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Physical laboratory 3

Task H Photomultiplier

Tasks

1. Determine the dependence of the secondary electron emission coefficient on the energy of the electrons impacting the dynode. Plot $\ln(\sigma/V) = f(V)$. Determine if the secondary electron emission coefficient σ depends on the light intensity on the photocathode.
2. Determine and plot the dependence of the integral photomultiplier sensitivity photomultiplier amplification on the multiplier voltage $S = f(U_a)$ a $M = f(U_a)$.
3. Determine the integral sensitivity of the photocathode $k = I_f/\Phi$.
4. Determine the effect of the dark current on the measurement.

Theory

The photomultiplier is an electro-optical device used for measuring very low-intensity light (e.g. optical spectra). Photomultipliers are used, for example, in scintillating detectors to regulate the brightness and exposure in some x-ray devices or in the sensitive measurement devices of light and luminous flux. Its working principle lies in a combination of two electron emission types – photoemission and secondary emission.

Fotoemise

The photoemission, also called the external photoelectric effect, is characterised by the emission of electrons from the surface of an illuminated body. Its essence is the conversion of the light quantum into the work function and the kinetic energy of an electron realising the electrical conductivity by its flight from one electrode to another. The following laws describe the external photoeffect:

1. The number of electrons emitted per one time unit is proportional to the intensity of the light, i.e. the number of incident photons. Such a formulation of Stoletov's law is valid if the spectral composition of the light does not change with the changing light intensity and that the photocathode is not saturated.
2. The velocity of the electrons emitted from the surface of the photocathode is independent of the light intensity.
3. The initial velocity v_0 of the electrons leaving the photocathode increases with increasing radiation frequency as per Einstein's law:

$$h\nu = w + \frac{mv_0^2}{2}, \tag{1}$$

where $h\nu$ is the energy of the quantum of monochromatic light of the frequency ν and w is the effective work function of the electrons from the photocathode material.

Einstein's law leads to the red limit of the photoeffect. If we select such lowest frequency of the incident radiation with the frequency ν_0, for which we can write

$$h\nu_0 = w \; , \tag{2}$$

the electrons from the photocathode are emitted with the velocity $v_0 = 0$. If the effective work function is $w > h\nu$, no electrons can be emitted from the photocathode because the energy of the light quantum is insufficient for their release from the material. The frequency ν_0 is called the red limit of the photoeffect, and it is dependent on the material of the photocathode. It is in the ultraviolet region for most metals, and only alkaline metals have the red limit in the visible region.

Stoletov's law defines the number of the emitted electrons – the magnitude of the photocurrent from the photocathode due to the effect of photocathode irradiation by spectrally constant light as

$$I_f = k(\lambda)\Phi. \tag{3}$$

The proportionality constant $k(\lambda)$ depends on the wavelength of the incident light. I_f is the current of the primary electrons emitted from the photocathode and Φ is the luminous flux irradiating the photocathode. The $k(\lambda) = f(\lambda)$ dependence is called the spectral characteristic of the photocathode.

Secondary emission

Electrons can also be emitted from an electrode by the impact of fast electrons with their energy higher than the work function of that electrode. Such secondary electrons include newly emitted electrons and electrons backscattered from the surface of the electrode. If the energy of the primary incident electrons is high enough (usually several times the work function of the electrode material), the number of the secondary electrons can be larger than the number of primary electrons. The ratio of the secondary electrons I_{sec} to the primary electrons I_{prim} is called the secondary electron emission coefficient σ.

$$\sigma = \frac{I_{sek}}{I_{prim}} \tag{4}$$

and its magnitude depends on the electrode material and the electron acceleration according to

$$\sigma = A \; E \quad \cdot \exp(-\mu E) \; , \tag{5}$$

where A and μ are electrode (so called dynode) material constants, E is the energy of the electrons incident on the electrode that can be set by the voltage between two neighbouring dynodes (V).

Photomultiplier's principle of operation

A simplified diagram of the principle of the photomultiplier operation is shown in figure 1. The main parts of a photomultiplier are the photocathode FK, a series of dynodes D_i and an anode A. The voltage between the electrodes is set to gradually increase from the cathode over the individual dynodes up to the anode.

Photoelectrons emitted from the photocathode by, e.g. white light, impact the first dynode when its potential accelerates them to a high enough energy. Secondary emission takes place on the first dynode, and $I_1 = \sigma I_f$ secondary electrons leave the first dynode. These secondary electrons of the first dynode become primary electrons of the second dynode, where the same process is repeated. The geometry and the potential distribution around the dynodes are so that

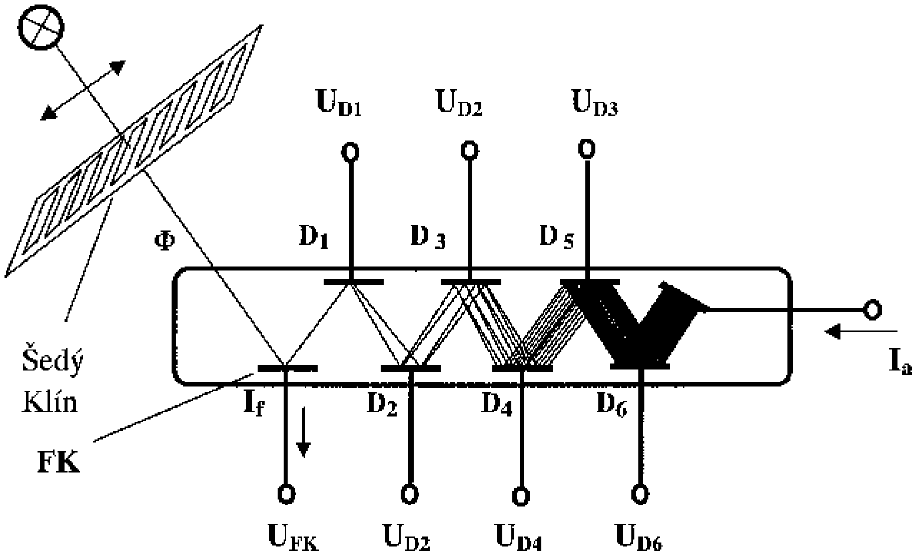

Figure 1: Photomultiplier with 6 dynodes and the coefficient of secondary emission $\sigma = 2$. Φ is the luminous flux, FK is the photocathode, $D_1 \sim D_6$ are the individual dynodes, A is the anode. The electrode potentials suffice the condition $U_A > U_{D6} > \cdots > U_{D1} > U_{FK}$.

nearly all the electrons ejected from the nth dynode are accelerated by the field of the $(n+1)$th dynode and impact it. Electrons from the last dynode then impact the anode.

The whole amplification process, in a simplified manner, can be described by the following equations. The flux of the electrons from the photocathode I_f depends on the luminous flux incident on the photocathode according to Stoletov's law for white light:

$$I_f = k \ \cdot \Phi, \tag{6}$$

where the proportionality constant k corresponds to the sensitivity of the photocathode to white light containing photons of all wavelengths. Therefore, it is known is integral sensitivity of the photocathode. The studied photomultiplier keeps the same voltage V between each dynode pair. If no electron losses in the photomultiplier are considered, the final anode current can be written as

$$I_a = \sigma^n \cdot I_f, \tag{7}$$

where n is the number of dynodes. The photomultiplier amplification M is given by the ratio of the anode current to the photocurrent according to

$$M = \sigma^n = \frac{I_a}{I_f}. \tag{8}$$

Mutually substituting these expressions, we obtain the relations between the amplification, the luminous flux and the final anode current:

$$I_a = Mk\ \Phi = S\ \Phi, \qquad\qquad S\ = Mk, \tag{9}$$

where S is the integral sensitivity of the photomultiplier and k is the integral sensitivity of the photocathode. The dependence of the amplification on the voltage over the photomultiplier $M = f_1(U_a)$ and the dependence of the integral sensitivity on the voltage over the photomultiplier $S = f_2(U_a)$ are the crucial properties of any photomultiplier.

The photomultiplier produces an unwanted current even without any light – the so-called dark current. Its origin is mostly in the thermoemission from the photocathode, and it can be reduced

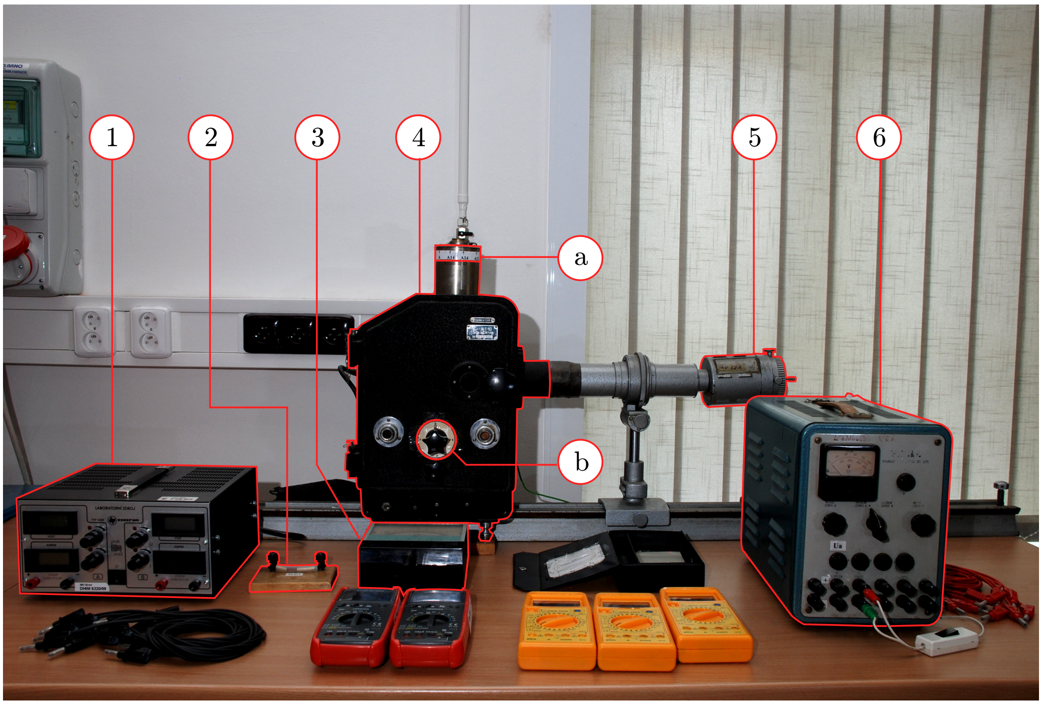

Figure 2: Measurement setup (1) Anode current I_a source. (2) Safety resistor. (3) Microammeter for the anode current measurement. (4) Photomultiplier chamber: a) Socket for electrical connection of the photomultipler. b) Rotating screw of the graded grey plate. (5) Light source. (6) High-voltage source U_a.

by cooling the photocathode. Generally, the dark current needs to be taken into account, and it needs to be subtracted from the measured currents.

Experimental procedure

Figure. 3 shows the diagram of the photomultiplier's connection. All the measurements will be done with this connection. There are 14 dynodes. Most of the dynodes are permanently connected, just connect microammeters to the voltage divider between the 10th and 12th dynode to measure the current on the dynodes (for the determination of the secondary emission coefficient). The high voltage DC power source supplies 400 – 1000 V to the voltage divider between the photocathode and the 14th dynode. A safety resistor, microammeter with the 100 μA range and an acceleration DC source set to 80 V and the polarity towards the anode are connected between the anode and the 14th dynode.

The photocathode illumination needs to be done with care in order not to damage it. The light flux can be changed by a graded grey plate placed in front of the light entrance of the photocathode. The description of the grey plate control, including a graph for estimation of the luminous flux Φ are available on-site. The light-sensitive layer on the photocathode can be damaged by light overexposure, and the cathode will then permanently lose its sensitivity. The photocathode may not be under any circumstances exposed to ambient sunlight when the voltage U_a between the photocathode and the anode is connected.

The assembled apparatus allows for the control of the voltage on the multiplier (U_a) and the luminous flux on the photocathode (Φ). You can measure the anode current (I_a), the current through the 10th (I_{10}) and 12th (I_{12}) dynode and the voltage on the multiplier (U_a).

For 3 different luminous flux values, measure all the parameters needed to calculate the dependence of the secondary electron emission coefficient, integral sensitivity of the photomultiplier and the photomultiplier amplification on the voltage on photomultiplier. Determine the influ-

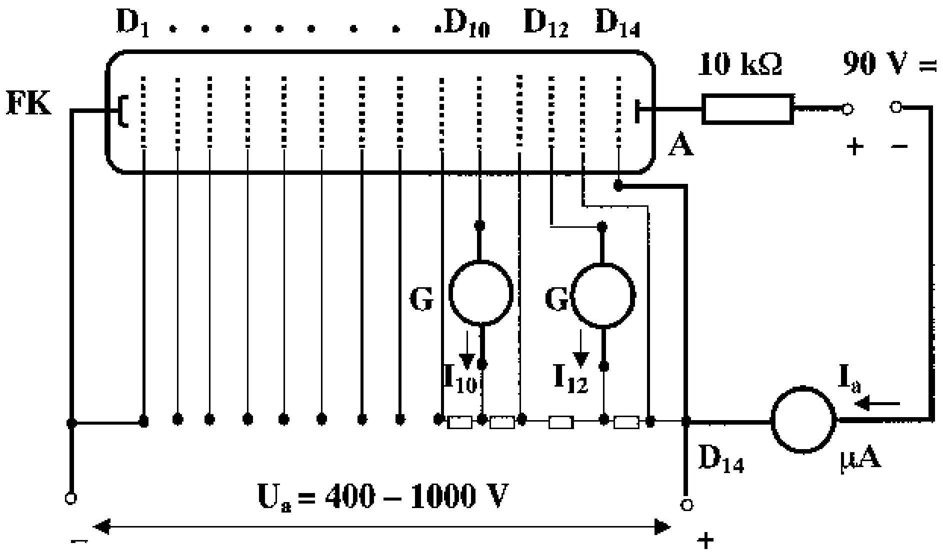

Figure 3: Photomultiplier electrical connection diagram: The photomultiplier voltage U_a is divided by a voltage divider between the individual dynodes. Only the highlighted parts (further specified by the teacher) need to be connected at the start of the task. Other parts are connected permanently.

ence of the dark current on the measurement while the light source is turned off. Determine if the secondary electron emission coefficient (σ) depends on the intensity of the irradiation of the photocathode. You can do this by measuring the secondary electron emission coefficient for all the different grey plate settings $\Phi_1, \ldots, \Phi_7$ at a constant voltage on the multiplier. Do so for 2 different multiplier voltages.

Assuming all the dynodes in the multiplier are of the same material and that the voltage between every two neighbouring dynodes is equal, the secondary electron emission coefficient can be determined from the I_{10} and I_{12} currents according to:

$$\sigma = \sqrt{\frac{I_{12}}{I_{10}}} \tag{10}$$

Using the calculated value of σ we can determine the photocurrent I_f. All of the remaining unknown parameters can be determined from the available quantities. According to the magnitude of the dark current on the dynodes I_{10}, I_{12} and the anode I_a at zero luminous flux on the photocathode $\Phi = 0$ determine if a correction of the measured values with non-zero luminous flux need to be corrected to the dark current.

Report tips: The results will be clearer when all the analogical dependencies measured for different photocathode illumination levels are plotted in a single graph. Different symbols mark the different dependencies. If a theoretical expression for a given measured dependence exists, it is appropriate to plot also the theoretical dependence based on the said expression.

- You will be using voltages of around 1 000 V during your measurements, be careful!
- The anode current I_a may never exceed 100 µA. Higher currents can cause photocathode damage.

Practical use

Photomultipliers are a part of elementary particle detection systems practically used in many fields, from light industry through medicine to particle physics and astrophysics.

From its principle of operation, a photomultiplier itself can be used only as a detector of visible light or in near-UV or near-IR light. In detectors of different elementary particles different from photons of said frequency interval (typically X-ray photons or electrons), a scintillation material is put in front of the photomultiplier. Interaction of the particles with the scintillating material will cause the emission of photons typically from the visible range. These are detected by the photomultiplier and pass the information about the particles impacting the scintillator.

Detectors of light, UV and IR radiation equipped by a photomultiplier

Photomultipliers are used as light detectors in spectrometers (absorption and emission) used for chemical analysis.

Measurements of light by a photomultiplier is also used while monitoring the environment. For example, the optical transmission of the environment can be measured, and the amount of dust in the air can be calculated from such measurements. Also, gas molecule excitation and consecutive measurement of the light emitted during the deexcitation is often used. The concentration of pollutants such as sulphur oxides or nitrogen oxides can be measured in such a manner. Photomultipliers are also used in biology and biotechnology. They are used to detect light emitted by or reflected from the investigated biological structures in devices such as cytometers, confocal laser microscopes or DNA sequencers.

In the field of experimental physics, photomultipliers are used as detectors of the Cherenkov radiation caused by the deceleration of particles created, e.g. by different collision processes in particle accelerators. A special device containing several thousand photomultipliers is the neutrino detector in Kamiokande in Japan.

Detectors combining a scintillator and a photomultiplier

In medicine, scintillator-photomultiplier detectors are used in different X-ray diagnostic devices such as gamma cameras or positron emission tomography.

Particle physics utilises such detectors in experimental devices such as TOF counters or calorimeters used for energy and trajectory determination of elementary particles.

Scintillator-photomultiplier detectors placed on satellites detect extraterrestrial X-ray radiation.

The combination of a scintillator and a photomultiplier is also used in radiation dose measurements. Areas around nuclear reactors or goods during customs check are measured this way.

In the industry, the combination of an X-ray radiation source and a scintillator-photomultiplier detector is used, for example, to measure oil content in the soil or to measure material thickness, e.g. in paper manufacturing.

The combination of a scintillator and a photomultiplier is used for electron detection in electron microscope imaging.

Semiconductor detectors are replacing photomultipliers in many of the aforementioned fields. This is due to miniaturisation as well as lowering the price of the device. We can nowadays find PIN diodes in backscattered electron detectors in electron microscopy. The avalanche Photo-Diode (APD) is now often used as a visible light detection in some applications.

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