PHYS2941 Lab Report 2

Samuel Allpass

Purpose of experiment (Keep relating to it):

To qualify a method of determining the distance between planes

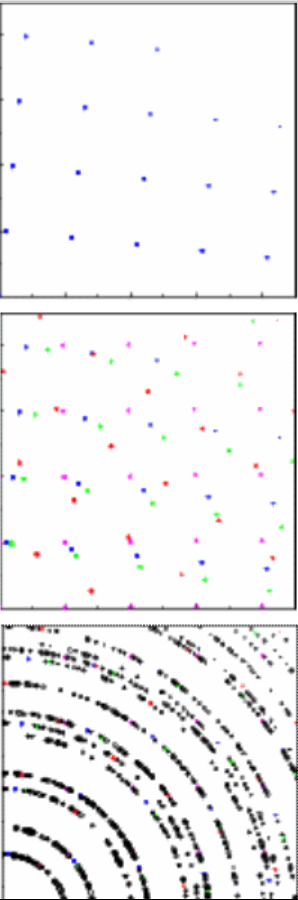
Theory:

* bragg condition

2dsin(theta) = nlambda

* unit cells/miller indices
* interplanar spacings
* plane waves
* de broglie wavelength
  + find order of magnitude of lambda in angstroms (relate to the range of kV you are using in lab)
* find ratio of lattices geometrically with working
* mention polycrystalline structure of graphite (look up powder diffraction)
* derive key equation for r and lambda from lab sheet
* describe what you will linearise for each experiment and how you will use it

(c)



Method:

* need to describe both experiments
* experimental setups with diagrams and labels
* describe plane wave approximation and how that changed your method
* describe grazing angle and how you changed it by 1 degree increments
* describe process for electron diffraction and explain any decisions you made such as radius vs diameter measurements, number of trials, increments on volts

In order to accurately record the angle at which constructive interference voltage peaks occurred in the microwave diffraction experiment for both the 100 and 110 planes, the setup was initialised in the same method as the plane wave approximation. However, in separating the parallel receiver and transmitter horns, the lattice was placed with side perpendicular to the horns, such that the orientation was that of a 100 plane. In this position, it was hypothesised that measuring the multimeter voltage across varying angles would allow the construction of an intensity-angle graph with distinct construction peaks for each diffraction order. In order to validate the recorded data, it was determined that increments were taken every two degrees,

\documentclass[twocolumn,aps,floatfix,showpacs,prl]{revtex4-2}

\setcounter{secnumdepth}{3}

\usepackage{amsmath}

\usepackage{amssymb}

\usepackage{esint}

\usepackage{graphicx}

\usepackage{bbold}

\usepackage[normalem]{ulem}

\usepackage{setspace}

\usepackage{breakurl}

\usepackage{seqsplit}

\usepackage[hidelinks,colorlinks]{hyperref}

\hypersetup{citecolor=[rgb]{0.25,0.14,0.63}}

\hypersetup{urlcolor=[rgb]{0.25,0.14,0.63}}

\hypersetup{linkcolor=black}

\makeatletter

\usepackage[utf8]{inputenc}

\usepackage{mathrsfs}

\usepackage{xspace}

\usepackage[T1]{fontenc}

\usepackage{dcolumn}% Align table columns on decimal point

\usepackage{bm}% bold math

%\usepackage{hyperref}

\usepackage{float}% add hypertext capabilities

%\usepackage[mathlines]{lineno}% Enable numbering of text and display math

%\linenumbers\relax % Commence numbering lines

\usepackage[capitalise]{cleveref}

\usepackage[normalem]{ulem}

\usepackage{color}

\usepackage{esint}

\usepackage{setspace}

\usepackage{breakurl}

\usepackage{seqsplit}

\usepackage[hidelinks,colorlinks]{hyperref}

\hypersetup{citecolor=[rgb]{0.25,0.14,0.63}}

\hypersetup{urlcolor=[rgb]{0.25,0.14,0.63}}

\hypersetup{linkcolor=black}

\newcommand{\Rev}[1]{{\color{blue}{#1}\normalcolor}} % Revision

\newcommand{\Com}[1]{{\color{red}{#1}\normalcolor}} %Comment

\begin{document}

\title{PHYS2041/2941/7141 Lab Report 2}

\author{Samuel Allpass s4803050}

\affiliation{School of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia}

\begin{abstract}

The abstract should be no longer than around 150 words or about 900 characters. Keep in mind that the abstract and the introduction should read differently, that is one reason for the abstract to be short. Briefly state what topic was explored in the experiment. State what experiments were done in this investigation, state the final results along side the theoretical value with a reference. The lab report should be no longer than 8 pages, including references. All additional material, such as figures or tables of raw data, or lengthly derivations, should go into appendices, which go beyond the 8 page limit. Now the rest of this text will be copied to show what 150 words or about 900 characters looks like. The abstract should be no longer than around 150 words or about 900 characters. Keep in mind that the abstract and the introduction should read differently.

\end{abstract}

\maketitle

\section{Introduction}

Broad statement about the topic area, easing the reader into your report and providing context. This is a good place to include a link to the big picture. State the particular topic/phenomenon that is being explored. Typically, one central idea/topic that is explored through a series of connected experiments. Briefly state how each area will be explored, what experiments will be done, what will each of these show. Keep in mind not to include theory or images in this section, that will be covered in later sections.

\section{Theory}

With the discovery of the particle-wave duality of light demonstrated through experiments such as Young's double slit experiment, the field of optics was now equipped with properties applicable to the analysis of crystal atomic structures \cite{youngs\_double\_slit}. Crystallography, the study of crystal atomic lattices, employs the technique of reducing crystal structures into repetitive patterns of atoms named unit cells, basic of which provided in figure 1.

\begin{figure}[H]

\begin{center}

\includegraphics[width=1\columnwidth]{Images/Unit cells.png}

\end{center}

\caption{Depiction of basic crystal unit cells \cite{askiitians\_crystal\_lattices}}

\end{figure}

Further, a crystal can be described as the summation of unit cells separated by some inter-atomic spacing, usually denoted as a. As demonstrated in figure 1, such a summation leads to multiple atomic planes, lattice cross-sections of identical structure separated by some planer distance d. Such planes are described using a three dimensional (i,j,k) vector normal to the plane, the corresponding components of which being 0 or Miller's indices, 1 or 2 \cite{libretexts\_surface\_science}. The 1,0,0, 1,1,0 and 1,1,1 planes, often denoted without commas, are given as an example in figure 2.

\begin{figure}[H]

\begin{center}

\includegraphics[width=1\columnwidth]{Images/100 and 110 planes.png}

\end{center}

\caption{100, 110 and 111 planes of an atomic lattice with displayed $d\_{i,j,k}$ values \cite{springer\_chapter}}

\end{figure}

With the structure of crystals well defined, Australian father and son, W.H. and W.L. Bragg, observed and quantified a method of calculating these plane distances. The Nobel prize winning Bragg law, first published in 1913, reasons that for a fixed X-ray wavelength ($\lambda$) directed at a crystal lattice, the inter-planer distance d can be related to the angle of incident at which constructive interference occurs by the equation:

\[

2dsin\theta = n\lambda

\]

Where n is an integer corresponding to the diffraction order, as such, for known n, $\theta$ and $\lambda$, the inter-atomic plane distance d could be calculated. To understand how Bragg's condition is satisfied in such a case, a geometrical 2D interpretation was produced in figure 3.

\begin{figure}[H]

\begin{center}

\includegraphics[width=1\columnwidth]{Images/Braggs law.png}

\end{center}

\caption{2D geometry of Braggs law for given d and $\lambda$ \cite{researchgate\_braggs\_law}}

\end{figure}

Given the wavelength of X-rays are comparable to the inter atomic distances of a crystal lattice, it was proposed that the rays would interact with the planes much like visible light does with a mirror \cite{serc\_braggs\_law}. Figure 3 highlights the ray path on which constructive interference occurs, some integer n of the wavelength ($n\lambda$). Additionally, for each ascending order of diffraction, such that the X-ray passes through to the next layer, an extra distance of $2dsin\theta$ is traveled, and thus Bragg's condition outlines this trend.

Importantly, the incident X-rays must be both in phase and plane waves. Plane waves entail that a physical property of an electromagnetic wave must remain constant with respect to a plane perpendicular to the direction of motion \cite{nde\_ed\_plane\_waves}. As such, the constructive interference observed in the Bragg condition is only satisfied for plane waves. Further, this fact promoted that the wave generator used in the experiment first be assessed on how well it produced plane waves.

Further to this optical interpretation, in 1924 Louis de Broglie proposed that all matter share lights wave-particle duality \cite{libretexts\_university\_physics}. As such, investigations into how effectively Bragg's law could be utilised with matter as a substitute for X-rays. In order to quantify this relationship, the de Broglie relation is first employed:

\[

\lambda = \frac{h}{p}

\]

Where $\lambda$ is the de Broglie wavelength of the particle, h is Plank's constant and p is the momentum of the particle. For the given experiment, it was understood that the potential difference through which that particle travels, and its momentum are directly proportional. Given it is also known that the energy of an electron is achieved by solving:

\[

E = \frac{P^2}{2m} = eV

\]

We derive to be true:

\[

\lambda = \frac{h}{\sqrt{2eVm}}

\]

Where m is the mass of the electron. We can further derive for practical applications that:

\[

\lambda = \frac{6.626\*10^{-34}}{\sqrt{2\*1.6\*10^{-19}\*9.1\*10^{-31}}}\*\frac{1}{\sqrt{V}}

\]

\[

\lambda[Angstroms] = \frac{3.88\*10^{-10}\*10^{10}}{\sqrt{V}} = \sqrt{\frac{151.3}{V[volts]}}

\]

It was therefore justified that a voltage source on the kV order of magnitude would be used as to result in wavelengths of on the order of 0.1 Angstroms, comparable to that of X-ray wavelengths. For the purpose of this investigation, it was concluded that an electron diffraction tube of powdered graphite would be used to simulate electrons passing through a crystal lattice. Graphite unit cells consist of a hexagonal arrangement of carbon atoms as displayed in figure 4a, however, this experiment was to investigate powdered---.

\begin{figure}[H]

\begin{center}

\includegraphics[width=1\columnwidth]{Images/Graphite unit cells.png}

\end{center}

\caption{(a) Hexagonal unit cell of graphite and (b) 100 and 110 planes of graphite}

\end{figure}

As observed in figure 4b, it was hypothesised that the $d\_{100}$ and $d\_(110)$ for the graphite lattice should be related by:

----

\begin{figure}[H]

\begin{center}

\includegraphics[width=1\columnwidth]{Images/Apparatus diagram for proof.png}

\end{center}

\caption{Geometric diagram of the apparatus}

\end{figure}

Given the apparatus attains the geometric structure outlined in figure 5, the relationship between the radius observed on the screen, and the inter plane distance d was derived as followed.

\[

2dsin\theta = n\lambda

\]

We observe that $\alpha = 2\theta$. Additionally, given $\alpha$ is sufficiently small for the small angle approximation of sine:

\[

2d\_{i,j,k}\theta = d\_{i,j,k}\alpha = d\_{i,j,k}sin^{-1}(\frac{r\_{i,j,k}}{R}) = d\_{i,j,k}\frac{r\_{i,j,k}}{R} = n\lambda

\]

\[

r\_{i,j,k} = \frac{2R}{d\_{i,j,k}}n\lambda

\]

From this derivation it became apparent that for a given diffraction order and apparatus radius, the relationship between the radius of the constructive ring and the de Broglie wavelength could be linearised. As such, it was hypothesised that the gradient of such an equation could be used to find the inter-plane distance.

\section{Method}

\subsection{Uncertainties}

In order to minimise the uncertainty in the final conclusions drawn, it was observed that the two experiments each contained multiple sources of error. For the microwave diffraction system, it was first noticed that both the angle of the goniometer and the relative position of the lattice had associated uncertainties. Although the goniometer itself was incremented to 1 degree, indicating a device uncertainty of 0.5 degree, the group collectively justified that human measuring conditions only allowed for measurements accurate to 1 degree of uncertainty. Additionally, it was reasoned that the uncertainty in the relative angle of the lattice would roughly correlate with that of the goniometer's, however, given the investigation studies the trend between the angle and diffraction order rather than the angle itself, it was justified that the angle uncertainty would result negligible. Finally, the voltmeter used posed uncertainty of 0.005V which prove a potential limitation when determining the angle values at which constructive interference voltage peaks occurred. Despite this, when conducted, the extremely small fluctuations in voltage as well as extra measurements taken around suspected peaks provided reasoning that the construction peak angles could be estimated within reason.

The electron diffraction experiment similarly found three sources of uncertainty. Initial setup of the system informed the uncertainty of the voltage source, such that the analogue dial was only accurate to 0.2kV. Due to the large distances between each increment, such that we could be certain it was above or below a half increment, the group testified that the source could be accurately placed to an uncertainty of 0.1kV. Additionally, in accordance with the apparatus manual, the radius of the sphere was given to be 130$\pm$5mm. Finally, limitations in the caliper measuring capabilities were identified. Given the difficulties associated with measuring the diffraction radius with calipers over a spherical surface, it was concluded that the inner and outer radius of a given diffraction ring would be recorded to calculate and average value with appropriate uncertainty. Additionally, it was noted that the uncertainty of the caliper was negligible when compared to the uncertainty in the average.

\subsection{Apparatus}

\begin{figure}[H]

\begin{center}

\includegraphics[width=1\columnwidth]{Images/Microwave diffraction apparatus.png}

\end{center}

\caption{Microwave diffraction experiment labeled apparatus}

\end{figure}

As outlined in figure 6, the microwave diffraction apparatus consisted of a microwave transmitter and receiver pair (1 and 3 respectively) between which was placed a polystyrene atomic lattice simulator (2). The transmitter outputs a 10.5GHz frequency plane microwave. As a result of the plane wave output, it was essential that all experiments conducted maintained that the transmitter and receiver cones be parallel. The lattice was situated atop a goniometer (4) with the rotating arm fixed to the microwave receiver. To finalise the setup, plugged into the receivers banana lead terminals was a voltmeter (5).

\begin{figure}[H]

\begin{center}

\includegraphics[width=1\columnwidth]{Images/Electron diffraction apparatus.png}

\end{center}

\caption{Electron diffraction experiment labeled apparatus}

\end{figure}

In similar fashion to the apparatus displayed in figure 5, the electron diffraction employs a cathode ray tube to accelerate electrons through a poly-crystalline layer of graphite (3). The cathode ray tube uses high a high voltage node G3 to accelerate the electrons, with the remaining G1, G2 and G4 nodes focusing the electron beam into the graphite layer. The voltage for such nodes was provided by the displayed voltage source with analogue voltage display and shifting dial represented by 1 and 2 respectively. The apparatus displayed the electron diffraction rings onto the circular fluorescent screen (4) which could then be measured using the observed caliper.

\subsection{Procedure}

(Figure 7 – cos^2)

In order to validate the results of the microwave diffraction experiment, it was first evaluated how successfully the microwave transmitter produced a plane wave. This was achieved by maintaining the setup outlined in figure 6 without the polystyrene lattice. By then recording the voltmeter readings as the goniometer was rotated from 0 to 90 degrees with increments of 10 degrees. It was understood that the resulting uninterrupted microwaves would form a constructive interference pattern indicated by a squared cosine wave. Figure 7 clearly outlines that the receiver voltage only followed such a pattern for the first 45 degrees, as such it was concluded that the experiment would only investigate voltages between 0 and 45 degrees.

Start your procedure with an introduction sentence that explains what the following procedure will result in. The method should be clear, explicit and concise enough that a peer who has not read the lab sheet for your particular experiment could easily replicate the experiment just from reading your method. Often times, when you write a method, it makes complete sense at the time since you have completed the experiment. It is a good idea to re-read the method a day or two after first writing to check if it still makes sense. So be sure you do not start this component of the report the day it is due. Any mention of measurement/data must have the uncertainty value with it, in addition a justification of the measurement. For example, "The component was displaced in $5\pm1$cm increments between trials, for a total displacement of $50\pm1$cm, this increment size was chosen as to ensure a data spread to show the required effect was visible".

\section{Results}

This is where you include any plots or refined data tables that you acquired from data in the method. Note, raw data is never required to include anywhere in a lab report. Once you have data, you will want to analyse it to find useful values. This may include using an equation from your theory section with data acquired in the experiment. If this is the case, be sure to show either here or in the appendix an example calculation of each equation that is used. When doing a sample calculation, you must show how you propagated your errors. For plots, these should have a brief explanation of what the plot is in addition to an explanation of the process taken from raw data to refined plot.

\begin{table}[tbp]%note, the [h] makes sure the table goes where you want it

\begin{tabular}{ |c|c| }

\hline

Time [s]& Displacement [m]\\

%$[s]$ & $[m]$\\

\hline

0.42 $\pm$ 0.02 & 0.80$\pm$0.03\\

0.47 $\pm$ 0.02 & 1.00$\pm$0.03\\

0.51 $\pm$ 0.02 & 1.20$\pm$0.03\\

0.54 $\pm$ 0.02 & 1.40$\pm$0.03\\

0.59 $\pm$ 0.02 & 1.60$\pm$0.03\\

\hline

\end{tabular}

\caption{Time taken for mass to drop at each distance. [NOTE: this is RAW DATA and should not be included in the report; this is here for demonstration only.] }

\label{Table:time}

\end{table}

\subsection{Linearising Data}

In a lab experiment, you will plot some value against another, this will often show some relationship. This is almost always easier to view/see on a plot rather than a table, see Table \ref{Table:time} versus Fig.~\ref{Fig:time}. These figures/tables show data from the first year experiment "Measuring $g$ from free-fall time of a ball", which you should all be familiar with.

\begin{figure}[bp]

\begin{center}

\includegraphics[width=.9\columnwidth]{tut11.png}

\end{center}

\caption{Fall time at increasing initial displacement.}

\label{Fig:time}

\end{figure}

When it comes to plots, Fig~\ref{Fig:time} is a good example of how they should be presented. Data points clearly within the x and y bounds, error bars, x and y labels, legend, figure number with caption and most importantly, a fitted trend line. From theory, we might know the above data should take the form

\begin{equation}

s=\frac{1}{2} a t^2, \label{eq:1}

\end{equation}

where $s$ is displacement, $t$ is time and $a$ is gravitational acceleration. Then using MATLAB's cftool(x,y) tool (see Fig. \ref{Fig:fit}), we can fit an equation of the form shown in Eq.~\eqref{eq:1}, with an uncertainty value for the coefficient $a$,

\begin{equation}

s=\frac{1}{2} (9.3\pm0.3) t^2 \label{eq:2}

\end{equation}

\begin{figure\*}[tbp]

\begin{center}

\includegraphics[width=15cm]{tut10.png}

\end{center}

\caption{MATLAB curve fitting tool, top red box is input custom equation, bottom red box gives values with uncertainties for the coefficients. }

\label{Fig:fit}

\end{figure\*}

Since this is a simple equation to fit, we can immediately find the value of interest from this fit, that being $a=9.3\pm0.3$. However, extracting values is not always so simple/accurate. To aid in this process, if we know from theory that the data follows some trend, we can attempt to linearise it. This often makes extracting values of interest easier. We can see if we manipulate Eq.~\eqref{eq:1} to look like

\begin{equation}

a=\frac{2 s}{t^2}, \label{eq:3}

\end{equation}

then a plot of displacement multiplied by 2 over time squared will give a constant equal to the gravitational acceleration. The linearised data can be seen in Table~\ref{Table:lin}. Then, from the linear regression shown in Fig.~\ref{Fig:lin}, we get

\begin{table}[bp]

\begin{tabular}{ |c|c| }

\hline

time$^2$& Displacement$\cdot$2\\

$[s^2]$ & $[m]$\\

\hline

0.18$\pm0.01$&1.60$\pm0.06$\\

0.22$\pm0.01$& 2.00$\pm0.06$\\

0.26$\pm0.01$&2.40$\pm0.06$\\

0.29$\pm0.02$&2.80$\pm0.06$\\

0.35$\pm0.02$&3.20$\pm0.06$\\

\hline

\end{tabular}

\caption{Linearised data. [RAW DATA.] }

\label{Table:lin}

\end{table}

\begin{equation}

y=(9.7\pm0.3) x -(0.108\pm0.006). \label{eq:4}

\end{equation}

Note how the value for gravitational acceleration from the linear trend is $a=(9.7\pm0.3)$, while the quadratic fit was $a=(9.3\pm0.3)$. Which one looks like a better value to you?

\begin{figure}[tbp]

\begin{center}

\includegraphics[width=.9\columnwidth]{tut14.png}

\end{center}

\caption{Linearised relation between displacement and time. }

\label{Fig:lin}

\end{figure}

\subsection{Significant figures}

Significant figures are a profoundly important concept to understand when writing a lab report. Take the first entry in Table~\ref{Table:time}, $0.42\pm0.02$. The actual recorded time may have been $0.415689$ seconds, but our measurement devise only has an precision of $\pm0.02$ seconds. This means that any digits in our actual time after the precision of our uncertainty are not significant, which means $0.415689$ goes to $0.042$, where we round based on the uncertainty. Another important use of this is from computations. The linear regression script used to generate Fig.~\ref{Fig:lin} resulted in

\begin{align}

&m=9.6471, \Delta m= 0.30215,\\

&c= -0.10824, \Delta c=0.006482.

\end{align}

We can see that the uncertainly values have far too many digits, these need to be rounded to one significant figure, then the $m$ and $c$ will be rounded to match

\begin{align}

&m=9.6, \Delta m= 0.3,\\

&c= -0.108 , \Delta c=0.007.

\end{align}

Another important concept to consider is keeping consistent in scientific notation. The power of the scientific notation should match, and stay consistent when mentioning this value throughout the report. As such, writing $(1.54 10^4) \pm( 5 10^2)$

is not appropriate. This should instead be written as

$(1.54\pm0.05) \times 10^4$.

\section{Discussion}

In your discussion, you will thoroughly analyse each component of your experiment. Explain what your results are, how do they compare to theory. If the experimental results do not line up with theory, explain why this happened/ what could be done differently to improve the results. This should be a long portion of your report.

**Discussion:**

* analyse the ratio of the spacings you found against theory/logical judgement (for microwaves you can measure the spacings by hand)
* discuss plane wave approximation
* discuss how the experiment would differ if you did not know the orientation of the lattice points and what other planes you might be able to see (for microwave)
* describe restrictions on miller indicies (google selection rules for miller indicies)

**Validity/Reliability:**

* are your values in the right order of magnitude
* are they close to theory
* are the ratios close to theory
* discuss flaws with experimental model (for microwave consider microwave reflections off walls/people) (for electrons consider the thickness of each ring)

When comparing the experimentally calculated values for the distance between the 100 and 110 lattice planes using the microwave diffraction experiment outlined, a large discrepancy from the measured values was apparent. The microwave diffraction experiment calculated $d\_{100}$ and $d\_{110}$ values of (0.0016$\pm$0.0001)mm and (0.0015$\pm$0.0006)mm respectively, whilst the lattice truly comprised of roughly 38mm and 27.5mm spaced 100 and 110 planes. Additionally, the experimental results also violated the geometric relationship between the 100 and 110 planes, with $d\_{100}\*\sqrt{2} = 0.002$.

The findings indicated clear issues within the methodology. Given the emphasis placed on discussing how accurately the microwave generator approximated a plane wave, such that goniometer angle values were restricted to within 50 degrees, it became evident to the team that larger sources of error were present.

\section{Conclusion}

Brief summary of the experiment, state the final results again. Make a link to the big picture, what are the implication/applications of this experiment.

Example citation: \cite{Arrazola\_2020}

%\section{Bibliography}

%This is where you will give a list of all of your references. Note, you must also use in-text referencing throughout the entire report. This should be done when you use a statement, value, table or figure caption from a source. See below and example of a reference to Ref.~\cite{Ye:96}.

%\begin{thebibliography}{}

%\bibitem{Jun} J. Ye, J. Helmcke, J. L. Hall, B.P. Stoicheff,(1996) “Hyperfine structure and absolute frequency of the $^{87}$RB $5P\_{3/2}$ state,”, Optics Letters, 21(16), p.1280

%\end{thebibliography}

\bibliography{phys2941labreport2}

~

\newpage

\appendix

\section{What to include in Appendices}

The appendices should start from page No. 11 and should be referred to from the main text. Do not include raw data anywhere in the report, not even in the appendices. In an appendix, you can show an example calculation of each type you used in your report. In addition, you need to show an example error propagation calculation for each calculation type. Make sure you explain the steps in enough detail that the marker can understand; you can assume the marker knows how to do simple calculations.

\end{document}