Proceedings of the European Conference Physics of Magnetism 2011 (PM'11), Poznań, June 27–July 1, 2011

Magnetic Interaction by Exchange of Field Bosons

U. Köbler[a] and A. Hoser[b,*]

[a]Forschungszentrum Jülich, Institut für Festkörperforschung, 52425 Jülich, Germany

[b]Helmholtz-Zentrum Berlin, 14109 Berlin, Germany

It is shown that atomistic spin wave theory gives no correct account of the temperature dependence of the magnetic order parameter. The experimentally observed universal temperature dependence can be explained only by a field theory of magnetism. This means that instead by interacting spins (magnons) the dynamics is controlled by a boson field. The field quanta can be supposed to be magnetic density waves with dispersions that are simple power function of wave vector. This results in the observed universality. In three dimensions the field quanta have no mass and linear dispersion and cannot be observed using inelastic neutron scattering. Experiments on standing magnetic waves in thin ferromagnetic films provide direct information on the dispersion of the field quanta. A careful analysis of the available experimental data indicates that the dispersion of the field bosons is $\sim q$, $\sim q^2$, and $\sim q^{3/2}$ in three, two, and one dimensions.

PACS: 75.10.−b, 75.30.Ds

1. Introduction

Spin wave theory of magnetism [1] is a typical atomistic (or local) theory. It explains long range magnetic order by the Heisenberg interactions between neighbouring spins [2]. The excitations of this interaction are the well known magnons. For interactions limited to nearest magnetic neighbours magnon dispersion of antiferromagnets is given by pure sine function of wave vector but for ferromagnets by sine function squared. These predictions are confirmed essentially using inelastic neutron scattering. As a consequence, the order parameters of ferromagnets and antiferromagnets should exhibit different temperature dependence, if magnons are the relevant excitations. A rigorous and convincing experimental test whether the temperature dependence of the order parameter can be explained by the observed magnon dispersions was, however, never delivered. This has to do with the non-analytical structure of spin wave theory that makes power series expansions for the thermal decrease of the order parameter with respect to saturation at $T = 0$ [3]. Quantitative experimental determination of the pre-factors and exponents of the first few power terms is practically not possible in view of the inevitable experimental errors.

There are several qualitative observations casting severe doubts on the reliability of spin wave theory: 1. magnons commonly persist above the magnetic ordering temperature, 2. the critical behaviour shows universality, i.e. is identical for ferromagnets and antiferromagnets and 3. nearest neighbour interactions frequently are unreasonably too large compared to the ordering temperature.

Recent experimental studies have shown that universality is not limited to the critical range but holds for all lower temperatures as well — in disagreement with spin wave theory [4, 5]. In systematic investigations of many ordered magnets six universality classes could be identified empirically. The universality classes are represented by power functions of absolute temperature that describe the thermal decrease of the order parameter with respect to $T = 0$, commonly up to $\approx 0.85T_c$ (see Table).

Universality means a dynamic behaviour that is independent of atomistic structures such as spin structure and unit cell symmetry. Quite generally, universality can be explained by field theories only [6]. Let us note that power functions of absolute temperature result when the dispersion of the relevant excitations is a simple power function of wave vector. Only freely propagating field particles have such dispersion relations. In other words, in order to understand the exponents of Table we need a field theory of magnetism instead of spin wave theory. The big problem of a future field theory of magnetism is to specify the field quanta precisely. Table indicates that the field quanta are different in magnets with integer and half-integer spin. Since spins are the sources of the field this indicates that integer and half-integer spins generate different types of field quanta. This is different for the electromagnetic radiation field where electrons with $S = 1/2$ are the only sources of the field quanta, the photons.

An important step towards a field theory of magnetism was achieved by development of renormalization group

* corresponding author; e-mail: hoser@helmholtz-berlin.de

TABLE

Empirical universal power functions describing thermal decrease of the magnetic order parameter with respect to saturation at $T = 0$.

Dimensionality	Integer spin	Half-integer spin
3D	$T^{9/2}$	T^2
2D	T^2	$T^{3/2}$
1D	T^3	$T^{5/2}$

(RG) theory by Wilson and Kogut [7]. As Wilson and Kogut could show, on approaching the critical temperature from the paramagnetic side a new dynamic symmetry develops in such a way that the magnetic system assumes properties as a continuum. Spins and interaction between spins are no longer important for the dynamics. It is evident that instead of atomistic interactions between spins, i.e. magnons a completely different second type of excitation must be responsible for the dynamics of the ordered magnetic continuum.

According to quite general theoretical arguments due to Goldstone, Salam and Weinberg (GSW) translational invariance of the magnetic continuum gives rise to massless particles with linear dispersion [8]. In the following we will call the excitations of the continuous — or infinite — magnet GSW bosons. Since GSW bosons are the particles of the continuous translational symmetry, their momentum is a conserved quantity. In contrast to magnons they propagate ballistic. GSW bosons can be supposed to be magnetic density wave. Condition for GSW bosons to develop is a high magnetic polarizability. This is realized essentially in the ordered state, i.e. in the state with broken symmetry. Using the wave picture it is immediately clear that GSW bosons carry no magnetic moment in harmonic approximation. Since GSW bosons have neither mass nor magnetic moment, they cannot be observed using inelastic neutron scattering.

The magnetic density waves should not be confused with spin waves. They exist in addition to spin waves and have dispersions different from magnons. Let us note that the dispersion relation is defined by the propagation process of the particle. GSW bosons propagate ballistic while magnons propagate from spin to spin. Realistically GSW bosons must be coupled weakly to the atomistic background and their mean free path is large but not infinite. GSW bosons therefore average over all atomistic details. This is the origin of the observed universality. Magnons are scattered at any lattice defect and have a short mean free path.

As a consequence, there are strong arguments that there are two excitation spectra in ordered magnets: magnons and GSW bosons. We then have to ask: how do the two excitation spectra determine the dynamics. At this point a very important issue of RG theory becomes decisive: the principle of relevance. Due to the different symmetries of GSW bosons and magnons (global and local) they are never relevant at the same time but define the dynamics alternatively. In other words, the two symmetries do not mix meaning that there is either universality or not. Change of dynamics from atomistic interactions to the excitations of the continuum is called a crossover. At the crossover the interaction energy between spins is transferred to the field. The Heisenberg interactions then are responsible only for spin structure and magnon dispersion but not for the dynamics. Quite generally, the dynamics is defined by the excitations with the lowest dispersion energy. In nearly all ordered magnets these are the GSW bosons.

2. Experimental verification of GSW bosons

Up to now universality is the strongest indication for the existence of GSW bosons. Direct experimental evidence of GSW bosons seems to be possible by experiments on standing magnetic waves in thin ferromagnetic films. The standing waves are resonating GSW boson states and not magnons. The main argument for this is that the observed dispersion relations are in disagreement with spin wave theory. Moreover, magnons are too much scattered on lattice defects and do not propagate over a distance of several 100 nm in structurally disturbed films.

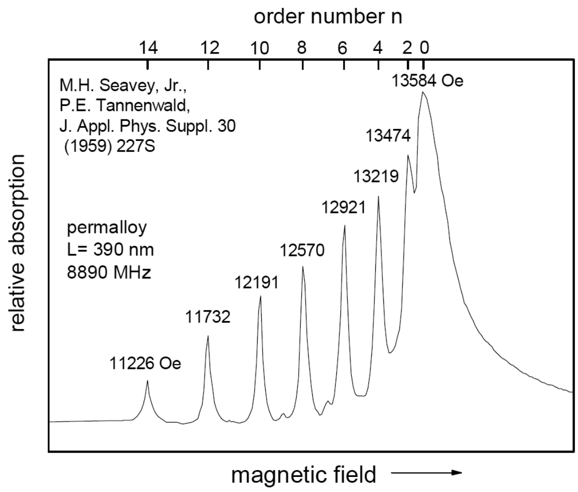

Fig. 1. Typical absorption spectrum of standing magnetic waves in thin ferromagnetic films. Strong peak at the right hand side is uniform precession mode. Lines at smaller fields are standing waves with order numbers given on top.

Figure 1 displays a typical absorption spectrum. The absorption line at the extreme right hand side is the uniform precession mode characterized by wave vector $q = 0$. The resonances at lower field values are standing waves with wavelength $\lambda = 2L/n$, where L is the thickness of the film and n — an integer.

Careful analyses of the available experimental data [9, 10] reveal dispersion relations as $\sim q$, $\sim q^2$, and $\sim q^{3/2}$ for the standing waves of various films with different thickness and quality. Let us note that strain in

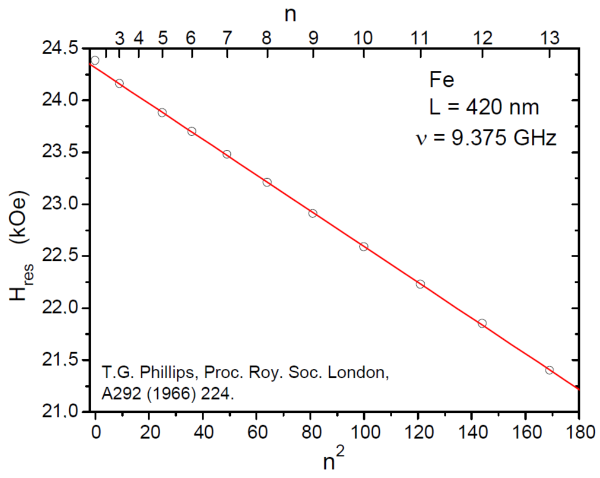

Fig. 2. Quadratic dispersion of standing wave modes in an iron film with thickness $L = 420$ nm indicating two-dimensional (2D) symmetry.

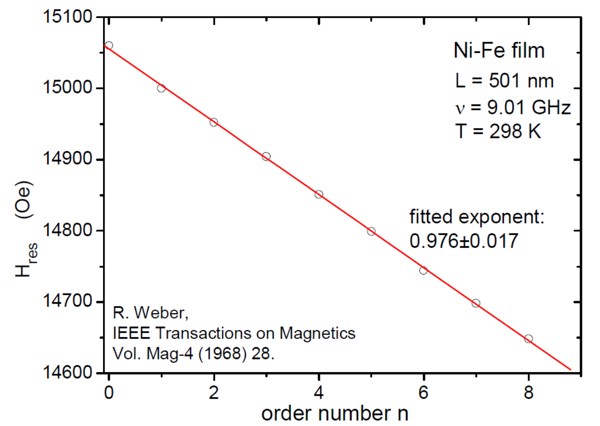

Fig. 3. Linear dispersion of standing wave modes of a thick permalloy film [10] indicating 3D symmetry.

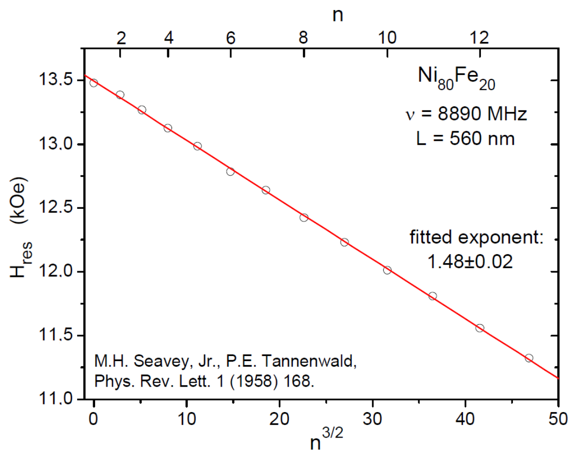

Fig. 4. Dispersion $\sim q^{3/2}$ is indicative of 1D films.

the film can reduce the dimensionality. For films with dispersion relation $\sim q^2$ (see Fig. 2) it was observed that the temperature dependence of the standing wave modes is $\sim T^{3/2}$ [11]. According to Table these films are two--dimensional (2D). Let us note that the here used dimensionality is a property of the boson field and is different from atomistic definitions.

In relatively thick films linear dispersion is observed (see Fig. 3). These films have to be identified as 3D. In strongly disturbed films dispersions as $\sim q^{3/2}$ can be identified (see Fig. 4). These films are 2D with strong axial distortions and belong to the same universality class as 1D magnets [4, 5].

3. Summary

For 3D, 2D, and 1D magnets the dispersions of the GSW bosons are $\sim q$, $\sim q^2$, and $\sim q^{3/2}$, respectively. In restricted dimensions $d < 3$ GSW bosons have nonlinear dispersions and, possibly a small mass. It can be seen that the exponents do not scale with dimension. This applies also to the exponents ε of the universality classes at $T = 0$ (Table). On the other hand, the two exponents can be expected to be correlated. In fact, writing the dispersion relation of the GSW bosons as $\sim q^m$ it follows:

$$2(\varepsilon + m) = 9 - d, \tag{1}$$

with d as dimension. This empirical relation applies to half-integer spins.

It is evident that much more experimental and theoretical work is necessary before a field theory of magnetism can be formulated. As a conclusion, it appears that our understanding of the dynamics of the long range ordered state is just at the beginning.

References

[1] F. Keffer, in: *Handbuch der Physik*, Eds. S. Flügge, H.P.J. Wijn, Springer, Berlin 1966, p. 1.

[2] W. Heisenberg, *Z. Phys.* **49**, 619 (1928).

[3] F.J. Dyson, *Phys. Rev.* **102**, 1230 (1956).

[4] U. Köbler, A. Hoser, *Physica B* **362**, 295 (2005).

[5] U. Köbler, A. Hoser, *Eur. Phys. J. B* **60**, 15 (2007).

[6] J.C. Le Guillou, J. Zinn-Justin, *Phys. Rev. B* **21**, 3976 (1980).

[7] K.G. Wilson, J. Kogut, *Phys. Rep.* **12C**, 75 (1974).

[8] J. Goldstone, A. Salam, S. Weinberg, *Phys. Rev.* **127**, 965 (1962).

[9] P.E. Wigen, C.F. Kooi, M.R. Shanabarger, *J. Appl. Phys.* **35**, 3302 (1964).

[10] R. Weber, *IEEE Trans. Magn.* **MAG-4**, 28 (1968).

[11] T.G. Phillips, H.M. Rosenberg, *Phys. Rev. Lett.* **11**, 198 (1963).