Characterization of the 1S-2S transition in antihydrogen

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Research interests

- Beam and plasma physics
- Trapping & measuring properties of antihydrogen

ARTICLES

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nature physics

Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

LETTER

doi:10.1038/nature09610

Trapped antihydrogen

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About Antimatter

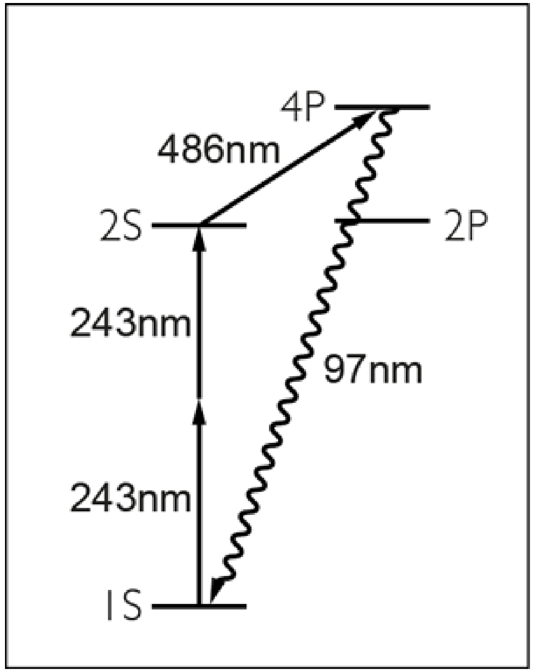
Theoretically predicted by Dirac in 1928.

Antielectron(positron) was first discovered by Carl D. Anderson in 1932.

Possesses the same properties with corresponding matter.

- This means that an antihydrogen has the same 1S-2S transition properties with that of a hydrogen.

1S-2S Transition



"1S-2S absolute frequency measurement." MPQ, April 10, 2019, http://www2.mpq.mpg.de/~haensch/hydrogen/index.php/Research/AbsoluteFrequency?from=H1s2sResearch.AbsoluteFrequency

Preparation

Antiproton

- Collide proton beam to metal block.
- After collision, decelerate them.

Positron

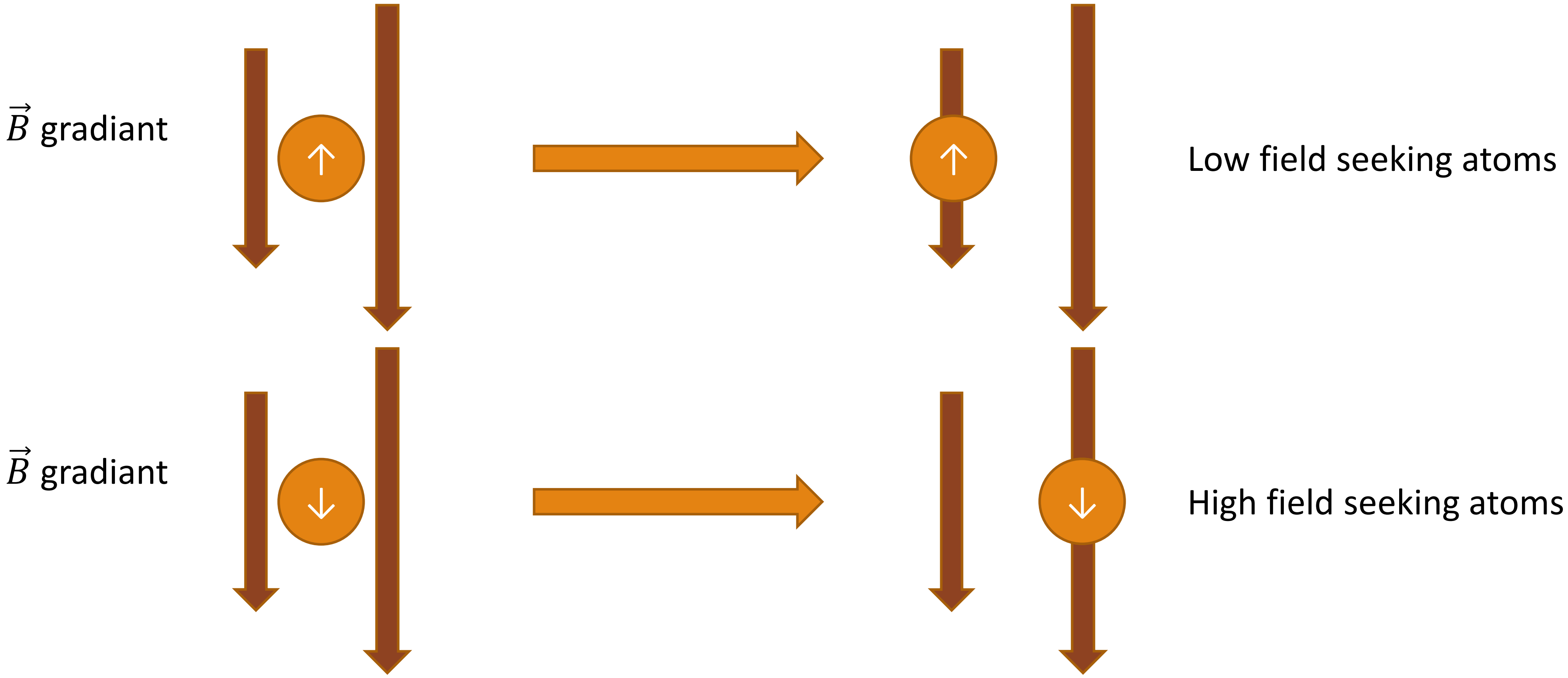
- Beta decay of Na-22 is a source usually.
- Make positrons go through a solid material.
- Most of them annihilates, but the survived ones have low energies.

Antihydrogen

- Low energy particles can be easily combined into atoms.
- Use gradient of the magnetic field to trap neutral antihydrogen.

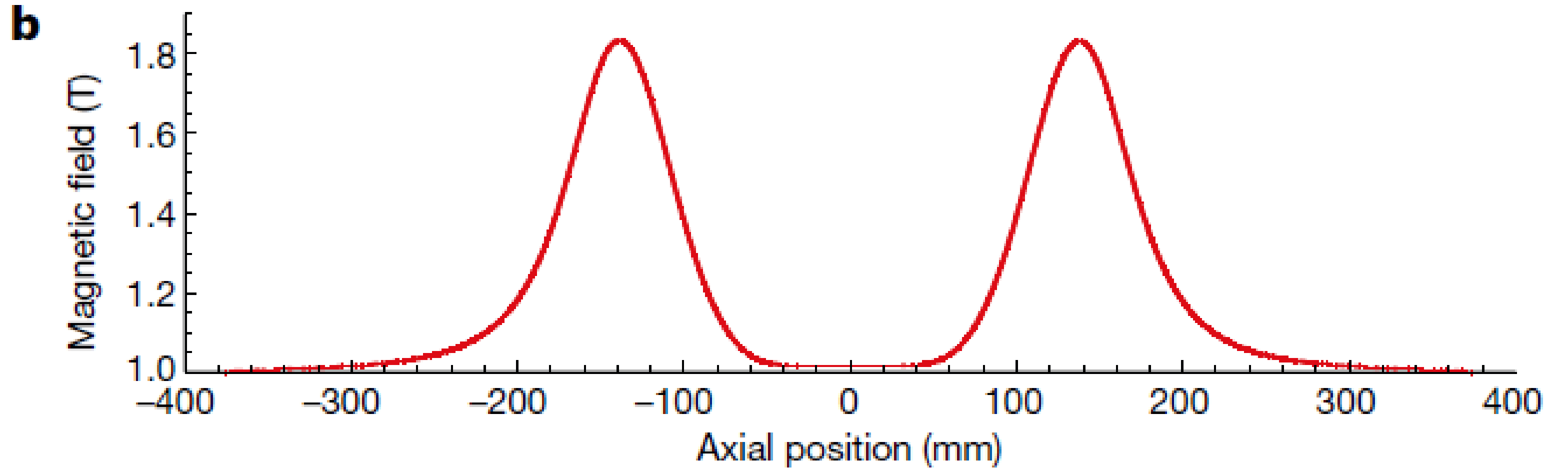
Magnetic Trap

$\Delta E = -\vec{\mu} \cdot \vec{B}$



Magnetic Trap Setup

Low field in the center to capture low field seeking atoms.



(Anti)Hydrogen Energy Levels

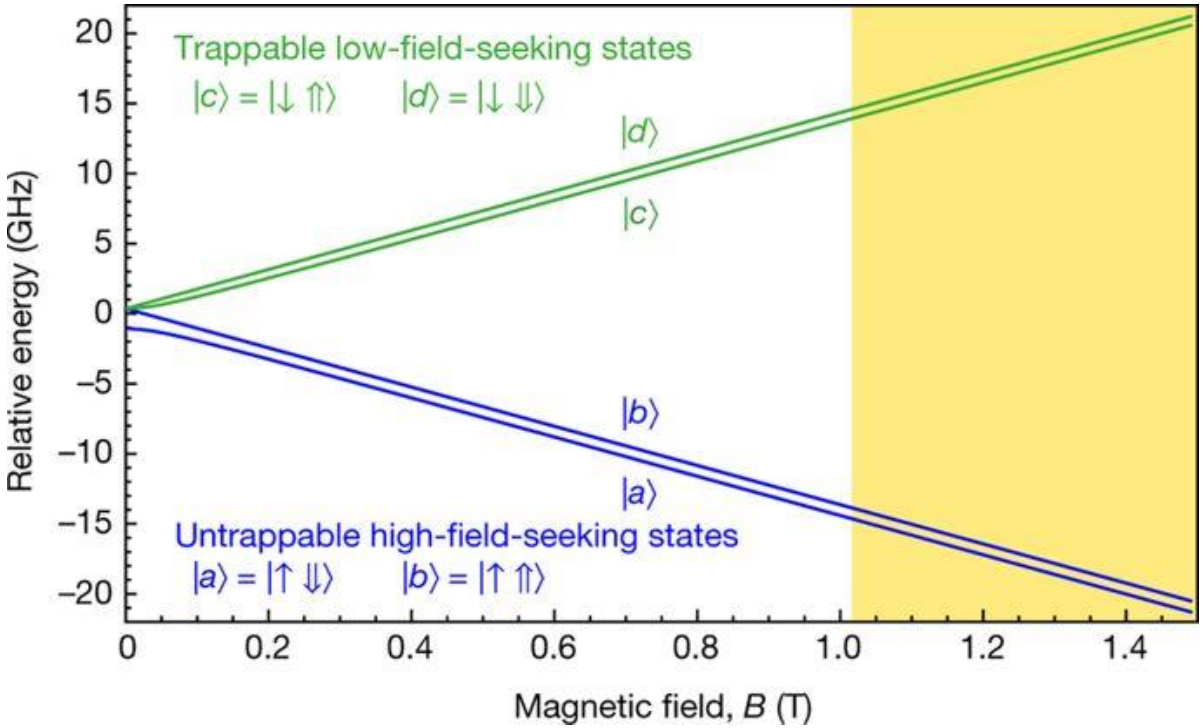


Fig. 1. M. Ahmadi et al, “Observation of the hyperfine spectrum of antihydrogen," Nature **548**, 66-69 (2017).

Experiment

General idea: Use laser and microwave to make atoms untrappable.

If resonance, spin flips and atoms seek for high field → escape the magnetic trap, and annihilate.

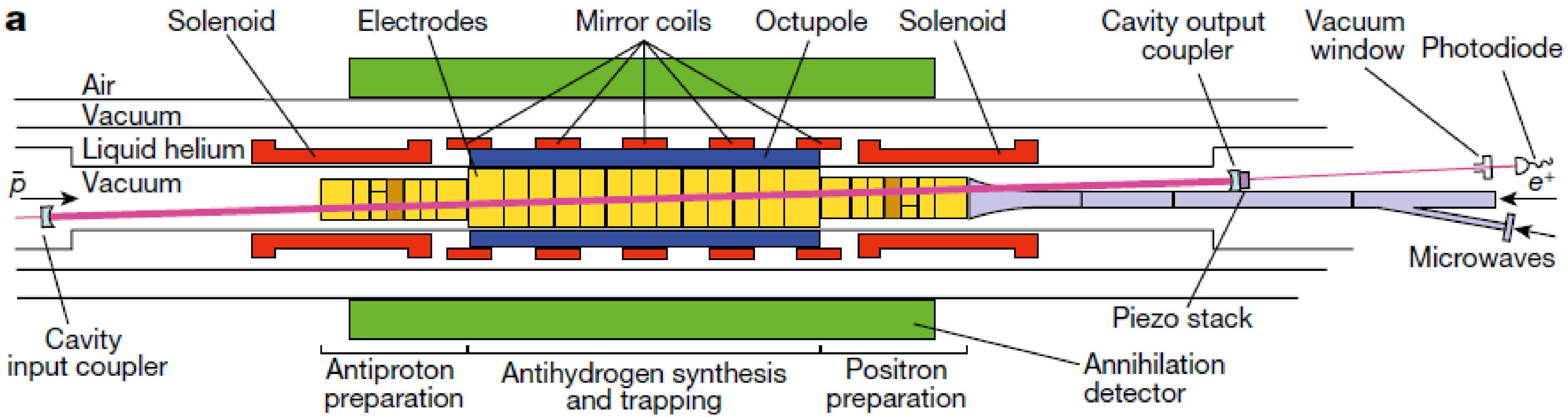
Detect particles like photons, pions etc. from annihilation to count the annihilation events.

Count number of annihilation events and obtain the number of escaped atoms. Turn off the magnetic trap and count the annihilation events and obtain the number of remained atoms.

Get the ratio of escaped atoms and use it as the spectroscopy intensity.

We find 2Sd-1Sd transition frequency especially with this method.

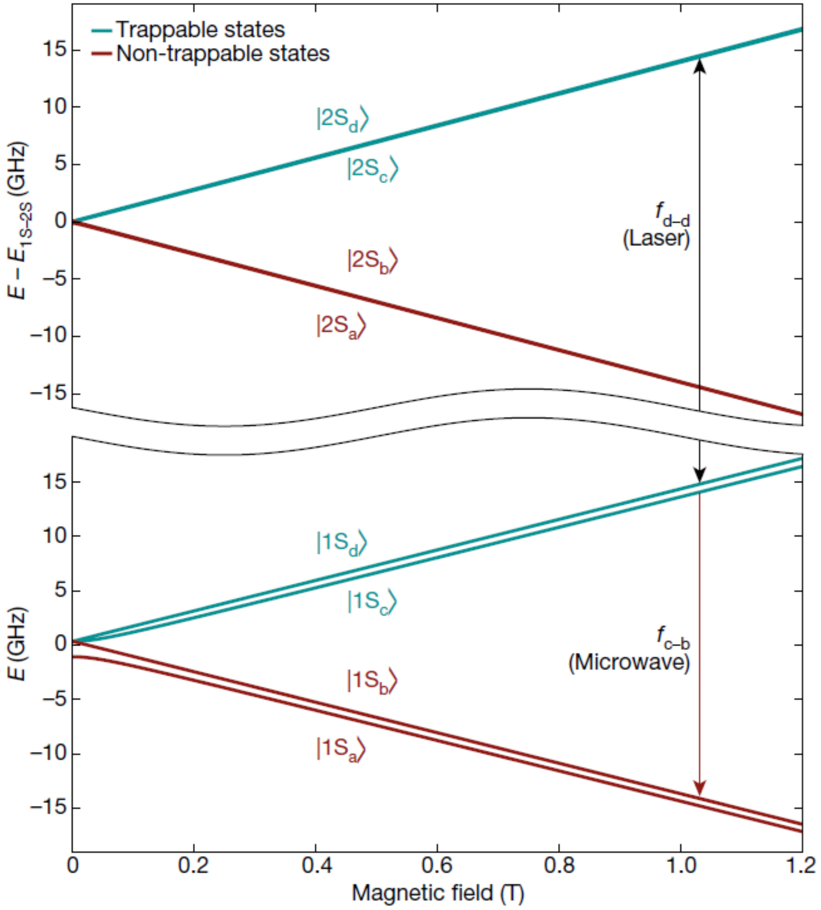
Experiment



a
Solenoid
Electrodes
Mirror coils
Octupole
Solenoid
Cavity output coupler
Vacuum window
Photodiode
Air
Vacuum
Liquid helium
$\bar{p}$
Vacuum
e^+
Microwaves
Piezo stack
Cavity input coupler
Antiproton preparation
Antihydrogen synthesis and trapping
Positron preparation
Annihilation detector

Experiment

- Accumulate antihydrogen, remove charged particles with electric field pulse.
- Rest about 10 s to let atoms fall to ground states. Population of 1Sc and 1Sd are very much equal.
- Put laser (with specific frequency and detuning) for 300 s to excite 1Sd
- 2Sd atom ionize with another photon and annihilate, or its coupling with 2P make it decay to untrappable states.
  - Indicates the escaped atoms were all 1Sd.



Experiment

- Put microwave with its frequency scanned over 9 MHz in 32 s to eliminate remaining 1Sc atoms, and count its annihilation events to obtain the number of 1Sc atoms.
- After 1Sc atoms annihilated, turn down magnetic trap and count the annihilation events to obtain remaining number of atoms, which are remaining 1Sd atoms with high probability.

Result

Table 1 | Antihydrogen atom counts

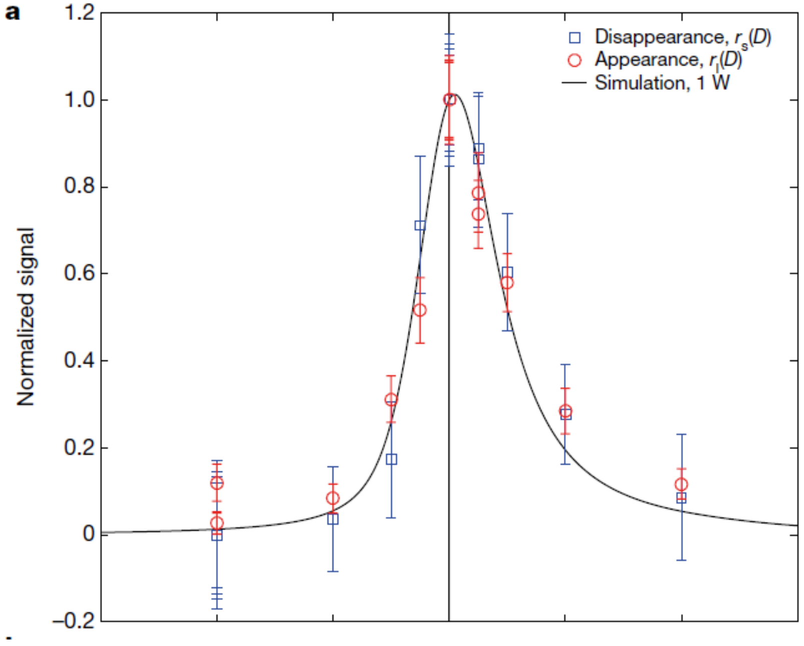
	Laser detuning, D (kHz)	Number of trials	Atoms lost during laser exposure, L	Atoms lost during microwave exposure, M	Surviving atoms, S	Initially trapped atoms, N_i
Set 1	−200	21	7±7	383±23	504±25	894±35
	−100	21	22±9	415±24	494±24	931±35
	0	21	264±24	423±24	217±16	904±38
	+100	21	75±14	411±23	424±23	910±35
Set 2	−200	21	26±9	394±23	466±24	886±34
	−25	21	113±16	423±24	326±20	862±35
	0	21	219±22	390±23	269±18	878±37
	+25	21	173±20	438±24	296±19	907±37
Set 3	−200	23	8±7	354±22	479±24	841±33
	0	23	303±26	454±25	248±17	1,005±40
	+50	23	176±20	390±23	339±20	905±37
	+200	23	36±11	446±24	459±23	941±35
Set 4	−200	21	7±7	525±26	541±25	1,073±37
	−50	21	86±15	475±25	495±24	1,056±38
	0	21	274±25	480±25	275±18	1,029±40
	+25	21	202±21	516±26	305±19	1,023±38
Total		344	1,991	6,917	6,137	15,045

The integrated number of antihydrogen atoms is listed for each laser detuning (at 243 nm) within each set of trials. The background has been subtracted. Uncertainties quoted are one standard deviation (s.d.) counting errors. We refer to L as the 'appearance signal'; S is used to infer the 'disappearance signal'.

Result

Normalize data

- appearance data $r_1(D) = L(D)/L(0)$.
- disappearance data $r_2(D) = [S(-200\text{ kHz}) - S(D)]/[S(-200\text{ kHz}) - S(0)]$.



Result

Compare with simulation and find out the d-d transition frequency.

Calculate with known formulas to calculate hydrogen d-d transition frequency.

- $f_{d-d}(B) = f_{1S2S} - \frac{1}{4}[f_{HF}(1) - f_{HF}(2)] + [\mu_e(2) - \mu_e(1)]\frac{B}{h} - [\mu_p(2) - \mu_p(1)]\frac{B}{h} + \left(\frac{m}{\mu}\right)^3 \frac{13e^2a_0^2}{4mh}B^2$
- Use field strength of B = 1.03285(63) T.

Result

Experimental antihydrogen d-d transition frequency:

$$f_{d-d} = 2{,}466{,}061{,}103{,}079.4(5.4)\ \mathrm{kHz}$$

Calculated hydrogen d-d transition frequency(the error is from uncertainty of the field strength):

$$f_{d-d} = 2{,}466{,}061{,}103{,}080.3(0.6)\ \mathrm{kHz}$$

Conclusion

Obtained measured resonance frequency of d-d transition in antihydrogen to a precision of about 2×10^{-12}

Q&A

What is the role of mirror coils?

- Its role appears to generate magnetic field.

Why did the team use magnetic trap laser even there are other options?

- Magnetic trap is easy to construct in ALPHA 2, and it can trap a lot of atoms at the same time.

Why did the team set two laser beams co propagate each other?

- In order to erase first order Doppler shift. When due to the movement of atoms, frequency of laser beam could change, but to the first order, co propagating beams can cancel out its changes as one laser’s change has exactly same magnitude with opposite sign of the other laser.