

so welcome all of you in continuation of the lectures on properties of nucleus their mass and their stability

so that is the theme for us

so as you can see on this slide i have again return masses and stability which is probably the third in the series of our lectures

so far our analysis has been rather qualitative and we have not used numbers to a great extent we have not analyzed things in a quantitative manner today what i shall do is to show that even at our level full standard level it is actually possible to draw a large number of conclusions and in fact attain a large number of consequences understand a large number of consequences and also appreciate physics at the cosmic scale for example what is happening inside the sun simply by looking at energetics energy conservation the associated masses and of course the famous relation $e = mc^2$ which follows from special theory of relativity

so that is something that we should know

so in that sense today's lecture covers an extraordinarily important topic because we are looking at an object of the order of 10 to the power of minus 15 meters one femtometer and we are going to work out the consequences of something which is of the order of 10 to the power of plus 15 let us say that is whatever are the processes that are happening inside a star at the end of the lecture i will also tell you that whatever we study about the nucleus also sheds very important light on the dynamics of our own planet the earth itself which has been a quite a mysterious object for a long long time for physicists and geologists i will also be able to make such a statement

so the message that we are trying to convey is that although we are studying one particular phenomenon at one particular length scale which is very very tiny microscopic which is even smaller than an atom the ramifications can be enormous and can extend to very very large areas which tells you actually how the unity of physics is all pervading you understand one thing you understand a whole lot of things in fact the same thing happens even in atomic physics once people understood the atomic spectrum through the bohr model they were able to understand appreciate the constituents of the sun because there is helium there are these atoms and there is a temperature because of which the atoms gets excited and they get de-excited

so what you do is to conclude what is the composition of the sun at least the surface of the sun the photosphere let us say by studying atoms in your laboratory that is one of the great achievements we are going to show a similarly great achievement or a triumph of physics today by looking at some very very simple properties which i have already listed

so just to set the ball rolling let me repeat a few things for you just to warm up nuclear forces are really interesting because they are independent of electrical charge

so the interaction between the proton and the neutron a neutron in the neutron and a neutron in the proton is

so strong that you can practically forget electromagnetic forces of course you cannot completely forget them i will come to that again but for all purposes most of the purposes you can forget about them

so the interaction is very strong it is typically about 100 times stronger than electromagnetic interaction and of course it is very short range whereas electromagnetic interaction is of an infinite range what is the potential between two charged particles

so if you look at for example the electromagnetic interaction if you put two charged particles the potential between them is given by e^2 / r

assuming that that both of them have the same charge

so this is what we mean by an infinite charge it is a kind of a very smooth polynomial which is decaying as the first power of the distance whereas if you look at a proton and a proton let us say or a nucleon

so let me show you a nucleon what would be the corresponding potential between them this would look more like apart from the strength i will call it as $\lambda e^{-\mu r}$ this is called the yukawa potential it is also called the d by screening which you will encounter for example in electrolytes you will encounter the same interaction even in plasma physics or for that matter in dielectric materials

so do not think it is something peculiar to nuclear physics and the important point here is that apart from this $1/r$ potential

so we have v of r is what we are writing apart from this $1/r$ potential there is a fast exponential fall

so if i put μ equal to one over r you will see the potential falls to one over r of its value

so what are we saying at very very short distances $e^{-\mu r}$ is very close to one

so that is the interesting thing about this curve

so i am writing v nuclear of r is some strength $\lambda e^{-\mu r}$

so for r very small what do you mean by r very very small by that you mean μr is very small r is not a dimensionless number

so it is meaningless to say distance is small or large but μr is dimensionless number because μ has the inverse dimension of length

so if μr is very very small then $e^{-\mu r}$ approximately equal to one

so for μr very very small my potential behaves like $1/r$ potential but for μr very very large

so μr much much greater than 1 you see this will go to 0 much more rapidly than $1/r$ goes to 0 that is what we have and then we say this potential is screened and we say the range of the potential μ is the range of the potential range of the interaction mind you what i have written is the potential you can always find out the force corresponding to this by differentiation with respect to r by putting a minus sign $-dv/dr$ i will leave that as an exercise for you people

so when i say that the nuclear forces have a range of femtometer 10^{-15} meter basically we are saying that μ inverse is 10^{-15} meter that is the precise statement you should not think that is something like a step function it is constant up to 10^{-15} meter and it is going to come down that is not what is going to happen

so this is precise meaning of what the sharp range is with this what we want to do is to combine whatever we have got with the mass defect idea and obtain some insight some appreciation of the dynamics that is going in the interior of the sun that is our great purpose today

so let me go on to the next slide

so we have to start with some illustrative data which i have already calculated and this is an exercise that you can do by opening up the periodic table or the

so called nuclear data book which will give you all the masses and of all the nuclei with the isotopes isobars whatever nuclei you may be able to you may be taking and here is an illustrative data where i am comparing the masses of proton neutron helium is that okay remember my helium consists of what two protons and two neutrons therefore what i am interested is i will find the combined mass of two protons and two neutrons i will find the mass of the helium nucleus and i

ask are they going to agree with each other what would mr newton tell you if you people remember in your 10 standard 11 standard or even probably even earlier you are told there is a mass conservation there is an energy conservation there is a momentum conservation that is what you always assume when you solve problems in dynamics that is exactly what you do let us say two particles come they collide and they go you do not say that the mass of the incoming particle has changed a ball goes and hits against the wall and it gets rebounded the ball has a massive before and after collision nothing is going to happen because total mass should be a conserved quantity but relativity tells us that mass is not a conserved quantity only energy can be a conserved quantity because total energy can be conserved because mass can become energy and energy become mass and with every mass there is always an associated energy which is given by mc^2 that is something that i told you repeatedly in the previous lectures now what i want you to do is to pay close attention to that and look at these numbers

so let us start looking at these numbers please notice that i have taken care to write the numbers to a large number of decimal places that is not because you know i have a calculator and i can calculate it up to the decimal places all of you have studied something about significant digits what i am doing is actually to employ the masses to the required number of significant digits

so this gives you an idea of the accuracy and the precision with which these masses are determined

so if you people become physicists you will appreciate it even much better how we keep on pushing the frontiers of how well we know the values and that itself requires deeper and deeper understanding of physical loss

so if you look at the mass of the proton which we already know we are working in the units of atomic mass units remember how do we define the atomic mass units you look at 12 carbon and to declare declaration because that is my standard declare that its mass is given by 12 atomic mass units and with respect to that you fix the masses of every other nucleus and every nucleon also

so if you remember that mass of the proton is given by 1.

007276 atomic mass units mass of the neutron is 1.

008664 atomic units something that will be important for us at a later time

although i have already told you is that my neutron is slightly heavier than a proton chadwick in his great experiment argued that they must be of the they should be roughly of the same mass today precision experiments tell us of course they are roughly of the same mass but neutron is slightly heavier than the proton when i am going to discuss beta dk for you this is something i am going to concentrate upon because a neutron decays by emitting a electron and an anti-neutrino and it decays into a proton that is something that is important and of course i am interested in the mass of the helium atom and mass of the helium atom is given by four point zero zero two six zero two atomic mass units

so the two is my atomic mass unit

so what is it that i am interested in i am interested in the difference between the daughter and the parents what are the parents the parents are the four nucleons two protons and neutral neutrons

so the four parents came they joined together to produce a daughter which is the nucleus that is the jargon that we are looking at

so what do i do i look at the mass of the helium atom i look at the sum of the proton mass and the neutron mass there are two protons there are two neutrons that is what i have

so this is minus 2 of m_p plus m_n when i do that low and behold what is it that we have what we have is that this difference is not equal to zero in fact it is negative minus point zero two nine two seven two eight u that is very important

what does it mean associated with this mass defect there is an energy $\Delta m c^2$ and that turns out to be minus 28.

3 mev million electron volts in the atomic scale your energies were of the order of electron volts in the nuclear scale your energies are of the order of million electron volts why is that

so in a way you can understand it from the uncertainty principle an atom is confined over a distance of one angstrom

so $\Delta p \Delta x$ whereas a nucleus is confined over a distance of one femtometer the order of magnitude difference between them is about 10^5 to the power of 5 or 10^6 to the power of 5 depending on which ratio you are going to take okay therefore the corresponding energy scales here are all given by μv

so what does this relation tell me this tells me that if i want to break a helium nucleus if i want to break a helium nucleus and separate them into four constituent nucleons how much energy should i supply i should supply a very large energy of 28.

3 million electron volts that is the most important thing in order to break the hydrogen atom i was supplying something like 13.

6 electron volts

so for example if i keep on heating hydrogen atom is it ok at temp at some temperature it will ionize it will become a plasma and that temperature is something of the order of let us say 10^5 to the power of 5 kelvin because 1 electron volt corresponds to about 10^4 to the power of 4 kelvin you know e is equal to kt all that you have to do is to substitute that formula but here you have million electron volts that is what i have

so what are we saying

so here is a good thermodynamic exercise or a kinetic theory of gas exercise that you can do

so what we are saying is that if i write is of the order kt i want to boil helium nucleus to completely dissociate this is the it into four nucleons that is what i want to do

so what is the binding energy my binding energy is of the order of 30 mev now i am not interested in the precise numbers we will get back to the precision numbers later and in order to supply one electron volt of energy you need about 10^4 to the power of 4 kelvin

so what are we saying for example if you are saying if you have a mono atomic gas and it is a 10^4 to the power of 4 kelvin let us say then the energy carried by that atom is of the order of an electron volt by equi partition principle when by substituting the boltzmann law therefore if i have to supply 30 mev what is the energy that i need

so this is 10^4 to the power of 4 into 10^6 to the power of 6 into 3 if you feel like do not worry about that you have to go to 10^{10} to the power of 10 kelvin

so that means that if i just want to make a soup of nucleons by heating helium atom let us say then your ordinary furnaces and heating instruments in your lab are not going to help is that ok you get very very high temperatures for smelting divorce for example in your metallurgy labs but they are not going to help in fact we do not have such a natural temperature anywhere on the earth not even deep inside the earth is that okay

so if you want to attain temperatures of this order if you want to break it you should be able to actually go somewhere where such a temperature is naturally available but that is not of interest to us what is of interest source is the other way around okay and that requires a different temperature altogether i will come to that but this is something that you have to remember at this particular point

so what i will do is i will know

so what i will do is i will come back to the slide and get back to 28.
3 muv and let us move on to the next slide what we are going to do is to make use of this 28.

3 mbv and unlock the doors to the secret of the solar energy at some point when i was introducing the bohr model or for that matter even the planck hypothesis i told you one of the great mysteries which 19th century physicists faced was who is it that sunny is able to produce such an enormous energy ok now there are some numbers which you have to remember our earth is about a few billion years old that means sun must also be of the same order in fact in fact a little bit older if you assume you know that the planetary system was formed at some particular time

so if the sun has to be burning for a billion years is that ok where is the energy going to come from at that time people knew nothing of atoms people use nothing of nuclei people only knew thermodynamics very very well which we are also going to use right now and the only source of fuel that they knew was the burning of coal

so the great hill molds made an estimate and said that i know the temperature i know how much energy is radiated from the surface of the sun they did not know anything about the interior of the sun either is that okay

so he estimated that the sun would not last for more than 5000 years but we know sun will last for much much more time

so that was one of the great mysteries is that okay

so now whatever you have learnt however little it may be from the viewpoint of you know physics because you have been just given some numbers you can still get an understanding an appreciation of what is happening inside the sun and that is the reason why i am saying we are not going to unlock the secret of solar energy and i am going to spend a fair amount of time going very very slowly is that ok

so that you people get an idea because in doing that not only do we understand the physics there are also other things conservation of charge conservation of lepton number conservation of energy etcetera etcetera

so all those things i am going to keep showing you

so that later when you look at problems you know when there is a nuclear decay and all that you know how to balance

so we actually shoot two bills with a single stone that is the thing

so what is the secret of solar energy the idea is that the two hydrogen atoms are going to combine to give a helium atom but before that we have to ask a few questions and that is the breaking of the coulomb barrier ok as i told you i am not interested in breaking boiling a helium nucleus i am actually interested in producing a helium nucleus and in producing the nucleus there will be a lot of energy that is generated and that energy that is generated will be responsible for the sun to grow

so very nicely because that is what is going to convert it into heat and then my thermodynamics there is going to be a radiation that is emitted at that temperature the stefan boltzmann law that is what i want to do

so what i want to do is to bring two protons plus two neutrons to form the helium

so $4\text{H} + 2\text{e}^-$.

so one notation the two people should remember at this particular stage is that i have already used it sometimes we write it as $4\text{H} + 2\text{e}^-$ and sometimes we write it as $4\text{H} + 2\text{e}^-$ it doesn't matter

so sometimes we write as $4\text{H} + 2\text{e}^-$ and sometimes we write as $4\text{H} + 2\text{e}^-$ they are identically the same

so please remember that what is it that we want to do we want to bring a forget

about the neutron because neutron is not electrically charged

so if i have a two protons and if i want to bring them together there is also a neutron there is also a neutron which i want them to bring together if they bring if the distance between the two protons is of the order of 10 to the power of minus 15 meters 10 to the power of minus 15 meters all distances are often to the power of minus 15 meters then we know that they can form a nucleus that is the whole idea but the problem is how do you bring them this close to each other because there is a coulomb repulsion this is repulsive equal to

so i am going to write e squared by r that means you have to supply an enormous energy in order to bring them together

so if indeed the energy produced in the sun is because of the nuclear fusion there must be a corresponding energy

so this energy should be equal to the kinetic energy when the kinetic energy corresponding to $k t$ i do not have to worry about 3 by 2 and all that corresponding to r equal to 10 to the power of minus 15 meters

so so somehow if i can impart a kinetic energy such that $k t$ equal to e squared over 10 to the power of minus 15 meters that is the number that we are giving then they can come that close and once they come that close the strong interactions will take over from the electromagnetic interactions the coulomb interaction and then we can worry about the strong forces a simple exercise that i would ask you people to do is to estimate the temperature and the temperature turns out to be something like 10 to the power of 10 kelvin i am not very sure of this number it could even be 10 to the power of eleven i don't know

so i will be a little bit more careful and say ten to the power of ten to ten to the power of twelve kelvin

so something of that order but how do i get this number you get this number by assuming an ideal equation of state $p v$ equal to $r t$ remember you were actually able to obtain the relation $p v$ equal to $r t$ starting from kinetic theory assuming no that there is no interaction there are only collisions etcetera etcetera but in the interior of the sun actually it is much more complicated because there is going to be a lot of pressure apart from the temperature itself is that ok

so if you look at the interior of the sun the temperature in the interior of the sun core of the sun maybe it is in a slide is of the order of 10 to the power of 6 to 10 to the power of 7 kelvin

so what i am trying to tell you is that a naive estimate gives you about 10 to the power of 10 to 11 or 12 kelvin but if you work out the equation of state more carefully and if you ask oh ok tell me what should be the energy then the required temperature goes down and it comes to 10 to the power of 6 or 10 to the power of 7 there is nothing surprising in that how do you bring two particles close to each other either you give them enormous energy or you keep on applying pressure when you keep on applying pressure the inter particle distance becomes smaller and smaller

so in the real scenario in the real situation both temperature and pressure play a role

so that the temperature is of the order of 10 to the power of 6 to 10 to the power of 7 kelvin and we are working in this particular regime now what you do is to work out the nuclear physics process and the process is shown in this slide okay

so this is something that people worked out soon after quantum mechanics was established and it is a great delight to see how it is happening

so the first step is that two protons they form a two h e two this is a diproton and it is a very very unstable state you should not think because how can two protons be together i told you that there is no bound state of two

protons there is no bound state of two neutrons there is always a bound state of only one proton in one neutron which we call as a deuteron in other words this is an intermediate state this is not a stable state actually i should put a star here

so it is formed for a short while but before its plates what happens this $2h + e^-$ ok that is exactly what is happening it breaks into $2h$ even plus a positron plus a neutrino that is what it breaks into that is what is going to happen i am going to check that because there may be an error sitting here

so what i have is two protons is what i am going to have i am very sorry for the error

so let us correct it

so let us let us see one of the protons

so another proton will emit a positron plus a neutrino that is what is going to happen plus a neutron that is what is going to happen

so the final state is something like this $2p$ goes to p plus n plus positron plus neutrino and this is nothing but your deuterium

so what i am trying to tell you is when i was making this slide i was not very careful but no problem about it i think the same error has crept into the next line also this must be $2h$ one is that okay one proton and one neutron is nothing but your this one don't treat it as h but an h plus a positron plus a neutrino and what is positron positron is the positively charged electron it has exactly the same same spin everything the only difference between a positron and an electron is in the charge sign and then there is a neutrino i want you to pay attention to this neutral no a little bit therefore what is the overall result as i told you this is an intermediate state the overall result is that two protons produced to form a deuteron i am very sorry this is not helium but a neutron this is incorrect plus an electron plus a neutrino and this is the most important thing it releases 0 .

42 mb of energy here we looked at only the matter we did not say whether the process is endothermic end of the exothermic and endothermic endothermic means you have to supply energy exothermic energy is given this gives a 0 .

4 to mb but then this process is very very slow why is it very very slow because if you come back to this slide i have written that my proton goes to electron positron plus neutron neutrino plus this one every time there is a neutron believe that it is something called weak interactions and weak interactions as their name suggests are always weak and whatever is weak those processes take place very very slowly

so this is a weak beta decay that is what is going to happen

so this is a process there is one more thing that you should notice at this particular point i have written a positron and a neutrino and a neutron my proton has a charge plus my e^- plus has a charge plus my neutrino is neutral neutron is neutral that means every time i write a process not only is energy conserved but what is conserved what is conserved is also the total charge mass is not a conserved quantity that is something that you should remember because for all practical purposes my neutron is massless if you add the mass of neutron and positron it will not add to the mass of the proton but total energy is certainly a conserved quantity because these are not produced at rest actually they will move apart is that okay the total energy the total rest energy of the proton for example if the proton decays at rest will be shared among the energies of all the three particles

so this is a deuterium what will happen for the positron you don't see positron anywhere is that right

so just as mr einstein tells us that energy can be converted to mass mass can also be converted into energy

so that is indicated in this what will happen this positron
so this is indicated in this slide this positron will encounter an electron
there are a lot of electrons inside the star right and they will immediately
decay into two gamma two photons and in that process release an energy of one
point zero to mav is that okay there is an energy because the rest energy of
each of them is of the order of some point five whatever

so it releases energy of one point zero to μba now you see energy is getting
generated this is a weak process whereas this is an electromagnetic process and
electromagnetic processes are always faster than weak processors and strong
processors are of course much much faster that is what you have okay now the
next thing that happens is that my two h one will go to three helium plus a
photon plus five point four nine $m e v$ i am going to show how the energy is
produced in its excessive stages

so i have not indicated the complete process there

so let me do that here is that okay

so what we are saying is that two h one is going to three h e two plus gamma
plus five point four nine muv now obviously there is a problem in this because
this means there is one proton and one neutron and what do we have here you have
two protons and one neutron and a gamma

so what should the correct process be then i should write two h one plus one h
1 that is what i should write this goes to 3 h e 2 plus gamma plus 5.

49

so if i were to use ordinary units my deuteron plus a proton goes to three
helium plus energy i am going to go back to the binding energy table very soon

so what have we done we started with protons and through an intermediate
process we were able to produce a neutron and this deuteron in combination with a
proton will go to a three helium plus a gamma plus 5.

49 mba this slide has omitted p but never mind about that we have actually
worked it out and show you now this is not the end of the story for us we are
interested in the production of the helium 4 because helium 4 is the most stable
in that neighborhood that is something that you have to remember and that
happens through many many routes because our end point is actually the
formulation of formation of helium 4.

so the first route is this quantity three of two three heliums will produce a
four helium will produce two protons and an energy of twelve point eight six
million electron volts

so what am i saying if i come back to this let me spend a few minutes

so that you understand what is happening three helium plus three helium they
come together it produces a 4 helium plus 2 $1 h 1$ that is 2 protons plus 12.

86 muv

so all these processes are producing energies

so let us keep track of these things

so what are we saying now this has two protons one neutron plus two proton one
neutron is what it is this goes to two protons two neutrons

so one neutron one neutron two neutron and this is nothing but here four helium
then there are these two protons which are left because total is four

so this is this two p this quantity is my 4 helium plus 12.

6 mbv this is the first route

so if you look at this i want you to concentrate on this here you have hydrogen
here you have helium and here you have helium and here you have lithium

so and then of course you have your 12 carbon let us forget about that get
concentrate on that that means the immediate neighborhood of helium consisting
of okay tritium hydrogen and lithium they all have less binding energy than four

helium that means once you go into 4 helium state that is going to the most stable state it is a different matter that well carbon is even more stable 16 oxygen is even more stable and iron is the most stable we are going to come to that later nothing is more stable than iron because that is the top if you look at the binding energy right now we are concentrated in the formation of helium therefore if you supply the right conditions then all these nuclei would like to go and sit in four helium state that is your analog of your inert gas okay that is the most strongly bound it is a noble nucleus if you feel like that is what we want to do

so we want the nucleus to sit in that state and in doing the in that process because it is the most bound that means it requires maximum energy to be broken that means when you are forming them a lot of energy is produced and that is what we are interested in

so this binding energy per nucleon is a very important thing for us to study is that ok

so let me come back to this slide whatever we are looking at the first root consists of two three heliums three helium two plus three helium 2 will produce a 4 helium plus 2 protons plus 12.

86 mbv now you have to do a addition energy auditing right like you put an electricity meter and it tells you how much energy you have consumed is that right

so in a similar manner what we should do is we should go back to the previous slides 5.

49 1.

02 0.

42

so we have to look at an energy audit and we say ok if i give the right condition what is the right condition here the right pressure combination of the right pressure and right temperature then my protons and neutrons will combine together to form helium and they will reduce

so much of energy mind you we are not speaking of energies of you know burning of a coal which may be you know 100 degree centigrade ok 300 kelvin we are not looking at electron volts which corresponds to 10 to the power of 4 kelvin 2 orders of magnitude we are speaking of million electron volts which corresponds to ten to the power of ten kelvin you get the point right ten to the power of six seven to the seven kelvin

so that is the kind of energy that is produced which can never be understood in terms of conventional fuel what we need is the nuclear fuel and that is what radioactivity nuclear physics has taught us and that is what we are looking at it very very slowly i told you that this is the first route that means there are many many ways of forming four helium this is one of the ways and there are other ways which you can worry about but before we do that as i told you we have to do the net contribution the net is if you add up all of them and remove all the intermediate stages like you do in your chemistry class is that right there are intermediate things that you are going to form for example when there is a catalysis

so it is somewhat like that in right temperature or whatever four protons and two electrons give you a helium atom plus six gamma plus twenty six seven power point seven million electron volts that is what you are going to get that is the synthesis of one helium atom with four protons and two electrons generates an energy of twenty six point seven milli electron volt which is an enormous energy

so this is the energy auditing i i am not going to was suffer this number mean i know that it is correct but it is your responsibility to verify when you add all of them you indeed get 26.

7 muv

so here is a cartoon which is picked up from wikipedia and whatever i showed you in terms of all these formulas it has been illustrated in this

so it is very very nice two protons they emit a neutron there is a this proton that becomes a 2H^1 again it produces a gamma then it becomes a 3He^4 the same process is happening here these 2He^3 helium nuclei what happens the emit 2 protons and they produce four helium

so whatever i wrote in equations has been shown here is that okay

so the reacting is a proton this is a helium and there is a neutron which is sitting there

so to see the neutron is sitting here

so this is something that is shown in a cartoon manner gamma of course always stands for the photon

so you can write these chain reaction processes this is a case of chain fusion with emission of energy and a few particles that is what you have and this is an illustration and as i was telling you the most important thing here is not this figure but this number the temperature inside the core of the sun is 1.5×10^7 kelvin

so i repeat when we were doing a naive estimate we were getting a number of 10^7 to the power of 10 kelvin but then the pressure inside this one sun is

so very large maybe i have a number somewhere down the slide even 10^7 to the power of 7 kelvin will do the job and this is the first route for producing the helium atom remember when i showed you the binding energy curve i was showing you lithium and i told you even for lithium the binding energy per nucleon is smaller than that of helium physics exploits that nature exploits that

so what happens in the case of the second route we are going to start with a three helium you have already produced a 4He you produce a beryllium now i am not going to work out you can see everything is matching $3 + 4 = 7$ $2 + 2 = 4$ because that should add a should add n should add you produce a gamma this seven beryllium four which is an unstable nucleus it combines with an electron to produce seven lithium three plus a neutrino plus eight point five it releases eight point five energy this seven lithium combines with a proton to produce two 4He nuclei

so again you see seven plus one is eight three plus one is four that is two into four h e two two into four is eight two into row is 4 and there is an energy that is released this is the second route there are two more routes i am not going to tell you what they are because there is no point in spending time on all that but the most important thing is we are interested in what is the total energy produced this is know the energy audit and this is something that you should know what will you do you know what is the how many protons are there how many neutrons are there how many electrons are there and you know what the temperature is and you know the radius of the core

so you make use of all these processes compute how many fusion processes are taking place each fusion process produces this much energy per and then you find out whatever is happening and this is something interesting radius of the sun score is about 99 percent of the total the total radius of the sun now what is the power generated the power generated because of this fusion is 300 watts per meter cubed it is very very important this number 300 watts per meter cubed is whatever is produced and how many protons are burnt that is how many protons are fused 3.

6×10^9 protons per second which is about 3×10^9 kg of protons that is hydrogen is getting burnt per second is that okay

so that is a furnace which is of enormous magnitude of enormous dimension is

that okay that is what is happening and what is the total energy that is produced 3.

8 into 10 to the power of 6 10 to the power of 26 joules per second look at the enormous number which is about 10 to the power of 27 watt hour

so there is a nuclear reactor what kind of a nuclear reactor it is it is not a fission reactor it is a fusion reactor the nuclei are continuously fusing in the temperature in that process they are producing lot of energy which actually sustains the temperature and more fusion will take place you know it is a self consistent self feeding phenomenon and what is the percentage of power produced sun can produce power through other ways this is the most dominant mechanism 99 91 percent of the energy produced by the sun is because of this process and just by looking at the nuclear stability curve and looking at the binding energy per nucleon by doing an experiment in the lab we are able to understand what is happening in the interior of the sun the great philosopher kant said of course physics was still in its infancy we only knew newtonian mechanics and planetary orbits that itself was a great accomplishment but the great philosopher kant said that there are two things which can moves him enormously and what was that the star is scared you know in the heavens and the moral order within the man moral order within the man is outside you know the purview of physics but whatever this story sky we are seeing you know stars all the stars up in the sky that we are seeing we are now getting a glimpse of what is the underlying physics for them to shine perennially right almost perennially because this is the energy 10 to the power of 27 watt is what we are producing which is 10 to the power of 26 joules per second now in order to get an appreciation for that number i want you to look at this curve if it is not completely visible which is possible i can actually write those numbers for you

so what we are interested is in total power generated by in earth by us on the earth i should be very careful by us by humans is that ok now we are producing power through many many ways one is coal then you have gas then you have hydro right then of course you have solar that is becoming very popular then you have wind if you go to holland or some such countries lot of general energy is generated for example on the seashore then you have oil and then you have other fellows ok nuclear i should not forget that and there is some percentage actually the maximum is because of the coal pollution it is about 40 percent gas is about 23 percent

so on and

so forth and nuclear is of interest to us is that okay nuclear is 10 percent this is not bad at all there are lot of nuclear reactors i will show you what it is

so that is what it is produced but how much energy is produced that is the most important thing total power is about twenty five thousand whatever terawatt the precise number is twenty four thousand three hundred and forty five

so you have two point five into ten to the power of four into ten to the power of twelve which is of the order of ten to the power of sixteen watts

so this is the energy that you are producing is that ok and how much is the sun go back and check what it was you will find

so actually i can go back and check

so let us do that exercise in case i have made a mistake i can correct it it is 10 to the power of 27

so earth is 10 to the power of 16 sun is 10 to the power of 27

so we are speaking of power sun divided by power earth is of the order of 10 to the power of eleven this is the enormous difference is that okay and of course we can never ever hope to catch up with it which is completely impossible because we are a mere planet and we are not a star although we are all formed of

stars because all nuclei are actually synthesized within the where all nuclei are synthesized within a star that is what we are going to see in a way

so this is some number which you should be able to appreciate and that is what we have now there is no reason for us to stop at this particular stage we could actually go a little bit ahead and do a few more things and let us see what we can do okay for that what i should do is to look at the binding energy table again actually i should have put it but anyway let us go back you see if you look at this binding energy table per nucleon my helium 4 has very large binding energy per nucleon which is about six point something but carbon is even better that is of the order of eight mev per nucleon

so given sufficient temperature i should be able to actually even produce carbon in which case even more energy will be liberated but then there is a catch what is the catch

so let us look at the catch the catch is the following for helium synthesis let us say a temperature t is required i am only making an estimate

so let us forget about the pressure for carbon synthesis we need a temperature t' or i will call it t_c and t_h e now my helium has four protons whereas my carbon has six protons

so you can make an estimate and you can find that to bring down six protons together requires much more energy than bringing four protons sorry two protons two protons together

so if you have 6 protons how many pairs are there that is what we have to count that will be 6 see 2 pairs are there because each of them have to come close to each other and what is this number this is $6 \times 5 / 2$ which is 15.

so you need at least an order of magnitude more of temperature

so as you keep on increasing the temperature inside the core that is the statement that we want to make then you can keep on synthesizing higher and higher nuclei until you hit iron will be the most stable that does not mean that other nuclei cannot be synthesized like molybdenum or whatever tungsten

so on and

so forth but then this is the most stable one eventually this is the most stable one all these will be in small quantities there will be some metastable states or whatever you don't have to worry that is the lesson that we want to learn from this

so what do we do let us come back and what i want you to do is to look at this picture

so we are going to look at the fusion number again

so what are we going to do now what we are going to do now is to repeat the same exercise with respect to carbon and remember 12 carbon has 6 protons and 6 neutrons

so i plug in the number again and carbon has a very beautiful number for its mass which is 12 atomic mass units we have to pair respect to what the significant digits i have written that many significant digits and a few people remember the error analysis which was taught to you in the 11th standard you were told whenever you have an exact integer and whenever you are multiplying it with another number which is not an exact number the number of significant digits that you attach to the exact number will be equal to the number of significant digits that are there in the measured quantity

so that is what i am doing i am putting all these six fellows because there are six significant digits are seven depending on whether you count this or not

so if i calculate my Δm it turns out to be point zero five six atomic mass units and now you see the energy difference is fifty four point six four million

electron volt whereas how much it was it for the helium if i go back to helium it was 28.

3

so this is roughly twice is that right for helium it was 28.

3 milli electron volt whereas for my carbon it is 54.

64 therefore if per chance there are the right conditions in the interior of a star may be inside the sun if not inside the sun another star is that ok if there are right conditions you should be able to produce even more energy which will be 54.

64 mbv through a cycle no that means i have to again work out how starting with protons and neutrons you should be able to synthesize the carbon and that is called the carbon cycle what i showed you was the helium cycle but what follows is the carbon cycle this great physicist beta hands with a he has contributed enormously to many a number of fields he is a nobel laureate he was the first person to realize that there could be a carbon cycle inside the sun and he worked out the full dynamics we are not doing dynamics we are only doing book keeping is that right we are only doing energy auditing he worked out is that ok and that process is shown in this cartoon i do not want to spend too much time as i have shown you the credit is in the wikipedia is that ok the final process carbon 12 carbon is shown here is that okay

so helium nitrogen 13 carbon

so on and

so forth ok you can go and look up the book the temperature inside the sun is of course 1.

5 into 10 to the power of 7 kelvin i am just giving you that information because i want you to find out whether such a process is possible inside the sun or not is that ok that is what i want you to do

so if you did that is that ok even more energy will be produced and what will happen as the temperature in the core of the sun keeps on increasing you can keep on producing more and more nuclei

so now look at let us look at our earth which has

so many

so many elements after all they were all discovered here molybdenum phosphorus silver and there are this whole range of rare earth metals then you have uranium with using which you make either a fission bomb or a nuclear reactor then you have polonium you have thorium where will they all produced that is a good question to ask and we say they were all produced in the interior of the stars if you look at the human body we have lithium we have magnesium we have stasis of phosphorus we need all of them right we have

so that means every element that inside our body you know apart from the earth after all we are knowing of that were all synthesized somewhere in the interior of a star and as carl sagan said in one of his presentations he made a series called cosmos a tv series he says for that reason they are all products of stars everything came out of the stars you know and for us our big grand dad is actually the sun is not okay there is something that we have to remember

so this is the carbon cycle now there is a interesting thing

so greater the temperature what is going to happen greater the energy released and greater the energy released that means the lifetime of the star goes down because as you keep on losing your energy eventually you are going to either form all of it as a carbon or oxygen or iron lettuce after that it cannot produce any more energy

so that is what we are saying

so if you look at the binding energy per nucleon it tells you that is the reason why i put it here that means that i should keep on producing more and

more stable nuclei your capability to produce energy decreases and at some point when you stop producing energy that is the depth of the star

so i want to conclude this lecture by showing what the lifetime is and this curve shows it

so what i shall do is just look at these numbers in the next lecture i will start with this and

so tell you how when the star becomes more and more massive actually its lifetime becomes smaller and smaller and then i will go on to discuss radioactivity which would essentially conclude your course as far as whatever our mandate was and we will take that up in the next lecture you