ELEMENTS OF MODERN PHYSICS

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Lec 28: Nuclear Models

Good morning, everyone. So we'll start a new topic called nuclear physics. This is a part of the course and we'll try to keep it brief because we have one week allocated for that and I'll only try to cover the ones that are of most importance from this perspective of nuclear physics. So we'll talk about the structure of the nucleus and then talk about radioactivity and various nuclear models. And in this lecture, we'll restrict ourselves to the structure of the nucleus, how the discoveries were made, what was thought to be the constituents of nucleus earlier on, and how that theory failed, giving rise to the present theory that we are all acquainted with.

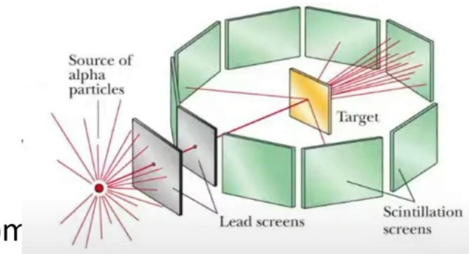
So we'll talk about that in this lecture. So just a brief recap of things, this Rutherford scattering of alpha particles by this gold foil. We have done this earlier. So there are these alpha particles that you see on the screen. So there are these alpha particles are, you know, there are these lead screens and then these are collimators and then they are made to pass through this and hit on the target that you see there.

It's yellow in color. That's a gold target. And then there are screens that are placed all around. And the experiment was to, you know, find out the scattering cross section of these alpha particles, which are nothing but these two He4. We'll discuss that.

Structure of the Nucleus:

Rutherford scattering of α-particles by Gold foil reveals:

(a) The positive charge or the nucleus is concentrated in a tiny region inside the atom



(b) The electrical neutrality of the atom demands that there are negative charges or electrons somewhere in the atom.

The fact that electrons revolve round the nucleus in '***stationary orbits***' came later.

Radius of the nucleus $\sim 10^{-12}\ cm - 10^{-13}\ cm,$ Volume: $\sim 10^{-36} cm^3$ (or less)

And it was found that most of these alpha particles, they went unscattered, which means that they continued on the surface. same line as that of the incidence and they sort of this angle that they suffer, the scattering angle is quite low for most of them. However, for some of them, they completely trace back the trajectory as the one that you actually see it here. And this made Rutherford to assume that that these atoms are in the structure of the atom is such that there is a very small space inside which is occupied by positive charges and which has been called as a nucleus and so it is concentrated in a very tiny region and the electrical neutrality of an atom demands that the negative charges must be placed somewhere.

And then if we follow Bohr's theory, Bohr has said that they are actually in the extra nuclear region or they are orbiting around the nucleus in some specified orbits. And these orbits are called the stationary orbits, which are given by this. I mean, when the electrons move around this orbit, the angular momentum is quantized in terms of h or h cross. So the radius of the nuclei or the space that these positive charges occupy, that comes out to be 10 to the power minus 12 to 10 to the power minus 13 centimeter or 1 fermimeter 10 to the power minus 15 meter, which approximately gives a volume of 10 to the power minus 36 cc or less than that. So, what are the experiments?

There are a number of experiments that were done in the late 1800 or early 19th century or the late 19th century and early 20th century to be more precise. And so these are measurement of the masses of atoms and obtaining them in the atomic unit, then their radioactivity, then transmutation of nuclei via bombardment with high-speed projectiles, optical spectroscopy in the visible and in the ultraviolet regime. And there are experiments to determine the spin or the magnetic moment of the nuclei. So these were some of the experiments and there are more.

The list is not exhaustive. And to understand the structure of the nucleus, constituents of the nucleus to be very precise. So this is the standard of writing formula for an element, say, X is with, you know, Z being the atomic number or which is the number of protons and the electrons. And A is the mass number. And one actually writes it like this, where you see this X, which is a chemical symbol for the element.

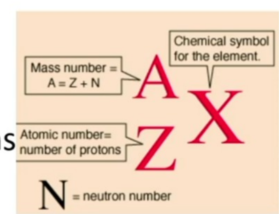
Experiments:

1. Measurement of the masses of atoms.
2. Radioactivity
3. Transmutation of nuclei via bombardment with high-speed projectiles.
4. Optical spectroscopy in visible and UV regime.
5. Experiments to determine spin or magnetic moment of nuclei.

Standard of writing formula for an element X

Z: Atomic Number (number of protons/electrons

A: Mass number (number of of nucleons)



And then there are these mass numbers is written as Z plus N, which means that it's a number of protons plus the number of neutrons. But that wasn't clear earlier. And these Z that of course is called as the atomic number, which is the number of protons or the electrons. However, we'll have to go through a series of, you know, postulates and their failures in order to understand what exactly is the constituent of a nucleus or any, I mean, of these nuclei of different elements. So to understand the constitution of the nucleus, radioactive atoms are found to emit alpha and beta rays.

And different species of the same element, despite having same atomic number and same chemical properties as well, they have different masses and these are called as isotopes. For example, these lead has seven isotopes. Four of them are radioactive with mass numbers 214, 212, 211 and 210. So these are radioactive, whereas these three that you see 206, 207 and 208 are non-radioactive. There are other examples and many examples in fact we are only quoting a few of them and chlorine has two isotopes with mass number equal to 34.98 and 36.98 and the smaller mass is found with a much larger abundance which is 75% abundance and little more than that actually while the larger one which is 36.98 is found with 25% abundance.

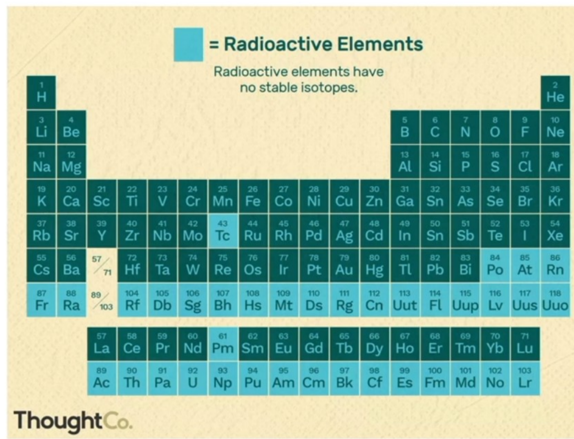
Constitution of the Nucleus:

Radioactive atoms emit α and β rays.

Different species of the same element, despite having same atomic number and chemical properties, have different masses . These are called as **Isotopes**.

Pb (Lead) has 7 isotopes.
4 (A= 214, 212, 211, 210) are radioactive.
2 (A= 206, 207, 208) are non-radioactive.

Cl (Chlorine) has 2 isotopes with A = 34.98 and 36.98. Smaller mass found with 75% abundance, while the larger one with 25%.



This periodic table that you see is taken from this website, which shows the number of, or rather, identifies the radioactive elements. And you see that the radium, then there are these uranium and so on and polonium and various other radons and so on. These are the radioactive elements. In fact, you might have heard of radium watches, which were very common earlier. But then radium, because of its radioactive properties, they are discontinued.

And there are these light blue colors actually show the radioactive elements, which means that one is that they have no stable isotopes and then they emit the nuclei of these elements emit alpha and beta rays. So this is something that's written here in red is that these atomic masses actually appear in whole numbers. And this is called as Aston's rule.

It's really an approximation, but a very good approximation. They're really very close to whole numbers.

As you see, that 34.98 can be interpreted as 35 and 36.98 certainly can be interpreted as 37. And that's how they are quoted, actually. So to be very precise, we have written these numbers with decimals for the mass number of chlorine, but they are usually quoted as 35 and 37. Alright, so now to account for the mass of a nucleus whose atomic weight is very close to an integer, okay, say that integer is A. If we now claim that there are A protons, because for the neutrality, there has to be equal number of positive and negative charges, they would cancel.

Now, if the nucleus has A protons, then the charge is not compensated, because the charge of the nucleus should be A, Instead of Z, Z is usually half or lesser than that of A, which means that if the nucleus is completely full with protons, then the atomic charge neutrality can never be achieved because there are Z electrons which would contribute to a minus ZE charge, whereas the protons would have a plus E charge. the charge being same with different sign with opposite sign. So this will be like a plus E. So plus E and minus Z E would not compensate each other. And as I said that Z is usually smaller, either half or lesser than that of A. So the charge neutrality is kind of violated.

So one has to get around this difficulty. And how to get around this difficulty? It was initially assumed that in addition to protons, The atomic nuclei contains A minus Z electrons, okay, along with Z orbiting electrons. So there are Z electrons in the extra nuclear region, which means outside the nucleus, which are orbiting in various energy levels.

And there are A protons and A minus Z electrons such that the electrical neutrality is at least, you know, satisfied. But that of course is not the case because this would give rise to some other problems as we'll see. It solves one problem and gave rise to another. So that picture that the nucleus contains A protons and A minus Z electrons are difficult to reconcile in view of either experiments or, you know, back of the envelope calculations or some other, you know, physical theories that prohibit such a picture to continue. So the charge, of course, becomes Z as required, but the electrons do not contribute, I mean, almost nothing to the atomic mass.

So it should entirely then come from the proton mass, which is certainly not enough to account for this large mass of these nuclei, which is seen through Rutherford experiment and otherwise. because the electronics charge is 2,000 times less than that of the proton charge. So this proton-electron picture, it has almost sort of no success, excepting one, and there are drawbacks. So we'll talk about the success first. So at least it's capable of explaining emission of alpha and beta rays from the nuclei.

However, other experiments such as radiofrequency spectroscopy, microwave spectroscopy, deflection by magnetic fields, external magnetic fields, etc. that showed that all these nuclei have a non-zero magnetic moment or they have a spin angular momentum. And these existence of spin degrees of freedom are confirmed from the detailed study of the spectral lines from the spectroscopy as mentioned above. And these are called as a hyperfine structure.

If you remember that we have talked about these hyperfine effects in hydrogen atom when we started discussing the perturbation theory. And these hyperfine structures have no relevance to the existence of electrons and are solely properties of the nucleus. And this is what Pauli had said in 1924, which means all these spectral lines or these lines you know, levels that you see have got nothing to do with electrons, but they are purely from nuclear properties. And because they are nuclear properties and have got nothing to do with electronic properties, so the electrons should not be the constituents of the nucleus, okay.

The magnetic moment of the nucleons interact with that of the extra-nuclear electrons.

This perturbs the atomic energy levels, thereby lifting degeneracies and yielding The hyperfine structure.

The nuclear magnetic moment (or spin) is designated by $\vec{I}$ having eigenvalue $\hbar\sqrt{I(I+1)}$, I depends on the mass number A.

Cases: (i) If A is even, $I = 0$ or an integer (called bosonic nuclei).
(ii) If A is odd, $I =$ half-integer (called fermionic nuclei).

And these lines are also, you know, associated with mass and angular momentum, these hyperfine lines, okay. So let us just discuss about these angular momentum or the spin angular momentum and so on so forth. We are talking about the total angular momentum which comprises of both the spin and the total angular momentum. So the magnetic moment of the nucleons interact with those of the extra nuclear electrons which what I mean by extra nuclear electrons is orbiting electrons. So these interaction effects, that perturbs the atomic energy levels, and thereby they lift the degeneracies and yielding the hyperfine structures that are obtained from these spectroscopy that we have mentioned here, such as microwave spectroscopy, radiofrequency spectroscopy, and so on.

So the nuclear magnetic moment or the spin, which is designated by I, I mean, it's not only spin, but magnetic moment is often, you know, equated with spin, but we are talking about the total angular momentum. So this is by this I vector. denoted by the I vector and it has eigenvalues which are I into I plus 1 root over of that into h cross and this is known I mean we know that for an angular momentum L it has eigenvalues which are you know h cross into root over L into L plus 1 where L is the orbital angular momentum quantum number and here I is the the total moment or total angular momentum quantum number for the nucleus. So, that tells us rather gives us two cases if A is even which means that the mass number is even and to remind you the mass number is the total you know the mass of the atom which is including or that is of the nucleus.

So, this is even then I is equal to 0 or it is an integer and they are called as bosonic nuclei and if A is odd, I becomes half integer and these are called as a fermionic nuclei. And these are actually obtained in experiments and these ultra-cold atoms which make these cold atomic gases and make B, C of the cold atomic gases, they deal with these a bosonic atoms or fermionic atoms, which really when we talk about a bosonic atom, we talk about the hyperfine spin or the spin that we are talking about here, the nuclear spin. And because these are, you know, fine structure, these are lower than the electronic effects by a fine structure constant, which is has a value which is alpha square equal to 1 over 137. So these effects are difficult to see unless one reduces the temperature.

And that's where all these studies of these ultra cold gases, they occur and where you need a variety of techniques, you know, cooling techniques in order to bring down the gases at, you know. temperature which are like 10 to the power minus 5 Kelvin, 10 to the power minus 6 Kelvin and so on. And there are examples of cooling the bosonic atoms. It started this ultra-cold atoms. They started with or making a BEC with ultra-cold atoms.

They started with the bosonic atoms such as rubidium, etc. And then there are, you know, other atoms that are cooled which are fermionic in nature, which means that the mass number is half, or rather odd, and the I is actually a half integer. So these are called as a fermionic nuclei. Now the concept of spin actually puts the first nail to this proton electron hypothesis that one has thought about for a model of the nucleus and how it does is that a nitrogen has Z which is atomic number equal to 7.

And the mass number equal to 14. So which means that it has 7 electrons and hence 7 protons at the nucleus. And so it should have, you know, half integer spins. So it is 14 protons and 7 electrons in the nucleus. So it actually should have the nucleus spin should be an integer, not a half integer because there are 14 protons.

Now we have given up on that. So we are still in that picture where the nucleus has protons and electrons. So there are 14 protons and 7 electrons in the nucleus. So the 14 protons would have given an integral spin and 7 electrons would give a half. integral spin, but the vector sum of which should yield a half-integer for the spin, but experimentally the total spin is found to be equal to 1 for nitrogen.

The concept of spin leads to the **breakdown** of proton-electron hypothesis.

Nitrogen (N) has $Z = 7$ and $A = 14$.

So N has 14 protons and 7 electrons in the nucleus.

14 protons should yield an integer spin, and 7 electrons should yield odd half-integral value in unit of $\hbar$.

A vector sum of which should yield an odd half-integer.

But, experimentally found that $I = 1$.

And then there are many other examples, which we do not list a lot of here, but we give these examples: cadmium where Z equals 48, mercury where Z equals 80, and lead where Z equals 82. should have, by the same argument that we have given earlier in the previous slide, zero or an integer angular momentum for the nucleus. However, they have been found to have half-integral spins. And as we have talked about, these existence of spins can be performed, or rather they can be obtained by Stern-Gerlach kind of experiments, which involve the presence of a non-uniform magnetic field. And one can find or confirm that they have half-integral spins or integral spins, which challenges the wisdom of having electrons and protons inside the nucleus.

There's also another argument, which is very elegant, and it says that if the electrons have to reside inside the nucleus, then their energies are too large for the nucleus to hold them. And again, it's a back-of-the-envelope calculation using the uncertainty relation where we have used delta X delta P equal to H cross, which gives a delta P equal to H cross by delta X. H cross is about 10 to the power minus 34 joule second. We are only taking these in order of magnitude. There are some numbers in front of these 10 to the power minus 34 and maybe 10 to the power minus 15 as well.

10 to the power of minus 15 is the nuclear radius. That's one femtometer. So delta x, which is taken as the uncertainty in the position of this electron, has to be within the nucleus, whose size is about 10 to the power of minus 15 meters. So once you look at this or rather work this out, so it becomes 10 to the power minus 19 joule second per meter and if you, this is the uncertainty in the momentum and we have no better estimate than to use this uncertainty as the momentum itself because the maximum uncertainty of the momentum should be equal to the momentum itself.

There are other examples:

Cd ($Z = 48$), Hg ($Z = 80$), Pb ($Z = 82$) should have $I = 0$ or an integer.
But they were found to have half-integral spins I.

There is also uncertainty argument that prohibits electrons to reside inside nucleus.

$$\Delta x \cdot \Delta p \sim \hbar \;\rightarrow\; \Delta p = \frac{\hbar}{\Delta x} = \frac{10^{-34}}{10^{-15}} = 10^{-19}\,\mathrm{J-s/m}$$

Assuming, $p \sim \Delta p \Rightarrow E = p^2c^2 + m_0^2c^4 \simeq 60\ \mathrm{MeV}$

Radioactive emissions eliminate emerging particles to have energy $> 4\ \mathrm{MeV}.$

It cannot be anything larger than that. Of course, it can be smaller than that. But to get an order of estimate, we use this P to be of the order of delta P, where E becomes equal to P square C square plus M naught square C4. That is a relativistic energy being used for electrons. We are treating that electron moves with a speed which is closer to that speed of light.

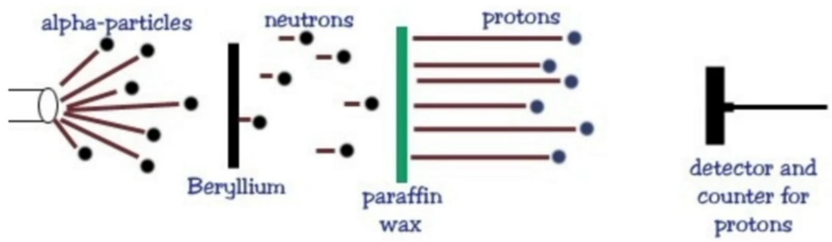
And then one actually gets these 60 MeV. And once you put all these things and then, you know, the radioactive emissions that eliminate the The emerging particles coming out of the nucleus to have any energy which is, you know, greater than 4 MeV. So it doesn't allow, eliminates the possibility that these particles coming out can have any energies which are greater than 4 MeV. Okay.

But of course, this argument does not apply to protons, which have, you know, the protons have energies, which are just a few MeV. And so, this above argument does not apply to protons and the protons can actually stay inside the nucleus, which it does or which they do. Okay. So let's take you over the discovery of neutrons, how they are discovered and so on. So this was Rutherford in 1920 made an attempt to restore the structure of the nucleus by saying that these electrons and protons, they reside inside the nucleus and they basically same as the electron proton picture that we have said earlier, but they combine to form chargeless particles.

They are called neutrons. Okay. But however, it didn't have too much of basis to say that and this one of the main reasons that this discovery of neutrons was delayed because of this chargeless property that neutrons do not found to have charge and the entire charge of the nucleus is coming from the protons which are whatever may be the number of protons they contribute to this charge. plus Zd and the extra nuclear electrons, they contribute a charge minus Zd, rendering an electrical neutrality of the system. Now Chadwick discovered neutrons in 1932 and by disintegration of the nuclei by the emission of alpha particles and alpha particles are nothing but this 2He4.

These are helium nuclei with Z equal to 2 and A equal to 4. So, these further evidences were obtained when nitrogen and actually beryllium, beryllium was the more sort of familiar in that context, was bombarded by these, you know, alpha particles. And the resultant energy is found to be much more than the projectile. So, you project something, you have a projectile and you project it towards a target and there is an emergent energy. particle with some energy and you expect that some energy would be dissipated because of the collision with whatever constitutes constituent atoms and nuclear.

Chadwick's experiment:



In 1932, Chadwick carried out an experiment in which a sample of Beryllium was bombarded with alpha particles, which caused emission of a mysterious radiation. He then discovered that this radiation, upon striking Paraffin Wax (proton-rich surface), would dislodged some of the protons. He was convinced that the beryllium was emitting neutrons and not γ rays.

But instead of that, you know, the outgoing energy is found to be much larger than the projectile energy, which means that there is some contribution of the nuclear energy that comes into the picture. And this is important to understand where this extra energy is coming from. So let me come to a sort of visual schematic diagram of Chadwick's experiment, and these are sources of alpha particles which are 2HE4, and they are bombarded towards the beryllium target, and then there are these neutrons that are coming in. And they are hitting this paraffin wax. And then there are highly energetic protons that are coming in to be detected by the detector.

Proton-neutron scenario of the nucleus

Number of protons is Z, number of neutrons is $A - Z$.

They have integral or half-integral spin depending on A is even or odd.

The magnetic moment of the nucleus is found to be $-2\mu_N$ ($\mu_N = \frac{e\hbar}{2m_N}$).

Also consistent with the radioactivity picture.

Neutrons have very high penetrating power.

So this detector and counter for the proton. So what are all these? Beryllium is, of course, a target and target. So, in 1932, Chadwick carried out this experiment in which a sample of beryllium was bombarded with alpha particles, which caused the emission of this mysterious radiation. So, these neutrons were not very well known at that time. So, it was...

It was only that one could call it a mysterious radiation. And initially, of course, he thought that it was gamma radiation. Gamma radiation is nothing but a kind of electromagnetic radiation. And then he sought to eliminate that whether he is really getting gamma rays. So you made the emergent particles to incident on this paraffin wax, which has a lot of protons.

So that's, you know, it's a proton rich surface. And so this would have dislodged some of the protons because of this, you know, highly energetic electrons. And these emerging protons were later detected by this proton. and he was convinced soon afterwards that this beryllium was emitting neutrons, which he called them, which the neutron term was already available, but he was convinced that they are not gamma rays. They are new particles which sort of would solve this mystery of what is actually the constituent of the nucleus.

So we are categorically coming that what were initially thought about and how those mysteries were resolved in order to arrive at the correct picture that we are familiar with now, okay. So, this implies that this extra energy which these highly energetic protons are coming out, this coming from the internal energy of the nucleus, okay. Later on, it was found by Irene Curie and Joliot in 1932 that this energetic radiation, when it falls on hydrogen, it produces highly energetic protons, okay, pretty similar to the beryllium. And it was later confirmed that these are not gamma rays.

And Chadwick confirmed that these are elementary particles, which means that they are particles that are there and indivisible particles. And they have masses very close to that of protons. And however, they are charge less and they leave no tracks on the cloud chamber, just like proton and electrons. They are posit electrons and positrons. They are produced in cloud chamber and they leave a mark there.

In fact, this is if electromagnetic radiation passes through or gamma rays pass through these cloud chamber, it causes electrons and positron pairs to produce. which can be, you know, realized if you apply an external magnetic field, which will give rise to equal but opposite trajectories for these electrons and positrons. However, neutrons leave no marks in the cloud chamber. So we are slowly arriving at a proton-neutron scenario of the nucleus, which is the correct one. So number of protons is Z. So the number of neutrons is equal to A minus Z. And you'll see that it's written that N is equal to A minus Z. So they have integral spin or half integral spin.

We are really talking about the angular momentum. This depends on whether A is even or odd, meaning the mass number of these nuclei is even or odd. The magnetic moment of the nucleus is found to be $-2\mu_n$, which is opposite in sign to that of protons. And it is defined by E h cross by 2 m n. And this is much larger than the magnetic moment of electrons and very close to the magnetic moment of protons. It's much smaller than the magnetic moment of electrons because there's a mass that divides here.

The mass of neutrons is almost the same as the mass of protons. And they are typically, you know, 2000 times larger than that of electrons. Since electrons are lighter, their magnetic moment is larger. Now, to have the nucleus with protons and neutrons, it is also consistent with the radioactivity picture. We are storing the discussion of radioactivity for the next discussion.

That is why we are not talking too much about it, but these radioactive emissions, etc., are important and would contribute to the knowledge about the nucleus. And neutrons also have very high penetrating power. In fact, if you want to know that how we actually use neutrons in various situations, one can give one example that the magnetic structure of a material can be understood by the neutron scattering. And neutrons do not have charge, so they do not couple to the charge degrees of freedom, but they have magnetic moment as we have been discussing. And these magnetic moments will couple.

Coupling means they will interact with the magnetic ordering of the system. And these neutron scattering data will be able to provide the information about the magnetic ordering that is there. That is whether you have a ferromagnet or you have other kind of magnetic ordering or you have no magnetic ordering at all. There is something very important that comes up that if there are these protons and neutrons inside the nucleus, then what are the kind of forces that are there because the protons would have, you know, they are charged and they are sort of they would repel each other. So, what is holding the nucleus together or what is contributing to the stability of the nucleus?

So wouldn't these protons have very strong repulsive interaction and wouldn't that destabilize the structure of the nucleus? So for this nucleus to be stable, Of course, we know that there are unstable nuclei and they result in disintegration by radioactive decay, but not all of them are unstable. So, if they are not unstable, then there has to be some strong attractive forces to overcome this repulsive forces coming from the interaction between the protons. And these attractive forces should be between protons and neutrons.

Now, we are mostly, you know, led by this fact that these are charged particles and then there are interactions between them and which are given by this Coulomb forces and so on. But these are not really Coulomb forces, nor do they originate as the electromagnetic forces that we know in either classical physics or even some of the semi-classical considerations that we have talked about. So they have a completely different origin. And these are called strong forces. They are responsible for the stability of the nucleus.

And these forces are very, very strong within the nuclear radii. And they are very short-range forces. And the forces are restricted within, you know, one fermi meter. OK, so which means about 10 to the power of minus 15 meters. And outside the nuclei, of course, they are not important and Coulomb scale takes over, okay.

Inside the nuclei, they are, you know, million times larger than that of the Coulomb force, okay. And once again, we reiterate that they do not have origin as the electromagnetic forces so you cannot reconcile that this fact that there are two charges repelling each other or attracting each other which will give rise to this force and because neutrons have no charge so these origins are completely different and this constitute one of the four fundamental forces in nature. So what are the other properties of neutrons? We have already told that they have angular momentum which is equal to I equal to L plus S. So it is a vector sum of L plus S. So if you add a precessing you know L vector and if on top of that if you take a S vector that is also precessing.

So this would be a vector sum of L plus S. And once again, just like, you know, we have talked about that whether the number of nucleons, that is the mass number, whether it's even or odd, it would, odd or even here, they would, you know, obey either Fermi-Dirac statistics or Bose-Einstein statistics. Another, you know, important properties of these nucleus is that it, there is a presence of a quadruple moment here. And this quadruple moment actually comes because there is a departure from spherical symmetry. So, Rutherford's early, you know, sort of picture, it gives you a spherical region which contains, which is, you know, positively charged and that's called as a nucleus.

Other properties of neutrons

The total angular momentum $\vec{I} = \vec{L} + \vec{S}$.

Obeys Fermi or Bose statistics depending on the number of nucleons to be odd or even.

Existence of a Quadrupole moment due to departure from spherical symmetry,

$$Q = \frac{2}{5} Z \left(a^2 - b^2\right)$$

a: semi-major axis, b: semi-minor axis.

For Deuterium: $Q = +0.00274 \times 10^{-24}\ \mathrm{cm}^2$.

And this, of course, very small region of space. But nevertheless, it was assumed to be spherical. But there is sort of even though very small, but there is a quadrupole moment that is being observed. So quadrupole moment, just like dipole moment, which is charged into the distance. There's a quadrupole moment, which is, you know, the.

It comes from the multipole expansion of these charge distributions. So there's a nuclear charge distribution. We have the monopole moment, which is a simple term. Then there's a dipole moment. The dipole moment cancels out here because there are no negative charges there.

So the only leading charge or rather term in the multipole expansion is the quadrupole moment given by Q. And one can actually do an experiment to determine these multiple moments. For deuterium, it came out to be a very small positive number, 10 to the power minus 24, this 0.00274 into 10 to the power minus 24. And for bigger atoms also, this number is slightly larger, but still measurable. So, why does radioactivity occur?

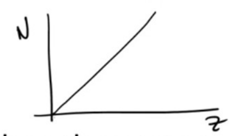
Why are some nuclei more stable than others? The stable nuclei are the ones for which the number of neutrons is same as the number of protons or the atomic number. So, when n is the number of protons. So if you actually plot N versus Z, so the ones that are, you know, stable would fall along this N equal to Z line. And for A to be less than 20, they are, most of these actually follow these lines.

n equal to z and hence they are stable. For heavier nuclei, the number of neutrons can be actually larger than that of protons, which means that there is a deviation from the n equal to z equation or this n equal to z condition. And if that happens, then n is not equal to z and so on. The tendency of N to be equal to Z is it follows from the existence of nuclear energies. So these are, you know, fermionic nuclei.

They obey exclusion principle. And as a result, each energy level have two neutrons. These nuclear energy level have two neutrons of opposite spins and two protons of opposite spins as well. So energy levels, of course, are filled in sequence, just like the electronic energy levels or the atomic energy levels to achieve the minimum energy. So, N equal to Z is a good condition and as you deviate from that, these become unstable and the instability leads to the decay of the nuclei in terms of radiation.

Why are some nuclei more stable than others?

The stable nuclei are the one for which $N \simeq Z, N$: number of Neutrons.



For lighter nuclei ($A < 20$), they are stable.

For heavier nuclei, the number of neutrons are larger than the protons, where $N \neq Z$.
The tendency of $N \simeq Z$ follows from the existence of nuclear energies. These Are fermionic nuclei, obeying Pauli's exclusion principle.

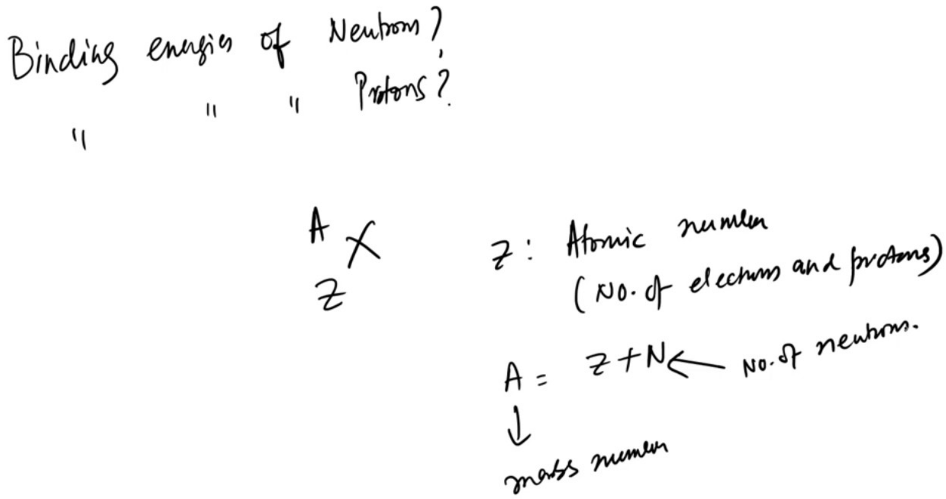
As a result, each energy level have two neutrons of opposite spins and two protor of opposite spins.

Energy levels are filled in sequence, just as the atomic levels to achieve minimum energy.

So, we can have other considerations such as the binding energies of neutrons, binding energies of of neutrons and binding energies of protons and so on. And so would they be same? That's the question. And they are not same because the neutrons, if you want to remove one neutron, then you know the mass of the neutron and then you multiply it by C square that will give you the binding energy of this neutron.

But the proton, when you remove a proton, you actually land up with an isotope. So these protons actually have, you know, a lower binding energy for the reason that there are these protons have a repulsive force with other protons and also have a strong force, which we have talked about with the neutrons. So that is why removing one proton from the nucleus would cause a different energy or rather would result in a different energy than if you try to remove one neutron from the nucleus and so on. There are other examples that one can give, but this by and large, the constituent of the nucleus and the kind of experiments that have gone through in those days to come to this fact which we are aware now that there are electrons in the orbit which are in different shells or different orbits.

These are called stationary orbits, and when the electrons move in these orbits, they do not emit electromagnetic radiation. And these orbits are characterized by what are called Bohr's rule or Bohr's law. That is, they have angular momentum quantized in units of H and so on. And the nucleus consists of neutrons and protons. And for an atomic number, which is written as ZXA, Z is the number; this is called the atomic number.



And these atomic numbers mean there is a number of either electrons or protons, and A is the mass number, which is equal to Z plus N. A is called the mass number and N is the number of neutrons. So with this preliminary introduction, we would like to stop here and then discuss these other topics called radioactivity and the various nuclear models, which will give you a preliminary idea of what nuclear physics was and how it developed in the early 20th century and the late 19th century. Overall, this development and some successes and failures and a lot of experiments developed contributed to arriving at the correct picture that we are all familiar with.

I'll stop here. Thank you.