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Bose-Einstein condensation in antiferromagnets at low temperatures

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Abstract. The Bose-Einstein condensation (BEC) was predicted by Einstein in 1925 and this effect is characterized by the formation of a collective quantum state, when macroscopic number of particles is governed by a single wave function. The BEC of magnons was discovered experimentally in superfluid phase of ^{3}He. In the present work we report our progress on the BEC of magnons investigations in solid antiferromagnets at low temperatures by magnetic resonance methods. The duration of the FID signal in two samples of easy-plane antiferromagnets $CsMnF_3$ has been studied. Obtained data confirm the formation of magnon BEC in antiferromagnet $CsMnF_3$.

1. Introduction

The Bose-Einstein condensation (BEC) corresponds to the formation of a collective quantum state in which macroscopic number of particles is governed by a single wave function. The formation of this state was predicted by Einstein in 1925 [1]. The BEC of magnons was discovered experimentally in superfluid phase of ^{3}He-B [2, 3]. It manifests itself by coherent precession of magnetization. Then 6 different states of superfluid ^{3}He with BEC formation were observed. The review of various experiments on the BEC observation can be found in [4-6]. In all cases BEC forms by excited non-equilibrium magnons. To excite it the pulse or continuous pumping at nuclear magnetic resonance (NMR) frequency was used.

In [7] it was assumed that the BEC formation is also possible in solid antiferromagnets $CsMnF_3$ and $MnCO_3$ with coupled nuclear-electron precession. The predictions were successfully confirmed. It was found that the coupled nuclear-electron precession shows all properties of coherent spin precession and magnon BEC [8]. The main experimental fact of magnon BEC evidence was independence of the nuclear-electron magnetic resonance (NEMR) signal amplitude on applied RF power [9-11]. These experiments were done by means of continuous wave NMR and “switch-off” NMR. Two regimes of radiofrequency (RF) pumping were found. In the first regime the induction signal is observed after short (about 1 μs) resonant RF pulse. This pumped state will be called as a normal one in the text. In this state spins precess with its local frequency due to the external magnetic field inhomogeneity. In the second regime the induction signal is observed after long (about hundreds of ms and longer) non-resonant RF pulse (so called “switch-off” NMR) and the signal amplitude is well described in framework of magnon BEC.

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We report here the experimental investigations of the free induction decay (FID) signal behaviour in both pumping regimes in two samples of easy-plane antiferromagnet $CsMnF_3$.

2. Results and discussion

The experiments on both $CsMnF_3$ were performed at the temperature of 1.5 K. The first sample $CsMnF_3$ was grown by S.V.Petrov in the P.L. Kapitza Institute for physical problems RAS. The second one was grown by L.I.Isaenko and S.A.Zhurkov in the V.S. Sobolev Institute of geology and mineralogy SB RAS. The main difference between samples is their quality. X-ray investigations show that the second sample is more homogeneous.

The complete details of the experimental setup were described in [12]. We applied RF pulses of different amplitudes and durations with resonant NEMR frequencies or higher ones for an applied external magnetic field. The FID signal was observed in our experiments. The typical FID signals in both RF pumping regimes in the first sample are shown in figure 1.

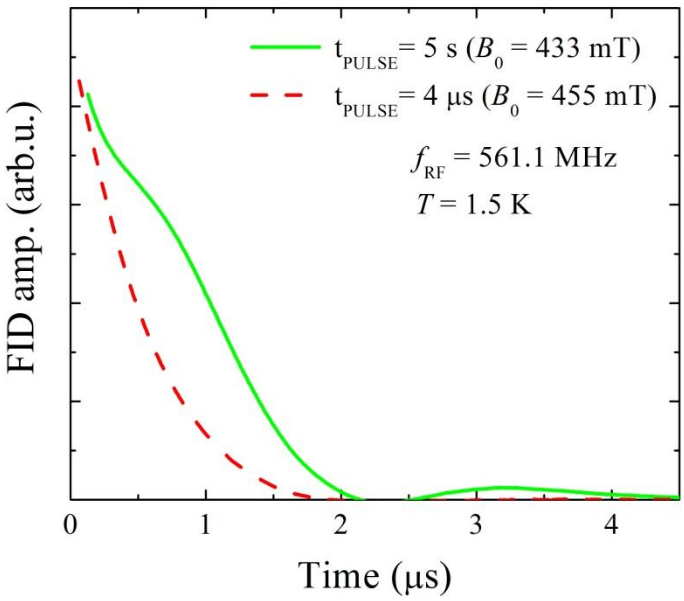

Figure 1. The FID signal $CsMnF_3$ amplitude in the first sample in two RF pumping regimes.

It can be seen that after the 5 s pulse the FID signal duration in BEC state is only about 2 times longer than in normal pumped state. Such negligible difference does not allow us to interpret data in terms of BEC. Why the FID is so short in time dimension? As an example, the process of magnon BEC state formation is very sensitive to impurities and magnetic defects in the experiments with ^{3}He. Thus, the formation of a BEC state of ^{3}He-B in aerogel (high porosity SiO_2) was observed for the first time in Grenoble as a formation of a signal localized in some region of the sample [13]. Later, a global BEC signal at the sample with better homogeneity was observed [14]. The same was observed in a pulsed NMR [15]. The FID of pure ^{3}He-B may have duration of a second, while from the ^{3}He-B in aerogel it occurs to be only about few milliseconds. The similar behavior of the FID signal was observed in superfluid ^{3}He-A in aerogel [16]. The FID duration in BEC state was only about an order of magnitude longer than in the normal state. Furthermore, the beating of a FID signals from a few local BEC states was observed in short pulse NMR. In the case of "switch-off" NMR the beats were not observed and the duration of the signal in BEC state increases (figure 2).

It is well known [17] that the relaxation times of CsMnF3 crystals can vary more than order of magnitude. The origin of the observed short FIDs in BEC state for the first sample can come from its low quality. The next experiments were performed on the second sample, that supposed to be much more homogenous The typical FID signals in both RF pumping regimes in the second sample are shown in figure 3.

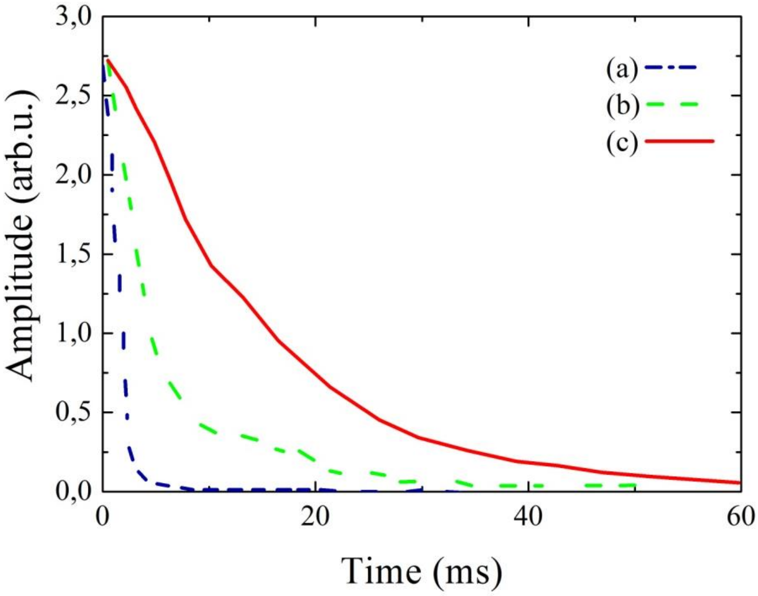

Figure 2. The FID signal amplitude in superfluid 3He-A in aerogel in two RF pumping regimes. (a) - FID from a normal ^{3}He-A. (b) - FID from a superfluid ^{3}He-A after short RF pulse . One can see the beating between different BEC signals; (c) - FID after "switch-off" NMR [16].

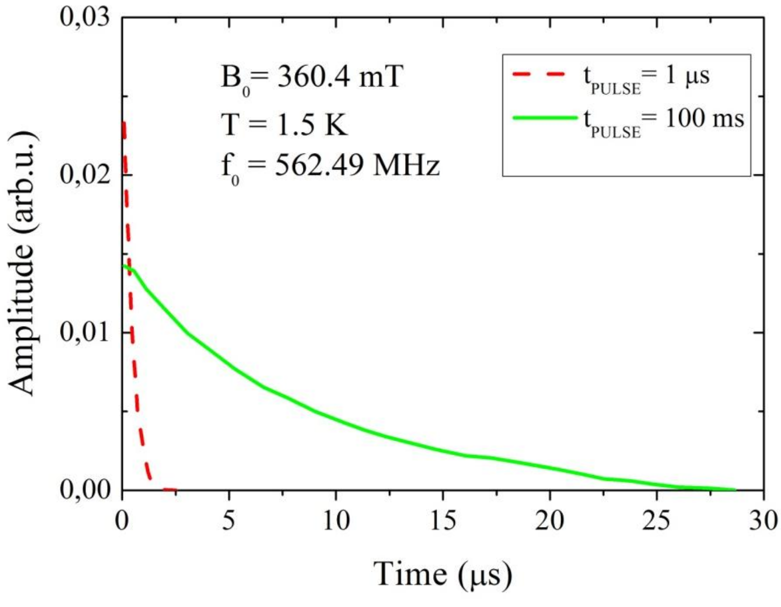

Figure 3. The FID signal $CsMnF_3$ amplitude in the second sample in two RF pumping regimes.

It is well seen in figure 3 that in both cases the FID time is well described by the exponential function. The FID time is about 0.5 µs in normal state and about 9.5 µs in magnon BEC state. The FID signal duration in BEC state is more than an order of magnitude longer than in normal pumped state for the second (more homogeneous) $CsMnF_3$ sample. Obtained results are in a full agreement with the ones observed in superfluid ^{3}He-A in aerogel (figure 2).

3. Conclusions

We have investigated the duration of the FID signal in two samples of easy-plane antiferromagnets $CsMnF_3$. In addition to our previous investigations of the signal amplitude by means of cw NMR and pulse NMR these results also confirm the formation of magnon BEC in antiferromagnet $CsMnF_3$. It is found out that the quality of samples plays significant role in BEC experiments: the long-lived free induction decay signal in the coherent precession state is observed only for higher quality sample.

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