GBAR principle: cool $\bar{H}^+$ to get ultra-slow $\bar{H}$

- $\bar{H}^+ = \bar{p} \ e^+ e^+$
- Sympathetic cooling with $\text{Be}^+ \rightarrow 10 \ \mu\text{K}$
- Photodetachment of $e^+$
- Time of flight

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$m_i \ddot{a} = m_g \ddot{g}$

$h = v_0^2 t + \frac{1}{2} \frac{m_g}{m_i} g t^2$

$\Delta g / g \leq 1\%$

Goal

- $L = 0.1 \ \text{m}$
- $h = 10 \ \text{cm}$
- $\Delta t = 143 \ \text{ms}$
- $v_h = 0.5 \ \text{m/s}$
- $T_H = 20 \ \mu\text{K} \sim 7 \ \text{neV}$

A recipe to produce anti ions

Standard $\bar{H}$ production via 3-body process:

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$$

Demonstrated by ATRAP (2004)

Idea for GBAR: 2nd charge exchange reaction:

$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$
$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

Expect cross-section enhancement if Ps excited to n=3

Binding energy of $\bar{H}^+ = 0.75$ eV = energy level of Ps(n=3)

CERN provides per bunch every 110 s

\[ \sim 0.5 \times 10^7 \bar{p} \]

\[ 10^{12} P_S /\text{cm}^2 \]

\[ \rightarrow \]

\[ 10^4 \bar{H} \]

\[ 1 \bar{H}^+ \]

\[ \text{SiO}_2 \text{ coating} \]

\[ 1-6 \text{ keV} \]

\[ \sim 3 \text{ keV} \]

\[ \text{threshold for } P_s(1s) \]

\[ 20\% P_s(2p) \]

\[ 100\% P_s(1s) \]

\[ 40\% P_s(3d) \]

\[ \sigma^{(2)} \left( \frac{(\pi a_0^2)^2}{(n a_0^2)^2} \right) \]

\[ \text{Impact energy (keV)} \]

\[ P. \text{ Comini and P-A. Hervieux, J. Phys.: Conf. Ser. 443, 012007 (2013)} \]

\[ P. \text{ Comini, P-A. Hervieux and F. Biraben, LEAP 2013} \]
Antiprotons: CERN AD / ELENA

1. Antiproton Production
2. Injection at 3.5 GeV/c
3. Deceleration and Cooling (3.5 - 0.1 GeV/c)
4. Extraction (3 \times 10^7 in <300 ns)

5 MeV

100 keV

Location for future ELENA installation

Electron Cooling

Stochastic Cooling
Layout
GBAR antiproton decelerator

1 pulse / 110 s
100 keV ā pulse
300 ns (1.3 m)

4π mm mrad

- 99 kV

switch

0 V

1 keV (0.2 m)

40π mm mrad
1 mm × 1 mm × 2 cm  
Si with mesoporous SiO₂ coating

Test on ETHZ beam line  
Transmission @ 5 keV ~ 100%  
Ps formation efficiency as for bare SiO₂  
Same Ps lifetime distribution

P. Crivelli, WAG2013
Ps excitation laser ($n=3$)

Presently developed at LKB – Paris
To be tested at Saclay
e+/Ps demonstrator at Saclay

- 4.3 MeV / 200 Hz / 2.5 μs / 120 μA
- 3 \(10^6\) slow e\(^+\)/s
- with first W mesh moderator
- Penning trap on beam line (from RIKEN)
- First trapping trials

- Secondary beam line
- \(\rightarrow\) moderator developments
- \(\rightarrow\) e+/Ps converters
- Ps* laser being prepared at LKB (Paris)
Concrete shielding

X rays

**e⁺/Ps demonstrator at Saclay**

- **e⁻ Linac**
  - \( Ec = 4.3 \text{ MeV} \)
  - \( I = 0.14 \text{ mA} \)

- **CERN version**: 10 MeV, 0.2 mA
  - Built by NCBJ Warsaw
  - \( 1-3 \times 10^8 \text{ e⁺/s} \)

1 Dec. 2014

P. Pérez - TCP2014
RIKEN Multi-Ring Trap

Must accumulate $3 \times 10^{10} \, e^+$ in 110 s
e\textsuperscript{+} trapping

electron plasma for cooling

- e\textsuperscript{+} pulse
- e\textsuperscript{+} trapped
- between barriers

Potential on axis (V)

Longitudinal Magnetic Field on axis (T)

Z position (m)

with electron plasma
without electron plasma

Trapped positions (arb. unit.)

Accumulation time (s)
H⁺ production scheme
Cooling challenges

Reaction chamber

Kinetic energy 1 .. 6 keV
Temperature 60 .. 300 eV
700 000 K

Capture + Cooling

Trapped particule
Temperature 3 neV
20 µK

Cold trapped $\bar{H}^+$

Classical world

Frontiers of Quantum world


H with $v < 1 \text{ m/s}$

NIST D. Wineland
Innsbruck R. Blatt
9/1 mass ratio: bad mechanical coupling
9/2 mass ratio: much better mechanical coupling

Idea: try an intermediate ion 9 / 3 / 1

C. B. Zhang, D. Oenberg, B. Roth, M. A. Wilson, and S. Schiller,
L. Hilico et al., IJMPCS 2014

few meV \( \bar{H}^+ \)

1800 Be\(^+\)
200 HD\(^+\)
1 \( \bar{H}^+ \)

L. Hilico et al., (2014)
Be$^+$ sub Doppler cooling

Stimulated & Spontaneous Raman transitions

Cycle sequence:
- $F = 2, \ n$ gives $F = 1, \ n-1$
- $F = 2, \ n-1$ gives $F = 2, \ n=0$

$T \sim 4.5$ or 9 $\mu$K for Be$^+$ ions

$\nu \sim 10$ cm/s ?

$\nu_{\text{hfs}} = 1.25$ GHz
Two cooling steps

First step
 Capture and sympathetic Doppler cooling by laser cooled Be$^+$ ions in the linear capture trap (Paul trap, $r_0 = 3.5$ mm, $\Omega = 13$ MHz)

$\div 3 \times 10^9$

Second step
 Transfer and ground state cooling of a Be$^+$/H$^+$ ion pair in the precision trap

Tests with H$_2^+$ / H$^+$ REMPI source
First Ca$^+$ ions and linear ion crystals trapped at Mainz

- **2015**: capture trap construction and tests of cooling of Ca$^+$/Be$^+$, transport of ions between traps
- **2016**: cooling of H$_2^+$ with Be$^+$/HD$^+$ mixture
- **2017**: transport to CERN
\[ \bar{H}^+ \rightarrow \bar{H} + e^+ \]

Detection | Requirement
--- | ---
TOF precision | 150 \( \mu s \)
Annihil. vertex precision | 2 mm
Background rejection | event topology

\( \bar{H} \) free fall detection
MicroMegas detector

Argon Isobutane (95%, 5%)
Pitch of strip ~ 400 microns
X and Y strips give track position directly

Genetic multiplexing of strips
S. Procureur et al, NIM A 729 (2013) 888

Microstrip Modules
Annihilation

1 cm 4 cm
4 cm 50 cm

Particle
MicroMegas detector
D. Banerjee, P. Crivelli
S. Aune, B. Vallage
HV1
HV2
1 kV/cm
40kV/cm

Amplification conversion 3 mm
Micromesh
Strips

MicroMegas detector

1 Dec. 2014
P. Pérez - TCP2014
Reflection probability

altitudes are quantized
→ spectroscopy
i.e. improved precision

already demonstrated with ultra cold neutrons at ILL (V. Nesvizhevsky)
The Velocity selector is depicted with dimensions and constraints:

- $h = 50 \mu m$
- $H = 20 \text{ cm}$
- $R_{\text{detector}} = 20 \text{ cm}$
- $R_{\text{min}} = 1 \text{ mm}$
- $R_{\text{max}} = 7 \text{ mm}$

For $\Delta g/g = 1\%$, the selection needs to be improved by producing 150 times less than in the proposal, resulting in a significantly lower spread compared to the existing proposal. The improvement is illustrated through simulations:

- With shaper:
  - $\bar{g} = -9.82$
  - $\sigma = 0.14$
  - Accuracy: 73 %

- No shaper:
  - $\bar{g} = -11.14$
  - $\sigma = 4.36$
  - Accuracy: 1.7 %

First simulations suggest optimising dimensions with these constraints.
15 institutes  ~ 50 researchers

2015  start installation
2016  ELENA commissioning with p and H⁻
2017  first antiprotons for GBAR
Output power: 400 mW at 820 nm for 6 W pump power.
CW Ti:Sa locked on wavemeter
1 MHz frequency stability at 822 nm
Quantum reflection on a step

Plane wave incident on a potential step:
\[ \Psi_{in}(z) \propto \exp(-ikz) \text{ with } k = \sqrt{2m(E-V)/\hbar} \]

Wave function partly transmitted, partly reflected

\begin{align*}
    r_{12} &= \frac{k_2 - k_1}{k_1 + k_2} \\
    t_{12} &= \frac{2\sqrt{k_1k_2}}{k_1 + k_2}
\end{align*}

Reflection from attractive potential

Reflection probability unchanged when \(1 \leftrightarrow 2\)

\[ |r_{12}|^2 = |r_{21}|^2 \]
Electromagnetic (EM) modes are modified when the atom comes close to the detector:

\[ \Rightarrow \text{the EM ground state (vacuum) energy changes} \]

\[ \Rightarrow \text{attractive Casimir-Polder force between atom and detector} \]

Casimir 1948: long-range interaction energy between an atom and a perfectly conducting mirror:

\[
V^*(z) = -\frac{3\hbar c}{8\pi z^4} \frac{\alpha(0)}{4\pi \varepsilon_0} = -\frac{C_4^{\text{perfect}}}{z^4}
\]

For \( \text{H} \) and \( \bar{\text{H}} \), \( C_4^{\text{perfect}} \approx 73.6 \ E_h a_0^4 \)
\( V(35 \text{ nm}) \approx -mg \times 10 \text{ cm} \)
Gravitational States of Neutrons