Select/Special Topics in Atomic Physics
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Lecture - 39
Zeeman Effect Fine Structure, Hyperfine Structure – Elemental, Rudimentary Introduction to Laser Cooling, BEC, Atomic Clock/ Attosecond Metrology

Greetings, and this will be the last class of this course, and I will provide a very rudimentary introduction to some further applications of atomic physics. And in particular we have been talking about atoms, which are in the presence of external fields, we consider the electric field, the magnetic fields and the other kinds of fields that we talk about.

So, there will be a very rudimentary introduction to things like laser cooling, Bose-Enstein condensation, and we will see how it will leads to very accurate measurements of time, we will talk a little bit about atto second metrology and so on. Essentially, we will discover that, we need additional tools to study these topics in details, because we will need further base in quantum collision physics, and also in relativistic effects and in studying electron correlation and so on. So, that really becomes a subject of our whole additional course, so let us go back to what we studied in Zeeman effect, and we studied the sodium atom in an magnetic field.

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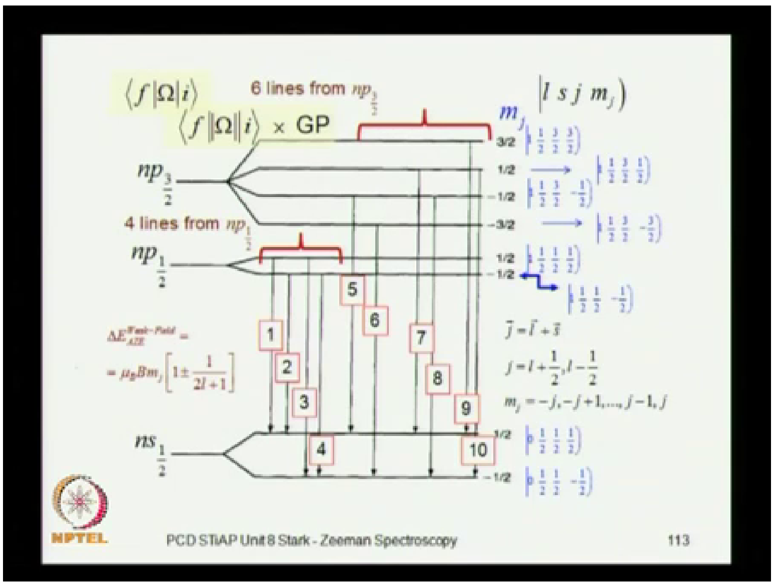

And we found that the d 1, d 2, 2 lines split into 10 lines, 4 lines from, the n p 1 by half and 6 lines from the n p 3 half, so in total of n lines what you get, but then there is motto atomic structure then, what we have considered, so far.

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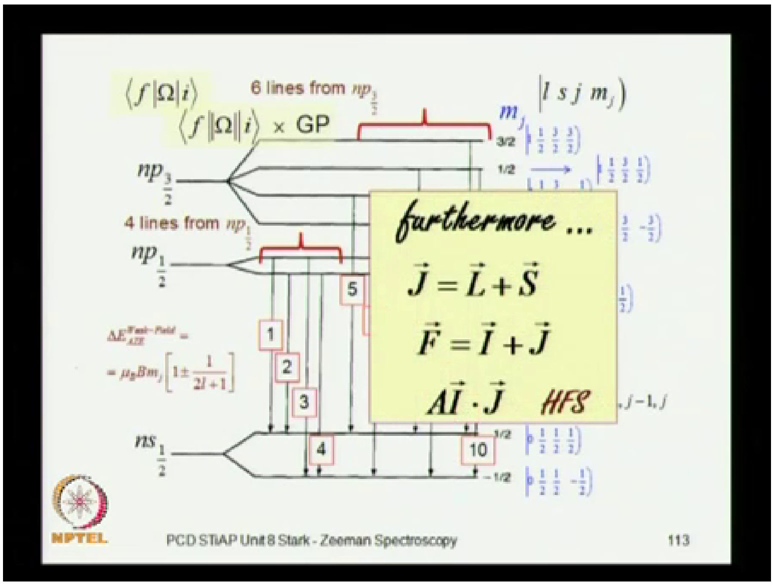

And that is the hyper fine structure, because we did you know in the context of perturbation theory, we always said that all perturbation which are of the same order of importance, must be considered together. And the most important ones must be considered first, and the less important later, and the perturbation can be, because of internal structure, which we not considered at that until that point.

Like earlier when we ignored the relativistic effects or when we ignored the spin orbit effects, spin orbit interactions, now these are internal to the atomic structure, the atom exists along with these properties. So, you cannot add these properties, when you put it in an external magnetic field or on a electric field, you have some control, so that you can switch on that wheel or switch it off, but you cannot switch off the spin orbit interaction in the atom it is there.

So, likewise there is an additional internal structure, which is the hyper fine structure, this comes from the nuclear spin, and the nuclear spin angular momentum, which we have represented here as this I. So, this is the nuclear spin angular momentum, and this would couple to the net angular momentum, which is coming from L plus S coupling, and you get the hyperfine structure coming from this I dot J interaction, and this has some very exciting, you know applications in atomic physics.

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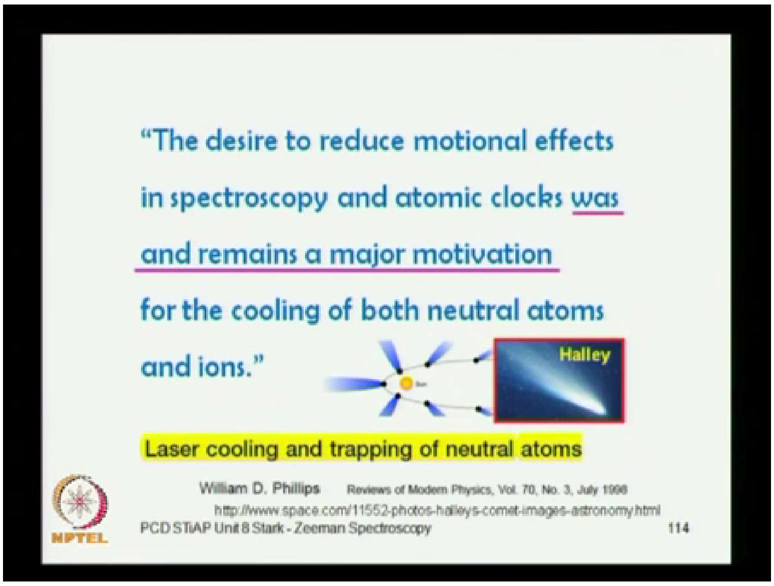

And this comes together in quest for measuring time, and here is the quote from an article by William Phillips, who got the Nobel prize for laser cooling, and this paper is in the review of atomic physics, which we have uploaded at the course web page. And Phillips points out in this article that, the desire to reduce motional effects in spectroscopy, and atomic clocks was and remains a major motivation for the cooling of both neutral atoms and ions.

And this is where the hyperfine structure plays a big role in enabling us to go for things like laser cooling, Bose-Enstein condensation, and measurement of time in a very precise manner. So, you need to slow down the atoms, to be able to see their structure and properties, and then measure the frequency of transition between two different levels. And accurate measurement of frequency is what will give you a standard for measuring time, because frequency is just the inverse of time.

So, how would you slow down an atom and 1 knows just by looking into the sky, that you can slow down the atom by shining light on it, because you always know that the comets have their tails, which are directed away from the sun. No matter, where they are on the orbits, it is not the tail trails the atom on the trajectory, but it is always directed away from the sun, and that is because of the radiation pressure. So, here is the nasal picture of the Halleys Comet and one knows, if you shine light on an atom, you can actually slow it down.

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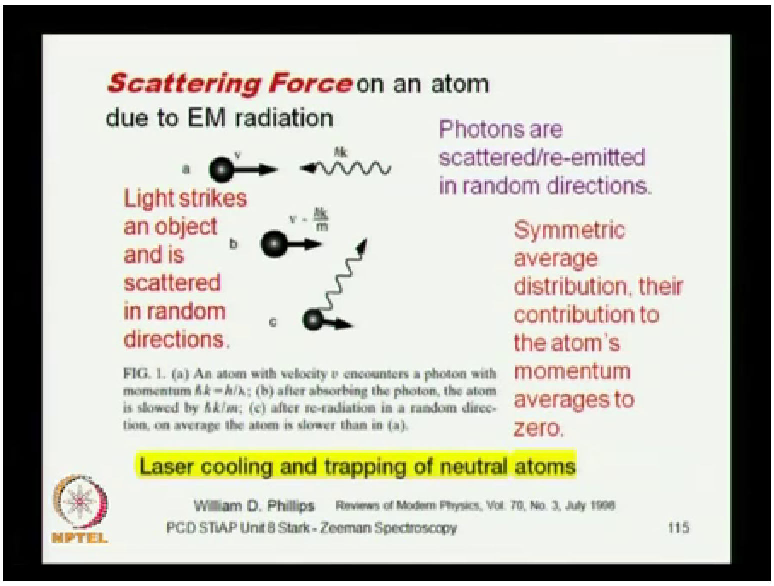

So, this is called as a scattering force, and this is again a figure from wonderful article by Phillips, which I very strongly recommend, and I will only provide a very brief introduction to this article. That when you have an atom, which is moving from left to right let us say and a photon which is moving from right to left, and they collide and the atom absorbs this light.

Then it is going to slow down, it is velocity will come down by the linear momentum of the photon divided by the mass of the photon, and eventually the atom will get excited, because it is absorbed that energy. And when it is exited it will also radiate that excess energy, after it has lived it is lifetime in the exited state, and then it will cool down. So, I will show you this cooling cycle, how this cooling actually takes place, because what is happening is the translational kinetic energy get gradually converted into the energy, which is radiated away from the atom.

So, there is a an average the energy, which is radiated away would be radiated in any orbitary direction, it not necessarily in a given direction, because that is coming out of spontaneous radiation of energy. So, this is the wonderful piece of work, for which Steven Chu, Cohen Tannoudji, and William Phillips are shared a Nobel prize on 1997 for laser cooling.

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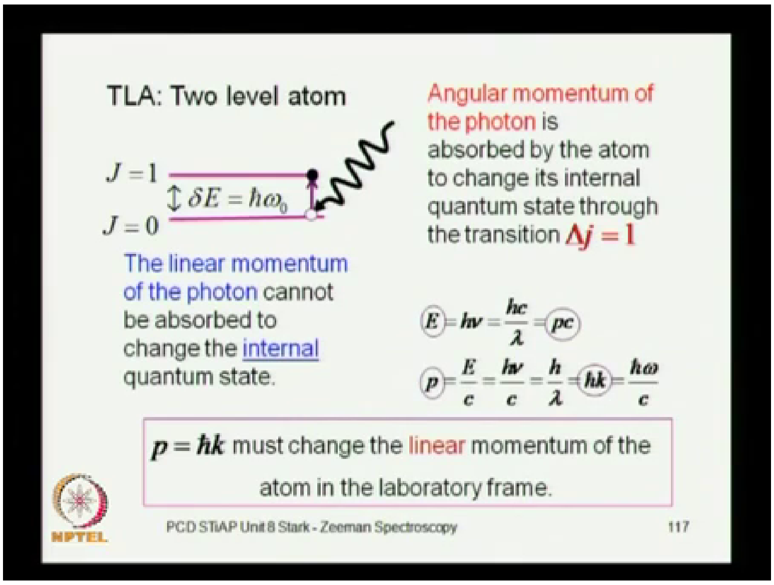

And to understand this process of cooling, we consider a two level atom, so let us consider a two level atom in a stage J is equal 0. And it is absorption of photon could raise it to J equal to 1 at exited state, and let us say that light falls on it, resonant light which is appropriate for this transition from the lowest state to the exited state, and the atom gets exited.

Now, what is going to happen is that the angular momentum of the photon is absorbed, and the internal atomic quantum number, the angular momentum quantum numbers, they change. And the internal changes in the atomic structure raises, it to through a delta J equal to 1, so that is where the angle of momentum is being taken care of, but what happens to the linear momentum of the photon. The linear momentum of the photon cannot change the internal structure of the atom, so the linear momentum of the photon ends are changing the velocity of the atom in the laboratory frame happens.

Because, it cannot change the internal structure the angular momentum changes the internal structure, but not the linear momentum. And if you look at the expression for energy which is equal to p c, which are my initial and there are actually no co incidence about this the momentum is h cross k. So, this momentum, which is absorbed by the photon must change, the momentum of the atom in the laboratory frame, so this is where the change in velocity of the atom will result.

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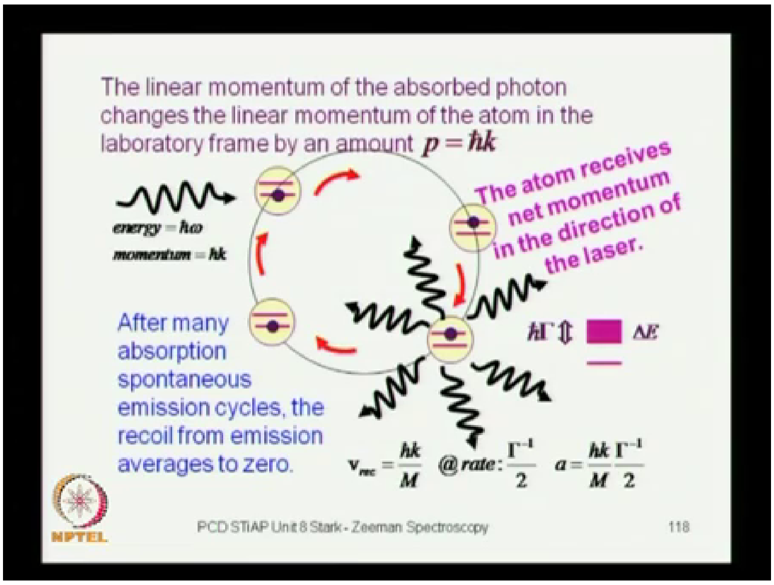

So, this is let us see how this p process actually takes place, so you have got energy, which is absorbed by the atom, the atom then goes to an exited state, so this is the cooling cycle by, which I am effecting in these picture. So, the atom is raised to an exited state, and then it loses energy now there are so many different possibilities. Of course, when there is one transition from the exited state to the lower state, only one photon is going to be emitted and it is going to be one of these.

So, it is not that there are so many different photons, which are been emitted in all the directions that will not even conserve energy, so only the energy difference between that is going to be radiated away. And it will go in one of these directions, but it could be any one of these, it does not have to be any chosen one of these, because this is happening through the process of spontaneous emission, and the radiation can take place in any orbitary direction.

So, what happens after the radiation is emitted through spontaneous emission, the atom would go down to the lower state as it started outward, so it comes back to the lowest state, and now it is ready to absorb another photon. And this what is called as the cooling cycle, because now it not becomes ready to absorb the next photon, and the next photon and the next photon raises it to an exited state. And now once again it is going to emit light through spontaneous emission, but it will be not necessarily in the earlier step, if it lost light in this direction.

In this type around it might lose it in this direction or it could lose light in some other direction, and when it goes through a number of such cycles, every time it is going to lose light in a different direction. Now this is where all of these different directions come into play, and what is the net average of all of these, when it goes through a number of cycles.

Whatever, you know kick it gets, because of the recoil coming from this spontaneous emission of a photon, it gets averaged to 0, and the result is that it is ends up getting a net extra momentum in the direction of the laser light, which is the original direction. So, that is how it gains momentum in a particular direction, because the recoil kick it gets by emitting the photon in different directions, in different cycles it gets averaged out. So, this the principle of laser cooling, because so it does not happens in a single step, but when it happens again and again and again and again, over a number of cycles.

And you can estimate how many times this will have to take place, because you know that the rate at, which it will lose energy will depend on what is the level width of the exited state. The exited state is of course, not a the sharp one, if it is shard the atom would never decay, because then it could have infinite life time. And it the exited state has got a certain width, and therefore a finite lifetime which goes inverse of the width through the certain principle, and that is what results in recoil, which is the momentum divided by the mass of the atom.

And this will happen at half life of the exited state, so if gamma h cross gamma is the energy width and this will happen at a rate which is gamma inverse by 2. So, this will result in an acceleration, which is the velocity multiplied by this rate, because the acceleration is just the rate of change of velocity. So, this is the rate at which, you know the atom will be accelerated, and it will be losing it is kinetic energy it will be losing it is velocity, in the direction in which it is approaching the laser, and that is what the results in cooling.

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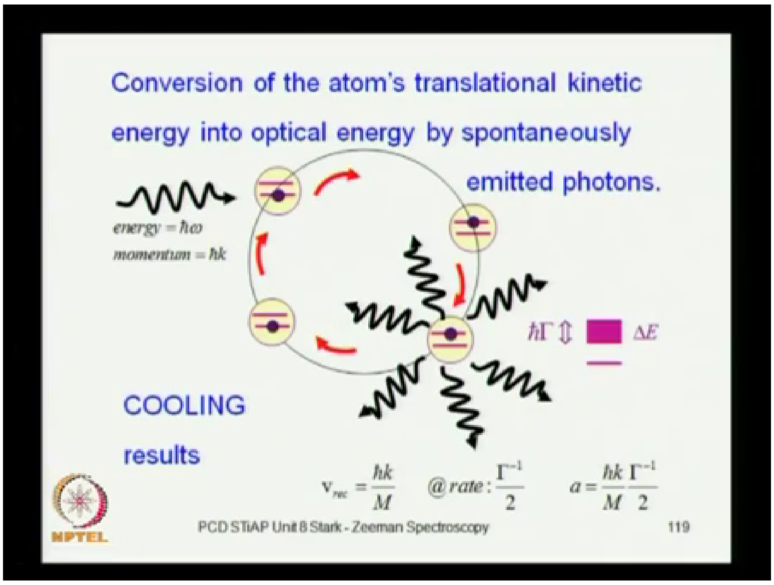

So, this is how cooling results what is happening is that the atoms translational kinetic energy, gets converted into optical energy through spontaneous emission of photons, so there is an energy transform through this process. So, this is like taking an additional degree of freedom into account, which was not there originally which is losing light through to the surrounding.

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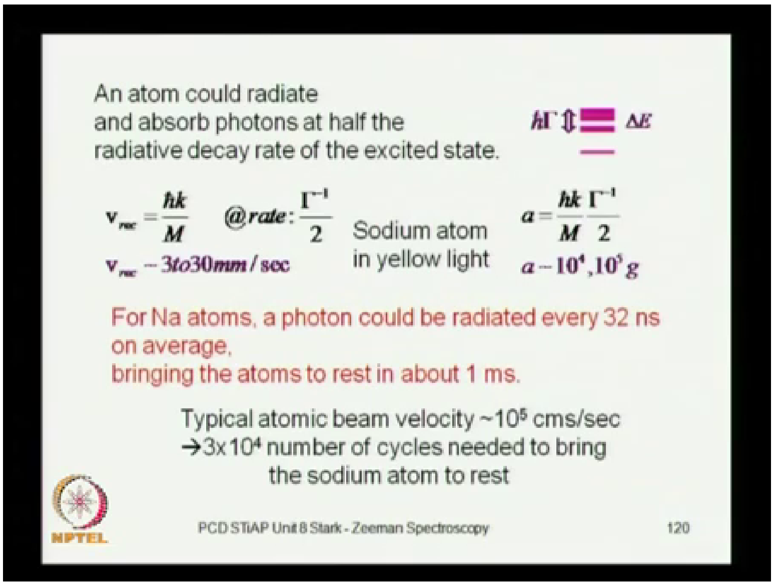

So, you can estimate how long it will take, because if you plug in these numbers, for sodium atom for example, if you consider it is lifetime and mass and the so on. The resulting accelerations are as large as 10 to the 4 or 10 to the 5 times the acceleration, due to gravity. So, you the atom goes through very high you know acceleration, because of this and you can work out these numbers, and if you have the sodium atoms of photon can be radiated at about every 30 32 nano seconds on an average, and the atom can be brought to rest in a about a milli second.

So, this is you need altogether a number of something like 10 to the 4 cycles for this to have, because every time it goes through this cycle. It is losing a little bit of kinetic energy, it is losing a little bit of velocity, and then that is what results in cooling, because thermodynamically, we are associated temperature with velocity of motion.

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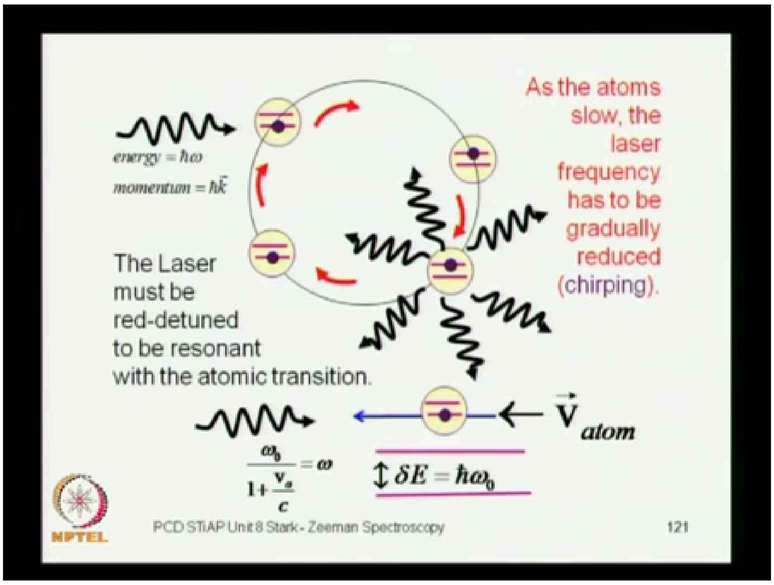

So, this is the cooling cycle, as we have seen, and the other thing you must remember is that the atom, and the laser of course, approach each other in different directions, so they are coming opposite to each other. So, now, there are some complicating factor, you have to worry about that, because what you really need is not a laser of a frequency, which is exactly appropriate corresponding to the energy difference of the atom when it is addressed.

But, the energy difference which is appropriate, when it is in motion and there will be Doppler correction which is required, and if the Doppler correction is not done the atom will not be able to absorb that energy. So, you need the energy to absorb this energy radiated, re absorbed, re radiated, re absorbed, and go through this cooling cycles, so the Doppler effect is going to play a big role in this.

So, you really need a laser, which is red de tuned, you know with respect to the resonant atomic transition there must be a red de tuning, but then when you have a red de tuning you have done it for the initial velocity, but then the atom now get slowed. So, this red detuning has to be continuously changed, and you can do this by changing the frequency of the laser that you are using, and this is what as called as chirpy. So, you can you need to do some chirping, so that you can achieve this cyclic, you know loss of translational energy into the energy, which is radiated away.

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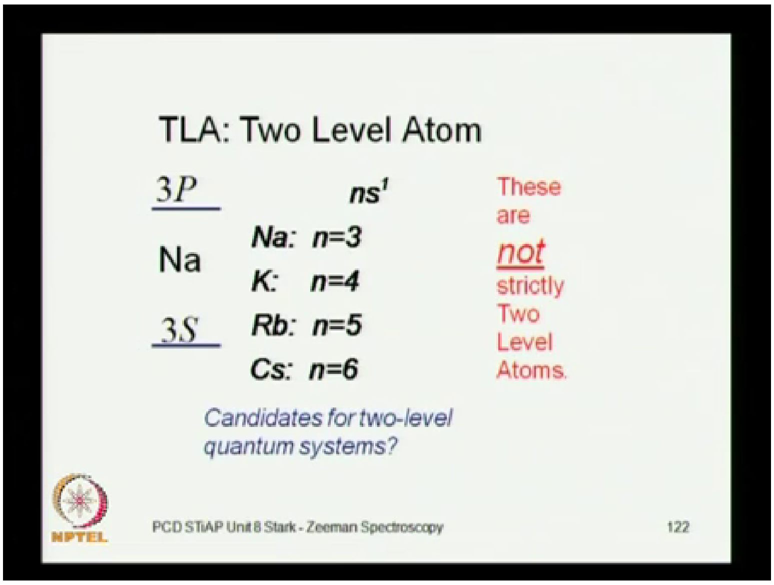

So, there are other thing that one has to worry about that if of course, you need a 2 level atom, and you might think of taking something like this a sodium atom, which has got the 3 s ground state and 3 p exited state. But, then of course, there are other candidates in the alkali atom, you know group 1, you can work with potassium, rubidium, cesium and so on, all of these are candidates for 2 level quantum systems, but then these are not strictly 2 level atoms.

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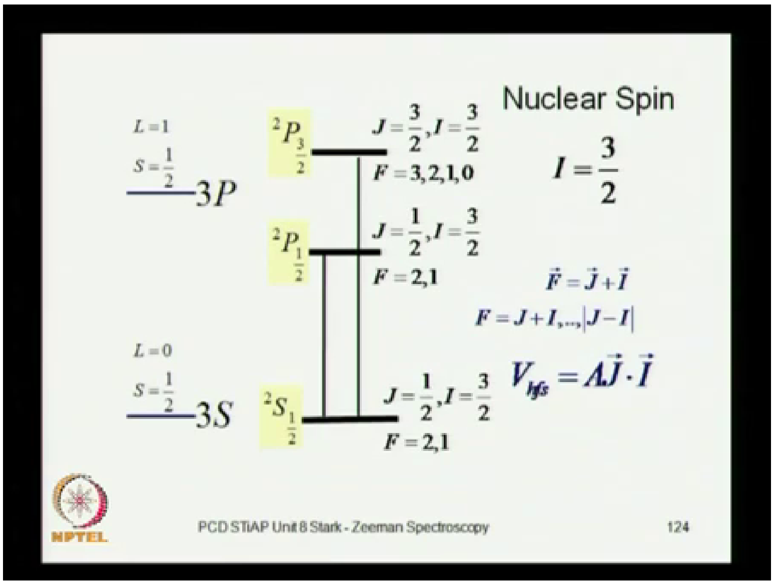

Because, we know that there is a fine structure, so exited state 3 p is already doubled it, so this is the spin orbit double it, and then there is a hyperfine structure, there is a nuclear spin which for the sodium atom is 3 half. And there is a hyper fine interaction, which I mention in the beginning of the class, so you have to take this interaction into the account. Now, when you do that the resultant angular momentum will be given by angular momentum coupling J with I, and the F value will go from J plus I modulus of J minus I, according to the loss of angular momentum coupling.

And this means that if you take this value of j which is 3 half, and this value of I which is 3 half, the resultant value of F will go from 3 2 1 and 0, so you will get a product. So, you get 4 levels from the exited 2 p 3 half state, likewise for J equal to half and I equal to 3 half, you will get F equal to 2 and 1 for the 2 p 1 half. That also splits into a double it, because of the hyper fine structure, and the lower level is also not unique that will also split into F equal 2 and F equal 1 levels. So, there is a lot of detail, that one has to be really concerned, so these are the this is how the spreading takes place, and now you have a very large number of transition which are possible.

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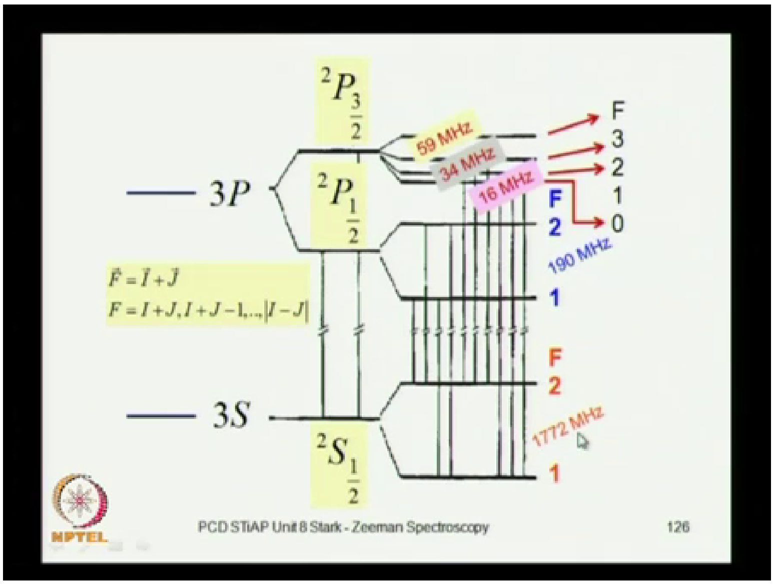

So, you have got a quoted coming out of this 2 p 3 half state, and then you can have a large number of transitions, which are possible, and all of them are conduce for the cycling process. This creates some creates some difficulties, it also unable some solutions, and difficulty it posses is coming, because of this additional hyperfine structure. And there is this considerable spreading between these energies, and this is her for the sodium atom of frequency, so this multiplied by h would be there energy differences.

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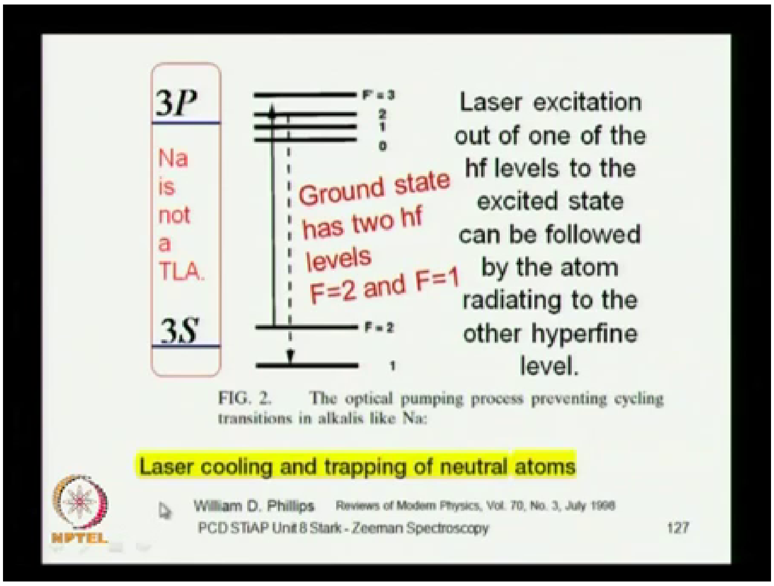

So, let us see what how we deal with this additional splitting, and the additional lines which result from this, so the ground state we have seen it is not unique level, it is split by the hyperfine structure into 2 levels F equal to 2 and F equal to 1. And what it means if you have any excitation from F equal to 2 to this excitation, and then in the cooling cycle, when the d execution takes place, those spontaneous emission is quite possible. That the atom would lose energy, and come down to this state rather than to F equal to 2, of that is not good for cooling, so this is difficulty, which William Phillips observed his in experiments.

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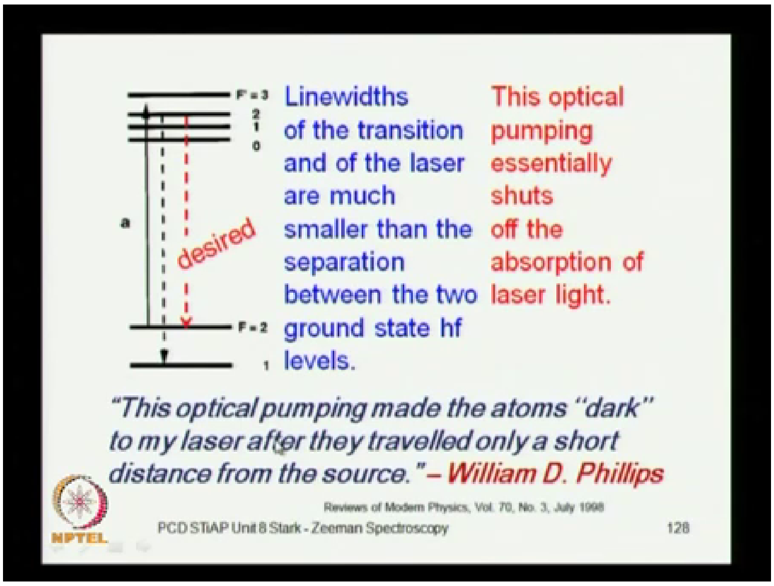

And actually, it towards to come down to the same level, you could re pump, and then you would have an appropriate cooling cycle, but in the absent of that. Since, it decay or it has the possibility of decay to a different level, then you not have the appropriate cooling cycle available. So, the line width of the transition of course, are much smaller than the differences between these energies, that we have taken for this, it is not the case over here.

And what Phillips observe is that the absorption of light would get shut off, when you carrying out is experiments found that you know the cycle would not continue. So, I coat from this article here in the reviews of modern physics, that this optical pumping made the atoms dark to my laser, after they travelled only a short distance from the sources.

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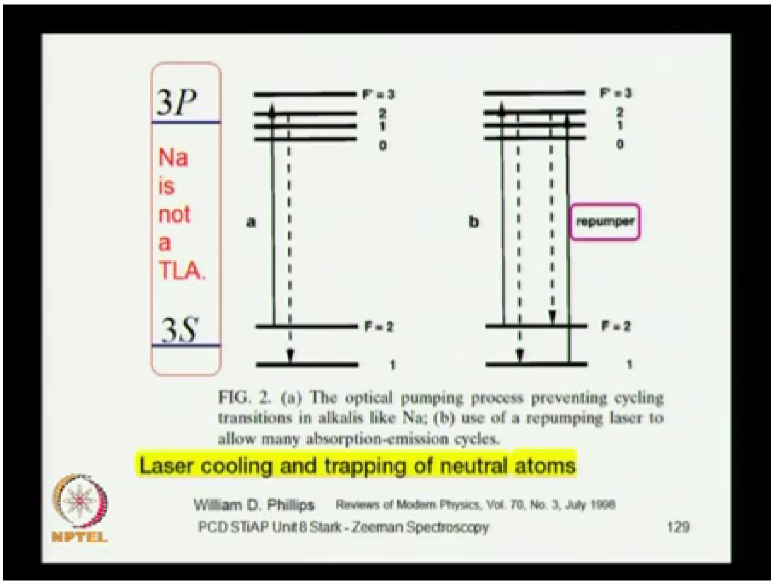

So, this is the difficulty that he faced and for reasons that we understand, and the solution, therefore involved using the re pumping laser, so that is arises from this level back to this, but puts it back over here. And then you know regenerate the exited state, which will then d k into the desire level, so these are some of the ticks which are use the lot of details, one has to really work with. And this is certainly not an easy task, but which is why it ends of Nobel price, so I strongly recommend that you read the article by physics.

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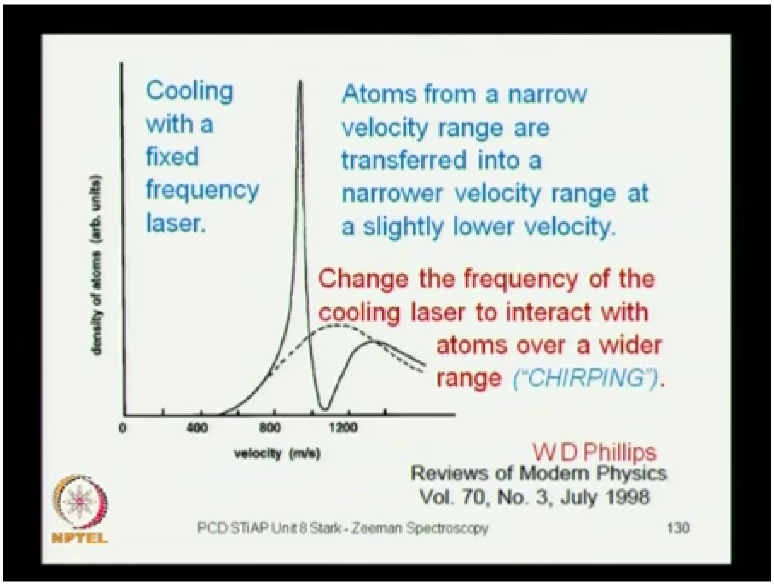

So, using the re pump he is using to get a good amount of laser cooling achieve, what essentially is happening is that atoms very the narrow velocity range, are transferred in to a narrower range. And you gradually step by step tell you really achieve a lot of cooling, so this is to be done using chirping is one way of doing it, so adjusting the frequency of the cooling laser.

So, that you know the cycling process is unable is one strategy, which is the chirping technique, then as we are alerted by a common from Metcalf, article one has to careful in using the thermodynamic idea of temperature. Because, you really dealing with quantum systems, and there are from Metcalf strategy point out in this article and also in the book.

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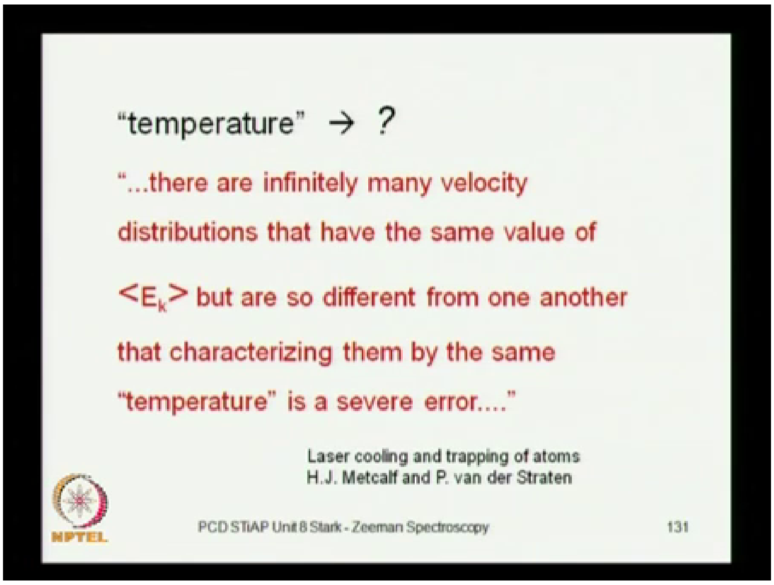

That there are very many differences distributions, which have the same energy, but the very different from each other, so the idea of temperature is not completely appropriate as such, but never for the less used, in this sense in which slowing down of the atoms consider. So, it is a that spirit that the idea of temperature is used, in the term cooling is used and not quite in the manner, in which is used in classical thermo dynamics.

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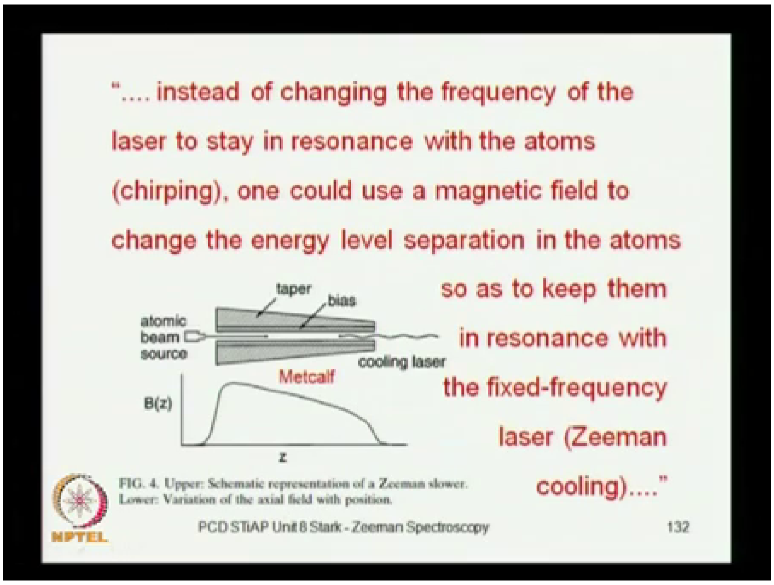

So, there are other ways of enabling the cooling cycle, chirping is what we mentioned earlier, and other thing you do you study the Zeeman effect, and now if switch on the magnetic field, very gently control this. If you switch on the magnetic field, the again energy levels passing between the different, hyperfine levels can be control using the magnetic field. This is what exactly coming in the way of the cycling process, and this was compensated to certain by charping, alternatively of doing it would be to use the Zeeman effects.

Use an external magnetic field, and this is done by having a large number of solemnize of different lengths and this is called an Zeeman cooling. The whole processes some time call as Zeeman slower, and using the Zeeman effect, which you known that there is the mew dot d coupling and that is proportional to the magnitude of the applied field. And that is something you can control, and that will you know give you control on the spacing between the energy levels, which is what you want to optimize to enable the cooling cycle.

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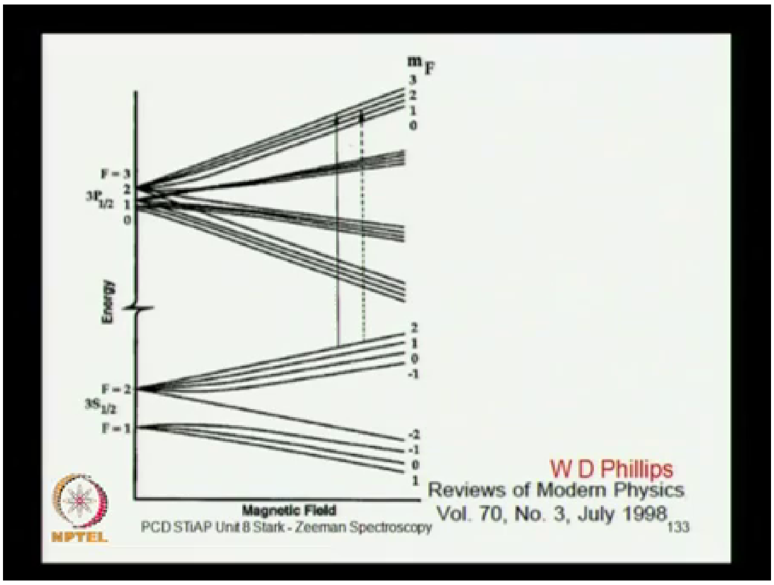

So, the Zeeman effect will finite out the hyperfine structure in to a large number of different levels, and then you can pick the transitions, which are lot interest to you and it just the magnetic fields. Because, your ultimate goal in these process is to enable a large number of these cycles of electrometric radiation absorption, and subsequent ambition through spontaneous d k in arbitrary different directions. So, that over a number of cycles the recoil from the spontaneous summation is averaged out 0, and the atom slows down.

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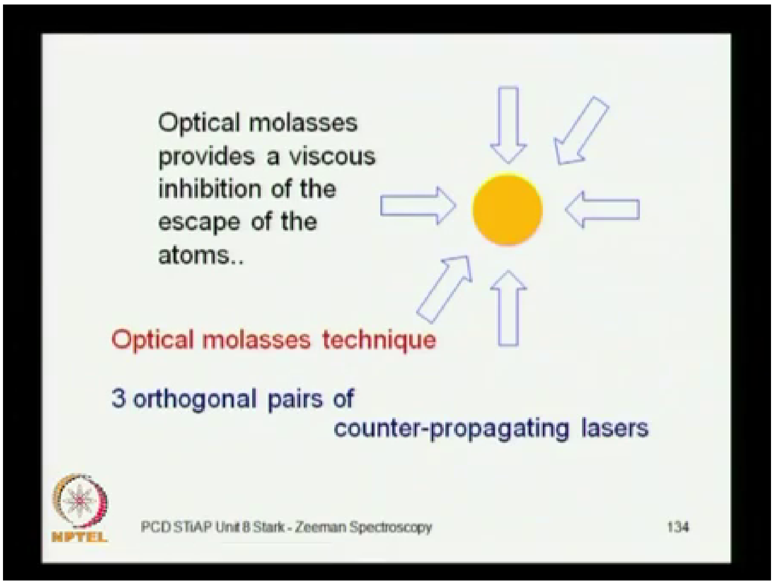

So, this is enabled further you have to worry about the fact, if you just slow down an atom in wonder action, it can still escape, because it has got velocity in different directions. That if it is got a very high velocity in some other direction, it is going to escape, so somehow you have to make sure that it remains there, and you have to inhabit it is escapes in other directions.

So, one way of inhabiting it is escape in other directions is to put it in a molasses, and what the molasses, this is an optical molasses, that you have 3 orthogonal phase of lasers, which are traveling opposite to each other. And they generate a molasses kind of atmosphere for the atom, which prevence the escape of the atom, and a molasses the something like that molasses is actually, it is a very thick you know kind of liquid kind of thing you like honey and so on.

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And it is lovely picture that mouth watering perhaps, but then as you can see something is stacked this, it is not going to escape, so that is the idea over here.

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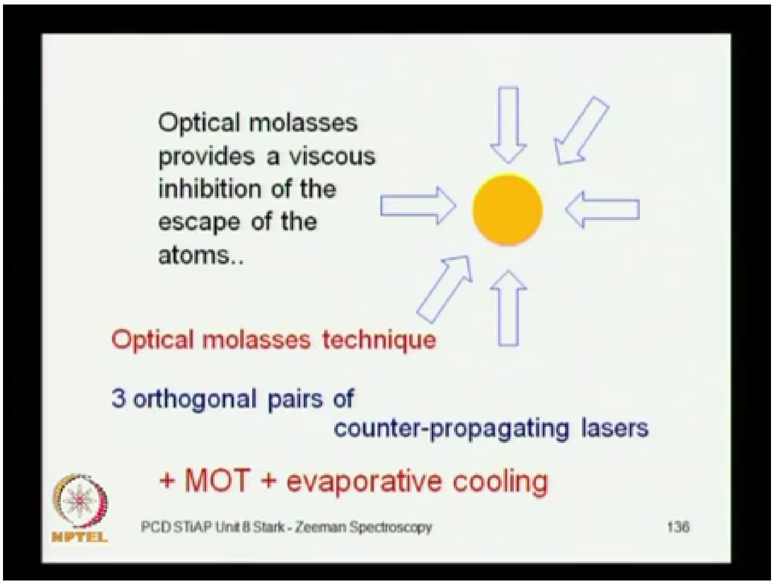

That these is an optical molasses, in which you inhabit the escape of the atom out of these zone, so that is the reason this is called optical molasses. Then you do use additional you know techniques like magnetic optical traps, and then you also exploit what is called as a evaporative cooling, you know what evaporative cooling is that if you have a hot cup of tea over here.

It eventually cools down, because you know the hotter molecules, they are jumping out of the surface and they just escape, so what is left behind is cooler then what was along with the faster molecules, the faster molecules other once which run away from the cup of tea. So, that is evaporative cooling in all of this really is exploited in the laser cooling process, and what is going to happen as the atom cools. As, the atom cools is momentum would go down, because the whole idea or it is rather the other way round, it is because the momentum is lower that the atom cools, so the momentum goes down through this cycling process, and correspondingly the temperature gets lower.

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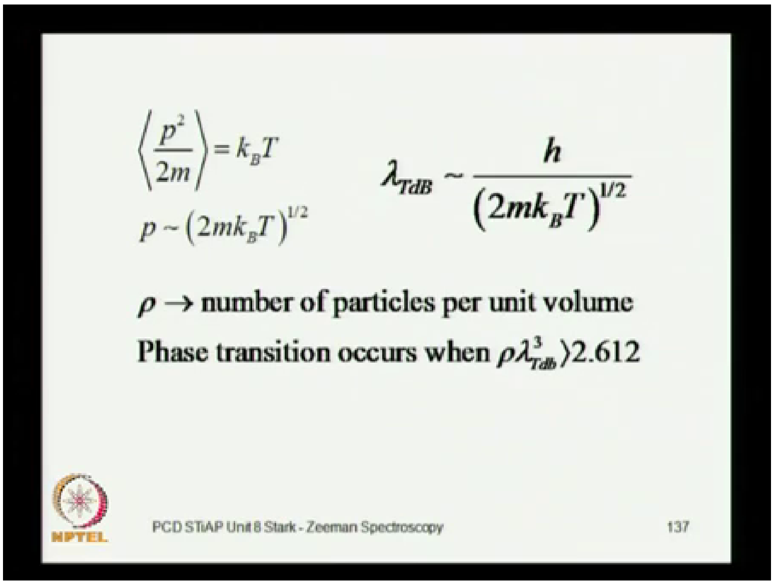

And as the momentum goes down, the dibarly the wave length is going to increase, because the dibarly wave length goes as inverse momentum, so as the atom is slowed down, the dibarly wave length increases, and if it increases significantly to overlap with the wave length of the neighbor. You will start losing the distinction between the first atom and the other atom, so that depends on how many atoms are packed together in a certain reason.

So, it has to do with the density of atoms, and you can work out these calculations in details, that if you have if row is the number of article per unit volume, then if this product of row times lambda q, where lambda is the dibraly wave length corresponding a certain temperature t, then it tells out that is this number is greater than 2.612. You can expect to see that you begin to lose the distinction between different atoms, and all the atoms then until go a phase transition into a condensate, which is the Bose condense matter.

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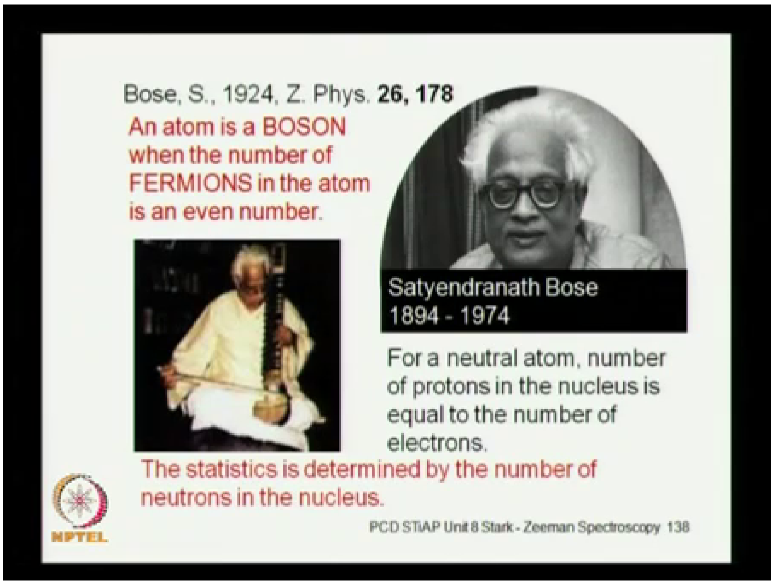

So, this is completely new kind of phase and you can the achieve Bose-Estien condensation which was predicted by Satyendranath Bose, in his very famous article, and you can then get boson condensate of atoms. But, then of course, atom has to be Boson on for that and an atom is Boson, if the number of Fermions in the atom is an even number, so that is the criterion to get a boson condensate.

So, for any neutral atom the number of protons is equal to number of electrons, so that gives you un even number when you add them up. So, whether not an atom is boson depends on the number of neutrons in the atom m, so certain isentropic will be boson, and some other isotope may not be our bosons are the same atom. So, this statistics determine essentially by the number of neutrons in the nucleus, you recognize the instrument Boson explain, what is it, loudly, what is it call is it. I do not know, but may be you have the correct name I thought it was the [FL], any way it is a Bole instrument, and for achieving boson and condensation, you have the Nobel prize was awarded in 2001.

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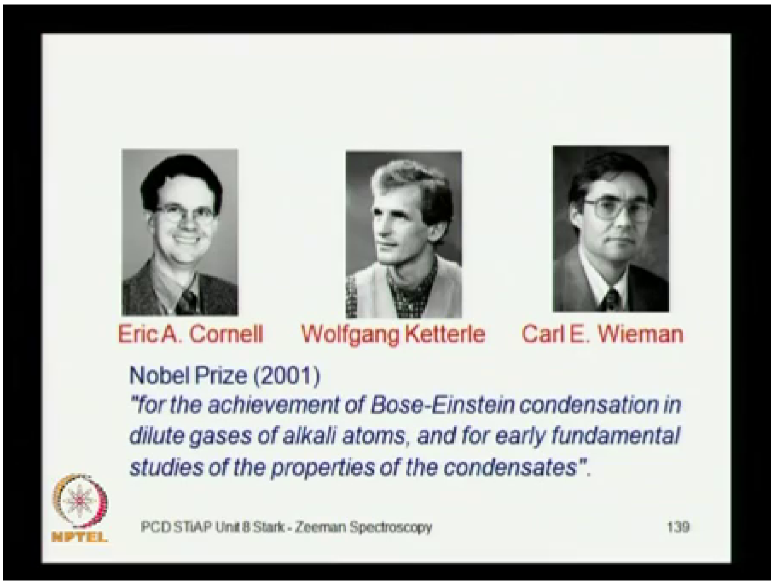

And this was the lovely experiment done with the alkali atoms.

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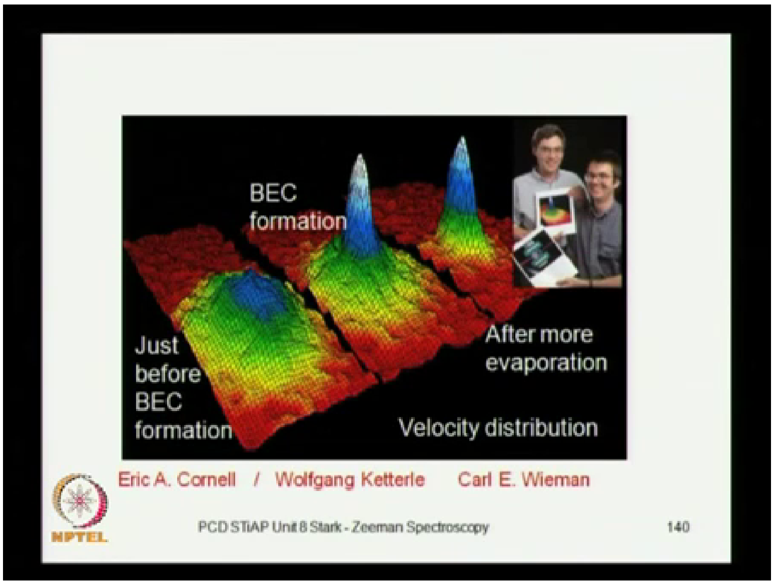

And you see that in this picture, you have got the number of atoms, and the pictures are just color codes, and they only tell you, that there are cooler atoms with the white color in this particular figure. And there is a small number which is really leads to the Bose Einstein, and condensates, and this is what the Nobel prize to Cornell Ketterle and Wieman.

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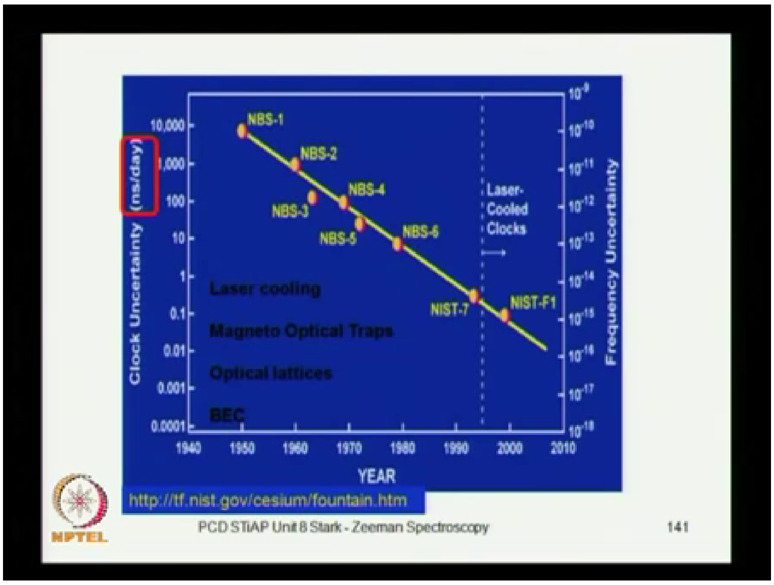

And this has an important consequence, as I mentioned at the very beginning on the accuracy with which time is measured, because that was and remains as Phillips is an article major motivation of cooling atoms, because if you look at the clock uncertainty, and this is picture from this web site over here, if you look at the clock uncertainty, these is listed here in units of nano seconds per day. Then in 1950 it was about 10,000 nano second per day, that was accuracy of the clock according to the technology, which was available at the time.

And then slowly this improved, and you get more and more accurate clocks, and now it is approaching these numbers over here, then also you get extremely accurate clocks, which we really need to monitor your global positioning system and many other you know processes.

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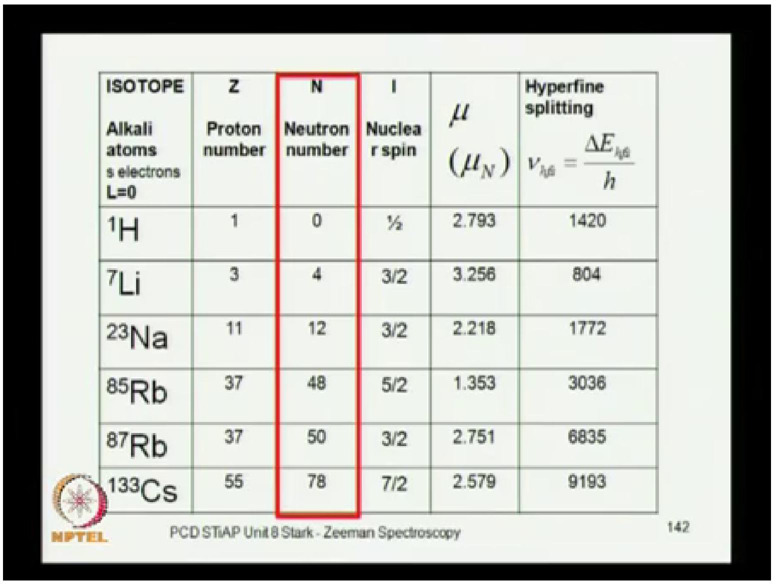

ISOTOPE Alkali atoms s electrons L=0	Z Proton number	N Neutron number	I Nuclear spin	μ (μ_N)	Hyperfine splitting $\nu_{hfs} = \frac{\Delta E_{hfs}}{h}$
^{1}H	1	0	½	2.793	1420
^{7}Li	3	4	3/2	3.256	804
^{23}Na	11	12	3/2	2.218	1772
^{85}Rb	37	48	5/2	1.353	3036
^{87}Rb	37	50	3/2	2.751	6835
^{133}Cs	55	78	7/2	2.579	9193

So, here is the table which is some of the alkali atoms are listed, and you notice that the number of neutrons over here is evens, so these are good candidates to condense. And they have a certain nuclear spin, you will have the hyperfine structure, and then you can use all the techniques, which have been develop to exploit this.

You know that the chirping the Zeeman slower, that evaporative cooling the optical molasses and so on, so and you can get Bose Einstein condensate. Now, what is going to happen, if the atoms that you are cooling are not Bosons, because that going to depend on the total number of the Fermions in these system.

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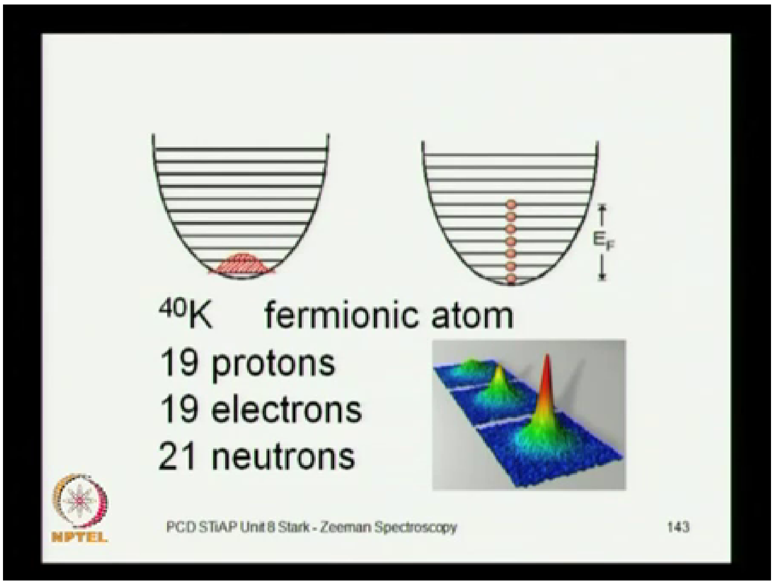

you will not expect a condense, because all the bosons can fall into the lower state, but Fermi particle cannot do that. And you know that Fermi statistics is it has this additional property, which is the exclusion principle, because the total wave functions has to be anti symmetric. So, because of the exclusion principle, if you have Fermi atoms they will not fall into condensates, but they will occupy the lowest states, but 1 by 1 and you cannot then get a condensate from Fermion atoms. Now, if you look at this isotope of potassium, this is the Fermion, it has got 21 neutrons, the numbers of protons and electrons are equal both equal to 19. So, it is Fermi atom and this is one has we achieved with this atom, and this is certain in boson atoms.

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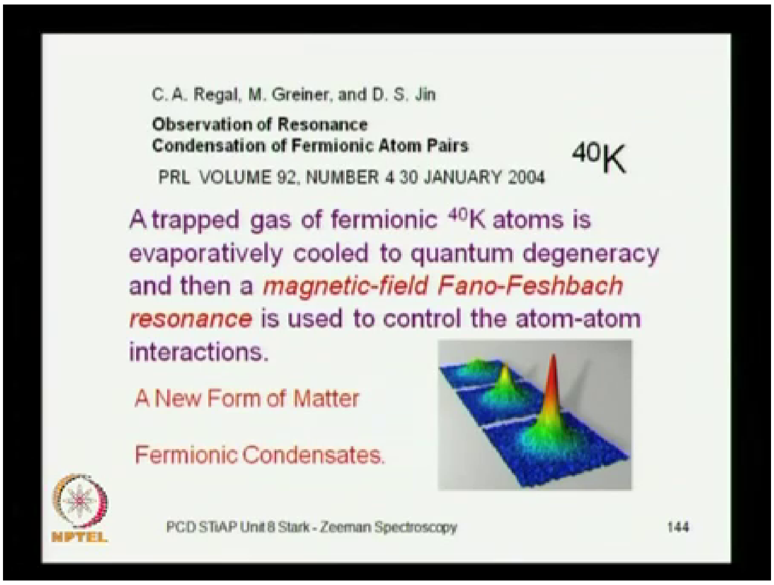

Now, these experiment was done by Greiner, Regal group Regal Greiner and Jin, and this is reported in the physical review letters of 2004, on a this particular isotope of potassium. So, these is a radial vector isotope, but it is got a very large life time, and condensate of these atom has been achieved by Regal, and the way it is done is by having additional controls.

Because, they had this magnetic field, which influences what are known as Fano Feshbach resonance, and then Fano Feshbach resonance is very fascinate phenomenon, which comes from, and interaction between bound to bound transitions to continuum transitions. So, it is a resonance phenomenon, and on one side of it you have Bose Einstein condensate and so that is what has been achieved through a correlation effect. These is essentially like getting a correlation effect, and this is what led to the Fermionic condensates, because the 2 Fermions can clear to give a boson like state just like two electrons give you the copper pair in super conductivity.

So, that is the ((Refer Time: 38:22)) transition and all of these is very fascinating, but you need some additional technique, additional tools to study these process, you need to understand what is called as a fano feshbch resonance. And these comes from quantum collision theory in atomic physics, so you need some additional tools, so these I has lead to some very high precision development high precession atomic clocks.

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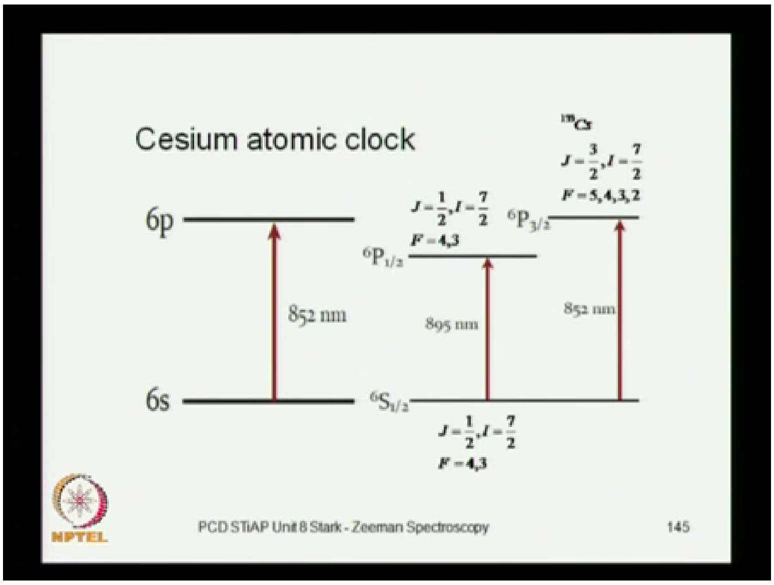

The cesium atomic clock comes 6 s to 6 p which has brought a fine structure, and then hyperfine structure coming from the nucleus spin, which is 7 half. So, the 6 p 3 half state gives you additional levels gives you this quadrate, with F equal to 4 5 4 3 and 2 coming from the combination of these two angular of momentum. And then the 6 p 1 half states, gives you this F equal to for and 3 double it and the lowers states is also double it with the F equal to 4.

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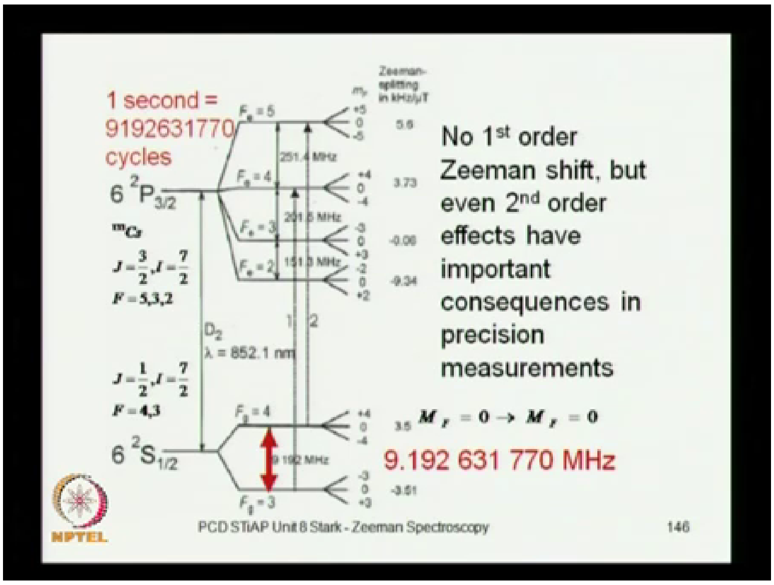

If you look at the cesium transitions, then the particular transition between these two states, these transition is between m equal to 0, to m equal to 0 state. And that is 9, because there will be no first order Zeeman effect, from these never the less see these is second order effects are of some importance, and these is what gives you the frequency standard of the standard for measurement of time.

So, this transition takes place at a frequency 9.192631770 mega hertz, and this is what gives us the definition of a second, the second that we speak about all the time is defined as these number of cycles corresponding these transition. So, these is how the second is defined technically and strictly speaking, so these are very high precession measurements and this really brings us to other techniques, which are required in measuring time, because you need to be able to measure time the that level of accuracy.

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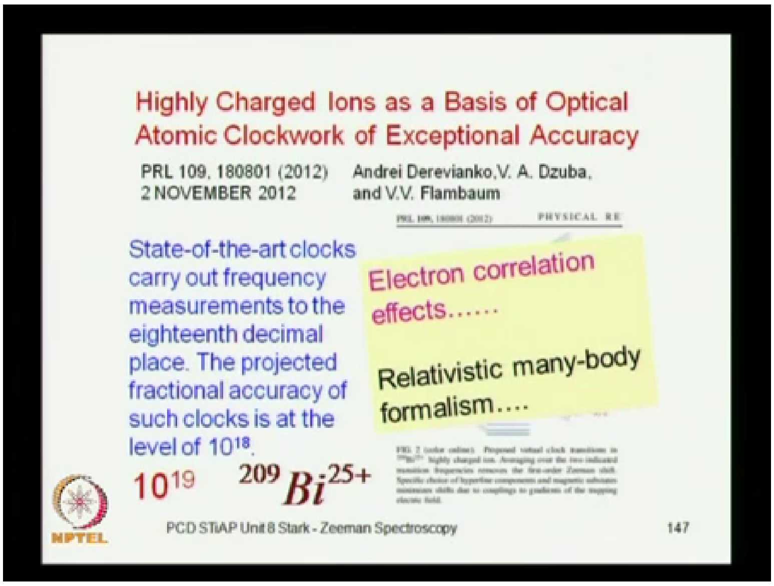

And when you develop the theoretical models, you need to take into account electron correlations effect relativistic many body effects, collision effects and so on. So, there is a whole worst you know techniques and quantum mechanics some relativistic quantum mechanics learn about, calls for an independent complete course. The projected accuracy is like ten to the 18 at this current level, but only few days ago paper came out, in which an accuracy of 10 to the 19 is projected.

So, you can imagine, how far it would be to raise accuracy by even one order, and this is a paper which is came out just a few days ago PRL by Derevianko, and his collaborate

Dzuba, Flumbaum. And they form that is the take highly charge ions like dismiss ions 25 times, they predicted and accuracy of 10 to the 19 and what the age of the universe, tell me in seconds.

It is about 10 to the 17 second also the age of the universe is 10 to the 17 second, and that is the kind of accuracy, that these clocks are really aiming for, so you are not going to go wrong. And this really needs very sophisticated technique quantum mechanics to steady this processes, and they clearly go beyond the scope of our introductory course an atomic physics. But, the prediction of the remind collaborates, as that highly charged ions will be excellent candidates to build atomic clocks.

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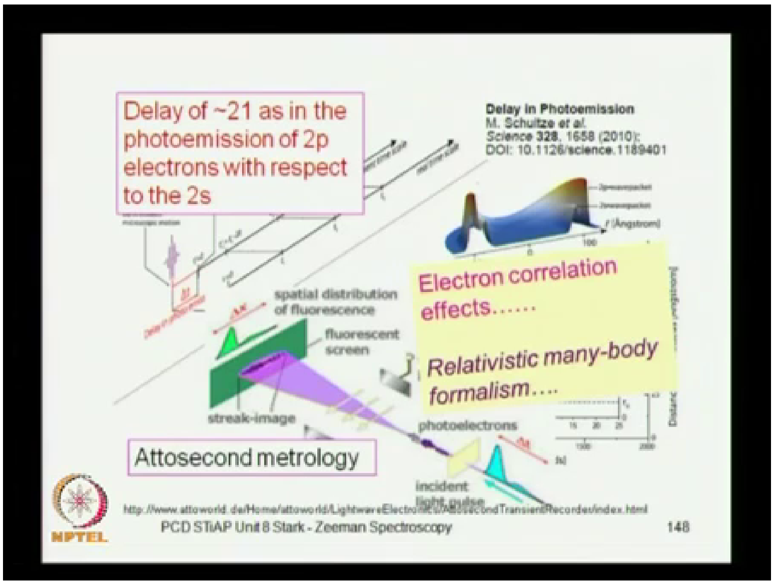

So, that brings us to techniques, which are able to measure time at that accuracy, this is a calculation, this is first highly child ion, which is predicted to give this accuracy, of 10 to the 19. So, you need to be able to measure time, and very short time intervals, you want to able to measure like 10 to the you know means earlier nano second was big thing in then the fem to second. And now this is like a 1000 order you know quicker nano, fem to second, so that brings us to what is called as auto second metrology, in auto second is 10 to the minus 18 seconds.

And to be able to measure process of this kind, you need tools which are high procession electronics, which can really record this value. And if you look at a photoemission process light is observe by an atom, in the electron is not doubt. Then it turns out that you can actually measure, whether the electrons comes out, right at the instead photoemission observed or does it come out little late.

And if it comes out a little late, how much is the dealing, and these are measure using technique, which are called as electron streaking techniques, and using these techniques in this experiment which will find in the article issues. They find that if you have neon atom and subjected to photoionization, you will get electrons which are coming out of the neon atom, from the 2 p shell and also from the 2 s shell.

Now, it tells out that there is a little delay in the 2 p electrons compare to the 2 s, and that dealing is of the order of 20 21 or 2 seconds. If the certain degree of you know accuracy, it is not exact 21 second with their instruments, accuracy you are able to measure these within plus or minus 5 auto seconds. Also this is these are extremely hyper measurement, which can be carried out, which is really amazing, and there is little bit of delay in the photo emission of the two p electrons with respect to the 2 s electrons.

And that delay is the order of you know some auto second, so that is the current trend atomic physics, in which there is lot of excitement it cooling atom getting boson, and condensation, auto second metrology and so on. And this; obviously, needs taro understanding of electrons co relation effects, because these when you think of a 2 p electron coming out, you think of a single electron it is undergoing a transitions from a 2 p bound states, to in to the continuum.

That is not exactly what is happening, because the 2 p electrons has got this one over element 2 interaction the rest of the electrons, so the neon has got ten electrons. And the 2 p electrons has the 1 over element to interaction with the remaining 9 electrons, and you can average out this in the ((Refer Time: 46:23)) as consistence field. But, that is does not take into an account to the co relation between the electrons, thus something that we studied in an earlier unit.

So, you have to consider the electron co relation between these two process, so the time delay in the 2 p, and the 2 s is also determine by this co relation effect, and to be able to study this co relation effects. You really need very sophisticated tools use relativistic many body formalism, and then if you are looking at these BEC to BCS transition effected by these magnetic field controlled fano feshbach renounces you need.

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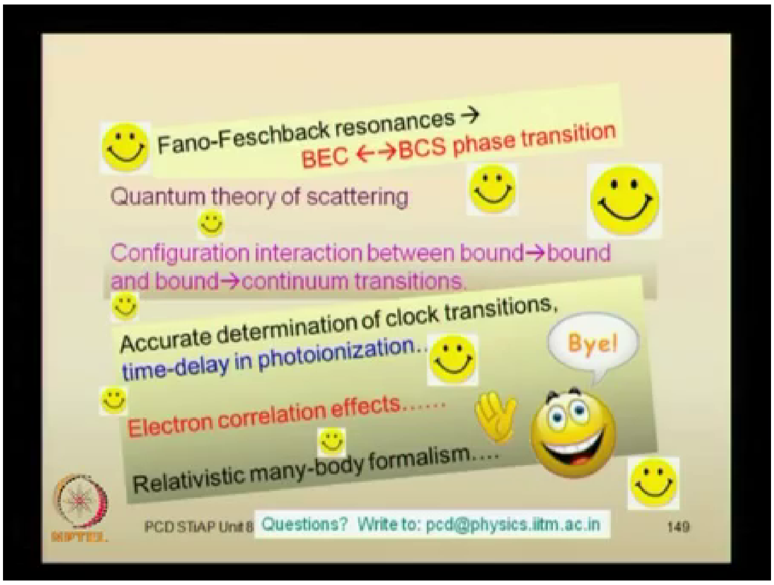

To study quantum collision theory, actually it is a parameter called as scattering length and quantum collision theory, which is controlled by magnetic fields to bring about this transitions. And then you also need to study electron correlation effects, relativistic many body theory and so on, so that subject for a different course and we pretty much conclude this course over here, if the any questions you will be happy to take otherwise smiles everybody questions.

Student: How can we be sure that the transition involved is spontaneous.

Spontaneous emission is what will give you the randomness, so there will be some stimulated emission, you are not going to be able to choose one or the other, but those atoms which are participating, which are getting the exited in spontaneous emissions or the once which will emits an arbitrary random directions, and then they are there in the system.

They are the once which will lose that excess symmetry energy, and get ready to observed laser light once again, and when they go through the next cycle, again and again. May be one of those cycle they will end up emitting through stimulated emission does not matter, even if that happens once twice 10 time, 100 times you are talking about something like 10 to the 4, 10 to the 5 cycles of the excitation, and through this there will be a number of spontaneous emissions.

And those spontaneous emissions will end up providing a recall, which is effectively 0, because spontaneous emissions will be random directions, and because that is a in random directions. The net transfer of momentum to the atom is what will opposite in initial velocity, and reduce it velocity decelerated, again the direction of the laser and cool it.

So very well thank you all very much.