Towards a spin polarized antihydrogen beam

N. KURODA

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Atomic **S**pectroscopy **A**nd **C**ollisions **U**sing **Sl**ow **A**ntiprotons

- $\overline{p}$He laser spectroscopy : $m_{\overline{p}}$ vs. m_p
- $\overline{p}$He microwave spectroscopy : $\mu_{\overline{p}}$
- $\overline{p}$A collision : formation and ionization cross section
- $\overline{p}$N collision : in flight annihilation cross section
- $\overline{p}e^+ = \overline{H}$ beam microwave spectroscopy :

$$\mu_{\overline{p}},\ \ G_E(-q^2),\ \ G_M(-q^2)$$

  - CUSP trap
  - RF trap

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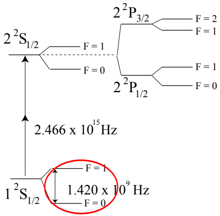
Ground-state hyperfine splitting of $\overline{\mathrm{H}}$

quantity	exp. value [Hz]	δ_{exp}/ν	δ_{th}/ν
ν_{1S-2S}	2 466 061 413 187 103(46)	1.7×10^{-14}	1×10^{-11}
ν_{2S-2P}	$1\,057\,8450(29) \times 10^3$	2.7×10^{-6}	3.8×10^{-11}
ν_{HFS}	1 420 405 751.7667(9)	6.3×10^{-13}	$(3.5 \pm 0.9) \times 10^{-6}$

$$\nu_{FC} = \frac{16}{3}\left(\frac{m_{\bar{p}}}{m_{\bar{p}} + m_{e^+}}\right)^3 \frac{m_{e^+}}{m_{\bar{p}}} \frac{\mu_{e^+}}{\mu_B} \frac{\mu_{\bar{p}}}{\mu_N}$$

$$\Delta\nu = \nu_{FC} \frac{2Z\alpha m_{e^+}}{\pi^2} \int \frac{d^3q}{q^4}\left[\frac{G_E(-q^2)G_M(-q^2)}{1+\kappa} - 1\right]$$

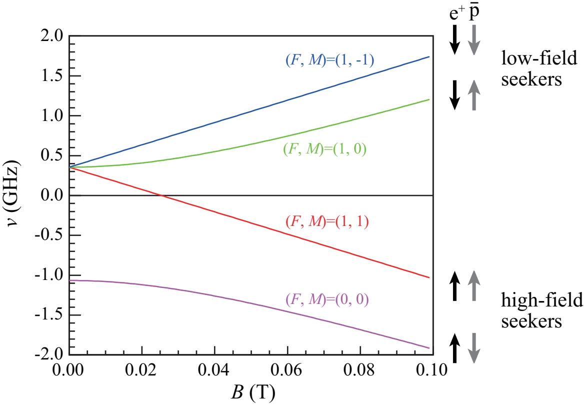


- Magnetic moment of $\bar{\mathbf{p}}$

  $\Delta_{CPT} = 5 \times 10^{-6}$ (by ATRAP)
- Antiproton's magnetic form factor

  electric form factor

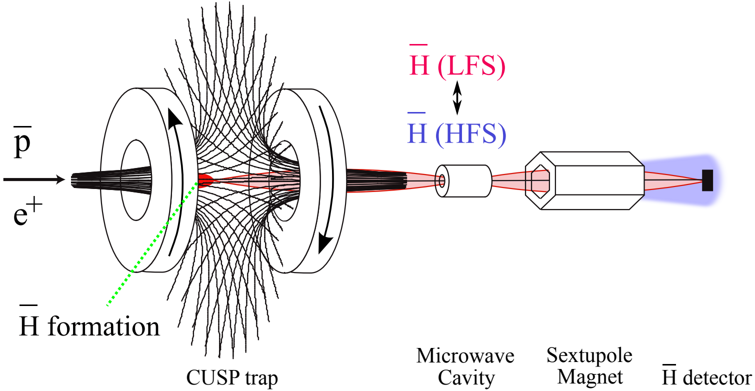
GS-HFS measurement



total Spin : F, total magnetic quantum number M_F

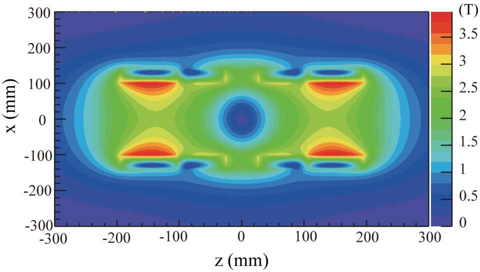
- parallel to B : low field seeker (F,M) = (1,-1), (1,0)
- anti-parallel to B : high field seeker (F,M) = (1,1), (0,0)

Anti-atomic beam experiment



1. inhomogeneous magnetic field → spin state selection by a cusp magnetic field
2. spin flip by microwave cavity
3. investigate by sextupole magnetic field

Anti-atomic beam experiment



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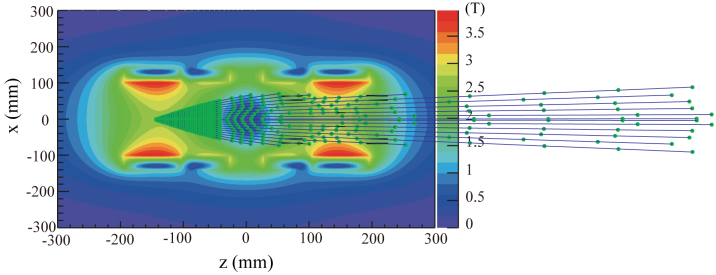

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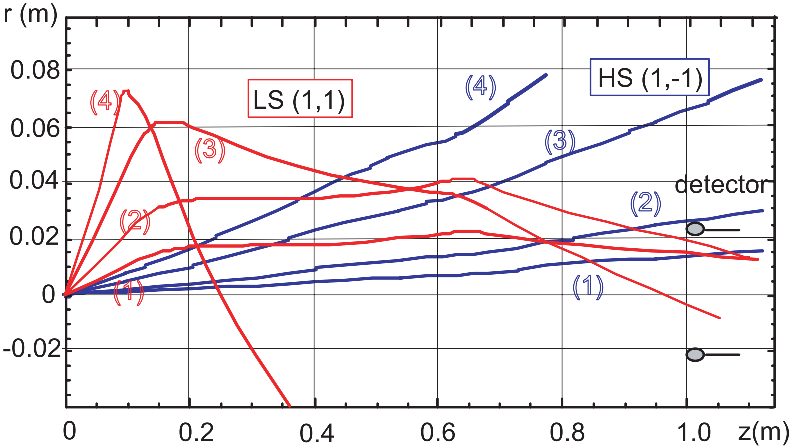
a cusp magnetic field

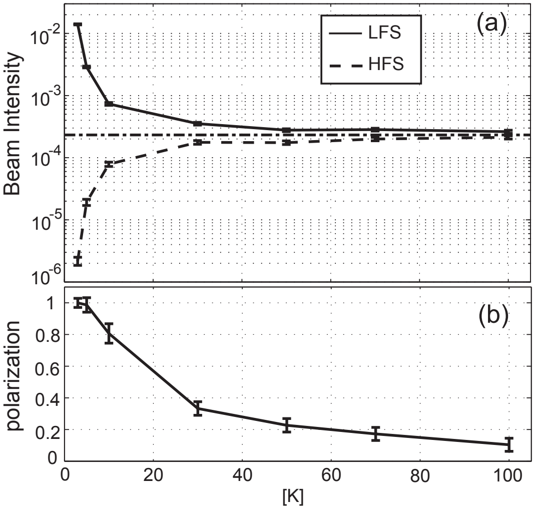


for 3 K $\overline{\mathbf{H}}$

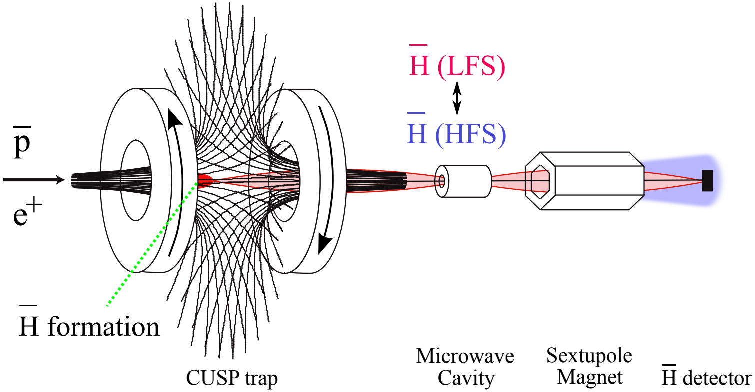
- inhomogeneous magnetic field → spin state selection by a cusp magnetic field

spin polarization

expected polarization of $\overline{\mathbf{H}}$ beam



Anti-atomic beam experiment



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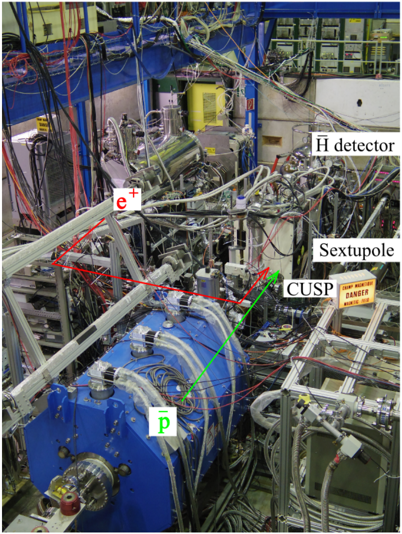
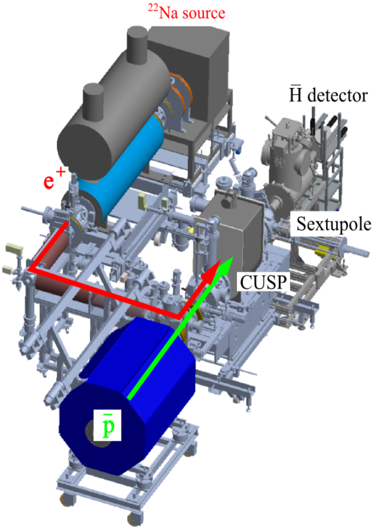
Whole setup



- e^+: Ne moderator, N_2 gas moderator, MRE
- $\bar{p}$: MUSASHI trap
- $\bar{H}$ formation: CUSP trap
- $\bar{H}$ spin-state analysis: Sextupole
- $\bar{H}$ beam detection: BGO-$\bar{H}$ detector
- detectors:
  3D scintillator bar detector
  track detector

1. e^+ accumulation (10–100 stacks)
2. $\bar{p}$ accumulation, compression in MUSASHI (3–5 AD shots)
3. $\bar{p}$ transport
4. mixing ($\bar{H}$ formation)

Whole setup



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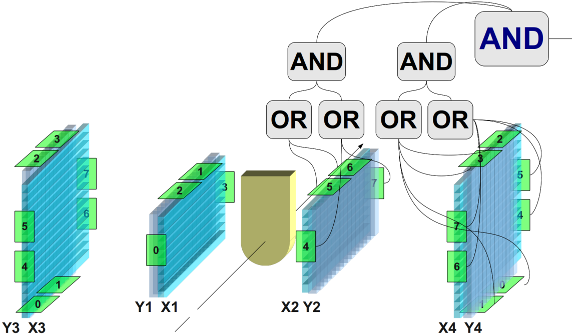
Pion tracking detector

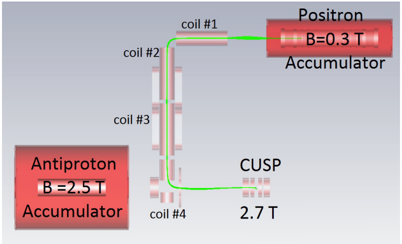
- Scintillator bars
  15 mm × 15 mm
  960 mm in length
- $\Omega/4\pi$ = 6.6% + 8.6%
  for each side
- for $\pi^{\pm}$ multiplicity 3
  ⇒ 39%
- double coincidence
  ⇒ 3.3%

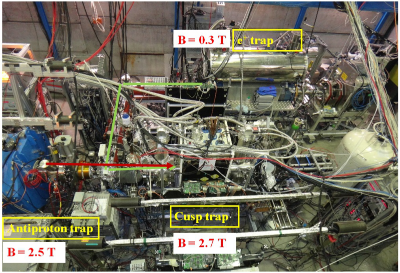


low energy e^+ transport

modification from the previous "compact" $\mathbf{e^+}$ source:

- solid $\mathbf{Ne}$ moderator
- for evacuation, $^{22}\mathbf{Na}$ source and moderator were located outside the solenoid
- transfer $\mathbf{e^+}$ of $\mathbf{10^7}$ in total within 10 min or so to the cusp

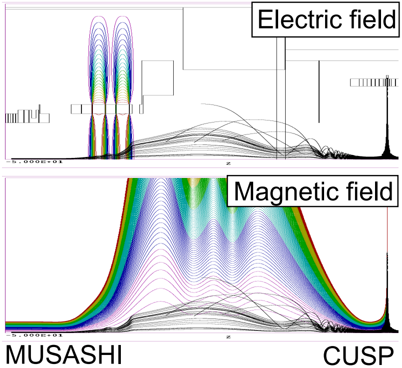




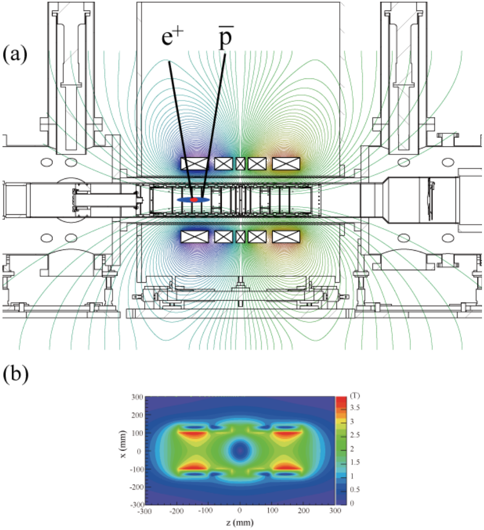
ultraslow $\bar{p}$ beam transport

pulse extraction from the MUSASHI trap

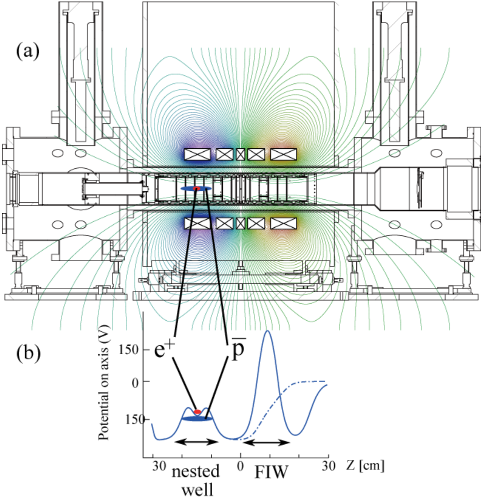
- transfer $3 \times 10^5 \bar{p}$
- $\sim$ 150 eV
- $\sim$ 2 μs width
- guided by magnetic fields
- ...but non adiabatic transport?



CUSP trap


(a)
e+
p̄
(b)
x (mm)
z (mm)
(T)
300
200
100
0
-100
-200
-300
100
200
300
3.5
3
2.5
2
1.5
1
0.5
0

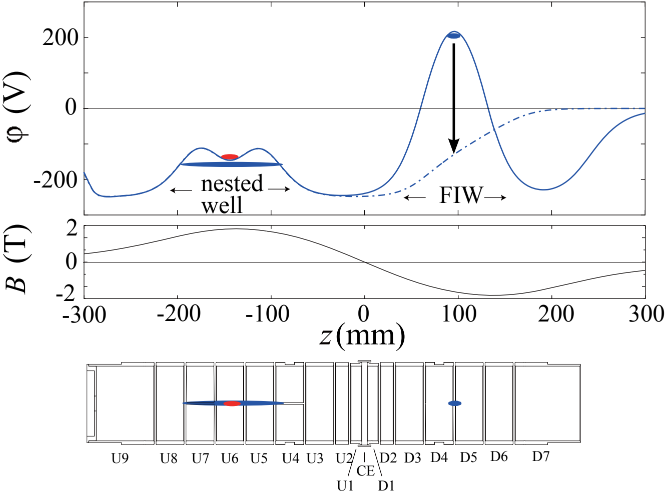
CUSP trap



Synthesis of $\bar{\mathbf{H}}$

How to mix? ⇒ Nested well

How to detect? ⇒ Field Ionization of $\bar{\mathbf{H}}$



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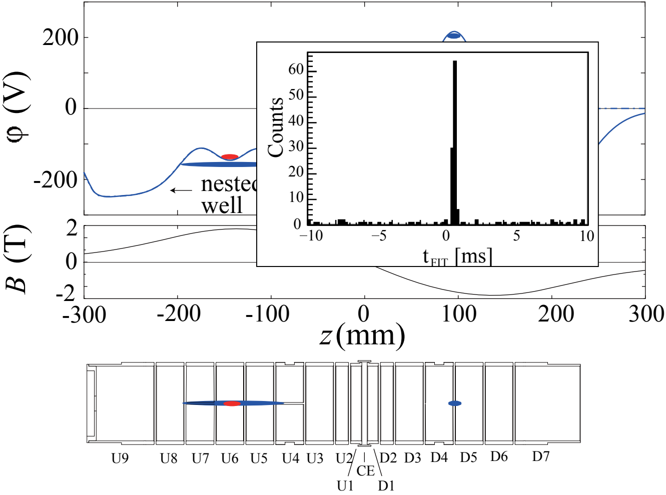
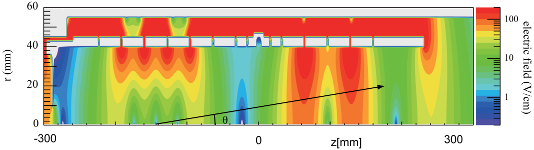
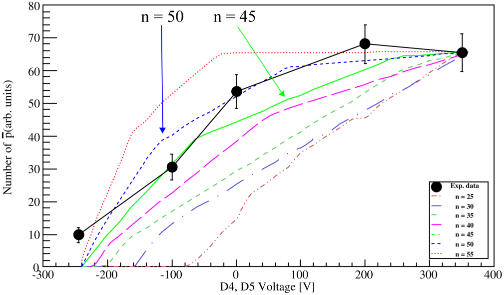


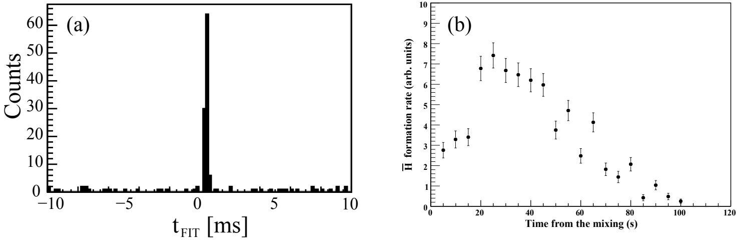
Field Ionization measurement

- considering electric field map
- $\mathcal{E} \sim 3.2 \times 10^8 n^{-4}$ (V/cm)
- changing F.I. well depth
- on average $n \sim 45$–50
- $n \sim 400/\sqrt{T_{e^+}}$
- observed $\mathbf{e^+}$ temperature $T_{e^+} \sim 1 \times 10^2$ K





Field Ionized measurements



e^+ : 3×10^6

$\bar{p}$: 3×10^5

110 s mixing
on average 70 counts/cycle ⇒ 7000 events/cycle were expected

Assuming isotropic distribution, 2.3%

- In 2012 we have 10 times more e^+ ⇒ only ∼ 3 time more $\overline{H}$
- limitation of total number?
- stop the reaction?

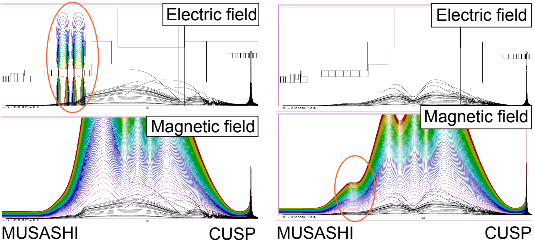
What does limit the number?

Direct injection

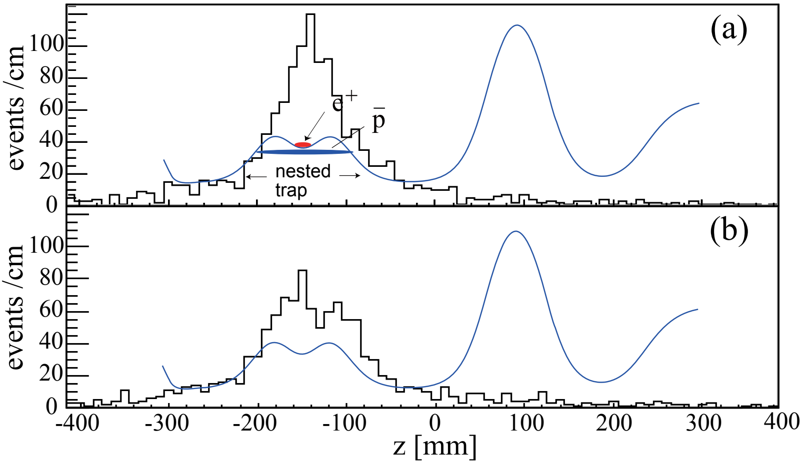
limited total number/rate ⇐ $\bar{p}$ beam energy width?

⇒ adiabatic transport

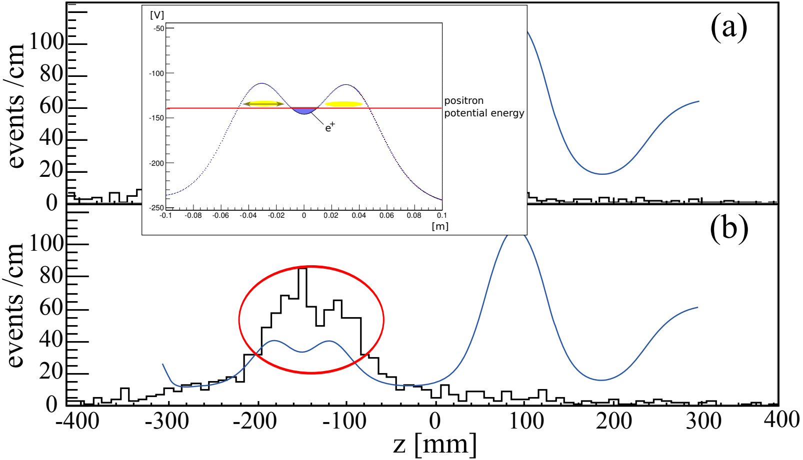
- new transport optics
- lower transport energy



Annihilation position

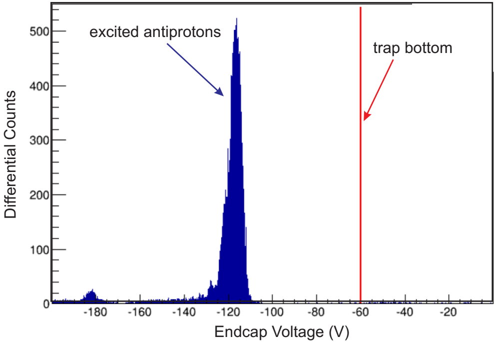


Suppress the synthesis?



Cold $\overline{H}$?

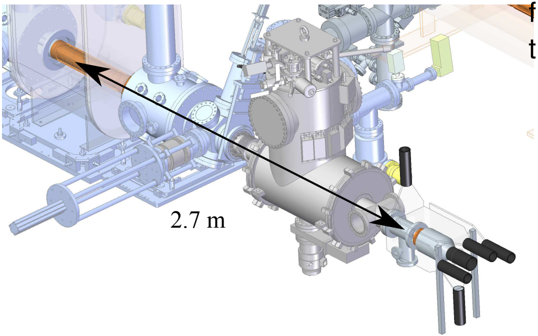
Autoresonant excitation?



It is expected to produce cold $\overline{\mathbf{H}}$, but yield?

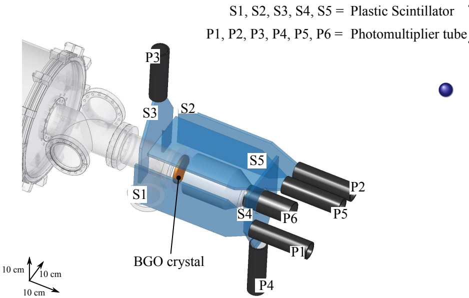
But we have not confirmed $\overline{\mathbf{H}}$ signals yet...

$\overline{\text{H}}$ beam detector



- located 2.7 m downstream from the $\overline{\mathbf{H}}$ production region in the cusp trap

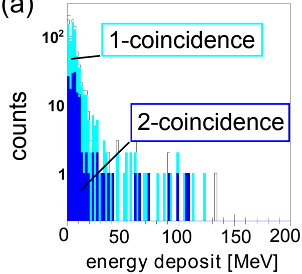
$\bar{H}$ beam detector



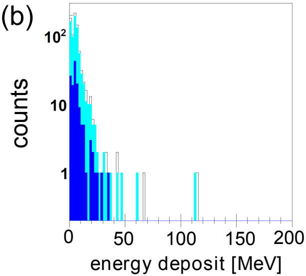
- located 2.7 m downstream from the $\bar{H}$ production region in the cusp trap
- BGO single-crystal
  - determine energy deposits by $\bar{H}$ annihilation
  - energy calibration
    - cosmic rays
    - πs from upstream.
- 5 plastic scintillator
  - require a multiplicity

Detector test with ultraslow antiproton beams and cosmic rays

(a)



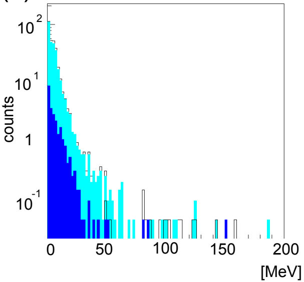
(b)



Preliminary results

- slow extraction from the MUSASHI trap
  - (a) beam hit
  - (b) repel $\bar{p}$ beam
- (c) cosmic ray + Pions from upstream

(c)



Summary

A cusp trap scheme

for spectroscopic studies of ground-state hyperfine splitting of $\bar{\mathbf{H}}$

- increased $\mathbf{e}^{+}$ numbers
- study of $\bar{\mathbf{H}}$ synthesis
  suppress by the separation?
- test experiments with the BGO $\bar{\mathbf{H}}$ detector

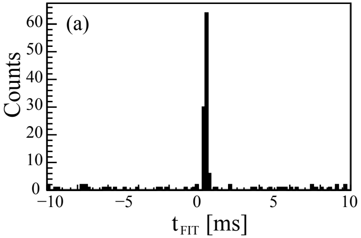
Analysis is ongoing.

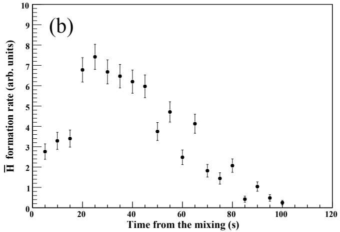
For the planned spectroscopy, we need to know/improve

- total number of $\bar{\mathbf{H}}$?
- n-state?
- spin-state?
- temperature?

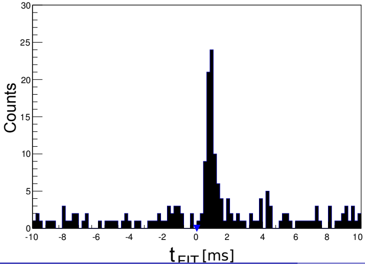
Field Ionized measurements

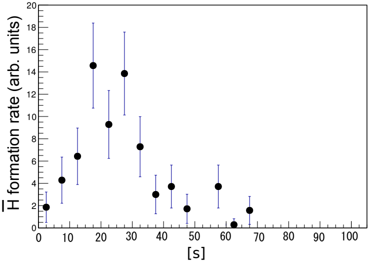
2010



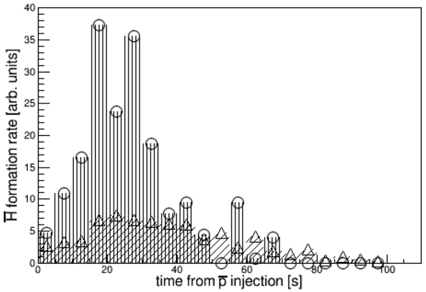


2012





Field Ionized measurements



△ for 2010, ○ for 2012

$\mathbf{e}^+$: $3 \times 10^6 \Rightarrow 3 \times 10^7$ (10 times more)
190 counts/mix (in 2012) should be compared to 50–70 counts/mix (in 2010)

Assuming isotropic distribution, 6.3% (in 2012) vs. 2.3% (in 2010)

- only ~ 3 time more $\overline{\mathbf{H}}$, even though 10 times more $\mathbf{e}^+$
- from a simple solid angle $\longrightarrow$ 2 Rydberg $\overline{\mathbf{H}}$ at the end of the spectrometer line