СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
Дубна

E2 - 5766

G. Heber , K. Elk

ЛАБОРАТОРИЯ ТЕОРЕТИЧЕСКОЙ ФИЗИКИ

ON POSSIBILITIES OF OBSERVATION OF MAGNETIC SURFACE MODES USING INELASTIC NEUTRON SCATTERING

1971

E2 - 5766

G. Heber*, K. Elk **

ON POSSIBILITIES OF OBSERVATION OF MAGNETIC SURFACE MODES USING INELASTIC NEUTRON SCATTERING

* Sektion Physik, Technische Universität Dresden, GDR.

** On leave of absence from Sektion Physik, TU, Dresden, GDR.

1. Introduction

In the last years the properties of magnetic excitations at surfaces of crystals with magnetic order, shortly surface magnons (SM), have been considered. These SM are caused either by the surface anisotropy /1/, or by change of the exchange energy at the surface /2/, or they are of magnetostatic nature /3/. Generally, the dispersion relation of SM follows from the dispersion relation of bulk modes (BM) allowing imaginary values for the component of momentum in the normal direction of the surface (z - direction),

$$k \to (k^{\perp}, i/\lambda). \tag{1}$$

Here λ is the damping length of SM in Z -direction, $k^{\perp}$ describes the other components of k . For the dispersion relation then we get with usual approximations /4/ the form

$$\omega_m^{SM}(k) = 2 g \mu_B H^a + D(k^{\perp 2} - 1/\lambda^2). \tag{2}$$

(H^a is the external field and D the stiffness constant of BM). For λ equations follow from the boundary conditions at the surface, which yield only a discrete set of λ -values. These sets are distinctive for each type of SM, see e.g. (12). The order of magnitude is $\lambda \approx 10 \ldots 100$ Å .

Although the SM are theoretically studied in many papers, they have been found experimentally at present only in a single case, using FMR /5/. This fact is in contrast to other surface modes, e.g. plasmons or electrons, which are experimentally studied very broad. Therefore, in this paper we try to discuss the possibilities of observation using inelastic neutron scattering.

2. Thin Layers

The usual bulk scattering does not yield a contribution of the SM, since these exist only in a small layer of width λ at the surface and show only a two-dimensional variety (we have only few values λ). Therefore we must choose other conditions, as shows a simple discussion of the cross section. Taking into account only 1-magnon-processes the cross section of BM has the form /4/

$$\frac{d^2 \sigma^{BM}}{d\Omega \, dE'} = A \cdot L \cdot \delta(\omega - \omega_m^{BM}(k))\, \delta(\kappa - k) \tag{3}$$

(L -width of crystal in z -direction, $\omega_m^{BM}(k)$ and k - energy and quasi-impulse of BM, ω and κ -energy and momentum transfer of neutrons). A depends on κ , but does not depend on L . The conservation of momentum has for finite crystals the form

$$\delta(\kappa - k) = \delta(\kappa^{\perp} - k^{\perp}) \cdot \frac{1/L\pi}{(\kappa_z - k_z)^2 + 1/L^2} \tag{4}$$

Calculating the cross section of SM we replace k_z by i/λ , hence in contrast to (3) and (4)

$$\frac{d^2 \sigma^{SM}}{d\Omega \, dE'} = A \lambda \, \delta(\omega - \omega_m^{SM}(k))\, \delta(\kappa^{\perp} - k^{\perp}) \frac{1/\lambda\pi}{\kappa_z^2 + 1/\lambda^2} \tag{5}$$

with the same A as in (3).

The comparison of (4) and (5) shows, there are peaks of BM at $\kappa_z = k_z$ (following from the dispersion relation), but the peak of the SM (with the same ω and $\kappa^{\perp}$) is always at $\kappa_z = 0$. Denoting the maximum intensity by I_m , the general intensity by I_g and the width of the peaks by Γ it follows

$$I_m^{SM} / I_m^{BM} = \lambda^2 / L^2 , \; I_g^{SM} / I_g^{BM} = \lambda / L , \; \Gamma^{SM} / \Gamma^{BM} = L / \lambda . \tag{6}$$

From (6) we see, that we must choose $L \approx 2 \ldots 10\lambda$ for measurable effects. On the other hand the different positions of the peaks allow to distinguish them. For separation from small angle scattering we choose $|\kappa^{\perp}| \neq 0$.

3. Total Reflection

But also by arbitrary thickness of the crystal we can get a favourable relation between SM and BM, using the effect of total reflection of neutrons. If the wave length of neutrons is larger than the lattice constant (cold neutrons), then it is possible to smooth out the potential over a lattice cell /6/. This gives a potential jump of $4\pi a / v_c$ at the surface (a = Fermi scattering length, v_o = volume of the unit cell), acting on the neutrons. For $a > 0$ total reflection of the neutron beam is obtained, if the angle of incidence (measured between beam and surface) corresponds to

$$k \sin\theta < \sqrt{4\pi a / v_c} \, . \tag{7}$$

For such angles the neutrons penetrate the target only in a layer δ with

$$\delta^{-1} = \sqrt{4\pi a / v_c - k^2 \sin^2\theta} \, . \tag{8}$$

Only in this layer scattering processes take place, and the SM are better measurable in relation to BM, especially with $\delta \approx \lambda$.

Of course in consequence of (7) this method is only possible, if a is not too small. But then we must consider the perturbation by the nonmagnetic scattering. And also large surfaces are necessary, but this is not a very hard problem, since monocrystals are not necessary. A practical possibility is, for instance, to lay surfaces of neutron conductors with ferromagnetic layers.

4. Depolarization of Neutrons

A very sensitive method for the observation of SM should be the measurement of depolarization of polarized neutrons. With integration of the inelastic cross section of polarized neutrons /6,7/ over all scattering energies and angles we get for the contribution of the BM to the transition probability of the neutron spin

$$\gamma^{BM}_{s_N \to s'_N} \approx (9-7\eta^2)\delta_{s'_N, s_N} + (11+10\eta+7\eta^2)\delta_{s'_N, -s_N} . \qquad (9)$$

Here only the angular part of γ is considered; η is the cosine of the angle between the direction of neutron polarization and internal magnetic field of the target. For the SM we have in consequence of (5) additionally the normal direction of the surface. The integration over the angle is performed only over the directions of $k^{\perp}$ (see the appendix) and yields

$$\gamma^{SM}_{SN \to SN'} = [1 - \frac{1}{2}\sin^2\alpha_p - \frac{1}{8}\sin^2\alpha_s \sin^2\alpha_p - \eta^2(1-\frac{1}{2}\sin\alpha_s\sin\alpha_p)^2] * \qquad (10)$$

$$* \delta_{s'_N, s_N} + [\frac{1}{2}\sin^2\alpha_s + \frac{1}{2}\sin^2\alpha_p + \frac{\eta}{2}\sin\alpha_s\sin\alpha_p +$$

$$+ \frac{1}{8}\sin^2\alpha_s\sin^2\alpha_p + \eta^2(1-\frac{1}{2}\sin\alpha_s\sin\alpha_p)^2]\,\delta_{s'_N, -s_N} .$$

Here α_s (α_p) are the angles between internal field (direction of polarization) and the normal direction of the surface. (9) does not depend on the orientation of the crystal in consequence of the summation over all scattering angles, but γ^{SM} in (10) depends very sensitively on this orientation. Especially with $\sin \alpha_s = 1$ and $\eta = 0$, that means with constant direction of the polarization the crystal turns only on the axis of the internal magnetic field with the angle α_p, (10) obtains the simpler form

$$\gamma^{SM}_{s_N \to s'_N} = (1 - \frac{5}{8} \sin^2 \alpha_p) \delta_{s'_N, s_N} + (\frac{1}{2} + \frac{5}{8} \sin^2 \alpha_p) \delta_{s'_N, -s_N} . \qquad (11)$$

Simultaneously γ^{BM} (and also the elastic part γ^{el}) is independent of α_p. So from the measured angular distribution of the transition probability we conclude the existence of surface magnons SM.

5. Surface Anisotropy

For those SM, caused mainly by the surface anisotropy, further possibilities exist. Following /1/, then the equation for the damping constant λ has the form

$$e^{-L/\lambda} = \pm \frac{\gamma\lambda + 1}{\gamma\lambda - 1}, \quad \gamma = \pm \frac{K_S}{B} \quad \text{for } e^L \cdot e^S = \left\{ \begin{matrix} 1 \\ 0 \end{matrix} \right. \qquad (12)$$

with K_S -constant of anisotropy, B -exchange energy. Herein the direction e^L of the surface anisotropy (light axis) is containing, relatively to the direction e^S of the magnetic field. (12) yields real solutions, connected with the SM, only if $\gamma < 0$, that is if the magnetic field is parallel to e^L. Hence with rotation of the crystal on 90° the peak of the SM vanishes (or originates).

Furthemore it is possible to change the surface anisotropy K^S in a wide range. For instance this is possible at permalloy or Ni -surfaces by gradual oxidation of the surface /8/. Then also λ is influenced, and the dispersion relation (2) as well as the scattered intensity (6) are changed. For a more accurate study of the connection surface anisotropy and SM a simultaneous examination with the method LEED is useful.

6. Conclusions

The possibilities discussed here show, that the search for magnetic surface modes using inelastic scattering of neutrons is suitable. New apparatuses are not necessary, since all proposed methods already have been used by other experiments. But for the verification of theoretical conceptions the experimental observation of such SM is very useful.

We are grateful to I.M. Frank, F.L. Shapiro, N. Kroo, R. Nathans and M.K. Wilkinson for many discussions.

Appendix

In paragraph 4 is used the transition probability $\gamma_{s_N \to s'_N}$. If we approximately assume, that the dispersion relation (see, e.g. (2)) depends only on $|k|$ or $(|k^{\perp}|, 1/\lambda)$ for bulk modes or surface modes, resp. then it is possible to separate the angular part. With summation over all scattering angles we get

for bulk magnons

$$\gamma^{BM}_{s_N \to s_N'} = \overline{e^S_+ P \sigma P e^S_-}^{\Omega_k} \tag{A.1}$$

with e^S_z = direction of the magnetization,

$$e^S_\pm = e^S_x \pm i e^S_y \ , \quad P = I - kk/k^2 \ , \tag{A.2}$$

$$\sigma = e^P_z e^P_z \delta_{s'_N, s_N} + e^P_- e^P_+ \delta_{s'_N, -s_N},$$

e^P_z = direction of the polarization, and

$$\bar{A}^{\Omega_k} = \frac{1}{4\pi} \int d\Omega_k A(k) . \tag{A.3}$$

Using relations between the angles containing in (A.4) and performing the averaging (A.3) we obtain ($\eta = e^S_z \cdot e^P_z$)

$$\gamma^{BM}_{s_N \to s_N'} = \frac{1}{15}[(9-7\eta^2)\delta_{s_N', s_N} + (11+10\eta+7\eta^2)\delta_{s_N', -s_N}], \qquad (A.4)$$

which is used in (9).

Analogously to this for the contribution of the elastic scattering we get

$$\gamma^{el}_{s_N \to s_N'} = \frac{1}{15}[(1+7\eta^2)\delta_{s_N', s_N} + (9-7\eta^2)\delta_{s_N', -s_N}]. \qquad (A.5)$$

But for the surface magnons in consequence of (1) k_z is replaced by i/λ. Hence instead of (A.1) we have

$$\gamma^{SM}_{s_N \to s_N'} = \overline{e^S_+ \; P \sigma P \; e^S_-}^{\,\Omega_k \perp} \qquad (A.6)$$

with

$$\bar{A}^{\Omega_k \perp} = \frac{1}{2\pi} \int_0^{2\pi} d\phi \, A(k^\perp), \quad \cos\phi = k^\perp_x / |k^\perp| . \qquad (A.7)$$

Here we must explicitly consider the normal direction e_z of the surface, which yields additional dependence on the angles α_p and α_s with

$$\cos\alpha_p = e^P_z \cdot e_z , \quad \cos\alpha_s = e^S_z \cdot e_z . \qquad (A.8)$$

The results for γ^{SM} is written down in equation (10).

References

1. F. Goedsche, G. Heber and H. Wenzel. Acta Phys. Polon., A37, 825 (1970).
   J. Monecke. Phys. Stat. Sol., 38, K81 (1970).
   H. Puszkarski. Acta Phys. Polon., A38, 217 (1970).
2. R.E. De Wames and T. Wolfram. Phys. Rev., 185, 720 (1969);
   J. Appl. Phys., 41, 987 (1970).
   M. Sparks. Phys. Rev., B1, 4439 (1970).

3. V.M. Sokolov and B.A. Tavger. Fiz. Tverd. Tela, 10, 1793 (1968).
4. S.V. Tyablikov. "Metody kwantowoj teorii magnetizma", Nauka, Moskva (1965).
5. N.M. Salanskij and S.S. Lichajlovskij. Fiz. Tverd. Tela, 12, 3639 (1970).
6. I.I. Gurevich and L.V. Tarasov. "Fizika nejtronov niskich energy", Nauka, Moskva (1965).
7. J.A. Izjumov and R.P. Ozerov. "Magnitnaja nejtronografija", Nauka, Moskva (1966).
8. C.W. Searle, A.H. Morrish and R.J. Prosen. Physica, 29, 1219 (1963).
M.M.P. Janssen. J. Appl. Phys., 41, 399 (1970).

Received by Publishing Department
on April 21, 1971.