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DESIGN OF A MAGNETIC SPECTROMETER FOR PHOTOELECTRON SPECTROSCOPY*

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ABSTRACT

We present the results of a computer design study for an iron-free double-focusing magnetic spectrometer specifically intended for photoelectron spectroscopy. With single detector operation the proposed design is more efficient than any existing magnetic double-focusing spectrometer, and the focal-plane characteristics allow more than a 100-fold increase in data accumulation rate with a multichannel detector. This design also has very high physical accessibility near the source and detector areas and it is compatible with either normal or ultra-high vacuum operation.

*This work performed under the auspices of the U. S. Atomic Energy Commission.

Precise energy analysis of photoelectrons expelled by x-rays¹⁻³ and ultraviolet radiation^{4,5} has been used extensively in the last few years to obtain fundamental information about organic and inorganic solids and gases. In an instrument designed specifically for photoelectron spectroscopy a number of primary features are desirable. The most important of these are: 1) high energy resolution (approximately 1 part in 10^4) for electron energies in the range 1 to 2000 eV, 2) high overall electron collection efficiency, as defined by the fraction of electrons leaving the source which can be energy-analyzed and detected simultaneously, 3) unrestricted physical access to the source and detector areas, so as to be compatible with a variety of sample arrangements (heated or cooled solids, gases, reaction chambers, etc.) and radiation sources (e.g., x-ray or UV) as well as complicated detector systems, 4) possibility of ultrahigh vacuum operation in the source area for control of surface conditions in work with solids and 5) relative simplicity of construction. We have carried out a computer design study of an iron-free double-focusing magnetic spectrometer in which the above features were considered as design objectives.^{6,7} Previous experience has shown that, with careful construction, such studies provide results that agree excellently with experimental performance.^{8,9}

Energy analysis in such a double-focusing spectrometer is accomplished by magnetically deflecting the electrons in roughly circular orbits centered on the symmetry axis of a cylindrically symmetric field. This magnetic field, which decreases approximately as $1/\sqrt{r}$ near the optic circle of the instrument, has the property that electrons with both axial

and radial departure angles are focused to first order at the same distance around the optic circle (corresponding to $\pi\sqrt{2}$ radians $\approx 254^\circ$). We treat here the "high aperture" field wherein axial departure angles can be larger than radial departure angles (a higher-order focusing property).⁷ A further property of the high-aperture field is that it possesses a focal plane^{8,10}; that is, electrons of different energies are brought to a focus at different radii along a plane at $\pi\sqrt{2}$. Therefore, more than one energy (channel) can be detected at a time without significant loss of resolution and the overall collection efficiency thereby increased. Due to detector limitations it has only been practical in the past to exploit the focal plane properties of double-focusing electron spectrometers to the extent of 4-5 channel detection.³ However, we anticipate the development of detector arrays with the order of several hundred channels in the near future.¹¹

The basic design problem is to find a set of cylindrically symmetric coils which reproduces the chosen theoretical field with sufficient accuracy over the region occupied by the electron orbits to give the desired focusing properties.¹² We note several features of this work that differ significantly from previous design studies: 1) the theoretical "optimum" field¹⁰ was fitted over a region corresponding to much higher axial departure angles, in order to achieve a larger usable solid angle, 2) so as to permit good access to source and detector areas, the location of all coils was constrained to be entirely inside (i.e., at smaller radius than) the vacuum chamber housing the electron orbits, and 3) the focal plane properties of several theoretical fields, existing spectrometers, and our own design were studied in detail to determine relative overall collection efficiencies with multichannel detection.

The coil geometry of a typical design case, shown in Fig. 1(a), consists of one main coil with four pairs of smaller coils wound on it.⁶ Coil dimensions are consistent with integral numbers of turns of fixed diameter wire, and all coils are in series so that only one power supply is needed. With the choice of 30 cm for the optic circle radius the height of the main coil is approximately 200 cm and its outer radius is 20 cm. Our calculations indicate that coil winding and positioning need only be done to reasonable tolerances (± 0.025 cm). For operation at energies up to 2000 eV, no cooling of the coils should be required. An important feature of this design is that vacuum chambers can be easily interchanged for different types of experiments.

The electron optical properties of this design have been calculated in terms of contours of equal focusing aberration of monoenergetic electrons in the plane of radial and axial departure angles.⁷ The optimum field exhibits only negative aberration (electrons at angle $\pi\sqrt{2}$ fall at smaller radius than the optic circle radius), but in most real designs the effective solid angle is determined by how high a vertical departure angle one can use before unacceptably high positive aberrations are encountered. Our design case has a vertical acceptance window for operation at 0.02% energy resolution of approximately ± 17 degrees, compared to ± 22 degrees for the theoretical optimum field, ± 14 degrees for the $1/\sqrt{r}$ field, ± 9 degrees for the Chalk River spectrometer (four pairs of coils),⁸ and ± 3 degrees for a recent Uppsala spectrometer (two pairs of coils).⁹

In the single channel mode of operation (detection of one narrow electron energy interval at a time) the relative collection efficiency of

a spectrometer is proportional to the fractional solid angle into which electrons can be emitted without exceeding the desired resolution because of focusing aberrations. This solid angle is in practice controlled by baffles. In Fig. 1(b) we show resolution-fractional solid angle curves for the two primary theoretical fields, the two previously mentioned spectrometers, and for our design case. The present design approaches theoretical optimum performance much more closely than the existing spectrometers, and is better in performance than the $1/\sqrt{r}$ field.

We have also studied the focal plane behavior of the cases in Fig. 1(b). In general, it is found that as the range of energies analyzed increases (that is, as the radial width of the detector increases), it is necessary to decrease the vertical acceptance angle of the common electron baffle to avoid introducing significant line broadening at the edges of the detector. The radial acceptance angle of the baffle, on the other hand, can be kept roughly constant. Furthermore, the distance of the baffle from the electron source must be decreased as the range of energies is increased in order to accurately discriminate all particles on the basis of departure angles. Where comparison is possible with previous focal plane studies,^{8,9} the agreement is good.

The overall collection efficiency for multichannel operation will be proportional to the fractional solid angle times the number of channels in the detector. A channel width is defined to be the width of the image of a monoenergetic beam of electrons on the optic circle at $\pi\sqrt{2}$. Efficiency estimates were made on the basis of a multichannel detector centered on the optic circle. In Fig. 2 we plot the relative overall collection

efficiencies of the design cases of Fig. 1, for 0.02% energy resolution, as a function of detector width (expressed as ΔE = detection bandwidth in % of mean energy). From these curves it is clear that data accumulation rates can be increased by at least two orders of magnitude if multichannel detection is fully exploited. Our design case is essentially equivalent to theoretical optimum, and is approximately twice as efficient as the Chalk River spectrometer⁸ up to $\Delta E \approx 8\%$. It also represents a marked improvement over the Uppsala spectrometer,⁹ especially for $\Delta E > \sim 4\%$. We also note that for multichannel operation at $\Delta E > \sim 2\%$, the $1/\sqrt{r}$ field gives superior performance to the theoretical optimum field; this behavior was qualitatively predicted by Lee-Whiting.¹⁰

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FIGURE CAPTIONS

Fig. 1. (a) Coil geometry for the proposed spectrometer design. Only one quadrant of cross section is shown.

(b) Fractional solid angle of acceptance plotted against resolution for various theoretical fields and spectrometers. (Single channel detection.)

Fig. 2. Relative collection efficiency for multichannel detection at 0.02% energy resolution plotted against width of detector array in % of mean kinetic energy. All values divided by the theoretical optimum efficiency for single channel detection.

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Fig. 1

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Fig. 2

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