Effect of direct exchange on spin current scattering in Pd and Pt

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Abstract

We show evidence for a magnetic proximity effect on spin current scattering in Pt and Pd. The return loss of pumped spin current, measured through the interface-related Gilbert damping $\Delta \alpha$, is found to be linear in thickness for Pd and Pt in contact with Ni$_{81}$Fe$_{19}$, but exponential in thickness for the same layers separated from Ni$_{81}$Fe$_{19}$ by Cu(3nm). The linear onset is attributed to ferromagnetic order in Pd and Pt, verified through x-ray magnetic circular dichroism (XMCD) measurements. The measurements show that the scattering of pure spin current is configuration-dependent in these paramagnets and not described by a single characteristic length.
Ultrathin Pd and Pt layers exert strong effects on spin polarized currents in magnetic heterostructures. The $F/N$ bilayer systems $\text{Ni}_{81}\text{Fe}_{19}/\text{Pt}$ and $\text{Ni}_{81}\text{Fe}_{19}/\text{Pd}$ are of intense interest due to their large spin Hall effects[1], enabling conversion between charge and spin current in devices, with emerging applications in mesoscale spin torque. The so-called inverse spin hall effect (ISHE)[2], in which a DC voltage is generated from pure spin current precessionally "pumped" into Pt or Pd[3, 4], is often used to study spin-Hall phenomenology.

High current densities generate large torques on the magnetization in ultrathin, asymmetric Pt/Co bilayers, effective for the electrical manipulation of domain walls[5].

Pd and Pt have very large paramagnetic susceptibilities. It is presently unclear whether magnetic moments in Pd or Pt, which can be induced through direct exchange with ferromagnets like $\text{Ni}_{81}\text{Fe}_{19}$, affect these novel spin transport phenomena. On the basis of anomalous Hall and Nernst effect measurements, Huang et al[6] have suggested that induced magnetic moments in Pt generate spurious ISHE signals when placed in direct contact with ferromagnetic YIG[7]. Some have conjectured that induced moments play an important role in current-induced torques, as well[8]. On the other hand, Tserkovnyak et al point out in ref[4] that induced moments in $N$ are a priori included in calculations of the spin mixing conductance[9, 10] $g^{\uparrow\downarrow}$ of $F/N$, which governs the spin pumping effect[11].

In this Manuscript, we show that proximity-induced magnetic moments have a strong effect on spin current absorption in Pd and Pt. Measurements of the spin pumping effect indicate a transformation in the scattering mechanism from a point process, exponential in ($N=\) Pd and Pt thickness ($t_N$) under weak exchange in $\text{Ni}_{81}\text{Fe}_{19}/\text{Cu}(3\text{nm})/N(t_N)$, to a correlated process, linear in Pd and Pt thickness under strong exchange in $\text{Ni}_{81}\text{Fe}_{19}/N(t_N)$. We find that the spatial extent of spin current absorption is inversely proportional to interfacial exchange, quantified using x-ray magnetic circular dichroism (XMCD) measurements of Pd and Pt.

We have characterized the interface-related damping in $\text{Ni}_{81}\text{Fe}_{19}(10\text{nm})/N(t_N)$ and $\text{Ni}_{81}\text{Fe}_{19}(10\text{nm})/\text{Cu}(3\text{nm})/N(t_N)$ thickness series, $N=(\text{Pd},\text{Pt})$, by ferromagnetic resonance (FMR.) In the $\text{Ni}_{81}\text{Fe}_{19}/N$ structures, strong direct exchange coupling acts on the paramagnet $N$. In the $\text{Ni}_{81}\text{Fe}_{19}/\text{Cu}(3\text{nm})/N$ structures, much weaker indirect exchange coupling acts on $N$. Layers have been prepared by sputtering on ion-cleaned Si/SiO$_2$ substrates, seeded in every case with Ta(5nm)/Cu(5nm) bilayers, capped in every case with 3 nm Al layers, oxidized in air. The smallest $N$ layer thickness deposited is 0.4 nm, the maximum...
extent of intermixing observed for similar multilayers, see e.g. [12]. A fifth sample series, with variable $t_F$ and constant $t_{Pt}$, has also been characterized; the central layers here are Ni$_{81}$Fe$_{19}$(t$_F$)/Pt(4 nm).

We consider the interface-related damping $\Delta \alpha$ where the damping $\alpha$ of a reference structure, excluding the $N$ layer, has been subtracted away. Note that each measurement of $\alpha$ is fitted from 12 FMR traces, field-swept, at variable frequency (2-24 Ghz), through linear fits to $\Delta H(\omega) = \Delta H_0 + 2/\sqrt{3}\omega\alpha/\gamma$, as in prior work [13, 14].

Two similarly prepared multilayers were characterized by x-ray magnetic circular dichroism (XMCD). Each multilayer consists of 20 repeats, as substrate/seed/[repeat]$_{20}$/cap, in order to obtain adequate signal with the low x-ray absorption cross-section presented by Pt and Pd L-edges. Seeds were identical as before; cap layers were Cu(5nm)/Py(5nm)/Al(3nm). The ”Py/Pd” sample had a repeat unit of [Py(5nm)/Pd(2.5nm)]; the ”Py/Pt” sample had a repeat unit of [Py(5nm)/Pt(1.0nm)]. The different Pt and Pd thicknesses were chosen to correspond to roughly equal values of spin pumping damping $\Delta \alpha$, as will be shown.

XMCD spectra were measured at Beamline ID-12 of the European Synchrotron Radiation Facility (ESRF). Measurements were taken in florescence yield (FY), at grazing incidence of 15°, with static photon helicity and switching of the magnetic field. For details on the technique, see Ref. [15].

The damping enhancement due to the introduction of the paramagnetic layer, $\Delta \alpha(t_N)$, is shown for the series in paramagnetic layer thickness, Figure 1 (for Pd) and Figure 2 (for Pt.) We find that the thickness dependence of the damping enhancement $\Delta \alpha(t_N)$ is quite different for direct and indirect exchange coupling in Pd and Pt. Directly exchange coupled Pd and Pt layers show a linear increase in $\Delta \alpha$ extending $\sim 80\%$ towards a saturation value at a ”cutoff thickness” $t_c$. We fit this region by $\Delta \alpha(t_N) \simeq \Delta \alpha_0 t_N/t_c$, where $\Delta \alpha_0$ is the saturation value, finding $t_c = 1.9$ nm for Pt and $t_c = 5.0$ nm for Pd. Indirectly (weakly) exchange-coupled Pd and Pt layers exhibit an exponential approach to saturation, fitted well as $\Delta \alpha = \Delta \alpha_0 (1 - \exp(-t_N/\lambda_\alpha))$.

We first consider spin current scattering in indirectly (weakly) exchange-coupled Pd and Pt. Damping behavior in these systems has been understood through spin pumping with diffusive transport in $N$, first identified in ref. [3]. The diffusive model has been applied very recently to inverse spin Hall data for Ni$_{81}$Fe$_{19}$/Pt [17], for thick Pt layers, $t_{Pt} \geq 10$ nm. In these references, the (exponential) characteristic length for spin current absorption $\lambda_\alpha$, is
taken as the spin diffusion length $\lambda_{SD}$, as $\lambda = \lambda_{SD}/2$.

For reasons first identified in Ref\[18\], the diffusive model is not applicable to our data. By definition, the spin diffusion length $\lambda_{SD}$ must exceed the electronic mean free path: $\lambda_{SD} \gg \lambda_M$. Given our measured resistivities for Pd and Pt of $\rho_{\text{Pd}} = 18 \mu\Omega\text{cm}$, $\rho_{\text{Pt}} = 20 \mu\Omega\text{cm}$, and taking tabulated resistivity-mean-free- path products $\rho \cdot \lambda_M$ of $200 \mu\Omega \cdot \text{cm} \cdot \text{nm}$, we estimate $\lambda_M \sim 10 \text{ nm}$. Our experimental values of $\lambda$ of 0.67 nm for Pt in Cu/Pt(t) and 2.3 nm for Pd in Cu/Pd(t), respectively, are far shorter than the mean free path: $\lambda_M \gg \lambda$. The inequality is even more pronounced in Pt than it is in Pd, and no less present in our polycrystalline films than in the epitaxial films of ref. \[18\]. Transport is essentially ballistic over the range of spin current scattering.

Next, we consider the directly exchange coupled structures, $\text{Ni}_{81}\text{Fe}_{19}/N(t_N)$, shown with triangles in in Fig. 1 for $N = \text{Pd}$ and Fig. 2 for $N = \text{Pt}$. In these structures, the damping enhancement $\Delta\alpha$ is proportional to thickness $t_N$ over most (80\%) of the range to a cutoff thickness, $0 < t_N < t_c$, after which it remains constant. A linear thickness dependence with sharp cutoff is characteristic of spin current absorption by layers with ferromagnetic order, as seen for several $\text{Ni}_{81}\text{Fe}_{19}/\text{Cu}(3\text{nm})/F(t_F)$ structures in \[14\]. We fit the data to $\Delta\alpha(t_N) = \Delta\alpha_0 t_N/t_c$, finding $g_{\text{eff}}^{\uparrow\downarrow}(\text{Py}/\text{Pd}) = 15 \text{ nm}^{-2}$ and $g_{\text{eff}}^{\uparrow\downarrow}(\text{Py}/\text{Pt}) = 32 \text{ nm}^{-2}$.

The linearity of spin current scattering in paramagnetic layer thickness suggests the presence of induced ferromagnetic order in Pd and Pt. We have verified induced ferromagnetic order using XMCD, as shown in Figure 4a). In direct-exchange coupled $\text{Ni}_{81}\text{Fe}_{19}/\text{Pt}(1\text{nm})$ and $\text{Ni}_{81}\text{Fe}_{19}/\text{Pd}(2.5 \text{ nm})$, magnetic moments develop on Pt and Pd sites of 0.27$\mu_B$ at Pt and 0.12$\mu_B$ at Pd. Induced Pt moments have a relatively high orbital character, $m_L/m_S = 0.18$ compared with Pd, for which $m_L/m_S = 0.05$ is very close to the values seen in Fe\[20\].

The higher value of damping for the $\text{Ni}_{81}\text{Fe}_{19}/\text{Pt}(t_N)$ layer series might be interpreted as the result of a bilayer structure, with high $\alpha$ in ferromagnetic Pt and low $\alpha$ in ferromagnetic $\text{Ni}_{81}\text{Fe}_{19}$. To investigate whether damping is of bilayer type\[21\], or truly interfacial, we show the $t_F$ thickness dependence of the damping enhancement $\Delta\alpha$ in Fig 3. The power law thickness dependence adheres very closely to $t_F^{-1}$, as shown in the logarithmic plot. The assumption of composite damping, as $\Delta\alpha(t_1) = (\alpha_1 t_1 + \alpha_2 t_2)/(t_1 + t_2)$, shown here for $t_2 = 0.25 \text{ nm}$ and 1.0 nm, cannot follow an inverse thickness dependence over the decade of $\Delta\alpha$ observed. Damping is observed to be truly interfacial and thus most consistent with a spin-pumping mechanism.
In ref. [14], we proposed that $t_c$ in ferromagnets is on the order of the transverse spin coherence length $\lambda_J$. In terms of the exchange splitting, $\lambda_J = h v_g / 2 \Delta_{ex}$, where $v_g$ is the electronic group velocity at the Fermi level and $\Delta_{ex}$ is an exchange splitting energy. This form, found from hot-electron Mott polarimetry [22], is expressed equivalently for free electrons as $\pi / |k^\uparrow - k^\downarrow|$, which is a scaling length for geometrical dephasing in spin momentum transfer [23]. Electrons which enter the spin sink at $E_F$ do so at a distribution of angles with respect to the interface normal, traverse a distribution of path lengths, and precess by different angles (from minority to majority or vice versa) before being reflected back into the ferromagnet. For constant $v_g$, it is predicted that $t_C$ is inversely proportional to the exchange energy.

For the Ni$_{81}$Fe$_{19}$/Pt and Ni$_{81}$Fe$_{19}$/Pd systems, we can estimate interfacial exchange coupling energies from induced magnetic moments in Pd and Pt. Equating interatomic exchange energy $J_{ex}^i$ and Zeeman energy for an interface paramagnetic atom, we have

$$J_{ex} = \frac{1}{2} \frac{<M>}{\mu_B N_0 F t_i}$$

where $<M>$ is the thickness-averaged paramagnetic moment, $N_0$ is the single-spin density of states (in eV$^{-1}$at$^{-1}$), $F$ is the Stoner factor, and $t_p$ and $t_i = a/\sqrt{3}$ are the paramagnetic layer thickness and interface layer thickness. We make the simplifying assumption that all the magnetic moment is confined to the interface Pd or Pt layer and assume experimental bulk susceptibility parameters for $\chi_v$ of Pd and Pt, giving $J_{ex}^i = 83$ meV for Pd and $J_{ex}^i = 217$ meV for Pt.

For the ferromagnets Py and Co, we estimate interatomic exchange parameters $J_{ex}$ from the Curie temperature $T_C$, through $J_0 \simeq 6k_B T_C / (m/\mu_B)^2$, where $m$ is the atomic moment ($\mu_B$/at). Experimental Curie temperatures of 870K and 1388 K give estimates of $J_0 = 293$ meV for Co and $J_0 = 393$ meV for Py. See Supplemental Information for further details on the calculations.

In Figure 4b) we plot the dependence of the cutoff thickness $t_c$ upon the inverse exchange energy $J_{ex}^{-1}$. We verify a rough proportionality, in agreement with expected behavior of the transverse spin coherence length. These data show a length scale for spin current scattering with a common origin in ferromagnetic layers and paramagnetic Pd and Pt under the influence of direct exchange.

Summary: We have found that the character of spin current absorption in the ultrathin
paramagnets Pd and Pt is modified by direct exchange with ferromagnetic Ni$_{81}$Fe$_{19}$. A (shorter) characteristic thickness for spin current absorption is replaced with a (longer) linear approach towards a maximum value. The range of linear increase is observed to be inversely proportional to the exchange energy, inferred through induced Pd and Pt moments measured by XMCD. We acknowledge support from the U.S. NSF-ECCS-0925829.

FIGURES

FIG. 1. Damping enhancement due to pumped spin current absorption as a function of Pd layer thickness, $\Delta \alpha (t_{\text{Pd}})$, for Ni$_{81}$Fe$_{19}$/Pd($t_{\text{Pd}}$) and Ni$_{81}$Fe$_{19}$/Cu(3nm)/Pd($t_{\text{Pd}}$) heterostructures. Fits are indicated to ballistic spin pumping ($\alpha_0 = 1.42 \times 10^{-3}$ ↔ $g_{\text{eff}}^{\text{eff}} = 7.8$ nm$^{-2}$) and linear cutoff ($\Delta \alpha_0 = 2.73 \times 10^{-3}$, $t_c = 5.0$ nm.)
FIG. 2. Damping enhancement due to pumped spin current absorption as a function of Pt layer thickness $\Delta \alpha(t_{Pt})$, for Ni$_{81}$Fe$_{19}$/Pt($t_{Pt}$) and Ni$_{81}$Fe$_{19}$/Cu(3nm)/Pt($t_{Pt}$) heterostructures. Fits shown to ballistic spin pumping ($\alpha_0 = 1.53 \times 10^{-3} \leftrightarrow g_{eff}^{\uparrow\downarrow} = 8.6 \text{ nm}^{-2}$) and linear cutoff ($\Delta \alpha_0 = 5.8 \times 10^{-3}$), $t_c = 1.9 \text{ nm}$.
FIG. 3. Inset: damping $\alpha$ for Ni$_{81}$Fe$_{19}(t_F)$ and Ni$_{81}$Fe$_{19}(t_F)$/Pt(4nm). Main panel: Logarithmic plot, additional damping due to Pt(4nm) $\Delta \alpha(t_F)$. Fit to the (interfacial) spin pumping model $\Delta \alpha = K t_F^{-1.00}$, compared with fits to a high-$\alpha(t_2)$/low-$\alpha(t_F)$ (bilayer) model.
FIG. 4. Left: X-ray magnetic circular dichroism (XMCD) measurements of element-specific magnetic moments in [Ni$_{81}$Fe$_{19}$(5nm)/X]$_{20}$, X = [Pt(1.0 nm), Pd(2.5nm)]. Right: Effect of direct exchange strength on length scale of spin current absorption. Cutoff thickness $t_c$ extracted from the $\Delta \alpha (t_N)$ data in Figs [1] and [2] as a function of reciprocal interfacial exchange energy $1/A_{ex}$ extracted from XMCD. Labels are given in terms of $A_{ex}$. The ferromagnetic (FM) point is from ref. [14]. See text for details.

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TABLES

| P     | $\chi_{mol}$ [24] | F [24] | $N_0$ [0.83±0.03] | $< M >$ | a  | $t_P$ | $J_{ex}$ |
|-------|------------------|--------|------------------|--------|----|-------|---------|
| Pd    | 5.5±0.2 (10⁻⁴ cm²/mol) | 9.3    | 0.116            | 0.389  | 2.5| 83    |
| Pt    | 1.96±0.1 (10⁻⁴ cm²/mol) | 3.7    | 0.27             | 0.392  | 1.0| 217   |

TABLE I. Paramagnet ($P$) densities of states $N_0$ from tabulated experimental molar susceptibilities $\chi_{mol}$ at 20 °C and Stoner parameters $F$ in ref [24]. XMCD moments $< M >$ are measured for $P$ layer thicknesses $t_P$; lattice parameter is $a$. Interatomic Py-Pd or Py-Pt exchange energy per interface atom $J_{ex}'$ are found from Eq[4] See text for details.
Supplementary information

Effect of direct exchange on spin current scattering in Pd and Pt

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This document provides additional details on the estimates of interatomic exchange $J_{ex}$ and induced moments $m_i$ presented in Table 1 and Figure 4 of the manuscript. Section 1 gives details on the estimated relationship between $J_{ex}$ and $m_i$ for paramagnets, followed by a review of estimated $J_{ex}$ for ferromagnets in Section 2.

1. PARAMAGNETS

We will show estimates for exchange energy based on XMCD-measured moments in $[\text{Ni}_{81}\text{Fe}_{19}/(\text{Pt},\text{Pd})]_{N}$ superlattices. Calculations of susceptibility are validated against experimental data for Pd and Pt. Bulk susceptibilities will be used to infer interfacial exchange parameters $J_{ex}^{i}$.

Pauli susceptibility

For an itinerant electron system characterized by a density of states at the Fermi energy $N_0$, if an energy $\Delta E$ splits the spin-up and spin-down electrons, the magnetization resulting from the (single-spin) exchange energy $\Delta E$ is

$$M = \mu_B \left( N^\uparrow - N^\downarrow \right) = 2\mu_B N_0 F \Delta E$$

where $N_0$ is the density of states in $#/\text{eV}/\text{at}$, $F$ is the Stoner parameter, and $2\Delta E$ is the exchange splitting in eV. Moments are then given in $\mu_B/\text{at}$. Solving for $\Delta E$,

$$\Delta E = \frac{M}{2\mu_B N_0 F}$$

If the exchange splitting is generated through the application of a magnetic field, $\Delta E = \mu_B H$,

$$\mu_B H = \frac{M}{2\mu_B N_0 F}$$

and the dimensionless volume magnetic susceptibility can be expressed

$$\chi_v \equiv \frac{M}{H} = 2\mu_B^2 N_0 F$$

In this expression, the prefactor can be evaluated through

$$\mu_B^2 = 59.218 \text{eV}\cdot\text{Å}^3$$

so with $N_0 = 1.00/\text{eV}/\text{at}$, $\chi_v$ takes units of volume per atom, and is then also called an atomic susceptibility, in $\text{cm}^3/\text{at}$, as printed in Ref [1].

*Molar susceptibility*

Experimental values are tabulated as molar susceptibilities. The atomic susceptibility $\chi_v$ can be contrasted with the mass susceptibility $\chi_m$ and molar susceptibility $\chi_{mol}$

$$\chi_{mass} = \frac{\chi_v}{\rho} \quad \chi_{mol} = \frac{\text{ATWT}}{\rho} \chi_v$$

where ATWT is the atomic weight ($\text{g/mol}$) and $\rho$ is the density ($\text{g/cm}^3$). These have units of $\text{cm}^3/\text{g}$ and $\text{cm}^3/\text{mol}$. The molar susceptibility $\chi_{mol}$ is then

$$\chi_{mol} = 2\mu_B^2 N_0 N_A F$$

in $\text{cm}^3/\text{mol}$, where $\mu_B$ is the Bohr magneton, and

$$2N_0 F = \frac{\chi_{mol}}{N_A \mu_B^2}$$

Eq. 8 provides a convenient method to estimate experimental unknowns, the density of states $N_0$ and Stoner parameter $F$, from measurements of $\chi_{mol}$.

*Example:* for Pd, the low-temperature measurement (different from the room-temperature measurement in Table I) is $\chi_{mol} \sim 7.0 \times 10^{-4} \text{cm}^3/\text{mol}$. In the denominator, $(N_A \mu_B^2) = 2.622 \times 10^{-6} \text{Ry} \cdot \text{cm}^3/\text{mol}$. The value $2N_0 F$ consistent with the experiment is $266/(\text{Ry-at})$ or $19.6/(\text{eV-at})$. For the tabulated measurement of $F = 9.3$, the inferred density of states is then $N_0 = 1.05/\text{eV}/\text{at}$.
TABLE I. Paramagnet \((P)\) densities of states \(N_0\) extracted through Eq 8 from experimental molar susceptibilities \(\chi_{mol}\) at 20 °C and Stoner parameters \(F\) tabulated in ref 1. Interfacial exchange \(A_{ex}\) extracted from moments in paramagnets \(P\), thickness \(t_P\), induced through direct exchange in a superlattice with \(\text{Ni}_{81}\text{Fe}_{19}\) (Py).

| \(P\) | \(\chi_{mol}\) \((10^{-4} \text{ cm}^3/\text{mol})\) | \(F\) | \(N_0\) \((\text{eV} \text{at})^{-1}\) | \(< M >\) \((\mu_B/\text{at})\) | \(a\) \((\text{nm})\) | \(t_p\) \((\text{nm})\) | \(J_{ex}\) \((\text{meV})\) |
|------|-------------------|------|-----------------|-----------------|-------|--------|----------------|
| Pd   | 5.5±0.2           | 9.3  | 0.83±0.03       | 0.116           | 0.389 | 2.5    | 83             |
| Pt   | 1.96±0.1          | 3.7  | 0.74±0.04       | 0.27            | 0.392 | 1.0    | 217            |

\(M_{p}\) is the magnetization of the paramagnet, with the atomic moment of the paramagnet \(m_{p}\) in terms of its per-atom spin \(S_{p}\),

\[
M_{p} = \frac{m_{p}}{V_{at}} \quad m_{p} = 2\mu BS_{p}
\]

\(V_{at}\) is the volume of the paramagnetic site, \(S_{f,p}\) are the per-atom spin numbers for the ferromagnetic and paramagnetic sites, and \(J_{ex}^{i}\) is the (interatomic) exchange energy acting on the paramagnetic site from the ferromagnetic layers on the other side of the interface. Interatomic exchange energy has been distinguished from intraatomic (Stoner) exchange involved in flipping the spin of a single electron. Rewriting Eq 8

\[
\frac{M_{p}^{2}}{\chi_{v}}V_{at} = 2J_{ex}^{i}S_{f}S_{p}
\]

if \(S_{f} = 1/2\), appropriate for \(4\pi M_{s} \approx 10 \text{ kG}\),

\[
J_{ex}^{i} = 2\mu BS_{p}
\]

and substituting for \(\chi_{v}\) through Eq 8

\[
J_{ex}^{i} = \frac{M_{p}}{\mu_{B}N_{0}F}
\]

In the XMCD experiment, we measure the thickness-averaged magnetization as \(< M >\) in a \([F/P]_{xN}\) superlattice. We make a simplifying assumption that the exchange acts only on nearest-neighbors and so only the near-interface atomic layer has a substantial magnetization. We can then estimate \(M_{p}\) from \(< M >\) through

\[
< M > t_p = 2M_{p}t_i
\]

where \(t_i\) is the interface layer thickness of \(P\). We take this to be \(a/\sqrt{3}\), the thickness of a (111) plane. Since the interface exists on both sides of the \(P\) layer, \(2t_i\) is the thickness in contact with \(F\). Finally,

\[
J_{ex} = \frac{1}{2\mu_{B}N_{0}F} t_i
\]

The exchange energy acting on each interface atom, from all neighbors, is \(J_{ex}^{Pd} = 217 \text{ meV}\) for Pt and \(J_{ex}^{Pd} = 83 \text{ meV}\) for Pd. Per nearest neighbor for an ideal \(F/N(111)\) interface, it is \(J_{ex}^{F-Pt} = 72 \text{ meV}\) and \(J_{ex}^{F-Pd} = 27 \text{ meV}\). Per nearest neighbor for an intermixed interface (6 NN), the values drop to 36 meV and 14 meV, respectively.

Since explicit calculations for these systems are not in the literature, we can compare indirectly with theoretical values. Demler [2] showed that at a \((3d)F/(4d)N\) interface (e.g. Co/Rh), there is a geometrical enhancement in the moment induced in \(N\) per nearest-neighbor of \(F\). The 4d \(N\) atoms near the \(F\) interface have larger induced magnetic moments per NN of \(F\) by a factor of four. Specific calculations exist of \(J_{ex}^{N-F}\) (per neighbor) for dilute Co impurities in Pt and dilute Fe impurities in Pd [2]. \(J_{ex}^{N-F} \approx 3 \text{ meV}\) is calculated, roughly independent of composition up to 20% Fe. If this value is scaled up by a factor of four, to be consistent with the interface geometry in the XMCD experiment, it is \(\sim 12 \text{ meV}\), comparable with the value for Pd, assuming intermixing. Therefore the values calculated have the correct order of magnitude.

2. FERROMAGNETS

The Weiss molecular field,

\[
H_W = \beta M_s
\]

where \(\beta\) is a constant of order \(10^3\), can be used to give an estimate of the Curie temperature, as

\[
T_C = \frac{\mu_B g J (J + 1)}{3k_B} H_W
\]

Density functional theory calculations have been used to estimate the molecular field recently [2, 4]; for spin type, the \(J (J + 1)\) term is substituted with \(< s >^2\), giving an estimate of

\[
T_C = \frac{2 < s >^2 J_0}{3k_B}
\]
where \( < s > \) is the number of spins on the atom as in Eq. 10, see the text by Stöhr and Siegmann. \( < s > \) can be estimated from \( m = 1.07 \mu_B \) for Py and \( 1.7 \mu_B \) for Co, respectively. Then

\[
J_0 \simeq \frac{6k_B T_C}{(m/\mu_B)^2}
\]  

(19)

with experimental Curie temperatures of 870 and 1388 K, respectively, gives estimates of \( J_0 = 293 \) meV for Co and \( J_0 = 393 \) meV for Py.

Note that there is also a much older, simpler method. Kikuchi has related the exchange energies to the Curie temperature for FCC lattices through

\[
J = 0.247 k_B T_C
\]

(20)

Taking 12 NN, \( 12J \) gives a total energy of 222 meV for Py (870 K) and 358 meV for FCC Co (1400 K), not too far off from the DFT estimates.

**Other estimates** The \( J_0 \) exchange parameter is interatomic, describing the interaction between spin-clusters located on atoms. Reversing the spin of one of these clusters would change the energy \( J_0 \). The Stoner exchange \( \Delta \) is different, since it is the energy involved in reversing the spin of a single electron in the electron sea. Generally \( \Delta \) is understood to be greater than \( J_0 \) because it involves more coulomb repulsion; interatomic exchange can be screened more easily by \( sp \) electrons, according to the argument in ref. [6].

This exchange energy is that which is measured by photoemission and inverse photoemission. Measurements are quite different for Py and Co. Himpsel finds an exchange splitting of \( \Delta = 270 \) meV for Py, which is not too far away from the Weiss \( J_0 \) value. For Co, however, the value is between 0.9 and 1.2 eV, different by a factor of four. For Co the splitting needs to be estimated by a combination of photoemission and inverse photoemission because the splitting straddles \( E_F \).

For comparison with the paramagnetic values of \( J_{ex}^i \), we use the \( J_0 \) estimates, since they both involve a balance between Zeeman energy (here in the Weiss field) and Heisenberg interatomic exchange. Nevertheless the exchange splitting \( \Delta_{ex} \) is more relevant for the estimate of \( \lambda_c = h \nu_g / (2\Delta_{ex}) \). For Py, the predicted value of \( \lambda_c \) from the photoemission value (through \( \lambda_c = \pi / k^\uparrow - k^\downarrow \)) is 1.9 nm, not far from the experimental value of 1.2 nm.

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