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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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RESEARCH WORKSHOP ON CONDENSED MATTER PHYSICS
(21 June - 3 September 1993)

WORKING GROUP ON MAGNETIC MULTILAYERS
(9 - 13 August 1993)

INTERFACIAL AND INTERLAYER MAGNETIC COUPLING IN METALLIC SUPERLATTICES

PART I

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These are preliminary lecture notes, intended only for distribution to participants

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INTERLAYER MAGNETIC COUPLINGS IN METALLIC SUPERLATTICES

- a brief survey -
- of the theoretical understanding -

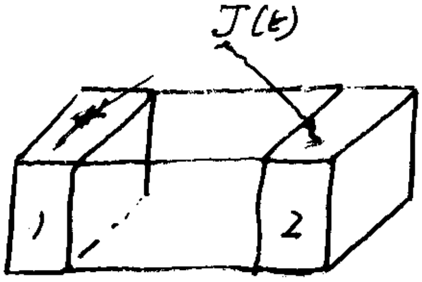
$A_m B_n$

A	B	
Fe, Co, Ni	Cu, Al	NM
	Ru Ir	
	Pd	NFM
	Cr, Mn ...	AF
		F
FERRO LAYERS	SPACERS	

m, n SOME MONOLAYERS

D. Stoeffler, K. Ounadjela, J. Sticht, F. G.

- MAGNETIC COUPLINGS



MAGNETIC ORDER — AF / F / HELI ?

J(t) ?

- LONG RANGED
- OSCILLATING $\sim 3 - 10$ Å PERIOD
- SET MOSTLY BY THE SPACER (NM, M. AF...)
- DEPEND STRONGLY ON THE NATURE OF THE INTERFACES

- NECESSITY OF OF BETTER CONTROL OF THE QUALITY OF THE SL TO UNDERSTAND THE ORIGIN OF THE MAGNETIC [illegible]

- AS AN EXAMPLE THE Cr-Fe SUPERLATT.

Cr Fe SUPERLATTICES

1 AF COUPLINGS BY SPLEED AND BRILLOUIN
Grunberg 1986 Carbone Alvarado 1987

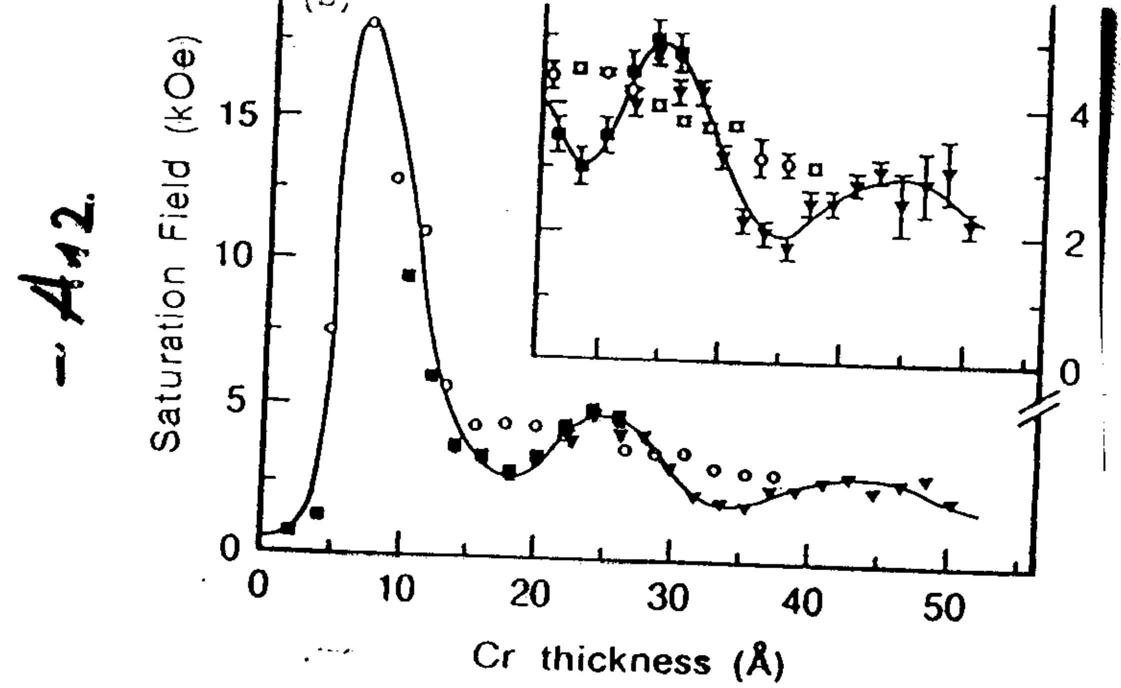
2 AF COUPLINGS FOR m < 15
GIANT MAGNETORESISTANCE Baibich et al 1988

3 OSCILLATING COUPLINGS :

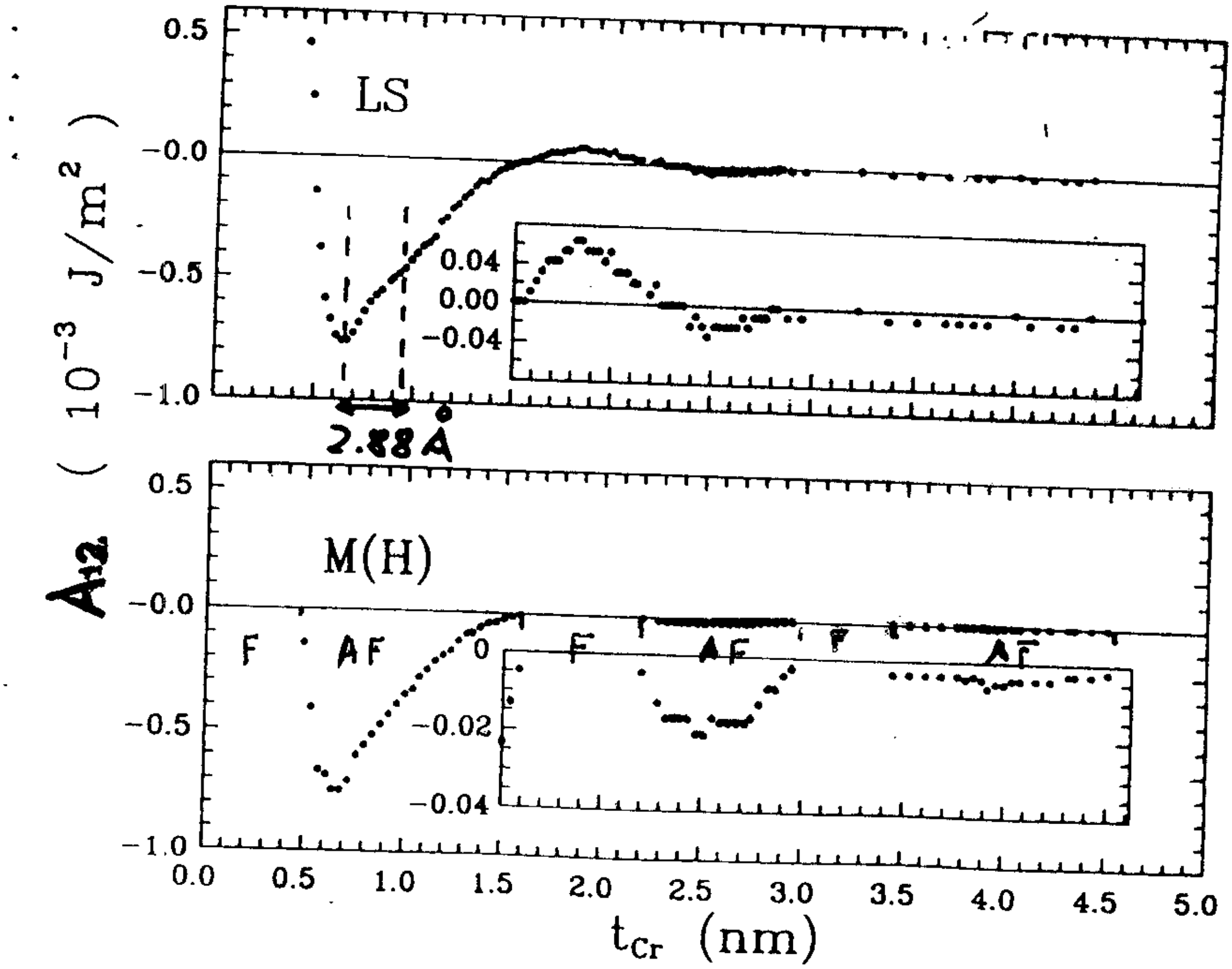
- EXP LONG PERIOD (~ 18 Å)
  Parkin 1990
  Grunberg 1991
- THEORY SHORT PERIOD (~ 4 Å)
  Stoeffler F.G. 1990
  Herman 1991
- EXP : SYSTEMATICS FOR ALL TM SPACERS
  Fe / A Parkin 1991

4 SHORT AND LONG RANGED OSCILLATIONS ACCORDING TO THE CRYSTALLINE QUALITY OF THE LAYERS
Unguris 91
(4 Å and 10 Å)

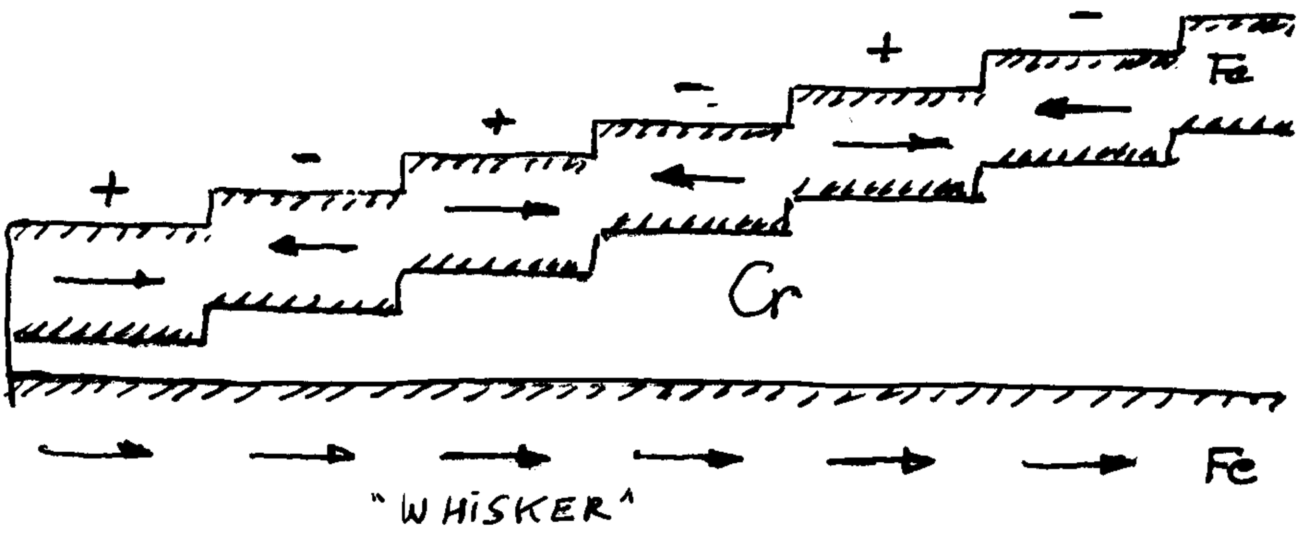
5 Cr is AF AT HIGH TEMPERATURE
"AF SPACER" Unguris 92.



saturation field (4.5 K) vs Cr layer thickness for three series of structures of the form Si(111)/(100 Å) Cr/[(20 Å) Fe/t_{Cr} Cr]$_N$/(50 Å) Cr, deposited at temperatures of △,■, 40 °C (N=30); ○,125 °C (N=20).



Grunberg et al 1992

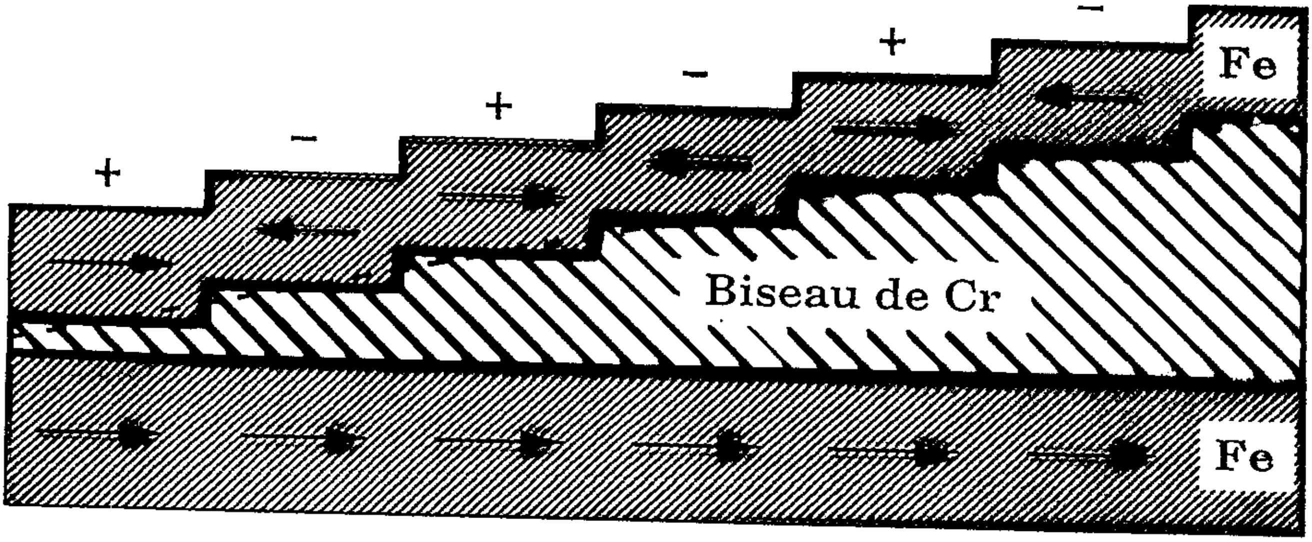


GOOD CRYSTALLINE QUALITY → $\Lambda \cong 2$ MC

$\Lambda \approx 9$ MC

Unguris et al 1991

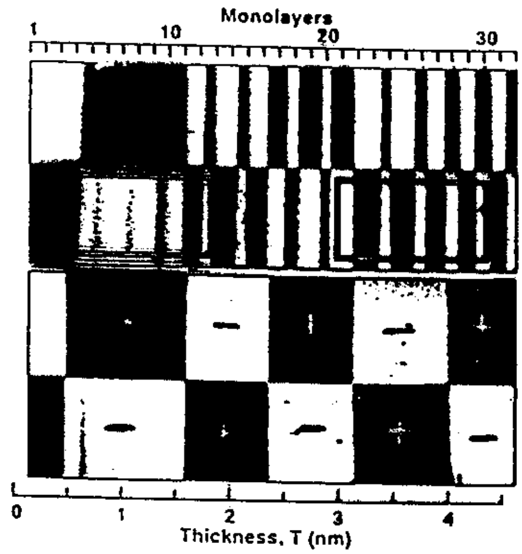
–Mise en évidence de deux périodes d'oscillation: rôle de la rugosité interfaciale (Unguris et al., 1991)



"WHISKER" de Fer

Bonne qualité cristalline à l'interface: COURTES PERIODES ⟶

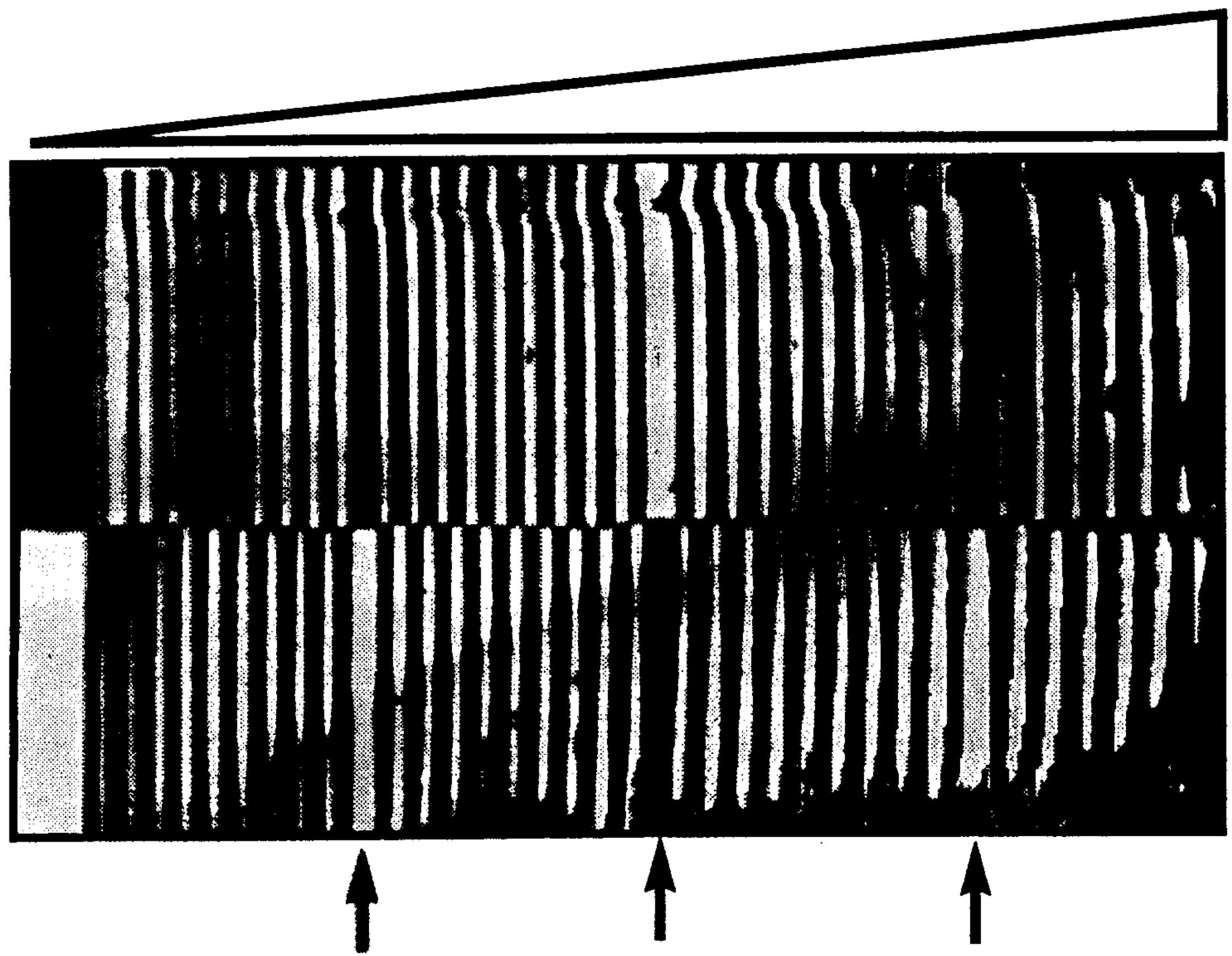
Moins bonne qualité cristalline à l'interface: LONGUES PERIODES ⟶



Unguris et al 1992

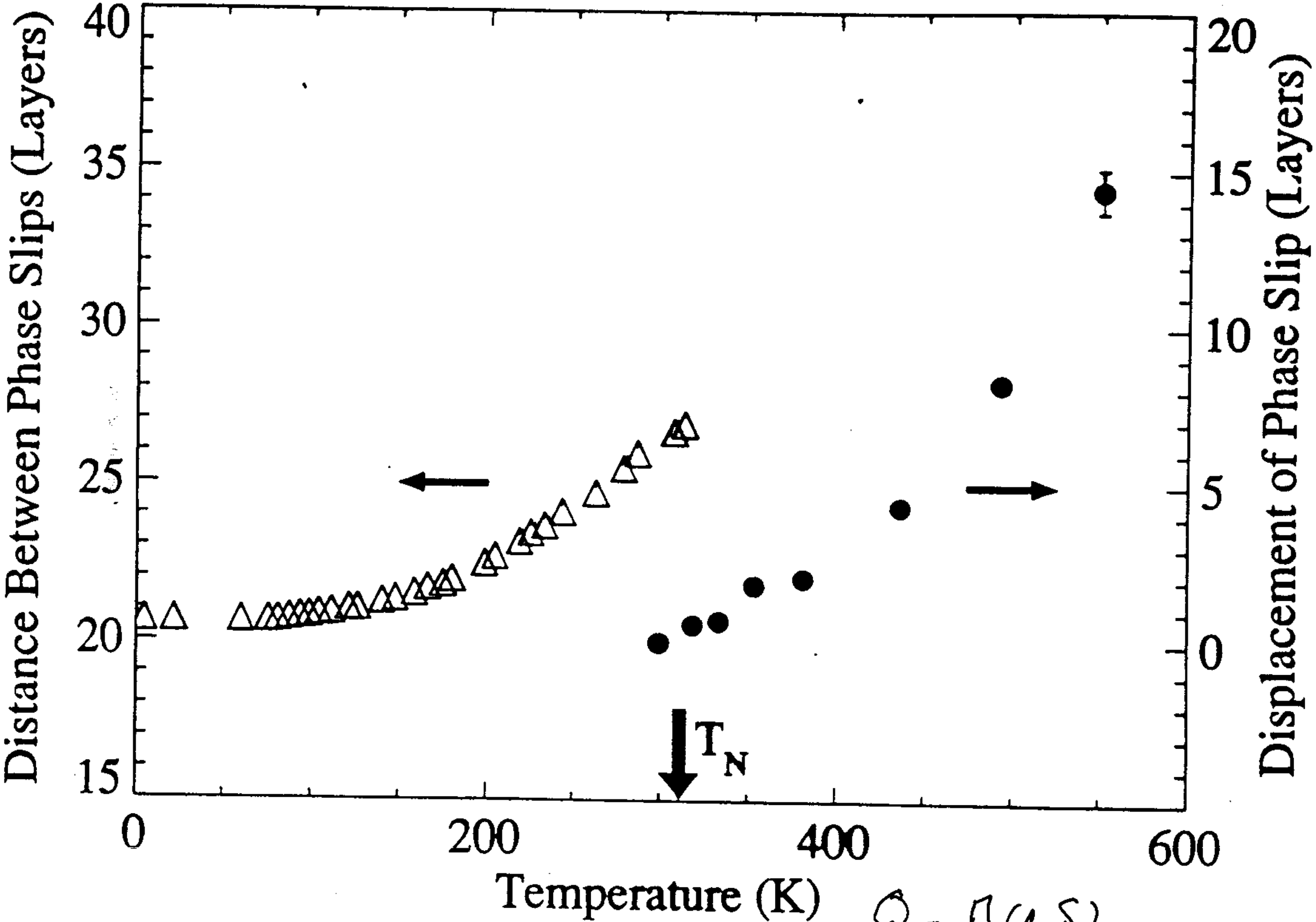
SHORT AND LONG PERIODS!

.6



➡ PHASE SLIPS

FIG 1



$Q = \frac{\Pi}{d}(1-\delta)$

$1/\delta$ = nb of layers between phase slips.

I.M.C

- 1 INTRODUCTION
- 2 IMC : THE THEORETICAL SITUATION
- 3 CALCULATION OF THE IMC - METHODS
- 4 1st EXAMPLE : THE PdFe SYSTEM
- 5 2d EXAMPLE : THE CrFe SYSTEM

- POINT OUT THE LIMITATIONS (and POSSIBILITIES OF THE METHODS
- CONSIDER MOSTLY THE RESULTS OF BAND STRUCT CALCULATIONS

2 IMC : THE THEORETICAL SITUATION

2-1 "RKKY" MODELS

Yafet 1987 Gd Y

Levy Wang 1990

* Bruno Chappert 1991 – 1993

Edwards Mathon 1990 - 1993

2-2 BAND STRUCTURE MODELS

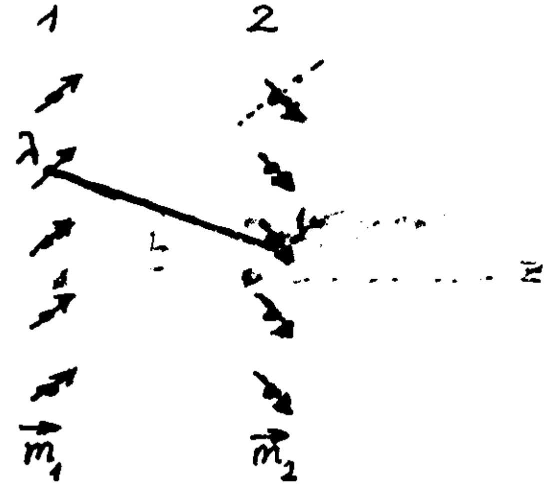
- L.S.D.A
  - Ounadjela et al 1989-1991 Fe Cr
  - Koenig Knab 1991 – 1993 Fe Ru
  - Herman Schrieffer 1991 – 1993 Fe Cr [illegible]
  - Stoeffler et al 1992 – 1993 Co Ru, Pd [illegible]
- TIGHT BINDING MODELS (TB)
  - Stoeffler et al 1990 . 1993

2.3 LIMITATIONS

- RKKY — ASYMPTOTIC REGIME $t > t_1$ + SIMPLIFYING ASSUMPTION
- BAND STRUCTURE MODELS — SMALL t ($t <$ [illegible]
  - "ab initio" + LSDA + STRUCTURE +
  - "TB" + SEMI EMP PAR

3. DETERMINATION OF THE INTERLAYER COUPL.

a) INTERLAYER MAGNETIC COUPLINGS "RKKY"



- 2 FERRO. PLANES 1, 2 A PERTURBING AN EL GAS B (ex A = Co, B = Cu)

- EACH IMPURITY A INTRODUCES A PERTURBING POTENTIAL $V_\sigma(r)$ AND A SPIN POLARIZATION $\vec{m}_1(r)$

- THE INTERACTION ENERGY BETWEEN THE PLANES OF A RESULTS FROM THE SUPERPOSITION OF THE PAIR INTERACT. BETWEEN $\lambda \in 1$ AND $\mu \in 2$

"QUADRATIC EXCHANGE" $$E(t) = \sum_{\lambda,\mu}{}' v(\lambda-\mu)\, \hat{m}_\lambda \cdot \hat{m}_\mu$$

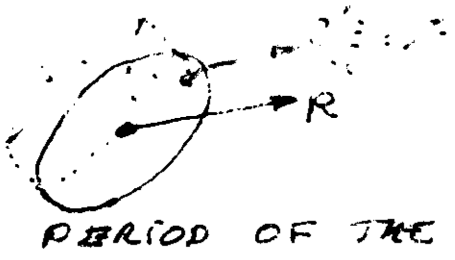
- ASYMPTOTIC FORM $t \to \infty$ (the V_σ are assumed to be localized)

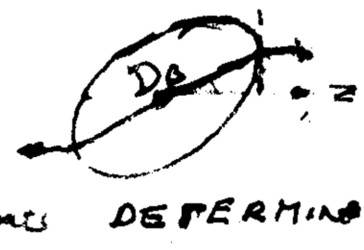
IMPURITY — Blandin 1960, Caroli 1964

$$v(\underbrace{\lambda-\mu}_{R}) \sim \sum_\alpha A_\alpha \frac{\cos(D_\alpha R + \varphi_\alpha)}{R^3} \Rightarrow$$

PLANES — Bruno

$$E(t) \sim \sum_\beta A_\beta \frac{\cos(D^\beta t + \varphi^\beta)}{t^2}$$

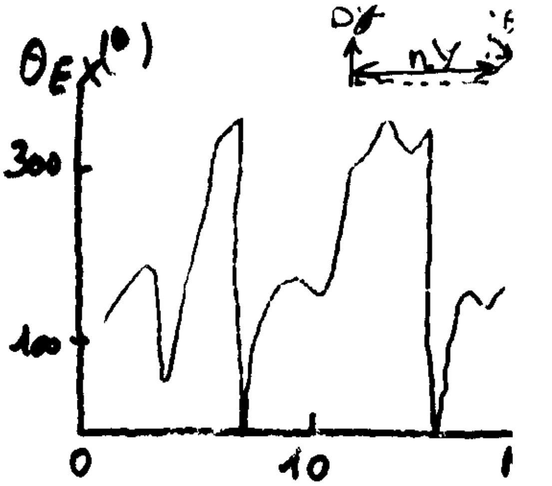




THE PERIOD OF THE IMC OSCILLATIONS DETERMINED BY THE TOPOLOGY OF THE FERMI SURFACE

AMPLITUDE ? PHASE ? BIQUADRATIC !

Dy Gd



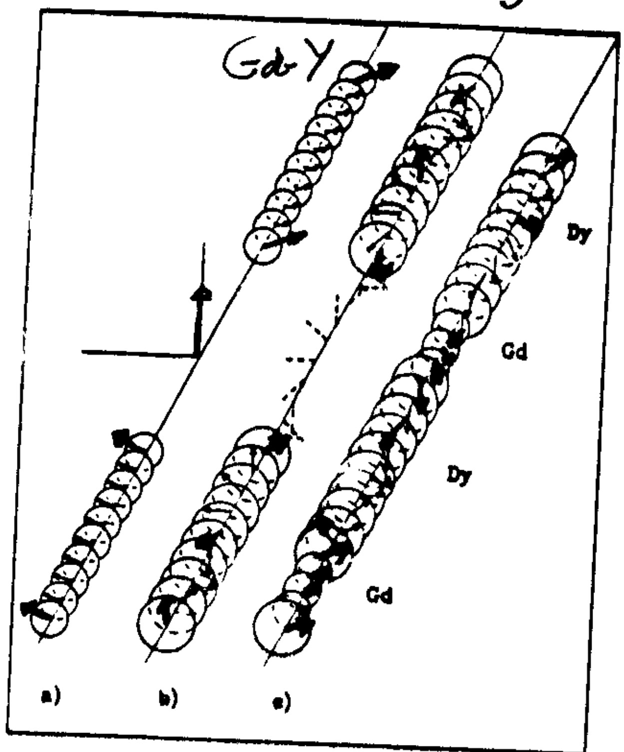
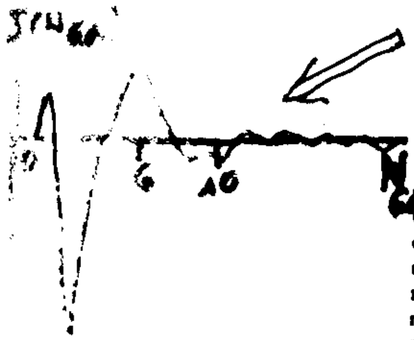


FIG. 5. Schematic representation of the basal-plane component directions in three RE superlattice systems at representative values of H and T as described in the text: (a) Gd-Y canted antiphase domain structure; (b) Dy-Y coherent, incommensurate spiral; and (c) Gd-Dy "asymmetric" state. The case of Ho-Y is similar to that of the Dy-Y except that the spiral wave vector may be locked into commensurate values corresponding to a spin-slip moment configuration. The effect of compositional modulation on the average magnitude of the moment in a given basal plane is not represented nor are possible c-axis or disorder components.



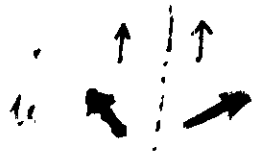
$T_c(Gd) = 285K$ $T_N(Dy) = 180K$ $T_c(Dy) = 90K$

$(Gd_{N_{Gd}} Y_{N_Y})_M$

$N_y = 6, 10, 20$

$N_{Gd} = 10$

$= 200$



cf BRUNO'S LECTURE

FOR A DISCUSSION OF THE RESULTS

VS EXP FOR NOBLE METAL SPACERS

—

3 b BAND STRUCTURE CALCULATIONS

- FROM A GIVEN CRYSTALLINE STRUCTURE
  (bcc, bct. hcp fcc ...
- USING A GIVEN EXPRESSION FOR THE EXCHANGE CORRELATION POTENTIAL
- USING ALSO SOME SIMPLIFICATIONS FOR THE POTENTIAL SHAPE TO TREAT LARGER CELLS

- CALCULATE THE ENERGY DIFFERENCE

$$\Delta E = E_F - E_{AF} = 2J(t)$$

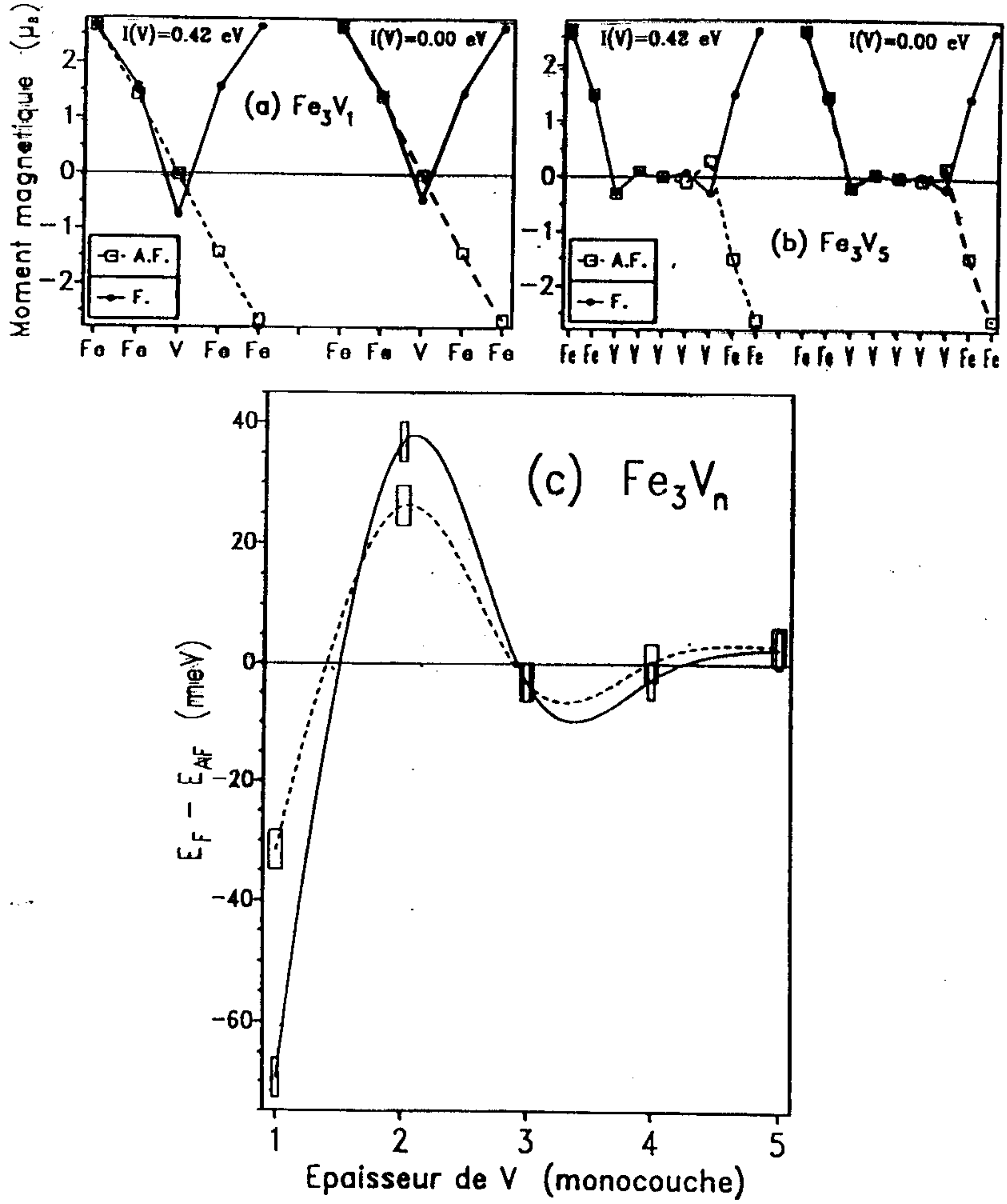
BETWEEN FERRO AND ANTIFERRO MAGNETIC ARRANGEMENTS

→ DETERMINE THE SELF CONSISTENT BAND STRUCT.
Via THE LOCAL DENSITIES OF STATES

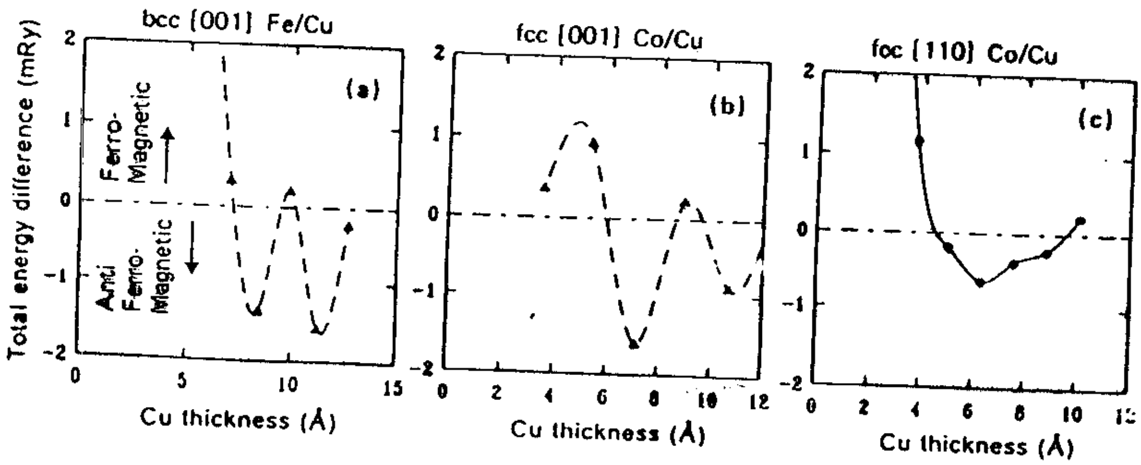
- IN THE DIRECT SPACE "TB"
- IN THE RECIPROCAL SPACE NB k POINTS

$J(t) \gtrsim$ meV / unit at

T. E. 4.


I(V)=0.42 eV
I(V)=0.00 eV
(a) Fe_3V_1
(b) Fe_3V_5
Moment magnetique (μ_B)
A.F.
F.
Fe Fe V Fe Fe Fe Fe V Fe Fe
Fe Fe V V V V V Fe Fe Fe Fe V V V V V Fe Fe
(c) Fe_3V_n
$E_F - E_{AF}$ (meV)
Epaisseur de V (monocouche)

LSDA



Herman / Sticht

depends strongly on the orientation

4 A FIRST EXAMPLE : THE Pd Fe SL.

a) EXPERIMENTAL

- Fe | Pd_n (100) | Fe(100) SANDWICHES
  Celinski et al $n \leq 12$
  ferromagnetic + oscillations
- Fe_m Pd_n SL A. Schul et al
  ferromagn $n \leq 25$
- EPITAXY BUT PRECISE STRUCTURE UNKNOWN
  starting from bcc Fe
  between Pd { fct $\frac{\Delta\Omega}{\Omega} = 0$ CAV
  fcc $\frac{\Delta\Omega}{\Omega} \sim 13\%$ EAV

b) THEORY

- ASW CALCULATIONS
- TWO EXTREME STRUCTURES EAV / CAV
- IMC — LDOS.
- DETERMINATION OF TETRAGONALITY c/a

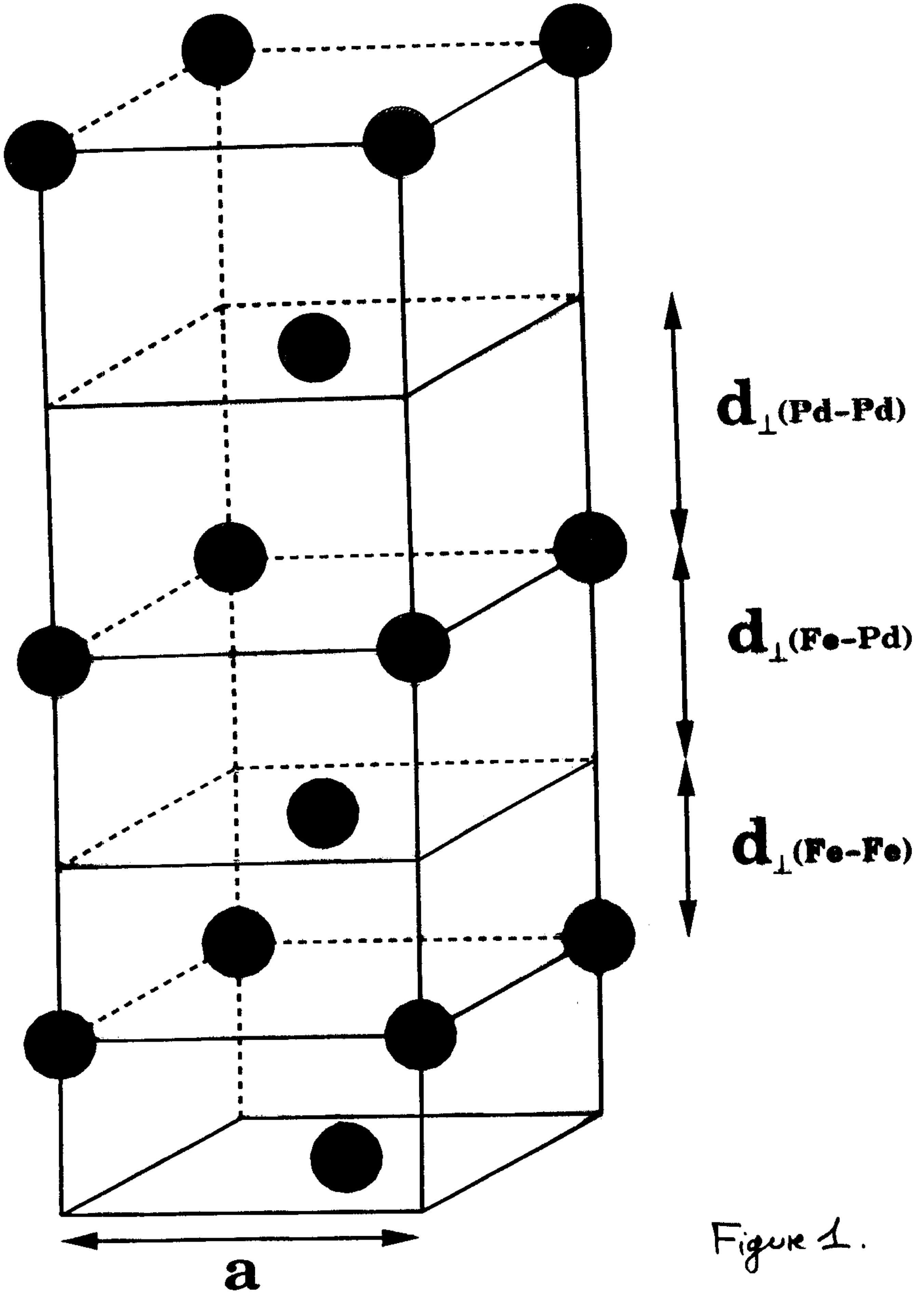
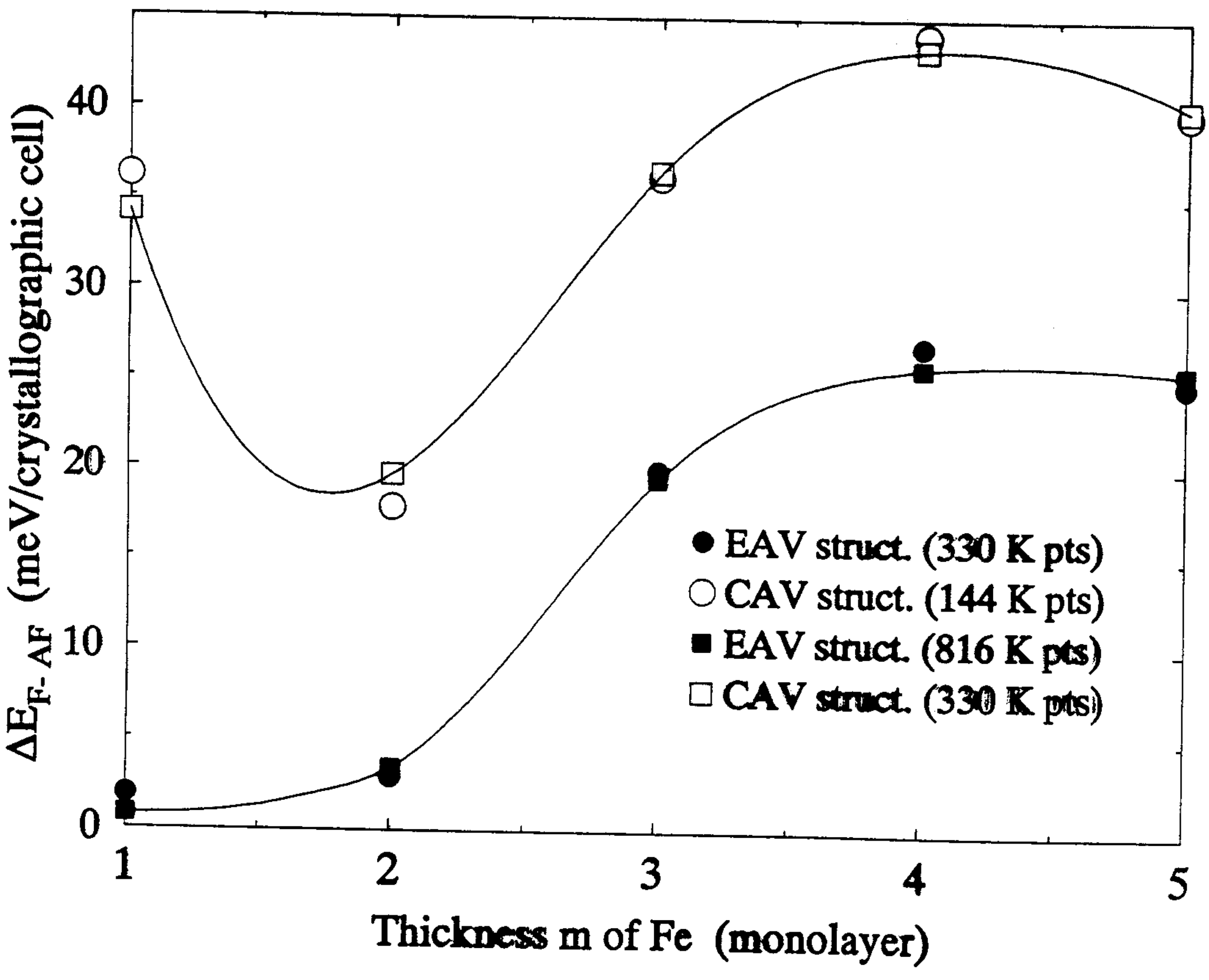


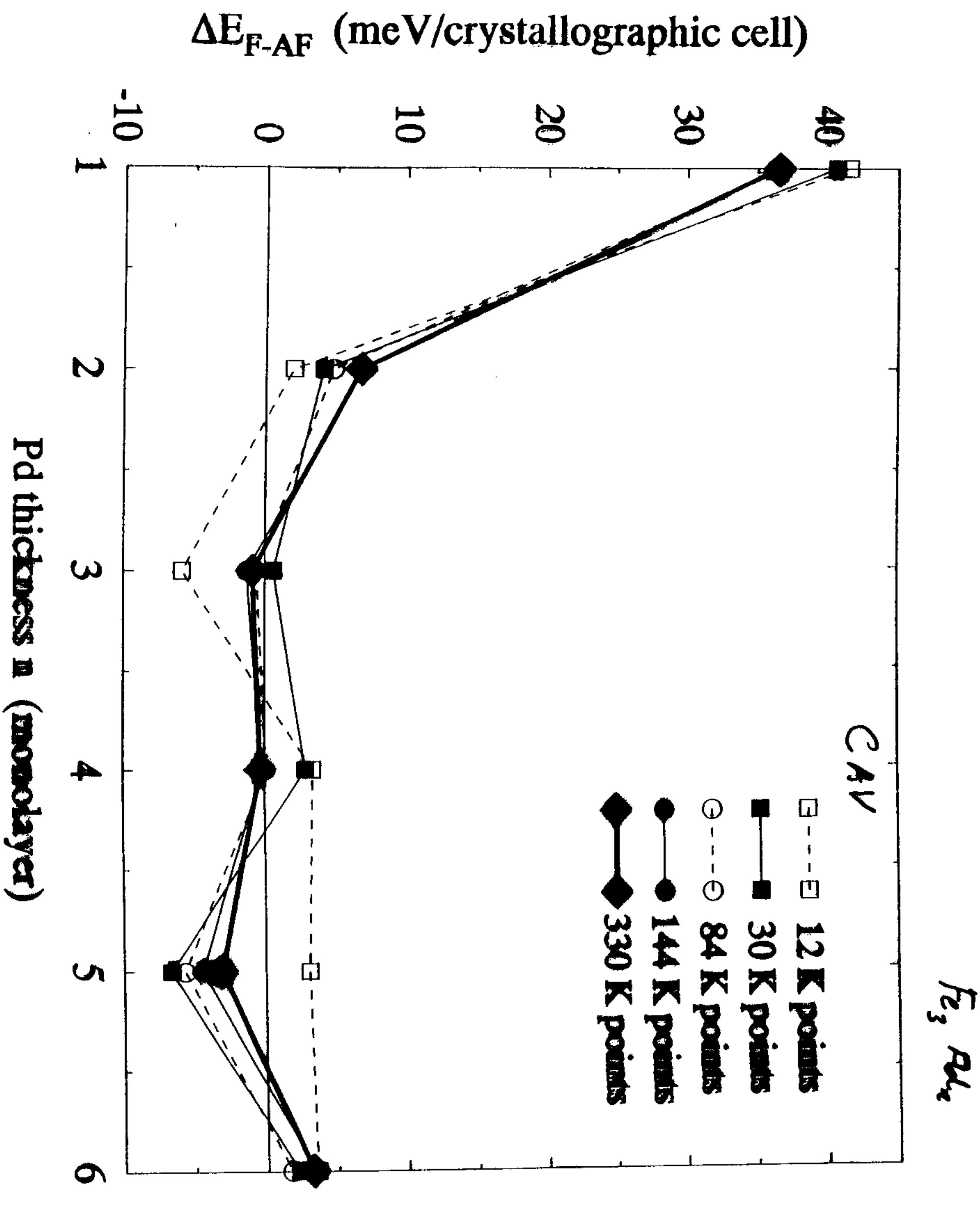
Figure 1.



Fe m Pt 1

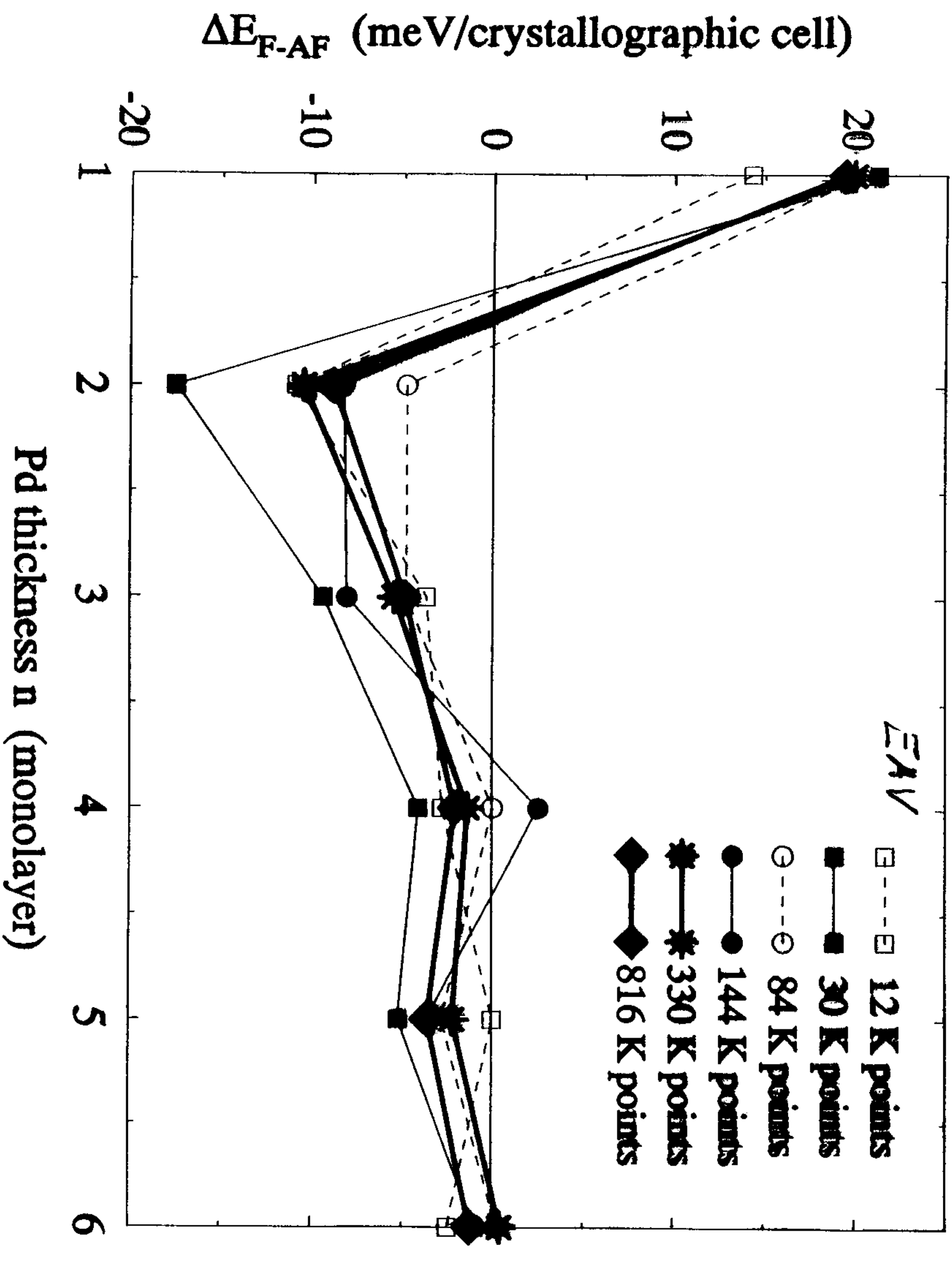
Figure 1.

19

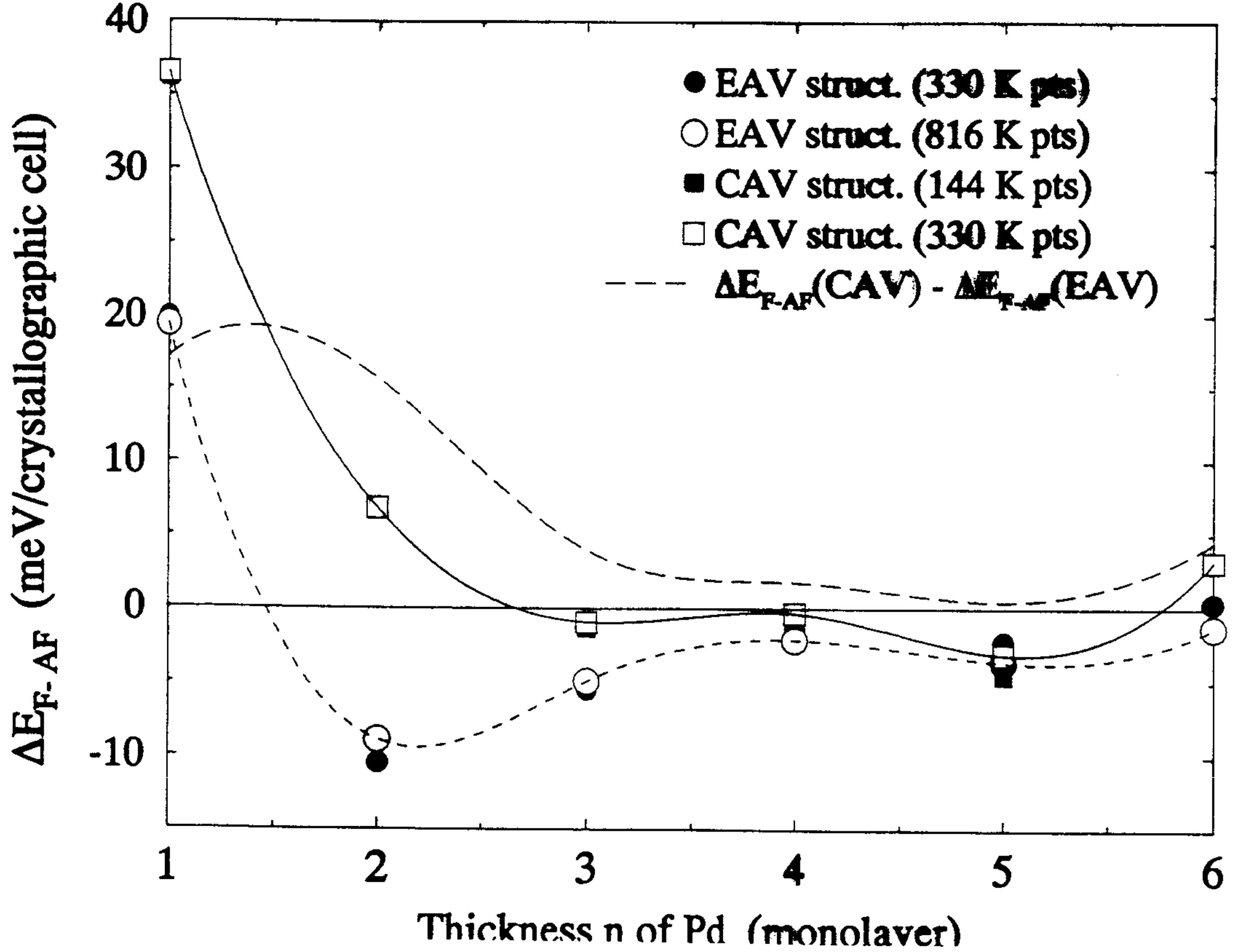


ΔE_F-AF (meV/crystallographic cell)
-10
0
10
20
30
40
1
2
3
4
5
6
Pd thickness n (monolayer)
CAV
12 K points
30 K points
84 K points
144 K points
330 K points

Figure 3-a


ΔE_F-AF (meV/crystallographic cell)
Pd thickness n (monolayer)
EAV
12 K points
30 K points
84 K points
144 K points
330 K points
816 K points
-20
-10
0
10
20
1
2
3
4
5
6

Figur 3-b



ΔE_F-AF (meV/crystallographic cell)
40
30
20
10
0
-10
1
2
3
4
5
6
Thickness n of Pd (monolayer)
EAV struct. (330 K pts)
EAV struct. (816 K pts)
CAV struct. (144 K pts)
CAV struct. (330 K pts)
ΔE_F-AF(CAV) - ΔE_F-AF(EAV)

Figure 4

Figure 7 Fe_3Pd_1

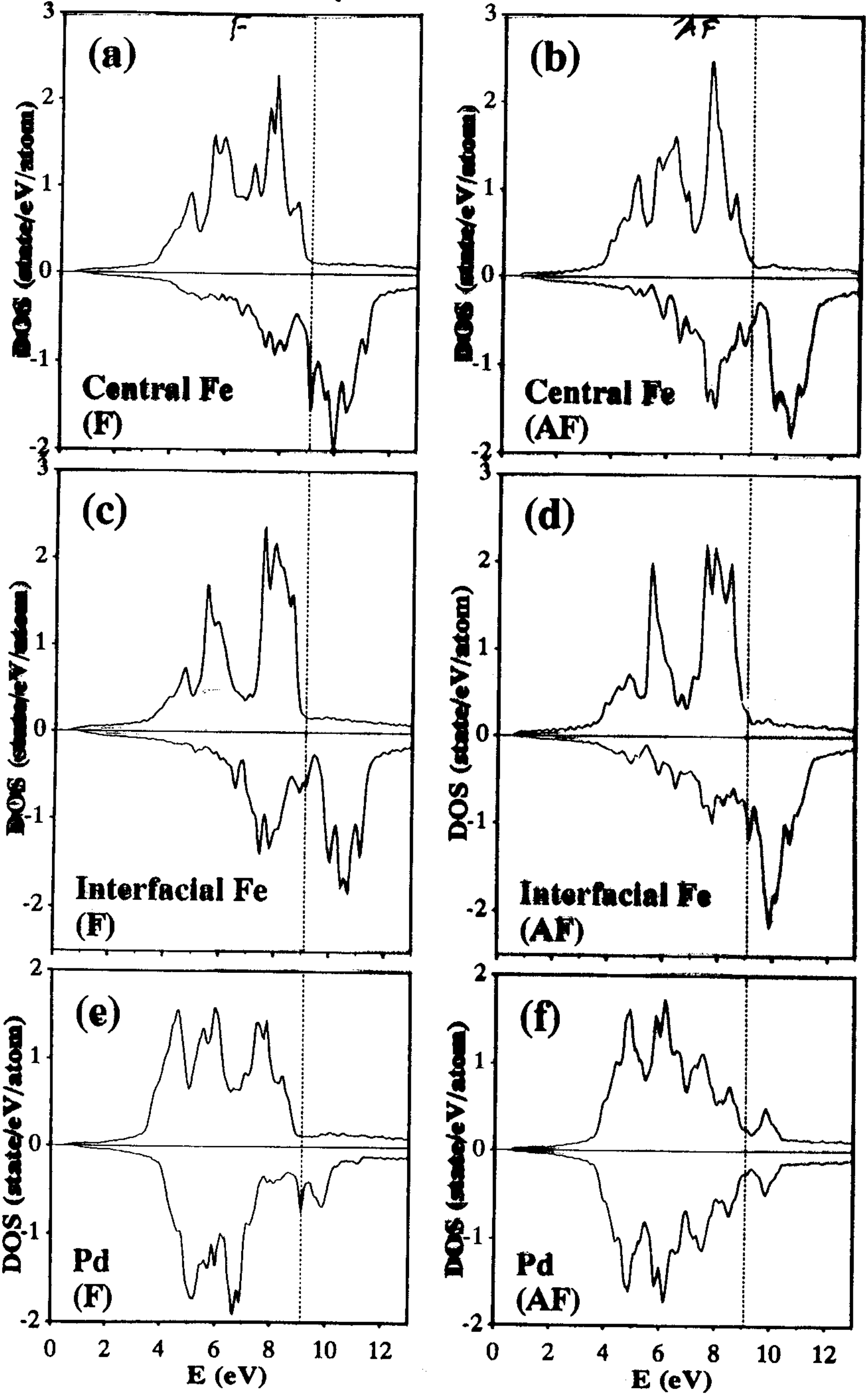


Figure 6 [redacted] Fe_3Pd_1 (LAV)

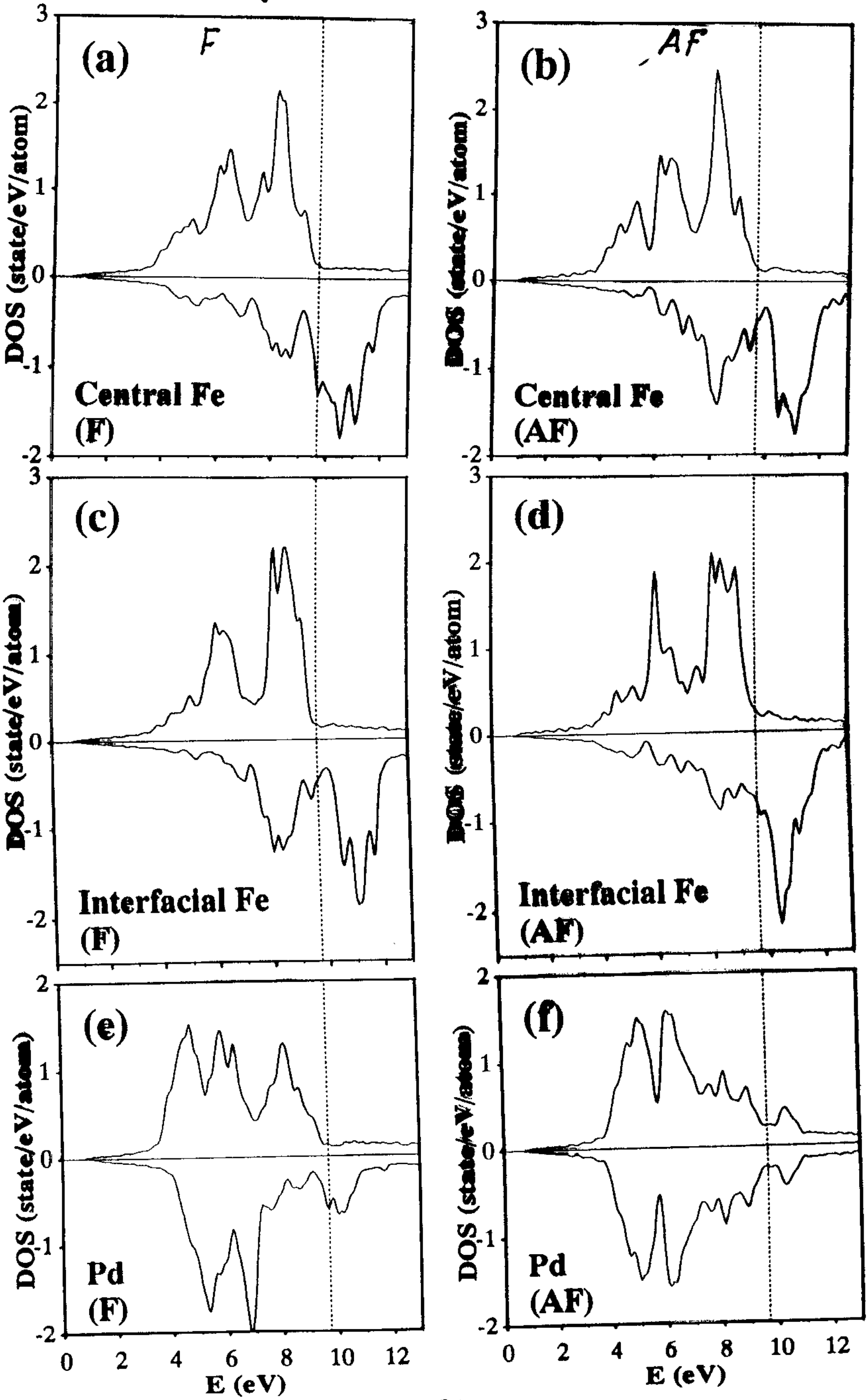
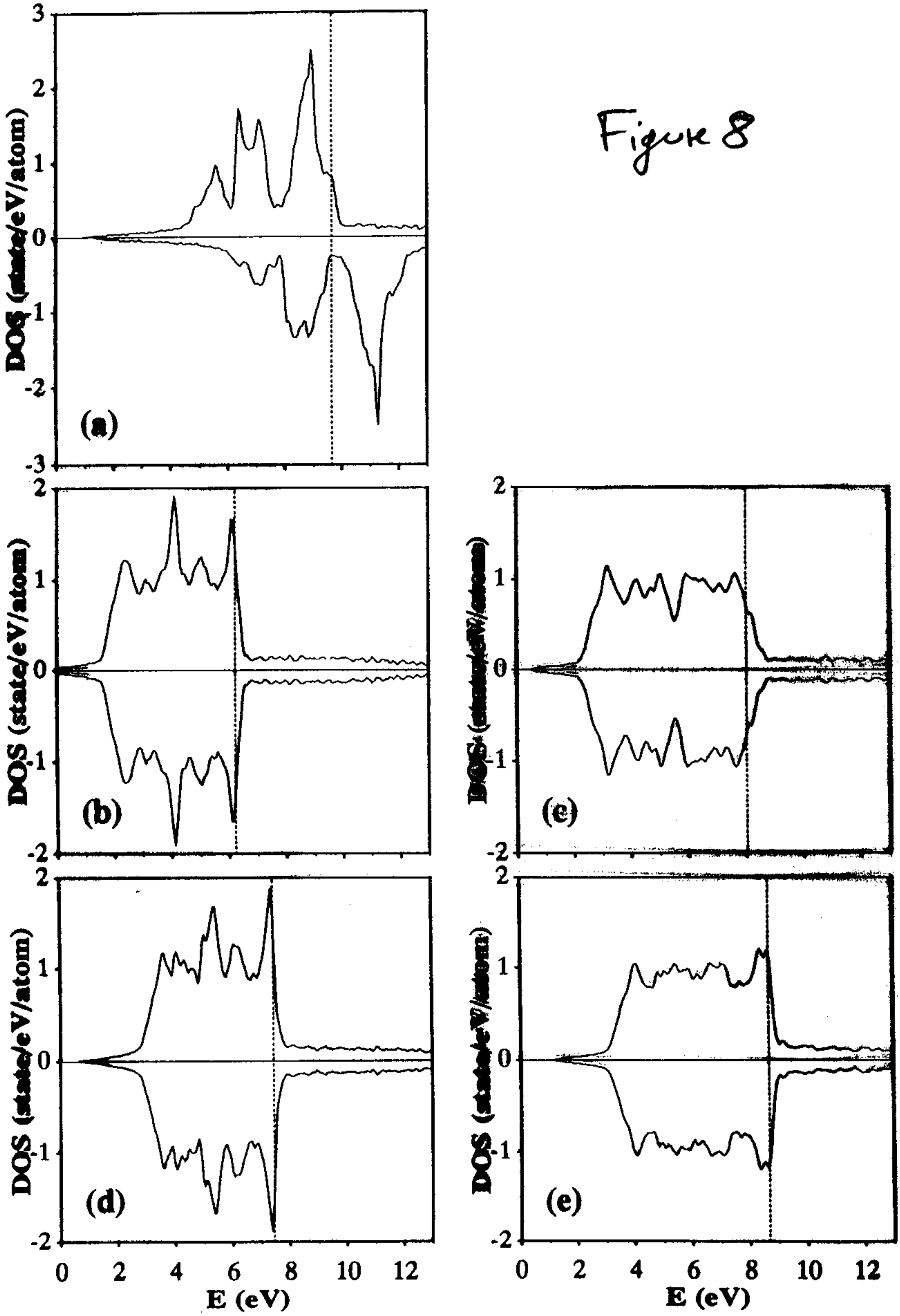


Figure 8



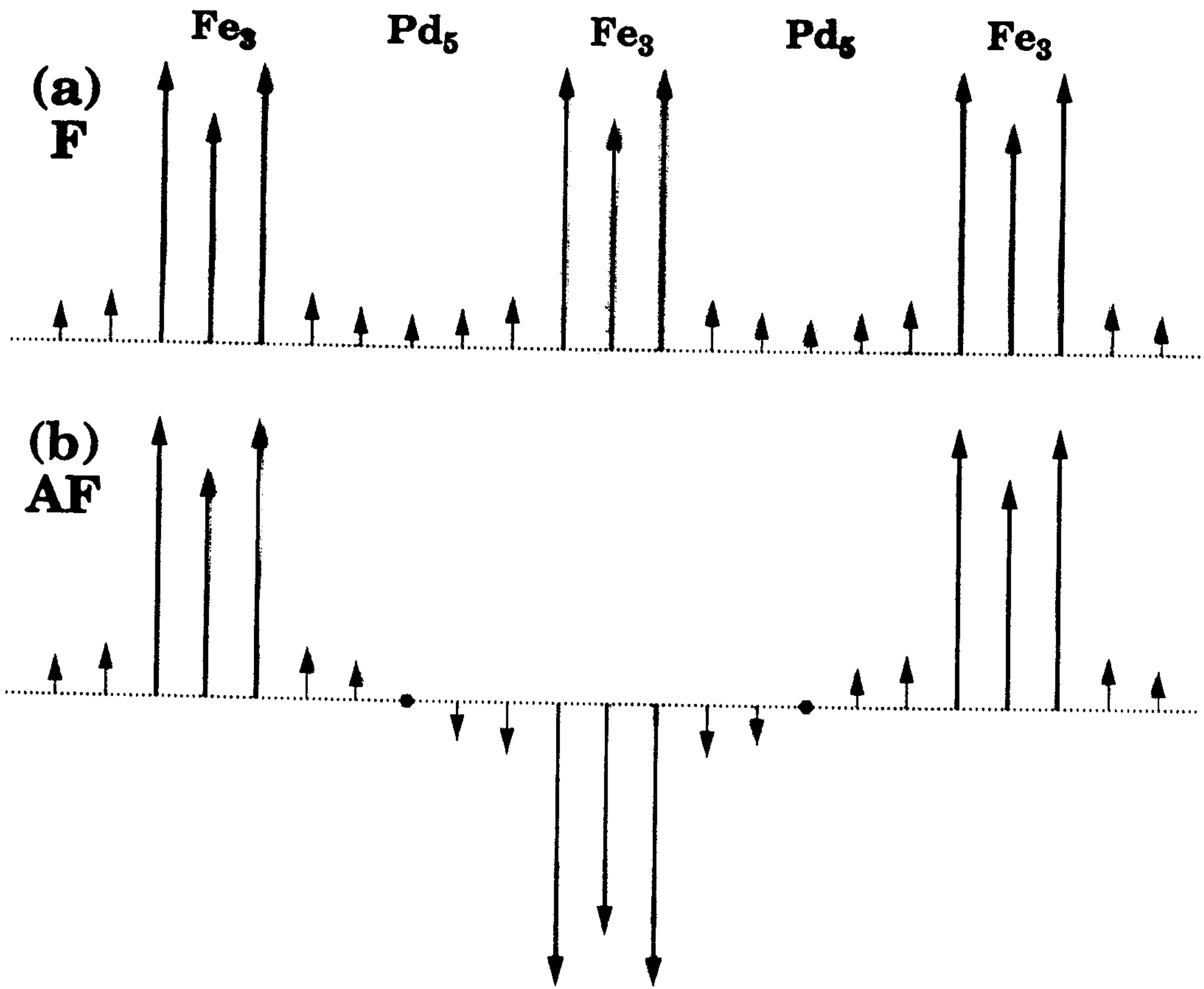
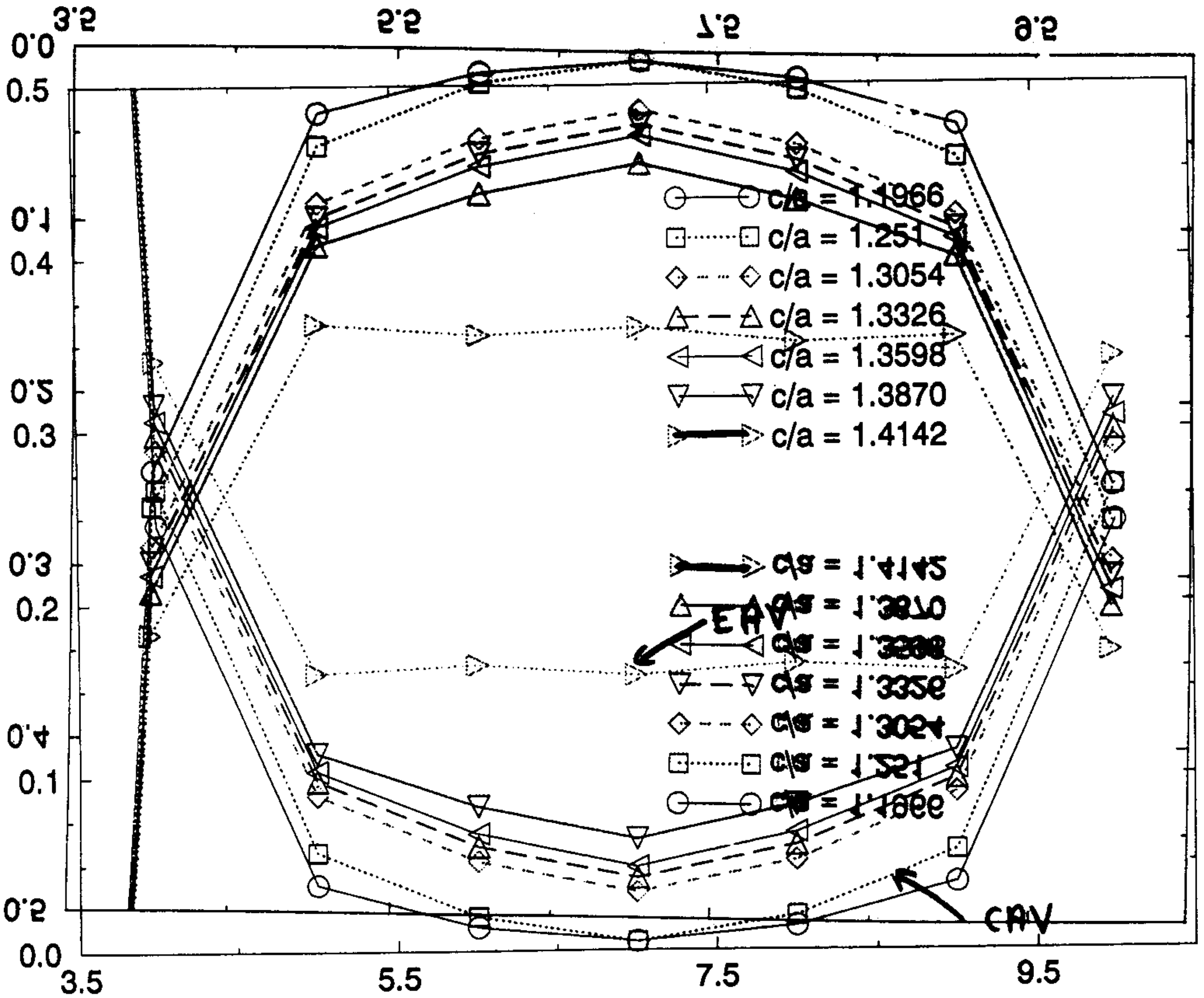


Figure 2

Fe_3Pd_7

312 kpb.



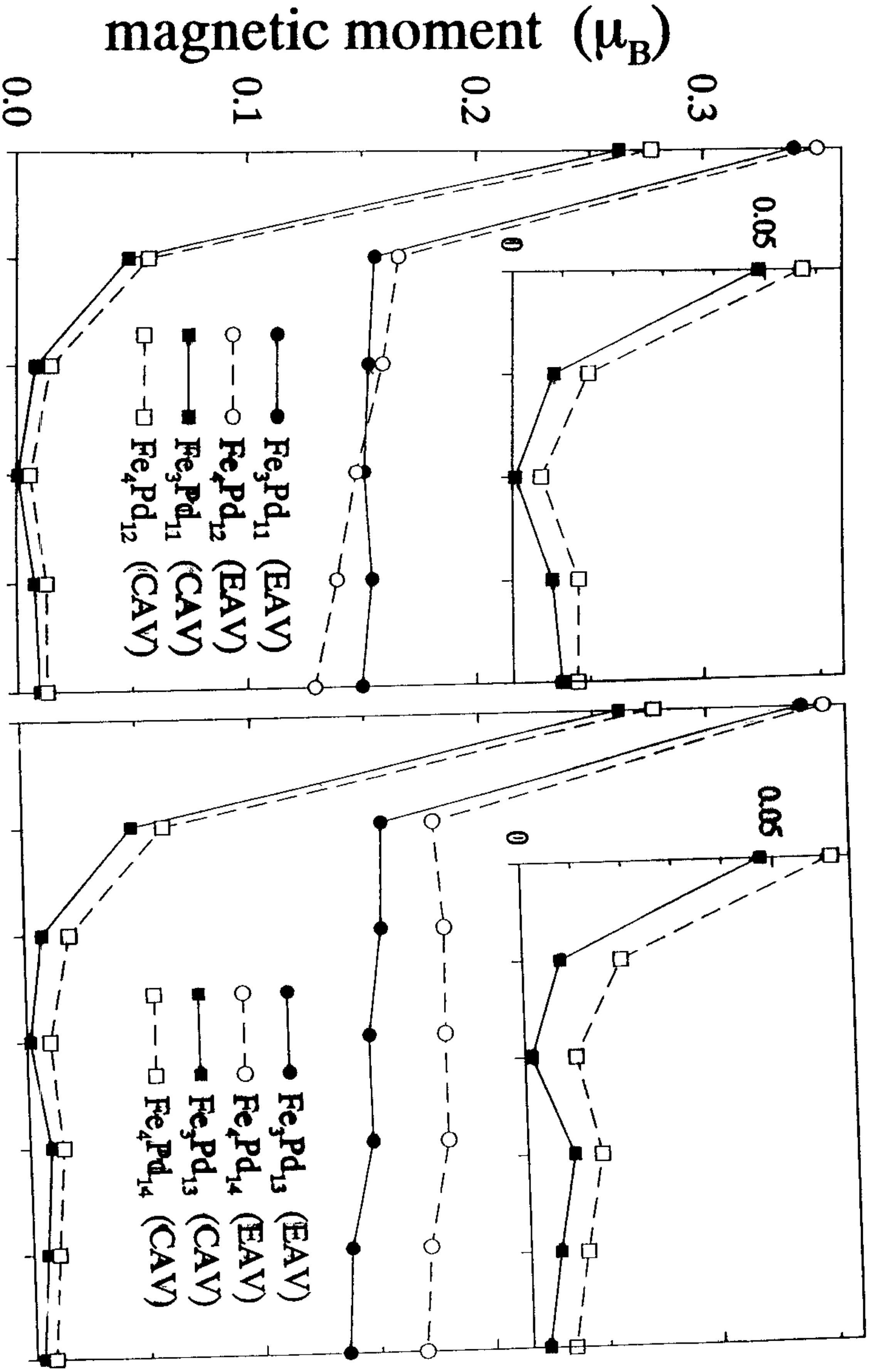
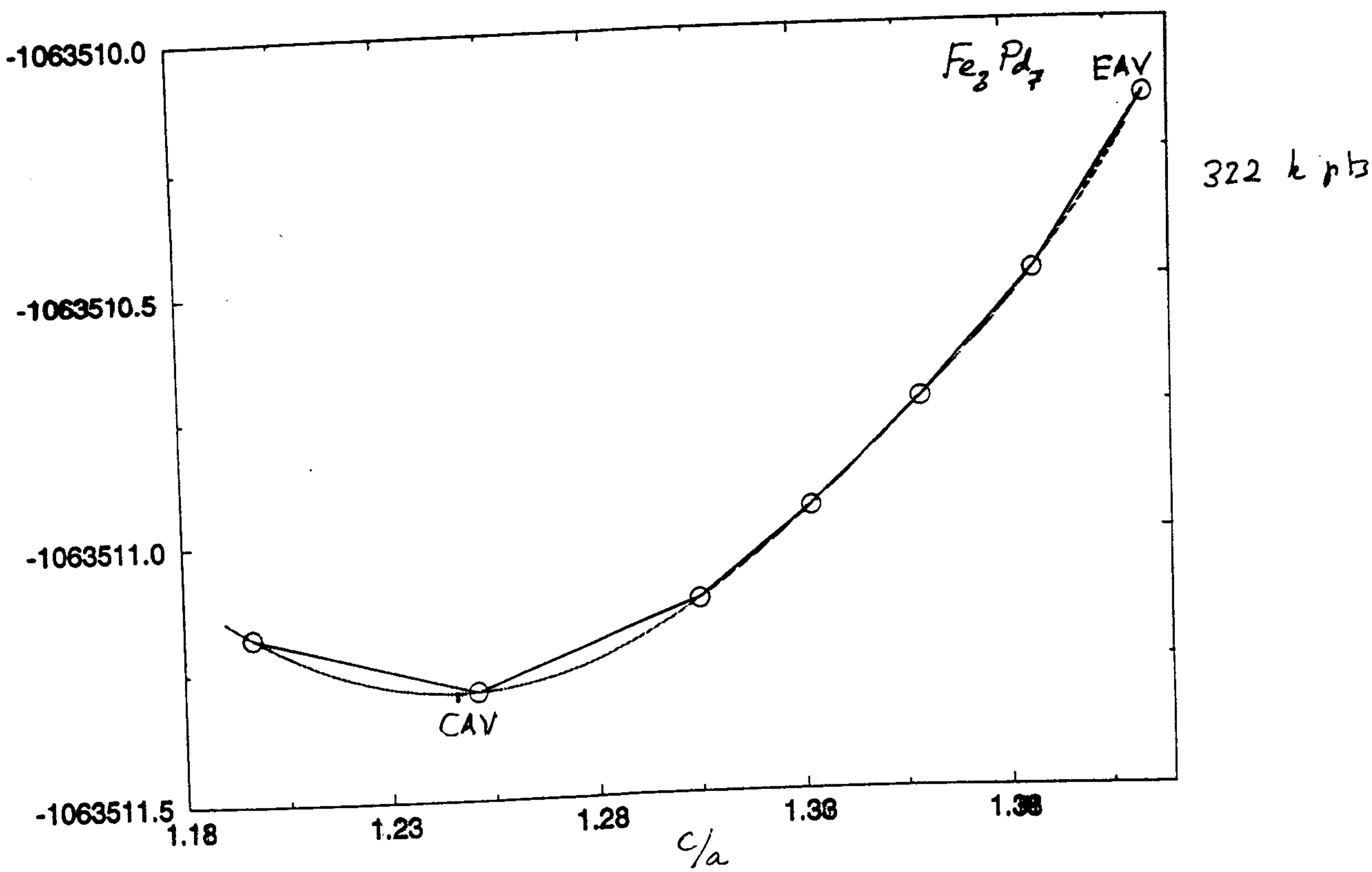

magnetic moment (μB)
0.0
0.1
0.2
0.3
0.05
0
Fe3Pd11 (EAV)
Fe4Pd12 (EAV)
Fe3Pd11 (CAV)
Fe4Pd12 (CAV)
Fe3Pd13 (EAV)
Fe4Pd14 (EAV)
Fe3Pd13 (CAV)
Fe4Pd14 (CAV)

Figure 9



-1063510.0
-1063510.5
-1063511.0
-1063511.5
1.18
1.23
1.28
1.33
1.38
c/a
Fe3 Pd7
EAV
CAV
322 k pts

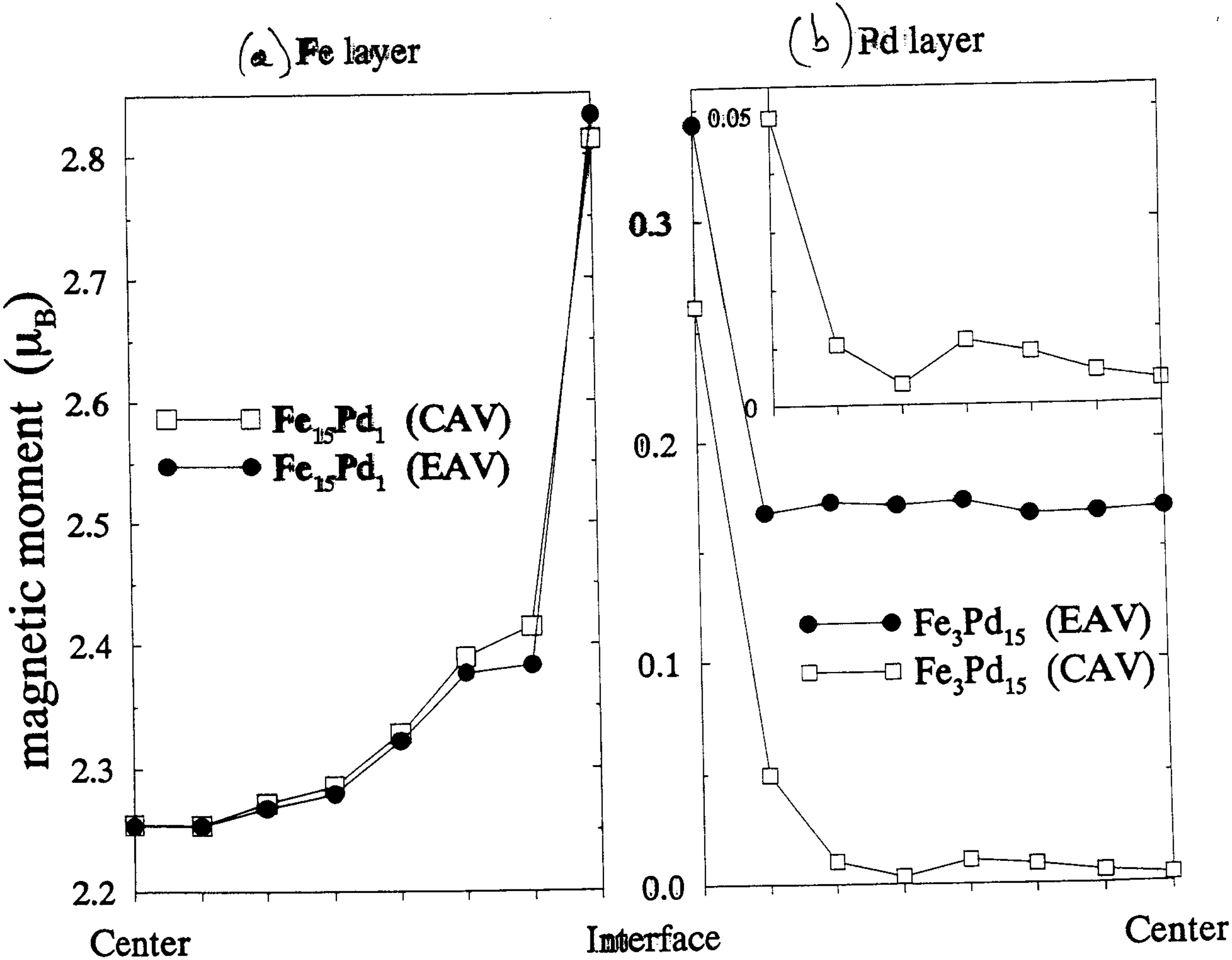

(a) Fe layer
magnetic moment (μB)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
Fe15Pd1 (CAV)
Fe15Pd1 (EAV)
Center
Interface
(b) Pd layer
0.3
0.2
0.1
0.0
0.05
0
Fe3Pd15 (EAV)
Fe3Pd15 (CAV)
Center

Figure3