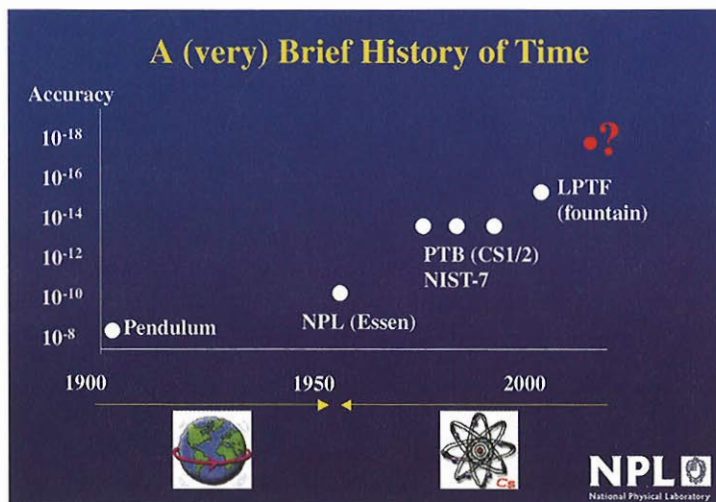


Cold, single atoms: quantum standards for length and time

Dr Paul Taylor
NPL

» *"The production of an optical frequency standard or atomic clock which is accurate to a part in 10^{18} is a viable prospect for the next 10 to 20 years. A clock which is accurate to a part in 10^{18} is equivalent to being accurate to 1 second in 10 billion years. That is about the known age of the universe. Such a device will no doubt augment the applications of navigation, communication and astronomy."*

I would like to talk to you today about the work we are doing in the Wavelength Standards section of NPL, developing optical frequency standards which are based on cold, single, electrically charged atoms. Optical frequency standards have applications both as future quantum atomic clocks and, because the second and the metre are intimately related by the speed of light, they also have applications for the realisation of the metre. I would like to concentrate primarily on the time aspects of the work today.



Essentially, the second has been defined in two ways over history. Before the atomic clock came into being, the second had always been related to the rotation of the earth and the mean solar day. The mean solar day of 24 hours could be split up into seconds and that is how the second was defined. Clocks had an accuracy of around about 1 second in 3 years because the rotation of the earth isn't perfectly constant.

With the advent of the atomic clock around about the mid 1950s and caesium beam standards, we saw great improvement in the accuracy with which the second could be defined and measured. The atomic clock led to GPS, and other applications in navigation, and high-speed communications, where the sender and receiver must be very well synchronised. There were also applications in physics, such as radio-astronomy, where two spatially separated radio

dishes can have the effective sensitivity of one large dish of that diameter if the data of the two dishes are synchronised by an atomic clock. Not only have there been practical applications but as also has been mentioned earlier on today, there have been eight Nobel prizes awarded over the last century for work which is either directly or indirectly related to atomic time keeping. So you can see that pushing the frontiers of time measurement has really given contributions to physics itself.

Single Ion Optical Clocks

Clock

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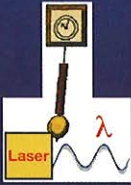
oscillator

+

reference

Optical clock

=



+





Well, what is a single ion optical clock? An optical clock is one where the oscillator is light itself. Light is an electromagnetic wave and the oscillation of the electric field can be used as the oscillator for an optical clock. The light oscillates at some 6 hundred million million times a second. So it is much faster than the pendulum of our grandfather clock and that leads us to be able to make it much more stable. In fact the world record currently stands at about 1 part in 10^{15} every few seconds. That was for a laser built in NIST which, I would also like to mention, pioneered the work on the ion trapping which I am going to talk about just now.

To go along with our super stable oscillator, we need a reference. For this we are going to use a single electrically charged atom, a single ion of a rare metal called ytterbium. It is an element way down at the bottom of the periodic table. Why use a single atom? Well, with our single ion of ytterbium we have a quantum reference. The ion of ytterbium will only absorb the light from our oscillator when its frequency exactly matches a quantum property of our single ion. That leads us to be able to make clocks which are referenced to a single ion of ytterbium. Because all single ions of ytterbium should be identical, our clocks should operate in an identical fashion. In particular, by not having lots of atoms within our system, there are no interactions between them. So by just isolating a single ion, we think that we have got maybe close to the ideal reference.

What I would like to talk to you about today though is where do we see all this going in the next 10 or 20 years? This is where we think that a single ion optical clock could contribute. A clock has two constituent parts. It has an oscillator and a reference. I think we are all familiar with the oscillator of say, a grandfather clock. That is just the pendulum that oscillates from side to side and it keeps the short-term stability of the clock, of the seconds, minutes and hours. But over a few days we need to reset it - we need to recalibrate it. For that we need a universal reference. So, in the past, this would have been the mean solar day and the rotation of the earth. What we are looking for in our reference is something which is unaffected by any external influence. This is why the rotation of the earth isn't so good because the motion of the moon, and to a lesser degree, the sun, perturbs the motion of the earth and leads to that inaccuracy of 1 second in 3 years. So where would a single ion optical clock come in?

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Catching an Ion



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How do we go about catching an ion? Well, to catch an ion we need a trap. The photograph shows an NPL ion trap which is used for trapping ytterbium ions. The most important part of the ion trap are the two electrodes which are separated by around about half a millimetre and held apart by a white ceramic material. If we apply an oscillating electric field to these electrodes, it forms a confining potential well or an electromagnetic cage, if you like. Once we have our cage set up, we need some ions. To generate ions we need atoms and electrons. The atoms come from one of two ovens. The ovens are made from isotopically enriched ytterbium material which is electrically heated to form a weak vapour of atoms. Electrons from a simple, hot filament interact with the ytterbium atoms to form ytterbium ions. How do we get just one? Well, if we set the currents just right, then on average over a minute or so we'll only load a single ion. Once loaded, we switch off the oven and the filament. We can keep our ion more or less indefinitely, certainly for times of longer than a month - and certainly long enough for us to give each one a name!

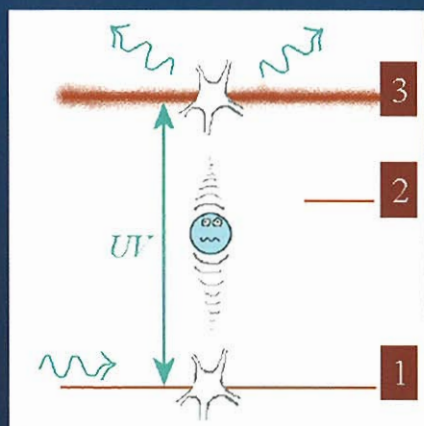
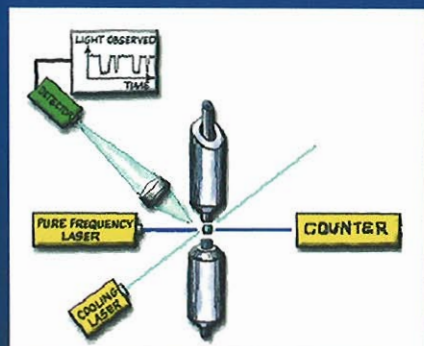
So how can we make this ion into a clock? The slide shows the electrodes and a trapped ion. Well, at the moment it is not a very good reference because the ion has just come out of a hot oven. It is very hot and so it has lots of motion. What we want is for our ion to be more or less at rest so that it is not perturbed by the Doppler effect. So all we need to do is to reduce the motion of the ion.

To do this, we use one of those Nobel prize winning ideas of *laser cooling*. In laser cooling, we take an ultraviolet laser and we shine the photons of the laser at the ion. If you imagine a double-decker bus coming towards you and you try to stop it by throwing ping-pong balls at it, that gives you the essence of laser cooling! Each laser photon only has a tiny amount of momentum, but taken all together, you can reduce the large amount of momentum from the hot ion and cool it down until it is almost stationary. After a few milliseconds of laser cooling, the temperature of the ion is reduced to about a thousandth of a kelvin above absolute zero. At this stage it makes a pretty good reference.

But how do we know we have an ion? An ion, after all, is just an electrically charged atom. How can we see that? It is so tiny. In fact, we can see it because the ion fluoresces - it glows in the centre of the trap. This is a side effect of the laser cooling process. I would like to talk you through a simple representation of an ion. An ion is a quantum mechanical entity, and so its energy levels are quantised. It can't have just any old energy. It can only have certain levels of energy. So normally our ion sits in the ground level as we can see from the diagram. It sits there quite happily until a photon of ultraviolet light comes along and excites it into a short-lived excited level where it stays for maybe ten nanoseconds before decaying back down to the ground state. Now we can do this repeatedly and every time the ion decays back down it emits a UV photon. This is to conserve the energy - so one photon in, one photon out. We can scatter around about a hundred million photons every second and of those, we can collect with a powerful lens and a sensitive detector a large proportion of them and see just a single ion in the centre of our ion trap. It is glowing that brightly.

We have the essence of an optical clock shown in the diagram. The key idea is that the atom will only absorb the UV photon when the energy of the UV photon exactly matches the gap between levels 1 and 3. Now, when I say the energy of the photon, I also mean its frequency because the energy and the frequency of the photon are directly proportional. So only when the UV frequency exactly matches the gap between levels 1 and 3 will the atom fluoresce and allow us to see it.

Using an Ion as a Clock



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In the diagram, the level 3 has been drawn to be very fuzzy. The reason it is very fuzzy is due to Heisenberg's uncertainty principle. The principle states that if the level is very short-lived, which it must be if we are going to scatter lots of photons, then its energy uncertainty is going to be very large. That is no good because that means that our atom can absorb a wide range of ultraviolet frequencies. So it doesn't make a very precise standard. What I would ideally like is another energy level, say level 2 shown in the diagram, which is very long-lived. In being very long-lived, by the uncertainty principle, it means its energy is extremely well defined. I haven't yet said why we use ytterbium atoms for our optical clock. The reason is

that this energy level in an ytterbium ion happens to have a life time of 10 years. Now, this is extraordinarily long for an atomic state.

As I said, there appear life times of 10 nanoseconds and typically you might find atoms with stable states of 1 second. So, 10 years makes it extremely well defined. It also makes it rather difficult to find. However, we can make an estimate of where we think it is, based on other spectroscopic measurements involving the level. Then we try to excite the ion to this level by using a laser tuned to the estimated energy gap between this level and level 1, in a way that I describe next.

Our laser is the ultra-stable laser that I mentioned at the beginning of the talk, and this is going to be the pendulum for our clock. We tune in the frequency of this laser until it exactly matches the gap between levels 1 and 2. When that happens, our atom is excited to our stable level. How do we know this has happened? Fortunately, we have only one ion and one ion can only do one thing at a time. When it is sitting on the shelf, it can't absorb a photon of ultraviolet light because the energy gap here is wrong for the energy of the ultraviolet photon and so we see that the light from the ion disappears. When the ion does eventually get back to the ground state, it can be cooled again. We can see that the fluorescence from the ion comes back on. This phenomenon, called quantum jumps, is one of the reasons why Dehmelt won a Nobel prize. The idea of quantum jumps says that our one ion can only do one thing at a time. It means that we know with a hundred percent certainty what the ion is doing. It is either being excited between levels 1 and 3 and we see the light or it is being lodged in the long-lived state 2 and we don't see the light.

This allows us a method of calibrating the frequency of our laser. We tune its frequency until the light from the ion flashes on and off. That means that the atom is going into level 2 and out of it again. When this happens we know that the frequency exactly matches this extremely well defined gap. So we can monitor the light from our ion and see that it flashes on and off. A side effect of this is that we know now that we have only got one ion because the ion is flashing on and off. If we had two ions the intensity of the fluorescence would go between two, one and zero.

NPL Optical Clock Apparatus

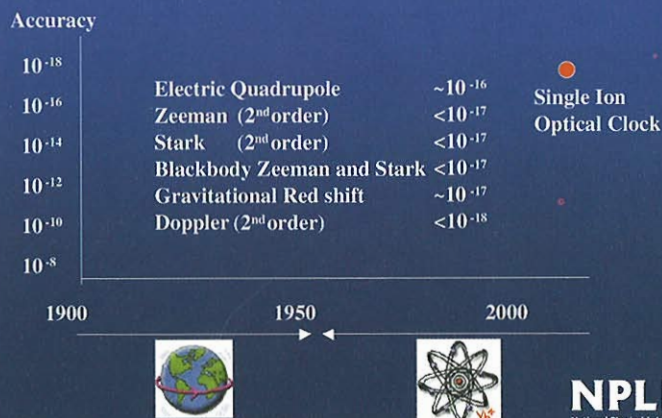


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So, now we have more or less everything. We have our ultra stable pendulum, which we have to tune in until the light flashes on and off so we know it is referenced to our stable frequency gap in our single ytterbium ion. All that remains to be done is for that to be calibrated regularly, maybe every few seconds and to have some sort of electronic servo control. Then we need to count some 6 hundred million million oscillations of the light field and say, that is one second. For that we need a counter: 6 hundred million million times a second - that is rather faster than I can count and is rather faster than electronics can count too. So we need a trick. Fortunately, a whole new field has been open in the last year or so with a device called a femtosecond laser. The Max Planck Institute and NIST have shown that such a device can count these very high optical frequencies.

And so, we can now make our optical clock. How well do we think such a device will work? Before I say that, I would just like to show you what the apparatus looks like. The photograph shows an ion trap and my colleague working on it. The ion trap itself is fairly small. It is located in a vacuum vessel so there is no interaction between the ion and the background gas. But the actual table it is on is quite large because at the moment the laser systems are quite complicated and we need a lot of associated electronics.

Expected performance



Finally, how well do we think such a device will work? I mentioned at the beginning that the single ion optical clock relies for its accuracy on the fact that it is based on a single ion of ytterbium and that all single ions of ytterbium are identical. So if we have ion traps in different places they should give exactly the same answer. That is not quite true. If we have an external influence which affects one ion but it does not affect a second one, then the two will disagree slightly. But this is not a problem because we have a single ion and we can actually calculate all the different systematic effects which are going to affect the ion's frequency. We can see in the diagram that these go from parts in 10^{16} down to just parts in 10^{18} . Even the largest of these systematic effects can be characterised to the 10% or even 1% level. That means that the production of an optical frequency standard or atomic clock which is accurate to a part in 10^{18} is a viable prospect for the next 10 to 20 years.

A clock which is accurate to a part in 10^{18} is equivalent to being accurate to 1 second in 10 billion years. That is about the known age of the universe. Such a device will no doubt augment the applications of navigation, communication and astronomy. But let us hark back to what Terry Quinn and Steve Chu have said. Pushing the frontiers of measurement with a device like this, even if it does not bring new advances in physics in itself, may lead to the possibility of using such a device to examine new physical phenomena. It might be used, for example, to examine the stability of the fundamental constants. «

Professor Sir John Rowlinson (chairman)

Thank you Dr Taylor for that fascinating account. I should perhaps say that Dr Gill, the Head of the Wavelength Standards group, Dr Taylor and other colleagues published a paper in this field in Physical Review Letters in 1997, which was subsequently chosen by the American Institute of Physics as being among the top 20 physics stories published in the USA in 1997. It is obviously well recognised work.

The next speaker is Dr Jan-Theodoor Janssen. He will also speak about a not dissimilar subject, '*Single electron transport: a quantum standard for current*'.