What’s the matter with antimatter?

H.A. Tanaka (UBC/IPP)
On the web:
What’s the big deal?

• Energy and (anti) matter
• What is antimatter?
• What’s the big deal about it?
• Current research into antimatter
  • what distinguishes matter from antimatter?
    • why is there so little antimatter around us?
  • why do we exist?
  • what are we doing at TRIUMF to understand this better?
Possibly the most famous equation
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\[ E=mc^2 \]
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• “energy = mass \times \text{speed of light} \times \text{speed of light}”
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- “energy = mass x speed of light x speed of light”
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- mass (matter) is a form of energy
- 1 kg of mass \( \rightarrow 9 \times 10^{16} \) Joules of energy
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  - some illustrations . . . .
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T1-class “ultra large crude carrier”
6x larger than the largest aircraft carriers
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  - primary fuel of nuclear reactors
- Bruce Power Generating Station
  - (2nd largest in world)
  - 6,700 MW = MJ/sec
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1 kg of matter contains 10% of the annual output of Bruce Power Generating Station
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8 m radius of complete destruction (35 km)

radius of fireball (3.5 km)

8.1 on the Richter scale
So what?

• Can we tap into this energy?
• In principle yes, but there are some fundamental issues that make it less than straightforward . . .
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• Energy conservation allows transformations between all forms of energy so long as the total is the same
Aside . . .

- There is a profound connection between “symmetries” and conservation laws
  - symmetry: transformation that leaves laws of physics unchanged
- Symmetries of space and time:
  - time ↔ energy conservation
  - space ↔ momentum conservation
  - rotation ↔ angular momentum conservation
- Other “quantum” symmetries give rise to electric charge conservation
  - there are other forms of “charge” conservation
- Noether’s symmetry
  - symmetries in law of physics ↔ conserved quantity
Breakdown of Matter
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Water Molecule

$+ 8 \, e^-$
Breakdown of Matter

Water Molecule

Proton Neutron

+ 8 e⁻
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• Protons/neutrons are ~2000 times more massive than an electron
  • hence “baryon” and “lepton”
  • fundamental distinction:
    • baryons consist of three quarks, leptons are fundamental particles which do not interact via the strong interaction
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• However, so long as we have the same number of n,p before and after, most of the energy still remains in the form of mass
  • we are not able to convert a large fraction of the mass into other forms of energy
• is there a way around this?
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  • a partner to each particle that has “opposite” properties but the same mass
  • antielectron (“positron” or $e^+$) is a particle that has:
    • +1 charge (rather than -1)
    • -1 lepton number (rather than +1)
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- Antimatter is “stuff” comprised of antiparticles
Do such things exist?

- First evidence for the existence of antimatter (1932)
- Particle that looks just like an electron, but has opposite charge
A Loophole

- The fact that antiparticles have opposite charge and baryon/lepton number allow the following reactions:
  - $e^+ + e^- \rightarrow \text{energy}$
    - lepton number zero before/after reaction
  - $p + \bar{p} \rightarrow \text{energy}$
    - baryon number zero before/after reaction

- “Reverse” reactions also possible: e.g.
  - light (energy) $\rightarrow e^+ + e^-$
Examples:

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  - energy (light) coming in and producing $e^+ + e^-$ pair

- Right:
  - “shower” induced by alternating release of energy (light) and subsequent conversion to $e^+ + e^-$ pairs
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Examples: antiproton

- antiprotons produced by accelerator annihilating with proton in hydrogen to produce “star” of light particles
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• We have talked about matter having positive baryon/lepton number, antimatter having negative but:
  • the essential point is that they are “opposite”
  • “opposite” is a relative
  • it would be exactly the same if it were the other way around.
Left vs. Right

- In some countries (red), one drives on the right side of the road
- In others (blue), on drives on the left side of the road
- All is fine as long as one stays within one colour
  - but if a left-side driver drives on the left in right-side country (or vice versa) there will be some problems
“Symmetry Breaking”

- We could also consider “left” and “right” to be purely an arbitrary social conventions.
- However, the fact that ~70% of the world is right-handed makes the world different for left- and right-handed people.
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Likewise, a bit of antimatter is very much out of place in a world full of matter.
The puzzle (again):
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• We do not have a good understanding of why more people are right-handed (dextral) as opposed to left-handed (sinistral)
  • genetics?
  • position of fetus in womb?
  • exposure to hormones in utero?
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- We do not have a good understanding of why more people are right-handed (dextral) as opposed to left-handed (sinistral)
  - genetics?
  - position of fetus in womb?
  - exposure to hormones in utero?
- Likewise, we have a very poor understanding of why our universe is dominated by matter
  - Big Bang: conversion of energy $\rightarrow$ matter + antimatter
  - what happened to all the antimatter?
    - why would the fate of matter be different any different then antimatter?
    - if we created matter/antimatter equally, why does anything exist?
“Sorry Doc, we had a load of Anti-Matter around 13 billion years ago, but it got lost when we moved”
The imbalance

• The Cosmic Microwave Background:
  • light left over from the primordial processes following the big bang including matter/antimatter annihilations
The amount of matter and antimatter produced in the early universe was equal to one part in 10 billion.
A cosmic

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• The extremely tiny imbalance left behind a bit of matter

• This is all the matter we see in the Universe

• How did this happen?
matter vs. antimatter revisited
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• The search for matter/antimatter differences is a very active effort in physics.
  • Fundamentally understand the (anti)particles and interactions
  • Explain why there was ever so slightly more matter than antimatter in the early universe
Antihydrogen

• When excited, hydrogen emits light at particular wavelengths (colours)
  • determined by how the electron is attached to the proton in quantum mechanics
  • one of the most precisely studied and understood systems in physics
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  - antiproton + antielectron (positron) bound together
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  - does antihydrogen emit the same light spectrum as hydrogen?

- Challenge:
  - produce antihydrogen by combining antiprotons and positrons
  - trap it long enough to study its emission spectrum
Making antihydrogen

AD
p- Production (GeV)
Deceleration (MeV)
Trapping (keV)
Cooling (~ meV)

Na-22
e+ Production (MeV)
Moderation
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Diagram showing the production and accumulation processes.

- Trap potential (V)
- Axial Position (z) (cm)

antiprotons
positrons
antihydrogen
Trapping and Detection

- Once antihydrogen is formed:
  - it is electrically neutral!
  - electric fields are ineffective in trapping it
- However, it has a magnetic moment (behaves like a tiny magnet)
  - it can be pushed by a sloping magnetic field
Trapping and Detection

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- However, it has a magnetic moment (behaves like a tiny magnet)
  - it can be pushed by a sloping magnetic field
- The trapped antihydrogen “wanders” around the volume
  - eventually, it will run into the wall of the electrodes and annihilate
  - annihilation products detected by silicon strip detectors that precisely measure the position of charged particles passing through them
Trapping and Flipping

• How long can we trap antihydrogen?
  • recently demonstrated >1000 sec (16 min) confinement time

• Microwaves can be used to flip the magnetic moment of the antihydrogen
  • successful flip results in it being ejected from the trap
2011 John Dawson Award for Excellence in Plasma Physics Research Recipient

Makoto Fujiwara (TRIUMF)

Citation:
"For the introduction and use of innovative plasma techniques which produced the first demonstration of the trapping of antihydrogen."
antigravity?

- Does antimatter “fall” upwards or downwards?
  - indirect tests indicate that antimatter behaves just like matter in this regard
  - however, there have been no direct tests of this phenomenon

- Analysis of antihydrogen produced in ALPHA
  - if antimatter “falls” like normal matter, it will tend annihilate at the bottom of the detector
  - if it “antifalls” then it will annihilate at the top

Simulation studies

its direction is assumed to adiabatically track the external magnetic field. The red circles are the sub-sample of these simulated anti-atoms. The blue dotted line includes the 900,000 anti-atoms; the green points are the annihilation locations of a 1 ms intervals. The average was taken by simulating approximately atoms to annihilate in the bottom half (Figure 2 | Annihilation locations.

Because

antimatter behaves just like matter in this regard

we extended these simulations to include gravity by the force; to aid in our interpretation of the current experimental simulations discussed in ref. 38 did not include a gravitational effect; of the trap. This tendency is pronounced for anti-atoms initial energy because it can take some time for an anti-atom to find the ‘hole’ in the trap potential. Computer simulations of this

addition of a gravitational term to the equation of motion:

where

are shown in Fig. 2 for positions, and then propagated in the post-shutdown decaying magnetic fields, as found by simulations of equation 1 with

Time (ms)
Conservation Laws revisited:

- We discussed how “baryon/lepton number conservation” lies at the inability to easily convert matter directly into matter
  - this also ensures the stability of matter
  - otherwise it would turn into other forms of energy
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> It is conceivable, for instance, that a conservation law for the number of heavy particles (protons and neutrons) is responsible for the stability of the protons in the same way as the conservation law for charges is responsible for the stability of the electron. Without the conservation law in question, the proton could disintegrate, under emission of a light quantum, into a positron, just as the electron could disintegrate, were it not for the conservation law for the electric charge, into a light quantum and a neutrino.

E. Wigner (1949)

adapted from E. Kearns (IF lecture, FNAL)
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• However, unlike energy, momentum, electric charge conservation, the basis for baryon/lepton conservation is not so fundamental

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Why believe it?
“Why did these three learned gentlemen, Weyl, Stückelberg, and Wigner, feel so sure that baryons are conserved? Well, you might say that it’s very simple: they felt it in their bones. Had their bones been irradiated by the decays of nucleons, they would have noticed effects considerably exceeding “permissible radiological limits” if the nucleon lifetime were $<10^{16}$ years and if at least 10% of the nucleon rest mass were to appear as radiation absorbable in the body. That is a fairly sensitive measurement, but one can do much better by a deliberate experiment.”
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• To put in context:
  • Age of the universe: 13.7 billion years
  • other considerations: proton lifetime is $>10^{23}$ years

• We can:
  • watch one proton and wait $>10^{23}$ years for it to decay.
  • “lifetime” = “average lifetime”: watch many protons
  • each has $\sim 1$/lifetime probability of decaying in a year.
Example:
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• If we have 1 g of hydrogen
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- How would they decay?
  - Many possibilities (depending on underlying mechanism)
  - \( p \rightarrow e^+ + \pi^0 \) is one possibility
  - \( \pi^0 \) is a short-lived particle that decays to two photons (particles of light)
    - \( \pi^0 \rightarrow \gamma + \gamma \)
Extreme Science:

• Super-Kamiokande:
  • Observe 22.5 kton of water for the decay of proton
  • $\sim 7.5 \times 10^{33}$ protons $\rightarrow$ 1 decay/year if the average lifetime is $10^{33}$ years
Cherenkov Radiation

light emitted in when a charged particle exceeds velocity of light in a dielectric medium

- optical analog of “sonic boom”
- For water, $n \sim 1.33$
  - “threshold” for Č radiation is $0.75 \times c$
    - $225,000$ km/sec
  - $\Theta \sim 42^\circ$ for $v \sim c$
• Each particle produces a cone of Cherenkov radiation that is imaged by an array of light sensors (photomultipliers)
Results:
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- Should we keep looking?
  - Super-Kamiokande has been running for ~15 years
    - looking for a few years will only incrementally improve sensitivity
    - need a much bigger detector to make a step forward
    - e.g. if we had a detector 20x larger, we would be 20x more sensitive
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- As it turns out, there is another reason why we might consider building such an enormous detector.
  - Searching for proton decay then comes “for free”
Neutrinos:
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• A subatomic particle that is a “cousin” of the electron
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Properties:

• among the most abundant particles in the universe:
  • left over from the big bang
  • produced by the Sun (70 billion neutrinos/cm²/sec on earth)
• electrically neutral
• doesn’t experience “strong” interaction which binds nucleus together
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Observing neutrinos

• Neutrinos the most elusive of the known elementary particles
  • depending on its energy, a neutrino can traverse (on average) 1 light-year (10 trillion km) of lead without interacting
• we can improve the chances we observe a neutrino by:
  • making as many neutrinos as possible
    • = intense source
  • the number of interactions is proportional to “targets”
    • = enormous detector
Neutrinos oscillations:

- Neutrinos exhibit a phenomenon where they “age”
  - a neutrino born in one flavor ($\nu_e$, $\nu_\mu$, $\nu_\tau$) can appear as a different type some time later.
  - “neutrino oscillations”: wavelike-variation in probability that we appear a neutrino in a particular flavour.
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[Image of detectors in Kamioka and Tokai, labelled as ND280 “near” detector and J-PARC, showing a distance of 295 km.]
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![Diagram of neutrino oscillations setup](image)
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Observe other neutrino flavor

Super Kamiokande “far” detector

ND280 “near” detector

J-PARC

produce a pure $\nu_\mu$ beam

Kamioka

Tokai

295 km
Recent developments
Recent developments
Recent developments

• 28 $\nu_e$ observed in initially pure $\nu_\mu$ beam
• first observation of a new neutrino flavour appearing in a beam of neutrinos of initially of a different flavour.
So what?
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  • with current setup (SK) we can hope to collect ~50/year
  • we would need an upgrade to the detector
    • 20x bigger to get ~1000 events/year
Japanese Neutrino Finding Could Explain Why There Is Matter in the Universe

A new kind of oscillation could be the key to life, the universe, and everything.
“Hyper-Kamiokande”
"Hyper-Kamiokande"

- x20 upgrade of Super-Kamiokande to 1 megatonne of detector.
- Canadian physicists are playing a major role in the R&D for HK
What is science, what is fiction?

- Antimatter definitely exists
  - it is naturally produced by cosmic rays
  - we can produce it and study it
  - it is part of “everyday life” in the form of PET machines
- It is not:
  - an untapped source of energy
    - (you have to make the antimatter)
  - an effective means of storing energy
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  • . . . . . if only we could make antimatter efficiently
• Behind this incredible potential is a profound mystery
  • what distinguishes matter from antimatter?
  • why is there so little antimatter in the universe?
Conclusions
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• Scientists at TRIUMF and associated universities are actively trying to find clues and answers
  • are the conservation laws that “protect” matter valid?
    • does the proton decay?
    • can electron pairs without neutrinos be spontaneously produced by radioactive decay?
  • does antimatter behave differently from matter?
    • Trapped antihydrogen will allow us to answer whether
      • do antiatoms have a different spectrum?
      • does antimatter fall upwards?
    • Intense neutrino beams and enormous detectors may answer:
      • do neutrinos oscillate differently from antineutrinos?
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• Recent breakthroughs in setting the stage for the answers
  • please stay tuned for further progress . . . .
  • or join the fun!