An accidental prediction: the saga of antimatter's discovery

The saga of how antimatter was discovered is one of the great physical accomplishments of the 20th-century. Like most scientific discoveries, its existence was rigorously tested and proven by both mathematical theory and empirical data. What set antimatter apart, however, is that the first antiparticle discovered – which was a positive electron or *positron* – was not the result of an intense search to find new and undiscovered particles. In fact, the research efforts that led to its discovery were unexpected and completely accidental results of the work being done by theoretical physicist Paul A.M. Dirac and experimental physicist Carl. D. Anderson, both of whom were working entirely independent of each other. Even more remarkable is the fact that Dirac's work mathematically predicted antimatter's existence four years before Anderson experimentally located the first positron!

To understand the discovery of antimatter, we must first define it and relate it back to its more common counterpart: matter. Matter can be defined as "…[a] material substance that occupies space, has mass, and is composed predominantly of atoms consisting of protons, neutrons, and electrons, that constitutes the observable universe, and that is interconvertible with energy" (Merriam-Webster). Antimatter particles have the same mass as regular matter particles, but contain equal and opposite charges. For example, the electron, a fundamental component of the atom, has a mass of 9.1×10^{-31} kilograms and an elementary charge value of -1.6×10^{-19} coulombs, or -*e* (NIST Reference on Constants, Units and Uncertainty). Its antimatter counterpart, the positron, has the same mass but a positive value of the elementary charge *e*.

When antimatter and matter particles come into contact with each other, they self-destruct, resulting in the emission of several gamma ray photons (Aryal 19). Since most of our universe is composed of ordinary matter, free antimatter particles only exist for a short time before they annihilate with a matter particle, making them very difficult to locate. It was this elusive tendency which made antimatter's very existence difficult to imagine. It was not until the early 1930s that the first positron would be successfully located, paving the way for the theory and subsequent discovery of more antiparticles.

The positron's initial discovery resulted from its prediction as a consequence of solving an entirely different problem: creating a more encompassing model of a microscopic particle. The reason why such a model was needed was because classical mechanics, the laws of which govern macroscopic objects, cannot accurately explain the behavior of particles at the atomic level. At the atomic level, matter no longer acts like an individual particle; rather, its behavior is better modeled using waves. This theory was first suggested by Louis de Broglie, who in his Ph.D. thesis postulated that matter at a microscopic level can be represented by a wave called a *matter wave* (Rosen 60).

The 1927 Davisson-Germer experiment was the first to provide evidence that a matter wave existed. Physicists Clinton Davisson and Lester Germer had been researching atomic arrangement on the surface of a nickel plate. To do so, they sealed a nickel plate within a vacuum chamber and bombarded the plate with electrons. By moving a

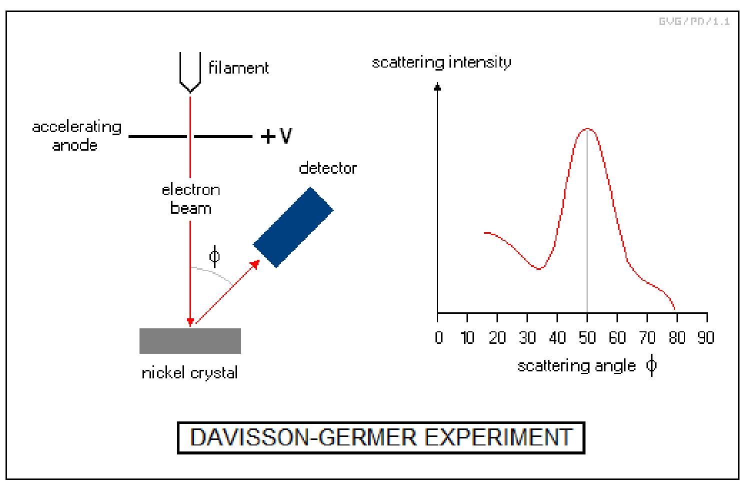

Figure 1: Electrons being accelerated towards a nickel crystal, and a graph of their scattering intensity as a function of scattering angle.

Sengupta, Gautam. "Matter Waves." *Quantum Physics PHY204/GS/2011.* IIT Kanpur. Blogspot. 7 Feb. 2011. Web. 12 Dec. 2012.

detector around, they were able to observe scattering intensity at different angles (Serway 147). Initially, the scattering intensity decreased steadily as the angle increased. Unfortunately, an accident happened in which the vacuum chamber broke and the nickel plate oxidized due to contact with air. To remove the oxide, Davisson and Germer heated the nickel plate to a very high temperature, which unbeknownst to them changed the nickel and gave it a crystalline structure. (Serway 147) When they repeated the experiment they observed a diffraction pattern with an increase in scattering angle (see figure 1). After performing more experiments, Davisson and Germer concluded that this could only happen if electrons, consistent with De Broglie's theory, acted like waves when hitting the nickel's crystalline structure and interfered with each other to form diffraction patterns (Serway 148).

Now that it had been established that matter could take on a wave nature, the field of quantum mechanics was founded in order to mathematically model such behavior. Formulating such a model eventually resulted in the accidental prediction of antimatter. In 1925, Austrian physicist Erwin Schrödinger provided an initial stab at modeling particle-wave nature in the form of his famous equation, written as $-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + U\psi = i\hbar\frac{\partial\psi}{\partial t}$ (Serway 186). It describes the law of conservation of energy at the quantum mechanical level, analogous to the classical mechanics equation $Kinetic\ energy + Potential\ energy = Total\ energy$. Additionally, the partial differential equation representing kinetic energy in the first term of Schrödinger's equation can be solved to find the particle's *wavefunction.* Typically denoted using the Greek letter ψ, the wavefunction is used to mathematically model the wave behavior of any microscopic particle. For instance, the absolute square of a wavefunction, written as $|\psi^*\psi|$, can be used to find the probability density of a particle – namely, the probability of a particle existing at a certain place or time (Lichtenberg 159).

The Schrödinger equation worked very well, and remains a fundamental basis of subsequent quantum treatments of particle systems (Serway 187). Unfortunately, the Schordinger equation neglected an important factor: Special Relativity, which takes effect as particles approach the speed of light and results in altered and unexpected particle behavior.

Formulated in 1905 by Albert Einstein, the theory of Special Relativity consists of two main postulates. The first postulate is that nothing can travel faster than the speed of light, which is denoted by the letter *c* and is equivalent to 3×10^8 meters per second (Einstein). Using only classical mechanics as a model, an object would be able to attain the speed of light with a reasonable input of energy, as can be seen by the pink line in figure 2. In reality, the effects of special relativity begin to take place when an object travels at half the speed of light or higher. The red asymptotic line on the graph in figure 2 demonstrates that an object can have an infinite amount of kinetic energy as it approaches *c*, but still be unable to attain the speed of light. The second postulate of special relativity states that the laws of physics must be the same for all observers in all reference frames (Einstein). This implies that classical mechanics and its concepts, including energy, mass and momentum, must be extended to incorporate special relativity. As a consequence of extending classical mechanics to include relativity, Einstein found that mass can be transformed into energy at high speeds, and vice versa. This effect can

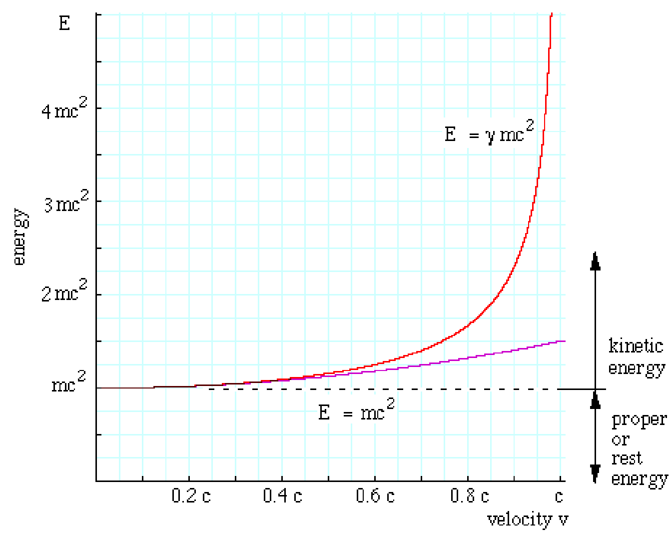

Figure 2: Energy input needed for particle to travel at a certain velocity. The red line takes into account the effects of special relativity.

Gal, Mike. "E = mc² - How relativistic mechanics leads to E = mc²." *EinsteinLight.* University of New South Wales. Web. 13 Dec. 2012.

be described using the famous equation $E = mc^2$, and also describes the *rest energy*, or energy equivalence, of a particle's mass (Serway 46).

Special Relativity was a new and important component of physics that could not be ignored. Therefore, it was important to incorporate it into quantum mechanics and thus come up with an even better particle-wave model. In 1926, physicists Oskar Klein and Walter Gordon proposed one such model by modifying Schrödinger's equation. Unfortunately, their equation, called the Klein-Gordon equation, had several flaws. First, the absolute squares of wavefunctions from the Klein-Gordon equation could not be used to determine probability densities from a physical standpoint (Lichtenberg 160). Second, solving for the rest energy of an electron resulted in both a positive and negative value for energy, the latter of which cannot exist (Steiner 100).

In 1928, British physicist Paul Dirac decided to tackle these dilemmas by creating his own relativistic Schrodinger equation. This equation eventually predicted the existence of antimatter. To ensure that Special relativity was fully incorporated, Dirac modified the Klein-Gordon equation to include coefficients of 4-by-4 matrices (Quantum Theory of Electron 614). In this way he took into account all variables–including the newly discovered phenomena of particle spin, which had been ignored in the Klein-Gordon and Schrödinger equation – and completed the model (Steiner 101). Dirac's equation solved the problem of non-feasible probability densities that the Klein-Gordon had. However, the problem of having both negative and positive solutions for energy continued, even when Dirac's equation was again solved for the rest energy of an electron.

Most physicists would have disregarded the negative solutions as being "unphysical" and thrown them out of the model. However, Dirac resisted this notion, for in addition to being a physicist he was also a meticulous mathematician. Throwing out the negative energy solutions would be like throwing away a fundamental part of the physics! (Siegfried, "Negativity").

To explain the negative values, Dirac made a bold postulate: that these solutions were not a result of negative energy states. Rather, they implied the existence of "…a new kind of particle, *unknown* to experimental physics, having the same mass and opposite charge to an electron" (Dirac, "Quantized Singularities" 1931).

Though there was no experimental proof at the time to support Dirac's assertion, his theory was soon to be verified: Four years later, the positron was experimentally located and confirmed to exist. Similar to its prediction, the positron's discovery was a consequence of researching an entirely different subject. Carl D. Anderson, at the time a Caltech Ph.D. candidate under physicist Robert A. Millikan, had just begun research on cosmic radiation – high energy particles that originate from outer space, penetrate the Earth's atmosphere and can then be detected ("Cosmic Radiation"). Crucial to his research was a new particle-detecting apparatus developed and discovered only a few decades earlier: the Wilson cloud chamber.

In 1911, Scottish physicist Charles Wilson had invented the cloud chamber in order to perform experiments on cloud formations ("C.T.R. Wilson"). The apparatus consists of a sealed chamber filled with supersaturated alcohol or water vapor. When charged particles enter the chamber, they ionize the vapor inside. The ionized vapor then condenses into "cloud trails" that, when illuminated by a light source, can easily be seen with the naked eye (Gupta 226).

In order to distinguish between the numerous particles that can pass through the chamber, a magnetic field is applied to it. A charged particle passing perpendicularly through a magnetic field will then feel the effects of the Lorentz force, which will cause the particle to curve to the left or right as it moves. This allows the particle to leave a circular trail in the chamber that can

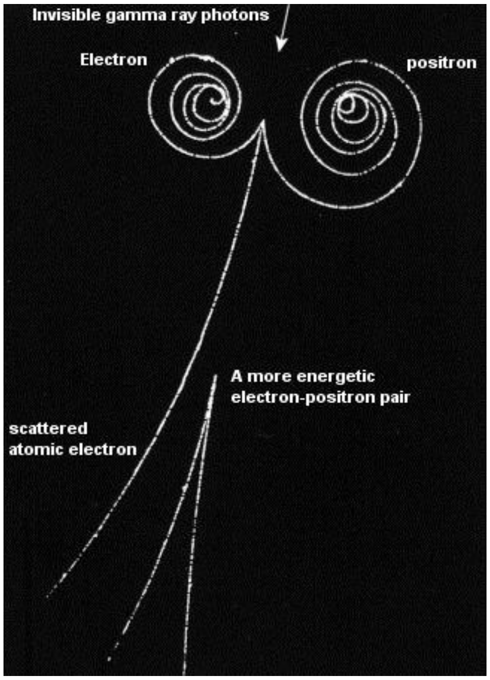

Figure 3: Positron and electron tracks in a cloud chamber.

Burchell, Bernard. "Matter-Energy Conversion – Part 2." ***Alternative Physics.*** **Web. 13 Dec. 2012**

easily be observed and measured ("Lorentz Force"). Multiple particle properties can be determined by looking at this trail. For example, the direction in which the particle curves can determine whether the particle is positively or negatively charged (see figure 3). Further, by measuring the length of the particle track and its change in curvature along the track, one can determine the energy with which it was originally emitted. From there, a charge-to-mass ratio can be determined, allowing the particle to be identified (Galison 118).

While performing cosmic ray research in 1933, Anderson discovered a mystery particle (see figure 4). It did not seem to resemble any other particle previously discovered, including the well-known ones such as the proton and electron. By comparing the mystery particle trail to known particles, Anderson faithfully adhered to the scientific method and began to determine deduce what the particle might be.

To begin, Anderson took over 1300 cloud chamber photographs to see if he could find more instances of the mystery particle. Of these photographs, 15 seemed to share the same properties as the mystery particle (Anderson 1). While looking at his data, Anderson noted that the mystery particles curved in the same direction as the proton, indicating that like the proton, it had a positive charge. However, after measuring the length and curvature of the mystery particle's trail, Anderson realized that it could not have the same value of charge as a proton, since the length of the mystery particle's path was 10 times greater than the length of a proton's path with the same curvature (Anderson 3). In fact, it seemed to have a charge value closer to that of the electron. Anderson came up with several alternative explanations for this phenomenon, including the possibility of "…two independent electrons [happening] to produce two tracks so placed as to give the impression of a single particle shooting through…" (Anderson 2). but had to eliminate these options due to their extremely small probability of occurrence. He was finally led to conclude that "…either of the two remaining possibilities leads to the existence of the positive electron" (Anderson 2).

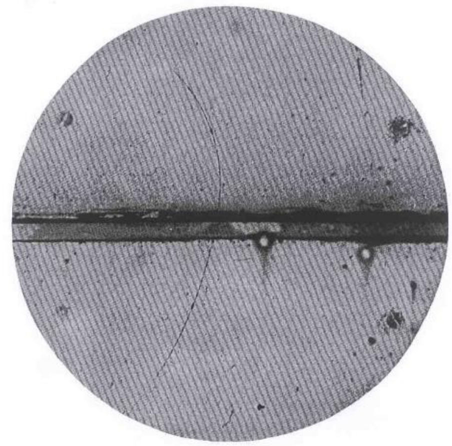

Figure 4: Anderson's photograph of the first positron cloud trail.

Anderson, Carl D. "The Positive Electron". *Physical Review*. 43.6 (1933): 491-494. Web. 3 Dec. 2012

Throughout his experiment, Anderson did not allow himself to be influenced by Dirac's theory of the positron. In an interview from 1966, Anderson mentioned that prior to his discovery he had read Dirac's papers. He stated, however, "…I was looking at the cloud chamber data and going by that…the Dirac work was not an important ingredient in deciding which way the experiments should be carried out or what should be done experimentally" (AIP: Carl D. Anderson).

Thus, the saga of the positron's discovery came to a close. However, it was only the first antimatter particle to be discovered. The antiproton was discovered in 1955 by physicists Emilio Segre and Owen Chamberlain ("Nobel Prize in Physics 1959"), and the antineutron a year later with the Bevatron Particle accelerator at the Lawrence Berkeley National Laboratory ("Breaking Through…"). In 1995, the European Organization for Nuclear Research (CERN) successfully produced nine antihydrogen atoms in a particle accelerator, thus demonstrating that not only could antimatter atoms be created, but that there was a distinct symmetry between regular matter atoms and antimatter atoms (Golden Jubilee Photos…, 2004).

Positrons have since been put to extensive use in modern medical imaging. To explain why, we need to use our knowledge of Special Relativity to understand what happens during positron-electron annihilation. When an electron and a positron are near each other, they attract and accelerate towards each other due to their having equal and opposite charges. When colliding, they do so at speeds close to that of light. All the mass of the positron and electron are then converted to energy in the form of two or three emitted gamma ray photons (Zetilli 17).

The emitted gamma photons can be detected using light sensors, which is why positron-electron annihilations have since been used in medical PET scanning, or Positron Electron Tomography. A small amount of fluorodeoxyglucose, a short-lived radioactive compound which naturally emits positrons as it decays, is injected into a patient (Fluorodeoxyglucose F 18). Because of its chemical similarity to glucose, it is rapidly metabolized in body tissues with high uptake capacities of glucose, such as active areas of the brain, the liver and cancerous tissues (Valk 1). As the fluorodeoxyglucose localizes in areas of the body, it emits positrons. The gamma ray photons given off by the positron-electron decays can be detected by having the patient lie within a PET scanner ring containing a series of photomultiplier tubes (Aryal 20). These tubes detect the light given off by the photons and process them into a comprehensive image. The areas that have more positron-electron decays, and therefore more detected photon emissions, visually show where cancerous growth or brain activity is most concentrated.

All of these advances in both medical and particle research resulted from the discovery of the positron. Through a simple solution to an equation, Dirac predicted the positron's existence and demonstrated the precision of using mathematics as a tool to delineate physical phenomena.

Four years later, Anderson made use of the scientific method to help him uncover his mystery particle's identity as the positron. Ultimately, their work demonstrates that the crux of the positron's prediction lay in the two scientists' adhering to solid scientific practices and relying on evidence to deduce that what their research was telling them was indeed correct.

Works Cited

"C.T.R. Wilson." *Encyclopædia Britannica. Encyclopædia Britannica Online Academic Edition.* Encyclopædia Britannica Inc., 2012. Web. 14 Dec. 2012. <http://www.britannica.com/EBchecked/topic/644646/C-T-R-Wilson>.

"Lorentz force." *Encyclopædia Britannica. Encyclopædia Britannica Online Academic Edition.* Encyclopædia Britannica Inc., 2012. Web. 14 Dec. 2012. <http://www.britannica.com/EBchecked/topic/348139/Lorentz-force>.

"The Nobel Prize in Physics 1959". Nobelprize.org. Web. 14 Dec 2012 http://www.nobelprize.org/nobel_prizes/physics/laureates/1959/

"Breaking Through: A Century of Physics at Berkeley, 1868–1968". Regents of the University of California. 8 Dec. 2006. Web. 14 Dec. 2012.

"Cosmic Radiation." *NRC Library: Basic References: Glossary.* United States Nuclear Regulatory Comission. 10 Dec. 2012. Web. 14 Dec. 2012.

"Fludeoxyglucose F 18 (Systemic)" Drugs.com. Web. 13 Dec. 2012.

"GOLDEN JUBILEE PHOTOS: WELCOME TO THE ANTIWORLD." *CERN Bulletin* 29 (2004): *CERN Document Server*. Web. 14 Dec 2012. < http://cdsweb.cern.ch/record/768811>

"Matter." Merriam Webster. Encyclopedia Britannica. Web. 2 Dec. 2012.

Anderson, Carl D. "The Positive Electron". *Physical Review*. 43.6 (1933): 491-494. Web. 3 Dec. 2012

Anderson, Carl D. Interview by Charles Weiner. *Niels Bohr Library & Archives*. American Institute of Physics, 1966. Web. 22 Nov. 2012.

Aryal, Bijaya. *Transfer of Learning with an Application to the Physics of Positron Emission Tomography*. Proquest: 2007. Web. 11 Dec. 2012

Dirac, Paul A. M. "The Quantum Theory of the Electron." *Proceedings of the Royal Society A.* 117 (1928): 610-624. Web. 1 Dec. 2012

Dirac, Paul A. M. "Quantised Singularities in the Electromagnetic Field." *Proceedings of the Royal Society A.* 133.821 (1931): 60-72. Web. 3 Dec. 2012.

Einstein, Albert. "Zur Elektrodynamik bewegter Körper." Trans. W. Perret. *Annalen der Physik*. 17:891, 1905.

Galison, Peter. *How Experiments End.* 2nd. Ed. Chicago: University of Chicago Press 1987. Print.

Lichtenberg, Don Bernett. *The Universe and the Atom.* World Scientific 2007. Print.

NIST Reference on Constants, Units and Uncertainty. *National Institute of Standards and Technology*. Oct. 1994. Web. 8 Dec. 2012

Rosen, Joe and Lisa Quinn Gothard. "Broglie, Louis de." Encyclopedia of Physical Science, Volume 1. 2009. Print.

Seigfried, Tom. Strange *Matters: Undiscovered Ideas at the Frontiers of Space and Time.* Joseph Henry Press, 2002. Print.

Serway, Raymond A, Clement J. Moses and Curt A. Moyer. *Modern Physics*. 3rd ed. Delhi: Cengage Learning India Private Limited, 2005. Print.

Steiner, Mark. *The Applicability of Mathematics as a Philosophical Problem.* Boston: Harvard University Press 2002. Print.

Valk, Peter E. *Positron Electron Tomography: Clinical Practice.* Springer 2006. Print.

Zettili, Nouredine. *Quantum Mechanics: Concepts and Applications.* Wiltshire: John Wiley and Sons 2009. Print.