

good morning all of you

so what we are going to discuss today is an extraordinarily important topic in modern physics the so-called modern physics and that is about the matter waves so if you can remember what we have been doing in the last eight or ten lectures we had a rather detailed discussion an in-depth discussion on the particular nature of light although there was an overwhelming evidence for light to behave like a wave because of interference because of diffraction and polarization yet planck found it necessary to introduce quant of light which were later called photons and he associated an energy which is not proportional to the amplitude but which is proportional to the frequency  $e$  equal to  $h \nu$  this idea as we found was taken very seriously by einstein who used this concept of quantization of light where an incoming plane wave can be looked upon as an incoming particles set of particles all of them with the same frequency and an energy  $e$  equal to  $h \nu$  and einstein was able to explain very satisfactorily photoelectric effect as i told you we spent a long long time many many lectures discussing the experiment discussing its conflict with the explanation coming from the wave theory in fact we showed that the discrepancy between the predictions of wave theory and the experimental observations were of the order of  $10$  to the power of  $10$  or  $10$  to the power of  $12$  gigantic discrepancy and then we also showed how einstein was able to give a satisfactory explanation by invoking the concept of a photon

so this was one of the most radical steps that a physicist took at the beginning of the 20th century in 1905 and that together with the rutherford experiment and the bohr model ushered in a new era what we call as the year of quantum physics and it is still continuing today what i am going to discuss is the counterpart of what we discussed in the case of the light

so what happened was that historically

so let us look at historically history historically light had two possible explanations particle wave the first one was advocated by none other than newton and the second one was advocated by huygens all of you have heard of hygen's principle what later experiments did was to confirm the hypothesis of hygienes for example if light behaved like particles then its speed inside a medium should be greater than the speed in free space whereas if it behaved like a wave the speed of the wave in a medium whenever it gets refracted should be smaller than the speed in free space that is something that you can experimentally verify and then of course as i told you you have the phenomena of interference and diffraction

so all of them conclusively established that light behaves like a wave young's double slit experiment newton's rings all these are examples of the wave like nature of light however when it came to photoelectric effect the wave explanation failed wave explanation failed and what einstein did was to invoke the idea that light is composed of quanta where each quanta carries an energy  $h \nu$

so this is the energy carried by each quantum each quantum

so you essentially attribute a particle like nature to light and to imagine that photoelectric effect is essentially because of the absorption of individual quanta by the electron in fact one single quantum by the electron because of which it gets ejected

so what you do is to make use of energy conservation as i told you classically the energy of a wave would depend on the square of the amplitude but here it is depending on the frequency of each quantum whereas classically frequency would only give you the degree of freedom it would not have anything to do with energy so that was a great thing

so in the world of waves and particles we find an extraordinary dichotomy that

is initially it appeared that there is nothing that relates waves and particles of course there was an underlying picture that waves are collective phenomena coming because of the undulation of the molecules

so it is a collective phenomenon and it has no existence by itself but what einstein essentially showed was that what can be understood as an undulating phenomenon of the underlying ether particles or any other medium molecules even the molecular hypothesis was not established at that time is that they can also be equivalently looked upon as particles although not in every context because after all interference diffraction polarization all these require wave nature and photoelectric effect compton scattering and some more phenomena which we will see later like frank content experiment they would require the quantum nature of light

so it is as if light has some kind of a double faced existence sometimes it behaves like a wave and sometimes it behaves like a particle and it seems to behave like a particle when the dimensions become very very small mean there is a crude way of putting

so if that be the case we could ask a question and what is the question that we are going to ask if a wave can at times behave like a particle let me explain that to you a wave is an extended object because i speak of a wavelength and i speak of a frequency it is extended in space whereas when i speak of a particle it is something that is localized in space wave is extended in space it undulates in time whereas a particle is localized in space and it moves from one point to another as time progresses and yet photoelectric effect tells me that what was a wave can actually start exhibiting particle like nature you are not looking at the wavelength but you are looking at a particle like nature because of the association of the energy

so if a wave can at times behave like a particle is it possible i am going to write everything clearly

so that that the

so called particles classical particles whatever we are used to can behave like waves mind you there were compelling reasons for us to attribute a particle like nature to light because we were forced by experiments it is not as if blank or einstein suddenly had a fanciful idea and then they said ok let us declare light to be made of particles that is not it we had the problem with black body radiation we had the problem with photoelectric effect

so if that be the case we should ask ourselves if there is any compelling reason why matter should behave like particles the answer to that historically is rather quite complicated and rather different from the way we are going to discuss right now because historically what happened was that 1905 was when einstein explained gave an explanation of the photoelectric effect

so if i remember right 1913 was when the bohr model was proposed now in the bohr model all of you will study it in the coming lectures or you might have studied in your classroom already what you do is to invoke very special orbits and deep rawley realized that if you actually attribute a wave like nature to the electron that will give rise to that can be looked upon as standing waves min and that is the reason why he proposed that matter can also exhibit wave-like behavior in other words there is no great distinction between matter and waves they are both manifestations of the same underlying substance and d brawl is hypothesis was poised at the right moment in history because 1924 was when he proposed the matter by hypothesis and in 1926 is when schrodinger wrote his famous schrodinger equation but that is not the way path that we are going to take in this lecture because in your textbook the deep broly waves have been introduced immediately after the photon concept of light the particle nature of light

so what i will try to do is to motivate you to look at the wave aspect of matter from an aesthetic view point and later when i start discussing bohr model i will complete the argument by showing how it can be a standing wave

so in other words

so far what we have done is to look at the historical development and follow that even in our presentation but now we are going to reverse history we are going to discuss deep brawly waves first and then we are going to discuss how he was motivated by the bohr model

so these were indeed very very revolutionary

so if you look at the slide which i have here you can see the picture of dee brawley and let us see what is it that deep broly did

so as i told you that we want to look at the whole phenomena in an aesthetic manner

so what is aesthetic aesthetic is whatever pleases our mind and in this case it is our intellect it is not our sensory it is not our eyes here sir tongue or touch it is our intellect and that can be summarized in a single word namely symmetry

so what is the symmetry that we want to establish we had a very clear division of the world between wave-like phenomena and matter corpuscles and waves to put it in the world language now if waves started behaving as corpuscles probably there is a symmetry which says that under certain circumstances particles will also start behaving like waves how exactly the wave like nature will emerge from localized particles is a different question altogether because after all we have not answered how exactly the particle like nature will emerge from the wave either all that we have done is to make a hypothesis in order to understand an experiment give a plausible explanation of the experiment

so a deeper understanding of what the connection behave between a wave like behavior and a corpus like behavior that will come at a much much later stage when you people take up more advanced courses in quantum mechanics when you go for your graduation it is not a matter for the 12th standard course but however it does not harm us to establish symmetry between what i shall call as classical waves and classical particles classical waves get quantized and they show quantum behavior there are quanta corpuscles which behave like particles

so probably classical particles can behave like quantum waves which we shall call as matter waves

so that is the statement that we want to make

so the most important motivation for that is symmetry now symmetry is a vague idea i want to establish parity i want to treat them on the same footing nobody need a reasoning and the reasoning that deep broadly employed was by analogy we have to make use of analogy and the way we make use of analogy is not a trivial thing you have to meander our way we have to find our way our way through the maze carefully and let us see how it comes about

so this slide contains something more on analogy i have collected it here and i am going to discuss it at great length what the consequences of this are for matter waves at the end of the lecture

so let us go back to what planck and einstein did planck associated energy  $e$  with every frequency  $\nu$

so i am also going to write that down

so that it settles clearly in your mind

so  $\nu$  is given and energy is deduced that is the plank hypothesis and this is completely non classical non classical however classically there is another relation between frequency and wavelength we are looking at a monochromatic light all the light having the same frequency ok and what is that relation and that is  $v$  equal to  $\nu \lambda$   $v$  of course is  $c$  for light in free space the speed

of light in vacuum which is  $3 \times 10^8$  meters per second or whatever that is what we have

so what we are writing is now the relation between  $\mu$  and  $\lambda$  everybody knows that therefore my  $\lambda$  is given by  $c$  by  $\nu$  that is what I have

so if I were to write it in terms of energy my  $\nu$  is  $e$  by  $h$

so  $1/\nu$

so  $\nu$  is  $e$  by  $h$   $1/\nu$  is  $h$  by  $e$

so I am going to write  $\lambda$  is equal to  $h c$  by  $\nu$  I am sorry  $h c$  by  $e$  that is what we are writing

so that means not only do we associate a frequency with the energy or energy with the frequency we are also associating energy with the wavelength now if you people go back and remember our rather lengthy discussion on photoelectric effect I argued that the momentum density and the energy density are related by a factor of  $c$

so what did we say let me go to the next slide

so if I write down the energy density of a monochromatic wave let us say a plane wave with a given frequency then this is related to the momentum density by a factor of  $c$  what is energy density that is the total energy in a given volume that is my energy density and what is my momentum density that is the momentum carried by the wave in a given volume these two are related by a factor of  $c$  and this is dimensionally correct

so this is my energy density and this is my momentum density now what is energy density from the Planck view point from the bank view point it is nothing but the number density multiplied by  $h \nu$  each quantum is carrying an energy  $h \nu$  that is the energy of each quantum and they multiplied by the number density that is what I am going to get and what would be my momentum density it is again the number density multiplied by momentum carried by each quantum multiplied by  $c$

so in other words this  $p$  is the momentum carried by the quantum to be sure this analysis of connecting momentum to energy was not done by Einstein in the photoelectric effect because nowhere did he bother about the momentum of the photon he only worried about the energy of the photon only energy was matched balanced in the photoelectric effect like explanation momentum was not taken into consideration at all but now if you look at this you can actually cancel this relation and you have got a beautiful relation the energy of a photon carrying a frequency  $\nu$  is nothing but  $p$  corresponding to that frequency into  $c$

so this is the relation between the energy of the momentum energy of a photon and the momentum of a photon this is completely different from what we find either for a massive particle in relativity or in non relativistic case is that ok for example you write  $e$  equal to  $p^2$  by  $2m$  as a relation between the momentum and energy for a particle but here what we have is  $e$   $\nu$  equal to  $p$   $\nu$   $c$  therefore what we have is that as the energy keeps on increasing my energy also keeps on increasing momentum also keeps on increasing but in such a way that it always travels with the same speed  $c$  contrast this with a massive particle where as you keep on increasing the energy the momentum also keeps on increasing but then the velocity also keeps on increasing you cannot increase the momentum of a massive particle without increasing the speed but here there is a very beautiful way of looking at it you have  $e$   $\nu$  equal to  $p$   $\nu$   $c$  this is very very important for us and we are going to make use of that

so if we did that and I substitute back into the equation now I can also write the relation  $p$  equal to  $h$  by  $\lambda$

so  $e$  equal to  $h \nu$  is what Planck plus Einstein did use but if you make use of the energy density momentum density argument not only is my quantum carrying

an energy you knew  $e$  corresponding to the frequency  $\nu$  there is a momentum corresponding to the wavelength it is an entirely different matter at this point that  $\lambda$  and  $\nu$  are of course not independent of each other because  $\lambda \nu = c$  that is not very important for us at this point although I used it in my derivation I will tell you why what de Broglie did was to take this as a fundamental relation as a fundamental relation and this is non-trivial

so the message that I am trying to convey to you is that it is not as if de Broglie simply extended whatever was known in the realm of electromagnetic waves to matter he had to choose whereas in the case of electromagnetic wave  $e = h \nu$  was the fundamental starting point for de Broglie  $p = h / \lambda$  was the starting point

so what is the deep de Broglie assertion

so let us write the thing de Broglie conjectured let us call it de Broglie conjecture was that  $p = h / \lambda$  is a universal relation

so what does universal mean universal means it holds for all waves and all matter it holds for all waves and all matter this is a fundamental relation the only freedom that you have is in choosing the form of  $p$

so  $p$  can be  $mv$  or it can be  $mv / \sqrt{1 - v^2/c^2}$   $m$  is relativistic this is the earlier one is non relativistic let me write that more carefully again  $p$  Newtonian is  $mv$  and  $p$  Einsteinian relativistic is  $mv / \sqrt{1 - v^2/c^2}$

so to conclude whatever we have done

so far to summarize what we are saying is that de Broglie hypothesized he conjectured that  $p = h / \lambda$  is valid even for particles

so in the case of Planck frequency was known and energy was deduced in the case of de Broglie what is happening you know the momentum and you are deducing the wavelength that is extraordinarily important in other words  $p$  is the input and  $\lambda$  is the output

so this essentially is a deep de Broglie hypothesis and this requires experimental confirmation because we have tried to treat both waves and matters and we have also deduced the relation  $p = h / \lambda$  all that we are asserting is that it is not only peculiar to light but it is also valid for all waves and matter this is the statement that we made

so this slide essentially contains the summary of whatever I told you

so two questions that we asked without explicitly mentioning was that how important is the deep de Broglie extension and how non trivial it is these are the two important questions that we have to ask

so what are the fundamental relations that we are making use of we write  $\lambda = h / p$  meaning if you give me  $p$  I will give you  $\lambda$  and who is going to give you  $p$  it is either Mr Newton or Einstein Newton will tell you that  $p = mv$  and Einstein will tell you that the relation between energy and momentum is given by  $E^2 = p^2 c^2 + m_0^2 c^4$  which is the same as writing  $m = \gamma m_0$  the two relations are the same

so I have written it not in the way I wrote in my on the sheet of paper in this particular form because what matters to us is really the relation between energy and momentum we can always deduce what the velocity is given the relation between energy and momentum that is going to be important for us in at the end of the lecture and that is why I wrote it in this particular form ok

so we have made a conjecture that matter can also exhibit wave like phenomena now what do we mean by matter

so one thing that I can do is to make an estimate of what  $\lambda$  is by  $h / p$  I am not going to work it out for you

so anyway it is given in your textbooks

so what you can do is to take your matter to be let us say a tennis ball  
so imagine a very very fast bowler who is bowling the ball at let us say 100  
kilometers per hour or 120 kilometers per hour that is a very fast ball that is  
going around and you know what the mass of a ball is maybe 100 grams or whatever  
if you put in and you find out what this lambda is this will turn out to be an  
incredibly small number

so this number could be of the order of  $10$  to the power of minus 30 or  $10$  to  
the power of minus 34 centimeter or whatever this number is

so incredibly small that it cannot reveal the wave like nature of the object  
you want a reasonably large wavelength in order to realize that it is a wave if  
the wavelength becomes very very small it almost becomes like corpus color

so we do not want to get into that situation we want a fairly large wavelength

so in order to get a large wavelength what is it that we have here we have  $p$   
sitting in the denominator i can control velocity all right i mean i can even  
throw my ball at a slow speed but my  $m$  is

so large even for very very small speeds what is going to happen my lambda is  
going to be quite small

so in a way i gave you a wrong analogy i am very sorry what i should be saying  
is that even if my tennis ball is moving very very slowly i just slide it on the  
ground my lambda will be very small because mass is very very large

so i should look for very very light particles i should look for very very  
light particles and those particles should actually be able to interact with  
something in order to show a wave like behavior like for example it may be a  
double slit experiment or it may be a diffraction as we are going to discuss in  
a while and the best candidate is electron because electron has a rest mass of  
 $0$ .

$5 m e v$  by  $c$  squared which is very very small and therefore if i can actually  
make use of electrons of varying energy and therefore of varying momentum then i  
should be able to verify whether the deep broghe hypothesis is correct or not of  
course we are going to work in the non relativistic regime therefore my momentum  
will be nothing but  $m$  into  $v$  that is what i will have and mass is given by point  
may be  $0$ .

$5 \mu v$  by  $c$  squared and this will be nothing but  $0$ .

$5 m e v$  into  $v$  by  $c$

so this will be your momentum of the particle and it will not be too large  
therefore my lambda can be large enough if  $p$  is small my lambda can be large  
enough d brawley did not stop at the hypothesis he suggested that wave like  
nature of electrons can be seen in diffraction from crystals deep valley was  
fortunate that by that time the crystal structure was known it was supposed to  
be a regular symmetric object and brag the two bracks the father brag and the  
sun brag had actually obtained the condition for diffraction and that is  
illustrated in this slide here which i would like to explain to you now if you  
look at this slide carefully what we have is a periodic array of atoms and we  
are going to send light this argument is for light and we want to make use of  
the same argument for the electrons also now what is going to happen is that  
when you send light of the right wavelength i am going to come to the  
denominator what the right wavelength is then what happens these light beams get  
reflected by successive planes because every crystal can be looked upon as what  
arrangement of atoms in each plane and then there is a plane below that there is  
a plane below that and the separation between the planes is what is indicated by  
 $d$  here

so let me illustrate that in bigger letters here if it is not visible to you  
so what we have is i am exaggerating it

so imagine the atoms to be arranged in an array and i am saying that the

distance between them is  $d$  that is what I have here now what happens let us come back to this slide here if you imagine that a ray of light is coming it can get reflected either in the top layer or in the bottom layer

so these two atoms lattice points are shown and then when they get reflected you can see that there is a path difference and there is a phase difference

so let me again illustrate that in big letters here big picture here

so I have this

so here is a light ray which comes here and gets reflected here and there is another light ray which comes here and gets reflected here

so this is my upper ray and this is my lower ray

so everyone agrees that the upper ray traverses a smaller distance compared to the lower ray because it has to reach the plane and it has to come back and we are asserting that this is  $d$  and I have to define my design my  $\theta$  divide this is my  $\theta$  and this is my  $\theta$  by law of reflection angle of incidence is the same as angle of reflection that is what I have this is my  $\theta$

so a very simple trigonometric exercise will tell you what is the extra distance that is traveled the extra distance traveled is nothing but  $2d \sin \theta$  that is what we are showing here

so now if I therefore look at this extra distance that has been travelled by light there is a corresponding phase difference now what you are going to do is to demand that there must be a constructive interference please remember when we started discussing evidence for wave like nature for light we actually worked out the interference condition and the condition is that this must be an integer multiple of  $\lambda$

so if a wavelength of a certain frequency is hitting a crystal and it is getting reflected back then what we find is  $2d \sin \theta$  equal to  $n \lambda$  for constructive interference and what is the condition  $n$  should be an integer

so in other words for a light of a given wavelength if you for example keep on rotating the crystal

so that you can change the angle or you can rotate your detector

so that you can look at the change of the angle because the wave is coming like this there should be specific values of  $\theta$  at which you are going to find the peak maximum constructive interference and therefore the intensity will peak there and that sine  $\theta$  will be given by  $n \lambda$  by  $2d$

so  $\theta$  will be sine inverse and  $\lambda$  by  $2d n$  equal to 1 will give you the first maxima  $n$  equal to 2 will give the second maxima

so on and

so forth we should be able to find that and this is exactly the Bragg condition

so you should interest you to know that both the father Bragg and the junior Bragg got a Nobel prize for this very important piece of work and Lord Röntgen actually recognized that if you are given a crystal like sodium or copper or any of the metals ok then the right wavelength or the frequency in order to see this kind of diffraction is in the x-ray region there is your famous x-ray diffraction and today it is an extraordinarily important tool for us to determine the crystal structure

so at this point I should tell you that what I have shown you is a very simplistic view  $d$  depending on which face of the crystal that you are going to look at this  $d$  can change it will come with three indices  $h k l$

so people generally say one one plane one one one plane two two two plane one one zero plane

so on and

so forth

so by looking at the crystal for at various angles you should be able to determine the crystal structure if you know the wavelength very precisely and

even today x-ray diffraction xrd as it is commonly called is a very very powerful tool and this is one deep broly wanted to make use of

so deep broly made the hypothesis he was a theorist and he wrote his thesis on matter waves not only did he get a phd he also got a nobel prize very soon

so it is one of those rare cases which happened at the around 1920s when all the thesis got nobel prizes heisenberg um dee brawley dirac all these people did their thesis work in order to get their nobel prize but the two gentlemen who did the experiments i am showing you their picture here davison and germa these people were not working in a university they were in bell labs and they were doing experiments and these people verified the deep broly hypothesis in nineteen twenty seven

so what are we saying nineteen twenty four is the matter wave hypothesis and 1927 when it was verified on nickel crystal it is not that people took deep broly hypothesis very seriously but it also did not encounter the kind of very harsh criticism that einstein's belief in photon encountered because meanwhile content scattering had been very well understood through the concept of a photon and bohr in his bohr model had argued that when an electron makes a transition from an excited state to higher excited state to a lower excited state or to the ground state the radiation emitted actually obeys the planck law  $e$  is equal to  $h \nu$

so in that sense d broly was fortunate therefore after he made the hypothesis in 1927 davison and germa made a performed a very beautiful experiment which verified that

so this is the famous paper that everyone alludes to which was published in physical review but subsequently in 1928 they published another paper in proceedings of national academy of sciences where they again verified the result and they wrote a detailed description and critique of both their experiment and the deep broadly hypothesis at this point i want to take a digression and i want to tell you how this experiment came about because really speaking davis and germa were not into the business of verifying deep broly hypothesis they were interested in verifying something else and some time back maybe a year back or whatever when they were doing an experiment there was some glass tube containing air and some liquid and because of high temperature the tube exploded and they had a crystal which was nickel actually but it was poly crystalline it was not a single crystal

so the whole thing fell on the crystal and it created quite a mess but david and germa were not to give that up they wanted to get the crystal back and remove all the fluid that had accumulated on the surface it had been absorbed on the surface

so what they did was to carefully heat cool heat cool

so that all the liquid or other gases that had been absorbed would be removed and it took them quite some time months actually but their patient work gave them something extraordinary and they suddenly discovered that what they had got was actually a almost perfect single crystal it was not a polycrystalline quantity but it was a single crystal single crystals are not easy to get today of course we know how to get extraordinarily good perfect single crystals like for silicon or things like that but not

so in nineteen twenties and they verified that it was a single crystal by making use of the brag diffraction rule

so they identified the one one plane one one one plane using the fondlover rules then what they did was to direct electrons towards the one one one plane because they thought electrons are particles

so they would get scattered and some of them would actually pass through and they expected them all to be channelized in some particular direction like like

it would happen in the case of a particle nature

so they certainly did not think that they were trying to verify either prove or disprove deliberate hypothesis they were working under the conventional assumptions of electron behaving like a particle after all that is what cathode rays tell you but what they found was something really extraordinary

so what exactly is the experiment that they performed

so if you look at your slide you find a schematic explanation schematic diagram so what does the schematic diagram tell you this schematic diagram essentially tells you

so you have to look at a few things there is an electron gun which produces an electron beam now the most crucial thing here is that you should be actually able to accelerate you should be able to vary the momentum that is what you should be able to do

so what you do is to put a voltage difference accelerated by a certain voltage then what happens as it accelerates its energy increases its momentum increases and as the momentum increases its wavelength changes it starts from a small value to a larger value and starts going to a smaller value

so it is then under control then you see at that angle  $\theta$  there is a nickel target my electrons are getting reflected and i put a movable collector

so the mobile collector simply does not try to distinguish between individual electrons it will simply ask how much charge has been collected how much charge has been collected will be known by looking at how much current flows

so the current is a measure of the intensity and that is known through the galvanometer which you show here of course you do not want loss because of collision with the air molecules you do not want any disturbance for the electron beam you should be fairly monochromatic i should not use the word monochromatic you should be fairly be mono energetic therefore mono momentum

so there is a vacuum chamber that is what you have there and then what you do is to move your galvanometer measure the current or look at the deflection the deflection is a measure of how much of current is flowing you all have done experiments with your galvanometer and you look at what it is

so this is a very beautifully done schematic diagram in your ncert book and this is exactly what davidson and germa did but what the next plate shows is actually the apparatus itself

so this is the 1927 apparatus that those people used it is from physical review in 1927 physical review was then still a rather young journal because most of the great papers were published in european journals

so you see there is something called g which is the electron gun and t is the target there is a voltage difference between them and what we call as c is the collector and this collector actually moves along that arc which is rather hemispherical and you start looking at it and the rest of it is all controls how you move the thing there are the springs there are these levers and what not they are tell you and what they did was to actually perform the experiment very very carefully and the most important thing for you to know is that the target was a nice single crystal and for the for those of you who are a little bit familiar with crystallography what they were looking at was actually the one one one plane if you do not understand the meaning of what one one plane is never mind about that but this is the apparatus ok now these are the experimental results that is something that we want to discuss at some length now

so probably before i yeah i can show that here your book tells you that the experiments were done sometime between 40 to 64 volts

so the voltage drop was varying from 48 to 64.

so if you assume that the electrons started at very very low energies almost at

rest what is the energy gained by them either 48 electron volts or 64 electron volt or something in between them now what you do is to say let us say 60 electron volts equate it to  $p^2$  by  $2m$  and then find out your  $p$  then you make use of your deep broly hypothesis and find your  $\lambda$

so essentially the message is that when your energy is changing from 48 to 65 volts the momentum is correspondingly changing and i am looking at this scattered cross section that is what we are looking at and in this figure you can see there are two such figures what have you done you have fixed your voltage and you are changing your and you are changing your azimuth angle your azimuth angle is something like the  $\theta$  that we have written there is a mismatch of the notation and you see that there are very well defined peaks both for 65 volts and for 54 volt 54 volt corresponds to larger wavelength 65 volts corresponds to the shorter wavelength because the momentum has increased and what davis and germa found in their experiment contrary to their expectation was that this peaks that is where the maximum constructive interference is taking place according to d brawley agrees very very well with what agrees very very well with the deep broglie formula  $p$  equal to  $h$  by  $\lambda$  that is what they found out and this was indeed a landmark experiment it was a path breaking experiment which established the wavelength property of matter this is a figure which they published in the next year 1928 here what they have done is to plot it against square root of  $v$  and you should explain that

so let me do a little bit of simple algebra which is not too difficult and let us come back to this slide later

so what i am trying to tell you is that  $p^2$  by  $2m$  is my energy and that is nothing but the charge of the electron multiplied by the voltage that is what i have

so i will my  $p$  is therefore given by square root of  $2 m e$  into the voltage that is the most important thing now my mass of the electron is known my charge is select of the electron is known my two of course is a number therefore this is some constant into root  $v$  where where is the voltage drop and what is  $d$  probably telling us deep roll is telling us that this is equal to  $h$  by  $\lambda$   $d$  brawl is telling that it is equal to  $h$  by  $\lambda$  therefore if i transfer it my  $\lambda$  is nothing but  $h$  over  $k$  root  $v$  this is the hypothesis

so let me repeat that expression here  $\lambda$  is equal to  $h$  over  $k$  root  $v$   $k$  is known  $h$  is not necessarily known we will come to that in a minute and our constructive condition was that  $n \lambda$  equal to  $2 d \sin \theta$

so this is equal to  $n$  into  $h$  over  $k$  root  $v$  that is what we have

so what you are now doing is to look at the variation of  $\sin \theta$  with respect to root  $v$  and not only that you are trying to determine this slope  $h$  by  $k$  if the deep broccoli hypothesis is correct

so in other words not only should you be able to find the peak at the right position but you should also be able to fit it to the deep braley formula and what davisson and german found was that it was indeed correct and that is the reason why they are plotting it as a function of root  $v$  ok all that you have to do is to transfer it to the right hand side and they are plotting the intensity the intensity peak as a function of root  $v$  at a fixed angle that is what you are doing the angle is fixed is not ok and they found a beautiful confirmation for the maxima in fact there is a confirmation for the minima also which corresponds to  $n$  plus half where  $n$  is an integer

so in their paper they mention that to their great surprise they found that it was agreeing their experimental results were agreeing with the deep broly hypothesis now you may ask how good is this experiment compared to the modern days or x-ray diffraction

so i am showing you a number of figures look at these peaks these experiments

were done in 1925 26 27 that when the experiment technical techniques were not completely developed that is what we are looking at now if you look at a modern day x-ray diffraction experiment our diffractometers are much more advanced today our crystals are much much better single crystals you see sharp peaks which is almost in quite a good agreement with the peaks that we are seeing here okay

so that is the accelerative fraction result and this is my deep broly result modern day experiments of course do show such a sharp feature probably in the next class i am going to show you some of them but basically what we are saying is that we are now doing something very funny we are making use of the wave nature of the light to support and substantiate the hypothesis that particles can show wave-like behavior whereas in the photoelectric effect we just did the opposite we said that light actually behaves like particles

so we are in an extraordinary situation where we do not know whether something is a particle or a wave unless you give me the circumstances under which i am going to look at

so that is a message that we are going to look at

so you see these features are extraordinarily nice and this is what we have

so these are the mandatory numbers which i should show you these are there in your textbook and there are all these very simple problems which you can do now given the diffraction peak find the wavelength or given the wavelength and extraction peak find the lattice spacing

so on and

so forth but in the davis and german experiment as i told you it was between something like 48 to 64 volts the maximum occurred at 50 degrees at 54 volts and the corresponding de broglie wavelength is  $\lambda$ .

165 nanometer which is close to what you find in the x-ray range actually

so this is quite an interesting and spectacular demonstration of the wave nature of the electron

so so far what we have done is to give a free range over imagination even if you assume that ok there is a bohr model and i want to produce a standing wave

so on and

so forth but one thing that this kind of an analysis and this experimental verification does is to throw up a number of questions a wave is characterized not only by its frequency but it by wavelength but it is also characterized by its frequency now what i have done is to associate a wavelength with the momentum but what about the frequency and if there is a certain frequency what is the velocity of the wave it is very tempting to imagine that you know the wave with which the wave associated with the particle let me put that away the wave with which the wave moves when it is associated with the particle should also be the velocity of the particle but we are not at liberty to draw such a conclusion

so here are the questions which are shown on this slide for you what is the frequency what is the relation between frequency wavelength and speed

so unless we answer this question we have not completed our task

so this is something that we should know although it is technically not in our syllabus

so what we shall do is to start looking at them at some length

so what we are going to ask is for relation ship between frequency wavelength and velocity we need to work it out and let us see what we are going to get what i will do is since i am running out of time i will give all the basic expressions for you both relativistically and non relativistically and then we will see that we are going to run in trouble

so the question is how we are going to get out of trouble and there you have to

know that there is a distinction between what is called phase velocity and the group velocity group velocity is something that you are not exposed to

so i will introduce this concept although it is not technically in your syllabus and i will show you how you can recover the relations

so the important equations that i am going to make use of are obviously  $p$  equal to  $m v$  equal to  $h$  by  $\lambda$  and  $d$  is equal to  $p$  squared by two  $m$  and what we may like to do is to write it as  $h \nu$  i will put a question mark on this but i have another relation we should not forget  $v$  is equal to  $p$  by  $m$  we should not forget this and this is new  $\lambda$  i put a question mark that is something that we have to do

so what i will do is i will ask you to look at all these three equations play around and try to see whether you get a consistent set of relationships between energy momentum velocity wavelength and frequency

so you please play around with these symbols is that okay i have put two question marks because this has been established experimentally and in the next lecture what we are going to do is to take this further analyze these relations i will also write down the corresponding relativistic equations and then after doing this we will start a discussion of the great rutherford experiment

so let us stop here have a good you