

hello welcome all of you for the next lecture on the properties of the atomic nucleus

so in the last lecture we briefly summarized whatever we had discussed in the lecture prior to that as to how neutron was discovered and the results of scattering of alpha particles on various nuclei were correctly interpreted by Chadwick that was a very great accomplishment then after that what we did was to look at the scattering of the electrons very high energy electrons actually on nuclei this was elastic scattering from which we extracted information on the radius of the atoms the size of the atoms as I told you at this point we are not too very much interested in finding out the precise shape of the nucleus

so called precise shape because anyway it is way beyond us at this particular juncture but if you assume that it is spherical then you can estimate what the radius is and you can also estimate what the mass distribution or the charge distribution inside the new places and we got this beautiful concept of saturation that is what we found

so all of it can be summarized in the simple formula as I told you

so let us call it as nuclear saturation that the radius as a function of  $A$  is given by some constant  $r_0$  into  $A$  to the power of  $1/3$  and please remember this  $A$  is the atomic weight

so called but strictly speaking this is equal to number of protons plus number of neutrons in the nucleus if you grow minute mass differences between the proton and the neutron and also minute mass differences because of the mass defect or the binding energy then  $A$  also would represent atomic weight to a fairly good approximation that is what we did

so if you know about the size then the next question is to know about what the masses are and what the stabilities are now to put it in a very very simple way if you do not want to get into too much of a complication then you can immediately extract what the mass dependence should be as a function of  $A$

so what are we going to assume we are going to assume that charge distribution is a constant in the nuclear volume of course it is not exactly a constant if you people remember the figure looked something like this it looked like something like this

so basically we are going to isolate this particular point or it could be even this particular point and roughly call it as the radius of the nucleus because it is in this region that the charge distribution is a constant and this is the information which we get from elastic scattering

so if you also take the neutron distribution to be a constant

so this will imply  $\rho$  matter is a constant

so in making this statement I am ignoring this tapering off we had a fairly long discussion on that

so we are going to assume that  $\rho$  matter is a constant in that case we are going to get a relation that  $M$  as a function of  $A$  grows roughly linearly with  $A$

so it will look like  $M \propto A$  because the volume also grows linearly with it this is a very excellent starting point for us to understand the properties of the nucleus but as they say the devil lies in the details and now what we want to do is to look at the microscopic differences and that is what I started with and when we look at microscopic differences it is important for us to remember that Newtonian mechanics is not going to be important it is not going to be enough for us what we need is a better formulation a correct formulation which was due to Einstein namely the relativistic formula and I made a brief presentation of what those formulae were

so what I propose to do today is to take off from that particular point and tell you how to understand how to interpret the

so called mass dependence the true mass dependence not the  
so called the true mass dependence of various nucleates as a function of  $a$  and  $z$  from that we can get information on the stability of the nucleus energetics of the nucleus on radioactivity on fission on fusion

so on and

so forth in fact without doing too much of complicated physics or mathematics if you understand this we can straight away get a glimpse of what is happening for example the interior of stars let us say sun that is one of the great great advantages of looking at it rather carefully and slowly

so let us get into that

so that is what we wish to do now

so the lecture that we are going to start today i have called it as the atomic nucleus this is the second one in the atomic nucleus and our main focus will be on masses and stability

so you people should be aware that all throughout to have been speaking of stability when i worried about the atom i worried about the stability of the atom why is it that the electron is not going to fall off into the nucleus why is it that the hydrogen atom is stable

so we have to make use of the uncertainty principle we have to make use of the poly exclusion principle in a similar manner we have to worry about the stability of the nucleus some nucleus are nuclear are stable some nuclei are not stable and when they are not stable they go they get transmuted to other nuclei which are more stable and the chain goes on until it hits a point which is completely stable

so we want to understand that

so in order to understand that what we shall do is to first of all spend a few minutes briefly recapitulating whatever i said in the last class and then proceed to make a detailed analysis

so as i told you in the last lecture the first observation is that no material particle can move with the speed  $v$  greater than or equal to  $c$  in fact i took some time to tell you the distinction between what i mean by a material particle to distinguish it from something like a photon there are other particles like a photon what we call in physics like a gluon or a graviton you will come across them later but at this point when we say a material particle by that we mean it can be at rest and when it is at rest it will have a finite mass non zero finite mass however although there is a restriction on the speed of the particle there is no restriction either on the energy of the particle or on the momentum of the particle

so given this what einstein did was to essentially solve this conundrum i want to keep on increasing my energy without necessarily continuously increasing my speed that is the speed would increase but it cannot cross the light barrier it can never exceed the speed of light in fact it cannot even touch the speed of light that is something that we have and secondly in the same way i should be able to increase the momentum also by keeping  $v$  bounded between  $0$  and  $c$  that is what i want to do and the solution the brilliant solution that einstein gave was to say that inertia or mass depends on the speed

so this slide collects the relevant formulae that i used  $m$  of  $v$  is given by  $m$  naught into  $1$  over root  $1$  minus  $v$  square by  $c$  square and this factor  $1$  over root  $1$  minus  $v$  square by  $c$  squared is many times called gamma it is the gamma factor and the  $v$  by  $c$  itself

so  $v$  squared by  $c$  square  $v$  by  $c$  itself is called beta

so many times people write  $m$  equal to  $m$  naught into  $1$  over root  $1$  minus beta square or simply  $m$  naught into gamma my energy in a similar way is  $m$  of  $v$  into  $c$  squared now remember my inertia is depending on the velocity momentum is  $p$  of  $v$

$m$  of  $v$  into  $v$  and just as you write  $e$  equal to  $p$  squared by two  $m$  in newtonian mechanics in einsteinian mechanics and relativistic mechanics you can check that you can write  $e$  squared equal to  $p$  square  $c$  squared plus  $m$  naught squared  $c$  to the power of four

so this figure is important for us and that is the reason why i am showing you again you see that all the way up to  $\beta$  equal to 0.

8 that is  $v$  equal to 0.

8 times the speed of light my mass barely changes that is what we are finding but we should not be misplayed by this because although my  $\Delta m$  may be very very small my  $\Delta e$  can be very very large because my  $\Delta e$  will be given by  $\Delta m$  into  $c$  square and  $c$  remember in ordinary units has a very very large value  $3$  into  $10$  to the power of 8 meters per second that is to say in order to create a small mass you need a lot of energy or even if you lose a small amount of mass you produce a lot of energy there is something that we have to remember and that is what we are going to use in our discussion and this is what i summarized in this particular slide with only two equations  $a$  equal to  $m c$  squared is of course there all of us are familiar with it but  $c$  is a universal constant and therefore we write  $\Delta e$  equal to  $\Delta m c$  squared this is the most important thing as i told you in the last lecture historically einstein was able to argue  $\Delta e$  equal to  $\Delta m c$  squared and with great insight he speculated that this  $\Delta$  can be removed and we can write  $e$  equal to  $m c$  squared that is if you go historically we go from bottom to top but now what we are going to do is assume this equation and make use of the second relation that is what we want to do i think this is where i had stopped first i have to establish some units because for whatever reasons the physics community there is something called international union for pure and applied physics they have agreed to adhere to a convention and it has come after many many iterations it is not that we cannot use other units but it is always good to adhere to convention

so that everybody understands easily with what we are saying

so what i am trying to tell you is the following thing the question is how am i going to denote masses

so when it comes to masses there is this  $sa$  unit which is in the unit of  $kg$  now this is a very very convenient unit when we look at let us say the human scale the weight of a table how much does a man wait is that ok or for that matter how much does an even elephant weigh or if you are buying grains from a grocery shop how much you are going to buy this  $kg$  is a very very good system of unit and pound is not very different from  $kg$

so you could continue to use that also but the minute you go to something like atomic scale when you are looking at elementary particles or if you are looking at molecules or atoms electrons protons this becomes inconvenient for example i do not give you the distance between let us say delhi and mumbai units of centimeters i cannot do that it is a very very inconvenient unit and probably it is also not a very appropriate unit in a similar manner if you have very very sharp distances is that ok for example if i want to know what is the distance between the tip of these two thumbs if i am going to look at it i am not going to give it in the unit of meters therefore the units that we employ depend on the natural length scales time scales and the mass scales that are inherent in the physical system it is a matter of convenience

so if you remember that what we are going to do is to start a new  $u$  set of units and that is to start with the mass of carbon

so if you look at it very very carefully carbon has many many isotopes i have already given you the definition of what an isotope is

so you take carbon 12 with exactly six protons

so we are speaking of 6 protons 6 neutrons constituting carbon 12

so what i could have done is to either start with the mass of the proton or the mass of the neutron if you give me the mass of the proton that fixes the mass of the neutron in the units of the mass of the proton that fixes the mass of carbon but that is not what is going to do as i told you for historical reasons we take the mass of carbon to be the fundamental unit that is the most important thing

so how to assign what i do is to assign 12 units of mass to carbon 12 that is what i am going to use that is what i am going to say therefore my single unit that is called as the atomic mass unit amu and that is further length and shortened to you 1u is given by mass of carbon divided by 12 that is what i am going to assume now if i were to write it in terms of conventional units whatever we are used to in the units of kgs that will turn out to be 1.

660539 into  $10$  to the power of minus 15 kgs that is what we have

so henceforth we are not going to look at kgs anymore is that okay we know the conversion from may kg is to one atomic mass unit although i write it as u it is actually atomic mass unit earlier people were using the notation a mu now people have shortened it to you

so one unit is given by 1.

660539 into  $10$  to the power of minus fifteen kg

so from this you can immediately infer what the mass of carbon is mass of carbon would be this one point six six zero five three nine into twelve

so you can estimate what it is twelve six or seventy 72 12 6r 72 plus 7 79 12 months are 12 plus 7 19 that is what you are going to see it is something like 19.

77 whatever into  $10$  to the power of minus 15 kgs that is what you are going to get once we have zeroed on to this unit one unit is equal to 1.

660539 into  $10$  to the power of minus 15 kg now what do we find my mass of the proton will given by this number all of them are expressed up to six decimal places six significant digits apart from  $10$  to the power of minus 15 1.

00727 units and mass of the neutron is 1.

008664u remember i discussed the relation between the mass of the neutron and the proton when we were discussing chadwick's experiment he estimated it to be something like 1.

1 times then we said that no no there was a 10 percent error in that calculation so that is what we have

so for example if you look at two isotopes of carbon the chlorine this is here in your exam as an example in nc art book it has two isotopes one is mass number 35 another with 37 then one with 35 has mass of 34.

98 another fellow has a mass of 36.

98

so that is what we have

so this is how the masses look like is that okay and if you know the ratio in which my isotope with 35 and isotopic 37 comes then i can find the mean mass of chlorine there is a worked out example in your ncr textbook you can verify but the main message that we have to take from this is that we are going to express everything in terms of one atomic mass unit that is our fundamental unit and in s units it has this number okay now i want to discuss the binding energies

so what do you mean by binding energy let us go back to the case of hydrogen atom what is it that we have

so in the case of hydrogen atom what i have is i have the mass of the hydrogen atom then i have mass of the proton and mass of the electron if the total energy of the hydrogen atom were equal to the total energy of the proton and the total energy of the electron then there is no bound state at all what do i mean by a bound state by bound state i mean that assuming that my electron is going around

the proton let us say as in the hydrogen atom that is the minimum energy for me to take this electron to infinity i should be able to take this if you want you can even move the proton to infinity in the other direction and in the other direction they should be when they are having infinite distance between them what is the total energy what is the binding energy they should be at rest and the energy that they supply is given by the binding energy and we associate it with 13.

6 electron volt

so in some sense the mass defect is 13.

6 electron volt the difference between the mass of the hydrogen atom and the sum of the masses of the proton in the electron is 13.

6 electron volt which is a very very small number this is the idea that we want to perfect by making use of einstein's mass energy relation

so what do you do you start with a nucleus as i told you x a z don't forget that this is my

so called atomic weight this is my atomic number in fact a better notation for atomic weight is nucleon number

so if you feel like forget whatever i told you all these days henceforth we shall only use the word nucleon number and nucleon number means the total number of nucleons and nucleons include both protons and neutrons and this is my atomic number which is the total number of protons that is what i have

so what i will do this has z number of protons and a minus that number of neutrons and d h proton has a mass  $m_p$  and each neutron has a mass  $m_n$  and what are their masses i have already given you 1.

007 something 1.

008 something in atomic mass units

so what do we do what we do is to first find the sum of the masses

so my sum of the masses will be given by z into  $m_p$

so each proton has a mass  $m_p$  and there are set of them and then i will write a minus z into  $m_n$  if z number of protons and a minus z number of neutrons had not come together because of the force of attraction and if they had not formed the bound state then if you bring them all together the total mass will still be given by z  $m_p$  plus a minus z  $m_n$  but that is not going to happen what we do is to look at the mass of x that is what i am going to look at this x of course is labeled by a inside which i am not showing and i look at the mass difference that is what i have i say that this nucleus is bound because i have to supply energy in order to remove the protons and neutrons

so what does it mean if i look at this quantity and i call it as  $\Delta m$  identical equal to  $\Delta m$  this must be less than zero now we are not speaking of mass but we are speaking of energy

so i should modify that

so what do i do i will say  $\Delta m c^2$  is less than zero and this is my binding energy

so and this  $\Delta m$  is my mass defect defect means it is wanting

so because of the force of attraction my incoming protons and neutrons they shed some of their energy and they went and sat in this bound state and if they want to recover their free state we have to supply that energy and that is what i have summarized in these two equations

so i write my  $\Delta m$  x whatever i wrote in this slide to be z  $m_p$  plus a minus z  $m_n$  minus  $m_x$  that is my this one the way i have defined here my  $\Delta m$  x is a positive quantity if i had changed the sign it would have been a negative quantity but my binding energy is always a positive quantity therefore binding energy is given by  $\Delta m$  x into  $c^2$  therefore this  $\Delta m$  x is the negative of the mass defect that i defined when i wrote it on the sheet of paper

so that is what we have now what is the binding energy now binding energy is a rather complicated concept because suppose you give me a nucleus or for that matter suppose you give me an atom what is it that we do

so this is a very interesting exercise that you can do

so let us start with the hydrogen atom let us start with the hydrogen atom i have my proton i have my electron assume proton to be infinitely massive we are not worried about that it is a very meaningful and an unambiguous question to ask what is the binding energy of the hydrogen atom and that is simply the energy as i told you to take it away to infinity

so you have 13.

6 electron volts let us say that is what you have however if you were to come to helium for example

so you have the alpha particle as your nucleus two protons and two neutrons and there are two electrons that is what you have what would you expect the binding energy to be this is a very interesting thing for example if you ignore let us say this electron this electron will be seeing the coulomb field produced by the alpha particle and you can make use of the hydrogen atom formula and you can immediately write the binding energy for this but then this electron is also going to interact with this electron and therefore there is a repulsive energy therefore my binding energy for the first electron let us say binding energy for first electron will be whatever the binding energy coming from bohr model minus repulsion and where is this repulsion coming from electron electron repulsion therefore the binding energy for the first electron what do you mean by the first electron whichever remove will be smaller than the binding energy for example if this other electron were not there at all now this is my helium not ionized neutral not ionized now what i will do i will ionize my helium atom

so what do i have now i have again an alpha particle and there is only one electron now i can calculate the binding energy of this electron this is my second electron the first electron has already been brought to infinity by making use of the bohr model you know how to do that therefore the binding energy required the amount of energy required to remove the first electron is smaller than the amount of energy required to remove the second electron if i proceed sequentially this is a problem that we are going to encounter even in the case of nuclei and in order to not get into too many complications we introduce a concept and that is the binding energy per nucleon one could argue that if i had given two electrons i don't know which one of them i would remove for the first time after all they are identical particles therefore what i will do is i will calculate the total binding energy what is the total binding energy strip of this helium atom of both the electrons and then divided by two that will become the binding energy per electron in a similar manner what will be the binding energy of a nucleon you have something like an alpha deuterium let us say one proton and one neutron then there is no problem if you go to helium then what is it that we have we have two protons and two neutrons

so i will ask what is the energy to remove all of them away from each other to infinity

so i will get a binding energy i will divide it by four that will become the binding energy per nucleon and that is a good way of representing

so in other words if you give me the binding energy for nucleon if i multiply it by a the total nuclear number that should give me the total binding energy

so it is more convenient to plot the binding energy per nucleon rather than the total binding energy and that is shown in this very beautiful curve which is again taken from your textbook 12 standard in crt textbook and what is it that you find the most interesting that you find in this is that of course you start with deuterium which has a very very low binding energy then you come to tritium

it has a higher binding energy then you go to 4 helium there is a spike that is a very important thing but when you go to 6 lithium actually the binding energy goes down then again it sees a peak in 12 carbon all these are important numbers for us what are the important numbers for us i'll tell you deuterium is important for us tritium is important for us helium is important for us carbon is important for us

so that is what we have and then when you come to 14 neutrogen nitrogen it will go come down again and 16 oxygen will go up again

so on and

so forth but once you reach sulphur 32 sulphur it has hit a plateau and after that it is roughly constant you see that it is roughly constant hovering around something like 8.

1 or 8.

2 mb per nucleon the natural units for discussing energies in the nuclear scale is always million electron volts just as the natural scale in the atomic scale is always given by electron volts and fractions of electron volt of course if you go to atoms then can become you know milli electron volts

so on and

so forth when you do for example spectroscopy etcetera will not worry about that but the important thing is all the way from 32 sulfur that is nuclear number is equal to 32 to all the way up to 236 you find it is roughly a constant except you know after 100 molybdenum it starts off slowly tapering down and it achieves a plato this is a very very important thing for us to remember because this is exactly just the opposite of for example what happens in an atom in the case of an atom what happens is that as i keep on adding more and more electrons the electron repulsion will keep on increasing but here of course there is no concept of a core atom has a cold called the positive core here there is no concept you find that the binding energy is roughly constant roughly a constant and this phenomenon is again what is called as the saturation in fact one of the important problems in nuclear physics on which people work for many many years is to understand this saturation phenomenon and just as in the case of atoms you have these inert gases they are the least interacting they have the greatest binding energy obviously for that reason and there are your noble gases helium neon xeon krypton

so on and

so forth the analogues of those quantities are you can see helium carbon oxygen 16 for instance which

so sudden spike with respect to their neighbors

so if you people were to pursue a course on physics later and if you did a nuclear physics course you will actually build a model which is very much like the shell model of the atoms and you will be able to understand that of course there are more complications but there is something that you can remember about

so this figure is very very important for us and let me summarize them in this slide okay the most important point is that it started with a very very small value it got saturated and it came down

so whenever a function behaves in this particular manner apart from these fluctuations the natural question task is where is the maxima of the curve and it turns out that the maxima of the curve lies in iron 56 ion that is where it lies

so that means you give me all possible nuclei you know all the way starting from let us say deuterium to a very very heavy nucleus like a uranium or a polonium or whatever which contains about 200 and odd number of nucleons is that okay the maximum energy energy that you have to supply per nucleon if you want to completely dismantle the nucleus is iron

so what do you conclude from that you would conclude that of all the nuclei iron is the most stable of nuclei iron comes in many many isotopes remember what is isotopes isotope means what the same  $z$  but different value of  $a$  that means you have added or removed a few neutrons but you have kept the number of protons fixed that is what you have done

so iron is the most stable nucleus actually silicon is also fairly stable close to that it has not been shown in this particular figure

so what i would like to do is to ask you people to remember this fact that iron is the most stable nucleus we do not have an explanation for this at this particular point we will take it as an accepted fact although some explanation can be given qualitative description can be given as to how the saturation takes place

so this is something again that i have summarized in this particular slide

so iron 56 has the largest binding energy which is about 8.

75 million electron volts it is roughly constant in the range 30 to 170 mev and it has smaller values for both small  $a$  and  $a$  greater than 200

so if you were to invert this if you were to invert this in terms of the minimum energy what would what is going to happen the maxima would become minima and these quantities will go to the top and purely from a viewpoint of stability analysis everyone would like and go like to go and sit in the state of iron

so eventually you should sort of imagine that the whole world will be consisting of some big iron lattice let us say that is what you would imagine of course physics is much much more complicated but there is a nice picture to make that is what we have and it has smaller values for both  $a$  small and  $a$  greater than 200 that is something that we have to remember a small means what i was speaking of lithium boron beryllium carbon ok after that things are going to change these are the things that we have to remember now i cannot do a quantum mechanical calculation at your level in fact even if you knew quantum mechanics it is not going to be easy for me to actually work out these things

so what i will do instead is to try to make some qualitative statements that is the most important thing i will try to make some qualitative statements and see how much i should be able to extract from these qualitative statements is that okay that is what i would like to do

so let us see what it is we spoke the language of protons and neutrons

so let me come back to my slide and tell you a few interesting things

so if you remember my protons are positively charged and neutrons not charged in fact i can be very very careful positively electrically charged not charged electrically i will tell you why i am using the word its electric charge is zero that is what we have for your information all the neutron is not electrically charged it has a magnetic moment in terms of nuclear bore magnetons it is given by minus one point nine one ok it has a magnetic moment

so if i pulled a bunch of protons let us say pulled a bunch of neutrons and pulled a bunch of protons and neutrons together their interactions would be completely different this will be very very strongly repulsive where are here this will be weak why will it be weak because they interact only through the magnetic moment and magnetic moment forces how do they go they will get one over  $r$  cubed whereas the repulsion goes like one over  $r$  squared that is what i have and if you put protons and neutrons again all the protons will ripple each other very strongly the interaction among neutrons will be very very small interaction among the protons will also be very very small

so if this kind of a situation had persisted in the case of nuclei also then the concept of a binding energy per nucleon would have been meaningless but that is not what happens what happens is what i have collected in this slide

so i should probably start with the second point all protons are bound to

each other with the same strength

so what is the operative important word here bound if it were electromagnetic interactions they cannot be bound they are going to repel each other that means my protons not only participate in electromagnetic interactions they also participate in a new interaction a new kind of interaction which i will call as the nuclear force and what is the nuclear force that has to be attractive i am going to qualify this statement in the next slide

so don't take it with complete seriousness

so i will become a little bit more careful inside a nucleus my protons are bound with the same strength and neutrons are also bound with the same strength as the protons inside a nucleus but then since protons actually are positively charged and they should be repelling each other what do we conclude from this nuclear forces are much stronger than the coulomb repulsion

so when the two protons come close to each other of the order of one fermi and how much is suffer me  $10$  to the power of minus  $15$  meter there is an enormous coulomb repulsion you can work that out but my attractive nuclear force more than compensates the triple sun okay but then in that case i should be able to bring lot of protons and neutrons and protons and neutrons together and make very very big objects it does not happen i am at most able to make about a nucleus with about  $200$  atomic nucleon number that means the interaction distance the range between of the nuclear forces must be very very small let us say of the order of a fermi again of the order of a fermi a femtometer may be one function two femtometer five femtometer because if you have a to the power of one third cube root of hundred is not a very big number because six cubed is already something like two hundred

so the nuclear size is only six times larger than the original nucleus

so they are short-ranged and that short-rangeness is also suggested by saturation the binding energy roughly remains the same what does it mean by that let me explain to you and tell you a few more subtle things that are important for us i have not written down in the slide but i am going to explain that to you and these are interesting aspects nuclear forces let me list them for you number one nuclear forces are strong that we have seen but two is not a point but a question are they always attractive this is very very important for us and what is the answer no this is something that you have to remember

so you have to listen to this carefully because otherwise whatever is there in this slide would become completely misleading

so let us look at the periodic table you have hydrogen consisting of one proton then you have two h one which is one proton one neutron and what is it called deuteron then they have three h one which is tritium which is one proton 2 neutrons then i am going to make a list of some more nuclei for you for example you have 3 helium consisting of what two protons one neutron and then of course you have the very very stable nucleus two protons two neutrons you look at twelve carbon six six protons six neutrons that is what you have similarly i can write one more which i do remember after that i will have to look up some data

so if you look at for example oxygen 16 eight protons eight neutrons these are very stable but on the other hand for example if you look at something like 235 uranium this has only 92 protons

so 92 protons i hope i am correct and what will be the number of neutrons

so  $235$  minus  $92$   $143$  neutrons

so what i would do is to invite you people to look up the periodic table look at the data of how  $A$  and  $Z$  are distributed and you will find the following things there are roughly equal number of protons and neutrons number one there is something that you should look at number two that you should look at as  $A$  increases

so let us say beyond 100 number of neutrons in is more than number of protons as  $A$  increases the binding energy per nucleon also decreases therefore they are not all that stable and most stable nuclei have equal number like helium or twelve carbon or oxygen

so on and

so forth and what is the most dramatic thing i have to write that most dramatic no nucleus with only protons no nucleus with only neutrons you need both protons and neutrons to form a nucleus what do you conclude from that

so what we conclude from this is that the nuclear force between two protons is repulsive very very important the nuclear force between two protons is always repulsive just as the electromagnetic force between any two protons is repulsive number one similarly the nuclear force between two neutrons is also repulsive but i told you you have deuteron it has a binding energy of something like 4mb or some such thing or maybe 2.

5 mb

so but force between a proton and a neutron can be attractive can be attractive and this is a very very important feature for us and if you want to model it as an interaction then you have to very carefully assign the appropriate nuclear charges they are much more complicated than what you would imagine at this point let me not get into that and you have to build a theory

so that is what it is

so what i am trying to tell you is that this periodic table what is there in the periodic table and what is not there in the periodic table tells us that there is a lot of foot for thought and still even though we are not able to get a completely satisfactory theory of how nuclear phenomena works is that ok by looking at energetics we should be able to actually get a fair idea of understanding what the processes are

so that is the whole thing

so that is what i have summarized in this particular slide

so it is in some particular order but no i hope you people will understand these statements in the correct perspective neutrons are as strongly bound to protons in the nucleus protons are bound to each other with the same strength because of the existence of the neutrons nuclear forces are much stronger saturation suggests that nuclear forces are short-ranged and most important for us the energetics for understanding relativity fusion and fission is completely supplied to us by what by the periodic table by the great figure that i showed you namely the binding energy per nucleon curve

so this is a curve which merits a very good a very deep and a careful study and that is what the community of nuclear physicist has done and that is something that we have to remember

so let me repeat for you please read this statement protons are bound to each other with the same strength must be interpreted very very carefully they are bound to each other with extreme strength in the sense that the binding energy per nucleon is the same that does not mean that pro two protons attract each other by a nuclear forces it is a kind of an abuse of language because people say nuclear forces are charge independent that means an entirely different thing than what we would naively unthinkingly assume and that is the reason why i am giving this clarification

so these are the questions that i would like you to ponder about because i do not have time to get into that but i have already given you some kind of a qualitative answer

so the question is why is there no proton proton bound state why is there no neutron neutron bounds dead and why does the number of neutrons become larger than the number of protons with increasing  $A$

so these are the questions that attracted the attention of a whole lot of people starting from let us say 1920 to 1900 even though people are doing very sophisticated calculations to understand nuclear structure and nuclear reaction is that okay and two good examples are lead 208 and oh sorry this must be uranium 235 uranium you see the number of protons is much much smaller than the number of neutrons

so please correct it this is actually you and not pb this is a transcription error a complete understanding of the nuclear forces you might be interested to know is a million dollar question normally the word million dollar is used in a figurative sense you know you say do you think that this person will come for the meeting today we say it is a million dollar question by that we mean we do not know the answer but in this case it is literally a million dollar question because there is a very celebrated prize called millennium prize actually millennium price if somebody can answer the problem of nuclear forces completely starting with any fundamental particles you must have heard of quarks and all that then that person will become extraordinarily famous and also rich and what are the crucial features it depends on electric charge it depends on nuclear charge i gave you an idea of what nuclear charge is it is a strong interaction it is probably something like 100 times or thousand times stronger than the electromagnetic interaction and it is of a short range and what is the range of these interactions it is about a femtometer this is the take away from the binding energy

so here is a figure which illustrates what the binding energy is is that what the potential between let us say a proton and neutron is i have called it as a nucleon nucleon interaction at very large distances there is no nuclear force they have shown it up to 2.

5 meters almost dead but if i switch on the coulomb force of course it will be there but even the coulomb force goes to 0 at very short distances it actually becomes triple c is that okay this repulsion is not entirely due to the coulomb repulsion actually even the nuclear forces can have something called the hard core and then you have a valley

so this is something like you know the van der waals force you must be familiar with your molecular forces which you would have studied is that ok and my electron my proton in neutron try to convince it in this minima classically speaking of course you can have any number of bound states between a proton and a neutron but by uncertainty principle it cannot sit here it will have to sit somewhere here and if you look at a deuteron there is only one energy state that is allowed because my deuteron does not have an excited state

so this is some kind of a cartoon or a picture for the potential that is acting between a proton and neutron but please do not take it very very seriously it is only one part of the interaction that is indicated by one yes not i will explain to you what it means qualitatively just as electromagnetic forces are dependent on both position and momentum because my magnetic force depends on my momentum my nuclear forces also depend on position momentum and whether it is a proton neutron or what their isospin is isospin is the analog of the nuclear charge and also on angular momentum they are also angular momentum dependent forces they are very complicated but then this is a cartoon if you feel like at this particular point for you to get an idea of what the interaction is and what you should notice is that it is hitting a peak around 0.

5 for me 0.

5 femtometer and it is getting saturated let us say around 2.

5 for me which is about 2.

5 femtometers

so the size will be of the order of a femtometer or whatever that is what we

have

so this is something that we have to remember ok now all this time we have been very very qualitative now is the time for us to make it quantitative because physics after all is the science of numbers it is not numerology but what we do is to give principles we make it quantitative we convert them into numbers and the experimentals verify them and based on the experimental results either the theory is confirmed or it allows you to propose a better theory

so on and

so forth

so now let us start looking at some numbers and i would advise all of you urge all of you to go back and work out many such examples you do not have to necessarily look at problems at the end of your class book text or anything pick up the periodic table and start working them out it is a great joy let me assure you and let me show you some numbers as you can see i am being quite fussy because i am keeping numbers to up to a very large number of significant digits and that is not because you know my calculator gives me values up to that many points because as i told you very very small changes in mass can give rise to very large changes in energy that is something that you have to do

so let us start looking at the mass of the proton my mass of the proton as i told you is 1.

007276 atomic mass units my neutron is slightly heavier 1.

08664 atomic units

so later you will see that purely in terms of stability my neutron must be less stable than proton the question is my neutron can become a proton in fact it does happen that is what is called as the beta decay let us not get into it now then you have my helium which is 4.

002602u these numbers you should note them down and you should work out now how do i calculate the mass defect very simple i look at the mass of the helium atom okay when i say mass of the helium atom i mean four helium is that okay two protons two neutrons the most stable isotope

so if you look at it then you have mass of the helium minus two into  $m_p$  plus  $m_n$  there are two protons there are two neutrons

so i add the masses and multiply them by two and lo and behold what do i get the total mass of the helium atom is less than the combined mass of what the protons and the neutrons that constitute the atom and how much is the difference the difference is minus point zero two nine two seven eight u that is what i have okay now i compute the binding energy for that and what do i get the binding energy is simply given by  $\Delta m c^2$  ok this is the energy defect if i multiplied by minus one it becomes the binding energy and this turns out to be minus two eight three zero zero point seven kgb are converted into  $m e v$  it is minus twenty eight point three  $m e v$

so what do i mean by that i need to supply twenty eight point three million electron volts to rip apart a helium nucleus it's an enormous number you get the point right to rip apart an electron from the hydrogen atom you needed how many you need at 13.

6 if you reply if you want to reposition two of them the sorry it is not 13.

6 it will be 13.

6 into 4 some such thing 13.

6 into 4 is what you will get because my set is equal to 2.

if you want to rip apart 2 of them roughly it's again of the order of let us say 200 electron volts or 100 electron volt but here we are speaking of million electron volts you have to supply a lot of energy and that is the reason why it is very very difficult and hardest to build nuclear reactors etcetera etcetera i will come to that in a minute now that means given the right conditions the

operative where it is neighbor is right conditions because i have to prepare the right physical condition if you bring two protons and two neutrons together they should prefer to form a helium atom but it is easily said that then why is it

so because these are short range

so let me explain to you what is happening

so let us say i have two protons

so i should write probably like this

so let me use some other one

so this is a proton this is a neutron neutron and let us say all of them are at rest at infinity and i start bringing them together ok the interaction between neutron neutron and neutron proton you don't have to worry but when i start bringing them together i experience coulomb repulsion and my nuclear forces will not operate unless  $r$  is of the order of a femtometer that means there must be enough energy that i should initially supply such that my protons are able to approach each other at two or one femtometer and once they reach there no problem at all the nuclear forces will take over and what do i get i get a nice attraction of course in the presence of the neutrons these are very very important

so if you look at that i can draw some kind of a effective potential how will the effective potential look like my effective potential will look something like this

so i come from infinity my thing goes on increasing at some point it becomes attractive and it comes here this is an effective potential in the presence of the neutrons and protons all of them and this distance will be of the order of a fermi and at this point my coulomb repulsion is very very powerful actually it is very very strong i ask you to plug in the numbers and find out what it should be even better what i would ask you to find out is if you are given a gas of protons proton gas what is proton gas ionized hydrogen atom is that right if i am giving you that at a certain temperature  $t$  you can ask the temperature at which the kinetic energy will be able to bring them to such a close distance

so we want to write three by two  $kt$  is  $e$  squared over  $r$   $1$  over  $4$  pi epsilon naught and this  $r$  is  $10$  to the power of minus 15 meters okay

so whatever i was telling you i have written it here

so you can look at it is that ok what i have is that i have this figure is that ok i have this figure where up to this particular point i am going to get a coulomb repulsion and from this point my nuclear force is going to take over and it becomes an attractive force that is what is going to happen and i told you that if i had hydrogen atom what is going to happen is that i would have to equate the mean kinetic energy with this and you will find my temperatures to be of the orders of thousands of kelvin in fact it should be of the order of  $10$  to the power of 8 kelvin it could even be  $10$  to the power of 9 kelvin and this is something that we have to remember

so what we have done is to argue that if the protons and neutrons come sufficiently close to each other they will form a bound state but then to bring them

so close is very very tough you people must have heard of tocomax or fusion reactor

so on and

so forth is that okay

so if you remember that they try to actually make a fusion of these quantities which is very very tough but then we can always ask are there such reactors are there such processes taking place in nature where i can actually bring them together and produce a helium atom and what is the great advantage since the mass of the helium is smaller than the mass of the constituents i will be

liberating energy

so if that is the viewpoint that you have to take and if you look around indeed there is such a thing and that is nothing but your sun

so what i am going to do is to spend the next few minutes describing the dynamics of sun and show how this simple fusion process producing helium can actually explain many many aspects of energy production in the sun sun was a great mystery for thousands of years even after the advent of newtonian mechanics and thermodynamics it was a great mystery

so what we will do is to start discussing the physics inside the sun with whatever knowledge we have obtained by simply looking at the binding energy curve for the atoms

so let us get into that

so here is a beautiful picture from nasa which is currency wikipedia and you find here that sun is a very complicated object very very big of course we will come to that oh here

so what is it that you find is what is more important for us is this core this core occupies about 20 percent of the area of the sun which is very important for us and the temperatures are enormous it is of the order of  $10$  to the power of 6 kelvin and the pressure is very very large

so i want you to remember this picture at this particular point what we shall do is starting from here look at how the temperatures and the pressures are large enough for the fusion process to take place and explain how sun as a star is able to shine very brilliantly that shall be the topic for the next lecture and let us stop at this instant ok good bye you