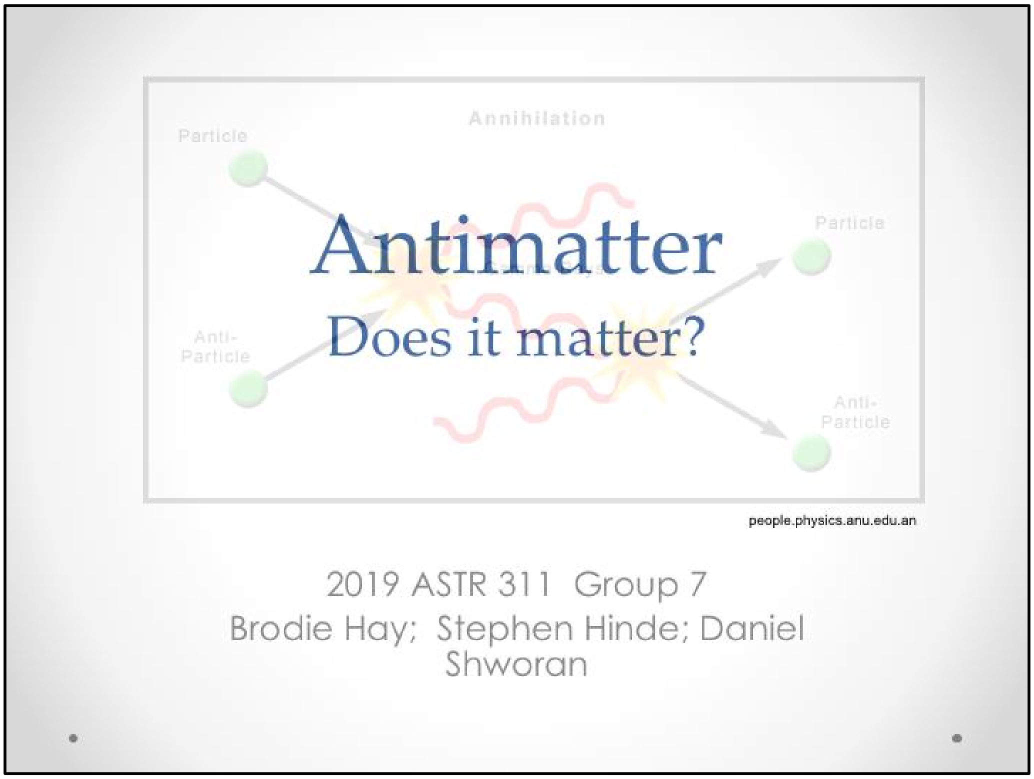

Antimatter. What is it? Where does it come from? What do we do with it? Why is it important? These are some of the questions we hope to answer during this short overview.

Image 1:
http://people.physics.anu.edu.au/~cms130/phys2013/antimatter/id11.htm
(Note: Australian National University, 2005)

Before we look at antimatter, we need to understand matter. Matter is all around us. It is us. It is the stuff we see, the stuff we stand on, the stuff we breathe and eat…even this photograph is composed of matter.

But what makes matter?

Democritus, nearly 2500 years ago, proposed that matter was composed of indivisible particles—atoms. [5]

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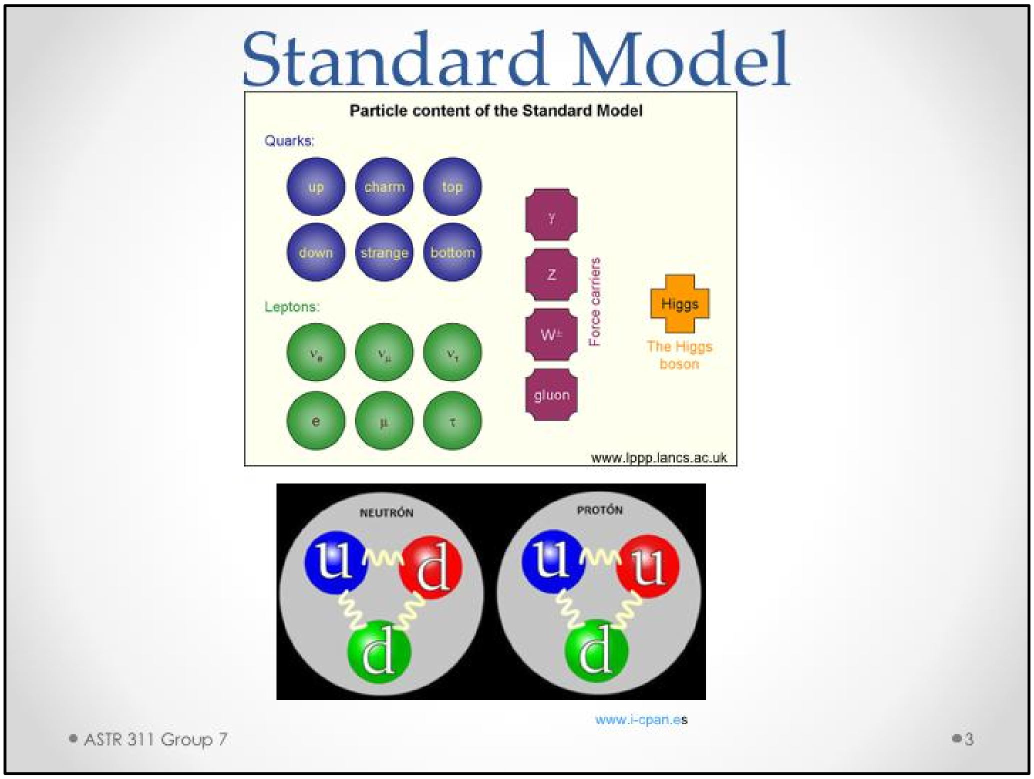
[5]Berryman, Sylvia (2016). Democritus: 2. Atomist Doctrine. Stanford Encyclopedia of Philosophy.

https://plato.stanford.edu/entries/democritus/#2

Image 2: Stephen Hinde 5B220254



More than 2 millenia later....

Experiments starting near the beginning of the 20th century explored not only the different types of atoms, but showed that atoms themselves were composed of smaller particles. In the 1960s, physicist Murray Gell-Mann proposed a classification of these "subatomic" particles, a classification known as the standard model. [1]

All normal (everyday) matter "is comprised of electrons, up-quarks, down-quarks and photons and gluons which hold them together. All the other particles of the standard model can only be observed in accelerator experiments or in cosmic ray showers." [3] Protons and neutrons are built from a combination of 3 up and down quarks. (Proton = uud; Neutron = udd).

–

[1]Bennett, Jeffrey O.; et al (2017). The Cosmic Perspective: Stars, Galaxies & Cosmology, 8th ed.

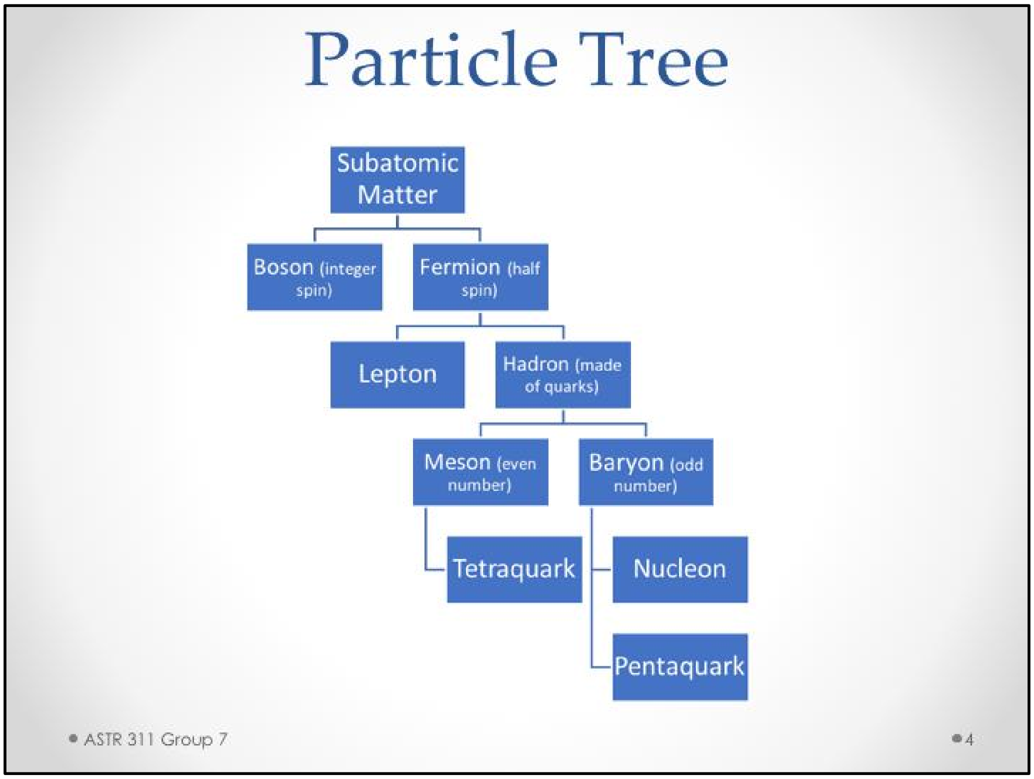
Pearson Education Inc., ISBN 978-0-134-05906-8

[3]Lancaster University Particle Physics Package (2011).

http://www.lppp.lancs.ac.uk/index.html?LPPPSession=1554341185026

Image 3: http://www.lppp.lancs.ac.uk/higgs/higgs.html (Note: Lancaster University (England) physics department 2019)

Image 4: https://www.i-cpan.es/detallePregunta.php?id=2 (Note: CPAN=Centro Nacional de Física de Partículas, Astropartículas y Nuclear, the Spanish National Center for Particle, Astroparticle and Nuclear Physics 2010)(labels in Spanish)

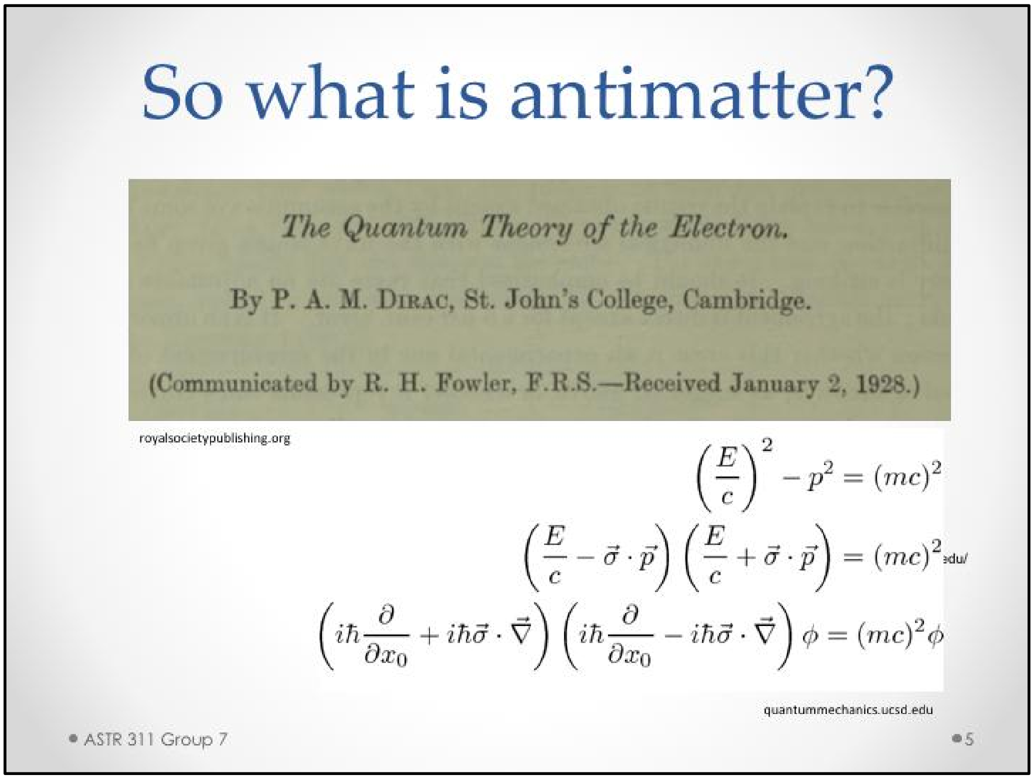


And just like biological organisms, subatomic particles have a family tree.

The classification is based on properties such as quantum spin and mass (or number of quarks). Nucleons are the proton and neutron. Leptons include the electron. Bosons include the photon. Mesons include the normal 2 quark mesons, and the tetraquark, and hypothesised hexaquark.

Note that we have not yet mentioned antimatter.

Image 5: Stephen Hinde 20190404



In 1928, physicist Paul Dirac published a paper solving Schrodinger's wave equation for the electron. This combined quantum theory and special relativity. The solution allowed for 2 possible cases, a positive and a negative example, which Dirac referred to as the "duplexity phenomenon". [2]

Antimatter, as it is now known as, consists of a particle that has an opposite value (usually charge) but the same mass as the matter version of the particle. For example, an electron (charge -1eV) and antimatter equivalent positron (charge +1 eV).

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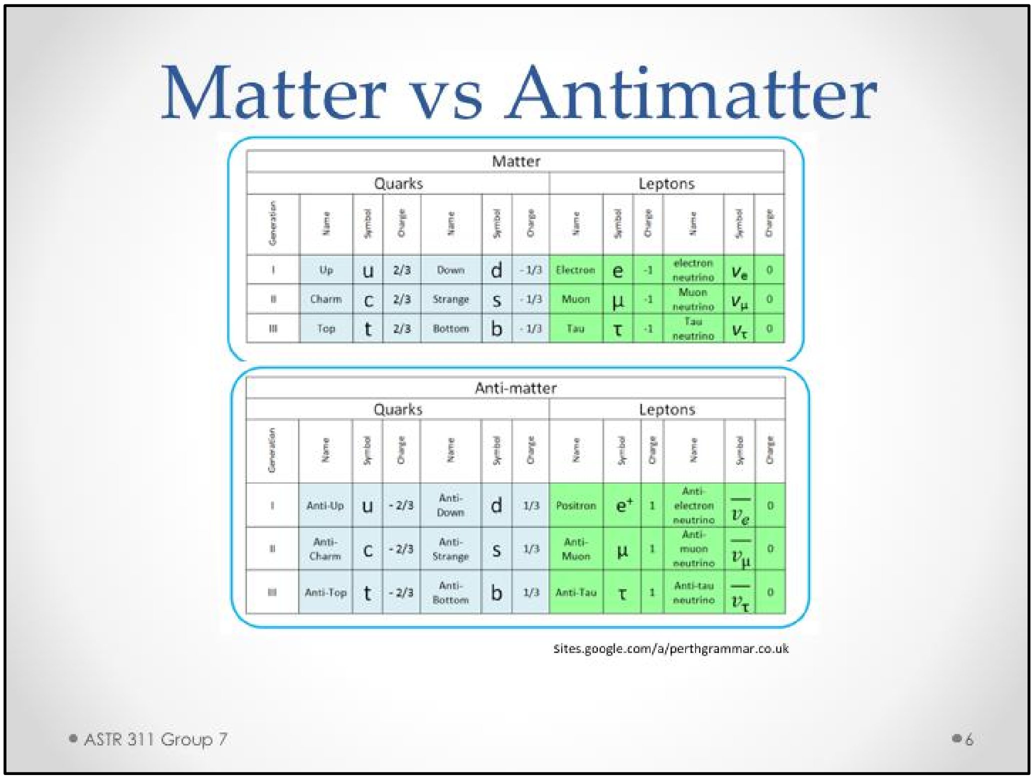
[2]Dirac, P. A. M. (1st February 1928). Proceedings of the Royal Society, Vol. 117, Iss. 778.

ISSN 2053-9150

Image 6: https://royalsocietypublishing.org/doi/pdf/10.1098/rspa.1928.0023 retrieved from https://royalsocietypublishing.org/doi/abs/10.1098/rspa.1928.0023
Image 7: https://quantummechanics.ucsd.edu/ph130a/130_notes/node45.html (Note: This is a physics 130 curriculum from University of California, San Diego, 2003)



As this chart illustrates, particles, and their antiparticles, differ in their charge. The case of the neutrino is interesting. Neutrinos have mass but are charge neutral particles. They are "anti" in their quantum spin. [6] This is a bigger topic for another day.

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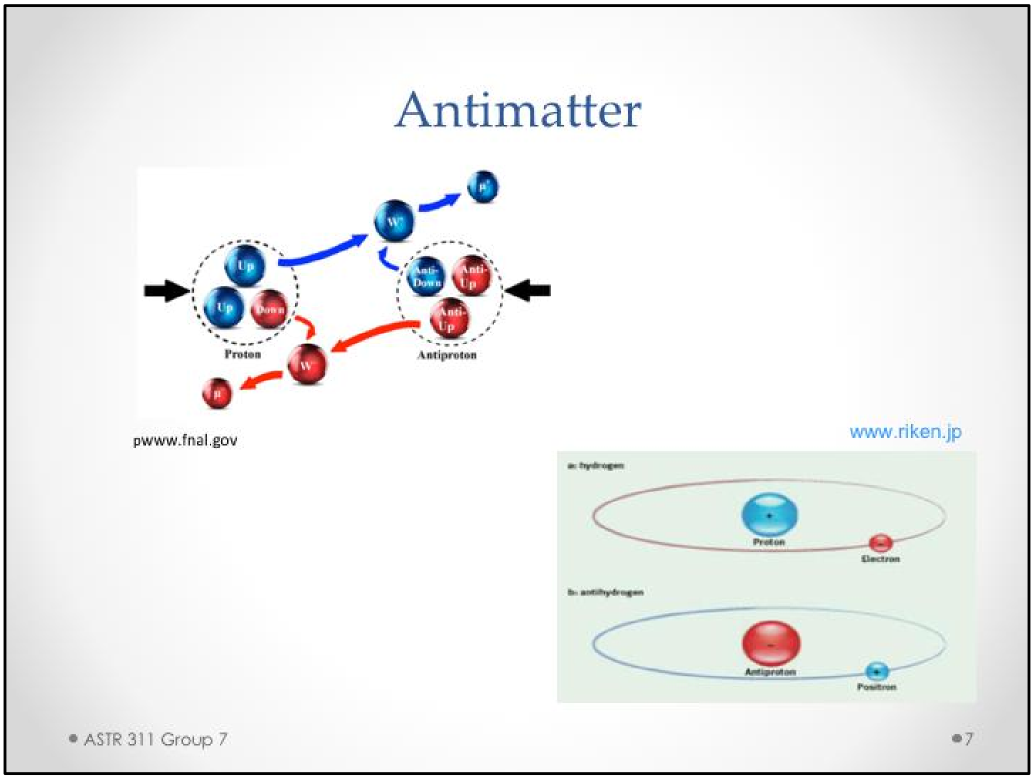
[6]Preuss, Paul (2009). The Surprising Neutrino. Berkeley Lab.
https://www2.lbl.gov/Publications/YOS/Mar/neutrinos-2.html
Images 8,9: https://sites.google.com/a/perthgrammar.co.uk/pgs-chemistry/courses/higher/higher-31-the-standard-model/311-the-standard-model (Note: Perth Grammar School, UK)



- Quarks combine to form a proton. Anti-quarks form antiprotons. *The image shows a proton/antiproton collision producing W+ and W- bosons,* [6B] *massive particles (about 700 times the proton) responsible for the weak force.* [6C]

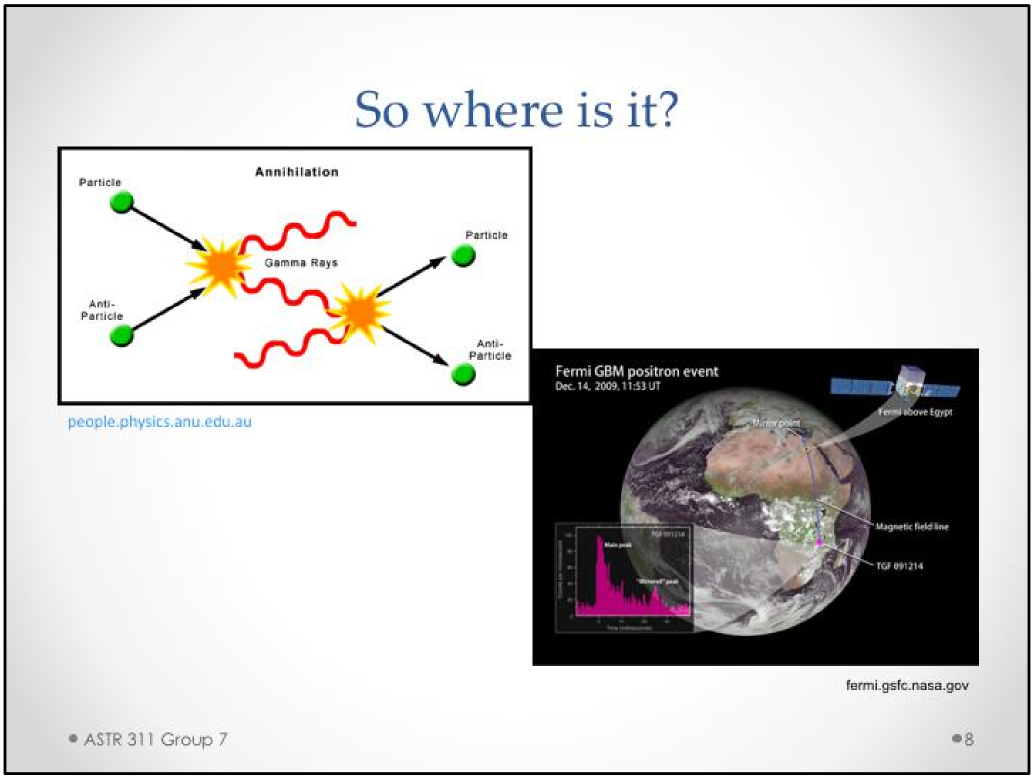
- Antiproton and an antielectron (positron) make up anti-hydrogen

- Question: if there were an antimatter apple, what would it look like? Answer: just like a regular apple—its just made of antiparticles, but the conglomeration looks the same.[6A] Of course, you wouldn't be able to eat it!

[6A]Lincoln, Don (7 Sep 2012). What's the deal with antimatter?. FermiLab Today.
http://www.fnal.gov/pub/today/archive/archive_2012/today12-09-07_NutshellReadMore.html
[6B]Williams, Mark (12 Sep 2013). Muons point towards proton's inner workings. FermiLab Today.
http://www.fnal.gov/pub/today/archive/archive_2013/today13-09-12.html
[6C]Margaroli, Fabrizio, and Beretvas, Andy (9 April 2015). Happy Hunting Grounds. FermiLab Today.
http://www.fnal.gov/pub/today/archive/archive_2015/today15-04-09.html

Image 10: http://www.fnal.gov/pub/today/archive/archive_2013/images/ROW_Figure01_130912.jpg (Note: FermiLab, 2013)

Image 11: http://www.riken.jp/en/research/rikenresearch/highlights/4724/ (Note: RIKEN Research Institute, Japan, 2007)



Matter and antimatter have opposite properties—if the corresponding antiparticle/particle collide, they annihilate each other, releasing their total mass as energy. And if two photons of sufficient energy collide they can produce an antiparticle/particle pair, such as a positron/electron.[6A]

The Fermi Gamma-ray Space Telescope was designed to detect gamma radiation from space, but it also detects radiation from the annihilation of electron/positron pairs in the earth's atmosphere, caused by highly energetic interactions, such as found in thunderstorms. [4] Other naturally-occurring antiparticles be found in solar flares, [6D] and in cosmic rays. [6E]

As we discussed previously in the course, the early stages of "the Big Bang" produced quarks, antiquarks, and other subatomic particles. A small fraction of those survive today as regular matter, but there is no antimatter (or at least, none surviving more than a tiny fraction of a second that we know of).

Apart from natural sources, antimatter can be produced in the laboratory and from radioactive decay. *(More on this in the next section.)*

[4] Reddy, Francis (2011): Spotting Terrestrial Gamma-Ray Flashes. NASA Goddard Space Flight Center

https://fermi.gsfc.nasa.gov/science/eteu/tgfs/

[6A]Lincoln, Don (7 Sep 2012). What's the deal with antimatter?. FermiLab Today.

http://www.fnal.gov/pub/today/archive/archive_2012/today12-09-07_NutshellReadMore.html

[6D]Goddard Space Flight Center (2 Sep 2003). Antimatter Factory on Sun Yield Clues to Solar Explosions. NASA.

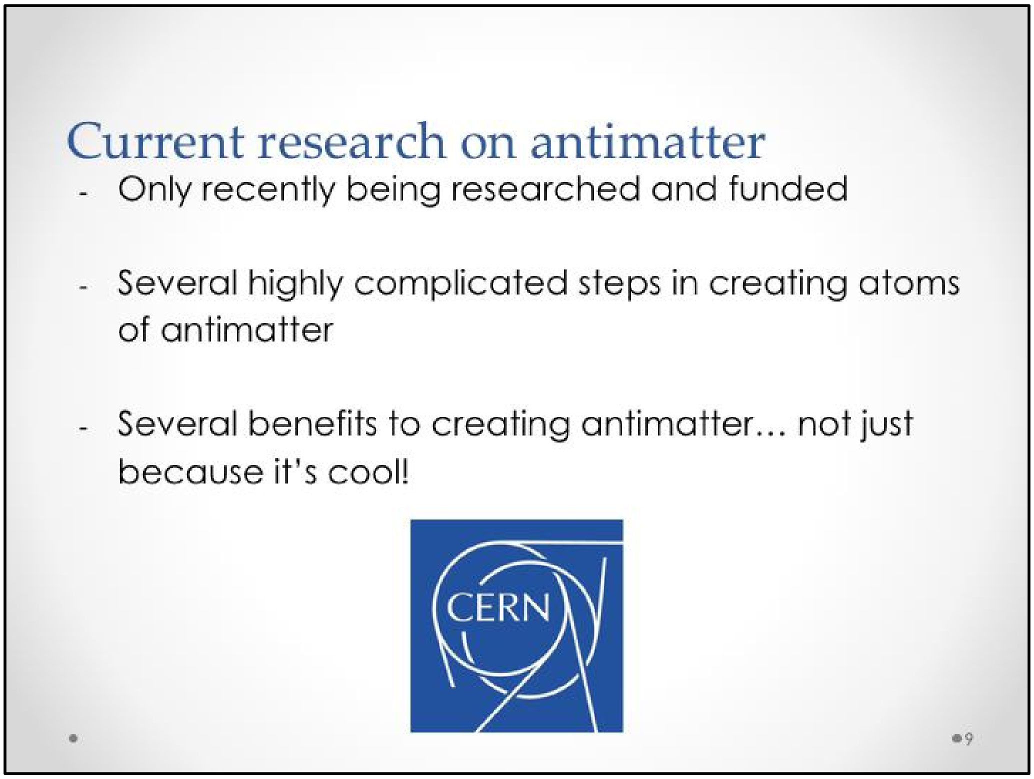
https://www.nasa.gov/centers/goddard/news/topstory/2003/0903rhessi.html

[6E]Jepsen, Kathryn (12 Dec 2016). Space Station Experiment Marks Five Years Probing Cosmic Ray Mysteries. NASA.

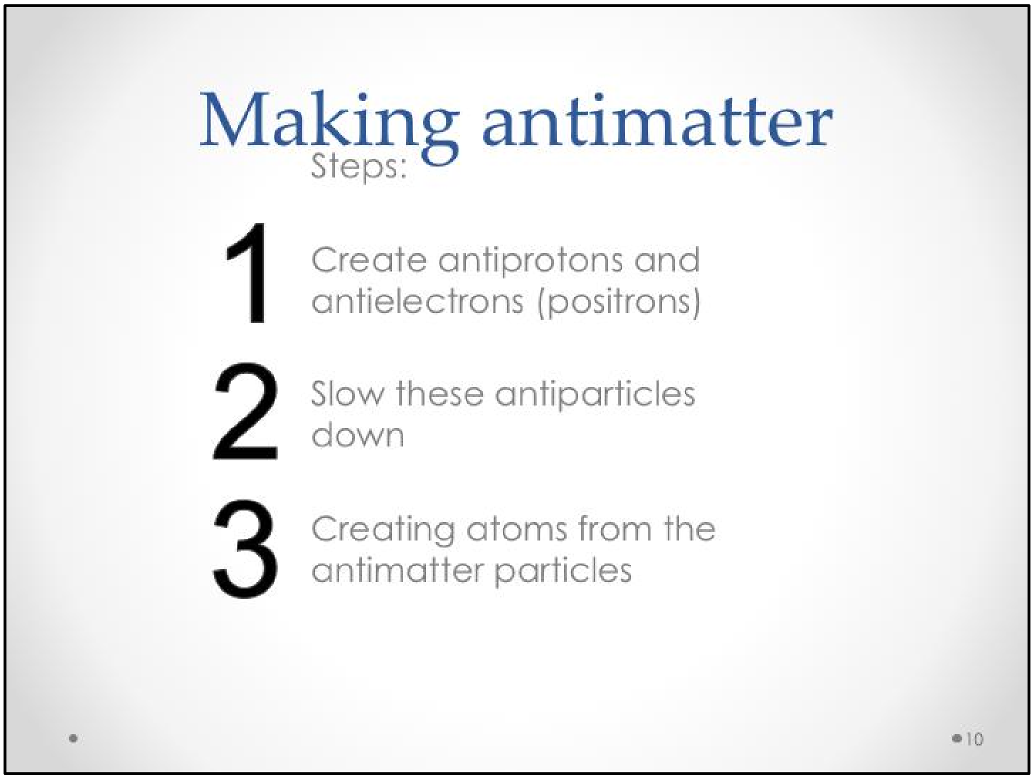
https://www.nasa.gov/feature/space-station-experiment-marks-five-years-probing-cosmic-ray-mysteries

Image 12: http://people.physics.anu.edu.au/~cms130/phys2013/antimatter/id11.htm (Note: Australian National University, 2005)

Image 13: https://fermi.gsfc.nasa.gov/science/eteu/tgfs/figure3.jpg (Note: NASA Goddard Space Flight Center, Fermi Gamma-ray Space Telescope site, 2016)

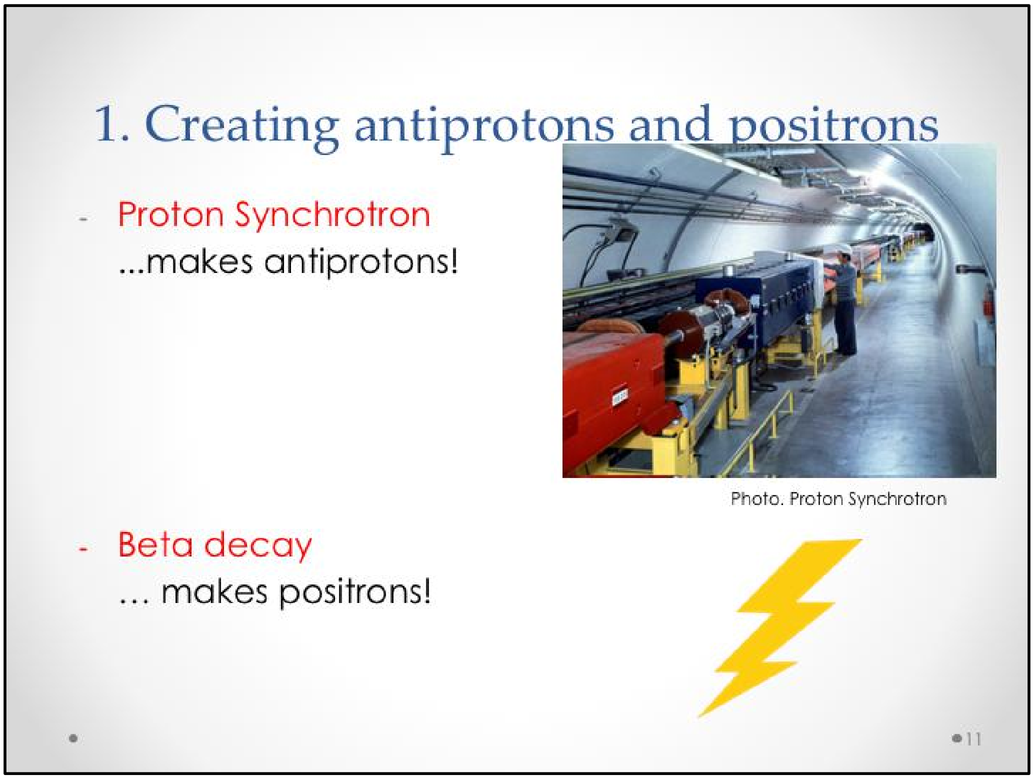


- Only recently being researched in lab
  - First atoms of antimatter produced at CERN in 1996
- Several highly complicated steps in creating atoms of antimatter
- Several benefits to creating antimatter… not just because it's cool!



[7] How the Heck Do Scientists CREATE Antimatter? Science Plus. 2016. https://www.youtube.com/watch?v=PL2F046-PQw

[8] How Can We Make Antimatter. James Lloyd, 2014. Science Focus. https://www.sciencefocus.com/science/how-can-we-make-antimatter/



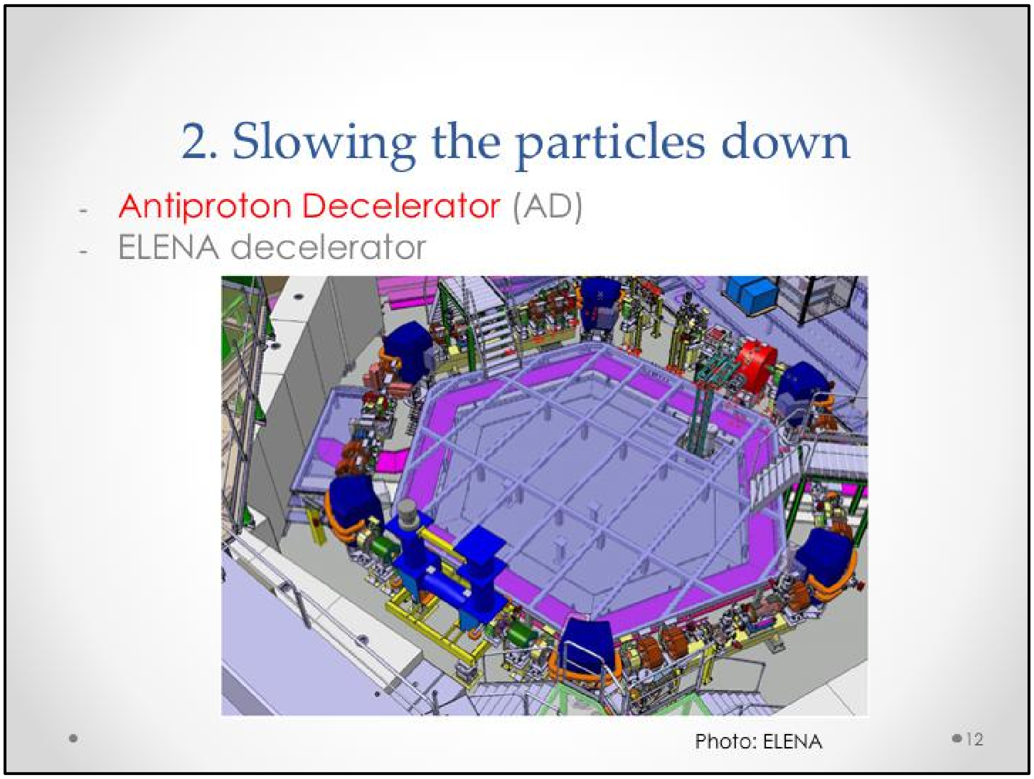
- Proton Synchrotron makes antiprotons
- It fires the protons into a block of metal. These collisions create a multitude of secondary particles, including lots of antiprotons. These antiprotons have too much energy to be useful for making antiatoms. They also have different energies and move randomly in all directions.

[9] Positron. 2013. Encyclopedia Britannica. https://www.britannica.com/science/positron

Photo. Proton Synchrotron. 2012: https://cds.cern.ch/record/1997188

[10] Beta decay. Wikipedia. https://en.wikipedia.org/wiki/Beta_decay

- Positrons are produced by using radioactive Beta decay, which is basically the disintegration of a radioactive nucleus, emitting gamma rays which can be converted into positrons
- Thunderstorms also emit positrons

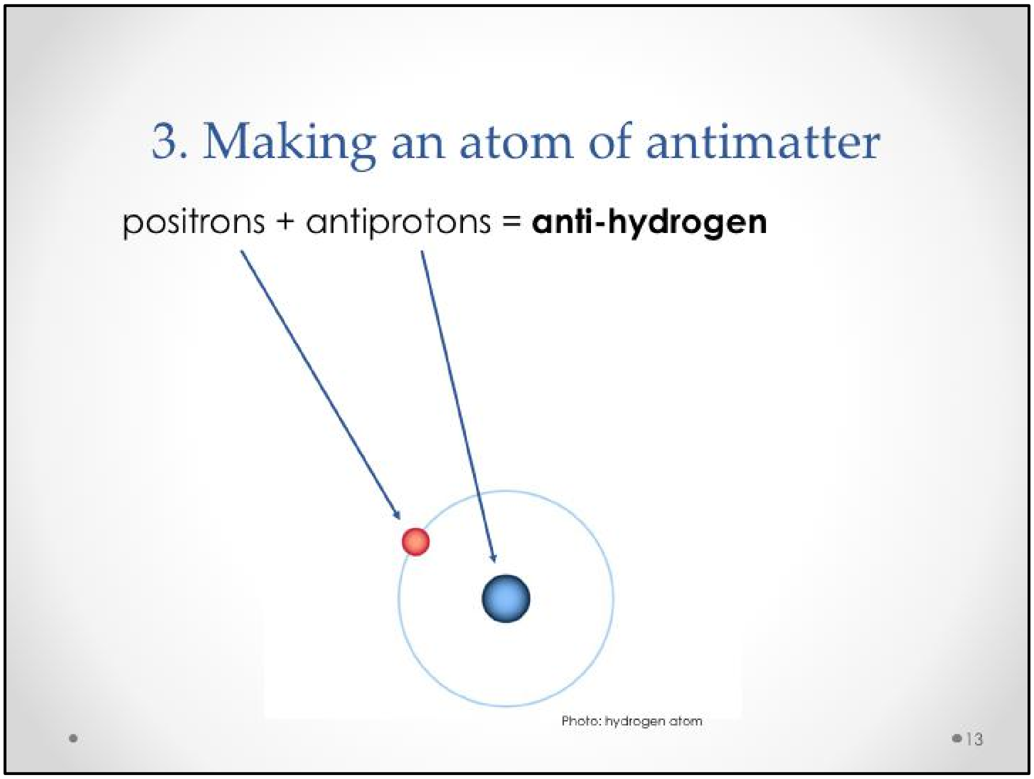


- Antiproton decelerator
    - The job of the AD is to tame these unruly particles and turn them into a useful, low-energy beam that can be used to produce antimatter.
- ELENA particle decelerator built in 2011 [7]
    - Further slows antiprotons from the AD to increase the likelihood they are trapped in the magnetic field.
    - 30 metres in circumference
- Capturing these "slowed down" antiprotons…
    - Positrons and antiprotons trapped using magnetic fields and electric fields put together in a particular configuration…record is 16 minutes!

[11] Antiproton Decelerator. CERN. https://home.cern/science/accelerators/antiproton-decelerator

[12] ELENA Project. 2011. CERN. https://espace.cern.ch/elena-project/SitePages/Home.aspx

ELENA Photo. 2011. CERN https://espace.cern.ch/elena-project/SitePages/Home.aspx



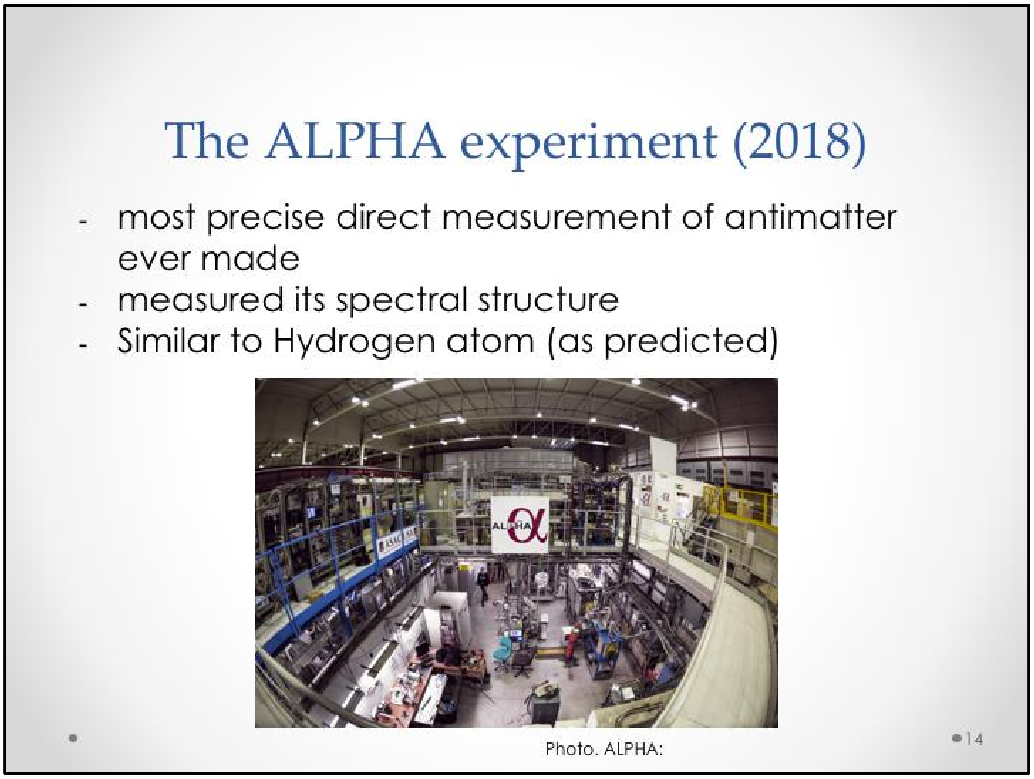
- Ultimately, these decelerators allow us to harvest a small amount of antimatter, which was largely abundant in the early stages of the universe after the big bang. The antimatter is made by combining the antiprotons with antielectrons (positrons) inside these magnetic “bathtubs” to create antihydrogen (antimatter!)

Ultimate physics goal is to perform spectroscopy on antihydrogen atoms at rest and to investigate the effect of the gravitational force on matter and antimatter.

- Over the past decade, CERN has worked to improve its efficiency in producing antimatter, and now they are now testing the characteristics of the antimatter.

Photo. Hydrogen Atom:

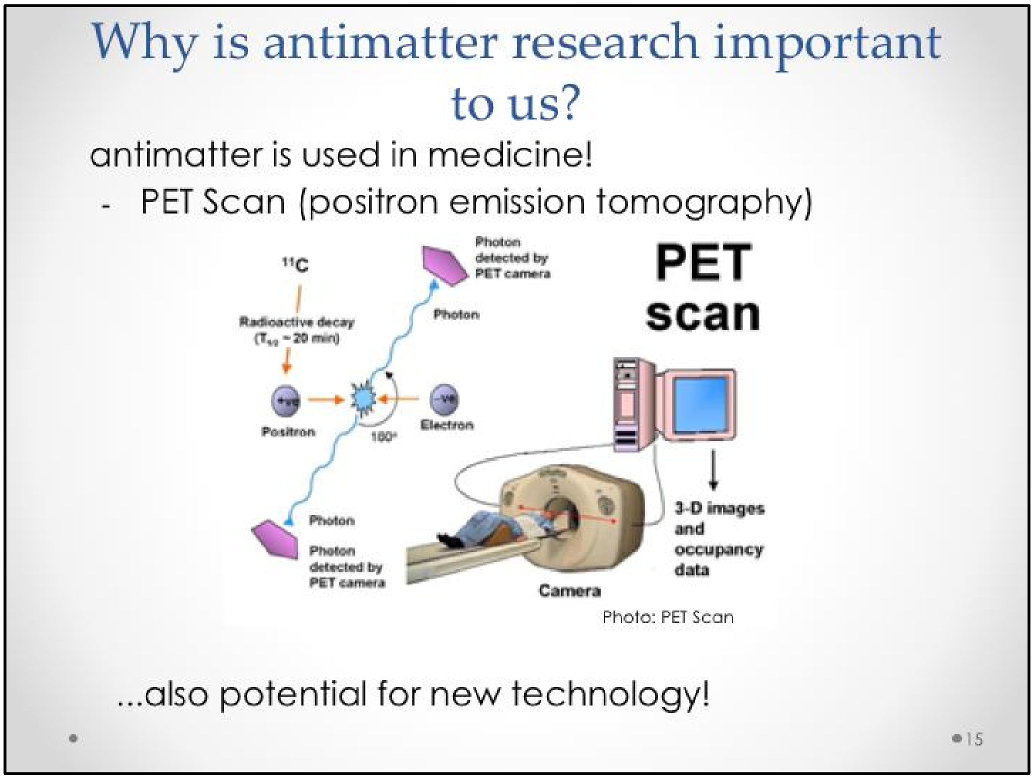
https://www.proprofs.com/discuss/q/167664/the-number-of-hydrogen-atoms-that-fuse-to-form-helium-atom-i



- Currently at CERN, the physicists have made the most precise direct measurement of antimatter ever made, revealing the spectral structure of the antihydrogen atom in unprecedented colour. Measured at precision of a few parts per trillion. This research shows precise similarities between the hydrogen atom (matter) and the antihydrogen (antimatter).

[13] ALPHA project. CERN. 2018. https://home.cern/news/news/physics/new-era-precision-antimatter-research

Photo. ALPHA: https://home.cern/news/news/physics/alpha-experiment-explores-secrets-antimatter



Why is antimatter research important to us?

o Commercially, antimatter is used in medical techniques such as positron emission tomography (PET)… used for cancer diagnostics… ingest a drug that decays and produces a positron inside your body… meets its opposing twin (the electron) in tumor tissue … combine and annihilate producing photons shooting off in opposing directions… allows us to see where this occurred and allows us to see tumor growth!

point at picture and explain

Also… Allows for greater understanding of physics of the big bang?
Potentially allows us to advance our technology!

Photo. PET scan: https://www.pinterest.ca/pin/319122323570619212/

Thank you Daniel, so i am talking about the future of antimatter, there are currently 3 main applications for antimatter that are being explored

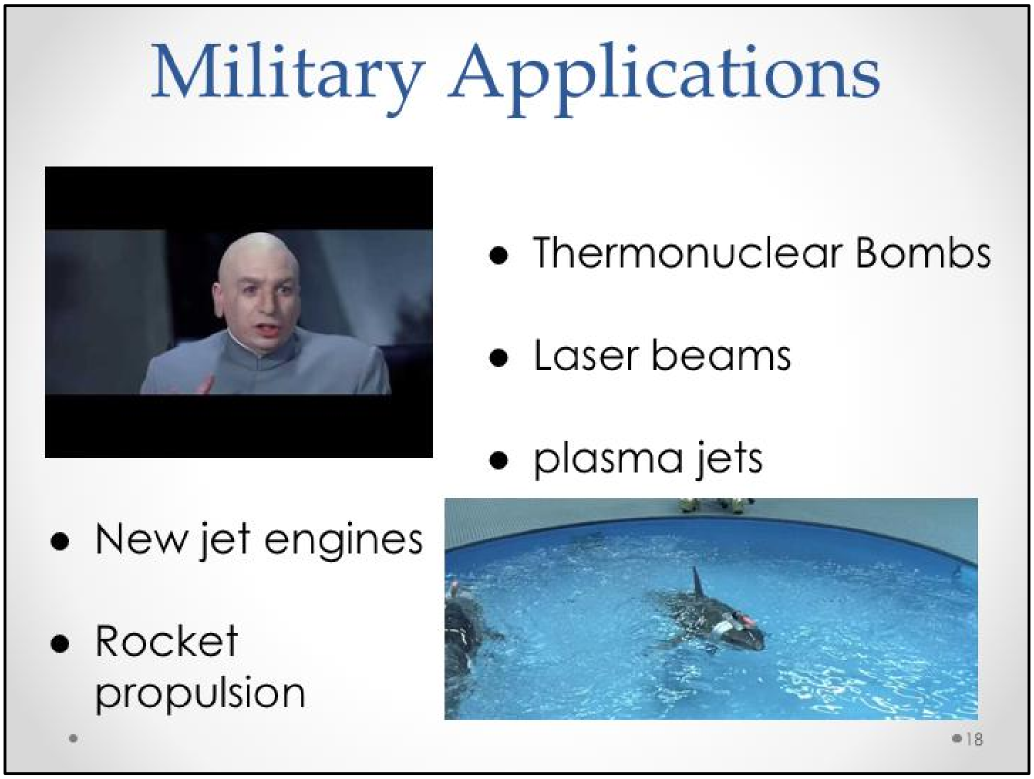
Medical Applications

military Applications

As a Fuel Source: for here on earth and for traveling the universe

The Antiproton Cell Experiment (ACE) took place between 2003 and 2013. The ACE team consisted of a group of researchers at Cern's particle accelerator laboratory in Geneva, the found that shooting an antiproton beam at a group of cells suspended in gelatine, was four times more efficient when destroying a targeted area than a standard proton beam! This experiment was intended to simulate irradiating a section of tissue in the body, to destroy malicious cell groupings like tumors.[14]

When a proton beam is shot through a medium, it slows down and once it stops the target cell is destroyed, but this reaction has a slight effect on the healthy cells around it, which, after repeated treatments can become detrimental to the patient health. Because the use of antiprotons is so much more efficient in destroying the malicious cells, there is a much smaller effect on the healthy cells in the surrounding area, this means that using an antiproton beam in place of a regular proton beam yields a much safer and precise result.[15]

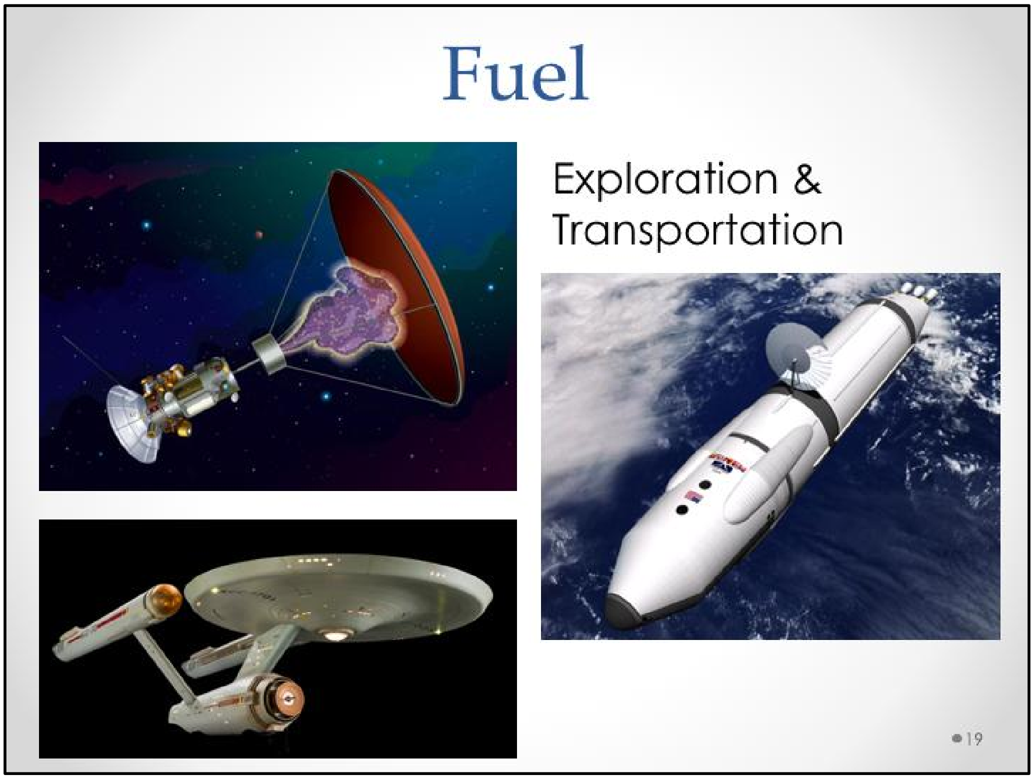


For military applications, there are two big driving forces behind the research of antimatter. The first is that the release of usable energy from an annihilation is 100%. Right now we are only able to yield 50% of this energy, but this is still far better than the 7% yield that we get from standard fission! The second is the use of antimatter as a trigger, when antimatter is brought into the proximity of matter, the matter and antimatter start to annihilate each other immediately.

Antimatter brings the ability to build nuclear weapons free of radioactive fall-out, beam weapons that can project thermonuclear plasma jets, or gamma and X-ray lasers, all triggered by antimatter reactions.

Only extremely small amounts of antiprotons are needed to create huge thermonuclear explosions. To put this into perspective, using only a kilogram each of both matter and antimatter would yield an explosion 3000 times the size of Hiroshima.

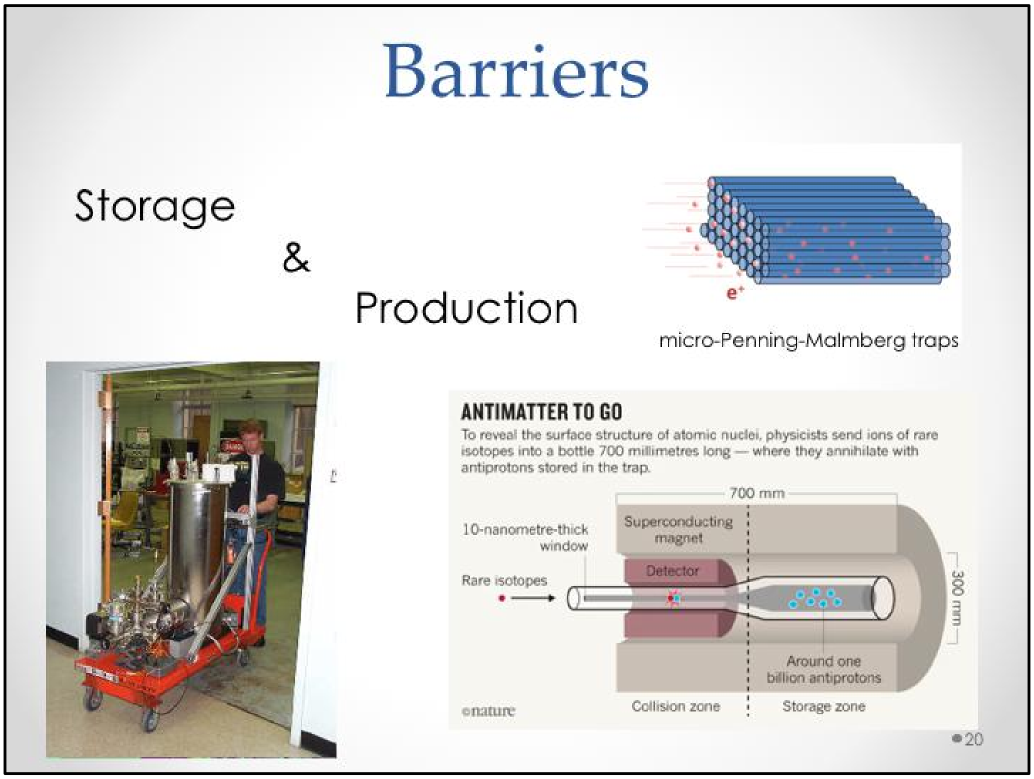
Buuut for such uses to be even remotely realistic, we would need technology that allows us to produce an amount of antimatter six orders of magnitude higher than what we are currently able to produce (10^7 antiprotons per second). [16]



Possibly the most important application of antimatter is as a fuel

One possibility for a propulsion system is a fusion drive system that uses an antiproton beam to annihilate small pellets, containing deuterium and tritium, that are surrounded by another material such as uranium. The antiproton beam would then hit the uranium, annihilate, and spark fusion reactions in the pellets. [17]

Another possibility is for a more direct use of the antimatter/matter annihilations. These annihilations will produce charged pions, unfortunately this method produces much slower pions that previous simulations had produced. So, what kind of speeds are we talking about here? the current simulations state that the pions should be able to hit 80% the speed of light, while the previous estimates were up to 90 percent. But the good news is that the old estimates were using a magnetic nozzle to focus the pions that only lead to an overall efficiency of one third the speed of light, and the new simulations boast a nozzle efficiency of 85 percent, translating to an total exhaust velocity of 70 percent the speed of light, that is pretty dang fast [18]. Currently the record for the fastest speed any human has ever traveled relative to the Earth was set by Apollo 10, which reached 39,897 kph. That's approximately 0.0037% the speed of light.



So, why aren't we seeing the use of antimatter applied to military or transportation? The two biggest hurdles to using antimatter are cost and storage.

The cost to produce just one gram of antiprotons is estimated to cost $250 billion, and for a gram of antihydrogen? $62.5 trillion [19], to give you some perspective on that, Apple has a value of around $1 trillion, and that is the world's most valuable company! So essentially it is pretty pricey! [20]

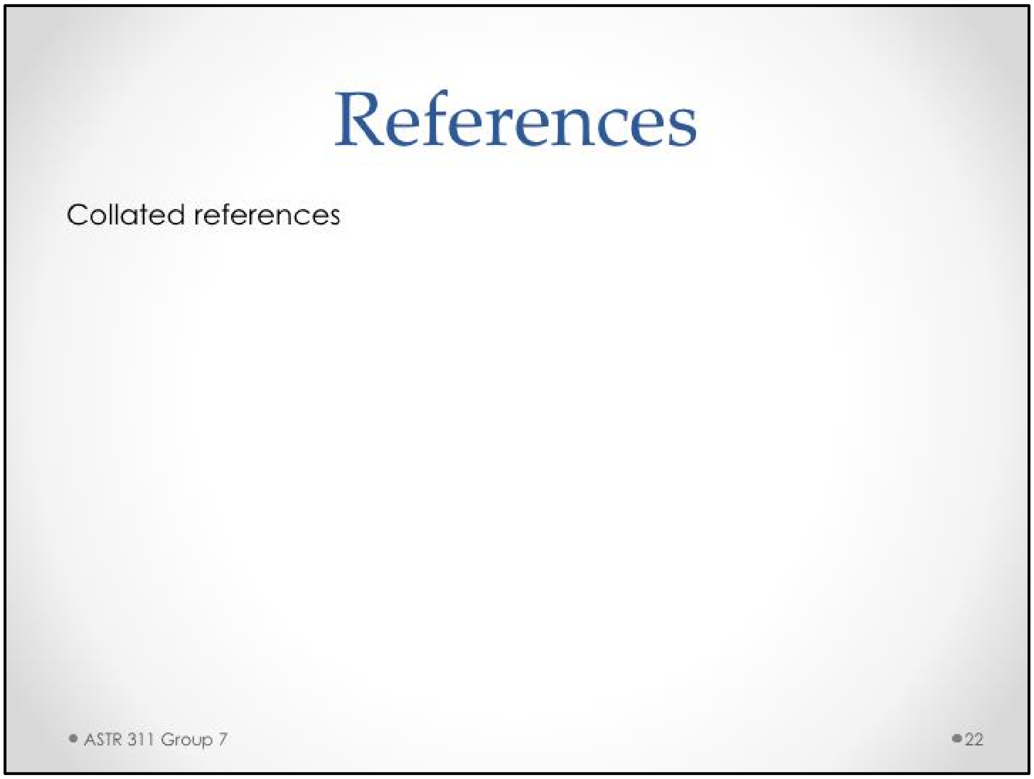
Even if we can afford to produce antimatter, just storing it is a arduous task. Antimatter particles must be suspended in a magnetic field because if they happen to touch any matter, like the side of a container, the matter and antimatter will immediately annihilate each other. [21]

And the more antimatter that we create and contain, the harder it gets to store without any annihilations. This is also an extremely important idea to remember when we are trying to transport antimatter!

Why does this matter (hehe)

- It has massive implications regarding current and future medicine
- It could keep us safe from Aliens!
- It can fuel society and space travel quickly and efficiently
- It can teach us more about our universe and its history

21



[1]Bennett, Jeffrey O.; et al (2017). The Cosmic Perspective: Stars, Galaxies & Cosmology, 8th ed.

Pearson Education Inc., ISBN 978-0-134-05906-8

[2]Dirac, P. A. M. (1st February 1928). Proceedings of the Royal Society, Vol. 117, Iss. 778.

ISSN 2053-9150

[3]Lancaster University Particle Physics Package (2011).

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[4] Reddy, Francis (2011): Spotting Terrestrial Gamma-Ray Flashes. NASA Goddard Space Flight Center

https://fermi.gsfc.nasa.gov/science/eteu/tgfs/

[5]Berryman, Sylvia (2016). Democritus: 2. Atomist Doctrine. Stanford Encyclopedia of Philosophy.

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https://www2.lbl.gov/Publications/YOS/Mar/neutrinos-2.html

[6A]Lincoln, Don (7 Sep 2012). What's the deal with antimatter?. FermiLab Today.
http://www.fnal.gov/pub/today/archive/archive_2012/today12-09-07_NutshellReadMore.html
[6B]Williams, Mark (12 Sep 2013). Muons point towards proton's inner workings. FermiLab Today.
http://www.fnal.gov/pub/today/archive/archive_2013/today13-09-12.html
[6C]Margaroli, Fabrizio, and Beretvas, Andy (9 April 2015). Happy Hunting Grounds. FermiLab Today.
http://www.fnal.gov/pub/today/archive/archive_2015/today15-04-09.html
[6D]Goddard Space Flight Center (2 Sep 2003). Antimatter Factory on Sun Yield Clues to Solar Explosions. NASA.
https://www.nasa.gov/centers/goddard/news/topstory/2003/0903rhessi.html
[6E]Jepsen, Kathryn (12 Dec 2016). Space Station Experiment Marks Five Years Probing Cosmic Ray Mysteries. NASA.
https://www.nasa.gov/feature/space-station-experiment-marks-five-years-probing-cosmic-ray-mysteries
Image 1,12:
http://people.physics.anu.edu.au/~cms130/phys2013/antimatter/id11.htm
Image 2: Stephen Hinde 5B220254
Image 3: http://www.lppp.lancs.ac.uk/higgs/higgs.html
Image 4: https://www.i-cpan.es/detallePregunta.php?id=2
Image 5: Stephen Hinde 20190404
Image 6: https://royalsocietypublishing.org/doi/pdf/10.1098/rspa.1928.0023
Image 7:
https://quantummechanics.ucsd.edu/ph130a/130_notes/node45.html
Images 8,9: https://sites.google.com/a/perthgrammar.co.uk/pgs-chemistry/courses/higher/higher-31-the-standard-model/311-the-standard-model
Image 10:
http://www.fnal.gov/pub/today/archive/archive_2013/images/ROW_Figure01_130912.jpg
Image 11: http://www.riken.jp/en/research/rikenresearch/highlights/4724/
Image 13: https://fermi.gsfc.nasa.gov/science/eteu/tgfs/figure3.jpg

[7] How the Heck Do Scientists CREATE Antimatter? Science Plus. 2016. https://www.youtube.com/watch?v=PL2F046-PQw

[8] How Can We Make Antimatter. James Lloyd, 2014. Science Focus.

https://www.sciencefocus.com/science/how-can-we-make-antimatter/

[9] Positron. 2013. Encyclopedia Britannica. https://www.britannica.com/science/positron

Photo. Proton Synchrotron. 2012: https://cds.cern.ch/record/1997188

[10] Beta decay. Wikipedia. https://en.wikipedia.org/wiki/Beta_decay

[11] Antiproton Decelerator. CERN. https://home.cern/science/accelerators/antiproton-decelerator

[12] ELENA Project. 2011. CERN. https://espace.cern.ch/elena-project/SitePages/Home.aspx

ELENA Photo. 2011. CERN https://espace.cern.ch/elena-project/SitePages/Home.aspx

[13] ALPHA project. CERN. 2018. https://home.cern/news/news/physics/new-era-precision-antimatter-research

Photo. ALPHA: https://home.cern/news/news/physics/alpha-experiment-explores-secrets-antimatter

Photo. Hydrogen Atom:

https://www.proprofs.com/discuss/q/167664/the-number-of-hydrogen-atoms-that-fuse-to-form-helium-atom-i

Photo. PET scan: https://www.pinterest.ca/pin/319122323570619212/

[14] Antimatter cancer treatment. Chemistry World. https://www.chemistryworld.com/news/antimatter-cancer-treatment/3000368.article

[15] The Antiproton Cell Experiment (ACE). CERN. https://home.cern/science/experiments/ace

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[18] Antimatter Propulsion engine. Technology Review. https://www.technologyreview.com/s/427923/antimatter-propulsion-engine-redesigned-using-cerns-particle-physics-simulation-toolkit/

[19] Antimatter. Wikipedia. https://en.wikipedia.org/wiki/Antimatter

[20] What is a Trillion. Information is Beautiful. https://informationisbeautiful.net/visualizations/trillions-what-is-a-trillion-dollars/

[21] Antimatter Storage. Cornell University. https://arxiv.org/abs/1301.0030

Photo 19. Antimatter as medicine. https://www.symmetrymagazine.org/article/april-2015/ten-things-you-might-not-know-about-antimatter
Photo 20. Antimatter as fuel. https://www.symmetrymagazine.org/article/april-2015/ten-things-you-might-not-know-about-antimatter
Photo 21. Antimatter and gravity. https://www.symmetrymagazine.org/article/april-2015/ten-things-you-might-not-know-about-antimatter
Photo 22. Proton Therapy. http://tomi-em.com.au/product/proton-beam-therapy/
Photo 23. Beam Accuracy. https://medicalxpress.com/news/2015-09-simple-method-accuracy-proton-therapy.html
Photo 24. Nasa Antimatter Spaceship. https://www.nasa.gov/exploration/home/antimatter_spaceship.html
Photo 25. Antimatter propulsion. https://www.forbes.com/sites/brucedorminey/2016/02/24/antimatter-space-propulsion-possible-within-a-decade-say-physicists/#172cd7a85849
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