The magnetic moments and their long range ordering for Fe atoms in a wide variety of metallic environments

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Abstract

The magnitudes of Fe magnetic moments, together with their long-range ordering when appropriate, are compared and contrasted in a variety of metallic environments. Thus, Fe, in its stable body-centered-cubic (bcc) phase under ambient conditions, is considered under pressures p , which can yield different crystal structures at high p , including fcc. The modification of the ferromagnetism in bcc Fe is surveyed as one passes through a bc-tetragonal lattice to the fcc form. In the latter, evidence is presented, both from theory and experiment, that the ordering is antiferromagnetic in character. Then, binary metallic alloys with Fe atoms as the majority component are considered, Fe-Co and Fe-Ga being focal points in both ordered and disordered materials. Finally, some discussion is given, involving again both experiment and theory, of the possible spin polarization of neighboring Cs atoms when Fe impurity atoms are inserted into the low conduction electron density characterizing this heavy alkali metal under ambient conditions.

I. INTRODUCTION

Iron, under ambient conditions, is of course a ferromagnetic metal. Its crystal structure is normally body-centred-cubic (bcc) and it has an experimentally determined magnetic moment μ per atom of $2.2 \mu_B$, where μ_B is the Bohr magneton. Fe in this bcc phase has a Curie temperature $T_C = 1043$ K. We have recently studied experimental data for magnetization $\Delta M(T) = M(0) - M(T)$ and for internal energy $\Delta E(T) = E(T) - E(0)$. Our representation¹ of the experimental data² was motivated by the low-temperature theory get out by Grout and March³, which yielded the temperature dependencies of ΔM and ΔE as $T \rightarrow 0$ to have the forms

$$\Delta M(T) \sim T^{\frac{3}{2}} \quad (1)$$

and

$$\Delta E(T) \sim T^2. \quad (2)$$

These eqns (1) and (2) yield immediately for itinerant ferromagnets like Fe, Co and Ni the fact that

$$\Delta E \sim \Delta M^{\frac{4}{3}} \text{ as } T \rightarrow 0. \quad (3)$$

In (1), we plotted the experimental data for Fe and, for comparison, similar measurements for Ni in a form from $0 < T < T_C$ motivated by the low-temperature relation (3).

We have redrawn these results in Fig. 1 and it can be seen that they are barely distinguishable to graphical accuracy. Following equation (3), $\Delta E^{4/3}$ should be linear with the magnetization ΔM for $T \rightarrow 0$. This linearity is seen in Fig. 1 for M close to $M(0)$ i.e. for ΔM or the scaled magnetization $\frac{M-M(0)}{M(0)}$ going to zero. In (1), by using a spin Hamiltonian due to Blume, Emery and Griffiths (BEG)⁴, we were able to gain some insight by displaying similar plots to Fig. 1 for the BEG two parameters of this model.

Before turning to the outline of the present article, let us record a few further facts for bcc ferromagnetic Fe. Spin wave theory going back at least to Bloch⁵ yields the dispersion relation $w(k)$ for ferromagnons, the quasiparticles of the spin waves, as

$$w(k) = Dk^2 \quad (4)$$

where D is the spin wave stiffness. A formula for D from itinerant ferromagnets like Fe and Ni is given in the review by Callaway and March⁶ in terms of energy band theory eigenfunctions and eigenvalues.

FIG. 1: (*Color online*) Reduced internal energy to the 4/3 versus scaled magnetization $1 - \frac{M}{M(0)}$. We denote iron and nickel data by the full and dotted lines, respectively. This figure is redrawn from our Ref.¹. Following eq (3), we show the linear behaviour for the internal energy to 4/3 when $\Delta M \rightarrow 0$ equivalent to $T \rightarrow 0$.

There is some previous work of one of the authors on spin wave stiffness. For Ni, Callaway and March⁶ quote a theoretical value $D_{calc} = 0.148 Rya_0^2$ where a_0 is the Bohr radius, while the experimental value determined by Mook et al⁷ using neutron scattering at 4.2 K is $D_{exp} = 0.146 Rya_0^2$. As noted already in Ref. 6, though such close agreement between theory and experiment may be somewhat fortuitous, in view of DFT inevitably approximate functionals, it strongly suggests that DFT is capable of giving a reasonably good account of magnetic excitations near $T=0$ in the monoatomic metals under discussion here. Recent calculations show for Ni fcc a larger value $0.198 Rya_0^2$. The same work includes a calculated value for Fe bcc of $0.066 Rya_0^2$ to be compared with the neutron measured values that when extrapolated to 0 K give $0.087 Rya_0^2$. The differences between the new calculated values and the experiments seem larger and non systematic. Anyhow these differences are small enough to see that they really describe the difference between Fe and Ni at low temperatures.

The outline is given in the following. After a discussion of some experimental facts, including pressure investigations, of the effect of lattice structure on the magnitude of the magnetic moment of Fe in different crystalline forms, other areas considered are (i) ordered and disordered binary alloys containing Fe (ii) films of Fe in various substrates and (iii) dilute Fe impurities in some metallic matrices, with particular reference to (a) Cs and (b) Pd.

II. PURE METALLIC FE CRYSTALS WITH DIFFERENT STRUCTURES (EG BCC AND FCC), INCLUDING PRESSURE STUDIES

In early work on the transition from a bcc to an fcc structure, Perrin, Taylor, and March¹⁰ considered Li metal and its changed Fermi surface as one distorted bcc via body-centered-tetragonal to fcc.

Recently, a related transformation path for Fe has been considered by Okatov et al¹¹. The energetics of such a lattice transformation has been calculated by these authors for both magnetically ordered and paramagnetic (disordered local moment) configurations of iron and redrawn in Fig. 2. Some discussion is also given by these workers of the relation between the Curie temperature of α -Fe (bcc) and the temperature which heralds the start of the martensitic transformation. In important early work of Zener¹², he contended that ferromagnetism stabilizes α -Fe. The above quoted study of Okatov et al¹¹ is in accord with Zener's expectations.

The magnetic ordering is, of course as discussed above, of ferromagnetic character in the bcc phase, whereas (see also Ref. 13) in the fcc structure, the long-range order is antiferromagnetic. The fcc crystalline phase is accessible with the temperature at ambient pressure, $T_{bcc \rightarrow fcc} = 1183$ K.

For the fcc structure the decrease in the iron density of states at the Fermi level means that the ferromagnetic limit given by the Stoner criteria is not fulfilled. Therefore, the fcc phase has a very unstable magnetic moment. In fact it can adopt the form of either of two spin solutions. The magnetic moment of the high spin phase, $2.8 \mu_B$ is larger than in bcc iron, while the low spin moment is around, or less than, $1 \mu_B$ ¹⁴. These fcc magnetic configurations are strongly coupled to the lattice instabilities which depend strongly on the lattice constant of bulk iron. This dependence will be important in the next section where

FIG. 2: (*Color online*) Variation of total energy per atom as bcc structure deformed through body-centred tetragonal lattice to fcc form: as a function of c/a ratio. Redraw from Ref. 11.

the growth of fcc iron on thin films is discussed.

Thus far we have commented mainly on iron phases at ambient pressure. We now center on iron phases at higher pressures. Bulk iron is stable in the bcc phase up to 13 GPa. Then, in a narrow margin depending strongly on the experimental conditions, which can be in later experiments as small as 2-3 GPa,¹⁵ iron becomes an hcp phase. The search for magnetic ordering in hcp iron has been initiated already in the past, as given for instance in Ref. 16, due to its interest in the study of the Earth's core. We summarize in the following some recent experiments on the iron bcc-hcp transitions¹⁵. In this work, the authors were able to follow the bcc-hcp transition both structurally and magnetically by measuring at the same time with X-ray magnetic circular dichroism (XMCD) and with X-ray absorption fine structure (EXAFS). The small sample inside an anvil cell is crucial for determining that the transition extends only about 2.4 ± 0.2 GPa. The origin of this instability supports the theoretical interpretation of a decrease in the d band density of states during the transition and consequently according to the Stoner criterion the ferromagnetism disappears¹⁷.

These structural and magnetic data¹⁵ have no uncertainty in pressure as they are measured at the same time. Thus, the authors are able to distinguish that the magnetic transition happens within a slightly narrow margin of pressures just before the structural one. Recent calculations¹⁸ have shown that the bcc-hcp can be interpreted as a mechanism that combines both a shear and a shuffling transformation: the distorted (110) hexagons transform into the perfect hcp hexagonal planes. These results show that exactly at the structural transition point the magnetism is also killed. In the bcc basin, before reaching the transition point, the phase attempted to gain volume and increase slightly the magnetic moment. But under pressure the coupled shear-shuffling transition becomes almost a shuffle transformation. To constrain the volume because of pressure could kill the magnetism before accomplishing fully the structural transformation. Additionally, other magnetic phases may appear on the (in principle) non-magnetic hcp side of the transition. Then, the possibility of having low spin phases before the bcc-hcp transformation is completed could also be realized¹⁵. This last comment has originated from the beginning of the studies in hcp iron. For a summary of the interest in antiferromagnetic and non-collinear studies in the high pressure behaviour of iron, see Ref 19 and references therein. But now we must remark that no experimental evidence of magnetic ordering in the iron hcp phases using Mössbauer and XMCD measurements have yet been found.

III. FE AS COMPONENT IN ORDERED AND DISORDERED BINARY METALLIC ALLOYS (INCLUDING SLATER-PAULING CURVE)

As we are dealing with the magnetic properties of Fe, we address its mixing with the adjacent Co element to form metallic alloys. Co-Fe alloys are interesting because they present quite high saturation magnetizations and Curie temperatures. For several measurements^{20–22} we plot the experimental magnetic moment per atom as a function of Co concentration in Fig 3 (a). The magnetic moments have a maxima at 70 % Fe. In fact this caps the top of the Slater-Pauling curve, basic both for the description and for the engineering of magnetic alloys. Also we plot together the theoretical values of the magnetic moments²³ for the fully disordered phases with a continuous line. We do not show the ordered phases as they scatter around this line which can be considered as their average value. They were calculated within the density functional theory using the Perdew-Burke-Ernzerhof generalized gradient

FIG. 3: (*Color online*) (a) Experimental magnetic moment per atom for Fe-Co alloys with triangles: right (disordered) and left (ordered) from Ref.²⁰, up from Ref.²¹, and down from Ref.²². Also the theoretical moment for the random alloy is given with a full line²³. Note the shift between the curves and the Fe-rich region with theoretical moments over the experimental values. (b) Magnetic moments for bcc, fcc, hcp, and α' phases of Fe-Co alloys as function of Co concentration. The experimental results use marks such as triangles(bcc), circles(fcc), and squares (hcp). The thin lines are used for plotting the theoretical results obtained with the Coherent Potential Approximation in Ref.²⁶: full for bcc, long-dashed for fcc, dot dashed for hcp, and short-dashed for α' . The thick line reproduces again the previous random theoretical values without averaging potentials around atoms. Note the role of the average ASA approach specially in the Fe rich region.

approximation²⁴ and fully relaxing the structures. Both theoretical and experimental curves have a maxima. However, the theoretical curve is shifted to lower magnetic moments and to Fe-rich regions, in such a way that in the Fe-rich region, the magnetic moment increases over the experimental values of pure Fe. Certainly there is some discrepancy between experiment and theory.

The interpretation of the maxima between Fe and Co was already proposed in the pioneering work by Williams²⁵. The minority density of states (DOS) of both Fe and Co are similar with a minima for the bcc structure between bonding and antibonding main peaks. The DOS of Fe and Co differ by the occupation: the Fermi level is for Fe just at the minima, while it is for Co in one of the peaks. That is why iron is said to have weak magnetism,

and Co is termed a strong magnet. The competition between strong magnetism of Co and weak magnetism of Fe causes a maximum in the magnetic moment. In the later instance this competition is, in deeper terms, a way to talk about the electronic correlation. Doping Co with Fe makes the role of electronic correlation more important. We have in addition to consider the Coulomb shift of levels, but this affects both minority and majority levels. This shift brings into play the nearly occupied majority levels, as the Fermi energy is just touching them. Thus, to explain a theoretical shift to bring the experiments into better accord with the calculations, refined schemes within density functional theory or beyond must be constructed.

When other phases are involved the magnetic moment suffers large changes as a function of the Co concentration, as seen in Fig. 3 (b). Experimentally for the fcc phases the transition for the low spin to high spin is observed over a large concentration range. The Co-Fe alloys disorder can be simulated in averaged cases specially when dealing with neighboring atoms in the periodic table using the the coherent potential approximation²⁶ and the atomic sphere approximation that average more the potential around the atoms that the previous calculations²³. In this theoretical case, the magnetic moment of hcp phase smooths over Co concentration, while the magnetic moment of fcc phase jumps almost from zero to a value close to $2 \mu_B$. Continuing theoretical research will clearly provide more information on electronic correlations and spin non-collinear order during these transitions, specially for the description of spin states in fcc phases.

Let us turn now to the mixing of Fe with a more dissimilar element such as Ga. Recent experiments for $Fe_{1-x}Ga_x$ alloys²⁷ show that the addition of Ga to the bcc $\alpha-Fe$ phase produces a diversity of crystal structures which include: (i) chemically disordered bcc $A2(Fe)$, (ii) ordered bcc $DO_3(Fe_3Ga)$, (iii) ordered bcc $B_2(FeGa)$, and (iv) a new precipitated fcc $L2_1$ phase. We summarize next the magnetic moments in some of these phases. Chen and Cheng²⁸ calculated the magnetic moment in ordered and disordered structures for a small supercell. Their results are denoted by the empty circle in Fig. 4. The magnetic moments as a function of the concentration decrease below the bulk Fe magnetic moment.

Later calculations in Ref. 29 included the role of the chemical disorder in determining the magnetism. The authors describe the chemical disorder in the electronic structure using the coherent potential approximation (CPA). For $Fe_{1-x}Ga_x$ alloys they solved the Korringa-Kohn Rostoker in the atomic sphere approximation (KKR-ASA). In Fig. 4 the

FIG. 4: (*Color online*) Average moment per Fe atom. Calculated with KKR-ASA the A2 (diamond), B2 (empty square), and DO_3 structure (full square) are given²⁹, while more regular structures using supercells are given with empty circles²⁸.

magnetic moment increases up to $x \sim 0.1$, where it shows a maximum, and decreases for larger x . The magnetic moments decomposition in cell Fe-inequivalent atoms show that the ones responsible for the maximum with x are the ones surrounded by more Ga atoms. The effect is explained in terms of the interplay between magnetism and structure as in previous calculations for FeSi alloys³⁰. Following this interpretation the Ga atoms have a two fold effect. On the one hand they caused an overall expansion that made the magnetic moment of neighboring Fe atoms increase. On the other hand, as the Ga concentration increases, the p-d band hybridisation takes over and this results in the magnetism decreasing.

Either disorder or the spherical approach (ASA) imposes differences to the Ga-Fe bonding as to have even different trends concerning the magnetic moments with Ga concentration x . It is clear that this topic must be revisited beyond ASA and including disorder. Both disorder and atomic relaxations must be included in the previous models. This study could be done by using the self consistent Green-function techniques⁷ or using large supercell

models when both the disorder and atomic relaxations are included.

IV. FILMS OF FE ON VARIOUS METALLIC SUBSTRATES

The growth of Fe films in a large variety of metallic substrates has been undertaken using sputtering and molecular beam epitaxy. For a long and detailed review on the subject the reader is encouraged to consult Ref. 31. Concerning the magnetic properties, our focus in this work, we have to consider whether, when going to the nanoscale, iron films will have an enhanced magnetic moment due to two effects. First, the average coordination taking into account a smaller number of neighbours in films with respect to bulk properties will decrease the band width, so that the magnetic moment would increase. Second, in low-dimensional structures the quenching of the orbital magnetic moment can be questioned³². This means that the magnetization must include a sum of spin and orbital angular momentum components. Up to this point everything is clear and we have found numerous cases when the iron magnetic moment is enhanced, such as for bcc Fe/Ag(001) in contact with Ag, Au, Cu, Pd, and Ni³³.

However, experiments do not always show this increased magnetic moment. In such cases most of the experiments made in Fe/substrate systems claim that the magnetic moment in iron is decreased. Later experiments indicate in most of the cases that such claims must be softened for Fe/Ag³⁴ or enhanced for Fe/Pd³⁵ due mainly to two reasons. On the one hand we have to consider the interface roughness. This favors the killing of long-range magnetic order unless for the smaller wavelengths of the Fermi surface in the growth direction. Diffusion of metals at the interface can be also considered on the same footing, and it results again in the iron magnetic moment at the film surface decreasing. This is the occurrence of the so-called magnetically dead layers. To link temperature and atomic diffusion in iron films is not straightforward and we will discuss this issue further below.

On the other hand we have to consider that iron films can also polarize the substrates. This effect has been proved experimentally³⁵ for the Fe/Pd system. The Pd substrate polarizes in the first layers mediated by the proximity of the magnetic iron layers. This interaction has to be considered to renormalize the magnetic moment per iron atom, and drives naturally to an opposite effect to the previous layer roughening and atomic diffusion.

A prototype system with special magnetic properties is given by iron films grown on

tungsten, Fe/W(110)³⁶. Here, growth is aided by the natural segregation between Fe and W where iron spreads easily with a wetting layer on top of tungsten. When growing several layers, several workers find that the magnetization per iron atoms decrease slightly over the bulk value, 2.1 versus 2.21 μ_B ³⁷. However, the recent ab initio calculations show for 1 Fe monolayer on W(110) that the magnetic moment increases, and its change is larger than in the experiments, namely 2.56 μ_B ³⁸. To have several layers seems to impose some roughening which could be held already responsible for the decrease of the magnetic moment. More important is the misfit that the segregation imposes on iron films. Note that iron and tungsten have an strong misfit strain, of the order of 10 %. This strain must also be analyzed in the lateral dimensions, by examining the effects of lateral stacking faults and related magnetic properties, in order to bring accord between the theoretical results and the experimental values. The solution to this puzzle is going to require a more careful measurements simultaneously of surface topology and localized magnetic probe spectroscopies.

Under the strain imposed by substrates, iron films can adopt several of the previous bulk phases, obtained at different temperatures and even under pressure. For instance, the Fe fcc phase seems to grow with very small mismatch on fcc Cu substrates³¹. The iron films on these substrates have a puzzling behaviour with different magnetic phases and structures under different growth conditions. Growing iron on several substrates and with different growth conditions allows two cases to be distinguished using molecular beam epitaxy. When growing the iron film at small temperatures, the magnetization is perpendicular to the film plane up to 5 monolayers and it changes to in plane for a large number of layers³⁹. When it grows at room temperature, the complexity is served: the fcc phase appears mixed with other phases, fct and bcc, and have mixed also high and low spin states³¹. While the low-temperature growth seems almost clear at the moment, the growth at room temperature is more intriguing.

At first sight we can say that the temperature variation can have two effects as described in the scheme of Fig. 5. (i) Temperature in thin films helps to smooth the roughening of the outer film. It should be remembered that films at this size, as with many other nanosystems, can have a non-monotonic dependence of surface energy with the number of layers⁴⁰, so the temperature will induce their annealing. Thus, it favors the more stable Fe layer thicknesses, which may show even different magnetic moments. The study of the stability of magnetic films by examining the stability of surface films such as iron is under

FIG. 5: (*Color online*) Scheme concerning the (a) low and (b) room temperature growth. During the low temperature growth the annealing roughs the as grown-film because at the nanoscale other stable surfaces can appear. At the same time the most stable layers thickness with N+1 and N+2 monolayers in the exemplified case extend during the annealing.

investigation at the moment by one of us.⁴¹ (ii) However, temperature can also help the diffusion of surface substrate atoms inside iron films. This contamination leads to the fact that films can show normally a reduction of the magnetic moment and ends in the formation of a dead layer including iron atoms. In addition, temperature could even cause local structural deformations, seen as inclusions.

Other high iron pressure structures grow also on substrates, such as iron hcp phases. It is well known that in the Fe/Re systems, iron films follow the hcp structure⁴². For small number of layers, $< 9\ \text{\AA}$, the hcp Re layers using XMCD have stable magnetic moments close to the bcc bulk magnetic moment. Other systems such as the Fe/Ru layers show already more controversial results where they can grow as both hcp⁴³ or bcc⁴⁴. More surprising is the fact that other iron phases can be realized. Pan et al⁴⁵ have reported the preparation of Fe/Sb multilayers films varying Fe and Sb layer thickness in vapor deposition experiments. Their

finding was that a metastable rhombohedral Fe phase was created in the Fe/Sb multilayered films, when the Fe layer had thickness 1.7 nm and the Sb layer was of 10 nm. The metastable rhombohedral phase was found to be ferromagnetic with an average magnetic moment of $1.52 \mu_B$.

V. DILUTED FE IMPURITIES IN SOME METALLIC MATRICES: ESPECIALLY CS AND PD

Beckmann and Bergmann⁴⁶ have covered thin films of Cs with 1/100 of a monolayer of Fe. They then covered these impurities with several atomic layers of Cs. The anomalous Hall effect was used to measure the Fe magnetization. This was found to be well described by a Brillouin function with a magnetic moment of some $7 \mu_B$.

Early work of Bloch suggested for a homogeneous electron gas (HEG) model, that bulk Cs was according to Hartree-Fock (HF) theory, near to a ferromagnetic state. This was due to the low electron density, the mean interelectronic spacing r_S being $\sim 5.5 a_0$ with $a_0 = \hbar/mv_F$. But subsequently quantum simulations⁴⁷ on the HEG model show that electron correlation suppresses the ferromagnetism predicted by the HF approximation. Nevertheless, the low electron density of the itinerant electrons in metallic Cs can leave little doubt as to the importance of electron-electron correlations in Cs.

However, it is also plain that one should examine the likely distortion in both bulk Cs and in Cs films of surrounding atoms to an inserted Fe impurity. Work on Fe impurities in alkali clusters, before the experiments of Beckmann and Bergmann, by McHenry et al⁴⁸ may be relevant in the present context. If one accepts that metallic alkali hosts can be usefully simulated by such clusters, it is then relevant that McHenry et al found a different electronic structure for Fe impurities in alkali metals. Later experimental studies by Song and Bergmann⁴⁹, while focusing on V impurities in their films of Na and K, prompted them in the above reference to comment that they observed magnetic moments of $6 \mu_B$, or greater, in the alkali hosts Cs, Rb, K, and Na with Fe impurities on the surface and in the bulk.

Returning to remarks above about distortion of the Cs films (and the bulk lattice) in the local environment of an Fe impurity, Song and Bergmann⁴⁹ note also that impurities on the surface of Cs caused what they term 'an anomalous large increase of the resistance'. This, they believe, suggests that the alkali atoms may experience a rearrangement of their original

positions in the pure films over a relatively long range from the 'perturbing' impurity (in the present context an Fe atom). It is of interest to note that, in the bulk alkalis, early work of Flores and March⁵⁰ had shown that a model based entirely on atomic relaxation, gave a useful estimate of the vacancy formation energy in these metals, testifying already to the softness of the alkali lattice.

In concluding this section, we note, with Beckmann and Bergmann⁴⁶, the even more dramatic earlier observation, for Fe impurities in Pd films, of giant moments $\sim 16 \mu_B$ (see Ref. 51). But, of course, it has been known for a long time that Pd is a 'nearly ferromagnetic transition metal', because of a large Stoner enhancement factor⁵².

VI. SUMMARY AND FUTURE DIRECTIONS

We have been concerned here with the magnetic moments on Fe atoms when placed in a variety of metallic environments, and also when appropriate, with their long-range magnetic ordering. Thus the effect of high pressures applied to initially bcc Fe has been discussed, using findings from experiments plus some relevant available theoretical work. After a pressure-induced fcc phase transition, the ferromagnetism of the bcc phase is changed to antiferromagnetic ordering.

Next we have considered some binary metallic alloys, having iron as major component. Some theoretical results have been presented for Fe-Ga at different concentrations, where the nature of the structures are established experimentally. Also Fe-Co results are summarized, mainly from currently available experiments.

As to future directions, we wish to stress three areas that should be fruitful for further study. The first of these concerns a dilute concentration of Fe in or on films of the heavy alkali metal Cs. The pioneering experiments of Bergman and coworkers established beyond doubt the existence of an exceptionally large magnetic moment on Fe. These workers proposed that Fe polarized the surrounding Cs atoms. Thus our conclusion is that it is better in this case add approximate Löwdin⁵³ correlation to the HF method. Perhaps by low-order Möller-Plesset perturbation theory, than to correct the exact-exchange (EXX) approximation, which gives $1 \mu_B$ too high for the magnetic moment for Fe atom in the bcc phase. The third area we propose as likely to be fruitful for further study, both experimentally and theoretically, is that of Fe in disordered metallic films. We ourselves will report briefly on some theoretical

ideas appropriate to this area⁵⁴, but further experiments also on Ni and Co in disordered films should prove very valuable in understanding more deeply the mechanism for the suppression of itinerant ferromagnetism by disorder.

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