Experiment Protocol
OPTICAL SPECTROSCOPY

by

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Contents

1 Introduction

In the following protocol, certain characteristics of a prism are explained, examined, and discussed. Mainly, the color spectrum of two elements will be measured and discussed.

2 Physical Principles

2.1 Prisms

The resonance phenomena known as dispersion is the transmission of light through transparent media with the frequency or wavelength being dependent on the refractive index n. Therefore, light made up of different wavelengths is refracted differently and resolves into its spectral parts when hitting a boundary surface. When light passes through both boundary surfaces, the total deflection angle depends on the refractive index and the direction of the incident light.

Minimal deflection occurs when the light ray passes through the prisms parallel to the base, and therefore, the deflection angle is minimal.

The ratio of emerging and entrance angle follows from their respective geometrical ratios:

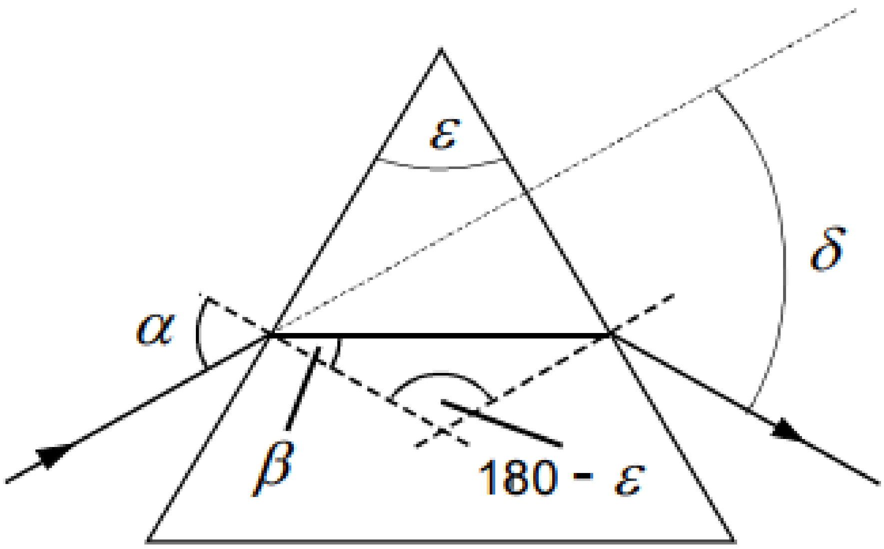


Figure 1: Refraction of Light at a Prism, source: script Basic Laboratory Course

$$\beta = \frac{\epsilon}{2} \quad \text{(inner triangle)} \tag{1}$$

and

$$\delta = 2(\alpha - \beta) \quad \Leftrightarrow \quad \alpha = \frac{\delta + \epsilon}{2}. \tag{2}$$

We then have from the law of refraction, with $n_0 = 1.0003$ being the refractive index of air and n_P being the refractive index of the prism:

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_0}{n_P} \tag{3}$$

$$n_P = n_0 \frac{\sin\frac{\delta+\epsilon}{2}}{\sin\frac{\epsilon}{2}} \tag{4}$$

2.2 Resolution Criterion

The Rayleigh Criterion states that two spectral lines can be considered separated if the diffraction maximum of one line coincides with the first diffraction minimum of the other.

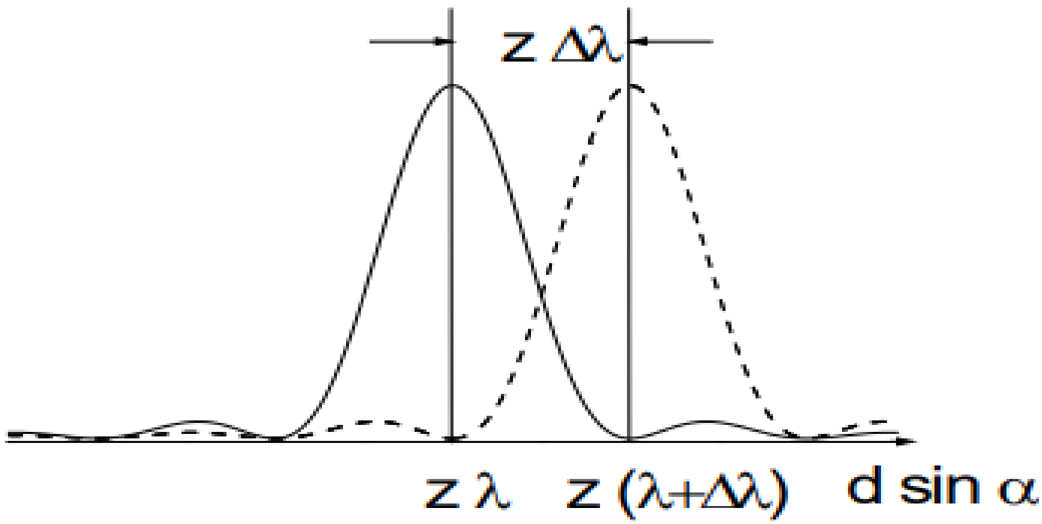


Figure 2: Rayleigh Criterion, source: script Basic Laboratory Course

Conditional on the diffraction is the finite resolution of a prism since diffraction is a limitation for the ray path and is derived from a consideration of the optical path length in the prism.

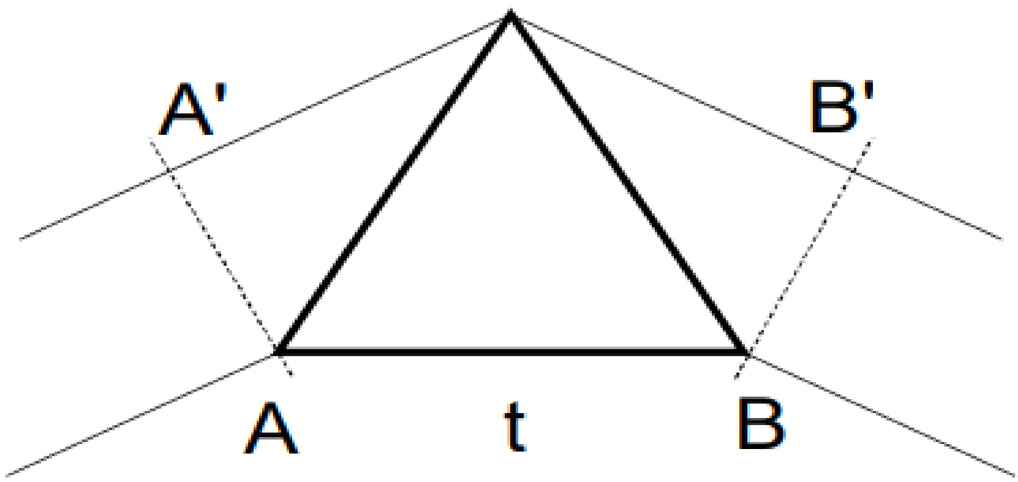


Figure 3: Resolution of the Prism, source: script Basic Laboratory Course

As projected in the figure A-A' and B-B' represent two wave fronts, one in front of the prism and one behind, which belong to a direction of deflection under which the main maximum and first adjacent minimum lie, corresponding to the wavelength λ and $\lambda + \Delta\lambda$ of the Rayleigh Criterion.

The rays should not exhibit a difference for the main maximum, and the first adjacent minimum originates in the diffraction pattern when the rays have a path difference of one wavelength at the edges.

The dependence of the refractive index on λ is approximately given by a linear relation if the difference of the wavelengths is small:

$$n(\lambda) = n \quad \text{and} \quad n(\lambda + \Delta\lambda) = n + \frac{dn}{d\lambda} \tag{5}$$

The optical path is the same for both wavelengths from A' to B' because $n \approx 1$, the path difference must arise at the base of the prism with base length t:

$$\left(n + \frac{dn}{d\lambda}\Delta\lambda\right)t - nt = \lambda \tag{6}$$

Therefore, the resolving power is, additionally to the base length t, dependent on the differential dispersion $\frac{dn}{d\lambda}$.

2.3 Diffraction Grating

A grating is an aperture with a sequence of sharp and impermeable slits. At the object, a transmission is recurring at the spacing d, which is called the grating constant.

Shining coherent and constant light at the grating, behind the grating, one observes an intensity distribution explained by diffraction and interference effects. Placing a convex lens behind the grating results in the intensity distribution called the Fraunhofer Diffraction Pattern, which is comparatively simple relations found in the plane of observation at infinity. These patterns are in the form of sharp maxima separated by wide extinction zones.

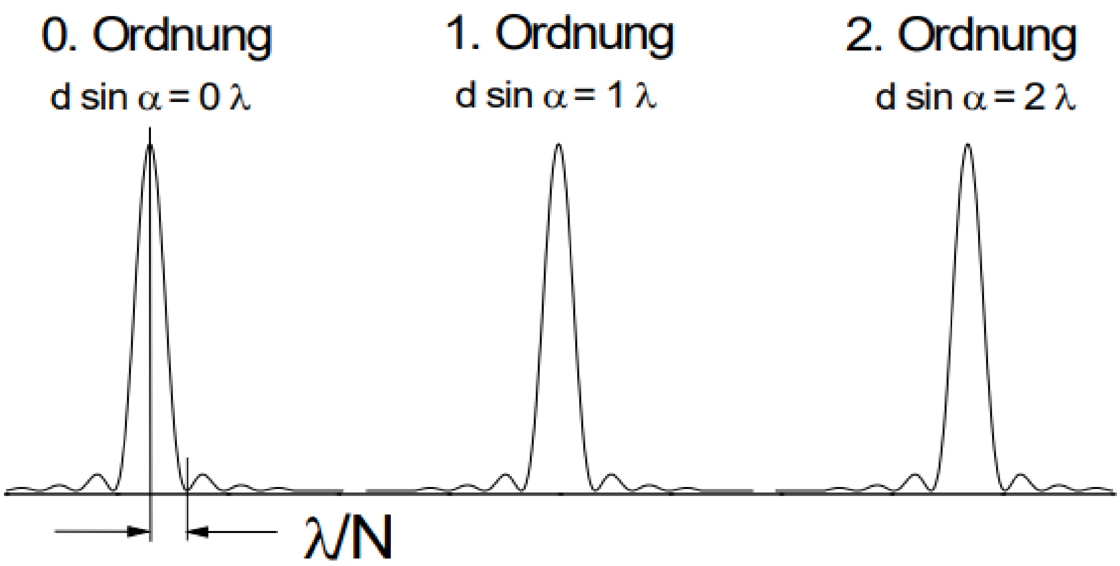


Figure 4: Fraunhofer Diffraction Pattern, source: script Basic Laboratory Course

The main maxima are derived from the grating constant and the wavelength for constructive interference to occur. z labels the order of the diffraction maxima. With all these variables, one can measure the wavelength.

$$d \sin \alpha = z\lambda, \quad Z = 0, 1, 2, \ldots \tag{7}$$

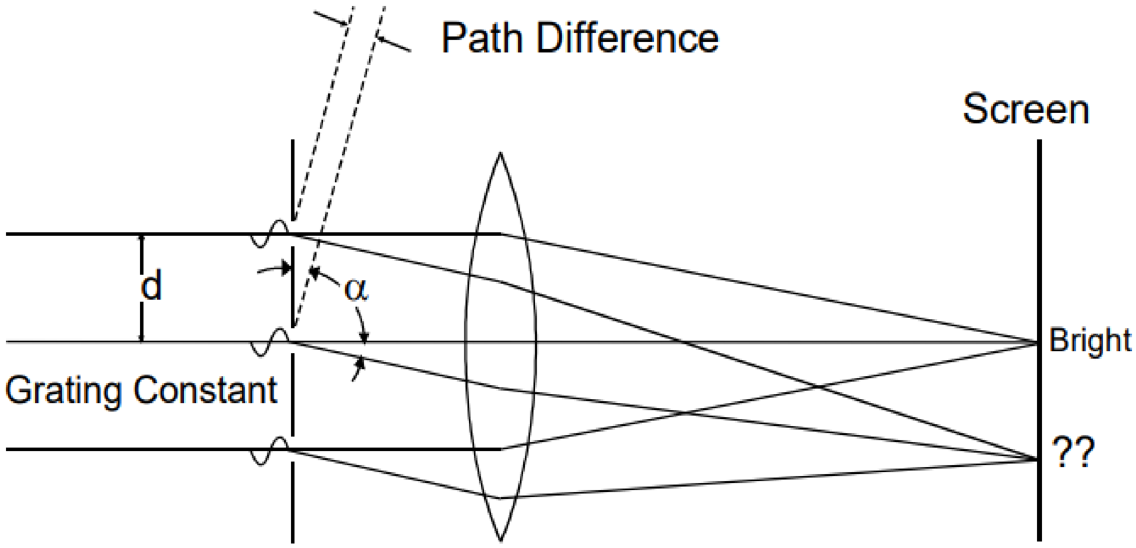


Figure 5

2.4 Resolution of a Grating

A series of adjacent maximas to the main maxima given by (7) exist, whose intensity rapidly approaches zero with increasing distance from the main maxima. The position of the first adjacent minimum of order z is given by:

$$d \sin \alpha_{\min} = \left(z + \frac{1}{N} \right) \lambda \tag{8}$$

with N being the total number of slits. According to the Rayleigh Criterion, if one sets condition (7) for the main maximum with the wavelength $\lambda + \Delta\lambda$ and for the minimum condition (5) with wavelength λ, it then follows that:

$$\Delta\lambda = \frac{\lambda}{zN} \tag{9}$$

The wave number of the lines can be described as the difference of two terms:

$$v = \frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \quad \text{with} \quad n = 3, 4, 5, \ldots \tag{10}$$

R is the Rydberg constant:

$$R = \frac{2\pi^2 m_e e^4}{h^3 c} \tag{11}$$

3 Experimental Procedure

3.1 Tasks

3.1.1 Task 1

The experiment should be constructed as shown in the illustration. A mirror is used in place of the prism shown in the illustration below, and the zero position will be determined.

3.1.2 Task 2

Determine the angles and the associated wavelengths of the colors of the spectrum of an Hg lamp and visualize it in a graph.

3.1.3 Task 3

Repeat the experiment from task 2 with an unknown lamp and use the graph produced by said task to determine the element from which the lamp is made.

3.1.4 Task 4

Use the Hg lamp and dissolve the yellow line into two lines and determine the angles α_1 and α_2 and the interval between them. Use the formula

$$\frac{\lambda}{\Delta\lambda} = \frac{\frac{1}{2}(\alpha_1 + \alpha_2)}{(\alpha_1 - \alpha_2)} \tag{12}$$

to calculate the resolving power of Mercury.

3.2 List of Devices

- collimating lens
- Hg lamp
- unknown lamp
- mirror
- slit
- goniometer assembly (angle measuring equipment)
- objective lens
- ocular

3.3 Illustration

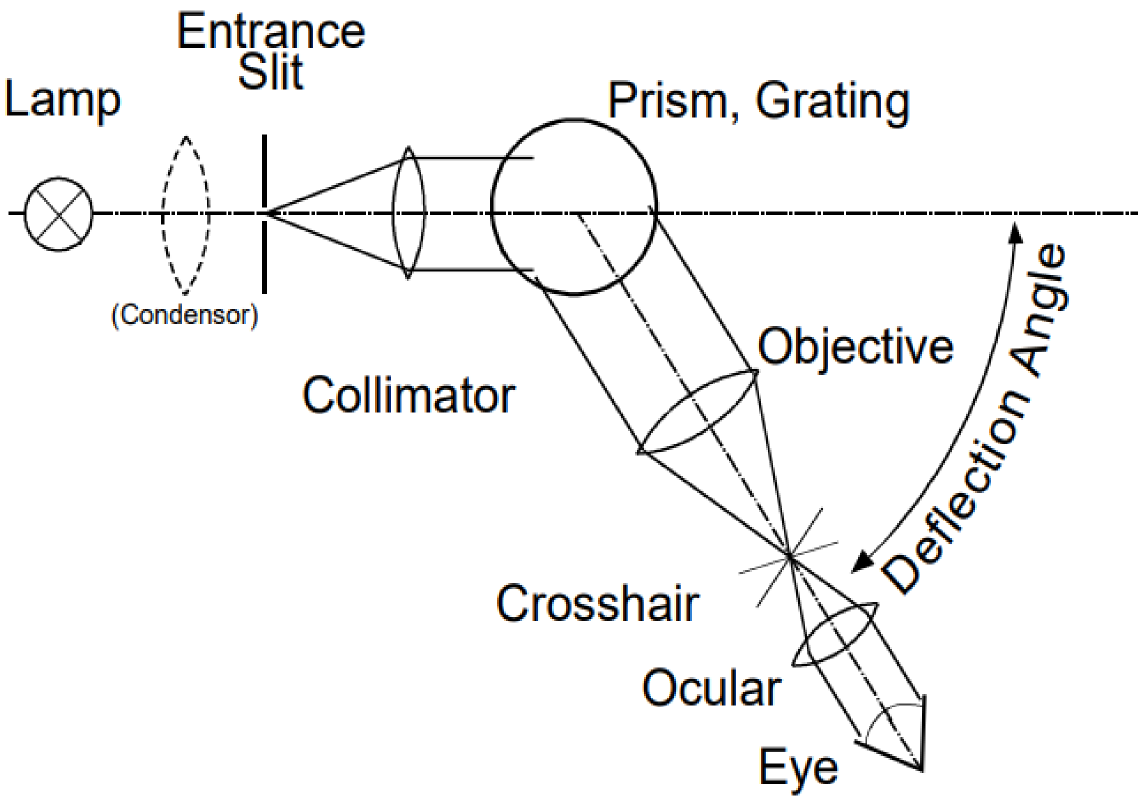


Figure 6: Illustration, source: script Basic Laboratory Course

3.4 Execution of the Experiment

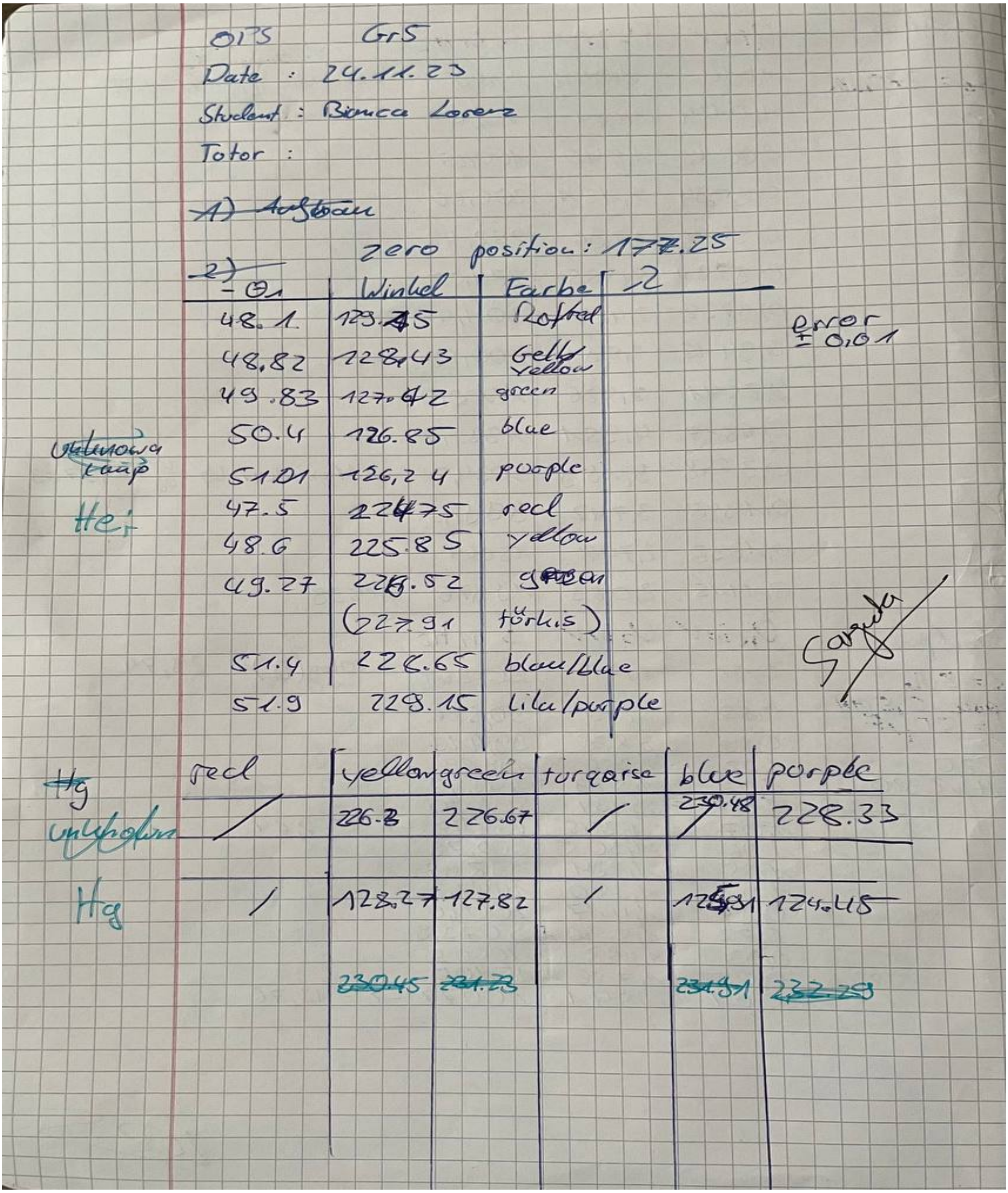
First, the setup is built according to the illustration with an Hg lamp, but instead of a prism, a mirror is used. With the help of the mirror, the light from two lines is adjusted into one clear line. The zero position is then determined by aligning all the components in one straight line.

Then, the mirror is replaced by the prism, and the angles at which each color is visible are recorded on both sides.

Afterwards, the slit is widened until two, instead of one, yellow lines are visible. The angles of both lines are recorded.

Lastly, the Hg lamp is swapped out for an unknown lamp, and the angles for all colors are recorded again exactly like the Hg lamp experiment.

4 Measurement Protocol



OPS Gr5

Date: 24.11.23

Student: Bianca Lorenz

Tutor:

~~A) Aufbau~~

zero position: 177.25

~~2)~~

	$-\theta_1$	Winkel	Farbe	λ
	48.1	129.15	Rotred	
	48.82	128.43	Gelb yellow	
	49.83	127.42	green	
	50.4	126.85	blue	
Ustawowa lamp	51.01	126.24	purple	
He:	47.5	224.75	red	
	48.6	225.85	yellow	
	49.27	226.52	green	
		(227.91	türkis)	
	51.4	228.65	blau/blue	
	51.9	229.15	lila/purple	

error ± 0,01

	red	yellow	green	turquoise	blue	purple
~~Hg~~ unfiltered	/	226.3	226.67	/	230.48	228.33
Hg	/	128.27	127.82	/	125.31	124.45
		~~230.45~~	~~231.73~~		~~234.51~~	~~232.29~~

Figure 7

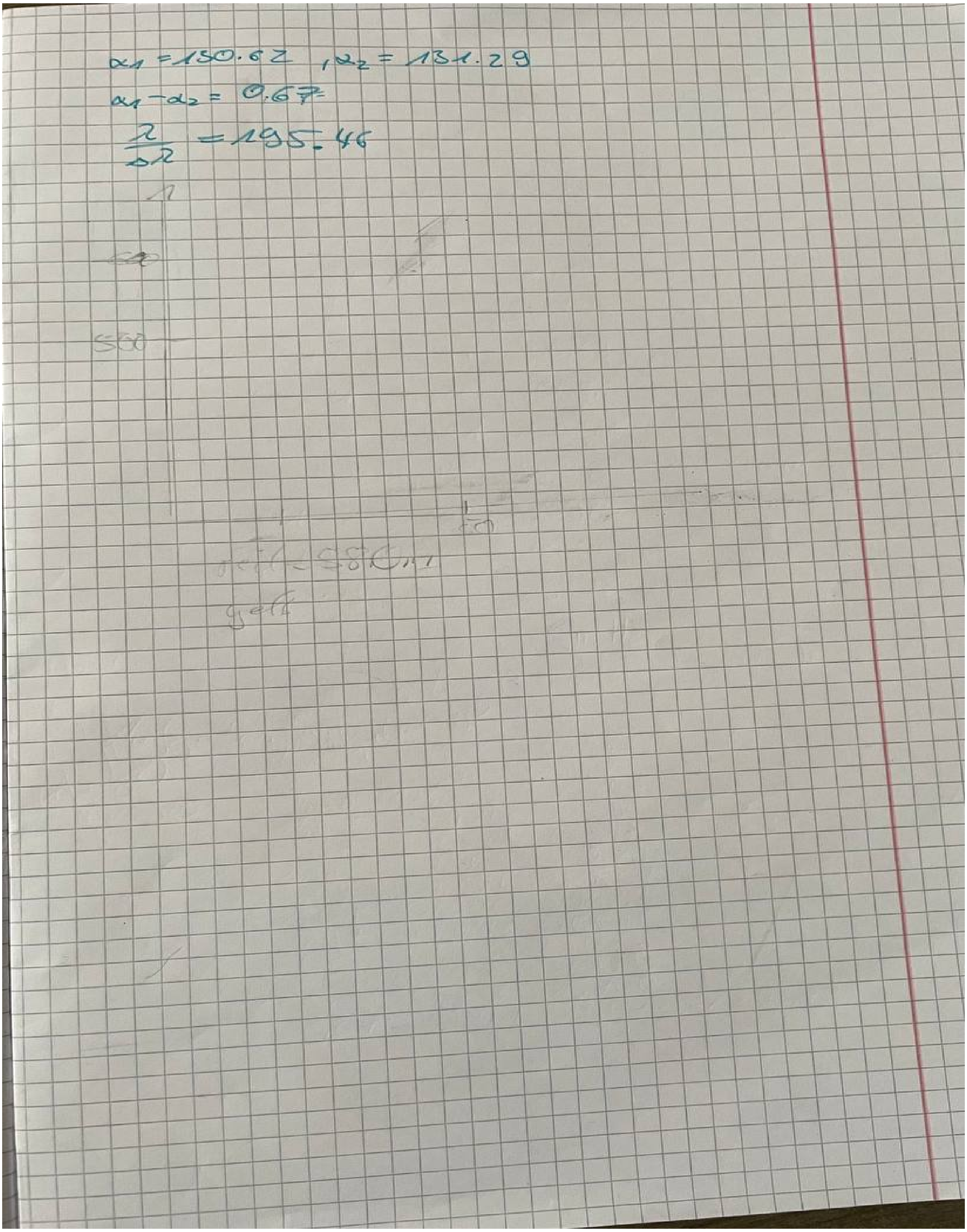


Figure 8

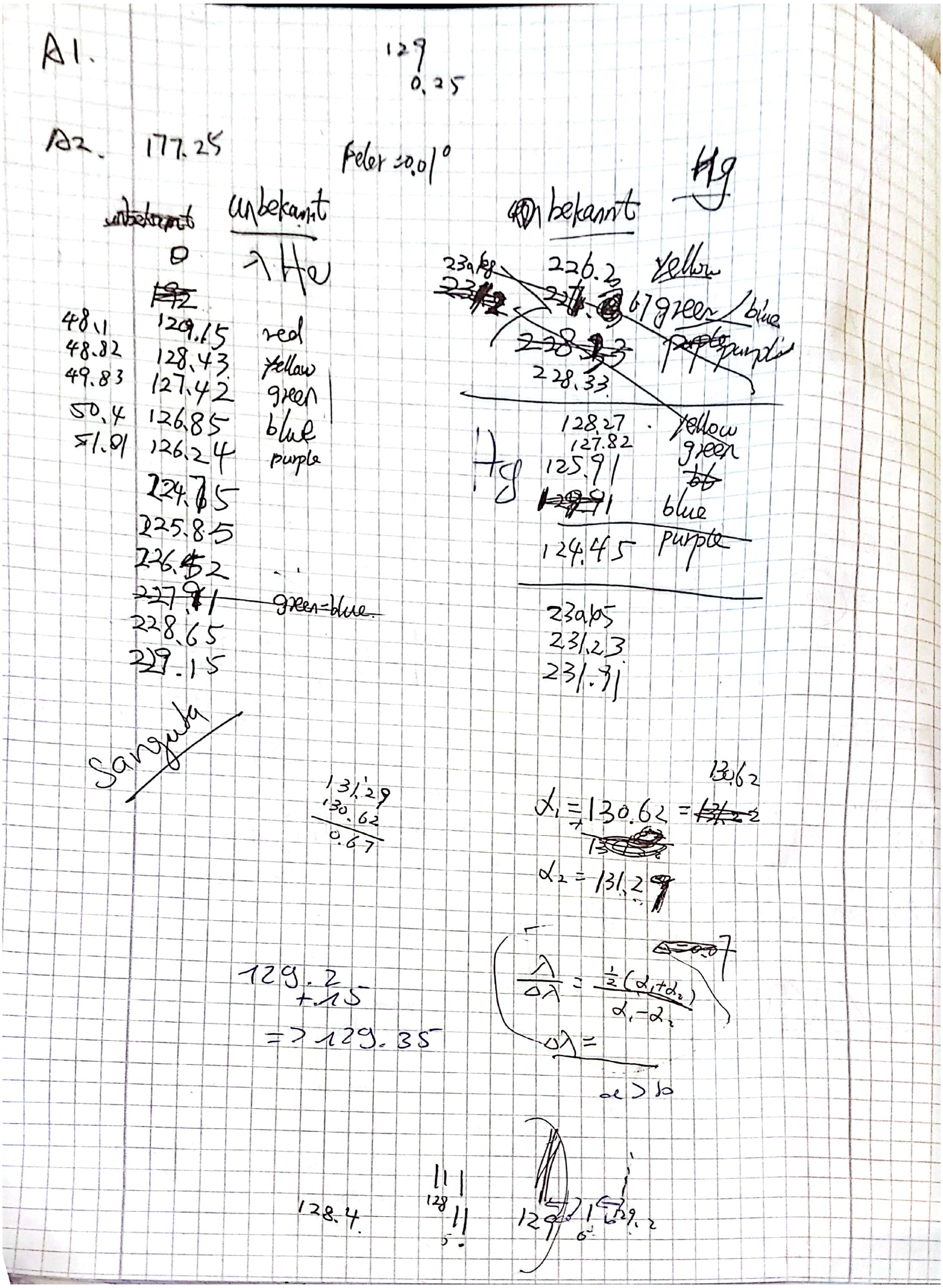

A1.
129
0,25
A2. 177.25
Feler ±0,01°
unbekannt
λ He
bekannt
Hg
48.1 129.15 red
48.82 128.43 yellow
49.83 127.42 green
50.4 126.85 blue
51.81 126.24 purple
225.85
228.65
green-blue
226.2 yellow
228.33
128.27 yellow
127.82 green
125.91
blue
124.45 purple
230.65
231.23
231.91
131.29
130.62
0.67
129.2
+.15
=> 129.35
128.4

Figure 9

5 Data Evaluation and Analysis

5.1 Task 1

The zero position, which was determined after constructing the experiment as shown in the illustration, with an estimated error of $\pm 0.02\,\text{deg}$ is $\theta = 177.25\,\text{deg} \pm 0.02\,\text{deg}$.

5.2 Task 2

For Task 2, the data consists of colors corresponding to the angles at which the spectrum of mercury is observed. We then determine and establish the values of wavelength associated with each angle using the correlation provided in (10).

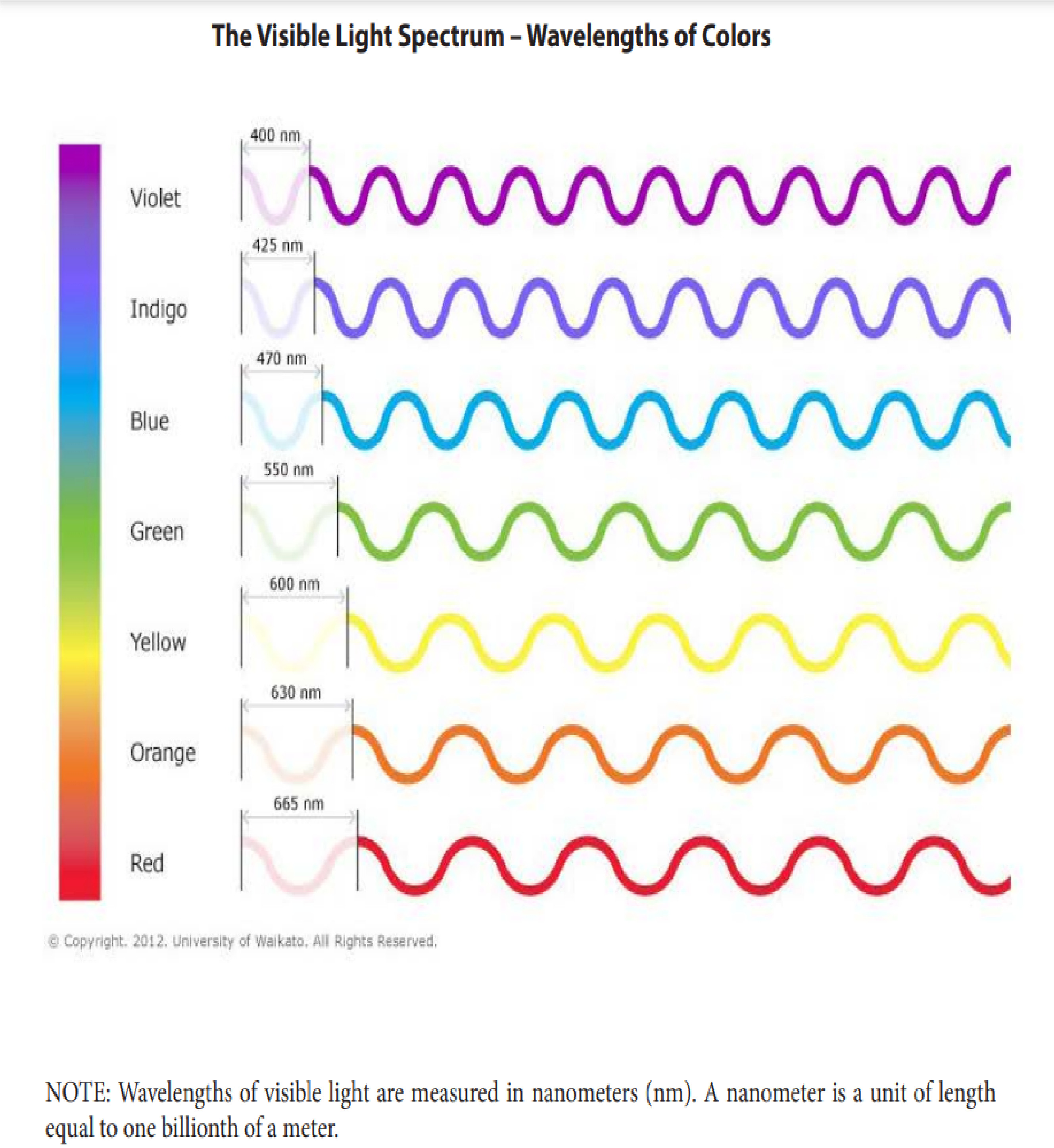


Figure 10: Wavelengths of Colors

The data we obtained afterwards is as follows: (11):

Hg		
Angles(°)	colours	wavelengths(nm)
49.05	yellow	600
53.23	green	550
49.42	blue	470
51.08	purple	400
48.98	yellow	600
49.43	green	550
51.34	blue	470
52.8	purple	400

Figure 11: Hg data

Next, we plot the actual data points, including error bars (As the error for angles, we have set 0.11°, and for the wavelength, 10 nm.), along with the fitted curve using polynomial regression in Python. The fitted curve represents the relationship between angles and wavelengths.

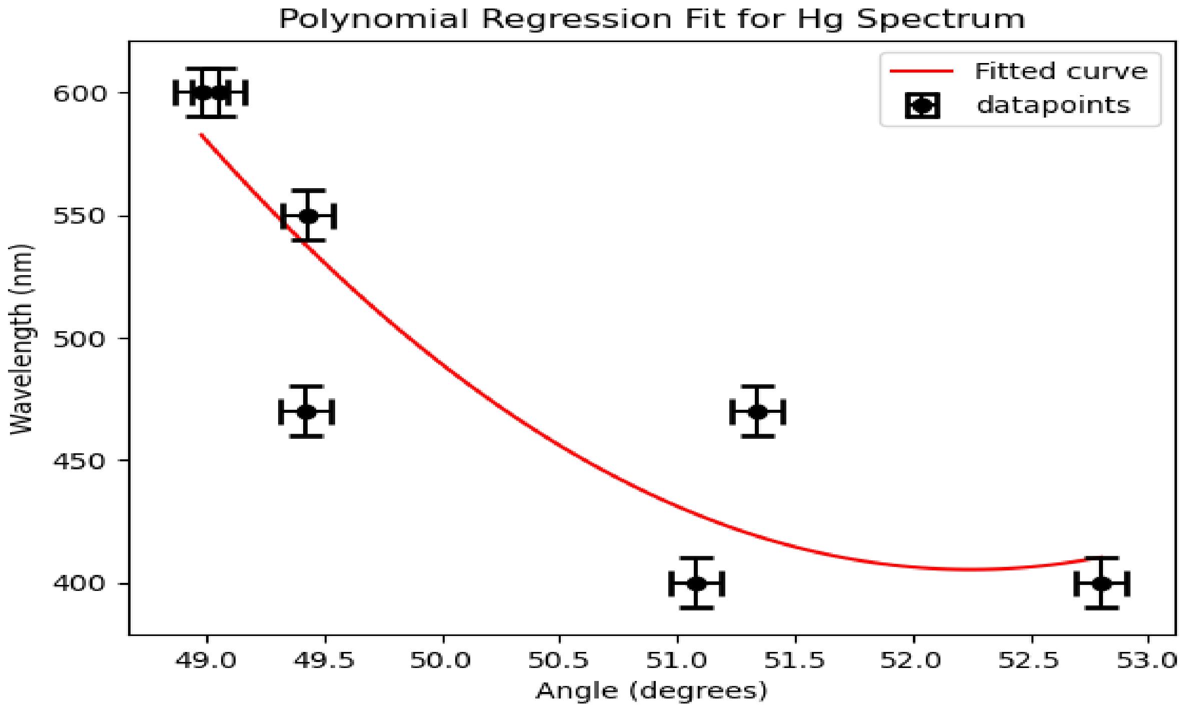


Figure 12: Mercury Spectrum: Wavelength vs. deflection angle

5.3 Task 3

For Task 3, the same process is to be followed, but with the data from an unknown spectrum of light. Here is the obtained data :

Unknown		
Angles(°)	colours	wavelengths(nm)
47.5	red	665
48.6	yellow	600
49.27	green	550
51.4	blue	470
51.9	purple	400
48.1	red	665
48.82	yellow	600
49.83	green	550
50.4	blue	470
51.01	purple	400

Figure 13: Unknown data

By analyzing the sequence of different colors observed and comparing it with the Spectral Table (14) for various materials, we can draw the conclusion that the unknown spectrum corresponds to helium (He).

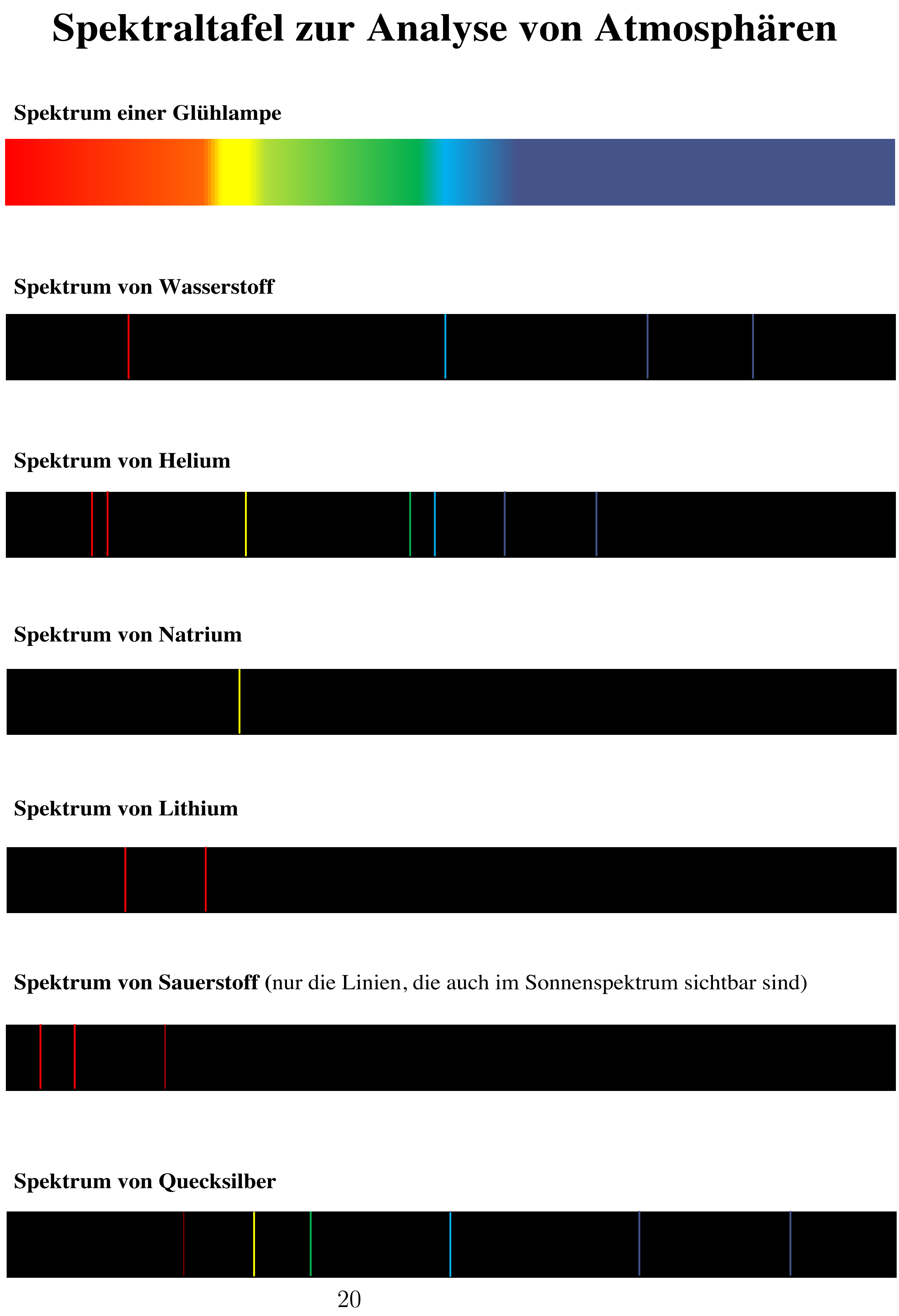


Figure 14: Spektraltafel-zur-Analyse-von-Atmosphären (spectral chart to analyse athmospheres)

Here is the graph:

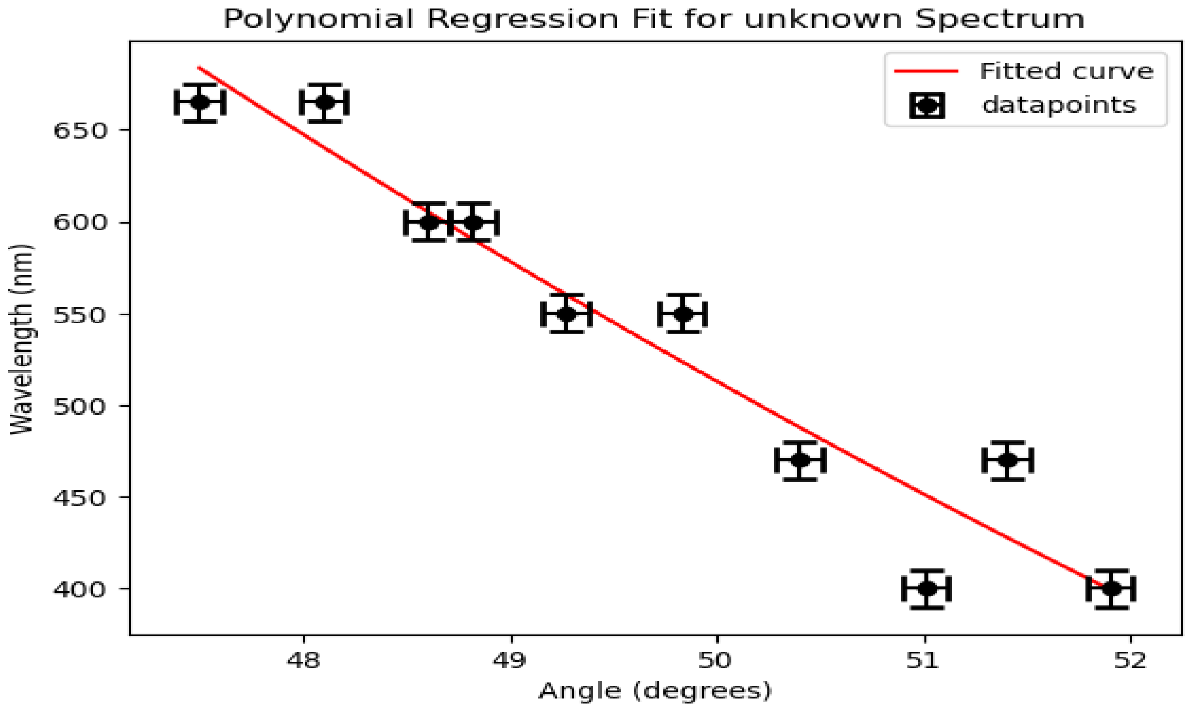


Figure 15: Unknown Spectrum: Wavelengths vs. Angles

5.4 Task 4

Task 4 is to calculate the resolving power of mercury using formula (12). The two angles α_1 and α_2 are 130.62° and 131.29°. For the error, we set it to 0.02°.

The error of the result is to be calculated using the Gaussian error propagation formula:

$$\Delta\left(\frac{\lambda}{\Delta\lambda}\right) = \sqrt{\left(\frac{\partial\frac{\lambda}{\Delta\lambda}}{\partial\alpha_1}\right)^2 \Delta(\alpha_1)^2 + \left(\frac{\partial\frac{\lambda}{\Delta\lambda}}{\partial\alpha_2}\right)^2 \Delta(\alpha_2)^2} \tag{13}$$

The result reads:

$$\frac{\lambda}{\Delta\lambda} = 195 \pm 8 \tag{14}$$

6 Discussion

6.1 Task 2

The data obtained in Task 2 appears plausible, and the curve aligns with our expectations.

6.2 Task 3

During Task 3, we determined that the unknown spectrum corresponds to helium, which has been verified to be accurate. The light utilized for this task was indeed helium.

7 Appendix

7.1 Sources

- Figures in Physical Principles:

  Refer to script OPTICAL SPECTROSCOPY GP II.

- Figure 10: Source: https://www.waikato.ac.nz/

- Figure 14: Source: https://commons.wikimedia.org/wiki/File:Atomic_emission_spectrum_of_helium.svg