ALPHA experiment at CERN

Experimental Techniques in High Energy Physics

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Overview

Overview

Introduction

Why Antihydrogen Research?

- At the Big Bang, matter and antimatter were present in equal amounts
- The particles in the Universe are dominated by those comprised of matter
- Why this imbalance has evolved? ← One of the central questions of physics beyond the Standard Model
- Any difference in the properties and behaviour between matter and antimatter, however small, will have profound consequences for our understanding of nature [1]

Overview

The CERN Meyrin site

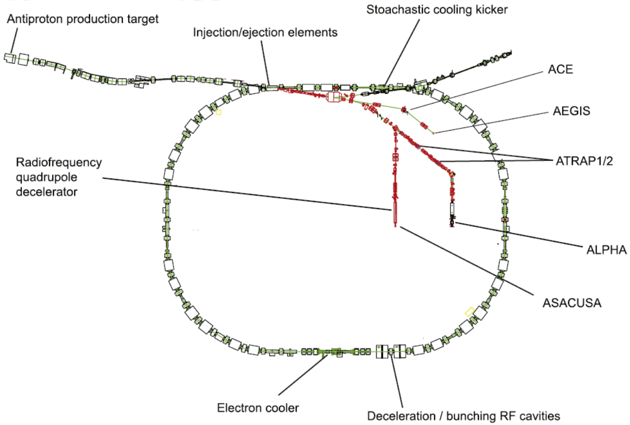
The Antimatter factory at the CERN Meyrin site

The Antimatter factory

AD:

- Antiproton
- Decelerator

Antiproton Decelerator



- The AD is an oval-shaped, 188-m circumference synchrotron [2]
- It consists of four straight sections where are placed:
  - instruments for cooling of the beam
  - RF cavities which decelerates the anti-protons
  - diagnostics equipment

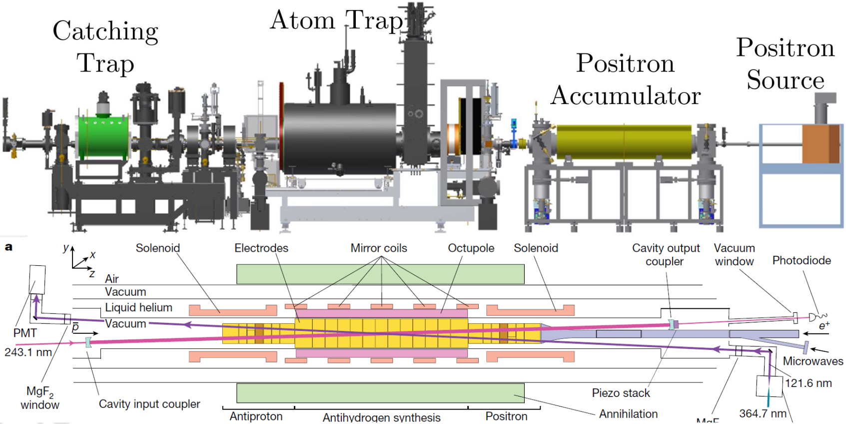
The ALPHA experiment at CERN

- Antihydrogen
- Laser
- PHysics
- Apparatus

ALPHA experimental cycle

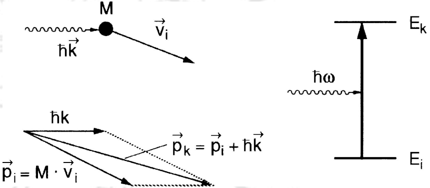
1. Get Antiprotons → from the AD
2. Get positrons → from a Na-22 radioactive source [3]
3. Catch antiprotons
4. Cool and compress antiprotons (with electrons)
5. Compress and cool positrons
6.
    - Measure plasma size or temperature or particle count
    - Mixing (synthesis of antihydrogen)
7. Store antihydrogen [4]
8. **Interact with antihydrogen**
9. Detect antihydrogen losses
10. Release antihydrogen

Slowing down antihydrogens



Overview

Photon absorption by an atom at rest in classical mechanics



- Conservation of momentum:

$$\overbrace{\boldsymbol{p}_i}^{0} + \hbar\boldsymbol{k} = \boldsymbol{p}_k \tag{1}$$

- Conservation of energy:

$$E_i + \hbar\omega_{ik} = E_k + \frac{1}{2}mv_k^2 \tag{2}$$

You get a second-order equation in $\hbar\omega_{ik}$

$$(\hbar\omega_{ik})^2 - 2mc^2\hbar\omega_{ik} + 2mc^2\hbar\omega_0 = 0 \tag{3}$$

with $\hbar\omega_0 \equiv E_k - E_i$

Photon absorption by an atom at rest in classical mechanics

- the solutions, the photon energies in the lab frame necessary to make transition, are:

$$\hbar\omega_{ik} = mc^2 \pm \sqrt{(mc^2)^2 - 2mc^2\hbar\omega_0} \tag{4}$$

- only the solution with the minus sign gives a value close to the energy levels gap $\hbar\omega_0$

$$\hbar\omega_{ik} = mc^2\left(1 - \sqrt{1 - \frac{2\hbar\omega_0}{mc^2}}\right) \tag{5}$$

- approximate for atom rest energy (mass) much bigger than the photon energy, using Taylor expansion in the form of

$$\sqrt{1+x} \simeq 1 + \frac{1}{2}x - \frac{1}{8}x^2 \tag{6}$$

we get

$$\hbar\omega_{ik} \simeq mc^2\left(1 - 1 + \frac{\hbar\omega_0}{mc^2} + \frac{(\hbar\omega_0)^2}{2(mc)^2}\right) = \underbrace{\hbar\omega_0}_{\text{energy level gap}} \underbrace{+\frac{(\hbar\omega_0)^2}{2mc}}_{\text{recoil energy}} \tag{7}$$

Photon absorption by a moving atom in classical mechanics

- Conservation of momentum:

$$\boldsymbol{p}_i + \hbar \boldsymbol{k} = \boldsymbol{p}_k \tag{8}$$

- Conservation of energy:

$$E_i + \frac{1}{2} m v_i^2 + \hbar\omega_{ik} = E_k + \frac{1}{2} m v_k^2 \tag{9}$$

  You get a second-order equation in $\hbar\omega_{ik}$

$$(\hbar\omega_{ik})^2 - 2mc^2 \hbar\omega_{ik} + 2mc^2(\hbar\omega_0 + \hbar \boldsymbol{v}_i \cdot \boldsymbol{k}) = 0 \tag{10}$$

  with $\hbar\omega_0 \equiv E_k - E_i$

- Note that the equation does not contain any term v_i^2, v_k^2, they got simplified

Photon absorption by a moving atom in classical mechanics

- the solutions are:

$$\hbar\omega_{ik} = mc^2 \pm \sqrt{(mc^2)^2 - 2mc^2(\hbar\omega_0 + \hbar\mathbf{v}_i \cdot \mathbf{k})} \tag{11}$$

- approximate for atom rest energy (mass) much bigger than its kinetic energy and the photon energy, using Taylor expansion in the form of

$$\sqrt{1+x} \simeq 1 + \frac{1}{2}x \tag{12}$$

we get

$$\hbar\omega_{ik} = mc^2\left(\mp\frac{\hbar\omega_0 + \hbar\mathbf{v}_i \cdot \mathbf{k}}{mc^2}\right) \tag{13}$$

note that we neglected the Taylor expansion term $-\frac{1}{8}x^2$ thus the recoil will be neglected (we have already discussed it in Eq. 7)

- only the solution with the minus sign gives positive photon energy

$$\hbar\omega_{ik} = \underbrace{\hbar\omega_0}_{\text{energy level gap}} + \underbrace{\hbar\mathbf{v}_i \cdot \mathbf{k}}_{\text{linear Doppler shift}} \tag{14}$$

Photon absorption by a moving atom in relativistic mechanics

- Conservation of momentum (same as in classical mechanics): [5]

$$\boldsymbol{p}_i + \hbar \boldsymbol{k} = \boldsymbol{p}_k \tag{15}$$

- Conservation of energy:

$$\sqrt{(mc^2 + E_i)^2 + (cp_i)^2} + \hbar\omega_{ik} = \sqrt{(mc^2 + E_k)^2 + (cp_k)^2} \tag{16}$$

- We find a second-order equation for $\hbar\omega_{ik}$

$$\sqrt{(mc^2 + E_i)^2 + (cp_i)^2} + \hbar\omega_{ik} = \sqrt{(mc^2 + E_k)^2 + (cp_i)^2 + (\hbar\omega_{ik})^2 + 2\hbar c^2 \boldsymbol{p}_i \cdot \boldsymbol{k}} \tag{17}$$

Photon absorption by a moving atom in relativistic mechanics

- mathematics is too complicated here so I skipped the calculations
- We use Taylor expansion for atom rest energy much bigger than its kinetic energy and than the photon energy

$$\hbar\omega_{ik} = \underbrace{\hbar\omega_0}_{\text{energy levels gap}} + \underbrace{\hbar\boldsymbol{k}\cdot\boldsymbol{v}_i}_{\text{linear Doppler shift}} - \underbrace{\hbar\omega_0\frac{v_i^2}{2c^2}}_{\text{quadratic Doppler shift}} + \underbrace{\frac{(\hbar\omega_0)^2}{2mc^2}}_{\text{atom recoil}} + \dots \tag{18}$$

- Quadratic Doppler shift is independent of the direction of the velocity $v \implies$ it cannot be eliminated by Doppler free techniques such as two-photon spectroscopy

Comparing on photon absorption - classical versus relativistic

Classical

$$\hbar\omega_{ik} = \underbrace{\hbar\omega_0}_{\text{energy level gap}} \underbrace{+\frac{(\hbar\omega_0)^2}{2mc}}_{\text{recoil energy}} \tag{19}$$

$$\hbar\omega_{ik} = \underbrace{\hbar\omega_0}_{\text{energy level gap}} + \underbrace{\hbar\mathbf{v}_i \cdot \mathbf{k}}_{\text{linear Doppler shift}} \tag{20}$$

Relativistic

$$\begin{aligned}\hbar\omega_{ik} = & \underbrace{\hbar\omega_0}_{\text{energy levels gap}} + \underbrace{\hbar\mathbf{k} \cdot \mathbf{v}_i}_{\text{linear Doppler shift}} + \\ & - \underbrace{\hbar\omega_0 \frac{v_i^2}{2c^2}}_{\text{quadratic Doppler shift}} + \underbrace{\frac{(\hbar\omega_0)^2}{2mc^2}}_{\text{atom recoil}} + \dots\end{aligned} \tag{21}$$

- Atom recoil is considered in both frameworks
- Linear Doppler shift is is considered in both frameworks
- Quadratic Doppler shift takes place only in relativity

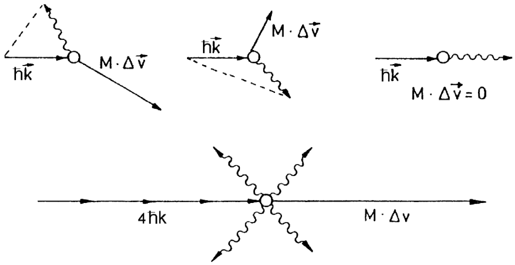
Photon emission by a moving atom in relativistic mechanics

- An atom decaying from E_k to E_i emits a photon with energy

$$\hbar\omega_{ik} = \underbrace{\hbar\omega_0}_{\text{energy levels gap}} + \underbrace{\hbar\boldsymbol{k}\cdot\boldsymbol{v}_k}_{\text{linear Doppler shift}} - \underbrace{\hbar\omega_0\frac{v_k^2}{2c^2}}_{\text{quadratic Doppler shift}} \underbrace{-\frac{(\hbar\omega_0)^2}{2mc^2}}_{\text{atom recoil}} + \dots \qquad (22)$$

- The energy levels gap is the same of the photon absorption case
- The linear Doppler shift is the same of the photon absorption case, from momentum conservation:
    - photon emitted along the atom trajectory in the lab $\implies$ less energy to the atom $\implies$ more energy to the photon
    - photon emitted contrary to the atom trajectory in the lab $\implies$ more energy to the atom $\implies$ less energy to the photon
- The quadratic Doppler shift is the same of the photon absorption case
- The atom has to recoil so it gives smaller energy to the emitted photon (minus sign instead of the plus sign of the absorption case)

Recoil transfer



- Assume a laser beam
- The atoms stay in the laser beam for a transit time T
- Each spontaneously emitted photon (LIF) transfers a momentum $\hbar k$ to the emitting atom
- If during the transit time T a high number of absorption ($\implies$ LIF emission) events q take place then the time-averaged momentum transfer tends to zero

Recoil transfer

- The absorbed photons, however, all come from the same direction. Therefore, the momentum transfer for q absorptions adds up to a total recoil momentum

$$\boldsymbol{p} = q\hbar\boldsymbol{k} \tag{23}$$

- This changes the velocity v of an atom which flies against the beam propagation by the amount

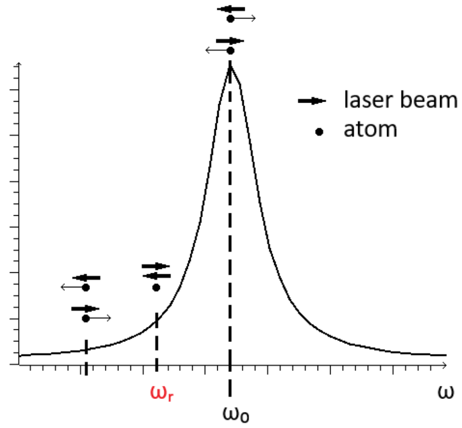
$$\Delta\boldsymbol{v} = \frac{\hbar\boldsymbol{k}}{m} \qquad \text{per absorption} \tag{24}$$

- For q absorption–emission cycles we get

$$\Delta\boldsymbol{v} = \frac{q\hbar\boldsymbol{k}}{m} \tag{25}$$

- Atoms in a collimated atomic beam can therefore be slowed down by a laser beam propagating anticollinearly to the atomic beam

Red detuning for optical cooling



- If the laser frequency is tuned to the red side of the atomic resonance

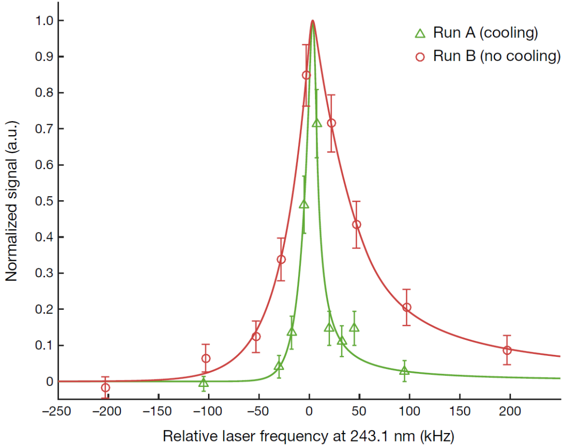
$$\omega - \omega_0 < 0 \tag{26}$$

a repulsive force is always slowing down the atoms

  - for atoms moving toward the laser wave ($\boldsymbol{k} \cdot \boldsymbol{v} < 0$) the Doppler-shifted absorption frequency is shifted toward the resonance frequency ω_0
  - whereas for the counterpropagating wave ($\boldsymbol{k} \cdot \boldsymbol{v} > 0$) it is shifted away from resonance

Overview

Spectroscopy of antihydrogen



- Here is a comparison of the $1S_d$–$2S_d$ transition spectral profiles between the laser-cooled (run A) and uncooled (run B) samples
- The data were fit with a function that has been developed to match simulated 1S–2S spectra
- The fitted linewidths are $57.6 \pm 12\,\text{kHz}$ (uncooled) and $14.4 \pm 4.0\,\text{kHz}$ (laser cooled)

Overview

Conclusions

- The ALPHA experiment is investigating the properties and behaviour of antihydrogen atoms
- up to now, no differences with respect to the hydrogen atoms have been found [6]
- The 1S–$2P_f$ transition is suitable for laser cooling of antihydrogen

Thank you for the attention

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Back-up

Doppler broadening

- this implies that the momenta p and kinetic energies E_{kin} of the various particle species follow a Maxwell-Boltzmann distribution

Maxwell-Boltzmann equations

$$n(p)dp = \sqrt{2}\pi N \left(\frac{1}{\pi m K_B T} \right)^{3/2} p^2 e^{-\frac{p^2}{2mK_B T}} dp \tag{27}$$

where N denotes the total number of particles in the system and m their mass

Recoil shift

- The difference between the resonant absorption and emission energies is

$$\hbar\omega_{ik}^{\text{abs}} - \hbar\omega_{ik}^{\text{em}} = \hbar\boldsymbol{k}\cdot(\boldsymbol{v}_i - \boldsymbol{v}_k) - \frac{\hbar\omega_0}{2c^2}(v_k^2 - v_i^2) + \frac{(\hbar\omega_0)^2}{mc^2} \tag{28}$$

- Assuming two atoms at rest

$$\hbar\omega_{ik}^{\text{abs}} - \hbar\omega_{ik}^{\text{em}} = \frac{(\hbar\omega_0)^2}{mc^2} \tag{29}$$

- The relative shift between absorbed and emitted photons is

$$\frac{\hbar\omega_{ik}^{\text{abs}} - \hbar\omega_{ik}^{\text{em}}}{\hbar\omega_0} = \frac{\hbar\omega_0}{mc^2} \tag{30}$$

- For γ-rays ($\sim$ MeV) this ratio may be larger than the linewidth of the absorbing transition $\Longrightarrow$ γ-rays emitted from a free nucleus cannot be absorbed by another identical nucleus (at rest)
- The recoil can be reduced if the atoms are embedded in a crystal structure → Mössbauer effect

Photon absorption in a laser cavity

- Consider the absorbing/emitting molecules inside a laser resonant cavity
- The cavity length selects a laser frequency ω
- There will be a standing wave in the cavity given by the contributions of two counter-propagating waves:

$$\boldsymbol{k} = \left(0, 0, \pm k\right) = \left(0, 0, \pm \frac{\omega}{c}\right) \tag{31}$$

- We substitute this photon momentum and energy in Eq. 18

$$\omega_{ik} = \omega = \omega_0 \pm k v_{iz} - \omega_0 \frac{v_i^2}{2c^2} + \frac{\hbar \omega_0^2}{2mc^2} \tag{32}$$

- We can see that the atoms able to absorb these photons to make the transition $E_i \rightarrow E_k$ are those with velocity component

$$v_{zi} = \pm \frac{1}{k}\left(\omega - \omega_0\left(1 - \frac{v_i^2}{2c^2}\right) - \frac{\hbar \omega_0^2}{2mc^2}\right) \tag{33}$$

Photon emission in a laser cavity

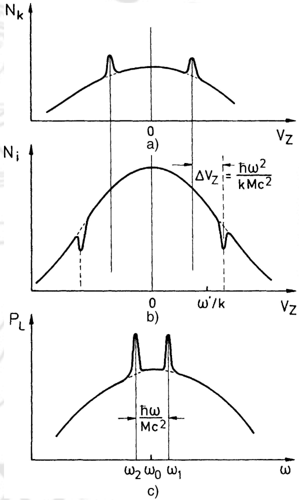
- We can substitute the shape of the lasing photons also in Eq. 22

$$\omega_{ik} = \omega = \omega_0 \pm k v_{kz} - \omega_0 \frac{v_k^2}{2c^2} - \frac{\hbar \omega_0^2}{2mc^2} \tag{34}$$

- We can see that the photons emitted in the transition $E_k \rightarrow E_i$ are only those emitted by atoms with velocity component

$$v_{zi} = \pm \frac{1}{k} \left(\omega - \omega_0 \left(1 - \frac{v_i^2}{2c^2} \right) + \frac{\hbar \omega_0^2}{2mc^2} \right) \tag{35}$$

Measurement of Recoil Shift



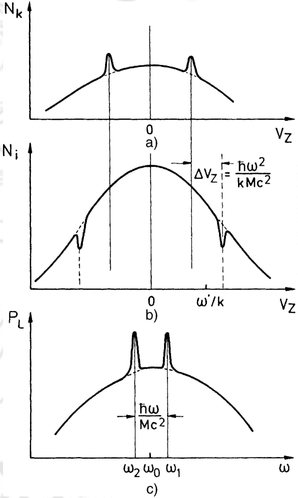
- The two holes in the velocity distribution of the absorbing atoms coincide at $v_{zi} = 0$ if

$$\omega = \omega_0 \left(1 - \frac{v_i^2}{2c^2}\right) + \frac{\hbar\omega_0^2}{2mc^2} \equiv \omega_1 \tag{36}$$

- The two holes in the velocity distribution of the emitting atoms coincide at $v_{zk} = 0$ if

$$\omega = \omega_0 \left(1 - \frac{v_i^2}{2c^2}\right) - \frac{\hbar\omega_0^2}{2mc^2} \equiv \omega_2 \tag{37}$$

Measurement of Recoil Shift



- The absorption of the laser (observable) is proportional to the population difference $\Delta N = N_i - N_k$
- This difference has two maxima at ω_1 and ω_2. The laser output therefore exhibits two Lamb peaks (inverse Lamb dips) at the laser frequencies ω_1 and ω_2, which are separated by twice the recoil energy

$$\Delta\omega = \omega_1 - \omega_2 = \frac{\hbar\omega_0^2}{mc^2} \qquad (38)$$

- Since such small splittings can only be observed if the width of the Lamb peaks is smaller than the recoil shift, all possible broadening effects, such as pressure broadening and transit-time broadening, must be carefully minimized

Problem Doppler shift during deceleration

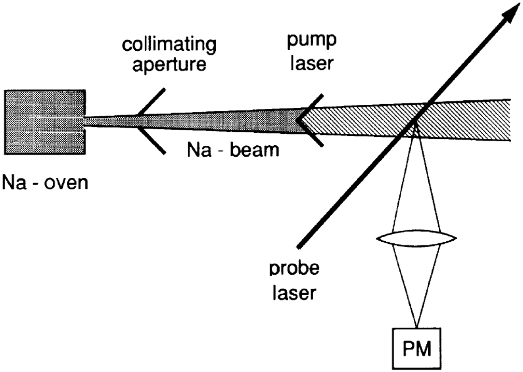
- During the deceleration time the Doppler-shifted absorption frequency changes

$$\omega(t) = \omega_0 + \boldsymbol{k} \cdot \boldsymbol{v}(t) \tag{39}$$

so the atoms would come out of resonance with the monochromatic laser

- Three solutions have been tried:
  1. the laser frequency $\omega(t)$ is synchronously tuned with the changing velocity $v(t)$
  2. the absorption frequency of the atom is appropriately altered along the deceleration path
  3. a broadband laser is used for cooling

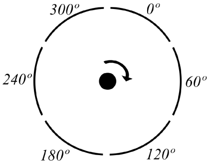
Experimental arrangements for optical cooling



Plasma manipulation

- In principle, a nonneutral plasma confined in a “perfect” Penning-Malmberg trap would be confined indefinitely because the angular momentum is a conserved quantity due to the cylindrical symmetry of the trap
- In reality, there are asymmetric imperfections in the trap which typically arise from small construction errors and misalignments
- These imperfections break the intended cylindrical symmetry resulting in a torque on the plasma that causes the plasma column to expand radially → loss of particles at the wall

Plasma manipulation - Rotating wall technique



- Charged plasmas trapped in a Penning-Malmberg trap rotate around the magnetic field axis at a well-defined frequency, which depends on the plasma density
- By applying a torque to the plasma we can increase this rotation frequency and therefore increase the density and reduce the radius of the plasma
- This torque is applied by a special trap electrode that is azimuthally segmented into six sectors. A sinusoidally varying voltage is applied to each sector with a different phase on each to create an electric field that appears to rotate (hence rotating wall)

Trapping of ions

- Since ions show stronger interactions with EM fields than neutral atoms, ions can be stored more effectively in EM traps
- Two different techniques have been developed:
  - radio frequency (RF) quadrupole trap
  - Penning trap
- Both traps can be used also to perform very precise measurements of their masses
- the signal is obtained from an induction voltage picked up by external electrodes from the ion motion
- Fourier analysis of this signal gives the frequencies of the three components. Since the cyclotron resonance frequency

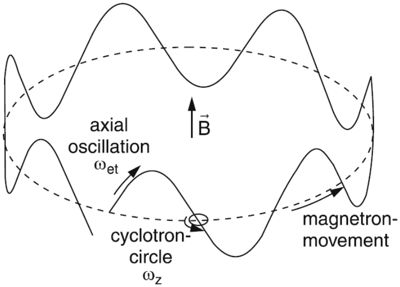
$$\omega_c = \frac{qB}{m} \qquad \Longrightarrow \qquad m = \frac{qB}{\omega_c} \tag{40}$$

- The trapped ions can also be monitored laser-induced fluorescence

Radio frequency quadrupole trap

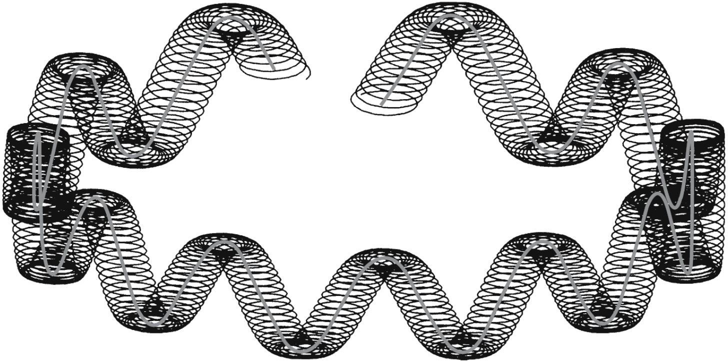
- the ions are confined within a hyperbolic electric dc field superimposed by a RF field

Penning trap



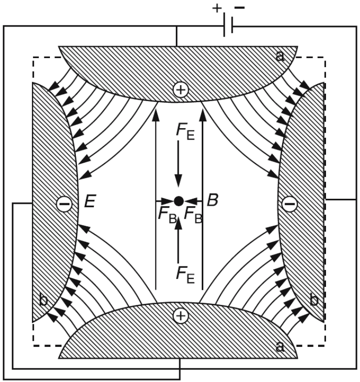
- a dc electric field between a ring electrode and the pole caps and a dc magnetic field in the z-direction
- The ionic motion is complex, it consists of three components:
  1. There is cyclotron resonance motion in circles around a point Q
  2. Q moves with the motion of the magnetron in a circle around the magnetic field lines
  3. Superimposed on this is an axial oscillation in the z-direction

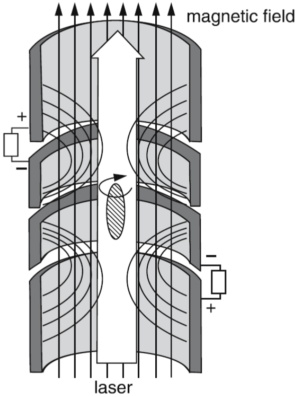
Penning trap



- Ion path due to the superposition of all three components

Penning trap





- Unlike the rf fields of the Paul trap, the Penning trap uses only dc fields: a dc electric field between a ring electrode and the pole caps and a dc magnetic field in the z-direction
- Two different designs are shown

Evaporative cooling

- Evaporative cooling is the mechanism that cools a hot cup of coffee
- The most energetic molecules are the ones most likely to escape as steam, and in the process lowering the average kinetic energy (and therefore the temperature) of the coffee

The same thing will happen with particles in a trap

- If the trap depth is low enough, the highest energy particles will be able to escape and lower the temperature of the remaining population
- We can encourage this process by intentionally lowering the trap depth to release more particles and force the temperature lower and lower

Two-level system

- Assume a two-level system E_i, E_k
- The ratio of the excited population over the whole population N is

$$\frac{N_k}{N} = \frac{S}{1 + 2S} \tag{41}$$

with saturation parameter equal to the ratio of the stimulated emission rate over the spontaneous emission one

$$S = \frac{B_{ik}\rho(\omega_{ik})}{A_{ik}} \tag{42}$$

- The fluorescence rate is

$$N_k A_k = \frac{N_k}{\tau_k} = \frac{N}{\left(\frac{1+2S}{S}\right)\tau_k} \equiv \frac{N}{\Delta T} \tag{43}$$

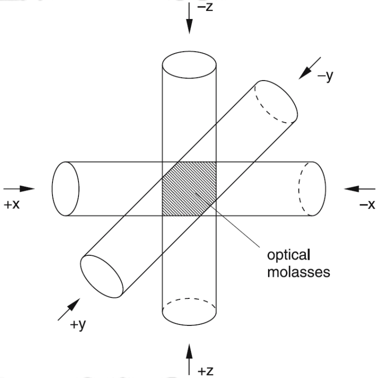
where ΔT is the recycling time

- The smallest recycling time is achieved for maximum saturation, $S \to \infty$, is $\Delta T \to 2\tau_k$

Recoil transfer

- Without additional tricks, this optical-cooling method is restricted to true two-level systems
- In case of stimulated emission the emitted induced photon has the same k-vector as the absorbed induced photon, thus the net momentum transfer is zero
- Increasing the intensity of the pump laser you can reach saturation parameters $S > 1$, here:
  - the decrease of the time ΔT for an absorption-emission cycle is limited at $2\tau_k$
  - the induced emission increases at the expense of spontaneous emission
- The total deceleration rate has a maximum at the optimum saturation parameter $S \simeq 1$

3D optical cooling



- Up to now we have only considered the cooling of atoms that all move into one direction → only one velocity component has been reduced by photon recoil
- For cooling of atoms in a thermal gas where all three velocity components $\pm(v_x, \pm v_y, \pm v_z)$ have to be reduced, six laser beams propagating into the $\pm x, \pm y, \pm z$ directions are required
- All six beams are generated by splitting a single laser beam

3D optical cooling

- The laser exerts a force

$$F_i = -av_i \tag{44}$$

with a constant depending also on the laser frequencies

- Considering Newton equation we get a differential equation

$$\frac{dv}{v} = -\frac{a}{m}dt \tag{45}$$

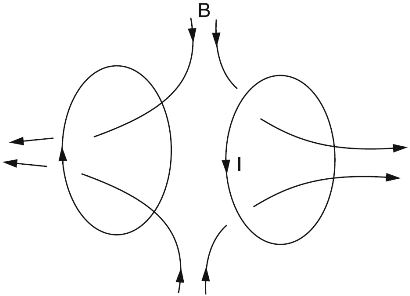
The solution is an exponentially damped velocity for the atom

$$v(t) = v_0 \exp\left(-\frac{t}{t_D}\right) \qquad \text{with damping time} \qquad t_D = \frac{m}{a} \tag{46}$$

Magneto-Optical Trap (MOT)

- The effectiveness of the optical molasses for cooling atoms anticipates that the atoms are trapped within the overlap region of the six laser beams for a sufficiently long time
- This demands that the potential energy of the atoms shows a sufficiently deep minimum at the center of the trapping volume → restoring forces must be present that will bring escaping atoms back to the center of the trapping volume
- The two most commonly used trapping arrangements are:
  1. The first is based on induced electric dipole forces in inhomogeneous electric fields
  2. The second on magnetic dipole forces in magnetic quadrupole fields → MOT

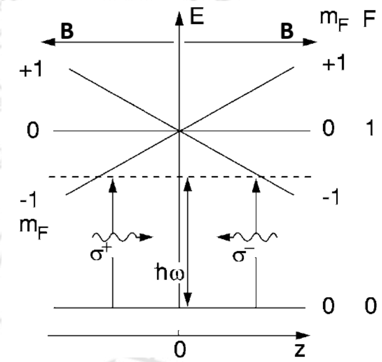
Anti-Helmholtz arrangement



- In the MOT the inhomogeneous field is produced by two equal electric currents flowing into opposite directions through two coils with radius R and distance $D = R$
- If we choose the z-direction as the symmetry axis through the center of the coils, the magnetic field around $z = 0$ in the middle of the arrangement can be described by the linear dependence

$$B = bz \tag{47}$$

Zeeman shift



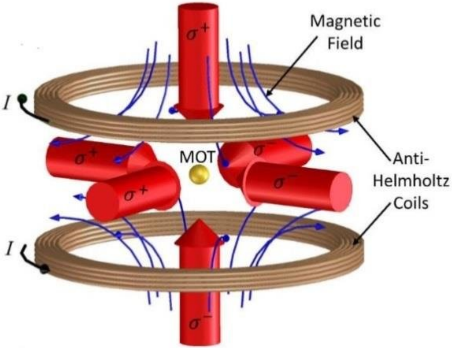
- In a magnetic field the atomic energy levels E_i experience Zeeman shifts

$$\Delta E_i = -\boldsymbol{\mu}_i \cdot \boldsymbol{B} = -\mu_B g_F m_F B = \begin{cases} \propto z & \text{for} \quad m_F = +1 \\ 0 & \text{for} \quad m_F = 0 \\ \propto -z & \text{for} \quad m_F = -1 \end{cases} \tag{48}$$

  with Lande g-factor g_F, Bohr's magneton μ_B, quantum number m_F of the projection of the total angular momentum F onto the field direction

- The Zeeman splittings of the transition from $F = 0$ to $F = 1$ are shown
- The circularly-polarized beams $\sigma_\pm$ enforce selection rules on the allowed electric dipole transitions

Magneto-Optical Trap (MOT)



- Picture from [7]
- The potential around the center of the MOT can be then described as

$$V(z) = \frac{1}{2}Dz^2 \tag{49}$$

- The atoms oscillate like harmonic oscillators around $z = 0$
- The restoring forces in the x- and y-directions are half of the forces in z-directions
- The trapped thermal cloud of atoms fills an ellipsoidal volume

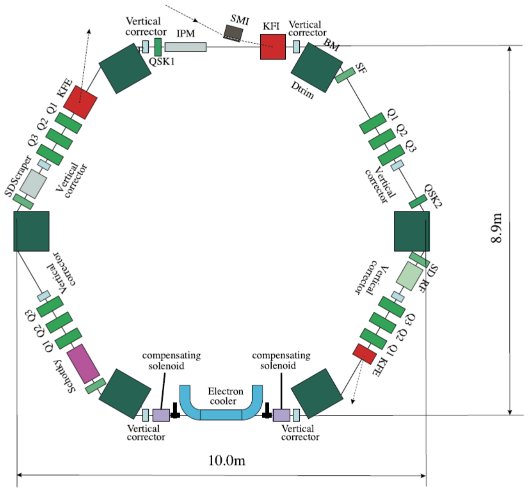
Antiproton Decelerator

- The Antiproton Decelerator (AD) facility of CERN began operation in 1999 to carry out high-precision laser spectroscopy of antihydrogen (H) and antiprotonic helium (pHe+) atoms [2]
- A 26 Gev proton beam coming from the Proton Synchrotron (PS) is fired into an Ir target

  $$p(\text{beam}) + p(\text{target}) \rightarrow p + p + p + \bar{p} \tag{50}$$

  The produced anti-protons have energy around 3.6 Gev
- This energy must be reduced by eight orders of magnitude before the $\bar{p}$ can be used for the trap and atomic spectroscopy experiments
- A simple deceleration of a cloud of anti-protons would lead to an adiabatic increase in its phase-space density

Extra Low ENergy Antiproton (ELENA) ring

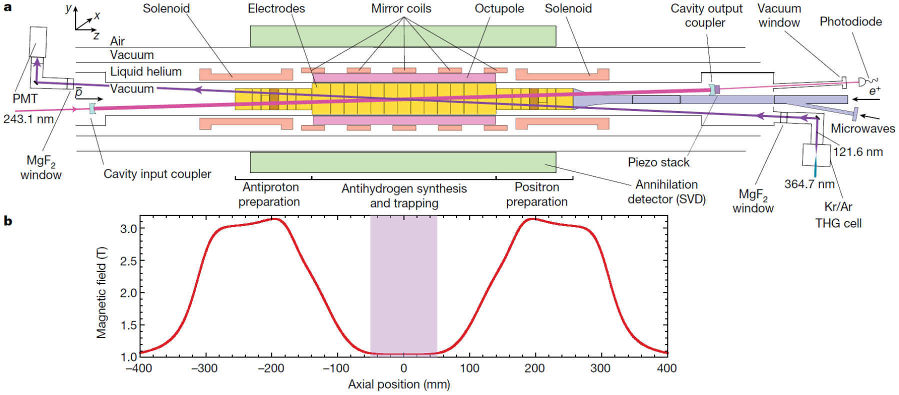


- CERN and the AD user community are now constructing the Extra-Low Energy Antiproton (ELENA) facility which is a magnetic storage ring of circumference about 30 m located inside the AD ring
- The 5.3 MeV anti-protons provided by AD will be injected into ELENA, where they will be decelerated over a 20-s cycle to energies as low as 100 keV
- The low energy and small emittance of the ELENA beam is expected to allow the existing ALPHA experiment to capture and accumulate about 100 times more anti-protons in Penning traps per unit time, compared to directly using the 5.3 MeV AD beam

Timeline

- ALPHA was active from 2005 to 2010
- ALPHA-2 from 2010 to 2018
- The construction of ALPHA-g began in the summer of 2018
- In 2021 ELENA provided ALPHA with low energy anti-protons for the first time [6]
- There are not many info regarding ALPHA-3, they are probably focusing on ALPHA-g
- From July 2026 to 2030 there will be the Long Shutdown 3 at CERN

The ALPHA II antihydrogen trapping apparatus

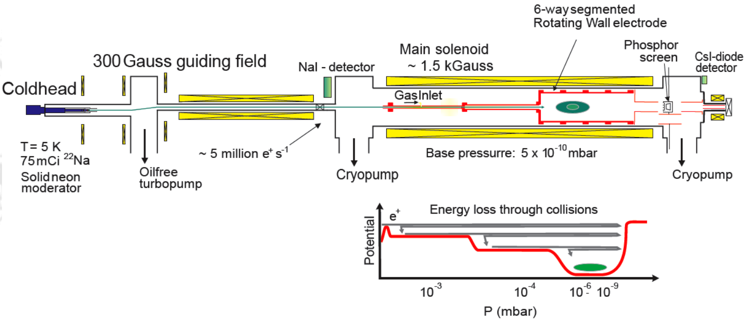


- From ALPHA to ALPHA II, optical access has been added to the apparatus [8]
- Optical cooling of the antihydrogen can be performed with the 121.6 nm laser
- Spectroscopy is performed with the 243.1 nm laser beam

Positron Source

- Positrons in ALPHA originate from a radioactive isotope of sodium Na-22 [3]
- The Na-22 source is manufactured at iThemba Labs in Cape Town, South Africa
- Na-22 has a long half-life of 2.6 years, and therefore emits a reproducible quantity of positrons on a day-to-day basis
- $\text{Na-22} \rightarrow \text{Ne-22} + e^{+} + \nu_e$
- The emitted positrons typically have an energy range in the hundreds of keV
- the emitted positrons pass through a layer of solid neon ($T = 8\,\text{K}$) which serves as a moderator
- a small fraction ($< 1\,\%$) make it through the moderator with significantly reduced kinetic energies ($E = 50\,\text{eV}$)

Positron accumulation



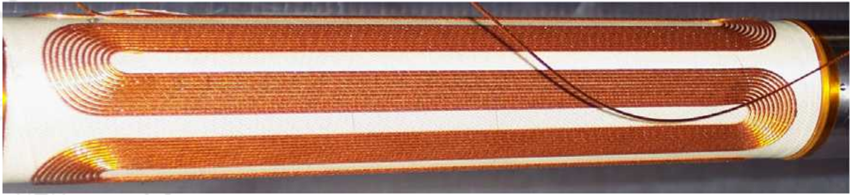
- To trap the positrons ALPHA uses a technique based upon buffer gas cooling [9]
- An elongated charged particle trap is erected in 3 stages
- In each stage gaseous molecular nitrogen N_2 is admitted at different pressure
- Positrons slow down due to the reaction

$$e^+ + N_2 \rightarrow e^+ + N_2^* \tag{51}$$

Ioffe-Pritchard Trap

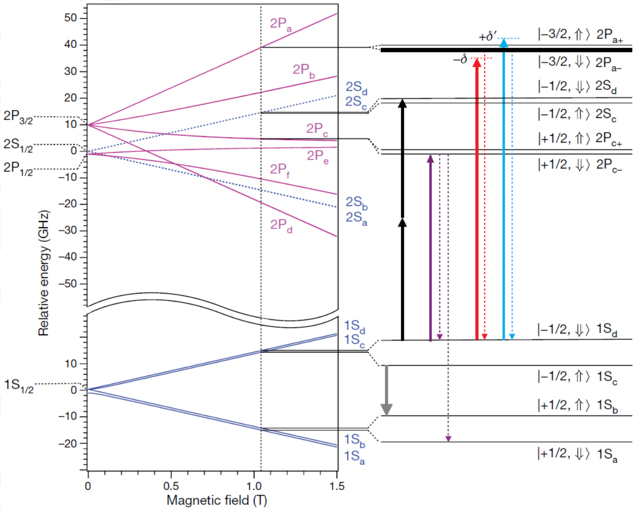
- The ALPHA magnetic trap is a variant of a type of atom trap called an 'Ioffe trap'
- Such traps work because most atoms interact with a magnetic field through a property called their magnetic dipole moment
- If the atom is moving in a magnetic field, it will gain and lose energy as the strength of the magnetic field near the atom changes
- Making a magnetic field that increases in all directions from a central minimum point means that some atoms will gain potential energy and lose kinetic energy if they move away from the minimum
- Atoms that have low enough total energy will convert all of their kinetic energy to potential energy and be reflected from higher magnetic fields and be trapped

ALPHA Ioffe-Pritchard Trap



- To produce a magnetic field that has a minimum like a bowl requires specially designed magnets:
    - In one direction, we use 'mirror coils' (that look just like short solenoids) that increase the field nearby to make two 'walls'
    - In the direction perpendicular to this, we use an octupole magnet
- the magnetic dipole moment for antihydrogen is very small, and to make traps that are strong enough, we need very high currents. Therefore, we use superconducting wire in our magnets.

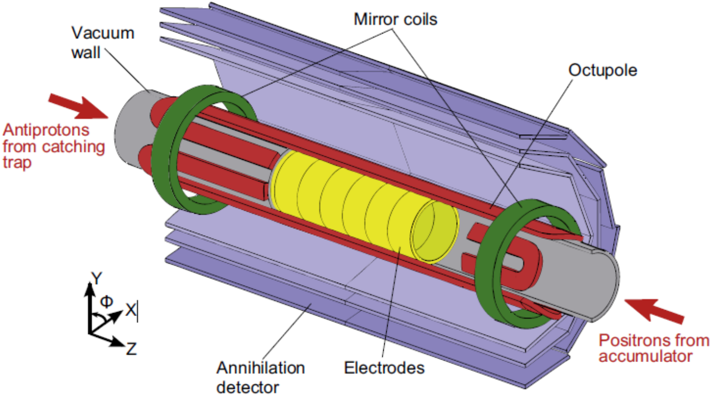
Antihydrogen energy levels



- The transition to the $1S_a$ state ('spin flipping') reverses the positron spin direction, leading to the loss of anti-atoms from the magnetic trap
- These transitions can be used to probe the sample's energy distribution via the detection of the annihilation signals of the spin-flipped anti-atoms
- $1S_d \rightarrow 2P_{a-}$ for cooling

The ALPHA antihydrogen trapping apparatus

The ALPHA antihydrogen trapping apparatus [4]



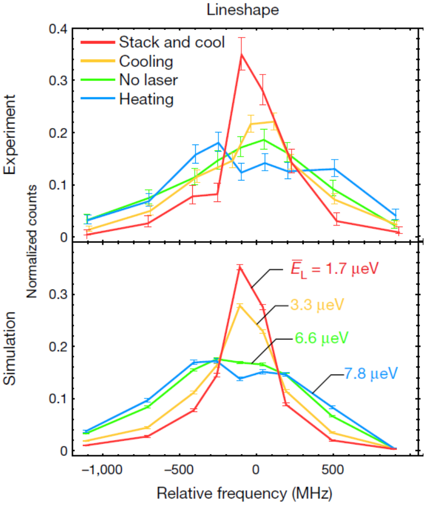
Laser cooling of antihydrogen

- Doppler cooling is performed by repeatedly driving single-photon transitions between the 1S state and the $2P_a$ state (one of the Zeeman sublevels of the $2P_{3/2}$ state) with a laser frequency that is slightly red-detuned from the resonance of the atom at rest. In a strong magnetic field, this is a closed cycling transition, hence suitable for cooling.

3D optical cooling in ALPHA

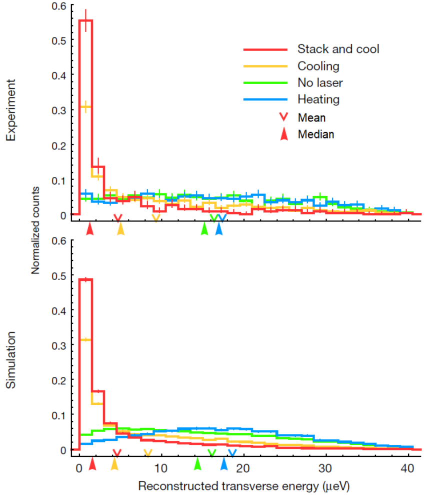
- With the red-detuned laser applied, both the longitudinal and transverse velocities are reduced
- this suggests that three-dimensional cooling is realized despite having essentially only one-dimensional laser access
- Cooling in the transverse plane is presumably enabled via the coupling of antihydrogen's motional degrees of freedom in the anharmonic magnetic trapping potential

Laser cooling of antihydrogen



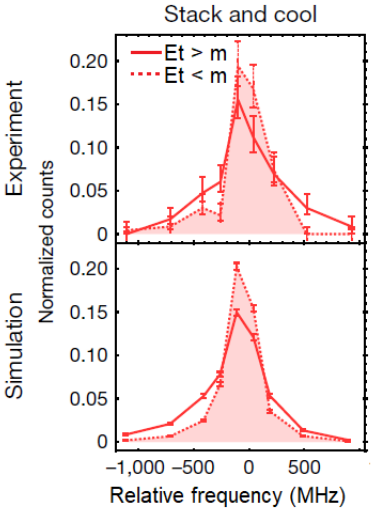
- The experimental lineshapes given by the number of annihilation counts within a TOF time window of 0 to 3 ms, as a function of the probe laser frequency relative to the resonant frequency [8]
- Each distribution is normalized to its total number of counts
- the error bars represent 1 s.d. counting statistical uncertainties
- The values labelled E_L represent the mean of 'true' longitudinal energies of the simulated atoms at the time of the spin-flip transitions

Reconstructed transverse energies



- Distributions of the transverse kinetic energies reconstructed from the TOF of antihydrogen
- The error bars represent 1 s.d. statistical uncertainties
- These characteristics in the transverse energy distributions reflect the highly non-thermal nature of our dilute antihydrogen samples, where collisions are negligible

Comparison of spectral lineshapes between transversely cold and hot anti-atoms



- The lineshape for the subsample with the transverse energy greater (smaller) than its median value is shown with a solid line (dashed line filled under the curve)
- This indicates that the longitudinally cooled population is also cooled transversely, implying that individual atoms are cooled in three dimensions