ASACUSA

Atomic Spectroscopy And Collisions Using Slow Antiprotons

Progress during 2004 and future plans

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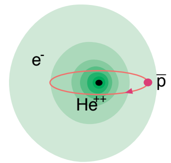
Part 1

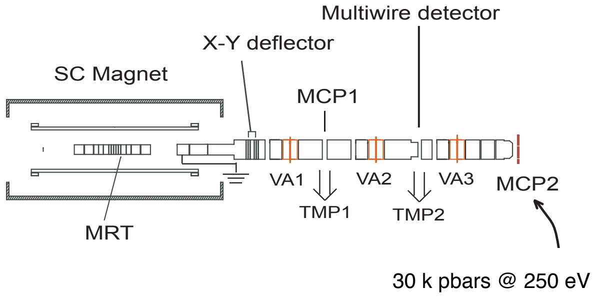
ASACUSA 2004

2004 Highlights

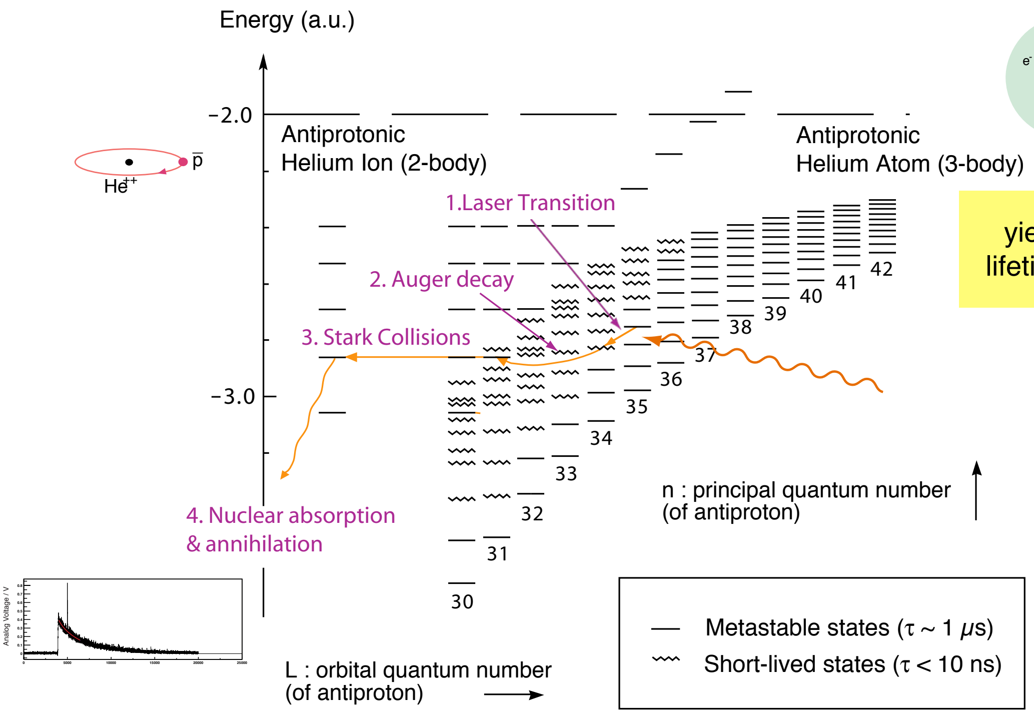
1. antiprotonic helium laser spectroscopy: ~10 fold improvement



2. >30,000 antiprotons @ 250 eV, slow-extracted over a period of 10 s

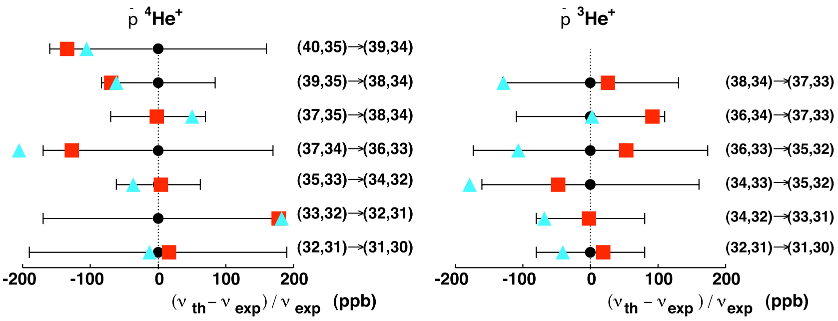


Antiprotonic helium - a closer look



yield ~3%
lifetime ~3μs

Before 2004



Two theory calculations (▲and■) compared with experiment ●
Experimental & theoretical errors ~ 100 ppb

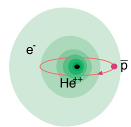
$|m_p - m_{\bar{p}}|/m_p$

A test of *CPT* invariance. Note that the comparison of the $\bar{p}$ and p charge-to-mass ratio, given in the next data block, is much better determined.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.0 × 10^{-8}	90	[1] HORI	03	SPEC	$\bar{p}e^-\,^4$He and $\bar{p}e^-\,^3$He

• • • We do not use the following data for averages, fits, limits, etc. • • •

From The Review of Particle Physics (2004)

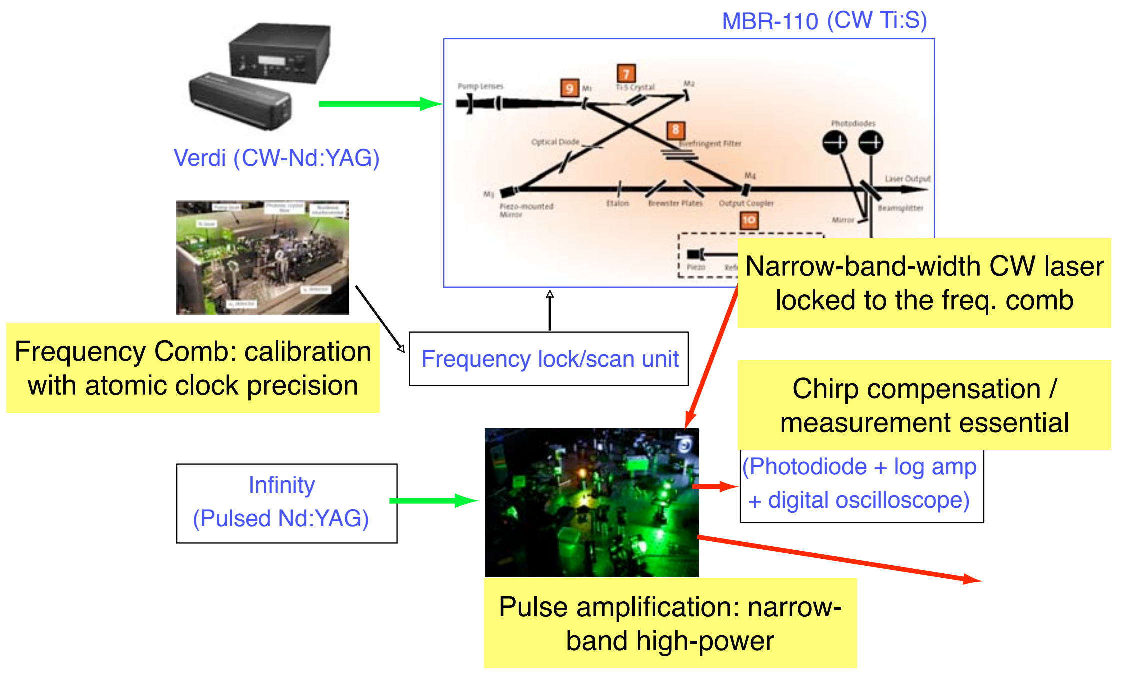


Antiprotonic helium

Improvements in 2004

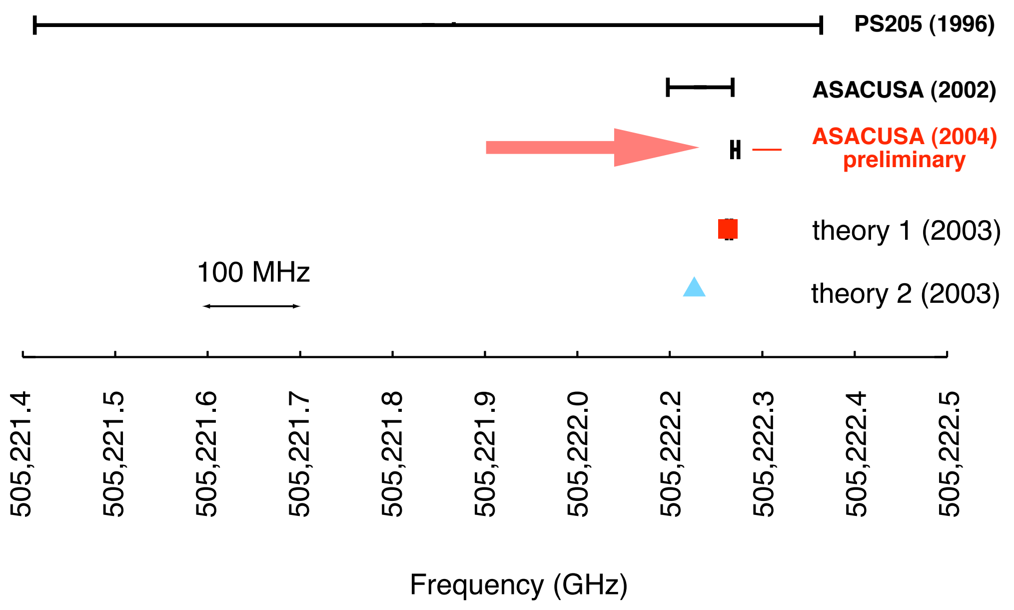
	AD Phase 1	Before 2004	2004
Natural width	0.1 - 100000 MHz	←	←
Collisional Shift	~~~500 MHz~~	<1 MHz	← RFQD
Collision width	~~~500 MHz~~	~1 MHz	
Doppler width	~500 MHz	←	Split by ~1/100
Laser band width beaware of chirp	~~800~2000 MHz~~	←	< 20 MHz (pulse amplified CW)
Calibration	~~10 - 60 MHz~~	←	~0 (frequency comb)
Achieved precision	60 ppb	10 ppb	work in progress
	PRL 87 (2001)	PRL 91 (2003)	

Improve laser band width and calibration

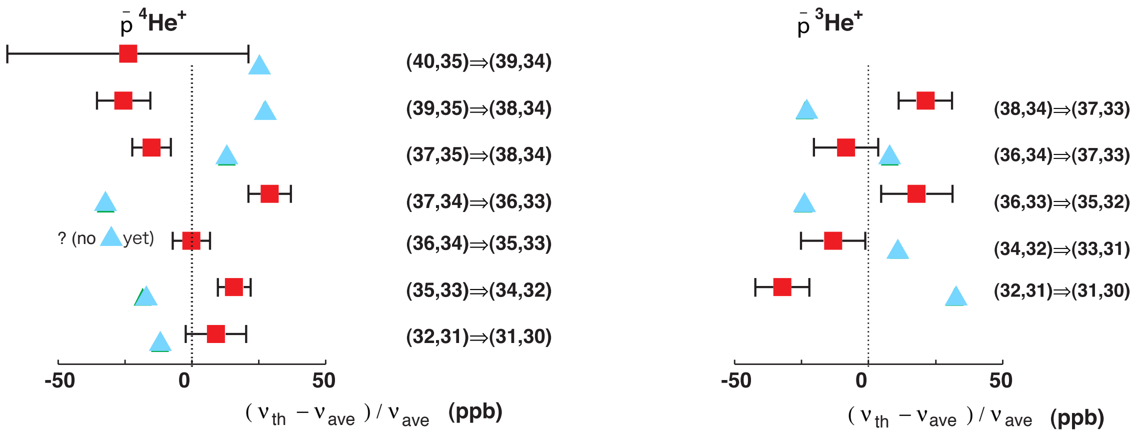


2004 result, preliminary

593-nm (505,222 GHz) resonance in helium3



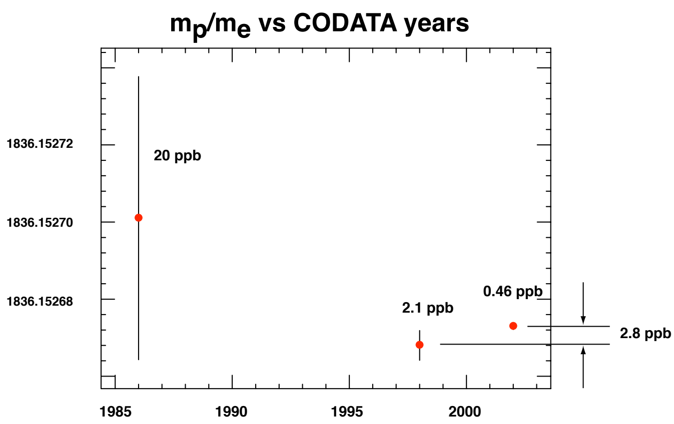
status of theoretical calculations



- theoretical errors have become smaller (still need to be improved)
- these are **pre**dictions, not **post**dictions
- experimental error bar < ±10 ppb (not shown in the figure)

Expected outcome

- Antiproton mass measured to ~ ppb (10-fold improvement)
- m(pbar)/m(e) may contribute to the fundamental constant



note: alpha mass/proton mass known to 0.13 ppb

2004 Highlights

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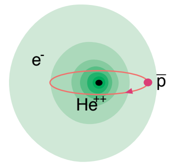
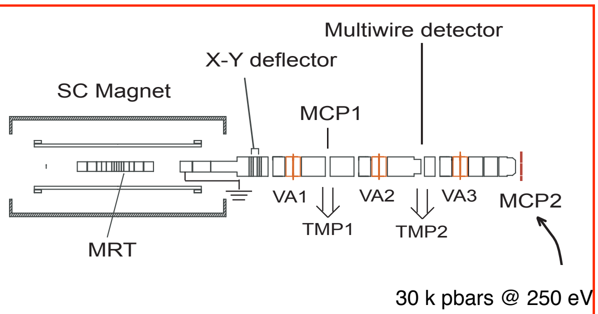
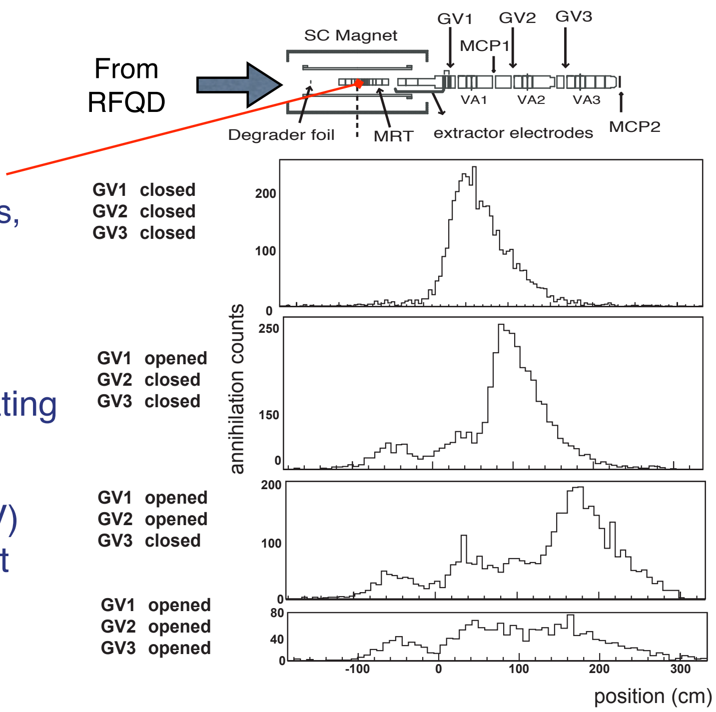


2. >30,000 antiprotons @ 250 eV, slow-extracted over a period of 10 s



Ultra-slow beam production scheme

catch,
cool,
compress,
extract



- compression of pbar cloud in the trap (rotating RF for 100~400 s)
- 30,000 pbars (250 eV) delivered to the target position
- pulse width ~10 s

Efficiency

	# of pbars	survival fraction	note
AD	3×10^7		
RFQD	9×10^6	30%	per AD shot
Isolation foil	6×10^6	20%	
Captured	1.5×10^6	5%	
Cooled	1.2×10^6	4%	compression time 100-400 s
Extracted	5×10^5	1.6%	every 3-5 AD shots
Delivered	3×10^5	1%	

Part 2

FUTURE

Collaborating institutes and funding

	Tokyo RIKEN	MEXT, Japan RIKEN
	Aarhus	Danish natural science foundation, ISA
	RMKI Debrecen	OMFB TeT OTKA
CERN	CERN	
	STEFAN MEYER INSTITUTE	Austrian Academy of Sciences
	Brescia	INFN

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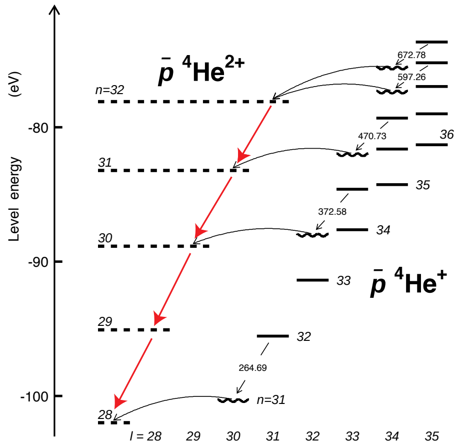
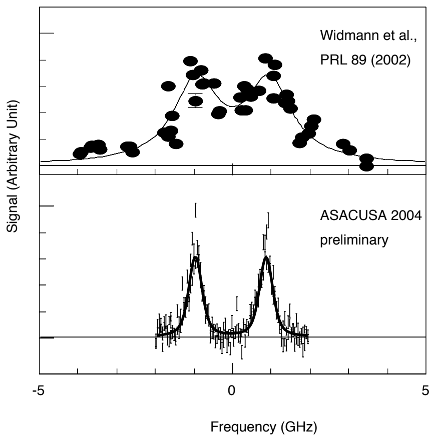
Part I: Continuation of the approved ASACUSA programme	Spectroscopy (CPT)	Antiprotonic helium atoms & ions	antiproton mass << 10^{-9} magnetic moment < 10^{-3}
	Collision	Ionization & atom formation cross section	Use ultra-slow antiprotons extracted from the trap
Part II: Extending ASACUSA programme	Spectroscopy (CPT)	Antihydrogen ground-state hyperfine splitting	Sensitivity to CPTV higher than the K^0 system
	Collision	antiproton-nucleus cross section	Extend the LEAR measurements to much lower energies, relevant to fundamental cosmology

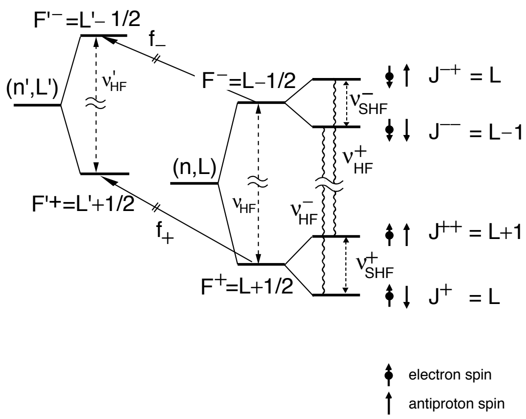
Antiprotonic helium atoms & ions

- antiprotonic helium atom: 2-photon spectroscopy to eliminate the Doppler width (to reach <<1 ppb)
- antiprotonic helium ion → free from theoretical errors
- antiprotonic helium atom microwave spectroscopy: improve antiproton magnetic moment



HFS → magnetic moment





- HFS measurement, 726-nm laser + 13GHz microwave, so far limited by laser
- with the new laser, accuracy improvement possible
- antiproton μ known only to 0.3%, ASACUSA 2001 was 1.6%
- In 2006 we will measure antiproton μ to << 0.1%

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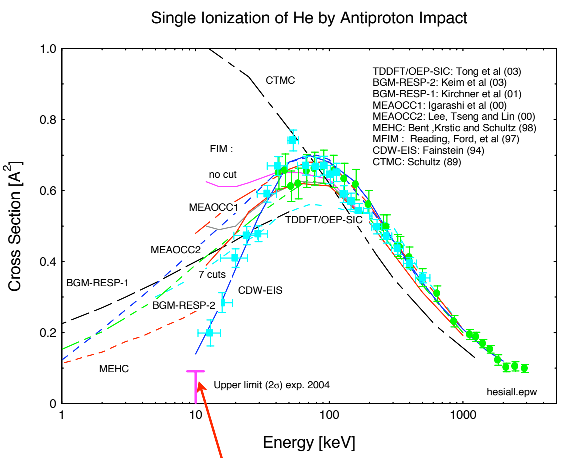
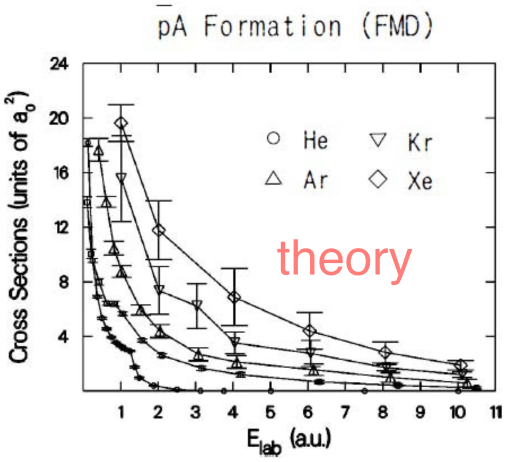
Ionization, antiprotonic atom formation

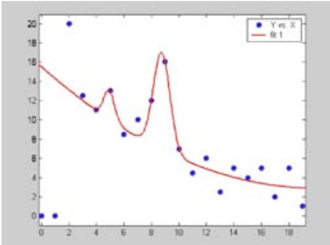
so far deferred, waiting for the phase-3 beam development

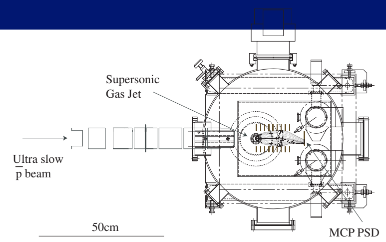


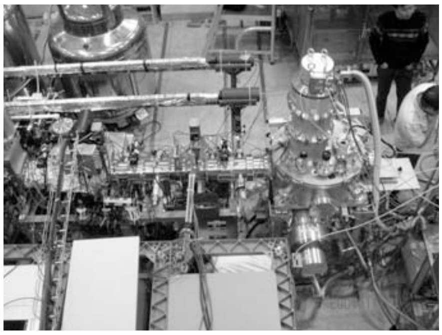


at the end of 2004, this point at 10 keV was added using the trap-extracted beam
- only upper limit, due to lack of time

ready to run in 2006







hydrogen & helium ionization cross section

antiprotonic atom formation cross section

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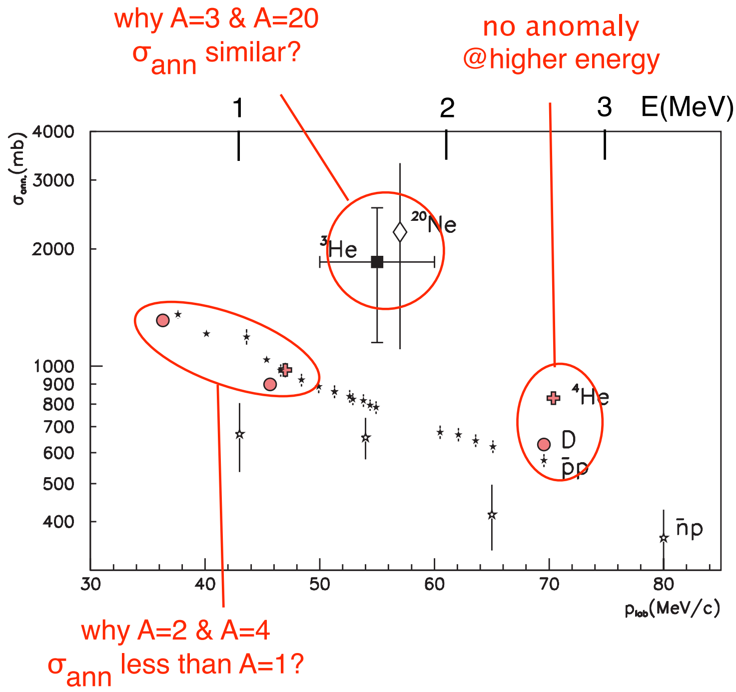
pbar-nucleus cross sections at low energies

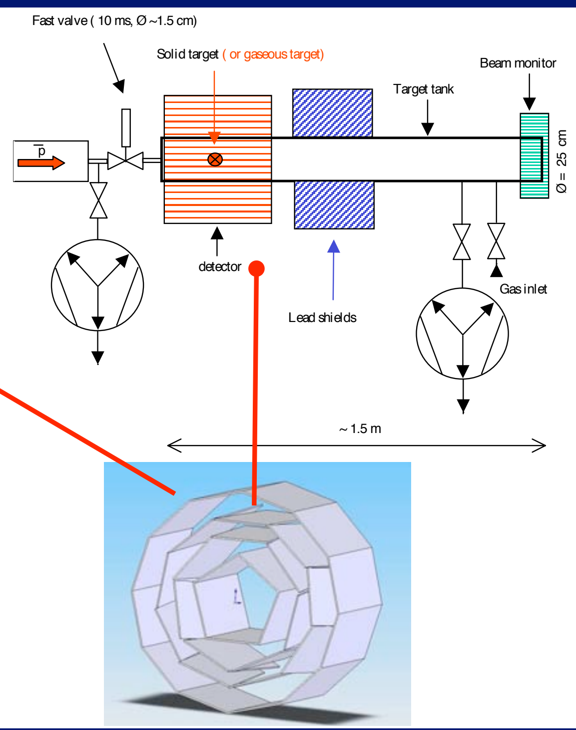
- Use ASACUSA low energy beams to study systematics of pbar-nucleus cross sections
- Relevance for fundamental cosmology

  T>70 keV - annihilation before nucleosynthesis, T<3 keV after nucleosynthesis



Measurement strategy

- low-pressure gas target with a fast valve
- reconstruct (and count) annihilation vertices using a Scintillating Fiber Tracker
- ~10 events per shot
- slightly modified setup can be used in the <1.5 keV energy region (ultra-slow beam from the trap)



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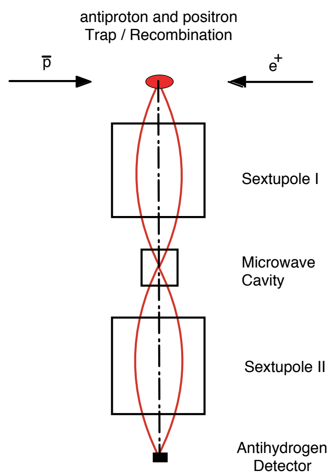
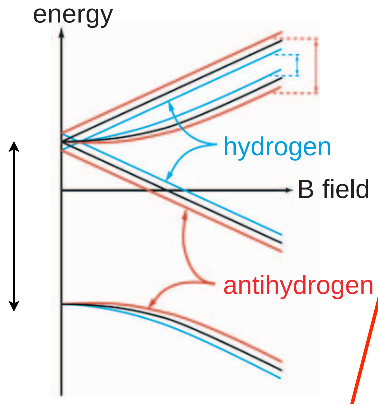
(anti) Hydrogen GS-HFS and CPTV



$\nu_{HFS} \sim 1.4$ GHz

use atomic-beam
(no trapping)



b^p

CPTV and LV
terms in the SME
(Kostelecky et al.)

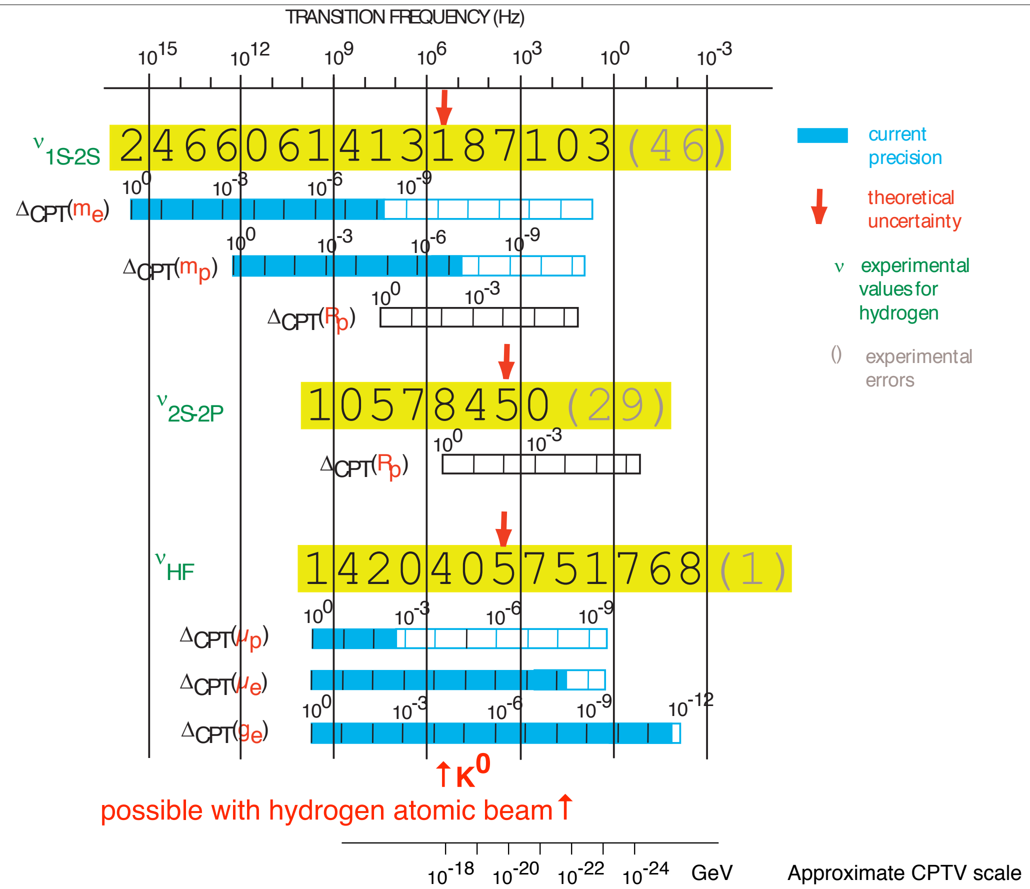
$$(i\gamma^\mu D_\mu - m_e - a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu - \tfrac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0.$$

CPTV in the SME framework

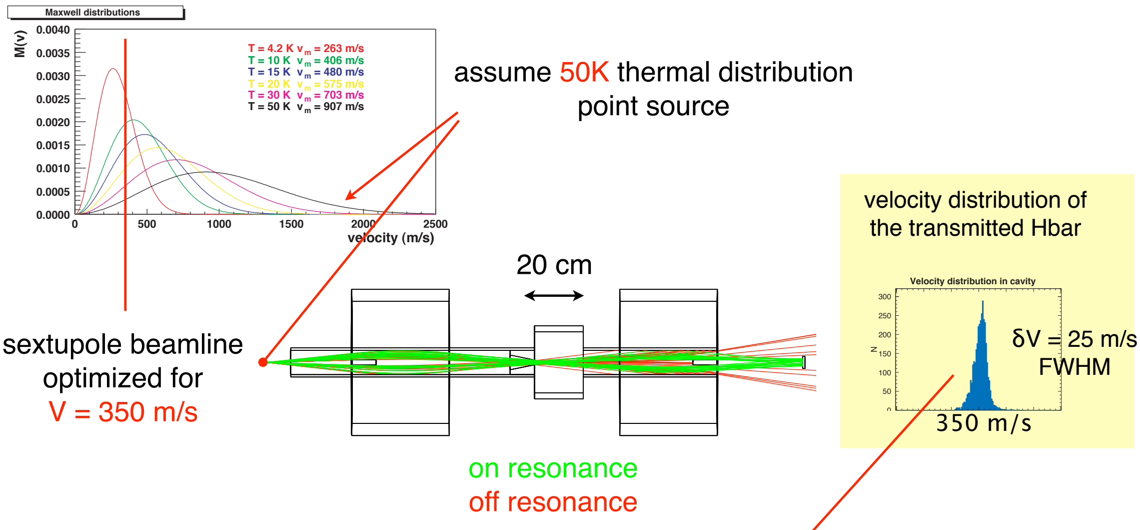
$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \tfrac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + i c^e_{\mu\nu}\gamma^\mu D^\nu + i d^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0.$$

- The CPTV parameters (***a*** & ***b***) of the SME (Kostelecky et al.) are dimensionful
- Within SME, δm/m comparison of CPTV sensitivity is not meaningful; must compare energy (frequency)
- δm/m~10^{-18} of K^0 system ⇔ 10^5 Hz;
  relative accuracy 10^{-4} of GS-HFS (~1 GHz x 10^{-4} =10^5Hz) can be already competitive

note: K^0 (sensitive to ***a***) and GS-HFS (sensitive to ***b***) cannot be directly compared
the numbers above are to illustrate the order of magnitude involved



Temperature, velocity, rate (Monte Carlo)



line width	$\delta v/v = 1.6\times10^{-6}$
efficiency (Ω and velocity fraction)	$\epsilon = 1\times10^{-4}$
rate	~ 1 / min

rate ~x10 @ T=4.2 K
~x1/2 @ T=150 K

Why need new Hbar production methods?

- Atomic-beam geometry works best if the source is point like
- Low temperature is desirable, but relatively high temperatures (T=50~150K) can be tolerated initially
- Nested Penning trap
  typical source size ~ 1cm^3 - too large
  limited access (optical & extraction), small solid angle, magnetic incompatibility
- Two-frequency Paul trap
  technically challenging, but meets our requirements
- Cusp trap
  source size larger, but polarized Hbar beam can eliminate the 1st sextupole

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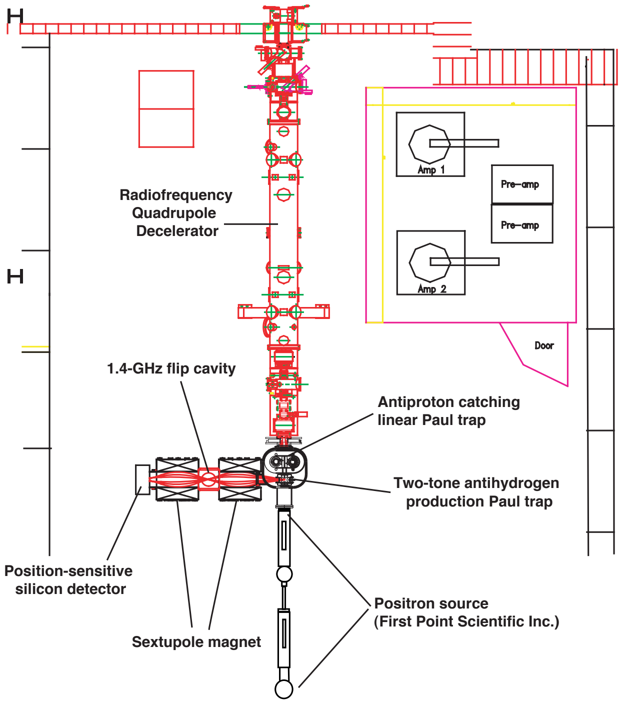
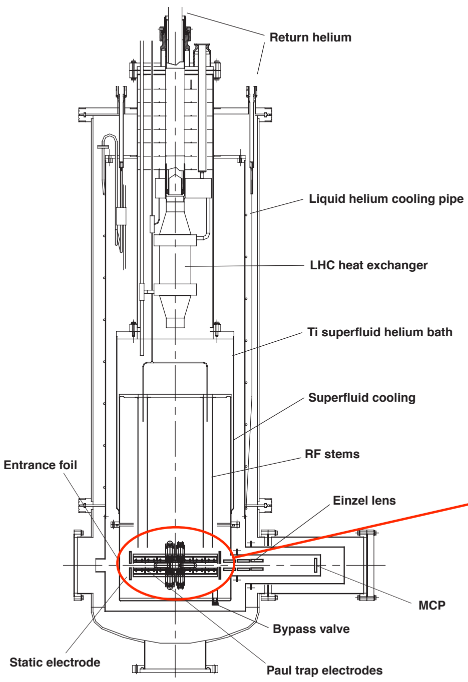
Proposed setup - overview

- RFQD
- SC Linear Paul trap (pbar capture)
- SC two-frequency trap (Hbar production)
- Sextupole & 1.4GHz cavity
- positron source



Superconducting Linear Paul Trap

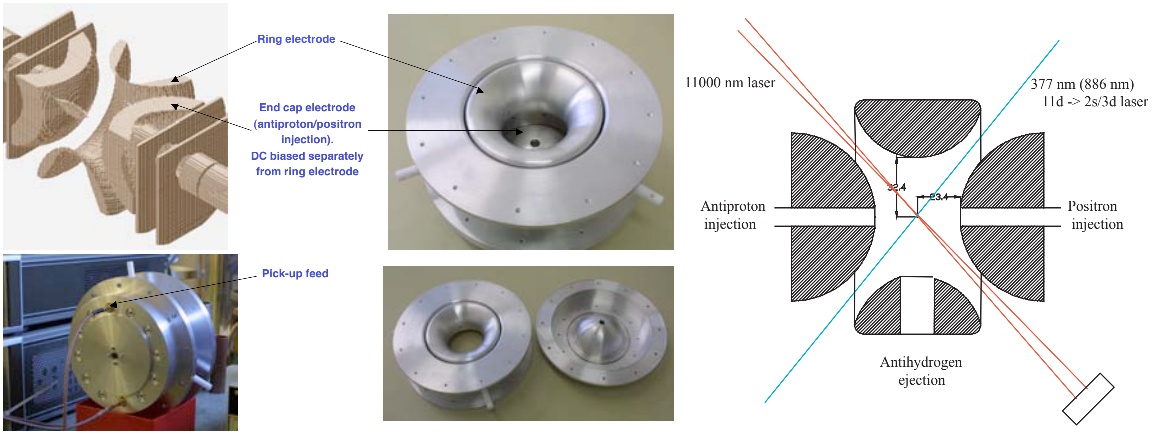


- This model will be tested using protons
- Cooling to superfluid 1.6 K
- demonstration of resistive cooling is essential

full-scale copper model (version 5)

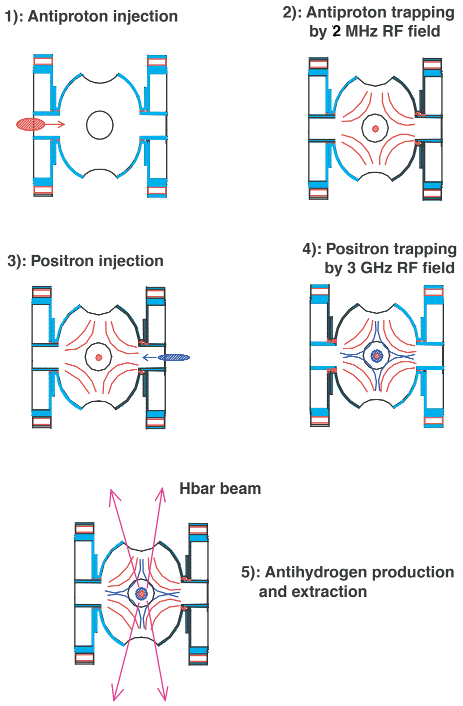
two-frequency Paul trap

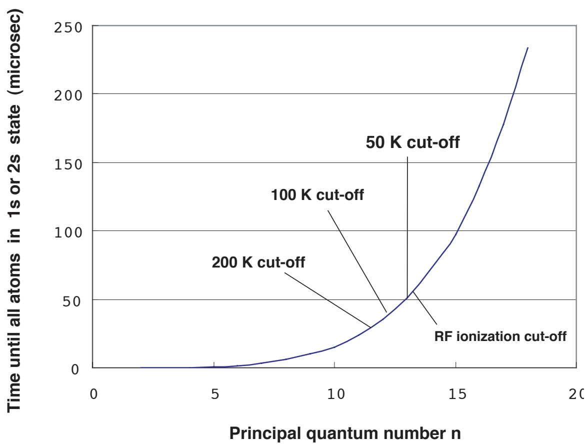
Antihydrogen production trap



- two-frequency trap (3GHz to confine positrons, 2MHz for antiprotons)
- Good laser access - point-like source, opening, no Zeeman splitting, efficient stabilization to the ground state

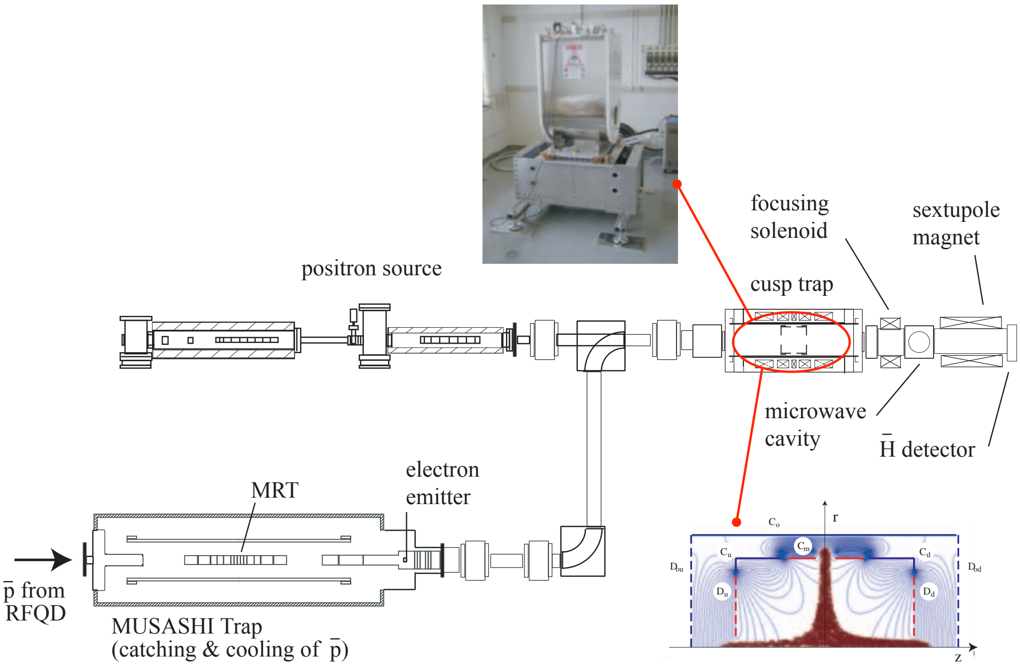
Antihydrogen production in the two-tone trap





Only ground-state (or 2s) antihydrogen are emitted

An alternative method (cusp trap) under study



Beam Usage, 2006

Experiments discussed in Part I

Measurement	Number of weeks
Spectroscopy	
$\bar{p}$ He two-photon spectroscopy, $\bar{p}$ He ion (Part I, Sect. 1.1,1.2)	4
$\bar{p}$ He hyperfine splitting (Part I, Sect. 1.3)	4
Atomic collision	
Ionization cross section (Part I, Sect. 2.3)	4
$\bar{p}$ A (Sec. 2.2)	3
Subtotal	15

Experiments discussed in Part II

Nuclear cross section (5 MeV beam: Part II, Sect. 2.2.1)	2
Antihydrogen GS-HFS (Part II, Sect. 1.1)	
Paul trap commissioning	2
Cusp trap commissioning	2
Subtotal	6
Total	21

allocation to these experiments will be increased in coming years