A 54: Photoeffekt

1. Introduction

The illumination of a metal surface can lead to a measurable emission of electrons. This phenomenon was first observed by H. Hertz (1887) and is explained by the quantum nature of light by A. Einstein (1905). If we consider a beam of light as a flow of particles (photons), each particle of which carries the energy Eph = hν, then it follows from the law of conservation of energy in the photoionization process:

$$h\nu - \phi = E_{kin,max}, \qquad (1)$$

i.e. the measured maximum of the kinetic energy of the emitted electrons (photoelectrons) represents a difference between the photon energy $E_{ph} = h\nu$ and the work function. So the maximum kinetic energy of the photoelectrons depends on the photon energy, i.e. on the wavelength λ of the light:

$$h\nu = hc/\lambda \qquad (2)$$

The aim of the practical experiment is to determine the work function of the existing metal surfaces and the Planck constant h.

2. Schematische Darstellung des Experiments

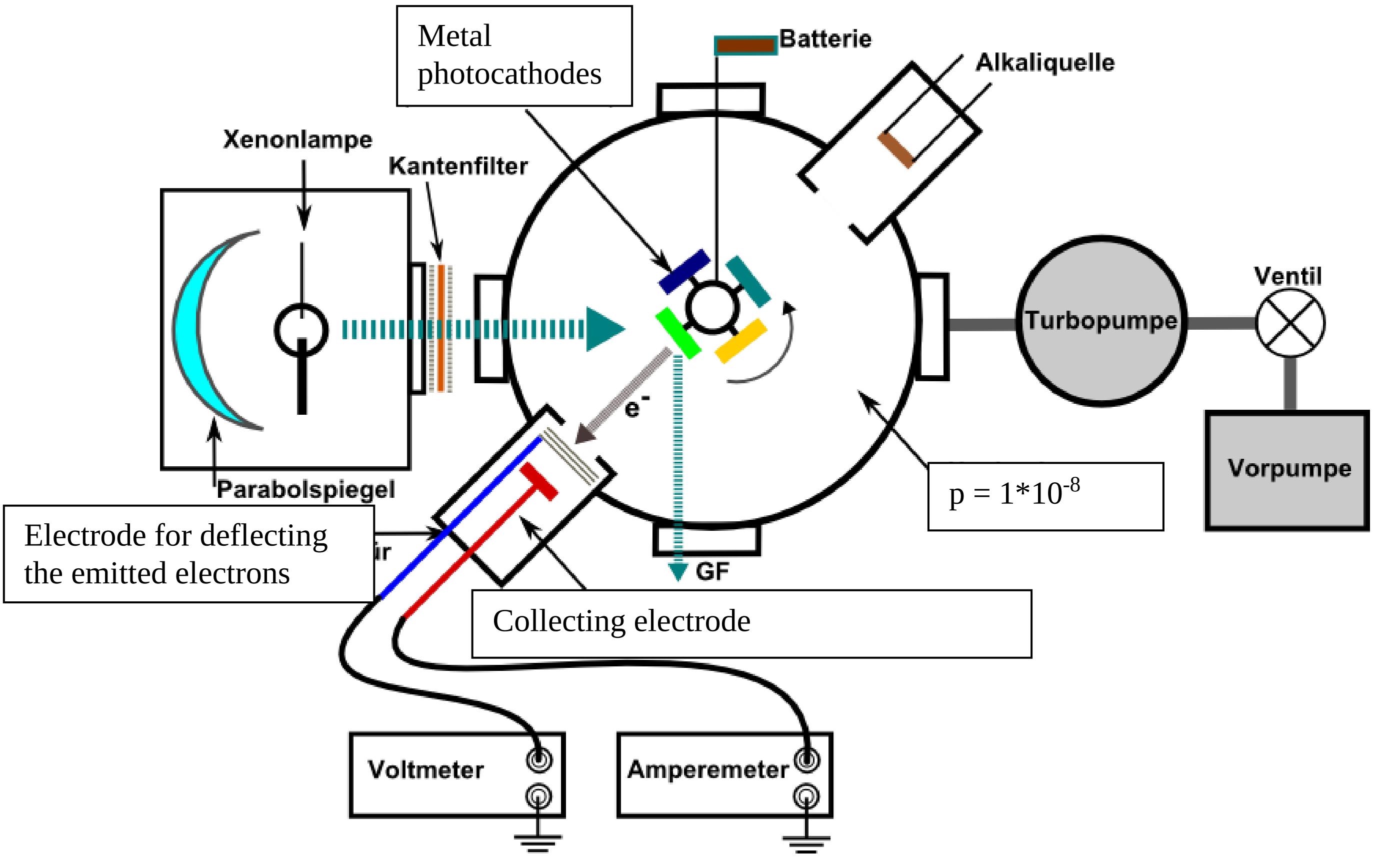

Abb. 1: Scheme of the Experiment

3. The Measurments

In this experiment the current *I* of the photoelectrons is measured, which leave the surface under illumination of a metal plate (photocathode) and reach the collecting electrode. The photoelectrons have to overcome the field of the grid electrode on their way to the detector. In order to determine the maximum kinetic energy of the photoelectrons, the retarding negative potential of the grid U is gradually increased until no more photoelectrons can reach the detector, i.e. at $U = U_{max}$ $(I = 0)$, $E_{kin,max} = eU_{max}$ (e – electroncharge) is valid. According to equation (2) the maximum kinetic energy of the photoelectrons depends on the selected wavelength of the light. To determine the work function of a selected metal surface, the measurement of $E_{kin.max}$ is repeated for several wavelengths and the dependence $U_{max}(\nu)$ is plotted.

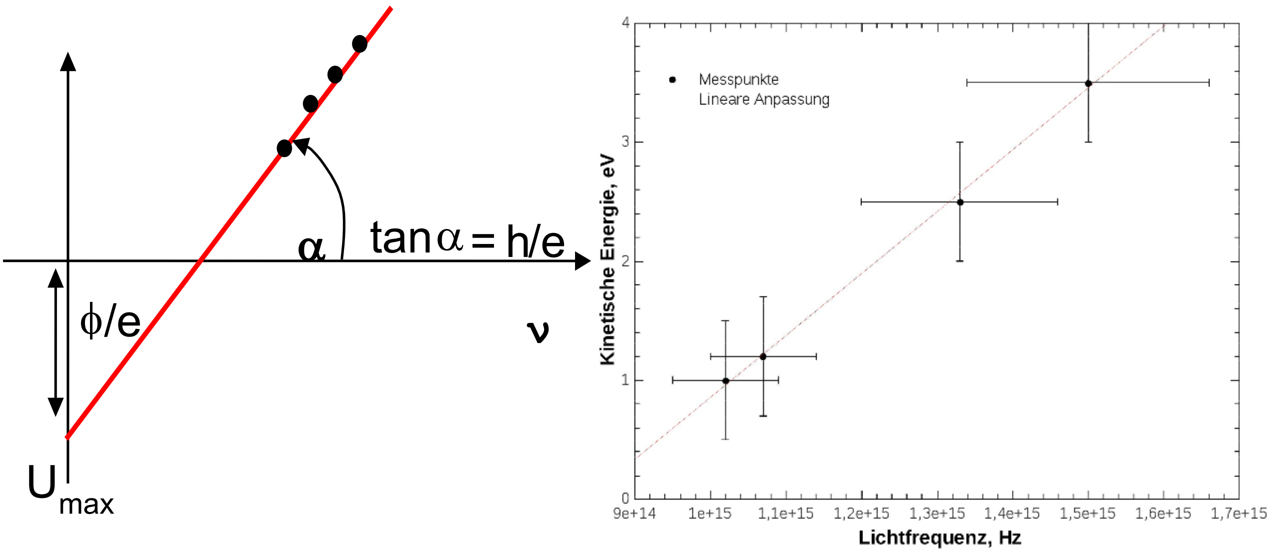

Fig. 2: Evaluation with schematic sketch (left) and with Origin (right)

The Planck constant is calculated from the slope of the straight line and the work function is calculated from the intercept of the straight line with the U axis.

4. Conducting des Experiments

The work on this experiment starts with the switching on of the backing pump VP. After about 20 minutes the turbomolecular pump TP is switched on and after about 2 minutes the separation valve V should be opened. Thus the vacuum in the main chamber is reached in the range 10^{-6} mbar (this part should be performed by the supervisor). Before starting the experiment the voltage of the battery pack U_{Batt} should be measured.
The measurement starts by switching on the power supply of the light source and igniting the discharge at the xenon lamp after approx. 2 minutes (fast pressure on the red start button). The lamp emits intense UV light. The light beam must be directed to the centre of the photocathode A, the calibration cathode (copper, 330°). The correct geometrical beam guidance can be

recognized by the fact that the light appears in the centre of the window GF after reflection at the photocathode (the orange filter is illuminated in the centre).
The dependence on the wavelength is measured by means of the edge filters. An edge filter blocks the high-energy part of the photon flux and thus defines the minimum wavelength λ^* as well as the maximum frequency of the transmitted light wave (see Fig. 3). The high-energy photons ($E^*=h\nu^*$, $\nu^*=c/\lambda^*$) of this light wave make the largest contribution to the photoelectric effect.

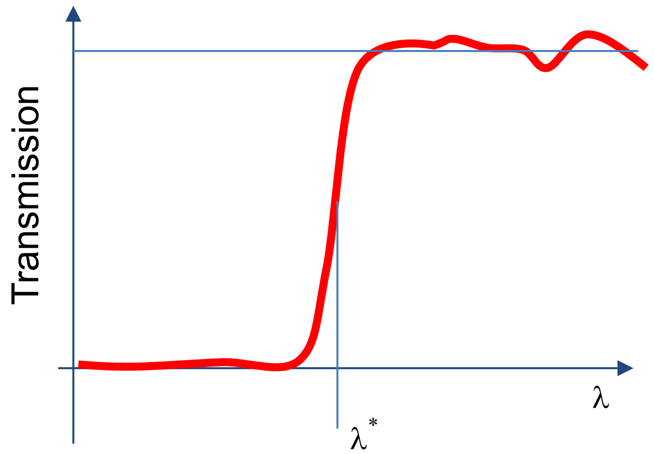

Fig. 3
Typical charakteristics of an edge filter: Transmission vs Wavelength, T(λ).

The measurement of the photoelectron current can now begin by switching on the picoamperemeter (measuring range <1µA). At a wavelength λ (the corresponding edge filter) and a selected photocathode (A, B, C or D), the photoelectron current I_e is measured as a function of the braking voltage U_{Brems}. Each measurement of the $I_e(U_{Brems})$ function is controlled by a Labview program. The computer-aided control is located on the desktop in the folder "PHOTOEFECT A54". The control consists of two parts: "Readme" and " Photoeffekt-Messprogramm". In the "Readme" the parameters of the measuring process are described in detail. In the second step, the "Photoelectric effect measuring program" is to be started. Before starting the automatic measurement of the $I_e(U_{Brems})$function, the optical arrangement (light beam photocathode detector) must be optimized. The maximization of the current Ie is activated by pressing the "Adjust Photocathode" key. Adjust the angle of the selected photocathode until the relative intensity meter reads 100 %. Then the maximum current can be read off the picoamperemeter (without edge filter). The $I_e(U_{Brems})$function is measured with the " Photoeffekt-Messprogramm". First, however, the measurement parameters taken from the "Readme" program must be set in the fields provided in the "Photoelectric effect measuring program": the initial voltage Ui=-20 V, the final voltage U_f=-35 V and the step size U (from -0.1 to -0.5 V). This voltage window is predefined by the current battery voltage (U_{batt} approx. -27 V) and can be varied accordingly. The measurement is activated with the "Start" key. The program increases the brake voltage U_{Brems} stepwise with an adjustable step size ΔU and the current strength of the picoamperemeter is automatically read out and plotted logarithmically as a Y-axis (-1*(current strength + offset)). The offset is fixed. The recorded $I_e(U_{Brems})$ function should be saved in the folder "My Documents" after stopping the measuring program ("Stop" button) (file name: group number, angle, wavelength). This procedure is carried out for all existing edge filters () to determine the work function of the photocathode A. This series should also be performed for the remaining 3 photocathodes B, C and D. After completion of the measurement, first switch off the light source and the power supply unit. Then the valve V is closed before first the turbomolecular pump and then the backing pump are switched off.

5. Evaluation

To read out the respective brake voltage, the data is plotted as shown in Figure 3. $U_{Brems,max}$ and its uncertainty are read out. In addition to U_{max}, the value obtained contains U_{Batt} and a construction-related systematic error of the system ΔU_{Syst}:

$$\frac{E_{kin}}{e} = U_{Brems,max} - U_{Batt} + \Delta U_{syst} \qquad (3)$$

This shift ΔU_{Syst} is determined from a measurement with a known metal plate and included for all unknown plates. The calculated U_{max} are plotted over the maximum frequency of the incident photons as in Figure 2 with the corresponding error intervals and the respective exit work is calculated. This should be evaluated for all cathodes. For the determination of Planck's constant h, the mean value from all 4 experiments is calculated with corresponding error calculation.
The photocurrent measured at the beginning of the experiment is now to be considered as a function of the excitation energy. For this purpose the function

$$I(hv) = a * \exp((hv - \varphi)/b)$$

is fitted to the calculated and measured values are fitted. **The parameters of the fit and considerations of their relevance, as well as Planck's constant and the 4 values of the exit work are among the relevant results of this experiment.**

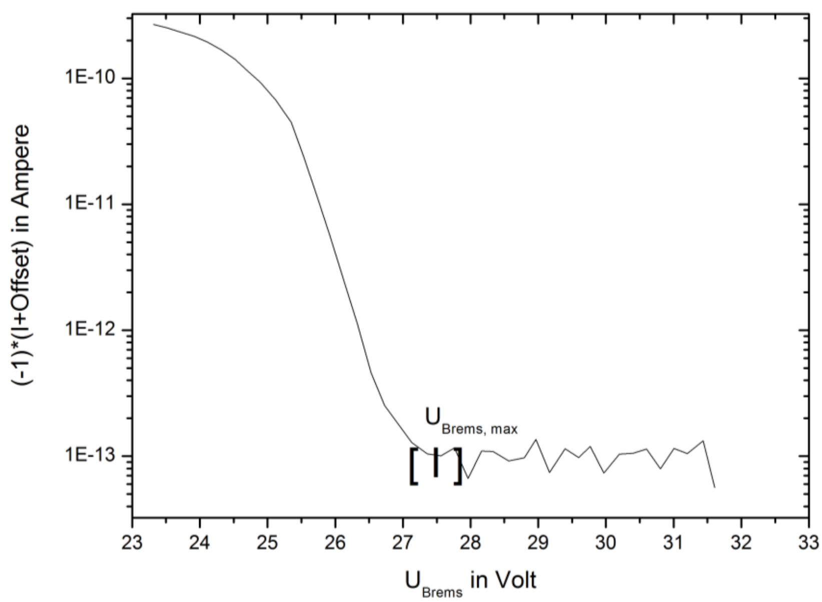

Fig. 4: Example measurement with estimated position of $U_{Brems,\ max}$ as 27,5±0,5V.
Compare the obtained exit work with tabular values to identify the material of the photocathodes used.

6. Error calculation

In this Experiment, the error of the linear regression shall be determined. The errors of the maximum brake voltage $U_{Brems,\ max}$ max are estimated from the $I(U_{Brems})$ graphs.
The shortest wavelength λ (indicated on the edge filters) corresponds to 50% light transmission. The errors of the wavelength for the evaluation could therefore be assumed as 20nm.

The determination of an error of the linear regression $y = ax + b$ with known measurement error and the confidence $K = 1 - \alpha$ is carried out as follows:

1. the slope a and the axis intercept b are determined by means of evaluation programs
2. a is determined from the equation $\Phi(x_a) = 1 - \frac{\alpha}{4}$, where $\Phi(x_a)$ represents the standard normal distribution and is tabulated. For the confidence K=0,8 (α=0,2) xa follows ≈1.65. In this experiment, the calculation is to be performed with the confidence 0.95.
3. the errors for slope a and intercept b are calculated as follows:

$$\Delta a = \frac{x_a \sigma}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}}, \quad \Delta b = x_a \sigma \sqrt{\frac{1}{n} + \frac{\bar{x}^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}}$$

Here σ is the known error of y_i.

Tip: Older versions of Origin calculate the linear regression error as:

$$\Delta a_{\text{Origin}} = \frac{s}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}}, \quad \Delta b_{Origin} = s \sqrt{\frac{1}{n} + \frac{\bar{x}^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}}$$

With the estimation of the standard deviation s (also shown in Origin when the "Root MSE" option is enabled in the "Properties to Calculate" section of the fitting)

$$s = \sqrt{\frac{1}{n-2}\sum_{i=1}^{n}(y_i - ax_i - b)^2}$$

Follows:

$$\Delta a = \frac{\Delta a_{Origin}\, x_a\, \sigma}{s}, \quad \Delta b = \frac{\Delta b_{Origin}\, x_a\, \sigma}{s}$$

With current origin versions, errors for a selected confidence range can also be displayed directly.
To display the result of the Planck's constant, an average value is formed from the various hi values and the uncertainty is given by the maximum error Δhi.

7. Knowledgebase

- **a)** Electron in the periodic potential of the solid (Bloch function)
- **b)** Fermi gas of electrons, Fermi statistics, state density and Fermi energy (Sommerfeld model)
- c) Definition of the work function and the chemical potential of the electrons in the solid
- d) Description of the light beam as electromagnetic wave
- e) Wave-particle duality
- f) Fundamentals of photoelectron spectroscopy

8. Literature

a) C. Kittel, Einführung in die Festkörperphysik, Oldenburg-Verlag, München, 2013.
b) G. Ertl, J. Küppers, Low energy electrons and surface chemistry, VCH, Weinheim, 1985.
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d) L. Bergmann et al., Optik, de Gruyter, Berlin, 1987.
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f) A. Einstein, Ann. Phys., 17, 132 (1905).
g) S. Hüfner, Photoelectron Spectroscopy, Springer-Verlag, Berlin, 1995.
h) M. Henzler, W. Göpel, Oberflächenphysik des Festkörpers, Teubner Studienbücher, Stuttgart, 1994.
i) Skript zur Vorlesung „Physikalische Chemie der Grenzflächen“, A. Böttcher im ILIAS 2017.

9. Additional questions

a) Which interactions contribute to the work function of a solid?
b) What happens with electrons in the solid when the temperature rises and how does thermal emission from metal surfaces occur (Richardson-Dushman equation)?