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A STUDY OF THE SPATIAL AND ENERGY DISTRIBUTION OF X-RAY PHOTOEMISSION FROM THICK CATHODES

L. G. ELISEENKO, V. N. SHCHEMELEV, and M. A. RUMSH

Leningrad State University

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It is shown that the energy and spatial distribution of x-ray photoemission can be studied by employing a quasispherical analyzer together with a secondary-electron multiplier. The spatial distribution of the x-ray photoemission was determined in this way and found to obey the cosine law both for photoelectrons and Auger electrons. It is concluded from this fact that the thickness of the layer in which the initial non-isotropic distribution is smeared out into a spherically symmetric one is smaller than the thickness of the region of x-ray photoelectron emission. The dependence of the energy distribution of photoemission on the angle α of electron emission is investigated. It was found to be practically the same for values of α between 0 and 60°. It is concluded that the laws describing the energy distribution of x-ray photoemission in a narrow solid angle are also valid for the emission as a whole.

1. STATEMENT OF THE PROBLEM AND METHOD OF MEASUREMENT

THE peculiarity of the elementary act of the x-ray photoeffect consists, as is well known,[1] in the fact that an atom, having absorbed a quantum, emits with some probability in addition to a photoelectron, also another so-called Auger electron. If the direction of emission of a photoelectron is related to the direction of propagation of the absorbed quantum by the Auger-Perrin law,[2] then the emission of the Auger electron in each direction is equally probable.

These assumptions cannot be directly transferred to the external x-ray photoemission of thick cathodes, since we are dealing in this case with a volume phenomenon, and for this reason the process of emission of the Auger and photoelectrons from within the cathode into vacuum may have an appreciable effect on the distribution of the electrons over the emission directions. Therefore the experimental study of the spatial distribution of the photo and Auger electrons in the external emission of a thick cathode is of interest not only for its own sake, but also because it may provide some information about the laws governing the emission, i.e., the laws of propagation of electron fluxes in a solid.

It is quite easy[3] to choose such combinations of the radiation (wavelength λ) and cathode material (atomic number Z) for which the external emission consists practically only of Auger or photoelectrons. Therefore their spatial distributions can be studied separately.

To study the distribution of the emission with respect to the emission angles, we employed the setup shown in Fig. 1, in which a secondary-electron multiplier of the open type,[4] which makes it

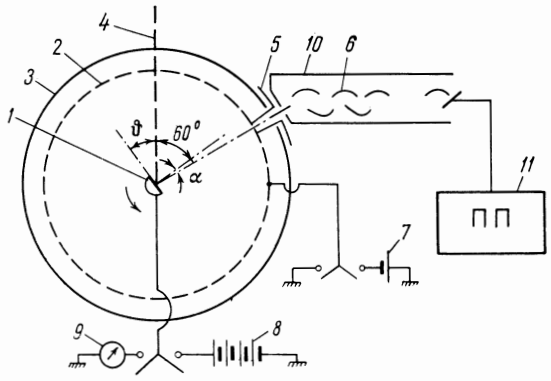

FIG. 1. Schematic diagram of the setup for measuring the spatial and energy distributions of x-ray photoemission: 1—plane 7 × 12 mm photocathode, 2—antidynatron grid, 3—collector, 4—direction of the x rays, 5—electron collimator placed at an angle β of 60 or 10° to the direction of the x-ray beam, 6—secondary-electron multiplier, 7 and 8—sources of retarding voltages, 9—tube electrometer with a sensitivity of 10^{-15} A, 10—secondary electron multiplier screen, 11—counting device.

possible to count individual photoelectrons, is used to measure the emission within a small angle. However, the use of a secondary-electron multiplier makes it difficult to place the detector in different positions with respect to the cathode normal, because of the bulkiness of the secondary-electron multiplier and the complexity of its electrical supply. An experiment employing a secondary-electron multiplier can be readily realized with a turning photocathode and a stationary detector and unchanged direction of the x-ray beam. Here one must bear in mind that the quantum yield of the x-ray photoeffect depends on the angle ϑ between the ray and the surface of the photocathode. This should be a cosecant dependence for the Auger electrons,[5] whereas for the photoelectrons it should be considerably more complicated because of the preferred initial direction. For Z, λ combinations giving a limiting deviation from the cosecant this dependence should to a first approximation[5] be of the form

$$\operatorname{cosec}\vartheta(^3/_4 + {}^3/_8\cos^2\vartheta). \qquad (1)$$

The setup allowed two modes of measurement. In the first mode—the integrated-current mode—the cathode was connected to an electrometer. For a zero or small positive potential of the grid the full current of the emission was measured. On applying increasing negative voltages to the grid, it was possible to obtain "retardation curves" containing information on the energy composition of the entire emission. For sufficiently large ratios of the grid diameter to the cathode dimensions, the plane shape of the cathode does not, as is well known,[6,7] lead to appreciable decrease of the energy resolution of the analyzer. To decrease distortions of the retardation curves of the secondary emission of the grid and the collector, the transparency of the tungsten grid was increased to 90 percent by sintering in the atmosphere and etching with a base. The inner surfaces of the grid and of the collector were covered with soot and the collector was kept at a positive potential of 300 volt relative to the grid (the source of this voltage is not shown in Fig. 1).

In connection with this mode of operation, we must immediately note that it was possible to measure the total current with good accuracy for arbitrary combinations of Z and λ, since the current varied from 10^{-13} to 10^{-11} A, i.e., it was many times larger than the sensitivity of the electrometer (10^{-15} A). On the other hand, the accuracy of the retardation curves was clearly unsatisfactory, since the current loss for sensible changes of the retarding voltage was of the order of 10^{-15} A. The photocurrent and consequently the accuracy of the retardation curves can be increased by resorting to monochromatization by means of filters, with which the intensity of the intensity of the flux increases by several orders compared with monochromatization by means of a crystal. However, an analysis carried out under such conditions makes it only possible to draw conclusions regarding the positions of the maxima of the main electron groups appearing in the photocathode on absorption of the chosen line. The details could hardly be reliable, since the photoeffect will be due not only to the separated line, but to the entire long-wave portion of the bremsstrahlung spectrum and to some portion of the short-wave spectrum which passed through the filter.

In the second mode—the mode of measuring and analyzing the emission in a narrow solid angle—the grid of the setup was grounded, and the cathode was supplied with a retarding voltage from the supply 8 (Fig. 1). The secondary-electron multiplier served to detect electrons which passed through the grid within the solid angle of the collimator. A positive voltage of 350 V was supplied to its housing 10 and the first dynode 6. This is essential for accelerating electrons which passed the grid having small velocities, and consequently for decreasing the probability of their being counted to a negligible value.

Regarding the operation of the quasispherical analyzer applied to analyzing the emission in a narrow solid angle, one must immediately state that it cannot be used with draining cathode-

collector voltage. In fact, in this case, because of the nonsphericity of the field near the photocathode, the entire slow part of the emission will be concentrated into solid angles close to the normal of the photocathode. With retarding voltages the nonsphericity of the field in the region of the cathode will also deflect the electron trajectories from radial straight lines, but towards the plane of the cathode. This will lead to the circumstance that for an arbitrary voltage the secondary-electron multiplier will accept electrons emitted not within the solid angle of the multiplier window, but emitted in some fan of angles displaced towards the normal. However, by decreasing the relative dimensions of the cathode, this fan should decrease and the energy composition of the emission averaged in the process of measurement within this fan of angles should characterize the emission within a narrow solid angle. We proceeded in this work by choosing experimentally such cathode dimensions which ensured practically the absence of the distorting effect of the nonsphericity of the field near the photocathode.

2. EXPERIMENTAL RESULTS AND DISCUSSION

Let us first consider the results which refer to the Auger electrons. To study the spatial and energy distributions of Auger electrons which escaped from the thick cathode into vacuum, we used the combination of an aluminum cathode and $M\alpha$ tungsten radiation. The external emission of this combination consists mainly of Auger electrons which accompany the x-ray photoemission. The experimental setup was employed in the second mode of operation. The emission within a narrow solid angle whose axis made an angle $\alpha = \vartheta + \beta - 90°$ with the normal to the cathode surface was measured by means of a secondary-electron multiplier with a retarding voltage of 250 V which ensured the elimination of secondary electrons.

When the angle ϑ was changed the emission in the given solid angle changed, in the first place, because of the explicit cosine dependence of the total emission on the angle ϑ, and, secondly, it could change because of a possible nonuniform distribution of the emission with respect to the angles α. In order to clarify the nature of the distribution over the emission angles, the emission in a narrow solid angle was measured for various ϑ, and divided by the corresponding values of cosec ϑ; it is presented in Fig. 2 as a function of the angle α. It is seen from Fig. 2 that within experimental error the Auger electrons emitted into the vacuum are distributed according to a cosine law.

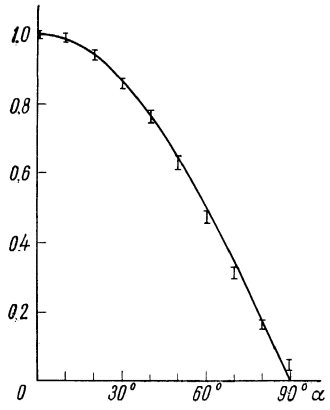

FIG. 2. Dependence of the number of Auger electrons emitted in a narrow solid angle on the angle α (aluminum photocathode and tungsten $M\alpha$ radiation). The experimental data are plotted as vertical lines whose length indicates the probable errors; the solid line corresponds to cos α.

One can readily understand the cosine distribution of the external emission if one considers that in the surface layer the distribution of Auger electrons, both of those produced at points within this layer and of those entering it from within the cathode, is spherically symmetric, i.e., each point of this layer is an isotropic source of electrons. To calculate the emission in the direction of the normal, one must sum the action of the sources located within a volume sl, where S is the area of the emitting surface and l is the free path of the electron without scattering. The electrons emitted in the direction of the normal from sources located at a depth greater than l are scattered and are not registered by the secondary-electron multiplier set up in a given direction. The role of these electrons is reduced to supplying those sources which are located at the points where scattering occurred. Calculation of the emission in a direction which makes an angle α with the normal requires an account of the sources located within a volume $Sl\cos\alpha$, the distance of whose points from the surface in the given direction does not exceed l. The fact that the volume which produces the emission in the direction making an angle α with the normal is proportional to $\cos\alpha$ explains the cosine distribution of the Auger electrons emitted into the vacuum.

Figure 3 shows a typical retardation curve of the emission current on a small section of the grid in front of the window of the secondary-electron multiplier, and Fig. 4 shows the energy composition of the Auger electrons emitted into the vacuum for various emission angles. It is seen from Fig. 4 that the energy composition of the emission for angles α of 60, 40, 20, and 0° is practically the same.

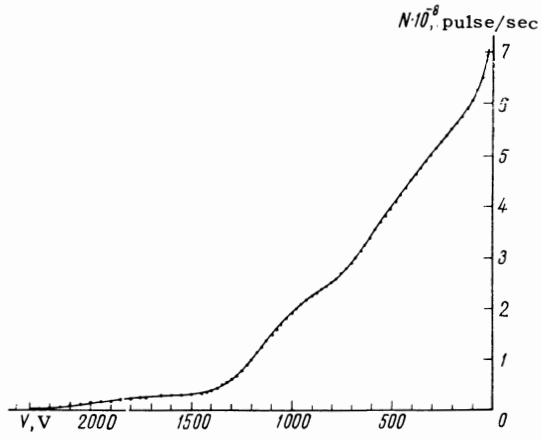

FIG. 3. Retardation curve of the emission current in a narrow solid angle about the normal to the plane of the photocathode for the combination of an aluminum photocathode and molybdenum $L\alpha$ radiation.

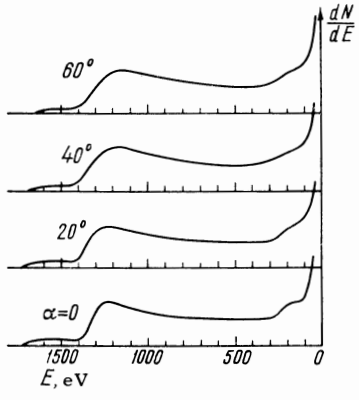

FIG. 4. Energy distribution of the emission of Auger electrons for various angles α at which the emission was detected (aluminum cathode, tungsten $M\alpha$ radiation).

Let us now proceed to consider the photoelectrons, whose distribution at the instant at which they are produced is related to the direction of the x ray by the Auger-Perrin law. In considering the points of the surface layer of the same thickness l, one can in this instance also liken them to sources of electrons which are emitted into the vacuum without scattering. However, in the case of photoelectrons one must not assume the strength of these sources to be isotropic. Here one must divide the source strength at least into two parts. One part is produced because of the photoeffect within the layer; in passing through this layer the electron fluxes conserve to some extent their Auger-Perrin directions which they possessed at the instant at which they were produced. This part of the source strength will be anisotropic and will be given by a smeared Auger-Perrin distribution. The second part of the source strength will be produced because of the photoeffect in deeper regions of the cathode, whence the photoelectrons

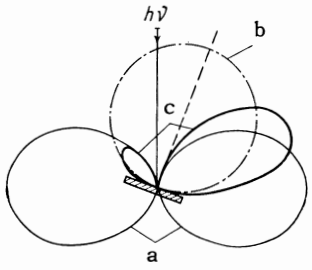

FIG. 5. Diagram of a possible spatial distribution of the x-ray photoelectrons.

will arrive in the layer adjoining the surface after undergoing en route so many collisions that their initial directions will be completely lost.

Depths which will ensure a full loss of the original directions correspond to a transition from the propagation of electron fluxes in a solid corresponding to their initial velocity to diffuse propagation. Therefore the second part of the source strength is due to the photoeffect at depths which exceed the depth of establishment of diffusion. This part of the source strength should, of course, be isotropic. If the depth of the diffusion is much less than the depth of generation of the x-ray photoeffect, then the second part of the source strength determines the phenomenon. The distribution of electrons in the layer adjoining the surface will be spherically symmetric, and the external emission will have a cosine distribution of directions of emission. If, on the other hand, the diffusion depth is commensurable with or even greater than the depth of generation of the x-ray photoeffect, then the source strength of the surface layer will be anisotropic, and this will distort the cosine distribution of the external emission with respect to the directions of emission.

In Fig. 5 curve a represents the limiting case of the distribution of electrons in the layer adjoining the surface, which one can expect to be approached under the condition when the diffusion depth exceeds considerably the depth of generation of the x-ray photoeffect. The symmetry axis of this distribution is the direction of the primary beam. Curve b represents the cosine law governing the change in the volume producing the emission at an angle α to the cathode normal. Curve c of Fig. 5 depicts the product of these laws which governs the distribution of the external emission with respect to the directions of emission. It is seen from Fig. 5 that in this limiting case the distribution will altogether not be a cosine distribution. As the diffusion depth decreases there will be a relative decrease of the first part of the source strength. The distribution of electrons in the layer adjoining the surface will to an ever increasing extent be determined by the second isotropic part of the source strength as a result of

which the external distribution will approach the cosine law.

Unfortunately, the method of rotating the cathode allows one to check directly only the cosine law of the change of the volume which produces the emission for a given angle α to the normal, since for fixed directions of the beam and of the detector (the angle β) the measurements always refer to the same source strength independently of whether the latter is isotropic or anisotropic.

Information on the distribution of x-ray photoelectrons over emission angles can be obtained by comparing the relative fractions of Auger and photoelectrons for at least two positions of the detector (the angle β) with respect to the beam; it is desirable that one of the positions be chosen at the minimum of the Auger-Perrin distribution (small β), and one in the range of angles where the values of this distribution are larger. If it turns out that the relative role of the photo and Auger electrons is identical for different β, then this will indicate that the distribution of photoelectrons is the same as that of the Auger electrons—the various directions of emission follow a cosine law. This will in turn indicate spherical symmetry of the photoelectron distribution in the layer adjoining the surface, i.e., the depth of generation of the x-ray photoeffect exceeds appreciably the diffusion depth. If, on the other hand, it will turn out that for small β there is a relative decrease of the fraction of the photoelectrons, then this will indicate an appreciable deviation of the distribution of the external emission from the cosine law, anisotropy of the distribution prior to emission, and the commensurability of the diffusion depth and the depth of generation of the x-ray photoeffect.

As has already been mentioned in Sec. 1, provision had been made in our setup for the possibility of setting the secondary-electron multiplier at $\beta = 10°$ and $\beta = 60°$. To determine the relative portion of photo and Auger electrons, we measured the emission in a narrow solid angle using a copper cathode and molybdenum Lα radiation and retarding voltages of 250 and 850 V for $\beta = 10°$ and $\beta = 60°$. For the 250-V retardation the current corresponded to the sum of the currents of photo and Auger electrons, since the secondary electrons returned to the cathode. For the 850-V retardation the current corresponded to the photoelectron current only, since the maximum energy of the Auger electrons amounted to 850 V. The ratio of the currents I_{250}/I_{850} for $\beta = 10°$ turned out to be 2.3 ± 0.2, and for $\beta = 60°$ it was 2.4 ± 0.2. The discrepancy in the obtained results lies, in the first place, within the limits of the experimental error exhibited by the spread of successive measurements and is, in the second place, opposite to that expected if it is assumed that the distribution of the electrons before they come out into the vacuum deviates from a spherically symmetric distribution in the direction of an Auger-Perrin distribution. This justifies us in asserting that, within experimental error, the distribution of the photoelectrons over the directions of emission also follows a cosine law.

Figure 6 shows the energy composition of the emission for various β obtained by differentiation of the corresponding retardation curves. The practically identical distributions attest to the fact that the Auger and photoelectrons are present in these directions in equal ratios.

Figure 7 shows a comparison of the energy composition of the emission at angles $\alpha = 0°$ and $\alpha = 30°$ with the energy composition of the total emission which was obtained in the first mode of operation of the setup and with the aluminum Kα radiation filtered with an aluminum filter. From a comparison of the curves it is seen that the energy composition of the emission at various angles is practically the same and corresponds to the composition of the total emission.

The following conclusions can therefore be drawn:

1. The combination of a quasispherical analyzer and a secondary-electron multiplier allows one to carry out an investigation of the x-ray photoemission in various directions and an investi-

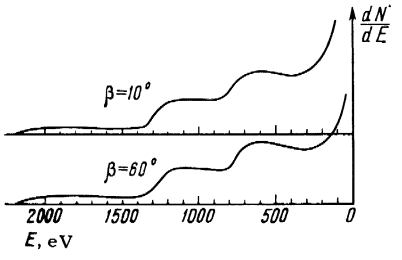

FIG. 6. Energy distribution of the x-ray photoemission with a copper photocathode excited by tungsten Lα radiation for two angles β. The angle $\vartheta = 90°$.

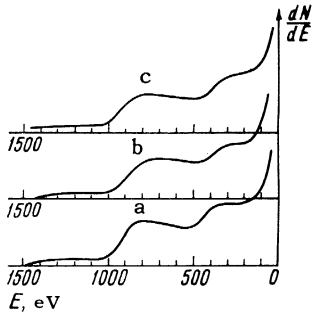

FIG. 7. Distribution curves of the x-ray photoemission in a narrow solid angle (curve a, $\alpha = 30°$ and curve b, $\alpha = 0°$) and of the total emission (curve c) for a titanium photocathode and aluminum Kα radiation.

gation of the energy composition of the emission in a narrow solid angle.

2. The distribution of x-ray photo and Auger electrons emitted into the vacuum over the directions corresponds to a cosine law.

3. The thickness of the layer in which the Auger-Perrin distribution becomes isotropic on account of the scattering is smaller than the thickness of the region of emission of the x-ray photoelectrons.

4. The energy composition of the emission is practically the same at various angles of emission.

5. The spherical analyzer with a secondary-electron multiplier proposed for the study of the energy composition of the emission in a narrow solid angle can be utilized for studying the energy composition of the total emission.

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