we will continue our discussions on what is light in the previous lecture we had discussed the evolution of the corpuscular model of light and also the wave theory of light which was put forward by christian huygens today we will start our discussions with the electromagnetic nature of light waves which was put forward by maxwell and the light quantum which was introduced by einstein in 1905

 so this diagram on the left represents an electromagnetic wave associated with which is an oscillating electric field and also an oscillating magnetic field and on the right is a photograph of a young girl from various number of photons
 so each dot on the photograph represents the photon which is essentially the light quantum as introduced by einstein in nineteen o five now as we had discussed in the previous lecture we had discussed the interference experiments where we could establish that light was indeed a wave phenomenon
 so the wave nature of the light was established in the beginning of the 19th century but the main question was how could it propagate through vacuum around the same time the laws of electricity and magnetism were getting developed we had the faradays law according to which a changing magnetic field produced by an oscillating magnet could induce an electromagnetic force and result in a current
 so physically a changing magnetic field produces a changing electric field this was faraday's law and which was put in the form of an equation by maxwell then there was this ampere law according to which if i have a conductor carrying current then surrounding it there is a magnetic field which is created
 so we have a conductor which carries a current i and which produces a magnetic field surrounding that this was first observed by oyster and then put in the form of a law by ampere which was put in a mathematical form by maxwell maxwell also said that not only a current produces a magnetic field but a changing electric field between the plates of a condenser for example also produces a magnetic field when a capacitor gets charged then there is a changing electric field here between the plates of a condenser there is vacuum let us suppose there is vacuum between the two plates
 so there cannot be any ordinary current flowing between the two plates of a condenser there is a changing electric field which produces a magnetic field
 so this changing electric field was named as the displacement current which resulted in the production of magnetic field
 so there was a symmetry in the laws of electricity and magnetism as was put forward by maxwell that a changing not only a changing magnetic field produced a changing electric field but a changing electric field also produced a changing magnetic field
 so maxwell wrote down all the laws of electricity and magnetism in the form of four equations they are slightly complicated and i am not going to write all those equations but i am going to only say that the equations describing the laws of electricity and magnetism were put forward by maxwell around 1864 and are known as maxwell's equations these equations are based on experimental laws and
 so therefore maxwell's equations cannot be derived and these as i mentioned was put forward around 1865 by maxwell in a in one of the classic books in the phys in physics on tree ties on electricity and magnetism now in these equations if we substitute an expression for an electric field as given by the above equation it says that electric field we assume an electric field in the x direction x cap represents an unit vector in the x direction e zero is the magnitude amplitude of the electric field and this is sine of k z minus omega t
 so its a wave like solution as we had discussed in our last lecture this sine or cosine of k z minus omega t represents a wave
 so if we substitute an equation of this type in maxwell's equations we would

get that the magnetic field will be in the y direction and and will have a same z and time dependence as the electric field where the amplitude where the amplitude of the magnetic field is zero is given by k divided by omega mu zero as we had discussed in the previous lecture k is equal to two pi by lambda and omega is equal to two pi nu lambda is the wavelength and nu is the frequency and mu naught represents the magnetic permeability of free space similarly if we substitute this expression for the magnetic field in maxwell's equations we would get the corresponding electric field as obtained by substituting this in maxwell's equations will be given by this

 so a changing magnetic field produces a changing electric field and as we had shown in the previous slide that a changing electric field produces a changing magnetic field both you you cannot have an oscillating electric field without creating an oscillating magnetic field and vice versa

 so if we substitute this expression in the maxwell's equations which describe the laws of electricity and magnetism and if i assume the h vector to be along the y direction y cap is the unit vector in the y direction then the corresponding electric field will be given by this

 so so an oscillating magnetic field will result in an oscillating electric field where the amplitude e zero is related to h zero through the following equation

 so thus we get two set of equations h zero is given by this and e zero is given by this

 so if i multiply these two equation then i get k square by omega square epsilon mu zero will become equal to one and

 so therefore omega square by k square i take omega square on this side and k square on this side

 so omega square by k square becomes one over epsilon mu naught and

 so therefore the velocity of the electromagnetic wave which is given by omega by k is equal to 1 over under root of epsilon may not

 so this was a remarkable contribution by maxwell he said he wrote down the laws of electricity and magnetism in the form of four equations and he showed that wave like expressions equations this of electric and magnetic field satisfy these equations and

 so therefore he predicted the existence of electromagnetic waves that the solutions of the maxwell's equations give rise to waves and

 so therefore he predicted the existence of electromagnetic waves and that the velocity of these waves he predicted would be equal to one over under root of epsilon mu naught in free space epsilon is the dielectric permittivity of the medium something like a dielectric in free space epsilon has the value epsilon naught and as we know the value of epsilon naught is equal to

 so much and mu naught is four pi into ten to the power of minus seven in mks units

 so so therefore if i substitute this i get a value which is 3 into 10 to the power of 8 meters per second

 so once again maxwell predicted the existence of electromagnetic waves and from his equations he derived an expression for the velocity of electromagnetic waves in vacuum and he predicted that the velocity of the electromagnetic waves was about 300 million meters per second this was around eighteen sixty one sixty two at that time the french physicist pizzo had determined the velocity of light in air and that value was also close to 300 million meters per second

 so maxwell said that these two numbers cannot be accidentally equal and therefore with faith in rationality of nature that these two numbers cannot be accidentally equal he said light must be an electromagnetic wave

 so i will repeat my argument and this is one of the most important arguments in

the development of science not only of physics but science he maxwell wrote down the laws of electricity and magnetism from that he from these equations he showed that wave like expressions for electric and magnetic fields are solutions of these equations and

so therefore he predicted the existence of electromagnetic waves he could calculate the velocity of the electromagnetic waves in vacuum and he found out that the value of the velocity of electromagnetic waves that he predicted was very close to the velocity of light waves as was measured by fisso and then he said these two numbers cannot be accidentally equal and therefore light must be an electromagnetic wave and

so therefore around 1864 in his famous book maxwell predicted the existence of electromagnetic waves and said that light itself is an electromagnetic wave

so in free space you have an oscillating electric field which which creates an oscillating magnetic field whose amplitude is proportional to epsilon zero we showed that

so if e zero is zero then h is all one field cannot exist without the other both of them have to exist if the propagation is assumed to be in the z direction the if the electric field is assumed to be in the x direction then the magnetic field is in the y direction

so therefore the propagation direction is at right angles to the direction of the electric field and the magnetic field and

so therefore the waves are said to be transverse

so this is the this is how these are the two equations describing the electromagnetic wave an oscillating electric field produces an oscillating magnetic field and oscillating magnetic field produces an oscillating electric field that is how fields propagate through space the concept of fields was this was first put forward by michael faraday and therefore the fields produced by a charge can exist even in vacuum and these oscillating magnetic fields will produce an oscillating electromagnetic electric field and oscillating electric field will produce an oscillating magnetic field that is how electromagnetic waves can propagate through vacuum if i have a charge in vacuum then it produces its electric field even in vacuum and if i make the charge go up and down then the electric field will also change with time associated with that changing electric field will be a changing magnetic field and associated with the changing magnetic field that will be a changing electric field

so therefore the velocity of the electromagnetic waves is given is about 300 million meters per second and maxwell said that light itself is an electromagnetic this is said to be one of the greatest synthesis in the development of science that optics the the the study of light and the study of electricity and magnetism are form one big one come under one umbrella it was only in 1887 that heinrich hertz generated electromagnetic waves of of by by electrical circuits and he allowed the electromagnetic waves to fall on a metal screen got them reflected and and found and obtained similar to stationary waves on a string

so so he could determine the wavelength and the frequency and from that he showed that the velocity of the electromagnetic waves was the same as as the speed of light and

so therefore it was very soon established that light was indeed an electromagnetic wave

so by the turn of the century by the turn of the 19th century people finally thought scientists finally thought that one finally understood what light really was that light was an electromagnetic wave and and because and changing electric field produces a changing magnetic field that is how the electromagnetic waves propagate through free space

so this happened this was around the end of the 19th century
so this is the entire which i had shown in my last lecture this is the entire electromagnetic spectrum from gamma rays to x-rays to ultraviolet to visible region of the spectrum to infrared to microwave to the radio waves to the waves that you receive on your cell phone or your on your tv they are all electromagnetic waves they all travel with an identical velocity in vacuum and the visible portion of the spectrum to which the retina of our eye is sensitive forms only a very small portion of the electromagnetic spectrum
so the gamma rays have a frequency of 10 to the power of 20 hertz and radio waves has a frequency of about 10 to the power of 6 hertz and as i had mentioned in my previous lecture the visible region of the spectrum has a frequency of about 10 to the power of 14 hertz which is about 100 terahertz
so this is the velocity if i have a dielectric which is characterized by the dielectric permittivity epsilon then the velocity of electromagnetic waves is given by this the velocity of light in free space is given by this
so the refractive index of the medium which is given by c by v is epsilon by epsilon not
so then light propagation through solids liquids everything was studied and maxwell's theory was found to be extremely successful max planck had said maxwell's theory remains for all time one of the greatest triumphs of human intellectual endeavor in fact indeed maxwell's contributions are for all three times or remains supremely remains supreme i mean he made tremendous contribution to electromagnetic theory
so this is my x polarized wave in which the electric field is associated with this electric field there is a there is a magnetic field
so so i am i am right now not mentioning about the many unity if i have a dancing electric field in the x direction we produce what is known as an x polarized wave if i have a electric field which is produced in the y direction then you have what is known as a y polarized wave the electric field oscillates in this direction in for a y polarized wave the electric field oscillates in the y direction and you can also have you can also have a circularly polarized electromagnetic wave in which the electric field root at a particular point rotates on the circumference of a circle you can superpose two light waves and produce a circularly polarized electromagnetic wave
so what moves on the circumference of the circle the tip of the electric vector rotates on the circumference of a circle
so the field for a right circularly polarized wave propagating in the z direction the electric field at this particular point the electric field vector rotates on the circumference of a circle that is a right circularly polarized electromagnetic wave now the light from a sodium lamp or from an ordinary bulb is unpolarized that is the electric field oscillates change its changes the direction at tremendous rapidity but if you pass through a plastic like material which is known as a polaroid the electric field that comes out of the polaroid is along the one direction
so what is happening is this plastic like material material has long chain molecules and let us suppose they are all horizontal now long chain for example there are iodine molecules and the electric field generates a current along the length of the molecules and it gets absorbed by joule heating only the component which is perpendicular to the length of the long chain molecules pass through and you obtain what is known as an x polarized light this polarized polaroid sheets looks like something like a plastic sheet and they are available in the market all of you must be familiar with that
so you allow the light beam under ordinary unpolarized light incident on a polaroid the output is x polarized light the electric field oscillates let us

suppose in the vertical direction then if the electric field oscillates along the x direction then this is known as a x polarite and the electric field after it comes out can be written in this particular form if i rotate this polaroid about the horizontal axis then there will be no variation of intensity that will be seen because this is unpolarized light if i now put another polaroid whose pass axis makes an angle theta with the x axis then the light that is falling on the second polaroid is x polarized the electric field is in this direction and the second polaroid is oriented in a manner

so that component along this passes through

so the electric field component along this direction is e cos theta and

so therefore the intensity which is proportional to the amplitude will vary as cos square theta

so if theta is zero almost the entire light will pass through and if theta is pi by two then zero intensity will pass through this equation represents what is known as the law of malus

so for an unpolarized wave propagating in the plus z direction this is the z direction the electric vector which lies in the x y plane continues to change its direction in a random manner that is what i have shown in the diagram on the left if an unpolarized light beam is allowed to fall on a polaroid then the emerging beam will be x polarized if we place another polaroid p 2 then the intensity of the transmitted v light will vary as i zero cos square theta and this law is known as law of malus here i have tried to show two polaroids which are parallel to each other

so therefore the angle theta is zero please notice the the red dot and the blue dot at the top right hand corner of the each sheet each polaroid sheet

so the theta is zero the two pass pass axis are parallel to each other and

so therefore cos theta is zero

so the entire light that comes out of the first polaroid passes through the second polaroid if the angle between the two axis are forty five degrees then cos square 45 is half and half of the intensity will pass through if they are made at right angles to each other then the path axis of one is at right angles to the path axis of the other you can see the blue dot has come here

so they are at right angles to each other

so almost zero intensity process through this is a manifestation of the law of malas

so actual photographs with two polaroids at different angles of relative orientation if the two polaroids are parallel to each other almost the entire light passes through when the two polaroids are at oriented at 45 degrees with respect to each other about 40 50 percent of the light passes through and when the two polaroids are at right angles to each other notice the position of the blue dot almost no light will pass through the there are crystals like calcite crystal if you put a calcite crystal on on a piece of paper on which something is written then you will see two images this will this is known as double refraction and indeed if i have an unpolarized laser beam falling on a crystal then the two emerging light beams coming out are linearly polarized are always linearly polarized this is one of the methods for producing polarized light

so the wave theory the electromagnetic wave theory of light as was put forward by maxwell could explain many experimental observations and by turn as i had mentioned earlier by turn of the century people thought one finally understood what light really was that light was indeed an electromagnetic wave then in the year 1905 when einstein was working in his in the swiss patent office he in the year 1905 he published five outstanding papers that year is said to be einstein's year of miracles and the five outstanding papers were the first paper was a method for determining the size of molecules and the second paper was in

which he put forward that light had a quantum nature which i will discuss in a moment in the third pope paper he gave the theory of brownian motion in which tiny particles inside water move around because of the thermal motion of water molecules and in fourth paper he put forward the special theory of relativity and in the fifth paper he wrote down he derived the equation e is equal to m c square people say that each one of these papers was worth a nobel prize

 so in the second paper of his year of miracles einstein said that radiation energy that is light consists of indivisible quanta of energy something like the corpuscular model put forward by newton and others and these quanta of energy these packets of energy was given by e is equal to h nu that radiation must therefore he wrote that radiation must therefore possess a kind of a molecular structure in energy which of course contradicts maxwell's theory wolfgang pauli a great physicist later said that this was one of the landmarks in the development of theoretical physics this paper was a landmark in the development of theoretical physics

 so using his corpuscular model as most of you would know he explained the photoelectric effect photoelectric effect if ultraviolet light what is photoelectric effect if ultraviolet light falls on a sodium potassium or a cesium plate then electrons are emitted this the electrons that are emitted through this process are known as photoelectrons and einstein using his quantum model showed that the maximum kinetic energy of the emitted electrons t maximum represents the maximum kinetic energy of the emitted electrons was equal to h nu where h is the planck's constant and nu is the frequency of the light that is used here minus a constant b which depends on the properties of the metal for potassium it has a certain value for sodium it will have a different value

 so this is usually known referred to as the einsteins photoelectric equation once again t max represents the maximum kinetic energy of the emitted photoelectrons

 so this he wrote down in 1905 and very careful experiments were carried out by robert milliken which verified einstein's equation this equation to a tremendous degree of accuracy

 so on the vertical axis is the maximum kinetic energy of the emitted electrons and then the horizontal axis is the frequency of the incident light and the three lines shows the variation of the maximum kinetic energy of the electrons as a function of frequency of the incident light for cesium sodium and copper for each one of them there is a critical frequency new c if the light incident is of a frequency less than nu c then no matter how intense the light may be it will not be able to produce the photoelectrons this was actually observed by philip leonard before einstein's 1905 paper and then he explained this photoelectric effect by using his quantum theory by photon theory and derived this equation and this equation was very carefully verified by robert milliken this is this this is adapted from the noble lecture of robert milliken and and he made a very very careful measurement of the maximum kinetic energy and he found that that to agree extremely well with einstein's formula

 so you have the single photon source let us suppose e you have one photon and the other photon comes and hits the heat shift polarizer polaroid of the type that i had talked about few minutes back it produces what is known as an x prime polarized photon let us suppose this is the direction of x prime axis now this is followed by a polaroid whose pass axis is along the x

 so this will it pass through or will it not pass through wave theory says that ah that the intensity should drop below by cos square theta quantum theory says that the probability of this photon to pass through the second polaroid is cos square theta the probability that the polarized photon coming out of the polaroid p one whose pass axis makes an angle theta with the x axis that will

pass through the second polaroid whose pass axis is along the x axis is cos square theta

so one identical one photon will pass through another identical photon may not pass through there is a certain probability that a particular polarized that a polarized photon may pass through the second polaroid or may not master the probability is cos square theta albert einstein received the 1921 nobel prize in physics for his services to theoretical physics and especially for his discovery of the law of the photoelectric effect and

so therefore einstein got the nobel prize not for his theory of relativity not for his theory of general relativity not even for the concept of the light quantum but for the einstein equation which was very carefully verified by robert milliken and robert milliken himself received the 1923 nobel prize in physics for his work on the elementary charge of electricity and on the photoelectric effect

so after milliken's work arthur compton did a very beautiful experiment he allowed for high energy photons to hit the electron and get scattered by it

so he and then the electron undergoes a recoil and it moves in this particular direction

so he in his analysis he assumed that the light that the consists of packets of energy which are h nu and its momentum of each photon is h nu by c as einstein had said and when it hits the electron this scattered electron will have an energy h nu prime the scattered photon will have an energy h nu prime and the momentum h nu prime by c and this electron will have a momentum given by m v using simple kinematics that laws of conservation of energy and momentum he could calculate the change in the wavelength of the incident radiation

so this wavelength the frequency of the scattered photon is little smaller

so therefore the wavelength is larger and this and the change in the wavelength which is equal to c by nu prime minus c by nu he calculated this and found as two h by mu m naught c sine square phi by two and this is arthur compton writing on the blackboard his famous ah this this particular formula and this he did a very beautiful set of experiments in which high energy photons were coming out from an x-ray tube they fall on a carbon target and the electrons and the and the photons get scattered at different angles he measured the wavelength very the wavelength shift and he compared with the with this expression and found excellent agreement it was only after the work of arthur compton that people finally started believing in einstein's light quantum that light indeed has a corpuscular behavior and that its energy is equal to h nu and its momentum is equal to h nu by c

so after only after arthur compton's beautiful work on scattering of photons one finally could believe that the energy of a photon is given by h nu and the momentum of the photon is given by h nu by c where h as we know is the planck's constant and c is the velocity of light in free space arthur compton received the 1927 nobel prize in physics for his discovery of the compton effect in 1926 gilbert lewis an american chemist coined the word photon to describe einstein's localized energy quantum

so therefore let us suppose we have a we have a sodium lamp

so the number of photons emitted by a 50 watt sodium lamp in one second will be 50 watts divided by h nu

so 50 watts is 50 joules per second that is the energy that is emitted by the sodium lamp divided by h which is 6.

6 into 10 to the power of minus 34 joule second and new the frequency of a sodium lamp is about 5 into 10 to the power of 14 hertz

so you multiply this out and you find that about 10 to the power of 20 photons per second

so if a 50 watt sodium lamp is placed at a distance of 10 meters from a circular hole of 0.
1 millimeter in radius then from this tiny hole about simple calculations will show about 40 million photons per second will come out of the circular hole and
 so therefore this is a remarkable picture for set series of photographs showing the photograph of a young girl with finite number of photons the top left hand photograph corresponds to 3000 photons each spot here corresponds to one photon and slowly as the number of photons increase the last one corresponds to 28 million spots quantum theory gives us a probability distribution for the arrival of the photons where an individual photon will arrive no one can say one can only give according to quantum theory a probability distribution and when you have very few photons you will have few scattered spots because you will always detect one photon or no photon you can never detect half of a photon but when you have a very large number of photons like millions and millions of photons then slowly the structure of the image will be obtained which is consistent with the classical wave theory
 so physics with the advent of quantum theory has become probabilistic in nature classical physics is deterministic in nature and i will give you one simple example of this probabilistic concept let us suppose you take uranium solid now it has about say 10000 atoms it has a half life of let us suppose one day then you say that 5000 will decay in one day then in the second day another 2500 will decay in the third day about 1250 will decay
 so see all the atoms are identical all the nuclei are identical a few of them will decay in the first second and few some of them will not decay for for days which one will decay when no one can predict and in fact quantum mechanics allows you to predict the probability of decay and predict the half-life of isotopes as you indeed obtained in radioactivity
 so entire quantum theory is probabilistic in nature the probability that the polarized photon coming out of the polaroid p one whose path axis is along the x axis will pass through the second polaroid is cos square theta if the experiment is conducted with n photons and if n is very large then about n cos square theta photons will pass through one can never predict the fate of an individual photon thus the fact that the energy associated with electromagnetic radiation is quantized immediately leads to a probabilistic point of view
 so here is a very beautiful experiment here is a partially silvered glass plate which has 50 percent reflection 50 percent transmission
 so you say half the light is reflected half the light is transmitted
 so you carry out with a single photon source one photon comes in
 so you say that half of them will go this side half of them will go this side that is not a correct statement the correct statement is that a photon appears in this beam as well as in this beam is described by a function which is present here and here if i make a detection if i put a detector then it would be either detected here or detected there there is a 50 percent probability of it getting detected by detector d1 and there is a 50 percent probability of getting it detected by detector d2 let us suppose i generate the number 0 whenever the detector d1 clicks and i generate the number 1 when the detector d2 clicks then when the large number of photons are coming in i will generate a set of completely random numbers
 so quantum theory this simple experiment allows you to generate completely random numbers because of the indeterministic nature of quantum mechanics we can generate true random numbers such a device is known as quantum random number generator in fact there is a company which sells these quantum number random number generators and they cost about thousand dollars and if you can read this qantas this is the name of the product is a random number generator exploiting

an elementary quantum optics process photons are sent one by one onto a semi transparent mirror and detected the exclusive events reflection or transmission are associated to zero or one bit values the electron was discovered by j. j thomson in 1997 and now we know that the electron mass is known to a tremendous degree of accuracy to 10 decimal places the charge of the electron is also known to tremendous degree of accuracy it can be bent by an electric field or a magnetic field

 so on the back of our mind we think that it is a tiny particle with a definite mass and a definite charge louis de broglie around 1923 wrote i was convinced that the wave particle duality discovered by einstein einstein discovered the wave particle duality because he put forward the corpuscular nature of radiation which was known to be an electromagnetic wave

 so i was convinced that the wave particle duality discovered by einstein in his theory of light quanta was absolutely general and extended to electron proton or any other

 so he said that the momentum of the photon is given by this this was put forward by einstein

 so this is equal to h by lambda

 so this relation de broglie said has to be valid for electrons also he predicted that

 so he said that p is equal to h by lambda is also valid for electrons and that he justified by saying these are the bohr orbits this is the proton sitting at the center and these are the discrete bohr orbits as you all know the bohr orbits corresponds to mvr the angular momentum which is an integral multiple of h by two pi n is one two three four h is the planche constant and divided by two pi this implies that if i take two pi in this side two pi r is equal to n h by m v and m v is the momentum

 so n h by p which is equal to h by p according to deep broly is the wavelength

 so he said that if i assume the relation lambda is equal to h by p as was suggested by einstein for photons

 so he said that if it is valid for electrons then each bohr orbit will contain an even number of wavelengths

 so he justified the expression the de broglie wavelength through this analysis and therefore he said in 1923 that was his doctoral thesis that lambda is equal to h by p is not only valid for photons but is also valid for electrons protons and photons and this is the diffraction pattern these were the experiments carried out in 1927 by thomson and others that diffraction pattern of aluminum produced by x-rays and by electrons

 so there is a tremendous similarity between the two this shows that whatever the electron is the photon is the same

 so the electron also demonstrated wave 9 like nature

 so deep broglie received the 1927 nobel prize in physics for his discovery of the wave nature of electrons and as you can see de broglie writing down the equation on the blackboard lambda is equal to h by m v

 so the question arises is the electron or a proton a wave or a particle this is the fundamental questions the correct answer is it is neither a particle nor a wave then what is it quantum theory describes it by the wave function psi and what is this psi this psi is the solution of a complicated equation i will not go into the details but i will just briefly describe the solutions of this equation but where did we get that equation from richard feynman who is considered to be one of the greatest physicists of all times says where did we get that equation from where did we get that schrodinger equation from the answer is nowhere it is not possible to derive it from anything you know and find one says it came out of the mind of stranger

so so the electron or the proton or the neutron are described by the wave function psi what is this side it is the solution of a complicated equation and it cannot be derived but the solution that you obtained by solving this equation agrees extremely well with experiment as i will try to briefly show

so schrodinger received the 1933 nobel prize in physics for the discovery of new productive forms of atomic theory actually he shared the nobel prize with dirac and on his grave is written the famous schninger equation

so this is the solution of the schredinger equation a free particle like an electron or a proton or a neutron is described by a wave packet

so the electron is somewhere localized here and as it move the wave packet moves and it is a superposition of waves of different frequencies

so if or different momentum and

so therefore if you do the analysis carefully if a particle is localized within a distance of delta x then it necessarily is a superposition of waves whose momentum spread is delta p such that delta x delta p is of the order of h cross which is the heisenberg uncertainty principle

so heisenberg uncertainty principle is contained in the solution of the schrodinger equation

so let us suppose i have this electron falling on a on a on a potential barrier then i know that it is partially reflected and partially transmitted something like that the beam splitted experiment that i did with photons that light beam comes in the photon is reflected as well as transmitted

so the according to quantum theory the electron is here as well as there and if you make a measurement then it is either here or there

so that is the most fundamental concept of quantum mechanics before the measurement the electron is here as well as there and this may be 1000 kilometers apart it is described by a wave function which is finite here and finite there

so there is a certain probability of getting making it found here or making it found here but when you make the measurement then it is either here or there

so in the beam splitter experiment you represent a photon by a light pulse it is incident on the beam splitter then the there is partial reflection and partial transmission

so the photon is here as well as here and this may be millions of kilometers apart but if i have a detector then it is either detected here or detected there

so i conclude by saying that if i have a electron beam or a proton beam or a photon beam then wave theory predicts that there is a diffraction why on a slit the the beam is the electrons are incident on a slit of width b the wave undergoes diffraction and the intensity distribution is sine square beta by beta square quantum theory that is the solution of the schrodinger equation for this particular problem predicts that the slit imparts a momentum in the x direction x direction is the vertical direction and the probability that the x component of the momentum will lie between p x and p x plus d p x is the same as the intensity distribution

so where does this momentum come from it comes from the slit the slit undergoes a recoil and the and the electron undergoes diffraction smaller the width of the slit greater will be the momentum that is important and that follows from the solution of the schrodinger equation similarly i can do the double slit experiment interference experiment

so when i have an electron gun falling on the two hole experiment the electron is described by a wave function which is present here as well as there

so if one of the hole is open you get an intensity distribution like this normally you should expect that when both holes are open the incident distribution should be p one plus p two because the electron are tiny particles

which either go through whole number one or whole number two but when you do the experiment you get an interference pattern and that can only be explained if the electron or the proton or the photon passes through both the slits at the same time it is not the splitting of the electron but that the electron is described by a wave function psi which is present here as well as here

 so therefore this is considered to be depth the most beautiful experiment in physics if you carried out this experiment with 10 electrons you get 10 spots quantum theory gives us the probability but if you did this experiment with 70000 electrons then slowly the interference pattern will develop

 so these experiments have been carried out by carbon sixty molecules also

 so the most fundamental theory now available is probabilistic in form and not deterministic this is david bohm who is considered as one of the best quantum physicists of all times

 so this is the reference the another reference is this my own book on optics in which i have discussed all the experiments that i have discussed today and in my last lecture but there is also this feynman lectures on physics volume 3 that i would advise all of you to read through thank you very much you