Chapter 15

Femtoworld

0.000 000 000 000 001 (1.0 x 10^{-15}) f

15.1 Femtoworld Length

1 – 1000 femtometers (fm) 1.0 x 10^{-15} meters

Femtometers describe the smallest portion of the subatomic realm, which is approximately the size of electrons. The classical electron radius is 2.82 femtometers. The particles found at this dimension are of discreet values and therefore fewer and fewer objects are described within this range. There is also scientific dispute about the radius of a proton, which is thought to be the next largest constituent of an atom. Recent measurements of the "charge radius" of a proton indicate it has an astonishingly small radius of around 0.85 femtometers or 850 attometers.

The strong nuclear force is one of the four fundamental forces in nature, the others are the weak nuclear force, the electromagnetic force, and gravity. At a range of one femtometer, the strong force is about 137 times as strong as the electromagnetic force, and 10^{38} times as strong as gravity. The strong nuclear force is responsible for holding matter together. The force acts over a range just below a femtometer to about 3 femtometers.

15.2 Femtoworld Area

1 – 1 000 000 square femtometers (fm^2) 1 x 10^{-30} m^2

The surface area of an electron is approximately 100 square femtometers.

15.3 Femtoworld Volume

1 – 1000 femtoliters (fL) 1.0 x 10^{-15} L

The volume of a typical human red blood cell is about 90 femtoliters.

15.4 Femtoworld Mass

1 – 1000 femtograms (fg) 1 x 10^{-15} g

The human immunodeficiency virus (HIV) which causes AIDS has a mass of about one femtogram, as does the COVID-19 virus.

Mycoplasma are a type of bacterium which lack a cell wall. They are immune to antibiotics, such as penicillin, which target the synthesis of cell walls. Mycoplasma are the smallest living cells yet discovered, with a diameter of about 100 nanometers. They are so small, Mycoplasma were thought to be viruses for many years after their detection. One version of Mycoplasma, M. pneumoniae, is responsible for atypical pneumonia, commonly known as “walking pneumonia.” Mycoplasma have a mass of about 20 femtograms.

The Vaccinia virus is a member of the same family of viruses responsible for small pox, cow pox, and monkey pox. It has a mass in the range of 5-10 femtograms.

The joule is the unit of energy in the metric system. An apple with a mass of 100 grams, when dropped from a distance of one meter above the ground, will impact with an energy of approximately one joule. The famous equation E=mc^2 expresses the fact

Objects with Femtogram Mass

Example	**Mass**
HIV-1 Virus	1 fg
SARS-CoV-2 (COVID-19) Virus	1 fg
Vaccinia Virus	5-10 fg
1 Joule Mass Equivalent	11 fg
Mycoplasma	20 fg
Cyanobacteria	300 fg
E. Coli Bacterium	1000 fg

Table 15.1

that energy and mass are equivalent. A small amount of mass possesses a large amount of energy. The amount of mass equivalent to a joule of energy is 11 femtograms.

Cyanobacteria are a photosynthesizing bacterium which are often blue in color. The word cyan is derived from an ancient Greek word which means dark-blue. Cyanobacteria are commonly called blue-green algae, although they are not technically algae. They are found almost everywhere on the planet, and have a mass of about 300 femtograms.

Cyanobacteria synthesize oxygen, and are thought to have created the environment which allowed for the evolution of oxygen-metabolizing bacteria. Prior to the evolution of cyanobacteria, bacteria existed and grew without oxygen. These types of bacteria are called *anaerobic bacteria*.

Clostridium botulinum is an anaerobic bacterium responsible for producing botulinum toxin, the cause of the life-threatening paralytic illness called botulism. Botulism toxin can be produced when low-acid foods are canned improperly. It only takes 75 nanograms of botulism toxin to kill a human. It would only take one Kilogram to kill the entire human population of earth.

The E. coli bacterium, found in the lower intestines of humans, has the ability to be anaerobic or aerobic depending on whether oxygen is present. It is generally harmless, but some variations of this bacterium can produce dangerous food poisoning. The E. coli bacterium has a mass of about 1000 femtograms.

Chapter 16

Attoworld

0.000 000 000 000 000 001 (1.0 x 10^{-18}) a

16.1 Attoworld Length

1 – 1000 attometers (am) 1.0 x 10^{-18} meters

The dimensions of Attoworld apply only to the realm of particles smaller than electrons, protons and neutrons. Assigning a dimension to particles of this size is at best a tenuous exercise. In the case of a proton, recent measurements indicate it has a "charge radius" of about 830 attometers.[1] One attometer currently appears to be the upper limit for the size of quarks and electrons.

. . .

Lead-208 is an isotope of lead. Its nucleus consists of 82 protons and 126 neutrons. Lead-208's high ratio of neutrons to protons causes a mixture of protons and neutrons to exist within the center of the nucleus, with a surrounding layer of only neutrons that is referred to as a "neutron skin." Lead-208 is relatively stable, allowing for researchers to measure the thickness of its neutron skin. The layer is about 280 attometers thick, slightly thicker than expected.[2]

. . .

The weak nuclear force acts at distances that are less than the diameter of a proton. Its effective range is only from about 10 to 100 attometers. At a distance of about one attometer, the weak nuclear force is about the same strength as the electromagnetic force, but decreases exponentially with increasing distance. When the separation is increased to 30 attometers, the magnitude of the weak nuclear force has decreased by about 10 000 times. The weak nuclear force is used to explain the radioactive decay of atoms.

16.2 Attoworld Area

1 – 1 000 000 square attometers (am^2) 1 x 10^{-36} m^2

Assuming the charge radius of a proton is 850 attometers, and that it is spherical, its cross-sectional area is 2 269 800 square attometers.

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If we were able to fold a sheet of A0 paper 100 times, we would obtain a stack of about 1.26765 x 10^{30} connected sheets of (hypothetical) A100 paper. The area of each sheet of paper would be 788 861 square attometers, smaller than the cross-sectional area of a proton.

16.3 Attoworld Volume

1 – 1000 attoliters (aL) 1.0 x 10^{-18} Liters

The volume of a typical virus is about 5 attoliters. A pit on a common audio compact disc has a volume somewhere between 6 and 225 attoliters. Ultra-small bacterial cells have a volume of about 9 attoliters.

16.4 Attoworld Mass

1 – 1000 attograms (ag) 1 x 10^{-18} g

Examples of Objects with Attoliter Volume

Example	Volume
SARS-CoV-2 (COVID-19) Virus	1 aL
Typical Virus	5 aL
Ultra-Small Bacterial Cell	9 aL
Pits on Compact Disc	6-225 aL

Table 16.1

Examples of Objects with Attoliter Mass

Example	Mass
Brome Mosaic Virus	7.6 ag
Tobacco Mosaic Virus	68 ag
Human Adenovirus	250 ag

Table 16.2

Attogram-sized particles can no longer form colloidal suspensions, but become true solutions at this mass.

Small viruses are in the attogram range. The Brome Mosaic Virus infects grasses, and has a mass of approximately 8 attograms. The Tobacco Mosaic Virus is the first virus ever isolated, and possesses a mass of about 68 attograms. The human adenovirus, which was first isolated in human adenoids in 1953, causes respiratory infections in young children, and has a mass of 250 attograms.

References

[1] "Closing in on true size of protons" *New Scientist*, September 14, 2019 2019-09-14 pg 16

[2] "Neutron skin of an atom found to be very, very thin" *New Scientist*, May 15, 2021 2021-05-15 pg 12

Chapter 17

Zeptoworld

0.000 000 000 000 000 000 001 (1.0×10^{-21}) a

17.1 Zeptoworld Length

1 – 1000 zeptometers (zm) 1.0×10^{-21} meters

The area of interaction a subatomic particle presents is called the *cross section* of the particle. This area has a radius of approximately 7 zeptometers for high-energy neutrinos.

The neutrino is often called the "ghost particle" of the atom. Its name is derived from the fact it is electrically neutral and has a very tiny rest mass. On Earth, about 65×10^9 solar neutrinos per second pass through every 10 square millimeters of area perpendicular to the direction of the Sun. They are so neutral that only about 1 neutrino can be expected to interact with a person's body in their lifetime.

In February of 1987, a burst of neutrinos was detected at three neutrino observatories. Three hours later, visible light from supernova SN 1987A arrived. When a supernova occurs, 98-99% of the energy released is in the form of neutrinos. SN 1987A is the only confirmed measurement of non-solar neutrinos by neutrino detectors. The number of detected neutrinos correlated well with models for the predicted number of neutrinos expected from SN 1987A.

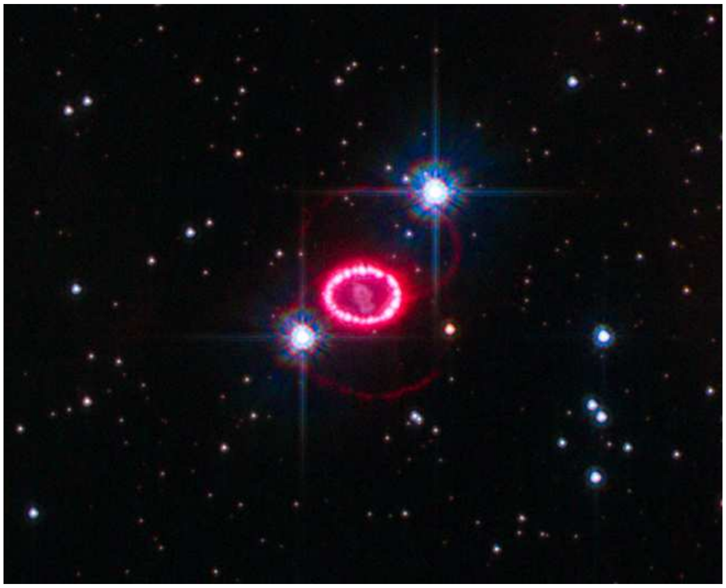

Figure 17.1: Remnant of Supernova 1987A – NASA Goddard Space Flight Center

A person orbiting Sanduleak -69 202, the star which produced the 1987 supernova SN 1987A, at a distance of 100 Gigameters,[*] would be killed by a radiation pulse of neutrinos, long before the flash of light from the explosion arrived. Despite the neutrino's well-known insignificant interaction with matter, when 10^{58} neutrinos are released, with a combined total energy of 10^{46} joules,[†] and when even a small fraction of the total pass through a human, the neutrino interactions with electrons quickly kills them, as they heat up and are roasted by the absorbed energy.

When created, neutrinos immediately travel outward at the speed of light, independent of any matter present. By comparison, the stellar explosion, and generated light, linger behind as the inner core starts to collapse, and so one is murdered by "ghost

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[*] About the distance Venus orbits our sun.

[†] Each neutrino packs an energy of about 1.6 picojoule (pJ)

particles" long before the other executioners can arrive.

When a photon (particle of light) is generated in the core of our sun, it takes it about 10 000 years to reach the Sun's corona, where it then propagates at about 300 Megameters per second. The reason a photon takes to long to arrive at the surface, is because it bumps into the enormous amount of matter contained within the Sun, bouncing back-and-forth, rather than traveling in a straight line. When a solar neutrino is formed, matter is essentially transparent to it, and neutrinos travel out of the Sun at 300 Megameters per second, the speed of light in a vacuum. After creation, a neutrino arrives at the Sun's surface in only 2.3 seconds, whereas a photon takes 100 centuries to travel the same distance.

Measurement Baseline Length
vs.
Induced Gravitational Wave Distortion

Measurement Length	**Gravitational Distortion**
1 meter	1 zeptometer
1 Kilometer	1 attometer
1 Megameter	1 femtometer
1 Gigameter	1 picometer
1 Terameter	1 nanometer
1 Petameter	1 micrometer
1 Exameter	1 millimeter
1 Zettameter	1 meter

Table 17.1

In 1916, Albert Einstein predicted the existence of gravitational waves as a consequence of his general theory of relativity. Gravitational waves are thought to propagate energy in the form of gravitational radiation. This radiation mechanism is analogous to how accelerating electrons produce electromagnetic radiation. When electrons move in circular paths, they are by definition accelerating, and radiate electromagnetic waves. A pair of massive objects revolving around one another are thought to generate gravitational waves in a similar manner.[1] These waves, like electromagnetic waves, will travel at the speed of light. Gravitational waves are thought to be generated by massive pairs of binary stars which rotate about one another, and are composed of white dwarfs, neutron stars, black holes, or combinations thereof.

When a gravitational wave passes by an observer, it will distort the physical dimensions of objects at a rate equal to the frequency of the passing gravitational wave. The amount of dimensional change produced is infinitesimal. A one-meter-long gravitational wave detector would need the sensitivity to measure a physical variation of 1 zeptometer, or 1 x 10^{-21} meters. This is smaller than the atoms of the measurement device.

Assuming a source of gravitational waves remains at a constant location, the amount of measured change for larger and larger measurement lengths is given in Table 17.1. Increasing the measurement length to one Kilometer still requires one to measure a dimensional distortion smaller than most subatomic particles. A measurement length equal to the diameter of the Earth would require one to measure a change of 12 femtometers, which is still in the subatomic realm. It would take a measurement length about the diameter of the Milky Way Galaxy to produce a gravitational wave dimensional change of one meter along its length.

The very thought of making a zeptometer magnitude measurement seemed unlikely. Einstein himself doubted it was possible. In 1967, Rainer Weiss (1932 –) produced an analysis using an interferometer as a means of measuring gravitational waves at MIT. Beginning in 1968, Kip Thorne (1940 –) at Caltech explored the theoretical possibility of measuring gravitational waves, and became convinced that gravitational waves could be, and would be eventually measured. The groups at MIT and Caltech finally joined together to work on a Laser Interferometer Gravitational-Wave Observatory (LIGO) project. The project languished from the mid 1980s to the mid 1990s, when it finally achieved funding by the skin of its teeth. The difficulty of the task was clear. LIGO co-founder Rainer Weiss stated:

> I’ve been on many committees for NASA. When an engineer hears ten-to-the-minus-twenty-one they think you’re out of your mind. That’s the very first response that most people have. You’re going to measure something at ten-to-the-minus-twenty-one of anything—I don’t care what it is you’re not going to be able to do it.

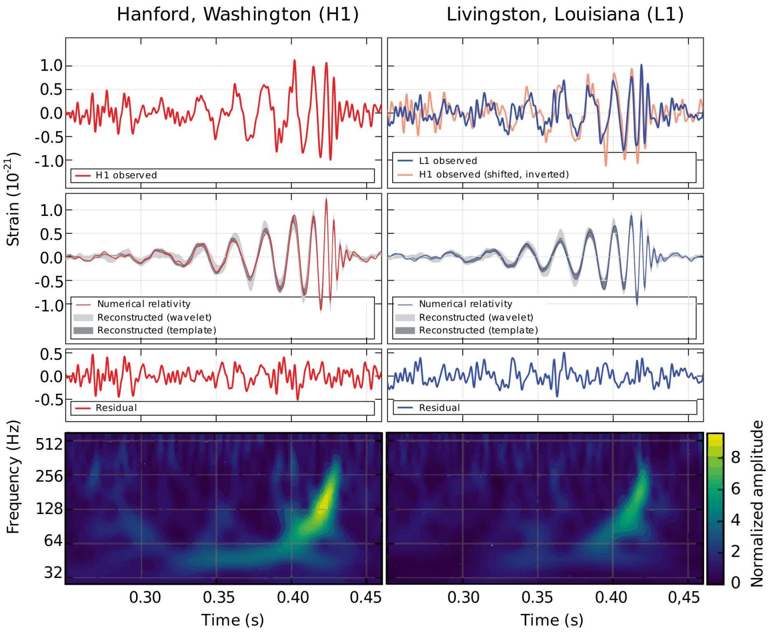

Figure 17.2: LIGO measurement of the gravitational waves at the Livingston (right) and Hanford (left) detectors, compared with the theoretical predicted values (2015-09-14) - Wikimedia Commons

The method used relies on the interference of light waves. A single laser beam is split in half. Half of the beam travels along one 4 Kilometer long leg to a mirror and is reflected back to location of its origin. The second half of the beam propagates along a leg that is 90 degrees from the first tunnel, forming an L shape. The two beams are purposefully reflected around 280 times before their recombination. The optics are then adjusted so the two beams cancel. When a gravity wave propagates through, it generally will affect one beam more than the other, this change decreases interference, which increases the light intensity, and signals the detection of a gravitational wave. "Because the arms extend for such a [long] distance, their supports have to gradually increase in height along their length to cope with the curvature of the Earth. From one end to the other, there is more than a metre difference in height, needed to keep the tube perfectly straight." [2]

Two LIGO sites were constructed, one in Hanford Washington, and another in Livingston Louisiana. The straight line distance through the Earth between the sites is 3 002 Kilometers, and 3 030 Km along the surface.

On September 14, 2015 the first direct observation of gravitational waves occurred. See Figure 17.2 The signal is consistent with a pair of black holes, with about 36 and 29 solar masses, spiraling inward toward one other until, and after, they merged. This was the first observation of a binary black hole system merging, which confirmed their existence. This ripple in space-time perturbed the length of LIGO by around one-thousandth of the width of a proton.

After the Big Bang, 13.4 Billion years ago,[‡] the universe was so hot, that for about 380 000 years, it was effectively opaque to light, and electromagnetic waves in general. It is not possible to observe the details of the universe electromagnetically before that time, but gravitational waves have no such limitation. They have the potential to provide data about this early period of the universe, even to the Big Bang itself.

The Earth-Sun system is also thought to generate gravitational waves. The energy lost to these gravitational waves is expected to cause the two bodies to move toward one another by about 1

[‡] 13.4 Giga-years ago

femtometer per day. This is about the width of a proton.

17.2 Zeptoworld Area

1 – 1 000 000 square zeptometers (zm^2) 1 x 10^{-42} m^2

Assuming the area of interaction presented by a neutrino is approximately spherical, it has a surface area of 616 square zeptometers.

17.3 Zeptoworld Volume

1 – 1000 zeptoliters (zL) 1.0 x 10^{-21} L

The volume of an approximately spherical cosmic dust particle, with a radius of 50 picometers, is 524 zeptoliters. An HIV virus has a volume of about 905 zeptoliters.

17.4 Zeptoworld Mass

1 – 1000 zeptograms (zg) 1 x 10^{-21} g

The mass of a single molecule of Buckminsterfullerene is 1.2 zeptograms.

A molecule of insulin has a mass of about 10 zeptograms.

Objects with Zeptogram Mass

Item	Mass
Bucky-Ball	1.2 zg
Hemocyanin	2.5 zg
Insulin Molecule	10 zg
Trypsin	40 zg
Hemoglobin	110 zg

Table 17.2

A Hemoglobin molecule is an iron-containing protein which transports oxygen in our blood. It is responsible for the red coloring of oxygenated blood, and has a mass of 110 zeptograms. In some animals, such as horseshoe crabs and scorpions, a different molecule called hemocyanin is used to transport oxygen. Hemocyanin is based on copper, rather than iron, and has a number of variations. It is blue colored when transporting oxygen, and colorless when deoxygenated. Its mass is on the order of 2.5 zeptograms.

Trypsin is an enzyme, secreted by the pancreas which helps the digestive track break down protein molecules. It has a mass of about 40 zeptograms.

References

[1] Kraus, J. “Will Gravity-Wave Communication Be Possible?” *IEEE Antennas and Propagation Magazine*, Vol. 33, No. 4, August 1991

[2] Brian Clegg *Gravitational Waves* Icon Books LTD, 2018 pg 5