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Antihydrogen and Fundamental Physics

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Contents

Chapter 1
Introduction

The recent measurement by the ALPHA collaboration of the $1S$–$2S$ spectral line in antihydrogen with a precision of a couple of parts in 10^{12} [1, 2] marks the beginning of a new era of precision anti-atomic physics. Future experiments on antihydrogen and other antimatter species will enable exceptionally high-precision tests of many of the fundamental tenets of relativistic quantum field theory and general relativity, such as CPT invariance, Lorentz symmetry and the Equivalence Principle. It is therefore timely to examine critically what each of these experiments may be said to test and what any violation from standard expectations would mean for fundamental physics.

Experiments on pure antimatter systems, whether elementary particles or bound states such as antihydrogen, are especially interesting from this point of view since they are constrained so directly by the fundamental principles underlying the standard model. For example, the discovery of a new Z' boson, right-handed neutrinos, a supersymmetric dark matter candidate etc. would be of immense interest but could readily be assimilated into an extension of the standard model. In contrast, an anomalous result on the charge neutrality of antihydrogen, or a difference in the $1S$–$2S$ transitions of hydrogen and antihydrogen, would impact directly on the foundations of local relativistic QFT. In these theories, the existence of antiparticles with precisely the mass and spin, and opposite charge, of the corresponding particles is required by Lorentz invariance and causality. Moreover, for a *local* QFT, Lorentz invariance implies invariance under CPT, according to the celebrated theorem [3–6]. Antimatter experiments therefore directly test these principles.

The situation is not so clear when we consider gravity, where such experiments are often presented as tests of "the equivalence principle". The difficulty is that there are several versions of the equivalence principle in the literature—weak, strong, Einstein—with definitions which are not always either unique or well-defined. Indeed, as emphasised by Damour [7], it should not really be considered as a 'principle' of GR in the more rigorous sense that Lorentz symmetry and causality are principles of QFT. A more satisfactory approach is to recognise that we have a well-

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defined, and extraordinarily successful, theory of gravity in GR, which makes clear and precise predictions for the gravitational interactions of all forms of matter. Like other experiments, those on antimatter should simply be viewed as tests of this theory.

General Relativity is based on the idea that gravitational interactions may be described in terms of a curved spacetime. As described more precisely in Sect. 2.4, this spacetime is taken to be a Riemannian manifold, since this has the property that at each point it locally resembles Minkowski spacetime. The global Lorentz symmetry of non-gravitational physics is reduced to *local Lorentz symmetry* in curved spacetime. This is the mathematical realisation of the physical requirement of the existence of local inertial frames (i.e. freely-falling frames) even in the presence of gravity. Further to this, the standard formulation of GR makes a simplifying, though well-motivated, choice of dynamics for the interaction of matter and gravity, which is encapsulated in the following statement of the Strong Equivalence Principle:

- *In a local inertial frame, the laws of physics take their special relativistic form* (SEP).

  We will also discuss frequently two further expressions of the universality at the heart of GR. These are best viewed as experimental predictions of GR, though we refer to them here as versions of the Weak Equivalence Principle:
- *Universality of free-fall—all particles (or antiparticles) fall with the same acceleration in a gravitational field* (WEPff).
- *Universality of clocks—all dynamical systems which can be viewed as clocks, e.g. atomic or anti-atomic transition frequencies, measure the same gravitational time dilation independently of their composition* (WEPc).

Taken together, these three properties of GR are usually referred to as the *Einstein Equivalence Principle*.[1]

Apparent violations of these predictions, especially WEPff, can also arise not from the actual violation of any fundamental principle of QFT or GR but from the existence of new interactions not present in the standard model, so-called ‘fifth forces’. Low-energy precision experiments on antimatter, whether involving spectroscopy or free-fall equivalence principle tests, may be sensitive to such new interactions and can place limits on their range and coupling strength. Here, we consider two such possibilities, both well-motivated by fundamental theory. The first is an extension of the standard model gauge group to include a new $U(1)_{B-L}$ factor, with a corresponding gauge boson Z' coupling to $B - L$ (baryon minus lepton number) charge. The second involves the spin 1 ‘gravivector’ boson which arises in some supergravity

[1] The Einstein Equivalence Principle may be stated in various essentially equivalent ways. In [8], the three principles are referred to as *Local Lorentz Invariance* (LLI), which we have called SEP; the *Weak Equivalence Principle* (WEP), which is simply our WEPff; and *Local Position Invariance* (LPI), which states that ‘the outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed’ [8]. LPI implies the universality of gravitational redshift, or WEPc, and can also be tested through the space and time-independence of fundamental constants. Note that while GR implies WEPc, the latter is a more general property of any metric theory of spacetime. Also note that, as described above, a metric theory like GR on a Riemannian spacetime manifold exhibits LLI, but the dynamics need not be the same as special relativity, or be independent of the local curvature, if SEP is violated.

theories with extended, $\mathcal{N} \geq 2$, supersymmetry. Both have the potential to modify gravitational free-fall in violation of WEPff, distinguishing between matter and antimatter. We also consider a more general phenomenological approach to the possible existence of new, gravitational strength, vector or scalar interactions.

From an experimental perspective, the study of the fundamental properties of antiparticles and atomic systems constituted wholly, or partially, from them is a growing area of endeavour. In this book, our main focus is on antihydrogen, and in particular the current experiments being performed by the ALPHA collaboration at CERN and their implications as tests of fundamental physics. Later, we briefly consider a range of other antimatter species which may offer complementary opportunities for such tests.

We start by describing some of the practical aspects of current experiments with $\overline{\mathrm{H}}$ at low energy. Positrons (e^+) are available in the laboratory, typically via pair production and from radioactive materials (see e.g. [9] for a review). We concentrate on the latter, and the isotope ^{22}Na (half-life around 2.6 years, β^+ fraction about 90%) is the typical choice of source. Sealed capsules of around GBq activity can be held in vacuum and, using well-documented procedures (see e.g. [10]), eV-energy beams can be produced with efficiencies of 0.1–1% of the source strength. Such beams can be readily transported in vacuum to devices which enable their trapping and accumulation: the most common instrument to achieve this is the so-called buffer gas trap which, using a Penning-type trap and energy loss via inelastic positron-gas collisions, can accumulate around 10^8 e^+ in a few minutes, if required. The positrons can then be transferred [11] on demand for further experimentation, and of most relevance here for $\overline{\mathrm{H}}$ production and trapping.

Antiprotons ($\overline{p}$) are only available at laboratories such as CERN where high energy protons (typically 20–30 GeV) produce the $\overline{p}$s in collision with fixed targets. CERN's unique Antiproton Decelerator (AD) [12, 13] syphons off $\overline{p}$s at a kinetic energy of about 3.5 GeV and then decelerates and cools them in stages to reach 5.3 MeV, whereupon they are ejected to experiments in bursts of 100 ns duration containing around 10^7 particles, about once every 100 s. The kinetic energy of the $\overline{p}$s is typically moderated using foils whose thickness is carefully adjusted to maximise the transmitted yield (of around $10^{-2} - 10^{-3}$ of the incident flux) below 5–10 keV, and these are then captured in dynamically switched high field Penning traps [14] where they can be efficiently electron cooled [15, 16] to sub-eV energies. The $\overline{p}$s and electrons can then easily be separated, and the former then transferred to another apparatus or stored for further manipulation and experimentation.

The mixing of $\overline{p}$s and e^+s to form $\overline{\mathrm{H}}$ has been described in detail elsewhere [17, 18], and a number of techniques have been developed to hold the antiparticle species in close proximity and manipulate the properties of the respective clouds (e.g. number, density and temperature) in a system of Penning traps to facilitate anti-atom creation. Under the conditions of e^+ cloud density (around 10^{14} m^{-3}) and temperature (typically in the range 5–20 K) commonly used in $\overline{\mathrm{H}}$ experiments, the dominant formation reaction is the three body process $e^+ + e^+ + \overline{p} \rightarrow \overline{\mathrm{H}} + e^+$. It is well-documented (see e.g. [19, 20]) that this reaction produces highly excited $\overline{\mathrm{H}}$ states: thus, if experimentation on the ground state is required, the neutral should be