Angle- and energy-resolved charged particle spectroscopies—a simple way

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The acquisition of angular and energy distribution information is of growing importance in a number of charged particle spectroscopies used for surface studies. A simple, inexpensive method is outlined for obtaining a visual display of angular distributions containing energy distribution information in the form of color. In essence, a detector optical bandpass is varied synchronously with an energy-selecting element of a spectrometer having a visual display in order to convert the analyzed particle energy distribution to a corresponding chromatic map. The primary utility of the method would be to obtain qualitative information rapidly in those cases where the particle energy spectra have distinct and strong features or when features of interest lie at the higher-energy end. Examples of the latter are plasma loss structure in low-energy electron diffraction, electron-stimulated desorption ion angular distributions, and the higher-energy structure in ultraviolet photoelectron spectroscopy. Other applications are also considered. The practical sensitivity limit for the case of visual observation is 1.0% $[I(\Delta E)/I_{\text{total}}]$. This sensitivity is not sufficient for application of the method to Auger electron spectroscopy or electron spectroscopy for chemical analysis.

INTRODUCTION

The demand for improved geometrical and electronic characterization of solid surfaces has led to the evolution of surface spectroscopies that require the measurement of both the energy and angular distributions of charged particles. Interest in both types of data is apparent in several charged particle spectroscopies, including elastic and inelastic low-energy electron diffraction (LEED, ILEED),[1] Auger electron spectroscopy (AES),[2] photoelectron spectroscopies (XPS, UPS),[3,4] electron-stimulated desorption ion angular distributions (ESDIAD),[5] and field-ion microscopy (FIM).[6] A gridded display device is suitable for measurements of the angular distributions of particles with energies greater than a given pass energy, and, using retarding-potential difference (RPD) methods,[7] can be used for measurements of angle-averaged energy distributions. Energy-analyzed angular distributions may be obtained by combining the RPD method with either a movable Faraday cup or a scanning optical technique.[4,8,9] The disadvantage of such serial data collection methods is that signal-to-noise limitations make collection a long process relative to the available times for clean surface experiments. Furthermore, the data have to be reconstructed later into a usable form and are not especially suitable for obtaining rapid characterization of the surface or a qualitative overview of the most interesting features for further study.

A form of parallel output, the observation of the angular distribution of a differential energy window in real time, would be useful both for obtaining a feel for the parameter space and for discriminating between competitive theoretical structures, e.g., in ultraviolet photoelectron spectroscopy (UPS).[10,11] A device capable of parallel output and real-time operation is the subject of this article.

The device to be described is intended for use with display devices, representative of which one can consider a LEED display. The typical LEED display consists of two or more concentric wire mesh grids and an outer concentric fluorescent screen. The grids form a high-pass energy filter and are also the point of modulation for the RPD technique, when used. Similar display devices have been utilized for ESDIAD[5] and UPS[4] employing channel-plate intensification. The standard field-ion microscope consists of an intensified display but has no energy-selecting elements. Application to FIM will be considered below.

The problem of obtaining whole-screen, nonscanned images of a differential slice of an energy distribution can be solved by fairly conventional methods, for example, the subtraction of photographic images of the transmitted-particle angular distributions for two closely spaced analyzer pass energies. A method which is faster than the above is point-by-point digital subtraction of similar images stored as charge in a vidicon and subsequent display on a cathode ray tube. Both of these methods, although workable, are either cumbersome or expensive. The method to be described, although having a signal-to-noise ratio inferior to the above methods and being qualitative rather than quantitative, can be implemented for very little outlay and provides direct and

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immediate observation of energy-analyzed angular distributions.

THEORY

Using the example of a LEED display, a gridded RPD device consists of a high-pass particle filter set at an energy E_P. A modulation is applied to the energy-selecting grid. Current received at the fluorescent screen is the integral of the distribution $I(E)$ from E_p to E_{max}, the maximum energy of electrons entering the optics. The components of the current, which vary synchronously with the modulation voltage and its harmonics, contain information on $I(E)$ and $d^nI(E)/dE^n$. Electrons of energy greater than E_p form a background signal which decreases the signal-to-noise ratio. Removal of the background is accomplished via synchronous detection of the modulated component.

The method of synchronous detection proposed here is accomplished by translating the energy spectrum into a chromatic map. Current arriving at the detector during one half of the modulation cycle is presented to the observer (or camera) through a color filter located between the eye and the phosphor. Current arriving at the screen during the other half-cycle is viewed through a second filter. The two filters are alternated continuously by being mounted on a rotating apertured disk. The filters are chosen so that, in conjunction with the phosphor response, equal screen current seen through the filters produces a neutral color, one having very low saturation. That is, the filters are complementary. Thus, current associated with electrons of energy larger than E_p is not gated by the modulation voltage and always appears as a neutral display. Electrons of energies within the modulation width at E_p are gated by the modulation and become visible as a color imbalance. The angular distribution of these electrons is therefore observable as a chromatic image.

This mapping can conveniently be understood with the aid of a color cone,[12] which is a simple way to represent the space of visible colors. Such a cone is reproduced in Fig. 1. The visible spectrum is arranged on the circumference of a circle so that diametrically opposite colors are complementary. Radii of the circle represent lines of constant hue. Since the center of the circle is grey, points on each radius are values of saturation. Perceived color is a function of intensity, vanishing at low and high values of illumination. This is represented by constructing an axis normal to the plane of the color circle at its center, and calling this direction intensity. If zero intensity is located below the color circle and very high intensity above, the space of visible color is contained within the double cone illustrated.

Colors produced by the electro-optical device can then be expressed in terms of hue, saturation, and brightness. These colors are constrained to lie on the diameter connecting the two complementary filters, and therefore can only have two values of hue. Brightness depends on the total electron current reaching the screen at each point. Saturation is the parameter of most interest. In terms of the electron energy spectrum, electron currents above E_p increase the overall brightness while decreasing the saturation of the observed color. If $I(E_p)$ is a measure of the current averaged over the modulation width at E_p and I_t is the total screen current, then saturation can be expressed as

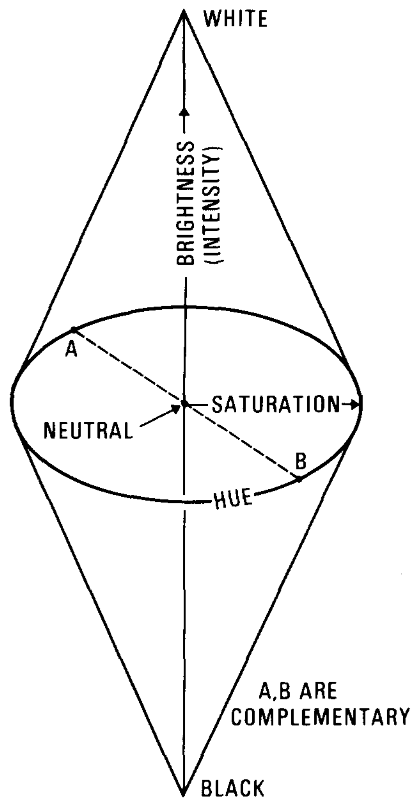

FIG. 1. A conventional representation of color space.

$$S = [I(E_p)/I_t]F(I_t),$$

where $F(I_t)$ relates the perceived saturation to the intensity and is adjusted so that maximal saturation (pure spectral color) is given the value 1 or 100%, and minimum saturation the value 0. One can then define the sensitivity of the technique, or the minimum detectable signal, to correspond to the minimum distinguishable difference in a color stimulus as generated by the device. Since the primary concern at present is with visual observation, one can use Weber's law,[13] which states that for medium values of a stimulus A,

$$\Delta A/A = k$$

if ΔA is the minimum detectable difference. For brightness, $k = 1/62$.[14] For saturation, k is a function of wavelength[15,16] and varies between approximately 1/10 and 1/100. There is a strong minimum in sensitivity (maximum in k) between 5500 (green) and 6000 Å (yellow). The minimum saturation detectable is therefore about 1% (near the red or blue). It should be noted that hue becomes a variable, for mixed noncomplementary colors, and that the minimum detectable difference in hue is about 20 Å,[17] so that a comparable k value exists for an experiment done this way.

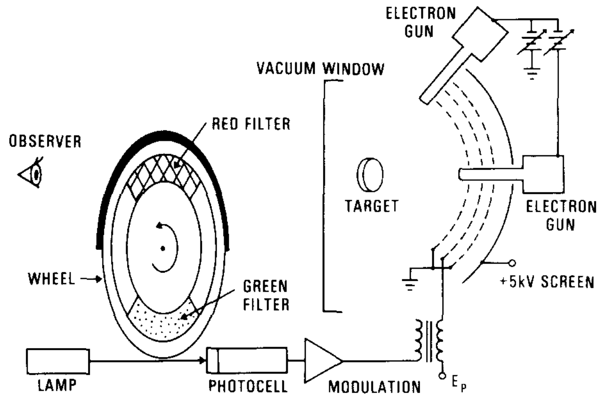

FIG. 2. Apparatus used in a preliminary experiment to test a filter-wheel energy and angle spectrometer. The observer is interchangeable with a camera.

Thus one could not expect a color translation spectroscopy as described to be of use in XPS or AES where features of interest are a very small fraction of the passed background. On the other hand, in ILEED or ESDIAD or possibly UPS, where strong features can be found or where the higher energy elements of the distribution are of interest, such a technique could be used provided sufficient intensity is available.

APPARATUS

A rudimentary apparatus constructed to test the technique is pictured in Fig. 2. A LEED system was equipped with two electron sources aimed at a metal crystal sample in the usual position. Two guns were used in this test for reasons to be discussed below. The phosphor screen fortuitously had a blue–white response and was left unaltered. The time constant for decay of the fluorescence of the screen is important in that it must be smaller than the modulation frequency. The two complementary color filters are mounted on a chopper wheel. [The filters are red and green (Edmund's 828 Follies Pink and 871 Light Green) plastic sheets having approximately equal total transmission for incandescent light.[18]] A photocell on the chopper provides the synchronization between the modulation and the rotation of the wheel. The frequency of the wheel is controlled by motor voltage and is variable. The upper limit for modulation is controlled by the phosphor response and the lower limit by the critical flicker frequency.[19,20] It should be noted that at lower illumination levels, up to 10^3 times the color threshold of approximately 10^{-2} lux, the critical flicker frequency is a function of color[21] so that the illumination or the frequency have to be raised to avoid artifacts.

Equal areas of filter were used and the total filter sector covered half of the filter wheel. Adjustment of relative areas in order to generate a neutral background may be accomplished by moving opaque paper strips on the wheel, but this was not found to be necessary. An alternative arrangement utilizing two separate optical paths through the two filters, allowing easy balancing of intensities, was designed but not constructed.

The electron beam energies used were in the range of 100–400 eV and beam currents were equal to usual incident LEED currents (1–10 μA). Modulation amplitudes were variable up to 15 V, peak to peak.

Observations were made either by eye or with a camera. Because of the properties of color films used with long exposures at low light levels, a certain amount of experimentation may be required in a particular application to either replicate the visual observation or produce the best color discrimination.

RESULTS

In the first test of the apparatus it was found that the normal LEED image was too dim to yield observable colors, so the crystal was allowed to float electrically and two separate electron beams were totally reflected by the crystal, raising the available intensity at the screen 50–100 times. The two beams of different energy were used to simulate two features of an energy spectrum. Their relative intensities, positions, and energy difference could be changed in a predetermined way. Since the crystal was floating, no change in the incident energy structure was caused by its presence; hence the necessity for two sources. This test, therefore, is not of a LEED system as normally used, but is rather a simulation of the energy spectroscopy problem. Approximately 10 μA were incident on the screen. Modulation voltages and beam energy differences were varied. It was found that, with two distinct monochromatic electron beams in an overlapping spatial arrangement, color differences could be observed for energy differences as small as 0.25 eV when the modulation included the width of one entire beam. These color differences were readily visible and could be photographed.

The list of artifacts which can appear is long, and includes psychological effects and instrumental effects. The perception of color is an exceedingly complex event where interactions between variables such as contrast and spatial frequency as well as those previously mentioned can lead to problems. Among the instrumental effects are magnetic field deflection of images and electrostatic defects in the display system. The seriousness of the artifacts produced would have to be examined in each case.

Aside from such difficulties, the basic observation is that the angular distribution of electrons within the modulation width about E_p is visible as a color image and can be recognized even when parts or all of the image are reduced in saturation by the presence of electron current at higher energies. The limit of sensitivity is 1% of total passed current or greater, and illumination of the display must be relatively high, at least equal to room level ambient. The poor sensitivity implies that the largest utility of the method is for spectra having distinct and few components in energy or angle or both, or for the highest-energy components of more complex spectra, for example, levels near the Fermi edge in UPS, or plasma loss structures in ILEED, or ESDIAD ion peaks.

Because of the necessity for relatively high levels of illumination, implementation in these cases might require time exposures, additional image intensification for visual observation, or higher than normal excitation levels. Despite this drawback, the rate of data acquisition should still be higher than alternative methods.

It should be obvious that a color-translating device is not inherently restricted to retarding grid display devices but can be used in a much wider class of experiments. It can be used when either a phenomenon can be modulated synchronously with the detector, or when the time dependence of a phenomenon is not controllable, but of interest. An example of the former usage would be modulation of the tip voltage in a field-ion microscope at various frequencies to study imaging processes having substantial time constants.[22] In this case, differences between images at different energies would appear in color, and would diminish as the modulation frequency was raised beyond the response time of the process.

When the phenomenon is not reversibly controllable but proceeds at a relatively rapid rate, the device described could be used to strobe the movement of an edge in an image with possibly less confusion than simple (monochrome) strobing. A very low-frequency example can be found in current practice in field-ion microscopy where atomic adsorption or desorption changes are studied in successive color photographs through filters. With a continuously rotating filter wheel, an atom diffusing on a surface could be made visible as a succession of color images on a monochrome background under the proper conditions. There is also some current interest in determining which portions of a mainly static image have changed in order to reduce the bandwidth required to transmit the image, and this device could also be used in this application.

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