# Candidate 1 evidence

# Determining Wavelength

*3,529 words*

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**Abstract:**
An investigation into the principles of wave-mechanics, specifically those dictating wavelength of EM and particle-waves.

Experimentally this is to be achieved by determining the wavelength of EM radiation (or other wave-type emissions) under conditions where certain quantum-level effects become noticeable on the macroscopic scale.

Three separate experiments to ascertain the wavelength were undertaken: an experiment with the diffraction of charged particles from an electron-beam; another demonstrating Young's Double-Slit Diffraction with the synchronised phase-beam from a laser; the third involving Newton's Rings as a further demonstration of photo-interference.

The wavelength of the electron-beam was calculated as:

**3.7nm**

The wavelength of the laser-beam was calculated as:

**590nm**

The wavelength of the light used in Newton's Rings was calculated as:

**872nm**

**Physics Principles:**

Wave-particle duality is the fundamental principle that under certain circumstances, particles can exhibit certain properties traditionally associated with waves under the classical perspective on particle-wave theories of light.

Although this principle has been experimentally established to function with larger compound particles up to atomic and molecular scale, over the course of this investigation the principle was proved with more elemental emission types: simple light as EM radiation (both laser-synchronised & diffuse); and electrons exhibiting duality.

Particles- in this case, electrons- can exhibit wave-like properties, namely diffracting as they pass through an electromagnetic barrier. As electrons and other leptons are charged particles that interact with baryonic matter through means of Coulomb forces, the degree to which their wavelength varies relative to other particles and EM waves; this effect is calculated as the Atomic Form Factor. This factor influences the wavelength of the electrons, given by the de Broglie equation:

$$\lambda = \frac{h}{p}$$

…whereby *h* is Planck's Constant, (recognised as $6.63 \times 10^{-34}$ Js); and *p* constitutes the velocity of the electron, which may be sufficiently close to the speed of light to induce relativistic effects. [1]

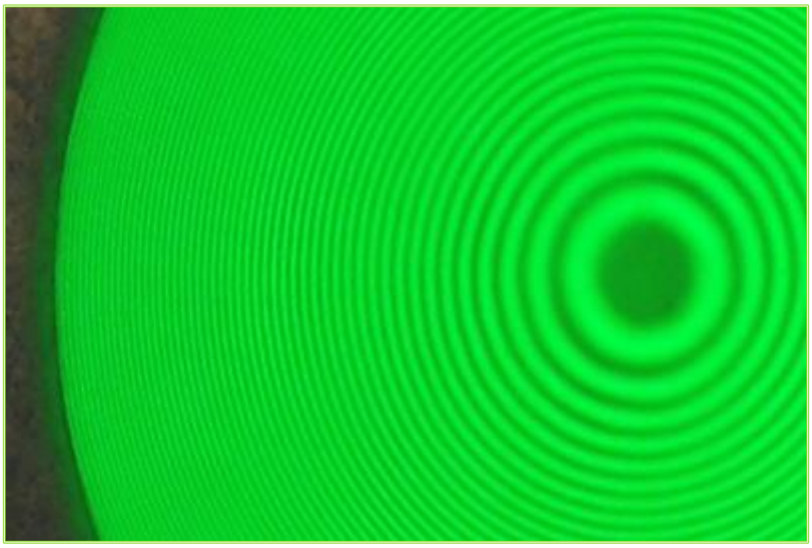
Due to this principle, it is possible to calculate the wavelength of ordinary baryonic particles in addition to massless photons, even including leptons such as electrons. Accordingly, once the wavelength of these 'matter-waves' is known, the principle can be applied to predict the way matter-beams can behave as waves- with wave-like properties such as diffraction, refraction, and (as tested here) interference.

In the case of electron-beams, the formula for the diffraction of the electrons as a matter-wave is:

...where $\vartheta$ is the angle of incidence, *d* is the separation between the grating through which the beam is projected, and *m* refers to the number of the wave-maxima.[2]

$$\lambda = \frac{d \sin \theta}{n}$$

At each maxima, the two matter-waves from the electron-gun will be in phase and undergo constructive interference, producing a point where the waves have a higher amplitude. In particle terms, this is expressed as an area where the particles in question impact more frequently. Evenly spaced between these maxima are points where the waves are precisely out of phase and undergo destructive interference, resulting in rings of darkness.

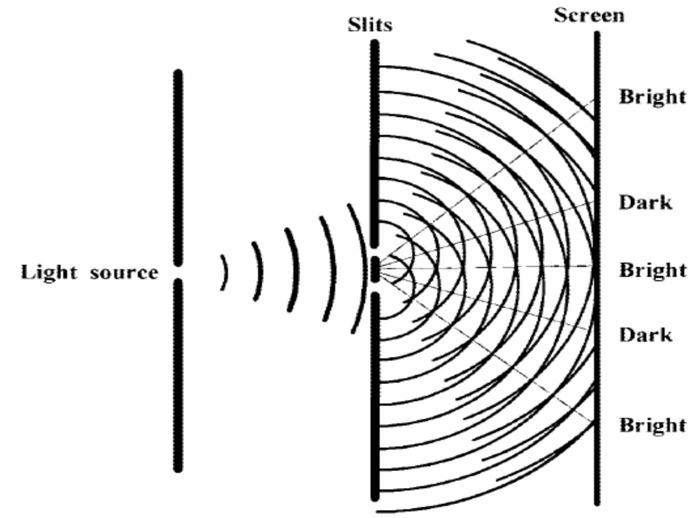


This effect is equally valid with linear spread (through a double-slit diffractor onto a flat screen) or radial spread (through an even grille onto a curved concave surface), and with massive or massless particles, as both can act as waves and produce the same set of glowing maxima. (Of course, as the impact from an individual electron is far too small to see, the effect visually appears closer to a set of smoothly glowing 'rings' of interference, as depicted left.)

If it is possible to measure the interference patterns from a matter- or energy-wave through a known slit-separation, the wavelength can be calculated and compared with a 'known' value. The formula in the case of double-slit diffraction against a flat planar surface:

$$\sin\theta = m\lambda d.$$

…where sin $\vartheta$ is the sine of the angle between each maxima, *d* is the slit-separation distance, and $\lambda$ the wavelength of the beam.[3]

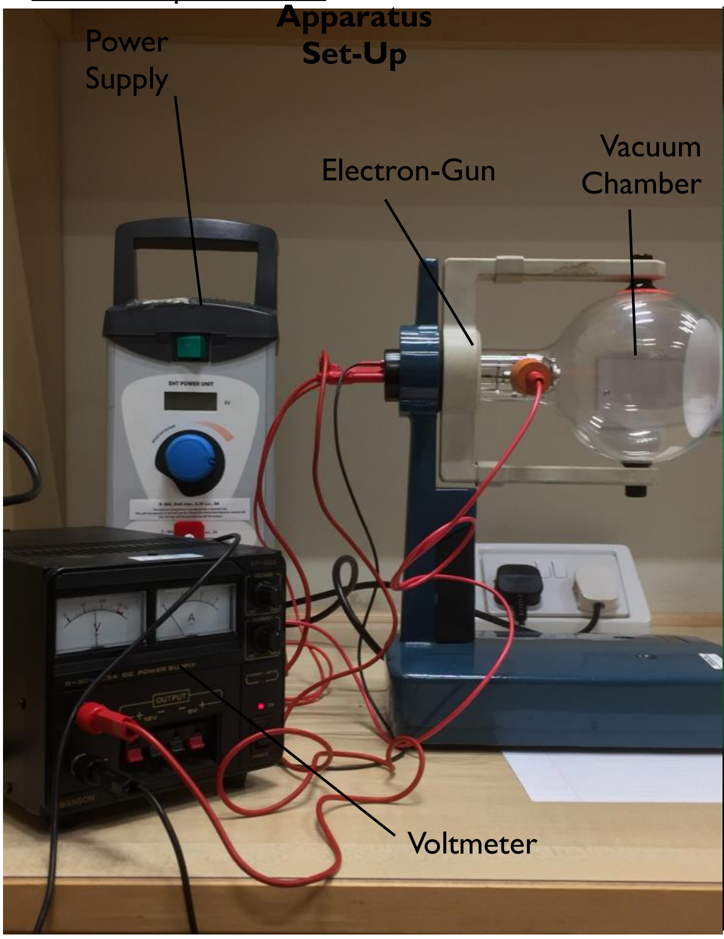


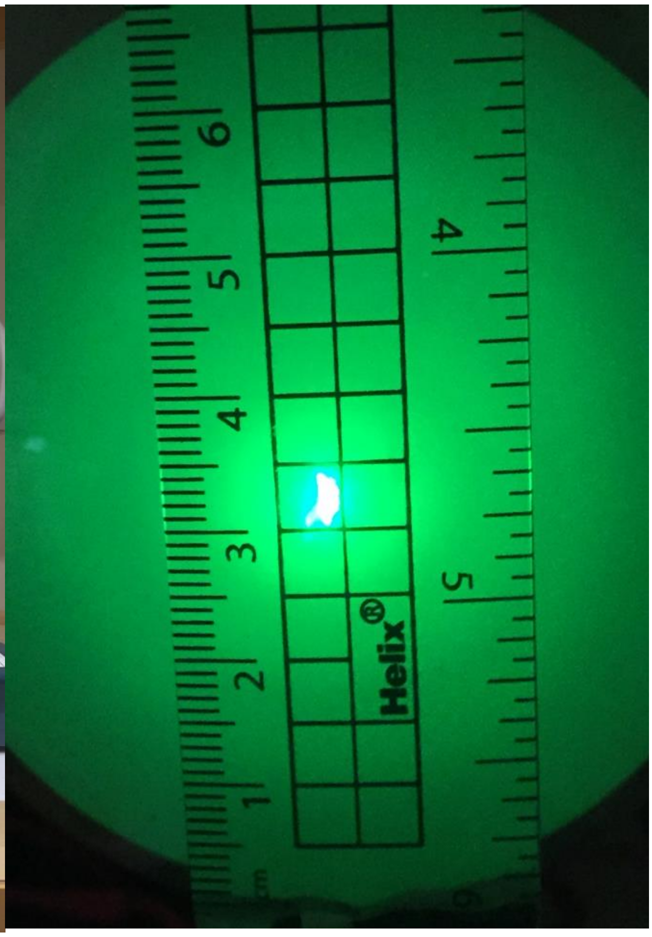

[4]

The objective, therefore, of the following experiments is to measure relevant variables relating to the behaviour of both classical ‘waves’ and particles exhibiting wave-like properties under duality, so as to ascertain values for the wavelength in each case. If the wavelength calculated from these experimental measurements corresponds with a ‘known’ value (either from the apparatus of emission, or else from de Broglie calculation), then the principle of wave-particle duality is demonstrated through the prediction and observation of wave-like behaviour.

## Experiment I: Electron-Beam Diffraction

<u>Technical Specification:</u>




FILAMENT VOLTAGE (Vf) --- 6.3V ac/dc (8V max)
ANODE VOLTAGE (Va) ---2500-5000V (6000V max)
ANODE CURRENT (Ia) ---0.15mA @ 4000V (0.2mA max)

<u>Experimental Procedure</u>

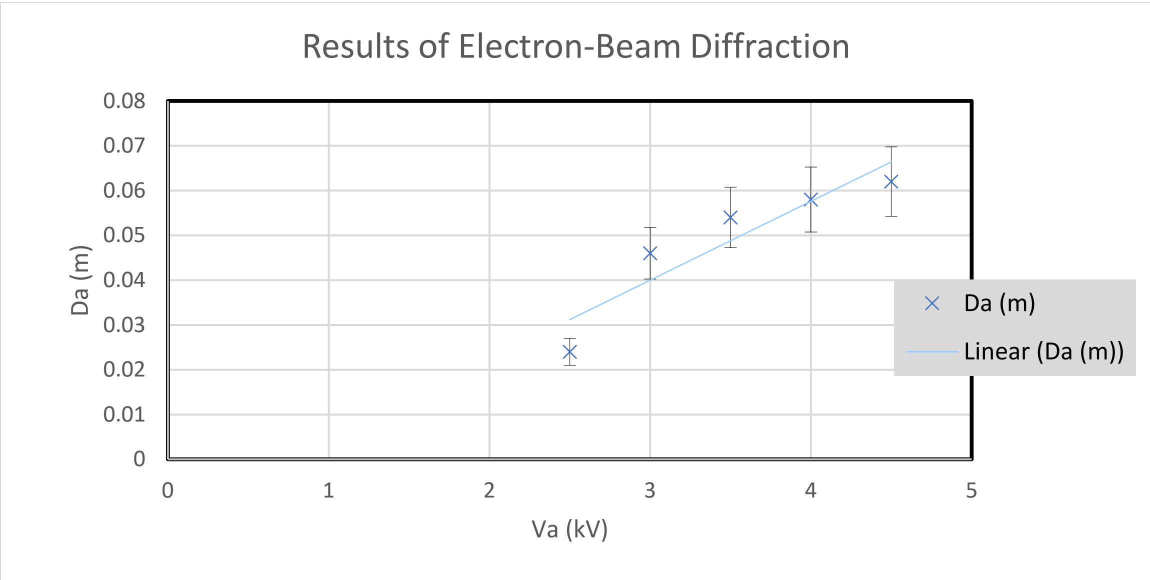
An electron-diffraction tube (Telford Electronics model 555) had a carbon-screen grating inserted and was connected to a 6V AC power-supply. The heater was switched on, after which the temperature-gradient was given a minute to stabilise. The E.H.T. was set to 4kV and the lights in the room darkened.

Glowing green rings around a central spot were observed, the radius of the inner ring being roughly of the mathematically-derived theoretical value. There was an inverse relationship between the anode voltage and the diameter of the ring.

Once the apparatus has stabilised in temperature, the electron-beam power-supply was set to the desired voltage- this being measured through the voltmeter in volts. The radius of the glowing green ring was then measured five times with a ruler- the distance being taken in meters- for the purposes of accuracy before moving on to the subsequent value.

Results-

| Va (kV) | Va −½ (V) | D1 (m) | D2 (m) | D3 (m) | D4 (m) | D5 (m) | **Da (m)** |
|---|---|---|---|---|---|---|---|
| 2.5 | 0.0200 | 0.025 | 0.023 | 0.026 | 0.021 | 0.023 | **0.0240** |
| 3. | 0.0183 | 0.046 | 0.048 | 0.045 | 0.045 | 0.041 | **0.0460** |
| 3.5 | 0.0169 | 0.053 | 0.056 | 0.053 | 0.052 | 0.054 | **0.0536** |
| 4 | 0.0158 | 0.058 | 0.057 | 0.057 | 0.058 | 0.059 | **0.0578** |
| 4.5 | 0.0149 | 0.062 | 0.060 | 0.064 | 0.063 | 0.063 | **0.0624** |
| 5 | 0.0141 | 0.069 | 0.069 | 0.071 | 0.069 | 0.070 | **0.0690** |




As we know, the de Broglie wavelength of a particle- in this case an electron- is-

**$\lambda = h/mv$**

The velocity, *v*, can be derived as:

$eV_a = \frac{1}{2} m v^2$

…which is then substituted into the de Broglie equation, giving us:

$\lambda = h/mv = h/\text{sqrt}(2emV_a) = 1.23\, V_a^{-1/2}$

…finally, we can substitute in the inverse relationship for Va, producing a final equation:

$\lambda = 1.23 \times (1/0.0176\text{-}0.0128)^{-1/2}$ m

In conclusion, here we have calculated a final value for the wavelength of the electron as:

$6.63\times10^{-34}/\text{sqrt}(2 \times 9.11\times10^{-31} \times 0.0176 \times 10^{3})$

**$= 3.702 \times 10^{-12}$ m.**

**i.e. 3.7nm**

This, therefore, is the experimentally-derived value.

The calculated value of the wavelength one would expect for an electron with a kinetic energy of 2500V is $0.572 \times 10^{-12}$ m, e.g. 0.572nm. Although this is an average value and therefore will not be applicable to all electrons travelling at different voltages (as seen in the experiment), it is still noticeably off our calculated value by a factor of over 5.3, or 533%.

<u>Uncertainties:</u>

Random uncertainties (max-min/no.of values) in the values of D are as follows:

| Va (kV) | Random uncertainty in D (m) |
|---|---|
| 2.5 | 0.001 |
| 3 | 0.0014 |
| 3.5 | 0.0008 |
| 4 | 0.0004 |
| 4.5 | 0.0008 |
| 5 | 0.0004 |

A scale reading uncertainty exists for both measurements:

V ± 0.1kV
D ± 0.0005 m

No information could be found about calibration uncertainty.

<u>Evaluation</u>-

There are a number of respects in which the experiment suffered from inferiorities that could have interfered with the accuracy and precision of the calculated result.

One issue experienced was the difficulty in accurately measuring the diameter of the luminescent interference rings. As electron-diffraction occurs over the diameter of the tube, the rings themselves became very blurry and lacked distinct outlines, as can be observed in the photography, making it difficult to measure an exact diameter with the ruler.

Although taking five repeated measurements per voltage doubtless helped to mitigate this issue to an extent, the degree of subjectivity involved may well have contributed to the unreliability of the data-points and final gradient.

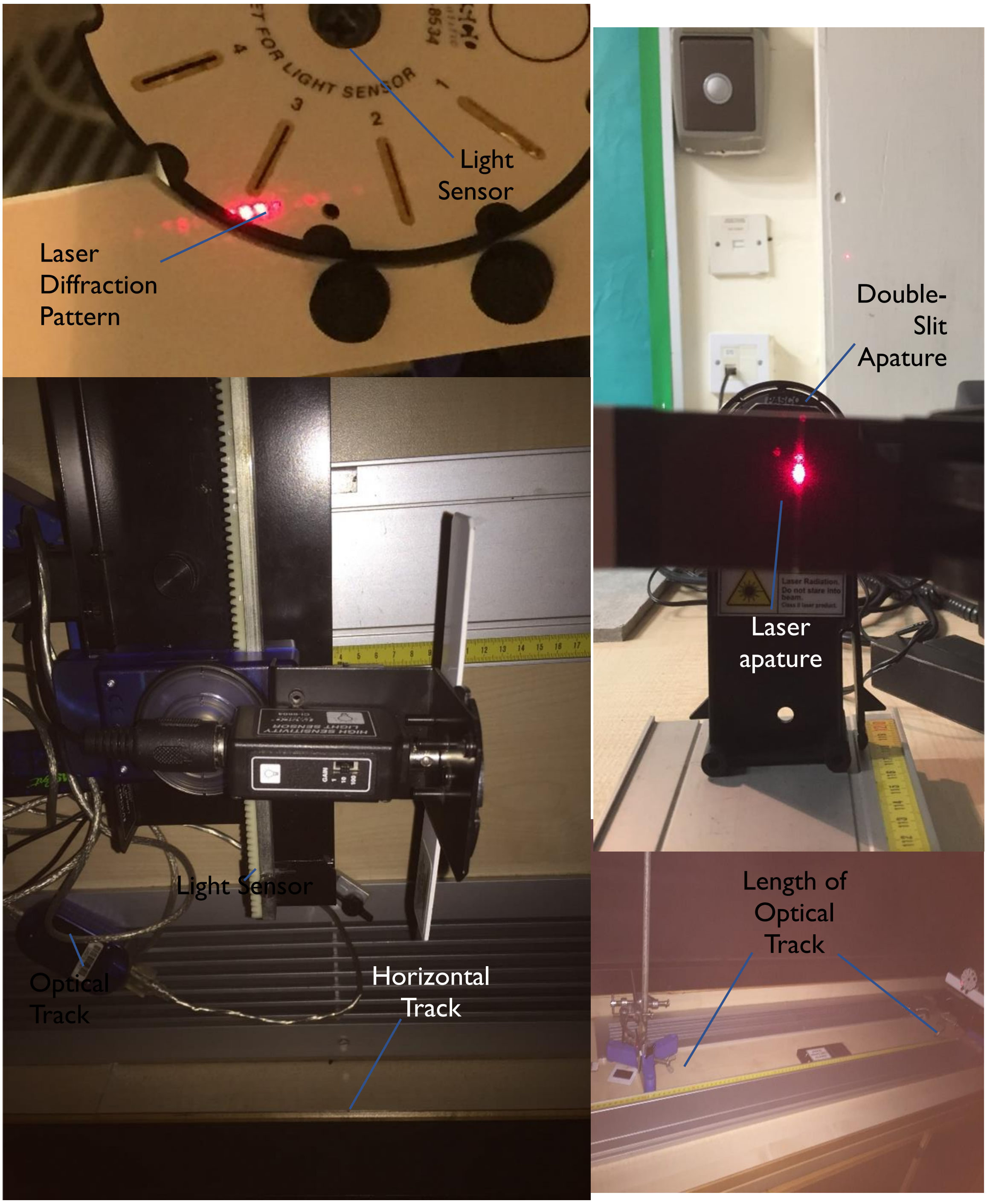
The range of variables involved was most probably a lesser issue, as the maximum voltage possible would have been 6.3 volts, and five measurements still gave a workable set of averages. Extending the voltages to which measurements were taken to 6 or 6.3 volts would have extended our data set by over 20%, but trying to take more measurements at shorter intervals of voltage may have proved counter-productive in light of the accuracy issues imposed by the vagueness of the rings, as it would have become even more difficult to observe- let alone measure accurately- subtle differences in ring diameter. Random interference (or, for that matter, the placebo effect!) would likely have proved a greater problem than the benefits brought by more readings.

Control over the independent variable was not much of an issue in this experiment. The only adjustment that needed to be made was the supply voltage, and as the mains AC was stable and the gauges perfectly easy to read, there is no reason to suppose that the supplied voltages were inaccurate. However, it is plausible to assume that a small portion of the supply voltage was lost due to inefficiency and inherent resistance in the electron-gun. Therefore, the actual voltage conveyed to the electrons may be slightly lesser than these calculations indicate.

I am doubtful that equipment limitations contributed hugely to the results of this experiment. The electron-gun, although potentially inefficient, did not appear to waver or be inconsistent in its production of the interference-patterns and there is no indication that the supply-voltage was inconsistent. I suppose that the ruler may have a small measurement uncertainty, but this is almost certainly overwhelmed by the vagueness of the rings.

Perhaps regrettably, I cannot think of a way to better de-alienate the exact diameter of the rings with the equipment we have available. I suppose, given the theoretical availability of extremely precise digital sensors, that the experiment could be conducted over a far smaller diameter vacuum-tube, thereby reducing the distance over which the electron-beams would diffract, but as this would make the luminescent rings themselves extremely small, the sensors would need to be extremely accurate to measure them precisely.

## Experiment II: Young's Double-Slit Diffraction (Laser Variant)




Procedures-

The aim of this experiment was to measure the wavelength of the light from the laser-beam, by means of projecting it through a fine grille so as to induce double-slit diffraction and produce an interference pattern, from which slit-separation can be measured and the wavelength calculated.

The laser was installed on one end of the optical-track and the first of the grilles to produce the slit-separation effect fixed in front of it. Each grille had been labelled with its effective slit separation on it, and these readings were accepted as the independent variable.

At the other end of the track, an electronic light-sensor was affixed to a horizontal track travelling perpendicular to the optical track, and then plugged into a computer running the PASCO Capstone software. The distance between the grille and the front of the light-sensor was then measured with the scale on the optical track itself, which for the purposes of this demonstration has been theorised to possess the same accuracy as a ruler, and in the event this was determined to be 0.82m. This distance was kept the same over the course of the experiment; care was taken to ensure this between repeats and exchanging each grille for the next.

The laser was then switched on after Health and Safety precautions (such as installing warning signs on adjacent surfaces, mitigating the risks of potential laser-reflection, and ensuring the beam was not firing toward anything of consequence) had been taken into consideration. At this point, a luminous interference-pattern was observed being projected from the laser. The apparatus was adjusted slightly so that the pattern fell across the path of the light-sensor on the track.

The light-sensor was pulled across the path of the interference-pattern on the horizontal-track. The light-sensor was then switched-on and the PASCO Capstone software set to record and save its measurements electronically. The light-sensor was then pushed slowly along the horizontal-track so as to pass under the complete interference pattern. For each measurement, the result produced was a complicated line-graph corresponding to the intensity of the light (with each peak representing a bright maxima and each trough corresponding to a dark minima).

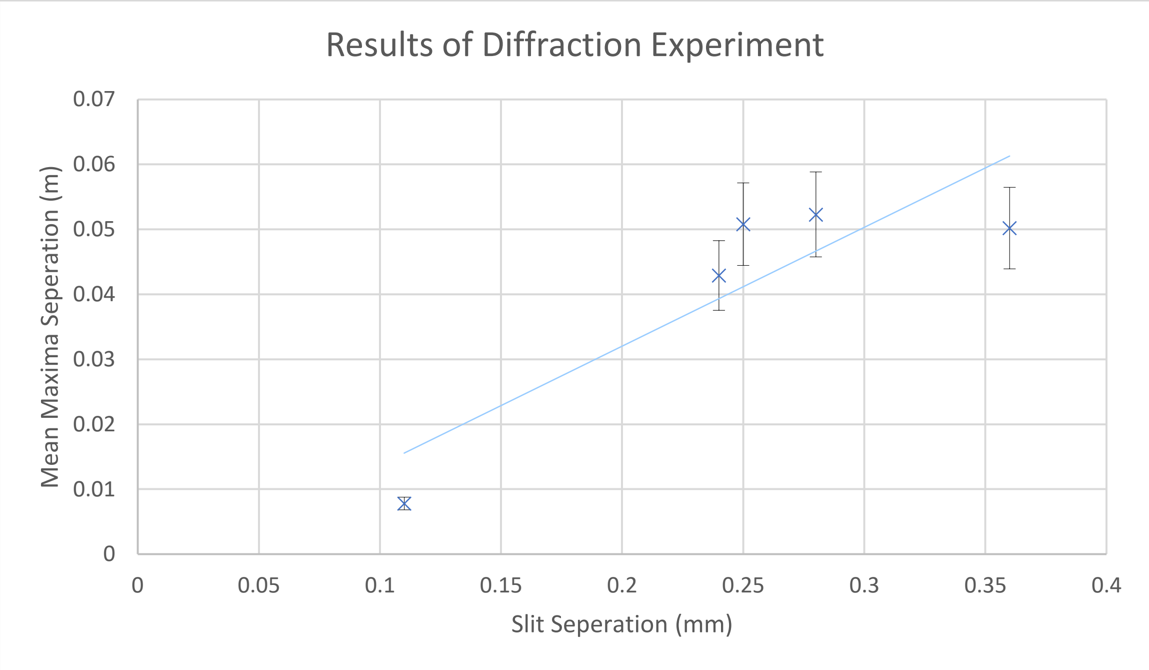
This procedure was then repeated five times for each grille. After each set had been completed, the grille was exchanged for the next one, with its slit-separation also being noted.

Each graph (see appendix for an example) was then subjected to simple analysis whereby the width of the overall pattern was divided by the number of clear peaks on the line, so as to calculate the maxima-separation. These results were then processed as follows-

<u>Results-</u>

| Slit Separation (mm) | 0.11 | 0.24 | 0.25 | 0.28 | 0.36 |
|---|---|---|---|---|---|
| Maxima Separation #1 (m) | 0.00750 | 0.0438 | 0.0546 | 0.0636 | 0.0630 |
| Maxima Separation #2 (m) | 0.00750 | 0.0460 | 0.0545 | 0.0514 | 0.0500 |
| Maxima Separation #3 (m) | 0.00813 | 0.0417 | 0.0571 | 0.0411 | 0.0425 |
| Maxima Separation #4 (m) | 0.00775 | 0.0414 | 0.0423 | 0.0529 | 0.0525 |

| | | | | | |
|---|---|---|---|---|---|
| Maxima Separation #5 (m) | 0.00813 | 0.0415 | 0.0457 | 0.0523 | 0.0430 |
| **Mean Maxima Separation (m)** | **0.00780** | **0.0429** | **0.0508** | **0.0523** | **0.0502** |




*m* = 0.042m / 0.25mm = 169.592
λ = 1/(169.592 x sin(1.571 × $10^{10}$ rad)) = 0.589652 x $10^{-12}$ m

$$\lambda = \frac{d \sin \theta}{n}$$

In conclusion, this gives us a final measurement as per

as- λ = **589.650nm**
or- **590nm** (3sf)

This is not entirely consistent with the stated value of the wavelength of the laser, which is given as 650nm (being in the red portion of the spectrum). It is, in fact, about 60nm (or 9.81%) off.

Uncertainties:

Random uncertainties (max-min/no.of values) in the values of maxima separation are as follows:

| Slit separation (m) | Random uncertainty in maxima separation (m) |
|---|---|
| 0.11 | 0.000126 |
| 0.24 | 0.00092 |
| 0.25 | 0.00296 |
| 0.28 | 0.0045 |
| 0.36 | 0.0041 |

No calibration uncertainty could be established and slit separation was assumed correct.

A scale reading uncertainty existed for the measurement of slit separation = ±0.00005m

<u>Evaluation-</u>

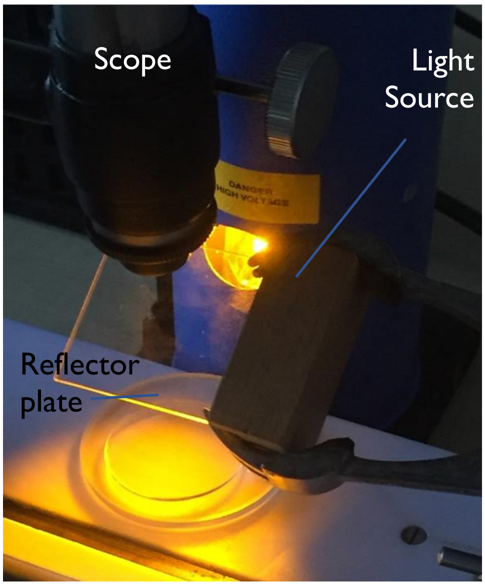
Although this experiment appears reasonably successful, there is still a slight discrepancy between the calculated value (which would be more orange or yellow in hue) and the wavelength of the light itself. Accordingly, a number of potential reasons could exist for this inaccuracy.

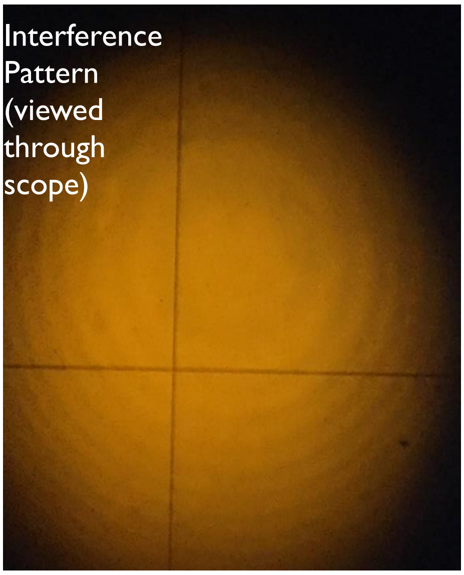
The experimental measurements, being taken as they are by a computer-controlled electronic light-sensor, are probably fairly accurate. One issue that could affect the accuracy of the results is the stability of the angle upon which the horizontal track rests on the optical track. If the horizontal track were to become slightly slanted, the light-sensor might slip outwith the interference-pattern at one end, resulting in the intensity of the measured light-pattern becoming asymmetric. If a maxima or minima were to be missed by this problem, it could interfere with the accuracy of the results, although taking multiple measurements and averaging them should help to mitigate this problem to a significant extent. As care was taken to ensure that the distance along the length of the optical-track between the grille and the sensor remained the same at all points, this should prove less of an issue compared to the risk of angular displacement.

Each measurement per slit-separation was repeated five times, which should be enough to ensure that any risk of individual anomalous measurement (or calculation, as each graph's slit-separation had to be painstakingly calculated by hand) affecting the mean unduly remains low.

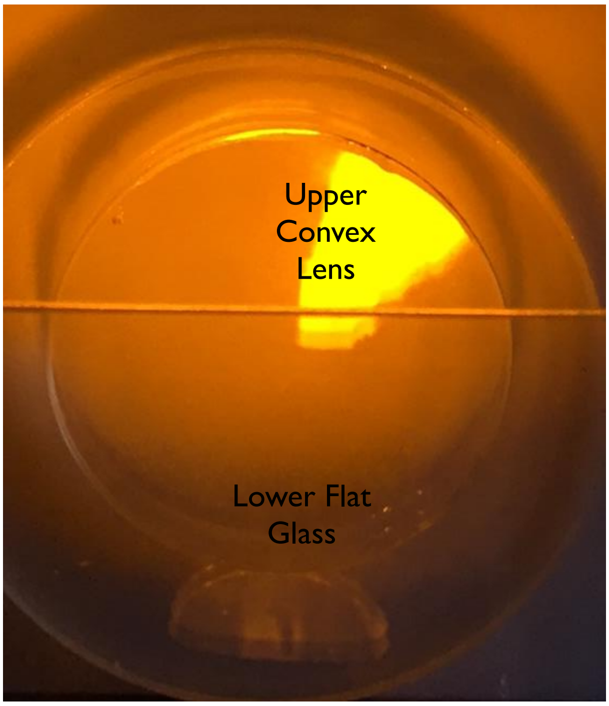
The slit-separations vary over a 0.25mm range, which is probably reasonably sufficient to ensure a good variety of result. However, as can be observed from the above graph, the final measurement (of the 0.36mm grille) is not significantly higher in terms of slit-separation than the preceding 0.28mm grille. It is possible that either the grille is labelled inaccurately, or else that the great intensity of the brightness of the light through the final grille overloaded the light-sensor (as can be observed on the final set of graphs) and produced anomalous results.

**Experiment III: Newton's Rings**


Scope
Light
Source
Reflector
plate


Interference
Pattern
(viewed
through
scope)


Horizontal
Scope
Track


Upper
Convex
Lens
Lower Flat
Glass

Procedures-

The aim of this experiment was to demonstrate the principle of interference through the process of refractive diffraction. Much as the preceding two experiments, monochromatic light produces an interference pattern known as "Newton's Rings", the diameter of which can then be used to calculate the wavelength of the incident light.

The equipment was set up with a sodium lamp reflecting off a semi-silvered glass plate set at a ninety-degree angle, so as to reflect the light into the apparatus of a single convex lens balanced atop a flat glass plate. This created the interference-pattern between the two glasses and the circular air-wedge between them, resulting in the aforementioned pattern of interference.

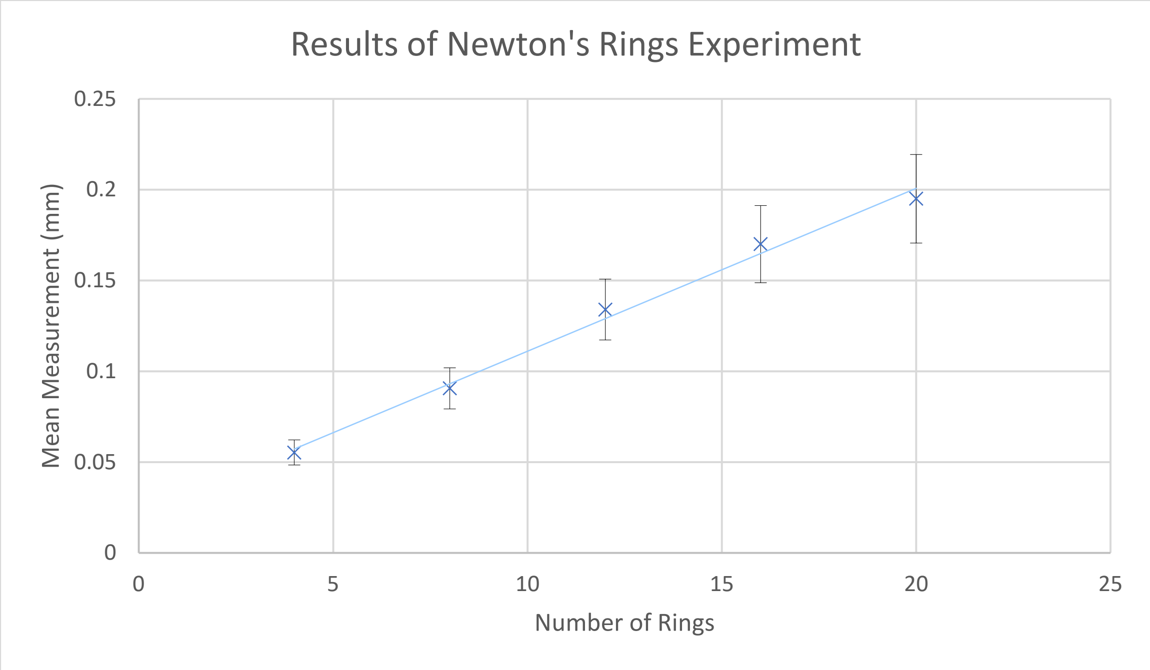
This pattern was observed through means of an optical scope mounted on a horizontal track running perpendicular to the path of the light and pointing directly down at the two glasses so as to capture the pattern. The scope was laboriously pointed at the centre of the interference pattern before measurements were taken.

The scope was then moved horizontally along the track to the extremity of each indicated dark 'ring' of destructive interference- in effect, each is a circular minima. The diameter of each ring was then measured from the centre-point by means of the vernier scale on the horizontal-scope track, allowing highly precise (if not necessarily *accurate*) measurements to be made in millimetres.

In order to counteract interference caused by any inherent asymmetry of the lens, it was decided to take measurements of the diameter of each successive ring five times at both its leftward and rightward extremities, at the fourth, eighth, twelfth, sixteenth, and twentieth rings. These results were then collocated in the following table, and means calculated for each ring.

Results-

| Measurement (mm) | 4 | 8 | 12 | 16 | 20 |
|---|---|---|---|---|---|
| L1 | 0.050 | 0.092 | 0.133 | 0.169 | 0.192 |
| R1 | 0.045 | 0.098 | 0.135 | 0.167 | 0.188 |
| L2 | 0.061 | 0.085 | 0.131 | 0.172 | 0.196 |
| R2 | 0.062 | 0.089 | 0.153 | 0.167 | 0.209 |
| L3 | 0.046 | 0.093 | 0.115 | 0.175 | 0.199 |
| R3 | 0.065 | 0.095 | 0.135 | 0.170 | 0.193 |
| L4 | 0.054 | 0.087 | 0.135 | 0.168 | 0.196 |
| R4 | 0.053 | 0.089 | 0.148 | 0.172 | 0.197 |
| L5 | 0.055 | 0.086 | 0.137 | 0.174 | 0.194 |
| R5 | 0.062 | 0.092 | 0.122 | 0.166 | 0.184 |
| **Mean Measurement (mm)** | **0.0553** | **0.0906** | **0.134** | **0.170** | **0.195** |




Conclusively, from this gradient, we can calculate a wavelength of **872nm**. This is also rather anomalous, as one would expect the yellow-coloured sodium light source to be somewhere in the wavelength region of 570nm-520nm. This results in an excess wavelength of around 40-45%.

Uncertainties:

No uncertainty in number of rings.
No calibration uncertainty could be established.
A scale reading uncertainty exists in the measurement of radius of ±0.0005m

Random uncertainties (max-min/no.of values) in the values of radius are as follows:

| No of rings | Random uncertainty in radius to (m) |
|---|---|
| 4 | 0.002 |
| 8 | 0.001 |
| 12 | 0.0033 |
| 16 | 0.0009 |
| 20 | 0.0025 |

Evaluation-

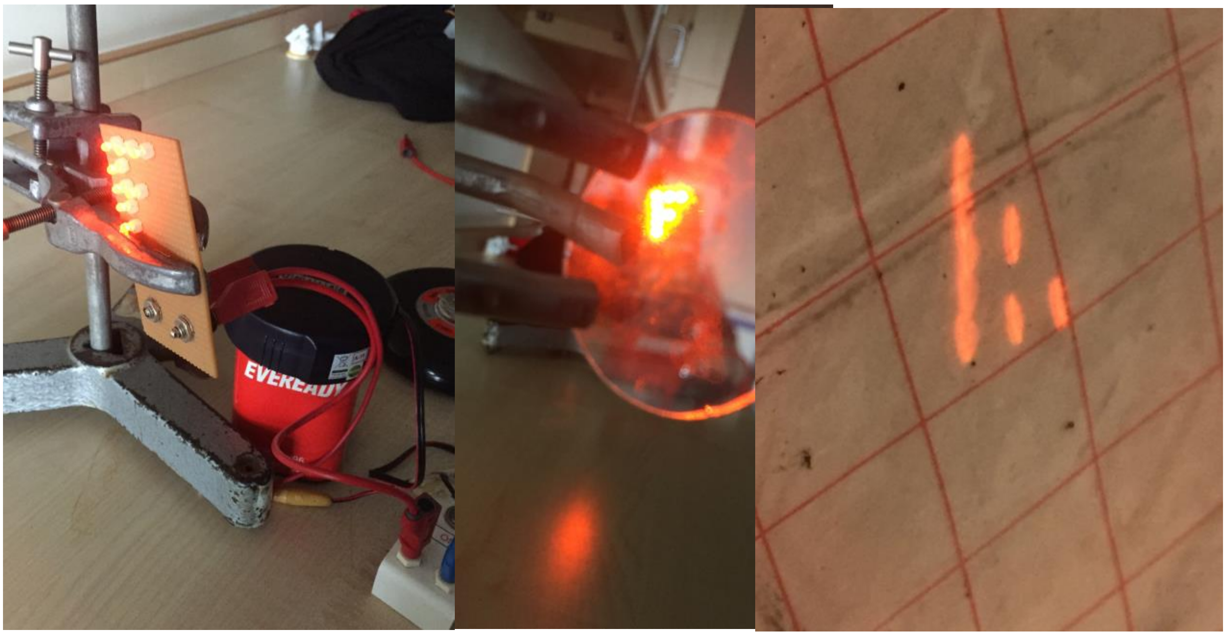
Unfortunately this experiment was racked with a number of issues regarding the accuracy and hence reliability of the results. The central issue at hand was that it proved extremely difficult not only to focus the optical set-up correctly so as to produce a clear set of rings centred precisely on the scope, but also to move the scope from side-to-side with the precision necessary (minute fractions of a millimetre) to focus on incredibly small sets of minima.

Whilst the vernier scales provided enormous precision, it was extremely difficult to maintain accuracy whilst using then and this is regrettably reflected in the large random uncertainties displayed in the results. It may potentially prove easier to make measurements of this precision digitally using machine-heuristics or other forms of image-analysis software.

The number of unique rings measured began to prove an increasing issue toward the end of this experiment, as the rings become progressively closer-spaced the further out they travel. This is reflected in a further increase in random uncertainty, particularly toward the later rings.

One positive remark that can be observed with regards to uncertainty is the procedure of taking additional measurements to both sides of the rings, effectively doubling the number of results obtained. Not only did this have a substantial impact on reducing the damage caused to the accuracy by the occasional anomalous reading (thereby reducing random uncertainty) but also helping to counteract the issues caused by the substantial asymmetry of the lens.

The most critical issue experience with this experiment, however, was undoubtedly the great asymmetry of the convex lens used. Although not apparently obvious whilst placing the lens on the glass, and not necessarily adversely affected the results due to the two-sided method of averages used, after the experiment it was determined that the lens was, in fact, strongly asymmetric, needing to be held at a thirty-five degree angle in order to focus properly, as can be evidenced by the following photographs of subsequent attempts to rectify this situation:



Whilst the effects on the geometry of the rings themselves was compensated for by the double-sided weighing approach, the effect of the asymmetry did result in the rings being physically positioned vastly further away from the geometric centre of the lens than might have been expected, leading to the unnecessary and undesirable expenditure of a lot of time and energy chasing down the cause of a precision issue initially attributed to human error. In retrospect, this portion of the experiment would have been far better for the presence of superior optics.

## Conclusion:

The objective of this set of experiments was to investigate the principles of wave-mechanics, specifically by investigating the wavelength of different particle and EM waves undergoing interference in different contexts.

The wavelength of the electron-beams undergoing diffractive interference in the vacuum-tube was calculated as **3.7nm.**

The wavelength of the laser undergoing Young's double-slit diffraction was calculated as **590nm.**

The wavelength of the sodium-lamp-light undergoing refractive interference in the Newton's Rings experiment was calculated as **872nm.**

References:

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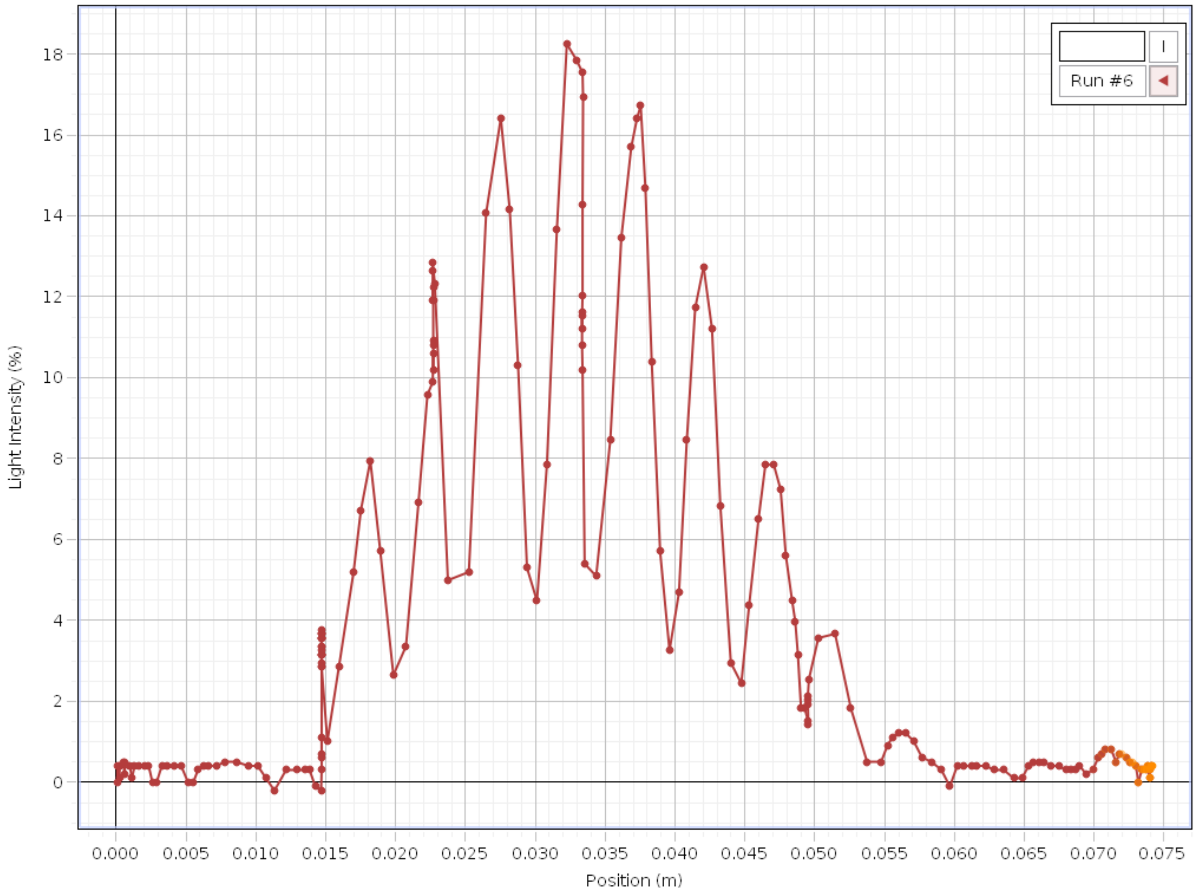
4. Opentextbc.ca. 2020. Young'S Double Slit Experiment. [online] Available at: <https://opentextbc.ca/physicstestbook2/chapter/youngs-double-slit-experiment/> [Accessed 23 March 2020].

## Appendix- Example of a Laser Graph

### Table of Results (0.24mm)
### 0.04375m

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