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исследований
дубна

E14-86-294

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ON THE OBSERVATION OF CROSSOVER CRITICAL BEHAVIOUR IN Ni BY μSR METHOD

Submitted to "Physics Letters A"

1986

The critival phenomena in isotropic Heisenberg ferromagnet Ni have been investigated in /1/ at $T>T_c$ via the muon spin relaxation (μSR) method. The investigation has been based on the temperature dependence measurement of the μSR rate Λ. The spin of a particular muon stopped in a magnetic sample under investigation interacts with fluctuating magnetic moments of surrounding electrons by dipole-dipole and hyperfine forces. It was supposed that the slowing-down of critical fluctuations would cause a strong increase in the relaxation rate Λ as temperature tends to the critical value $T \to T_c$. However, instead of a singular behaviour of Λ the following one has been observed in Ni /1/: after increasing in the reduced temperature range $10^{-2} \lesssim \tau$, $(\tau = T_c^{-1}(T-T_c))$, no visible alteration of Λ was practically revealed for $10^{-3} \lesssim \tau \lesssim 10^{-2}$. For $\tau \lesssim 10^{-3}$ no data have been reported in /1/. Below it will be shown that the observed temperature behaviour of Λ in Ni may be understood on the basis of recent theoretical and experimental results concerning critical phenomena in isotropic ferromagnets /2,3/.

The current theory (review /2,3/ and references therein) predicts existence of two dynamic critical regions. The first one is for $\tau \gg \tau_d$, where τ_d is some characteristic reduced temperature. It is described by the spin-conserving Heisenberg model and is called the exchange critical region. The second one, called the dipolar region, is for $\tau \ll \tau_d$. The critical phenomena in it are sufficiently influenced by dipolar forces which do not conserve an order parameter. Thus one should expect existence of crossover between two critical regimes in some temperature range near τ_d. As the approximate value of τ_d for Ni is $\tau_d \simeq 4 \cdot 10^{-3}$ /2/, the temperature range $10^{-3} \lesssim \tau \lesssim 10^{-2}$ with the above-mentioned unexpected temperature behaviour of Λ is the one where crossover features would manifest themselves. The recent perturbed angular correlation (PAC) experiment on Ni /3,4/ has confirmed this consideration. It is important to emphasize here that due to obvious proximity of the μSR and the PAC methods one should suppose a similar temperature behaviour of the μSR rate Λ and of the inverse nuclear relaxation time t_R^{-1} measured in the PAC experiment. Despite this proximity, however, the observed behaviour of Λ and t_R^{-1} in the crossover region in Ni have a pronounced distinction /1,3,4/. The reason for this distinction will be discussed quantitatively below.

Let us define the operator of a local magnetic field $\vec{B}(\vec{r},t)$ at a muon site $\vec{r}$ in a magnetic crystal. This field is produced by fluctuating electronic spins $\vec{S}(\vec{l},t)$ at the lattice sites $\vec{l}$ and is represented in a usual way ($\beta = x,y,z$):

$$B_\beta(\vec{r},t) = -g\mu_B \sum_{\vec{l}} \sum_{\xi=x,y,z} F_{\beta\xi}(\vec{l}-\vec{r})\, S_\xi(\vec{l},t). \qquad (1)$$

Here μ_B and g are the Bohr magneton and the Lande factor. For the sake of brevity it is better to define the tensor $F_{\beta\xi}(\vec{l}-\vec{r})$ for the fcc lattive of Ni by means of its Fourier transform

$$F_{\beta\xi}(\vec{q}) = \frac{1}{\sqrt{N}} \sum_{\vec{l}} e^{i(\vec{q}\vec{l})} F_{\beta\xi}(\vec{l}) = \qquad (2)$$
$$= \frac{4\pi}{v_0}\left(\frac{1}{3}\delta_{\beta\xi} - q_\beta q_\xi / q^2\right) + \frac{1}{v_0} A_{hf}\, \delta_{\beta\xi},$$

where N is the number of magnetic atoms in the crystal, v_0 is the volume per magnetic atom and the wave vectors $\vec{q}$ are restricted by $0 < |\vec{q}| \ll v_0^{-1/3}$. The first term in (2) arises due to dipole-dipole interaction and the second term - due to hyperfine one. To estimate the hyperfine field coupling constant A_{hf} one should use the known values of the hyperfine field affecting a muon in Ni. This field has been measured both at $T<T_c$ /1/ and at $T>T_c$ /5/. With the available data observed in /1/ a simple calculation yields $A_{hf} \simeq -0{,}19 \cdot 8\pi/3 \simeq -1{,}5$. Analogously, from /5/ one deduced $A_{hf} \simeq -1{,}4$. It is very important that there is no singificant temperature alteration of A_{hf} (and, hence, of $F_{\beta\xi}(\vec{q})$) in the critical point T_c.

As is well-known /6/, the fast fluctuating magnetic field $\vec{B}(\vec{r},t)$ evokes muon polarization damping of the exponential type $P_\alpha(t) = \exp(-\Lambda_\alpha t)$. Here the index α denotes the observation direction chosen along the initial muon polarization. The relaxation rate Λ_α may be expressed in the following form

$$\Lambda_\alpha = c N^{-1} \sum_{\beta \neq \alpha} \sum_{\gamma\xi} \sum_{\vec{q}} F_{\beta\gamma}(\vec{q}) F_{\beta\xi}(-\vec{q})\, S^{\gamma\xi}(\vec{q}, \omega=0), \qquad (3)$$

where $c = \pi \gamma_\mu^2 g^2 \mu_B^2$, γ_μ is the muon gyromagnetic ratio and the wave vectors $\vec{q}$ run over the first Brillouin zone. The spin-spin correlation function $S^{\gamma\xi}(\vec{q},\omega)$ for the γ-th and ξ-th spin components describing the critical fluctuations of the wave vector $\vec{q}$ and the frequency ω has a usual form /7/. As critical fluctuations of sufficiently small $\vec{q}$ contribute to (3) one can use the form (2) for $F_{\beta\xi}(\vec{q})$. To elucidate the origin of expression (3) it is useful to compare (3) with the well-known results obtained by Moriya /8/ in the NMR theory for the inverse relaxation times $T_{1,2}^{-1}$. Expression (3) may be considered as a generalization of these results to the case of the zero external magnetic field. Moreover, the inverse time t_R^{-1} measured in the PAC experiment, may be expressed like Λ_α by means of (3). To do this one should make the substitution $F_{\beta\xi}(\vec{q}) \to \delta_0^{-1} A_{hf}^{PAC} \delta_{\beta\xi}$ with the appropriate constant A_{hf}^{PAC}, as the interaction of relaxing nuclear spin with surrounding electron moments is considered to be pure hyperfine and isotropic.

To extract temperature dependence of Λ_α let us begin with the exchange region where critical fluctuations are isotropic, and $S^{\gamma\xi}(\vec{q},\omega)$ is given by /9/:

$$S^{\gamma\xi}(\vec{q},\omega) = \frac{2\pi}{\omega_\varkappa(\vec{q})} S_\varkappa(\vec{q}) f_\varkappa\left[q, \frac{\omega}{\omega_\varkappa(\vec{q})}\right] \delta_{\gamma\xi}. \quad (4)$$

According to the scaling theory /7,9/ one has

$$S_\varkappa(\vec{q}) = q^{-2+\eta} g(q/\varkappa),$$
$$\omega_\varkappa(\vec{q}) = q^{z} \Omega(q/\varkappa), \quad (5)$$

where $g(q/\varkappa)$ and $\Omega(q/\varkappa)$ are the scaling functions. Temperature dependence of (4) and (5) is governed by the inverse correlation length $\varkappa$ with the asymptotic form $\varkappa = a^{-1}\tau^{\nu}$ /2/, where a is the length of the order of the lattice constant /2/. Here η, ν are the universal static exponents and z is the dynamic exponent. For isotropic three-dimensional ferromagnets one adopts $\nu \simeq 0,7$ and $\eta < 0,1$. Besides, the value of z is conventionally adopted to be $z \simeq 5/2$ in the exchange region /2/. Now it is essential to emphasize that as τ decreases, the summation over q in (3) is increasingly weighted by smaller $\vec{q}$ /10/. So, turning to the dipolar region, one should take into account two facts. First of all, the dynamic exponent z changes to the value $z \simeq 2$ /11/. Secondly, correlation function (4) must contain the factor $[\delta_{\gamma\xi} - q_\gamma q_\xi/q^2]$ instead of $\delta_{\gamma\xi}$, as longitudinal spin fluctuations of small $\vec{q}$ are suppressed by dipolar forces /12/.

In order to reveal temperature dependence of Λ_α in both critical regimes one should substitute (4) and (5) into (3) and replace the summation over $\vec{q}$ by the integration over the spherical Brillouin zone. The result is the power law behaviour

$$\Lambda_\alpha = \lambda \tau^{-n}, \quad (6)$$

where

$$n = \nu(z - \eta - 1) \quad (7)$$

$$\lambda = \lambda_0 \sum_{\beta\neq\alpha} \sum_{\gamma\xi} \int_{4\pi} d\Omega_{\vec{x}}\, P_{\gamma\xi}(\vec{x}) F_{\beta\gamma}(\vec{x}) F_{\beta\xi}(-\vec{x}). \quad (8)$$

Here $\vec{x} \equiv \vec{q}/q$, $P_{\gamma\xi}(\vec{x})$ is equal to $\delta_{\gamma\xi}$ in the exchange region and to $[\delta_{\gamma\xi} - x_\gamma x_\xi]$ in the dipolar one. The integration $\int d\Omega_{\vec{x}}$ must be evaluated over the whole spherical angle in the Brillouin zone. A slowly varying value λ_0 in (8) is written as

$$\lambda_0 = c a^{z-\eta-1} \int_0^\infty dx\, x^{\eta-z} g(x) f(x,0) \Omega^{-1}(x). \quad (9)$$

As we see, the results are independent of observation direction, which is a consequence of isotropy of critical phenomena in Ni in the zero external magnetic field.

Analyzing obtained expressions (6)-(9), one may easily see that, first of all, the critical exponent n, characterizing divergence of the μSR rate Λ, changes from $n \simeq 1$ in the exchange region to $n \simeq 0,7$, in the dipolar one. The analogous exponent measured in the PAC experiment is shown /3,4/ to be subjected to the same alteration. An additional and distinguished feature of the μSR rate behaviour in Ni is strong reduction of the coefficient λ in (6) as temperature decreases and passes through the crossover region. To be convinced of this one should make use of (8) and (2), where $A_{hf} \simeq -1,5$. The result is

$$\frac{\sum_{\beta\neq\alpha} \sum_{\gamma\xi} \int_{4\pi} d\Omega_{\vec{x}} [\delta_{\gamma\xi} - x_\gamma x_\xi] F_{\beta\gamma}(\vec{x}) F_{\beta\xi}(-\vec{x})}{\sum_{\beta\neq\alpha} \sum_{\gamma} \int_{4\pi} d\Omega_{\vec{x}} [F_{\beta\gamma}(\vec{x})]^2} \approx 0,11. \quad (10)$$

Thus, if in the exchange region $\lambda = \lambda^{(ex)}$ than in the dipolar one $\lambda = \lambda^{(dip)} \simeq 0,11 \lambda^{(ex)}$. This additional temperature reduction of λ by a factor of ten is a consequence, firstly, of mixed dipolar and hyperfine (not pure isotropic hyperfine, as in the PAC experiment) nature of the probing spin interaction (1), (2) with critical fluctuations, and, secondly, of suppression of longitudinal fluctuations. The strong decrease of λ in (6), obtained here, leads to softening of singular dependence of Λ which appears in τ^{-n} as $\tau \to 0^+$. It is probably just the same softening as the one observed in Ni for $10^{-3} \lesssim \tau \lesssim 10^{-2}$ /1/. Now it is very desirable to carry out similar μSR measurements in Ni for $\tau < 10^{-3}$. There one should expect reaching the dipolar critical regime with the law

$$\Lambda^{(dip)} \simeq 0{,}11\, \lambda^{(ex)}\, \tau^{-0{,}7}.$$

The author wishes to thank A.V.Lazuta, S.V.Maleyev and B.P.Toperverg for many helpful discussions.

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Received by Publishing Department on May 6, 1986.

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К наблюдению кроссовера критических явлений в Ni методом μSR

Развита теория спиновой релаксации положительных мюонов в изотропных ферромагнетиках вблизи температуры фазового перехода T_c. На основе гипотезы о скейлинговом поведении критических магнитных явлений вблизи T_c выведено степенное поведение скорости мюонной релаксации $\Lambda = \lambda \tau^{-n}$, где $\tau = T_c^{-1}(T - T_c)$. Показано, что в обменном режиме критический показатель $n \simeq 1$, в дипольном режиме $n \simeq 0{,}7$. Кроме того, для никеля получено, что подавление продольных критических флуктуаций при прохождении температуры через область кроссовера между двумя режимами приводит к сильному уменьшению величины коэффициента λ. Такое сокращение λ позволяет объяснить ярко выраженную особенность температурной зависимости $\Lambda(\tau)$, измеренной в никеле. Количественно обсуждается соответствие между экспериментальными данными для никеля, полученными методом мюонной спиновой релаксации и методом возмущенных угловых корреляций.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1986

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On the Observation of Crossover Critical behaviour in Ni by μSR Method

The theory of positive muons spin relaxation has been developed for the case of isotropic ferromagnets near the phase transition temperature T_c. The power temperature dependence $\Lambda = \lambda \tau^{-n}$, where $\tau = T_c^{-1}(T - T_c)$ for muon spin relaxation rate Λ has been derived on the basis of scaling hypothesis concerning critical magnetic phenomena near T_c. It is shown that $n \simeq 1$ in the exchange critical regime and $n \simeq 0{,}7$ in the dipolar one. Besides, the suppression of longitudinal critical fluctuations is obtained to lead to the strong reduction of the coefficient λ as the temperature passes through the crossover region between two regimes. This reduction of λ allows elucidating an unexpected temperature behaviour of Λ measured in nickel. A correspondence between experimental data for Ni via muon spin relaxation method and perturbed angular correlation method are discussed on the quantitative basis.

The investigation has been performed at the Laboratory of Nuclear Problem, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1986