Trento Institute for
Fundamental Physics
and Applications

UNIVERSITÀ
DI TRENTO
Dipartimento di
Fisica

Prospects from a cold antideuteron beam in AD/ELENA

an initial excursion

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The AEgIS collaboration

The Antimatter Experiment: Gravity, Interferometry, Spectroscopy (**AEgIS**) collaboration aims at performing direct experimental tests of the Weak Equivalence Principle (**WEP**) using **anti-atoms**.

The chosen method is the **direct detection of the free-fall trajectory** of antihydrogen atoms, produced in a **pulsed** way

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UNIVERSITY OF LIVERPOOL

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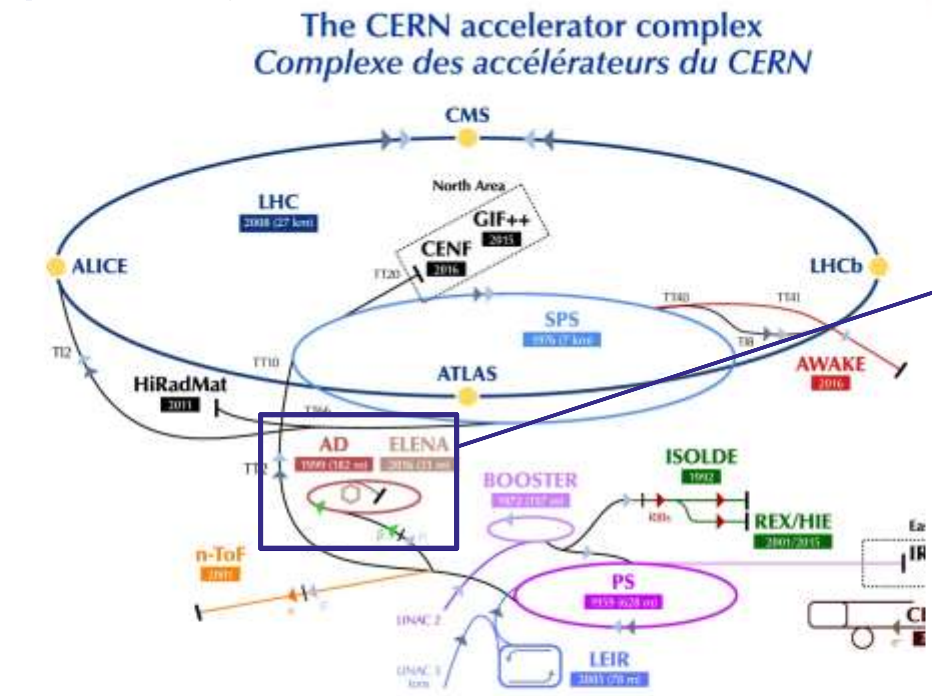
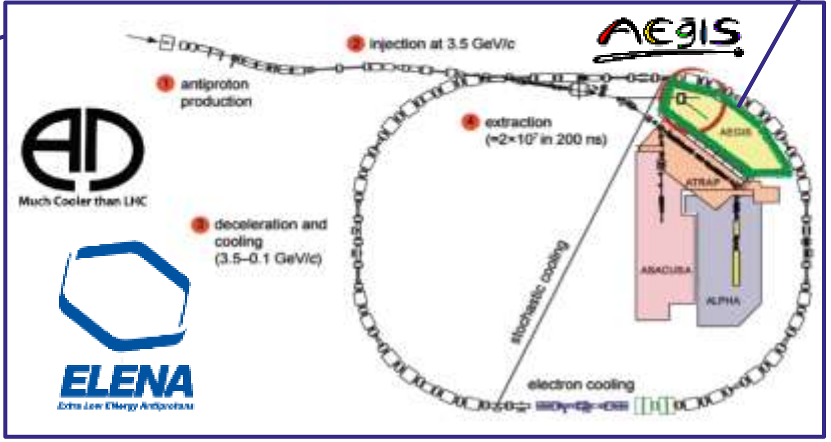
NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

RRI





AEgIS research lines

Shared dev + **$\bar{H}$** + **Ps** + **p̄ atoms** + **R&D**

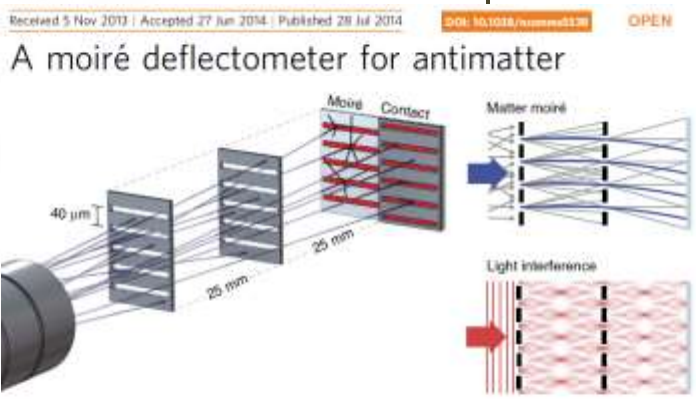
PROPOSAL

2008

Construction began

2012

2014



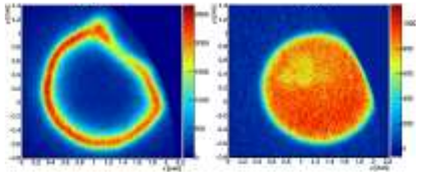
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014
DOI: 10.1038/ncomms5538
OPEN

A moiré deflectometer for antimatter

2016

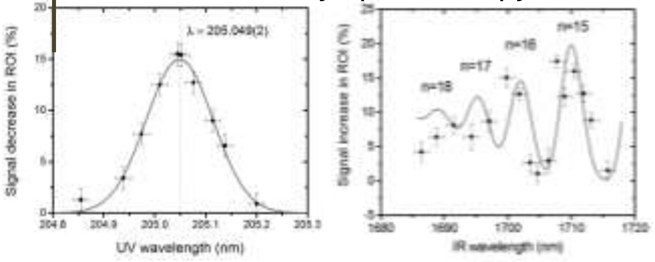
2017

Pbar compression to mm radius



S. Aghion et al., Eur. Phys. J. D (2018) 72: 76

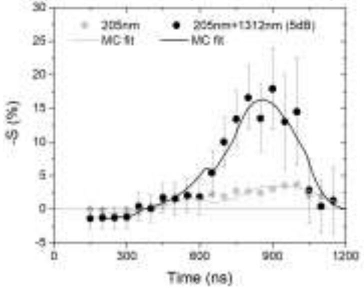
Ps 1S-3P-Ry spectroscopy



S. Aghion et al., PRA **94,** 012507 (2016)

2018

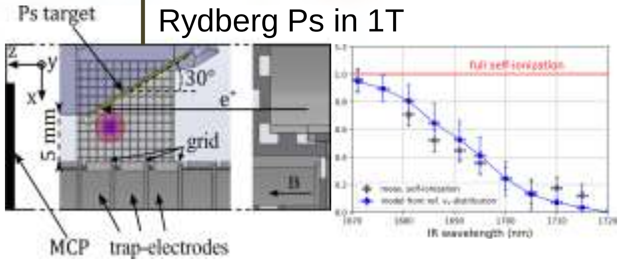
Ps 2S-3P spectroscopy



M. Antonello et al., PRA **100,** 063414 (2019)

2019

Rydberg Ps in 1T



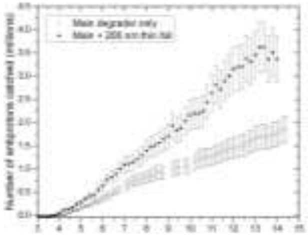
M. Antonello et al., PRA **102,** 013101 (2020)

2020

https://doi.org/10.1038/s42005-020-00494-z
OPEN

Pulsed production of antihydrogen

2023

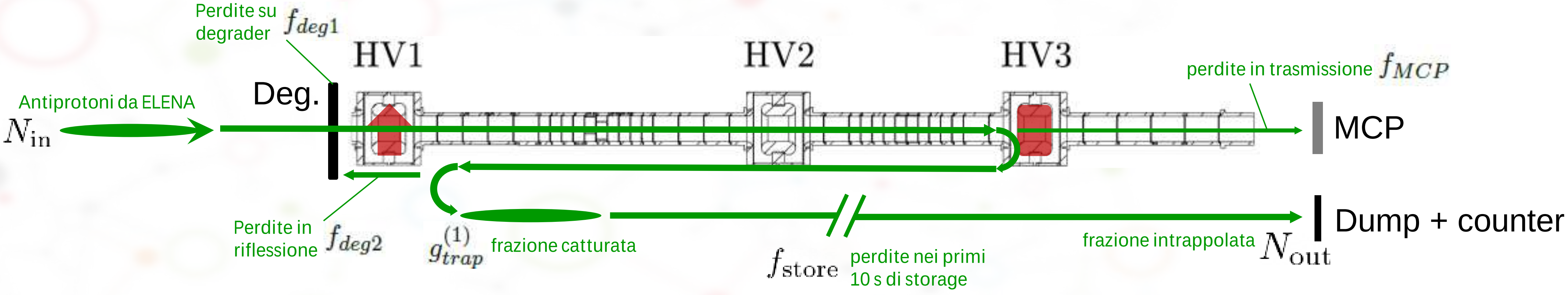


Efficient catching
from ELENA

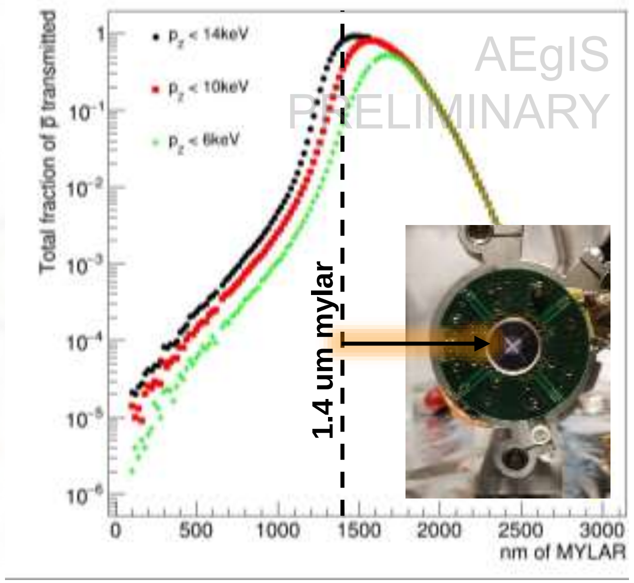
Search of hexaquark DM candidate via pbar-^{3}He in traps

(M. Doser & G. Farrar talks)

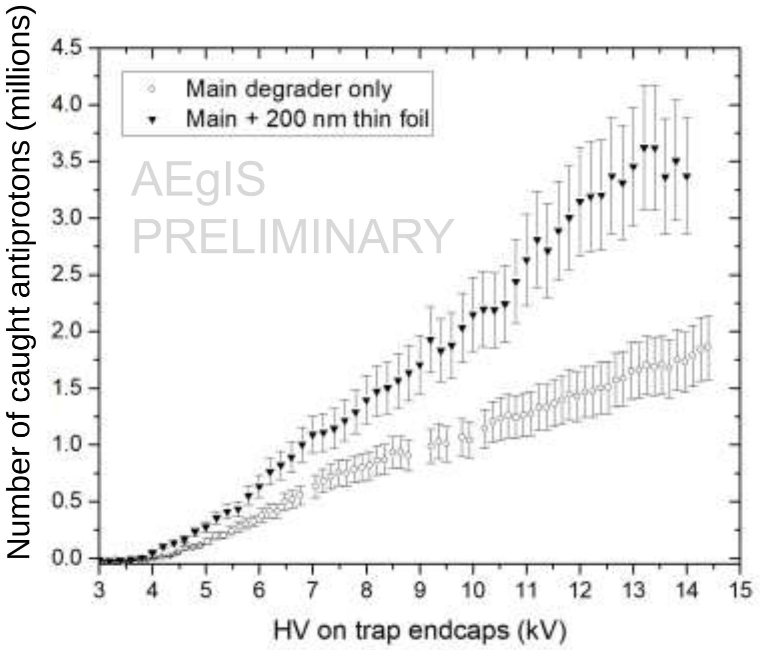
Recent achievements: efficient catching from ELENA



Geant4 optimized degrader



Trapped antiproton counting



Capture efficiency measurements

$$f_{deg1} \approx 0.5 \div 1.5\,\%$$

$$f_{MCP} \approx 16 \div 21\,\%,$$

$$f_{deg2} \approx 4 \div 6\,\%$$

$$f_{\rm store} \approx 10\%$$

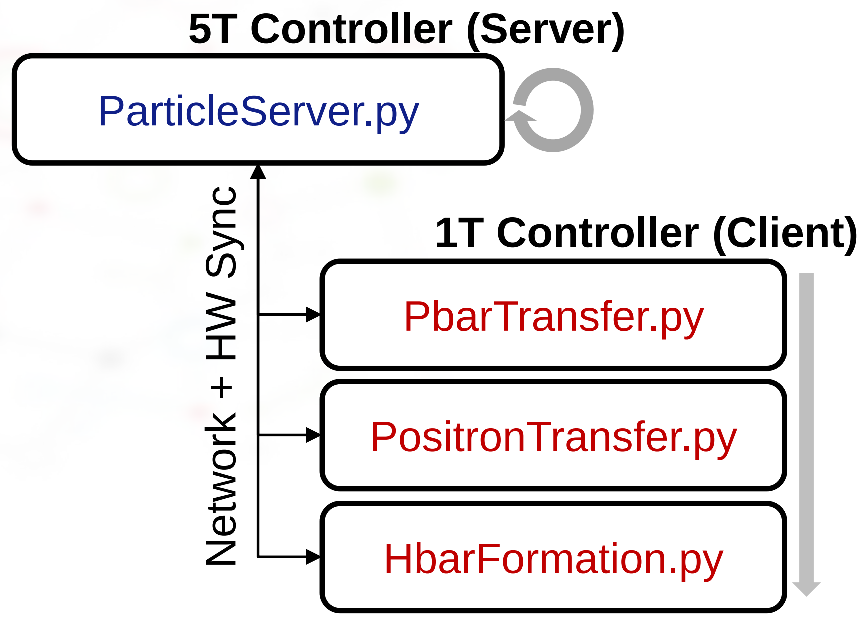
$$g_{trap}^{(1)} \approx 71 \div 79\,\%$$

$$g_{\rm trap}^{(2)} = N_{\rm out}/N_{\rm in} \approx 62\%$$

Recent achievements: constant accumulation

Client-Server asynchronous architecture

- 5T catching trap controller in a continuous accumulation and listen for messages loop
- 1T interaction trap controller runs custom experimental sequences and allows debugging



5T Controller (Server)

ParticleServer.py

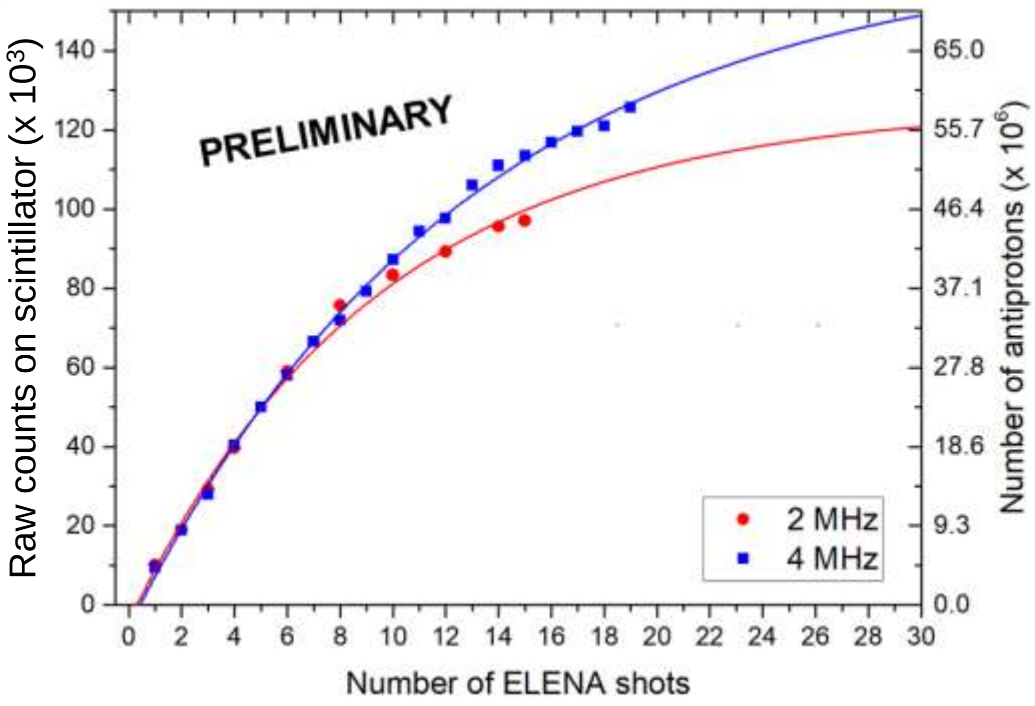
Network + HW Sync

1T Controller (Client)

PbarTransfer.py

PositronTransfer.py

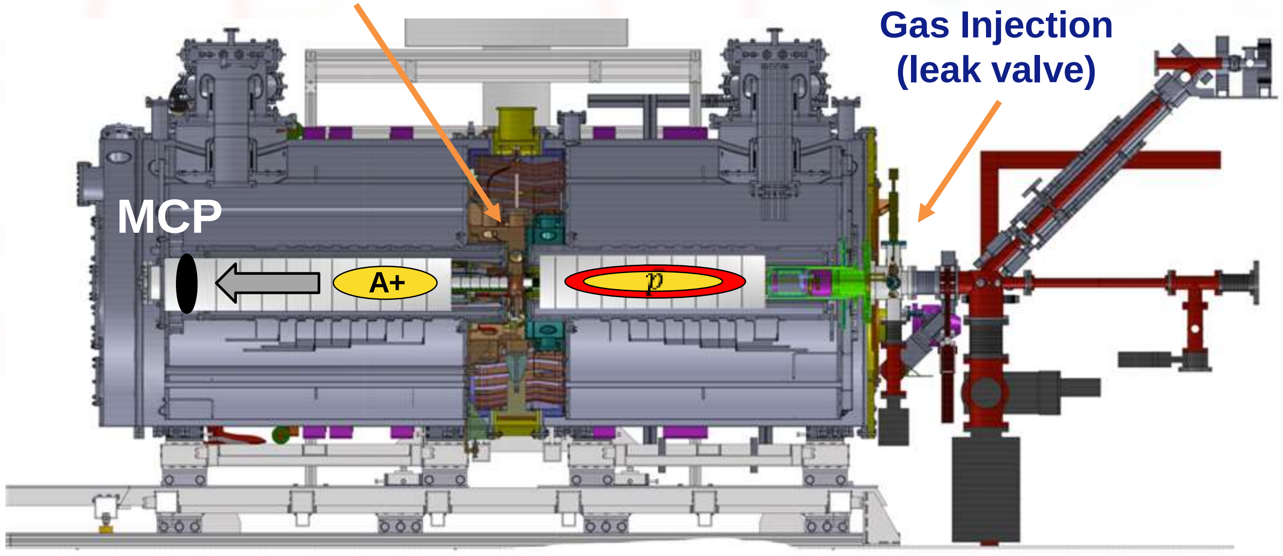
HbarFormation.py



Achievements

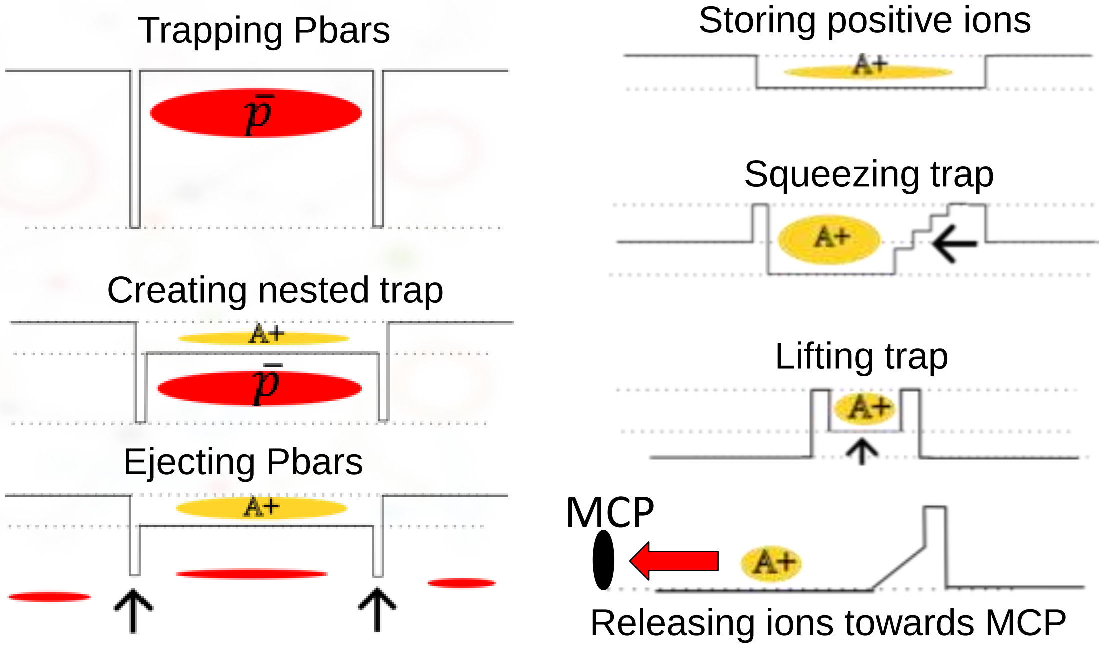
- Stable operation for weeks in constant accumulation
- While constantly accumulating, we reached up to **~100 million antiprotons** in our traps

Recent achievements: antiprotonic atoms formation



Heaters for cryo-surfaces reconditioning

Gas Injection (leak valve)



Trapping Pbars

Creating nested trap

Ejecting Pbars

Storing positive ions

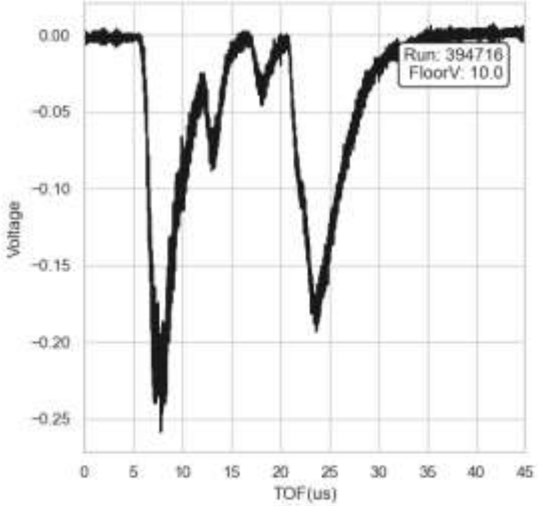
Squeezing trap

Lifting trap

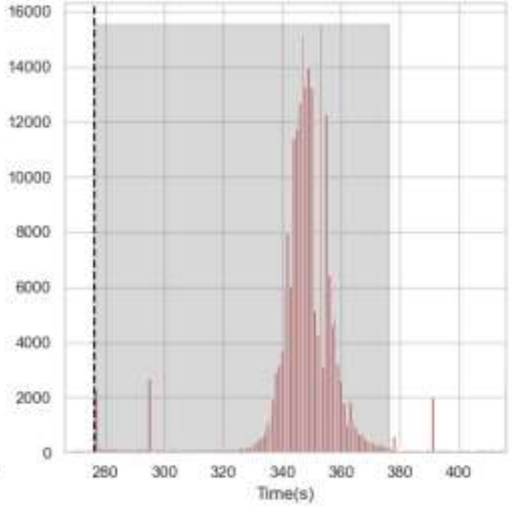
MCP

Releasing ions towards MCP

MCP TOF spectrum



Scintillator monitoring



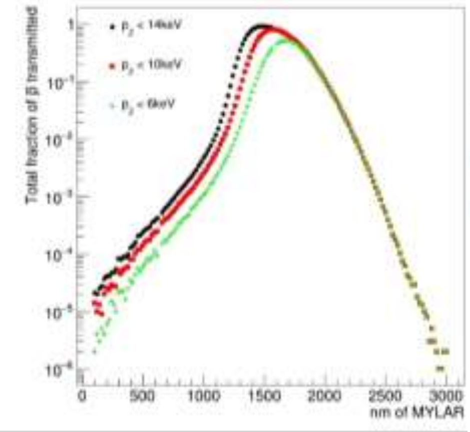
Achievements

- Procedure for controlled gas injection and cleaning
- Technique to trap the positive ions resulting from antiproton interactions with the rest gas target
- Time-of-flight spectroscopy of trapped positive ions

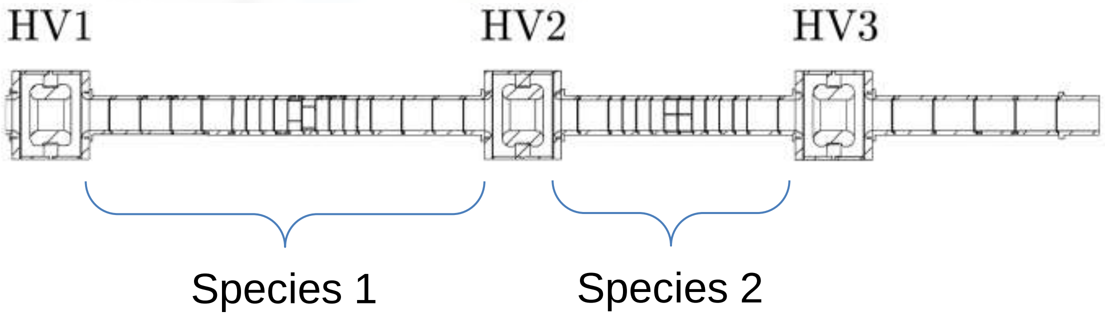
This technique leads to

- Fully stripped and highly charged ions in Penning traps
- TOF spectroscopy of annihilation fragments
- Produce short-lived nuclei directly in Penning traps
- Interact antiprotons with ^{3}He

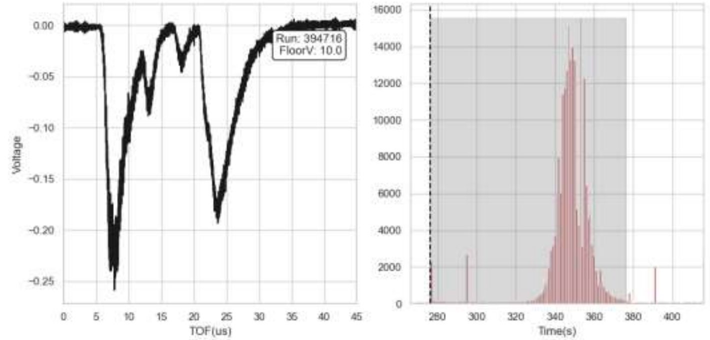
Efficient in catching and tunable in thickness ...



… our apparatus is ready to accumulate two antimatter species (tested with antiprotons & e^+/H^-) …



… we have an established technique to interact antiprotons with gases …



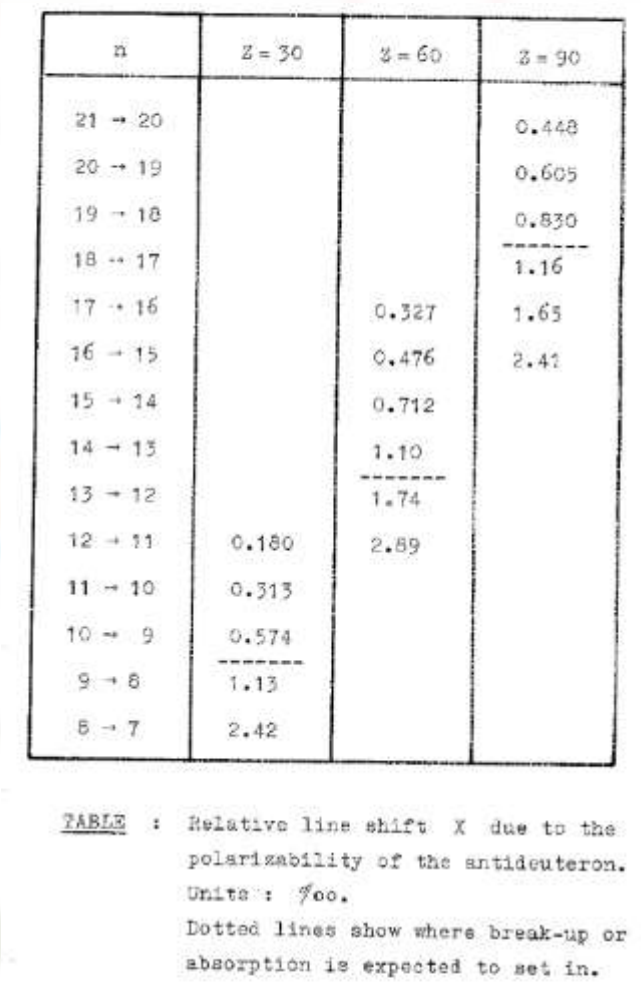
… if we would receive antideuterons like H^- , we would be ready from time 0 to do experiments with them

TRAPPED ANTIDEUTERONS

Antideuteronic atoms

- Mix dbar and protons obtained by H^- stripping (dbar – p)
- Mix dbar and low-Z nuclei by buffer gas (X-ray)
- Mix dbar and high-Z nuclei from anionic sources (see next)

Mix dbar and high-Z nuclei from anionic sources



n	Z = 30	Z = 60	Z = 90
21 → 20			0.448
20 → 19			0.605
19 → 18			0.830
18 → 17			1.16
17 → 16		0.327	1.65
16 → 15		0.476	2.41
15 → 14		0.712	
14 → 13		1.10	
13 → 12		1.74	
12 → 11	0.180	2.89	
11 → 10	0.313		
10 → 9	0.574		
9 → 8	1.13		
8 → 7	2.42		

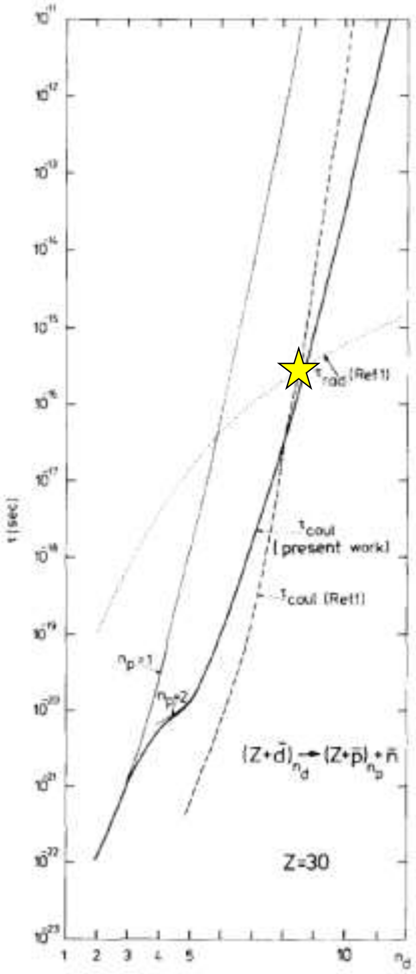
TABLE : Relative line shift X due to the polarizability of the antideuteron. Units : ‰. Dotted lines show where break-up or absorption is expected to set in.

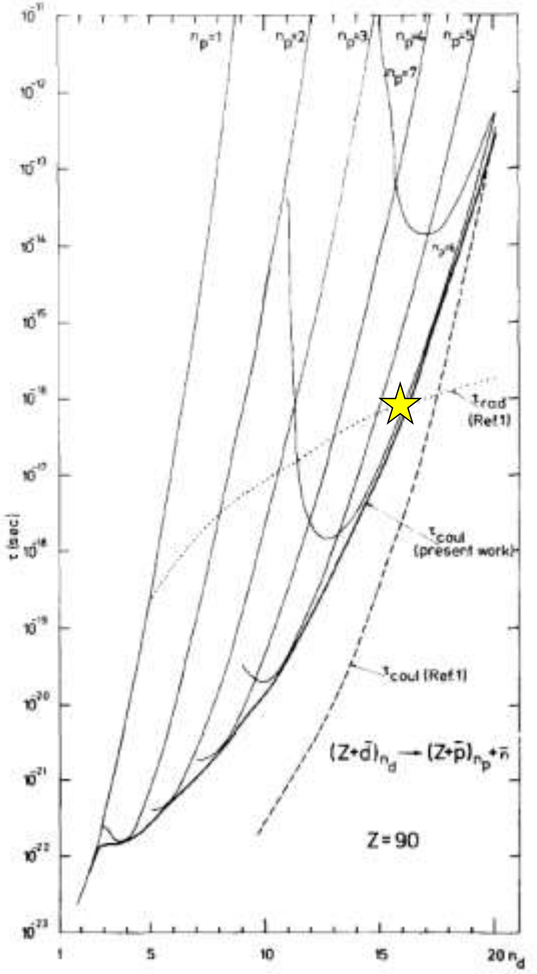
Antideuteronic atoms with high Z

- Polarization of the dbar induces observable line shifts (part-per-mil): observable in the X-ray cascade

[1] G. Baur, *The break-up of antideuterons in the Coulomb field of the nuclei*
[2] T. E. O. Ericson and P. Osland, *Polarization break-up of antideuterons in the nuclear Coulomb field*

Mix dbar and high-Z nuclei from anionic sources





Antideuteronic atoms with high Z

- Polarization of the dbar induces observable line shifts (part-per-mil): observable in the X-ray cascade
- For heavy nuclei, the antideuteron dissociated by Coulomb interaction before it reaches the nucleus

$$E_{\bar{d}} = -13.6\,\mathrm{eV}\,\frac{\mu_{\bar{d}}}{\mu_e}\frac{Z^2}{n_{\bar{d}}^2} = 50\,\mathrm{keV}\,\frac{M+m_e}{M+m_{\bar{d}}}\frac{Z^2}{n_{\bar{d}}^2}$$

$$E_{\bar{p}} = -13.6\,\mathrm{eV}\,\frac{\mu_{\bar{p}}}{\mu_e}\frac{Z^2}{n_{\bar{p}}^2} = 25\,\mathrm{keV}\,\frac{M+m_e}{M+m_{\bar{p}}}\frac{Z^2}{n_{\bar{p}}^2}$$

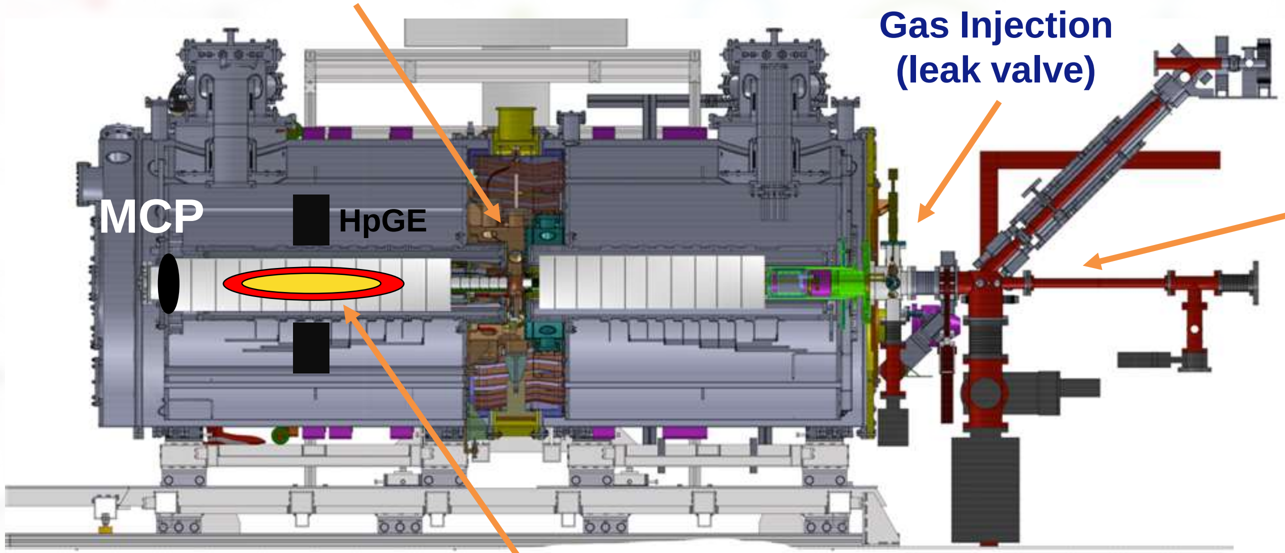
$$E_{\bar{n}} = -|\epsilon_b| - |E_{\bar{d}}| + |E_{\bar{p}}|$$

$$E_{\bar{n}}^{(90)} = 1.0 \div 1.8\,\mathrm{MeV}$$
$$E_{\bar{n}}^{(30)} = 2.5 \div 2.8\,\mathrm{MeV}$$

a technique to produce MeV antineutrons.

[1] G. Baur, *The break-up of antideuterons in the Coulomb field of the nuclei*
[2] T. E. O. Ericson and P. Osland, *Polarization break-up of antideuterons in the nuclear Coulomb field*

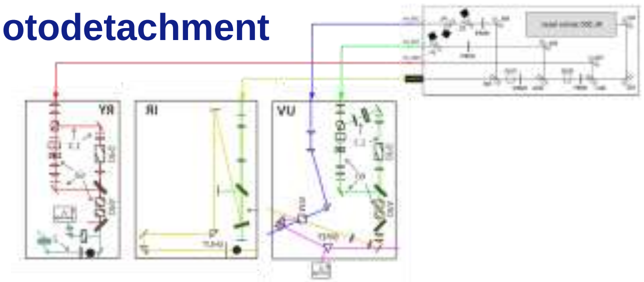
Setting up the stage for antiprotonic atom studies

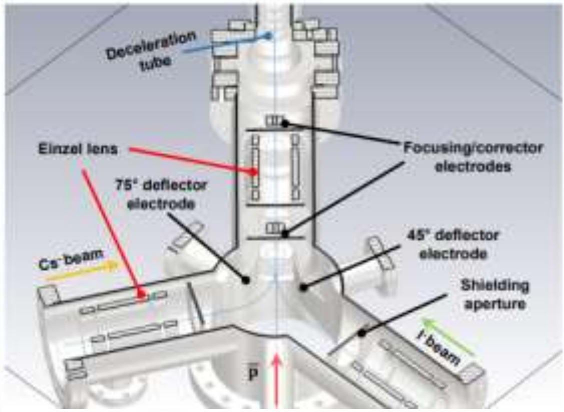


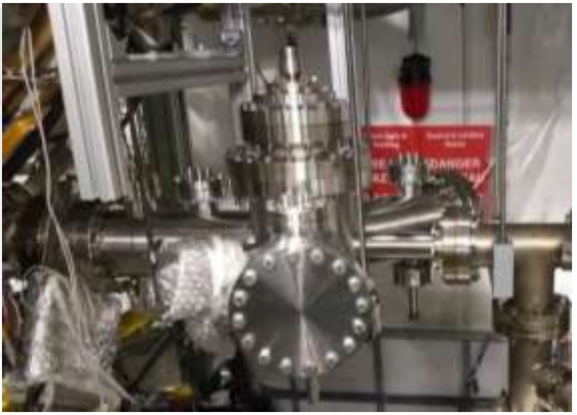
Heaters for cryo-surfaces reconditioning

Gas Injection (leak valve)

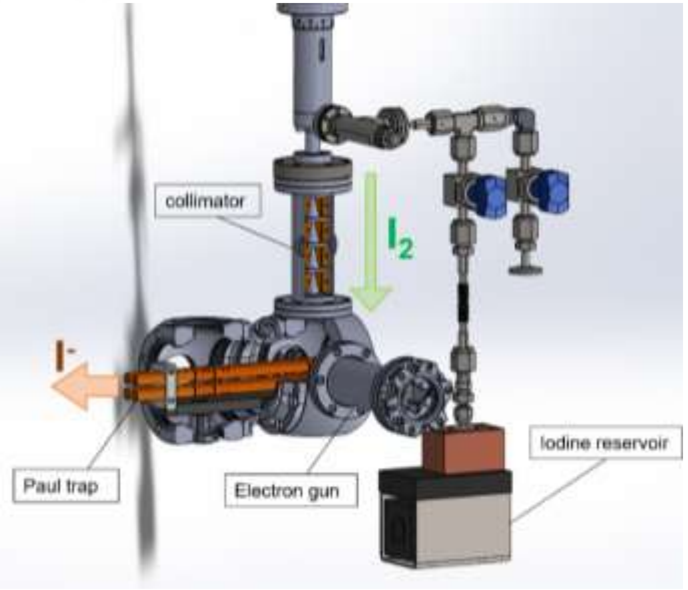
Nd:YAG for laser photodetachment







Switchyard and anionic source for negative iodine



TRAPPED ANTIDEUTERONS

Antideuteronic atoms

- Mix dbar and protons obtained by H^- stripping
- Mix dbar and low-Z nuclei by buffer gas
- Mix dbar and high-Z nuclei from anionic sources

Antideuteron

- Measure precisely the dbar mass
- Measure the magnetic moment
- Measure the binding energy

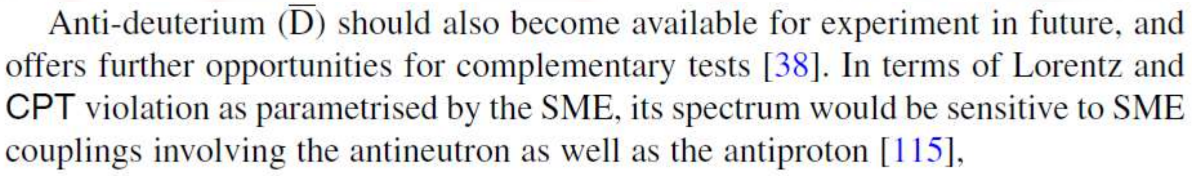
Synthesize heavier antinuclei

- Fuse antideuterons together

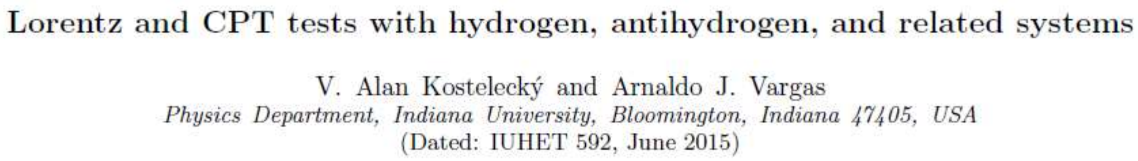
Antideuterium

- Form and trap Dbar
- Test CPT by Dbar spectroscopy
- Test the WEP by free-falling Dbar

CPT and Lorentz invariance motivations



Anti-deuterium ($\overline{\mathrm{D}}$) should also become available for experiment in future, and offers further opportunities for complementary tests [38]. In terms of Lorentz and CPT violation as parametrised by the SME, its spectrum would be sensitive to SME couplings involving the antineutron as well as the antiproton [115],



Lorentz and CPT tests with hydrogen, antihydrogen, and related systems

V. Alan Kostelecký and Arnaldo J. Vargas
Physics Department, Indiana University, Bloomington, Indiana 47405, USA
(Dated: IUHET 592, June 2015)

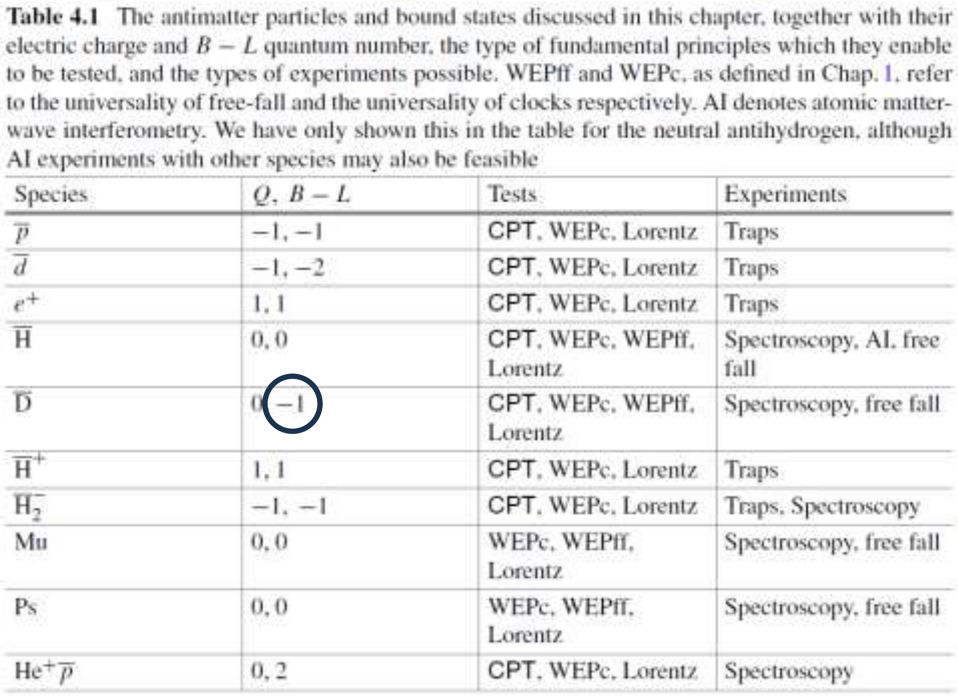


Table 4.1 The antimatter particles and bound states discussed in this chapter, together with their electric charge and $B-L$ quantum number, the type of fundamental principles which they enable to be tested, and the types of experiments possible. WEPff and WEPc, as defined in Chap. 1, refer to the universality of free-fall and the universality of clocks respectively. AI denotes atomic matter-wave interferometry. We have only shown this in the table for the neutral antihydrogen, although AI experiments with other species may also be feasible

Species	Q, $B-L$	Tests	Experiments
$\overline{p}$	−1, −1	CPT, WEPc, Lorentz	Traps
$\overline{d}$	−1, −2	CPT, WEPc, Lorentz	Traps
e^+	1, 1	CPT, WEPc, Lorentz	Traps
$\overline{\mathrm{H}}$	0, 0	CPT, WEPc, WEPff, Lorentz	Spectroscopy, AI, free fall
$\overline{\mathrm{D}}$	0, −1	CPT, WEPc, WEPff, Lorentz	Spectroscopy, free fall
$\overline{\mathrm{H}}^+$	1, 1	CPT, WEPc, Lorentz	Traps
$\overline{\mathrm{H}}_2^-$	−1, −1	CPT, WEPc, Lorentz	Traps, Spectroscopy
Mu	0, 0	WEPc, WEPff, Lorentz	Spectroscopy, free fall
Ps	0, 0	WEPc, WEPff, Lorentz	Spectroscopy, free fall
He$^+\overline{p}$	0, 2	CPT, WEPc, Lorentz	Spectroscopy

M. Charlton et al., *Antihydrogen and Fundamental Physics*,

Some theoretical insights

- Antideuterons can be a tool to set constraints on SME coefficients not accessible by other means in the antineutron sector
- Antideuterium has a net *B* – *L* charge: in principle can be used to test gauged *B* – *L* interactions (stringent tests with matter already there) or other *B* – *L* interactions specific of antimatter (subject to be deepened)

Further theoretical investigation is required to work out the full list of coefficients constrained by antideuteron/antideuterium experiments.

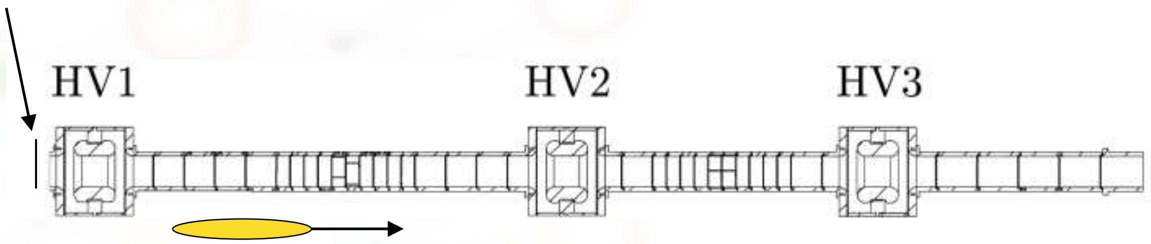
Fusing antideuterons in Penning traps

Assumptions

Cross-section: 100 mb at 160 keV (c.m)

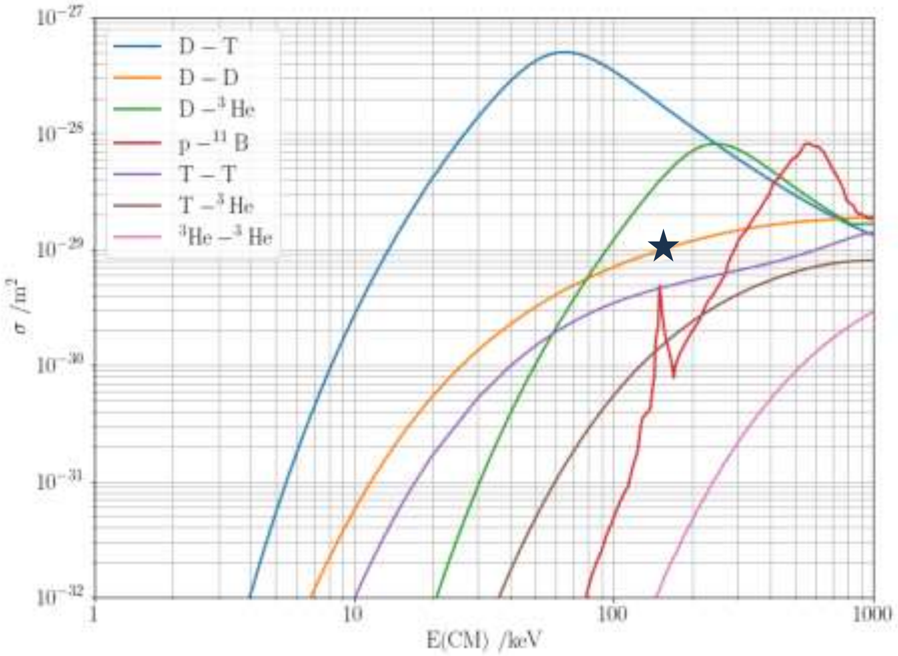
dbars in trap (24 h at 1000 /shot): $3.6 \cdot 10^5$

Plasma volume: $10\ \mathrm{cm} \cdot \pi\ (1\ \mathrm{mm})^2$



Degrader

80 keV, no cooling



$$\bar{\mathrm{d}} + \bar{\mathrm{d}} \rightarrow \overline{{}^3\mathrm{He}} + \mathrm{n}$$

$$\bar{\mathrm{d}} + \bar{\mathrm{d}} \rightarrow \overline{{}^3\mathrm{H}} + \mathrm{p}$$

$$R_{\bar{d}\bar{d}} = \frac{N_{\bar{d}}^2}{V_{trap}}\, \sigma\, v_{rel} \approx 2.0\,\mathrm{evt/day}$$

Motivates a study of “hot storage” for long periods of time

Antideuterons production in fixed target experiments

Production rate and momentum from exp. data

- Absolute production cross-section at 30 GeV in fixed target experiments estimated at 10 nb / (sr · GeV/c)
- Three orders of magnitude higher dbar yield at 200 GeV compared to 20 GeV (unfortunately unaccessible at PS)
- Momentum distribution peaked at the center-of-mass momentum: antideuterons formed at rest in the c.-m. by coalescence of pbar and nbar
- At 26 GeV incoming protons, secondary momentum is a broad peak centered at 7 GeV/c with moderate dependence on the target material

Production mechanism

- For E < 30 GeV: cascade model of [2]
- For E > 100 GeV: nucleon-nucleon collisions

CERN-PS proton beam	
Energy	26 GeV
Bunches	5
p delivered	$1.75 \cdot 10^{13}$

Production thresholds	
$\bar{p}$	5.6 GeV
$\bar{d}$	16 GeV
$^3\overline{He}$	28 GeV
$^4\overline{He}$	45 GeV

E_p	Z_{target}	Obs. K’	Calc. K’
26 GeV	9	7 GeV/c	9.5 GeV/c
70 GeV	9	17 GeV/c	16.7 GeV/c
200 GeV	9	30 GeV/c	28.8 GeV/c

[1] H. Koch, 10.1007/bf02398657
[2] S. T. Butler, C. A. Pearson, 10.1103/physrev.129.836

Antideuterons production: the cascade model

Optical potential $\kappa^2 = mV_0/\hbar^2$

Binding energy $E_b = \hbar^2\gamma^2/m$

Momentum c.m

Antiproton distribution

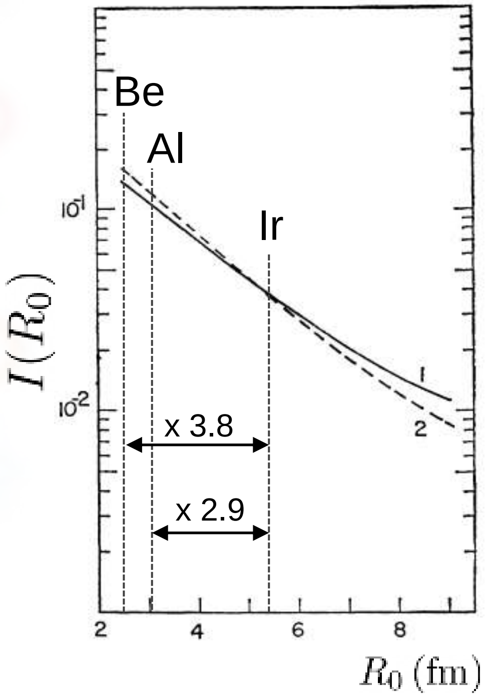
$$n_{\bar{d}}(\vec{K}) = \frac{3(48)^2\pi}{\eta}\,\frac{\kappa^4}{K^4}\,\frac{\gamma}{\Lambda}\underbrace{\left(\frac{\hbar^2K^2}{4m^2c^2}+1\right)}_{\text{Relativistic correction}}{}^{3/2}\, I(R_0)\left[n_{\bar{p}}\left(\frac{\vec{K}}{2}\right)\right]^2$$

Target efficiency

Wavenumber $\Lambda \equiv 1\,\mathrm{GeV/c}$

Relativistic correction

Nuclear scattering



Cascade model

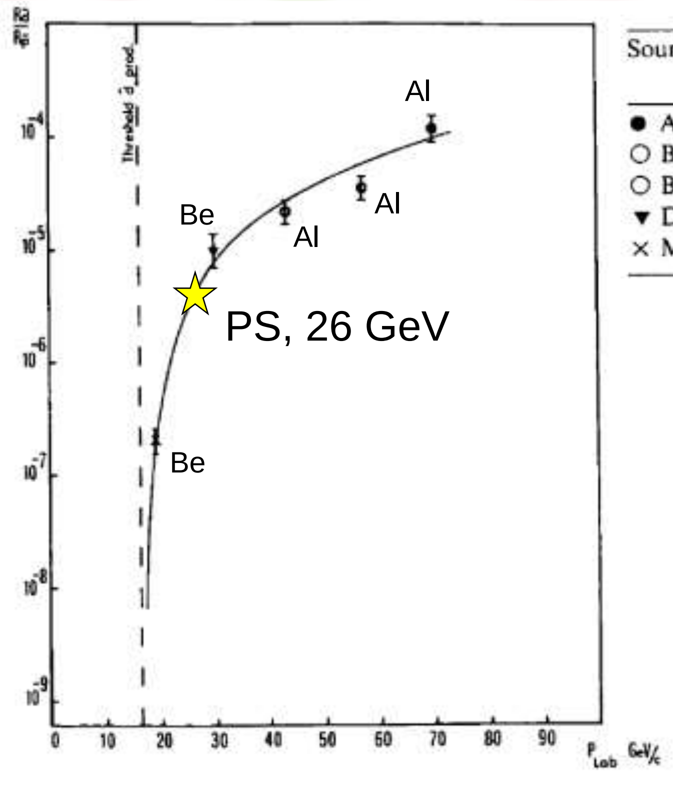
- The proton initiates a hadronic cascade including baryons and antibaryons
- Antiproton and antineutrons of small relative momentum coalesce into an antideuteron
- Nuclear scattering contribution
- Connection between momentum distribution of (anti)deuterons and (anti)protons at a given angle

Consequences

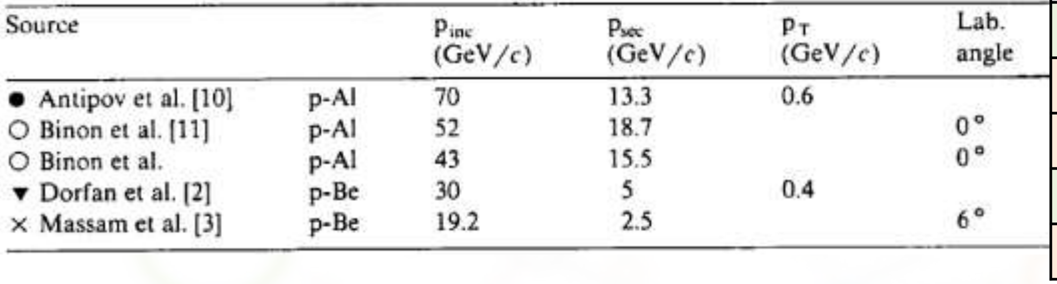
- *A*-dependance of the dbar production rate: Be and Al better target choices than Ir
- The production maximum momentum for antideuterons is always twice the maximum for antiprotons

[1] S. T. Butler, C. A. Pearson, 10.1103/physrev.129.836

Expected antideuterons production from the AD target



Antiproton equivalent



Source		p_{inc} (GeV/c)	p_{sec} (GeV/c)	p_T (GeV/c)	Lab. angle
● Antipov et al. [10]	p-Al	70	13.3	0.6	
○ Binon et al. [11]	p-Al	52	18.7		0°
○ Binon et al.	p-Al	43	15.5		0°
▼ Dorfan et al. [2]	p-Be	30	5	0.4	
× Massam et al. [3]	p-Be	19.2	2.5		6°

E_p	Z_{target}	K'_{pbar}	K'_{dbar}
70 GeV	27	13.7 GeV/c	27.4 GeV/c
52 GeV	27	11.5 GeV/c	23.0 GeV/c
43 GeV	27	10.2 GeV/c	20.5 GeV/c
30 GeV	9	5.3 GeV/c	10.5 GeV/c
19.2 GeV	9	4.0 GeV/c	8.1 GeV/c

Interpolated value for 26 GeV/c primary, 3.5 GeV/c secondary:
(in beryllium, a bit pessimistic as the peak is at 4.8 GeV/c)

$$\frac{R_{\bar d}}{R_{\bar p}} = 4 \cdot 10^{-6}$$

Flux estimation from the AD target

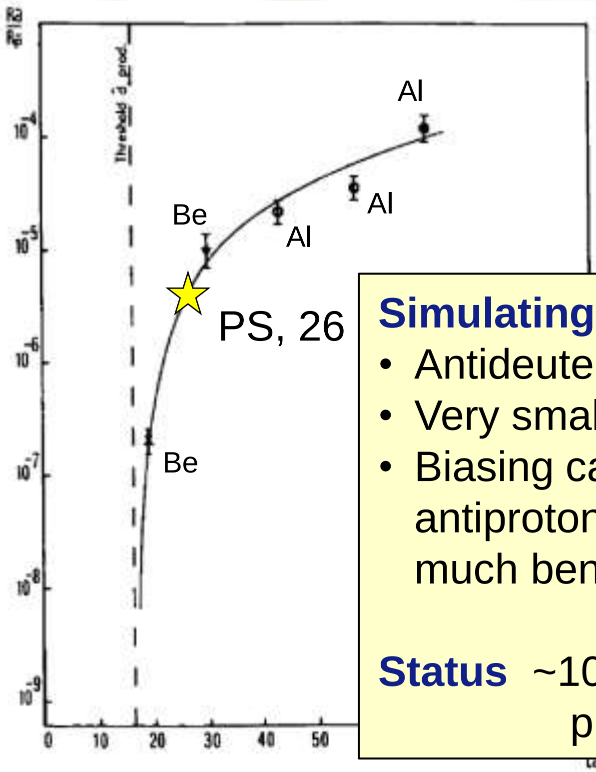
- Produced antiprotons $40 \cdot 10^6$ shot^{-1}
- Factor of 1/3.8 Be-Ir conversion
- Expected flux: 42 dbar shot^{-1}
- Peak momentum: 11.4 GeV/c

E_p	Z_{target}	K'	Yield
26 GeV	9	4.85 GeV/c	3.8
26 GeV	27	7.43 GeV/c	2.9
26 GeV	192	11.4 GeV/c	1

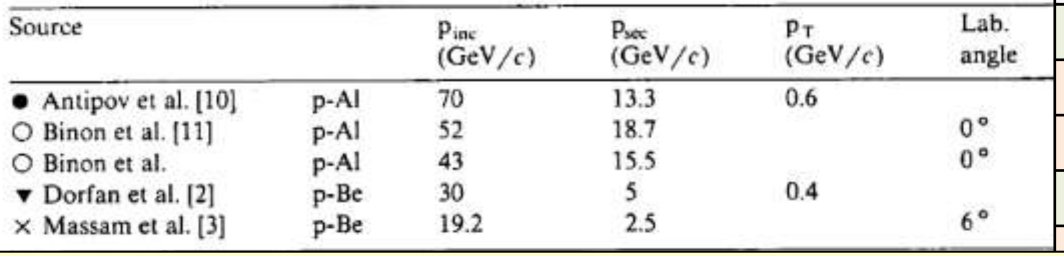
[1] C. D. Johnson, T. R. Sherwood, 10.1007/bf02398658

To be re-evaluated from Monte Carlo

Expected antideuterons production from the AD target



Antiproton equivalent



Source		p_{inc} (GeV/c)	p_{sec} (GeV/c)	p_T (GeV/c)	Lab. angle
● Antipov et al. [10]	p-Al	70	13.3	0.6	
○ Binon et al. [11]	p-Al	52	18.7		0°
○ Binon et al.	p-Al	43	15.5		0°
▼ Dorfan et al. [2]	p-Be	30	5	0.4	
× Massam et al. [3]	p-Be	19.2	2.5		6°

E_p	Z_{target}	K'_{pbar}	K'_{dbar}
70 GeV	27	13.7 GeV/c	27.4 GeV/c
52 GeV	27	11.5 GeV/c	23.0 GeV/c
43 GeV	27	10.2 GeV/c	20.5 GeV/c
30 GeV	9	5.3 GeV/c	10.5 GeV/c
19.2 GeV	9	4.0 GeV/c	8.1 GeV/c

Simulating the production with Geant4

- Antideuteron production is possible in Geant4
- Very small cross-section (1 event per 10^{12}): no easy and fast way
- Biasing can be applied only to an initial proton inelastic process (including antiproton/antineutron production), and thus scales everything altogether without much benefit for rare processes: 10^{13} simulated particles are needed

Status ~10^5 antiprotons and ~5 10^4 antineutrons in 3 days. For coalescence processes 10^6 of each species are needed (moving to a server farm)

$\cdot\ 10^{-6}$

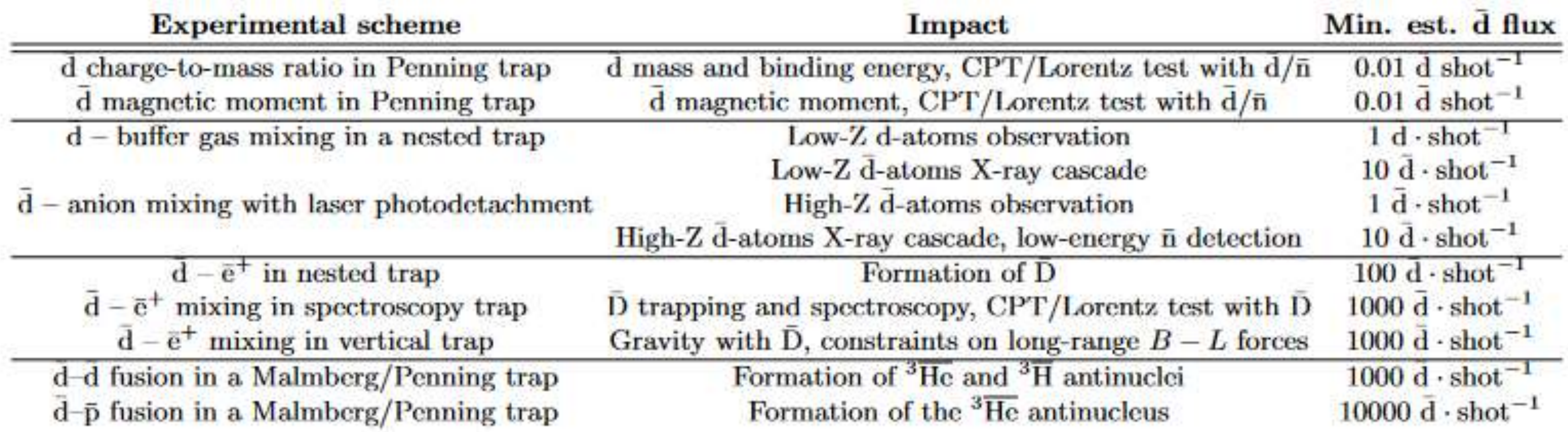
- Produced antiprotons 40 · 10^6 shot^{-1}
- Factor of 1/3.8 Be-Ir conversion
- Expected flux: 42 dbar shot^{-1}
- Peak momentum: 11.4 GeV/c

			Yield
26 GeV	9	4.85 GeV/c	3.8
26 GeV	27	7.43 GeV/c	2.9
26 GeV	192	11.4 GeV/c	1

To be re-evaluated from Monte Carlo

[1] C. D. Johnson, T. R. Sherwood, 10.1007/bf02398658

Some flux orders of magnitude for trapped antideuteron experiments



Experimental scheme	Impact	Min. est. $\bar{d}$ flux
$\bar{d}$ charge-to-mass ratio in Penning trap	$\bar{d}$ mass and binding energy, CPT/Lorentz test with $\bar{d}/\bar{n}$	0.01 $\bar{d}$ shot^{-1}
$\bar{d}$ magnetic moment in Penning trap	$\bar{d}$ magnetic moment, CPT/Lorentz test with $\bar{d}/\bar{n}$	0.01 $\bar{d}$ shot^{-1}
$\bar{d}$ – buffer gas mixing in a nested trap	Low-Z $\bar{d}$-atoms observation	1 $\bar{d}\cdot$shot^{-1}
$\bar{d}$ – anion mixing with laser photodetachment	Low-Z $\bar{d}$-atoms X-ray cascade	10 $\bar{d}\cdot$shot^{-1}
	High-Z $\bar{d}$-atoms observation	1 $\bar{d}\cdot$shot^{-1}
	High-Z $\bar{d}$-atoms X-ray cascade, low-energy $\bar{n}$ detection	10 $\bar{d}\cdot$shot^{-1}
$\bar{d}-\bar{e}^+$ in nested trap	Formation of $\bar{D}$	100 $\bar{d}\cdot$shot^{-1}
$\bar{d}-\bar{e}^+$ mixing in spectroscopy trap	$\bar{D}$ trapping and spectroscopy, CPT/Lorentz test with $\bar{D}$	1000 $\bar{d}\cdot$shot^{-1}
$\bar{d}-\bar{e}^+$ mixing in vertical trap	Gravity with $\bar{D}$, constraints on long-range $B-L$ forces	1000 $\bar{d}\cdot$shot^{-1}
$\bar{d}$–$\bar{d}$ fusion in a Malmberg/Penning trap	Formation of $^3\overline{\mathrm{He}}$ and $^3\overline{\mathrm{H}}$ antinuclei	1000 $\bar{d}\cdot$shot^{-1}
$\bar{d}$–$\bar{p}$ fusion in a Malmberg/Penning trap	Formation of the $^3\overline{\mathrm{He}}$ antinucleus	10000 $\bar{d}\cdot$shot^{-1}

Table I: Summary of the prospects enabled by experimental schemes employing cold antideuterons and estimate of the required flux

Increase in intensity

R. Caravita, *Perspectives from a cold antideuteron beam in the AD/ELENA facility*, arXiv

Wrapping up

Experiment prospects:

- Technologies from experiment-side are very developed

Production prospects

- From the current target, ~42 dbar shot^{-1} at 11.4 GeV/c
- Increase possibility by going to lower Z targets
- Detailed Geant4 simulation is a necessity: in progress

Physics prospects

- Physics prospects of testing CPT already with less than 1 /shot
- Detecting antideuteronic atoms requires fluxes of at least 10 /shot
- Complementary to antihydrogen: more theoretical insight is required

Machine operation

- Would need operation diagnostics for very small number of particles
- Background of antiprotons most likely present: to be estimated
- Machine tuning is most likely very challenging: tuning with pbars? A guiding deuterium beam? A lot of open questions

an initial excursion

THANKS FOR THE ATTENTION