**Atomic Clock Article**

**Skim-Read Questions**

What is Geodesy?

Geodesy is the science of accurately measuring the Earth’s geometric shape, orientation in space and gravitational field. In the context of the paper, it is noting that the calculations involved in keeping International Atomic Time when considering this factor is very difficult.

Source: <https://oceanservice.noaa.gov/facts/geodesy.html>

What is Lorentz Invariance?

Lorentz Invariance is the proposition that the laws of physics are the same for different observers and is a fundamental idea in Einstein’s special theory of relativity. In the context of this paper, the use of this atomic clock technology will help progress the efforts to test this theory more rigorously, since it can be tested at even more precise levels. There is also potential in searching for dark matter, given the advancements in precise measurement.

Source Used: <https://www.aps.org/publications/apsnews/200606/lorentz.cfm#:~:text=Lorentz%20invariance%20expresses%20the%20proposition,to%20the%20observer%20at%20rest.>

<https://www.discovermagazine.com/the-sciences/a-new-generation-of-atomic-clocks-could-help-find-dark-matter>

What is Laser Cooling?

Although light has no mass, it carries momentum. Matter consists of atoms randomly moving at very fast speeds in different directions, and so each particle will carry momentum. Atoms also have discrete energy levels, and a photon (light quanta) with a specific frequency can absorb this photon, and subsequently its momentum. Laser Cooling makes use of the doppler effect: when the atom is moving away from the laser the wavelength of the wave increases so the frequency of the wave decreases. Therefore, the light quanta will not be absorbed in this particular scenario, but when the atom is moving towards the laser the photon will be absorbed. Since the two objects are travelling in opposite directions, the total momentum of the atom afterwards will decrease. When lasers are shone all over the sample large numbers of the atoms will slow down which will decrease their temperature.

What is a Diode Laser?

Diode lasers are a type of laser that generate laser radiation through electrons jumping from the N to P junction: electrons in the conduction band on the N junction going down an energy level to the valence band in the P junction to fill in the “holes”, emitting a photon of specific frequency in the process. In the context of the article, diode lasers are used for the laser cooling in order to negate any interactions between atoms, which would contribute to noise.

What is Gravitational Redshift?

Gravitational Redshift is the frequency difference between two identical clocks at different gravitational potentials. Although the difference in frequency is very small, it can become significant with technologies such as satellites.

**Summary Questions**

What makes this article important?

This article is important because it addresses a real issue with atomic clocks and their degree of precision, specifically gravitational redshift, and will help with testing General Relativity more rigorously, as gravitational redshifts can be measured more precisely. This article is also important as it represents the advancement of the technology: laboratory precision clocks which are usually exceptionally specialist can now be transported.

Describe how an Atomic Clock works

The frequency of a quartz oscillator is 32768 Hz. That frequency is satisfactory for general use like on watches, but if we want to define the second as a unit of time more rigorously, we must base it off something which will allow it to be defined to a greater degree of accuracy. That is where atomic clocks come in. By defining the second from a hyperfine energy transition of a ground state of cesium-133, which is 9,192,631,770 cycles per second, we can define the second much more precisely. The atomic clocks are cooled down very close to absolute zero using laser cooling, as the hyperfine transition is defined at the ground state of the Caesium-133 atom, and cooling the atom down so much ensures that the energy transitions are the ones wanted. In order to measure the number of oscillations in a second, the caesium atoms are hit with radio waves to excite them this small amount, then channelled through a magnet, where the excited atoms hit a detector which is connected to a quartz oscillator. The pulses of oscillation from the quartz oscillator creates mechanical stress which is turned into pulses of electric charge – quartz is piezoelectric. This is then measured and if the frequency of the pulses is not as defined by the SI unit then the radio wave is increased slightly in frequency, essentially a feedback mechanism.

How does the typical atomic clock differ to the one described in the article?

The typical atomic clock works by exciting caesium atoms with radio waves and having the atoms channelled through and filtered by a magnet, and then connected to a feedback mechanism. The atomic clock described in this article, the atomic lattice clock, works slightly differently. In the atomic lattice clock, a lattice of atoms is trapped in a chamber, and a laser will be fired at them. The closer the laser is to the frequency of the hyperfine transitions at the ground state, the more atoms will become excited. The atoms trapped in this chamber are then transported out of the chamber so that the fraction of excited atoms can be measured, and the frequency of the laser is then adjusted until it finds the maximum, which can be assumed to be the frequency of the hyperfine transition at the ground state. They both work through feedback mechanisms, but the lattice clock uses a laser to excite rather than radio waves.

What are the applications of this technology?

Atomic clocks have great application in the modern world. They are used in communication systems, such as GPS, and are used as primary standards in international time distribution services. They are needed because relying on clocks made from quartz oscillators can create an error of a full millisecond after six weeks, which will severely affect the accuracy of services such as GPS, where an error of one microsecond will constitute an error of around 300m on the ground. They are also important in tracking long distance spacecraft: a millisecond error on a spacecraft can constitute 300 kilometres of positioning error, which can become very significant.