Scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR (25 December 1991)

Usp. Fiz. Nauk **162**, 158–163 (April 1992)

A scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR was held on 25 December 1991 at the P. L. Kapitsa Institute of Physics Problems. The following reports were presented at the session:

1. *R. A. Syunyaev, M. R. Gil'fanov, S. A. Bebenev, O. V. Terekhov, and E. M. Churazov.* Results of the GRANAT satellite. Discoveries and location of sources of positron-annihilation line emission at the center of the galaxy and in the Nova in the Musca Constellation. Observation of the 2.2 MeV deuterium fusion γ-ray in a solar-flare spectrum.

2. *S. O. Demokritov.* Direct observation of oscillations of the RKKY-interaction in layered magnetic systems.

A brief summary of one report is given below.

S. O. Demokritov. Direct observation of oscillations of RKKY-interaction in layered magnetic systems. During the five years following its discovery antiferromagnetic (AF) interaction in the layered system Fe/Cr/Fe has been investigated in detail.[1–4] The observation of gigantic magnetoresistance accompanying a change in the mutual orientation of the magnetizations of neighboring Fe-films is of special interest.[2,4,5] It was found that this is a general phenomenon, and this effect has now been observed in many layered systems.[6] Strongly damped oscillations of the magnitude of the AF interaction as a function of the thickness *d* of the nonmagnetic field in the systems Fe/Cr/Fe, Cl/Cr/Co, as well as Co/Ru/Co were discovered in 1990.[4] However the first results were obtained on polycrystalline samples. Moreover, the method of investigation employed—analysis of magnetization curves—did not yield any information about the magnitude of the ferromagnetic interaction. For this reason, further investigations proceeded in the direction of improving the quality of the sample studied and obtaining more complete information about phenomena occurring in such magnetic layered systsm.

In order to obtain single-crystal simples the films were sputtered in an ultrahigh vacuum (better than $2 \cdot 10^{-9}$ Torr) by means of molecular-beam epitaxy. The substrate consisted of GaAs. Using the well-known method,[7] a buffer layer consisting of 1 mm Fe/150 nm Ag, on which the system to be studied was deposited, was formed first. The Fe films had characteristic thicknesses of 3–10 nm; the nonmagnetic interlayers (Cr, Al, Au) were 0–7 nm thick. During preparation the composition of the samples was monitored with the help of an Auger spectrometer, and the crystalline properties and morphology of the interfilm boundaries were monitored with the help of low- and high-energy electron diffractometers (LEED, RHEED). All this permits asserting that the films were single-crystalline and had flat boundaries. No contamination of the films (for example, with oxygen) and no diffusion of Ga and As through the buffer were observed. As the quantity characterizing the quality of the magnetic films, we give the measured coercive force, which was equal to 4–5 Oe.

In order to study the dependence of the strength of the magnetic interaction in the layered system on the thickness *d* of the nonmagnetic film, these films were prepared in the form of a wedge. This made it possible to investigate practically in one sample a wide range of thicknesses *d* with identical properties of the magnetic Fe-films. This wedge-shaped geometry did not distort the magnetic properties of the layered system, a fact which was checked by comparing with samples in which the interlayer had a constant thickness. Since the wedge was 16 mm long and the change in thickness was equal to 5–6 nm, the wedge did not distort in any manner the surface morphology of the films. Indeed, the thickness of the wedge changed by one monolayer over a distance of not less than 0.5 nm.

Experimental information about the strength of the interaction between the magnetic layers was obtained by analyzing the magnetization curves $M(H)$ as well as from the frequencies of spin waves propagating in the layered system. The curves $M(H)$ were measured with the help of a scanning magnetometer, operating on the basis of the magnetooptic Kerr effect (MOKE). The spin-wave frequencies were measured with the help of Brillouin–Mandel'shtam scattering (BMS) of light. In both cases the light source consisted of a focused laser beam. Layered systems with different values of *d* can actually be studied by scanning this beam along the wedge. As compared with MOKE, the BMS method has the advantage that it permits measuring not only antiferromagnetic but also ferromagnetic (FM) interaction.

In order to make a quantitative assessment of the exchange interaction between neighboring ferromagnetic films, the surface exchange energy is written in the form[8]

$$E_s = -2A_{12} \cos \delta\theta \qquad (1)$$

where E_S is the energy per unit area of the film and $\delta\theta$ is the angle between the magnetization vectors of the two films. The parameter A_{12}, defined in Eq. (1), is obtained from the curve $M(H)$ from the magnitude of the saturation field B_S at which the magnetizations of both films become aligned parallel to the field. Hence it is clear that this method makes it possible to measure only the AF interaction, since in the case of the FM interaction between films the magnetizations of the films are parallel to one another even in zero field. In the case when the anisotropy is negligibly small, A_{12} is calculated from B_S:

$$A_{12} = -B_s M d_0 / 4, \qquad (2)$$

where M and d_0 are, respectively, the magnetization and thickness of the magnetic film.

A different method for measuring A_{12} is to analyze the frequencies of the spin waves. This method is described in detail in Ref. 9. Two spin-wave branches are observed in a layered system consisting of two magnetic films. The first

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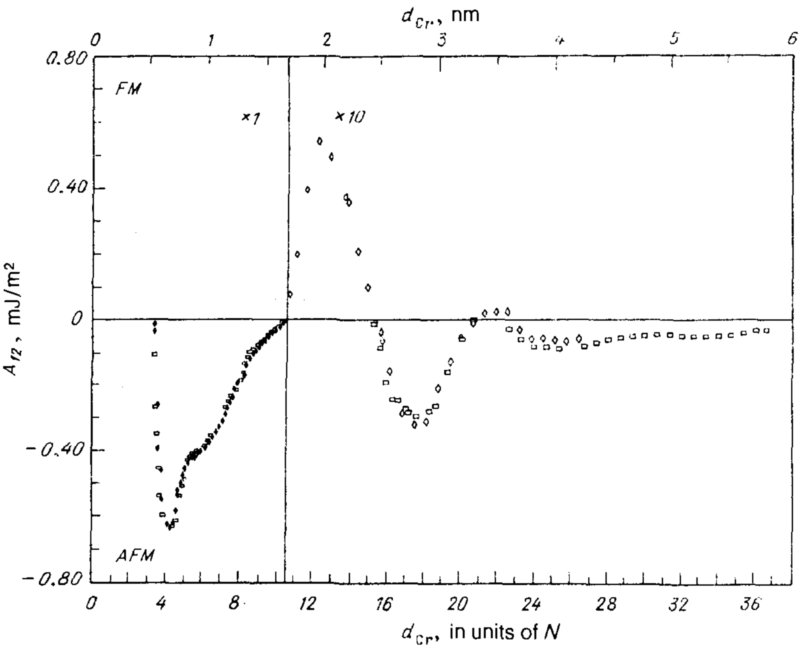

FIG. 1. A_{12} as a function of the thickness of the Cr interlayer in the Fe/Cr/Fe system at room temperature. The dependence was obtained from MOKE and BMS experiments. FM—ferromagnetism; AFM—antiferromagnetism; N—film thickness, expressed in monolayers.

branch represents the Damon–Eshbach (DE) mode, whose frequency does not depend on the interfilm interaction period. The frequency of the second "optical" mode already depends on the strength of the interaction, and this frequency can be used to calculate A_{12}.

Interaction oscillations of the type AF–FM–AF... were observed already in the first experiments on single-crystalline samples of Fe/Cr/Fe (Fig. 1).[10] It also was found that the damping of these oscillations depends on the temperature and the d^{-2}-law predicted for the two-dimensional system by the Ruderman–Kittel–Kosiya–Yosida (RKKY) theory is observed only at low temperatures. At room temperature, for example, a law close to d^{-5} is observed. As in Ref. 4, the period of the oscillations was equal to about 1.7–1.8 nm, which when compared with the RKKY theory, leads to an exceedingly small value of k_F, corresponding to these oscillations. Attempts were made to explain this contradiction by the existence on the Fermi surface of Cr of regions close to the boundary of the Brillouin zone. Such "long-wavelength" oscillations were also associated with beats between RKKY oscillations and periodicity of the atomic lattice. However, irrespective of the proposed models, there should also exist "short-wavelength" oscillations whose period is close to two interatomic lattice spacings of the nonmagnetic metal. Indeed, fine structure was observed in A_{12}, obtained in Ref. 10, as a function of d. This fine structure can be considered to be a manifestation of strongly suppressed short-wavelength oscillations. It has already been noted in Ref. 11 that RKKY oscilations are suppressed by surface roughness, and for short-wavelength oscillations the surface quality must be higher than in the case of long-wavelength oscillations (in proportion to the ratio of the periods). For this reason, further searches for short-wavelength oscillations were directed toward improving the surface quality of the films. It was found that in the system Fe/Cr/Fe, obtained by epitaxy on a AsGa substrate, the boundary between the Cr film and the top Fe film is of lower quality than the boundary between the bottom Fe film and the Cr film. However a special method was found for processing the surface of the Cr film *in situ* with the help of an electron beam. This method improves the quality of the surface to such an extent that the short-wavelength oscillations of the function $A_{12}(d)$ become easily observable.[12] Figure 2 shows comparative data for the normal and electron-beam processed samples. One can see that the oscillations manifested in the normal sample as weak fine structure can be clearly observed after electron-beam processing.

A technology of layered systems, which employed iron whiskers, has also been developed.[13–15] As electron diffractrometry has shown, the film surfaces in such systems were found to be of much higher quality than in the systems prepared on GaAs. It is thus not surprising that short-wavelength RKKY-oscillations in them turned out to be even more pronounced. In Ref. 14, about 20 periods of short-wavelength oscillations were found with the help of a method that does not permit measuring the value of A_{12} but only permits recording its sign.

The system Fe/Cr/Fe is the first, but not the only, system in which short-wavelength oscillations of A_{12} were observed. The same type of oscillations were observed in Fe/Mn/Fe prepared on the basis of a whisker,[16] as well as in the system Fe/Au/Fe.[17] In addition, the surface quality of Fe/Au/Fe films deposited epitaxially on GaAs is high enough, even without special processing, in order to observe short-wavelength oscillations, though in Fe/Au/Fe the value of A_{12} itself is much smaller than in the Fe/Cr/Fe system. We also call attention to the Fe/Al/Fe system, where RKKY interaction was observed, in spite of the fact that Al has no d-electrons.[17]

In the course of investigations of layered magnetic systems, an effect which at first glance is not associated with oscillations of A_{12} was observed. In the Fe/Cr/Fe system there exists, together with the standard exchange interaction, which is described by the parameter A_{12}, a higher-order interaction of the form

$$E_s = B_{12}(\cos \delta\theta)^2, \qquad (3)$$

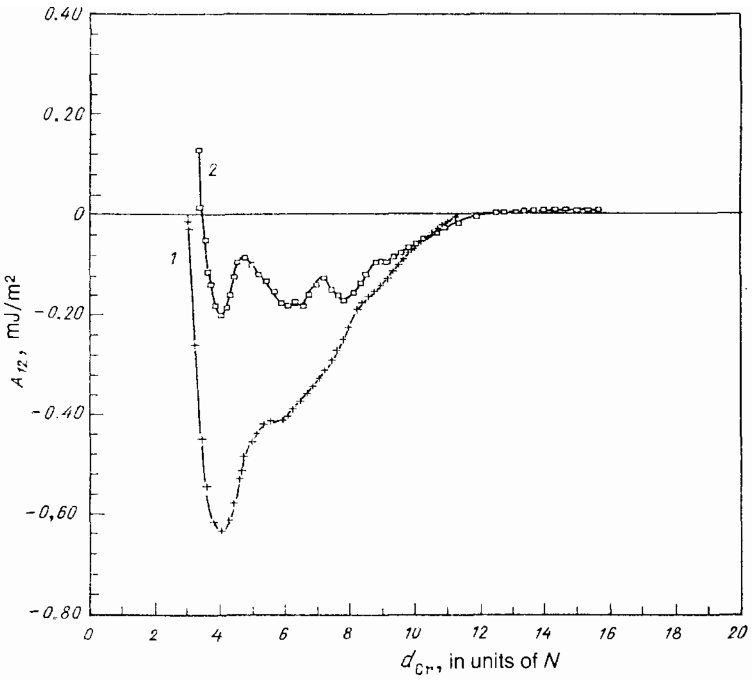

FIG. 2. A_{12} as a function of the thickness of the Cr interlayer for normal (*1*) and (*2*) electron-beam-processed samples.

which for positive B_{12} makes energetically favorable a configuration in which the magnetizations of the two films are mutually perpendicular.[18] In addition, for certain values of d this 90-degree interaction becomes dominant and in the absence of an external field a perpendicular configuration is realized. Several microscopic mechanisms for such an interaction were proposed.[12,8] However, after this effect was also discovered in other systems (Fe/Al/Fe, Fe/Au/Fe), it became clear that this phenomenon is of a general character and is not associated with specific properties of Cr. Recently papers have appeared in which the behavior of two magnetic fields coupled by an oscillating RKKY-interaction under conditions of a definite nonuniformity of the thickness of the interlayer was studied in detail.[19] In this case, as has already been pointed out more than once, the oscillations themselves are suppressed, but, as first shown in Ref. 19, the initial existence of the oscillations results in the appearance of an effective 90-degree interaction.

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Translated by M. E. Alferieff