

## SPIN DYNAMICS AND MAGNETIC ORDER NEAR THE FIELD-INDUCED QUANTUM CRITICAL POINT IN $\text{Pr}_2\text{CuO}_4$

D. Petitgrand<sup>1</sup> and A.S. Ivanov<sup>2</sup>

<sup>1</sup> Laboratoire Léon Brillouin (CEA-CNRS)

<sup>2</sup> Institut Laue-Langevin

Most of the cuprate compounds become high- $T_c$  superconductors when they are doped by an appropriate substitution. Among them, the family of tetragonal  $\text{R}_2\text{CuO}_4$  ( $\text{R} = \text{Nd}, \text{Pr}$ ) cuprates has shown n-type superconductivity upon Ce doping. This has led to an increasing effort to understand the magnetic properties of the pure compounds. For the investigation of the Cu magnetic properties,  $\text{Pr}_2\text{CuO}_4$  gets advantage of the non magnetic state of Pr, on the contrary to  $\text{Nd}_2\text{CuO}_4$ .

$\text{Pr}_2\text{CuO}_4$  is a non-collinear antiferromagnet made of strongly coupled  $\text{CuO}_2$  AF planes with spin direction at right angle in adjacent planes.

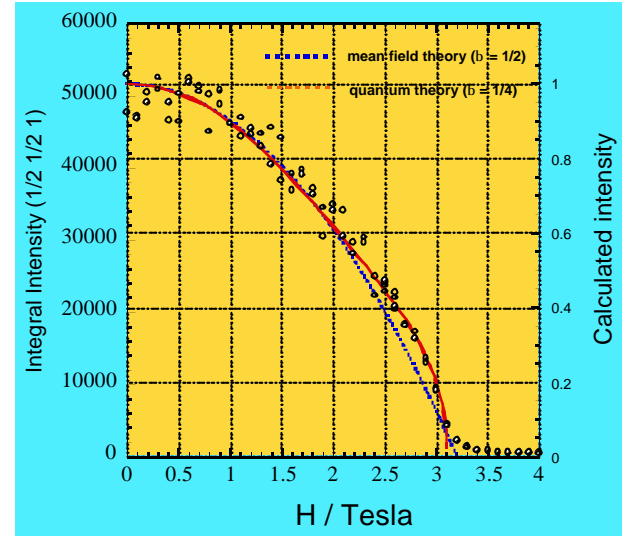
The main magnetic properties of  $\text{Pr}_2\text{CuO}_4$  can be described within a simple model of a planar antiferromagnet with a very large ( $J = 1400 \text{ K}$ )<sup>[1]</sup> and slightly anisotropic Heisenberg interaction between in-plane neighbouring Cu ions on a square lattice. However the 3D magnetic structure as well as the low energy magnetic excitations have revealed that some subtle additional interactions are involved.

- Neighbouring planes are loosely coupled along the c-axis through a weak pseudo-dipolar exchange interaction<sup>[2]</sup>.
- Due to quantum effects in the 2D  $S=1/2$  antiferromagnet, the intraplane exchange interactions also acquire pseudo-dipolar terms which open a small gap in the excitation spectrum<sup>[2,3]</sup> and stabilise the spin direction along (100)<sup>[4]</sup>.

Using a triple-axis spectrometer, we have studied the magnetic order and the spin dynamics of  $\text{Pr}_2\text{CuO}_4$  under a magnetic field. The experiments have been performed with cold neutrons ( $k_i = 1.3 \text{ \AA}^{-1}$ ), the sample being oriented with (110) and (001) in the scattering plane. The applied field produced by a superconducting coil, was vertical along (1 -1 0).

When a magnetic field is applied along (1 1 0), the direction of the staggered magnetisation of both types of planes gradually moves towards the direction perpendicular to the field, up to a second order transition line  $H_c(T)$ , which ends at the quantum critical point ( $H_c, T=0$ ).

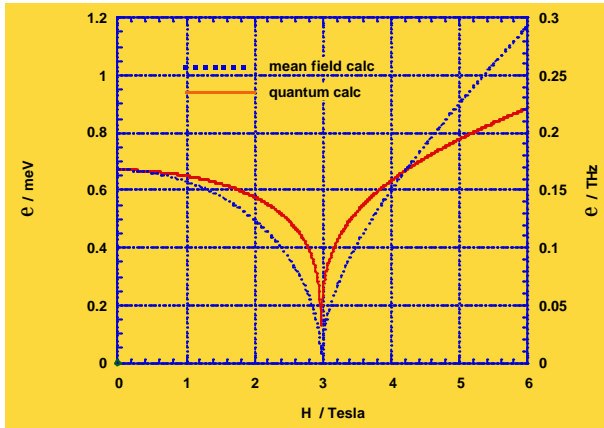
We have measured the magnetic Bragg intensity with  $k_i=(1/2 \ 1/2 \ 1)$  as a function of field at several temperatures. Figure 1 shows the experimental results at  $T=1.5 \text{ K}$  together with a classical mean-field calculation ( $\beta=1/2$ , dotted curve). Our results suggest that the magnetic order parameter vanishes at the quantum critical point ( $H_c, 0$ ) with a non-classical critical exponent.



**Figure 1** Intensity of the magnetic Bragg peak ( $1/2 \ 1/2 \ 1$ ) as a function of the applied field. Lines are fits with theoretical calculations of ref [2].

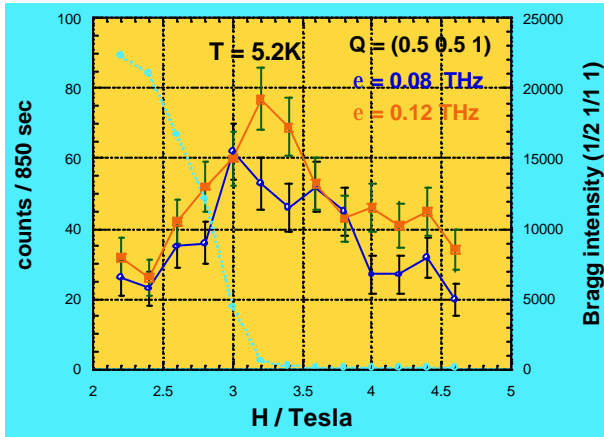
Full line of Figure 1 shows that our results can be accounted for by the theoretical curve exhibiting a critical exponent  $\beta=1/4$  as recently suggested<sup>[2]</sup>.

Another prediction associated with this phase transition is a softening of the magnetic excitation small gap as  $H$  approaches  $H_c$  (Figure 2).



**Figure 2** Theoretical field dependence of the small magnetic gap according theoretical calculations of ref [2].

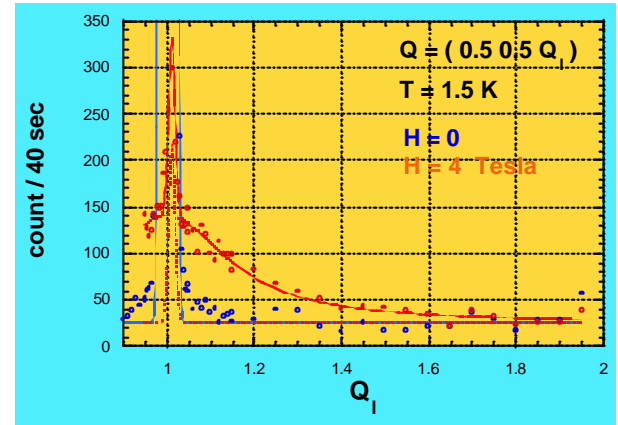
To investigate this prediction, we have measured the magnetic inelastic scattering at  $Q=(1/2 \ 1/2 \ 1)$  for energy transfers of  $\epsilon = 0.08$  and  $0.12$  THz, which are below the zero field spin-wave gap, as a function of field.



**Figure 3** Inelastic intensities within the zero-field gap as a function of the applied field. Blue points show the decrease of the magnetic Bragg intensity towards the transition field. The maximum of the inelastic signal thus coincides with the transition field.

The results (Figure 3) show that, as the field approaches  $H_c$ , an additional intensity comes into the energy window, as a consequence of the softening of the gap. This gives an experimental evidence that, the gap  $\Delta_0$  of the in-plane acoustic magnetic excitation also vanishes at  $H_c$ .

Finally we have measured the interplane magnetic correlations along the  $(1/2 \ 1/2 \ q_z)$  line. Results obtained at  $T = 1.5$  K for  $H = 4$  Teslas, compared to  $H = 0$  show the persistence of mid-range correlations well above the transition field  $H_c = 3$  Tesla (Figure 4). The lineshape is well accounted for by a Lorentzian convoluted by the resolution function, with a correlation along  $c$  of  $\xi = 12$  Å which corresponds to two interplane spacings. In the direction perpendicular to the rod, the magnetic scattering appears resolution limited. Thus the point  $(H_c, T=0)$  appears as a 3D-2D quantum critical point for this component of the order parameter.



**Figure 4** Magnetic elastic intensities along the  $(1/2 \ 1/2 \ q_z)$  rod at  $T = 1.5$  K for  $H = 0$  and 4 Tesla. The full line is a resolution-convoluted Lorentzian fit with a correlation length  $\xi = 12$  Å, corresponding to 2 interplane spacings

Our experiments on magnetic order, magnetic correlations and magnetic excitations in  $\text{Pr}_2\text{CuO}_4$  strongly suggest that this system shows a field-induced quantum critical point at  $(H_c = 3 \text{ Tesla}, T=0)$  with unusual critical exponent, soft mode and short range 2D correlations extending far from the critical point.

- [1] Ph. Bourges, H. Casalta, A.S. Ivanov and D. Petitgrand, Physical Review Letters, **79** (1997) 4906
- [2] D. Petitgrand, S.V. Maleyev, Ph Bourges and A. S. Ivanov, Physical Review B **59** (1999) 1079
- [3] A. S. Ivanov, P. Bourges and D. Petitgrand, Physica B **259** (1999) 879
- [4] S. V. Maleyev, D. Petitgrand, Ph. Bourges and A.S. Ivanov, Physica B **259** (1999) 870