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Charge Parity Time (CPT) from the lens of an experimental physicist

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Abstract. The domain of Charge Parity Time (CPT) symmetries has intrigued physicists for the better part of a century. Whilst the CPT theorem—a core principle asserting the combined invariance of charge conjugation, parity transformation and time reversal in quantum field theories—is foundational in modern theoretical physics, its implications are rooted deeply in the experiments that have confirmed or refuted our understanding. This paper delves into the world of CPT from an experimental physicist's viewpoint.

1. Introduction

Physics possesses a fascination with reductive simplicity, a desire to make evident both patterns and symmetries in the Universe. This has served us well with our ability to model and predict the world around us. Yet grasping these symmetries especially discrete ones like CPT proves tantalising. They can seem common-sense, yet frustrating to explain and harder to apply. The nature of this challenge is embedded in the mathematics and conceptual frameworks needed to describe these symmetries, which lie firmly in the realm of theoretical physics and beyond the scope here. Nonetheless it is often the tangible manifestations of these symmetries where experiments play a crucial role, which drives our curiosity.

Freeman Dyson has written [1], "*New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained*." This paper offers a narrative from the standpoint of a detector builder, not a comprehensive review of the field or its history or its theory. In it the reader will hopefully appreciate that it is possible to begin to approach these key concepts through the consideration of physical observations and that this approach is not only complementary but vital with apologies in advance for any oversimplifications made for the sake of clarity. Useful references for further reading have been included for those who wish to delve deeper into the subject.

2. The Standard Model and forces of Nature

Before diving into the symmetries (C, P, T), which are paramount to our understanding of the cosmos, it is important to briefly touch upon the Standard Model of physics [2], [3]. This model is our primary framework for describing the fundamental forces and elementary particles that make up our Universe. It is fantastically predictive and prescriptive, accounting for a large fraction of all phenomena encountered. It describes three forces: the electromagnetic, weak and the strong. Conspicuously the Standard Model lacks a quantum explanation for gravity, a phenomenon with which we are very well

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acquainted. This omission remains one of the great challenges in physics but one which will not be dealt with here.

The electromagnetic force, central to interactions between charged entities, binds atoms together and underpins phenomena like electricity and magnetism. In contrast mediated by W and Z bosons the weak force governs processes like beta decay. Unique to the weak force is its ability to allow the six types of quarks to mutate to each other. Lastly the strong force mediated by gluons binds quarks to form protons, neutrons and other hadronic particles, ensuring the atom's nucleus remains intact despite the repulsive force among protons.

In the Standard Model elementary particles are classified as fermions or bosons. Fermions—quarks and leptons—are the Universe's building blocks. The bosons are exchange particles and they pass forces between the fermions: photons for the electromagnetic force, W and Z bosons for the weak force and gluons for the strong force. The recently discovered Higgs boson stands apart from the other particles, its function being to impart mass to the other particles.

Part of the bedrock of the Standard Model is the symmetrical treatment of matter and antimatter—electrons and positrons, protons and antiprotons – each particle having a mirror "anti-particle" associated with it. The allure of this antimatter is profound from theoretical physics [4] to popular culture [5]. Its spontaneous annihilation upon contact with matter producing intense bursts of energy hints at the early Universe's inherent symmetries and asymmetries, and provokes our curiosity. Such primeval environments were dense and energetic with constant matter and antimatter creation and annihilation. Indeed in the very earliest Universe before the formation of hadrons (and stars) it is supposed that there was an equal prevalence of matter and anti-matter.

In contrast the striking lack of antimatter in the world around us is quantified by what is called the baryon-antibaryon asymmetry [6], [7]. This measure of the disparity between baryons, for example protons, and their antimatter counterparts in comparison to the Universe's photon count underscores a deep lacuna in our model of the cosmos's inception and the events that tipped the scales in favour of matter. It should be noted that it is not as though antimatter is utterly unknown to us. Remarkably about ten thousand particles, half being antimatter, traverse our bodies every second. Beyond theoretical fascination antimatter finds practical use in PET scanners for medical imaging. Nature in its eclectic ways also produces antimatter here on earth. Many people are surprised to learn that certain fruits like bananas release trace amounts due to the radioactive decay of their potassium content.

The lack of a clear narrative for the prevailing matter-antimatter asymmetry is more than a little disappointing since our existence hinges on this phenomenon. It remains a problem for the Standard Model and its resolution will mark a major milestone in our progress in physics. Despite the lack of a precise mechanism for generating this asymmetry Sakharov has [6] described three pre-requisite conditions for it to happen. Among these conditions is the manifestation of CP-violating effects, underscoring the imperative to understand the discrete symmetries of C, P and T and is an indicator of their profound importance.

3. Discrete symmetries: The building blocks

Let us start by reviewing what is meant by the C, P, T symmetries [8]-[10].

3.1. C – Charge Conjugation

This symmetry involves flipping the sign of the charge. It can be applied to classic equations like the Schrödinger equations or indeed electromagnetism. The notion of charge conjugation that starts with this charge inversion rapidly develops a deeper interpretation when applied to the Dirac equation. There a charge "flip" is associated with changing a particle, for example, and electron into its anti-particle (a positron). In the modern usage when C-symmetry is referred to, it is always assumed that there is matter-antimatter reversal as part of its definition.

3.2. P – Parity

In the realm of discrete symmetries, parity is quickly encountered, symbolised as 'P'. This is a curious transformation: spatial coordinates flip, changing $\vec{r} \rightarrow -\vec{r}$. It is important to note that parity is distinct

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from translation symmetries, which are responsible for the conservation of momentum. One motivation for P as a symmetry of nature is that some of the classical laws of physics remain unaltered under this spatial inversion. After all a game of pool or snooker follows the same Newtonian dynamics whether observed directly or in a mirror. Thus, the question can be asked, does all the physics of the Universe stay the same when the spatial coordinates are flipped? If so, what can be learnt? But even the simplest question and motivation is fraught with difficulty. For example, is P akin to looking in a mirror?

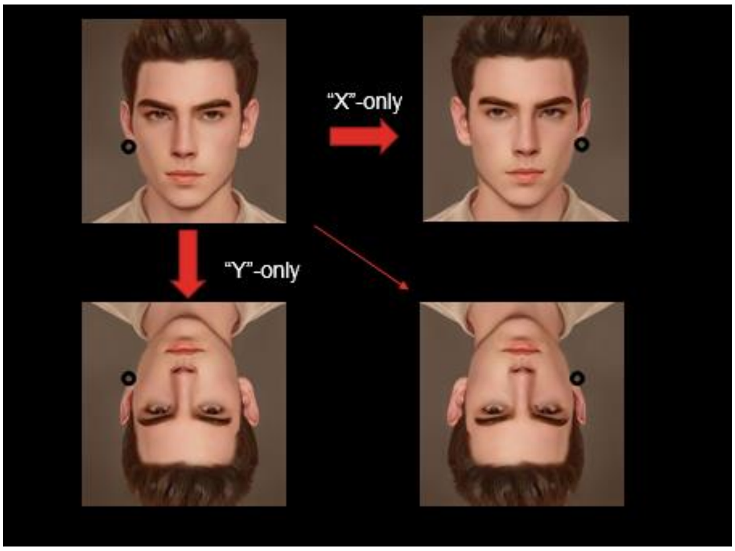

Figure 1. Mirror reflection and parity.

For clarity consider a visual example as shown in Figure 1. A person is depicted with an indicator pointing to their right ear. "Mirror" reflections are going to be applied to these images. These can be about either the x or y axes in a Cartesian coordinate system. The x-operation would entail reversing the left and right sides of the image, mirroring it along a vertical axis passing through the person's centre. This operation alone would cause the indicator to point to the person's left ear. Now to achieve the desired 'right ear' indication, the y-flip operation needs to be performed a**s** well. The y-flip operation mirrors the entire image along a horizontal axis, flipping it upside down. When combined with the x-flip the result is a complete transformation where the person's right ear is once again indicated just as it was in the original image. This combination of x-flip and y-flip demonstrates how Parity (P) symmetry works in a visual context, illustrating that it takes both transformations to restore the image to its initial state (right-handed) – although it will be upside down!

Thus, when mirror reflection is talked about it is best to understand this in the more precise sense of $\vec{r} \rightarrow -\vec{r}$ rather than the mental snapshot of a mirror image. If one must talk about a mirror that retains left-handed v right-handedness then one actually needs to look at a retro-reflecting cube which delivers the correct inversions! So, although the phrase "mirror" will be used here it will only be shorthand for $\vec{r} \rightarrow -\vec{r}$.

3.3. T – Time reversal symmetry

This is by far the most complicated symmetry in that it explores the profound consequences of reversing the arrow of time. At macroscopic scales time's direction is unmistakable, driven by the inexorable increase in entropy often referred to as the arrow of time. In her 2009 work Quinn [11] identified three distinct types of time asymmetry, shedding light on the deep-rooted intricacies of this concept.

The first is the Universal Time Asymmetry, a reflection of our Universe's history. It becomes evident when the early moments of cosmic existence are considered, marked by a period of exponential expansion known as inflation. This epoch of rapid growth violates the symmetry of time reversal (t goes to -t) and plays a pivotal role in shaping the cosmos.

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The second facet is the Microscopic Time Asymmetry, where T violation implies an asymmetry not only under the reversal of the sign of time (*t*) as seen in the equations of motion, but also under the interchange of in-states and out-states. It is in the intricate dance of subatomic particles and their interactions that this form of time asymmetry emerges. This is the T that is most often considered by particle physicists.

Lastly the third dimension of time asymmetry is the Macroscopic Time Asymmetry often synonymous with the arrow of time. This aspect is deeply rooted in the Second Law of Thermodynamics, which dictates that ordered systems inevitably evolve towards increased entropy, becoming more disordered over time. This inexorable march towards disorder is a feature of our Universe, underpinning the behaviour of everything from galaxies to the smallest particles. It emphasises that unlike the reversibility of physical laws at microscopic scales complex systems rarely return to their original states, marking the inescapable directionality of time on a macroscopic level.

These three forms of time asymmetry collectively contribute to our understanding of scientific interplay between the microscopic and macroscopic. But T is the hardest to grapple with not least because it is the one for which there is the most prejudice. Time for humans, whether we like it or not, marches inexorably forwards. The discussion here will focus on microscopic time asymmetry when talking about T.

3.3. Combined symmetries: CP and CPT

It is possible to consider these symmetries compounded. i.e. the question can be asked, does P conserve the laws of physics? Are the physical implications laws invariant under CP (Charge and Parity applied simultaneously) or CPT? These are all valid questions and follow broadly the historical development of the subject. As each level of symmetry has been discovered to be slightly violated, a deeper symmetry has been invoked. Unlike continuous symmetries subject to Noether's Theorem [12], the C, P, T symmetries are discrete and there is no dynamic observable connected with each symmetry. Nonetheless the most comprehensive of all these symmetries (CPT) transcends individual physical theories. It serves as a bedrock upon which our theoretical frameworks are built and contains fascinating predictions. For instance if Charge-Parity (CP) symmetry is found to be violated, it implies a simultaneous violation of Time (T) symmetry, which has profound implications for the behaviour of particles and their interactions and is testable in the laboratory. An even clearer and simply testable consequence of CPT is the requirement that the mass of an antiparticle is identical to that of its corresponding particle.

Let us now look back to see how our understanding of C, P, T, and the combined symmetries of CP and CPT has shaped the evolution of physics and continues to inform our present day perspectives.

4. A historical journey – the first fifty years

Three experimental campaigns have been picked that have played major roles in our understanding of CP and CPT to illuminate the way. These span almost fifty years of research from the early era of post-War particle physics to a seminal experiment conducted at CERN [13] at the end of the last millennium**.**

4.1. 1956-1957: A shift in understanding Parity

The first stop is 1956: this year and the following twelve months marked a significant shift in our understanding of parity. Prior to this point it had been assumed that parity was a conserved quantity. All evidence pointed to it being so in strong and electromagnetic interactions. Nonetheless physicists Tsung-Dao Lee and Chen-Ning Yang proposed that this might not be the case for weak interactions in their famous paper "*Question of Parity in Weak Interactions*" [14]. This proposition was monumental as it was not at the time a widely supported idea. Lev Landau wrote that *"… in my view a simple denial of Parity-Conservation would place theoretical physics in an unhappy situation*" [15]. However, he did presciently note: "… *we can suppose we still have invariance with respect to the product of two operations, which we call combined inversion [ed. CP]. Combined inversion consists of a space reflection with an interchange of particles and anti-particles.*"

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Chien-Shiung Wu's seminal 1957 experiment [16] was pivotal in confirming that neither the parity operator nor the charge conjugation operator was conserved in certain decay processes. She categorically stated that "*... if an asymmetry is observed, it provides unequivocal proof that parity is not conserved in beta decay. This asymmetry has been observed in the case of oriented Co*^{60}." Chien-Shiung Wu was awarded the Wolf Prize in Physics in 1978 [17].

In one of the most elegant experiments on record ^{60}Co was polarised by the application of strong magnetic fields and the direction of the beta rays from the cobalt decay observed. In the experiment P-parity conservation would require that the beta emission should remain invariant. Instead a visible anisotropy was observed (see Figure 2), leading to the inescapable conclusion that P is not a conserved symmetry.

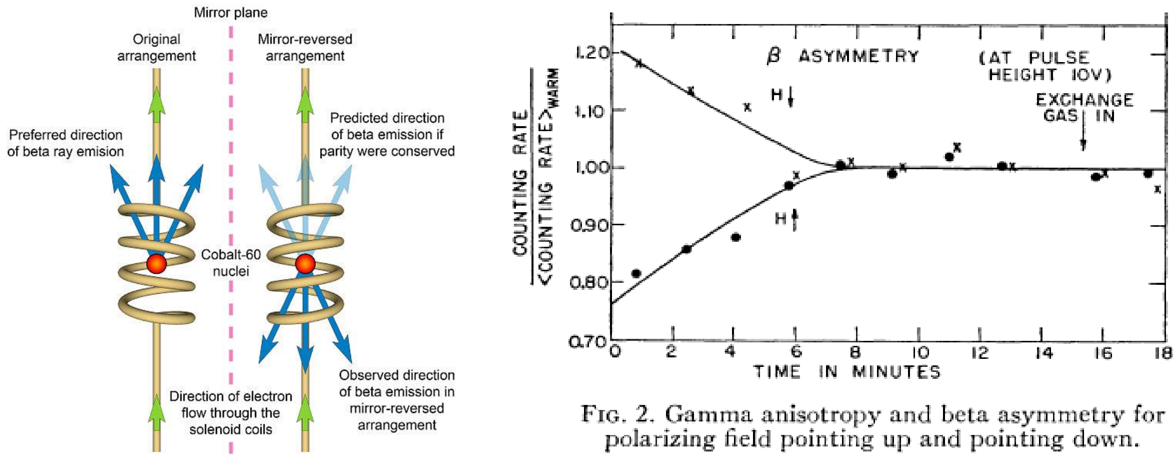

Figure 2. (Left) A representation of the experimental setup in Wu's 1957 experiment (Source: Wikipedia Commons) and (right) the plot from her paper [16], showing the anisotropy of the beta decays.

Lee in his 1957 Nobel Lecture [18] entitled "*Weak Interactions and Non-Conservation of Parity*" summed this up. "*... the non-conservation of parity or the non-invariance under a mirror reflection can be established without any reference to theory*."

At the same time the understanding of C conjugation was coming under scrutiny. Richard Garwin, Leon Lederman and Marcel Weinrich reported in their 1957 paper [19] "*Observation of the failure of conservation of Parity and Charge Conjugation in Meson Decays*", which also famously measured the anomalous magnetic moment of the muon and introduced a particle-antiparticle test of C conservation. In the UK a study of matter and antimatter properties was made by Culligan, Frank and Holt at Liverpool (see Figure 3) [20]. They stated in their abstract "*it is shown that the positrons have positive helicity and the negatrons negative helicity, thus providing a clear demonstration of violation of invariance under charge conjugation.*"

The "common sense" certainties about P and C that influenced and informed scientists had been comprehensively dismantled. One is reminded of a quote from Wolfgang Pauli in his correspondence with Carl Jung [22] where he discussed a dream he had on the 27th November 1954, "*I am with the ′dark woman′ in a room where experiments are being conducted. These experiments consist in the appearance of ′reflections′. The other people in the room regard the reflections as′ real objects′, whereas the dark woman and I know that they are ′just reflections.′ This creates a secret, which separates us from the other people. This secret fills us with apprehension.*" A similar deep uncertainty circa 1960 now faced the physics community.

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Figure 3. Liverpool's 136" Cyclotron used in Holt's paper [20], [21].

4.2. The emergence of CP conservation

Seeking deeper symmetry it became fashionable following Landau's proposal [15] to believe in the conservation of a combination of C and P. Indeed Richard Feynman in his 1962 lectures humorously expounded that CP was such a good symmetry that one could tell if aliens were made of matter or antimatter [23] by communicating with them the results of physics experiments by radio only!

The following argument often used to teach students demonstrates CP conservation. A positive muon decays to a positron with the positron preferably emitted aligned with the muon polarisation. A simple C transformation would see the direction of the muon's polarisation reversed (imagine the polarisation of a classically circulating charge) and the electron being emitted in the opposite direction to the (negatively) charged muon. This is not experimentally seen. Under a parity operation the polarisation (and charge) of the muon does not change under P. P conservation would imply that the positron is emitted backwards in which case the positron would be emitted against the direction of the muon polarisation. It is only if both CP are applied together that the electrons are emitted in the same direction as the muon's polarisation.

4.2. 1964: The shock of CP violation

A major step forwards in our understanding and this time "out of the blue" was a discovery that CP was itself violated. This happened in 1964 when Val Fitch and James Cronin performed an experiment [24], the interpretation of which was nothing short of revolutionary. By studying the behaviour of mesons, they unveiled inconsistencies in previously held beliefs regarding CP conservation. Their "shocking" discovery led to the award of the 1980 Nobel Prize in Physics of which Fitch said "*This year Prof. Cronin and I are being honoured for a purely experimental discovery, a discovery for which there were no precursive indications, either theoretical or experimental*" and "*it touches on our understanding of nature at its deepest level*" [25]. Their experiment is one of the few that can match Wu's discovery of parity violation in terms of its importance.

The experiment, although not of itself complicated, does need a little explanation. Cronin and Fitch were studying strange mesons. Neutral strange mesons are made up of a strange antiquark and a down-quark and mesons had a negative parity. It was further known that there were two different types of known neutral kaons, K_S^0 and K_L^0. The short lived K_S^0 decayed to two pions and was considered CP positive, and the long lived K_L^0 decayed to three pions and was considered negative. If CP were a conserved symmetry, then K_S^0 could not decay to a two pion CP even state. Nonetheless looking at a beam of neutral kaons, long after the K_S^0 should have died away they discovered a remaining significant fraction of 2-pion decays. This was evidence that CP violation was indeed taking place in K_L^0 decays.

In modern parlance the Cronin-Fitch experiment is interpreted as saying that the rate of oscillation from $K^0 \to \overline{K^0}$ is not quite the same as the rate $\overline{K^0} \to K^0$ (see Figure 4), i.e. that microscopically events are not totally reversible under time. Different "superpositions" of $K^0, \overline{K^0}$ can be constructed with different CP eigenstates, thus evidence of the CP violation in the decays is manifested by T-breaking.

The mechanism through which the CP violation takes place is via interference. A parallel is taken with an electron impinging on two narrow slits. If one wishes to correctly describe the pattern the electrons make on a screen placed behind the slits, interference needs to be invoked. The electron "experiences" both slits and the resulting pattern is the superposition of both amplitudes. In the same way a kaon must make a transition (for example, from $K^0 \to \overline{K^0}$) through all available intermediary states. Different intermediate states are typified by different amplitudes and phases. Even in classical quantum mechanics this can result in CP violation.

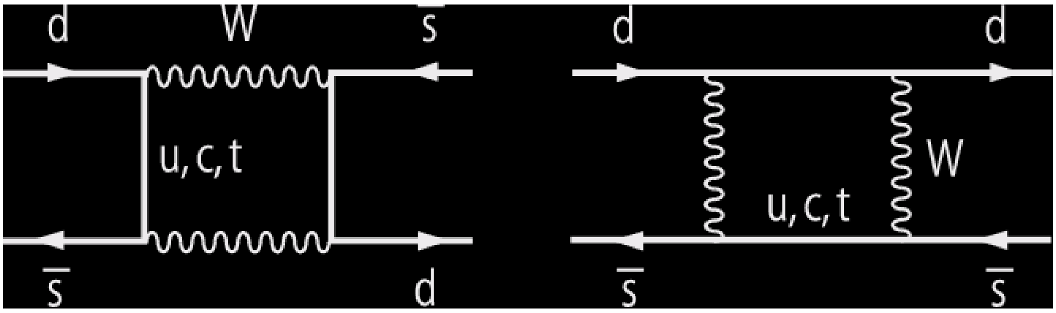

Figure 4. Feynman diagram of the decay of K^0 to its anti-particle via "box-diagrams" and vice versa.

Cronin and Fitch's experiment demonstrated that CP was violated. Thus if one needs to believe in discrete symmetries in particle physics, C and CP are not an adequate explanation. The next step was the replacement of CP invariance with CPT invariance. For more detail see the excellent review "*The Genesis of the CPT Theorem*" by Blum and de Velasco [26].

4.3. 1992: CPT and CPLEAR experiment at CERN

The final element in this history of C, P, CP and CPT comes with the exposition of one of the most important predictions of CPT by the CPLEAR Experiment [27], [28] at CERN in 1992. CPLEAR was an experiment which studied the symmetries between anti-matter by annihilating matter (protons) and anti-matter (anti-protons) almost at rest and studying the properties of the particles produced:

$$p\bar{p} = \pi^+ K^- K^0$$
$$p\bar{p} = \pi^- K^+ \bar{K}^0$$

One of the major proponents of this experiment was Erwin Gabathuler who had served as Research Director at CERN during the discovery of the W and Z particles. CPLEAR made several key measurements of CP but most spectacularly they were able to test a fundamental prediction of CPT with unprecedented accuracy. The prediction is that the mass of the particle and anti-particle should be the same. CPLEAR were able to confirm that the kaon and anti-kaon had the same mass to about 1 part per billion [29]. Thus reassurance was given that our understanding of particle physics was embedded in CPT as the overarching symmetry.

4.3. CPT in the modern era

The implications of the CPT theorem became more evident and new generations of experiments have sought to study both CP and CPT in new systems. Preeminent amongst these has been the development

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of detectors to study B-mesons (mesons containing b quarks or $\bar{b}$ quarks). The families of B-mesons are the heaviest mesons that may be created and although they decay with a lifetime of O(10^{-12} s) they form superb laboratories for the study of CP violating effects. Initially it was hoped that the CP violation as observed in these hadronic systems could be sufficient to explain the Universe. Several generations of experiment at e^+e^- machines (BaBar [30] at SLAC, Belle-I and II in Japan [31]) and the LHCb experiment [32] at CERN's Large Hadron Collider have been focussed on revealing the finest details of CP violation available. Subtle and interesting effects have been found but none demonstrate enough CP to drive the observed baryon-asymmetry. None have found any evidence of CPT violation. Nevertheless the studies from these experiments are a magnificent testimony to what may be achieved when theoretical understanding and detector technology are harnessed together.

The last few pages of this paper will switch focus. It will start by returning attention to the muon and then to one of our most fundamental and pervasive hadrons, the proton and attempt to explain why another generation of experiments with CP(T) tests at their heart are being planned.

5. Muons and protons and CPT

The muon has been as explained central to our earliest understanding of CP. Modern muon experiments like the FNAL g-2 [33] aim to measure the anomalous magnetic moment and the electric dipole moment of muons.

The muon itself was discovered as a constituent of cosmic-ray particle in 1936 by Carl Anderson and Seth Neddermeyer [34]. Before being understood as a heavy electron it was originally thought to be the particle predicted by the Japanese physicist Hideki Yukawa in 1935 to explain the strong force that binds protons and neutrons [35]. The intrinsic spin of the electrons and muons is related to their magnetic dipole moment by the famous g-factor. A result that is the culmination of the synthesis of the work by Erwin Schrödinger, Albert Einstein and Paul Dirac [4]. In the simplest analysis for a point-like particle such as the muon the predictions are that g=2. Importantly the existence of substructure would tend to modify this prediction. Consequently it became important to know the precise value of g, a theoretical challenge that occupied some of our finest theorists. Julian Schwinger [36], Sin-Itiro Tomanaga [37] and Feynman [38] are credited with being some of the first to make major contributions to this problem with Schwinger even having the correction to the electron gyromagnetic ratio $g_e \approx 2(1+\frac{\alpha}{2\pi})$ engraved on his headstone.

Since the 1950s there have been generations of g-2 measurements which measure the deviation of the muon magnetic moment from the expected Standard Model values. This includes the first precision measurement of muon g-2 by Cassels [39] at Liverpool which yielded g = 2.004 ± 0.014, which was published just after the famous Columbia measurement by Garwin, Lederman and Weinrich [19] result for the muon 2.00 ± 0.10 in Phys Rev 105, 1415 (January 1957) and whose paper was titled "*Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decay*" which shows the tight link between C, P and moment calculations. Modern theorists, notably Kinoshita [40], [41], have extended the calculations of g for both the electron and muon with the modern predictions being measured in parts per trillion (ppt). Experimental techniques pioneered for the electron by teams including those of Gabrielse [42] have pushed out measurements to the same level. This agreement between the electron g and its measured values to ppt has been called the "*Standard Model's greatest triumph*" [43].

In the Standard Model CP violation comes into the g (magnetic) and the electric dipole measurements through the calculation of higher order loops. Processes proceed by all possible vacuum loops, which in turn are sampling all the quark interactions (as analogy with the Kaon example above). Typically quantities like the Jarlskog [44] invariant come into play and represent the CP violation introduced because of the superposition of loops and the properties of the quarks. Muons are of particular interest because they are leptons that easily permit study (they are relatively long lived) and are heavier than the electron, thus able to interact with different sample of the "vacuum".

That muon g-2 does not agree with simple SM predictions (although there is some suggestion that "ab initio" lattice gauge calculations reduce the measured anomaly) to a statistically significant degree has been well advertised. The recent (2023) results of the g-2 experiment [45] reinforces the earlier (Standard Model divergent values) from both Fermilab [46] earlier and then Brookhaven [47]. New physics that could interact with the muon would also manifest itself in small deviations of the muon *g*.

These super-precise (100 ppb) experiments by FNAL *g*-2 open new avenues to the study of CPT in ways that have not been available since CPLEAR. In particular the proposed measurement of *g*-2 for both $\mu^{\pm}$ (echoing Holt's early measurement) provides a sensitive test of CPT. Furthermore, the study of the muon magnetic moment also permits as a by-product the measurement of its electric dipole moment (edm). The edms are critical tests of CP and CPT. As early as 1950 Purcell and Ramsey had written their famous paper [48] ("*On the Possibility of Electric Dipole Moments of Elementary Particles and Nuclei*") where the symmetry principles were discussed. They focussed their attention on edms, saying: "*The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle ... becomes a purely experimental matter*". This has been a guiding principle for generations of physicists.

Electric dipole moments (edm) are particularly powerful tools. Imagine for a moment a simple point-like particle with a magnetic moment and an edm, both of which start off aligned. A P flip changes the sign of the edm but not the magnetic moment. In addition a T flip (on the original system) will flip the sign of the magnetic moment but not the edm. Such a system with an edm and magnetic moment is clearly not invariant under T (therefore CP) and also under a P transform. Following this approach, studying the electric and magnetic moments of fundamental particles becomes a tool for searching for new sources of CP. There is of course a Standard Model prediction (based on fifth order loops) for the edm and CP violation expected of these particles is minute at values of less than O(10^{-30}) e.cm (for example, for the proton). Numbers larger than these miniscule values are "smoking guns" for new physics.

The goal of making precision measurement of the edms of both protons and muons is at the forefront of current discussions across continents. The US is considering a proposal to build a pEDM experiment at Brookhaven [49] whilst in Switzerland at PSI a new dedicated muon edm experiment is being planned. Both pEDM and muEDM owe their underlying experimental technique to that developed by *g*-2 measurements.

7. Into the future

As the precision of the experiments becomes ever greater and our body of understanding increases the implications of CPT have become ever wider and deeper. Schwinger, Gerhart Lüders [50] and Pauli's early work in the history of C/P developed the understanding that CPT was critical for Lorentz invariance of any theory [51]. Conversely evidence of CPT violation is now searched for to look for evidence of Lorentz (usually large scale) violation. This in turn opens the door for one to use the tool of CPT (for example in trying to study Lorentz violating where we do not necessarily assume such concepts – see the Bekenstein [52] thought experiment) to search for effects at the Planck scale on the tabletop. This is both a tremendous technological challenge and an exciting opportunity.

8. Conclusion

The historical journey of understanding CPT symmetry is an exemplar of the ever-evolving nature of scientific knowledge. To the practising physicist the interplay between theory and practice rapidly becomes evident, each informing and refining the other. One is almost obligated to be driven by the fabulous progress of technology to attempt ever more sensitive tests of CP and CPT. As the sensitivity expands, so does the potential scope for what may be discovered at both the smallest and largest scales. Those with a wider perspective will see this as another demonstration of different ideas in action and how this rich, active field of endeavour is feeding into our understanding and appreciation of our cosmos.

Acknowledgements
The pioneering work of many physicists from Wu to Fitch and Cronin, and the many others not mentioned has paved the way for our current understanding of CPT. To all these giants we unreservedly,

owe our deepest gratitude. I have been fortunate to work on many projects which have provided me with some of the most exciting times and the deepest insights into the workings of symmetries and fundamental particles. To my past colleagues on CLEO and my current collaborators on LHCb and FNAL g-2 I am deeply indebted. Special thanks are due to Yannis Semertzidis and Bill Morse for showing me the elegance and power of the proposed pEDM experiment at Brookhaven.

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