ELEMENTS OF MODERN PHYSICS

Prof. Saurabh Basu
Department of Physics
IIT Guwahati

Lec 33: Periodic Table of Elementary Particles, Quark Model

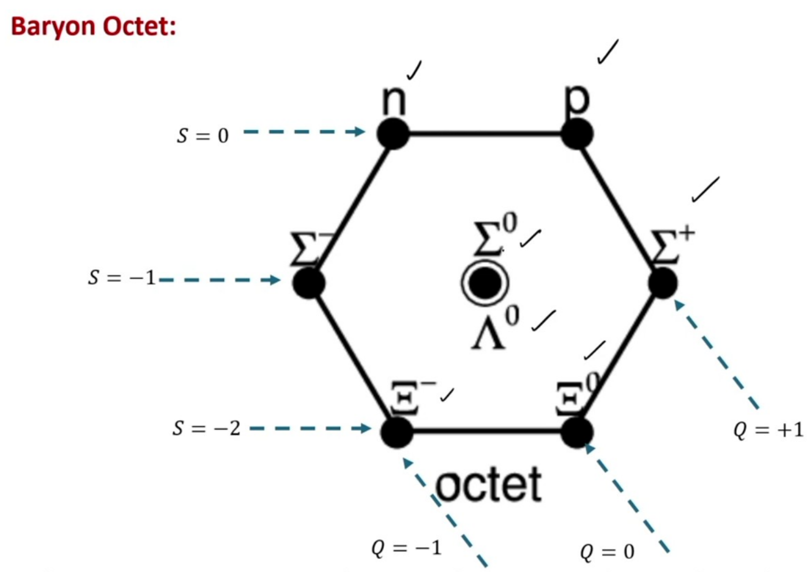
Welcome to this last class for the course called Elements of Modern Physics. And what we will be doing is discussing the periodic table of elementary particles. And this is very similar to what Mendeleev did for the chemical elements. And these elementary particles will be put upon some regular kind of structures, mostly hexagons or triangles. And this is called as the Eightfold Way.

And in particular, we'll talk about baryon octet, meson octet, baryon decouplet, and super multiplets. And finally, we'll talk about these composition of each of these hadrons, which are the quarks. So we'll talk about six quarks and talk about the eightfold way of quarks. We'll talk about this baryon decouplet again in terms of this quarks and the meson nonet. And finally, we'll give you particle data for your, you know, so that you can store them or use them later, which will contain the masses, et cetera, and different particles and all these elementary particles and so on.

So let me start with this periodic classification of these elements and these are very useful and are extremely sort of used, widely used in order to sort of make a repository of these particles and in terms of their strangeness, their charge and maybe even isospin which We talk about only the bare minimum that is required for you to know that these are elementary particles and they have a sort of arrangement which make them discernible or they are easily identified by their charge or the strangeness number, etc., So as I said earlier that it's very similar to what Mendeleev did with the chemical elements who, you know, in terms of electronegativities and ionic radii, etc. He arranged them in some kind of a table, you know, that the table has a rectangular structure while we have here a sort of hexagonal or triangular structure. And in particular, we will be talking about the baryon octet, the meson octet, baryon decouplets and meson nonets and so on.

So this is a baryon octet and these are the moderately heavy particles are, you know, put in this honeycomb where you see that this is neutron, proton and the sigma plus particles and these sigma 0 and this lambda 0 and these particles with, you know, all these 0 and minus and then you have a sigma minus particle and so on. So if you look at the strangeness numbers, which are noted as s equal to 0, s equal to minus 1, s equal to minus

2, and you also have these sigma 0, lambda 0 particles here, which are sort of characterized by these. So along these slanted lines, we have charge equal to plus 1 in unit of charge. Proton charge. So proton and the sigma plus particle, they have this charge Q equal to plus one.



Eight Baryons are put into a hexagonal array according to their Charge and Strangeness.

And then along this diagonal where all these neutrons, sigma zero, et cetera, they are there. So the charge is equal to zero. And then there are these along this slanted line where, you know, sigma minus and this particle is there. So there is this it is the charge is equal to minus one. And the strangeness numbers are 0 for neutron and proton and this middle line, the sigma minus, etc.

They have a strangeness minus 1 and then there's a strangeness minus 2. And these are the moderately heavy or kind of the lightest of actually the baryons are placed here. So there are 8 baryons, 6 at the corners of the hexagon and 2 in the middle. And they're according to their charge and strangeness. So these are what it is, you know, they are arranged like that.

And the charge and the strangeness number. So charge is Q and the strangeness is given by S. So strangeness is, you know, classified along the horizontal direction. And along the slanted lines, that is a downward slope or you can say that it is the rightward slope. These are given by particular, you know, kind of charges plus 1, 0 and minus 1. Similarly, we will do the meson octet.

But let us do a sort of summary of what we have seen. So the particles with same charge that lie along the downward sloping line of the hexagon. This is what we said. The charge Q is such that Q equals plus 1 for proton and sigma plus. Q equal to 0 for neutron lambda sigma 0 and this particle which is written by this symbol.

Description of the Baryon Octet

The particles with same charge lie along the downward sloping line of the hexagon.
The charge Q:
$Q = +1$ is for the proton (p) and Σ^+.

$Q = 0$ for the neutron (n), Λ, Σ^0 and Ξ^0

$Q = -1$ for Σ^- and Ξ^-

Similarly, the horizontal lines yields for the Strangeness S

$S = 0$ for n and p.

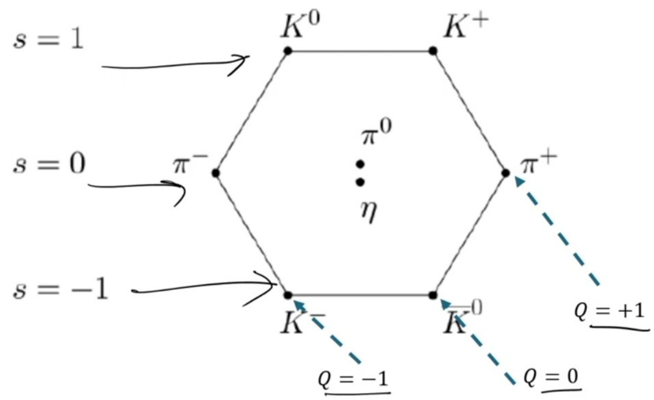
$S = -1$ for Σ^- and Σ^+.

$S = -2$ for Ξ^0 and Ξ^-.

Q equal to minus 1 for sigma minus and this minus and similarly the horizontal lines yield the strangeness which is equal to 0 for N and P and it is sigma minus and sigma plus for S equal to minus 1 and S equal to minus 2 for these particles. So this is how the baryon octet is formed and all these lightest baryons are put along a honeycomb or hexagonal structure and that is what is done. So then coming to the meson octet once again this is like this is the s equal to 1, s equal to 0, s equal to minus 1. Now you see that Gelman actually deliberately did it instead of

The octet that we saw there is 0, minus 1, and minus 2. He made it symmetrically plus 1, 0, and minus 1, and these are k-ons, the k-0 neutral particle, k-plus, pi-plus, and all that. You have a pi-0 and eta particle, and there is a k-minus negatively charged k-on. and pi minus, so they have a charge minus 1, and for all these particles, they have a charge equal to 0, and k plus and pi plus have charge equal to 1, and the strangeness numbers are shown as plus 1, 0 and minus 1.

Meson Octet:



Once again, the horizontal lines direction denotes Strangeness (S) and the slopy lines denote Charge (Q), but now instead S acquiring values $0, -1, -2$, here they take $1, 0 \; -1$.

So once again, you know, the horizontal line, they denote the strangeness and the slopey lines, basically the rightward slope, they denote the charge. But this anomaly is there with the baryon octet that S acquiring instead of these values 0, minus 1, minus 2, they take values 1, 0 and minus 1. So after 1961, so this was, you know, as we have discussed that as Gelman in 1961, he formulated this scheme. And after 61, there was a term called hypercharge was introduced, which was equal to the strangeness for mesons. And I mean, which was S equal to S for mesons and S plus one for baryons.

But later on it was decided that the strangeness actually provides a better description and the hypercharge was reserved for something else later on. So it was found that the hexagons are not the only figures which are allowed by the 8-fold way, there can also be triangles accommodating 10 heavy baryons. So, we have talked about the light baryons, now we talk about the heavy baryons and these triangular shape in which 10 heavy baryons are arranged or they are accommodated is known as the baryon decouplet. And this looks like this inverted triangle where you have this as the, you know, sort of s equal to 0.

After 1961, a term called '*hypercharge*' was introduced which was equal to S for Mesons and $S + 1$ for Baryons.

Later on, it was decided that '*Strangeness*' provides a better description.

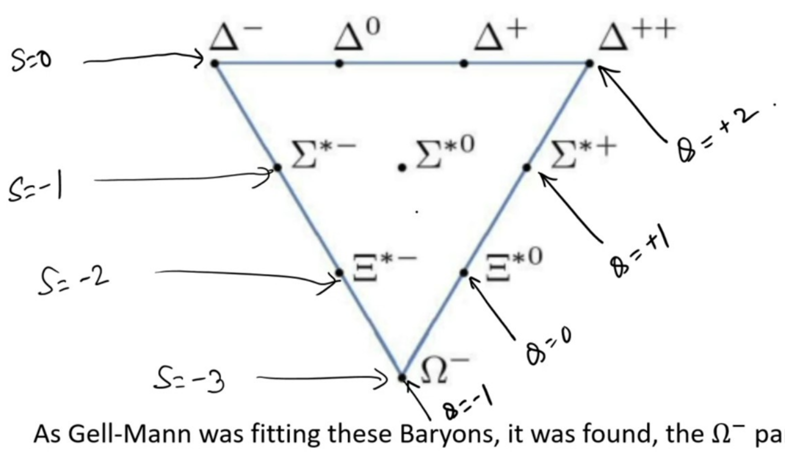
It was also found that hexagons are not the only figures allowed by the 'Eightfold way', there can be triangles accommodating 10 '*heavy*' Baryons.

The latter is called as the Baryon decuplet.

So this is s equal to 0. And then you have this as s equal to minus 1. And then you have this as s equal to minus 2. And this has s equal to minus 3 and so on. And these charges are again in this direction.

So you have a Q equal to minus 1 and then you have along this you have a Q equal to 0 and along this you have a Q equal to plus 1 and then you have a Q equal to plus 2. Okay, so these are the assignments and these various heavy variance, delta minus, delta 0, delta plus, delta double plus, then all these sigma star minus, sigma star 0, etc. That is there in the middle and then you have a sigma star plus and all these other particles are there. And so when Gell-Man actually accommodated all these particles and this omega minus was still not found. And it was later discovered in 1964.

Baryon Decuplet:



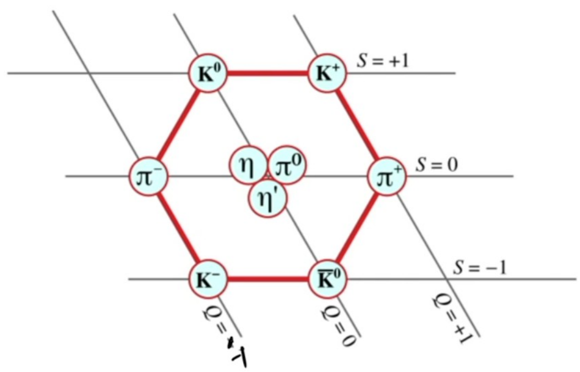
As Gell-Mann was fitting these Baryons, it was found, the Ω^- particle was not discovered. He calculated the mass and life time. It was later discovered in 1964.

In fact, Gelman had categorically said that he would find this particle and he calculated the mass and the lifetime, etc. And it was later actually experimentally discovered. And this really made this eightfold way or these classifications seem to be very robust. And it is still continuing to be the classification of the elementary particles. So all these particles were found experimentally.

And so basically, you know, after 1964, after these omega minus particle was discovered, then this for the next 10 years, all the hadrons, the mesons and the baryons, they can be fitted onto one or the other multiplets. And one of the multiplet is shown where you have these Kaons. So these are the meson multiplets. So there is a K0 and these are medium sized particles. So pi minus, eta, pi zero, pi plus, Kaon, K0 bar and all that.

After 1964, the eightfold way received robustness and within next 10 years all the Hadrons can be fitted into one or the other *supermultiplets*.

One of them is:



All the anti-particles found a place in the same *supermultiplets* as the particles.

And their charges are shown. So this is minus one charge. So, Q equal to 0 and Q equal to plus 1 and the strangeness are also indicated. So, all these particles and also the antiparticles, it is not only the particles, the antiparticles also being accommodated in this super multipliers and there are many of them. I just show one of them here and basically the classification of the elementary particles were complete by these 1964.

So that brings us to the quark model and a question that should be asked at this point that how do these hadrons or why do these hadrons fit into such regular and geometric patterns, okay. Like sometimes we have a hexagon or sometimes we have a triangle but we are able to fit everything putting something at the middle and this classification seem to be complete, okay. So in 1964, again, Gelman and Zwick, quite independently, they proposed that these hadrons are composed of even more elementary particles, and these are called as quarks. And the quarks actually come in three types, and these types are, for quarks, they're called as flavors, and these quarks actually follow a similar eight-fold pattern as the mesons or the baryons. So there are six quirks, up, down, charm, strange, top and bottom.

So this is written as U and then D and then C and then S, then T and B. So these are the six quirks. They have wide range of masses. They have fractional charge. We will see soon that they have fractional charge and they experience all the fundamental forces of nature. So going back to the quark picture, so there's a DUS quark.

The Quark Model:

A central question still prevailed: Why do the Hadrons fit into such Regular and geometrical patterns?

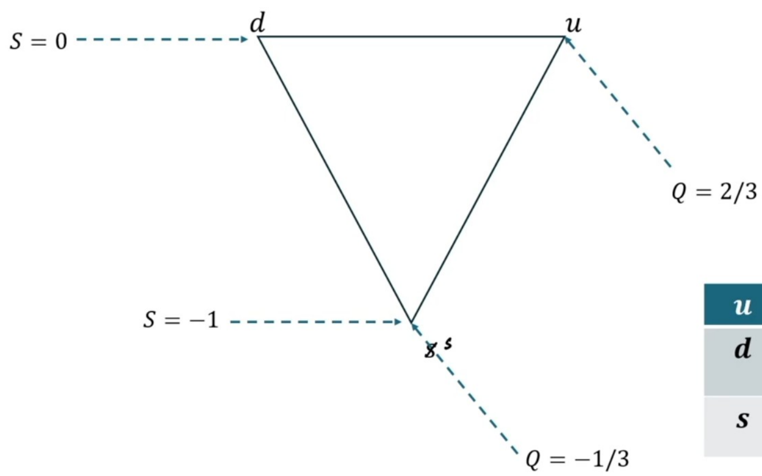
In 1964, Gell-Mann and Zweig independently proposed that the Hadrons are composed of even more elementary particles, called as *Quarks*.

Quarks come in three types, which are called as '*flavors*', that follow a similar Eightfold-way pattern.

There are in fact, 6 quarks, named as ***up, down, charm, strange, top, and bottom.***
u d c s t b.
They:
(a) have wide range of masses,
(b) Fractional charge,
(b) experience all the fundamental forces of nature.

I mean, this is really should be written with a small s. So it's like a small s. So UDS. And if you put it in the vertices of the inverted triangle, then the U quark has a charge which is two-third. The S quark has a charge which is minus one-third. D quark also has a charge minus one-third. The strangest number for the S quark is minus 1 and the strangest number for D and U quarks are S equal to 0.

Eightfold way for quarks



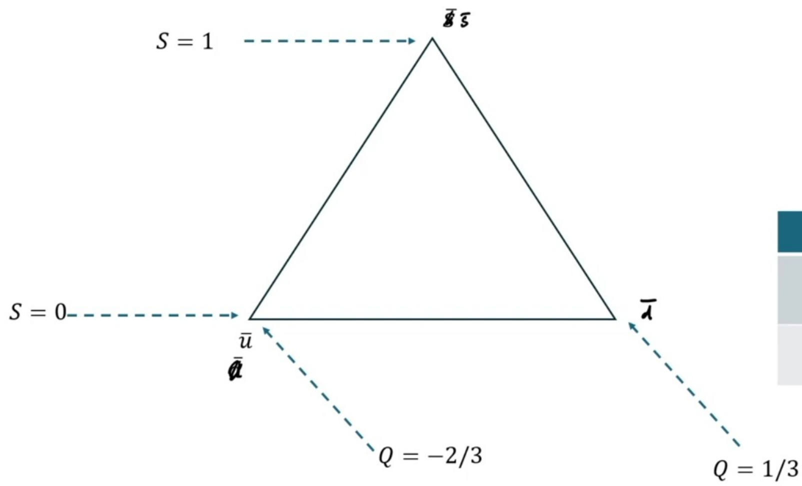
u	$Q = 2/3$	$S = 0$
d	$Q = -1/3$	$S = 0$
s	$Q = -1/3$	$S = -1$

So this is what you get for the UDS, Q equal to two-third, Q equal to minus one-third and Q equal to minus one-third, S equal to 0, S equal to 0 and S equal to minus 1. So that is the characteristics of these quarks. Similarly, for the anti-quarks, you can have the normal triangle, upright triangle, where we have this as S bar. So, that is S quark with anti-quark basically. So, this eightfold way for anti-quarks is shown.

So, it is S bar, U bar and so you have a D bar. So, the D bar has to be here. And once again, the S bar and the D bar have a charge, which is Q equal to one third. And the U bar has a charge, which is minus two third. Again, the strangeness numbers are for the S bar.

It's equal to S equal to one. And for the U bar and D bar, the strangest number is equal to zero. And this is, you know, compiled in this small table. You, this is actually a bars. I don't know why it's not seen, but anyway, these are bars.

Eightfold way for anti-quarks



$\bar{u}$	$Q = -2/3$	$S = 0$
$\bar{d}$	$Q = 1/3$	$S = 0$
$\bar{s}$	$Q = 1/3$	$S = 1$

Okay. All right. So, so Q equal to minus two-third, Q equal to one-third, and Q equal to one-third for this U bar, D bar, S bar. And the strenuous number is 0, 0, and 1. Okay.

So these are the eight-fold way of the quarks and the anti-quarks. Okay. So further there are composition rules so each baryon is composed of three quarks and also each antibaryon consists of three antiquarks. So actually this is so the antibaryon of course we have not written there but each meson is composed of a quark and an antiquark okay so this is important. So we actually put the chart.

I mean, this QQQ is basically the quark. So UUU quark will make an A++ variant with Q equal to, so this is Q, if it's not visible, this is taken from this book of Griffiths called The Introduction to Elementary Particles. It's a very, very nice book. And if you want to have a glimpse of particle physics, you can start with this book. So you have a UUU quark with charge equal to 2 because each U quark has a charge 2 third.

So 3 into 2 third will give you 2. Strangest number equal to 0 and this is the variant. The name of the variant is A++. Similarly, UUD will have these Q and S values and we have A+. UDD is delta 0.

Further, there are composition rules:

1. Each Baryon is composed of three quarks.
2. Likewise, each anti-Baryon is composed of three anti-quarks.
3. Each Meson is composed of a quark and an anti-quark.

THE BARYON DECUPLET (10 combination of 3 quarks)

qqq	Q	S	Baryon
uuu	2	0	A++
uud	1	0	A+
udd	0	0	Δ^0
ddd	−1	0	Δ^-
uus	1	−1	Z*+
uds	0	−1	Σ^{*0}
dds	−1	−1	Σ^{*-}
uss	0	−2	Ξ^{*0}
dss	−1	−2	Ξ^{*-}
sss	−1	−3	R−

THE MESON NONET (9 combination of quark-antiquark)

$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	7r+
$d\bar{u}$	−1	0	π^-
$d\bar{d}$	0	0	η
US	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	−1	−1	K^-
$s\bar{d}$	0	−1	$\bar{K}^0$
$s\bar{s}$	0	0	??

Source: Griffiths book on 'Introduction to elementary particles'

DDD is delta minus. UUS is Z star, the Z particle. UDS is sigma star 0, DDS is sigma minus, USS is this, DSS is that thing and S equal to SSS is this particle that is there. So, all these particles are the baryons are listed and their quark compositions are listed as well. And you have a meson on it as well.

So there is a UU bar and a UD bar, then the DU bar. So UU bar makes a pi 0 meson. And then you have a UD bar which makes a pi plus. So this is pi plus. And then you have a DU bar which makes a pi minus, then eta particle, then kaons.

which are US and so on. So if you write it is like US, then DS bar, SU bar, etc., etc., all these k-ons are there. Interesting that this does not have any analog in the sense that SS bar, the total charge is zero and the total strength is zero and it is not known. So this way, you know, the baryons and the mesons, they also can be described in terms of the quarks. And finally, I give you a list of particle data.

It's only for your record. So these are leptons with spin half. So these, like electrons and neutrinos, and so on. The charges are given, and the masses are given as well. So masses are in MeV.

Leptons (spin-1/2)

Flavor	Charge	Mass (MeV)
e (electron) ν_e (e neutrino)	-1 0	0.51099 0
μ (muon) ν_μ (μ neutrino)	-1 0	105.659 0
τ (tau) ν_τ (τ neutrino)	-1 0	1776.99 0

Quarks (spin 1/2)

Flavor	Charge	Mass (MeV)
d (down) u (up)	$-1/3$ $2/3$	7 3
s (strange) c (charm)	$-1/3$ $2/3$	120 1200
b (bottom) t (top)	$-1/3$ $2/3$	4300 17400

So, there is a mu meson and then neutrino and then tau neutrino and so on and their masses are given in MeV. Electron is of course the lightest and then you have muons and mu neutrinos have mu neutrino. Neutrino has no mass, so that mass is 0 and muon has a mass which is 105 MeV. Tau is really heavy which is 1777 MeV nearly. So these are quirks with spin half so we have a down up strange charm bottom top

with the charges minus one-third, two-third, minus one-third, two-third, minus one-third, two-third. And as we have said earlier that the masses vary widely. It goes from 7 MeV to 17,400 MeV. That's a large variation in the mass. Then these mediators of force, which are spin-1 mediators, the mediators of strong force, Mediators (spin 1)

Force	Mediator	Charge	Mass (MeV)
Strong	g (gluons)	0	0
electromagnetic	γ (photon)	0	0
Weak	$W^{\pm}$ (charged) Z^0 (neutral)	± 1 0	80.420 91.190

They are called gluons just like the mediator of electromagnetic force is called as photon. So these are strong forces called gluons which have charge zero. So these are charge neutral objects and mass is also zero. Electromagnetic is of course photon with no charge and no mass, just like gluons. And the weak has for the W plus minus charge, it is a charge plus minus 1 with a mass which is 80.4 MeV and Z0.

Again a neutral particle charge 0 but mass is equal to 91.19 MeV. So these are the mediators spin 1. Then there are these baryons which we have talked about this proton UUD charge is equal to 1 and mass is known to be 940 close to 940 MeV 938.27 MeV. Similarly, neutron is UDD, charge 0, 939.56, almost same as that of proton, lambda particles and so on so forth, UDS and these are the masses that are given. So, there is only data, you can store them and if there is any question on this.

Baryons (spin 1/2)

Baryon	Quark Content	Charge	Mass (MeV)
p	uud	1	938.272
n	udd	0	939.565
Λ	uds	0	1115.68
Σ^+	uus	1	1189.37
Σ^0	uds	0	1192.64
Σ^-	dds	-1	1197.45
Ξ^0	uss	0	1314.8
Ξ^-	dss	-1	1321.3
Λ_c^+	udc	1	2286.5

you could, you know, refer to this table that is there. So, all these particles and their core content or the composition is mentioned along with the charge and the mass. So, finally, the variance which are high spin variance, the spin is not half, but the spin three half variance such as delta particles, We have not talked about the spin or the isospin, we are just presenting it still in data. So, delta is u u u u d u d d d d d and each come with a charge.

Baryons (spin 3/2)

Baryon	Quark Content	Charge	Mass (MeV)
Δ	uuu, uud, udd, ddd	$2, 1, 0, -1, -2$	1232
Σ^*	uus, uds, dds	$1, 0, -1$	1385
Ξ^*	uss, dss	$0, -1$	1533
Ω^-	sss	-1	1672

So, u u u u three u's will have a 2 charge equal to 2 in the unit of proton charge. And then you have a UUD, which has a charge of 1. udd has a charge of 0. And ddd has a charge, you know, minus 1, and so on.

Yeah, so then there are the sigma star particles, which are 1, 0, minus 1 for these. uss, dss, sigma minus is sss, and so on. Then there are pseudo-scalar mesons, which are, so these are lighter particles or intermediate particles. So we have a pi meson, pi plus-minus meson, pi zero. They are formed by the combination of this, and you see that they are combinations of quark and antiquark with a variety of charges and masses and so on, and the vector mesons.

Pseudoscalar Mesons (spin 0)

Meson	Quark Content	Charge	Mass (MeV)
$\pi^{\pm}$	$u\bar{d}, d\bar{u}$	$1, -1$	139.570
π^{0}	$(u\bar{u} - d\bar{d})/\sqrt{2}$	0	134.977
$K^{\pm}$	$u\bar{s}, s\bar{u}$	$1, -1$	493.68
$K^{0}, \bar{K}^{0}$	$d\bar{s}, s\bar{d}$	0	497.65
η	$(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$	0	547.51
η'	$(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$	0	957.78
$D^{\pm}$	$c\bar{d}, d\bar{c}$	$1, -1$	1869.3
$D^{0}, \bar{D}^{0}$	$c\bar{u}, u\bar{c}$	0	1864.5
$D_s^{\pm}$	$c\bar{s}, s\bar{c}$	$1, -1$	1968.2
$B^{\pm}$	$u\bar{b}, b\bar{u}$	$1, -1$	5279.0
$B^{0}, \bar{B}^{0}$	$d\bar{b}, b\bar{d}$	0	5279.4

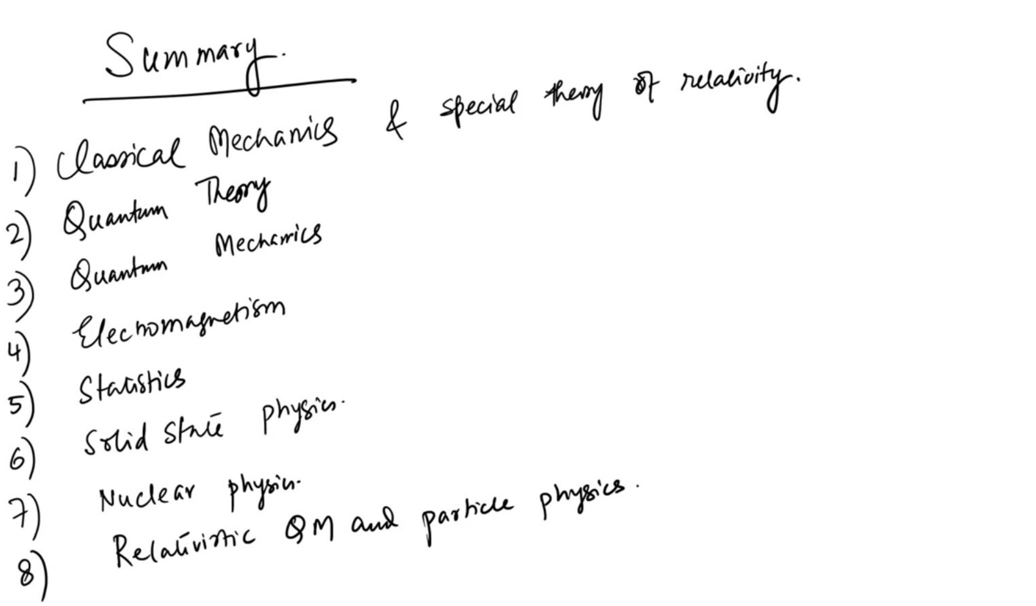
which are spin 0, so that they are rho, k star, omega, psi, d star, and these gamma. And so these are spin 0 things, and with their quark content is shown. And that is precisely what the course is all about. And if I try to give you a final overview of the course that we have done so far, we have started with, you know, a summary. Summary of the course: we have started with classical mechanics.

Vector Mesons (spin 0)

Meson	Quark Content	Charge	Mass (MeV)
ρ	$u\bar{d}, (u\bar{u} - d\bar{d})/\sqrt{2}, d\bar{u}$	$1, 0, -1$	775.5
K^{*}	$u\bar{s}, d\bar{s}, s\bar{d}, s\bar{u}$	$1, 0, -1$	894
ω	$(u\bar{u} + d\bar{d})/\sqrt{2}$	0	782.6
ψ	$c\bar{c}$	0	3097
D^{*}	$c\bar{d}, c\bar{u}, u\bar{c}, d\bar{c}$	$1, 0, -1$	2008
Υ	$b\bar{b}$	0	9460

in which we have talked about a little about Newtonian mechanics and Lagrangian mechanics and then we have talked about relativity as well. So, we have a special theory of relativity which was briefly discussed and Lorentz transformation equation etcetera were you know told special theory of relativity in which we found that you know in very large velocities the space and time are coupled Then we have talked about these quantum theory, the development of basically quantum mechanics that is what led to the formulation of quantum mechanics and so on. So we've talked about quantum theory, and then we have talked about quite elaborately on quantum mechanics. We have done a lot of problems on barrier transmission, hydrogen atom, harmonic oscillator, and so on.

And we also have done perturbation theory, which are called as approximate methods, when you cannot solve the Hamiltonian exactly. We have done that. Then we have done also electromagnetism in which, you know, we started from these electrostatics and magnetostatics and have landed up with the Maxwell's equations and various boundary conditions have been discussed. Then we have done statistical mechanics in which all these ensembles and the three distributions, namely the Maxwell-Boltzmann, Bose-Einstein and Fermi-Dirac distributions are discussed. Then we have done solid state physics.



And the solid state physics comprises of, you know, a little bit of crystal structure. And then we have done these phonons and the free electron theory and some results which are of importance at this level. They have been discussed. So solid state physics, then we have done nuclear physics in which we have talked about structure of the atom, radioactivity, etc., So, we have done nuclear physics as well.

So, all these more or less apart from quantum mechanics where we have spent about three weeks or so, other than that most of these we have either spent a week or two weeks or week and a half and so on. And then finally, we have done briefly relativistic quantum mechanics and particle physics. And particle physics. So the course really ends here and where these are really the elements of modern physics, which means that we have picked up each one of the topics that constitute modern physics and have tried to justify as much as we could do in one week or two weeks or even three to four weeks. I mean quantum mechanics, even if we have spent three to four weeks, that's not enough.

One needs to have a complete course on that. But I've tried to cover and touch upon the ones that are of utmost importance and one should know. And if you supplement this course material by the problems that will be given for the homework or the assignments, then you would know what these, you know, this modern physics course is all about. There are books on modern physics, a number of them we have published. Crane and we have Beiser and we have many other books which are really good and one should also take a look at that.

They are probably more elaborate for most of these topics but at least the bare minimum along with the ones that are of importance in learning the subject that have been given. So I'll stop here, thanking each one of you for attending the course and benefiting from it. It'll be a pleasure to hear more about the course and where you want me to improve. Or if some concepts and fundamentals have not been cleared, I'll be most happy to answer. Thank you very much.

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