welcome all of you for the next lecture on photoelectric effect which is a part of what we may broadly call as set of lectures on modern physics because after discussing photoelectric effect we will be discussing the bohr model of the atom and then the matter waves as postulated by deep rawley and after that we will be going on to discuss nuclear physics

so so far what we have done is to spend a great deal of time studying what the experimental results on the so-called photoelectric effect tell us in fact all of last lecture was a detailed discussion on the findings made by hertz lennard and milikan in their very careful and very famous experiments and we were able to extract the universal features of these experiments

so what we are going to try to do today is to point out that these experiments actually show that there is a deep problem in fact a big glacuna in our understanding of electromagnetic theory electromagnetic theory and especially properties of light seem to be very well established in the earlier experiments from the earlier experiments through

so called the wave properties of light but here we are going to encounter that we will face serious problems if we just adhere to the wave property of light that is what we want to show and we also want to show how a very radical proposal from einstein actually solves this problem it does not solve the problem of classical electrodynamics or classical theory of radiation it does explain what photoelectric effect is in a new language but eventually the development of quantum mechanics reconciled both of them but that is beyond the scope of your study one thing that we have to remember is that the paper on photoelectric effect was written by einstein in 1905

so let me spend some time on the timeline we know hertz started his experiment sometime in late 1880s 1890s and experiments of lennard went on till 1903

so we have 1903 experiments lennard and the great mullikan kept on performing experiments from 1904 to 1915 over a period of 10 years his most famous experiment the most celebrated experiment actually came around 1915 but einstein wrote his famous paper in 1905

so this was a theoretical explanation

so you people may know that in 1905 einstein was a young man of 26 years old he did not hold any position in any university he was actually a clerk in the swiss patent office and he wrote this paper even more important is that he not only wrote this paper he wrote two more fundamental papers

so 1905 is called anus mirabilis this is latin

so if we translate it into english this will call the miraculous year

so einstein wrote three fundamental papers in 1905 the first paper that he published was on photoelectric effect and then he published his paper on special relativity and the third one on brownian motion all these three papers are of fundamental importance to physics they changed the way we look at physics and the way physics allows us to look at nature to describe nature and most of you have of course heard of special relativity you will certainly learn photoelectric effect you have been learning about photoelectric effect in this course the paper on brownian motion is also extraordinarily important because this is the paper which actually showed how to verify the

so called molecular hypothesis of boltzmann

so this is a theoretical paper on molecule or hypothesis

so in your kinetic theory of gas classes you would have heard of equipartition of energy the gas is made of a large number of molecules they will collide with each other

so on and

so forth one needs a direct experimental evidence for that for which it was not there the avocado number etcetera they were all hypothesis it is this

fundamental paper of 1905 on brownian motion that actually allowed experimentalists to directly measure the avogadro number these experiments were in fact performed by the french physicist peron and he also got a nobel prize for that and einstein himself got a nobel prize for his fundamental work on the photoelectric effect

so there is much depend on why he did not get a nobel prize for special theory of relativity there are many many reasons but for us the important physics reason is that einstein himself said that special theory of relativity was a cake walk compared to developing the theory of photoelectric effect because for special theory of relativity here the earlier works of maxwell maxwell's equations were there lauren's transformations were already derived by lorenz all that he had to do was to put them together in a coherent way i mean that is what he said we don't belittle his work but photoelectric effect and it was a completely difficult experiment to understand and it required a radical explanation which was much which required much much more courage than what was required in the case of special theory of relativity

so it is no wonder that he got a nobel prize for the photoelectric effect

so what i have going to do today is to briefly summarize what the experimental results are it is good to summarize before we start with the theoretical discussion then i am going to show what the great conflict between the experimental result and the classical theory is it is not a small discrepancy it is a very very large discrepancy i am going to show you that and then i am going to tell you how the concept of a photon arose and how einstein was able to use it very profitably this is a model that we proposed but it is a very very powerful model because at the end we are going to show that this model can explain one more phenomenon which seems to be quite unconnected and that is what is called as the stokes law and there we are going to conclude a discussion on photoelectric effect

so let us start with a brief discussion of facts and then look at the prospects okay let us get into a recap of what the photoelectric effect is this is a graph that i have shown you earlier and this is essentially a reformulation of the famous experiment performed by milliken in 1913 on the y axis what you have is the maximum kinetic energy of the photoelectron

so what is happening

so let us remember that recall that

so you have a metal surface and you have radiation falling on it and it is emitting electrons that is what we have and these are collected these are not exactly collected

so what you do is to put a plate here and apply an opposite voltage that is a force in this particular direction and you ask what is the voltage that i have to apply to stop all the electrons that are reaching the plate that means i should be able to stop even the fastest moving or the most energetic electron

so that voltage multiplied by the electron charge will give the maximum energy maximum energy what you do is you keep on changing the frequency of the radiation

so let us come back to this figure we keep on changing the energy of this radiation and ask how does the maximum kinetic energy of the electron change along the y axis and the maximum kinetic energy is simply nothing but the stopping potential the stopping potential is the minimum potential that is required to stop all the electrons

so when you plot them this graph clearly shows that you are going to get a straight line and the slope delta a by delta nu it has the dimension of energy into time or angular momentum that is a universal constant this experimental result is for sodium and the x axis is in electron volts

so that is what you have and the y axis is also in the electron world the same experiment can be repeated on zinc on nickel on many many atoms on gold the frequencies will be different the maximum photoelectron energy will be different but the slope is a universal constant that is the most important thing slope is a universal constant

so we have two tasks cut out for ourselves how do i understand this linear behavior from whatever they know from electromagnetic theory and what is the meaning of this universal constant

so these are the two jobs that are cut out for us and let us see what we can do with that

so whatever i told you in words i have collected again in this particular slide these are the important points and basically what we are going to look at is universality coupled with the interplay between the intensity of the radiation and the frequency of the radiation

so here is point number one first of all we notice you take any metal there is a minimum frequency that is required for photo emission if the frequency is less than that minimum frequency the threshold frequency you can keep on increasing the intensity but no photoelectron will be emitted there is an experimental observation now once i cross that minimum frequency you cross the threshold then as i keep on increasing the intensity more and more electrons are emitted that is the next thing

so what is the statement that we are making there is a threshold frequency below the threshold frequency no emission whatever the intensity may be and after the threshold frequency

so let us call the threshold frequency nu naught if nu is greater than u naught then it is proportional to the intensity

so no emission below minimum frequency and how does it depend on the frequency as i keep on increasing the frequency there is a linear relation between frequency and this stopping power this does not depend on intensity the stopping power does not depend on the intensity the total number of electrons which are emitted depends on the intensity but the stopping potential does not depend on the intensity it depends only on the frequency that is what we find in this particular figure

so your the stopping potential is exactly the same as the maximum kinetic energy and this is something that we have to understand and these results are actually mysterious they appear to be very simple because most of the time when we plot graphs in our laboratory we want to have a straight line even when it is not a straight line we convert our units such that we are going to get a straight line but here we have a serious problem because if my electrons are getting ejected from the metal that means my electrons are bound to the metal if they are getting ejected you have to supply energy and where does the energy come from the energy comes from the radiation radiation carries energy radiation carries momentum that is what maxwell taught us and that is what was verified by experiments all of us know how to do an experiment take a lens focus sunlight on a sheet of paper and the sheet starts burning we have all done that when we are children

so radiation does carry energy

so that is not a problem the real problem is in the expression for the energy density i have already discussed it earlier i am reconciling that the expression for the energy density is given by epsilon naught e squared where e is the electric field now if there is a monochromatic plane wave remember that

so let us go through that quickly

so that we are not going to miss the point if you have a monochromatic plane wave that means my frequency or wavelength is fixed then my electric field is e

naught let us say sine k z minus omega t k is the wave number and omega is the circular frequency then my energy is nothing but epsilon naught e squared that is what i have which is epsilon naught e naught square sine square k z minus omega t

so at any given point the energy oscillates between 0 to epsilon not e square in the visible range the frequencies of the order of about 10 to the power of 14 hertz are 15 hertz that means in 10 to the power of 14 or 15 seconds it is oscillating in one second it is oscillating 10 to the power of 14 or 15 times we cannot measure that

so what you do is to look at the average and that is going to give me epsilon naught e naught squared by 2 that means all reference to the frequency or the wavelength goes away your energy density depends only on the amplitude squared e naught squared which is the magnitude of the electric field which is the magnitude of the electric field the maximum value that the electric field can take that means if energy is being transferred from the radiation to the electron that transfer should depend entirely on my e square that is what this sliding is showing to me u equal to epsilon naught e square implies u equal to epsilon naught by two e naught square you should not depend on the frequency however if i go back and look at this diagram this great experimental diagram my x axis is actually the frequency and you see less than 4.

5 electron volts in this particular diagram there is no emission you can keep on increasing the intensity there is no emission therefore we are in for trouble we are not able to understand this very elegant this very simple beautiful figure from the classical theory of electrodynamics

so what do we do now now there is one way of qualitatively seeing the discrepancy between the classical theory and the quantum with this photoelectric effect there is another way of estimating the discrepancy between what maxwell tells us and what the experiment is finding now let us imagine that an electron is bound to a metal

so there is this metal and there is this radiation that is falling and there is an electron which is sitting here a good question to ask is how does this electron get liberated by this radiation

so what is happening

so if you imagine this electron is bound to the lattice through a spring is that right

so that is how we imagine the atom to be then this radiation comes it hits the electron therefore it will start oscillating

so what you are getting is a forced oscillation which you have studied in your mechanics which you also will study in your lcr circuit

so on and

so forth you have a forced oscillation

so if my electron has a natural frequency omega naught and if the radiation is coming with a certain frequency omega what happens as you keep on hitting the electron will start oscillating with more and more energy and eventually when the amplitude keeps on increasing and eventually when the amplitude hits the breaking amplitude at that point the spring snaps then you say that the electron is liberated

so what i can do is to ask what is the time required for an electron to get liberated if i keep sending my energy that is the question that we are asking and that is a very very easy thing to estimate

so what we are going to do is to ask how much energy is absorbed per unit time by the electron

so let us come back to this slide

so the energy absorbed is energy per unit time which is falling on the metal

divided by the total number of electrons that is what i want

so what i have i have a plate here the radiation is coming like this

so i am asking how much of radiation is falling per unit time per unit area and i am assuming that all of them are going to be absorbed then i know how much is absorbed by each electron because i know the number of electrons in that area and then i find the time required and that is what i have written here

so i take the energy density i will multiply it by the area i will multiply it by the speed of light

so that will give me energy falling per unit volume per unit time and i will divide by the number of electrons which is actually the density of the electrons and what should that be that should be nothing but your stopping potential divided by that absolute your time required must be nothing but that and we want to look at that

so here is some relevant data

so let me come up here and you will get the complete information these numbers are real numbers

so please take them seriously i am looking at sodium sodium has a work function of 2.
36 electron volts number of electrons by the time in the electron density is 10 to the power of 19 the wavelength is about 300 to 400 nanometers let us say intensity is 10 to the power of minus 6 watt per meter square because i calculate that therefore the energy per atom that you supply is 10 to the power of minus 25 watts per second you are supplying 10 to the power of minus 25 watts per second now you can compute how much is the energy for the electron how much is the time for the electron for it to gain an energy of how much about 2 electron volt or 3 electron volt plug in all the numbers if you did a computation you will get 2.
6 into 10 to the power of 6 seconds

so please take this as a home assignment note down all these numbers work function is 2.
36 electron volt density is 10 to the power of 19 wavelength is 300 to 400 nanometer i am giving you the intensity 10 to the power of minus 6 watts per meter squared all these are the numbers employed in the experiment and the time taken will be 2.
6 into 10 to the power of 6 seconds how much is 2.
6 into 10 to the power of 6 seconds well you have 24 hours in a day then you multiplied by 3600 that gives you the number of seconds in a day and then you multiply it by 30 that gives you the number of days in a month

so if you multiply this you are going to get 2.
6 into 10 to the power of 6 that is what you are going to get

so that means that this number corresponds to waiting for one whole month that is what we are saying

so take the millikan experiment or the lenard experiment they have very very low intensities but sufficient frequency this low intensity radiation is coming the energy absorbed depends on the intensity

so that is the calculation that i am doing if the classical theory is correct i would have had to wait for one whole month which is 2.
6 into 10 to the power of 6 seconds what is the real time required the early experimenter has told us that it was instantaneous it took place immediately no we don't know what the meaning of immediate is that depends on the clock that you have

so let us imagine that millican had a clock with a resolution of half a second or even one second that means there is a discrepancy of 10 to the power of 6 a factor of 10 to the power of 6 i will give you an idea of what 10 to the power

of 6 is in a minute the radius of the earth is about 6 400 kilometers the radius of the earth is about 6 400 kilometers
 so that is 6.
4 into 10 cubed
 so it is 10 to the power of 6 meters
 so it is like confusing your meter scale to be the radius of the earth it is as bad as that but actually it is much worse than that because today we know that the real time that is required we have much much better clocks okay the real time required is 10 to the power of minus 9 seconds all transitions take place over 10 to the power of minus 9 seconds therefore if you look at this slide what is it that we are finding classical theory it says one month which is 10 to the power of 6 seconds my experiment is saying 10 to the power of minus 9 seconds therefore the discrepancy the ratio is 10 to the power of 15 it is a mind-boggling number 10 to the power of 15 is enormous it is like the lifetime of a person
 so if classical theory were correct if millikan or lenard had spent their whole lifetime during their experiment maybe they would have found a few electrons and that would not be photoelectric effect at all
 so there is another estimate for you to see the discrepancy the earth sun distance is 10 to the power of 11 meters
 so that is the distance between the earth and the sun and size of a dust particle is about 10 to the power of minus 5 meters 10 to the power of minus 5 to 10 to the power of minus 6
 so what you are saying is that the dust particle is
 so big that it fills all the space between the earth and the sun if i made such a statement i would be star craving mad nobody can make such a statement
 so exactly the same way once you accept the validity of these experimental results it is impossible to reconcile the classical theory with whatever we have observed
 so in other words there is a modern terminology which people like to use we need a very drastic method you need what a surgical incursion you have to do a drastic surgery right that is what we have to do and that is exactly what einstein did when he gave his explanation for the photoelectric effect you might wonder whether the three papers of einstein had anything to do with each other at all the people on special theory of relativity the paper on the brownian motion actually all the three of them have to do something with each other einstein is speaking the language of a photon gas you will see and of course he speaks the language of an atom because the electrons are coming therefore you need validity for the molecular hypothesis which the brownian motion gives the photon hypothesis is not only inconsistent it cannot be understood from classical electromagnetism it also cannot be understood from the viewpoint of newtonian mechanics the only way we can understand the concept of a photon is through a special theory of relativity we want to see how it is
 so what einstein accomplished is something extraordinary which will happen probably once in many many centuries he did three independent pieces of work all of them fundamental all of them very very original all of them independent of each other but still they interact with each other to give us a complete picture of what is happening
 so 1905 was something that was truly revolutionary and that is something you people should appreciate
 so what has happened we have reached a crisis in physics we have reached a crisis of enormous proportion and all this was started by none other than hertz there are very very interesting stories about hertz and apparently hertz said that he was very unfortunate to have been born in any age where he cannot make

fundamental discoveries poor man he thought all that has to be known about laws of nature have been done newton gave us gravitation einstein gave us maxwell gave us electromagnetism

so we understand particles we understand waves and then of course you have constitutive equations you know permittivity permeability everything rest of physics was all what matter of detail it is left for ordinary people

so mr hurts thought you know i am an intelligent person i am talented but there is nothing much to do for me he was not the only person who had that idea when somebody went to michaelson and asked him should i pursue physics michaelson told him no no don't get into physics everything is over in physics we know planetary motion we know universe we know everything everything left is all again matter of detail somebody will determine something to greater accuracy greater precision or whatever whatever you pursue some other subject what neither michael said nor hertz realized was that they were actually preparing the stage preparing the ground for what for a completely new physics which has transformed our lives completely einstein came planck came they gave us quantum theory einstein gave a special theory of relativity einstein gave us general theory of relativity today all our gps satellite motion is because of general theory of relativity we have to use them

so this happened not in a smooth manner but in a very violent way there was a real deep crisis

so what we shall do is pause for a minute and look at what that crisis is see wave nature of electromagnetic radiation has solid experimental support we cannot doubt that in fact it is

so solid that even a very very powerful person influential person like newton who believed in corpuscle or theory of light his hypothesis had to be abandoned how does he get the solid support from you have loss of reflection and refraction you have diffraction you have interference these are the experiments which conclusively show that light is a wave phenomenon and remember we spent a long time in our second lecture looking at the evidence for all these things

so you have young's double expiry double slit experiment in the visible region hertz and jc boss they repeated the experiment in the microwave region jc boss and marconi were able to produce radio waves marconi got a nobel prize jc bose did not get that's a different matter altogether but we see this way the region of applicability of the electromagnetic theory it is working everywhere

so wave nature of electromagnetic radiation has solid support from reflection refraction interference and diffraction over a large range of wavelengths not just in the visible range but also outside the visible range

so that is very very firmly established but on the other hand photoelectric effect is telling me that i cannot understand this linear dependence on the frequency the maximum energy depending on the linearly on the frequency from the electromagnetic wave phenomenon this is the great crisis is there a way out that is what we have to ask and this is where the 1905 revolution of albert einstein is very very important for us and what did einstein do einstein said that i will leave all that aside the problems with waves etcetera etcetera aside and i am going to come up with the particle explanation a radical particle explanation and i am going to explain photoelectric effect at this point we should remember that einstein was not aiming at consistency consistency is reconciliation of wave nature with the particle nature einstein was not doing that and he was wise enough not to try to do that because we cannot achieve everything at the same time the consistency between the wave picture and the

so called particle picture in fact i should say the

so called wave picture and the

so called particle picture came much much later in 1930s

so it had to wait for another 25-30 years and that is something that students of physics study in their very very advanced courses in when they do physics in their quantum mechanics courses

so at this point please remember that what we are doing is to come up with a viable explanation but this viable explanation is not completely off the hat it has a nice rational basis and you will not be in a position to reconcile between waves and particles

so when you do optics you will do all interference double slit experiment diffraction etcetera when you do modern physics when you do bohr model you will use the photon but please be patient you will get to know what it is in your later studies maybe after another three or four years

so this is the picture of einstein when he was 26 years old

so the acknowledgement is getty images

so all the figures have acknowledgments ok but this requires a prehistory einstein did not create the concept of photon the creator of the concept of photon was none other than max planck and this came in 1900 and i want to spend some time on this although this is not a part of your syllabus no there is something called a black body concept of a black body in thermodynamics it is an ideal body and the property of the black body is that if it is heated to a certain temperature then it starts emitting radiation now normally you take a piece of wood you take a spoon you take a piece of paper and you start burning them or you expose them to heat their responses are all different but this black body is an ideal substance in the sense that ideal object in the sense that at a given temperature the radiation that is emitted is quite independent of what the object is made of that is the idea of a black body

so it is a kind of perfect body now you can think of black body in your imagination the big question is do black bodies really exist it turns out that they do exist and an excellent example of black body is actually a metal which is white hot you understand that no what does white hot mean

so take a piece of iron you start heating it okay you can go home and do this experiment you take a spoon and you keep it in the gas flame it starts becoming what redder and redder it becomes red because it starts emitting radiation in that range you keep increasing the temperature it starts emitting radiation in more and more frequencies and what is white light white light is a mixture of all these frequencies therefore it becomes white hot that is what we mean by white

so a very good example in fact a very good approximation for a black body is a white hot metal and that is around something like three thousand to five thousand kelvin

so you do not see it at three hundred kelvin or five hundred kelvin or eight hundred kelvin

so these are the very important experiments which were performed by loomer and print shine they built a bolo meter which will look at the energy radiated by the black body radiation i do remember performing that experiment as an undergraduate student

so they built a polo meter and they measured that and now you ask what is the energy intensity as a function of the frequency emitted because different frequencies are emitted at a given temperature

so for every temperature i will ask i will plot what is the intensity of the radiation for every frequency there are other good examples of a black body an even better example in a better approximation for black body is actually the sun the surface temperature of the sun is about 5000 kelvin

so you know we get about 4 kilowatt of power is that right from the sun the mean power is that

so imagine repeating newton's experiment of splitting that white light into all the seven colors and measure the intensity as a function of each of the wavelength or the frequency that is an excellent approximation for a black body it will agree very well with what you find with your metal sun is not a metal not the surface will be made of gases it will agree extraordinarily well and here in this slide you have a picture of the dependence of spectral radiance or the intensity along the y-axis with respect to the wavelength
 so we want to spend some time on that okay i have magnified that
 so that you people get a feeling now you see that if i make use of the classical theory this curve the black curve is the classical theory and it is telling me
 so let us come back to that you see the x axis is increasing wavelength that is decreasing frequency and y axis is intensity look at the rightmost curve this is all at 5000 kelvin the rightmost curve agrees with experimental numbers this is a theoretical curve the blue the green the red they are all what they are experimental curves the red curve is at three thousand kelvin the green curve is at 4000 kelvin and the blue curve is 5000 kelvin now this black curve is plotted at 5000 kelvin
 so what is happening if you go to very very large wavelength or it is in micrometer
 so you are speaking of something like 3 micrometers or correspondingly very very small frequency this curve agrees with the experimental number which is the blue curve but as you keep on decreasing the wavelength that is as you keep on increasing the frequency the classical theory keeps on going higher and higher whereas the experimental number what is happening to the experimental number it comes here and it reaches a peak and starts going down classical theory tells you that the intensity should go to infinity it should diverge as the frequency becomes very very large whereas experiments tell us no there is always a frequency at which the intensity is maximum that is there is a minimum wavelength at which the intensity is maximum and after that if i further decrease the what if i further decrease the wavelength or increase the frequency the intensity will go down
 so you see that there is a great discrepancy between what classical theory predicts and what experiments are finding now this is not just a matter of discrepancy this is again a discrepancy of orders of magnitude in fact i cannot given an even an order of magnitude because if i want the total intensity i have to integrate over all frequencies now at any given temperature my black body has some energy and it is in equilibrium with radiation
 so that radiation should also have a finite energy but if i integrate the classical curve because it is going up to infinity if i integrate the classical curve i will get a divergent energy that means at every temperature except t equal to zero absolute zero which nobody can achieve my radiation will be carrying infinite energy which is nonsense because we cannot deal with infinite energy and this is called ultraviolet catastrophe the divergence is taking place at very very small frequencies smaller the frequency greater you move to sorry at very very large frequencies larger the frequency small large smaller the wavelength you are moving towards the violet region violet ultraviolet x-rays gamma rays
 so on and
 so forth since the divergence is occurring in that region we call it the ultraviolet catastrophe and this had to be resolved
 so this is what we call as a pre-crisis as far as photoelectric effect is concerned photoelectric effect is not the first example where we ran into trouble actually in 1890s already this problem was there and max planck whose

picture you see here was one of the great experts on thermodynamics he said i am going to understand this and how do i understand this i will see what is a model that will correctly fit the experimental numbers because classical theory will not work i will have to make a model that is what blank said

so here is a little bit of more explanation for that let me go back to the slide and explain that to you what planck did because it is not beyond your reach blank hypothesis

so you have a curve like this

so this is my increase in wavelength or this means my increasing energy because as i move in this direction my wavelength decreases my frequency increases

so increasing frequency i should not use the word energy frequency that is what i have now suppose the same curve was found not for black body but for particles suppose the same curve was found for particles you see there is a peak here e max and at both the ends it is going to zero at both the ends it is going to zero your spectrum and this is not surprising from the viewpoint of a particles at all because equipartition energy tells me the mean energy is 3 by 2 kt but at any given temperature if you go to very very small energies the probability is 0 if you go to very very high energies the probability is also zero why is that

so if you are boiling water the probability of a water molecule at rest is zero

so the probability goes to zero and the probability that at that temperature one water molecule has an energy such that it will escape from the surface of the earth is also zero it cannot

so the distribution is such that it peaks at some energy that is what we mean by three by two kt it might be something more complicated than that

so the energy the distribution of energy that is what we are going to look at should fall off to zero both for very small energy and very large energy and the mean is at about 3 by 2 kt now if you look at this experimental result this is agreeing very well in the classical limit

so what will planck do planck will say i will associate that is very very important thing for us i will associate the large wavelength limit with small energy limit and the small wavelength limit with a large energy limit that is what i am going to associate in fact if you inverted this curve at very high temperature it will look very much like the maxwell boltzmann distribution as a function of energy okay all that you have to do is to interchange lambda will not increase in this direction but lambda will increase in the other direction there are small corrections that is what is going to happen

so what you will like to imagine and that is what planche did is to say that i will look upon my radiation as a gas of photons gas of particles of light this is a very crude language but never mind gas of particles of light and that is what he did i don't know whether he called it as a photon or not it was not used this was called as a quanta in fact it was a chemist who introduced the jargon photon much later after the 1905 paper came probably around the compton effect if you did that equipartition theorem will tell me that each photon on an average carries an energy 3 by 2 kt that is what it is in order to reconcile this experiment planck introduced the new constant h and he said that the energy carried by each quantity is e equal to h nu

so this is the planck hypothesis

so what are you going to imagine when i take a black body something like a metal heat it to very very high temperatures then it starts emitting radiation there is a stefan law which you people have studied now from the classical theory viewpoint waves of all possible frequencies are emitted from the point of view of plank photons of all possible frequencies are emitted and the energy of each photon depends on the frequency e is given by h nu that is what you are going to have

so this 3 by 2 kt can be related to the new mean the mean frequency and on the either side it falls off that is what frank did this appears like a qualitative explanation but of course prank did something much much better

so he was able to derive this expression for the intensity as a function of frequency and temperature

so you have e to the power of h nu by kt h is the planck's constant and you see that in the limit h going to 0 or t going to infinity you get back the classical limit he was able to recover the classical limit 2 nu squared over c squared over kt that is one thing or if you say that this exponential is much much larger than 1 if h nu by kt is very very large it will look like the maxwell boltzmann distribution that is what we have planck very reluctantly gives this formulation does it mean that planck believed that light is made of photons or particle like properties the answer is no he did not believe he said that this is an effective way of understanding the interaction between the black body and radiation there is no doubt that radiation is what please tell me there is no doubt that radiation is waves let us not question that but when the radiation starts interacting with the black body

so imagine black body a cavity what is happening it emits radiation it absorbs radiation that is how it is there will be an equilibrium during this interaction process it is as if you pretend that it has particle like property like for example you know i am attending these sounds and imagine there are lot of pulses which are coming if you don't resolve the width of the pulse and if you don't look at it very carefully it is as if you know the bullets are coming and hitting your ears if i am shouting very very loudly

so you pretend as if it is particles but deep down what is it it is nothing but what it is nothing but a wave

so this was some kind of an effective description which should be understandable which we should be able to explain by working out the details of interaction between the blackbody and radiation but fundamentally speaking what did planck believe in planck believed that radiation is only a wave like phenomenon planck did not believe in the concept of a photon or a quantum that is something that we have to remember

so this is where the einstein revolution comes because not only was he trying to give an explanation in terms of the concept of a photon he was actually propagating advocating that photon is real that is the most important thing he said we should take the concept of a photon very very seriously

so the difference between planck and einstein is that they make use of the same hypothesis prank thinks it is some kind of a make do phenomenal i am making a tentative explanation we will not take it seriously but einstein is saying no no we are going to take it seriously we are going to assume that radiation is like a gas of photons each photon carrying an energy h nu depending on what it is and i am going to explain photoelectric effect and that is the reason why after about 20 years around 1921 or 23 15 16 years einstein got a nobel prize for this photoelectric effect

so what is the reconciliation

so the reconciliation is in writing these two expressions the classical expression for my energy density is given by epsilon naught by two e naught square but for photoelectric effect we are going to write it to be the number density of the photons multiplied by h nu

so what are we saying classically speaking there is a plane wave let me explain that

so we are looking at classical quantum classically there is a plane wave it is carrying energy and u is given by epsilon naught by 2 e naught squared the mean energy this is classical quantum mechanically you have stream of particles

so this is frequency neo associated with this frequency in you you have a stream of particles coming with energy h nu and u is the number density of the photons into h nu number density of the photons multiplied by the energy of each photon will give me the energy density

so what will i do there is a classical expression there is a quantum mechanical expression classical is coming from a wave this is coming from particle wave has nothing to do with particle particle has nothing to do with wave but we are courageous people i mean einstein was courageous we are going to equate the two of them that is how you solve all your problems in your 12th standard for your je or cbse or anything

so given u and given frequency you can find n gamma

so on and

so forth this is the radical proposition by ice time and we are going to see that with this simple identification however illogical it may be we will be in a position to understand the photoelectric effect we need a few hypotheses they are all reasonable and what we shall do is to start listing them

so that is what i have collected in this particular slide the prank hypothesis is a reluctant explanation taken to be of limited validity and limited applicability but not the einstein hypothesis

so what i will do today is to simply state the hypothesis i will not go beyond that and in the next lecture i will elaborate upon that i will show how the einstein explanation correctly and completely explains the photoelectric effect and i will also give you one application that is the stokes law that will conclude our study of the photoelectric effect and after that we go on to the bohr model where again the concept of a photon will become very very important

so what are the assumptions that we are going to make and let us stop here

so i have written that down here

so that we can read them at leisure the incident radiation of frequency nu can be looked upon as a stream of photon gas with each photon carrying an energy h nu that is the planck hypothesis now comes the 2 3 4 refer to what einstein invoked what einstein postulated we say that electrons in the metal escape to free space by transfer of energy from an individual photon

so what are we saying my electron is in this metal this photon comes i am not writing the wave picture my electron absorbs the energy and it comes out

so it is a collision between an individual photon and an indian electron collision between individual photon and electron the second assumption that we have to make and that is a very very reasonable assumption is that energy is strictly conserved in this process no problem but the third assumption is very very crucial which is not often mentioned in books or in lectures on photoelectric effect the maximum kinetic energy of the electron corresponds to complete absorption of the photon

so you can imagine a situation a photon comes my electron is here electron gets a part of the energy and photon continues

so the energy of the photon will be displeated that is perfectly possible

so this is what we call as a collision

so my electron is coming here my photon is coming here electron gets the energy some energy from the photon and the photon propagates but the complete absorption means this does not exist all the energy is gobbled up by the electron that is a very very important assumption for us

so if you make these three assumptions then the explanation for the photoelectric effect becomes quite easy and we will take that up in the next lecture

so let us stop for today have a good day you