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Antimatter Pushing Boundaries

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Antimatter, normally the realm of science fiction, is one of the frontiers that CERN is pushing. The quote 'There is nothing new to be discovered in physics now', which has often been attributed to Lord Kelvin around the year 1900[1] – that is, before the discovery of quantum mechanics and relativity – well illustrates the dangers of underestimating apparently simple discrepancies. The Standard Model of physics, the great masterpiece of the twentieth century physics, is facing a number of small discrepancies that could have significant consequences. Antimatter is one of a number of promising means by which these issues are being tackled, the small problem with antimatter being that about half the Universe should be made of it – but effectively none is observed. Pushing the small problems in the early twentieth century led to a technological revolution driven by quantum mechanics that could not possibly have been predicted by contemporaries. Pushing today's frontiers is what CERN is all about, and antimatter plays a key role.

8.1
Science and the Unknown

While it is often purported that science is about the search for truth, it is more correct to say that science is the search for and the elimination of untruths. Along the way, temporary or partial truths are built up, such as *Newton's laws of gravitation*,[2] but it is in the nature of science to continuously question assumed truths and not to sweep anything under the carpet. The quote above, which is perhaps more correctly attributed to A.A. Michelson, who in 1894 remarked that in physics there were no more fundamental discoveries to be made, illustrates how wrong one can be when not sticking to the basic principle of scientific thought – which is precisely not about it being all over.

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[1] There is no evidence Lord Kelvin said this, but A.A. Michelson said something similar and seemed to allude to Lord Kelvin in 1894. See: L. Badash, *The completeness of nineteenth-century science*, Isis, Volume 63, p. 48, 1972.

[2] I. Newton, *Philosophiae Naturalis Principia Mathematica*, London, 1687.

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The current, possibly temporary, truth in our physical understanding of the Universe has led us to four fundamental forces of Nature to which (almost) all observed interactions can be attributed. One may split these fundamental forces into two categories. The three strongest forces, in descending order of strength, are the strong nuclear force, the electromagnetic force, and the weak nuclear force, and these are incorporated in what is referred to as the Standard Model.[3] The weak force and the strong force are those that dominate at the subatomic level, whereas the electromagnetic force governs the interaction between electrically charged particles. Beyond the Standard Model there is gravity, which regulates for example the movement of the planets. Gravity is the weakest of the known forces of Nature, something that remains a puzzle, as the current understanding is that the other forces, at high energies (i.e. in the early Universe), converge towards the same strength. Both our understanding of gravity, which is described by the *General Theory of Relativity*, and the Standard Model have celebrated great successes, though Gravity remains far less tested than the Standard Model due to its weakness. The Standard Model's latest success was the confirmation of the existence of a Higgs Boson at CERN,[4] announced on 4th July 2012.[5]

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3) The Standard Model includes all the known particles present in Nature, differentiating them by statistical properties and physical laws which they obey, into two families: *bosons* (which govern the interactions); and *fermions* (which make up matter). The latter are divided into two groups, *quarks* and *leptons*, with their respective antiparticles. The six types of quark are coupled in three generations: the lighter more-stable (*quark up*, *quark down*), the heavier less-stable (*quark charm*, *quark strange*), followed by the *quark top*, *quark bottom*. Quarks are electrically charged, and therefore are subjected to electromagnetic interactions; in Nature they are not isolated but are held together within the nucleus by strong interactions. There are six leptons, subdivided into three generations: the *electron*, the *muon* and the *tau*. To each of these three particles with electric charge and mass, is associated a neutral particle called the *neutrino*: the *electron neutrino*, the *muon neutrino* and the *tau neutrino*. The leptons are elementary particles which are subject to weak interactions, electromagnetic interactions (with the exception of the neutrinos which, being electrically neutral, do not interact via electromagnetic interactions) and, like all objects having a mass, to gravitational interactions. In the Standard Model each fundamental interaction is described by a boson field and the boson carriers are the *quanta* of this field; however, in this theoretical framework massless particles are introduced, because otherwise the symmetry of the system would no longer be respected. To avoid this, the physicist Peter W. Higgs, together with François Englert and Robert Broût, speculated in 1964 that all space was permeated by a field (the *Higgs field*) that, interacting with the fields associated to the particles, would give them the right mass, thus creating a spontaneous breaking of the symmetry without altering the original one of the system.

4) ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Physics Letters B, Volume 716, Issue 1, p. 1, 2012; CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Physics Letters B, Volume 716, Issue 1, p. 30, 2012.

5) In 2013, the Nobel Prize in Physics was awarded to F. Englert and P.W. Higgs ' . . . for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider.': http://www.nobelprize.org/nobel_prizes/physics/laureates/2013.

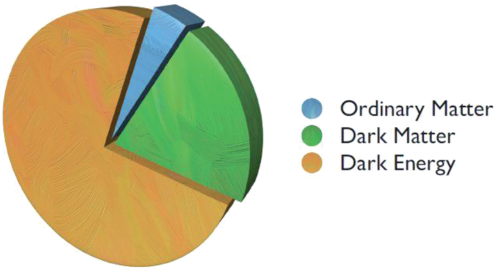

Figure 8.1 The energy budget of the Universe. It is estimated that ordinary matter makes up only 4% of the Universe, while antimatter makes up about 0%.

The success of our current understanding does not mean that it is done, to use the words of nineteenth century physicists. Significant issues remain, and as with the issues that remained at the end of the nineteenth century, it is essentially impossible to predict what will be found and therefore what impact this may have on both our understanding of the Universe and on our everyday lives. To mention a few, we can start by highlighting the simple diagram in Figure 8.1 that shows how we believe the Universe is made up today.

Figure 8.1 highlights two main points. First, that more than 90% of the energy in the Universe is in the form of dark matter and dark energy, both of which are place holders for unknown particles, fields, or something else. They are both called 'dark' as they are invisible, unlike stars, and as we have yet to detect their interaction with anything but gravity. Furthermore, their interaction with gravity has thus far only been inferred through indirect means; that is, to make the movements of galaxies be self-consistent with our understanding of gravity. Thus, neither the Standard Model nor the *General Theory of Relativity* incorporates dark matter and energy at this point, and there is not enough information yet to say how this might happen nor anything about the practical impact from such understanding. Second, no bulk antimatter in the Universe is observed. The Standard Model predicts, with considerable success in the laboratory, that matter and antimatter are – to a large extent – mirror images of each other (in a metaphorical sense; see Section 8.2). This has been tested with some precision, and thus far holds sufficiently well to lead to the expectation that rather than the Universe all being made of ordinary matter, about half of the Universe should have consisted of antimatter, but it does not.

As was the case in late nineteenth century, we have a number of outstanding issues to deal with in physics today, of which two examples are given above. The issues that had to be addressed at the end of the nineteenth century eventually led to the discovery/invention of general relativity and quantum mechanics. Quantum mechanics is a cornerstone of materials science and has given us almost everything that we take for granted in our modern society today, from computers and lasers to advanced materials and chemicals, to technological breakthroughs that have brought us great leaps ahead in medicine, as described

Color Fig.: 8.2

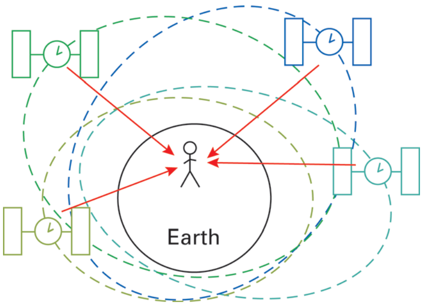

Figure 8.2 Schematic of the GPS System. The GPS system relies on very precise atomic clocks on satellites that transmit the time to a receiver on Earth. By knowing the satellites' orbits, receiving the times from four satellites will give the position. Atomic clocks build on decades of ever better measurements of atomic transitions, like those that are pursued on antihydrogen. Understanding General Relativity is necessary, as it explains how the clocks on satellites tick slightly faster than those at the surface.

in the first volume of this book. General relativity, while perhaps more abstract, has for example allowed us to have a functioning and relatively precise Global Positioning System (GPS), which would not have been possible by relying on the nineteenth century understanding of gravity (Figure 8.2). All of these developments have been a long time coming since the days of Niels Bohr and others in the early twentieth century, and it would be premature to say what developments may result from resolving the current outstanding issues. How antimatter fits into this program of understanding the basic nature of the Universe, and how CERN is pushing this edge, will be discussed in the following.

8.2
Antimatter and CERN

The visible Universe – the part we deal with directly in our everyday lives – is made up of relatively few fundamental building blocks. Protons, neutrons and electrons make up the bulk of what we see. For every such particle there exists – or one may say the possibility exists – of a so-called 'antiparticle' with the same mass but opposite charge. This curious fact was first realized by Paul Dirac during the late 1920s,6) when he derived a version of quantum mechanics that took Einstein's theory of relativity into account. This was a key problem that needed solving at the time, and it is easy to see why; Rutherford, Bohr and others had realized that atoms are made up of a nucleus surrounded by orbiting electrons. However, these same electrons could easily find themselves orbiting with speeds approaching that of the speed of light, which was known to be the ultimate limit. Thus, in order to be able to describe these systems the effect of the speed limit

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6) H.S. Kragh, *Dirac: A Scientific Biography*, Cambridge University Press, 1990.

had to be taken into account. It is in fact the relativistic effect that is the reason why gold is golden and not greyish, like most metals.[7)]

After the postulated existence of such 'opposite' particles to the already known particles, the first observation came quickly by Anderson in 1933.[8),9)] Anderson discovered a so-called 'positive electron', that has been named the 'positron' and that is the antiparticle of the electron or antielectron. However, other antiparticles took a while to discover. The delay in discovering more types of antiparticles was due to a number of reasons, the first reason being that they are rare (as discussed above) and the Universe contains essentially none in stable conditions. The second reason was that even if they do appear, they will quickly disintegrate. This stems from a feature that gave these particles their name. When an antiparticle meets its particle 'twin' – that is, when a positron meets an electron – the two particles may disintegrate in a so-called 'annihilation'. Energy is conserved, so the energy they represent will be released, in this case in its purest form, namely that of electromagnetic waves or light. The energy can be calculated with Einstein's famous equation $E = mc^2$, where m is the mass of the particles and c^2 is the speed of light squared – a very large number. Thus, Einstein's equation gives us the exchange rate between energy and mass. Conversion between energy and mass is by no means a phenomenon unique to antimatter. In a nuclear reactor, the nuclei are split into lighter nuclei in a process called 'fission', and the energy released corresponds to the difference in mass of the fission products relative to the initial nuclei. In nuclear fission less than 1% of the mass is converted to energy whereas, in an annihilation, all of the mass is converted to energy. This brings us to a final reason for the length of time it took to discover more massive antiparticles, such as the antiproton that was discovered in 1955 at the Bevatron at Berkeley in California, US.[10)] Antiparticles as well as particles may be created by converting energy to mass, thus the opposite process to the one just described. More massive particles will require more energy to be produced. The antiproton, which has a mass almost 2000-fold larger than the positron, therefore had to await the advent of accelerators, such as the Bevatron, to be created in the laboratory.

Thus, antimatter and matter can be created by converting energy to mass. One way of doing this is by accelerating particles to very high energies and colliding them with each other, or with a target material at rest. This is where CERN

[7)] N. Bartlett, *Relativistic Effects and the Chemistry of Gold*, Gold Bulletin, Volume 31, Issue 1, p. 22, 1998.

[8)] C.D. Anderson, *The Positive Electron*, Physical Review, Volume 43, Issue 6, p. 491, 1933.

[9)] The time from discovery to practical application has been much longer. The first mouse image acquired with Positron Emission Tomography (PET), using a small High-Density Avalanche Chamber (HIDAC), dates from 1977, while the prototype of the Advanced Rotating Tomograph (ART) scanner, the Partial Ring Tomograph (PRT), was also developed at CERN between 1989 and 1990. See: D. Townsend, *Detection and Imaging*, in B. Bressan (Ed.), *From Physics to Daily Life: Applications in Biology, Medicine and Healthcare*, Volume 1, Chapter 2, Wiley, 2014.

[10)] O. Chamberlain *et al.*, Physical Review, *Observation of Antiprotons*, Volume 100, Issue 3, p. 947, 1955.

comes into the picture. In fact, a key feature of the Large Hadron Collider (LHC) that accelerates particles to the highest energies is that it converts some of this energy to mass, creating for example the Higgs boson. Less will do to make antiprotons, but in the collisions of the LHC a large number of antiparticles are also created for brief moments until they decay or annihilate with surrounding matter. CERN serves a number of experiments that examine antimatter.

8.2.1
Antimatter at the LHC

At the LHC, protons are collided on protons with a nominal energy of each beam of 7 TeV. In such collisions a host of different particles and antiparticles are created, and the LHC was also constructed to create new more massive particles that could not be seen in previous machines, such as the Higgs boson.

However, as the available energy is increased in order to induce more massive particles or energy-demanding processes, as well as lower energy, previously rare Q1 processes may become more common. Some of these rare processes can shed light on small asymmetries between matter and antimatter. The Large Hadron Collider beauty (LHCb) experiment at the LHC is one example of an experiment that seeks such asymmetries specifically by examining how small fundamental particles called quarks – some of which make up protons and neutrons – actually decay.

8.2.2
The CERN Antimatter Facility

There is another approach to studying antimatter that is also being pursued at CERN, that of precision measurements. Today, the heart of this effort is the Antiproton Decelerator (AD),[11] a unique machine that decelerates antiprotons to a low enough energy to be usable for a host of specialized experiments (Figure 8.3). The AD is the last in a long line of machines that has served to provide antiprotons to the CERN physics community. Initially, in the 1970s, antiprotons at CERN were collided with protons to create new particles, and this led to the discovery in 1981 of the Z and W bosons that carry the weak nuclear force.[12],[13] However, in 1982 CERN started the Low-Energy Antiproton Ring (LEAR),[14] a precursor to the AD, to decelerate antiprotons. It was at the LEAR facility that

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[11] S. Maury, *The Antiproton Decelerator: AD*, Hyperfine Interactions, Volume 109, Issue 1, p. 43, 1997.

[12] The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer ‘ . . . for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction’: http://www.nobelprize.org/nobel_prizes/physics/laureates/1984.

[13] P. Watkins, *Story of the W and Z*, Cambridge University Press, 1986.

[14] R. Klapisch, *The LEAR Project and Physics with Low Energy Antiprotons at CERN (A Summary)*, Physica Scripta, Volume 5, N. T5, p. 140, 1983.

Color Fig.: 8.3

Figure 8.3 Part of the Antiproton Decelerator (AD) at CERN (Courtesy of CERN).

the first antihydrogen – the bound state of an antiproton and a positron – was made in 1995.[15] The low-energy antiproton facility involved three accelerators (LEAR plus the Antiproton Accumulator and the Antiproton Collector), and as CERN entered the LHC era and no longer used antiprotons at high energy, the antiproton complex was replaced by a single machine – the AD – that started delivering antiprotons for our physics community in 2000.

Precision measurements of atomic structure have for more than a century driven our understanding of atoms and quantum mechanics. This drive has led to the advent of atomic clocks, which now serve as the standards for timekeeping and that has given us the GPS. The best atomic clocks now have a precision of better than 1 part in 10^{18}, a precision which would be equivalent to measuring the distance to the Sun with a one-tenth of a micron precision.[16] As more precise measurements regularly lead to new discoveries, it has long been a dream to use these atomic physics tools on antimatter, and this dream is slowly coming true at CERN.

Precision measurements on antimatter to detect small differences between matter and antimatter take several forms at the CERN AD. The ATRAP[17] (Antihydrogen Trap) and Baryon Antibaryon Symmetry Experiment (BASE[18]) Collaborations are working with single antiprotons to detect minute variations in the magnetic moment (the small magnetic field) of the antiproton from that of the proton. Another group, Atomic Spectroscopy And Collisions Using Slow Antiprotons (ASACUSA)[19] is creating a bound state of a helium nucleus, an electron and an antiproton, which is also a sensitive probe of the antiproton magnetic moment.

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15) G. Baur *et al.*, *Production of Antihydrogen*, Physics Letters B, Volume 368, Issue 3, p. 251, 1996.

16) N. Hinkley *et al.*, *An Atomic Clock with* 10^{-18}*Instability*, Science, Volume 341, N. 1215, p. 1215, 2013.

17) http://home.web.cern.ch/about/experiments/atrap.

18) base.web.cern.ch.

19) asacusa.web.cern.ch.

Color Fig.: 8.4

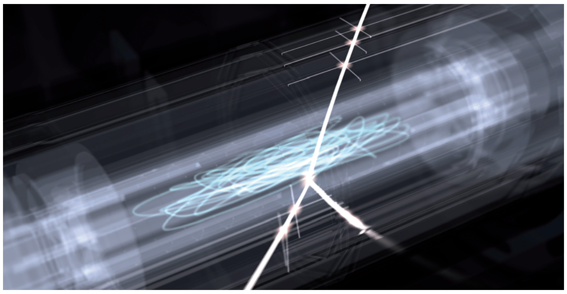

Figure 8.4 An artist's impression of an antiproton annihilation in the Antihydrogen Laser Physics Apparatus (ALPHA) experiment. The bright lines are the reconstructed tracks of the pions that result from an antiproton the annihilation. Illustration courtesy of Chukman So, ALPHA Collaboration, 2011.

The activity that has caught the most headlines, and which holds promise for the highest precision comparisons is from several groups, including the Antihydrogen Laser Physics Apparatus (ALPHA),[20] Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy (AEGIS),[21] ASACUSA, ATRAP and Gravitational Behaviour of Antihydrogen at Rest (GBAR)[22] that are – or will be – making antihydrogen atoms; that is, atoms composed of an antiproton and a positron.

Some recent breakthroughs were made by the ALPHA Collaboration, which was the first to observe a resonant quantum transition in an antihydrogen atom, albeit without great precision at this early stage.[23] A separate (but potentially equally fruitful) endeavour is to compare the gravitational influence on hydrogen and antihydrogen. Due to the relative weakness of gravity, such measurements are essentially impossible with charged particles, and antihydrogen is therefore a perfect, pure and neutral antimatter candidate for such measurements. While it is not expected that antimatter behaves differently, the Standard Model does not incorporate gravity, and there is therefore only indirect evidence for how antimatter would behave. ALPHA recently made a first, very crude but direct, effort at detecting the gravitational influence on antihydrogen (Figure 8.4).[24]

The many successes of the antimatter facility and the very promising prospects for more precise measurements have led CERN to increase its investment in the facility. Currently, the facility is being upgraded with an additional small decelerator called 'ELENA' (Extra Low-Energy Antiprotons).[25]

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20) alpha.web.cern.ch.

21) aegis.web.cern.ch.

22) gbar.web.cern.ch.

23) ALPHA Collaboration, *Resonant Quantum Transitions In Trapped Antihydrogen Atoms*, Nature, Volume 483, Issue 7390, p. 439, 2012.

24) The ALPHA Collaboration and A.E. Charman, *Description and first application of a new technique to measure the gravitational mass of antihydrogen*, Nature Communications, Volume 4, N. 1785, 2013.

25) W. Oelert *et al.*, *AD performance and its extension towards ELENA*, Hyperfine Interactions, Volume 213, Issue 1–3, p. 227, 2012.

8.3
The Anti-World in Everyday Life

While antimatter research is an exciting field that is trying to answer some of our most basic questions about the Universe, antimatter has for a long time made its mark on science fiction. However, antimatter is not just food for science fiction authors; it also holds the key to some of today's – and perhaps some of the future's – problems. Without being exhaustive, a few of the current uses of antimatter in everyday life will be highlighted here.

The energy that would be released if we managed to completely annihilate 1 g of antimatter on 1 g of matter – that is, in total 2 grams of mass – is approximately 1.8×10^{14} Joules, or the equivalent of 42 kilotons of TNT (trinitrotoluene). This enormous amount of energy has inspired science fiction authors to use antimatter as an energy storage medium for interstellar travel. However, as there is no bulk antimatter in the Universe, it would all have to be made by hand, so for every Joule of energy we wish to take out we must supply at least the same amount of energy. For comparison, the total world energy supply in 2011 was 5×10^{20} Joule;[26] thus, with 100% conversion efficiency and doing nothing else, the entire human race could manage to make about 8 kg of antimatter per day. In practice there are many competing processes, so the loss in converting energy to mass is enormous. For example, when making antiprotons about one million high-energy protons are needed for each antiproton created. Taken together, these processes and the difficulty of storing antimatter would render antimatter economically unviable and practically irrelevant as a bulk energy storage medium.

Yet, while larger amounts of antimatter are beyond our reach, small amounts already play an important role for some practical applications. When a positron annihilates on an electron the energy is typically released as two gamma-ray photons[27] (high-energy light). These gamma-rays will pass through the human body unhindered and can be identified by detectors that can reconstruct the path they took. By injecting a positron source into the human body that attaches itself to, for example, the red blood cells that transport oxygen, one may track where the red blood cells accumulate and, thus, identify the locations in the body with the largest oxygen consumption. This technique is known as Positron Emission Tomography (PET),[28] and is widely used in hospitals worldwide. The relative ease with which a positron-emitting radioactive source can be produced

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[26] IEA, *Key World Energy Statistics*: www.iea.org, 2013.

[27] As unstable atoms decay, they release radiation in the form of electromagnetic waves and subatomic particles. Some forms of this radiation can detach electrons from, or ionize, other atoms as they pass through matter; this is referred to as ionizing radiation. Alpha- and beta-particles, X-rays and gamma-rays, are all forms of ionizing radiation. Gamma-ray photons refer to electromagnetic radiation of extremely high frequency and therefore high energy per photon.

[28] D.W. Townsend *et al.*, *Positron Emission Tomography: Basic Sciences*, Springer-Verlag, 2003.

has consequently led to the positron becoming a workhorse of modern medical diagnostics.[29]

More recently, the technique has also been expanded to study live flows in particulate systems as an engineering aid; this procedure is referred to as Positron Emission Particle Tracking (PEPT) and was pioneered at the University of Birmingham, UK, during the 1990s.[30]

The relative ease of obtaining positrons and monitoring their annihilation has also driven the development of low-energy positron sources (often based on moderating positrons from a radioactive source) that are being used for studies of both inert and biological materials using Positron Annihilation Lifetime Spectroscopy (PALS).[31] PALS works by injecting low-energy positrons into a material and observing their lifetime. A positron may form a short-lived bound state with an electron, termed a 'Positronium' (Ps); the latter tend to seek out pores in a material where it will be bouncing until it eventually annihilates. The lifetime of a positron since its creation can therefore be used to elucidate information regarding the porosity of a material. More exotic uses of positrons and Ps have also been proposed, such as a gamma-ray laser.[32]

While positrons are relatively easy to obtain from radioactive sources, the larger mass of antiprotons requires higher energies and accelerator installations for their creation. Currently, CERN is one of the very few places in the world that provide a steady flow of antiprotons for experiments, and it is unique in providing low-energy antiprotons. Beyond the antiproton-based research discussed previously, antiprotons could also serve as a potential treatment for cancer. The irradiation of tumours is a standard component of the cancer therapy 'toolbox', where the most common types of radiation are X-rays and electron beams. However, heavier particles may be advantageous due to their loss profile when passing through biological material.[33] Heavier particles, such as protons or carbon nuclei that are used in more expensive (and therefore more scarce) facilities, will tend to have a limited penetration depth, close to which they deposit most of their kinetic energy, thus avoiding exposure of any living healthy tissue 'behind' the tumour. Antiprotons will, until they annihilate, deposit energy almost like protons. However, the annihilation causes an added energy deposition that is fairly localized and therefore, potentially, may only influence the tumour.

Measurements to characterize the influence of antiprotons on biological materials are also part of the CERN antimatter program, with a group called the

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[29] D. Townsend, *Detection and Imaging*, in B. Bressan (Ed.), *From Physics to Daily Life: Applications in Biology, Medicine and Healthcare*, Volume 1, Chapter 2, Wiley, 2014.

[30] D. J. Parker, *et al.*, *Positron emission particle tracking - a technique for studying flow within engineering equipment*, Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 326, Issue 3, p. 592, 1993.

[31] J. Calloo, *Characterizing Defects in Metals Using PALS*, LAP (Lambert Academic Publishing), 2012.

[32] D. Shiga, *How to build a gamma-ray laser with antimatter hybrid*, New Scientist, Volume 212, Issue 2844, p. 6, 2011.

[33] W.R. Hendee *et al.*, *Radiation Therapy Physics*, Wiley-Liss, 2004.

Antiproton Cell Experiment (ACE).[34] When the first biological samples were irradiated in 2003 they showed interesting results; however, until cheaper and smaller antiproton facilities can be produced, the benefit from using antiprotons for cancer therapy will be swamped by the increased costs of creating antiproton facilities relative to the cost of carbon ions and proton facilities.

8.4
Beyond the Present Day

While antimatter is unlikely to become a household item in the foreseeable future, the applications discussed here demonstrate how fundamental research also generates wealth for society through serendipity. The discovery of the positron and other antimatter particles was motivated solely by the desire to understand and describe the world around us to the best of our ability. It is – and always has been – very difficult, if not impossible, to predict the future, and we will not fall into the trap here and try to do so. Science is no exception to this rule, as has been amply demonstrated.[35]

However, we have brought up a number of parallels – perhaps exaggerated – to the late nineteenth century, where seemingly good descriptions existed of most known physical phenomena, with only a few remaining to be clarified. This should serve as an inspiration for the present day where we have an almost complete Standard Model, but also a number of unexplained phenomena. The precision comparisons of matter and antimatter that are being pursued at CERN may help to elucidate some of these remaining unknowns. There is currently no reason to believe that matter and antimatter should be different in such a way that antihydrogen would 'fall' up, or that the spectrum of antihydrogen should be different from that of hydrogen. However, the effort involved in investigating these assumptions is outweighed by the momentous impact on physics that would result from any such difference being observed.

Seeing how quantum mechanics has had a finger in an uncountable number of technological breakthroughs since its discovery, probing the foundations of the theory using antimatter could potentially lead to truly groundbreaking discoveries and breakthroughs would follow thereof. Antimatter research is, therefore, a potential new vehicle by which the pursuit of ever more precise measurements will pay off to both science and society. This was perhaps the original point of A.A. Michelson's Kelvin quotation that said ' . . .our future discoveries must be looked for in the sixth place of decimals'.[36]

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[34] http://home.web.cern.ch/about/experiments/ace.

[35] M. Irvine and B.R. Martin, *Foresight in science: picking the winners*, Frances Pinter, 1984.

[36] A.A. Michelson, *Speech at the dedication of Ryerson Physics Laboratory*, University of Chicago, US, 1984.

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