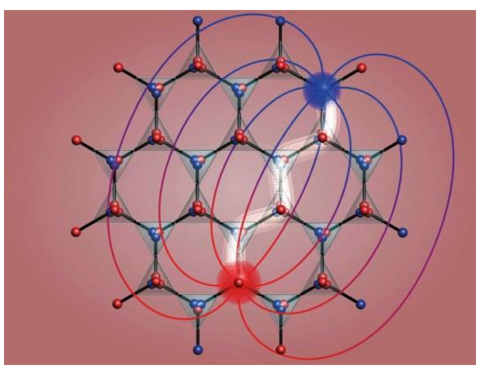
Magnetic Field , Multipolar interactions

Practical volume now > 10 mm3 HN

High q_{max} needed and data redundancy for various corrections HN

[1] W. Witczak-Krempa W. al. Annual Review of Cond. Matt. Phys., 5, 57, 2014

● Emergent Phenomena



SAZONOV, GUKASOV, MIREBEAU, AND BONVILLE PHYSICAL REVIEW B **85**, 214420 (2012)

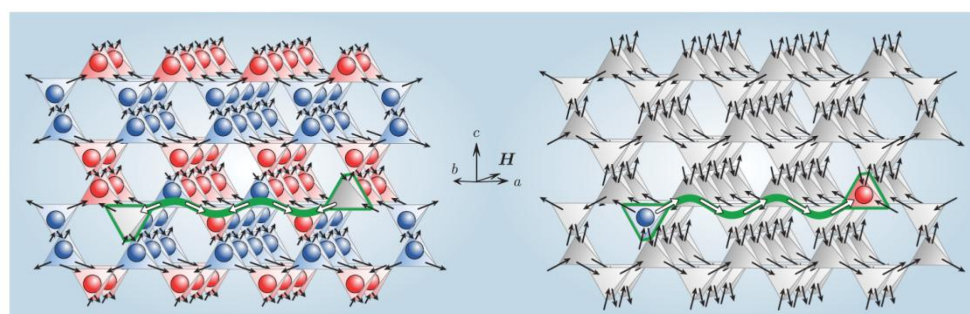
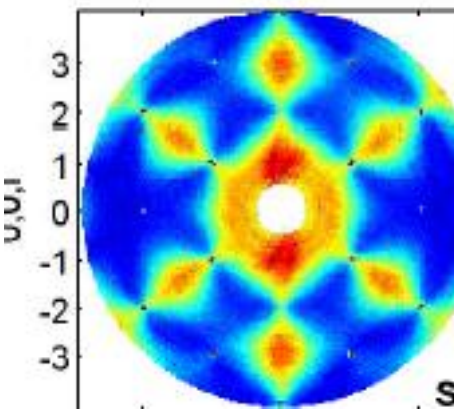


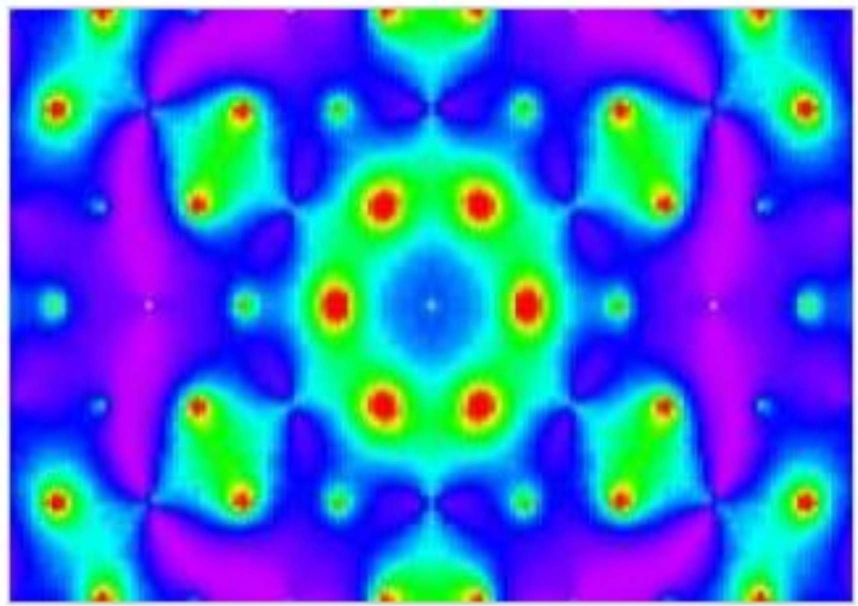
FIG. 5. (Color online) Left panel: Double-layered monopolar structure of $Tb_2Ti_2O_7$ with vacuum pair excitations. Right panel: Magnetically vacuum state of $Ho_2Ti_2O_7$ with monopole pair excitation.

Magnetic monopoles in spi

C. Castelnovo[1], R. Moessner[1,2] & S. L. Sondhi[3]

Emergent Phenomena

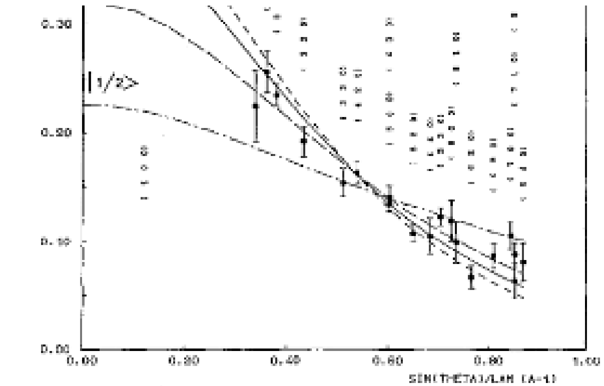




Dirac Strings as cosmic plasma filaments without attached dark matter components connecting galaxies together by magnetic currents to form the fractal filamentary web of the universe.

components connecting galaxies together by magnetic currents to form the
fractal filamentary web of the universe.

$$|\phi\rangle = 0.80(1)\,|5/2,5/2\rangle - 0.58(2)\,|5/2,1/2\rangle - 0.16(9)\,|5/2,-3/2\rangle$$



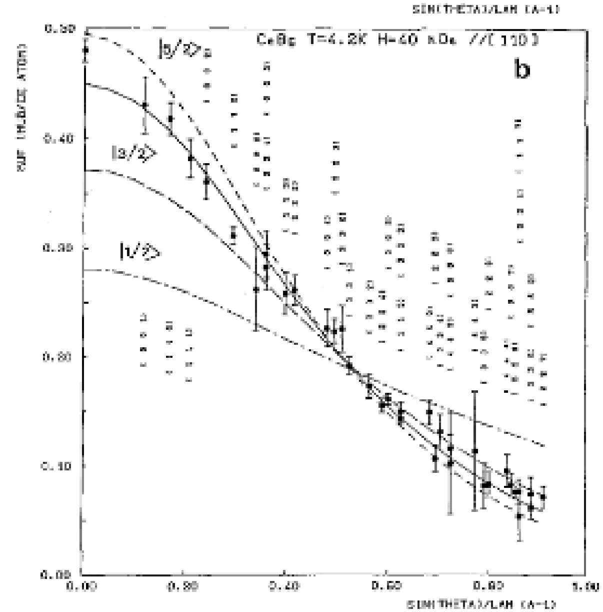
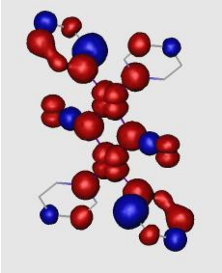


Figure 2 – Magnetic form factor of Ce^{3+} ion in CeB_6. Experimental points correspond to measurements at T = 4.2 K and H = 40 kOe parallel to the [001] (a) and [110] (b) direction. The calculated values for the dipole approximation (full line), a |1/2> (dash-dotted line), a |3/2> and a

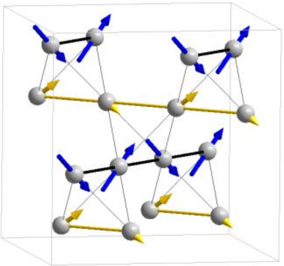
$$\vec{m} = \overline{\overline{\chi}}\vec{H}$$

$$\vec{F}_M(\vec{Q}) = \sum_k^{atoms} \overline{\overline{\chi_k}}\vec{H}\, f_k(\vec{Q}) \exp\left(i\vec{Q}\cdot\vec{r}_k\right)$$

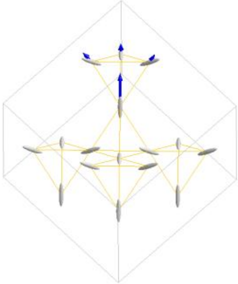
PND PROVIDES



- Spin Densities



- Magnetic structure refinement



- Atomic Susceptibility Parameters
- Non-collinear Magnetization Densities ?