# Observation of Spontaneous Coherence in Bose-Einstein Condensate of Magnons

V. E. Demidov,[1,*] O. Dzyapko,[1] S. O. Demokritov,[1] G. A. Melkov,[2] and A. N. Slavin[3]
[1]*Institute for Applied Physics and Center for Nonlinear Science, University of Muenster, Corrensstrasse 2-4, 48149 Muenster, Germany*
[2]*Department of Radiophysics, National Taras Schevchenko University of Kiev, Kiev, Ukraine*
[3]*Department of Physics, Oakland University, Rochester, Michigan, USA*
(Received 6 September 2007; published 31 January 2008)

The room-temperature dynamics of a magnon gas driven by short microwave pumping pulses is studied. An overpopulation of the lowest energy level of the system following the pumping is observed. Using the sensitivity of the Brillouin light scattering technique to the coherence degree of the scattering magnons we demonstrate the spontaneous emergence of coherence of the magnons at the lowest level, if their density exceeds a critical value. This finding is clear proof of the quantum nature of the observed phenomenon and direct evidence of Bose-Einstein condensation of magnons at room temperature.

DOI: 10.1103/PhysRevLett.100.047205 PACS numbers: 75.30.Ds, 03.75.Nt

The considerable continuous interest in Bose-Einstein condensation (BEC) is related to the fact that it is one of the few phenomena that manifests itself on the macroscopic scale. The phenomenon occurs when a macroscopic number of particles with integer spin (bosons) occupies the lowest available quantum level and these particles are described by the same wave function. For atomic gases this means that the atomic wave function can be directly visualized through the interference of two condensates [1], which gives a possibility to observe in direct experiments such quantum phenomena as tunneling and the resulting Josephson effect between two phase-coherent wave functions [2]. In order to achieve BEC in atomic gases extremely low temperatures in the nK region are needed [3]. Since the temperature of the Bose-Einstein transition is proportional to $n^{2/3}/m$, where $n$ is the density of the particles and $m$ is their mass, this transition temperature can be significantly increased in dense gases of light quasiparticles in solids. Although the observations of BEC of different quasiparticles (excitons, biexcitons, polaritons, phonons, and magnons) [4–16] were reported in the last few decades, all these observations were done at cryogenic temperatures. Only recently it has been shown that in a gas of magnons continuously driven by microwave parametric pumping, magnons enormously overpopulate the lowest energy level even at room temperature [17]. This observation has been associated with the Bose-Einstein condensation of magnons. Nevertheless, the question of spontaneous coherence of the magnons overpopulating the lowest level was not addressed in this early study. Since the spontaneous emergence of coherence is an obligatory manifestation of BEC [18], the existence of room-temperature BEC of magnons was not fully proven up to now. In this Letter we present experimental results clearly demonstrating the creation of a coherent magnon condensate from incoherent magnons with increasing magnon density. This finding brings the first direct evidence of room-temperature Bose-Einstein condensation of quasiparticles.

In our experiments we used monocrystalline epitaxial films of yttrium-iron garnet (YIG) with the thickness of 5 $\mu$m. These films are characterized by very small magnetic losses providing a long magnon lifetime. For YIG the magnon lifetime appears to be much longer than the characteristic time of magnon-magnon interaction [19]. This relation is a necessary precondition for the Bose-Einstein condensation in a gas of quasiparticles whose number is not exactly conserved [20]. The samples were cut from YIG films in the form of stripes with lateral dimensions of 1.5 mm by 30 mm. The stripes were placed into a uniform static magnetic field of $H = 700$–$2000$ Oe oriented in the plane of the stripe along its axis. The injection of magnons was performed by means of parallel parametric pumping with a frequency of 8.1 GHz. The pumping field was created using a wire resonator with the diameter of 25 $\mu$m attached to the surface of the sample perpendicularly to its axis. Further details on the pumping process can be found in [17,19,21]. The principal difference of the pumping technique used in this work from that applied in [17,19,21] is that, instead of continuous driving of the magnon gas, magnons were injected using short pumping pulses with the duration of 30 ns, which is smaller than the characteristic thermalization time in the magnon gas [19]. Consequently, the processes of magnon redistribution over the spectrum and the formation of BEC were studied in a magnon gas, which was free from any influence of the external driving force.

Figure 1(a) shows the low-frequency part of the dispersion spectrum of magnons in a YIG film calculated for the static field of $H = 1000$ Oe and the film thickness of 5 $\mu$m. Two solid lines show the curves corresponding to magnons with the wave vector $\mathbf{k}$ oriented perpendicularly and parallel to the direction of the static field $\mathbf{H}$, as indicated. The allowed magnon frequencies for intermediate angles between $\mathbf{k}$ and $\mathbf{H}$ occupy the manifold between the two shown curves. As seen in Fig. 1(a), the magnon state with the lowest energy corresponds to a nonzero frequency

 

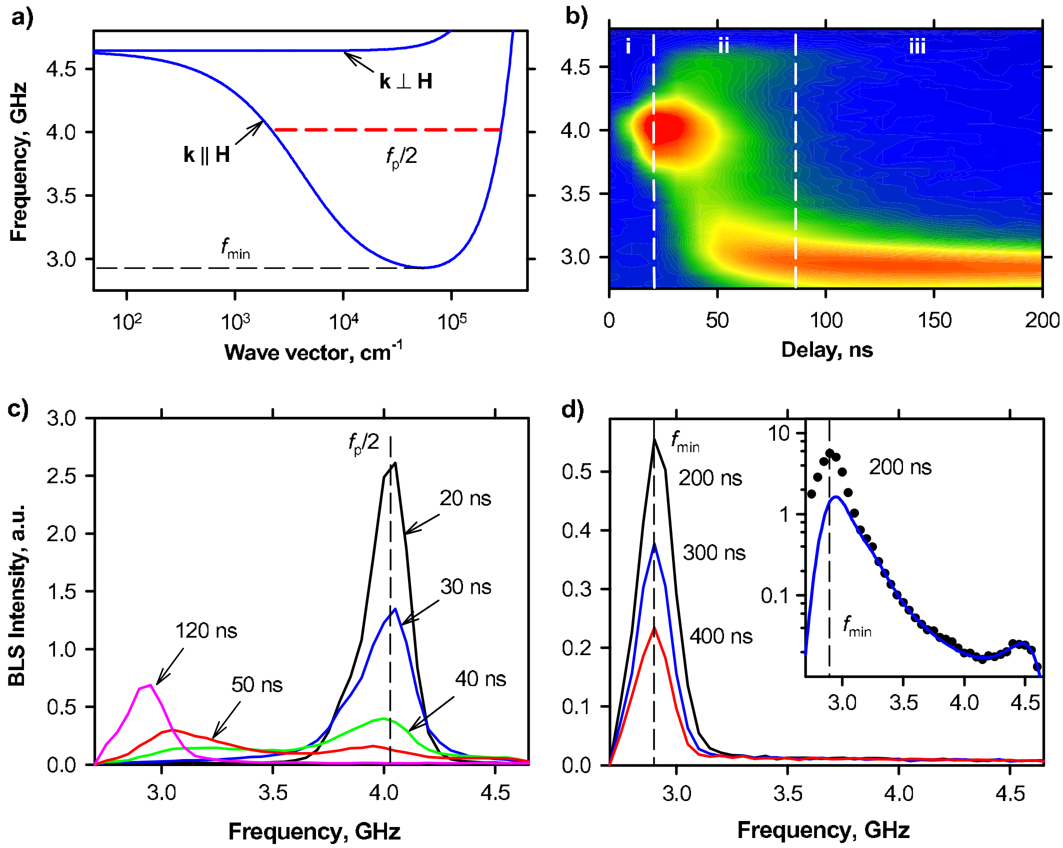


FIG. 1 (color online). (a) Low-frequency part of the dispersion spectrum of magnons in YIG films with the thickness of 5 $\mu$m placed into the in-plane static magnetic field of $H = 1000$ Oe. The solid lines correspond to the limiting cases of magnons with the wave vectors **k** oriented perpendicularly and parallel to the static field **H**. The magnon states for intermediate angles occupy the manifold between the curves. $f_p/2$—frequency of the primary magnons injected by the parametric pumping. $f_{\min}$—the lowest magnon frequency. (b)–(d) Redistribution of magnons injected by a short-pulse parametric pumping with the peak power of $P = 3$ W over frequencies. (b) Color representation of the Brillouin light scattering (BLS) intensity portraying the spectral density of magnons as a function of the frequency and the delay time with respect to the start of the pumping pulse. (c)–(d) BLS spectra for different delays, as indicated. The inset in (d) shows an example of the fit of the measured magnon distributions based on Bose-Einstein statistics.

$f_{\min}$ and a nonzero wave vector aligned parallel to the static field. Note that the change of the static magnetic field shifts $f_{\min}$, whereas by changing the film thickness one varies the corresponding wave vector.

Primary magnons at a frequency 4.05 GHz, which is one-half of the frequency of the electromagnetic pumping field $f_p = 8.1$ GHz, are injected into the magnon gas by means of a short pumping pulse. In this way a nonequilibrium magnon gas with a high density of magnons at $f_p/2$ was created. The evolution of the magnon distribution during and after the pumping pulse was investigated by means of the time-resolved inelastic Brillouin light scattering technique [22]. BLS is a very powerful technique for addressing this problem, since the BLS intensity at a given frequency is determined by the magnon population at this frequency. The injection and relaxation of magnons is illustrated in Fig. 1(b), where the BLS intensity, recorded for the static magnetic field of $H = 1000$ Oe and the pumping power of $P = 3$ W, is shown as a function of the delay time with respect to the start of the pumping pulse, $\tau$, and the magnon frequency. In Fig. 1(b) one can distinguish three stages of the process: (i) the pumping injects a large number of primary magnons at the frequency $f_p/2$, (ii) the primary magnons quickly relax and spread over the whole spectrum, and (iii) the magnons accumulate at the frequency of the lowest state $f_{\min}$. The evolution of magnon population in different parts of the magnon spectrum is illustrated in detail in Figs. 1(c) and 1(d), where BLS spectra at different delay times are shown. As seen from Fig. 1(c), as the pumping is switched on, a strong peak appears at the frequency $f_p/2$ corresponding to the primary injected magnons ($\tau = 20$ ns). Then the magnon population quickly spreads ($\tau = 30$–40 ns) and shifts toward the minimum magnon frequency $f_{\min} = 2.9$ GHz ($\tau = 50$–120 ns). Finally, at delays of about $\tau = 200$ ns a strong and narrow peak close to $f_{\min}$ is formed [see Fig. 1(d)]. Note that a similar relaxation process was observed in [19] under conditions of continuous magnon injection by the parametric pumping. The present results obtained for the short-pulse injection demonstrate that the formation of a quasiequilibrium state with a nonzero chemical potential is due to the internal interactions inside the gas rather than being caused by the external driving force.

In order to prove that the thermalization in the magnon gas is achieved under conditions of short-pulse injection, we performed a quantitative analysis of the measured magnon distributions. As an example of this analysis, the experimental data for the maximum used pumping power $P = 6$ W, where all the main features of the distributions can be clearly seen, are shown in the inset in Fig. 1(d) together with results of the fit using the Bose-Einstein distribution function similar to that used in [17,21]. The shown data were taken at the time delay corresponding to the end of the magnon redistribution process. One can see from Fig. 1(d) that Bose-Einstein statistics nicely describes the magnon distribution in the entire frequency range except the point $f_{\min}$ where a narrow peak (note the logarithmic scale) is created indicating the existence of a magnon condensate [17]. Similar good agreement with Bose-Einstein statistics was also obtained for smaller pumping powers.

For delay times above 200 ns the peak in the magnon population at $f_{\min}$ slowly decreases its intensity due to the weak interaction of the magnon gas with the lattice, but does not change its form [see Fig. 1(d)]. After a sufficiently long time, exponential decay of the magnon population determined by the magnon lifetime brings the magnon gas close to the state of a true thermal equilibrium with the lattice, characterized by the zero chemical potential [17]. The decay of the magnon population at $f_{\min}$ is further illustrated by Fig. 2, where the temporal dependences of the BLS intensity are shown for different pumping powers corresponding to different numbers of magnons injected during the pumping pulse. The data are shown in the logarithmic scale and are normalized at $\tau = 1000$ ns. The dashed lines represent the results of the best fit of the experimental points by the exponential decay function. Since the formation of the overpopulated state at $f_{\min}$ happens faster for higher pumping powers, the data for smaller powers start at larger delays.

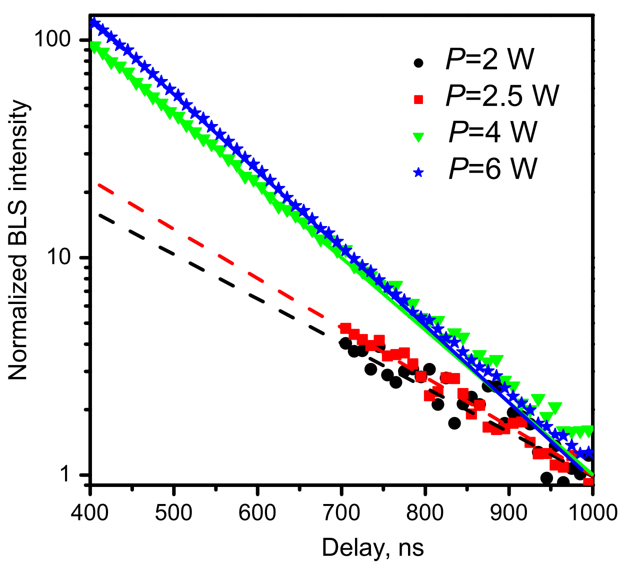


FIG. 2 (color online). Decay of the BLS intensity at the lowest magnon frequency $f_{\min}$ after the formation of the overpopulated state is finished for different values of the pumping power, as indicated. Lines—best fit of the experimental points by the exponential decay function.

Surprisingly, the decay rate of the BLS intensity for the magnons accumulated at $f_{\min}$ noticeably depends on the pumping power. To understand this effect one should consider the relation between the BLS intensity and the magnon density in more detail. The BLS intensity is proportional to the temporal average of the square of the electric field of the scattered light, $E$ (see, e.g., [23]). In the case of many scatterers the total scattering intensity is proportional to $\langle(\sum E_i)^2\rangle$, where $E_i$ is the scattered field of the $i$th scatterer. It is obvious that the total scattering intensity of incoherent scatterers is proportional to $\langle\sum E_i{}^2\rangle$, i.e., to the number of the scatterers, $N$, due to zeroing of all cross correlators of scattered fields: $\langle E_i E_j\rangle = 0$, $i \neq j$. On the contrary, in the case of in-phase coherent scatterers with equal scattering amplitudes the above cross correlators are not zero $\langle E_i E_j\rangle = \langle E_i^2\rangle$ and the scattering intensity is proportional to $N^2$. Thus, comparing the temporal dependence of the BLS intensity and that of the number of scattering magnons one can detect the magnon coherence. In fact, if the magnon density decays $\propto \exp(-\alpha t)$, where $\alpha$ is the decay rate determined by the magnon lifetime, the BLS intensity in the case of incoherent magnons should follow the same function. However, for the case of coherent magnons the BLS intensity should follow $[\exp(-\alpha t)]^2 = \exp(-2\alpha t)$. In other words, for the same decay of the magnon density, the BLS intensity decays twice as fast for coherent magnons than that for incoherent magnons. The experimentally measured decay rate of the BLS intensity at $f_{\min}$ as a function of the pumping power $P$ is presented in Fig. 3. It is clearly seen from Fig. 3 that the decay rate exhibits a stepwise doubling of its value with pumping power increasing from 2.5 to 4 W. Based on the above analysis one has to conclude that for pumping powers $P \geq 2.5$ W the magnons at $f_{\min}$ start to form a coherent Bose-Einstein condensate and the contribution of the condensate to BLS dominates for $P \geq 4$ W. In this way our experimental data clearly show that the magnons accumulated at the lowest energy level are coherent at high enough pumping powers, and this coherence emerges spontaneously if the density of magnons exceeds a certain critical value. This finding gives the direct experimental evidence of the BEC transition in a magnon gas at room temperature.

The BEC transition and emergence of coherence in the magnon gas should also lead to an abrupt increase of the BLS intensity at $f_{\min}$, since $N^2 \gg N$. In order to demonstrate this fact the maximum value of the BLS intensity at

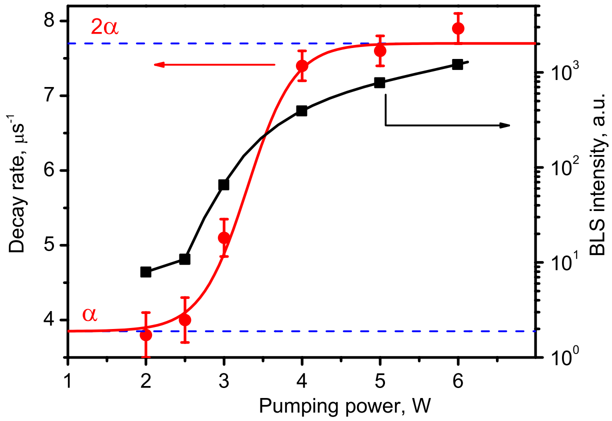


FIG. 3 (color online). Circles—dependence of the measured decay rate of the BLS intensity at the lowest magnon frequency $f_{\min}$ on the pumping power. Corresponding line—fit of the experimental points with the sigmoid function. Squares—dependence of the maximum detected BLS intensity at the frequency $f_{\min}$ on the pumping power. Corresponding line—guide for the eye.

$f_{\min}$ versus pumping power $P$ is plotted in Fig. 3 as well. One should pay attention to the logarithmic scale for the $y$ axis and to the fact that experimental error for this curve is smaller than the size of the tokens. As seen from Fig. 3, the dependence demonstrates a clear kink at $P = 2.5$ W, marking the onset of the observed BEC transition and corroborating the conclusion of the above paragraph. Although the quantitative relation between the measured BLS intensity and the true order parameter for the transition (density of the condensate) is not clear at the moment, one can conclude that a phase transition characterized by a continuous change of the order parameter at the transition point is observed. Such a behavior is typical, e.g., for the superfluid transition in liquid helium or superconductivity in metals.

An alternative, albeit more speculative, explanation of the observed doubling of the BLS decay rate could be the formation of a standing bright soliton of the BEC of magnons. It is well known (see, e.g., [24,25]), that the measured dissipative decay rate of the soliton amplitude is twice larger than that of a linear pulse due to simultaneous broadening of the solitons. We would like to emphasize, however, that mutual phase locking of the magnons is a precondition for formation of such a soliton. Thus, the realization of the soliton scenario would also be an evidence of the coherence in the magnon gas.

In conclusion, we have studied a room-temperature magnon gas driven from its true thermal equilibrium by short pulsed magnon injection. We show that magnons injected into the gas at a frequency far from the lowest magnon frequency quickly relax and redistribute over the spectrum in such a way that a new quasiequilibrium state of the magnon gas is formed. This state is free from any influence of the external driving force and is mainly governed by the internal interactions between magnons. The state is characterized by the overpopulation of the magnon spectrum close to the lowest energy level. We found that starting from a certain critical density, the accumulated magnons become coherent. The obtained results are in accordance with the concept of Bose-Einstein condensation and give the first undoubted experimental evidence of the existence of a Bose-Einstein condensate at room temperature.

Support by the Deutsche Forschungsgemeinschaft, by the U.S. Army Research Office (MURI Grant No. W911NF-04-1-0247), and by the Science & Technology Center of Ukraine is gratefully acknowledged.

*Corresponding author.
demidov@uni-muenster.de

[1] M. R. Andrews, C. G. Townsend, H.-J. Miesner, D. S. Durfee, D. M. Kurn, and W. Ketterle, Science **275**, 637 (1997).
[2] M. Albiez, R. Gati, J. Foiling, S. Hunsmann, M. Cristiani, and M. K. Oberthaler, Phys. Rev. Lett. **95**, 010402 (2005).
[3] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, Science **269**, 198 (1995).
[4] Y. D. Kalafati and V. L. Safonov, Sov. Phys. JETP **68**, 1162 (1989).
[5] T. Fukuzawa, E. E. Mendez, and J. M. Hong, Phys. Rev. Lett. **64**, 3066 (1990).
[6] Y. Yamamoto, Nature (London) **405**, 629 (2000).
[7] T. Nikuni, M. Oshikawa, A. Oosawa, and H. Tanaka, Phys. Rev. Lett. **84**, 5868 (2000).
[8] R. Coldea *et al.*, Phys. Rev. Lett. **88**, 137203 (2002).
[9] Ch. Riiegg *et al.*, Nature (London) **423**, 62 (2003).
[10] L. V. Butov, J. Phys. Condens. Matter **16**, R1577 (2004).
[11] J. P. Eisenstein and A. H. MacDonald, Nature (London) **432**, 691 (2004).
[12] O. V. Misochko, M. Hase, K. Ishioka, and M. Kitajima, Phys. Lett. A **321**, 381 (2004).
[13] M. Jaime *et al.*, Phys. Rev. Lett. **93**, 087203 (2004).
[14] T. Radu *et al.*, Phys. Rev. Lett. **95**, 127202 (2005).
[15] J. Kasprzak *et al.*, Nature (London) **443**, 409 (2006).
[16] R. Balili, V. Hartwell, D. Snoke, L. Pfeiffer, and K. West, Science **316**, 1007 (2007).
[17] S. O. Demokritov *et al.*, Nature (London) **443**, 430 (2006).
[18] D. Snoke, Nature (London) **443**, 403 (2006).
[19] V. E. Demidov, O. Dzyapko, S. O. Demokritov, G. A. Melkov, and A. N. Slavin, Phys. Rev. Lett. **99**, 037205 (2007).
[20] D. W. Snoke and J. P. Wolfe, Phys. Rev. B **39**, 4030 (1989).
[21] O. Dzyapko, V. E. Demidov, S. O. Demokritov, G. A. Melkov, and A. N. Slavin, New J. Phys. **9**, 64 (2007).
[22] S. O. Demokritov, B. Hillebrands, and A. N. Slavin, Phys. Rep. **348**, 441 (2001).
[23] M. Cottam and D. Lockwood, *Light Scattering in Magnetic Solids* (Wiley, New York, 1986).
[24] Hua Xia, P. Kabos, C. E. Patton, and H. E. Ensle, Phys. Rev. B **55**, 15 018 (1997).
[25] Lei Wu, Jie-Fang Zhang, and Lu Li, New J. Phys. **9**, 69 (2007).