A GUIDED INQUIRY APPROACH TO TEACHING THE DIFFRACTION OF LIGHT

Wen-Tang Lee, I-Chun Huang
National Chia-Yi Senior High School, Chia-Yi, Taiwan
wtlee157@gmail.com

Abstract: The purpose of this paper is to design a guided inquiry approach to teaching the diffraction of light. Two guided inquiry physics experiments of the diffraction of light hair and CD are used for students to do labs. The equipment involved is very simple, which increases the students' level of self-confidence and understanding during their exploratory lab work. When a laser beam passes through a single narrow slit, a few diffraction fringes are formed on the screen. It explores the relationship between the radius of a hair, the average width of diffraction maximum, and wavelength of the laser. Students then construct a formula and a graphical representation using the formula to calculate the radius of the hair. When a laser beam passes through a transparent CD some diffraction maxima occurs symmetrically on both sides of the central maximum. Students find the relationship between the position of diffraction maxima and wavelength of the laser, and the distance between the CD and screen. By measuring the position of the fringes, student can calculate the wavelength of the laser beam. Position a light source behind a ruler and observe the diffraction fringes on the ruler from a distance between a transparent CD and the ruler. By measuring the position of the fringes, student can calculate the wavelength of visible light. The following guided inquiry lesson provides senior high school students the opportunity to experiment like a scientist and apply the inherent scientific concept.

Keywords: Guided-inquiry, Diffraction of light, Diffraction grating.

Ⅰ. Introduction

Inquiry-based science instruction continues to be a focus in education. Scientific inquiry refers to diverse ways in which scientists study the natural world and propose explanations based on evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world (NRC, 1996). However, inquiry does not consist of a single fact. There are varying ranges from a more traditional approach, to a more open inductive approach where students are generating their own experiments.

The National Science Standards (1996) determined that inquiry contains five essential characteristics: (a) learners are engaged by scientifically oriented questions, (b) learners have the ability to determine what data allows them to develop an evaluate scientific explanations, (c) the students will have the ability to formulate their own explanations from the evidence they have obtained, (d) students can expand upon their findings and relate those findings to similar situations, (e) the learners will then be able to communicate their experimental finding to others in class via small group work, presentations to the entire class, or written laboratory reports.

Keys and Kennedy (1999) revealed challenges in implementing inquiry-based instruction, these challenges included: (a) lack of time, (b) difficulty refraining from directly answering student questions, (c) teaching abstract curriculum objectives that did not lend themselves easily to inquiry-based instruction, and (d) district assessment instruments that focused on vocabulary. Chatterjee et al. (2009) described their use of a well-designed survey to compare students' attitudes toward guided- and open-inquiry labs. They concluded that the students have a preference for guided-inquiry labs and responded more positively to them compared to open-inquiry labs.

Diffraction phenomenon is a basic property of wave. High school physics courses, including the elementary physics courses for 10th grade, introduce qualitatively the diffraction phenomenon of water, sound, and light waves. If an obstacle with a small gap, which size is comparable to the wavelength of the ripples, is placed in the ripple tank, the ripples emerge in an almost semicircular pattern. If the gap is large however, the diffraction is much more limited. In the physics course for 12th grade, light diffracted by a single narrow slit is introduced. Monochromatic light passes through a slit whose width is comparable to the wavelength and falls on a screen at a large distance. Without elaborate mathematics, by using the Huygens' wavelets from different parts of the slit interfere and produce the diffraction pattern, a diffraction formula is deduced. The width of diffraction maximum, the position of diffraction minimum is discussed quantitatively. An experiment is followed by using a laser and a single slit.

Ⅱ. Experiment

1. Experiment A

Purpose: To measure the radius of a hair.

Required equipments and supplies: Optical bench (meter stick with supports), a holder which can attach a hair vertically, a He-Ne laser, a green laser, a screen, a meter rule.

Time: 2 hours.

Prelab:

Prior to the lab, students are given a half-hour instruction on the diffraction of a single narrow slit (Stephen, 2007). When a laser beam passes through a single narrow slit, a few diffraction fringes are formed on the screen as shown in Fig. 1. The minimum in the intensity occurs when $a\sin\theta = m\lambda \ (m = \pm 1, \pm 2, \cdots) \cdots (1)$

a: the width of the slit

θ: the angular position of the minimum.

m: the order of the diffraction minimum

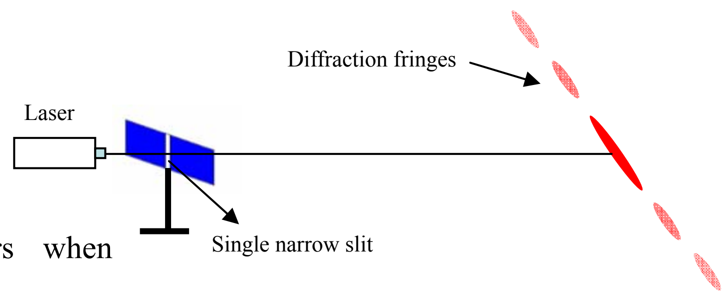


Fig. 1. Laser light diffraction by a single narrow slit.

Exploration:

In the laboratory, students, working in groups of three, construct the equipment on the lab bench. Almost all students construct the equipment as shown in figure 1, but the single slit is substituted by a single hair. They find the diffraction pattern of a hair is similar to the diffraction pattern of a single narrow slit. I ask them to measure the width of the diffraction first and they can record experiment data. Students work in groups to measure the distance L between the hair and the screen, and the width of maximum.

After collecting data, students work in groups to discover the relationship between their data and the theoretical model to the data. At this time, I move among between student groups following their discussions, asking, and answering questions, but the responsibility of making the connection between their lab data and theoretical model is left to each group. After some time, I ask each student group to share their method of measuring the width of maximums. A lot of groups measure the width of the central maximum directly. But some groups measure the total width, including the central maximum and 4 to 6 other maximums, to get the average width of the maximum. This is a great “Aha” moment for many students who have learned the concept of: when the width is smaller, the error of measurement will be larger; the more sample, the less margin of error. At this point, it is useful to generate a discussion on independent and dependent variables, and invite student groups to identify these in relation to their data. It is vital that instructor exercise patience at this time and refrain from directing students to the answer. Instead he should ask questions and encourage students to find the solution.

I ask students to explore by experiment the relationship between the radius of a hair a, average width of diffraction minimum Δy, and wavelength of laser λ. I ask them to keep working and end the lab 30minutes before the class, so we can share our findings. I move along between groups again. Students measured the average width Δy of red color (λ=633nm) which is wider than the green color (λ=580nm). They can infer that Δy is proportional to the wavelength λ. Since they find that Δy grows wider as the distance between the hair and the screen becomes larger, they infer Δy is proportional to the distance D. Some students ask me how to find the relationship between Δy and the radius of the hair b. I suggest to them that they may use the method of the dimensional analysis (Gayle, 2007). Finally they find Δy is inversely related to the radius of the hair b by dimensional analysis. Putting all of these ideas together, they come to the equation:

$$\Delta y = \frac{D\lambda}{a} \cdots (2)$$

Student measure 5 different distances D, and get 5 corresponding width of maximum Δy. A few groups construct a graphical representation of the Δy versus D, and they calculate the radius of the hair directly by using equation (2), to obtain 5 data of radius, and then calculate the average radius of the hair, as shown in Table Ⅰ. One group of students who had the experience of Olympian physics training in Taiwan construct a graph representation of the Δy versus D by Microsoft Excel as shown in Fig. 2. They get the slope of this figure, and calculate the radius of the hair from the slope and wavelength, by using equation (2). Some groups reach this conclusion before others, providing an opportunity for peer teaching and learning (Timothy, 2010).

Table Ⅰ The measured Δy, D, and a

	D (cm)	Δy (cm)	a (mm)
1.	30	0.126	0.15
2.	40	0.158	0.16
3.	50	0.198	0.14
4.	60	0.253	0.15
5.	70	0.295	0.13
Average:			0.15 ± 0.02

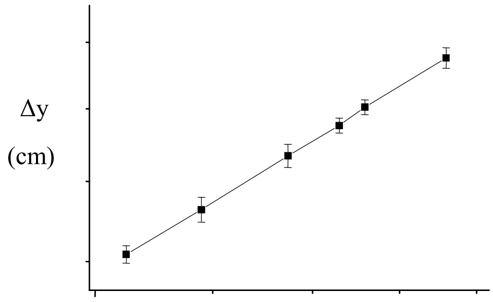


Fig. 2. The relationship between Δy and D

Concept Development

After, data collection and a graphical representation of the average width of the diffraction maximum Δy versus the distance between the hair and screen D takes place. It is in these interactions (with the textbook and the peers) that real learning take place. Like a scientist, they construct the diffraction equation:

$$\Delta y = \frac{D\lambda}{a} \cdots (2)$$

But they wonder why equation (2) they constructed is different from equation (1) $a\sin\theta = m\lambda$. I instruct them equation (2) is just the approximation of equation (1).They can try to derive equation (2) from equation (1). Because D is over ten thousand times of y, $\sin\theta \approx \tan\theta = \frac{y}{L}$ approximately, y is the distance between a minimum to the central line of the diffraction pattern. From equation (1), $a\sin\theta \approx a\tan\theta = a\frac{x}{D} = m\lambda$, for $m = 1, y_1 = \frac{D\lambda}{a}$, for $m = 2, y_2 = \frac{2D\lambda}{a}$, we can get

$$\Delta y = y_2 - y_1 = \frac{D\lambda}{a} \cdots (2)$$

Students obtain the formula of single narrow slit diffraction by experiment and math interpretation. They construct the concept of light diffraction by experiment.

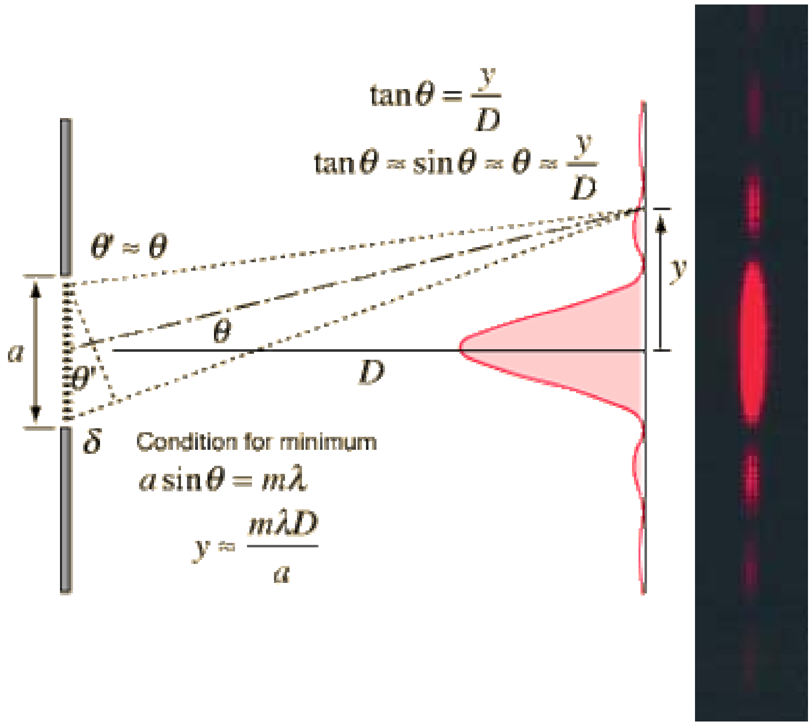


Fig. 3. Diffraction of a single narrow slit

Another question students have is that why do two noticeable different experiments, the experiment with a slit (a gap which light can pass through) compared to the experiment with a hair (an obstacle which light is blocked), have the same diffraction pattern. I encourage them to explain it by using the principle of Huygens wavelet. This is the essence of the phenomenon of diffraction.

2. Experiment B

Purpose: To measure the wavelength of light

Required equipments and supplies: Optical bench (meter stick with supports), a holder that can attach a CD vertically, a He-Ne laser, a green laser, a wood box with a narrow slit, a screen, a meter rule.

Time: 2 hours.

Prelab:

Prior to the lab, students are given a half-hour lecture on the grating and CD (Ivanov, 2010). A diffraction grating consists of a piece of metal or glass with a very large number of evenly spaced parallel lines or grooves. Common laboratory gratings have 300 grooves per mm.

There are two types of gratings: reflection gratings are marked on polished metal surface and light is reflected from the unmarked areas which act as a row of “slits”. Transmission gratings are ruled on glass and the unmarked slit areas transmit light (it is very expensive for any high school’s budget).

A standard compact disk (CD) has 20,625 turns tracks of spirals (Kettler, 1991), similar to the reflection grating of metal, which has 625grooves per mm. If we remove the aluminum coating of a CD with a sharp knife and the blue azo dye with isopropanal, the CD will behave as a transmission grating- we call it the 'transparent CD grating' (Byme, 2003). When a laser beam passes through a diffraction pattern is shown as in Fig. 4. The bright spot (diffraction maximum) occurs symmetrically on both sides of the central maximum.

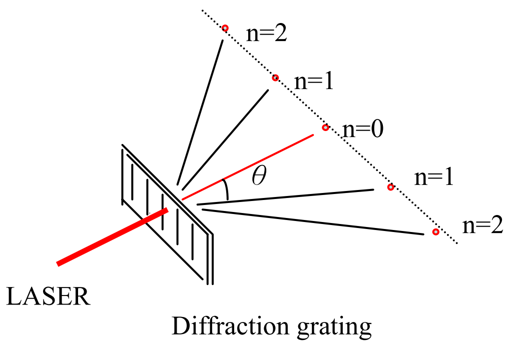


Fig. 4. Diffraction of grating

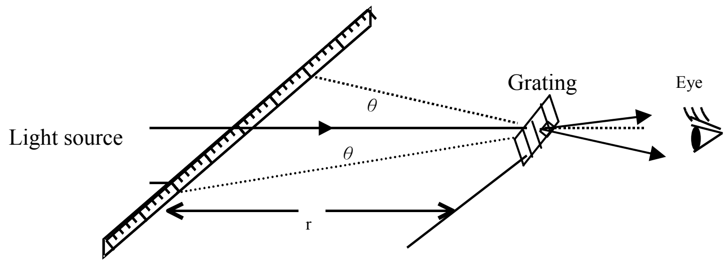


Fig. 5. Measurement of the wavelength of visible length

Since the intensity of visible light is too low, it is hard to form the diffraction pattern as shown in Fig. 4. One can measure the wavelength of visible light as shown in Fig. 5. Position a light source behind a ruler and observe the diffraction fringes on the ruler with distance r between the grating and the ruler. By measuring the position of the fringes, one can calculate the wavelength of light.

Exploration (1):

Students work in the same groups as in Experiment A. I ask them to measure the distance d between two spirals of the CD first; they can record experiment data. I move along between student groups. They construct the equipment on the lab bench as shown in figure 6. Some groups of students note that the image for a given order does not appear at equal distances from the center point o, which means that the distance between o and x_1 is larger or smaller than the distance between o and x_1'. I suggest them may rotate the CD slightly until they appear at

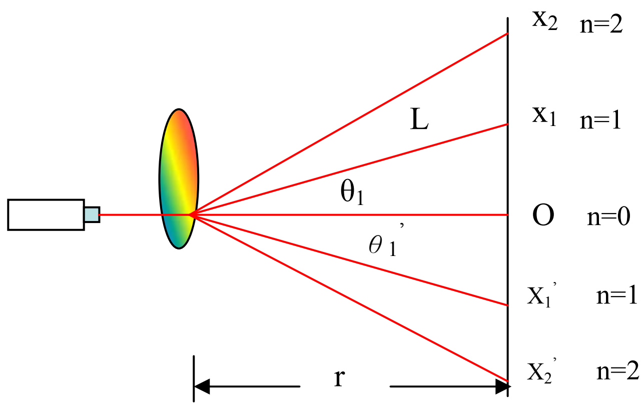


Fig. 6. Light pass through a transparent CD

n =order of diffraction

equal distances. After 15 minutes, a group reports the result they have measured-the distance d between two spirals of the CD by using the equation:

$$\Delta y = \frac{L\lambda}{b} \cdots (2)$$

They forget equation (2) is derived from equation (1) at the condition that the distance between the grating and screen r is over thousand times of the space between two diffraction maxima. But for the experiment of diffraction by a CD grating, L is almost at the same order of magnitude with x, it is not suitable to use equation (2) to calculate the space of the CD grating. I suggest them to find the relationship between the position of diffraction maximum x with λ, and L.

They find by experiment that x is proportional to the wavelength λ, L, and order of diffraction n. Put all of these ideas together, they come to the equation: $x \propto mL\lambda$

They construct a graph representation of x versus L by Microsoft Excel. They get the slope of this figure to form the equation:

$$d \sin\theta = n\lambda (n = 0, \pm 1, \pm 2 \cdots) \cdots (4)$$

d: space of the grating

θ: angular position of diffraction

n: order of diffraction maximum

Some students ask me a good question- in Experiment A there are a lot of diffraction maxima, why are there only 5 bright points on the screen in this Experiment B.

I suggest that they can think about it from equation (4) by trigonometric function.

The fact of sinθ≦1 will make the numbers of n less than d/λ. Since the distance d between two spirals of a CD is d=1.6μm, the wavelength λ of He-Ne laser is λ=633nm, so, d/λ=2.53. Student can find 5 bright maximum at the position: n=0, n=1, n=2, n=-1, n=-2. But the deeper physical meaning is worthwhile to think about and discuss. Students measure the positions of x and the distance L to obtain the angular position of diffraction θ, by using equation (4), and they get the distance between two spirals of in a CD is d= (1.635±0.003) μm.

Exploration (2):

Student groups begin to measure the wavelength of a compact fluorescent lamp. They placed a lamp inside a wooden box with a slit on the side. Arrange the lamp, a transparent CD

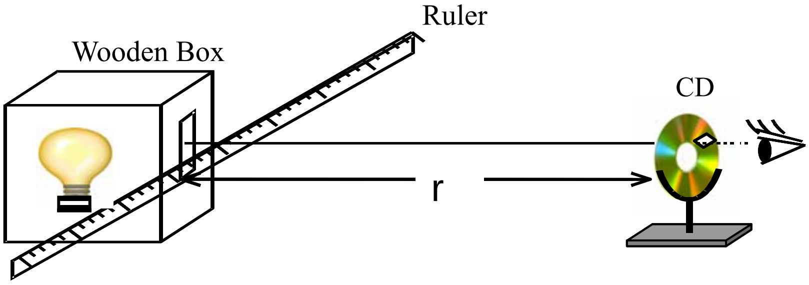


Fig. 7 Measure the wavelength of a lamp

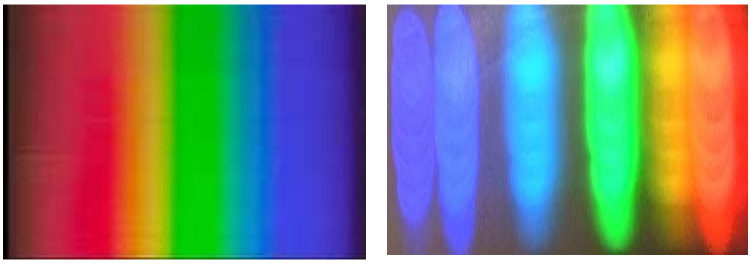
and the eye at the same horizontal level as the slit and the CD, as shown in Fig. 7. They find the diffraction orders of spectrum superimposed on the ruler with distance r between the ruler and the CD. Looking through the transparent CD, they find the central image of the slit is white and there are two repeating spectra on either side of the central image. The central image, also called the zero order, is an image of the source. The spectra of the first order and second order is in accordance with the order of red, orange, green, blue-green, blue, and blue-purple.

They note that the blue-purple spectrum is the closest to the center and red spectrum is the farthest out from the center. I remind them the images of the same color of spectrum for a given order should appear at equal distances from the center point. If they do not, students need rotate the CD slightly until they do. By using equation (4), they calculate the wavelength λ of the spectra emitted from a compact fluorescent lamp, as shown in table Ⅱ.

Table Ⅱ Measured spectrum of a compact fluorescent lamp

Color	red	orange	green	blue-green	blue	blue-purple
λ (nm)	700±12	610±6	520±6	490±8	420±10	400±10

After this experiment students ask why there are only 6 colors of spectra emitted from a compact fluorescent lamp. I give each group an incandescent light bulb and ask them to observe the spectrum of those bulbs. They observe the diffraction orders of the continuous spectrum. I suggest them to put a camera in place of the eye, so the camera can take pictures of the spectra. Fig. 8. shows the spectra of two light sources taken by a student using a 'cell-phone', Fig. 8(a) is the spectra of a 60W incandescent light bulb, Fig. 8(b) is the spectra of a 15W compact fluorescent lamp.



(a) (b)

Fig. 8. Spectra of (a) 60W Incandescent bulb, (b) Phillips 15W compact fluorescent lamp.

Students begin to explore the difference of the two types of spectra. I instruct: In chemistry the spectrum is often discussed when talking about evidence for different electron energy levels and characteristic properties of elements. In physics, it is a part of the study of waves, electricity and magnetism, and modern physics, in which the last two topics will be studied in next semester.

Concept Development:

Student knows from chemistry that the diffraction grating is widely used in spectroscopy. Now they know that if the grating spacing is known, then from a measurement of the angle of deviation of any wavelength, the value of this wavelength may be computed. A maximum in the intensity occurs when

$d\sin\theta = n\lambda (n = 0, \pm1, \pm2 \cdots) \cdots (4)$

This is the same formula as was found for the angular positions of the maximum in the two-slit apparatus. However, here the fringes are much more intense, since the amplitudes from each slit increases. Equally important is the fact that the fringes of diffraction by a grating are now much narrower. This happens because the waves from the slits cancel almost completely as soon as the angle differs slightly from a value at which a maximum intensity occurs. Both the intensity increases and the line narrowing are accentuated as the number of slits per mm increases.

Ⅲ. Application

After those two labs, I ask students to design an experiment as an independent subject of study. I choose the best 6 independent experiments done within the three years.

1. *Determine the grating spacing of an ordinary CD using a laser beam:*

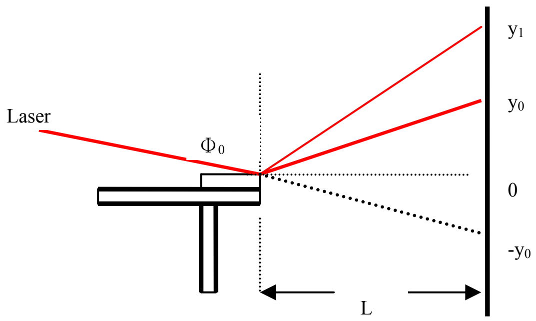


Fig. 9. Determine grating spacing of a CD

A CD is placed near the edge of a table, when a laser beam is shined at an incident angle of φ_0 to the surface of the CD, a diffraction pattern is observed on a screen placed a distance L away, as shown in Fig.9, where y_1, y_2, are the midpoints of the first-order, second-order, by the diffracted beam. By deriving the grating equation (4) we find

$d\cos\varphi_0 - d\cos\varphi_m = m\lambda \cdots (5)$

By measuring φ_0, φ_m and using equation (5), one can calculate the spacing of an ordinary CD which is $d = (1.635 \pm 0.003)\mu m$.

2. *Measure the wavelengths of sunlight using a transparent CD:*: Glue a black paper circle of radius 5cm to the center of a transparent CD (with radius 6cm), and mount the CD onto a wooden board with a hole of radius 5.98cm in the center which allows sunlight to pass through a ring of width 0.98cm as shown in Fig.10. The board is clamped to an ordinary lab stand, and a screen of white wood is positioned both beneath and parallel to the CD. Take the apparatus outside on a sunny day and adjust it so that the surface of the CD is perpendicular to the sun's rays. When the distance (h) between the CD and the screen is gradually adjusted, different colors will be focused on the screen. Measure the radius of the transparent part of the CD and h.

By the formulas $\tan\theta = r/h$ and $d\sin\theta = \lambda$ we can calculate the wavelengths of sunlight as shown here (Bopegedera, 2011).

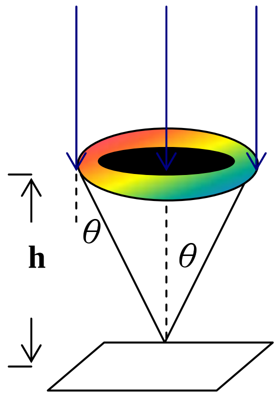


Fig.10. Measure wavelength of sunlight

Table Ⅲ Measured wavelengths of sunlight.

Color	red	orange	yellow	green	blue	purple
λ (nm)	729±22	624±17	589±24	524±18	486±18	388±21

3. *Take a picture of the visible light spectrum formed by a CD with a camera:*

Place a lamp inside a wooden box with a pinhole on the side. Arrange the lamp, the hole, a convex lens, a transparent CD and a camera as shown in Fig. 11. Adjust the relative position of the CD and camera until you see a series of circular diffraction patterns on the CD. Then you can take a picture of the visible light spectrum. Fig.12, 13, 14, and15 show the different spectra emitted from a 60W incandescent bulb, a 15W compact fluorescent lamp, a white light LED, and a red LED respectively (Coley, 2005).

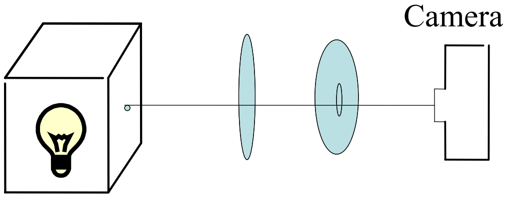


Fig.11 Take a picture of visible light

Fig. 12 Spectrum of a 60W incandescent bulb.

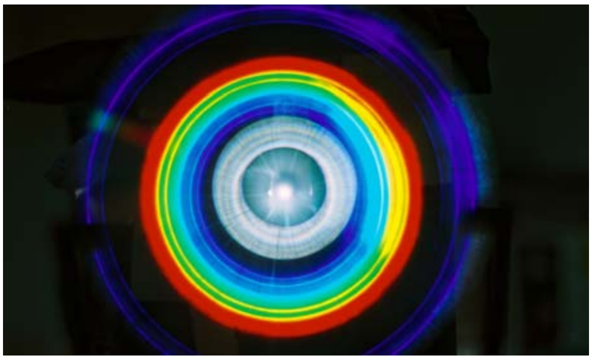


Fig. 13. Spectrum of a 15W compact fluorescent lamp.

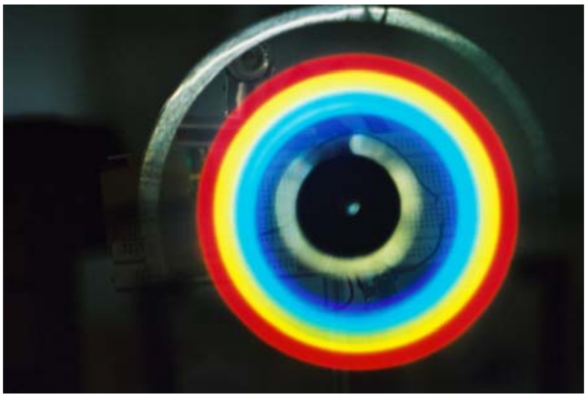


Fig. 14. Spectrum of a white LED

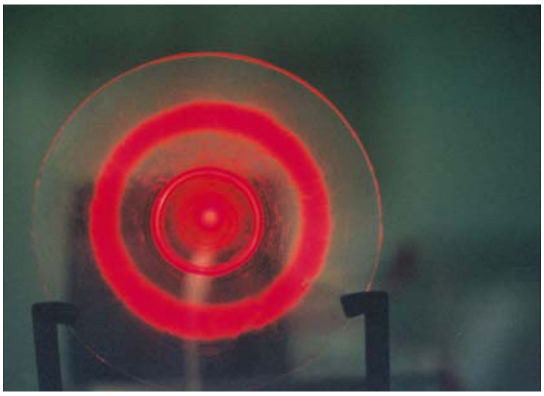


Fig. 15. Spectrum of a red LED

4. *Use a Document Camera to Measure the Wavelength of Diodes:*

When LEDs and an IRED are connected in parallel circuits and put on the platform of a document camera, The color spots of LEDs and white spots of IRED appear on the screen. As a diffraction grating is placed in front of the lens of the document camera, a series of diffraction patterns are shown on the screen. One can measure the wavelengths of the visible light of LEDs and infrared of IRED directly on the screen.

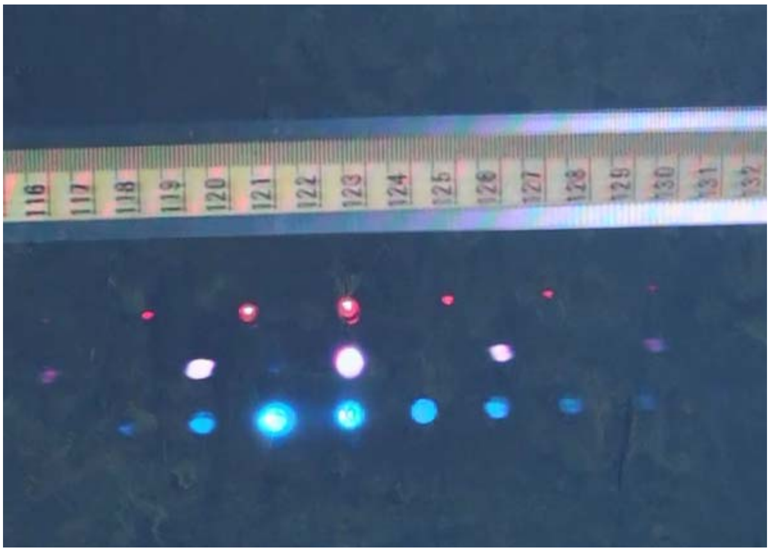


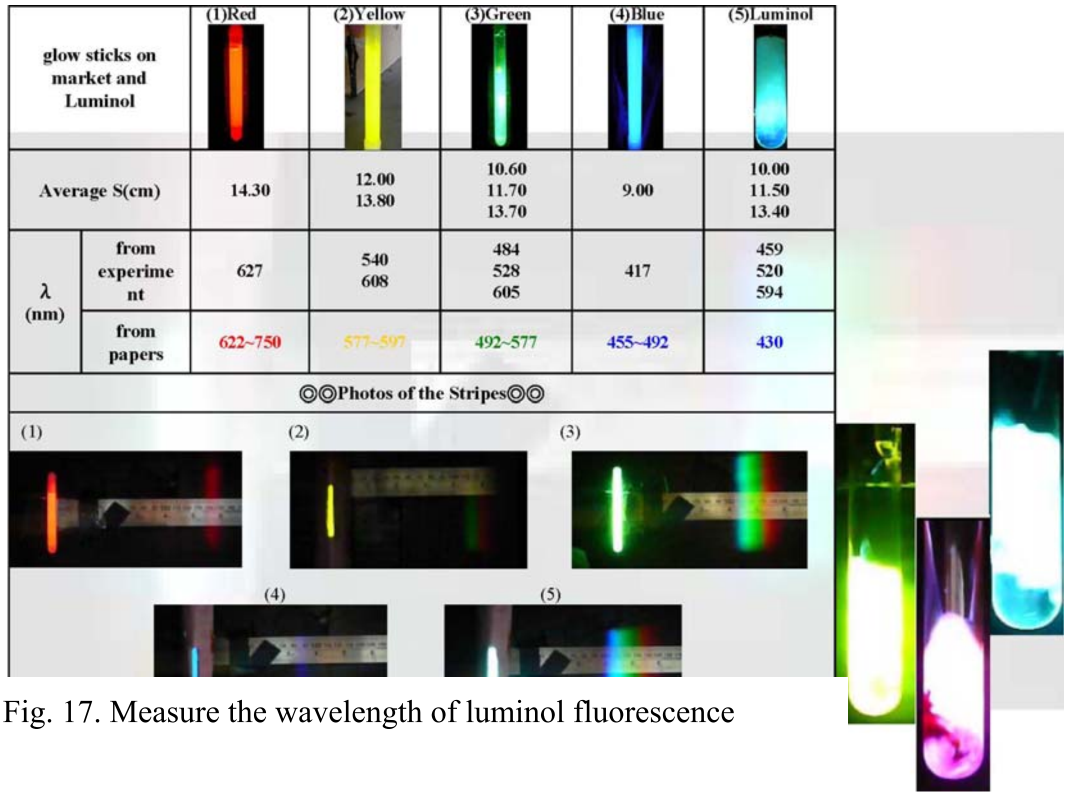
Fig. 16. Interference patterns of the red LED, IRED and blue LED

5. *Form a rainbow using a transparent CD:*

Completely cover a window with a wooden board with a circular hole of radius 5.98cm in the center. Affix a transparent CD to the board so that it allows the sunlight to pass through the CD only. At sunset (or sunrise), a complete circular rainbow will be formed on a screen placed near the window. Since λ differs from color to color and decreases from red to purple, and the radius of the ring of color increases from purple to red. I suggest them to demonstrate this experiment with an overhead projector, can be substituted for sunlight (Hatzikraniotis, 2010).

6. *Research on luminol fluorescence with a simple device:*

Students put a transparent CD in front of a digital camera connected to a high sensitive sensor (Michael, 2001) in order to: (a) detect the wavelength of fluorescence and filming the stripe at the moment the reaction occurs, (b) research on how concentrations of chemicals affect the fluorescence, as shown in Fig. 17.



glow sticks on market and Luminol		(1)Red	(2)Yellow	(3)Green	(4)Blue	(5)Luminol
Average S(cm)		14.30	12.00 13.80	10.60 11.70 13.70	9.00	10.00 11.50 13.40
λ (nm)	from experiment	627	540 608	484 528 605	417	459 520 594
	from papers	622~750	577~597	492~577	455~492	430

◎◎Photos of the Stripes◎◎

(1) (2) (3) (4) (5)

Fig. 17. Measure the wavelength of luminol fluorescence

Ⅳ. Conclusion

From the experiment of light diffracted by a hair and by using the method of dimensional analysis students derive a diffraction formula. They can calculate the radius of a hair by this formula. The method of guided inquiry is used throughout this part of the lab. Using a CD as a diffraction grating, students can measure the wavelength of visible light and conduct a series of activities from qualitative experiments to quantitative measurements which allow students to observe and measure various spectra and optical phenomena. These guided-inquiry labs enable students to recognize the concept of the diffraction of light. The equipments involved are very simple and easy to obtain, which increase the students' level of self-confidence and understanding during their exploratory lab work.

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References

Bopegedera, A. (2011) A guided-inquiry lab for the analysis of the Balmer series of the hydrogen atom spectrum. *Journal of Chemical Education, 88(1), 1507-1509.*

Byme, A. (2003) Compact disk spectroscope revisited. *The Physics Teacher, 41, 144-145.*

Coley, L. (2005) Ring around the sun and moon: coronae and diffraction. *Physics Education, 40, 51-59.*

Chatterjee, S., & Williamson, V. M. (2009) Attitude and perception of students towards guided and open inquiry laboratories. *Journal of Chemistry Education, 86(12), 1427-1432.*

Gayle, A., & Margaret, A. (2007) Learning how to make inquiry into electricity and magnetism discernible to middle level teachers. *Journal of Scientific Teacher Education, 18, 377-397.*

Hatzikraniotis, E. & Kallery, M. (2010) Students' design of experiments: an inquiry module on the conduction of heat. *Physics Education, 45, 335-344.*

Ivanov, D. T., & Nikoleav, S. (2010) White-light diffraction with a CD. *Physics Education, 5, 227-228.*

Kettler, J. E. (1991) The compact disk as a diffraction grating. *American Journal of Physics, 59, 367-368.*

Keys, C., & Kennedy, V. (1999) Understanding inquiry science teaching in context: A case study of an elementary teacher. *Journal of Science Teacher Education, 10(4), 315-333.*

Michael, A. & James, W. (2001) Using guided inquiry to study optical activity and optical rotatory dispersion in a cross-disciplinary chemistry lab. *Journal of Chemical Education, 78(11), 1507-1509.*

National Research Council. (1996) *National Science Education Standards.* National Academy Press: Washington, D. C.

Stephen, J., & Van. H. (2007) Inquiry with laser printer diffraction gratings, *The Physics Teacher, 45, 340-343.*

Timothy A., & Laubach, L. A. (2010) Quantum dotting the "i" of inquiry: A guided inquiry approach to teaching nanotechnology. *The Physics Teacher, 48, 186-188.*