Multiple small angle neutron scattering in ferromagnets

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The conclusions of the multiple small angle neutron scattering theory, developed recently by Maleyev, Pomortsev, and Skryabin (MPS) for the Born parameter \( \alpha \gg 1 \) are experimentally confirmed by magnetic scattering from domain structure of pure Fe and Ni, as well as Fe\(_{65}\)Ni\(_{35}\) alloy. The crossover from multiple refraction to multiple Fraunhofer diffraction is found at a critical thickness, \( L_0 \), where the neutron beam broadening \( w \) vs. sample thickness \( L \) changes from \( w \sim \sqrt{L} \) to \( w \sim L \).

Small angle neutron scattering measurements on unmagnetized ferromagnetic materials accompany by additional broadening of the incident neutron beam due to multiple magnetic scattering on domain structure. There are some theoretical approaches to describe the analogical broadening for nonmagnetic materials in a diffraction range. Recently a new theory was developed in [6] for a refraction regime of scattering, where the mean free path of neutrons \( l \) essentially more than an inhomogeneity radius \( R (l \gg R) \).

According to this theory the multiple neutron scattering intensity \( I(q, L) \) can be considered for two extents of sample thickness \( L < L_0 \) and \( L > L_0 \), where the critical sample thickness \( L_0 \) is given by \( L_0 = l\alpha^2 \ln \alpha \) and \( \alpha = \text{Const} \lambda R U \). At \( L = L_0 \) the crossover from the multiple refraction effect to the multiple Fraunhofer diffraction turns out. Respectively the broadening of incident neutron beam \( q_1 = (\alpha/2R) [(L/l) \ln (L/l)]^{1/2} \) is changed to \( q_2 = (1/2R) (1 + 1/\pi) (L/l) \).

For magnetic neutron scattering we can write the potential energy as \( U = -\mu_n \delta B \), where \( \mu_n \) is the neutron magnetic moment and \( \delta B = B_1 - B_2 \) the magnetic contrast. Considering ferromagnetic domain as inhomogeneity within two component model, we can write \( B_1 = -B_2 \) and \( \delta B = 2B \), while the mean free path for spherical inhomogeneities of radius \( R_{\text{eff}} \) is expressed as \( l = 2R_{\text{eff}} \mu V = 2R_{\text{eff}} \mu \), where \( V \sim R_{\text{eff}}^3 \) is the sample volume and \( \delta V = V/2 \) the part occupied by inhomogeneities. Therefore the condition \( l > R \) of availability of MPS theory is valid for a multidomain structure.

To verify the theory we have performed experiments on thickness dependence of incident neutron beam broadening intensities in ferromagnetic pure iron, nickel and Fe\(_{65}\)Ni\(_{35}\) disordered alloy by using the small angle neutron scattering diffractometer with \( \lambda = 0.5 \) nm, installed on IVV-2M reactor. To obtain the highest broadening of neutron beam the plates of samples were subjected preliminary to a 15-20\% impact-plastic deformation at room temperature. The magnetic domain structure of as-deformed iron samples was changes by annealing of samples at 1000 K. All measured small angle neutron scattering in these materials have a magnetic nature because the intensity disappear when the magnetic saturation state occurs in a sample.

Fig. 1 shows neutron beam broadening as a function of thickness for deformed and annealed iron samples. Here the broadening is \( w = \frac{1}{2\pi} q = (w_1^2 - w_0^2)^{1/2} \), where \( w_1 \) is the full width at the half-height of the measured beam intensity maximum, \( w_0 \) is the incident beam width. It is seen that the dependence of \( w \) on sample thickness is described by a power law \( w(L) \sim L^\beta \), which has a break in logarithmic scale for the deformed iron at \( L_0 = 1.55 \) cm, where \( \beta = 1/2 \) when \( L < L_0 \) and \( \beta = 1 \) when \( L > L_0 \). This break disappears when we change the size of magnetic domains by

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annealing. On the contrary the break occurs for pure Ni when we change the wave length from $\lambda = 0.5$ nm up to $\lambda = 0.16$ nm. Some standpoint for invar alloy do not change the linear dependence of the broadening vs. thickness (Fig.2).

The incident beam broadening vs. thickness curves allows evaluation of the effective domain radius and magnetic contrast. Taking into account the additional relation between $R_{\text{eff}}$ and $l$ we have obtained for pure iron $R = 18 \mu$m and $\delta B = 35$ kGs. It is seen that $\delta B$ occurs to be close to twice induction $B$ on this materials. For Fe$_{65}$Ni$_{35}$ alloy the both linear dependencies $w(L)$ obtained at different wave length of neutron give us the values of $R_{\text{eff}}$ close to each other $R \simeq 19 \mu$m ($\lambda = 0.5$ nm) and $R \simeq 23 \mu$m ($\lambda = 0.175$ nm). Using the experimental induction value $B \simeq 5$ kGs for this alloy we have obtained $L_0 \simeq 0.06$ cm, a value what is much less than the smallest sample thickness (0.2 cm), used in our measurements.

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