Angels & Demons

The Physics Behind the Movie

Rolf Landua
CERN
Dan Brown’s “Angels + Demons”

... steal 1 g of antimatter from a physicist at the ‘LHC’ in a place called “CERN” ...

... to blow up the Vatican, an old “enemy of science and CERN”.

What’s true ? What’s false ? Antimatter seems mysterious ...

Angels & Demons - The Physics behind the Movie
Antimatter Questions

What is antimatter?
Antimatter in the LHC?
The mystery of antimatter?
How to study antimatter?
Energy source? A bomb? Anything useful?

Many questions
Angels & Demons: The Director

In 2007, to prepare his movie, Ron Howard visited CERN to find out more about antimatter traps.

What did he say after his guided tour at CERN?

A. That’s how much I understood from this nerd guiding me around ...
B. This much science will be in the “Angels and Demons” movie ...
C. That’s the budget of my new movie “Angels and Demons”
D. This is what Dan Brown understands about antimatter ....

Who wants to be a millionaire?
1. What is antimatter?
1 What is antimatter?

Everything is made of matter
(We, animals, plants, rocks)

Hierarchy of matter

Matter is made of particles
The whole (visible) Universe is made of 3 building blocks

Electrons
Protons
Neutrons

Quarks
1. **What is antimatter?**

Particles have specific **masses** and **charges**

<table>
<thead>
<tr>
<th>Name</th>
<th>Electric Charge [e]</th>
<th>Mass [GeV*]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>- 1</td>
<td>0.0005</td>
</tr>
<tr>
<td>Proton</td>
<td>+ 1</td>
<td>0.938</td>
</tr>
<tr>
<td>Neutron</td>
<td>0</td>
<td>0.941</td>
</tr>
</tbody>
</table>

*GeV = Giga-Electron Volt = 1,000,000,000 Electron-Volt = 1.8 \cdot 10^{-27} \text{ kg}
1. What is antimatter?

Anti-particles have the same mass, but opposite charge.

<table>
<thead>
<tr>
<th>Name</th>
<th>Electric Charge [e]</th>
<th>Mass</th>
<th>Electric Charge [e]</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>-1</td>
<td>0.0005</td>
<td>+1</td>
<td>Positron</td>
</tr>
<tr>
<td>Proton</td>
<td>+1</td>
<td>0.938</td>
<td>-1</td>
<td>Antiproton</td>
</tr>
<tr>
<td>Neutron</td>
<td>0</td>
<td>0.941</td>
<td>0</td>
<td>Antineutron</td>
</tr>
</tbody>
</table>

Particles vs. Anti-particles:

Angels & Demons - The Physics behind the Movie.
1 What is antimatter?

Predicted by Paul Dirac (1928) ...

... first antiparticle (positron) found by Carl Anderson (1932)
1. What is antimatter?

Particles and anti-particles are always created in pairs ...

\[ E = mc^2 \]

Energy to mass:

... and they can also annihilate each other

\[ E = mc^2 \]

Mass to energy:
1 What is antimatter?

When Energy is converted to mass, an equal amount of matter and antimatter particles are created.

Key: high energy density
1 What is antimatter?

Metaphors for the relation between particles and anti-particles.
1 What is antimatter?

Anti-particles are as real as particles

A world made of antiparticles would look the same as our world.

Matter becomes antimatter

Press here
1 What is antimatter?

Careful with “antimatter E.T.”!
2 Antimatter in the LHC ?
2 Antimatter in the LHC?
2 Antimatter in the LHC?

Large Hadron Collider

27 km long
100 m underground

Angels & Demons - The Physics behind the Movie
Proton-proton collision at 8,000,000,000,000,000 eV
300-800 new particles ... and antiparticles (1:1)
2 Antimatter in the LHC?

For example: 400 new particles - average energy 20 GeV
New particles and antiparticles are produced in collisions.
The real ATLAS cavern - 100 m underground
The noisy Hollywood version of antimatter production

Capture should begin at any moment.

Angels & Demons - The Physics behind the Movie
Bend 20 GeV antiprotons around 5 m radius?

\[ B = \frac{E \text{ [GeV]}}{0.3} \cdot \frac{1}{R \text{[m]}} = \frac{20}{0.3}/5 \sim 13 \text{T} \quad (?) \]

Decelerate 20 GeV antiprotons within 100 m?

Gradient \( = \frac{20000 \text{ MeV}}{100 \text{ m}} = 200 \text{ MeV/m} \)

Angels & Demons - The Physics behind the Movie
3 The mystery of antimatter

What did all these strange dialogues mean?

I should have become a movie star...

Who is this weird person next to me?

This movie will make me rich!

2009: Pre-premiere of Angels+Demons at CERN

Angels & Demons - The Physics behind the Movie
3 The mystery of antimatter

Tom Hanks explains the research at CERN

Angels & Demons - The Physics behind the Movie
3 The mystery of antimatter

Antimatter and ...

God particle ??  No.

Implications for energy research ?  Hmmm.

Combustible substance ?  May be.

An airtight nanocomposite container with magnets ....

The moment of creation ...  yes!!
3  The mystery of antimatter

Big Bang model: the evolution of the Universe

No sign of antimatter anywhere

Angels & Demons - The Physics behind the Movie
Where has the antimatter gone?

Solar System? No!
3 The mystery of antimatter

Where has the antimatter gone?

In galaxies far, far away? No.

There seems to be no antimatter in the Universe!
No antimatter in the Universe?

Why not???
3 The mystery of antimatter

Cosmic CSI

Big Bang:
Energy transforms to mass

< 1 μs: matter = antimatter

Annihilation battle

1 s: all antimatter has disappeared,

some particles left (all stars/planets)
loads of ‘photons’ (left from annihilation)

Universe filled with light
(cosmic microwave backg.)

Lots of antimatter here

Loads of photons here

Angels & Demons - The Physics behind the Movie
3 The mystery of antimatter

Why did all antimatter disappear, but a little bit of matter was left?

Matter and antimatter must have (very slightly) different properties!
But where do we have to look?

Mass, charge, magnetic moment (CERN: AD experiments)
CP violation (CERN: LHCb experiment)
4  How to study antimatter?

The antihydrogen route

...
4 How to study antimatter?

Make antihydrogen + compare with hydrogen atom

Electron

Proton

Antiproton

Positron

Measure differences to a precision of 0.000 000 000 000 001 %
4  How to study antimatter?

Same energy levels (1S-2S)?

Hydrogen

Anti-Hydrogen

AD experiments: ALPHA, ATRAP, ASACUSA
4  How to study antimatter?

Same gravity: \( g \equiv g \) ?

CPT-Symmetric Situation

Apple \( \downarrow G \)
Earth

Anti-Apple \( \downarrow G \)
Anti-Earth

Not

Anti-Apple \( \downarrow G ? \)

Earth

AD experiments: Aegis, Gbar

Angels & Demons - The Physics behind the Movie
Antiproton Decelerator at CERN
4 How to study antimatter?

Antiproton Decelerator produces 100,000,000 antiprotons per minute

Slows them down to 10% of the speed of light
Antiprotons are made in collisions of protons with nuclei.
4. How to study antimatter?

Principle of antiparticle trapping
4 How to study antimatter?

A real antimatter trap at CERN
The “Angels & Demons” version

Magnets

Electrodes

Magnets

Ultra-high vacuum

The “Angels & Demons” version
5 An energy source? A bomb?
Dan Brown: “Antimatter is the energy source of the future”!

Antimatter production requires energy

1,000,000,000 times more energy invested than released by annihilation
Antimatter explosion in “Angels & Demons”
Dan Brown:

“0.5 g antimatter makes a powerful bomb”

\[ E = mc^2 \]

22 kt TNT = \( 9 \cdot 10^{13} \) J = \( 0.5 \) g antimatter + \( 0.5 \) g matter

So this is correct, but ....
An energy source? A bomb?

0.5 g antimatter = $4.5 \cdot 10^{13}$ J

Total energy needed (efficiency $= 10^{-9}$) : $4.5 \cdot 10^{22}$ J

Even with electricity discount price CERN by EDF
[1 kWh = $3.6 \cdot 10^6$ J = 0.1 €]

Price 1,000,000,000,000,000,000 €

Delivery time 1,000,000,000 years
Anything useful??

Yes - the PET scanner can save lifes!

**Positron Emission Tomography**

Glucose supplies energy

Add **positron** emitting isotopes (e.g. F-18) to glucose

Inject into blood stream

Glucose accumulates where energy is needed

Positron emission and annihilation - detect where the glucose is!

Angels & Demons - The Physics behind the Movie
Antimatter helps
- to understand how the brain works
- to find tumours

Positron Emission Tomography ("PET Scan")
5  Antimatter in daily life?

Positron Emission Tomography ("PET Scan")

Antimatter helps to find tumours

Angels & Demons - The Physics behind the Movie
5 Antimatter in daily life?

Tumour therapy with antiprotons?

Gamma radiation destroys many healthy cells
Protons deliver radiation more specifically to tumour cells

Antiprotons would be 3 x more efficient than protons (annihilation!)

ACE experiment (AD)

Angels & Demons - The Physics behind the Movie
What did Ron Howard say?
Angels & Demons

The Physics Behind the Movie


http://www.youtube.com/watch?v=CtR5EkvLNfg

Thank you for your attention.
Teaching Resources - Antimatter Teaching Module

>> Lesson Plans

Back to Antimatter Teaching Module
Laser cooling

121 nm laser needed
Prototype at MPI Munich
... only 50 nW
Magnetic multipole traps?

Example: Sextupole magnet

Low field seeking atoms (50%) at r=0

BUT: Very shallow potential (~ 0.07 meV/T)

Realistic $\Delta B \sim 0.2$-$0.3$ T $\Leftrightarrow$ $E < 0.02$ meV

(reminder: produced antihydrogen has $E_{\text{kin}} \sim 1$-$200$ meV)

Trap antihydrogen from low energy ‘Boltzmann tail’?
• More than 1 million antihydrogen atoms produced
• Small kinetic energy (< 0.01 eV)
• Next step (in progress): trap antihydrogen atoms
Antihydrogen milestones

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

**Na-22**
- e^+ Production (MeV)
- Moderation
- Accumulation (eV)

p^- and e^+ in mixing trap (cooling)

Antihydrogen formation

Detection of annihilation

Antihydrogen milestones
Is that true? Make very precise comparisons!

Mass of proton and antiproton?

Present result: $\Delta M/M < 0.000\,000\,000\,001$

difference less than one dust grain

Magnetic moment of electron and positron?

Present result: $\Delta \mu/\mu < 0.000\,000\,000\,000\,001$

Present status: excellent agreement!
ATHENA Experiment (2002), at the AD facility

- More than 1 million antihydrogen atoms produced
- Small kinetic energy (< 0.01 eV)
- Next step (in progress): trap antihydrogen atoms

2002: ‘Cold’ antihydrogen production by AD experiments*
Recombination

• More than 1 million antihydrogen atoms produced
• Small kinetic energy (< 0.01 eV)
• Next step (in progress): trap antihydrogen atoms
Next step: Trapping antihydrogen

Neutral (anti-) atoms escape from Penning trap