A Revolutionary Rotatable Electron Energy Analyzer for Advanced High-Resolution Spin-Polarized Photoemission Studies

**Final Report
for Period September 1, 1996 through August 31, 1999**

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I. Final Report

This report details the progress of this project for the period from 9/1/96 through 8/31/99. Progress can be divided into two distinct areas. These are the fabrication, construction, and initial testing of the instrumentation, and the concurrent program of preliminary investigations into materials and experiments appropriate for future studies using the instrumentation developed. The analyzer complete with special input electron optics and Mott detector has been assembled in a special design UHV chamber equipped with all the capabilities needed to perform the described programs of research. These include a sophisticated five motorized axis sample manipulator with low and high temperature capability and rapid temperature cycling (acquired in collaboration with Dr. J.G. Tobin of LLNL), vacuum leak detection and gauging, *in situ* thin film growth instrumentation, and sample cleaning and magnetizing capabilities. The initial testing of the analyzer has been completed with successful data acquisition using both the multichannel detector mode, and spin-dependent using the Mott detector channeltrons. The data collected using the Mott detector were not truly spin-dependent (see below), but demonstrate the operation of the lens and detector design. Acquisition of truly spin-dependent data await use of the EPU. Preliminary indications suggest that the analyzer performs at or above the original design parameters. In the second area of progress, we have conducted a number of preliminary studies toward the ends of identifying appropriate initial systems for investigation, and to further explore new experiments that the new instrumentation will help to pioneer. More detailed descriptions of all of these advances follow.

A. Instrumentation

Prior to the assembly of the electron optics shown assembled in Figure 1 (right side), the hemispherical energy analyzer was tested using a standard Physical Electronics input lens assembly (the OMNI III lens). Of primary concern was the impact of the new micro-channel plate and anode detector system on the overall efficiency and resolution of the energy analyzer. The multichannel detector was designed with an exit slit which allows it to serve to pass electrons into the Mott electron spin detector (shown assembled in its vacuum housing on the left in Figure 1) by simply changing the voltage applied to the multichannel detector. This exit slit

Figure 1 Assembled input lens (right) and Mott detector (left).

effectively removes two detection channels from the center of the detector and could limit the sensitivity of spin-integrated operation, particularly at low pass energy and small sampling area (large angular acceptance). Results of these tests were reported in the previous progress report and showed count rates for the Ag $3d_{5/2}$ core level excited with Mg K_{α} x-rays as a function of lens aperture size and core level half width. For most of the conditions tested, the analyzer with the new multichannel detector/exit slit surpassed the required performance level of the same analyzer with a conventional detector. This is also true for angle resolved operation. Our preliminary results using the specially designed input optics are consistent with the results above once corrections due to different input acceptance angles are made. Further tests will require access to the elliptically polarized undulator (beamline 4.0) at the ALS which has yet to be completed or commissioned. Current schedules have EPU access occurring in Spring or Summer 1999.

We have also successfully recorded spectra with each of the four Mott detector channeltrons after electron acceleration and scattering from the Au target in the Mott detector. While these tests were not for a magnetic system (and the results correctly show no electron spin-polarization) this success coupled with our experience with the prototype Mott detection scheme of Dr. J.G. Tobin should make realization of spin-dependent data a formality once access to the elliptically polarized undulator is gained. We note that the prototype for this detection scheme which provides easy switching between spin-dependent and spin-integrated detection has recently been successfully tested by the combined groups of J.G. Tobin (LLNL), D.P. Pappas (NIST), and G.D. Waddill (UMR) at the ALS. The tested spin detection system has a more complicated transfer system from the hemispherical energy analyzer channelplates to the Mott detector than our variable angle system, but tests show that count rates in excess of several kHz in each of the four spin channels of the Mott detector are possible for the Ni 3p core levels using photon energies of about 200 eV. In addition, the results of earlier spin-polarized measurements of the Ni 3p core levels by Kisker *et al.*¹ were reproduced using the prototype system. These results clearly demonstrate the success of this unique spin-detection scheme. A detailed description of the design, construction, and performance of this instrument is currently being prepared for publication.²

In addition to instrumentation advances related to the electron analyzer/spin detector we have also designed and assembled the equipment for the analysis chamber and the supporting surface analytical and sample preparation facilities. Figure 2 shows a photograph of the system prior to (left) and after (right) installation of the electron energy analyzer. In the left panel, the rotatable optics can be seen above the 12" mounting flange. Part of the design philosophy of the chamber was to incorporate the currently available instrumentation, as well as to allow future expansion to house multitechnique characterization capability in a single analysis chamber. Toward that end, we have made provisions for the currently available instrumentation which includes a sophisticated automated x, y, z, θ , ϕ sample manipulator (not shown in the photograph, but currently at the ALS waiting installation), a cylindrical mirror analyzer with coaxial electron gun for Auger studies and future RHEED studies, thin film evaporators, LEED, and an assortment of ports that can serve to accommodate ion sputtering, pumping, gauging, and viewing. In addition, the chamber has been designed to allow future incorporation of a RHEED system as well as SMOKE capabilities. The manipulator was obtained by Prof. Waddill in collaboration with Dr. J.G. Tobin, and it provides for the wide range of sample translation, and high-resolution polar and azimuthal angle variations required for sophisticated investigations using the unique energy analyzer/spin detector system.

These capabilities will be coupled with heating and cooling systems that will ultimately provide sample temperatures between 100 and 1200 K with cycling times of a few minutes.

Figure 2a Spin-polarized photoemission system prior to attaching analyzer.

Figure 2b Assembled system.

Concurrently, the group at Penn State, directed by Prof. Roy Willis, has completed the design and testing of the thin film evaporators capable of depositing up to three different materials simultaneously or sequentially. These evaporators will be used in the analysis chamber for complex sample preparation, including the growth of magnetic alloy films. Finally, the Penn State group has procured a cylindrical mirror energy analyzer with a coaxial electron gun for Auger monitoring of deposited magnetic alloy films, and for future incorporation, using the electron gun, into a RHEED system for monitoring the growth of epitaxial systems.

B. Preliminary Studies

Concurrent with the advances in instrumentation design, construction, and testing described above, a program of preliminary investigations has been initiated at the Advanced Light Source. These investigations have focused on the use of dichroism (both linear and circular) techniques in core-level photoemission and their applications to magnetic systems such as magnetic alloys and

nanoscale magnetic systems. (A combined publication list of the Waddill and Willis groups relevant to this project since 1996 is included at the end of this report. The research of these groups is complementary and independent, and continued collaborative efforts are anticipated.) Two examples are provided below which involve the characterization of Gd films and a novel use of magnetic linear dichroism with these samples, and linear and circular dichroism investigations of ultrathin magnetic alloy films demonstrating the influence of alloy composition on the elemental spin moments. These studies were initiated in order to develop better capacity for performing and understanding the role of photon polarization in photoemission studies of magnetic materials. Ultimately the experience gained here will better enable us to perform the more demanding double-polarization variations of both core level and valence band photoemission.

Gd films grown on Y(0001) have been structurally characterized using x-ray photoelectron diffraction and LEED. These studies were performed by the groups led by J.G. Tobin (LLNL), D.P. Pappas (NIST), and G.D. Waddill (UMR). Gd films present a rich variety of magnetic properties with strong dependence on the geometric arrangement of the surface atoms.³ These results have characterized the Gd films grown on Y(0001) at room temperature suggesting a C_{6v} symmetry consistent with earlier studies on other hcp(0001) surfaces.⁴ Interestingly, the samples have also been characterized using magnetic linear dichroism, and this technique coupled with resonant photoemission at the Gd 4d giant resonance have led to significant new insights into the temporal nature of the resonant photoemission process that is the subject of a recently published Physical Review Letter.⁵ The use of dichroic techniques in photoemission (requisite for the complete-polarization core level and valence band studies) offers many opportunities for our understanding of the basic photoemission process, and therefore of our understanding of the materials studied by those means. Inclusion of photoelectron spin-polarization measurements will undoubtedly lead to further new and important findings.

Experimental results on ultrathin magnetic alloys have been obtained by the groups directed by R.F. Willis (PSU) and J.G. Tobin (LLNL). Here, linear and circular magnetic dichroism techniques have been used to examine the elemental spin magnetic moments in these films. These results demonstrate the effect of varying alloy composition on the elemental spin moments. In particular, a spin-moment instability has been observed in Fe_xNi_{1-x} alloy films above 70% Fe content. This is the subject of a recently published Physical Review Letter.⁶

The results of these preliminary studies provide a firm foundation for future experimental studies using the advanced instrumentation described above. Spin-polarized photoemission studies of the core-level and valence states of the systems outlined here will reveal further details of the magnetic properties of the materials and their relationship with the structural or stoichiometric properties as well. In addition, the incorporation of spin-polarized photoemission into these studies may well initiate further advances in our understanding of the nuances of the photoemission process, and thereby into the detailed electronic structure of these complex materials.

C. Summary

The following tasks have been completed:

1. Final assembly of the analyzer and vacuum system is complete.
2. The electron optics supplies have been built and tested.
3. Spin integrated spectra using the multichannel detector have been acquired.

4. A prototype Mott detector coupled with the unique multichannel detection scheme has been tested.
5. All support instrumentation required to begin initial investigations have been acquired and installed.

The following tasks are ongoing and will be accelerated with instrument completion:

1. Investigations of nanoscale magnetic systems and the effects of structure on magnetic properties.
2. Investigations of spin-polarized core-level and valence band photoemission.
3. Investigations into magnetic alloy films and the effects of stoichiometry on magnetic properties.

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