

# Magnetic instabilities in $\text{Fe}_3\text{C}$ (cementite) particles observed with Fe K-edge x-ray circular dichroism under pressure

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The ferromagnetic interstitial iron compound  $\text{Fe}_3\text{C}$  (cementite) is expected to have Invar properties, whereby a high-moment to low-moment transition should occur when the atomic volume is reduced below a critical value. We, therefore, examine the pressure dependence of the Fe K-edge x-ray magnetic circular dichroism in  $\text{Fe}_3\text{C}$  at ambient temperature and pressures up to 20 GPa. We find clear evidence for a high-moment to low-moment transition around 10 GPa.

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Metalloid atoms such as boron, carbon or nitrogen take up interstitial lattice positions in 3d metals when forming alloys and compounds. The outer p-states of the metalloid atoms hybridize with the host metal d-states in such a manner that the effective electron concentration of the metal increases [1]. Fe has a valence electron concentration  $e/a$  of 8 (s+d) electrons per atom, whereas in  $\text{Fe}_3\text{C}$  (cementite), in which C has two p electrons, the electron concentration per metal atom becomes  $[8(0.75)+2(0.25)]/0.75=8.67$ . This concentration corresponds to a value where large spontaneous magnetostriction associated with magnetovolume instabilities in the alloys of 3d systems are found. Such magnetostrictive phenomena are known as the Invar effect, and the archetype material is the face centered cubic  $\text{Fe}_{0.65}\text{Ni}_{0.35}$  Invar alloy with  $(e/a)=8.66$  [2].

A magnetovolume instability is a rapid change of the magnetic moment with respect to a small change in the atomic volume. Under applied pressure at low temperature, a system incorporating such an instability can undergo a transition from a large-volume high-moment state (about  $1.7 \mu_B$  for  $\text{Fe}_{0.65}\text{Ni}_{0.35}$ ) to a small-volume low-moment state of nearly vanishing magnetic moment. The physical origin of the high-moment to low moment transition is related to the features of the density of states characteristic to Invar alloys. In the high-moment state of  $\text{Fe}_{0.65}\text{Ni}_{0.35}$ , strongly repulsive anti-bonding  $t_{2g}$  states below the Fermi level are occupied (large atomic separation), whereas in the low-moment state, these states shift to above the Fermi level, and the less repulsive non-bonding  $e_{2g}$  states become occupied (smaller atomic sep-

aration) [3]. These states are separated by a small energy difference of several meV [4], which is a value within the thermal range of the solid state. Therefore, it is thought that by increasing the temperature, the less repulsive  $e_{2g}$  low-moment states are progressively occupied at the expense of the strongly repulsive  $t_{2g}$  high-moment states causing a contraction that counteracts the normal lattice expansion. The overall effect is then a nearly vanishing thermal expansion coefficient in a broad temperature range; namely, the Invar effect.

Differing from the structure of  $\text{Fe}_{0.65}\text{Ni}_{0.35}$ ,  $\text{Fe}_3\text{C}$  is orthorhombic, and the Fe atoms are arranged in a manner such that they have two different environments denoted as FeI and FeII [5]. However, both materials have nearly equivalent electron concentrations and exhibit nearly identical Invar-typical features in the temperature dependence of the thermal expansion [5] and the bulk modulus [6], although  $\text{Fe}_3\text{C}$  consists of only a single metal atom species. Such data are supporting evidence for the presence of the Invar effect in  $\text{Fe}_3\text{C}$ , however, they provide information only on the lattice properties, and do not give evidence for the presence of instabilities in the magnetic degrees of freedom. This evidence is necessary to understand that the spontaneous volume enhancements and the associated lattice anomalies in  $\text{Fe}_3\text{C}$  are related to its magnetism.

The direct method of detecting a presence of a magnetic instability that is coupled to the lattice degrees of freedom is to measure a magnetization related parameter under applied pressure. This may be done using techniques such as Mössbauer spectroscopy [7],

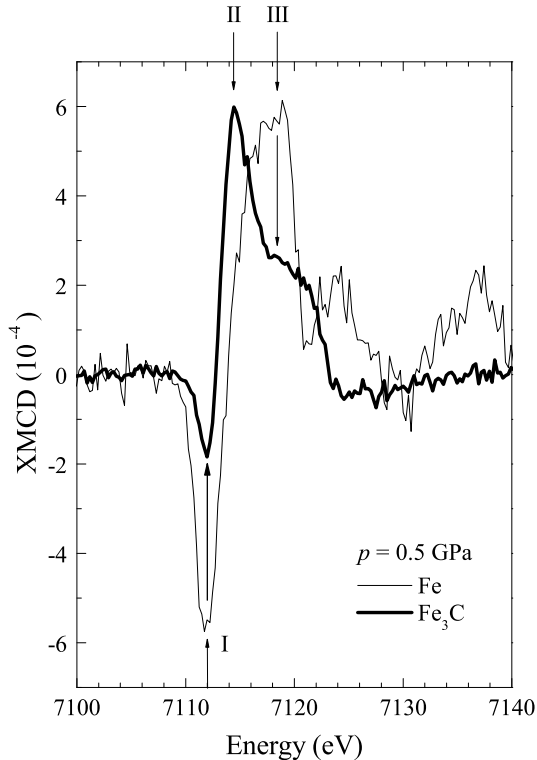


FIG. 1: XMCD of  $\text{Fe}_3\text{C}$  (heavy line) and Fe around the Fe K-edge.

ac-susceptibility [8], x-ray magnetic circular dichroism (XMCD) [9], or x-ray emission spectroscopy [10], usually with the sample located in a diamond anvil cell (DAC). For the case of  $\text{Fe}_3\text{C}$ , the Mössbauer technique has the drawback that it requires an  $^{57}\text{Fe}$  enriched sample because of the small quantity of sample material that can be brought between the diamond anvils. Unrealistic quantities of  $^{57}\text{Fe}$  would be required to prepare a sample by chemical separation from a starting Fe+ $\text{Fe}_3\text{C}$  ingot, or by any dissociation process of  $\text{Fe}(\text{CO})_5$ . The ac-susceptibility technique requires macroscopic size samples in the order of a cubic millimeter, and  $\text{Fe}_3\text{C}$  cannot be sintered in pure form, since it decomposes under pressure at the required high sintering temperatures. The XMCD technique with  $\text{Fe}_3\text{C}$  under pressure in a DAC, on the other hand, does not have any of the drawbacks mentioned above, and can be applied to observe variations in the magnetic degrees of freedom with applied pressure. Nevertheless, due to the strong absorption of the diamonds at low x-ray energies corresponding to the Fe L-edge, for which quantitative analysis has a chance, one must work at the alternative Fe K-edge [11, 12], for which the results can only be interpreted qualitatively at present due to complexities involved in theoretical modeling [13–17].

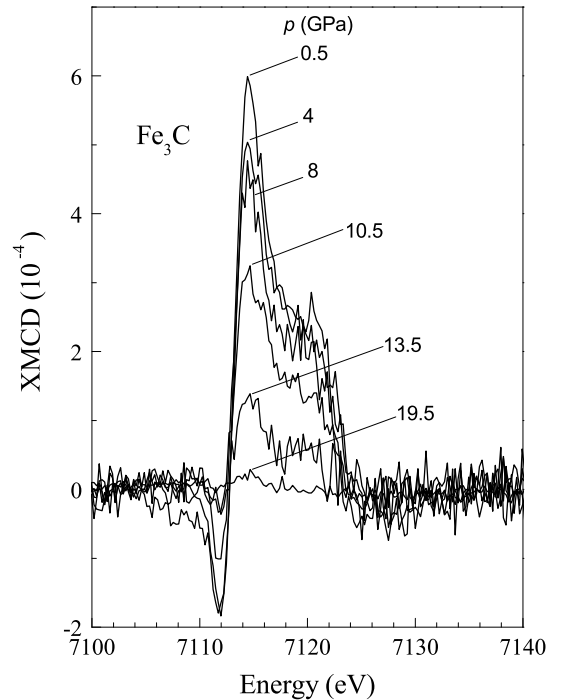


FIG. 2: XMCD of  $\text{Fe}_3\text{C}$  around the Fe K-edge at selected pressures.

We have investigated the pressure dependence of the XMCD at the K-edge of Fe in  $\text{Fe}_3\text{C}$  at room temperature and pressures up to 20 GPa on increasing and decreasing pressure. The measurements were carried out at the ESRF on the ID24 beam line installed on an undulator source. Circular polarization was attained using a quarter wave plate. Two sets of measurements at each pressure with both polarization helicities and both magnetic field directions were taken in order to eliminate systematic errors arising from the positioning of the quarter wave plate for the two helicities and changing the direction of the magnetic field. A magnetic field of 0.4 T was applied with an electromagnet. The magnetization in this field reaches about 80% of the saturation value of the sample used in the present experiments [18].  $\text{Fe}_3\text{C}$  particles of about 50 nm were prepared by the dissociation of  $\text{Fe}(\text{CO})_5$  in a hot wall reactor in the presence of methane and were separated from the admixture of C and Fe by chemical and physical methods [6]. After separation, their purity, morphology and structure were checked by electron microscopy and x-ray analysis. No foreign phase or any mixture with Fe was detected.

Figure 1 shows a comparison of the K-edge XMCD spectra of Fe and  $\text{Fe}_3\text{C}$  with both data obtained in the diamond anvil cell under a loading pressure of 0.5 GPa. The present data for Fe are similar to data at ambient pressure previously reported [12]. The position of the

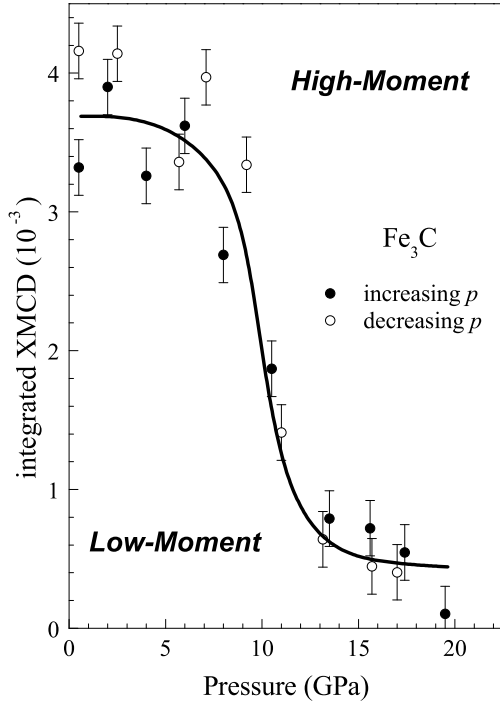


FIG. 3: Integrated XMCD of  $\text{Fe}_3\text{C}$ . The high-moment to low-moment transition takes place at about 10 GPa.

first dip on the low energy side of both the Fe and the  $\text{Fe}_3\text{C}$  spectra lie at about 7112 eV (position I). The feature at position II in the  $\text{Fe}_3\text{C}$  spectrum has no counterpart feature in the Fe spectrum. The broad maximum in the Fe spectrum around 7118 eV coincides with the position around the shoulder in the  $\text{Fe}_3\text{C}$  data at the position denoted as III. Since in  $\text{Fe}_3\text{C}$ , Fe occupies two electronically nonequivalent sites, the occurrence of features different from those in the Fe spectrum can be attributed to the different interactions of the excited 4p photoelectrons with the spin polarized d-bands for the two different Fe sites in  $\text{Fe}_3\text{C}$ .

Figure 2 shows the XMCD spectra from ambient pressure up to about 20 GPa taken on increasing pressure. The data on decreasing pressure are similar and are not shown here. The overall intensity of the spectra diminishes as the pressure increases, and only a remanent feature remains at 19.5 GPa.

The integrated XMCD intensity, obtained after subtracting the background intensity before and after the K-edge, is plotted in Fig. 3. The integration of the absolute values of the intensity was carried out in the range  $7107 \text{ eV} \leq E \leq 7125 \text{ eV}$ . A clear transition from a high-moment to a low-moment state is observed without any hysteresis in the increasing and decreasing pressure data. The intensity initially shows no appreciable vari-

ation with pressure and then begins to decrease rapidly around 8 GPa. At about 13 GPa, it has dropped down to about 80% of its value at ambient pressure. Assuming a direct proportionality between the integrated XMCD and the average magnetic moment, the moment of  $1.8 \mu_B$  in the ground state of  $\text{Fe}_3\text{C}$  (high-moment state) [19–22] can be estimated to drop down to about  $0.4 \mu_B$ . At about 12 GPa, the lattice constants acquire the values  $a=0.496 \text{ nm}$ ,  $b=0.662 \text{ nm}$ , and  $c=0.440 \text{ nm}$  and the cell volume is  $V=0.144 \text{ nm}^3$  [6]. Under ambient conditions,  $a=0.504 \text{ nm}$ ,  $b=0.673 \text{ nm}$ , and  $c=0.448$  and the equilibrium cell volume is  $V_0=0.151 \text{ nm}^3$ . Therefore, a change in atomic volume of about 5 % is required to induce the transition. This amount is about the same as for  $\text{Fe}_{0.65}\text{Ni}_{0.35}$  [7]. However, the pressure required to induce the transition is only about 5 GPa for  $\text{Fe}_{0.65}\text{Ni}_{0.35}$  because, it is softer with a bulk modulus of 130 GPa [23] as opposed to 174 GPa [6] for cementite.

We comment here that the non-hysteretic nature of the high-moment to low moment transition in  $\text{Fe}_3\text{C}$  displays a contrast situation to that observed in pressure dependent XMCD studies on  $\text{Fe}_{72}\text{Pt}_{28}$  Invar, where a broad hysteresis is found [9]. What exactly the pinning entity is in the electronic structure that leads to a hysteresis for  $\text{Fe}_{72}\text{Pt}_{28}$  and why it is absent for  $\text{Fe}_3\text{C}$  is an open issue.

In so much, pressure dependent XMCD spectroscopy at the Fe K-edge proves to be a useful tool to observe volume-driven magnetic instabilities in systems that incorporate Fe. By probing the magnetic degree of freedom with this method, we find direct evidence for the presence of a magnetovolume instability in  $\text{Fe}_3\text{C}$ . These instabilities are expected to be the source of the Invar-typical features observed in the temperature dependence of the thermodynamical parameters for this material. However, how the properties of the instability are related to the local characteristics of the two individual Fe sites (FeI and FeII) remain presently unanswered. To gain more information, it is necessary to provide more elaborate modeling for K-edge XMCD spectroscopy of Fe and  $\text{Fe}_3\text{C}$ . Also, to decide whether the Invar effect in  $\text{Fe}_3\text{C}$  can be explained within the framework of a two state high-moment low-moment model, as for  $\text{Fe}_{0.64}\text{Ni}_{0.36}$  [? ], or within a framework that relates the cause to a presence of disordered magnetic moments [25, 26], requires further investigation.

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