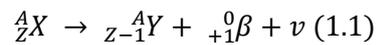


Introduction –

Antimatter strikes interest in modern physics with its hints towards the secrets of the universe, and its everyday uses, such as in PET scanners. Antimatter can be found in cosmic ray collisions or in some types of radioactive decay and an example of this can be seen when a proton changes into a neutron in an unstable nucleus, producing a positron (${}_{+1}^0\beta$) and a neutrino (ν):



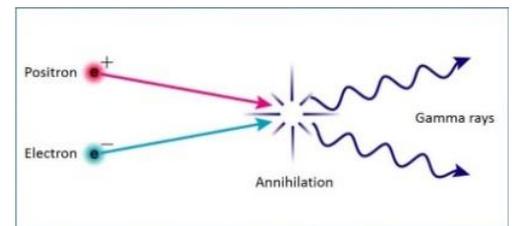
First predicted by Dirac in 1928, antimatter seemingly solved Einstein's "locked" rest energy of a particle. A particle and its antiparticle pair could 'annihilate' each other upon contact, releasing this energy (usually) in the form of two photons (Fig. 1.1). As $E = hf_{min}$ for a photon, the rest energy of the particle has now been unlocked during this interaction. Dirac's full prediction was as follows: For each particle there is an antiparticle pair that would "(I) annihilate the particle and itself if they met, converting their mass into photons (II) have the same mass as the particle (III) have exactly opposite charge to the particle if the particle has a charge." (Jim Breithaupt, 2015)¹. Dirac also predicted the reverse to be true. The process of 'pair production' would occur when a photon of high enough energy passes near a nucleus or electron, causing a particle-antiparticle pair to be created. This process will be touched upon later, however is important now in understanding energy transfers. As the rest mass of a particle can be calculated using $E = mc^2$ we know we are also able to calculate the rest energy of the particle and therefore its antiparticle pair. During the process of annihilation, a particle-antiparticle pair collide to create two photons. As we know the rest energy (E_0) of the particle and antiparticle we know the energy of each photon will be equal to the rest energy and so:

$$hf_{min} = E_0 \quad (1.2)$$

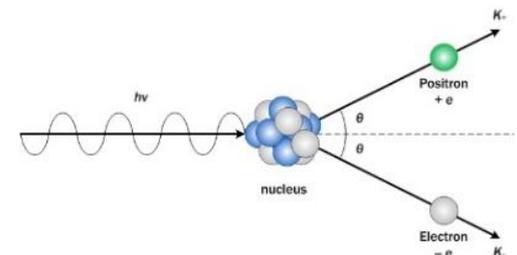
In the event of pair production, a photon is being used to create a particle and an antiparticle. The rest energies of these can be calculated as half of the minimum energy of the photon (as the mass of each is the same the rest energy will also have to be the same) and so:

$$hf_{min} = 2E_0 \quad (1.3)$$

This rule can be used to show that photons of certain energies can only create particles whose rest energies sum to less than its own.

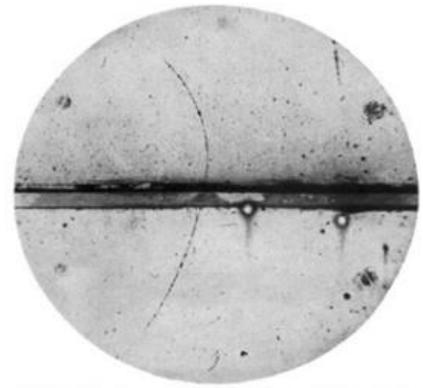


(Fig. 1.1) The process of annihilation. The energy of one photon is calculated to be equal to the rest energy of the particle.



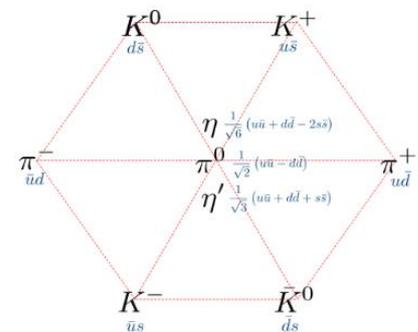
(Fig. 1.2) The process of pair production. The energy of the photon is shared between the antiparticle and particle.

As we have now covered the rules that govern antimatter interactions and how it may be created, it is important to note successful evidence of the existence of such a potent thing. It is ailing to have such a strong theory without significant evidence to back to up and so in 1932 when Carl Anderson was performing a cloud chamber experiment using magnets to bend the particles trail, the shock he felt to see some bend in the opposite direction to others rippled over the scientific community (Fig 1.3). Anderson had unintentionally proved the existence of the positron and in doing so had justified Dirac's earlier theory!



(Fig 1.3) A picture of a cloud chamber. The trails shown have been made by particles passing through vapor. It is easy to see where the trails separate.

The final paragraph of this introduction is taken up by quarks and antiquarks. "The quark model exists as the properties of hadrons, such as charge, strangeness, and rest mass can be explained by assuming they are composed of smaller particles known as quarks and antiquarks." (Jim Breithaupt, 2015)². Hadrons are particles of the standard model that can be divided into two groups: 1) Baryons – hadrons that decay into protons (such as neutrons) and 2) Mesons – hadrons that don't decay into protons (such as kaons and pions). To understand the distinction between these groups, combinations of quarks and antiquarks are used to distinguish certain hadrons from each other. Mesons are a combination of a quark and an antiquark (Fig 1.4), whereas baryons are a combination of either 3 quarks (e.g. proton is uud) or 3 antiquarks (e.g. antiproton is $\bar{u}\bar{u}\bar{d}$). As a proton is the most stable baryon, a free neutron will decay into a proton releasing an electron and electron antineutrino (β^- decay).



(Fig 1.4) The map of quark combinations for established Kaons and Pions.

Summary –

- Antiparticles can be created in a variety of different environments and are opposite in charge to their particle equivalent, however, share the same properties of mass and spin.
- The two major processes involving antimatter are annihilation (creation of photons) and pair production (creation of particles).
- Dirac theorised antimatter in 1928, yet it wasn't until 1932 that its existence was proven.
- Antiquarks are used to make specific hadronic particles.

1. Understanding Annihilation and Pair Production.

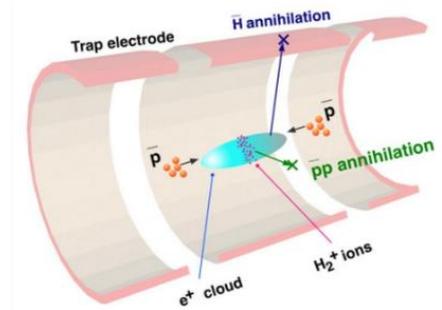
1.1 Annihilation -

As talked about in the introduction, antimatter controls a lot of the microscopic events that occur daily. These events are due to annihilation and pair production. Annihilation involves the collision of a particle and its coupled antiparticle. This process inevitably leads to the emission of EM radiation due to the 'unlocking' of the particles rest energy. The formula for a simple electron (e^-) positron (e^+) annihilation is given as:

$$E_\gamma = E_{e^-} + E_{e^+} \quad (2.1)$$

Where E_γ is the sum of the energy of each photon. However, the process to release this energy is not as simple as colliding a particle-antiparticle pair. We seem to be missing an important middle step in this procedure. As noted in Journal of Physics: Conference Series' "Matter-Antimatter Physics at Low Energy", "Fundamental development of the physics of particle-antiparticle interaction at low energy was achieved by ATHENA GROUP at CERN in 2006. It was proved for the first time that the collision of a proton with an Antihydrogen leads to the formation of a bound state composed of a proton and an antiproton, (identified by the Authors as antiprotonic hydrogen [Fig 2.1]), in which both particles are rotating around each other." (Mohamed Assaad Abdel-Raouf 2019)³. The analysis made by the ATHENA GROUP at CERN showed that in low energy states colliding a particle and its antiparticle equivalent would result in a 'quasi onium atom' or in the case of CERN 'antiprotonic hydrogen'. This confirmed the existence of atoms like 'Positronium', 'Protonium' and 'True Muonium' which share the feature of extremely short lifetimes (about $\tau \sim 1.0 \times 10^{-6}$ s in the case of antiprotonic hydrogen) and share the structure of a particle and an antiparticle rotating about each other.

Quasi atoms are the missing link in our annihilation puzzle. A quasi atom will have energy equal to the combined sums of the energies of each photon released (Eq 1.2). This is the case with Eq 2.1 which describes the process occurring after a Positronium atoms lifetime. Photons will be emitted at near 180° to each other in accordance with conservation of momentum, however, as worded by Alpen "the extent that the positron is not completely thermalized at the time of annihilation, the angular separation of the two photons may be slightly different from 180° ." (Edward L. Alpen 1998)⁴.



(Fig 2.1) Formation of Antiprotonic Hydrogen by ATHENA EXPERIMENT at CERN.

1.2 Pair Production –

We had mentioned previously that pair production involves the process of a photon converting its energy into mass with the creation of a particle-antiparticle pair. Much like annihilation, there are rules to be followed during this process. As we talked about in the previous chapter, all energy of a system will be converted during the process of annihilation; the same is the case for pair production. If we take the example of an electron-positron pair colliding and producing a muon-antimuon pair at high enough energy, we can see that during this process a neutral (Z^0) boson is produced and then decays into the particle-antiparticle pair*. This decay is actual a process of pair production as the Z boson becomes the particles produced (with remaining energy being used as a kinetic store in both). The rules that must be followed during this process are as follows: (I) The energy of the neutral boson must be significant enough to produce the particle-antiparticle pair (in accordance with the law of conservation of energy). (II) Conserved quantum numbers must sum to zero (in order to follow laws of conservation of energy). Notice here that both rules follow the law of conservation of energy. Simply playing with the first rule concludes that low energy phenomena of light-matter interactions lead to the Photoelectric effect, mid-energy leads to either Thomson or Compton scattering, and it is only at high energy interactions that one of Pair production, Photodisintegration or Photofission occurs (Fig 2.2). Each of these phenomena follows their own rules and can be identified through their individuality from each other inferring that the energy of a photon highly defines the outcome of light-matter interactions. The second rule provides us with far less flexibility. As mentioned in the introduction, to follow the conservation of momentum, particles produced during pair production will be emitted at the same angle. A kinematical proof of this is shown below⁹ but can be skipped:

$$p_\gamma = p_{e^-} + p_{e^+} + p_R$$

$$(p_\gamma)^2 = (p_{e^-} + p_{e^+} + p_R)^2$$

$$\text{As } p_R \approx 0^1$$

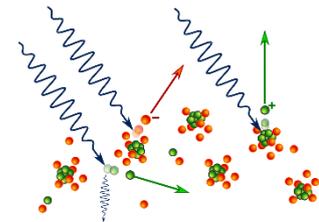
$$(p_\gamma)^2 \approx (p_{e^-})^2 + (p_{e^+})^2 + 2 p_{e^+} p_{e^-}$$

$$0 \approx -2m_e^2 c^2 + 2 \left(-\frac{E^2}{c^2} + \mathbf{p}_{e^+} \cdot \mathbf{p}_{e^-} \right)^2$$

$$0 \approx 2(\gamma^2 - 1)m_e^2 c^2 (\cos\theta_e - 1)$$

\therefore The angle between emitted particles must be ≈ 0 (or π) with a small amount of variation accounting for the displacement of the atomic nucleus.

*It is important to note here the use of the term 'neutral'. The conservation of energy requires the conservation of charge and so when a negatively and positively charged particle are created the net charge is neutral.



(Fig 2.2) Light-matter interactions lead to a variety of different phenomena depending on the amount of energy involved).

¹ This is as the displacement of the nucleus is minimal and so shouldn't be accounted for here.

² This can be shown using the 4-vector rule $A \equiv (A^0, \mathbf{A})$ so $A^2 = A^\mu A_\mu = -(A^0)^2 + \mathbf{A}^2$ implying $(p_\gamma)^2 = 0$ for all cases and $(p_{e^-})^2 = -2m_e^2 c^2$.

This concept leads us back to the idea of the conservation of energy. As all quantum numbers have been conserved it is easy to write the equations needed to calculate energy transfers during pair production. For example, during electron-positron production the equation may be written as:

$$(E_k^{pp})_{tr} = hv - 2m_e c^2 \quad (2.3)$$

Where hv is the energy of the neutral boson and $2m_e c^2$ is the combined rest energy of the electron-positron pair.

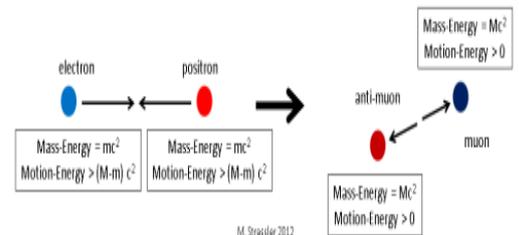
Another point to be addressed regarding pair production is the creation of heavier particles. As mentioned above, the minimum photonic energy is equal to the rest energy of the particle-antiparticle pair annihilating each other (Eq 1.2). This idea can be built upon. By using the Hamiltonian* of the system (particle-antiparticle pair) we can derive that an annihilation occurring between moving particles will produce an output energy equal to the sum of the rest energy (E_0) of the system and any extra motion-energy. Therefore Eq 1.2 now becomes:

$$hf = H\psi = i\hbar \frac{\partial \psi}{\partial t} = E\psi \quad (2.2)^\Delta$$

Where $H\psi(x)$ is the total energy of the system. Using this new equation, we find that while much lighter particles may undergo annihilation, if they are being operated on then the products of annihilation become much heavier. An example of this is taken by adding substantial motion to the electron and positron provided in Eq 2.1. Instead of producing two gamma rays that decay back into an electron and a positron, the products become a muon and an anti-muon (Fig 2.3). This is an increase in mass of approximately 207 times the original*.

*Hamiltonian function, also called Hamiltonian, mathematical definition introduced in 1835 by Sir William Rowan Hamilton to express the rate of change in time of the system of a dynamic body — one regarded as a set of moving particles.” (Swati Chopra 2012)⁵

^ΔYou may notice this is also just an application of the Schrodinger wave equation: $(-\frac{\hbar^2}{2m}\nabla^2 + V)\psi = i\hbar\frac{\partial}{\partial t}\psi$. Used to represent the total energy of the system in Eq 1.2.

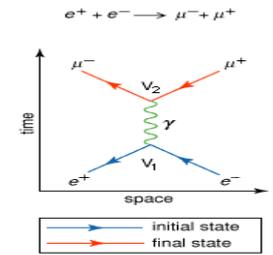


(Fig 2.3) The annihilation of an electron and positron. Excess energy not needed to make the mass energy of a muon-antimuon pair goes into their motion-energy (Matt Strassler 2012)⁶

*Electron rest mass = $9.1093837015 \times 10^{-31}$ kg (0.511MeV/c)⁷ while muon rest mass = 105.66 MeV/c⁸

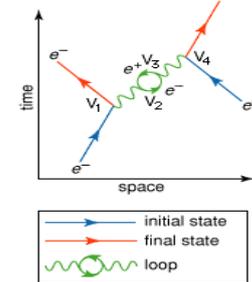
1.3 Feynman Diagrams -

A final consideration in this chapter is the use of Feynman diagrams*. The properties of Feynman diagrams are as follows: Straight lines are used to show Fermions, wavy lines depict bosons, the x-axis represents spatial position, and the y-axis portrays time. Figures 1.1 and 1.2 give semi-representations of how a Feynman diagram might look, but together create what is shown in Fig 2.4. You may notice that the pair production shown in Fig 2.4 is that of the electron's heavier counterpart, the muon. This is in reference to Fig 2.3 and occurs because as the electron-positron pair are moving along the x-axis, the electron (e^-) and positron (e^+) must collide with some velocity giving reference to Eq 2.2, and therefore as aforementioned, higher energy collisions producing heavier particles. Notice also how this interaction happens at the same spatial reference. This feature of the diagram shows the rules of conservation of quantum numbers (that were discussed earlier in the chapter) are still being observed here.



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(Fig 2.4) An electron and positron annihilate and form muon-antimuon pair¹⁰.



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(Fig2.5) A more complex Feynman diagram showing many particles¹¹.

There are of course more complicated examples of the Feynman diagram. Fig 2.5 shows an account of 2 electrons exchanging separate photons, producing separate interactions at V_1, V_2, V_3 and V_4 . The green 'loop' is representative of perturbation theory and is used to identify divergences in a QFT. The one present in this example is an ultraviolet divergency (as shown by the single loop). Even more complected systems would lead to a higher number of divergencies and as such a higher number of loops. In Fig 2.6 MannyC¹² gives a fantastic approach to understanding perturbed theory, however this can again be avoided.

The quantum mechanical equivalent would be [time-dependent perturbation theory](#). The transition amplitude from an unperturbed state $|\alpha\rangle$ at time t_0 to a state $|\beta\rangle$ at time t is given by

$$i\Omega_{\alpha\rightarrow\beta} = \langle\alpha|U|\beta\rangle,$$

where U is given by (assuming $\langle\alpha|\beta\rangle = 0$ at $t = t_0$ for simplicity)

$$U = \lambda \frac{\langle\alpha|V|\beta\rangle}{E_\alpha - E_\beta} + \lambda^2 \sum_n \frac{\langle\alpha|V|n\rangle\langle n|V|\beta\rangle}{(E_\alpha - E_n)(E_n - E_\beta)} + \dots,$$

where λV is the perturbation. (I am being schematic here just to get the point across.)

Now you might say: ok, but where are the loops here?

The "loop" is the sum over n .

Perturbation theory tells us that in order to compute the contribution of the perturbation λV to the transition amplitude, we should take into account all the states of the theory. Higher order corrections in λ result in more and more sums over the states $|n\rangle$.

(Fig 2.6) MannyC's approach to perturbation theory.

Summary –

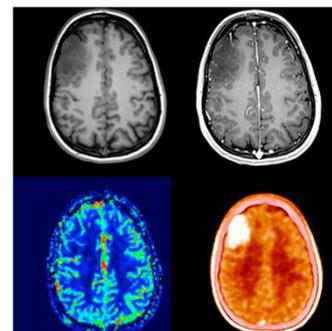
- The result of an annihilation is an incredibly brief-lived quasi atom which consists of a particle and an antiparticle rotating about each other.
- All energy is conserved during annihilation meaning heavier particles can be created later during pair production.
- Conserved quantum numbers lead to the emission of particles at near 180° to each other.
- Feynman diagrams can be used to solve a plethora of problems involving QFT, some of which relate to annihilation and pair production.

2. Real World Uses of Antimatter.

2.1 PET Scanners –

Possibly the most important use of antimatter in everyday life is Positron Emission Tomography (or PET for short). PET scanners make use of a radioactive glucose injection into a vein, which then cycle around the body with the flow of blood. A special camera will then detect positrons emitted by the radioactive glucose and depending on how much of the glucose has been absorbed a brighter or darker image will be created (more or less positrons have therefore been emitted). According to [Stanford Health Care](#)¹³ “Malignant tumour cells show up brighter in the picture because they are more active and take up more glucose than normal cells do.” Fig 3.1 shows an image taken from a PET scan showing an area of cancer in the brain. The region is clearly identified.

The uses of PET scans are not to be underestimated. Due to the biological nature of cancer, a PET scan can detect most cancer before they're evident in other examinations. This can lead to an incredibly fast diagnosis of a patient, leading to quick treatment and stopping the spread of a malignant cancer before it gets out of control. There are very limiting side effects as only a small amount of radioactive material is used in the glucose leading the PET scan to be a superior option to most in cancer diagnosis.



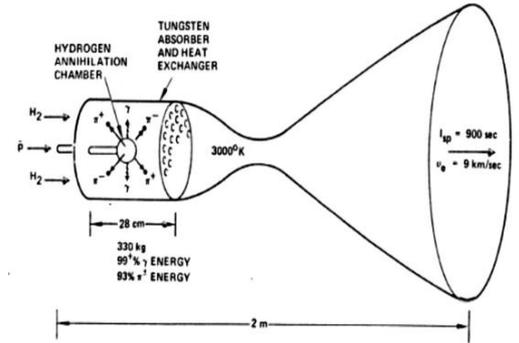
(Fig 3.1) An image taken from a PET scan showing a region of tumour.

2.2 Antimatter Fuel –

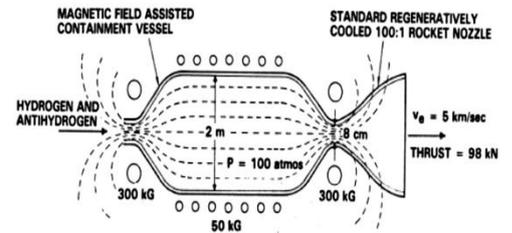
A concept toyed with by leading astrophysicist, antimatter propulsion may one day become a reality. While currently antimatter seems to be a terrible source of energy [about an efficiency of 10^{-10} times the energy invested (CERN¹⁴)] its future use may play the part of a major contribution to our society. An antimatter-matter annihilation is 100% efficient meaning all mass is converted to energy, none of which is wasted. This would allow for mass production of antimatter facilities that would cause no harm to the environment and could be used in the production of such things as rocket fuels [about 1kg of antimatter is equivalent to 43 megatons (1.8×10^{17} J) of energy¹⁵]. As calculated by NASA, energy released per unit mass of antimatter is approximately 300x greater than that of nuclear fusion making it an increasingly desirable source. All following information is provided by NASA¹⁶. The following are concept ideas of antimatter thrusts created by Proton-Antiproton interactions:

- 1) Solid Core engine – Energy from annihilation is transferred to a tungsten block with an estimated efficiency of 90%. It has a similar performance to a Nuclear Thermal Propulsion engine with an I_{sp}^* of about 900s and a high thrust and has a typical \bar{p} mass flow of several $\mu\text{g}/\text{sec}$. Fig 3.2 shows its concept art.
- 2) Gas Core engine – Energy is transferred to a high-pressure hydrogen propellant; variants including liquid hydrogen for easier energy transfer. It is only about 35% efficient, however, it has I_{sp} like chemical engines (500s) and high thrust, and has a typical \bar{p} mass flow of 10's $\mu\text{g}/\text{sec}$. Figure 3.3 shows its concept art.
- 3) Plasma Core engine – Charged particles are trapped and guided by strong magnetic fields leading to a much higher I_{sp} than chemical engines (several 1000s) and a moderate thrust, with a typical pulse producing 10^{18} \bar{p} (or 100's $\mu\text{g}/\text{sec}$). However, transferred energy is only 1-2%. Figure 3.4 shows its concept art.
- 4) Beam Core engine. Charged pions are directed by magnetic nozzles and contain about 40% of the initial annihilation energy. This concept has a much higher I_{sp} of 28×10^6 s but has a much lower thrust. It has a typical \bar{p} mass flow of 100's $\mu\text{g}/\text{sec}$. Fig 3.5 shows its concept art.

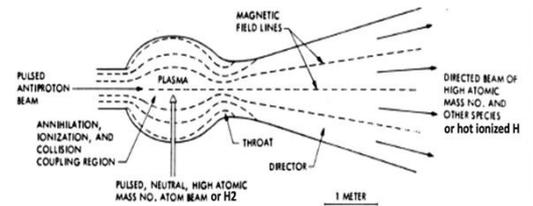
* I_{sp} = specific impulse, a measure of how efficiently a mass engine creates thrust.



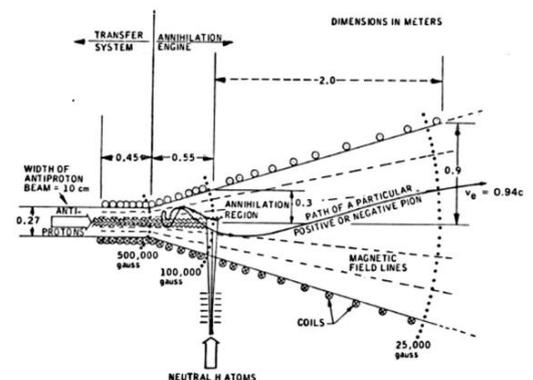
(Fig 3.2) Concept art for a Solid Core engine.



(Fig 3.3) Concept art for a Gas Core engine.



(Fig 3.4) Concept art for a Plasma Core engine.



(Fig 3.5) Concept art for a Beam core engine.

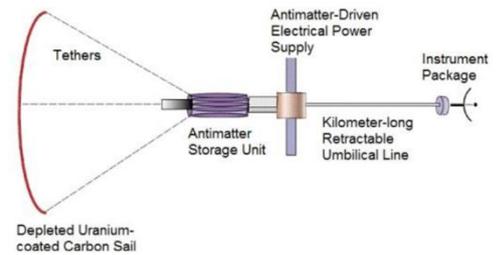
Should one of these thrusts one day be created, humanity may see the days of much, much faster travel. Our next step would be maintaining high speeds of travel throughout the cosmos. The current proposed idea is an antimatter driven sail. NASA's current proposal (Fig 3.6) could see speeds of up to 10^7 m/s, reaching places such as Alpha Centaur in 40 years with a single gram of antihydrogen, or using an equivalent 30mg to travel a huge 250AU in 10 years with only a 10kg payload. To achieve this, large output antimatter factories and storage units will be needed. Luckily for us, proposed ideas do exist. For example, J. Davis and R. Forward's 'Mirror Matter: Pioneering Antimatter Physics'¹⁷ (Fig 3.7) contains a detailed analysis of what an antimatter facility may look like. As put in the words of Dr. Mike LaPointe¹⁶ a facility should:

- Use high efficiency linear accelerator for multiple high energy proton beams.
- Positrons sent to decelerator, then to laser-enhanced antihydrogen generator.
- Antiprotons collected using an array of wide-angle collecting lenses and sent to stochastic coolers, then decelerator, then cooling ring before being sent to the antihydrogen generator to combine with positrons to make antihydrogen atoms.

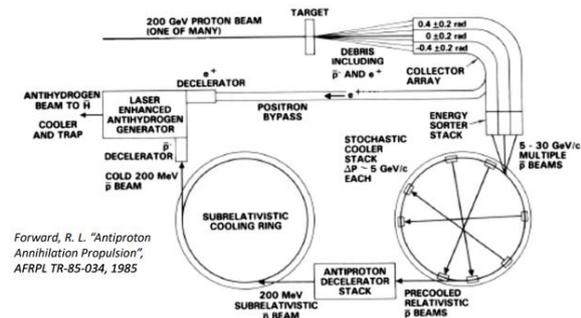
However, the cost estimate for the idea seems incredibly optimistic ($\$10^{10}$ /g) when compared to our current costs ($\$2.7 \times 10^{15}$ /g). Ignoring the costs, production at these facilities could produce upwards of $\mu\text{g}/\text{year}$, a huge upgrade to our current storage of little over 18ng of antimatter at FermiLab, DESY and CERN combined. The question then turns to storage of created antimatter. Facilities accumulator rings can already hold $10^{12} \bar{p}$ (1.7×10^{-12} g) for indefinite periods and a portable High Performance Antiproton Trap (HiPAT) can hold a similar amount using a Penning-Malmberg electromagnetic trap, although this would mean the use of 1000s of these traps would be needed to hold mere nanograms of antimatter. A more optimal solution to this problem might be creating solid antihydrogen by cooling and clustering antihydrogen atoms. This could be achieved by laser cooling the antihydrogen atoms (as they would react with any attempt at using solid objects) to form antihydrogen molecules. These could then be condensed to form microcrystals of antihydrogen ice. This solid antihydrogen can be trapped in a magnetic bottle, or electrostatically levitated between two charged electrodes (Fig 3.8). UV light could then be used to liberate positrons when necessary.

Summary –

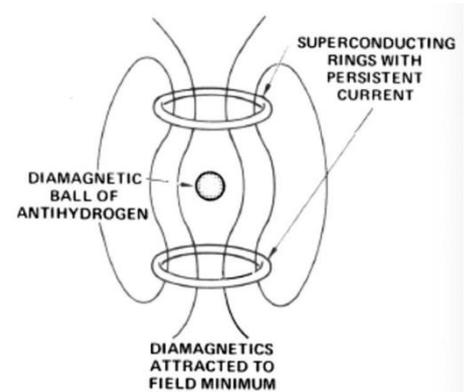
- Antimatter is already used in the detection of cancer.
- Antimatter could be used as a potential fuel.



(Fig 3.6) Current proposal of an antimatter-based sail-like system.



(Fig 3.7) An antimatter facility proposed by FNAL.

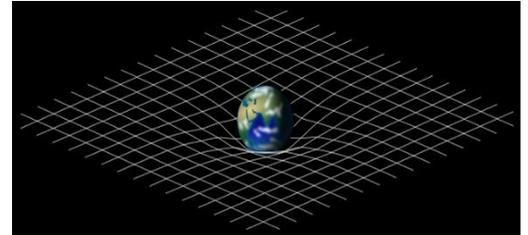


(Fig 3.8) A ball of antihydrogen is suspended between two superconducting rings.

3. The Future of Antimatter Research – What Comes Next?

3.1 An Imbalance at the Beginning of Time –

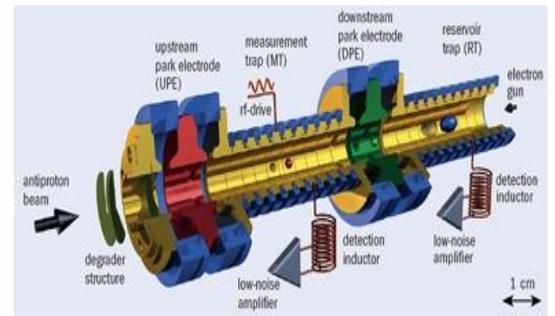
With the universe's origin at the big bang came a hot, dense region where particles and antiparticles popped in and out of existence. These pairs of particles are known as virtual particles and still contribute today to such theories as Hawking radiation. Virtual particles form a fundamental understanding to quantum field theory. They describe interactions between actual particles and are built into the fundamentals of perturbation theory. Calculations involving virtual particles are performed using Feynman diagrams (see chapter 1.3) where they are shown as internal lines. Virtual particles themselves can be seen as non-obedient of the energy-momentum relation and as such are considered 'off shell' due to their ability to have negative kinetic energy. As such, a real photon appears massless and has two polarisation states where a virtual photon appears massive and has three polarisation states. Virtual particles are important here regarding Vacuum polarization. Vacuum polarization involves a background electromagnetic field producing a virtual electron-positron pair. This becomes important in the future research of black holes due to the propagation of Hawking radiation – an idea first proposed by [Stephan Hawking](#) in 1974, published in the Journal 'Nature' and simply titled 'Black Hole Explosions?'¹⁸. Hawking proposed the idea that antimatter and matter fields would be disturbed by the curved spacetime of the black hole, causing antimatter and matter particles to appear (virtually). These would draw energy from the black hole itself causing it to slowly evaporate over time as they 'escape' its event horizon. A key idea in Hawking radiation is that no information about objects that have fallen into the black hole is needed, and instead only the mass, angular momentum and charge of the black hole itself are required. This adheres to our current understanding of the topic of black holes, wherein we require no matter to be able to escape the black hole (due to the escape velocity being faster than the speed of light) and thus no information from within the black hole can be identified. Hawking uses ideas of general relativity (Fig 4.1) and quantum field theory to nicely piece together this theory, with virtual particles and as such antimatter being at the core of his hypothesis. Of course, this wouldn't fall into a chapter about the future research of antimatter if it had already been proven and so our attention turns to how we'd prove such a theory.



(Fig 4.1) An example of Einstein's theory of general relativity. The earth bends the space around it¹⁹.

3.2 Exploring the Unexplorable –

One of the most puzzling and bizarre questions proposed to physicists is the matter-antimatter asymmetry we find ourselves with today. To trace the universe's lineage cosmologists have made predictions of the existence of dark matter and energy. These don't interact with matter in any traditional way and so are incredibly difficult to identify. One way of doing this proposed by physicists is the identification of an antimatter and dark-matter candidate, the Axion. The proof of this particle would not only show that dark energy and matter exist but would also provide substantial evidence for the asymmetry we now face. There are other hypotheses for this imbalance [such as the mirror universe hypothesis (more on this in 4.2)], however proving the existence of axions proves to be far more beneficial due to its cross-connections to superstring theory, dark matter and other theories stemming beyond the standard model. While experiments at BASE – CERN (Fig 4.3) have failed, as pointed out by CERN 'The lack of this signal allowed them to put lower limits on the axion-antiproton interaction strength for a range of possible axion masses.'²⁰ Due to the hypothetical mass of the axion being almost negligible, laboratory-based limits range from 0.1 GeV to 0.6 GeV compared to matter-based experiments having limits of 10000 GeV to 1000000 GeV. 'The observations of the explosion of the famous supernova SN1987A, however, set constraints on the axion-antiproton interaction strength that are about 100000x weaker than those obtained at BASE.' This in essence means that scientist working to study the axion may be limited by the boundaries laid out by our best equipment for many years to come. Physicists at CERN now hope that the colliders 4th run (which will feature a collider 4x the size of the current LHC) will play a key part in the discovery of such a particle, or in the very least another step in the correct direction.



(Fig 4.3) CERN's Baryon Antibaryon Symmetry Experiment (BASE) works to explore matter-antimatter interactions. Above is its internal structure.

Summary –

- **Hawking radiation makes a prediction towards a black hole's dissipation of energy involving virtual particles.**
- **To prove this dissipation correct, physicists have attempted to create microscopic black holes that would dissipate immediately however have failed so far.**
- **The proposal of the Axion is one strongest standing theories for the matter-antimatter asymmetry we now face.**

4. Further Endeavours into the field of antimatter: a deeper look and some additional questions.

4.1 The Purpose of Antimatter in QFT –

Quantum field theory is one of the most important studies into the realm of physics in modern time. It is perhaps the closest we may ever be towards unified field theory, trying to unify classical field theory, special relativity, and quantum mechanics. Taking a complex scalar field to be relativistic, we can canonically quantize the field by first writing its lagrangian density, then finding its momentum and Hamiltonian density, turning the fields into operators and enforcing the commutation relation at equal times, expressing the field in terms of a mode expansion, and finally evaluation the Hamiltonian density and normal ordering the results. The examples provided below are taken from [Tom Lancaster and Stephen Blundell's 'Quantum Field Theory for the Gifted Amateur'](#)²¹. If we canonically quantize the Lagrangian*:

$$\mathcal{L} = \partial^\mu \psi^\dagger(x) \partial_\mu \psi(x) - m^2 \psi^\dagger(x) \psi(x) \quad (5.1)$$

We are left with the normal order:

$$N[\hat{H}] = \int d^3 p E_p (\hat{a}_p^\dagger \hat{a}_p + \hat{b}_p^\dagger \hat{b}_p) \quad (5.2)$$

Where \hat{a}_p^\dagger is the creation operator for a particle with momentum \mathbf{p} , and \hat{b}_p^\dagger is the creation operator for an antiparticle with momentum \mathbf{p} . This is important in the justification of the creation of antimatter as an excitation of a complex scalar field. We can use Noether's theorem to assume that the field has conserved charge. This is shown as the particle number. Taking:

$$J_N^\mu = \sum_\sigma \Pi_\sigma^\mu D\sigma = \Pi_\psi^\mu D\psi + \Pi_{\psi^\dagger}^\mu D\psi^\dagger = i[(\partial^\mu \psi^\dagger)\psi - (\partial^\mu \psi)\psi^\dagger] \quad (5.3)$$

Where J_N^μ is our Noether current. We find here that we face similar terms in our Noether current to that of our Lagrangian as we are again using the momentum density. To find out what our conserved current means we must make it into a conserved charge operator \hat{Q}_N and taking normal order:

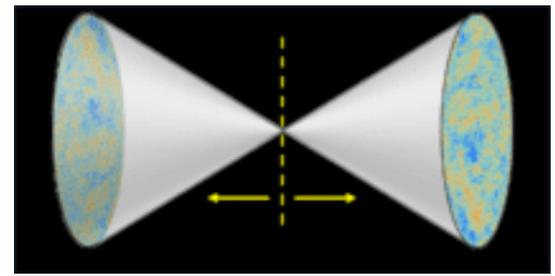
$$N[\hat{Q}_N] = \int d^3 p (\hat{b}_p^\dagger \hat{b}_p - \hat{a}_p^\dagger \hat{a}_p) \quad (5.4)$$

We find here that equation 5.4 looks very similar to that of 5.2 and that is simply because the conserved charge is given by the difference in the number of antiparticles ($n_p^{(b)}$) and the number of particles ($n_p^{(a)}$), concluding that particles carry Noether charge of one sign and therefore to have conserved charge a negative particle must cancel a positive one.

*A complete form of this can be found in 'Quantum field theory for the gifted amateur' pages 109-112.

4.2 The Mirror Universe Hypothesis –

We have discussed previously that at the big bang, an asymmetry between matter and antimatter was created leaving a universe of particles. We have talked about how the axion may have played its role in this asymmetry we face, however as mentioned prior, there are many other theories cosmologists and other physicists have derived for this. One such theory is the idea that at the big bang, a sort of mirror universe was created and accelerated 'backwards' in its own period of inflation. This universe is thought to be filled with antimatter as opposed to matter. The idea originates from the concept of Charge conjugate and Parity symmetry. CP symmetry claims that should a particle be replaced by its antimatter equivalent, and its special co-ordinates be inverted, the laws of physics should remain the same. However, research conducted by James Cronin on the decay of neutral Kaons provided a violation of the p-symmetry in regard to some aspects of the weak force. In adjustment to this, a more standard CPT symmetry has been proposed. In this case, an additional time reversal would be necessary for the laws of physics to be obeyed, however this is not as difficult as moving 'backwards' in time, but rather reversing the order of such things as momentum. CPT symmetry therefore derives that at the big bang, antimatter may have expanded in the opposite direction to matter (Fig 5.1), leading to a parallel antimatter universe running 'backwards' in time to our own. It is important to note that according to [Neil Turok](#) 'quantum uncertainty means that universe and antiuniverse are not exact mirror images of one another'²² meaning that while both expanded from the same point, and obey the same laws, free will is still considered.



(Fig 5.1) The picture above depicts the conic like structure of our universe (to the right) and that of the hypothesised antimatter universe (to the left).

Summary

- Antimatter is an important construct in QFT as it is needed so that charges are conserved.
- CPT symmetry has led cosmologists to the hypothesis of a 'mirror universe' with antimatter as opposed to matter.

