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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
СО АН СССР

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MEASUREMENT OF THE PARAMETERS OF A LINEAR CCD STRUCTURE AS AN ONE-DIMENSIONAL X-RAY IMAGING DETECTOR

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MEASUREMENT OF THE PARAMETERS OF A LINEAR CCD STRUCTURE AS AN ONE-DIMENSIONAL X-RAY IMAGING DETECTOR

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Abstract

The basic parameters of linear charge-coupled devices (CCD) as one-dimensional X-ray imaging detectors are measured at 5.4-19.6 keV photon energy range. Within this range, the sensitivity-wavelength dependence is obtained. In the maximum of this dependence, the threshold flux density of photons for such a device attains 3×10^6 cm^{-2} s^{-1} at a storage time of ~150 ms. This is equivalent to falling single photons on a CCD cell with 15 μm x 15 μm dimensions during a storage time which varies in 120 mcs - 30 s range. Within the photon energy range mentioned above, the sensitivity varies from 0.3 to 3 mV· photon $^{-1}$. cell. The linearity of the dependence of signal amplitude on flux density of photons remains up to 7×10^8 cm^{-2} s^{-1}. Any dependence of sensitivity on flux density of photons is not revealed. The spatial resolution is better than 100 μm and must be measured with micron accuracies. In addition to photosensitive region, the shift register one is successfully tried. The ways of improving the CCD parameters for registration of X-rays are discussed.

High energy physics needs for X-ray imaging detectors with high spatial resolution, sensitivity, and high quick-action for performing precise measurements of the sizes and coordinates of the electron and positron beams using their synchrotron radiation (SR). Along with many other studies on the VEPP-2M, VEPP-3 and VEPP-4 storage rings SR beams, the Institute of Nuclear Physics (Novosibirsk) is carrying out a number of researches on X-ray topography, medicine and structural "motion pictures" for which such detectors are also required.

In addition to X-ray vidicons and supervidicons with luminophor X-rays-to-light converters, which are used in tv techniques, linear and matrix charge-coupled devices (CCD) are being employed in the INP as X-ray imaging detectors. These devices are one of promising trends in today's microelectronics. The principle of their performance is based on the control by storage of localized electric charges (charge packets) and by directed transfer of them by varying the depths of the potential wells formed in the field of flat MDS (metal dielectric semiconductor) capacitors by a set of electrodes.

The principle of charge coupling has found the widest application in solid-state analogs of vidicons - matrix and linear converters of optic images - video signal shapers. In comparison with vacuum transmitting tubes, CCD have a number of essential advantages, namely: exact coordinate fixation, absolute stability of geometrical raster, fast response, absence of light aftereffect, large dynamical range, small overall dimensions and weight.

Practically all existing CCD - video signal shapers - are intended for operation in the visible or in the nearest infrared range of the spectrum. The advantages mentioned above and the revealed X-ray sensitivity of CCD structures (see Refs. /1/, /2/) promote more detailed measurements of their parameters as X-ray imaging detectors. Referred to such parameters are geometrical resolution, spectral and threshold sensitivity, dynamical range, linearity. The specific feature of performance of a CCD as the X-ray detector is the formation of signal charges of photogeneration (unbasic carriers) not only directly near the surface of a silicon substrate under the set of electrodes but throughout its volume. In view of this, the effective depth of the CCD as the X-ray detector is determined by the mobility and lifetime of unbasic carriers. In the present paper the results of the measurements are described, which have been carried out for a linear video signal shaper (LVSS). This LVSS represents a commercial silicon CCD with a surface channel, polysilicon set of electrodes, and a n-type substrate (see Ref. /2/). The optical window of the linear CCD was removed. In a given LVSS, at the chart regime, the charges are stored in the photosensitive region in which there are 1024 cells of 15 μm x 15 μm in size and from which the charge packets are transferred to the three-phase shift register and transported in sequence into the output device.

A device in the CAMAC standard on the basis of a LVSS has been designed, which comprises two blocks: a CCD with shapers of tact and control voltages, preamplifier of signal, and with a number of stabilizers and a CAMAC module of 2M wide; the latter block performs the double correlated sampling of a CCD signal (or the regime of connection to "rich zero"), control by ADC operation (the external ADC 8-500, designed at the INP, is employed), shaping of intervals of storage time, processing of external impulses of start-up, and synchronization with the mains. Application of the microprogramming control principles enabled, in addition to the chart regime at which the storage time cannot be less than the time of reading of the complete line (12 ms for a given device), three other regimes to be realized when the minimal time of storage is 120 mcs and there is the possibility of increasing the dynamic range from 300 to 1000 (with respect to light). The maximum time of storage is 30 s.

The parameters of the LVSS were measured at the 5.4 - 19.6 keV energies of photons with the apparatus described in Ref. /3/. The device is light-shielded with a thin black paper. The K-lines of various elements - the projections of the linear focus of X-ray tubes - were used (Fig. 1).

The lines are spaced by Bragg reflection on a grinded silicon crystal. For absolute measurement of the flux densities of monoenergetic photons, a proportional counter with the known efficiency-on-wavelength dependence was used. The spectrum, which is recorded by the photoplates with 10 μm spatial resolution in the case of their development at room temperature, has been taken as the standard of an one-dimensional X-ray image. The photometering of the photoplates were made with a 10 μm scanning slit.

The CCD signal was displayed on the oscillograph for preliminary tune of the system and was introduced, in the digital form, - through the connection system - into a computer ODRA-1325. This computer performed the control of the mode of CCD operation and provided the preliminary data processing (subtraction of the thermally generated current profile, averaging of several measurements, data storage), data output on a colour raster display CDR-1 (operative control), and outputting on a mosaic consecutive printer (Figs. 5-7). The print contains the ADC scale (NS АЦП), the number of signal (CS) and background (CF) measurements for averaging, storage time in ms (TNAK), scales over Y(RY) and X(RX), the initial cell of outputting (NX) at the display and regime of storage (RNL). The main measurements of the parameters of the LVSS were made under the following operation conditions: storage time 153.7 ms; synchronization from the 50 Hz mains; charge storage in the photosensitive region. All the measurements have been performed at the "warm" CCD, i.e. without the forced cooling as for the most typical case. Application of cooling (thermoelectric microcooler, blowing round by liquid nitrogen vapour, etc.) permits one to practically completely eliminate the background of dark current and to somewhat reduce the noise signal, what is equivalent to an increase in the device sensitivity. Scanning over the spectral range was carried out by means of installation of X-ray tubes with different anode materials, and scanning over the intensity of monochromatic X-rays was performed by means of introduction of aluminium filters - attenuators - or by means of variation of the current and voltage on the tube.

The dependences of the maximum amplitude of the device signal (the peak of the line) on a proper flux density of monoenergetic photons and the dependences of the sensitivity on the energy of photons and the flux density of monoenergetic photons have been obtained. The highest flux densities of photons and the corresponding output signals of the device (Fig. 2), which are both limited by the possibilities of the X-ray apparatus, were fairly far from the level of saturation of the signal amplitude revealed for the light. The width of the noise path at the device output was 2-5 mV. The number N of the photons which fall on one CCD cell during storage time (153.7 ms) is plotted (at the top) along the X-axis in Fig. 2 (and Fig. 3). The dependences of the signal amplitude (Fig. 2) and the sensitivity (Fig. 3) on the flux density of the photons indicate good linearity in the range of large output signals. Within the available precision of the measurements, it seems impossible to find any dependence of the sensitivity on the flux density of the photons. The accuracy of measurements is affected by the growth of the amplitude of small output signal because of the masking action of noise, and by the influence of the discreteness of the ADC on the measurement of the signals with a value in several units of the junior order of the scale, and by some nonlinearity of the CCD which is associated, for example, with incomplete transfer of charges from the storage section and in the register. The errors in measuring the fluxes densities of photons are due to the errors in the efficiency of a proportional counter used for calibration (20% for 17.5 and 19.6 keV and 2-4% for 5.4-8.9 keV; reliability is 90%); and to the error of mass coefficients of attenuation of filters, which achieves 10% (this causes the errors in measuring the fluxes densities of photons equal to 25-65% as the wavelength grows, for the case of the largest thicknesses of filters).

In the course of measurements, two specimens of linear CCD were employed. One of them was out of action accidentally after survey the K-lines of molybdenum and copper had been taken. In connection with this, the sensitivity-on-wavelength

dependence consists of two nonsewed together branches (Fig. 4) since the specimens are distinguished by the steepness of charge-to-voltage conversion. This is the case in the optic range as well. A decrease in the sensitivity in the long-wave range is caused by a decrease in the amount of generated unbasic carriers (holes) per one absorbed photon. Some decrease in sensitivity in hard region is connected with a decrease of the absorption of photons in the limits of the effective depth of a silicon substrate. The profiles of weak signals, presented in Fig. 5, demonstrate the reliable separation of the signal under charges corresponding to one photon per cell in the region of maximum sensitivity.

Information on spatial resolution of the LVSS is presented in Fig. 6. Location, on one print (figure), of the standard (photometering of the photoplate) scaled in the computer and of the corresponding X-ray images obtained by means of linear CCD was found to be impossible because of their coincidence (Figs. 6a-6f). Small broadenings, at half a height, of the CuK$_{\alpha_1}$ and NiK$_{\alpha_{1,2}}$ lines images (Figs. 6a,d) obtained with the LVSS, as compared to the standards ($\sim$5 and $\sim$20 μm), points out that the resolution of the linear CCD is, in any case, $\lesssim$100 μm and cannot be satisfactorily extracted from the broadenings of the images of CuK$_{\alpha_1}$ and NiK$_{\alpha_{1,2}}$ lines with corresponding, $\sim$240 and $\sim$630 μm, widths at half a height.

In addition to the measurements indicated above, particular measurements in the mode of charge storage in the shift register have been made. The larger transverse width of the shift register (in comparison with the photo-region) permits one to obtain the correspondingly higher sensitivity and higher maximum charge with conservation of the 15 μm longitudinal size of the cell (Fig. 7).

The performed measurements enable the CCD to be referred to as promising X-ray imaging detectors and make it necessary a detailed measurement of analogous characteristics of matrix shapers of video signal, which are two-coordinate imaging detectors.

The main disadvantage of CCD structures as the X-ray detectors lies in their insufficiently high radiation resistance. However, further perfecting of them and, in particular, appearance of CCD with the so-called "latent" or "deepened channel" make it possible to "move away" this limitation, simultaneously increasing the sensitivity to weak chargings at the expense of a decrease of the noise component of the output signal and bringing up the sensitivity to a guaranteed registration of single photons.

In conclusion, we would like to mention a number of problems to be solved for the development of technique of working with CCD and their effective application:

- measurement of the spatial resolution of LVSS with micron accuracies;

- measurement of the parameters of CCD up to the level of saturation of a signal (on monochromatized SR beams);

- study of the radiation resistance of CCD on their degradation using monochromatized and white SR beams;

- using the cooling of CCD, including those with "deepened channel", for broadening the spectral region of guaranteed registration of individual photons above the noise background for the purpose of using CCD as a detector-spectrometer;

- application of cooling in order to relatively increase the sensitivity of CCD for the purpose of using it as a detector of soft, including vacuum, X-rays;

- employment of CCD matrices for X-ray topographic study and check of defect structure of crystals and for measuring the sizes and coordinates of the electron and positron beams in storage rings using their SR;

- digitation of X-ray topographical images (static and then in situ).

References

/1/ N.M.Allinson, Solid-state imaging arrays for X-ray detection, Preprint Daresbury Laboratory DL/SCI/P270E, February 1981.

/2/ M.G.Fedotov, Electronic unit for measuring radiation spectrum of optic klystron, Diploma NSU-INF of the USSR Acad. of Sci., Novosibirsk (1981).

/3/ V.A.Karpenko, V.E.Panchenko, N.P.Soshchin, Measurement of the parameters of a supervidicon with phosphor screen as an X-ray imaging detector, To be published.

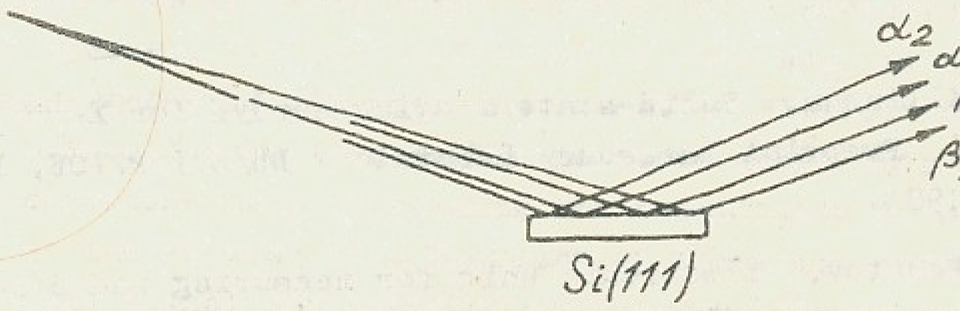


Fig. 1.

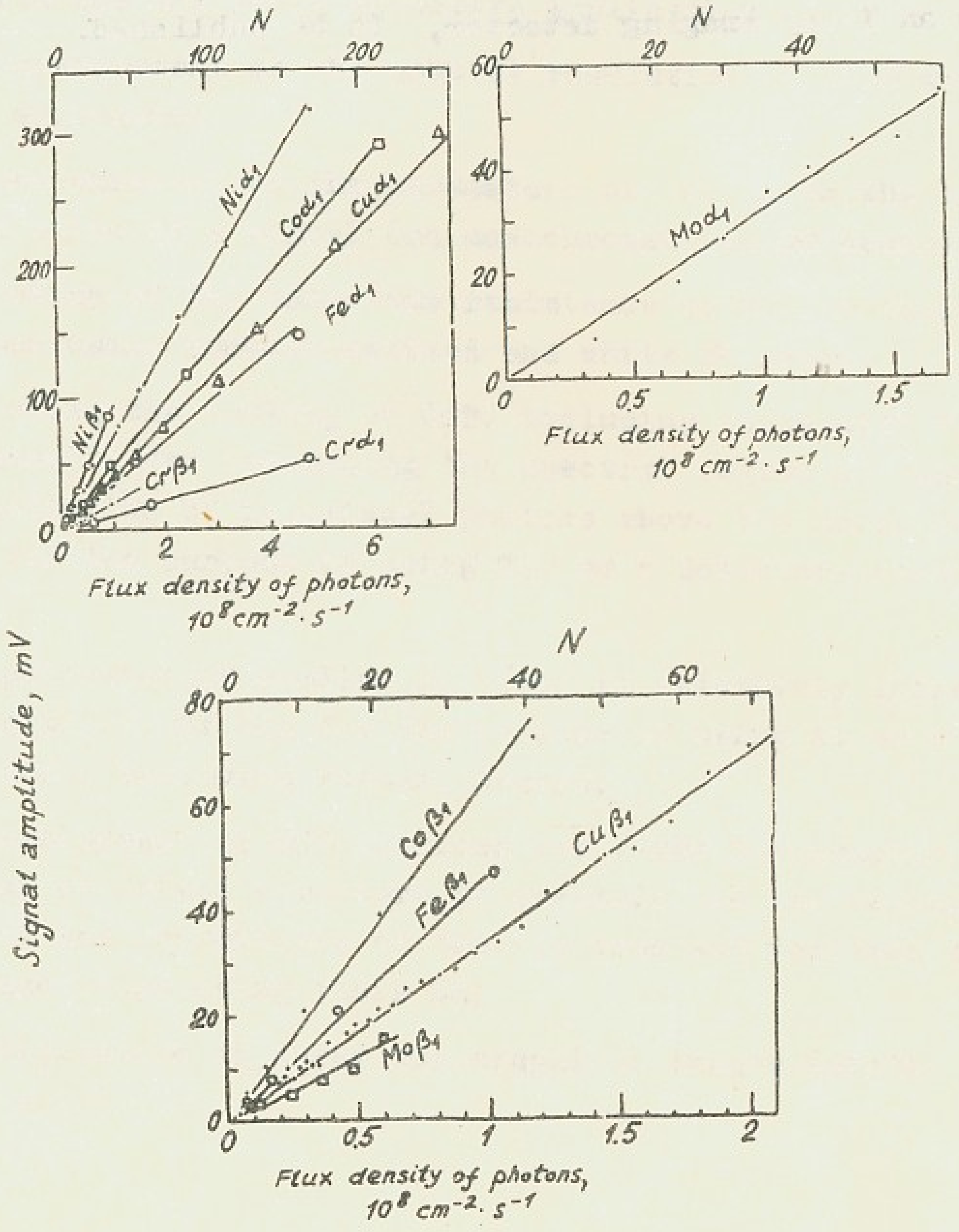


Fig. 2.

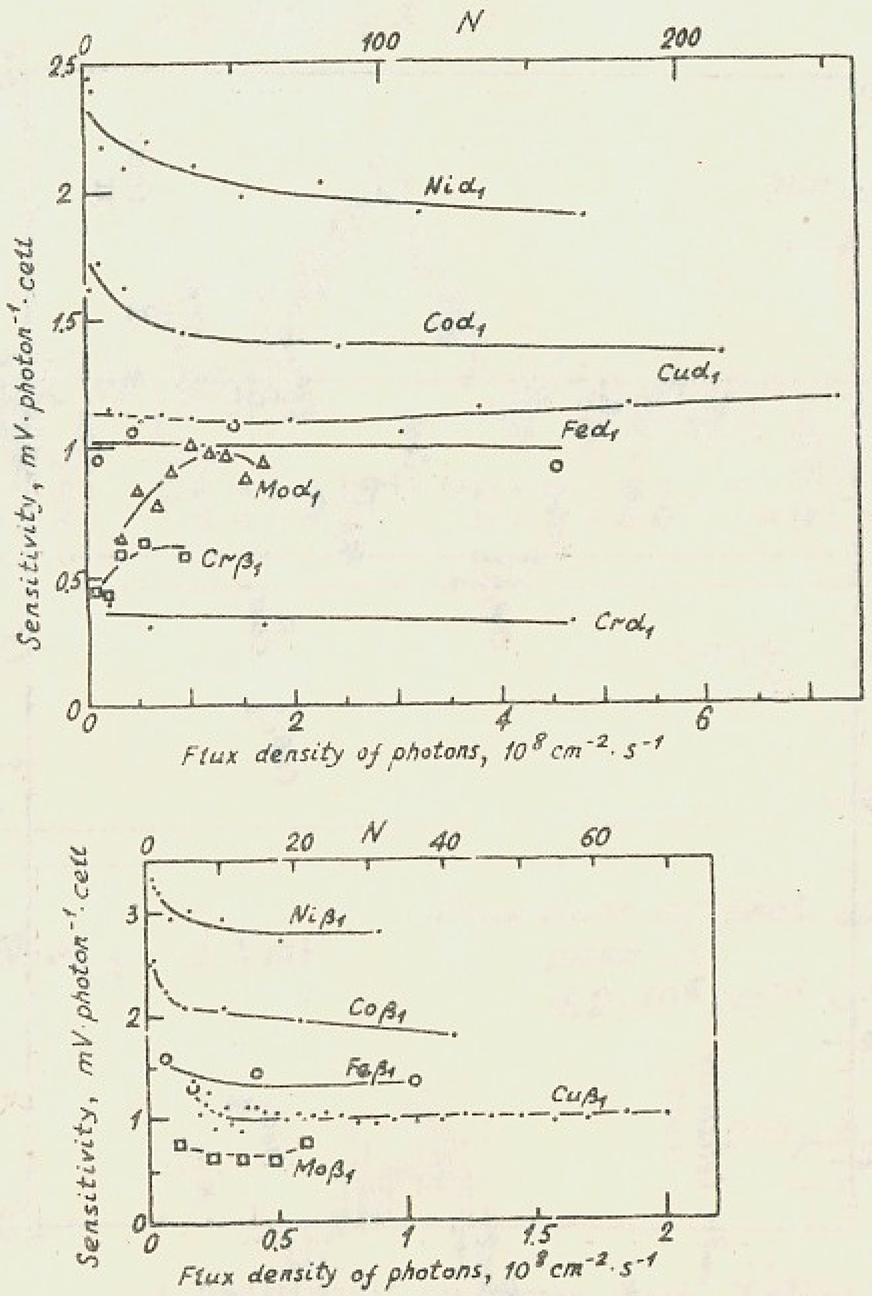


Fig. 3.

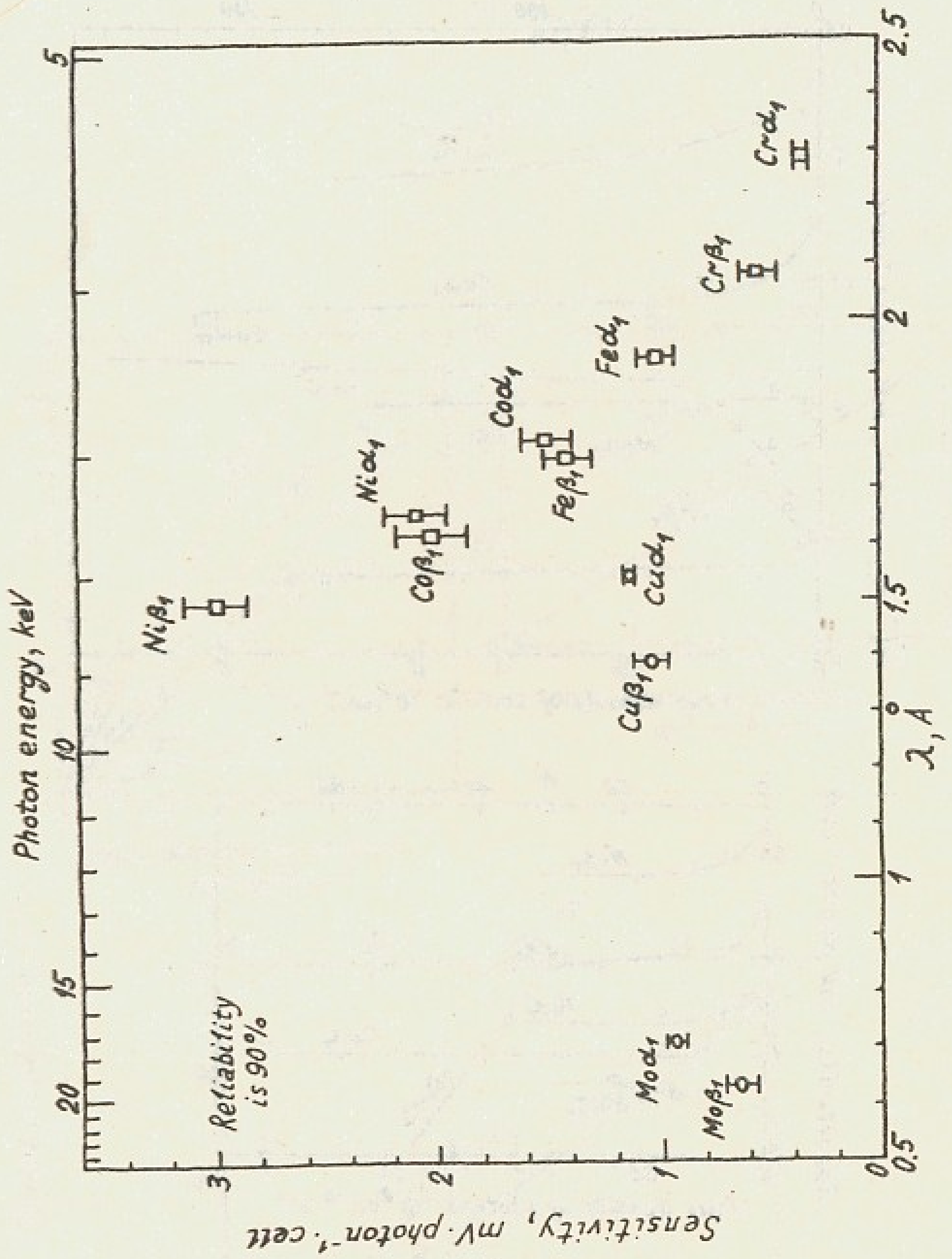

Photon energy, keV
5
10
15
20
Sensitivity, mV·photon⁻¹·cell
3
2
1
0
λ, Å
0.5
1
1.5
2
2.5
Niβ₁
Coβ₁
Niα₁
Coα₁
Feβ₁
Feα₁
Cuα₁
Cuβ₁
Crβ₁
Crα₁
Moα₁
Moβ₁
Reliability is 90%

Fig.4.

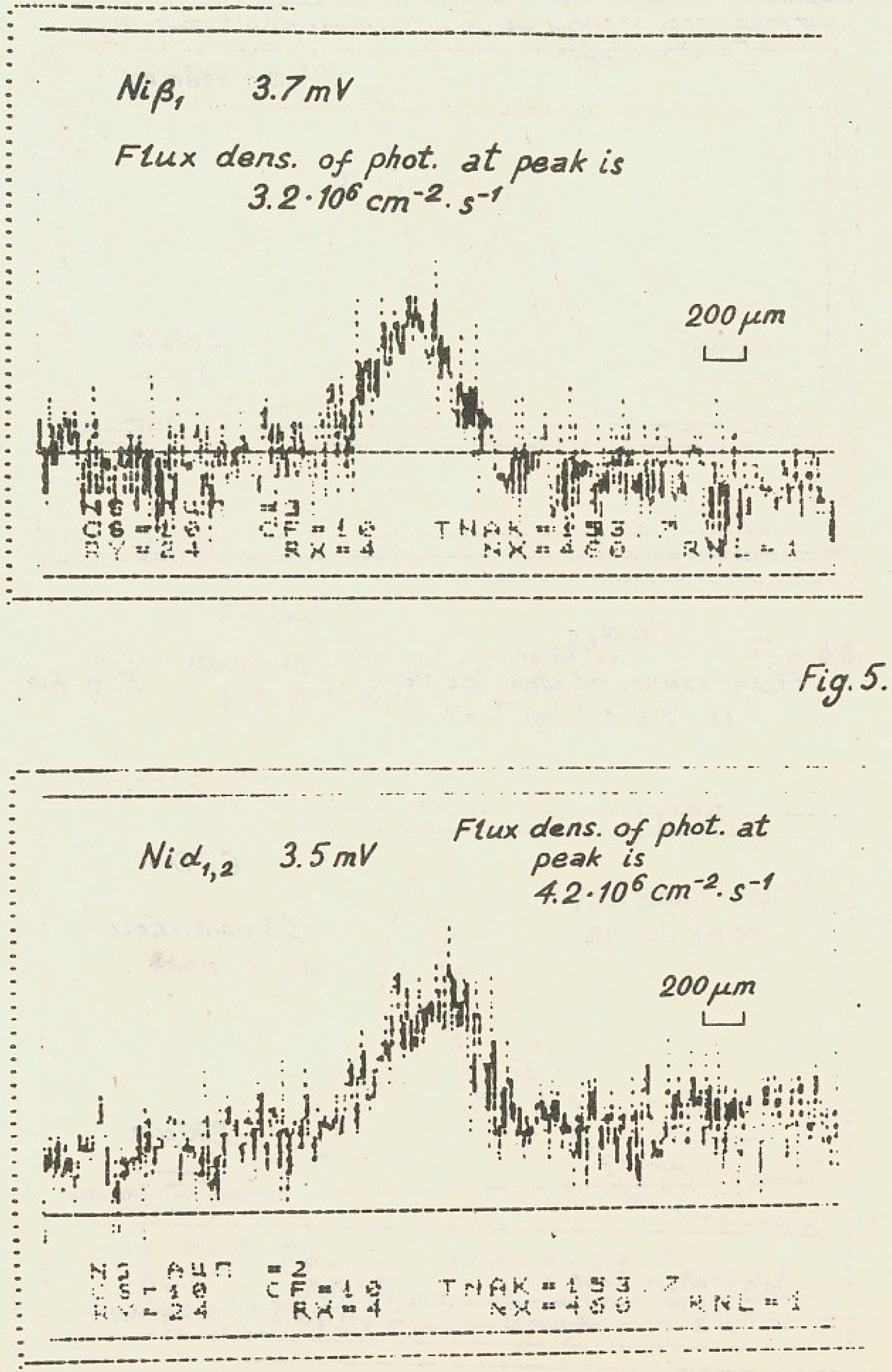
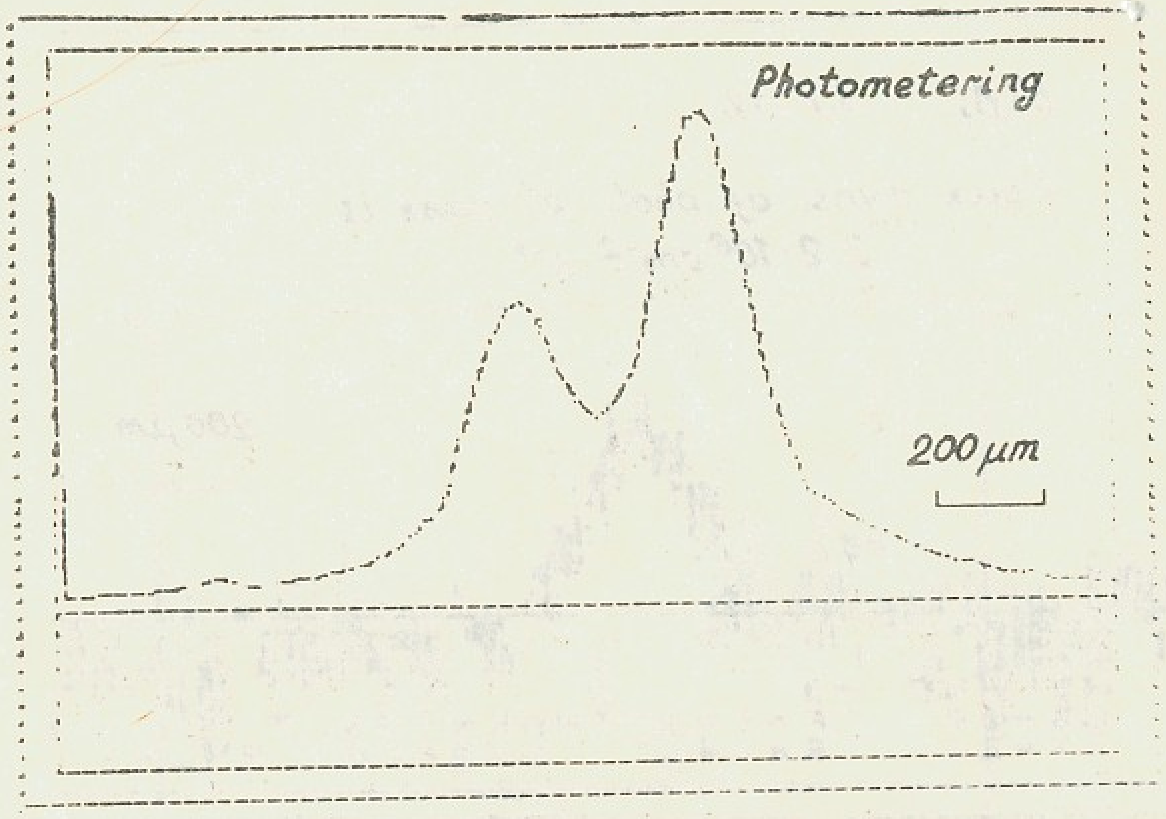

Niβ₁ 3.7 mV
Flux dens. of phot. at peak is 3.2·10⁶ cm⁻²·s⁻¹
200 µm
NS AUП =3
CS=10 CF=10 TNAK=153.7
RY=24 RX=4 NX=460 RNL=1
Niα₁,₂ 3.5 mV
Flux dens. of phot. at peak is 4.2·10⁶ cm⁻²·s⁻¹
200 µm
NS AUП =2
CS=10 CF=10 TNAK=153.7
RY=24 RX=4 NX=460 RNL=1

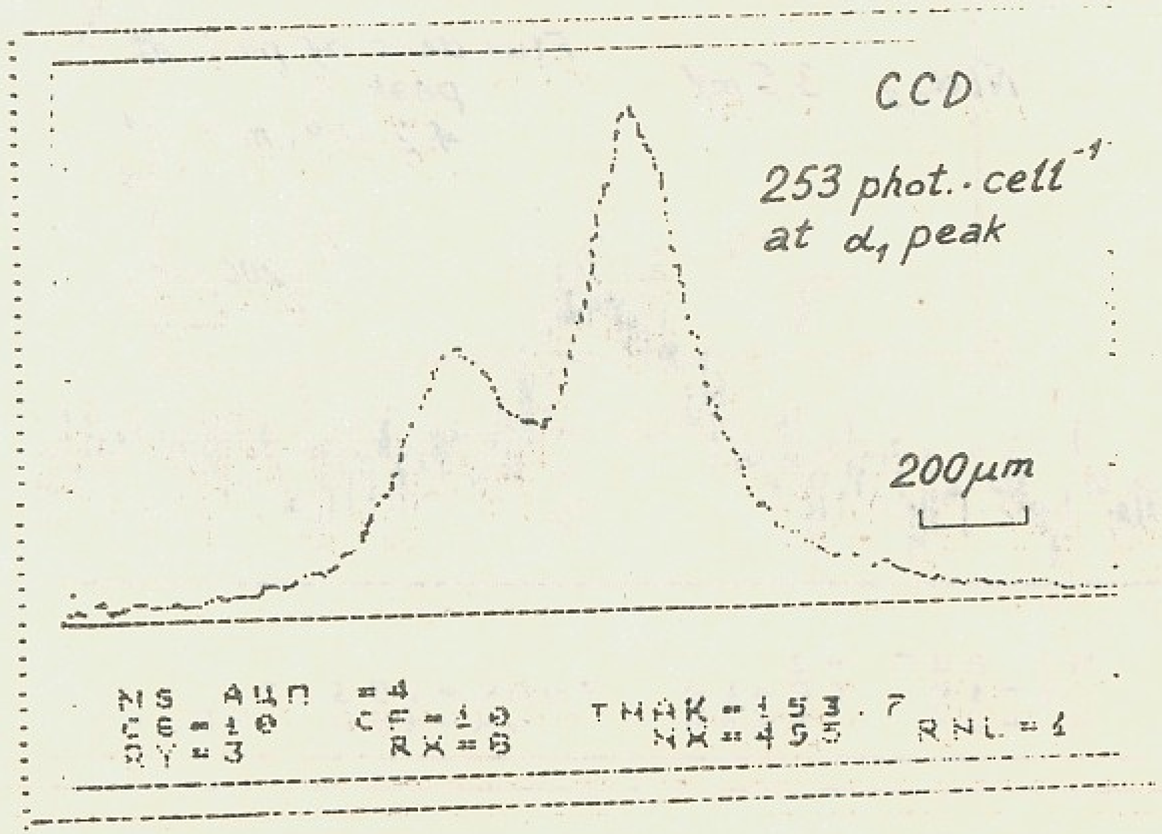
Fig. 5.



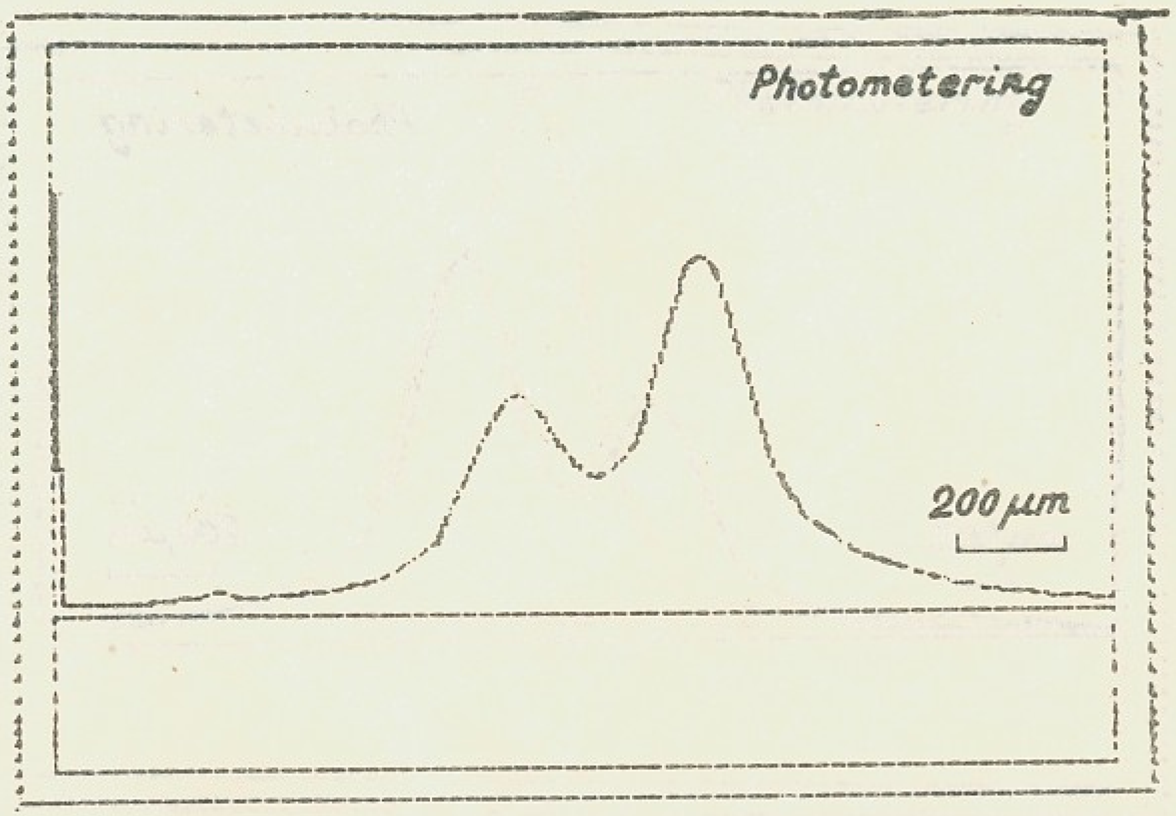
Cu $\alpha_{1,2}$

Flux dens. of phot. at peak is $7.3\cdot10^{8}\ cm^{-2}\cdot s^{-1}$

Fig. 6a.



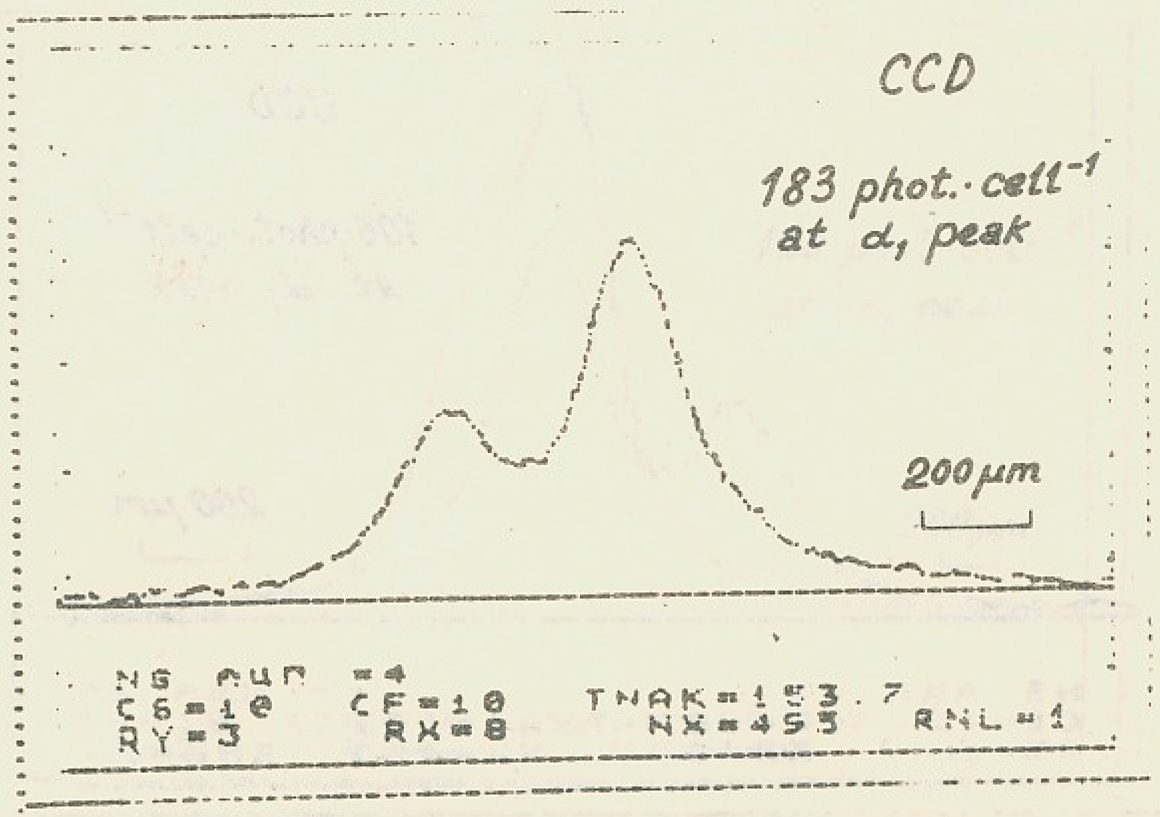
```
NS   АЦП  =4
C6=10     CF=10    THAK=153.7
RY=3        RX=8     NX=455    RNL=1
```



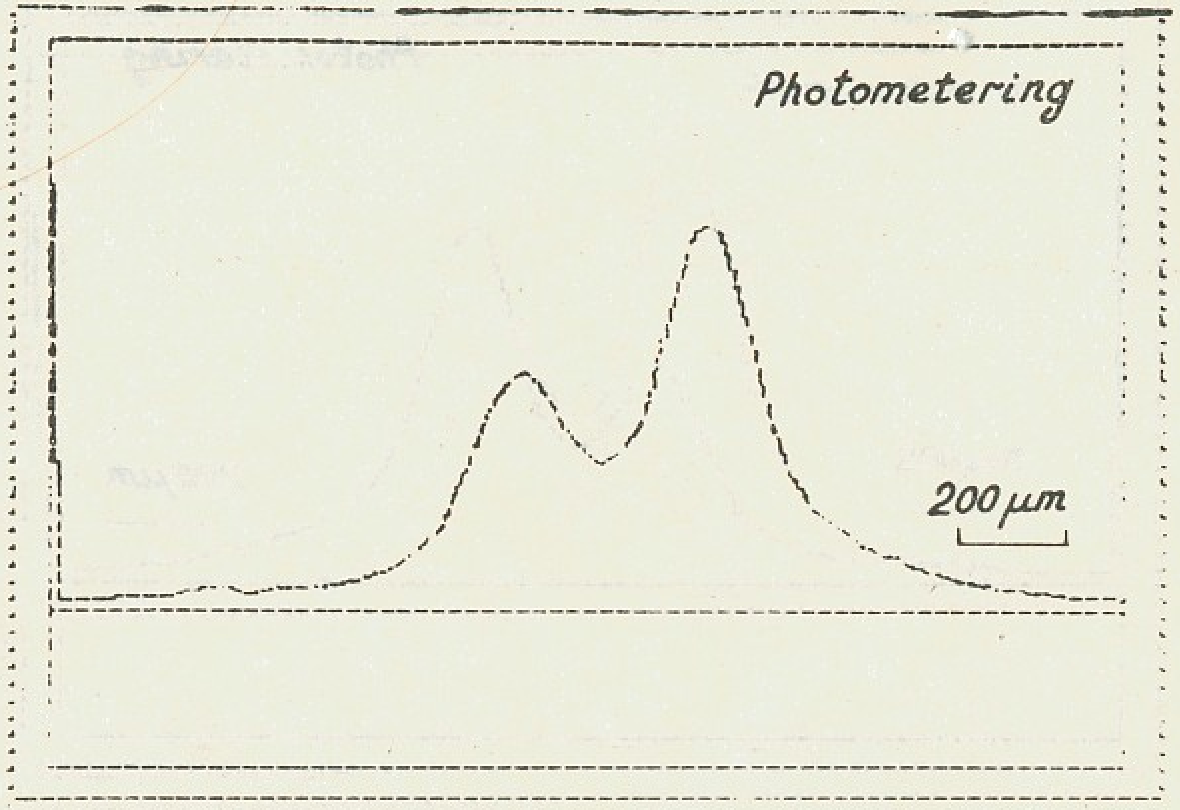
Cu $\alpha_{1,2}$

Flux dens. of phot. at α_1 peak is $5.3\cdot10^{8}\ cm^{-2}\cdot s^{-1}$

Fig. 6b.



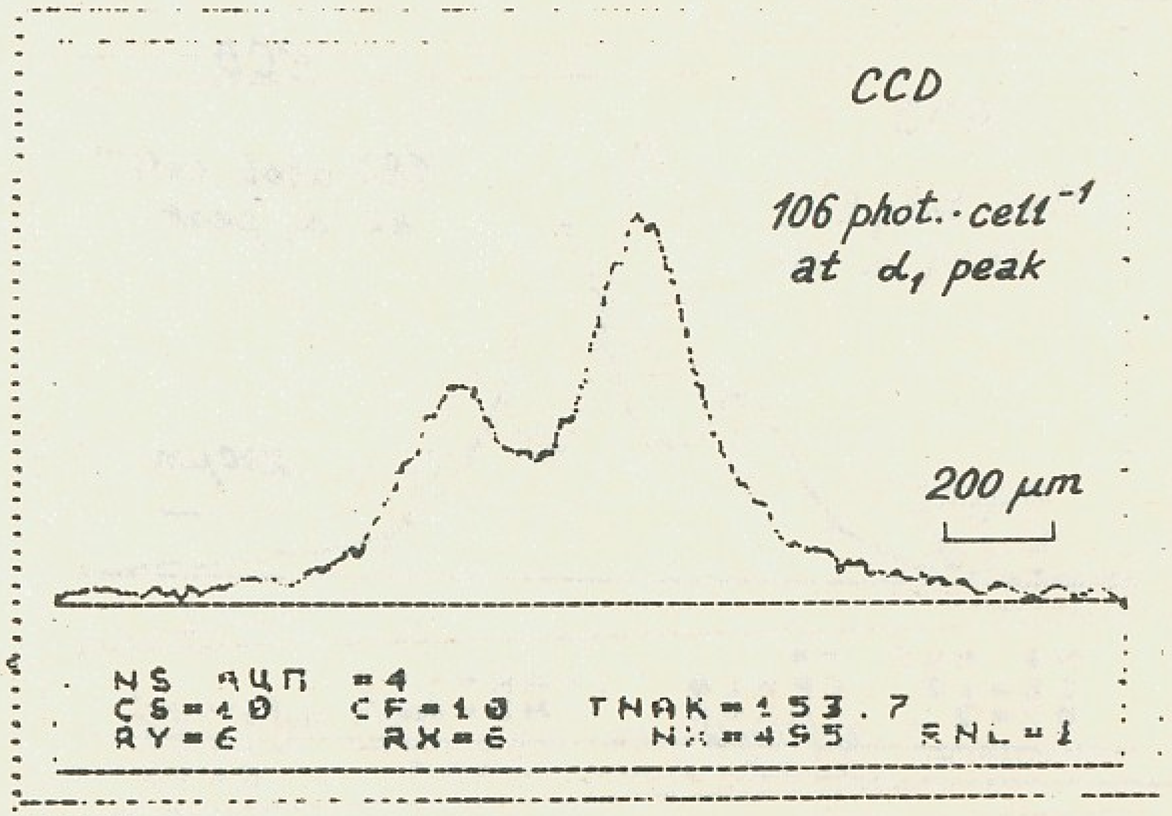
```
NG   АЦП  =4
C6=10     CF=10    TNAK=153.7
RY=3        RX=8     NX=455    RNL=1
```

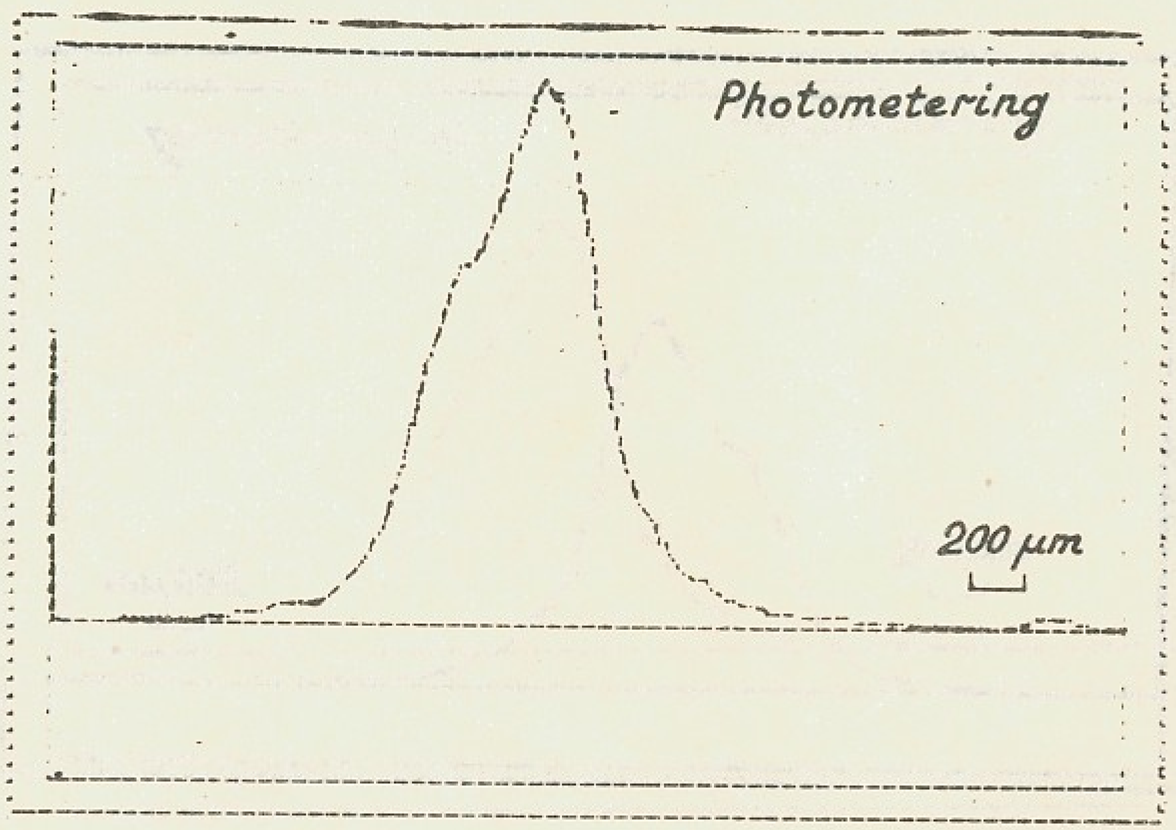


Cu $\alpha_{1,2}$

Flux dens. of phot. at α_1 peak is $3.1 \cdot 10^8\ cm^{-2} \cdot s^{-1}$

Fig. 6c.

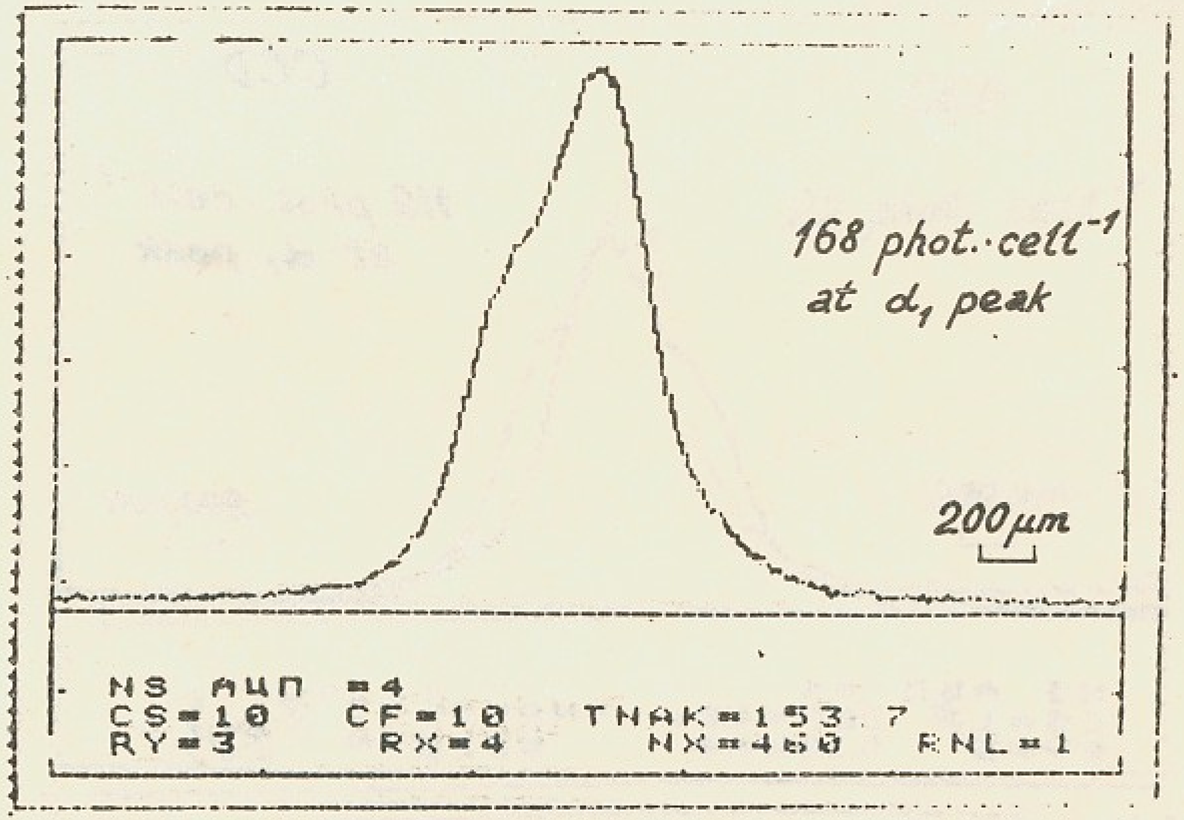


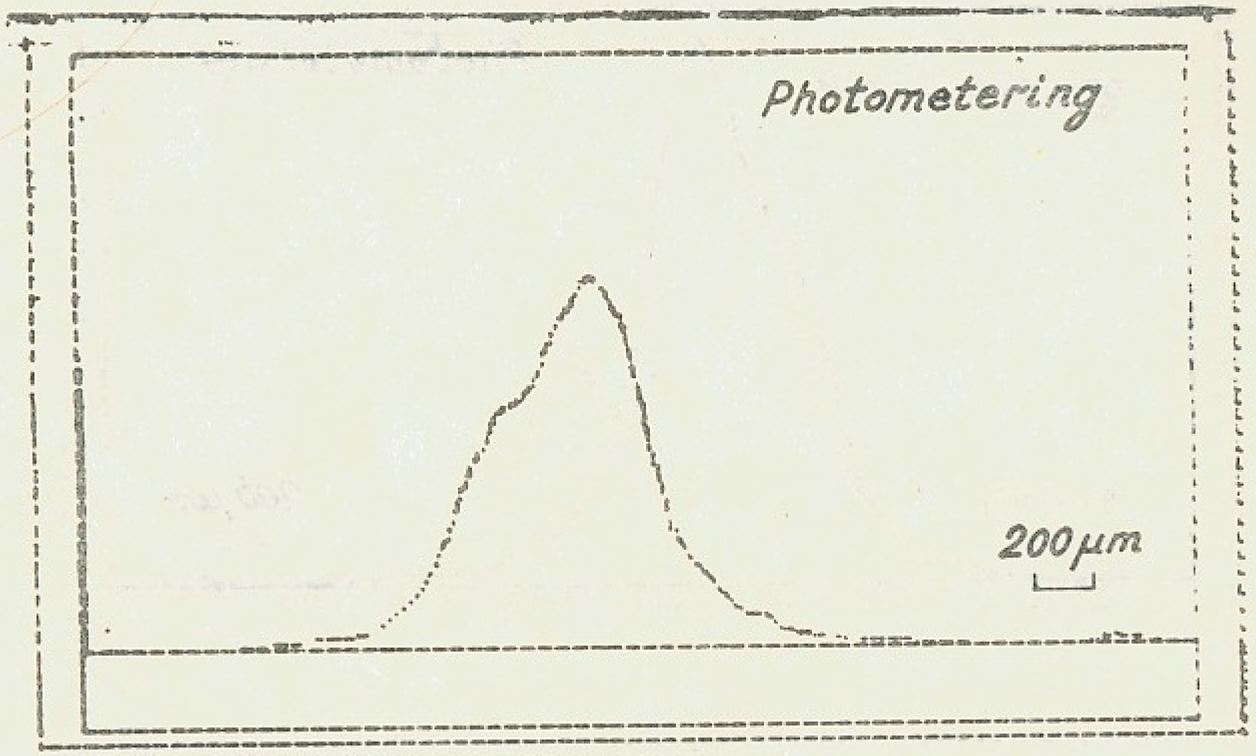


Ni $\alpha_{1,2}$

Flux dens. of phot. at α_1 peak is $4.8 \cdot 10^8\ cm^{-2} \cdot s^{-1}$

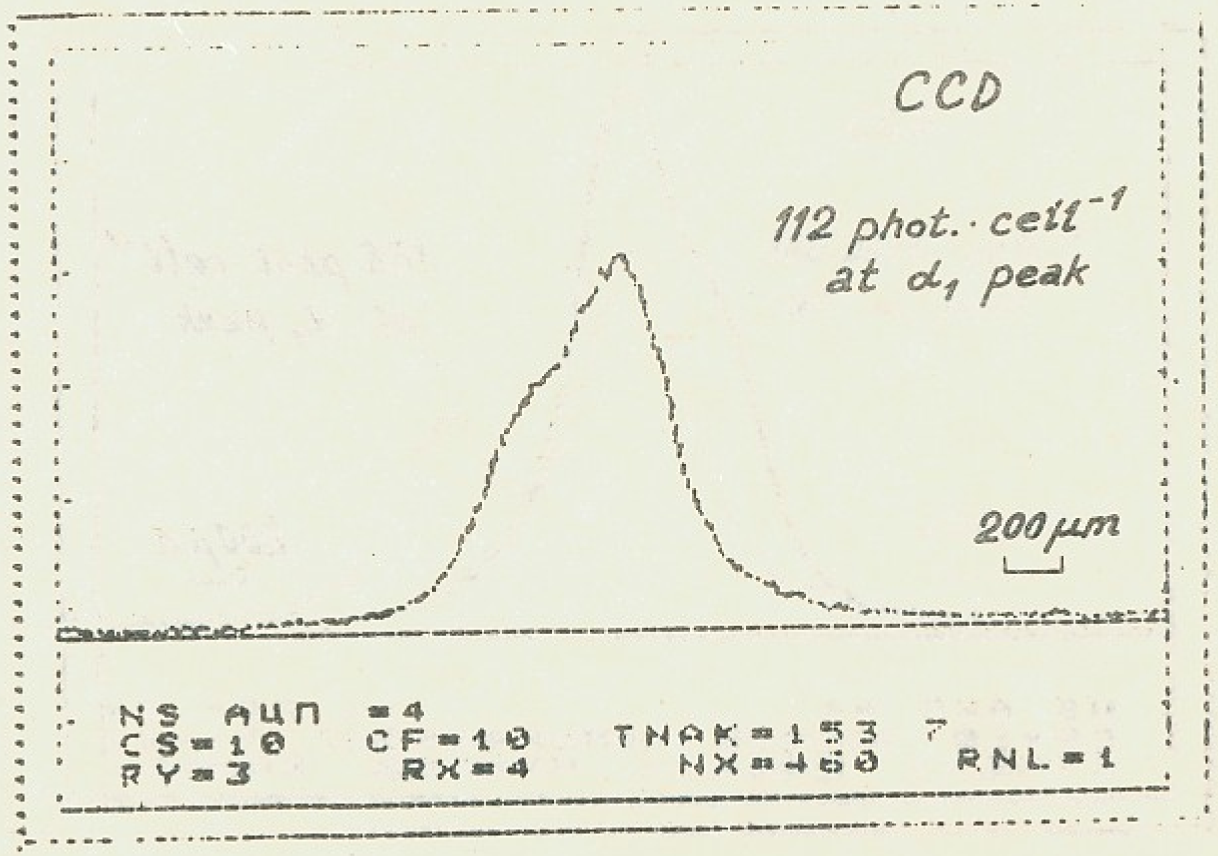
Fig. 6d.

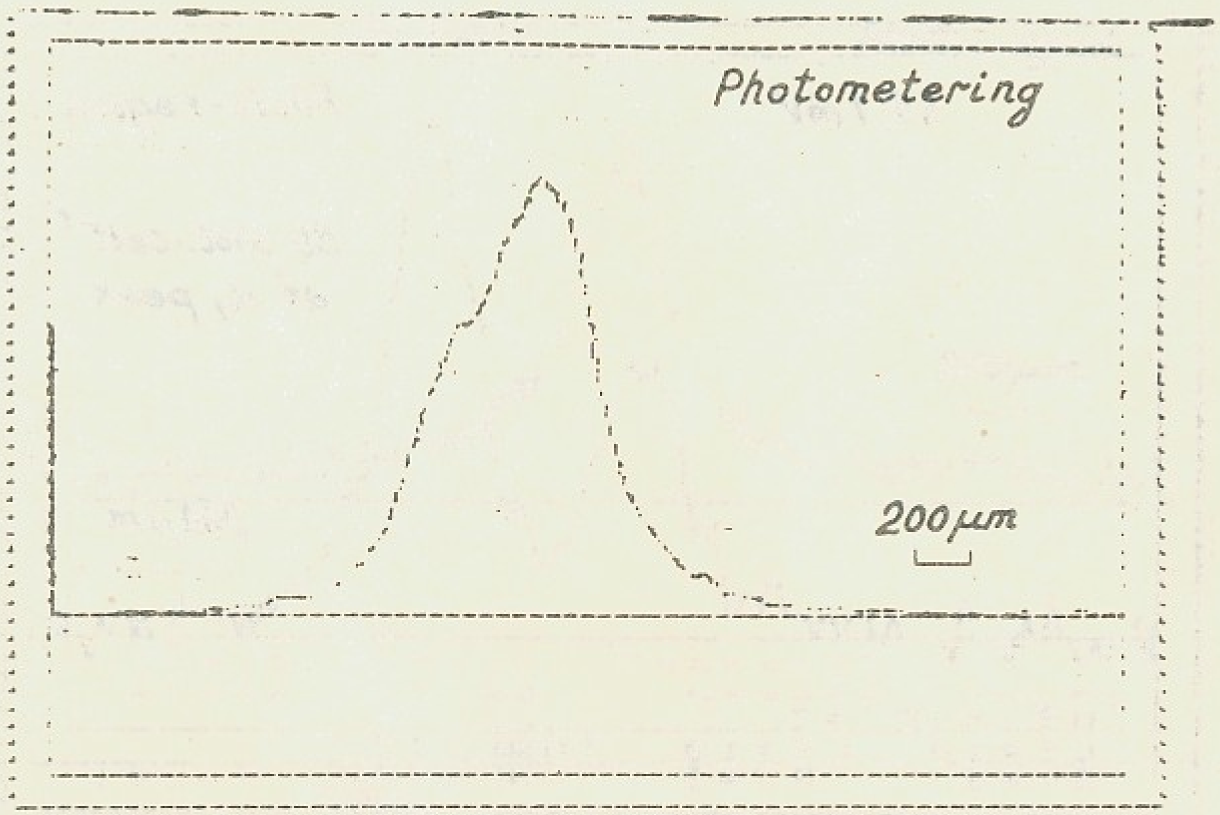




Ni $\alpha_{1,2}$

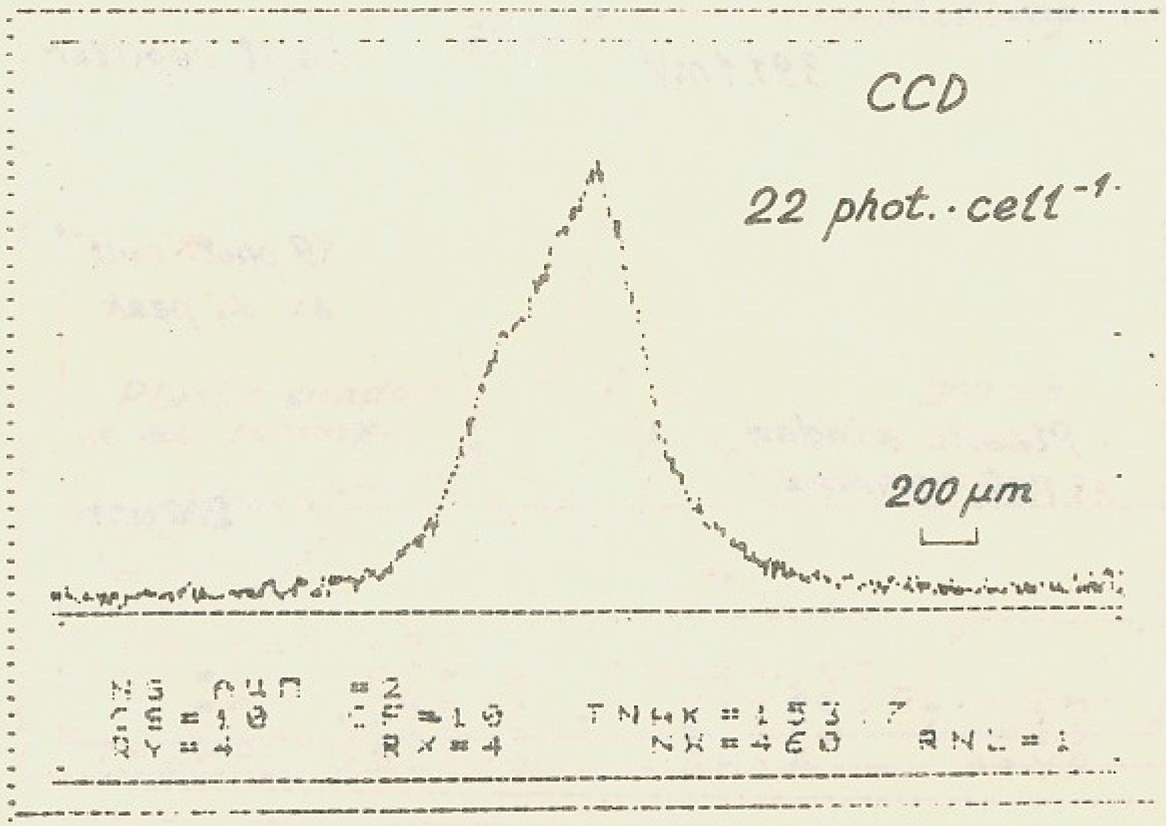
Flux dens. of phot. at α_1 peak is $3.2\cdot10^{8}\,cm^{-2}\cdot s^{-1}$ Fig. 6e.

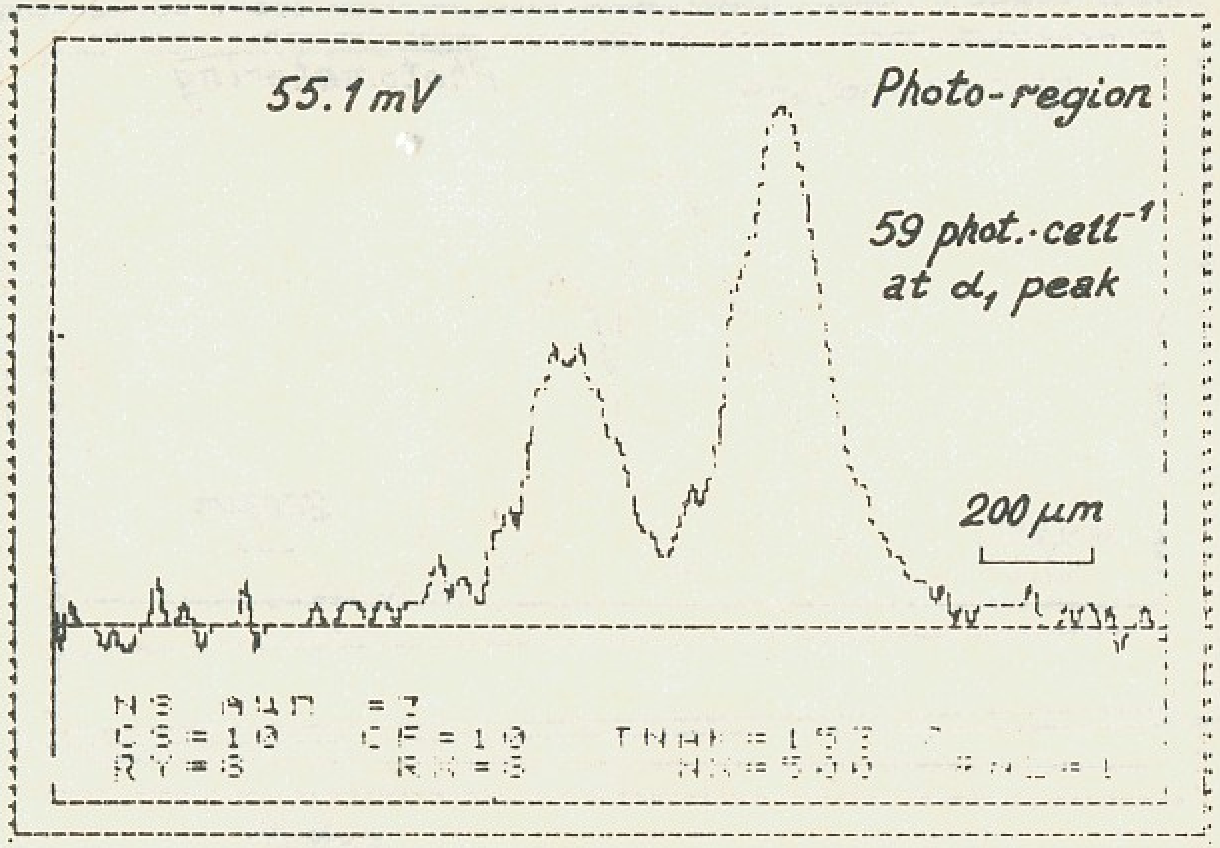




Ni $\alpha_{1,2}$

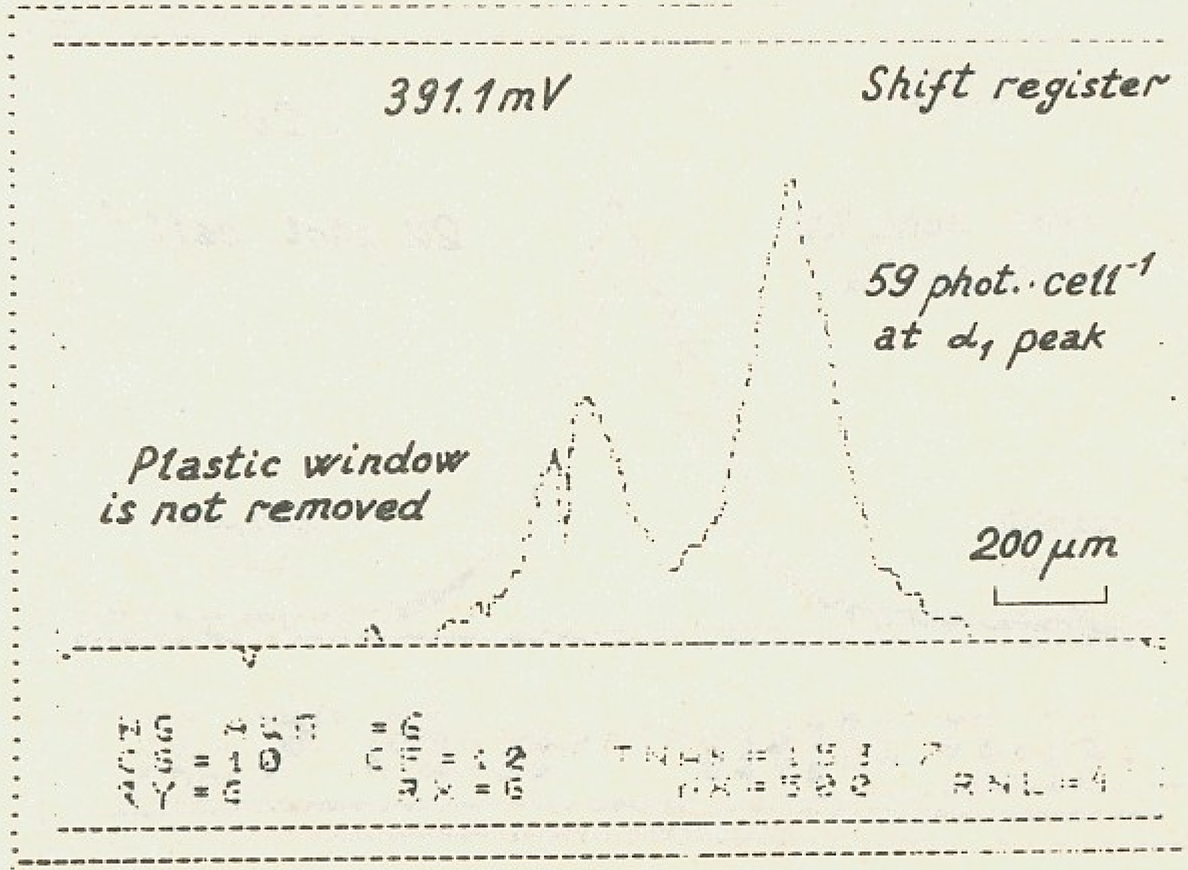
Flux dens. of phot. at α_1 peak is $6.3\cdot10^{7}\,cm^{-2}\cdot s^{-1}$ Fig. 6f.

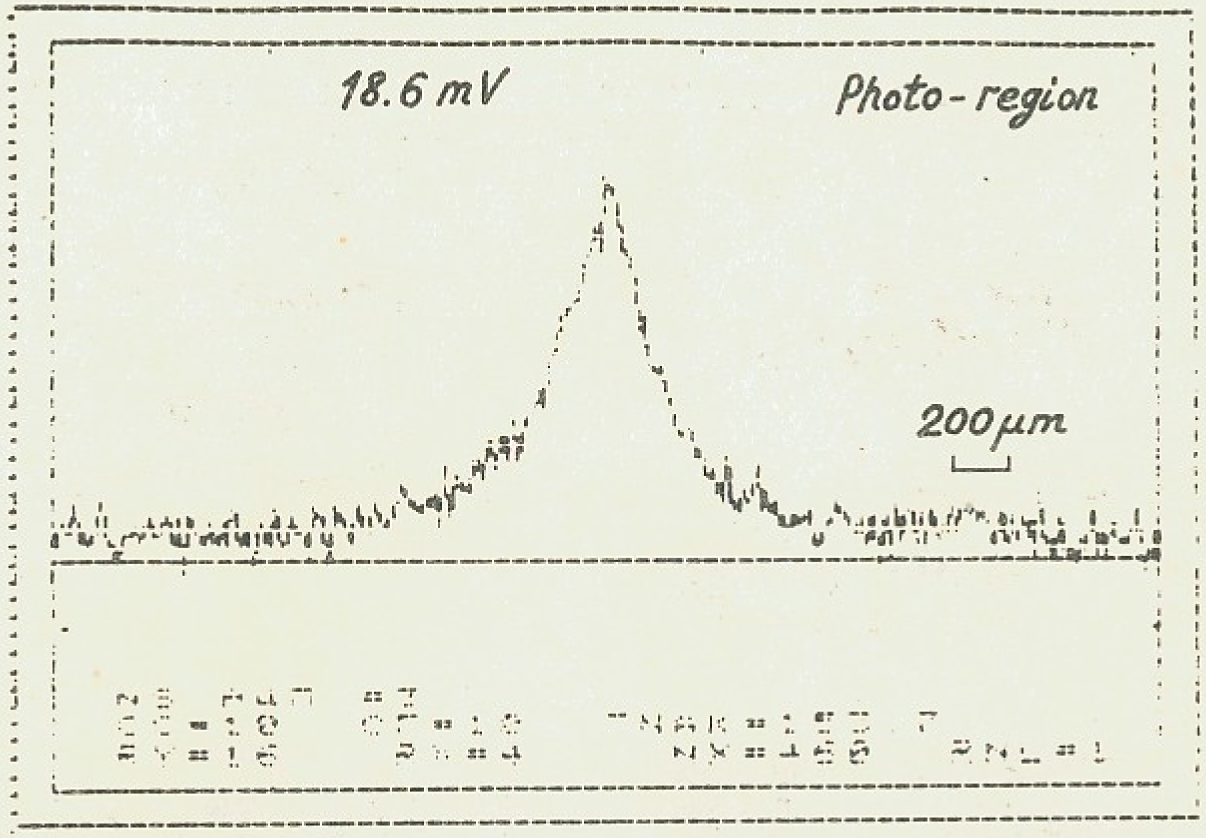




Mo $\alpha_{1,2}$
Flux dens. of phot. at α_1 peak is $1.7 \cdot 10^8\ cm^{-2} \cdot s^{-1}$

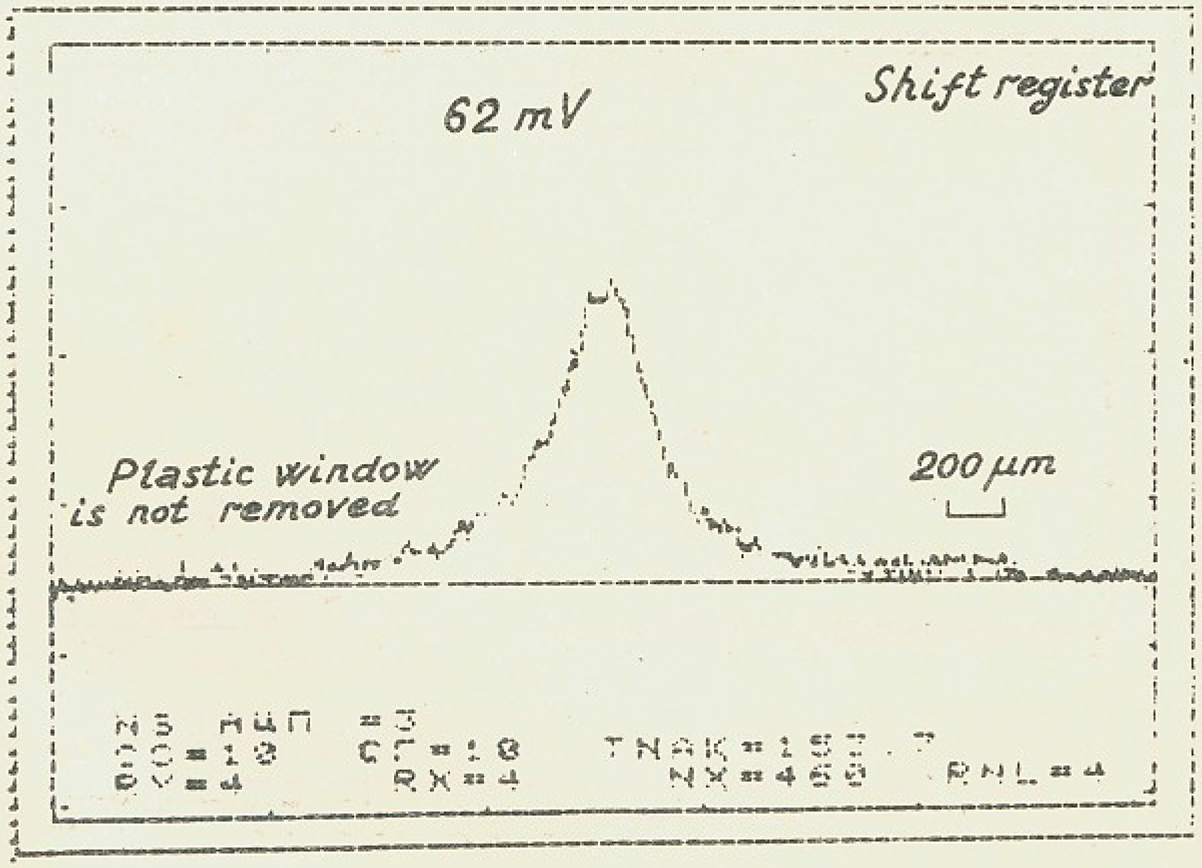
Fig. 7a.

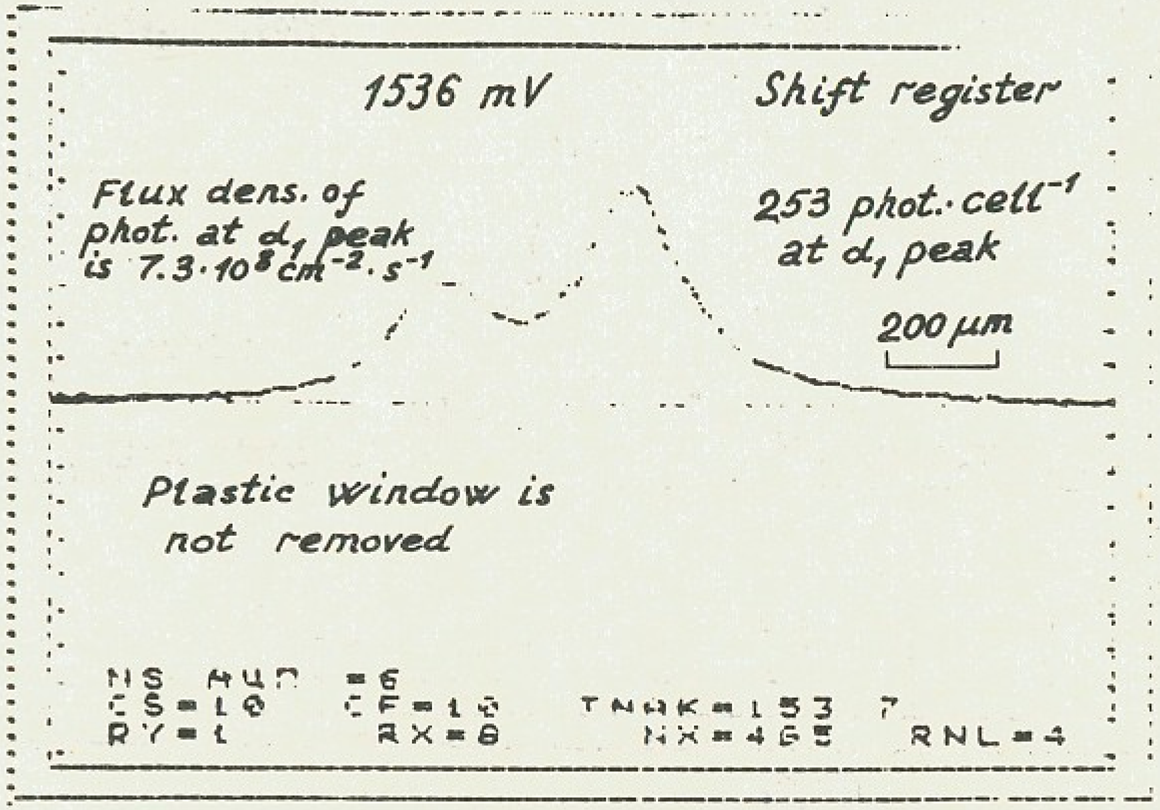




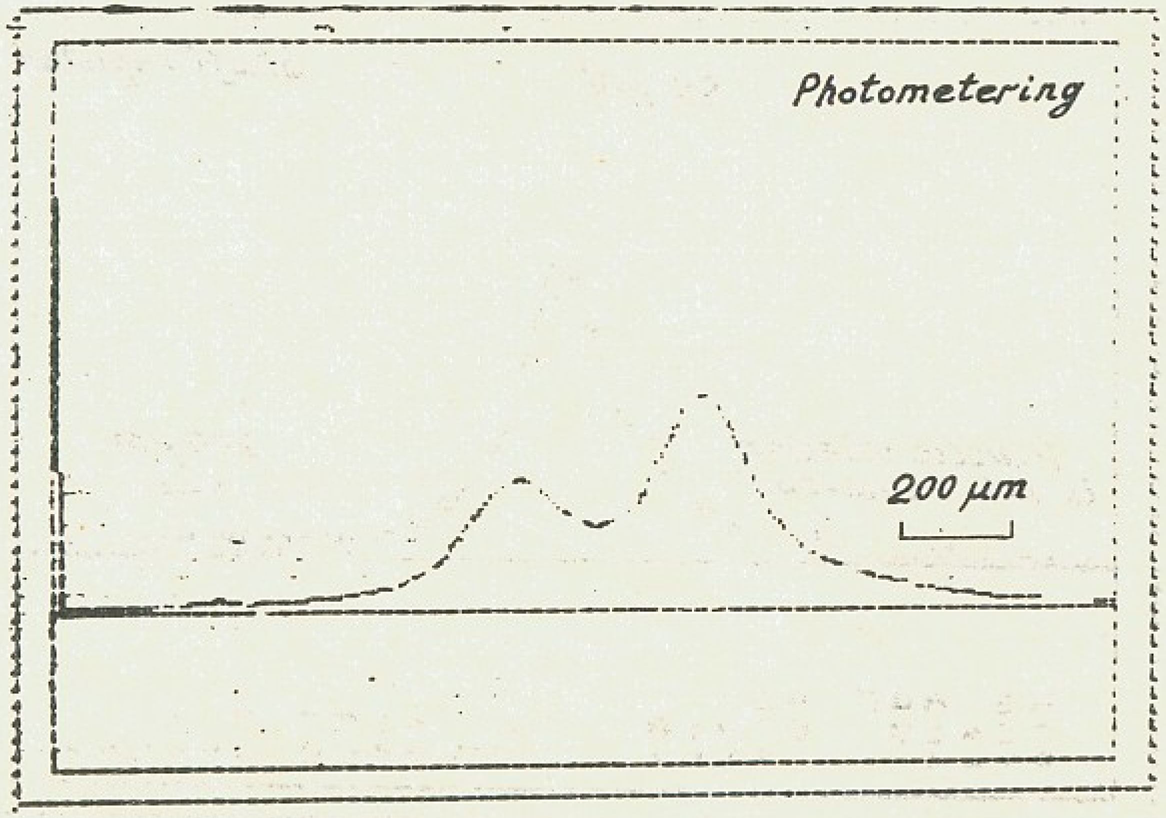
Cr β_1
Flux dens. of phot. at peak is $9.3 \cdot 10^7\ cm^{-2} \cdot s^{-1}$
(32 phot.·cell^{-1} at peak)

Fig. 7b.





$Cu\alpha_{1,2}$ Fig. 7c.



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ИЗМЕРЕНИЕ ПАРАМЕТРОВ ЛИНЕЙНОЙ ПЗС-СТРУКТУРЫ КАК ДЕТЕКТОРА ОДНОМЕРНЫХ РЕНТГЕНОВСКИХ ИЗОБРАЖЕНИЙ

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