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EXPERIMENTAL OBSERVATION OF LEFT-RIGHT ASYMMETRY OF POLARIZED NEUTRON SCATTERING FROM Fe ABOVE T_c

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Résumé. - Il est révélé que l'intensité de la diffusion critique des neutrons dans le fer au-dessus de T_c dépend de l'orientation relative de la polarisation initiale de neutrons et de la normale au plan de diffusion. La valeur obtenue de l'asymétrie est de $P_A = (1,5 \pm 0,2) \cdot 10^{-4}$ à $T - T_c = 3,5^\circ$. Les résultats sont en accord avec la théorie qui prédit le phénomène pareille, du aux corrélations dynamiques triples de spins.

Abstract. - The intensity of the neutron critical scattering from iron above T_c was found to depend on the relative orientation of the initial neutron polarization and the normal to the scattering plane. The magnitude of the asymmetry obtained is $P_A = (1.5 \pm 0.2) \times 10^{-4}$ at $T - T_c = 3.5^\circ$. The results are in agreement with the theory predicting this phenomenon which is due to three-spin dynamic correlations.

It is known that Landau's expansion for the free energy of a ferromagnet near the Curie point T_c does not contain terms with odd powers of the magnetic moment $\vec{M}(\vec{r})$, while above T_c there are no static odd correlation functions in the case of a zero magnetic field. This is a result of the system's symmetry under time reversal. This does not preclude, however, the existence of dynamic odd correlations of the type

$$\langle S_1^a(t_1) S_2^b(t_2) S_3^c(t_3) \rangle. \tag{1}$$

Until recently, only pair correlations

$$\langle \vec{S}_1(t_1) \vec{S}_2(t_2) \rangle \tag{2}$$

have been studied in the critical scattering, although higher order correlations carry additional information on the dynamics of ferromagnets. This results from the fact that the scattering cross section σ_2 due to pair correlations is large thus making it difficult to detect three-spin correlations against this background. The cross section σ_3 associated with the three-spin correlations was shown theoretically [1] to have a specific feature permitting the experimental detection against the background of another, stronger scattering. This feature consists in σ_3 having a spin-dependent left-right asymmetry:

$$\sigma_3 \propto I(\theta) = I_0(\theta) \left[1 + \frac{1}{2} A(\theta) \vec{n} \cdot \vec{\sigma} \right], \tag{3}$$

where $I(\theta)$ is the intensity of scattering to an angle θ , $\vec{n} = [\vec{k} \times \vec{k}'] / (kk')$, \vec{k} and \vec{k}' are the initial and final neutron wave vectors, respectively, $\frac{1}{2} \vec{\sigma}$ is the neutron spin. Because of the spin dependence of σ_3 in the scattering of unpolarized neutrons a polarization appears in the scattered beam

$$P(\theta) = (I^+ - I^-) / (I^+ + I^-) = A(\theta), \tag{4}$$

where I^+ and I^- are, respectively, the scattering intensities for neutrons with spin states $\sigma = +1$ and $\sigma = -1$.

This polarization is directed along the normal \vec{n} to the scattering plane and has opposite signs in scattering to angles $+\theta$ and $-\theta$ because of the reversal of the sign of \vec{n} . It was of interest to check this theoretical prediction [1] experimentally. Theoretical estimates yield for this polarization a value of $P \sim 10^{-5}$ for the paramagnetic region far from T_c . Near T_c a drastic enhancement of the effect occurs so that P may increase by 1-2 orders of magnitude.

We used in the experiment polarized neutrons of wavelength $\lambda \approx 4\text{\AA}$ and $P_0 = 0.97$. We measured the scattered neutron intensity as a function of the sign of the initial polarization \vec{P}_0 , the spin asymmetry of the scattering being calculated by expression (4). The experimental arrangement is shown in Fig.1.

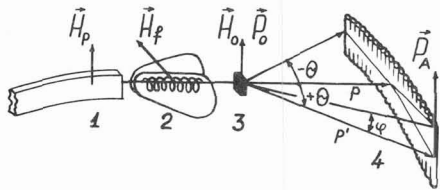


Fig.1. Experimental arrangement.

1 - polarizing neutronguide;
2 - flipper; 3 - sample; 4 - multichannel detector.

The arrows denote magnetic field directions in the polarizer (\vec{H}_p), flipper (\vec{H}_f) and sample (\vec{H}_0). P

The polarized beam $8.5 \times 60 \text{ mm}^2$ in cross section was shaped by a 5 m long neutronguide 1, after which it passed through an adiabatic flipper 2 and impinged on sample 3. The scattered neutrons were detected by neutron counters placed at 1.5 m from the sample. The armco iron sample measuring $5 \times 12 \times 70 \text{ mm}$ was placed in a thermostat capable of maintaining the maximum temperature of $\sim 1200 \text{ K}$ to within $\pm 0.5^\circ$.

The sample was fixed in a vertical guide magnetic field $H \leq 5 \text{ Oe}$.

Since the expected effect is small, measurements had to be carried out to within 10^{-5} . The selection of iron for the sample was optimal from the viewpoint of both the magnitude of T_c (the effect being proportional to T_c) and the magnitude of the critical scattering cross section. Indeed (Fig.2), in the experimental geometry chosen, the detector count rate at angles $\theta = 1^\circ$ was 10^4 c/s , and at $\theta = 5^\circ$; $I = 5 \times 10^2 \text{ c/s}$ thus ensuring the required accuracy in a reasonable measurement time. To reduce systematic instrumental errors, the polarization was reversed every 10 s in the sequence $+, -, +, -, \dots, -, +$. The time intervals with $+P$ and $-P$ were set to within 10^{-6} s . In the second half of the experiment the detector was turned through 180° with respect to beam axis. Measurements at different temperatures and with a depolarized beam (reference measurements) were alternated in time. Experiments with a reversed guiding magnetic field $H = -5 \text{ Oe}$ were also carried out. The measurements were delayed by 0.5 s to allow for the flipper switching.

The detector unit consisted of 21 counters, the central counter (No.11, $\theta=0$) being used for checking the polarization of the passing neutron beam. A miniature curved polarizing neutronguide of effective cross section $0.2 \times 15 \text{ mm}^2$ and 210 mm long was placed for this purpose before it. Scattering over a broad temperature range was studied to determine the Curie temperature T_c (Fig.2). We adopted for T the temperature corresponding to maximum critical scattering at an angle $\theta = 1^\circ$, since our previous small angle measurements [3] imply the temperature induced shift of the scattering maximum at angles up to 1° to be practically unobservable. Altogether, 18 day-long measurement runs were carried out at various temperatures. To reduce statistical errors in the data treatment, the results of the runs were averaged over the temperature intervals specified in Fig.2: $T_1 = T - T_c = 3.3^\circ - 3.6^\circ$; $T_2 = 4.5^\circ - 8^\circ$; $T_3 = 8^\circ - 11.5^\circ$; $T_4 = 28^\circ$ $T_5 =$

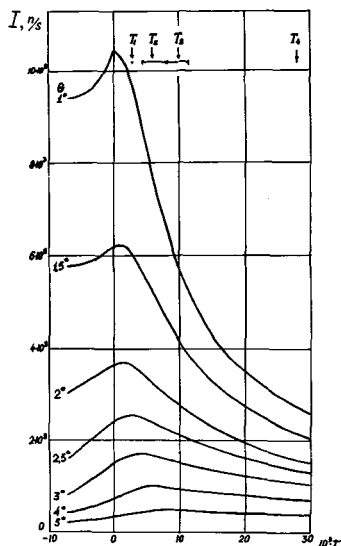


Fig. 2. Critical scattering intensity in iron vs. temperature at different scattering angles θ .

= 55°.

At temperatures T_1, T_2, T_3 both the effect itself and its left-right asymmetry were observed in each run. The positive polarization coinciding in direction with the initial polarization \vec{P}_0 appeared in the right wing counters in the magnetic field geometry shown in Fig. 1.

Fig. 3 displays the angular dependences $P(\theta)$ and $\Delta P(\theta) = P(\theta) - P(-\theta)$ averaged over the temperature intervals $T_1 + T_2$ and T_3 . The effect is clearly seen to exist at a level $P \approx 10^{-4}$. The dashed line in the $\Delta P(\theta)$ relations shows the angle-averaged mean for $\langle \Delta P(\theta) \rangle$ whose error does not exceed 2×10^{-5} .

At the temperatures T_1 and T_2 one observed a growth of polarization at small angles, and its drastic dropoff to zero at large angles. At $T - T_c = T_3$ the maximum of polarization was beyond the angular ranges covered.

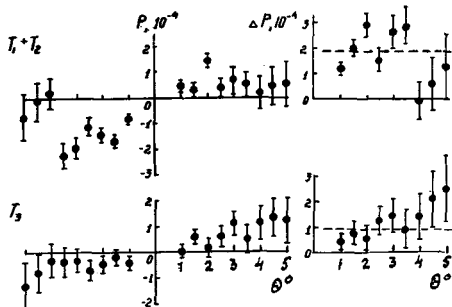


Fig. 3. P_A and ΔP vs. scattering angle in different temperature regions specified in Fig. 2.

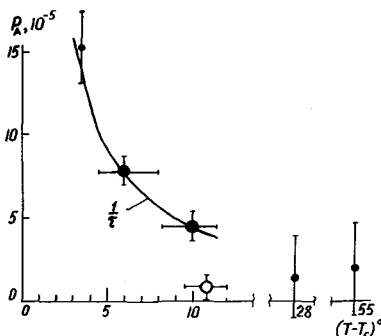


Fig. 4. The temperature dependence of asymmetry P_A averaged over scattering angles for the polarized (\bullet) and unpolarized (\circ) beams.

Fig. 4 shows the values of $P_A = \Delta P/2$ for various temperatures averaged over all angles from 1° to 5° . The point denoted by an open circle refers to a measurement with a shim depolarizing the incident beam. The polarization P_A is seen to increase as one approaches T_c approximately as τ^{-1} , where $\tau = (T - T_c)T_c^{-1}$.

The theory [1] predicts that P_A should have a maximum at the value of the scattering vector $q(=k\theta)$ equal to the characteristic inelasticity momentum q_i in the exchange temperature region, or to the dipolar momentum q_0 in the dipolar region of T . In our case for iron and $\lambda = 4 \text{ \AA}$ we have $q_0 = 4 \times 10^{-2} \text{ \AA}^{-1}$ (or $\theta_0 = 1.5^\circ$), $q_i = 11 \times 10^{-2} \text{ \AA}^{-1}$ (or $\theta_i = 4.2^\circ$). As seen from Fig. 3, the theory is apparently supported by the experiment despite the large statistical errors present.

In order to compare the observed and predicted temperature dependences, the corresponding expressions for $P(q, \tau)$ in ref. [1] were averaged over the angular region $1 - 5^\circ$. It turned out that the $P_A \propto \tau^{-1}$ law obtained from the experiment is valid for the exchange temperature region. Thus the experimental P_A vs. τ relations agrees with the theoretical predictions. Apart from this, the theory yields an order-of-magnitude estimate for the effect which also fits to the experimental data. The values of P_A obtained for the temperatures $T - T_c = 3.5^\circ; 6^\circ; 10^\circ; 28-55^\circ$ are, accordingly, $15.2 \pm 2.3; 7.88 \pm 0.9; 4.5 \pm 0.9; 1.6 \pm 1.8$ (in units of 10^{-5}).

Summing up, one can say that the proposed method of study of the critical dynamics by the scattered neutron polarization lies within the present experimental possibilities.

This method permits one to obtain information on the tree-spin correlation dynamics which could not be studied by other means up to now.

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