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TEMPERATURE AND MAGNETIC FIELD DEPENDENCE OF THE ELASTIC CONSTANTS IN Nd₃Se₄

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Abstract. – The elastic constants of Nd₃Se₄ show an anomalous behaviour above and below $T_c = 52$ K. Band effects are assumed to be the origin of the softening of $C'$ in the paramagnetic region. Below $T_c$ extra shifts arise from magneto-elastic coupling. An elastic hysteresis is observed which is directly related to the magnetic hysteresis loop.

The metallic rare earth chalcogenides of RE₃X₄ type have attracted thorough research work. Depending on composition these crystals can undergo superconducting, structural and/or magnetic phase transitions. As a common feature, marked elastic anomalies are observed in all these crystals in the cubic phase as well as in the ordered phase [1].

The present work is devoted to the study of elastic anomalies which appear in conjunction with a magnetic ordering transition. We report on results obtained from Nd₃Se₄ where a particular magnetic field dependence of the elastic constants has been observed.

Single crystals were grown by a Bridgeman-Stockbarger method. Using ultrasonic pulse overlap techniques the cubic elastic constants were measured as a function of temperature and of an external magnetic field. The ultrasonic experiments were complemented by magnetic measurements.

Nd₃Se₄ becomes ferromagnetic at $T_c = 52$ K [2]. The overall crystal field splitting of the Nd³⁺ ground state is roughly of same magnitude as the magnetic exchange interaction [2]. Approaching $T_c$ from above in zero magnetic field ($B_{ext} = 0$) the elastic constant $C' = (C_{11} - C_{12}) / 2$ softens by about 20% (Fig. 1). In the temperature range fairly above $T_c$ the renormalization of the shear elastic constant $C'$ can be quantitatively described by the deformation potential mechanism. In the scope of this model the softening of $C'$ originates from the redistribution of the conduction electrons between strain perturbed energy bands. This process seems to be a common feature of the metallic RE₃X₄ compounds [3]. The full line in figure 1 is the result of a fit on the basis of this model. $C_{44}$ remains unaffected because the trigonal shear does not couple to the $e_g$-band.

In the ferromagnetic phase ($T < T_c$) and without an external magnetic field ($B_{ext} = 0$) the anomalous behaviour of the elastic constants is governed by the coupling of the strain to the magnetization. The measured normalized extra-contribution to $C_{11}$ (Fig. 2) shows some correlation with the magnetization curve which roughly follows $B_{J=9/2}$. On the other hand, existing theories based on band or local models [4-6] do not fit satisfactorily the observed elastic behaviour.

Fig. 1. – Temperature dependence of the shear elastic constants $C'$ and $C_{44}$ of cubic Nd₃Se₄ in the paramagnetic phase above $T_c = 52$ K. The theoretical curve is based on the deformation potential coupling model.

Fig. 2. – Temperature dependence of the normalized relative change of the elastic constant $C_{11}$ in Nd₃Se₄ below $T_c = 52$ K. The reduced magnetization roughly follows the Brillouin function for $J = 9/2$ whereas $C_{11}$ is more close to $B_{J=3/2}$. 

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An external magnetic field \((B_{\text{ext}} \neq 0)\) affects the elastic constants in the paramagnetic phase as well as in the ferromagnetic phase. Above \(T_c\) the extra-shifts of the elastic constants display a \(B^2\)-field dependence. The coupling coefficient is positive for \(C'\), negative for \(C_{44}\) and the absolute values decrease with increasing temperature.

In the ferromagnetic phase \((T < T_c)\) the magnetic field dependence of the elastic constants is distinguished by a hysteresis effect. This elasto-magnetic hysteresis is directly correlated with the magnetic hysteresis loop (Fig. 3). The change of the elastic constants is independent of the sign of the magnetization, therefore \(\Delta C\) is within a reasonable experimental error proportional to the field derivative \(dM/dH\) of the magnetic hysteresis. Passing from saturation to demagnetised state \((M = 0)\) the elastic constants are found either to increase or to decrease. For \(C'\) the sign of the elasto-magnetic hysteresis is a function of the relative orientation of the magnetic field to the polarization plane of the shear wave. \(C_{44}\) always increases whereas \(C_{11}\) (Fig. 3) always decreases with increasing magnetic field amplitude. The total changes of the elastic constants in the first magnetization process are up to three times larger than those in the subsequent magnetization cycles.

The observed elasto-magnetic hysteresis obviously arises from domain-wall movements which can affect the ultrasonic measurement in three ways. At first, length changes of the crystal by magnetostriction can simulate a variation of the sound velocity, which would modify all elastic constants in the same direction. Secondly, the local stress associated with the ultrasonic wave can create elastic and magneto-elastic strain in the ferromagnetic sample [7]. This mechanism which is of same origin as the \(\Delta E\)-effect would reduce the elastic constants in the magnetized state by a smaller amount than in the demagnetized sample as it is observed for \(C_{11}\) (Fig. 3). Thirdly, the magnetostrictive stress changes the elastic properties in higher order (third order elastic constants). This mechanism depends on the sign of the magnetostriction as well as on the sign of the third order elastic constants. A final analysis therefore requires at least the knowledge of the magnetostriction constants by an independent measurement which are not yet available at present.

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