28. Measurement of Planck`s constant

Assignment

1. Measure the *V-A* characteristic of a vacuum photocell for various wavelengths.
2. Extrapolate the linear parts of characteristics to obtain the cut-off voltage U_z.
3. Plot U_z versus $1/\lambda$ and then read off the slope $\frac{U_z}{1/\lambda}$ using formula (10.3) to calculate the Planck constant.

Theoretical part

In year 1900 Max Planck presented a derivation of the black-body-radiation law. In this derivation of the theoretical expression for the intensity of radiation as a function of the wavelengths and temperature Planck departed from classical physics by making a radical assumption that an oscillator of natural frequency can take up or give off the frequency only in portions of magnitude

$$E = \omega\hbar, \tag{10.1}$$

where $\hbar$ is Planck s constant

Around the turn of this century it was know experimentally that the light (in the visible or ultraviolet region) when incident on a metal surface expelled electrons from it. The kinetic energy of the ejected electrons was independent of the intensity of the light but did depend on the frequency in every simple way. Namely, it increased linearly with frequency.

Albert Einstein in 1905 suggested a common explanation of the phenomena mentioned above. According to this explanation the energy in a beam of monochromatic light propagates in portions of magnitude $\hbar\omega$. If this quantum of energy is transferred to an electron it is transferred completely. The electron inside the metal acquires, in the other words, the energy $E = \omega\hbar$.

When the quanta of the light fall on the surface of metal, their energy is absorbing by the electrons of metal. Because the conductive electrons are bound very weakly in the crystal lattice they can escape easily. During this process they must overcome the attractive power from ions of the metal. We can characterise it by the work function of the metal, which represents the work needed for releasing an electron from the metal. The energy balance of an individual absorption act is

$$\hbar\omega = W + \frac{1}{2}mv^2, \qquad (10.2)$$

where W is the work, done in escaping from the surface of metal, $\hbar$ is Planck's constant and the second term on the right-hand side is the kinetic energy of the escaping electron. From this formula it follows immediately that the photoelectric effect can appear if the energy of photon is greater than the work needed for electron's escaping from the surface. It means that the frequency of the light causing the photoelectric effect must be greater than the critical value ω_0 given by

$$\hbar\omega_0 = W \qquad (10.3)$$

The frequency $\omega_0 = \dfrac{2\pi c}{\lambda_0}$, where c is the speed of light is called the red light threshold of photoelectric effect. Equation (10.2) is Einstein's photoelectric equation. Because the energy of the emitted electrons

$$E_{kin} = \hbar\omega - W \qquad (10.4)$$

increases linearly with the frequency, but is independent of the intensity of the light. The number of electrons emitted is proportional to the number of incident quanta and hence proportional to the intensity of the incident light.

Some of the most important characteristics of the photoelectric effects may be demonstrated in the vacuum cell. Monochromatic light is incident on a metal (usually an alkali metal: sodium or potassium electrode-cathode *K*) and causes the emission of photoelectrons. The photoelectrons are collected to the anode *A*, which can be kept at

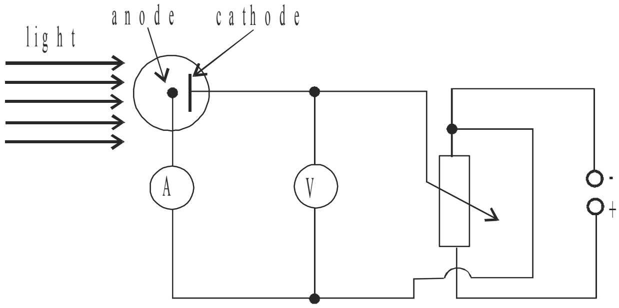

Fig. 10.1

an arbitrary potential *V* with respect to the cathode. The current of electrons is measured by a galvanometer or another sensitive device. Circuit for measuring

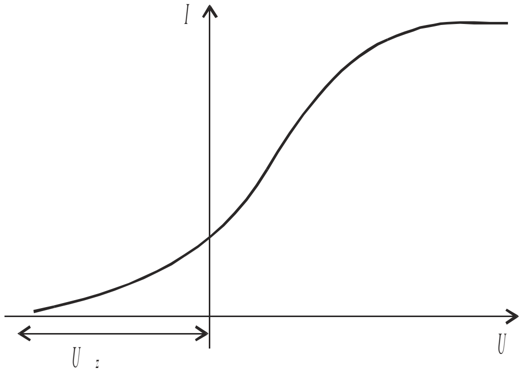

Fig. 10.2

photoelectric effect is shown in Fig. 10.1.

Typical V-A characteristic of the photocell is in Fig.10.2. In order to measure the maximal kinetic energy of the electrons we apply a negative potential to the anode to slow them down. If the negative potential increases the photocurrent decreases as fewer and fewer electrons are able to overcome it. If the potential reaches a certain value the photocurrent ceases completely. The following relation then holds

$$eU_z = E_{kin}\,, \qquad (10.5)$$

where *e* is the charge of electron U_z is retarding potential.

We can therefore observe the current as a function of the retarding potential *U*. If U_z is the potential at which the current just becomes zero, we have

$$\hbar\omega = \hbar\omega_0 + eU_z \tag{10.6}$$

$$U_z = \frac{\hbar c}{2\pi e}\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) \tag{10.7}$$

Now, we are going to show how the number of electrons emitted from cathode per unit time can be assessed. As shown in Fig. 10.2 if the potential of the anode is positive but small, only a little part of the electrons is incident on the anode. If the voltage of the anode is being increased the electrons are more and more attracted to the anode and photocurrent is linearly increasing. When the voltage achieves a certain value, all of the electrons emitted from cathode reach the anode.

Linear slope can be extrapolated to cut-off voltage U_z (for each wavelength). By plotting *I* versus *U* and extrapolating the linear parts of characteristics we can obtain one cut-off voltage for each wavelength. Then we draw a straight line U_z versus $1/\lambda$ and using equation (10.7) we calculate the Planck constant.

The method-practical part

At present, the photomultiplier is used as a photon detector. The Fig.10.3 shows such a tube schematically:

Photons enter through the glass window of the tube and release photoelectrons from a very thin alkali-metal film on the inner surface of the window. The electrons are accelerated and focused on the first dynode. Each electron which hits the first dynode gives rise to several are accelerated and focused on the second dynode, where they give

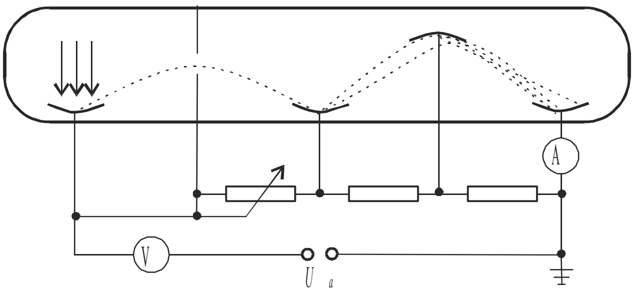

Fig. 10.4

rise to more secondary electrons. These are accelerated and focused on the next dynode, and so on. The last electrode is anode. For each detected photon an avalanche of electrons reaches the anode, which is coupled to an external amplifier. Voltage between neighbouring dynodes is from 100V to 150V (Fig. 10.4).

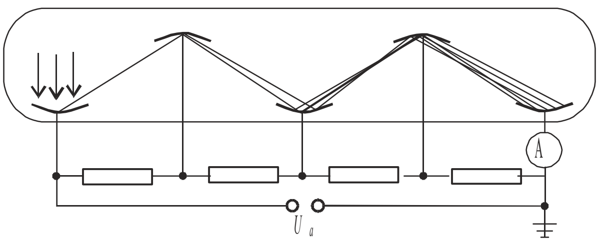

Fig. 10.3

The scheme of circuit with a photomultiplier is in Fig.10.5. In our arrangement the photocell is represented by the photocathode and the first dynode of the photomultiplier as anode. The selection of wavelengths is done by different colour of filters. Each filter, based on the light interference, transmits only a narrow interval of the wavelengths from the continuous spectrum emitted from the filament of a bulb. The midpoint of the wavelength interval is shown on the embrace of the filter. Photomultiplier is a very sensitive detector. If the illumination is very strong, the multiplier can be damaged. Therefore we must regulate light's flow by changing the slit of the shade.

Measurement

Apparatus: optical equipment, stabilised power source, sets of interference filters, objective, photomultiplier, potentiometer for regulation U_z, voltmeter, microammeter, lamp-shade.

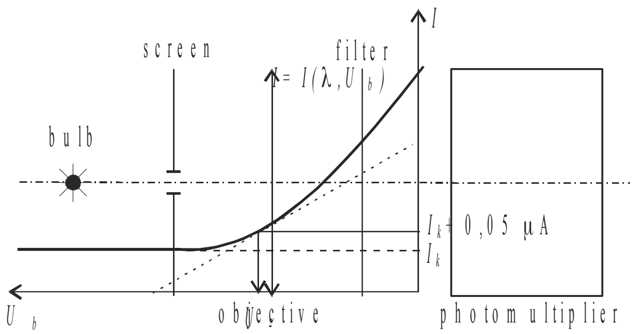

Fig.10.6 Fig.10.5

Experimental procedure: The details of apparatus may vary, so please consult the manual accompanying the set you will actually use. Measure *V-A* characteristics by stepwise setting of the voltage *U.* These measurements repeat for several wavelengths.

Extrapolate linear slopes to one cut-off voltage U_z for each wavelength. Draw a straight line U_z versus $1/\lambda$ in the graph.

Calculation: Fig. 10.6 shows the *V-A* characteristic for one wavelength. The current is slowly falling into its residual value I_k, which is independent of U_z. The point where the straight line $I = I_k + 0.05\ \mathrm{A}$ intersects the *V-A* characteristic determines U_z. Determine the slope of U_z versus $1/\lambda$ dependence by linear regression. This slope determines value $\frac{2\pi\hbar c}{\lambda}$ with the relative error up to 10%.

The remark: Value of Planck's constant established from short wavelength limit of the continuous part of Röntgen's spectra is $h = 2\pi\hbar = (6.626176 \pm 0.000036)\,10^{-34}\ \mathrm{J \cdot s}$, charge of the electron is $e = (1.6021892 \pm 0.0000046)\ 10^{-19}\,\mathrm{C}$, speed of light is $c = 2.99792458\ 10^{8}\,\mathrm{m \cdot s^{-1}}$