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Spectroscopy of local impurity levels in antiferromagnetic chromium alloys

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Abstract. The energy difference δE between the local impurity state levels in the spin-density-wave (SDW) alloys, Cr + 1.3 at.% Si and Cr + 2.7 at.% Fe, is estimated from interval δx between the peaks in the residual resistivity as the Fermi level E_F is tuned by doping with low concentrations x of V or Mn. The measured variation with doping of the SDW wavevector in Cr and the spin-wave velocity in Cr(Mn) are used to estimate dE_F/dx , and hence obtain δE from δx . The ratio of δE to the energy gap 2Δ determined from the infrared reflectivity gives the scattering parameter between the nesting parts of the Fermi surface.

1. Introduction

The concept of local impurity states within the energy gap of a commensurate spin-density-wave (SDW) system was first introduced by Volkov and Tugushev (1984). They showed that resonant scattering of conduction electrons at these states may lead to greatly enhanced zero-temperature impurity scattering. This impurity resonance scattering (IRS) model was employed by Galkin *et al* (1986) and Galkin (1987) to explain the variation of the low temperature residual resistivity R_0 of the SDW alloys, Cr + 1.3 at.% Si and Cr + 2.7 at.% Fe, when the Fermi level was 'tuned' by doping with V or Mn. The two peaks found for each alloy, as shown in figure 1 in a plot of $R_0(x)$ versus the electron concentration x , are identified with the IRS as the Fermi level passes through the upper (Mn doping) and lower (V doping) impurity levels.

In this paper we translate the interval δx between the concentrations at which peaks occur in the residual resistivity into the energy interval δE between the two impurity levels. We employ for this analysis the measured rate of change dQ/dx of the SDW wavevector Q with Mn and V doping (Koehler *et al* 1966, Komura *et al* 1967), and the spin-wave velocity c_s measured in the commensurate SDW system $\text{Cr}_{1-x}\text{Mn}_x$, with x ranging from 1.6 to 5 at.% Mn (Sinha *et al* 1969, 1977; Als-Nielsen *et al* 1971).

The resultant value of δE is compared with the energy gap 2Δ of the host commensurate SDW alloy obtained from the infrared reflectivity. Their ratio determines the potential impurity scattering parameter g_0 , which in the theory of Volkov and Tugushev (1984) determines the position of the impurity level relative to the gap centre.

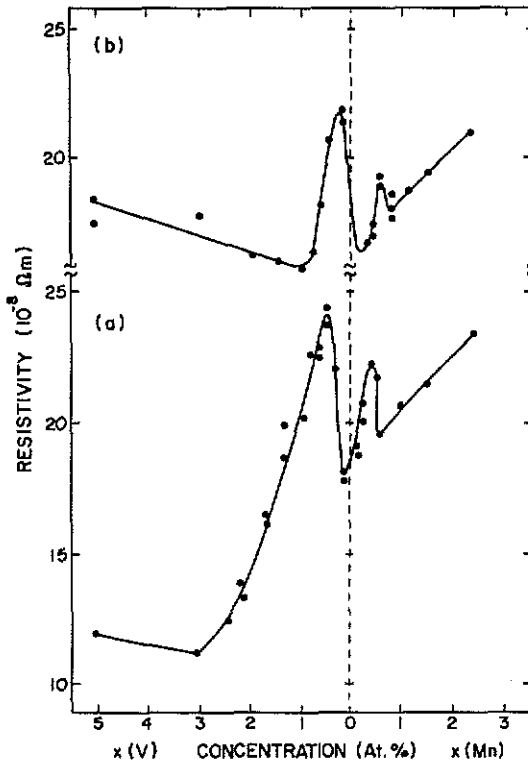


Figure 1. Concentration dependence of the residual resistivity at temperature 4.2 K of the Cr SDW alloy systems: (a) Cr + 2.7 at.% Fe; (b) Cr + 1.3 at.% Si, doped with V or Mn (from figure 1 of Galkin 1987; note that the caption to this figure incorrectly labels curve 1 (the present curve 6) as being data for Cr + 1.3 at.% Fe).

2. Experiment

According to the Overhauser (1962) model of itinerant antiferromagnetism, the spin-wave velocity for nesting electron and hole spheres (Fedders and Martin 1966), which is a rough approximation to the actual nesting Fermi surfaces in chromium (see Fawcett 1988), is given by the expression

$$c_s = \left(\frac{1}{3}v_e v_h\right)^{1/2} \quad (1)$$

If the electron and hole velocities, v_e and v_h , respectively, are assumed to be equal, c_s provides a measure of dE/dk , the wavevector dependence of the energy at the Fermi surface, and hence of dQ/dE , since reference to figure 50 of Fawcett (1988) shows that for this simple model

$$\frac{dQ}{dE} = 2 \frac{dk}{dE} = \frac{2}{\sqrt{3}} \frac{1}{\hbar c_s}. \quad (2)$$

If we assume the energy dependence of Q to be the same in the two SDW systems of interest, we obtain by combining dQ/dE with dQ/dx the dependence of the

Fermi level E_F on the concentration x of the dopants V and Mn. Thus the interval δx provides a measure of the energy difference between the two impurity levels

$$\delta E = \delta x \frac{\sqrt{3}}{2} \hbar c_s \frac{dQ}{dx}. \quad (3)$$

The experimental data for the wavevector Q in dilute binary and ternary alloys of Cr with V and Mn was represented by Komura *et al* (1967, figure 6) in the rigid band approximation, where each V and Mn atom contributes one hole and one electron per atom, respectively. Their plot of Q versus, $x = x(\text{Mn}) - x(\text{V})$, can be fitted by a linear relation over the range of x from -1.0 to 0.5 at.%, yielding a value, $dQ/dx = 0.020$ (at.%)⁻¹ (Griessen *et al* 1976).

A calculation in the random phase approximation of the enhanced paramagnetic susceptibility $\chi(q)$ of chromium gives a strong peak at a value of q corresponding to the nesting vector Q (Fry *et al* 1988). A comparison by Schwartzmann *et al* (1989, figure 3) of the dependence of Q on electron concentration, with the experimental values for Q in Cr(V) and Cr(Mn) alloys shows that, $dQ/dx \simeq \frac{1}{3} dQ/dx$. This apparent discrepancy between theory and experiment should be resolved in a self-consistent calculation for antiferromagnetic Cr (Shibatani *et al* 1969), but it is clear that we must use in our calculations the experimental value dQ/dx for the SDW alloys rather than the theoretical value dQ/dx for the paramagnetic system.

The spin-wave velocity in the commensurate SDW alloy Cr(Mn) is, $c_s = 1.3 \times 10^5$ m s⁻¹ (Fawcett 1988, table 1). We note, however, that Gupta and Sinha (1971) estimated from a band-structure calculation a somewhat higher value, $c_s = 2.9 \times 10^5$ m s⁻¹. Liu (1981) apparently resolved this discrepancy between the measured and calculated values of c_s . He calculated the long wavelength part of the magnon dispersion curve by a method analogous to the 'frozen phonon' method for calculating lattice vibrational modes. The spin wave is regarded as setting up a static periodic spin deviation, and the increase in total energy of the electron system gives the corresponding spin-wave energy. The resultant spin-wave velocity differs from the expression given in (1) by a factor $[N(0)U]^{1/2}$, $N(0)$ being the density of states per spin of the nesting part of the Fermi surface and U an effective Coulomb function. Liu estimated this factor to be anywhere between 0.55 and 0.38 for Cr, using Kübler's (1980) calculated value, $U = 0.86$ eV, and estimating $N(0)$ to lie between 0.18 and 0.09 states eV⁻¹. When Gupta and Sinha's (1971) calculated value for the velocity is multiplied by this factor, the resultant values of c_s ranging from 1.1 to 1.6 m s⁻¹ agree well with the experimental values given by Fawcett (1988, table 1).

These experimental values, $dQ/dx = 0.020$ (at.%)⁻¹, in units of $2\pi/a$, with the lattice parameter, $a = 2.88 \times 10^{-10}$ m, and $c_s = 1.3 \times 10^5$ m s⁻¹, yield a value for the variation with doping of the Fermi energy of Cr, $dE_F/dx = 32$ meV (at.%)⁻¹. We assume the value to be the same for the two SDW alloys that we are considering.

In figure 1 the two peaks in the residual resistivity for the Cr(Si) system occur at

$$x_0(\text{Si}, \text{Mn}) = 0.55 \text{ and } x_0(\text{Si}, \text{V}) = 0.2,$$

giving

$$\delta x(\text{Si}) = x_0(\text{Si}, \text{Mn}) + x_0(\text{Si}, \text{V}) = 0.75 \text{ at.}\% \quad (4)$$

The corresponding peak concentrations for the Cr(Fe) system are

$$\delta x(\text{Fe}) = x_0(\text{Fe}, \text{Mn}) + x_0(\text{Fe}, \text{V}) = 0.4 + 0.45 = 0.85 \text{ at.}\% \quad (5)$$

These intervals in doping concentration, when substituted in (3), with the above values of dQ/dx and c_s , yield values for the energy interval between the local impurity states, $\delta E(\text{Si}) = 24$ meV and $\delta E(\text{Fe}) = 28$ meV.

A somewhat smaller value of $\delta E(\text{Fe})$ was obtained by Galkin *et al* (1986), who calculated the magnetic phase diagram for the canonical model of nesting electron (e) and hole (h) surfaces of unequal size and a reservoir (r), which was first introduced by Shibatani *et al* (1969), and was later elaborated by several authors. Comparison with the observed variation of the Néel temperature on doping with Mn or V give $|dE_F/dx| = 20$ meV at.-%⁻¹, so that $\delta x(\text{Fe}) = 0.85$ at.-% gives $\delta E(\text{Fe}) = 17$ meV. We shall use the somewhat larger value, $\delta E(\text{Fe}) = 28$ meV, since it is more firmly rooted in analysis of experimental data without the intervention of theory.

It is important to note that, according to this model, both impurity levels of Fe are well below the middle of the antiferromagnetic energy gap. Sato and Maki (1974) and Nakanishi and Kasuya (1977) found that the Fermi level in pure Cr is 82 meV below the middle of the gap, while Galkin *et al* fit the phase diagram of Cr(Fe) with the parameter, $dE_F/dx = 8$ meV at.-%⁻¹Fe, which gives the Fermi level of Cr +2.7 at.-% Fe as being 60 meV below the middle of the gap.

3. Theory

The first treatment of local impurity states in a commensurate SDW system having impurities at r_j , by Volkov and Tugushev (1984), employed the Hamiltonian of Nakanishi and Kasuga (1977) for the canonical model

$$H = \sum_{j,k,k',\mu,\nu} \exp[i(k-k') \cdot r_j] \times [(V_{ee})_{\mu\nu} a_{k'\mu}^* a_{k\nu} + (V_{hh})_{\mu\nu} b_{k'\nu}^* b_{k\nu} \delta + (V_{rr})_{\mu\nu} c_{k'\mu}^* c_{k\nu} + (V_{eh})_{\mu\nu} a_{k'\mu}^* b_{k\nu} + (V_{er})_{\mu\nu} a_{k'\mu}^* c_{k\nu} + (V_{hr})_{\mu\nu} b_{k'\mu}^* c_{k\nu} + \text{hermitian conjugate}] \quad (6)$$

$a_{k'\mu}^*$, $a_{k\nu}$ being creation and annihilation operators for the nesting electron surface, $b_{k'\mu}^*$, $b_{k\nu}$ for the nesting hole surface, and $c_{k'\mu}^*$, $c_{k\nu}$ for the reservoir.

The matrix elements

$$(V_{ij})_{\mu\nu} = V_{ij} \delta_{\mu\nu} + J_{ij}(S\sigma)_{\mu\nu} \quad (7)$$

correspond to scattering of electrons between electron, hole and reservoir parts of the Fermi surface labelled by the indices i, j (e, h or r) having spin in directions labelled μ, ν . S is the spin corresponding to the local moment on the impurity and σ is the polarization of the SDW. The first term in (7) corresponds to potential impurity scattering, for which the spin direction of the scattered carrier is unchanged, i.e., $\mu = \nu$, and

$$V_{ee} = V_{hh} \quad V_{eh} = V_{he} \quad V_{er} = V_{re} = V_{hr} = V_{rh}. \quad (8)$$

The second term in (7) corresponds to exchange impurity scattering, for which in general $\mu \neq \nu$, and

$$J_{ee} = J_{hh} \quad J_{er} = J_{re} = J_{hr} = J_{rh}. \quad (9)$$

The SDW system Cr(Fe) is unique in exhibiting a Curie-Weiss law for the temperature dependence of the susceptibility in the ordered phase (Newman and Stevens 1959). This shows that the Fe atoms, or perhaps pairs or clusters of atoms (Friedel and Hedman 1978), carry a local moment. It might be appropriate in the case of the Cr(Fe) system therefore to consider the general form of the scattering matrix elements given in (7), but we shall discuss only the simpler case when $J_{ij} \equiv 0$ and there is no exchange impurity scattering.

The density of states for the electron and hole surfaces, which are assumed to be equal, as appropriate for a commensurate SDW system, and for the reservoir, are, $\rho_e = \rho_h (= \rho_0)$, and ρ_r , respectively. The parameters used to describe the potential impurity scattering are

$$g_0 = 2\pi V_0 \rho_0 \quad V_0 \equiv V_{ee} = V_{hh} \quad (10a)$$

$$g_1 = \pi V_1 \rho_r \quad V_1 \equiv V_{rr} \quad (10b)$$

$$g_2 = 2\pi^2 V_2^2 \rho_0 \rho_r \quad V_2 \equiv V_{er} = V_{hr} \quad (10c)$$

The energy levels of the local impurity states are symmetric relative to the middle of the energy gap 2Δ , to which they are referred as energy zero, and in the case when $g_2 = 0$ are given by the expression

$$E_{\pm} = \pm \Delta \left(\frac{1 - g_0^2}{1 + g_0^2} \right) \quad (11)$$

which gives

$$g_0 = \left(\frac{1 - y}{1 + y} \right)^{1/2} \quad y = \frac{E_+ - E_-}{2\Delta} = \frac{\delta E}{2\Delta}. \quad (12)$$

In the case when $g_2 = 0$, the positions of the impurity levels are the same as in (11), but they have a finite width, which is given, in the approximation, $g_1 \ll 1$, by the expression

$$\nu_{\text{res}}^*(E) = \frac{1}{\pi \rho_r} \left(\frac{\gamma}{E - E_0 + i\gamma} \right) \quad (13)$$

where the energy level of the impurity state is, $E_0 = E_+$ or E_- . Volkov and Tugushev (1984) go on to show that the momentum relaxation time at temperature T is

$$\tau_{\text{res}} = \frac{\pi \rho_r}{2} \left[1 + \left(\frac{E_0 - E_F}{\gamma} \right)^2 + \frac{\pi^2 k_B^2 T^2}{3\gamma^2} \right] \quad (14)$$

where E_F is the Fermi energy.

The electrical resistivity at low temperature, $k_B T \ll \gamma \ll k_B T_N$, is of the form

$$R(T) = R_0^0 + R_{\text{res}}^0 + R_{\text{ph}}(T) + R_{\text{res}}(T) \quad (15)$$

where R_0^0 is the residual resistivity at zero temperature due to non-resonant impurity scattering and $R_{\text{ph}}(T)$ is due to scattering by phonons, which is of course a positive contribution. The new and interesting terms in (15) are those associated with impurity-resonance scattering (IRS) and include an additional contribution to the residual resistivity

$$R_{\text{res}}^0 = \frac{b}{1 + [(1/\gamma)(E_0 - E_F)]^2} \quad b = \frac{2m^*}{\pi e^2 \rho_r} \quad (16)$$

m^* being an average effective mass, and a negative temperature dependent contribution

$$R_{\text{res}}(T) = -\frac{axk_B^2 T^2}{1 + [(1/\gamma)(E_0 - E_F)]^2} \quad a = \frac{\pi^2 b}{3\gamma^2} \quad (17)$$

According to Galkin *et al* (1986), the IRS term R_{res}^0 in the residual resistivity is responsible for the peaks in $R_0(x)$ seen in figure 1. The energy interval δE , which we have deduced from the interval δx between the concentrations at which the peaks occur, is thus identified in the IRS model with the interval, $E_+ - E_-$, between the local impurity levels given in (11). The ratio of δE to the energy gap 2Δ is equated to y in (12), which thus provides a measure of g_0 .

The expression for δE , in the case when both exchange and potential scattering must be included, is given by Galkin *et al* (1986, equations (19) and (20)). It is necessarily more complicated and involves at least two scattering parameters that cannot be determined independently from the single experimental datum, the value of δE for each system. Thus although in the Cr(Fe) system the temperature dependence of the susceptibility shows that the Fe atoms (or clusters) carry a local moment, we shall assume of necessity that the exchange scattering is negligible, in order to estimate g_0 by use of (12).

We note furthermore that in the general case the two impurity state levels are asymmetric relative to the middle of the energy gap, though one level still occurs in the upper and the other in the lower half-gap. We do not understand why in the present case, as noted above, both levels appear to be in the lower half-gap in both Cr(Si) and Cr(Fe).

4. Analysis

Figure 2 shows the magnetic phase diagram for the two Cr alloy systems of interest, and also for the system Cr + 1.5 at.% Fe(V, Mn). Evidently the Cr + 1.3 at.% Si(V, Mn) system has an incommensurate SDW at low temperatures over a good deal of the region of interest, between 1.0 at.% V $\lesssim x \lesssim$ 0.2 at.% Mn.

The phase boundary at temperature T_{1C} between the incommensurate SDW phase AF_1 and the commensurate SDW phase AF_0 in $Cr_{1-y}Si_y$ alloys had been determined by the anomaly in the temperature dependence of the thermal expansion in the range $1.0 \leq y \leq 1.3$ at.% Si (Suzuki 1977), and was seen to extend beyond, $y \gtrsim 1.3$ at.% Si, in measurements of thermoelectric power (Arajs *et al* 1971), magnetic susceptibility (Hedman *et al* 1973) and neutron diffraction (Cable 1977, Endoh *et al* 1982). The

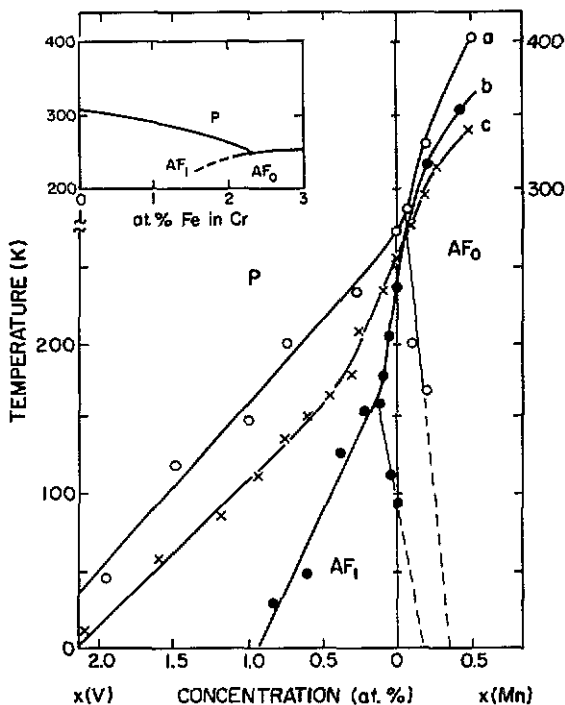


Figure 2. Magnetic phase diagram of the Cr SDW alloy systems: curve a, \circ , Cr + 1.5 at.% Fe; curve b, \bullet , Cr + 1.3 at.% Si; curve c, \times , Cr + 2.7 at.% Fe, doped with x at.% V or Mn. The lines are a guide to the eye. The magnetic phases are labelled: P, paramagnetic; AF_0 , commensurate SDW; AF_1 , incommensurate SDW (Galkin and Tugushev 1988, Galkin and Fawcett 1991). The inset shows the phase diagram of $Cr_{1-y}Fe_y$ compiled from all the available experimental data.

triple point is signalled also by the occurrence of a strong first order Néel transition at the P- AF_0 phase boundary, in contrast to the normal continuous (or weakly first order as in pure Cr) transition at the P- AF_1 phase boundary (Arajs and Katzenmeyer 1967, Hedman *et al* 1973, Suzuki 1977).

In $Cr_{1-y}Fe_y$ alloys the situation is somewhat different, since in this case the continuous Néel transition to the AF_1 phase was first seen in the thermal expansion by Ishikawa *et al* (1967) at a temperature 20 K above the strong first order transition to the commensurate phase, as illustrated in figure 2 in the inset phase diagram.

The phase diagrams for the Cr(Fe) and Cr(Si) alloy systems doped with V or Mn shown in figure 2 were also determined from the anomalies in the thermal expansion at the phase transitions (Galkin and Fawcett 1991). In the case of the Cr + 2.7 at.% Fe (V, Mn) system there appears not to be an AF_0 - AF_1 phase boundary, but the triple point may be identified as the point of maximum curvature of the P- AF_0 / AF_1 phase boundary to the paramagnetic phase, as for the other two systems shown in figure 2. This would be in accordance with the canonical model we are considering, and to which (6) applies, with the AF_0 - AF_1 phase boundary lying below the AF_0 phase (as for the two other ternary systems shown in figure 2) or alternatively below the AF_1 phase (as for $Cr_{1-y}Fe_y$ shown in the inset to figure 2), depending upon the values of the parameters in the theory of Nakanishi and Kasuya (1977), who explained

this remarkable feature of the phase diagram of $\text{Cr}_{1-y}\text{Fe}_y$. It seems likely that the $\text{AF}_0\text{-AF}_1$ phase boundary for this system is in fact roughly parallel to the temperature axis, which would account for its not being seen in the temperature dependence of the thermal expansion. Further evidence for there being a triple point at about the composition, Cr +2.7 at.% Fe (0.3 at.% V), is provided by the occurrence of a first order Néel transition for lower concentrations of V, $x(\text{V}) < 0.3$ at.%, and a continuous transition for higher, $x(\text{V}) > 0.3$ at.% (Fawcett and Galkin 1991), by analogy with $\text{Cr}_{1-y}\text{Fe}_y$ (Fukamichi and Saito 1977).

Thus the Cr +2.7 at.% Fe (V, Mn) system probably has a commensurate SDW at low temperatures over more than half the region of interest, but for alloys of composition around the peak in the residual resistivity at $x \simeq 0.45$ at.% V, as seen in figure 1, and for higher values of $x(\text{V})$, the SDW is incommensurate.

The Volkov-Tugushev theory, however, refers to a commensurate SDW system. In the case of an incommensurate SDW alloy, with impurity atoms at random locations relative to the antinodes of the SDW, the impurity levels are predicted by Buzdin *et al* (1986) to spread right across the energy gap. This would presumably make the phenomena associated with resonant scattering at a single impurity level unobservable. In practice, however, the phase of the incommensurate SDW might adjust in response to the perturbation produced by the impurity atoms, so that there would be some correlation between their location and the antinode of the SDW.

This is the explanation proposed by Major *et al* (1986) for their observation of a sharp spin precession line in pure Cr in zero magnetic field. The precession frequency of the muon corresponds to that expected at an interstitial site near the antinode of the SDW. It is speculated that the charge-density wave that accompanies the SDW in Cr (Pynn *et al* 1976) minimizes its Coulomb energy with the positive muon by adjusting its phase to bring the negative antinode close to the muon site. An alternative picture in the case of the muon, but obviously not that of the impurity, is that the muon migrates to the antinode of the CDW.

In figure 1 the IRS peaks for both the Mn-doped commensurate SDW alloys are in fact somewhat narrower than for the V-doped incommensurate SDW alloys. The amplitude of the IRS peak for the Mn-doped alloys is however considerably smaller than for the V-doped alloys, so that the *relative* width of the IRS peaks for the commensurate and incommensurate SDW alloys is roughly the same. In the SDW alloy system, Cr +3.2 at.% Co (V, Mn), both the IRS peaks are quite narrow, though one of them appears to be in the incommensurate SDW phase (Galkin and Tugushev 1991, figure 16). The experimental evidence, on the whole, seems to validate the application of the Volkov-Tugushev theory for a commensurate SDW to at least these incommensurate SDW alloy systems.

A further difficulty arises in the analysis of the data in that the infrared reflectivity experiments for incommensurate SDW Cr alloys indicate the existence of two energy gaps. The experimental evidence is provided in the papers referred to in table 1 and figure 3. In pure Cr itself the evidence for the two gaps is quite convincing (see Fawcett 1988). The systems $\text{Cr}_{1-y}\text{Fe}_y$ (Lynch *et al* 1975) and $\text{Cr}_{1-y}\text{Al}_y$ (Lind and Stanford 1984) show clearly the progression from the single energy gap, $2\Delta \lesssim 0.4$ eV, in the incommensurate SDW alloys, to the two energy gaps, $2\Delta_1 = 0.12$ eV and $2\Delta_2 = 0.45$ eV, in the commensurate SDW alloys.

The experimental results illustrated in figure 3 show another interesting feature of these infrared reflectivity data. The energy gap 2Δ in the commensurate SDW alloys is roughly constant, $2\Delta = 0.35 \pm 0.5$ eV, with the exception apparently of Cr

+15 at.% Re. The lower energy gap $2\Delta_1$ in the incommensurate SDW alloys, on the other hand, is found to be proportional to the Néel temperature T_N . This is to be expected for an itinerant electron antiferromagnet resulting from the condensation of electron-hole pairs, since the theory is formally analogous to the BCS theory of superconductivity (Overhauser 1962, Fedders and Martin 1966). The constant of proportionality between the energy gap and the Néel temperature is found to be, as illustrated in figure 3, a value somewhat larger than the value 3.5 for this ratio predicted for a weakly-coupled superconductor (Bardeen *et al* 1957).

Table 1. Energy gaps $2\Delta_1$ and $2\Delta_2$ for incommensurate spin-density-wave chromium alloys determined from the low-temperature infrared reflectivity.

Alloy $\text{Cr}_{1-x}\text{A}_x$		Energy gaps	
Solute A	x (at.%)	$2\Delta_1$ (eV)	$2\Delta_2$ (eV)
pure Cr ^a		0.12	0.45
Fe ^b	1.7	0.13	0.4
Co ^b	1.4	≈ 0.13	
Ni ^b	1.2	none	none
Al ^c	≤ 1.0	0.12	0.45

^a Machida *et al* (1984).

^b Lynch *et al* (1975).

^c Lind and Stanford (1984).

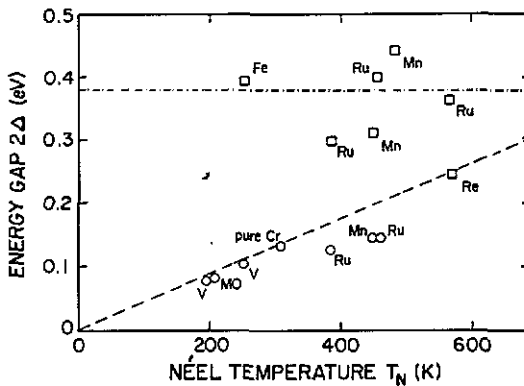


Figure 3. Energy gap 2Δ in Cr alloys determined at low temperatures from the peak in the infrared reflectivity for incommensurate SDW systems (O) and commensurate SDW systems (\square) plotted against the Néel temperature T_N . The chain line is a guide to the eye suggesting a constant value, $2\Delta = 0.38$ eV, for the gap in the commensurate SDW systems, while the dashed line of slope, $2\Delta/k_B T_N = 5.0$, shows the proportionality of the gap to the Néel temperature in the incommensurate SDW systems (after Barker and Ditzemberger 1970).

The situation in the commensurate SDW alloys summarised in table 2 and figure 3 is more straightforward. There is only one energy gap, and its value is roughly constant in the range, $2\Delta \approx 0.35$ to 0.40 eV.

Table 2. Energy gap 2Δ for commensurate spin-density-wave chromium alloys determined from the low-temperature infrared reflectivity.

Alloy $\text{Cr}_{1-x}\text{A}_x$		
Solute A	x (at.%)	Energy gap 2Δ (eV)
Fe ^a	3.0	0.39
Fe ^b	3.0	0.39
Fe ^c	2.7-4.0	0.41
Co ^c	4	0.38
Mn ^d	0.94	0.36
Re ^d	1.05	0.38
Al ^e	3-6.4	0.35
Ru ^e	1.5	0.38
Ru ^a	0.65	0.40

^a Barker and Ditzemberger (1970).

^b Kirillova and Nomerovannaya (1975).

^c Lynch *et al* (1975).

^d Bos and Lynch (1970).

^e Lind and Stanford (1984).

The origin of the two energy gaps in pure Cr and in incommensurate SDW alloys is still in doubt (see Fawcett 1988). It seems reasonable however to assume that the upper energy gap $2\Delta_2$ is the appropriate value to use, since its value is much closer than that of the lower energy gap to the value of the single energy gap in the commensurate SDW alloys.

Taking into account the data for all the alloys listed in tables 1 and 2 and illustrated in figure 3, and noting that infrared reflectivity data are not available for $\text{Cr}_{1-y}\text{Si}_y$ alloys, we make the reasonable approximation that the energy gap is, $2\Delta = 0.40 \pm 0.05$ eV, in the systems of interest.

We now proceed to analyse the experimental data for the two alloy systems using (12), with $\delta E(\text{Si}) = 24$ meV, giving $g_0(\text{Si}) = 0.94$, and with $\delta E(\text{Fe}) = 28$ meV, giving $g_0(\text{Fe}) = 0.93$. Thus the value of the potential scattering parameter g_0 is essentially the same in the Cr(Si) and Cr(Fe) alloy systems.

We could in principle go further with the analysis and extract another potential scattering parameter from the width γ of the resonance peak. Thus in the case when there is negligible intraband scattering in the reservoir, $g_1 \ll 1$, Volkov and Tugushev (1984, equation (27)) give an expression

$$\gamma = \frac{4\Delta g_0 g_2}{(1 + g_0^2)^2} \quad (19)$$

which would enable us to calculate the electron (hole)-reservoir scattering parameter g_2 from the width of the resonance peak.

We have not done this, since it is clear from an inspection of figure 1 that the quality of the data does not warrant such extensive analysis. Furthermore, the asymmetry between the two peaks, for both the Cr(Si) and the Cr(Fe) systems, remains unexplained, and a difference in width between the upper and lower local impurity levels could not be included in the analysis.

5. Conclusion

The new and important concept of local impurity states within the energy gap (the forbidden band) of a commensurate SDW in an itinerant electron antiferromagnet (Volkov and Tugushev 1984) leads to several predictions that have been verified experimentally (Galkin and Tugushev 1991). Here we exploit the phenomenon of impurity-resonance scattering to determine the difference in energy between the two impurity states in Cr(Si) and Cr(Fe) systems doped with V or Mn.

The results are useful in providing an estimate of the potential scattering parameter, but the method of analysis is even more interesting in that it shows how the energy difference δE between the energy levels determined from the dependence on doping of the SDW wavevector and the Néel temperature form a roughly self-consistent set of physical parameters.

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