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Atomic type magnon Bose-Einstein condensation in antiferromagnet.

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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}He-B. The same phenomena should exist in solid magnetic systems. We describe here the first observation of magnon BEC in solid easy plain antiferromagnet $CsMnF_3$. We have observed magnon BEC on a mode of coupled Nuclear-Electron precession. The dynamical properties of this mode have many similarities with NMR of superfluid ^{3}He-A. The frequency changes with deflection of nuclear magnetization. Furthermore, the involvement of electron ordered subsystem gives the magnon-magnon interaction, spin waves and spin supercurrent, while the nuclear subsystem gives the relatively long time of relaxation.

The conventional magnon BEC, the phase-coherent precession of magnetization was discovered in a first time in superfluid ^{3}He-B in 1984 [1]. It manifests itself by a domain with a fully phase-coherent precession of magnetization, known as the Homogeneously Precessing Domain (HPD). It exhibits all the properties of spin superfluidity: the supercurrent transports of magnetization and phase-slip processes at the critical current [2]; spin current Josephson effect [3]; spin current vortex [4] ets. The comprehensive review one can found in [5] and recent one in [6, 7]. The conventional magnon BEC has been also found in yttrium-iron garnet [8] for the magnons with non zero wave vector.

For a last 25 years there was found 5 different magnon BEC states in superfluid ^{3}He [6]. Particularly, the magnon BEC was observed and confirmed in superfluid ^{3}He-A immersed in aerogel squeezed along the magnetic field [9, 10]. In this case the aerogel reorients the orbital momentum of ^{3}He-A along the field [11, 12]. In this configuration the interaction of magnon is repulsive [13] the coherent precession is stable and the magnon BEC is possible. The same phenomena should exist in solid magnetic systems. Indeed, it was not observed up today. In this article we report the first observation of magnon BEC in solid easy plain antiferromagnet $CsMnF_3$. The preliminary results were published in [14]. We have observed this phenomena on a mode of coupled Nuclear-Electron precession, which shows the dynamical frequency shift (pulling). Magnetic systems with pulling were studied intensively in 70th of previous century [15]. This phenomenon takes place in the case when the frequencies of NMR and electronic magnetic resonance are comparable. The typical system with pulling is the easy plain antiferromagnets with ions of Mn. The NMR frequency of Mn^{55} in hyperfine field is very high, about 600 MHz, and the antiferromagnetic resonance frequency in easy plain and cubic antiferromagnets can be very low. Due to coupling throw the hyperfine field, the two modes of resonance appear, low frequency quasi NMR mode (NEMR) and high frequency quasi antiferromagnetic resonance mode (ENMR). Owing the couple precession, the properties of magnetic subsystems changes significantly. The hyperfine gap appears in a spectrum of antiferromagnetic spin waves. The quasinuclear spin waves appears, with the antiferromagnetic length of coherence. Other words, the nuclear magnetic system get some properties of magnetically ordered system.

The density of non-equilibrium magnons depends from the angle of magnetization deflection β:

$$N = \frac{m - m_z}{\hbar} = \frac{\chi H}{\hbar\gamma}(1 - \cos\beta)\ . \tag{1}$$

The NMR frequency for ^{3}He-A in aerogel dependence on the magnon density (for $\Omega_L << \omega_L$):

$$\Omega = \omega_L - \frac{\Omega_L^2}{2\omega_L}\cos\beta, \tag{2}$$

where ω_L and Ω_L are Larmore and Leggett frequencies and β is the angle of magnetization deflection. The frequency dependence for NEMR mode in $CsMnF_3$ is very similar:

$$\Omega = \omega_n - \omega_p\frac{m_z}{m_0} = \omega_n - \omega_p\cos\beta, \tag{3}$$

where ω_n and ω_p are the non-shifted NMR frequency in hyperfine field and pulling, m_0 is the equilibrium nuclear magnetization and m_z its projection on a hyperfine field. It means that the both systems may have a very similar properties and fulfilled the condition of dynamic stability of coherent precession, reads [6, 7]:

$$\frac{\partial\Omega}{\partial\cos\beta} < 0, \tag{4}$$

Owing this similarity we have suggest to try to observe magnon BEC on a quasi NMR mode in $CsMnF_3$ [16]

Indeed, there is one important question. The nuclear subsystem in $CsMnF_3$ is paramagnetic and after deflection should be dephased due to inhomogeneity of a superfine field. Furthermore, it should follows to Bloch equation. It means, that the nuclear system should thermalize for a time T_2 and the transverse component should vanish. In our experiments we have found that it is not a case! In CW NMR experiments the deflected nuclear magnetization precess homogeneously with the constant temperature and the NMR line does not saturated. The explanation can be found in the book [17]. This phenomena was also considered in[18]. There was considered two different scale for inhomogeneity. The microinhomogeneous broadening for a distance smaller then the length of coherence of Suhl-Nakamura interaction (about 10^4 of the lattice size), and the macroscopic broadening for a longer distances. The microscopic broadening can be suppressed in the case, when pulling is much bigger then a broadening. As a result the antiferromagnetic magnetization precess coherently at a short distance and force the nuclear subsystem precess coherently. For the longer distance it is not the case. It means that the nuclear subsystem shows the properties of ordered one, like the superfluid ^{3}He-A. The coherence length is even comparable. The magnetization follows the Landau-Lifshits scenario. It deflects but the module of magnetization does not change.

We performed the BEC formation experiments in $CsMnF_3$ similar to one in ^{3}He-A described in [9, 10]. The frequency shift of Mn^{55} NMR depends from an external magnetic field H in a easy plain of antiferromagnet[18]:

$$\omega_p = \omega_n\frac{H_E H_n}{2H^2}\frac{m_0}{M_0}, \tag{5}$$

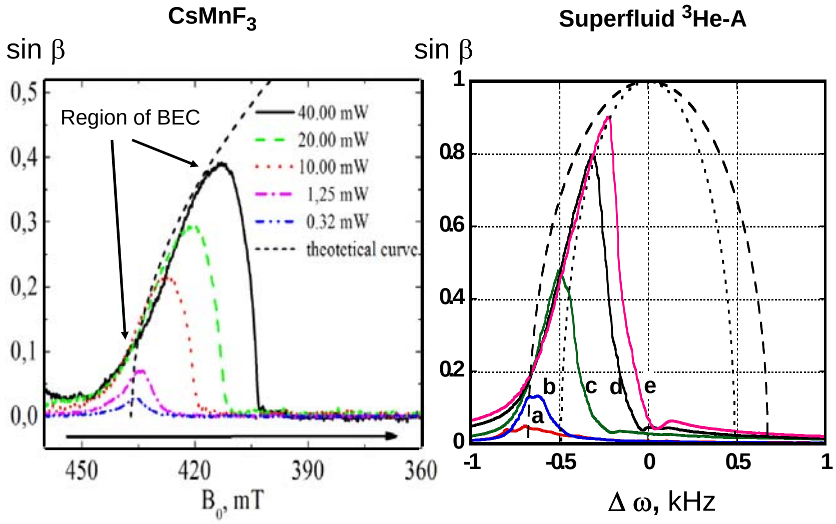

Figure 1. On a left side the amplitude of CW NMR signal from $CsMnF_3$ as a function of external magnetic field for different energy of excitation. The dashed line is a theoretical curve follows the equations (6,7). On the right side shown the similar results measured in ^{3}He-A in aerogel

where H_E and H_n are exchange and hyperfine fields on an electron sublattice and m_0 and M_0 are the magnetization of the nuclear and electron sublattices. Our experiments were done at the temperature of 1.5 K at a frequency of 566 MHz. The line of CW NMR at small RF excitation corresponds to 437 mT field. The broadening of the line is about 2 MHz. If we increase the excitation and sweep down the field, we can see enormous growing of the signal. As we know from the experiments with superfluid ^{3}He-A, this signal corresponds to formation of a state with coherent precession. That is the state with Bose - Einstein condensation of magnons. For the case of CW NMR its manifest itself by a coherent precession of the magnetization on the frequency of RF pumping, that is when the frequency of resonance adjusted to a RF frequency. For this the angle of magnetization deflection should be:

$$\cos\beta = \frac{\omega_n - \Omega}{\omega_p}, \tag{6}$$

If all the magnetization deflected on the angle β, and precess homogeneously then the amplitude of the signal should be:

$$A = A_0 \sin\beta, \tag{7}$$

We have calibrated the amplitude of the signal by the amplitude of induction after a short NMR pulse. In Fig.1 we can see that the signal corresponds to a homogeneous precession of all magnetization deflected on an angle β up to the angle of 23^0 for a highest excitation. At further sweep down of the fields the processes of magnetic relaxation increases. The RF field can not more compensate the energy loses at some part of the sample. That is why the signal starts to decrease. The deviation of the signal from the theoretical curve of coherent precession appears at a smaller angles if the excitation power is smaller. For the sweep back the coherent precession state creates at higher fields. As we know from an experiments with ^{3}He-A, this process is reversible with a hysteresis. All this effects corresponds very well to one we have observed in superfluid ^{3}He-A in aerogel. The results of these experiments are shown on a right side of Fig.1.

Finally, we have observed a coherent precession of a magnetization of all the sample. It is not a brut force coherence established by the RF pumping. The amplitude of RF field is only about 5 kHz, while the inhomogeneous broadening of the NMR line at small excitation is about 2 MHz. The external RF field gives the frequency of rotating frame in which the minimum of energy corresponds to a given angle of magnetization deflection (density of magnons). The magnon-magnon interaction and spin supercurrent establishing the coherent precession on a dimensions of all the sample. All this phenomena for superfluid ^{3}He-A well explained in [9, 10] and reviews [6, 7]

It is important to point out that a similar experiments was described in Ref.[19]. The qualitative behavior of the signal was very similar. Indeed, it is difficult to figure out all parameters of the experiments, described there. To explain those results authors was used the scenario of saturation (heating) of the nuclear subsystem under a RF pumping. This scenario strongly contradicts to our experiments, described here and the other our experiments, which are under preparation for the next publication.

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