ELEMENTS OF MODERN PHYSICS

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Lec 32: Elementary Particles, Detectors

So we are towards the end of this course, and we are going to talk about the physics of elementary particles. This is more like a description and it's, you know, will be presented like a tale. And remember, a lot of these things that come across—the terms that we come across—and some Some of the things are being told, but we are not going any deep into these topics because they are by themselves, they would take up a course. So, we will simply introduce some of the elementary particles and talk about a little bit of detection of these particles through detectors or accelerators.

So the ultimate question that is there, which one would like to answer is that what does the matter consist of at the most fundamental level? And we have asked this question even during the nuclear physics lectures. And we have come up with this electron, proton and neutron and so on. And if there are something more to it, if there are more particles that we have missed out in that description. And the useful input come in the form of that these are indistinguishable particles.

They are quantum particles and they have to be, you know, they are indistinguishable from one another. So the statistics that you form has to take into account this indistinguishability. And if these are electron-like particles, that is, they would obey Pauli's exclusion principle. And of course, not every particle obeys Pauli exclusion principle, but the ones which have anti-symmetrized wave function upon the exchange of particles, they would have this Pauli exclusion principle, which means that no two electrons or no two fermions, they would occupy the same energy state. Another question which is of utmost importance is that how do these particles interact with each other?

How do we know what's the nature of interaction? How do we probe the interaction? And are these direct or indirect interactions? Direct means just the way we are, you know, familiar in the classical domain that two particles come and collide against each other and they're scattered. Or there could be a wave or a medium that propagates this interaction.

So we'll see that some of these things as we sort of go through this lecture. And the determination techniques have to be indirect because if you, you know, try to go for a direct measurement, you would actually disturb the state of the particle and that would not be acceptable. So what is usually done in probing the interaction or the nature of the particles or the symmetry that they go through or the, you know, the decay of these particles, we have to look at scattering events with other particles. And these scattering events, as we shall see soon, that these scattering events have to be done at very large energies because these large energies would, you know, enable one to know the basic interaction or the fundamental interaction that takes place between these particles. and also through the decay into various daughter particles or products and then formation of bound states.

So these are usually the determination techniques that one follows in order to know more about these particles and their nature, their interaction, etc. So how are these elementary particles that would be, you know, detected? So we know about electrons. We already have studied them. photoelectric effect, thermionic emission, also from Compton effect and we know about protons as well which are obtained by ionizing hydrogen.

Hydrogen is the simplest atom which has got one proton at the nucleus and one electron which is in the extra nuclear region or in the outermost or the orbit, there is just one orbit. Other interesting particles are obtained from cosmic rays which are constantly penetrating each one of us. There are nuclear reactors and there are particle accelerators. And we'll give a very short introduction to each one of them. So this cosmic rays, the Earth is constantly, you know, bombarded by this.

Let's write this bombarded by high energy particles. And they are mainly protons, they're heavy particles and that origin in the outer space. Okay. And the source of this is not fully understood, but when they hit the outer atmosphere, they produce showers of secondary particles, which are muons and neutrinos and so on, and we'll introduce them as we go along. And these showers have also free, which are non-interacting particles and whose energies can be very, very large.

There is a problem with the detection because the strike rate for a reasonable size detector is very low. Even though they are passing everywhere, they are sort of passing the atmosphere, but some of the particles detection would require them to pass through the detector. Now, one question is that where do you put the detector? The other question is that how big would the detector be for an efficient capturing of all the information that you want to. So these are some of the, you know, the bottlenecks which have led to a slow growth of particle physics as we have seen over the years.

The nuclear reactors, so with the decay of a radioactive nucleus, there could be emission of a variety of particles which are neutrons, neutrinos, alpha particles, beta particles, gamma particles. We have seen all of that when we talked about radioactive decay or radioactivity. And the third one is the particle accelerators. And here the particles such as electrons and protons are accelerated to very, very large energies, sometimes several TVs, and made to strike a target. So there's a target, and this target consists of some atoms or ions.

So they would hit the target, and there'll be a flurry of daughter particles or the products that would come out, and you can study them. Now, by engineering the arrangement of the detectors is one of the main things in this detector technology that how do you place the detectors in which kind of orientation, what arrangement would give you orientation. maximum outcome. And all these magnets, you know, you also need magnetic field because these are charged particles. Some of them are or rather most of them are and they would get deflected by the magnetic field.

And these magnets have to be placed, you know, in a sort of suitably designed fashion so that you can detect them or rather they go and fall into the detector wherever you have kept them. So the particles which are under focus, they can be studied. For example, you know, when electromagnetic radiation passes through a cloud chamber, as electrons and positrons are formed, we'll see these positrons, and they have same but opposite radii of curvature in presence of a magnetic field. And the total energy of the electron and positron would be same as the combined energy would be same as the energy of the electromagnetic radiation. So it's possible to study a variety of particles.

These are positrons, kaons, beta mesons, antiprotons, pions, neutrinos, and so on. Traditionally, the heavier particles, they require larger collision energies. And the collision energies, you know, the requirement of larger collision energies sort of necessitate that they be, you know, collided head on. And that's one of the reasons that the lighter particles were discovered first and heavier particles had to wait till one is able to achieve or accelerate the particles to the desired energy, which is very large. So there are, you know, problems that have been faced with this particle accelerators and their designs.

So if you want to generate very high energy, it's advantageous to collide two fast particles instead of these, you know, one fast particle hitting a stationary target. Because the relative energy when two particles are moving opposite in opposite directions that produces much larger energies than stationary target being hit by a fast moving particle. So, this also made people to make the detectors to have a ring-like structure. It's not line, it's like ring-like structure, which means that and why it's a ring-like because they would, you know, kind of go around and if the collision is missed in one circle, they have the opportunity to again hit each other and produce the desired effect. Okay.

But then when we are talking about charged particles and they are going in the circular orbit, which means circular orbits means that they are accelerating, then they will radiate energy in the form of synchrotron radiation. And they would eventually slow down. So this is one of the things that are, you know, the problems or that impedes the usage of these ring-like structures is, So this acceleration that we talk about is less for heavier particles, but for lighter particles, the issue is, I mean, the issue is actually more, you know, important rather, not lesser, but it's important. What I mean to say is important.

So this, you know, is the ring-like structure is more used for heavier particles, whereas for lighter particles such as electrons, they are, you know, treated or they are rather accelerated in linear colliders and the rings are used for protons and other heavy particles, protons and neutrons and so on. So a second focus as important as the detection of the particles is what kind of interactions do these particles go through. What kind of, you know, is it like a direct interaction or it's mediated by a field? And is it strong? Is it weak?

Does it have an origin in classical electromagnetism or something else? One needs these energies to be high and a very easy way to see that why do you need larger energies to probe these interactions is that the particles will have to come very close to each other. And this is if you take the de Broglie relation, which is P equal to H over lambda, where P is the momentum of the particle and lambda is the description of or rather the wavelength of the wave that describes the particle. So the P needs to be very high if you want to scale the particle at very small distances. So if you want to get very close to the particle,

particle or two particles, then they need to go very close to one another so that you can understand the interaction that goes between them. So there is a continuous requirement of achieving higher and higher energies in these collision processes. So that brings us to a kind of different accelerators that we see all over the world. And in fact, this list is so huge that it would require sort of probably more than one class to cover and how they have moved from one form to an upgraded form or why some of the detectors have closed down their operation and why the new experiments have started or new colliders or new accelerators have been designed.

to take care of the problem that was there in the preceding version. And then these electron energy or rather the energies of the particles have been achieved to be something several TeVs and so on. So it's just a few being mentioned here. There's Tevatron at Fermilab, which yields an energy of 1 TeV. Large Hadron Collider at CERN, which yields an energy of 7 TeV.

International Linear Collider, 500 GeV to 1 TeV; SLAC, 100 GeV. Then there are KEK, then there are many others. These are not mentioned here. So this is just a small, very small list of the detectors that are there all over the world.

This is a linear collider. So this site is linearcollider.org and this is a part of the linear collider and it says that it's called ILC. It will be a necessary tool for unlocking some of the deepest mysteries about the universe. The ILC will allow physicists to precisely explore extremely high regions. Consisting of two linear accelerators, they'll stretch approximately 20 kilometers in length.

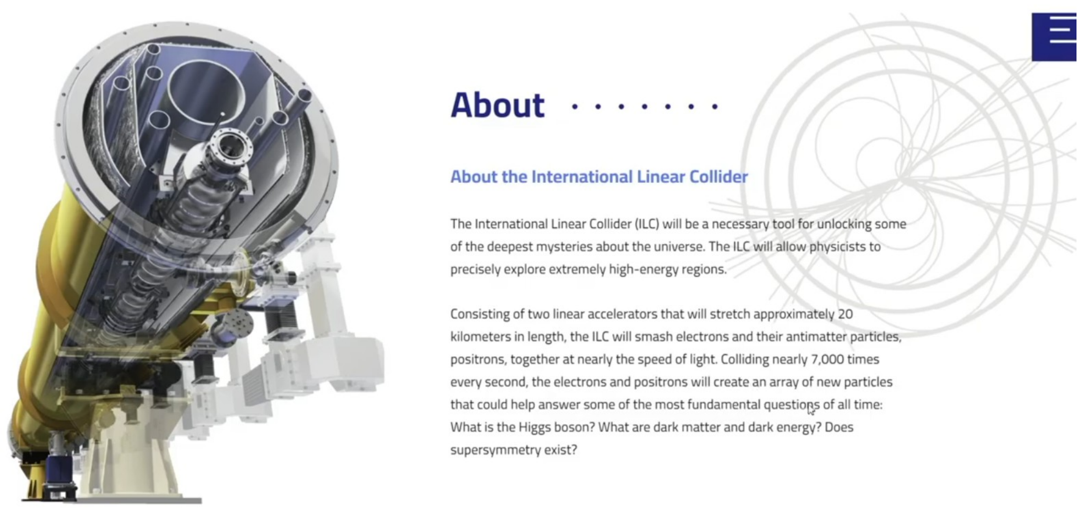

Photo taken from https://linearcollider.org/

The ILC will smash electrons and the antimatter particles, positrons, together at nearly the speed of light, colliding nearly 7,000 times every second. And the electrons and positrons will create an array of new particles that could help answer some of the most fundamental questions of all time. What is Higgs boson? What are dark matter and dark energy? Does supersymmetry exist?

So each one of these questions are important, extremely important in their own right. And we know the discovery of Higgs boson that created so much of excitement among the community. So I'll just have a slide on that. So this is the discovery of Higgs boson and this is from the CERN site where the Higgs boson discovery was done in July 4, 2012. So it says that what is Higgs boson?

In our current description of nature, every particle is a wave in a field. The most familiar example of this is light is simultaneously a wave in the electromagnetic field and a stream of particles called photons. I mean this really reiterates what we know about these microscopic particles of you know wave particle duality which has been encoded in this relation by de Broglie p equal to h over lambda. In the Higgs boson case, the field came first and the Higgs field was proposed in 1964, as early as 1964.

So, you know, nearly 60 years before as a new kind of field that fills the entire universe and gives mass to all the elementary particles. So, what Spring tried to say is that, you know, the field was discovered but the particle was missing. for all these years and it's basically it's a wave in that field the discovery confirms the existence of the Higgs field and so once again I did the Higgs boson is a particle that gives mass to all other particles it was predicted by Higgs, Englert and Braut as a part of the standard model of particle physics. So let me go into the various particles, elementary particles and their discoveries. It is more or less chronological.

So this is not 1997, it's 1897. So, Thomson discovered electron in 1897 and then the structure of the atoms were probed continuously and this Geiger-Mersden and rather for scattering experiment that found the structure of an atom and it found that there is a minuscule hard region positively charged inside an atom which is called as a nucleus and the nucleus which I've described in my earlier classes that how there was a confusion regarding the constituent particles of the nucleus, which later on got resolved. And one knows now that the nucleus contains protons and neutrons, and then there are strong forces inside that. Uh, photon was, uh, proposed by Planck in 1900.

So immediately after the, uh, discovery of electron, it was, um, uh, to, uh, the Planck actually proposed that this, uh, in the context of blackbody radiation. So this blackbody, this has also has been told, uh, the blackbody radiation intensity actually as a function of wavelength, uh, for different temperatures were studied. And it's found to have a nonmonotonic, uh, behavior, which means that at a given, lambda or the wavelength, the emitted intensity is the maximum. And this emitted intensity actually shifts with larger temperature and so on.

We will not talk about that here, but it could not be explained by invoking all the classical theories which are Vien's law and you know, Rayleigh-Jeans law. And then later on, so Planck actually explained it by saying that you multiply it by a distribution function of the photons. So he said that these, you know, electromagnetic radiation is emitted and absorbed in some quanta, this quanta called as photons, and we need to have a sort of distribution function for them that how they are distributed in various energy levels and he could fit the curve very well.

Later on Bose came and fixed this thing and he actually wrote down a statistics for these particles or these photons. as the ones which are indistinguishable, but there are no embargo on how many of them can occupy one energy state. And then, of course, this was backed up by Einstein's photoelectric effect where you shine a photon and an electron comes out and this is detected by a detector.

Discovery of various particles:

Thomson discovered electron in 1897.

Rutherford's scattering experiment to find the structure of an atom (1906-1913).

Photon was proposed by Planck in 1900 to explain blackbody radiation, backed up by Einstein's Photoelectric effect explanation (1905) & Compton effect (1923).

Quantum Electrodynamics was formulated by Feynman (1965) which treated EM field being quantized in terms of photons. The interaction between charges and photons was viewed as streams of photons passing back and forth between the charges, and the charges continuously emit and absorb this photons.

The electrons interact via the exchange of these quanta of the field.

And the explanation of that in 1905 and then Compton effect slightly later in which a photon comes and hits a stationary electron. And, well, I mean, it may not be stationary, but the approximation is good because the electron has much lesser velocity as compared to the photon, and the photon and the electron both scatter, and one measures the change in wavelength of the, you know, the radiation, that is, the incident minus the final radiation wavelength, so lambda minus lambda prime, and that measures gave a lot of information about, you know, this shift and all that they are detected in experiments. This reinforces the fact that, you know, all these microscopic particles, they can be, you know, sort of explained by invoking the particle characters such as, the energy and momentum conservation relations. In addition to that, there are other experiments such as interference and diffraction which necessitate one to go beyond this particle pictures and take into account the wave aspects. Then it was Feynman who formulated quantum electrodynamics which treated the electromagnetic field being quantized in terms of photons.

So in ordinary quantum mechanics these fields are taken as classical objects and it's only the electron its energy is quantized but here the background field is quantized I mean it was quantized as well And the interaction between these charges and photons was viewed as streams of photons, you know, passing back and forth between the charges, and the charges continuously emit and absorb these photons. And the interaction between with radiation and matter that was successfully explained. And the electrons are found to interact by exchange of this quantum of the field, which are nothing but the photons. Masons, on the other hand, this was 1934 onwards.

So people started worrying about the strong force that exists inside the nucleus. It is very strong and short-ranged and distinct from the electromagnetic force. That is, its origin does not lie in the electromagnetic force. Yukawa, in 1934, proposed that protons and neutrons interact via field whose quantum is just like photons, this field, the strong interaction field, has a quantum whose mass is about 300 times heavier than that of an electron, but lighter than that of a proton by about 6 times.

So it's in between the electron and the proton, and because of this intermediate mass, it's called mesons—meaning medium weight. And in that same spirit, protons and neutrons are called as baryons, which are heavyweight, and the electrons are called as leptons, which are lightweight. Now, systematic studies of cosmic rays confirm the presence of mesons. So again, this atmosphere is completely or continuously pierced by these cosmic rays, and they have confirmed the presence of mesons. But the confirmation came with a lot of disputes and discrepancies and debates such as the mass of the maisons and lifetime, etc.

And in 1947, several years after its proposal and discovery in various experiments, which I have neglected here, the debate was settled by, this is not due to Powell, who found the presence of pion and muon, which are called mu mesons. So pi mesons and mu mesons are called as the pions and muons. In fact, pions are the ones which are, you know, found in very large numbers in abundance in the upper atmosphere and they sort of decay as they enter into the atmosphere and the muons are mainly found at the sea level. Then there are discovery of antiparticles which proceeded from 1930 onwards.

Mesons (1934 onwards):

Strong force inside the nucleus is '*strong*' and '*short ranged*' and distinct from EM force.
Yukawa (1934) proposed that protons and neutrons interact via a field whose quantum has a mass heavier than an electron (300 times) and lighter than a proton ($\sim$ 6 times).

Because of its 'intermediate' mass, it is called as '*Mesons*' (medium weight).

Protons and Neutrons are called as *Baryons* (heavy weight).
Electrons are called as *Leptons* (light weight).

Systematic studies of Cosmic rays confirmed the presence of Mesons, however the Confirmation isn't free without discrepancies and debates (regarding mass, lifetime etc).

In 1947, the debate was settled ~~was~~ due to Powell found presence of π $(pion)$ and μ $(muon)$ $mesons$.
Pions are produced in large numbers in the upper atmosphere and *muons* at the sea level.

So this started from what we have done recently on the solution of Dirac equation. We have seen that Dirac equation admitted solutions which have both positive and negative values and these negative energy solutions or negative energy states are uniformly field and they are occupied by the Pauli exclusion principle. So if by some means one can knock off an electron from this negative state from the field negative state, it would be looked upon as a net positive energy and there will be a hole that is created in the pharmacy.

So this absence of an electron is called as a hole. So there is in that field pharmacy in the negative, I mean, which are occupying all the negative states, negative energy states. There'll be a sort of hole that is created and this absence of that electron is equivalent to a sort of a positive energy, a positive charge and positive energy, but same mass of that as an electron. So it's not a proton because proton has 2000 times larger mass that of an electron. And this is called as a positron.

We just described that positrons are really found in the cloud chamber experiments where the electromagnetic radiation splits into these electron and positron. So Dirac solution admitted particles of negative energy and antiparticles with positive energy. So there are a number of antiparticles that are discovered and some of them are written with a plus sign as a superscript and some of them are written with a bar. And like electron and positron are written with this E and E plus, mu and mu plus for the muons, mu mesons, P and P bar, and neutrons are N and N bar. And some of the neutral particles such as photons or gamma, they are same as their antiparticles.

Antiparticles (1930 onwards)

Dirac's solution of the wave equation admitted negative energy solutions and he assume that the negative energy states are uniformly filled and obeying Pauli exclusion principle.

Suppose '*an electron is knocked off from this negative states*' it would be looked upon as a net positive energy and there will be *a hole* in the Fermi sea. This hole would serve as an elementary particle of *positive charge and positive energy,* but *same mass as that of an electron*. This is called as *positron*.

Dirac's solution admitted 'particles' of negative energy and 'antiparticles' with positive energy.

$e \,\&\, e^+, \quad \mu \,\&\, \mu^+, \quad p \,\&\, \overline{p}, \quad n \,\&\, \overline{n}.$

Some neutral particles are same as their antiparticles, $\gamma \equiv \bar{\gamma}$.

So gamma is same as gamma bar. Then there were neutrinos that was discovered from 1930 onwards. So in the beta decay, what happens is that we have briefly talked about it earlier. A radioactive nucleus actually transforms into a lighter nucleus. with the emission of an electron.

So that's the equation A going to B plus E minus. And one is that, of course, I mean, B has to be having one, you know, more positive charge than A to account for the charge conservation. There was another anomaly that came that the experimentally obtained energy of this electron did not agree with the theoretical conservation of energy. So, it was probably at the verge of giving up the conservation of energy requirement. But then

Fermi actually proposed that let there be a new particle which carries these, you know, the difference in energy.

So this conservation of energy is still valid and he called it neutrino. It's actually anti-neutrino and this decay equation is in the modern terminology is written as neutron going to this P plus plus E minus and an anti-neutrino. and the neutrinos are also found in the decay of pi mesons, pi plus minus and mu plus minus. Then there are strange particles that are discovered from 1947 onwards, and by that time, you know, most of these things were understood, and people thought that the search for elementary particles is over, but it was far from over, and They discovered K on and this K0 is a neutral particle which really has a mass which is twice that of a pi on and you see the K0 actually disintegrates into pi plus and pi minus.

And later in 1949, a charged kaon was also found, which gives rise to 2 pi plus meson and 1 pi minus meson. In 1950, another new particle called as a lambda particle, which actually belonged to the proton, which resembled. proton and neutron in the baryon family and some along with that some strange facts emerge and the strange particles are produced abundantly with the time scale of 10 to the power minus 23 seconds so they are produced with this time scale because and it's easy to understand because the larger the energy is smaller will be the time scale by the uncertainty relation so this is they are produced at this rate and But they decay rather slowly. They decay with this time scale, which is much smaller, 10 to the power 13 times larger is the decay process time scale.

Strange particles (1947 onwards)

In 1947, the cloud chamber photographs reveal presence of a neutral particle, called *Kaon* (K_0), which has twice the mass of a *pion* and decays into

$$K_0 \rightarrow \pi^+ + \pi^-$$

Later (1949), a charged Kaon $K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$.

In 1950, a Λ particle was observed which resembled proton and neutron in the Baryon family.

$$\Lambda = p^+ + \pi^-$$

Some strange facts emerged:

These strange particles are produced abundantly with a time scale $10^{-23}\ sec$, however decay rather slowly ($10^{-10}\ sec$). Thus the production and disintegration mechanisms are distinct, viz, they are produced by strong interaction, and decay via weak interaction.

Gell-Mann and Nishijima assigned '*strangeness*' property to these 'strange' particles, in addition to charge, lepton number, baryon number etc. which should remain conserved.

So the production and disintegration mechanisms are different. That's what it says. And it's proposed that they are produced by strong interaction and decay via weak interaction. And because in keeping with this name, strange particles, Gelman and Nishijima, they assign strangeness property to these particles. And in addition to the charge, lepton number, baryon number, etc., which should remain conserved along with, you know, I mean, so the strangest property or strangest number also need to be conserved in a decay process.

However, in some decay processes, the strangeness number is not found to be conserved. And one of the important point that stands out here is that there exists, you know, consistent assignment of strangeness numbers to all the hedrons. Hedrons means the baryons and the mesons that accounts for the strong events to occur, but impedes some other to occur. For example, the leptons and the photons do not experience any strong forces at all, so they have no strangeness property. So we close these small, I mean brief and more like a story-like introduction by saying that there is a plethora of these elementary particles that are being discovered constantly from

you know, late 1900 and the early 20th century onwards, they are grouped into barions and maisons and the members are further identified by the charge, strangeness and mass. So, we have a lot of data, but that requires something like a periodic table, which the chemistry people faced that all these elements that are there, there was no consistent or systematic arrangement of that. So, one needs actually a periodic table for this particle physics and we will take up the subsequent discussions in the next class. So we'll stop here. We have provided a very brief introduction to these particles, how they are discovered and how the necessity of, you know, discovering them or rather predicting them first and then seeing them later.

That's usually the trend in particle physics. And this has happened from, you know, late 1900s from 1918, 1997 onwards. with the discovery of electrons and it went on and 2012 was the time when we have one has discovered Higgs boson. So that has added a lot of knowledge to this particle physics and we will see a little more before we conclude the course on modern physics. Thank you.

Amen.