Effects of Gravity on the Motion of Antimatter

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I. Introduction

Antimatter has the same mass and opposite charge as matter. Of the visible mass in the universe matter makes up almost all of it; current physics can explain the asymmetry. To explain it, experimentally measuring the properties of antimatter can determine if they are different from those of matter and potentially explain the asymmetry. Accurately measuring the properties of antimatter will verify the standard model and any discrepancy is a hint to potential new physics. There are many ongoing experiments to measure the properties of antimatter to identify any differences. One experiment to measure these properties is the Antihydrogen Laser Physics Apparatus (ALPHA) at CERNs Antiproton Decelerator (AD). The ALPHA experiment uses laser cooling to slow antihydrogen created by combining AD antiprotons with positrons to the point where its properties can be measured. The most recent test was ALPHA-g which measured the effect of gravity on antihydrogen [1], [2], [3].

ALPHA-g provided the first experimental evidence that antimatter falls towards the earth and experiences gravitational attraction with matter. This confirms that antimatter and matter have the same gravitational attraction and rules out cosmological models with repulsive gravity between matter and antimatter [1], [3].

II. Antimatter and its properties

$$\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0 \tag{1}$$

Antimatter was first predicted in 1928 by Paul Dirac, when developing the equation that bears his name (1). The only complete set of solutions included negative energy solutions. He interpreted these solutions as a sea of electrons filling the negative energy states. If an electron was excited out of one of these negative states it would leave behind a hole which would act like an electron with a positive charge [4]. In 1933 Carl D. Anderson observed this particle and named it the positron (Figure 1) [5]. Following this, other antiparticles were detected. A given antiparticle will have the opposite charge, the same mass and quantum numbers as its particle equivalent [4].

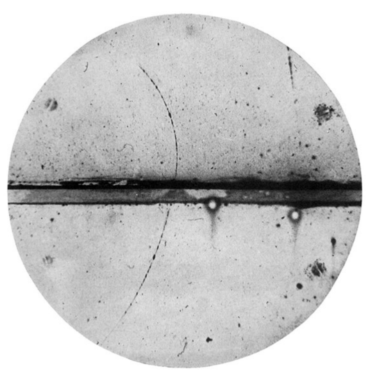

Figure 1; The first observation of a positron, the path is longer than a proton path and opposite the direction of an electron path. The particle was identified as positively charged electron which confirmed Dirac's prediction [5].

Later, Feynman and Stueckelberg created a quantum field theory explanation of antimatter. They described the positron as equivalent to an electron travelling backwards in time, which is how it is shown in Feynman diagrams (Figure 2). This eliminates the negative energy and is used to calculate the antiparticle v spinors which were used in PHYS 3500 to solve the Dirac Equation for antiparticles [4].

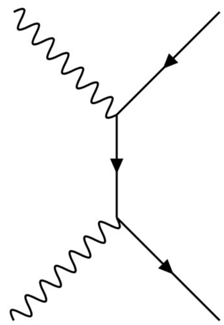

Figure 2; Electron positron pair production from two photons $(\gamma + \gamma \rightarrow e^- + e^+)$. The positron in the top right and is equivalent to an electron moving backwards in time [4].

Charge Parity Time (CPT) symmetry says that if every particle was replaced with its antiparticle, mirrored, and reversed in time it would be equivalent to the universe as we observe it. CPT symmetry is fundamental to Einsteins general theory of relativity and predicts that antimatter will behave the same as matter in a gravitational field [2] [3].

In astrophysical observations, there is no evidence for a similar amount of matter and antimatter in the universe. If the universe was made of pockets of matter and antimatter, we would expect to see boundaries between these regions which have few objects and produce high-energy gamma photons from annihilation. Nothing like this is observed in the visible universe so in the high energy environment just after the big bang slightly more antimatter was produced than matter. Some currently unknown process broke CP symmetry and produced more matter than antimatter. This process has not been detected, but it may be observable by measuring for any differences in properties between matter and antimatter. This is the goal of many antimatter experiments [3], [6], [7].

III. Experiments with antimatter

Antimatter is very difficult to do work with since it annihilates to photons if it impacts its matter counterpart. Low energy antimatter is especially likely to annihilate with matter since it is moving slowly and is attracted to oppositely charged matter; this makes it short lived in the matter universe. Antimatter is generally produced in high energy events through processes like pair production (Figure 2). The produced particles decay before the effects of weak forces like gravity can be detected [1],[8].

To measure how gravity effects antimatter, it needed to be cooled to the point where random thermal motion has low impacts compared to gravity. Many of these experiments are done with antihydrogen, a bound state of an antiproton and a positron. This is an electrically neutral gas which can be contained in a magnetic trap and used in experiments. Many AD experiments work with antihydrogen including ALPHA [1], [3], [9].

IV. The ALPHA experiment

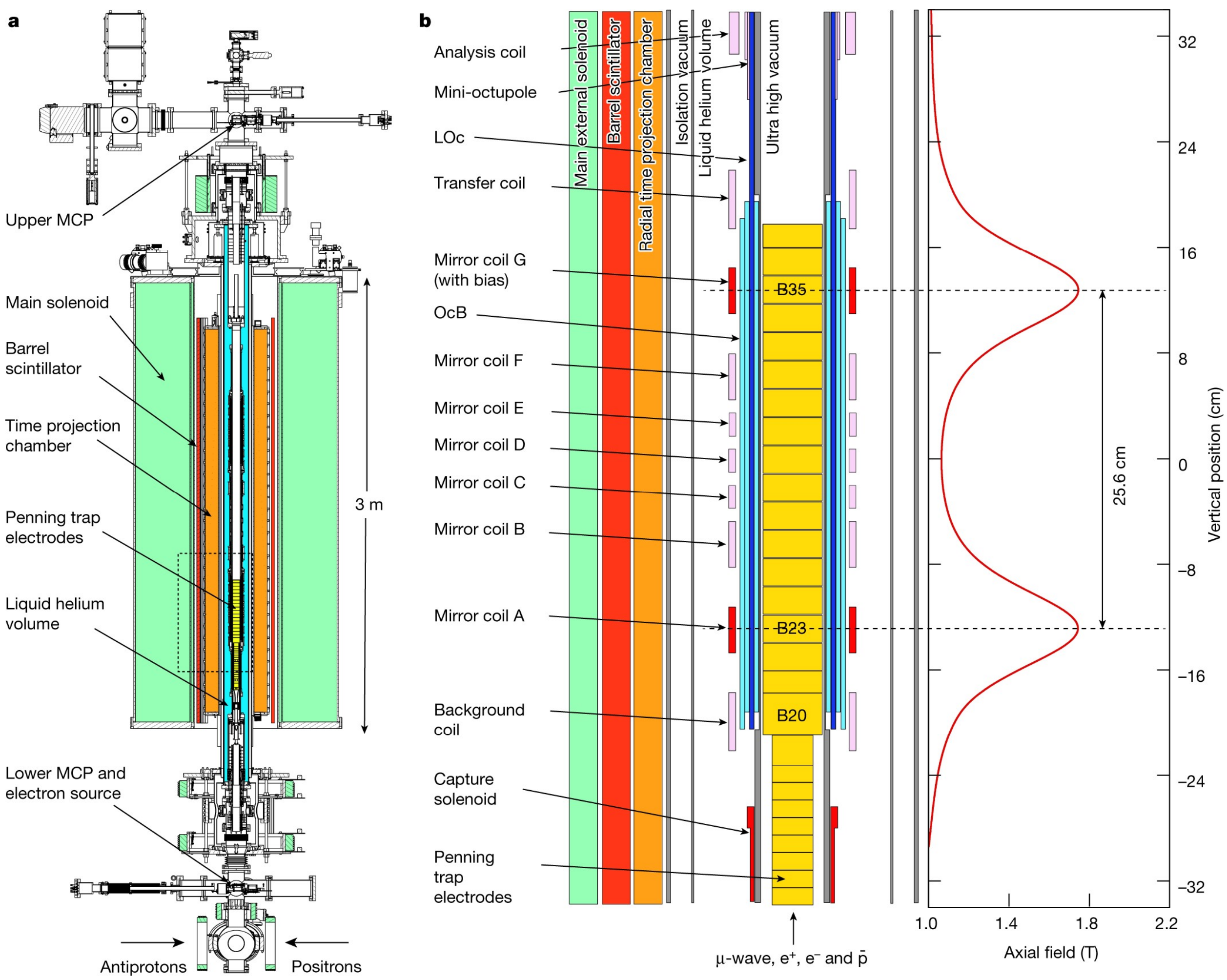

Figure 3, A cross-sectional diagram of the ALPHA-g apparatus, only the lower antihydrogen trap is used highlighted in yellow in **a** and shown in blown-up section **b**. Antiprotons are positrons enter the trap from the bottom and are combined into antihydrogen in the trap. The main solenoid confines the particles and mirror coils A and G are used to pinch the field and create a magnetic bottle with the field shown to the right. The top coil G is used to introduce a bias in acceleration into the trap [1].

Antiprotons are produced in CERNs accelerators and input into the antiproton decelerator to be cooled to nonrelativistic velocities. These antiprotons are then slowed further with laser cooling. A UV laser with just under the energy an antiproton can absorb is fired at antiprotons, antiprotons moving towards the laser absorb the laser light and slow down; those moving away cannot absorb it [2], [8]. Once the antiprotons are cooled, they are mixed with positrons into the

ALPHA trap. The trap is a magnetic bottle. The x and y motion is confined by large octupole magnets which centre the antiparticle. Inside smaller coils pinch the magnetic field off at the top and bottom of the trap confining the antihydrogen magnetically. Once antihydrogen is confined its properties can be experimentally measured [1], [2].

The ALPHA-g experiment tests the antihydrogen under gravitational influence; the antiparticle needs to be separated from matter long enough to fall a measurable amount. Since the antihydrogen is a gas, they will spread out to fill available space. The effect of gravity is measurable as a bias in the direction of its attraction. Antiparticles will be more likely to fall in the direction of the sign of gravitational attraction. The average distance particles fall is proportional to how much they are attracted or repelled by the gravity of matter [1], [8].

Once the antihydrogen bound state is created in the magnetic bottle the coils which confine it in z are turned off slowly over the course of 20s at the same rate. This lets the antihydrogen escape from either the top or the bottom and annihilate on the walls. The location of these annihilation is measured and matched with models to determine how strongly and in what direction matter gravitationally impacts antimatter. With a difference in the field between the top and bottom magnetic bottle coils a bias in acceleration applied to the trap, when the bias is equal and opposite to the attraction of antimatter to earth there is a fifty-fifty chance of each antiparticle moving up or down out of the trap. When the bias is opposite the attraction of gravity the differences between the different multiples of the attraction towards Earth are most different improving the experimental resolution [1], [3], [9].

V. The results

The result of the ALPHA-g measurement was reported in Nature on September 27, 2023. The measurements were matched with simulations of where annihilations would occur with different gravitational attractions (Figure 3). They measured an attraction towards Earth of 0.75 ± 0.13 (statistical $+$ systemic) $\pm$ 0.16 (simulation) g. This is within the margin of error of the $1\ g$ acceleration experienced by matter towards Earth. They calculated a probability of 2.9×10^{-4} that this result is possible with antimatter not gravitationally attracted to or repelled by matter ($0\ g$); and a probability of less than 10^{-15} that antimatter is gravitationally repelled by matter ($-1\ g$). This matches the predictions of CPT symmetry and is consistent with general relativity [1], [3], [9].

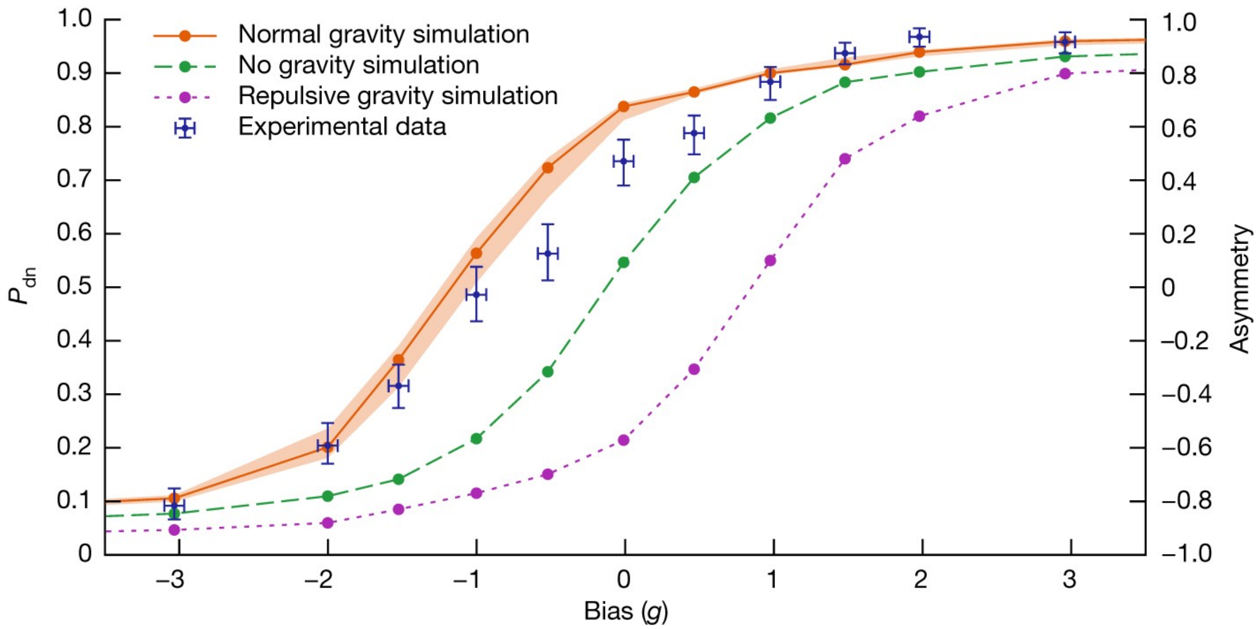

Figure 4, The probability of falling towards the earth at different biases with the experimental data plotted with simulations of the effects of $-1g$ normal gravity, no gravity, and $+1g$ repulsive gravity. The experimental results match the normal gravity simulation [1].

VII. Representation in media

The experiment and result are represented very well in the news pieces examined in this report. This explanation is helped by the fact that the principles of the are very simple; collect antimatter and drop it to see where it falls. The explanations of why the result are important are more complex but were generally well done. The overall goal of the experiment is the same as most other experiments with antimatter, to look for ways antimatter is different from matter and to explain why the universe is made of matter rather than antimatter. This is more difficult than Why this is relevant is much more complex than the principles of the experiment. All articles explained it with the Big Bang Theory, we expect based on currently known physics for equal amounts of matter and antimatter to be produced but that it not what we observe. Some of the pieces went into CPT symmetry but this was slightly weaker [3] [9].

VIII. Future work

Many properties of antimatter have still not been experimentally measured. Many collaborations including ALPHA and others at the AD are planning experiments to measure these more accurately and search for any differences with matter. Planned experiments of the influence of gravity on antimatter by ALPHA and other collaborations. The ALPHA-g experiment plans to decrease uncertainty and repeat to improve the measurement and further refine our knowledge of how antimatter affects gravity. Generally ALPHA and other experiments plan to conduct measurements of the properties of cold antimatter to compare it with those of matter [1], [3], [9].

IIX. Conclusion

The ALPHA-g experiment is very related to the course, we have spent most of the last third of the class working with the Dirac Equation. This included showing that an accurate model cannot be created with regular matter spinors alone. For the solutions to the equation to span 4-dimensional spacetime there need to be four separable solutions. Two of the solutions have opposite energy of the other two implying the existence of negative energy states which we call antimatter. The ALPHA-g experiment is an excellent example of a physics experiment, it is a measuring to confirm an extremely widely supported theoretical view. However, it is a very important experiment; to ensure the standard model works it needs to be tested in all cases. The ALPHA-g measurement is a stepping stone towards further experiments with antimatter to search for any differences in properties compared to regular matter [1], [8], [9].

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