Physics 2610H: Lab III

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March 14, 2025

Abstract

The helium spectrum was successfully observed and matched predicted values. A doublet was resolved by modifying entrance slit width of the measurement apparatus and the active component of two unknown light sources was determined. A subsequent experiment to investigate the absent lower wavelengths in the helium spectrum may be of value.

1 Introduction

Spectroscopy is a useful tool in many fields. A visible light spectrometer—such as the one employed in this experiment—can be used to determine the composition of an object by measuring emission or absorption of specific wavelengths of photons by that object.

This experiment seeks to employ a digital visible light spectrometer to verify calculated values for electron energy level transitions in a helium atom, determine the components of unknown visible light emitters, and determine a method to resolve merged spectral lines for energy level transitions with similar emitted photons.

2 Theory

Electrons in orbit around atomic nuclei exist in discrete, quantized, energy levels and may only move between these levels when a "hole" is available for them to do so. In order to "jump" up to a higher energy level an electron must be given energy, usually by a photon, who's energy is given by

$$E = \frac{hc}{\lambda}$$

where h is Planck's constant[3], c the speed of light in the medium through which the photon moves, and λ the wavelength of the photon. Electrons may also decay to a lower energy level, emitting the energy lost in that process as a photon of energy given by the difference in energy between the final and initial energy levels.

Visible light spectrometers record these energy level transitions by recording the intensity of light due to the emitted photons and mapping it to its corresponding wavelength.

3 Methods

This experiment utilized a software controlled device known as a monochromator to diffract incoming light into its component wavelengths and measure the intensity of each individually. The monochromator utilizes a reflective diffraction grating alongside entrance and exit slits and several internal mirrors to diffract, collimate, and deliver incoming light to a visible light sensitive photodiode connected to an Arduino. A MicroPython script was utilized to control the device and record data produced by the photodiode.

Three light sources were measured with the monochromator. The light from each was directed to a lens which focused it onto the input slit. The output slit width remained constant throughout the experiment and only the wavelength step, range, and input slit width were varied.

Light sources were placed such that the photodiode registered the maximum emission strength when the diffraction grating was in its rest position, reached by power cycling the device before beginning a measurement.

4 Discussion

4.1 Helium Spectrum

Assigned Transition	Pred. wavelength, λ_p(nm)	Obs. wavelength, λ_o(nm)	% Diff	Comments
$1s0s^1S$ $1s3p^1P$	392			
$1s0s^3S$ $1s3p^3P$	412			
$1s1s^1S$ $1s3p^1P$	505	505 ± 1.7	0.337	Extremely faint
$1s1s^3S$ $1s3p^3P$	471	471 ± 0.6	0.127	
$1s2s^1S$ $1s1p^1P$	397			
$1s2s^1S$ $1s2p^1P$	502	502 ± 1.6	0.319	
$1s2s^3S$ $1s3p^3P$	707	707 ± 1.5	0.212	
$1s3s^1P$ $1s0p^1D$	439			
$1s3s^1P$ $1s1p^1D$	492	492 ± 1.6	0.325	
$1s3s^1P$ $1s2p^1D$	668	668 ± 1.8	0.269	
$1s3s^1S$ $1s3p^1P$	728	728 ± 1.5	0.206	
$1s3s^3P$ $1s0p^3D$	403			
$1s3s^3P$ $1s1p^3D$	447	447 ± 1.6	0.358	
$1s3s^3P$ $1s2p^3D$	588	588 ± 1.5	0.255	
$1s3s^3S$ $1s2p^3P$	389	389 ± 1.4	0.360	

4.1.1 "Missing" Wavelengths

Five expected wavelengths (see Table 4.1) in the low wavelength region are missing from the recorded data. This could be because the diode is less sensitive at those lower wavelengths[2] however there is still a strong peak at (389.0 ± 1.4) nm which is the lowest expected approximately visible wavelength. The other possibility which better explains the lack of these wavelengths and the lower wavelength that was detected in the recorded data is that the initial states are unstable and decay down to the corresponding final states much quicker than other transitions. This could be verified and potentially resolved by increasing the number of samples at each wavelength.

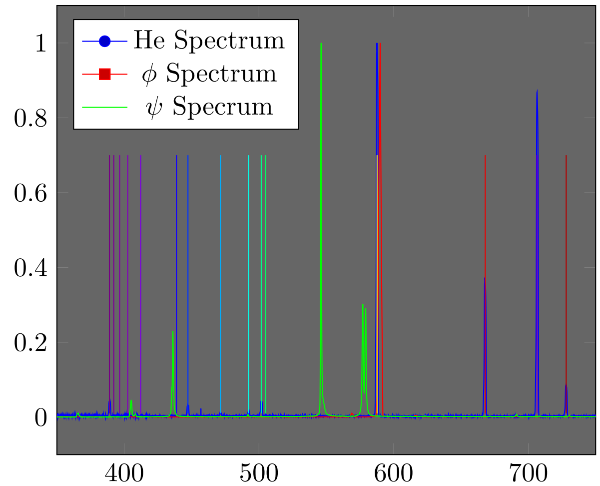

Figure 1: Helium, ψ, and ϕ lamp spectrum. Coloured lines denote predicted values for helium. See appendix for full size with log scale.

4.2 Doublet Resolution

The ψ lamp exhibited two doublets between 588 nm and 590.5 nm. As can be seen in Figure 4.2 the doublets were successfully resolved by decreasing the input slit width. And optimal value for this slit width is somewhere between 5 µm and 10 µm as a 0 µm slit significantly impacts the amount of light entering the apparatus whereas a slit widths above 10 µm do not resolve the doublet well.

4.3 Guessing the ϕ Lamp

As can be see in Figure 4.1 the ϕ lamp has strong peaks at approximately 436 nm,546 nm, 577 nm, 580 nm. Using the NIST Atomic Spectra Database[1] to determine materials with similar peaks suggests mercury as a likely match. It exhibits many of the same emission peaks as the recorded data, with the recorded data only missing the peaks on the far ends of the visible spectrum where the photodiode employed in this experiment may not be as sensitive as the instruments employed by NIST or, as discussed above, the transitions may be more rapid and require a greater number of samples.

4.4 Guessing the ψ Lamp

Again the NIST Atomic Spectra Database[1] suggests sodium as the likely active component of the ψ lamp. This fits with the extremely strong doublet at approximately 590 nm and the slightly weaker emission lines surrounding that peak.

4.5 Sources of error

4.5.1 Systematic Error

The most significant source of systematic error in this experiment stems from the fact that the experiment was not

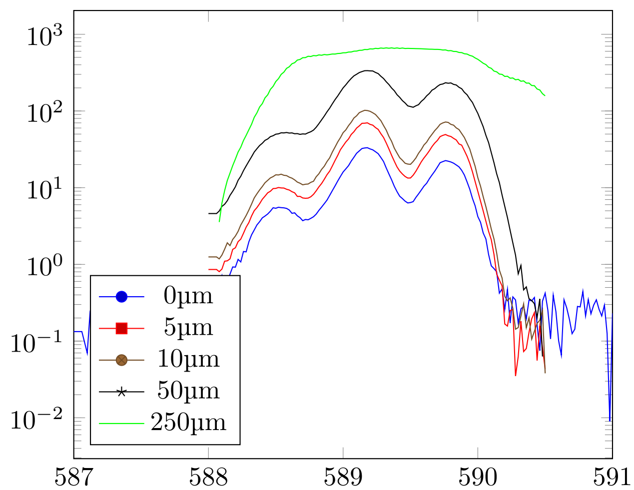

Figure 2: ψ lamp spectrum focused on yellow doublet. Note significantly decreased intensity for a 0µm slit width requiring semilog scale. See appendix for full size.

conducted in "total" darkness. A nearby window introduced not insignificant—though not quantified— levels of stray light alongside the screen of the computer used to control the monochromator and the lamps not being studied. These sources were largely constant throughout the experiment and the calibration of the raw data by subtracting the minimum nonzero reading from the photodiode eliminated the majority of their influence.

4.5.2 Random Error

The most significant source of random error in this experiment was likely the non-rigidity of the apparatus. Only the helium lamp was placed directly infront of the monochromator's entrance slit, the ψ and ϕ lamps both had their light directed towards the entrance slit using a mirror that was not securely fixed to any rigid mounting point. The simplest way of reducing the effects of this non-rigidity would likely be performing the experiment on an optical table with securely fixed mirrors, lenses, and lightsources.

4.5.3 Signal to Noise Ratio

The helium, ψ, and ϕ datasets exhibit SNRs of approximately -8 dB, -10 dB, and -8 dB respectively (see Figure 7.1 for calculation). The likely highest influence on this is again the non-rigidity of the experiment and light leakage from surrounding sources, methods to improve each are discussed above.

5 Conclusion

This experiment successfully verified the hydrogen emission spectrum save for some lower wavelength emission peaks, likely due to the lower sensitivity of the employed photodiode in this range. The experiment also matched the ϕ lamp to the emission spectrum of mercury and successfully resolved the yellow doublet of the ψ lamp using a decreased entrance slit width on the monochromator.

6 Bibliography

References

[1] A. Kramida, Yu. Ralchenko, J. Reader, and NIST ASD Team (2024). *NIST Atomic Spectra Database (version 5.12)*. 2025. URL: `https://physics.nist.gov/asd`.

[2] ThorLabs. *Calibrated Photodiodes*. 2025. URL: `https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2822`.

[3] Eite Tiesinga, Peter J. Mohr, David B. Newell, and Barry N. Taylor. *The 2022 CODATA Recommended Values of the Fundamental Physical Constants*. 2022. URL: `https://physics.nist.gov/constants`.

7 Appendix

7.1 Code

```python
from matplotlib import pyplot
import numpy as np


def plot_cal_norm(filename: str, plot=False, save_image=False, save_data=False) -> None:
    data = np.loadtxt(filename, delimiter=",")  # Load data from file
    lam = data[:, 0]  # Slice file array into x and y
    intens = data[:, 1]

    # Calibrate. Subtract min zon-zero value
    intens = intens - \
        np.min(np.ma.masked_array(intens, mask=intens == 0).min())
    # Normalize. Divide by greatest value so everything is scaled the same
    intens = intens / intens.max()
    if (plot):
        pyplot.plot(lam, intens)  # Plot with y log x lin
        pyplot.xlabel(r"Wavelength (nm)")
        pyplot.ylabel(r"Intensity (arbitrary)")
        if (save_image):
            pyplot.savefig(filename.removesuffix(".csv") + ".png")
    if (save_data):
        out = np.ndarray(data.shape)
        out[:, 0] = lam
        out[:, 1] = intens
        np.savetxt(filename.removesuffix(".csv") + "-PROCESSED" +
                   ".csv", out, delimiter=",", fmt='%f')
    pyplot.title(f"SNR: {10*np.log10(signaltonoise(intens))}")
    pyplot.show()


def signaltonoise(a, axis=0, ddof=0):
    # Borrowed from scipy v<1.0.0
    a = np.asanyarray(a)
    m = a.mean(axis)
    sd = a.std(axis=axis, ddof=ddof)
    return np.where(sd == 0, 0, m/sd)


plot_cal_norm(
    "PHYS 2610H/Lab 3/Phi/Phi_VIS_100_0.1nm_250um_350-750.csv", plot=True)
```

Figure 3: Code to process and plot data. Requires that headers generated using the given monochromator control script be removed.

```python
import pandas as pd

S1 = [1.9663, 1.9094, 1.66277, 1.84869]
S3 = [1.93347, 1.90298, 1.83241, 1.59856]
P1 = [1.93949, 1.91493, 1.86209, 1.71135]
P3 = [1.93808, 1.91217, 1.85564, 1.69087]
D1 = [1.93925, 1.91447, 1.86105]
D3 = [1.93925, 1.91444, 1.86102]

levels_list = dict()


def levels(E1, E2, E1n, E2n):
    for i in range(len(E1)):
        for j in range(len(E2)):
            dE = abs(E1[i]-E2[j])
            if dE > 0:
                wavelength = 1/dE*100
                if wavelength > 370 and wavelength < 750:
                    levels_list.update(
                        {"1s{}s{}-1s{}p{}".format(i, E1n, j, E2n): wavelength})


levels(S1, P1, "1S", "1P")
levels(P1, D1, "1P", "1D")
levels(S3, P3, "3S", "3P")
levels(P3, D3, "3P", "3D")
pd.DataFrame.from_dict(data=levels_list, orient="index").to_csv(
    "PHYS 2610H/Lab 3/predicted_vals.csv", header=False)
print(len(levels_list))
```

Figure 4: Code to predict visible energy level transitions.

7.2 Figures

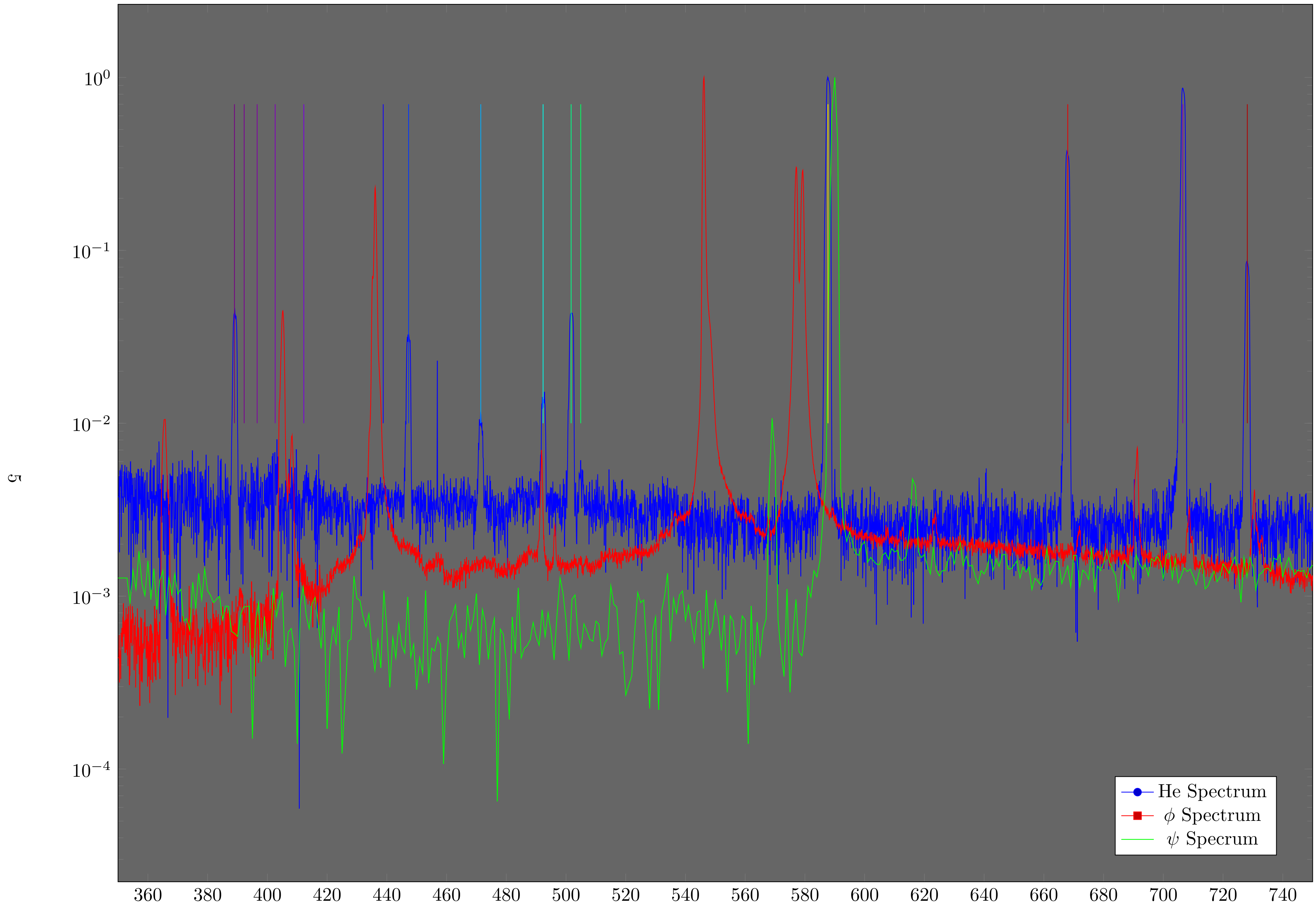

Figure 5: Helium, ψ, and ϕ lamp spectrum. Coloured lines denote predicted values for helium.

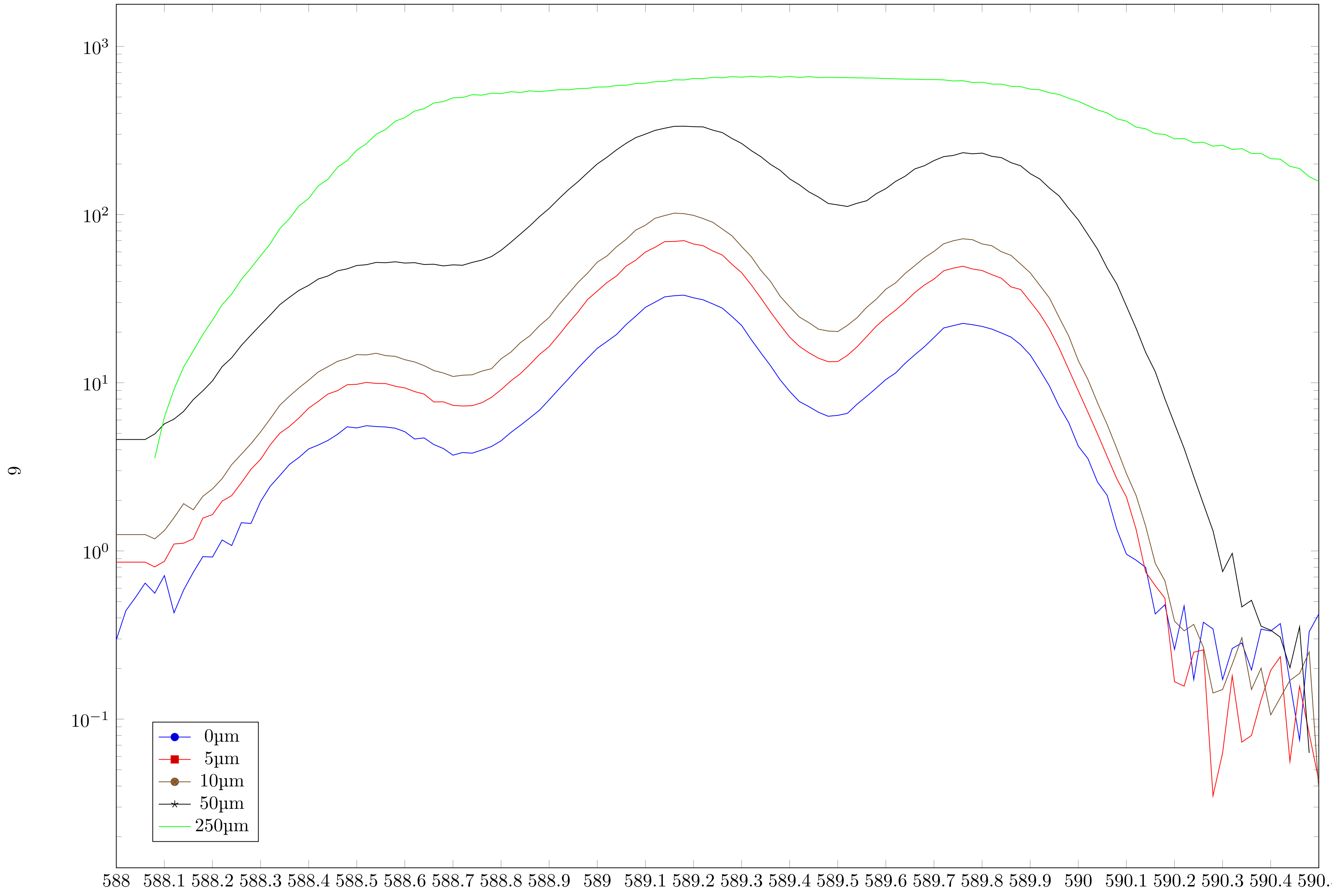

Figure 6: ψ lamp spectrum focused on yellow doublet. Note significantly decreased intensity for a 0μm slit width requiring semilog scale.