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MODEL FOR MAGNETOELASTIC INTERACTIONS IN CHROMIUM AND ITS AFM ALLOYS

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Abstract. – A theoretical model for the ultrasonic attenuation and elastic constants in chromium and its alloys, near the Neel transition is proposed. The model is based on the thermodynamics of a magnetic system under applied acoustic field. The calculated attenuation and longitudinal elastic constant show a good agreement with the experimental values.

The peculiar itinerant incommensurate antiferromagnetic (AFM) state in chromium and its dilute alloys have an extensive literature on experimental and theoretical aspects, however, many basic questions still remain unresolved [1].

At present, none of the available theories explain the observed ultrasonic attenuation near the Neel temperature, neither for chromium nor for its alloys. It is the aim of this paper to propose a model with a simple mechanism which describes resonably well, not only the ultrasonic attenuation, but also the elastic constant. Experimental data is shown for chromium, Cr-0,67 % V and Cr-1,5 % V samples.

Its is well known by neutron diffraction that chromium and its AFM alloys form an itinerant spin-density-wave (SDW) which is transversely polarized for temperatures between 123 K and 311 K.

The magnetic structure consists of domains of the type \((Q_i, S_j)\), where \(Q_i = (2\pi / a) (1 \pm \delta)\) is a wave vector perpendicular to the spin directions \(S_j\) and parallel to the cube axis.

Ultrasonic studies [2, 3] revealed that only longitudinal stress waves parallel to \(Q\) are significantly affected by the magnetoelastic coupling around \(T_N\). Therefore, we consider only one dimensional interaction [4] between the elastic deformation and the AFM-SDW system.

From a macroscopic thermodynamical point of view, we propose a mechanism which takes into account the interaction of an ultrasonic longitudinal stress plane wave with the SDW based on the steps: i) the perturbing elastic wave modulates the magnetic ordering, i.e., the ultrasound modulates the staggered magnetic field \((H)\) and its correspondent magnetization \((M)\) at temperatures close to \(T_N\); ii) the constitutive equations for the stress, \(\sigma (\varepsilon, H)\), and magnetization, \(M (\varepsilon, H)\), where \(\varepsilon\) is the strain, define the coupling between magnetic and elastic systems; iii) Poisson’s equation, \(\nabla \cdot M = -\rho_m\), defines a density of carriers of magnetic order \(\rho_m\), together with the continuity equation \(\nabla \cdot J_m = \partial \rho_m / \partial t\) which defines a current of magnetic order. Current \(J_m\) contains a drift term, \((-\mu H)\), plus a diffusion term \((D \nabla \rho_m)\), where \(\mu (D)\) is the mobility (Diffusion constant).

The solution of the wave equation, together with the above considerations, is found by taking into account only linear terms. The elastic constant \(C_{11}\) and the ultrasonic attenuation \(\alpha\) are then given by:

\[
C_{11} = \rho v_0^2 \left[ 1 - R \frac{r^2 + \frac{w}{w_0} \left( \frac{w}{w_0} + \frac{w_c}{w} \right)}{r^2 + \left( \frac{w}{w_0} + \frac{w_c}{w} \right)^2} \right] \]  

(1)

and

\[
\alpha = \frac{w}{v_0} R \frac{r \frac{w_c}{w}}{r^2 + \left( \frac{w}{w_0} + \frac{w_c}{w} \right)^2} \]  

(2)

where, \(R = c^2 / 2C_{11}\chi\) and \(r = 1 - |v_d/v_0|\)

\(\rho\) = density of material

\(v_0\) = ultrasonic velocity on PM state

\(w\) = ultrasonic frequency

\(\chi = (\delta M / \partial H)\) magnetic susceptibility

\(\varepsilon = - (\delta M / \partial \varepsilon)\) magnetoelastic constant

\(v_d = -\mu H\) drift velocity

\(C_{11}\) = longitudinal elastic constant along [100] in the PM state

\(\rho_m\) = density of carriers of magnetic order.

These are the usual form for a wave propagating in a dissipative medium. Here, the lattice itself is not considered to dissipate energy, but the magnetoelastic coupling with the SDW system is what causes the energy losses. The frequencies \(w_c = \mu \rho_m^0 / \chi\) and \(w_0 = v_0^2 / D\) represent the relaxation due to local staggered field \(H\) and frequency of fluctuations due to gradient of carriers, respectively. The expressions (1) and (2) were examined to find the best parameters \(w_c\) and \(w_0\) so that the attenuation \(\alpha\) vs. \(r\) would resemble the experimental result \(\alpha\) vs. temperature, close
to $T_N$. The next step is to define a proper scale which would convert ($r$) on a Kelvin scale. This was done assuming that the local field ($H$) would be proportional to $|T - T_N|$, close to $T_N$. Once the temperature scale is found, the velocity is calculated by using the same parameters.

Figure 1 shows experimental data [5, 6] together with theoretical results on attenuation and on elastic constant $C_{11}$ as a function of $T - T_N$ for chromium and the alloys.

The experimental values show deviations as $T$ gets away from $T_N$, because the proposed mechanism is good only within limits where the stress wave can modulate the magnetic order.

Table I shows the fitting parameters $w_0$ and $w_e$ with $T_N$ for chromium and alloys.

It is worth notice that $w_0$ is the most sensitive parameter indicating that the diffusion coefficient $D$ is the contribution which dominates the behaviour close to $T_N$.

Table I. - Parameters for Cr$_{1-x}$V$_x$.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Cr</th>
<th>0.67 %V</th>
<th>1.5 %V</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_c$ (MHz)</td>
<td>$4.4 \times 10^6$</td>
<td>$7.00 \times 10^6$</td>
<td>$3.00 \times 10^3$</td>
</tr>
<tr>
<td>$w_0$ (MHz)</td>
<td>$2.51 \times 10^5$</td>
<td>$4.00 \times 10^9$</td>
<td>$4.00 \times 10^8$</td>
</tr>
<tr>
<td>$D$ (m$^2$/s)</td>
<td>$2.0 \times 10^6$</td>
<td>$1.23 \times 10^9$</td>
<td>$1.23 \times 10^3$</td>
</tr>
<tr>
<td>$T_N$ (K)</td>
<td>311</td>
<td>245</td>
<td>165</td>
</tr>
</tbody>
</table>

It is striking that from $D = 2 \times 10^6$ m$^2$/s for Cr the diffusion coefficient drops to 12.3 m$^2$/s for the alloy 0.67 % V. This can be explained by pinning effects due to the vanadium random distribution. The latter increase on $D$ for larger vanadium concentration is attributed to the lower temperature where $T_N$ occurs.

In conclusion, we have proposed a simple mechanism which describes both ultrasonic attenuation and elastic constants for chromium and its antiferromagnetic alloys.

An estimate of the behaviour of attenuation and elastic constant $C_{11}$ for other compositions can be made by interpolation of $w_0$ and $w_e$.

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