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# Superfluid transition in superfluid $^3\text{He}$ in radially compressed aerogel.

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## **Abstract.**

The Spin Supercurrent and Bose-Einstein condensation of magnons similar to an atomic BEC was observed in 1984 in superfluid  $^3\text{He}$ -B. Recently we discovered 2 new types of BEC in superfluid  $^3\text{He}$  in deformed aerogel. The orbital part of the wave function orients along the deformation and changes the magnon-magnon interaction. In some cases it forms a magnon trap. We can do it for  $^3\text{He}$ -A by uniaxially compressing the aerogel along the magnetic field. The other BEC state was observed in  $^3\text{He}$ -B in aerogel stretched along the magnetic field. Both states show all properties of magnon BEC. We have also observed a splitting of NMR lines near  $T_c$ , which seems to indicate the formation of a new phase of superfluid  $^3\text{He}$  in aerogel. The latter looks like an analog of the  $^3\text{He}$ -A1 phase with strongly enhanced magnetic field.

## **1. Introduction**

Anisotropic aerogels allow to control the orientation of the order parameter of superfluid  $^3\text{He}$  independently of the magnetic field, pressure or temperature. The superfluid states in superfluid helium 3 immersed in aerogel have been investigated thoroughly and they are today generally understood. In this article we present new data that show unexpected behaviour close to the superfluid transition in aerogel.

In our case, where the anisotropy of the aerogel is strong enough (a compression of about 12% in volume), the influence of disorder can be described by a Larkin-Imry-Ma model [1, 2]. In superfluid  $^3\text{He}$  immersed in radially pressed aerogel, the orbital part of the order parameter is expected to be parallel to the axis of anisotropy, which is chosen in our experiment to be parallel to the magnetic field. Knowing this, one can then compute the NMR properties of the different phases of superfluid.

The theoretical predictions work well at temperatures low enough below the superfluid transition  $T_C$ , where one observes the usual A and B-like phases with the predicted NMR properties. However, close to  $T_C$ , we observe an unexpected behaviour of the NMR line.

## **2. Experimental setup**

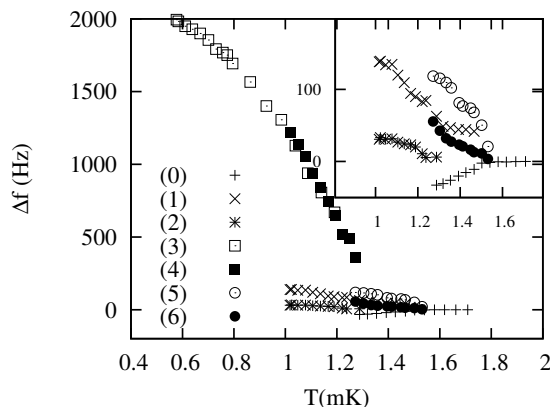
We used a nuclear demagnetization refrigerator to cool the aerogel sample to temperatures as low as 500  $\mu\text{K}$ . The NMR properties are measured via homemade saddle coil placed around the sample. The resonant frequency of the measurement circuit can be tuned between 700 kHz and 3MHz by adjusting a capacitor. These frequencies correspond to magnetic fields between 30 and 100 mT. Most of the experiments are done at a pressure of 29.3 bar in the experimental cell.

The anisotropy of the aerogel sample was ensured before cooling the experiment by radially compressing the sample by about 12% using a method described in a previous publication[3]. This produced an anisotropy axis parallel to the magnetic field of NMR. The aerogel was coated with  $^4\text{He}$  to ensure the absence of solid  $^3\text{He}$  that would perturb the NMR properties of the superfluid.

### 3. Splitting of the superfluid transition

We performed continuous wave NMR measurements near the superfluid transition temperature  $T_C$ . The NMR lines showed multiple peaks close to  $T_C$  that can be described as follows. One can define four temperatures :  $T_C^+$ ,  $T_C$ ,  $T_C^-$  and  $T_{AB}$  such as  $T_C^+ > T_C > T_C^- > T_{AB}$ . Above  $T_C^+$ , the NMR line has no shift, corresponding to the normal phase.

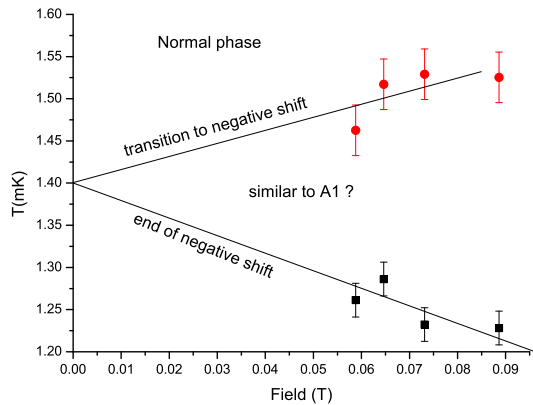
During cooling, the NMR line exhibits negative shift between  $T_C^+$  and  $T_C^-$ , a small positive shift between  $T_C^-$  and  $T_{AB}$ , corresponding to the A phase in aerogel and a large positive shift below  $T_{AB}$ , corresponding to the B phase in aerogel. During warming, the shift corresponding to the B phase is observed below  $T_C^-$ , and a positive shift is observed between  $T_C^-$  and  $T_C^+$ . These characteristics are showed Fig. 1.



**Figure 1.** Characteristics of the NMR lines as a function of temperature. (0) : negative shift when warming. (1) and (2) positive shift peaks when cooling, A like phase. (3) : B-like phase when cooling. (4) : B-like phase when warming. (5) and (6) : positive shifts when warming. This data was measured at about 3 MHz.

If one interpolates the shift of the B-like phase to zero to obtain a value of superfluid transition temperature, one finds that  $T_C$  is equal to  $(T_C^+ + T_C^-)/2$ . This property is typical of the  $A_1$  phase that appears in bulk  $^3\text{He}$  in strong magnetic fields and where only spin up cooper pairs are present. This phase appears slightly above the critical temperature in zero field and disappears slightly below to be replaced by the so called  $A_2$  phase which is the A phase slightly modified by the presence of a magnetic field. This led us to perform experiments at different values of the magnetic field.

In Fig. 2, we show the splitting of the superfluid transition as a function of the magnetic field. In the simplest approximation, one can adjust a linear law to this splitting, very similar to what one observes in the  $A_1$  phase. The slope of the  $T_C^-$  line is about  $-2.1 \text{ mK.T}^{-1}$  and that of the  $T_C^+$  line is about  $1.66 \text{ mK.T}^{-1}$ . These slopes are about fifty times bigger than those measured in isotropic aerogel [4] or in bulk superfluid  $^3\text{He}$ . This suggests a strong influence of the orientational effect of aerogel.

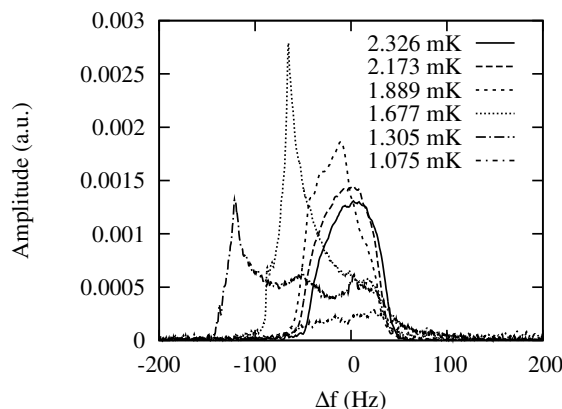


**Figure 2.** The frequency of precession of the first moments of the coherent precession for two different temperatures. The dashed line is the theoretical prediction. For  $1 - \cos \beta > 1.6$ , the experimental results deviate from the theoretical prediction.

#### 4. Non linear signature of the A<sub>1</sub>-like phase

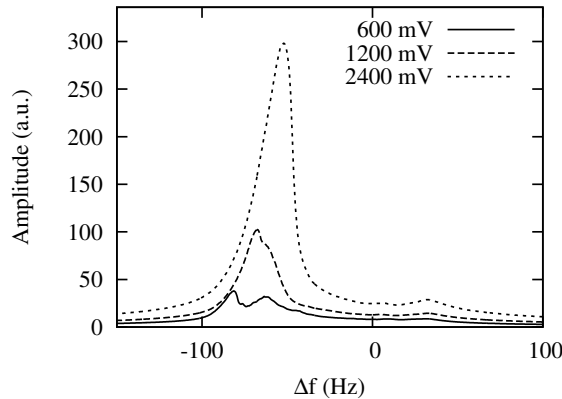
We investigated the non-linear NMR properties of superfluid helium 3 in our sample. To obtain a clearer picture of what happens, we made experiments at lower frequencies (about 700 kHz). This gives larger NMR shifts and less line broadening due to the field inhomogeneity, giving globally better results in continuous wave NMR. This change implied a cycle to room temperature to change the NMR coil that affected our sample by changing slightly its transition temperatures. The observed NMR shifts are qualitatively the same.

Fig. 3 shows typical NMR lines during cooling during an experiment made with a 700 kHz NMR frequency. In this case, the negative shift can be clearly seen for temperatures between 2.1 and 1.3 mK. At 1.075 mK, there has been a transition to the B-like phase and the main peak is out of the graph.



**Figure 3.** Typical NMR lines during cooling. A line at 2.326 mK is in the normal phase. Between 2.173 mK and 1.305 mK, the sample exhibits the negative frequency shift characteristic of the A<sub>1</sub>-like phase. At 1.075 mK, superfluid helium in the sample is in the B phase, and the line exhibits a peak at more than 200 Hz.

We measured the non linear properties of the  $A_1$ -like phase at different NMR excitation levels. On Fig. 4, we show the values of  $M_{\perp}$  as a function of excitation frequency for different excitation levels (600 mV, 1.2 V and 2.4 V). The perpendicular magnetization  $M_{\perp}$  is obtained as  $M_{\perp} = \sqrt{V_{abs}^2 + V_{disp}^2}$ , where  $V_{abs}$  and  $V_{disp}$  are respectively the in phase and out of phase response of the NMR spectrometer.



**Figure 4.** The component of magnetization orthogonal to the magnetic field as a function of frequency  $M_{\perp}$ . The amplitude of excitation varies between 600 mV and 2.4 V. The curve for 2400 mV has a small offset due to electronics heating in the NMR spectrometer.

These curves exhibit the general properties of coherent precession phenomena in superfluid  $^3\text{He}$ . These can be understood as the Bose-Einstein condensation of magnons [6]. One of the main signature being that the amplitude of  $M_{\perp}$  depends only on the frequency of the excitation radio-frequency field and not on its amplitude : all the NMR lines at different excitation levels follow the same universal curve. The magnetization precesses coherently in all the sample, at a frequency given by the excitation field. The losses are compensated by pumping. This explains why the increase in drive allows to explore the frequencies corresponding to bigger angles of deflections, where losses are bigger.

## 5. Conclusion

We measured unexpected properties of the superfluid transition in radially compressed aerogel. The transition exhibits a splitting dependent on magnetic field, looking like a fifty times enhanced  $A_1$  phase splitting. We also measured the non linear NMR properties of this  $A_1$ -like phase and observed that they show a signature typical of coherent precession phenomena.

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