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Joint INFM - the Abdus Salam ICTP School on
"Magnetic Properties of Condensed Matter Investigated by Neutron Scattering and Synchrotron Radiation Techniques"

1 - 11 February 2000

ULTRAFAST MAGNETIC DYNAMICS

PART II

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

TWO-CURRENT CONDUCTION IN NICKEL

A. Fert and I. A. Campbell
Physique des Solides,* Faculté des Sciences, Orsay, France
(Received 8 July 1968)

Measurements on the low-temperature electrical resistivity of dilute nickel-based alloys give strong evidence that spin-$\uparrow$ and spin-$\downarrow$ electrons carry current in parallel, providing important implications for the interpretation of transport properties of pure as well as alloy ferromagnets.

Electrical-resistance results on Ni[1] have recently been interpreted by Herring[2] by a model in which no account is taken of the ferromagnetic nature of the metal. On the basis of measurements on Fe containing a number of dilute impurities, we have suggested[3] that there is strong evidence that in ferromagnetic metals spin-$\uparrow$ and spin-$\downarrow$ electrons carry current in parallel with different conductivities (at least at low temperatures). This model has a direct bearing on the interpretation of transport properties of pure as well as alloy ferromagnets.

We report in this Letter experiments on the electrical resistivity of Ni containing Co, Mn, Cr, and Ti as dilute impurities. The results confirm the two-current model and can lead to a better understanding of the scattering processes in Ni.

The model used can be summarized as follows. It is assumed that the conduction electrons of the two half-bands of opposite spin have different relaxation times $\tau_\uparrow$ and $\tau_\downarrow$. In addition there are spin-flip and electron-electron collision processes characterized by a relaxation time $\tau_{\uparrow\downarrow}$ which

system of equations, it can be shown[3] that the total resistivity is

$$\rho = \frac{\rho_\uparrow \rho_\downarrow + \rho_{\uparrow\downarrow}(\rho_\uparrow + \rho_\downarrow)}{\rho_\uparrow + \rho_\downarrow + 4\rho_{\uparrow\downarrow}}, \tag{2}$$

where $\rho_\uparrow = m/ne^2\tau_\uparrow$, $\rho_\downarrow = m/ne^2\tau_\downarrow$, and $\rho_{\uparrow\downarrow} = m/ne^2\tau_{\uparrow\downarrow}$.

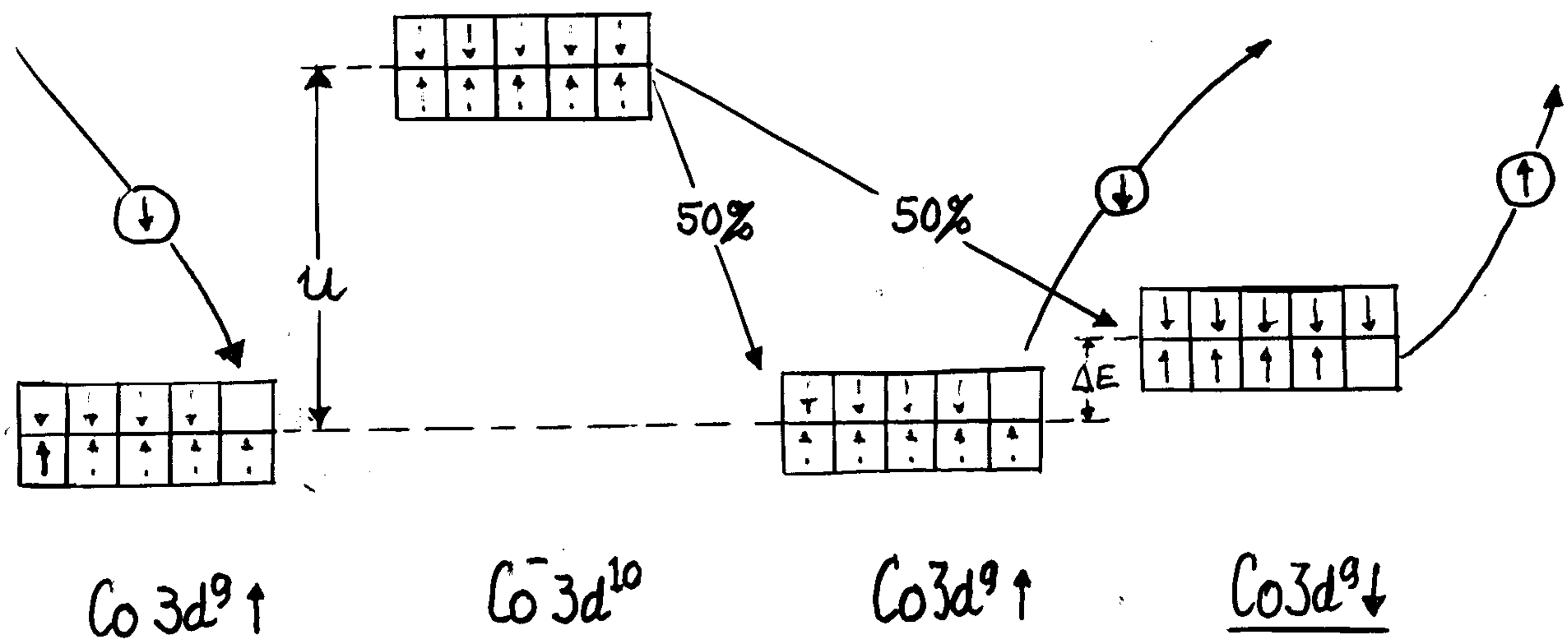
We will further assume for $\rho_\uparrow$ and $\rho_\downarrow$ that the effects of the various scattering mechanisms add together by the quasi-Matthiessen rules:

$$\rho_\uparrow(T) = \rho_\uparrow^0 + \rho_\uparrow^i(T),$$

$$\rho_\downarrow(T) = \rho_\downarrow^0 + \rho_\downarrow^i(T), \tag{3}$$

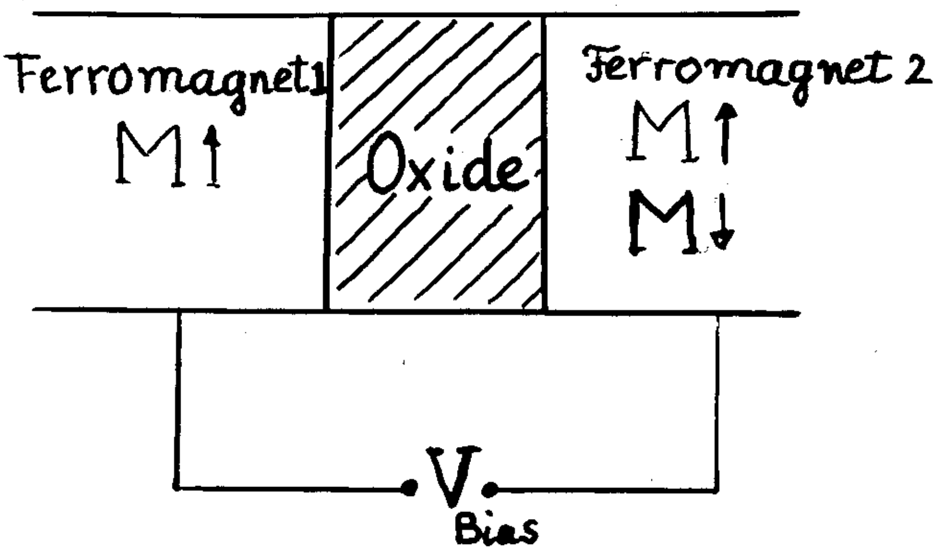
where $\rho_\uparrow^0, \rho_\downarrow^0$ are the temperature-independent scattering components due to the impurities while $\rho_\uparrow^i, \rho_\downarrow^i$ are the temperature-dependent parts of the scattering for the two half-bands. It will also be assumed that the temperature-independent part of $\rho_{\uparrow\downarrow}$ is zero.[6] We will concentrate attention on the low-temperature limit with-

Inverting the magnetization by electron scattering



Spin Polarized Tunneling:

Tunnel Magnetoresistance (TMR)



Normal TMR: R↑↑ small
R↑↓ large

- ∇ -

ELECTRON SPIN POLARIZATION IN FIELD EMISSION FROM Gd

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and

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Theoretisches Teilinstitut, Physik Department der Techn. Hochschule, München

Received 15 May 1967

Theoretical considerations of the conduction electron polarization in Gd are reported. They predict that 5-10% polarization ought to be measured in an electron beam produced by field emission.

The electron current from a field emission cathode is produced by tunneling from the electron states at and directly below the Fermi level within some 10^{-2} eV [1].

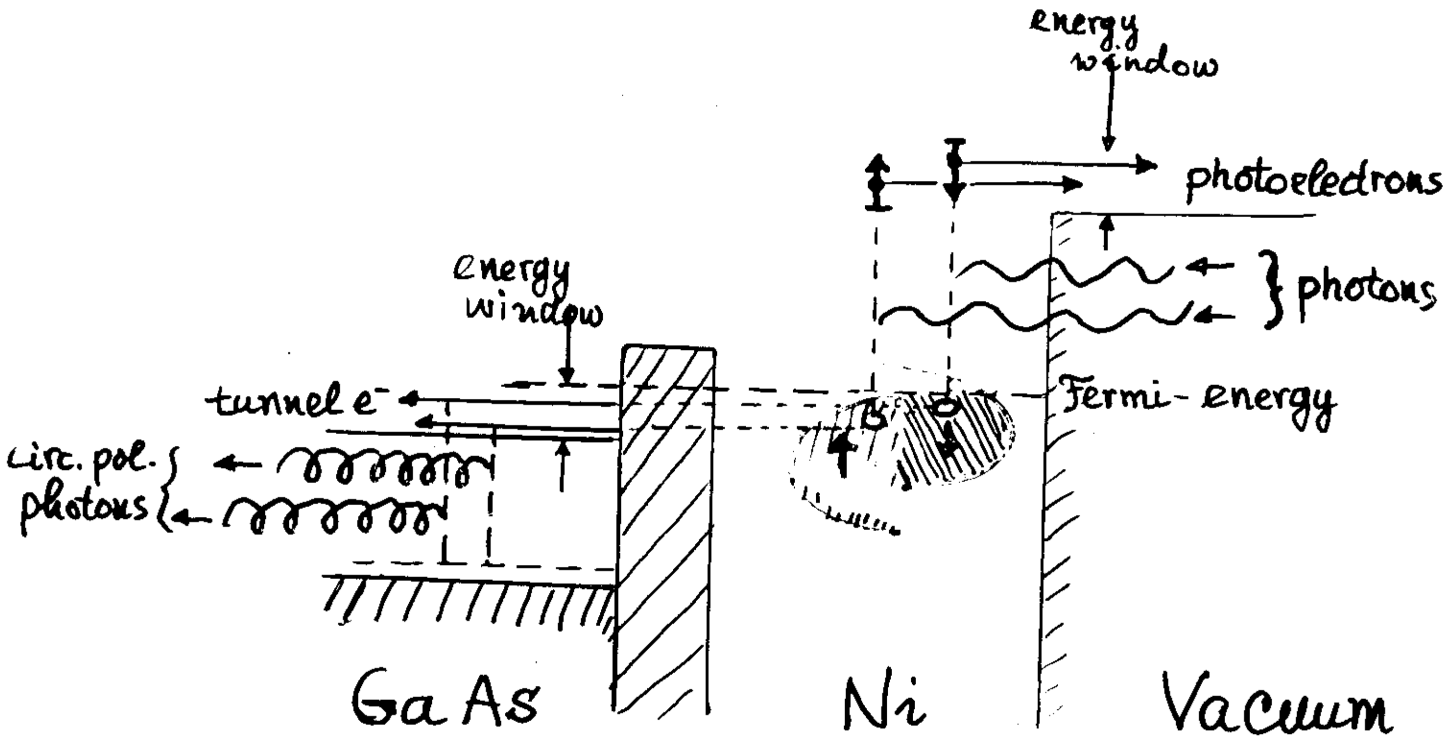
A field cathode, therefore, could be an intense source of polarized electrons, if one could produce sufficient electronic spin polarization at the Fermi edge and if this polarization remained unaffected by surface effects in the tunneling. Polarization at Fermi level E_F can be obtained in two ways: paramagnetic material in very high fields at very low temperatures shows the desired effect ("brute force method"); the obtainable difference in spin population at E_F, however, is extremely small [2] in most metals and semiconductors. Only a narrow gap semiconductor with very small Fermi energy in the conduction band ($m^* \ll m$) like InSb can be regarded as a hopeful candidate [3].

In ferromagnets a certain spontaneous spin polarization at the Fermi level should exist. Against some theoretical predictions no electron beam polarization was found in the case of Fe and in photo emission from Ni (references in [2]).

The failure of these attempts in 3d-ferromagnets can be explained in two ways: a) Surface effects in field emission lead to a complete destruction of the polarization existing in the interior of the metal at Fermi level. b) The "effective" density of states, i.e. the density averaged over the respective contributions of 3d and 4s electrons to the emission current is the same for the two spin directions. This could occur, if the density of states $n(E)$ were practically constant over the energy interval $E_\uparrow - E_\downarrow$ around $\overline{E}_F = \frac{1}{2}(E_\uparrow + E_\downarrow)$, where $E_\uparrow$ and $E_\downarrow$ are the effective Fermi levels for the two spin states, or if the 4s electrons with their probably vanishing polarization predominate in the emission.

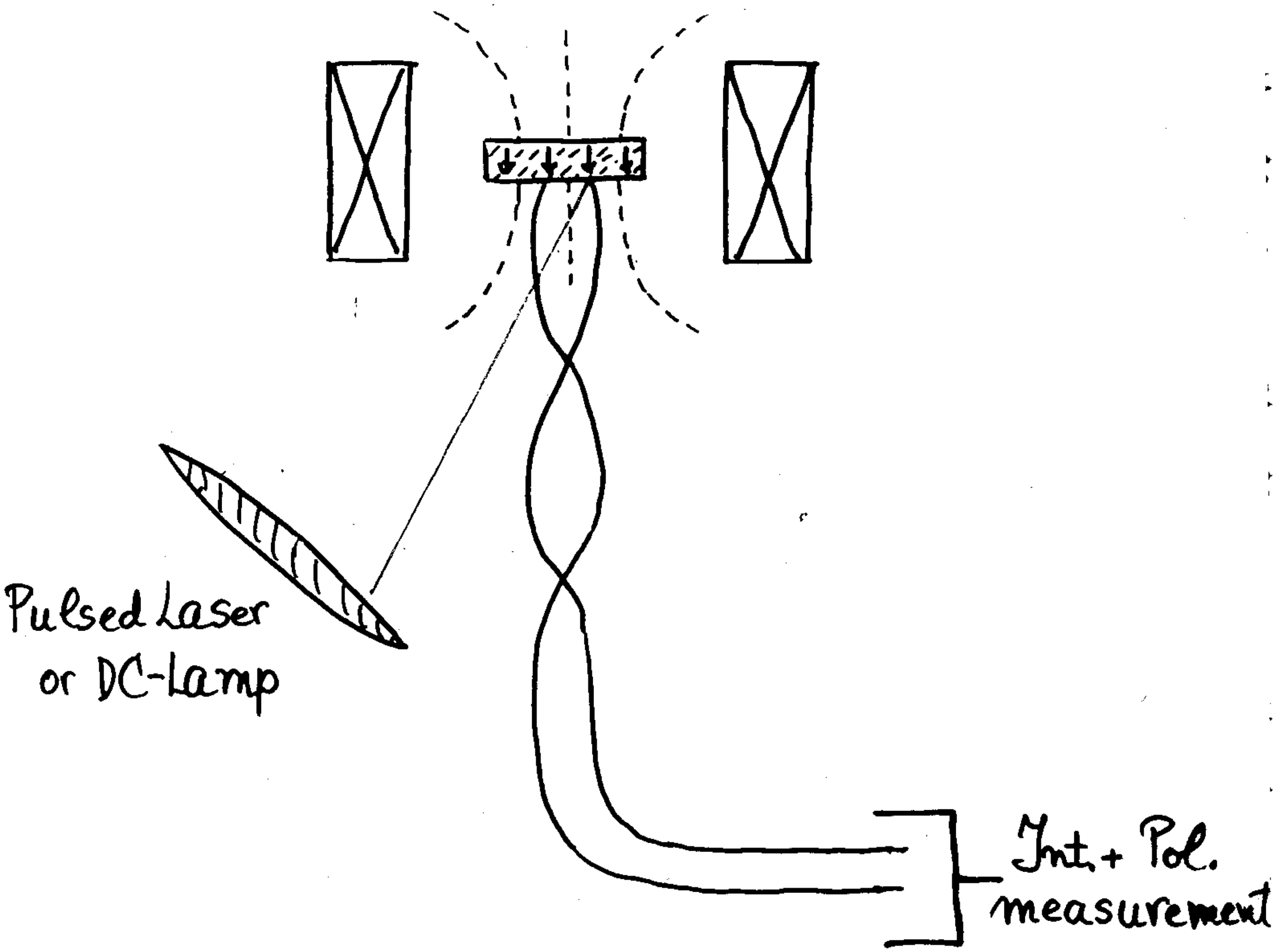
Assuming explanation b) to be true for Fe and Ni (for Co it should be the same, then) one can consider the situation in ferromagnetic Gd. Here we have the following facts:

a) The saturation magnetization is 7.55 μ_B per



Threshold photoemission and tunneling into GaAs

Spin Polarized Photoemission at Threshold



$$P = \langle \sigma_z \rangle = \frac{n\uparrow - n\downarrow}{n\uparrow + n\downarrow}$$

- material specific
- surface sensitive

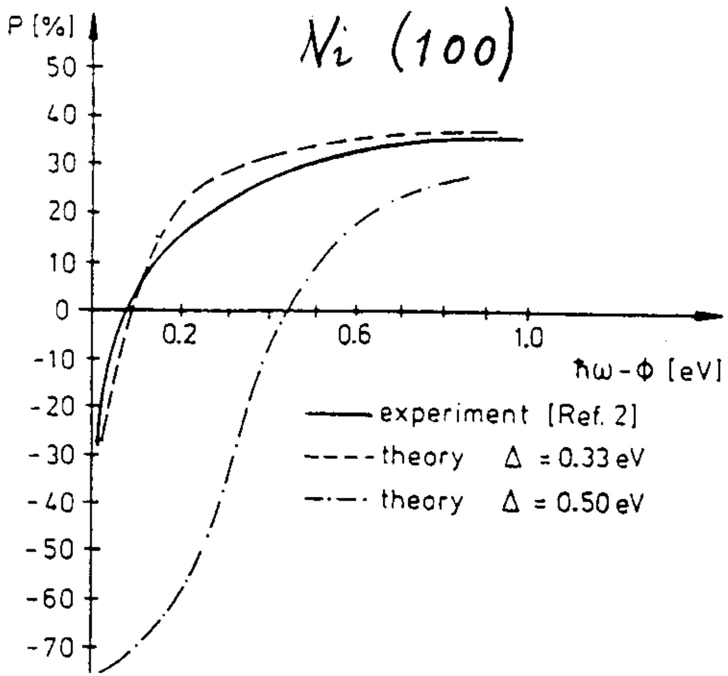


FIG. 2. Experimental (data from Ref. 2) and theoretical spin polarization of the photoyield from Ni(100). See also caption to Fig. 1.

W. Eib and S.F. Alvarado, Phys. Rev. Lett 37 (1976) 444

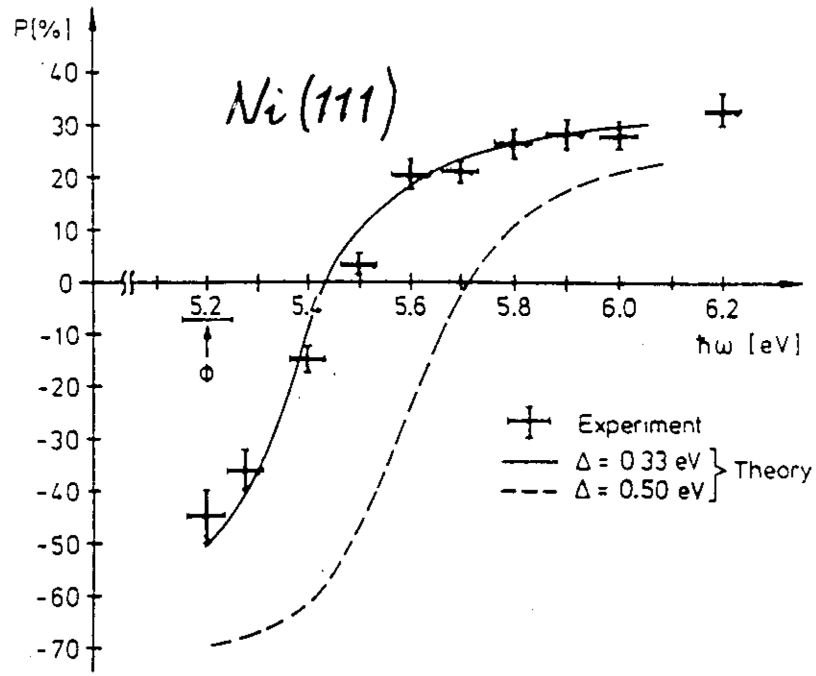


FIG. 1. Experimental and calculated electron spin polarization of the photoyield from Ni(111). The bars indicate the statistical error and the photon energy resolution of the experimental results. The values of the magnetic exchange splitting Δ used in the calculations are indicated. φ is the work function.

967

E Kisker et al., Phys. Rev. Lett. 43 (1979) 966

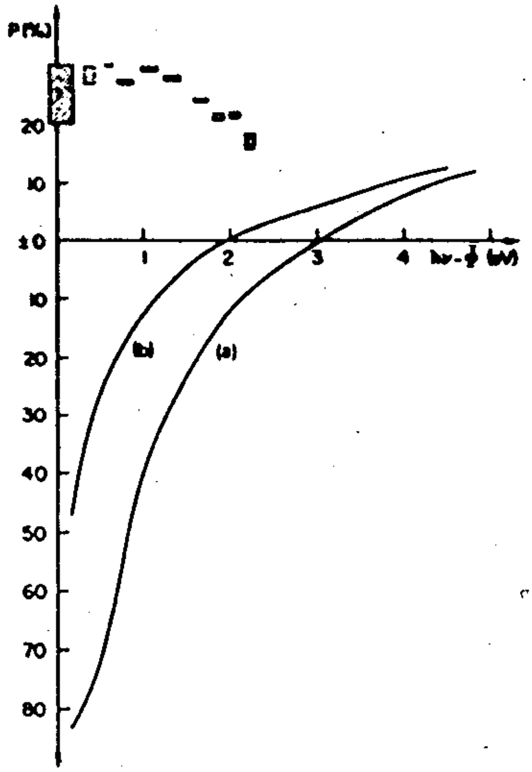
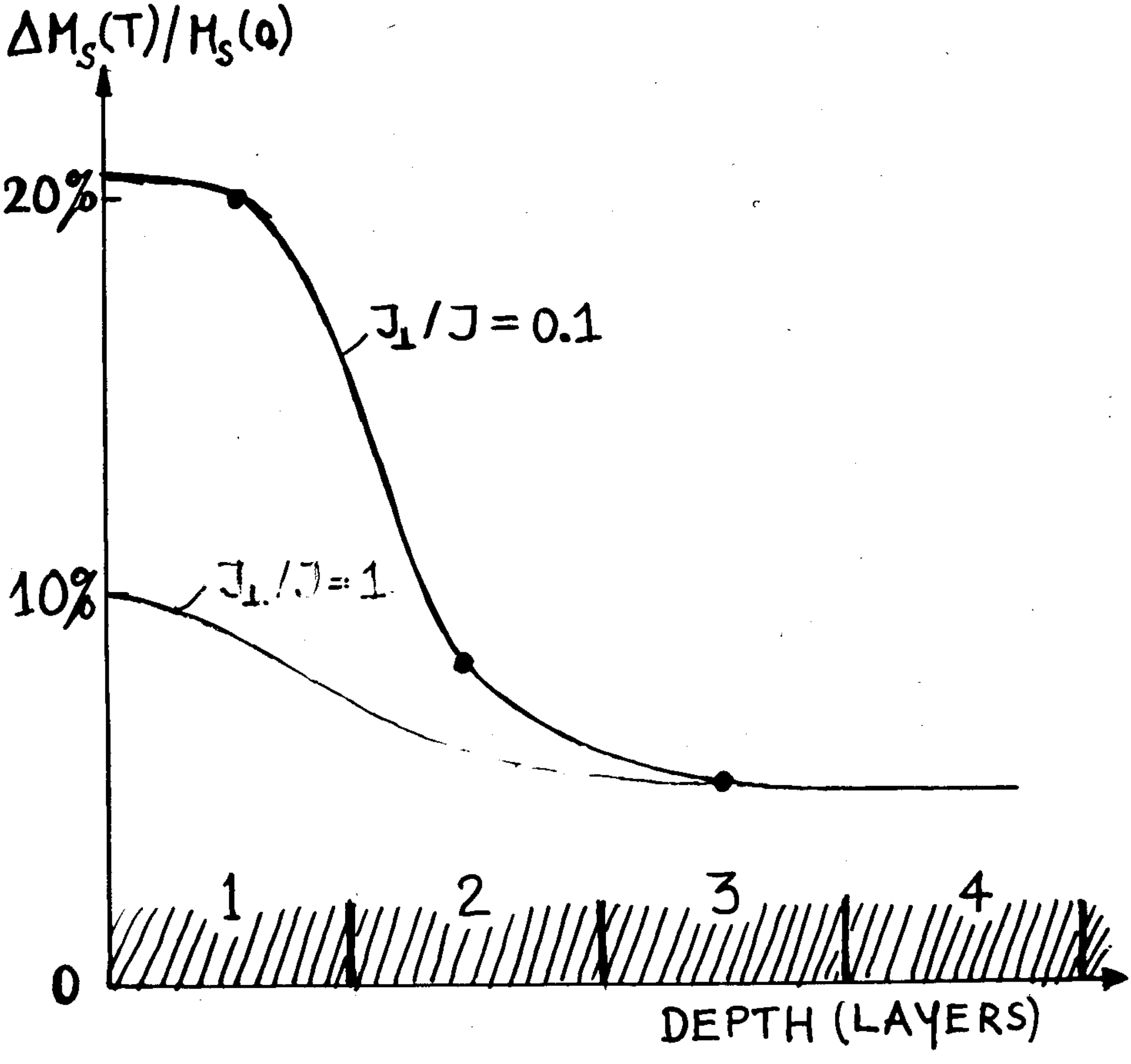


FIG. 2. The photoelectron spin polarization of Co predicted using the density-of-states model: curve *a*, the Co band structure calculated by Wong, Wohlfarth, and Hum (Ref. 15); curve *b*, with the best values of Δ and ΔE_{ex} suggested by Wohlfarth (Ref. 16). Curve *a* of Fig. 1 is also shown as an example of the experimental results.

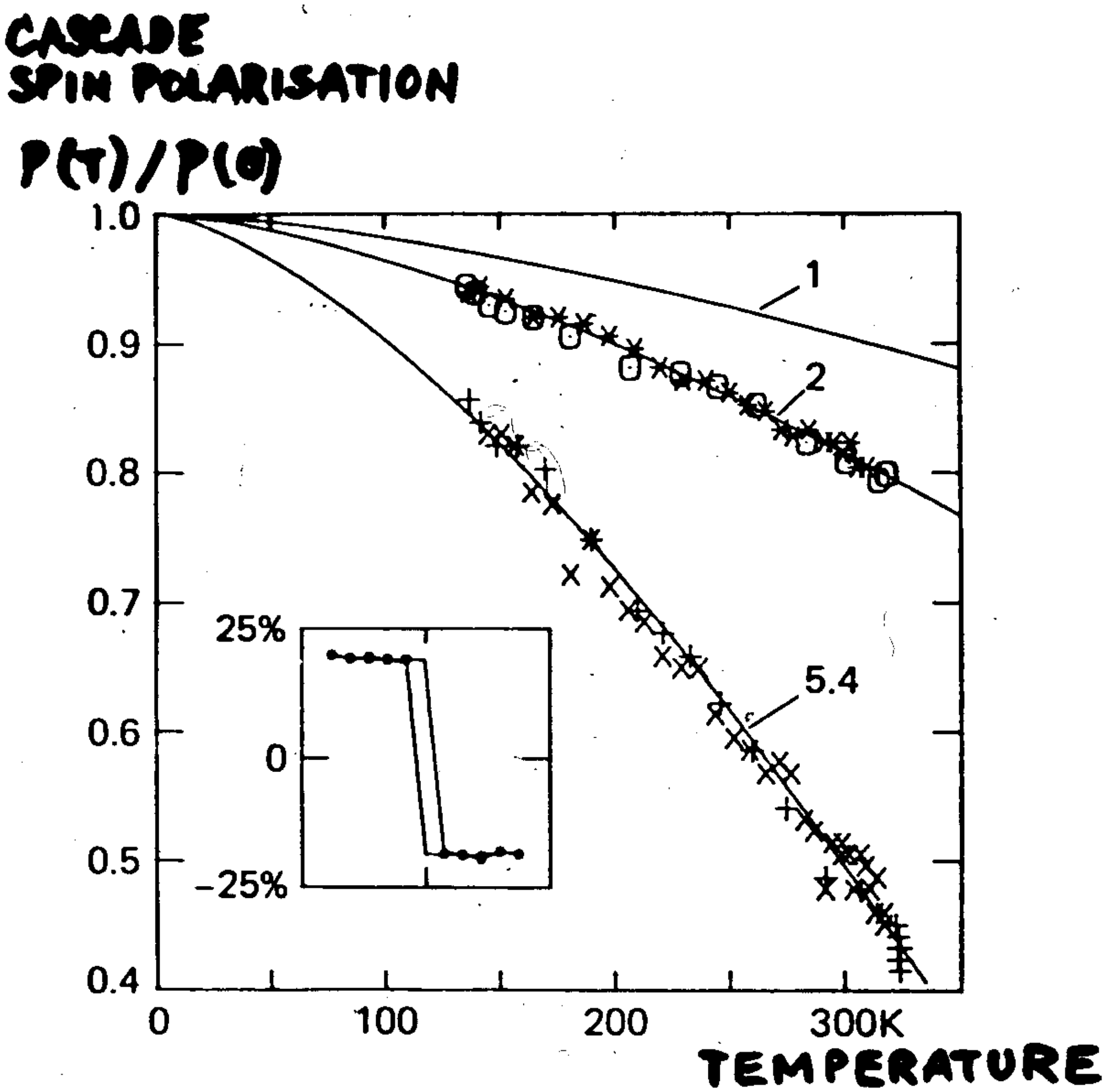
G. Busch et al, Phys. Rev. Lett. 28 (1972) 611

CALCULATED MAGNETIZATION PROFILE

$T \cong 200K, \Delta M_B(T)/M_B(0) = 0.05$



Amorphous FeNiB.5

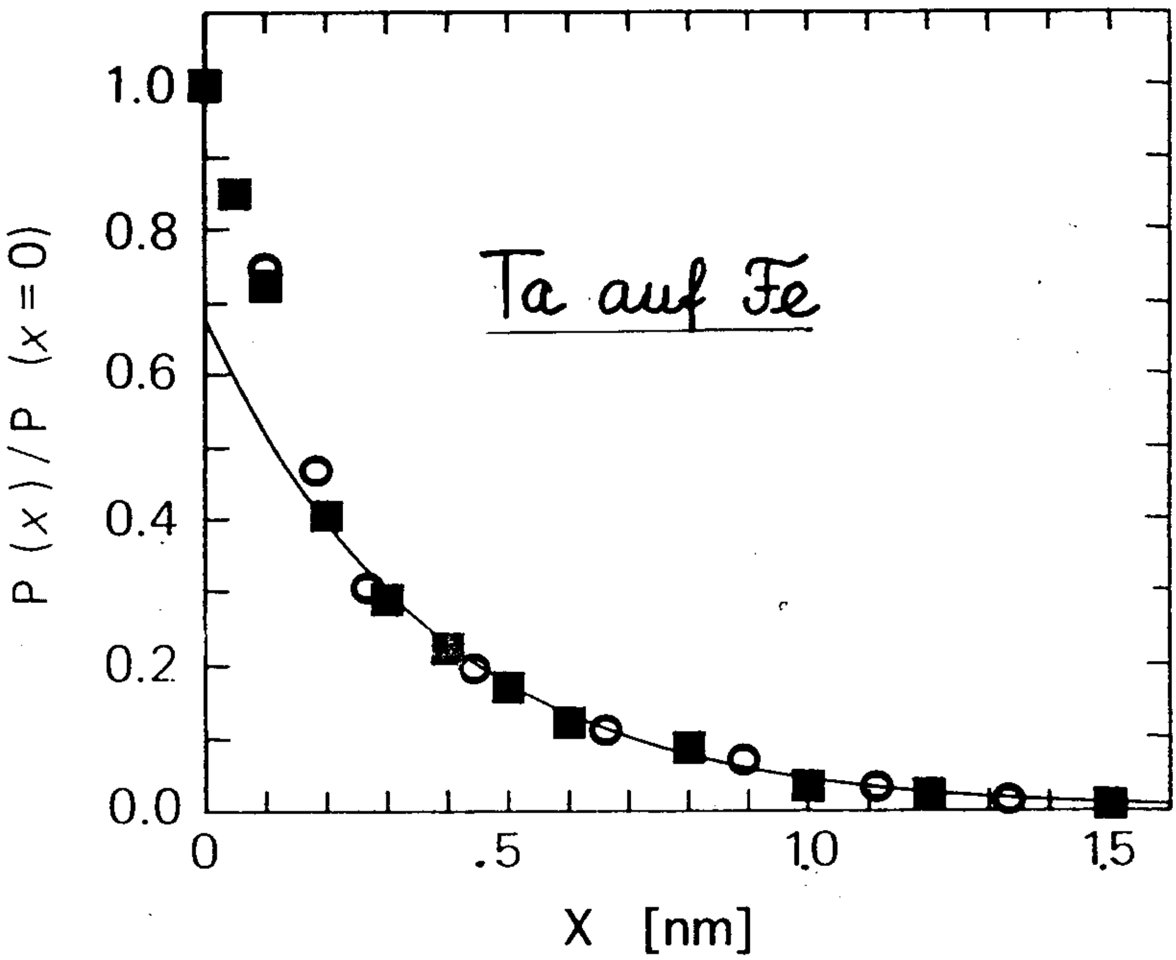


$$P(T)/P(0) = 1 - k\,C\,T^{3/2}$$

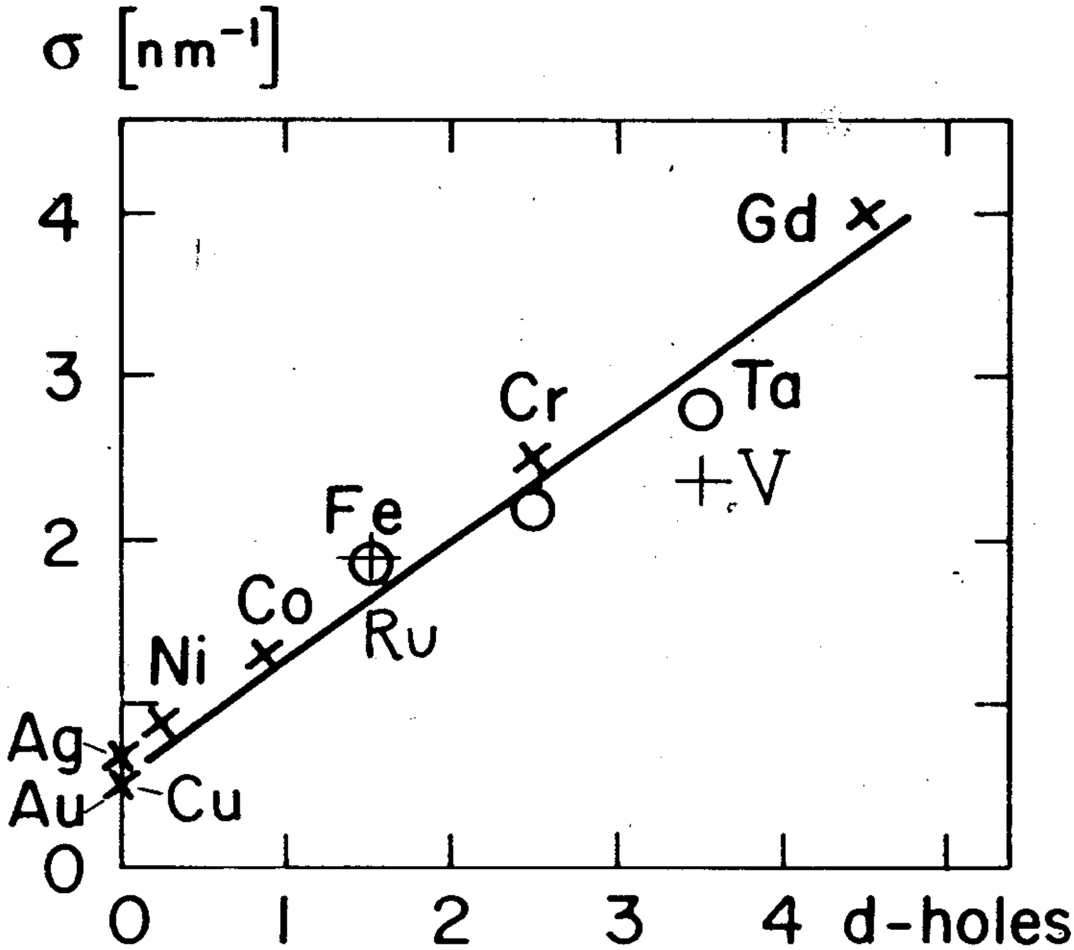
$k = 1$: Bulk Magnetization

$k = 2$: "clean" surface, $P(0) = 21\%$

$k = 5.4$: 1/2 monolayer Ta, $P(0) = 12\%$



■ M. Donath et al, Appl. Phys. A 52 (1991) 206
○ O. M. Paul, Diss. ETH No. 9210, 1990



$$\sigma = \sigma_0 + \sigma_d [5-n]$$

$$\sigma^{+}_{(-)} = \sigma_0 + \sigma_d [5-(n^{+}_{(-)} \Delta n)]$$

Transport-Polarization

$$a(x) = \frac{e^{(\sigma^- - \sigma^+)x} - 1}{e^{(\sigma^- - \sigma^+)x} + 1}$$

Electron absorption in ferromagnets.

$I = I_0 e^{-\sigma \cdot t}$, t = thickness

$I^+ = I_0 e^{-\sigma^+ t}$, $I^- = I_0 e^{-\sigma^- t}$

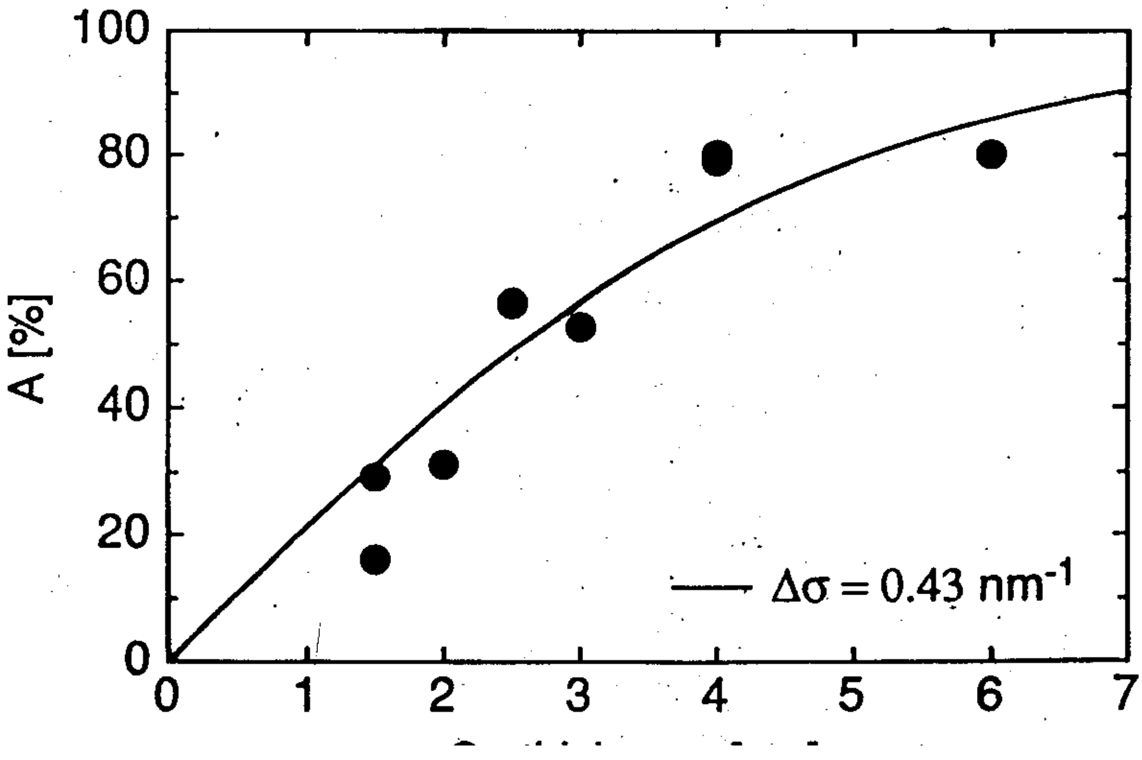
Polarization generated in transport:

$$A(t) = \frac{I^+ - I^-}{I^+ + I^-} = \frac{e^{\Delta\sigma \cdot t} - 1}{e^{\Delta\sigma t} + 1}$$

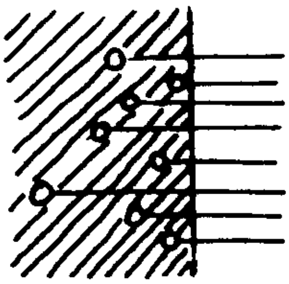
$\Delta\sigma = \sigma^+ - \sigma^-$, only the difference matters!

$\Delta\sigma = n_B \cdot \sigma_d$, σ_d: scattering into d-shell, n_B: Bohr magneton nr.

$$\lim_{t \to \infty} A(t) = 1$$



Emission of electrons from ferromagnets

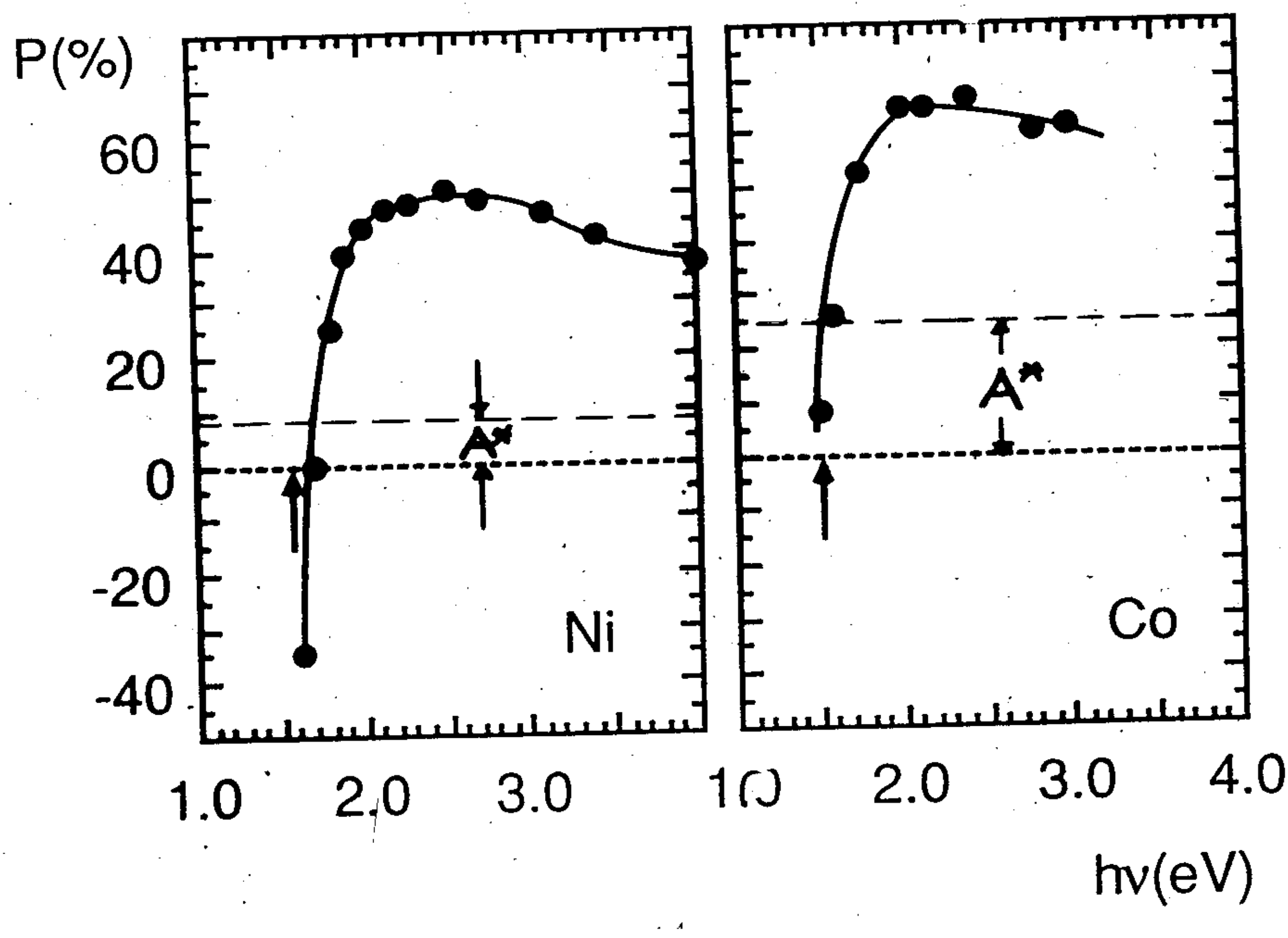


$$P \cong P_0 + A^*$$

$$A^* = \frac{\int_0^\infty A(t)I(t)dt}{\int_0^\infty I(t)dt} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A^* = \frac{1}{2}\,\frac{n_B}{\frac{\sigma_0}{\sigma_d} + (5-n)} = \frac{\Delta\sigma}{2\sigma}$$

Example: Photoemission from Ni & Co



Observation of Spin-Polarized-Electron Tunneling from a Ferromagnet into GaAs

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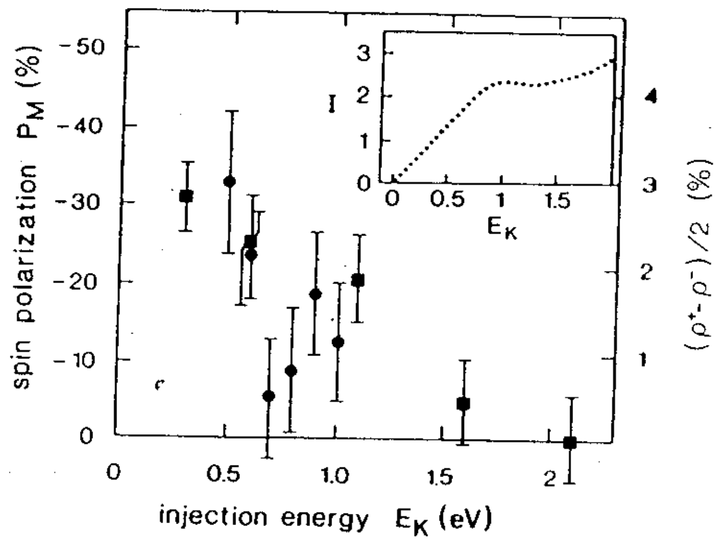
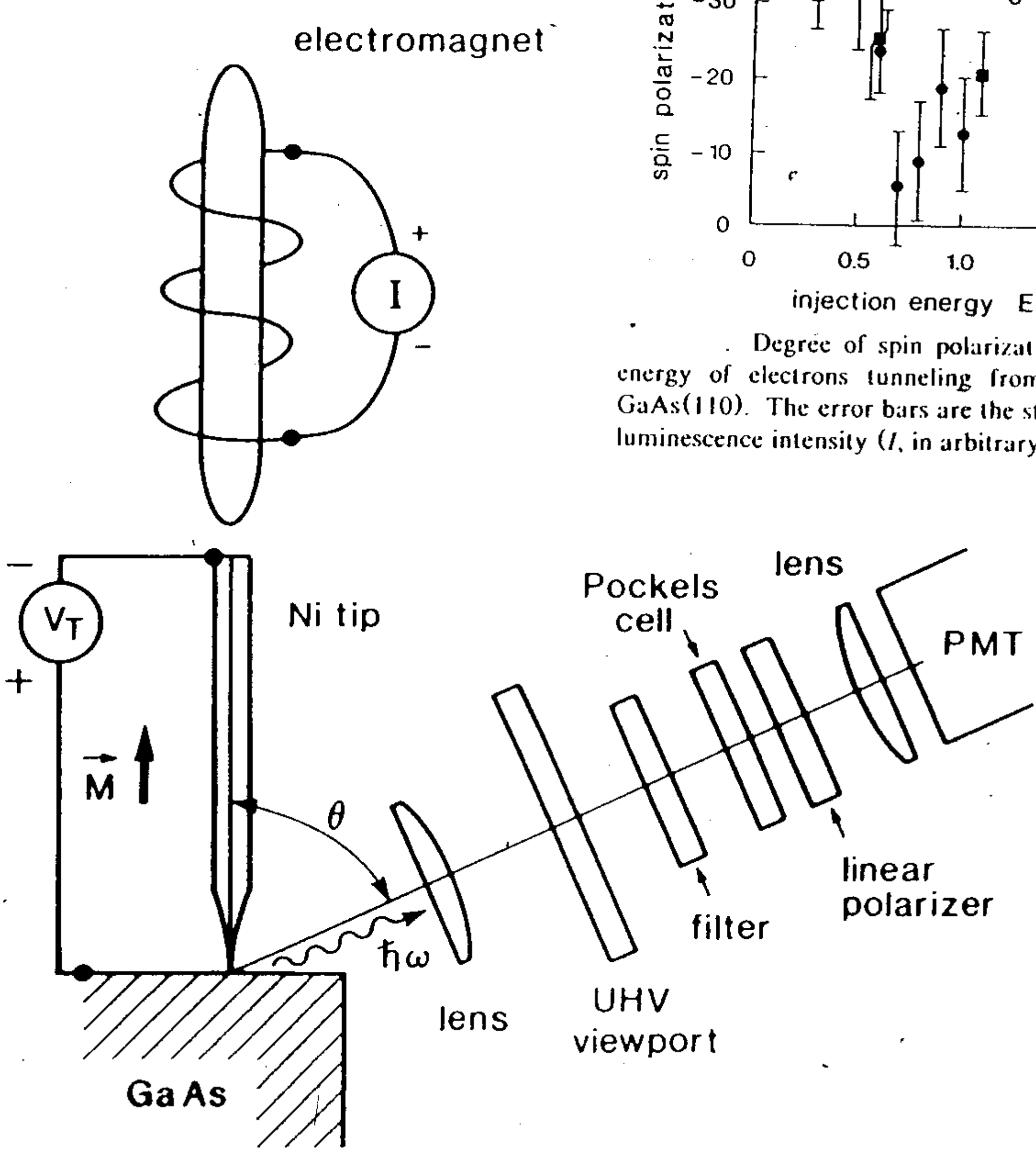
(Received 25 November 1991)

Experimental evidence is presented for the tunneling of polarized electrons from the apex of a ferromagnetic Ni tip into GaAs(110). The polarization is found to be negative and of highest magnitude at very low injection energies, which shows that highly polarized *minority* 3*d* electrons are preferentially extracted from the Fermi level of the tip.



Degree of spin polarization vs maximum injection energy of electrons tunneling from a Ni tip into *p*-doped GaAs(110). The error bars are the statistical error. Inset: The luminescence intensity (*I*, in arbitrary units).



Inverse Tunnel Magnetoresistance in $Co/SrTiO_3/La_{0.7}Sr_{0.3}MnO_3$: New Ideas on Spin-Polarized Tunneling

J. M. De Teresa, A. Barthélémy, A. Fert, J. P. Contour, R. Lyonnet, F. Montaigne, P. Seneor, and A. Vaurès
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and Université Paris-Sud, 91405 Orsay, France
(Received 9 December 1998)

We report tunnel magnetoresistance (TMR) measurements on $Co/SrTiO_3/La_{0.7}Sr_{0.3}MnO_3$ junctions. The half-metallic $La_{0.7}Sr_{0.3}MnO_3$ electrode is used as a spin analyzer. The large (−50%) inverse TMR indicates a negative spin polarization of Co, in agreement with the density of states (DOS) of the *d* band in Co. The bias dependence of the TMR, with a maximum inverse TMR at −0.4 V and a crossover to normal TMR above +0.8 V, reflects the structure of this DOS. Our results demonstrate that the choice of the insulating barrier can strongly influence and even reverse the spin polarization of tunneling electrons. [S0031-9007(99)09225-X]

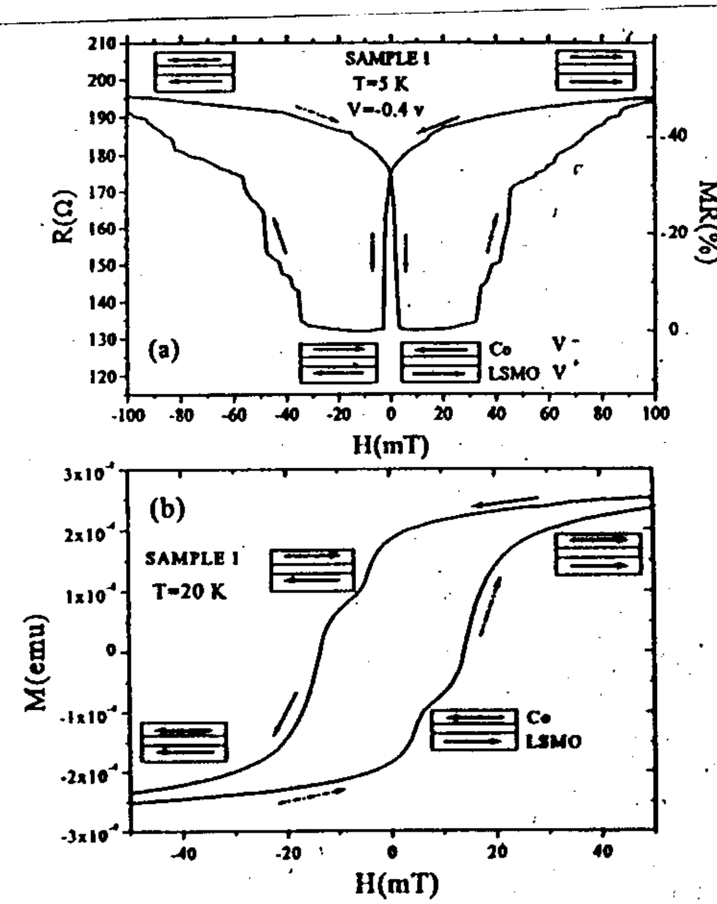


FIG. 1. (a) Resistance versus applied magnetic field for a 10 μm Co/STO/LSMO junction at 5 K (sample 1). The applied bias is −0.4 V. The resistance is minimum in the AP configuration, which we call an inverse TMR. (b) Magnetization versus field curve measured on the same sample at 20 K.

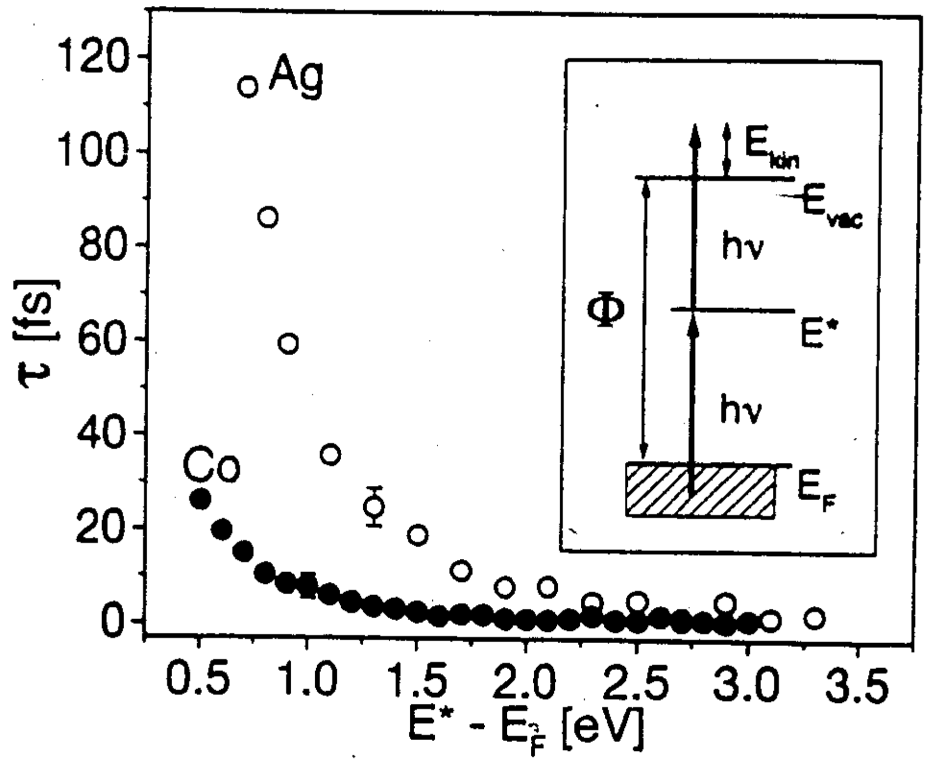


FIG. 2. The spin-integrated inelastic lifetime of cesiated Co(001) ($h\nu = 3$ eV, $\Phi = 3.5$ eV) and Ag(111) ($h\nu = 3.3$ eV, $\Phi = 4.1$ eV) as a function of the intermediate state energy above E_F. The inset shows a scheme of the energy levels involved in the 2PPE process.

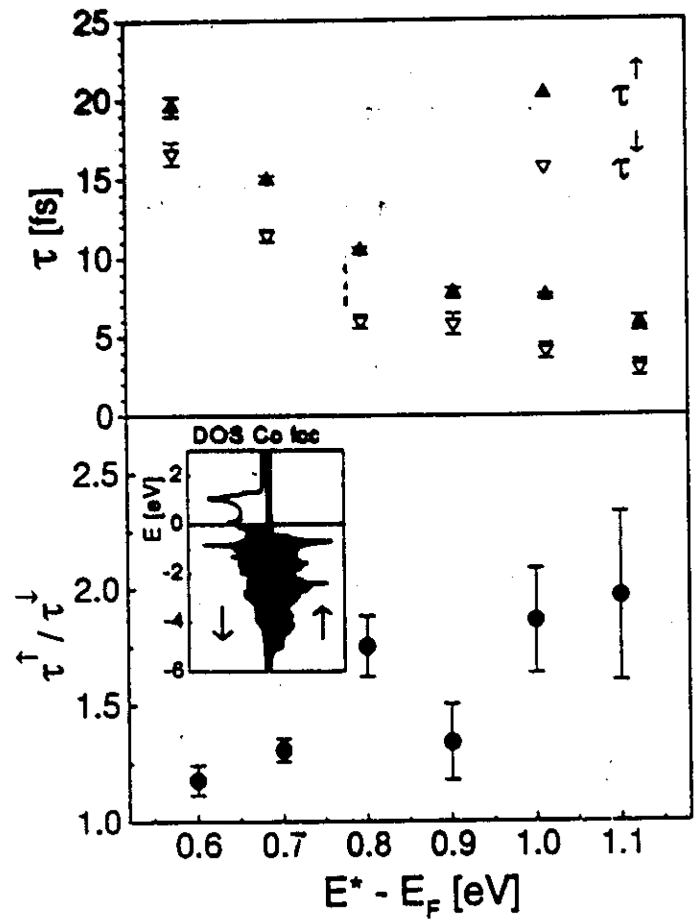


FIG. 3. The spin-resolved inelastic lifetime (top) and the ratio $\tau^{\uparrow}/\tau^{\downarrow}$ (bottom) of a cesiated 10 nm thick Co(001) film as a function of the intermediate state energy above E_F. In the top panel filled symbols correspond to the majority-spin direction and open symbols to the minority-spin direction. The photon energy is 3 eV. The inset in the bottom panel shows the spin-resolved density of states of fcc Co [26].

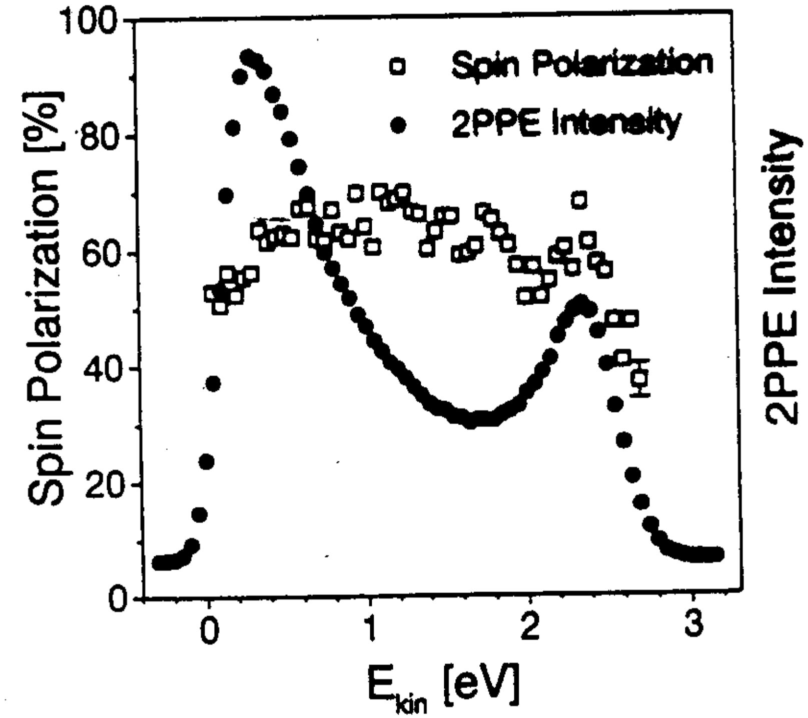
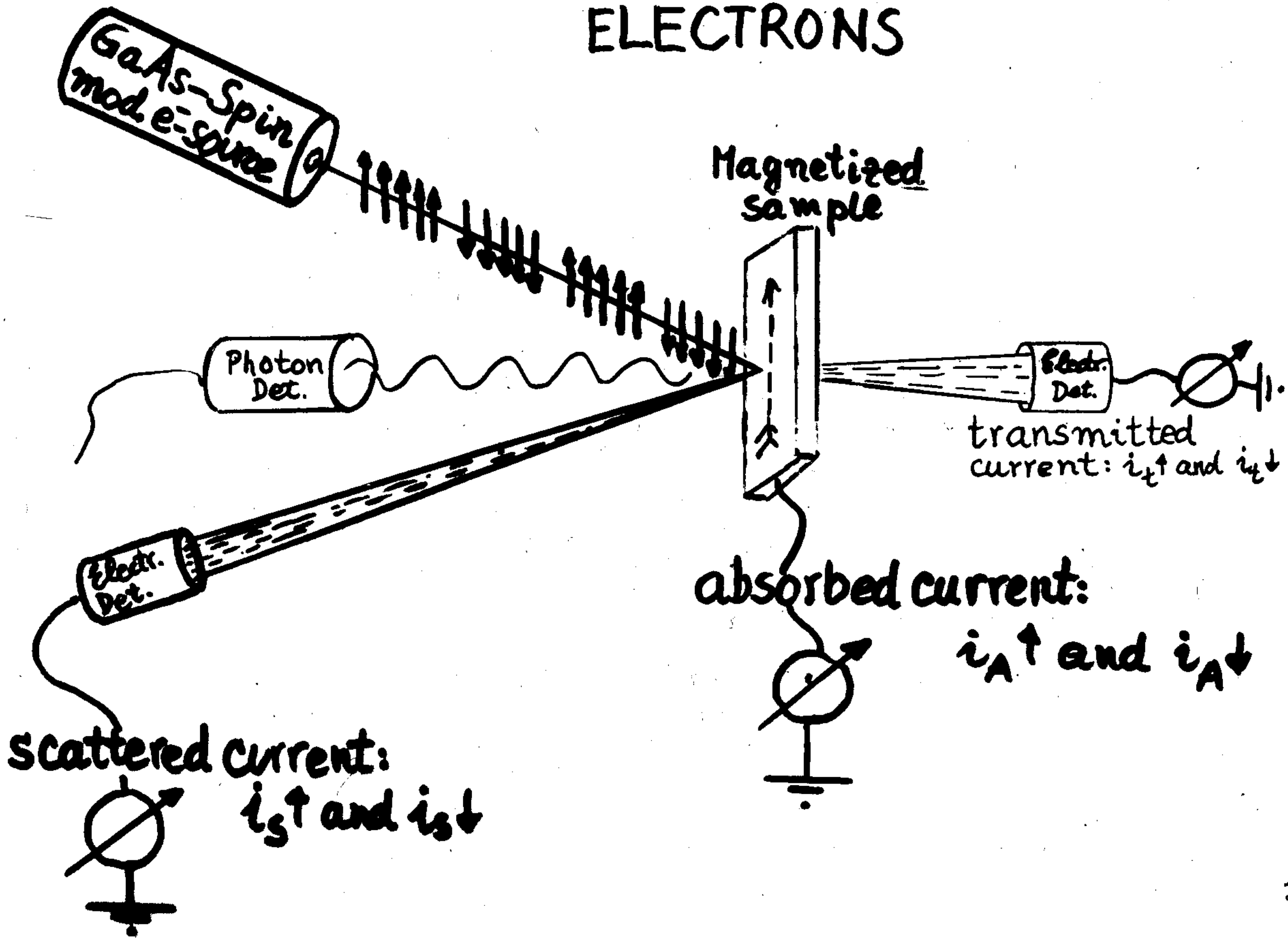
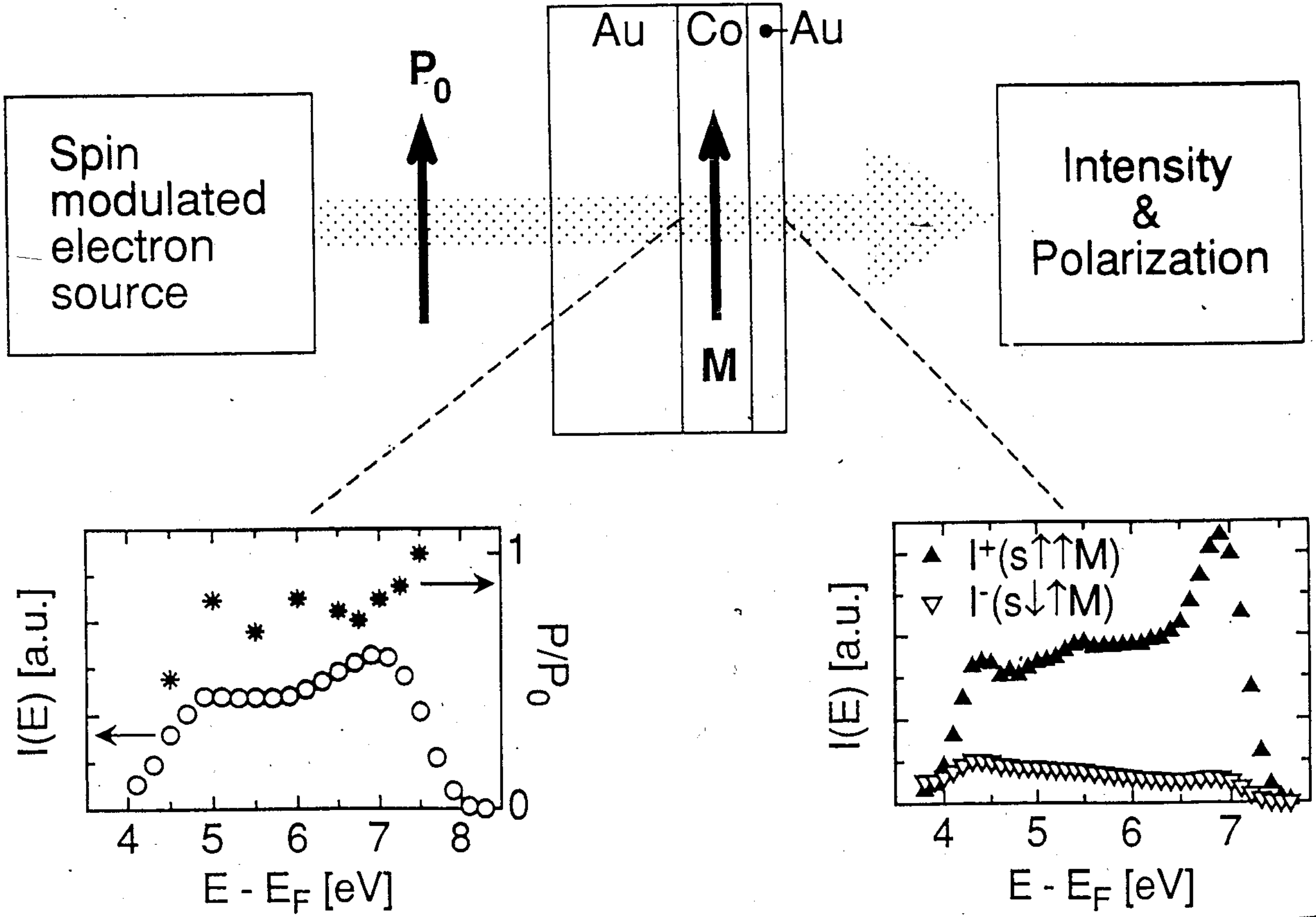


FIG. 1. Intensity (filled circles) and spin polarization (open squares) of a cesiated 10 nm thick Co(001) film as a function of the kinetic energy, obtained in a 2PPE experiment with one laser beam blocked. The photon energy of the laser light is 3 eV. The work function of this particular cesiated sample is 3.4 eV.

H. Aeschlimann et al.,
P.R.L. 79 (1997) 5158

SCATTERING OF SPIN POLARIZED ELECTRONS

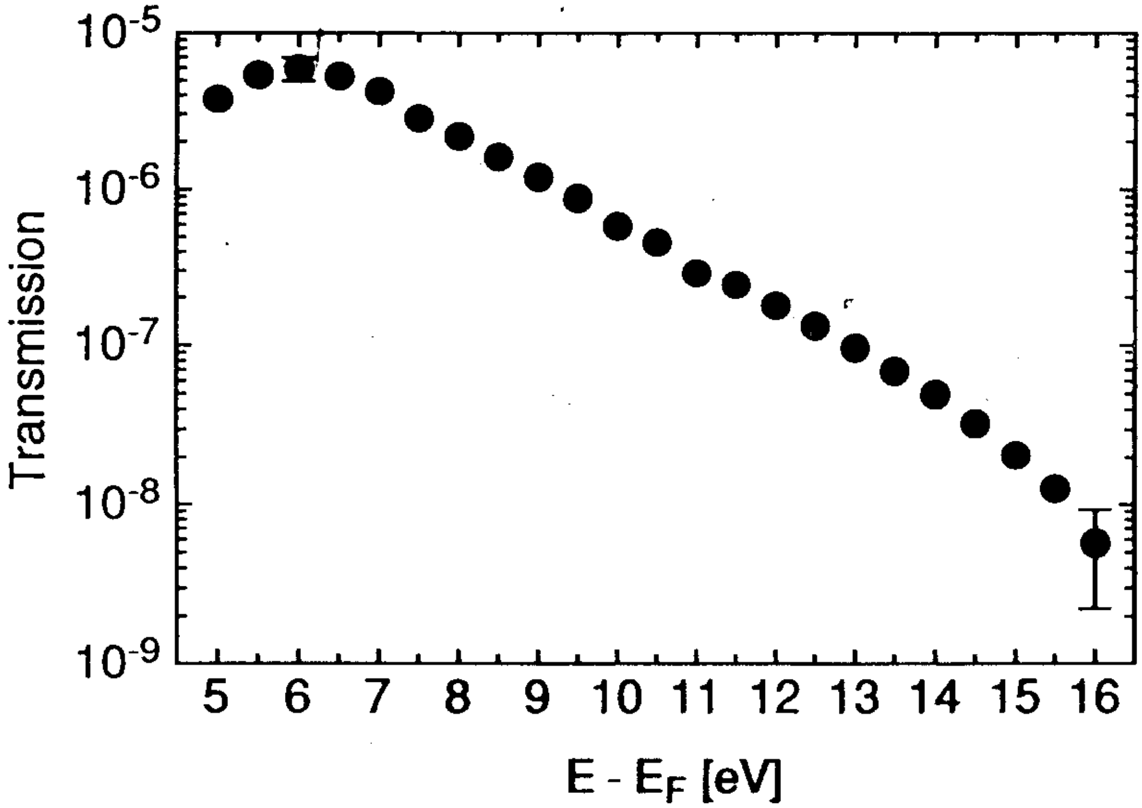




Spin modulated electron source
P_0
Au
Co
Au
M
Intensity & Polarization
I(E) [a.u.]
P/P_0
E - E_F [eV]
$I^+(s\uparrow\uparrow M)$
$I^-(s\downarrow\uparrow M)$

Fig 1

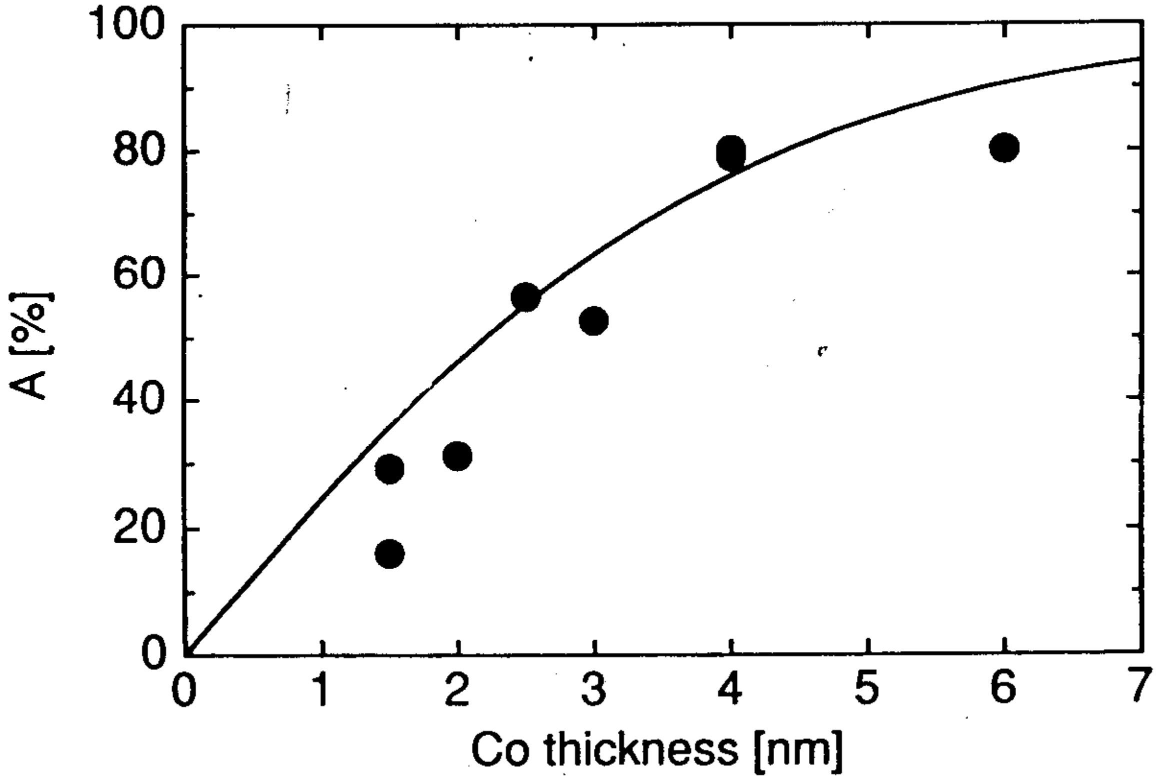
Transmission Through Trilayer



Spin Asymmetry of Elastic Current vs Co Thickness

Electron Energy 5 eV

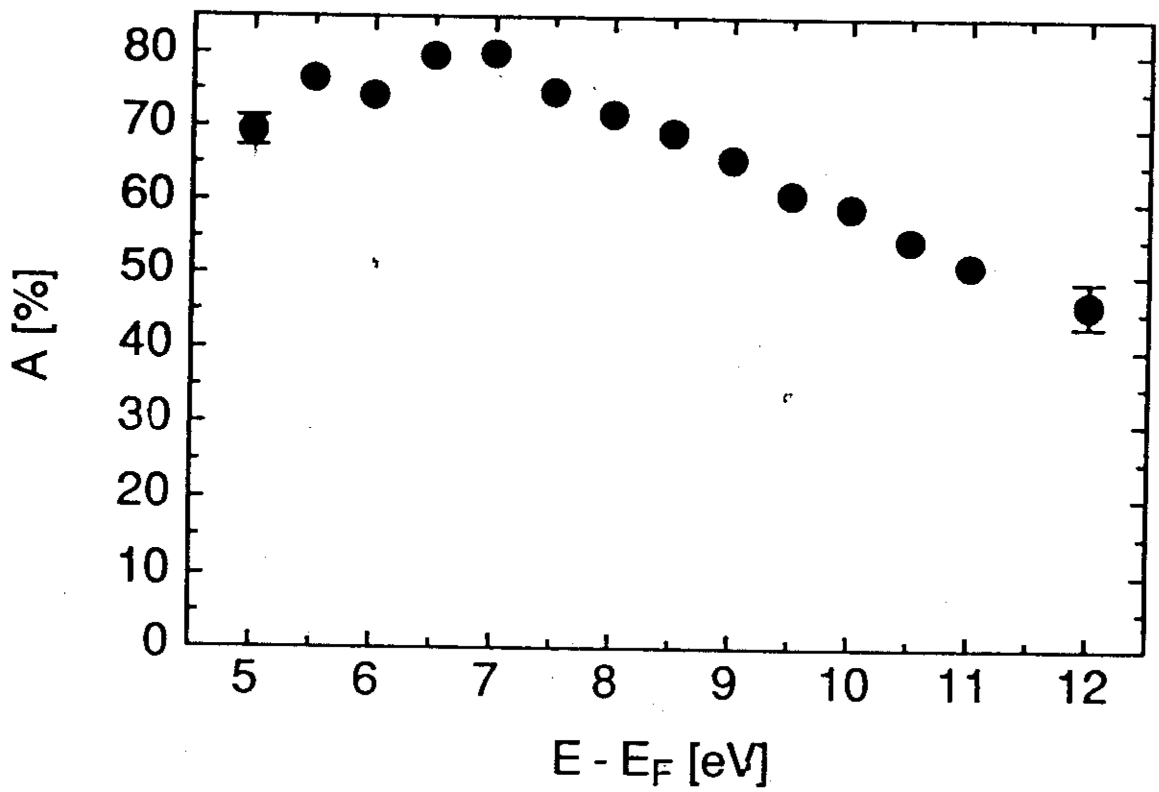
—— $\Delta\sigma = 0.5\ nm^{-1}$



$$A = \frac{e^{\Delta\sigma y} - 1}{e^{\Delta\sigma y} + 1}$$

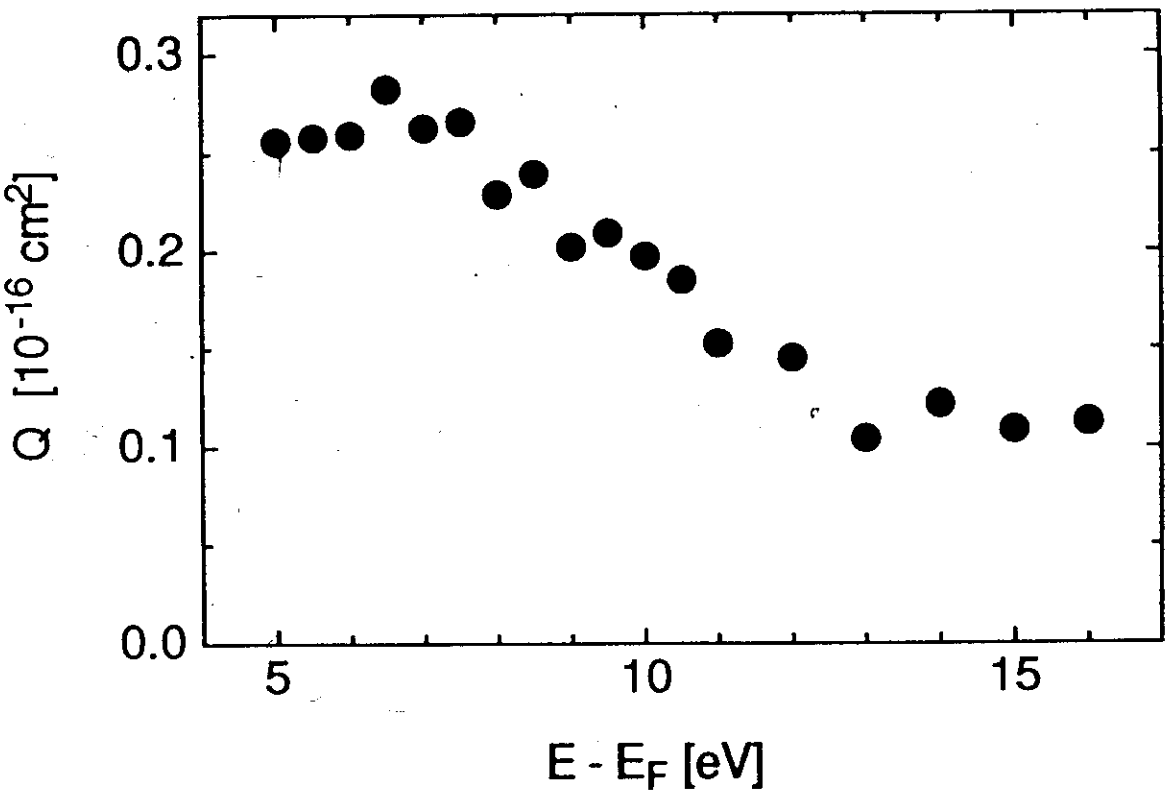
Spin Asymmetry vs Energy

Co film 4 nm



$$A = \frac{I^+ - I^-}{I^+ + I^-}$$

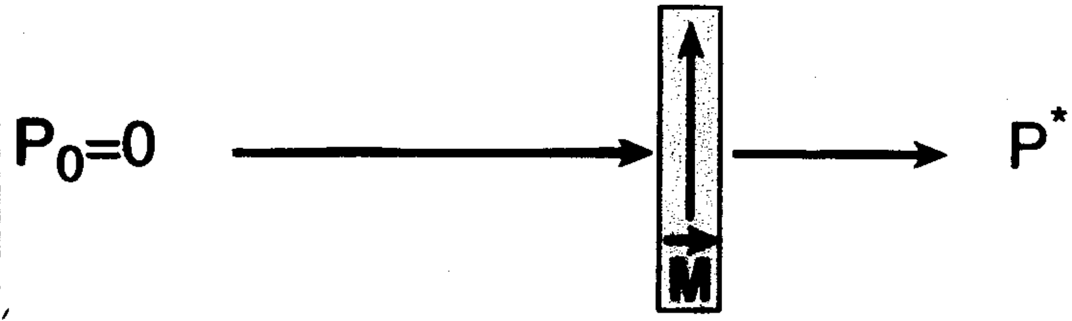
Total Scattering Cross Section



$$Q = \frac{1}{N\, n_B}\, \Delta\sigma$$

Spin-flip scattering ?

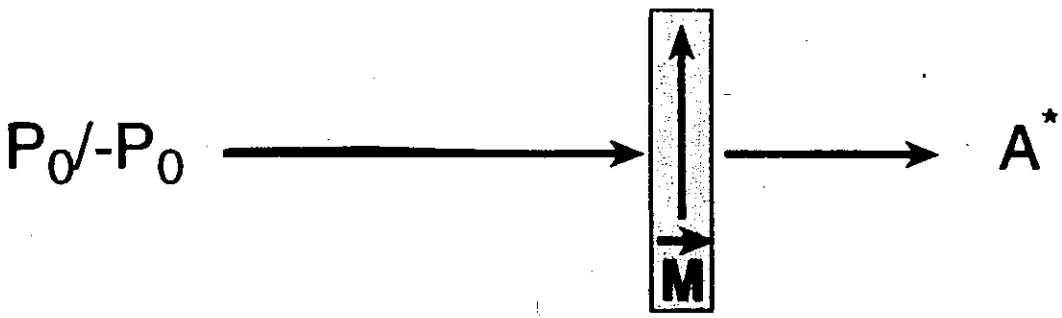
1. Experiment



$$P^* = P \quad + \quad \Delta P$$

Spin filter — Spin-flip

2. Experiment



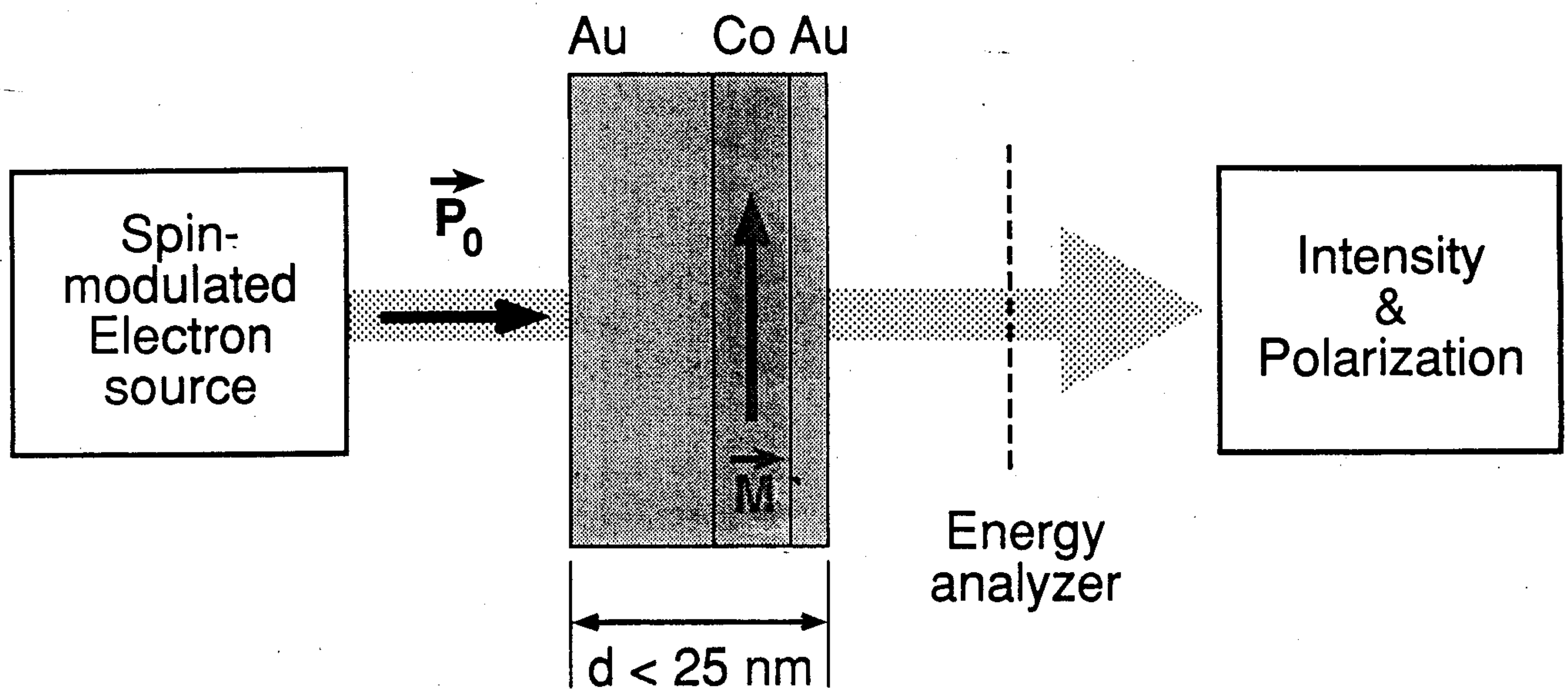
$$A^* = A \quad - \quad \Delta A$$

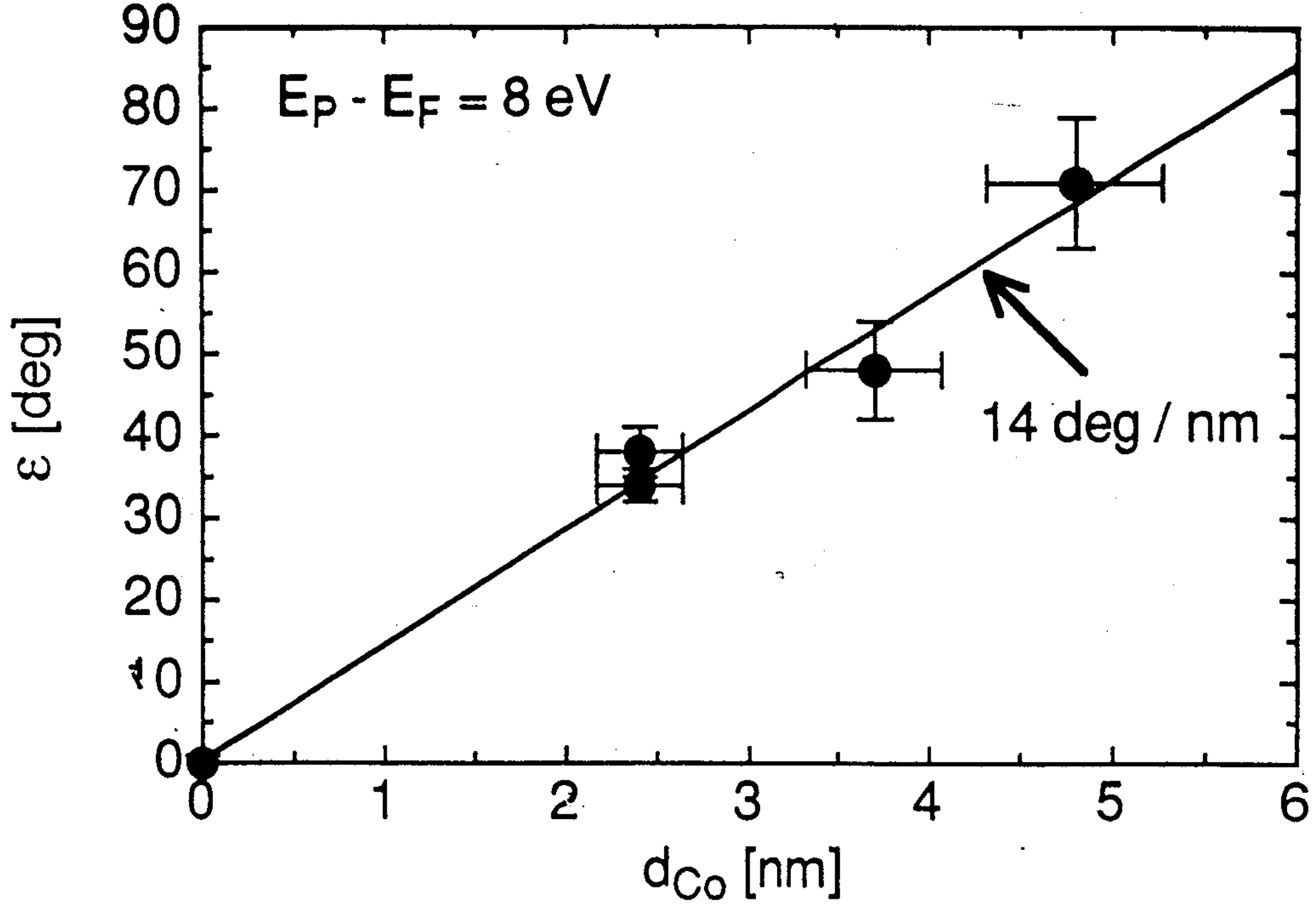
Spin filter — Spin-flip

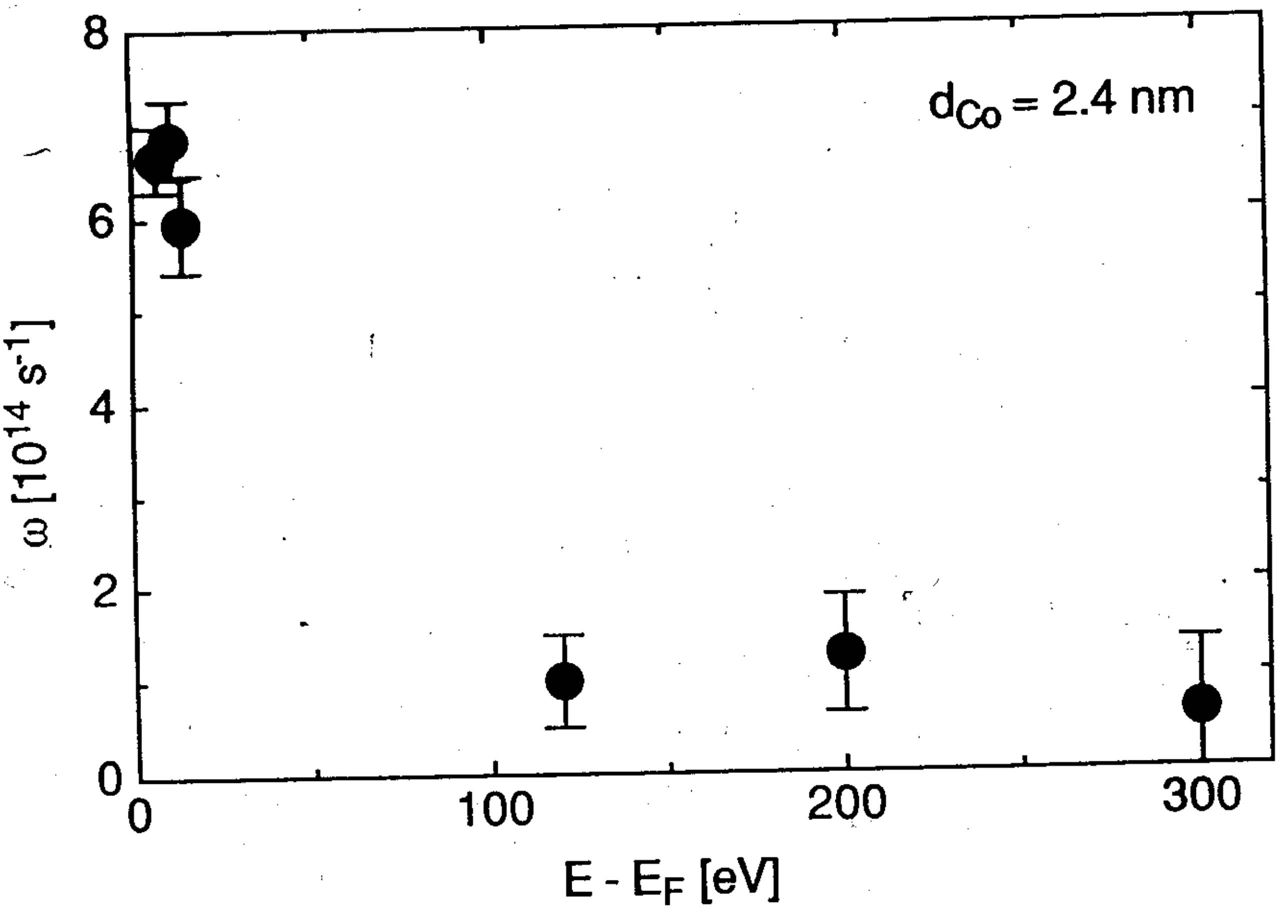
Only Spin filter: $P = A$

Experiments show: $P^* = A^*$

Thus: $\Delta P = \Delta A = 0$


Spin-
modulated
Electron
source
P0
Au
Co Au
M
d < 25 nm
Energy
analyzer
Intensity
&
Polarization


$E_P - E_F = 8$ eV
14 deg / nm
ε [deg]
d_{Co} [nm]
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6



d_Co = 2.4 nm
ω [10^14 s^-1]
E - E_F [eV]
0
2
4
6
8
0
100
200
300

$$\tau_{1,2} \propto I\hat{s}_{1,2} \times (\hat{s}_1 \times \hat{s}_2) \quad (1)$$

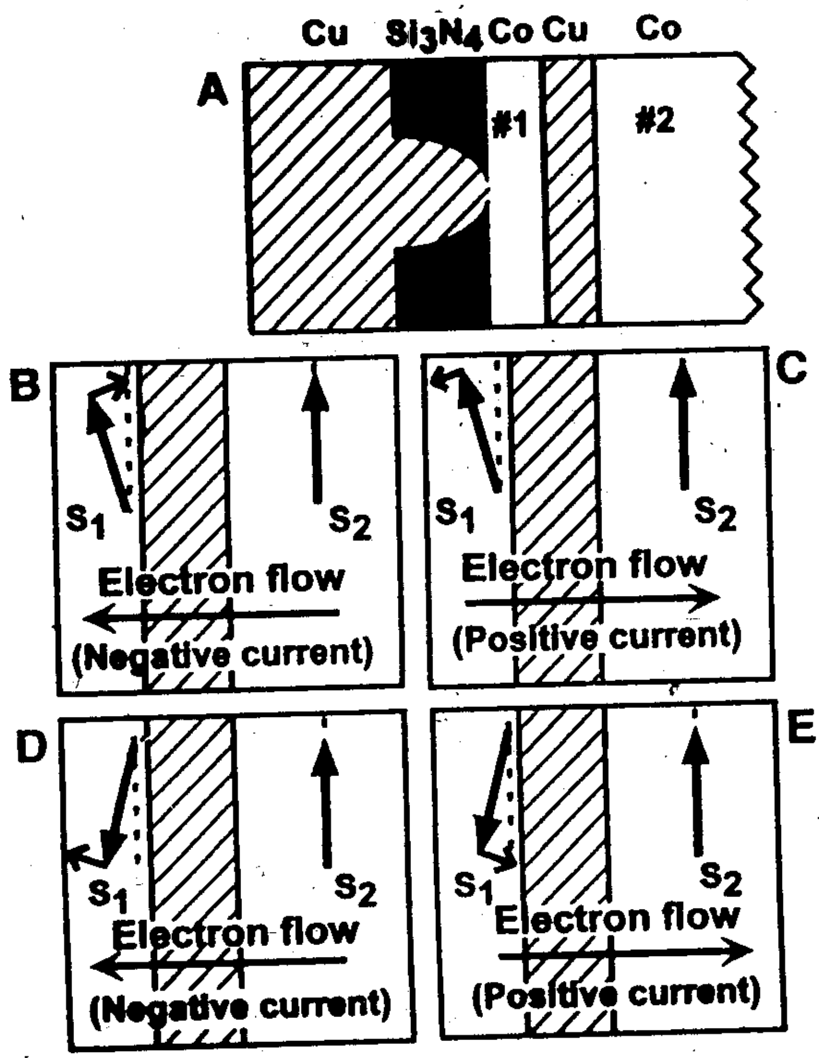


Fig. 1. (**A**) Cross-sectional device schematic, showing layer #1 and #2. (**B** through **E**) Directions of torque on the magnetic moments in layer 1, due to spin transfer by current flow. Parallel alignment of the moments in the two layers is unstable for sufficiently large positive currents, whereas antiparallel alignment is unstable for large negative currents.

E. B. Myers et al., Science 285 (1999) 867

Spin Polarized Electrons and Magnetism 2000
Summary

1. Determine spin polarized electronic structure and understand electronic excitations in solids.

2. Establish mechanism and correct interpretation of electron emission processes, e.g., in tunneling of electrons between solids and photoemission.

3. Understand spin dependent scattering and motion of spin polarization vector in transport of electrons through solids.