Spin-resolved Photoemission Studies of Gd(0001)

A.V. Fedorov #
T. Valla /Brookhaven/
P.D. Johnson /Brookhaven/
M. Weinert

P.B. Allen /Stony Brook/

# now at ALS
Spin Resolved Photoemission on Gd

★ Surface Curie temperature \((T_{\text{surf}} \sim T_{\text{bulk}} + 60K)\)
★ Canted magnetic moments
★ Stoner splitting vs. spin-mixing
★ Electron-magnon coupling

Plan

★ Photoemission, self energies, scattering rates, etc.
★ Micro-Mott spin polarimeter, achieving the high resolution
★ Scattering channels for the spin majority and minority photo-holes
★ Surface Curie temperature
Angle Resolved Photoemission /band structure mapping/

**Experiment**

Excitation Radiation
- photon energy
- polarization
- angle of incidence

Photoelectrons
- kinetic energy
- emission angle
- polarization

**Data**

Energy Distribution Curves (photocurrent vs. kinetic energy) measured at certain emission angle

- Kinetic energy
- Vacuum level
- Fermi level
- Binding energy
- Electron momentum (Å⁻¹)

E - E_F (eV)

Mo(110)
Angle Resolved Photoemission
/spectral function and self energy/

\[ A(\kappa, \omega) = \frac{1}{\pi} \frac{\text{Im} \Sigma(\kappa, \omega)}{[\omega - \varepsilon_{\kappa} - \text{Re}(k, \omega)]^2 + [\text{Im} \Sigma(\kappa, \omega)]^2} \]

\[ \text{Im} \Sigma(k, \omega) \sim \frac{1}{T} \] and gives the scattering rate /e-ph, e-e, e-imp, e-magnon/
High-efficiency retarding-potential Mott polarization analyzer

G. C. Burnett, T. J. Monroe, and F. B. Dunning
Department of Physics and the Rice Quantum Institute, Rice University, P.O. Box 1892, Houston, Texas 77251

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\[ P = \frac{1}{S} \frac{\sqrt{I_{L}^{+}I_{R}^{-}} - \sqrt{I_{L}^{-}I_{R}^{+}}}{\sqrt{I_{L}^{+}I_{R}^{-}} + \sqrt{I_{L}^{-}I_{R}^{+}}} \]

\[ A = \frac{\sqrt{I_{L}^{+}I_{L}^{-}}}{\sqrt{I_{R}^{+}I_{R}^{-}}} \]

\[ I^\uparrow = \langle I \rangle (1 + P) \]

\[ I^\downarrow = \langle I \rangle (1 - P) \]

\[ \langle I \rangle = \frac{I_{L}^{+} + I_{L}^{-} + I_{R}^{+} + I_{R}^{-}}{4} \]
Spin polarimeter in BNL

Energy resolution: \( \frac{\text{Aperture}/\text{ØMCP}}{10} \times \text{PE}/10 \)
Aperture plate
Channeltrons

90° deflector
Photoelectron Spectrometer
/200-mm hemispherical analyzer from Scienta/

Excitation radiation

Wide-band Energy Analyzer

2-Dimensional (Energy and Angle)
high-resolution electron detector

Magnifying
high-transmission imaging Electron Lens

Photoelectrons

Sample

$h_v$
Test results: “in-plane” polarization in ferromagnetic iron films

Fe(110)/Mo(110)
$\hbar \nu = 21.2$ eV
T = 85 K

Resolution: 50 meV / PE=10 eV/
Sherman function: 0.15
Surface state in Gd(0001)

D. Li et al., PRB 51, 13895

R. Wu and A.J. Freeman, PRB 44, 9400

∆E~175 meV

Spin-resolved

Spin-integrated

Spin-mixing

Stoner-like

E. Weschke et al., PRL 77, 3415
Sample Preparation:

Epitaxial films of Gd on Mo(110)
Deposition at 200÷300 K
Annealing at ~800 K
Result: Gd(0001)

Sample lifetime ~ 48 Hours

Temperature range 20 K÷3000 K

Base pressure $2 \times 10^{-11}$ mbar
Angle-resolved spin-integrated data
/suggests Stoner-like behavior/

Gd(0001)/Mo(110)
PE, $h\nu = 21.22$ eV

a) $T= 300$ K

b) $T= 82$ K
Spin-resolved data

Spectra were measured at six different temperatures: 20K, 80K, 98K, 117K, 140K, 160K

Temperature-dependent shift of spin-majority peak agrees with Stoner behavior

Spin-majority peak shows considerable broadening with temperature

Surface state is not 100% polarized even at 20K

Relative intensity of spin-minority component increases with temperature
Width of spin-majority peak vs. temperature

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FWHM (meV) vs. Temperature (K)

Broadening of majority peak reflects mostly phonon contribution to the line-width

"Spin-resolved" electron-phonon coupling constants:
\( \lambda^{\uparrow} \approx 0.73 \quad \lambda^{\downarrow} \approx 0.31 /P. Allen/ 

"Spin-averaged" constant: 0.4
/H.L. Skriver and I. Mertig, PRB 41, 6553

Experiment: \( \lambda \approx 0.9 \)

\[
\text{Im} \sum_{e-ph} (T, \omega) = \pi \int d\nu \alpha^2 F(\nu) \left[ 1 + 2n(\nu) + f(\nu + \omega) - f(\omega - \nu) \right]
\]

Debye model: 
\[
\alpha^2 F(w) = \lambda \left( \frac{\omega}{\Omega_m} \right)^2 \quad \frac{1}{\tau} \approx \text{const} + \pi \lambda k_B T
\]
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Extra broadening of spin-minority peak was detected at all temperatures

Least-square fits to Lorentzian + Fermi edge

Intrinsic width of the peak should not depend on the orientation of magnetic moment in domains
Broader minority spin channel indicates electron-magnon mechanism

\[
\frac{1}{\tau_{\downarrow}} \approx \frac{P(\uparrow)m^*}{S} \left( \frac{2JSa}{\eta} \right)^2
\]

\[
\frac{1}{\tau_{\downarrow}} \approx 0.095\text{eV}
\]

\[
\frac{1}{\tau_{\uparrow}} \approx 0.014\text{eV}
\]

P.B. Allen, PRB 63, 214410 (2001)
At low T majority spin hole decays primarily via lattice excitations, minority spin hole primarily via spin excitations

<table>
<thead>
<tr>
<th></th>
<th>Majority</th>
<th>Minority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phonons</td>
<td>46 meV</td>
<td>10 meV</td>
</tr>
<tr>
<td>Magnons</td>
<td>14 meV</td>
<td>95 meV</td>
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</tbody>
</table>

$E_r$

e-ph
e-magnon
Surface transition temperature: enhanced or regular?

C.S. Arnold and D.P. Pappas,
PRL 85, 5202 (2000):
Common Curie temperature
for surface and bulk

Present work at ~300 K:
Hint for the enhanced $T_c$

Gd(0001)/Mo(110)
$T=300$ K

Electron Polarization (%) vs. Temperature (K)

MOKE Intensity (arb. units)

in-plane

out-of-plane

Binding Energy (eV)

majority

minority
Polarization of the surface state vs. temperature

Polarization = \{n_{\uparrow} - n_{\downarrow}\}/\{n_{\uparrow} + n_{\downarrow}\}

Fit with “T^{3/2}” law found in bulk Gd:
\[ P(T) = P_0 \times (1 - T/T_C)^{3/2} \]

\[ T_C = 362 \text{ K} \] in agreement with reports on enhanced surface Curie temperature/

Polarization of the surface state

Polarization of background

Simulation for T_C = 293 K /bulk/
Measuring “out-of-plane” component in Gd

We can estimate the canting of magnetic moment: 6° with respect to the surface plane.