Department of Physics

8.13: Photoelectric Effect Experiment

Vinh Q. Tran

Vinh Q. Tran
BSc Physics Candidate at MIT

March 10th, 2025

Table of Contents

Photoelectric effect

- First observed by Heindrich Hertz in 1887 and later explained by Albert Einstein.

Photoelectric effect

- First observed by Heindrich Hertz in 1887 and later explained by Albert Einstein.
- Describe the phenomenon where charged particles are liberated from the metal surface by light of short wavelengths.

Photoelectric effect

- First observed by Heindrich Hertz in 1887 and later explained by Albert Einstein.
- Describe the phenomenon where charged particles are liberated from the metal surface by light of short wavelengths.
- Motivated by the idea of quanta of light (photon), and follow the formular

$$h\nu = K + \phi$$

  with h as the Plank constant, ν as the light frequency, K as the residual kinetic energy of the charge particle, and ϕ as the work function of the material.

Photoelectric effect

- First observed by Heindrich Hertz in 1887 and later explained by Albert Einstein.

- Describe the phenomenon where charged particles are liberated from the metal surface by light of short wavelengths.

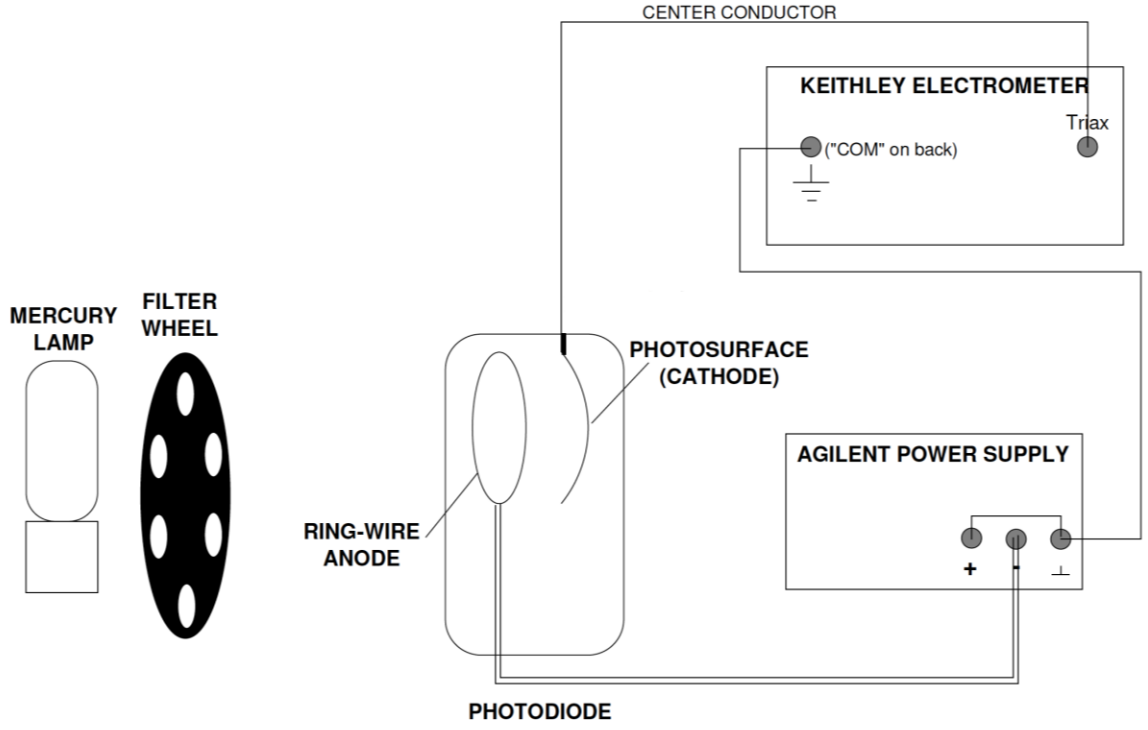
- Motivated by the idea of quanta of light (photon), and follow the formular

$$h\nu = K + \phi$$

  with h as the Plank constant, ν as the light frequency, K as the residual kinetic energy of the charge particle, and ϕ as the work function of the material.

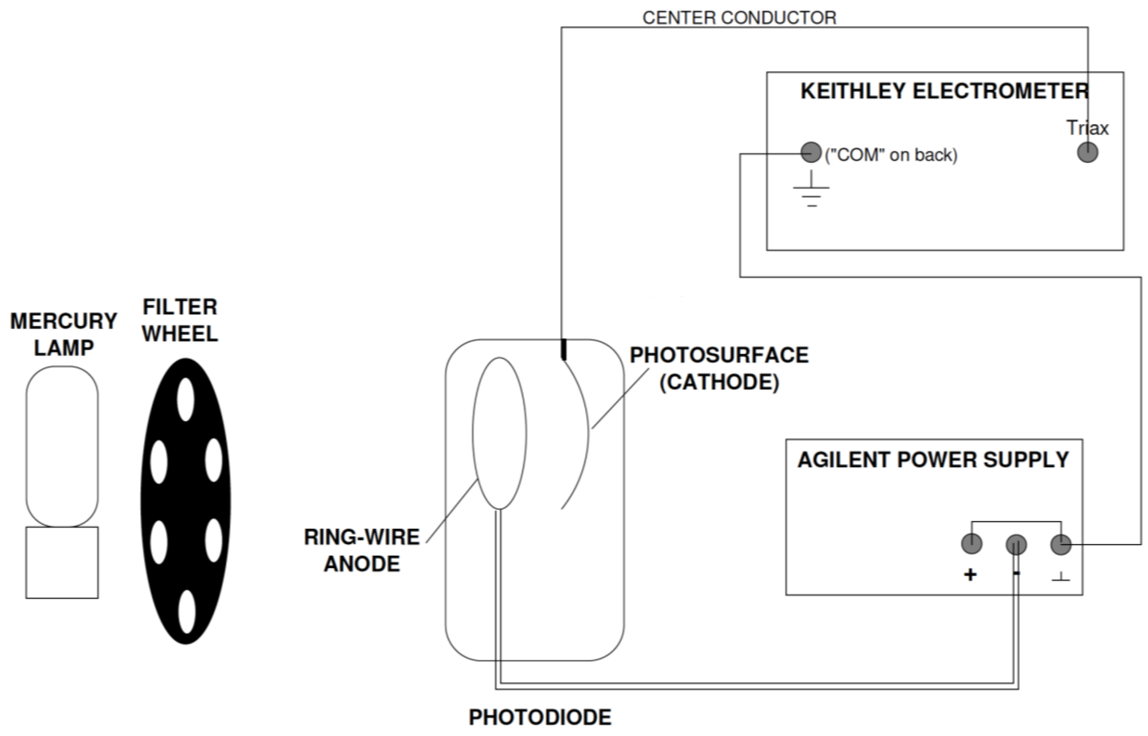
- In this experiment, we look at $K = eV_{\text{cutoff}}$, with V_{cutoff} as the (retarded) cutoff voltage.

Experiment apparatus



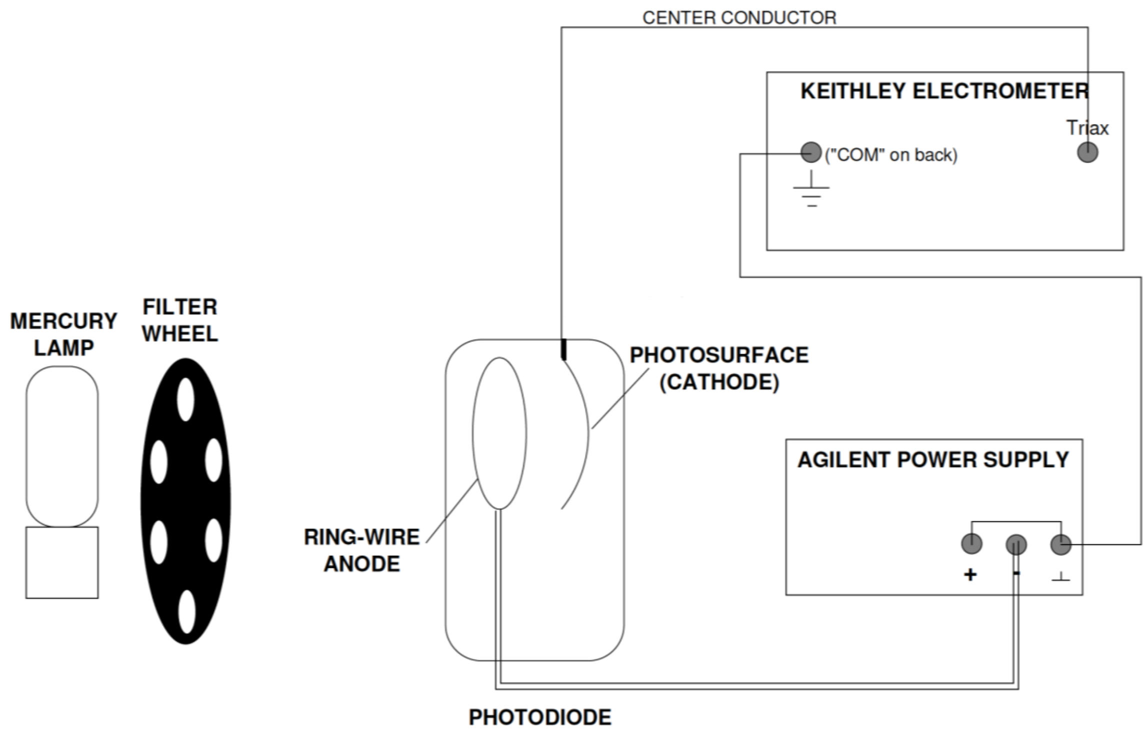
Experiment apparatus

- Measurements are made with the wavelengths of $\lambda = 365.0, 404.7, 435.8,$ and 546.2 nm, isolated using the filter wheel.



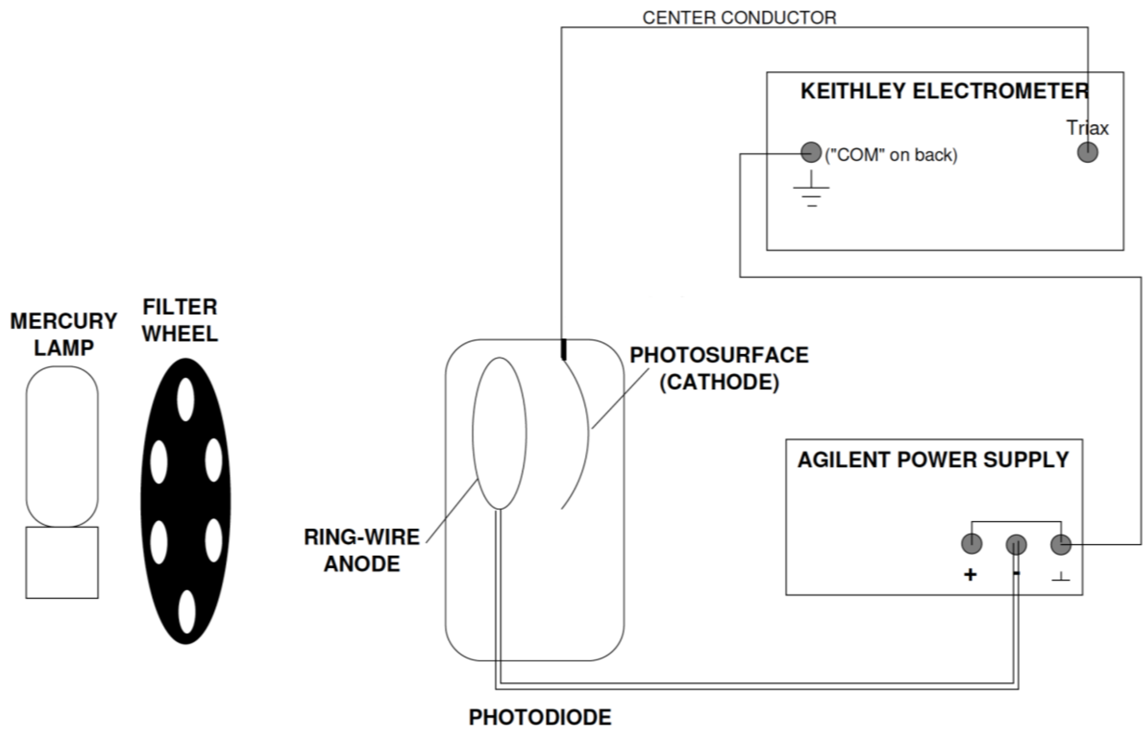
Experiment apparatus

- Measurements are made with the wavelengths of $\lambda = 365.0, 404.7, 435.8,\ \text{and}\ 546.2\ \text{nm}$, isolated using the filter wheel.
- Photodiode has a potassium photosurface (cathode) and platinum-rhodium alloy anode ring with high work function.



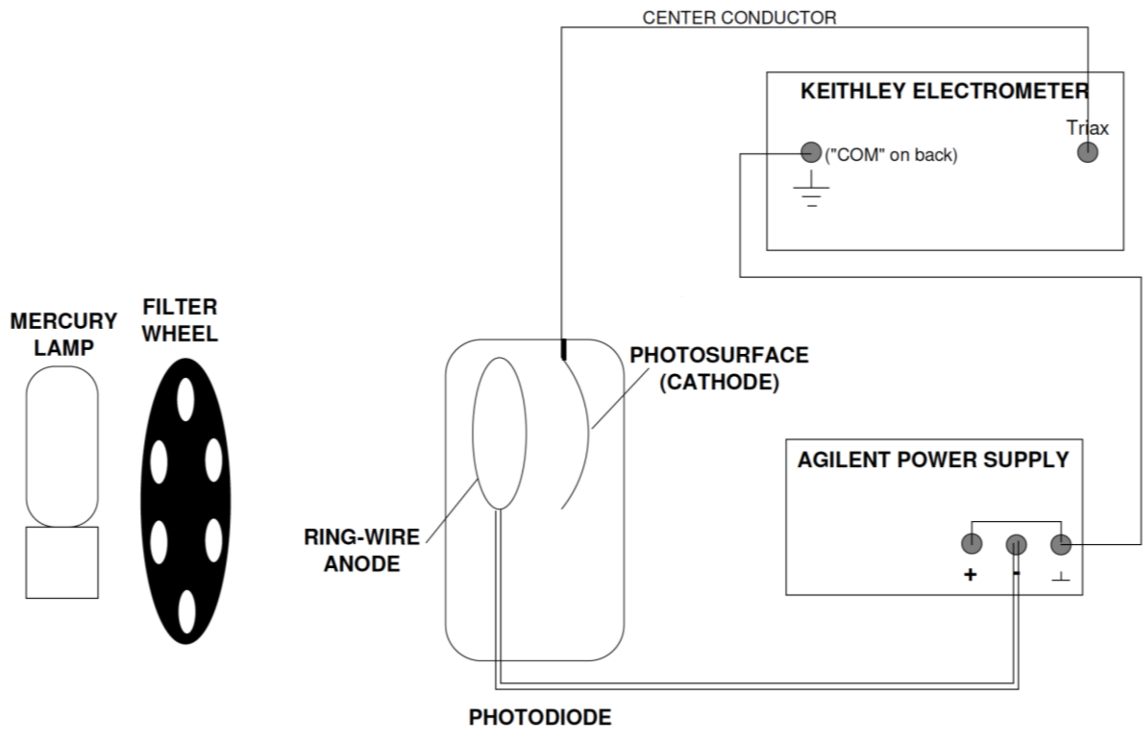
Experiment apparatus

- Measurements are made with the wavelengths of $\lambda = 365.0, 404.7, 435.8,$ and 546.2 nm, isolated using the filter wheel.
- Photodiode has a potassium photosurface (cathode) and platinum-rhodium alloy anode ring with high work function.
- A voltage supply provides a retarding potential V, with current I measured by a low-noise Keithley electrometer.



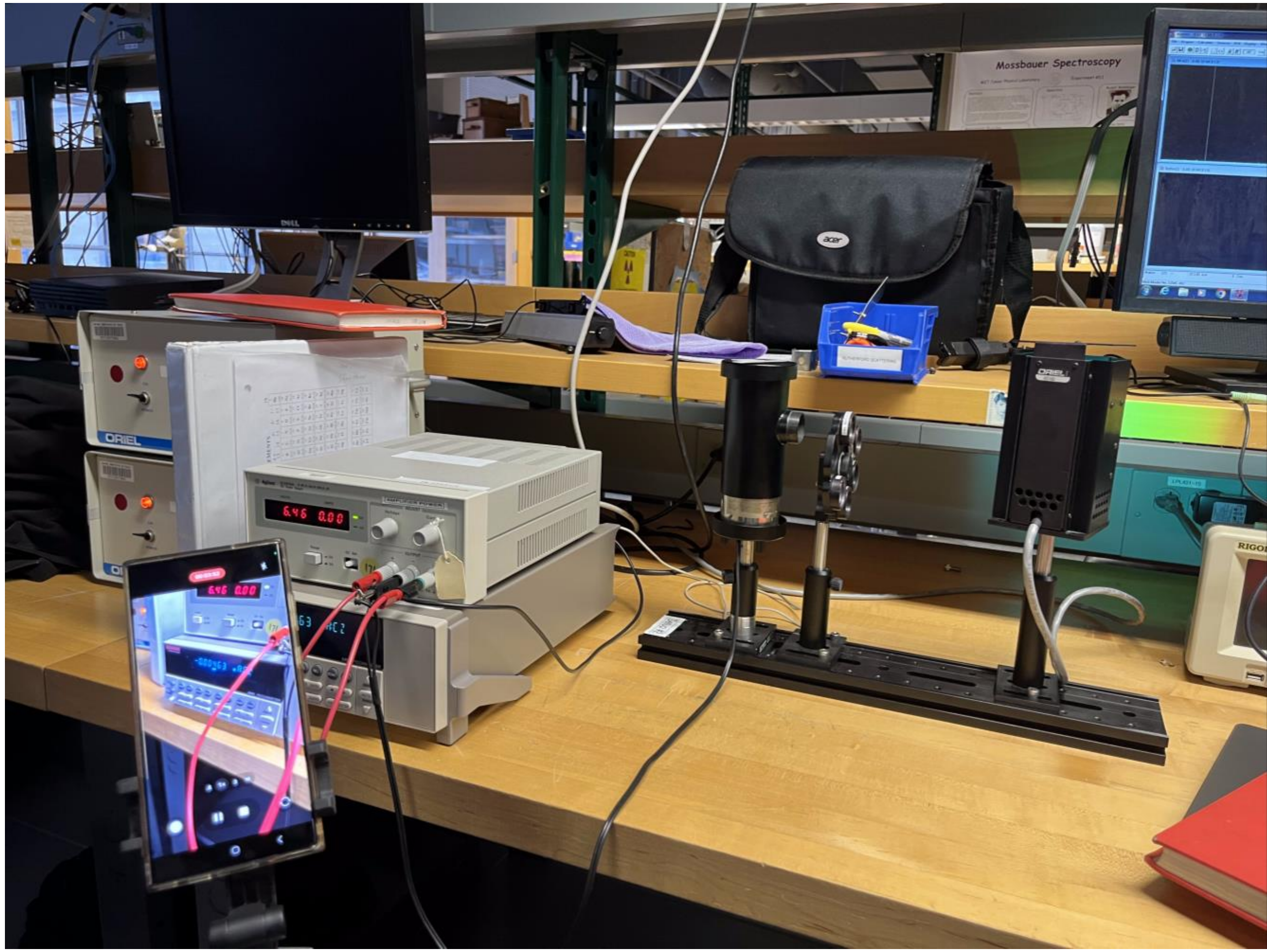
Experiment apparatus

- Measurements are made with the wavelengths of $\lambda = 365.0, 404.7, 435.8,$ and 546.2 nm, isolated using the filter wheel.
- Photodiode has a potassium photosurface (cathode) and platinum-rhodium alloy anode ring with high work function.
- A voltage supply provides a retarding potential V, with current I measured by a low-noise Keithley electrometer.
- All equipment are properly grounded and special care has been paid for geometrical alignment.



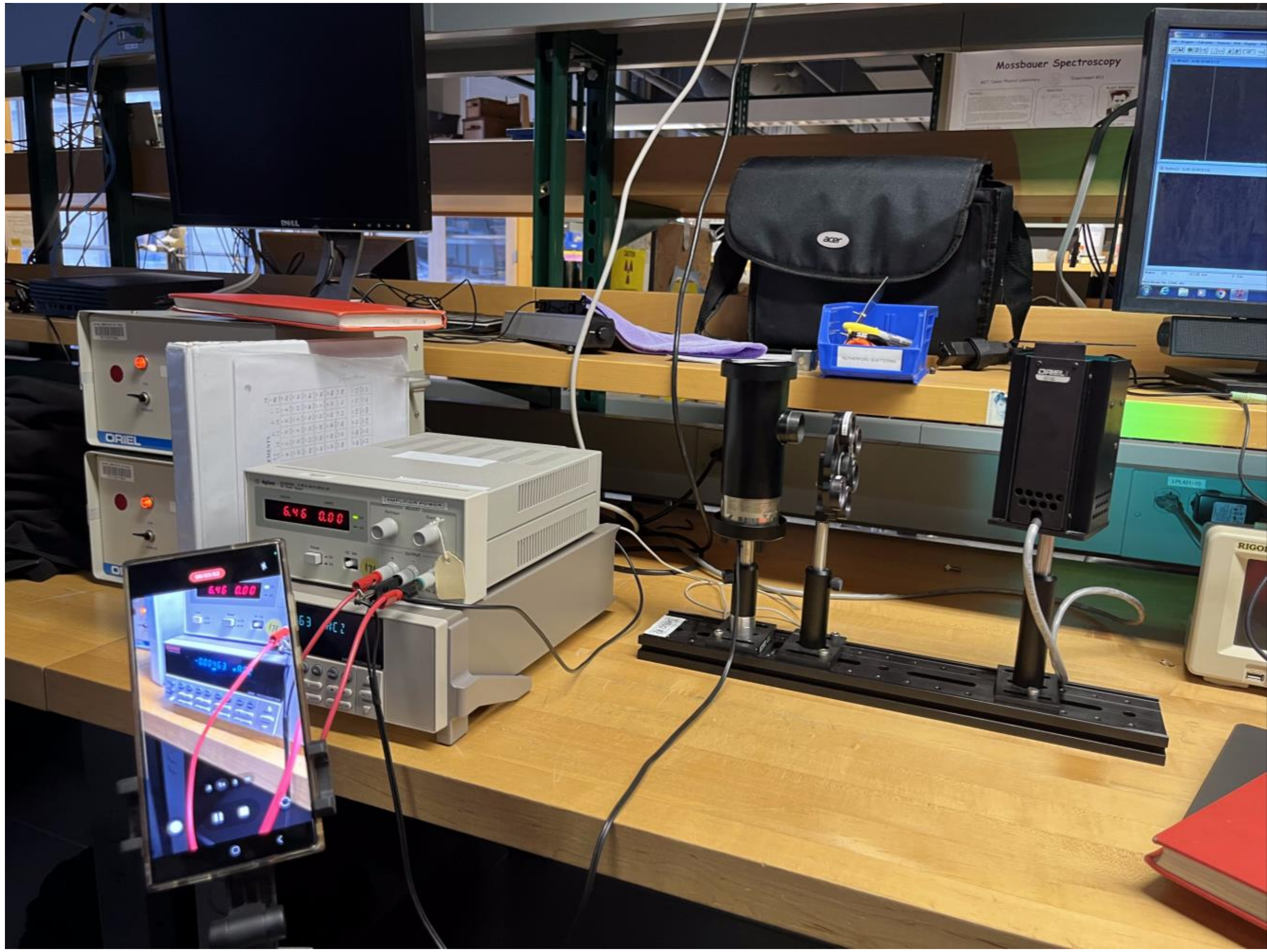
Data collection

- For each wavelength, we make measurements on a large range of voltage, from 0 to deep within the plateau regime, using similar voltage steps.



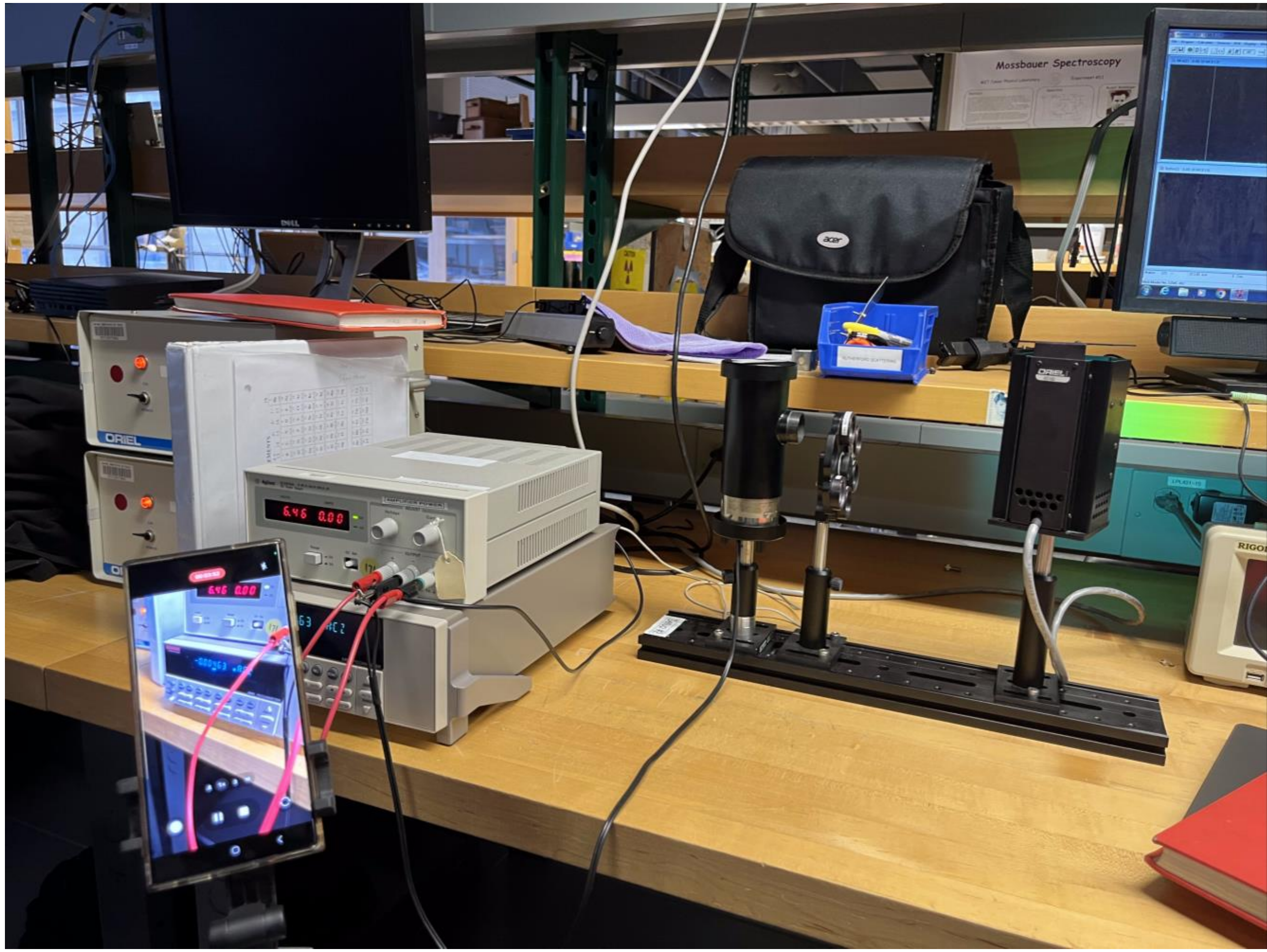
Data collection

- For each wavelength, we make measurements on a large range of voltage, from 0 to deep within the plateau regime, using similar voltage steps.
- In response to the high rate of fluctuation in the photoelectric current, for each voltage, we record (on average) 12 consecutive current values I_i.



Data collection

- For each wavelength, we make measurements on a large range of voltage, from 0 to deep within the plateau regime, using similar voltage steps.
- In response to the high rate of fluctuation in the photoelectric current, for each voltage, we record (on average) 12 consecutive current values I_i.
- For each voltage, we measure the photoelectric current, with the lamp blocked and unblock, surveying and removing background signals.



Data collection

- The current and its uncertainties are reduced following

$$-2\log(\mathcal{L}) = N.\log(2\pi\sigma_I^2) + \sum_i \left(\frac{I_i - \mu_I}{\sigma_I}\right)^2$$

$$\mu_I, \sigma_I = \arg\min_{\mu_I,\sigma_I} -2\log(\mathcal{L})$$

Data collection

- The current and its uncertainties are reduced following

$$-2\log(\mathcal{L}) = N.\log(2\pi\sigma_I^2) + \sum_i \left(\frac{I_i - \mu_I}{\sigma_I}\right)^2$$

$$\mu_I, \sigma_I = \underset{\mu_I,\sigma_I}{\arg\min} -2\log(\mathcal{L})$$

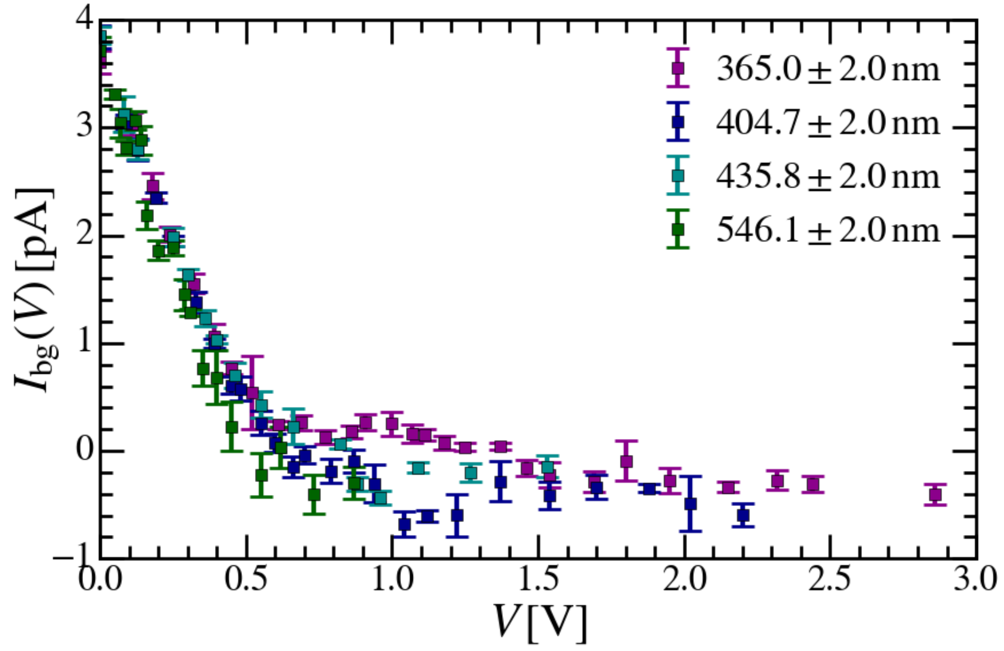
- The photoelectric current is then obtained

$$I_{\mathrm{pe}} = I_{\mathrm{total}} - I_{\mathrm{bg}}$$

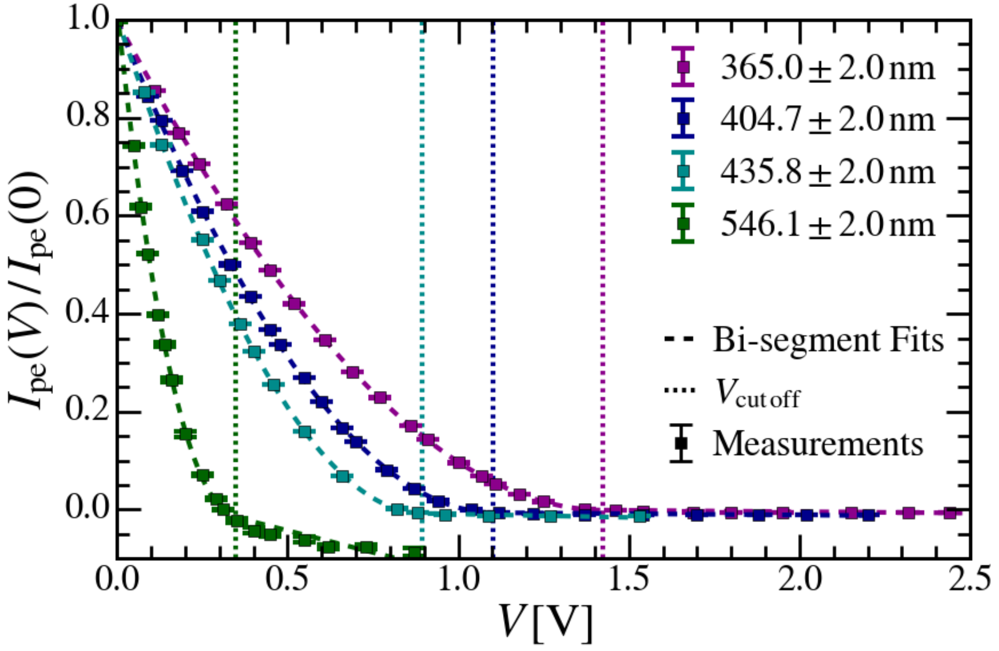
with I_{bg} and I_{total} as the measured currents when the lamp is blocked and unblocked.

Data collection

Background current I_{bg}

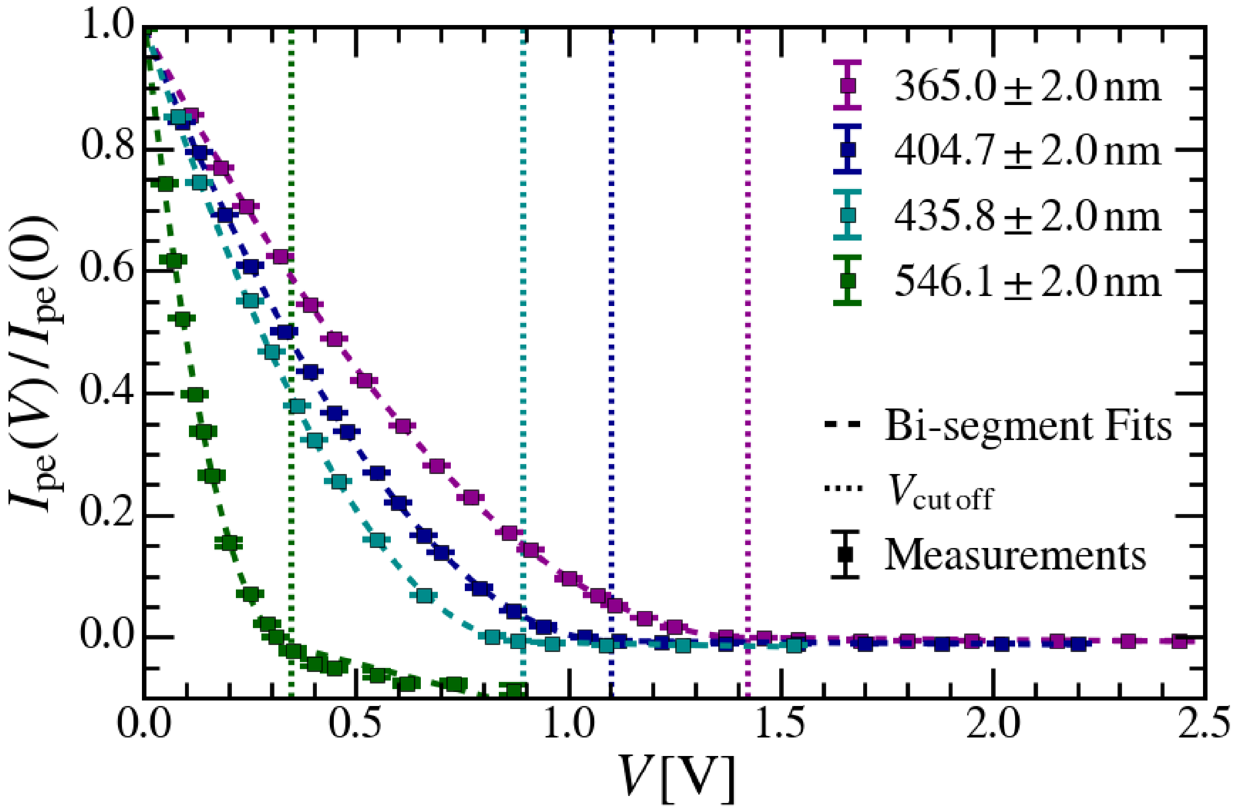


Photoelectric current I_{pe}



Cutoff voltage measurements

- We observe that the photoelectric regime (defined as where $I_{\text{pe}} > 0$) is well fitted by a polynomial, while the plateau regime can be represented by a linear fit (with near-zero slopes in most cases).

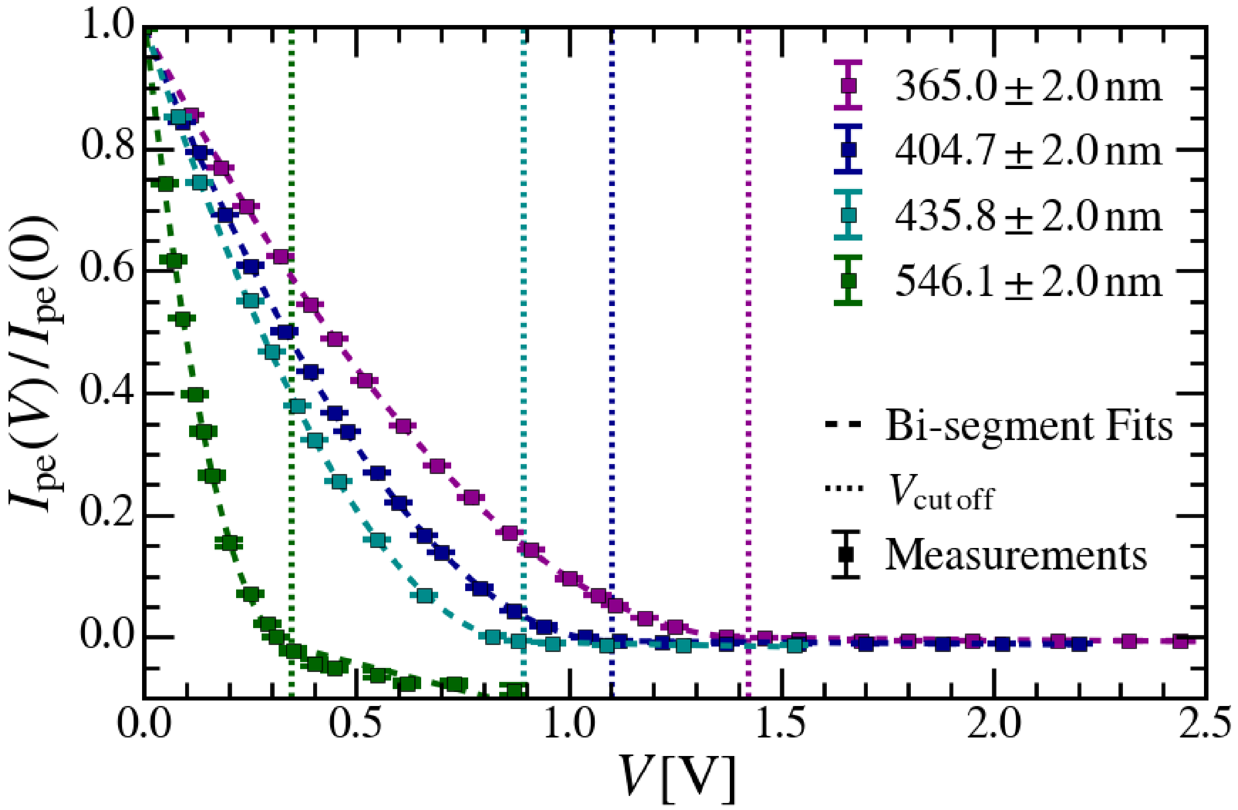


Cutoff voltage measurements

- We observe that the photoelectric regime (defined as where $I_{\text{pe}} > 0$) is well fitted by a polynomial, while the plateau regime can be represented by a linear fit (with near-zero slopes in most cases).
- Polynomial order is determined by the Chow test, with the f-statistics

$$F_{n,n'} = \frac{(\chi^2_{n'} - \chi^2_n)/(n - n')}{\chi^2_n/(N - n)}$$

Between polynomials of order n and $n' < n$, and comparing $F_{n,n'}$ to $F_{\alpha=0.05}$.



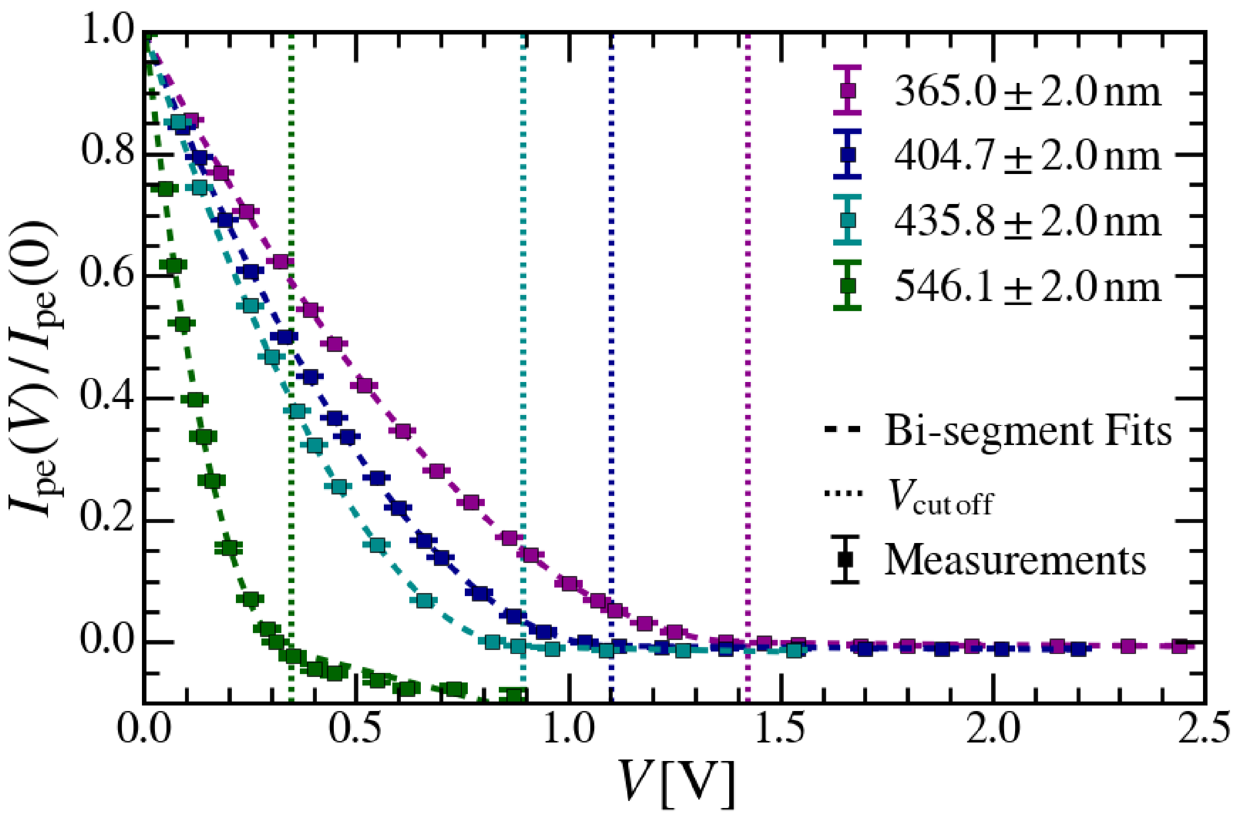
Cutoff voltage measurements

- We observe that the photoelectric regime (defined as where $I_{\mathrm{pe}} > 0$) is well fitted by a polynomial, while the plateau regime can be represented by a linear fit (with near-zero slopes in most cases).
- Polynomial order is determined by the Chow test, with the f-statistics

$$F_{n,n'} = \frac{(\chi^2_{n'} - \chi^2_n)/(n - n')}{\chi^2_n/(N - n)}$$

Between polynomials of order n and $n' < n$, and comparing $F_{n,n'}$ to $F_{\alpha=0.05}$.

- $n = 3$ provides the best results for our data.



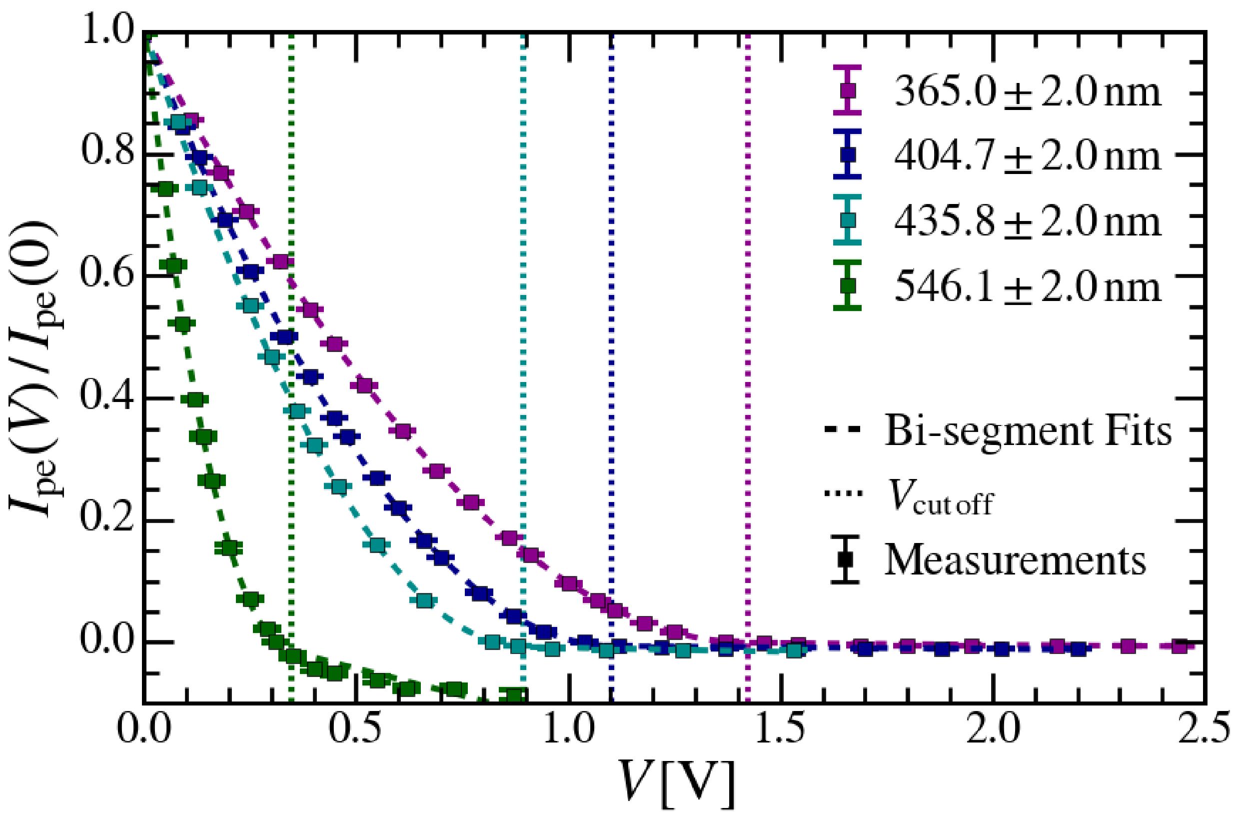
Cutoff voltage measurements

- We observe that the photoelectric regime (defined as where $I_{\mathrm{pe}} > 0$) is well fitted by a polynomial, while the plateau regime can be represented by a linear fit (with near-zero slopes in most cases).
- Polynomial order is determined by the Chow test, with the f-statistics

$$F_{n,n'} = \frac{(\chi^2_{n'} - \chi^2_n)/(n - n')}{\chi^2_n/(N - n)}$$

  Between polynomials of order n and $n' < n$, and comparing $F_{n,n'}$ to $F_{\alpha=0.05}$.

- $n = 3$ provides the best results for our data.
- Using a bi-segment fit (polynomial for $V < V_{\mathrm{cutoff}}$, and linear for $V \geq V_{\mathrm{cutoff}}$, with smooth transitioning) to determine V_{cutoff}.



Cutoff voltage measurements

- Uncertainties are propagated from the uncertainties in voltage as the uncertainties in current are insignificant.

λ [nm]	$V_{\text{cut off}}$ [V]	$\sim I_{\text{pe}}(V_{\text{cut off}})$ [pA]
365.0 ± 2.0	1.425 ± 0.010	-1.2
404.7 ± 2.0	1.104 ± 0.014	-2.2
435.8 ± 2.0	0.892 ± 0.015	-4.2
546.1 ± 2.0	0.366 ± 0.059	-0.8

Cutoff voltage measurements

- Uncertainties are propagated from the uncertainties in voltage as the uncertainties in current are insignificant.
- Each voltage measurement is treated as a uniform distribution centering at V_i with the width of $0.01\ \mathrm{V}$ (the instrument's resolution).

λ [nm]	$V_{\text{cut off}}$ [V]	$\sim I_{\text{pe}}(V_{\text{cut off}})$ [pA]
365.0 ± 2.0	1.425 ± 0.010	-1.2
404.7 ± 2.0	1.104 ± 0.014	-2.2
435.8 ± 2.0	0.892 ± 0.015	-4.2
546.1 ± 2.0	0.366 ± 0.059	-0.8

Cutoff voltage measurements

- Uncertainties are propagated from the uncertainties in voltage as the uncertainties in current are insignificant.
- Each voltage measurement is treated as a uniform distribution centering at V_i with the width of $0.01\ \mathrm{V}$ (the instrument's resolution).
- 10000 Monte Carlo samples of voltages are obtained, each is fitted to obtain a value of V_{cutoff}. The distribution of V_{cutoff} determine the

λ [nm]	$V_{\text{cut off}}$ [V]	$\sim I_{\text{pe}}(V_{\text{cut off}})$ [pA]
365.0 ± 2.0	1.425 ± 0.010	-1.2
404.7 ± 2.0	1.104 ± 0.014	-2.2
435.8 ± 2.0	0.892 ± 0.015	-4.2
546.1 ± 2.0	0.366 ± 0.059	-0.8

Cutoff voltage measurements

- Uncertainties are propagated from the uncertainties in voltage as the uncertainties in current are insignificant.
- Each voltage measurement is treated as a uniform distribution centering at V_i with the width of $0.01\ \mathrm{V}$ (the instrument's resolution).
- 10000 Monte Carlo samples of voltages are obtained, each is fitted to obtain a value of V_{cutoff}. The distribution of V_{cutoff} determine the uncertainty.
- The systematic error of the cutoff voltage measurements is taken as the typical deviation of V_{cutoff} from $V_{I_{\mathrm{pe}}=0}$, which is $\sim 0.04\ \mathrm{V}$.

λ [nm]	$V_{\text{cut off}}$ [V]	$\sim I_{\text{pe}}(V_{\text{cut off}})$ [pA]
365.0 ± 2.0	1.425 ± 0.010	-1.2
404.7 ± 2.0	1.104 ± 0.014	-2.2
435.8 ± 2.0	0.892 ± 0.015	-4.2
546.1 ± 2.0	0.366 ± 0.059	-0.8

Plank constant & work function

- Find the optimized values of h and ϕ using the prior

$$e\hat{V}_{\text{cutoff}}(\nu) = h\nu - \phi$$

and the negative log likelihood

$$-2\log(\mathcal{L}) = \sum_i \frac{\left(V_{\text{cutoff},i} - \hat{V}_{\text{cutoff}}(\nu_i)\right)^2}{\sigma^2_{V_{\text{cutoff},i}} + \left(\frac{\partial \hat{V}_{\text{cutoff}}(\nu_i)}{\partial \nu}\right)^2 \sigma^2_{\nu_i}}$$

Plank constant & work function

- Find the optimized values of h and ϕ using the prior

$$e\hat{V}_{\text{cutoff}}(\nu) = h\nu - \phi$$

and the negative log likelihood

$$-2\log(\mathcal{L}) = \sum_i \frac{\left(V_{\text{cutoff},i} - \hat{V}_{\text{cutoff}}(\nu_i)\right)^2}{\sigma^2_{V_{\text{cutoff},i}} + \left(\frac{\partial \hat{V}_{\text{cutoff}}(\nu_i)}{\partial \nu}\right)^2 \sigma^2_{\nu_i}}$$

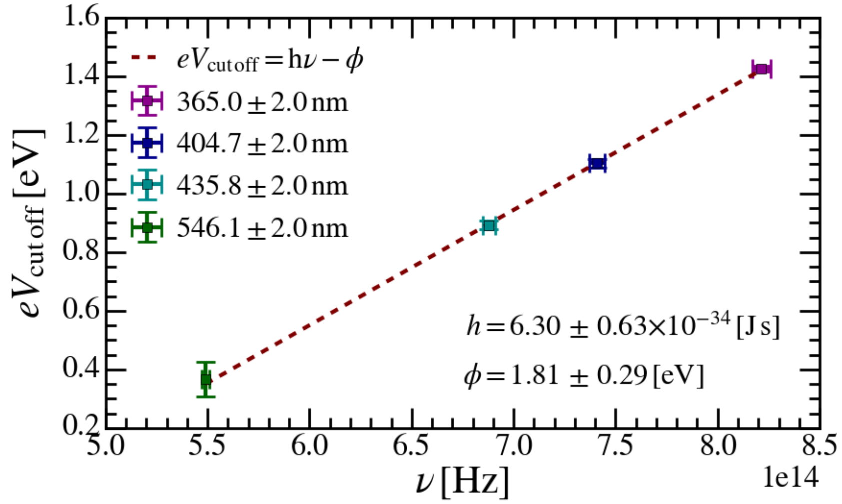
- The N-sigma gaussian-equivalent uncertainties are obtained using the covariance matrix C

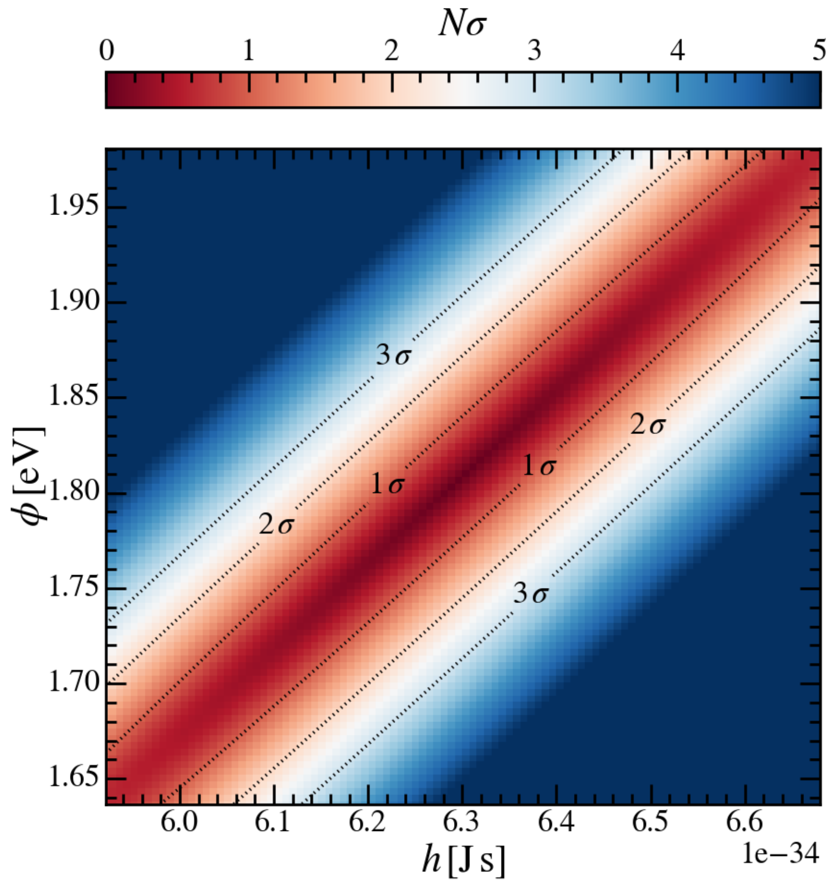
$$(C)^{-1}_{\theta,\theta'} \approx -\frac{\partial^2 \log(\mathcal{L})}{\partial\theta\,\partial\theta'}$$

$$N^2 = \sum_{\theta,\theta'} (\theta - \theta_0)\,(C)^{-1}_{\theta,\theta'}(\theta' - \theta'_0)$$

Plank constant & work function

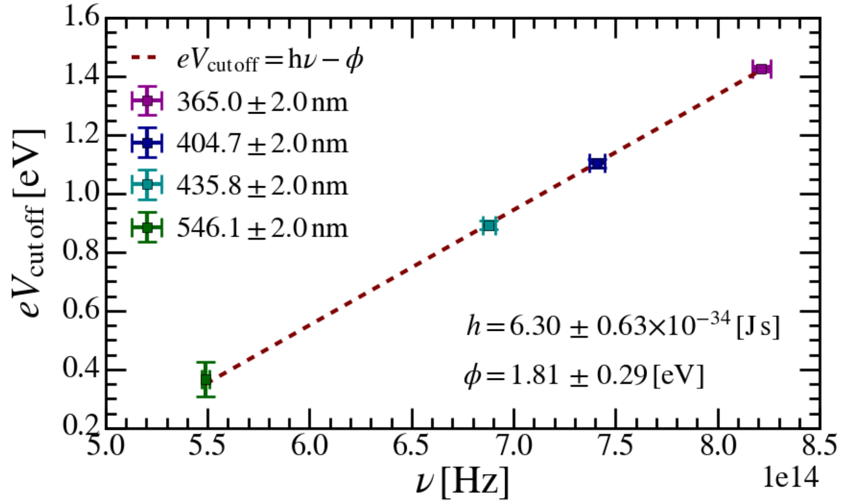
- The large uncertainties are due to the degeneration of fitting parameters.

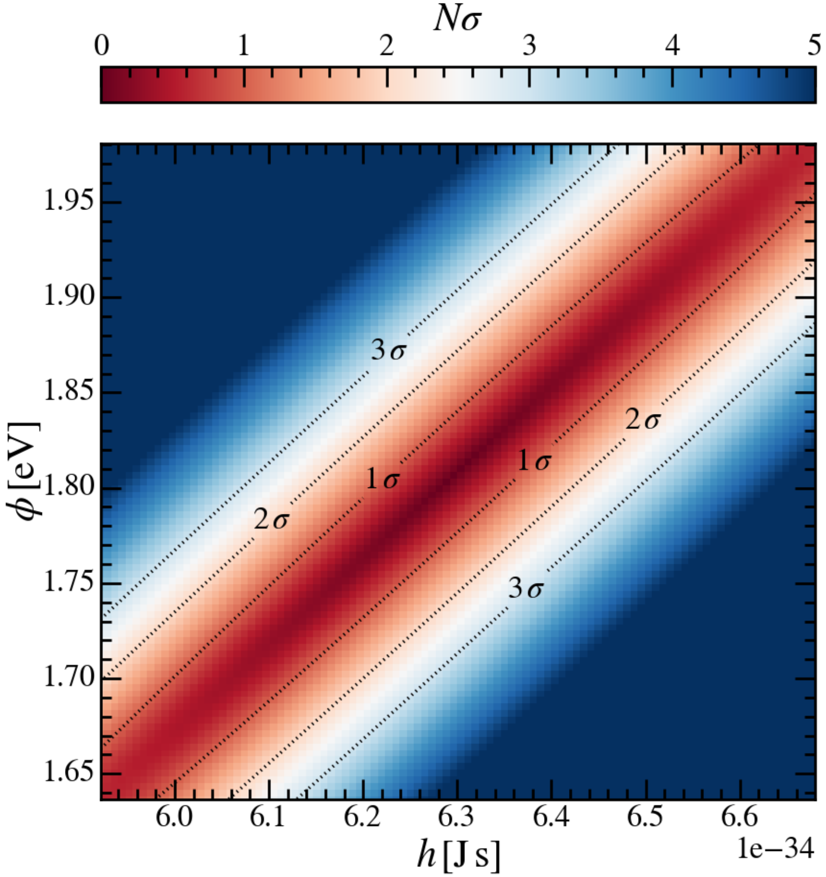




Plank constant & work function

- The large uncertainties are due to the degeneration of fitting parameters.
- Nevertheless, the obtained value of h remains close to the literature's $h = 6.63 \times 10^{-34}$ J s.





Plank constant & work function

- The large uncertainties are due to the degeneration of fitting parameters.
- Nevertheless, the obtained value of h remains close to the literature's $h = 6.63 \times 10^{-34}$ J s.
- Systematic error is propagated from the systematic error of the cutoff voltages and is of the order of $\sim 5\%$ (~ 0.32 J s).