Antimatter

DIRAC’S INCREDIBLE PREDICTION AND ITS CONSEQUENCES
First a little history which many of you already know

- Why tell it?

- For those here who do not already know it

- To celebrate the genius of Dirac

- To talk about the nature of mathematical physics and the importance of symmetries
Before the Dirac Equation - experiment

- Two known particles - electron and proton
- The existence of the neutron was not yet clear!
- Nuclei were thought to be proton-electron composites
  \[ A = \# \text{protons} \quad A-Z= \# \text{electrons} \]

- 1925 Uhlenbeck and Goudsmit - electron has spin \( \frac{1}{2} \)
  to fit spectrum of hydrogen excited states
Before the Dirac equation

classical physics

- Mathematical representation of phenomena encodes
  invariances (symmetries) and related conservation laws
  -- Noether’s theorem

  Abstract mathematical field $A_{\mu}$ “electromagnetic potential”
  representing both electric and magnetic “physical” fields

  Relativistic formulation of Maxwell’s equations using this field
Before the Dirac Equation
quantum theory

- Quantum mechanics
- Shrödinger Equation
- Heisenberg matrix approach
- Relativity
- Klein Gordan Equation – a relativistic wave eqn
  but no way to include spin
- Pauli spin matrices 3 2x2 matrices
  spin projection, raising or lowering
What problem was Dirac trying to solve?

- Hamiltonian quantum mechanics is not explicitly relativistic
- Heisenberg matrix mechanics does not fix this
- Pauli’s algebra of spins suggests matrix approach
- Quadratic Klein Gordan Eqn does not fit with that
Dirac’s inspired equation 1928

- “factorize” Shrödinger Eqn to get a linear and relativistic equation from each factor

- Square root of a sum of squares does not linearize without some additional matrix structure to generate options beyond algebra

- Needed a set of 4 4x4 matrices, \( \gamma_\mu \), for factorization to work
  -> 4 component wave function \( \psi \)

- Add coupling to electromagnetic field \( i e A^\mu \gamma_\mu \)
Any equation is a code
this one includes three parts

Kinetic term \( \partial \mu \gamma_{\mu} \psi(x,t) \)

Mass term \( m\psi(x,t) \)

Coupling to EM fields \( ieA^\mu(x,t)\gamma_{\mu} \psi(x,t) \)
One immediate success

Gives right answer

\[ g = 2 + \text{electromagnetic corrections} \]

for ratio, \( g \),

of electron gyromagnetic ratio

to its classical value \( |e|I/2m \)
An unexpected (sick) feature and its (temporary) resolution

- States with negative energies as well as positive ones

- The mathematicians answer – fill them up – exclusion principle makes it possible
  (don’t worry that the pit is bottomless, apply a cut off)

- Consequence –
  operators that can make “holes” in the sea of negative energy states

- Interpretation – these are particles with the opposite charge to that of the electron
What particles?

- Dirac knew the equation has a (discrete) symmetry \( C \) positive charged particles have the same mass as the electron.

- But the only known + charge particle was the proton.

- He tried to argue that somehow electromagnetic corrections could account for the mass difference \( \text{(What corrections???)} \)

- He must have known, at some level, that this was not so.
The parallel emergence of quantum field theory 1927-32

- Fields as particle creation and destruction operators acting on “Fock” states
- Energy lowering operators annihilate the vacuum state or remove particles from states containing them
- Gets rid of negative energy sea, puts “holes” where they belong (in materials)
A new disaster recognized

The 3 field operator coupling to the photon

\[ \bar{\psi} A^\mu \gamma_\mu \psi \]

describes multiple processes not just photon emission and absorption

- 1930 Oppenheimer and (separately) Tamm:
  positive and negative particles annihilate each other (to give photons)

If plus particles are protons this means hydrogen can self-destruct!
Which brings us to **antiparticles**

- Dirac finally accepts that his equation predicts a new positively charged particle with equal mass to the electron

- “if it exists, (it) would be an entirely new type of particle”
Notice the reluctance

- 2 years down the road Dirac is still hesitant to insist that these particles must exist.

- Another 2 years and they were an observed fact. Positrons observed by Anderson in cosmic ray experiments.

No mention yet that the proton also obeys a similar equation and thus also has antiparticles, but that is soon recognized.
Matter is not conserved!

Not only electrons and positrons, but protons and antiprotons and even (not obvious then) neutrons and antineutrons can be created or annihilated in pairs

With the mass-energy converted from or to photons

Conservation of matter is replaced by conservation of

Number of particles minus number of matching antiparticles
N.B. Scalar and vector theories have antiparticles too

Why was it first noticed for fermions?

Because the only known charged particles at that time were fermions

So no-one was trying to develop a theory of scalar or vector charges
Now we know that antimatter exists and that

- Every particle type except a totally neutral one has an antiparticle

- We regularly produce them in the laboratory

- Dirac’s equation has an exact symmetry C
  the laws of physics for matter and those for antimatter are identical

- generalizes to CP symmetry when weak interactions are added
  (opposite charge and opposite parity or chirality)
But the Universe appears asymmetric

Cosmological quandary
- why is there so little antimatter compared to matter?
Pauli 1933

letter to Heisenberg

After the observation of positrons in 1932!

I do not believe in the hole theory because I would like to have the asymmetry between positive and negative electricity in the laws of nature (it does not satisfy me to shift the empirically established asymmetry to one of initial state)
Answers that do not work

- Initial condition of imbalance
  inflation dilutes initial densities,
  matter and antimatter are in produced in thermal equilibrium

- Sorting to regions of matter and antimatter
  We would see the interface unless regions are as large as ~1/3 visible Universe

Sorting could not occur unless CP symmetry is broken
Such extreme sorting with a small asymmetry in the equations is not possible (or so extremely improbable as to be impossible in everyday language)
1967 Sakharov’s Conditions for generating an asymmetry

- No CP symmetry in the laws of physics
  (already an observed fact though not yet incorporated in theory)

- Some process that can change baryon number
  number of particles – number of antiparticles
  (annihilation changes them both, keeps the difference the same)

- Out of thermal equilibrium situation
  (and no possible return to equilibrium between matter and antimatter)
CP Breaking Effects
3 options

rate differences between any particle process and its antiparticle CP equivalent

For neutral but flavored states:

- CP eigenstates are not flavor eigenstates -- flavor mixing
- mass eigenstates that are not CP eigenstates (discovered on K decays, 1964)

Interference between decay amplitudes for decays before and after flavor mixing
CP Breaking in any theory requires multiple particle types

- All 3 types require interference terms between two contributions with different phases to their couplings.

- But phase redefinitions of fields can make most couplings real, until you have more possible coupling phases than field redefinitions.
In the Standard Model
CP Violation in the quark decays

- Requires 3 generations (Kobayashi and Maskawa)
- Parameters measured in B decays
- All Sakharov conditions satisfied at time quarks get mass
  (ie when the Higgs vacuum expectation value becomes non-zero)

**BUT** the calculated asymmetry in the Universe is too small –
by many orders of magnitude
What number is too small?

Energy density in matter compared to that in radiation (photons) at time of big bang nucleosynthesis

Affects calculated ratios of light nuclei (e.g., Hydrogen, Deuterium, Tritium, Barium, and Lithium)

Radiation comes mostly from annihilation so this reflects the excess of matter over antimatter before annihilation removed the antimatter (and most of the matter)
Composition of the Universe (energy density)

A long history of ideas and experiments leads us to the “concordance” view of the composition of the Universe.
Other possibilities

CP violation in Neutrino decays
add a heavy Majorana neutrino to get $\nu$ masses

Additional Higgs-like particles and couplings

Either way the Standard Model is not yet complete
We try to write theories that describe what we know.

Sometimes the mathematics forces us to add things we did not want or expect.

Dirac’s equation was the first to predict as-yet-unknown particles.

Particle physicists have recognized the need to add particles for many reasons, today have little hesitation in doing so.
How mathematics forces us to add particles – symmetries rule

- Because the symmetry demands it: antimatter (C and CP)

To allow an effect forbidden by the symmetries
- particle masses: break the symmetry using Higgs fields: Higgs particle
- CP violation – add more quark types (* or more Higgs, or heavy Neutrinos)

To remove an unwanted effect using symmetries
- no strangeness changing neutral processes: charm quark
  * hierarchy problem (low Higgs mass) – supersymmetry and superpartners
  * no strong CP violation – PQ symmetry and the axion

* = particles not yet observed
Questions?  Comments?
Another CP related puzzle

- Instantons introduce a term that violates CP in QCD
  \[ \theta \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta} \]

- But experimental limits on neutron electric dipole moment
  \[ \theta < 10^{-10} \]

How can this be?
What protects it from infection by weak CP breaking?
PQ Symmetry

1976 work with Roberto Peccei

Our answer – add yet another (almost) symmetry
(by adding more Higgs like fields)

Then vacuum Higgs phases adjust to cancel any theta value!

Like Dirac’s eqn, predicts a particle that came from the mathematics,
not because we wanted it, or even noticed it at first

Weinberg; Wilczek: axions
Dark matter and the axion

Dark matter is known to exist but it is not made of any known particle.

Another cosmological puzzle that requires extension of the SM.

It may be that axions provide the answer!
In the end the cosmological puzzles remain

- Matter-antimatter imbalance
- Dark Matter
- (Dark Energy)

- Particle Theories must be extended and adapted to explain these

- Experiment gives one set of tests (but may take years to reach sensitivity)

- Consistent history for the Universe and the objects in it gives us another