# Experimental report

19/03/2019

**Proposal:** **4-05-681**

**Council:** 4/2017

**Title:** Temperature dependence of the fragmentation in the quantum spin ice Nd2Zr2O7

**Research area:** Physics

**This proposal is a new proposal**


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**Samples:** Nd2Zr2O7

| Instrument | Requested days | Allocated days | From | To |
|---|---|---|---|---|
| IN5 | 6 | 6 | 29/03/2018 | 05/04/2018 |


## Abstract:

Recently, a new form of fractionalization has been put forward in spin ice [1]. This phenomenon is described as the fragmentation of the magnetic moment field, resulting in a dual ground state consisting in a fluctuating spin liquid, a so-called Coulomb phase, on top of a magnetic monopole crystal. The aim of the present proposal is to understand in detail this phenomenon and shed light on the formation of the dual fragments as a function of temperature.

**Experimental report on 4-05-681**
**Temperature dependence of the fragmentation in the quantum spin ice $Nd_2Zr_2O_7$**

In this proposal we asked for beam time on the IN5 time-of-flight spectrometer to study the temperature dependence of the spin dynamics in $Nd_2Zr_2O_7$, and address the issue of "magnetic moment fragmentation" [1] that we recently discovered in this compound [2,3,4]. The fragmentation manifests as a dual ground state consisting of a fluctuating spin liquid fragment, a so-called Coulomb phase, on top of a magnetic monopole crystal. Using a combination of elastic and inelastic neutron scattering measurements performed on D23, D7 and IN5, we recently proposed that such a phenomenon occurs in $Nd_2Zr_2O_7$. We indeed observed the spectacular coexistence of an antiferromagnetic "All-in All-out" order ($T_N$=285 mK) induced by the monopole crystallization and of a pinch point pattern typical of a Coulomb phase (see figure 1 and 2). Importantly, the spin ice pattern is not elastic as in classical spin ice, but an inelastic feature, which suggests that quantum effects are at play in this material. Furthermore, dispersing features akin to spin waves were observed above the dynamic spin ice mode, and the whole spectrum is well reproduced in the framework of the XYZ Hamiltonian [3,5].

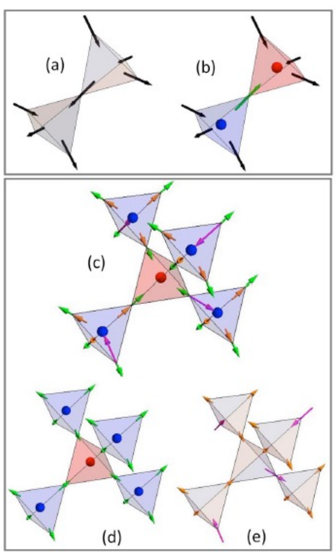


**Fig 1**: (a) Schematic of tetrahedra obeying the ice rule. (b) A spin-flip generates two magnetic monopoles. (c) in the fragmentation theory, the local magnetic moment field fragments through a Helmholtz decomposition into two parts, a divergence full and a divergence free part. For instance, a monopole (1,1,1,-1) decomposes into (½,½,½,½) + (½, ½,½, -3/2). (d) The divergence full contributions (green arrows) form an ``all in - all out" state and carry the charge. (e) The divergence free fragment. Note that the 3/2 moment can be freely moved, as a fingerprint of the degeneracy.

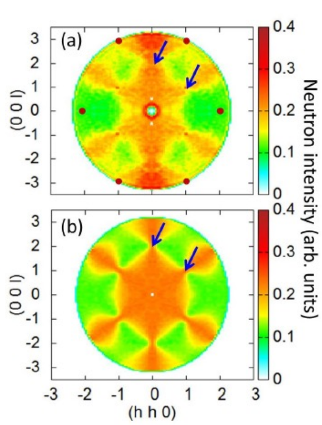


**Fig 2**: INS maps taken at 0.05 meV (top), along with the corresponding RPA calculations (bottom). Blue arrows indicate the pinch point position. Red spots denote the all-in all-out Bragg peaks (from D23 and [3]).

Our INS experiment has been carried out on IN5 in a standard set-up involving a cryomagnet and a dilution insert. The measurements were performed with a wavelength of 6 Å and 8.5 Å to ensure a good energy resolution required to resolve the small energy gap to the spin ice mode (about 70 μeV). S(Q,ω) was then measured for several temperatures from 45 mK up to 10 K.

Two main results have been obtained:

i) The spin ice dynamic mode does not soften at the Néel temperature but persists far beyond, up to 450 mK (Figure 3).

ii) An unexpected crossover is also observed with lowering temperature, which remains however to be confirmed, from elastic to inelastic spin ice like correlations.

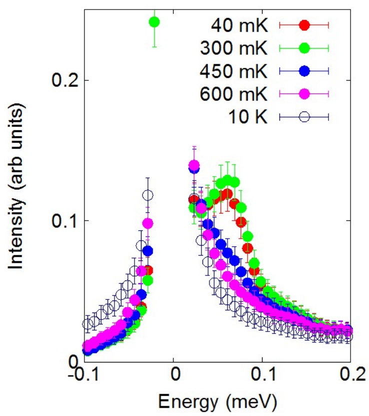


**Fig 3**: Temperature dependence of the spectral function from 45 mK up to 10K. The inelastic response is visible up to 450 mK, i.e. $T/T_N \approx 1.6$.

The analyses are on-going to understand these results and to check whether they are consistent with the quantum fragmentation mechanism recently proposed in ref [5].


[1] Brooks-Bartlett et al., Phys. Rev. X 4, 011007 (2014).
[2] Elsa Lhotel et al, Phys. Rev. Lett. 115, 197202 (2015).
[3] Sylvain Petit et al., Nature Phys. 12, 746 (2016).
[4] Elsa Lhotel et al, Nature Communications volume 9, Article number: 3786 (2018)
[5] Owen Benton, Phys. Rev. B 94, 104430 (2016).