ANGLE-RESOLVING PHOTOELECTRON ENERGY ANALYZER
DESIGNED FOR SYNCHROTRON RADIATION SPECTROSCOPY

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ABSTRACT

This paper describes design considerations, input lens analysis, ray-tracing studies, construction details and initial tests of a Kuyatt-Simpson-type photoelectron energy analyzer. The analyzer has been designed specifically for angle-resolved photoemission studies using synchrotron radiation. Design features include input and output lens systems which establish virtual slits and apertures which define the input solid angle and source region. Constant angular resolution, constant energy-resolution and constant transmission are achieved by the analyzer. The performance of the analyzer has been checked analytically using computer ray-tracing techniques and experimentally. Initial tests have verified the ray-tracing results and have shown that all the analyzer design specifications have been realized.

INTRODUCTION

Electron spectroscopy has emerged as one of the most useful probes of bulk and surface electronic structure. The present capability and broad range of current applications utilizing electron spectroscopy in the fields of condensed-matter physics, surface chemistry and material science are well established in the scientific literature and have been recently summarized in several review articles [1-4]. Parallel development of synchrotron facilities [5-6] providing a high-intensity source of polarized radiation extending from visible through X-ray wavelengths has stimulated the development of a new generation of monochromators and has also opened up new applications of photoelectron spectroscopy. These new applications of photoelectron spectroscopy have re-emphasized the need for versatile electron energy analyzers which achieve high angular and energy resolution and also have well-defined operating characteristics.

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In spite of the need for such instruments, there are currently no commercially available energy analyzers which have been designed specifically for synchrotron radiation applications. Of the analyzers available*, only a few are suited for angle-resolved spectroscopy and none offers all the features needed to take full advantage of the new storage-ring sources and monochromators.

These factors stimulated our present project to design, construct and thoroughly characterize an angle-resolving photoelectron spectrometer to be used specifically for synchrotron radiation work. This paper describes in detail basic design considerations, analysis of the electron optics, computer optimization, ray-tracing studies of the lens systems and construction details of our analyzer. The results of preliminary tests of the analyzer are included. These results indicate that our design objectives have been achieved and corroborate the optimization and ray-tracing results. The tests also include a performance comparison between our analyzer and a commercial instrument.

DESIGN CONSIDERATIONS

Primary design considerations for the energy analyzer were based on its anticipated use, with the major emphasis being placed on angle-resolved photoelectron work in the energy range from 20 to 200 eV. This range covers the valence and conduction bands of solids and the molecular levels of adsorbates, and also includes energies for which the de Broglie wavelength of electrons corresponds to typical atomic and molecular distances. In this range, geometrical properties of adsorbates can be probed using photoelectron diffraction techniques [7]. Use of the analyzer for detecting X-ray- or electron-excited Auger electrons and for measuring core-level binding energies has also been anticipated. Therefore, operation in the kinetic energy range around 1 keV has been considered in our design.

Angular resolution requirements for mapping bulk and surface band structure and studying surface states and molecular adsorbates are well established. If it is desired to probe a reasonably small region of $k$-space (representing a small fraction of a surface or bulk Brillouin-zone dimension) at electron kinetic energies around 50 eV, an angular resolution of $\sim 1^\circ$ is required. Photoelectron diffraction studies also require accurate angular resolution and positioning, however, the energy and angular resolution requirements for this type of work do not appear to be as stringent as those for electronic structure work. Based on our experience and the experience of other investigators,

* Commercial angle-resolving analyzers include a twin-pass cylindrical mirror analyzer (Physical Electronics Model 15-255GAR), a 150° spherical-capacitor analyzer (Vacuum Generators Model ADES-400), and 180° spherical-capacitor analyzers (Leybold—Heraeus Models LHS-10 and GEA-21)
we have chosen a nominal angular resolution of $\pm 1.5^\circ$ as a design parameter. We also require the design to permit increasing this angle to $\sim \pm 5^\circ$, if desired, by using different apertures.

High energy-resolution is particularly important for studying intrinsic surface states [8], lateral coupling of electronic states of adsorbed molecules [9], and exchange splitting of bands in ferromagnetic materials [10]. Photoemission peaks associated with surface states near the Fermi level have been observed with intrinsic widths less than 100 meV. Excited-state lifetime effects broaden peaks resulting from conduction bands with binding energies of more than one or two eV. Peaks associated with molecular orbitals of adsorbed molecules tend to have widths of several hundred meV, again due primarily to screening of the ion by conduction electrons. However, peak shifts and positions can be accurately determined using curve-fitting techniques. Therefore it is important that peak shapes and widths are not influenced by the analyzer. We have chosen a resolution design goal of 50 meV over a kinetic energy range extending up to 50 eV, and also require constant transmission (unity analyzer function) over all kinetic energies up to 200 eV. This requirement ensures that peak shapes and intensities are meaningful. It is important that signal intensity can be increased by reducing the resolution when high resolution is not required. This is necessary to optimize data acquisition under a variety of circumstances. The variable-resolution feature was also adopted as a design requirement.

Spectrometer requirements for Auger analysis and core-level binding energy studies are also well established, although very little work of this type has been conducted with variable photon energies or utilizing movable angle-resolving detectors. Core levels, of course, do not exhibit band-like dispersion, and probing conduction bands at higher photon energies requires cooling of samples in order to maintain $k$-conserving transitions [11]. Although angular resolution may be of limited use at keV energies, energy resolution is very important. Intrinsic core-level linewidths are fairly narrow (less than 1 eV) and important chemical information is available from shifts in core-level binding energies. New synchrotron sources and monochromators now provide good intensity into the 1 keV energy range at energy resolutions of $\sim 200$ meV. This should open up a broad range of new applications of Auger and ESCA techniques.

A final important design consideration is the source size and monochromator focal distance. Most monochromators installed at synchrotron radiation facilities provide exit slit optics which image the beam $\sim 50$ cm from the slit. The corresponding magnification produces a typical slit image $1\text{ mm} \times 2\text{ mm}$ in cross-section, depending on the specific monochromator and its slit setting. Usually, chambers of $14\text{--}18''$ diameter can be accommodated. We have decided to limit our chamber to $18''$ diameter.

The factors summarized in this Section along with figure-of-merit information [12] for various types of energy analyzers led us to adopt a design
concept based on hemispherical energy-dispersing elements* coupled with input and output lens systems which define virtual slits. Similar instruments have been designed, tested and successfully used for electron spectroscopy [14,15]

**KUYATT—SIMPSON ANALYZER**

A cross-sectional view of the energy analyzer adopted is shown in Fig 1. It consists of a nose cone, input and output lenses, Herzog elements (field terminators) and a pair of hemispheres. The source area and the input solid angle of electrons admitted into the analyzer are determined by the (real) apertures $A_1$ and $A_2$ of the nose cone. The lenses $L_1$ and $L_2$ image the source electrons at the entrance to the dispersing part of the analyzer, which consists of two concentric hemispheres and Herzog elements. The output lenses $L_3$ and $L_4$ focus the analyzed electrons emerging from the spheres at the (real) aperture $A_3$ which admits electrons to the channeltron detector.

*Properties of spherical deflection-analyzers have been covered by several authors. Suggested references are listed as ref 13 here.*
Spherical capacitor

The heart of the analyzer is a capacitor consisting of charged hemispheres with inner radius $R_1$ and outer radius $R_2$ [13]. An electron which is accelerated from rest to a kinetic energy $eV_0$ and enters the capacitor at its mean radius $R_0 = (R_1 + R_2)/2$ will be deflected through 180° as it travels along the arc defined by $R_0$ provided the path is an equipotential $V_0$. This requires that the inner sphere be held at the potential $V_0[(2R_0/R_1) - 1]$ and the outer sphere be held at the potential $V_0[(2R_0/R_2) - 1]$. An electron having initial kinetic energy $E$ must be retarded by a potential

$$V = - E$$

in order to pass through the analyzer along $R_0$. The corresponding potentials of the inner and outer hemispheres are

$$V_{\text{inner}} = V_0[(2R_0/R_1) - 1] - E$$
$$V_{\text{outer}} = V_0[(2R_0/R_2) - 1] - E$$

(2)

If the kinetic energy of electrons deflected through 180° along $R_0$ is $eV_0$ electronvolts (pass energy of the analyzer), the potential difference between the spheres is

$$\Delta V = V_0 \left( \frac{R_2}{R_1} - \frac{R_1}{R_2} \right)$$

(3)

An electron with energy $E \approx E_0$ entering the hemispheres at a distance $X_1$ from $R_0$ and at an angle $\alpha_0$ with respect to the axis perpendicular to the midplane of the hemispheres will be deflected through 180° and leave the hemispheres at the conjugate point at a distance $X_2$ from $R_0$, given by

$$\frac{X_2}{R_0} = - \frac{X_1}{R_0} + \frac{2\delta E}{E_0} + 2\alpha_0^2$$

(4)

where $\delta E = E - E_0$. The displacement $X_2$, therefore, depends on $\alpha_0$ only to second order, i.e., the spherical capacitor exhibits first-order focusing.

The trajectory of electrons traveling between the spheres can be expressed in terms of an angular displacement $X(\phi)$ from the central radius $R_0$. For an electron entering the spheres with energy $E_0$ (the pass energy) at a distance $X_1$ from $R_0$ and at an angle $\alpha_0$ as defined previously, the displacement is [13]

$$X(\phi)/R_0 = [\alpha_0 \sin \phi + (X_1/R_0) \cos \phi] + [\alpha_0 \sin \phi + (X_1/R_0) \cos \phi]^2$$
$$+ \alpha_0^2 (\cos \phi - 1) - (X_1/R_0)^2$$

(5)

An electron which enters parallel to the central trajectory ($\alpha_0 = 0$, $\phi = 0$) at a distance $X_1$ from it follows a path which crosses the central trajectory at $\phi = \pi/2$ and emerges (ignoring second-order terms) at $X_2 = -X_1$. 
The energy resolution $\Delta E_{1/2}/E_0$ is obtained by calculating the transmission of electrons as a function of energy, taking into account the distribution of the incident electrons over space and angle. Assuming equal entrance and exit slit widths $W_0$ and a uniform intensity distribution over the slit area, a triangular energy distribution function is obtained with full width at half-maximum given by

$$\Delta E_{1/2}/E_0 = \left( W_0/2R_0 \right) + \text{(terms in } \alpha_0^2 \text{)} \tag{6}$$

The angular contribution to the energy half-width is negligible (less than 10%) as long as $\alpha_0^2 \ll W_0/2R_0$. A conservative choice is

$$\alpha_0^2 < W_0/4R_0 \tag{7}$$

An important parameter for the spherical capacitor is related to the "filling factor" of the spheres. To avoid overfilling the gap between the hemispheres, the deviation of electrons from the central path (eqn (5)) must be considered in relation to the energy resolution and capacitor geometry. The maximum deviation $X_m$ can be written [17]

$$\frac{X_m}{R_0} = \frac{\delta E}{E_0} + \left[ \alpha_0^2 + \left( \frac{W_0}{2R_0} + \frac{\delta E}{E_0} \right)^2 \right]^{1/2} \tag{8}$$

In practical cases, $\delta E/E_0 \ll 1$, $W/2R_0 \ll 1$ and $\left( (W/2R_0) + (\delta E/E_0) \right)^2 \ll \alpha_0^2$, so that eqn (8) becomes

$$X_m/R_0 \approx (\delta E/E_0) + \alpha_0 \tag{9}$$

This equation implies that the maximum beam width divided by the mean radius is approximately equal to $\delta E/E_0$ plus an angular term. These two terms, of course, are related to the beam profile at the capacitor entrance. By choosing suitable margins for these parameters an equation may be obtained which yields a maximum value for $\Delta E_{1/2}$ in terms of $E_0$ and geometrical parameters. Reasonable choices are 20% margin for $X_m/R_0$ (0.8 $X_m/R_0$), a 20% margin for the beam entering the analyzer (1.25 $\Delta E_{1/2}/E_0$), and a 0% margin for conservatively chosen $\alpha_0$, $\alpha_{\text{max}} = W_0/4R_0 = \frac{1}{2} (\Delta E_{1/2}/E_0)$.

Using these restrictions and the analyzer parameters $R_1 = 2.5$ cm and $R_2 = 3.5$ cm, eqn (9) yields the condition

$$0.133 = 1.25 \Delta E_{1/2}/E_0 + \sqrt{\frac{1}{2} \Delta E_{1/2}/E_0}$$

Solving this equation for $\Delta E_{1/2}/E_0$ yields the constraint $\Delta E_{1/2}/E_0 \leq 0.0218$, or

$$E_0 \geq 45 \Delta E_{1/2} \tag{10}$$

**Input lens system**

The spherical capacitor can be operated in two distinct modes to measure electron kinetic energy. In one mode, the difference voltage $\Delta V$ applied to
the spheres is changed and the kinetic energy $E$ of the transmitted electrons is given by eqns (2) and (3) Equation (6) gives the energy resolution $\Delta E_{1/2}/E$ which depends on $E$. By slowing the incoming electrons from kinetic energy $E$ to a fixed pass energy $E_0 < E$, the resolution is increased to $\Delta E_{1/2}/E_0$ and is independent of $E$ as long as the slit width $W_0$ is maintained constant. The analyzer slits may be real (mechanical slits) or virtual (produced by an input lens system). One advantage of a virtual slit system is that the resolution, which is determined by the slit width and pass energy, can be adjusted electronically.

The analyzer chosen here employs virtual slits. Before entering the spherical capacitor, the electrons pass through a system of apertures and cylindrical electrostatic lenses. The behavior of an electron beam passing through a lens system is described by the Helmholtz—Lagrange law [16]. If $A$ is the area of the beam at some cross-section, $\Omega$ its solid-angular divergence, and $E$ its energy, then at any two points along the beam,

$$A_0 \Omega_0 E_0 = A \Omega E$$

(11)

or

$$W_0 \alpha_0 \sqrt{E_0} = W \alpha \sqrt{E}$$

(11, one-dimensional form)

The beam magnification between the sample and the virtual slit can be defined by

$$M = \frac{W_0}{W} = \sqrt{\frac{E}{E_0}} \left( \frac{\alpha}{\alpha_0} \right)$$

(12)

where the subscript 0 denotes parameters at the virtual slit.

The Helmholtz—Lagrange law places constraints on how electrons entering the nose cone from source area $A$ with energy $E$ and angle $\Omega$ can be imaged at the spherical-capacitor entrance after being decelerated to $E_0$, the analyzer pass energy. To maintain a given resolution $\Delta E_{1/2}/E_0$, the virtual slit width $W_0$ is constrained by eqn (6) and the entrance angle $\alpha_0$ by eqn (7). Equations (6) and (11) yield

$$M \leq \frac{(2R_0/W)(\Delta E_{1/2}/E_0)}{(\Delta E_{1/2}/E_0)}$$

(13)

Equations (7) and (11) yield

$$M \geq \sqrt{\frac{2E}{\Delta E_{1/2}}} \alpha$$

(14)

Equations (13) and (14) restrict $M$. An additional restriction resulting from the condition that the spheres not be overfilled is given by eqn (10).

Equations (10), (13), and (14) along with the sphere radius and input lens apertures determine the analyzer performance for a given slit width $W_0$ and pass energy $E_0$. Constant solid angle and source area result from the nose cone apertures. Constant energy-resolution is realized provided that the input optics achieve a fixed virtual slit width as the sphere potentials given by eqn (2) are ramped to sweep kinetic energy. Constant transmission
(unity instrument function) is achieved as long as the lenses and spheres are not overfilled and the final aperture $A_3$ admits only electrons which are deflected through $180^\circ$ and come from the output virtual slit of the capacitor.

The present nose cone geometry given in Fig 1 yields $W = 0.15$ cm and $\alpha = 1.35^\circ$. From eqn (10) we can choose $E_0 = 45\Delta E_{1/2}$. Equation (13) then yields $M < 0.88$. If we choose $M = 0.88$, eqn (14) can be used to determine the maximum kinetic energy (maximum retardation) permitted for a fixed pass energy (resolution). Table 1 has been generated for $M = 0.88$ and the geometrical parameters of the present analyzer.

Corresponding tables can be generated for other nose cone geometries (different source area and angular resolution) using the procedure just outlined. For electron-excited Auger work, the electron spot size will typically be less than 0.15 cm, and this will result in a smaller virtual slit image. This will yield resolution better than that given in the table.

**COMPUTER ANALYSIS**

*Input lens voltage optimization*

A fixed slit width $W_0$ is required to maintain a prescribed energy resolution when the spherical analyzer is operated in a fixed-pass-energy mode. In the previous Section it was shown that although the Helmholtz–Lagrange equation places restrictions on the deceleration and focusing of electrons from the source to the analyzer entrance slit, the resolution formulas for the spherical analyzer permit a reasonable variation of the input angle. Table 1 shows the approximate maximum kinetic energy accessible without violating the resolution conditions or the Helmholtz–Lagrange law for $E_0 / \Delta E_{1/2} = 45$ and the present analyzer geometry. For the parameters given in Table 1, the

**TABLE 1**

OPERATING CHARACTERISTICS FOR ANALYZER WITH $M = 0.88$ (see eqn (12))

<table>
<thead>
<tr>
<th>Analyzer pass energy, $E_0$ (eV)</th>
<th>Approximate resolution, $\Delta E$ (meV)</th>
<th>Approximate maximum KE, $E$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
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<td>200</td>
<td>160</td>
</tr>
<tr>
<td>16</td>
<td>400</td>
<td>320</td>
</tr>
<tr>
<td>32</td>
<td>800</td>
<td>640</td>
</tr>
<tr>
<td>64</td>
<td>1600</td>
<td>1280</td>
</tr>
</tbody>
</table>
analyzer should achieve constant resolution and unity transmission function for the prescribed entrance solid angle and source area. The main problem is to solve for the input lens voltages required to image properly the electrons admitted to the analyzer at the capacitor entrance as the potentials of the hemispheres and Herzog elements are swept according to eqns (1)-(3).

Computer optimization was used to obtain operating voltages for the input lens system. The optimizing program, COMOPT, was developed at the National Bureau of Standards (NBS) by C. E. Kuyatt, for the design of cylindrical-geometry electron optics in electron analyzers and monochromators [17]. The program incorporates a least-squares algorithm with matrix-optics subroutines. The user must define the length of the system (target to hemisphere-plane), the number of lenses desired, and the positions and diameters of beam-defining apertures. From this information the program can determine the combination of lens positions, diameters, and voltages to achieve prescribed virtual slit conditions which determine the analyzer resolution. The modular nature of the program permits flexibility in operation. For example, an existing lens geometry can be input and the program used to optimize the lens voltages to achieve a prescribed analyzer resolution.

A very brief overview of the NBS computer code as implemented on our computer is given in Appendix I of this paper. Additional documentation is available in unpublished reports [18], and from NBS [17]. Detailed descriptions are beyond the scope of this paper.

A set of lens voltages which produce a prescribed analyzer resolution as a function of transmitted electron kinetic energy represents an operating mode of the analyzer. One such operating mode which has been tested (both analytically and experimentally, as described below) is given in Table 2 and Fig. 2. This mode corresponds to a fixed energy-resolution of ~50 meV for initial kinetic energies up to 40 eV. Corresponding voltages for the Herzog elements and hemispheres are given by eqns (1)-(3). The output lens voltages (determined using ray-tracing techniques described below) were held fixed at 10 V and 750 V.

In the early stages of the lens optimization process, we calculated the image properties of the lens system for a fixed kinetic energy over a wide range of input lens voltages. A contour plot of the corresponding analyzer resolution as a function of the two lens voltages was then made. This plot was used to investigate possible solutions to the optimization problem and to choose a likely starting point for the iterative optimization process. These plots also gave insight into the effect of variation of lens voltages on analyzer performance.

**Ray-tracing studies of operating modes**

After we had obtained a set of lens voltages, we wished to corroborate the results of the optimization process. We wanted to know whether the beam
### TABLE 2
OPERATING VOLTAGES GIVEN IN FIG 2

<table>
<thead>
<tr>
<th>Electron energy (eV)</th>
<th>First lens voltage (V)</th>
<th>Second lens voltage (V)</th>
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</thead>
<tbody>
<tr>
<td>10</td>
<td>8833</td>
<td>16568</td>
</tr>
<tr>
<td>20</td>
<td>16146</td>
<td>18342</td>
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<tr>
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Fig 2 Plot of input lens voltages producing a prescribed analyzer resolution, as a function of transmitted electron kinetic energy, operating mode generated by computer program COMOPT [17] for fixed energy-resolution $\Delta E \approx 50 \text{ meV}$ and $M = 0.88$

would overfill the lens system and whether the beam would have the desired width at the analyzer entrance To answer these questions, we used an electron trajectory program, SLERT, written by W B Herrmannsfeldt at the Stanford Linear Accelerator Center [19] The program divides an axial plane of the cylindrical lens system into a square mesh and finds the potential at each of the mesh points The program then plots equipotential lines and traces several rays through the system

Some typical results are shown in Fig. 3 This plot shows trajectories for 20-eV electrons in an axial plane of the system from the second aperture to the analyzer entrance Beam plots for other energies differ in $\alpha_0$ and in the position of the crossover point, which moves nearer the entrance to the capacitor as the electrons' initial kinetic energy increases In all plots the electron beam stayed within the lens boundaries, was focused to the proper diameter at the analyzer entrance, and satisfied eqn (7)

Ray-tracing analysis of output lens system

Electron trajectory plots were also used to determine operating voltages for the electron optics between the Herzog element at the spherical-capacitor exit and the final aperture in front of the channeltron. The final aperture $A_3$ helps to mask the channeltron from electrons emerging from the capacitor at
Fig. 3 Results of ray-tracing study for 20-eV electrons in an axial plane of the system from the second aperture to the analyzer entrance, trajectories generated by computer program SLERT [19] for operating mode described in Fig. 2

the wrong kinetic energy, or from outside the output virtual slit. The output lens system functions to focus the virtual exit slit at $A_3$. Clearly, some unwanted electrons which scatter inside the spheres will appear at the exit slit image and will contribute an unavoidable background, but the output lens system and aperture $A_3$ minimize this effect. Trial and error led to the final values of 10 V for the first lens and 750 V for the second.

Construction details and geometrical parameters

The spherical analyzer described in this paper is constructed of molybdenum, a metal which is mechanically stable, non-magnetic, and has a uniform contact potential*. The analyzer's spheres are 2.5 and 3.5 cm in radius. The input optics system has a diameter of 1.0 cm and is 12.155 cm long. The diameter-to-spacing ratio of all lenses is 10. The first 7.155 cm of the nose cone is a field-free drift tube with an aperture at each end. The first aperture is 0.14 cm and the second aperture 0.43 cm in diameter. When the sample is placed 2.0 cm from the analyzer tip, the apertures define an acceptance half-angle of 1.35° (solid angle of 0.0017 steradians). The analyzer admits electrons from a sample area 0.14 cm in diameter. The shape of the nose cone allows it to be positioned within 8° of an incident photon beam. Both the nose cone tip and the second aperture are removable, allowing changes in angular resolution and sample spot size.

Test of analyzer performance

We tested the analyzer's performance by recording a UPS spectrum of a...
nickel (100) surface at normal emission, using a helium resonance lamp as the light source. Nickel produces a sharp Fermi edge because of the high density of d-states at the Fermi level, and the (100) face exhibits a feature at the Fermi level with a binding energy of less than 100 meV [8]. This is a good sample with which to check analyzer energy resolution. As a standard for comparison, we also recorded a normal-emission spectrum using a commercial twin-pass angle-resolving spectrometer in order to obtain an idea of the relative transmission efficiency of the two analyzers.

Eventually the present electron analyzer will be operated by a minicomputer, i.e., the nonlinear lens voltages will be programmed from a table stored in memory or generated from a polynomial fit to analytical functions. For the tests described here, it was necessary to make linear approximations to the lens voltages given by Table 2 and Fig. 2. The spectrum was recorded over a 5 eV range around kinetic energies corresponding to the Fermi energy of Ni(100), and in this range (12–17 eV) the linear approximation proved satisfactory.

Figure 4 shows a normal-emission spectrum of Ni(100) obtained using the present spherical analyzer at $\hbar \omega = 21.22$ eV. The count rate at the d-band
peak was \( \sim 2000 \) counts s\(^{-1}\). The angular resolution for this spectrum was \( \pm 1.3^\circ \), the source area was \( \sim 1.4 \) mm in diameter, and the energy resolution was \( \sim 100 \) meV.

For comparison, a spectrum obtained using a twin-pass Physical Electronics cylindrical mirror analyzer (CMA) (Model 255-GAR) is shown as an inset to Fig 4. The only difference in geometry is the incidence angle of the radiation, which is discussed below. For this spectrum the CMA was operated with an angular resolution \( \Delta \Omega = 4^\circ \) and a pass energy of 10 V, which yielded a resolution of \( \sim 100 \) meV. The count rate for the CMA spectrum was \( \sim 2500 \) counts s\(^{-1}\). Thus the count rate of the spherical analyzer compares quite favorably with that of the CMA, especially when differences of target geometry are considered, i.e., the entrance solid angles and source sizes for the two analyzers. The background count rates for both analyzers were \( \sim 1 \) count s\(^{-1}\); this is a typical "dark count" rate for channeltron detectors.

The different geometries of the CMA and the spherical analyzer require different target alignments. When the CMA was used, the chamber geometry required a \( 33^\circ \) angle between the fixed light source and the surface normal. The beam of diameter 2 mm projects onto the sample an oval 3.75 mm\(^2\) in area. When the spherical analyzer was used, a \( 60^\circ \) angle was necessary between the light and the surface normal, and the light was projected onto an area of 6.28 mm\(^2\). The intensity of the light is thus much diminished in the case of the spherical analyzer. The CMA has internal apertures 4 mm in diameter, which allows it to sample the entire source region. The spherical analyzer, on the other hand, samples 1.54 mm\(^2\) of the surface, just one-fourth of the illuminated surface. The CMA has an entrance half-angle of 2\(^\circ\), whereas the spherical analyzer's entrance half-angle is 1.34\(^\circ\). This means that the spherical analyzer has an entrance solid angle just 45% of that of the CMA. When this is combined with the fraction of the target sampled, it is found that the CMA admits nine times as many electrons as does the spherical analyzer, yet the CMA records only 25% more counts per second than the spherical analyzer. (The loss of intensity is due primarily to the presence of six grids in the CMA.)

The spherical-analyzer spectrum shown in Fig 4 has the same features (labeled A, B, and C) which appear in the CMA spectrum and in spectra reported in the literature \([8, 20, 21]\). Fairly large variations in input and output lens voltages could be made without producing changes in the count rate at fixed kinetic energy. This result suggests that all the voltages are nearly optimized and that the fill factors for the lenses and hemispheres are conservative. It was also found that the second output lens voltage could be decreased from 750 V to 500 V without affecting the count rate.
SUMMARY

We have presented design considerations, analysis, construction details and tests of an electron energy analyzer developed for use with synchrotron radiation. Source parameters were chosen based on typical output optics characteristic of existing synchrotron facility monochromators. Initial tests indicate that design goals (small size, high angular and energy resolution, and constant transmission) have been achieved. We plan to report additional operating voltages, ray-tracing results, and subsequent tests of this analyzer when other operating modes have been analyzed and tested.

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APPENDIX I BRIEF DESCRIPTION OF COMPUTER CODE COMOPT

The optimization of the present analyzer input lens system consists of finding a combination of lens positions, diameters, and voltages which properly image the electron beam at the hemisphere midplane. The program COMOPT uses a least-squares minimization routine to adjust selected lens parameters to produce an image (representing a virtual slit) which yields a prescribed analyzer resolution.

Electron lenses, similarly to their optical analogs, can be described by two-by-two matrices. The subroutine LENS calculates the matrix elements by interpolating from a table on file MATRIX. The lens matrices are used to trace several rays from the entrance apertures through the lens system to the analyzer entrance. The beam's maximum angle of inclination and displacement from the axis are used to characterize the virtual slit and to calculate the corresponding analyzer energy resolution. This calculated resolution is subtracted from the desired resolution in subroutine FCODE yielding a parameter called the residual. The square of the residual is the function minimized by the least-squares routine NL1N4. Every time NL1N4 adjusts the lens parameters, it calls LENS and FCODE to compare the new residual with that from the previous iteration. This process continues until the residual is
minimized and the lens parameters converge. The program then prints out
the results of each iteration with the focal lengths and other optical charac-
teristics of the optimized lens system.

Inquiries about COMOPT and its operation may be directed to the authors
of this paper.

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