Asymmetry of the critical scattering of polarized neutrons and critical dynamics of ferromagnets subjected to a magnetic field above T_c

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The nature of the asymmetry of the critical scattering of polarized neutrons in ferromagnets subjected to a magnetic field above T_c is elucidated. It is shown that the asymmetry is due to triple dynamic spin correlations. The results obtained for iron are in qualitative agreement with the theoretical predictions deduced from the three-spin critical dynamics.

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1. INTRODUCTION

Lazuta *et al.*[1] predicted that triple dynamic spin correlations in the critical scattering of nonpolarized neutrons in a ferromagnet above the Curie point T_c should give rise to polarization in the direction of the pseudovector $\mathbf{k}\times\mathbf{k}'$, i.e., perpendicular to the scattering plane (here, $\mathbf{k}$ and $\mathbf{k}'$ are the wave vectors of the incident and scattered neutrons). The scattering asymmetry of initially polarized neutrons, equivalent to the appearance of the polarization, was observed by Okorokov *et al.*[2] Their experiments were made using a beam of polarized neutrons with the wavelength $\lambda=4$ Å. Measurements were made of the intensities $I^+(\theta)$ and $I^-(\theta)$ for different signs of the initial polarization $\mathbf{P}_0$ relative to the $\mathbf{k}\times\mathbf{k}'$ direction. The relative difference in the intensities of the scattering through an angle θ

$$P(\theta)=\frac{I^+(\theta)-I^-(\theta)}{I^+(\theta)+I^-(\theta)}, \qquad (1)$$

which may be called conveniently the polarization asymmetry of the scattering, amounted to $\sim10^{-4}$ for iron in the range $\tau=(T-T_c)/T_c=(3-6)\times10^{-3}$, in agreement with the theoretical estimate of Lazuta *et al.*[1] and it had different signs for the scattering to the right and left, in accordance with reversal of the sign of the vector product $\mathbf{k}\times\mathbf{k}'$.

When these experiments were extended to a beam of cold neutrons with $\lambda=13$ Å and a two-dimensional detector was used,[3] it was found that the application of a magnetic field gave rise to a similar polarization asymmetry of $P(\theta)$ also in the case of neutrons initially polarized in the scattering plane. The two effects (for $\mathbf{P}_0$ perpendicular and parallel to the scattering plane, denoted by $P_\perp$ and $P_\parallel$, respectively) are illustrated in Fig. 1. The detector field is shown for each curve and it is denoted by a square with a black sector in which the measured intensity was averaged over rings corresponding to a constant value of $k\theta$, and the arrow indicates the direction of the field $\mathbf{H}$ (and, consequently, also of $\mathbf{P}_0$). For the results in Fig. 1 the field $\mathbf{H}$ was 20 Oe. An increase in the field caused $P_\parallel$ to rise to a few percent, whereas the dependence $P_\parallel(\theta)$ was bell-shaped with a clear maximum in the region of $p=k\theta\approx(3.5-4)\times10^{-2}$ Å^{-1}. It is clear from Fig. 1 that $P_\parallel(\theta)$ exhibited an angular asymmetry, i.e., $P_\parallel(\theta)\neq P_\parallel(-\theta)$. Therefore, in the subsequent analysis it was convenient to represent it by a sum of two terms $P_S(\theta)=P_S(-\theta)$ and $P_A(\theta)=-P_A(\theta)$ representing the components symmetric and antisymmetric in respect of the angles:

$$P_S(\theta)=[P_\parallel(\theta)+P_\parallel(-\theta)]/2, \quad P_A(\theta)=[P_\parallel(\theta)-P_\parallel(-\theta)]/2. \qquad (2)$$

Further experiments showed that the observed angular asymmetry of the $P_\parallel(\theta)$ curves appeared when the magnetization $\mathbf{m}$ of a sample (and, consequently, the internal field $\mathbf{H}$ and the polarization $\mathbf{P}_0$) had a component along $\mathbf{k}$. Thus, in the case of a sample in the form of a thin plate, the demagnetization effects important at temperatures sufficiently close to T_c ensured that the magnetization in such a sample was directed mainly along its plane. When the sample was subjected to a horizontal field $\mathbf{H}\perp\mathbf{k}$ and rotated about a vertical axis, so as to alter the angle between the direction $\mathbf{H}$ and the plane of the sample, there was a change in the projection of the magnetization onto the direction $\mathbf{k}$. Figure 2 shows how the scattering asymmetry changed in the horizontal plane when the angle between the plane of the plate and the perpendicular to the vector $\mathbf{k}$ was varied. This figure includes also the values of P_S and

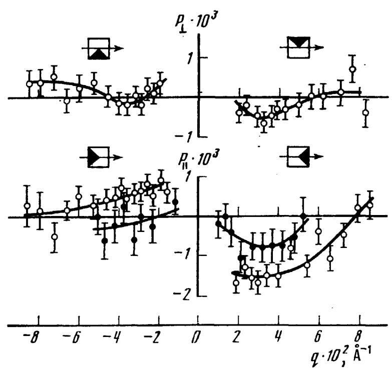

FIG. 1. Dependences of the polarization asymmetry of the scattering for $\mathbf{P}_0$ perpendicular to the scattering plane ($P_\perp$) and for P_0 lying in the scattering plane ($P_\parallel$) on the quasielastic transferred momentum $q=k\theta$ in a field $H_y=20$ Oe; $T=T_c+1°$ (o); $T=T_c+10°$ (●). The blackened sectors represent the detector area over which the results are averaged for rings with $k\theta=$ const. The arrows indicate the direction of the applied field H.

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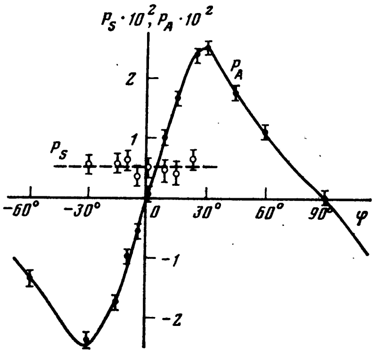

FIG. 2. Dependences of P_S and P_A on the angle of inclination of the plane of the sample φ relative to the perpendicular to **k**, obtained for $\tau = 2\times10^{-3}$ in a field H = 250 Oe.

P_A for a maximum of the angular dependence $P(\theta)$ at a temperature $\tau = 2\times10^{-3}$ when a field of $H = 250$ Oe was applied to an iron sample. It is clear that P_A exhibited an approximately sinusoidal dependence of φ, whereas P_S was independent of the angle φ.

Lazuta *et al.*[4] explained the observed $P_{\parallel}$ effect by showing that both components (P_S and P_A) were of the same origin, and that in weak fields they were associated with triple dynamic spin correlations. The essence of their theory is as follows. The intensity of the critical scattering of polarized neutrons in a magnetic material subjected to a weak magnetic field is

$$I(\theta, H) \sim \int \frac{d\omega}{\omega}\frac{k'}{k}\{\operatorname{Im} G^{(1)}(q,\omega) + g\mu H(\mathbf{eh})(\mathbf{eP}_0)\operatorname{Im} G^{(3)}(q,\omega;0,0)\}, \quad (3)$$

where $G^{(1)}$ and $G^{(3)}$ are the pair and triple spin Green functions in the absence of the field; $\mathbf{e} = \mathbf{q}q^{-1}$; $q = k' - k$; $\mathbf{h} = \mathbf{H}H^{-1}$; $\omega = E' - E$ (E and E' are the energies of the incident and scattered neutrons); $g\mu$ is the effective magnetic moment of an atom. In the inelastic scattering case the integral of the second term in Eq. (3) differs from zero and the angular factor $(\mathbf{e}\cdot\mathbf{h})(\mathbf{e}\cdot\mathbf{P}_0)$ makes it possible to identify the contribution of this term to the cross section by altering the sign of $\mathbf{P}_0$.

We shall now assume that in the scattering configuration shown in Fig. 3 the vectors $\mathbf{P}_0$, $\mathbf{H}$, and $\mathbf{q}$ are in the same plane, whereas $\mathbf{P}_0$ is parallel or antiparallel to H. In this case the quantity $(\mathbf{e}\cdot\mathbf{h})(\mathbf{e}\cdot\mathbf{P}_0)$ can be written in the form

$$(\mathbf{eh})(\mathbf{eP}_0) = e_y^2 h_y P_{0y} + e_z^2 h_z P_{0z} + e_y e_z (h_y P_{0z} + h_z P_{0y}). \quad (4)$$

We can thus see that if $\varphi \neq 0$ all the terms differ from zero. Then, the first two terms are quadratic in respect of the components $e_{y,z}$ and they represent the part of the scattering symmetric with respect to θ, whereas the other two e_y occur linearly and they represent the scattering asymmetric with respect to θ. We can thus see that the final result can be represented by a sum of two terms P_S and P_A, introduced earlier in Eq. (2) and identified by arrows in Fig. 3:

$$P_{\parallel}(\theta) = P_S(\theta) + P_A(\theta). \quad (5)$$

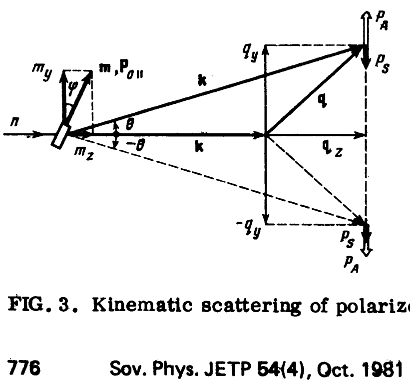

FIG. 3. Kinematic scattering of polarized neutrons.

Lazuta *et al.*[4] obtained theoretical expressions for P_S and P_A. The asymmetric P_A effect was found to be stronger than P_S by a factor $\theta^{-1}\sin 2\varphi$, which may be of the order of 10 for $\varphi \approx 45°$ and the angle θ represents a few degrees.

The agreement between the experimental and theoretical results was qualitative. One should point out that the theory was developed simultaneously with the acquisition of the experimental results so that the dependences shown in Figs. 1 and 2 were not obtained under conditions optimal in respect of φ and the demagnetization factor of a sample was not controlled. Most probably the maxima of P_A in Fig. 2 occurred not at $\varphi \approx 45°$ but at $\varphi \approx 30°$. We shall consider below the results obtained when a sample was magnetized along the easy axis so that the demagnetization factor could be ignored. We shall discuss the dependences of P_A on H, τ, and θ when making a comparison with the theoretical estimates. Since the spin-dependent part of the scattering cross section is proportional to the three-spin dynamic correlation function, an investigation of the $P_{\parallel}$ effect should make it possible to determine the three-spin critical dynamics and, in particular, to verify the predictions of the principle of merging of correlations enunciated by Polyakov[5] and to decide between two variants of the critical dynamics in the dipole temperature range[6,7] (for details see Ref. 4).

2. EXPERIMENTAL METHOD

The experiments were carried out in the fourth channel of the VVR-M reactor. The experimental arrangement did not differ fundamentally from that selected earlier[2,3]: a polarized neutron beam was incident on a sample and the intensities of the scattered neutrons $I^+(k\theta)$ and $I^-(k\theta)$ were determined as a function of the direction of polarization of the beam. A beam of cold neutrons with $\lambda = 10$ Å emerged from the reactor channel. The apparatus consisted of an intrachannel polarizer 1 (Fig. 4) representing an assembly of four mirrors of $210\times50\times5$ mm dimensions made of an Fe–Co alloy on Ti–Gd substrates[8] subjected to a static magnetic field of the order of 100 Oe. Spin reversal was produced by an adiabatic high-frequency flipper 2 at a frequency of $f \approx 40$ kHz; the flipper coil was wound on a drum of borated polyethylene, which also acted as a collimator for the reflected polarized beam. A sample 3 could be located at a distance of 4.5 m or 6 m from the reactor zone. The polarized beam parameters were as follows: the average wavelength was $\lambda = 10$ Å and the scatter was $\Delta\lambda/\lambda = 35\%$; the horizontal and vertical divergences of the beam were $\Delta\theta_y \approx 5\times10^{-3}$ and $\Delta\theta_x \approx 2.5\times10^{-2}$ rad, respectively; the neutron flux at the position of the sample was $I_0 \approx 2\times10^4$ neutrons/cm²; the area of the useful beam cross section was 5 cm²;

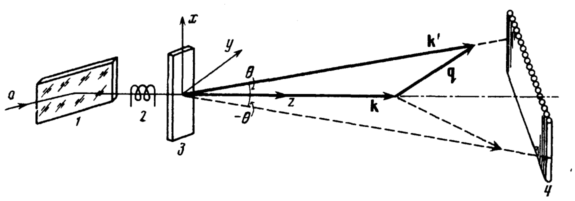

FIG. 4. Experimental arrangement: 1) intrachannel polarizer; 2) adiabatic rf flipper; 3) sample; 4) many-detector assembly.

the polarization was $P_0 \approx 90\%$. Samples of polycrystalline Armco iron of $13\times80\times4$ mm and $13\times80\times1$ mm dimensions were placed in a thermostat where a temperature was kept constant to within $\Delta T\approx 0.02°C$. This thermostat was located between the poles of an electromagnet so that measurements could be carried out in magnetic fields from 10 to 800 Oe. A sample in a thermostat could be rotated about its long axis through any angle φ, and the long axis together with the thermostat and the magnet could be inclined by angle up to 20°. The field could be parallel or perpendicular to the long axis in the plane of the sample.

The scattered neutrons were recorded with a many-detector system comprising 20 helium counters of the SNM-50 type. The detector assembly was shielded by water and it had a device for rotating it about the incident beam axis by 90 and 180°. The sample-detector base could be varied from 1 to 3.5 m. A special processor linked to a computer was used to control the flipper, set the temperature, and switch the magnetic fields. The primary data were recorded on a magnetic tape and were subsequently analyzed on a computer.

A typical measurement session consisted of 1-h series during which the flipper was switched every 3 sec. The data on the series were subjected to a preliminary analysis in order to determine the scatter of the results relative to the statistical error and they were then summed.

The principal series of measurements was carried out on a sample of thickness 1 mm magnetized parallel to its long side and rotated in a horizontal plane through an angle $\varphi=20°$. In this case the enhancement of the P_A polarization was not maximal, but the construction of the electromagnet and thermostat prevented us from making measurements in the range $\varphi>20°$. The parallel alignment of the initial polarization $\mathbf{P}_0$ to the applied magnetic field **H** was ensured by a selection of the main field between the electromagnet and the flipper.

Measurements were made under these conditions at the temperature intervals $T-T_c=1$, 2, 3.8, and 7.2° in magnetic fields $10<H<600$ Oe when the transferred momentum was $(0.75<k\theta<7)\times10^{-2}$ Å^{-1}. The maximum effect was $P=(4-6)\times10^{-2}$ for $k\theta=3.5\times10^{-2}$ Å^{-1}, $\tau=3.8\times10^{-3}$, and $H=440$ Oe. The data on $P(k\theta)$ and the expressions in Eq. (2) were used to calculate the dependences $P_S(k\theta)$ and $P_A(k\theta)$ for each value of τ and H. The Curie point was assumed to be the temperature at which the scattering of neutrons through small angles had its maximum value and the attenuation of the directly transmitted beam was strongest.[9]

3. DETERMINATION OF THE CRITICAL FIELD H_{cr}

It was established that when the temperature was fixed and the magnetic field was increased, then in weak fields H (the criterion of weakness will be given later) the value of P_A increased proportionally to H and then at some critical field H_{cr} the rise slowed down.

The value of H_{cr} was determined accurately for $\tau=$ const using the dependences $P_A(H)$ for five minimum transferred momenta $k\theta$; two such dependences are given by way of illustration in Fig. 5. (It was not possible to use the data for $k\theta>3.5\times10^{-2}$ Å^{-1} because the statistical accuracy of these results was insufficient, particularly at high temperatures.) In the range of small values of H the dependence $P_A(H)$ was approximated by a linear function (in agreement with the theory), whereas at high values of H use was made of a dependence of the type $P(H)\propto H^{2/5}$ predicted for $H>H_{cr}$. The point of interesection of these curves was assumed to be H_{cr}. For all five values of the transferred momenta the critical fields found for the same temperature were identical within the limits of the experimental error and, therefore, they were averaged on the assumption that H_{cr} was independent of the scattering vector.

In this way we obtained the values of H_{cr} at three temperatures: $T-T_c=1$, 2, and 3.8°. At $T-T_c=7.2°$ the critical field could not be determined because right up to $H=500$ Oe the value of P_A rose proportionally to the applied field.

The field H_{cr} introduced here represented the criterion of a change from weak to strong fields defined, in accordance with Ref. 4, by $g\mu H \ll T_c(\varkappa a)^{5/2}$ or $g\mu H\gg T_c(\varkappa a)^{5/2}$, where $T_c(\varkappa a)^{5/2}$ is the characteristic energy of the critical fluctuations, $\varkappa$ is the reciprocal correlation radius, and a is a constant of the order of the interatomic distance. Thus, H_{cr} is determined by the condition

$$g\mu H_{cr}\approx T_c(\varkappa a)^{5/2}. \tag{6}$$

If we substitute in the above formula the well-known temperature dependence of the correlation radius $\varkappa=a^{-1}\tau^{2/3}$, we find an expression for the critical field H_{cr} in which there should be a change in the dependence $P_A(H)$ and which can be written in the form

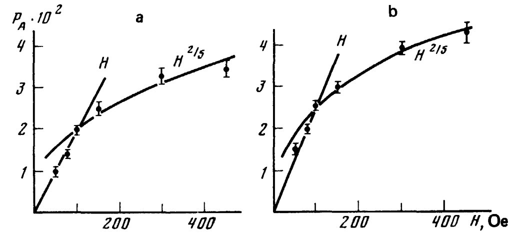

FIG. 5. Dependences of the asymmetry P_A on the applied field H for $\tau=2\times10^{-3}$ and $k\theta=2.25\times10^{-2}$ Å^{-1} (a) or $k\theta=3.4\times10^{-2}$ Å^{-1} (b).

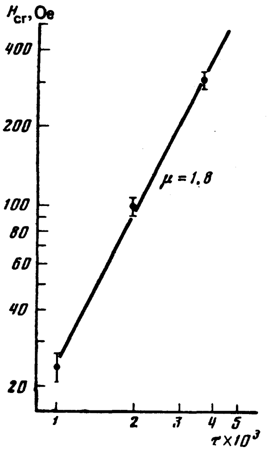

FIG. 6. Temperature dependence of the critical field H_{cr}, which obeys $H_{cr} = H_0\tau^{\mu}$, where $\mu = 1.8 \pm 0.2$, $H_0 = 6\ 10^6$ Oe.

$$H_{cr} = H_0\tau^{\mu}, \quad \mu = {}^5/_3. \tag{7}$$

Figure 6 shows the experimental dependence $H_{cr}(\tau)$, which was found to be close to a power law with an exponent $\mu = 1.8 \pm 0.2$, which agreed well (within the limits of the experimental error) with the theoretical value $\mu = 1.67$. The factor H_0 was found to be $H_0 = 6 \times 10^6$ Oe. Extrapolation of the experimental dependence (Fig. 6) to higher temperatures indicated that at $T - T_c = 7.2°$ the critical value should be $H_{cr} \approx 1000$ Oe. This estimate of H_{cr} was in agreement with the experimental results obtained at this temperature, because there were no deviations of $P_A(H)$ from linearity in fields up to 500 Oe.

We can thus conclude that the experimental results are in good agreement with the theoretical predictions of the behavior of the critical field with temperature. However, according to Eq. (6), $g\mu H_{cr}$ represents the characteristic energy of the critical fluctuations so that the experimental determination of H_{cr} gives essentially a direct estimate of the critical fluctuation energy.

4. VERIFICATION OF THE DIPOLE DYNAMICS

An excellent opportunity for a qualitative comparison of the theoretical predictions with the experimental results is provided by an analysis of the nature of the dependence $P_{\parallel}(\theta, \tau)$. According to the theory of Lazuta *et al.*,[4] both the form and nature of the temperature dependence $P_{\parallel}(\theta, \tau)$ are governed by the nature of the characteristic energy of critical fluctuations in the dipole region. We shall consider two variants of the dipole dynamics. In the first of them the energy of critical fluctuations in the dipole region has the form $\Omega \propto T_c(q_0 a)^{1/2}(\varkappa a)^2$ when $q \ll \varkappa \ll q_0$, where $q_0 = a^{-1}(\omega_0/T_c)^{1/2}$ is the dipole momentum, $\omega_0 = 4\pi\mu M_0$ is the dipole energy, and M_0 is the saturation magnetization. This form of Ω is obtained in the first order of perturbation theory[7] and is called conventional. In another variant,[6] an allowance is made for the interaction of fluctuations with one another and the energy of critical fluctuations is found to be $\Omega \propto T_c(q_0 a)^{3/2}\varkappa a$. This is known as the hard dynamics variant, which is distinguished from the conventional case by a higher power of q_0 in the expression for Ω and it represents stronger freezing if the dynamics when the dipole momentum q_0 obeys $\varkappa \ll q_0$, i.e., a harder spectrum of the critical fluctuations is predicted.

The theoretical analysis of Lazuta *et al.*[4] show that the dependence $P_S(k\theta)$ has a singularity which is entirely due to the hard dipole dynamics. This singularity represents the appearance of a maximum of $P_S(k\theta)$ at $k\theta \sim \varkappa$ together with a maximum at $k\theta \sim q_i$, where q_i is the characteristic inelasticity momentum amounting to $q_i \approx 6 \times 10^{-2}$ Å^{-1} in our case. Thus, the dependence $P_S(k\theta)$ should have a dip at $k\theta \sim q_0$. Experimental detection of this dip or, which is equivalent, of two maxima of $P_S(k\theta)$ would show unambiguously (without any additional analysis of the results) that the hard dynamics of the critical fluctuations applies.

In the experiments there was a systematic tendency for $P_S(k\theta)$ to decrease at $q \sim q_0$. Further measurements were made in order to improve the accuracy of P_S and P_A at $\tau = 1 \times 10^{-3}$ for $H = 16$ Oe. This gave the results shown in Fig. 7. They were obtained in four measurement runs in which a detector was displaced relative to the direct beam by half the distance between the neighboring counters so as to exclude the possible systematic errors due to differences between the counters. The results showed that a dip of P_S at $k\theta = q_0 = 3.8 \times 10^{-2}$ Å^{-1} was clearly present in spite of the fact that the accuracy of the experimental results was not very high. The difference between the maximum of $-P_S$ and the dip at $k\theta \approx q_0$ represented three standard errors. With this accuracy, one could say that the experimental results agreed with the hard variant of the dipole dynamics.

Another opportunity of determining the nature of the dipole dynamics was provided by a theoretical analysis of the temperature dependences of P_S and P_A for different ranges of $k\theta/\varkappa$. One could distinguish three cases in which an analysis of the critical dynamics should give rise to different temperature dependences $P_A \propto \tau^{-\alpha}$, i.e., different values of the power exponent α: the dynamics in the case of the exchange interaction alone, the conventional variant of the dipole dynamics, and the hard dipole dynamics. In all cases the theoretical prediction for $k\theta \gg \varkappa$ was the temperature dependence $P_A \propto \tau^{-2/3}$. For other values of $k\theta$ the power exponent α depended on the relationships between $k\theta$, $\varkappa$, q_0, and q_i, where q_0 was the dipole momentum introduced earlier and q_i was the characteristic inelasticity momentum deduced by equating the trans-

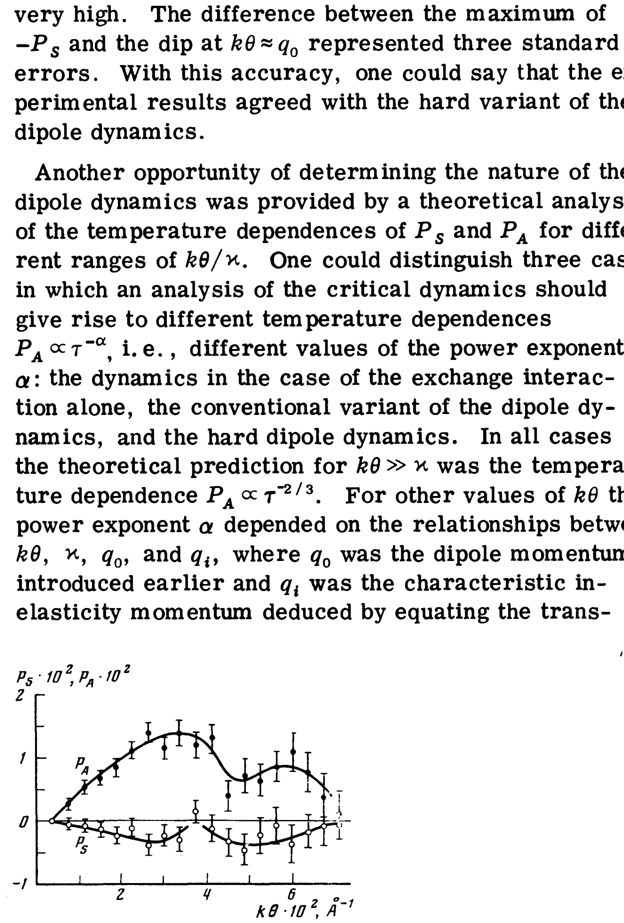

FIG. 7. Angular dependences of the symmetric P_S and asymmetric P_A effects for $\tau = 10^{-3}$, $H = 16$ Oe, and $H/H_{cr} = 0.8$.

ferred energy $\omega(q)$ to the energy of the critical fluctuations $\Omega(q)$ at $\theta=0$:

$$q_i=\frac{1}{a}\left(\frac{2E}{T_cka}\right)^{1/2}. \tag{8}$$

The theoretical values of the power exponent α corresponding to different ranges of $k\theta$ are as follows.

Exchange dynamics:

$$\alpha=-2,\quad k\theta \ll \underset{(0.6-17)}{q_0^4/(\varkappa q_i)^{3/2}};$$

$$\alpha=0,\quad \underset{(0.6-17)}{q_0^4/(\varkappa q_i)^{3/2}} \ll k\theta \ll \underset{(0.8-3.2)}{\varkappa}.$$

Conventional dipole dynamics:

$$\alpha=3,\quad k\theta \ll \underset{(0.14-1.2)}{(q_0/q_i)^{1/2}\varkappa^2/q_i};$$

$$\alpha={}^1/_3,\quad (q_0/q_i)^{1/2}\varkappa^2/q_i \ll k\theta \ll \varkappa.$$

Hard dipole dynamics:

$$\alpha={}^7/_3,\quad k\theta \ll \underset{(0.5-1.6)}{\varkappa(q_0/q_i)^{3/2}};$$

$$\alpha=1,\quad \varkappa(q_0/q_i)^{3/2} \ll k\theta \ll \varkappa.$$

Finally, in all the variants

$$\alpha={}^2/_3,\quad \underset{(0.75-4.9)}{k\theta} \gg \varkappa.$$

It should be pointed out that these values apply under asymptotic conditions defined by the inequalities given above and in reality the various ranges overlap, because $k\theta$, $\varkappa$, q_0, and q_i are not very different. (Estimated intervals, in units of 0.01 Å^{-1}, investigated experimentally at temperatures $10^{-3} \leqslant \tau \leqslant 7.5\cdot 10^{-3}$ are given in parentheses below the inequalities.) For this reason the theoretical dependences used in comparison with the experimental results are only approximate.

The experimental temperature dependences of P_A are plotted in Fig. 8. The statistical precision of the values of P_A determined in different fields H were averaged with respect to H. For example, in the range $H<H_{cr}$ the effect represented by P_A was proportional to H, so that the results were plotted as a dependence of the derivative dP_A/dH on τ. It is clear from Fig. 8 that the dependence $dP_A(\tau)/dH$ was close to the power law of the $\tau^{-\alpha}$ type. The values of the exponent α were $+0.9\pm0.1$, $+0.95\pm0.1$, $+1.1\pm0.1$, and $+1.2\pm0.1$ for $k\theta$ equal to 0.75, 1.5, 3.4, and 4.9 (all in units of 10^{-2} Å^{-1}), respectively.

It was not possible to find the temperature dependence of $P_A(\tau)$, i.e., the changes in the exponent α for different values of $k\theta$, from the experimental results. As pointed out earlier, this was due to the fact that the experimental conditions were not asymptotic and also because of three factors: the considerable indeterminacy in the experimental values of $k\theta$, the large width of the spectrum ($\Delta\lambda/\lambda\approx0.35$), and the strong vertical divergence of the beam ($\Delta\theta_x\approx2.5\times10^{-2}$). It was not possible to include properly these corrections to $P_A(k\theta)$, but it was known that the indeterminacy in $k\theta$ could reach $\Delta(k\theta)=(1-1.5)\times10^{-2}$ Å^{-1}. Hence, we concluded from the experimental results that the average value of the power exponent α in the investi‹ ›ted ranges of $k\theta$ and τ was $\langle\alpha\rangle\approx1\pm0.1$. In the theoretical asymptotes given above the value $\alpha=1$ corresponds to the

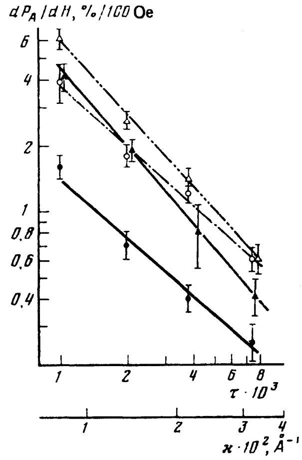

FIG. 8. Temperature dependences $dP_A/dH\propto\tau^{-\alpha}$ for four values of the quasielastic momentum $k\theta\times10^2$: ●) 0.75 Å^{-1}; ○)1.5 Å^{-1}; △) 3.4 Å^{-1}; ▲) 4.9 Å^{-1}. The slope averaged over all the values of $k\theta$ is $\langle\alpha\rangle=1\pm0.1$.

hard variant of the dipole dynamics. However, for the reasons listed above, we cannot yet say definitely that the experiment and theory agree. On the other hand, if we ignore the contribution of very small values $k\theta \ll 1\cdot10^{-2}$ Å^{-1}, the average value $\langle\alpha\rangle\approx1$ cannot be obtained from other variants of the theoretical predictions and this supports the hypothesis of the hard dynamics.

The experimental dependence $P_A\propto\tau^{-1}$ was confirmed also by an analysis of the temperature dependence $P_A(\tau)\propto\tau^{\beta}$ at $H=H_{cr}$. In fact, if $P_A\propto\tau^{-1}$ for $H=\text{const}$ in the region linear in H, then for $H=H_{cr}(\tau)$ we should have

$$P_A(\tau,H_{cr})\propto H_{cr}\,\tau^{-1}\propto\tau^{\mu}\tau^{-1}\propto\tau^{2/3}, \tag{9}$$

i.e., $\beta=2/3$. The relevant experimental results are given in Fig. 9. The slopes of the dependences $P_A(\tau)$ plotted on a logarithmic scale can be seen to exhibit a scatter from 0.57 to 0.73 for different values of $k\theta$ and the average value is $\langle\beta\rangle=0.63\pm0.03$, which is close to the expected value $\beta=2/3$. This result ensures consistency between the temperature and field dependences of the observed effect.

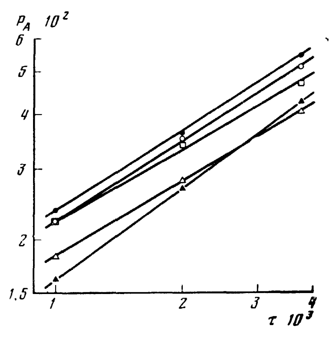

FIG. 9. Temperature dependence $P_A(\tau)=A\tau^{\beta}$ in a field $H=H_{cr}$ for different values of the quasielastic momentum $k\theta\times10^2$: ▲) 1.5 Å^{-1}, $\beta=0.73$; □) 2.25 Å^{-1}, $\beta=$ [illegible]7; [illegible] Å^{-1}, $\beta=0.63$; ○) 3.75 Å^{-1}, $\beta=0.63$; △) 4.5 Å^{-1}, $\beta=0.60$. The slope averaged over all the values of $k\theta$ is $\langle\beta\rangle=0.63\pm0.03$; $A=6\times10^{-7}$ Oe^{-1}.

It should be noted that in analyzing the experimental data we only allowed for the statistical experimental error. However, a systematic error could occur because of nuclear scattering (for example, by inhomogeneities in a sample) and this could result in apparent changes in the power exponents α and β. Such nuclear scattering is independent of the spin but in the calculation of P from Eq. (1) it would reduce the value of P by a factor $\sigma_m/(\sigma_n + \sigma_m)$ compared with the true value (here, σ_m and σ_n are the cross sections for the magnetic and nuclear scattering processes, respectively). This is particularly important at high values of τ, when σ_m is small, and it may result in an effective change of the total slope of the dependence $P_A(\tau)$ plotted on a logarithmic scale. Allowance for the nonmagnetic background in the critical scattering is quite difficult to make without analyzing the polarization. However, using the data on the cross sections at high temperatures ($T - T_c \approx 100°$) we can estimate possible corrections for the nuclear process. Such an analysis was made and it was found that the relative value of the corrections did not exceed 7–10% tending to reduce α and, consequently, to increase β. These corrections were compatible with the statistical error and did not alter the proposed interpretation of the results, and there was no need to obtain exact quantitative values of the average power exponents $\langle\alpha\rangle$ and $\langle\beta\rangle$.

5. VERIFICATION OF THE PRINCIPLE OF MERGING OF CORRELATIONS

Polyakov formulated the principle of merging of correlations in the theory of statistical similarity: this principle governs the behavior of the scattering amplitude of the critical fluctuations under conditions when the fluctuation pulses differ greatly from one another. In spite of the fact that this principle plays an important role in the theory of strongly interacting fields, no direct experimental verification has been attempted so far. Lazuta *et al.*[4] analyzed theoretically and angular and temperature dependence $P_{S,A}(\theta, \tau)$ throughout the whole critical range $k\theta \gg \varkappa$ essentially by generalizing this principle to triple dynamic vertices, i.e., to the amplitudes of an inelastic interaction of three critical fluctuations. It was found that if $k\theta \gg \varkappa$, then irrespective of the nature of the dynamics we should have $P_{S,A} \propto \tau^{-2/3}$. Moreover, it follows from the theory of Lazuta *et al.*[4] that if the principle applies, then the right-hand slope of $P_A(k\theta)$ in the range $q_0 < k\theta < q_i$ should exhibit a plateau, i.e., the value of $P_A(k\theta)$ should be practically constant in this range. Examination of Fig. 7 shows that in the region of $k\theta \approx 5\times10^{-2}$ Å^{-1} the dependence $P_A(k\theta)$ does indeed have an anomaly which is not in qualitative conflict with the prediction of a plateau: an estimate for iron gives $q_0 \approx 4\times10^{-2}$ Å^{-1} and $q_i \approx 6\times10^{-2}$ Å^{-1} (for $\lambda = 10$ Å). An extended horizontal region is not obtained in this interval only because the gap between q_0 and q_i is small and reliable conclusions can be obtained if this interval is extended by employing more energetic neutrons since $q_i \propto \lambda^{-2/3}$.

Our experimental temperature dependence $P_{S,A}(\tau)$ is outside the range $k\theta \gg \varkappa$ where, because of the above principle, we can expect $P_{S,A}(\tau) \propto \tau^{-2/3}$. The difficulty encountered in such measurements is that in obtaining the dependence on τ we have to investigate a sufficiently wide range of τ and the condition $k\theta \gg \varkappa$ should be satisfied for the largest values of $\varkappa$ in this temperature range. At high values of $k\theta$ there is a steep fall of the critical scattering cross section and measurements of this kind are possible only in the case of high-flux reactors. Acquisition of reliable data at high values of $k\theta$ will be the main task of future experiments.

6. CONCLUSIONS

We shall now formulate briefly the results of our investigation.

1. A high-speed system was assembled for investigating the scattering of polarized $\lambda = 10$ Å neutrons and this system could be used to study the critical phenomena in magnetic materials as well as to investigate nonmagnetic materials.

2. Experiments were carried out to determine the nature of the symmetry of the scattering of polarized neutrons in iron above T_c, which was detected by Okorokov *et al.*[3] It was found that the asymmetry appeared in the presence of the magnetization components m_z and for the initial neutron polarization P_{0z} parallel to the initial neutron wave vector k. This effect was explained by Lazuta *et al.*[4] by considering spin correlations in a magnetic field. The effect could be used, in particular, to study three-spin correlations.

3. An investigation was made of the asymmetry of the scattering of polarized neutrons in iron in the ranges $\tau = (1-7.2)\times10^{-3}$, $k\theta = (0.75-7)\times10^{-2}$ Å^{-1}, and $H = 10-500$ Oe in order to compare the experimental results with the theory of Lazuta *et al.*[4]

4. It was found that in weak fields the asymmetry P_A increased proportionally to the applied field, but when H exceeded a certain critical value H_{cr}, the rise of the asymmetry slowed down. The experimental values of H_{cr} found by extrapolation were the same (within the limits of the experimental error) for scattering vectors in the range $k\theta = (0.75-4.5)\times 10^{-2}$ Å^{-1} and they depended on temperature as $H_{cr} = H_0\tau^{\mu}$. The value of the exponent $\mu = 1.8 \pm 0.2$ was in good agreement with the theoretical value $\mu = 5/3$. The factor H_0 was found to be $H_0 = 6\times10^6$ Oe.

5. The derivative dP_A/dH found in the range $H < H_{cr}$ could be represented in the form $A\tau^{-\alpha}$. The values of the power exponent α obtained experimentally were within the range $(0.9-1.2)\pm0.1$ for the scattering vectors $k\theta = (1.5-4.4)\times10^{-2}$ Å^{-1}.

6. An experimental study of the three-spin correlations based on determination of the scattering asymmetry in a magnetic field was found to have considerable advantages over the method proposed earlier for investigating these correlations in zero magnetic field,[1] because the measured effect was $P \sim 10^{-2}$, which was two orders of magnitude greater than the asymmetry in zero field.[2)]

7. This investigation demonstrated that it was realistic to expect to verify experimentally the predictions of

the principle of merging of correlations and to select between the two variants of the dipole critical dynamics which could not be done at present by any other methods. Measurements are needed both in the range of very low values of $k\theta$ with an angular resolution of $\Delta\theta \sim 1'$ (for $\lambda \approx 3$ Å) and at low values of τ right down to $\tau \leq 10^{-4}$, as well as at high values of $k\theta \approx 0.1-0.2$ Å^{-1} and $\tau \approx 0.1$. These measurements should be carried out using neutrons with a wide range of wavelengths ($1 \leq \lambda \leq 15$ Å) so as to obtain different values of q_i, and they should be made on different magnetic materials so as to vary the dipole momentum q_0.

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[2)]In connection with the above effect occurring for $P_0 \parallel \mathbf{q}$, which is called the parallel $P_{\parallel}$ effect, and its large magnitude, we are faced with the natural question whether the perpendicular effect $P_{\perp}$ observed by us in Ref. 2 for $P_0 \perp \mathbf{q}$ is perhaps the projection of $P_{\parallel}$ on a "skew" instrumental coordinate system.[2] For example, it is clear from Fig. 1 that the $P_{\perp}$ effect for $\lambda = 13$ Å has a considerable symmetric component $P_S^{\perp}$ which, in principle, may be a manifestation of the $P_{\parallel}$ effect. However, for $\lambda = 4$ Å and the experimental conditions of Ref. 2, we find that various estimates indicate that a possible admixture of the $P_{\parallel}$ effect to $P_{\perp}$ cannot exceed the experimental error in the observation of $P_{\perp}$. However, if the observed $P_{\perp}$ effect is regarded as spurious, it is necessary to assume in Ref. 2 that the deviation of the longitudinal axis of the sample from the vertical is $\varphi = 10-15°$ and that the detector system is inclined in the xy plane by 20–30°, which is impossible because all the angles were set in Ref. 2 to an accuracy at least 10 times better.

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