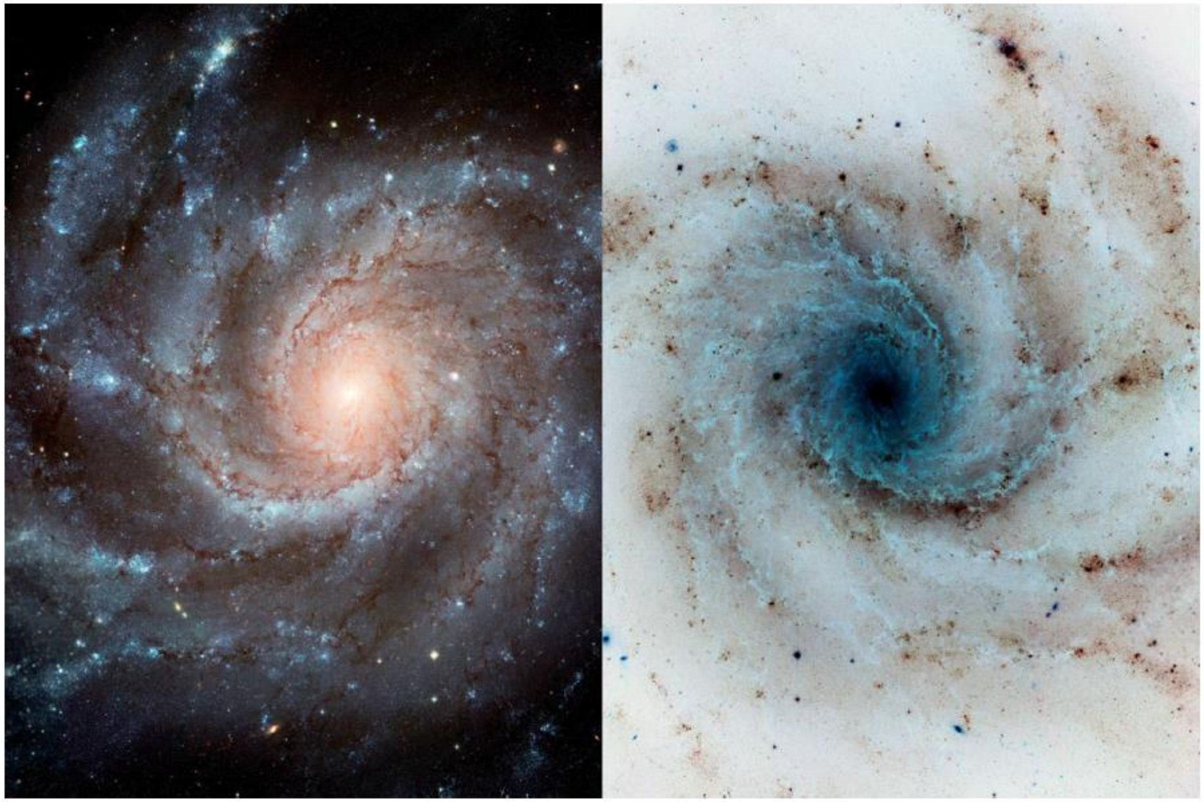
Production methods for precision experiments with protonium



Sebastian Gerber[1]

[1]CERN, Politecnico di Milano

European Nuclear Physics Conference, Bologna (IT), 6th Sept. 2018

Neutral antiprotonic matter… Motivation

Quest:
Tests of fundamental symmetries in comparative studies of neutral matter and antimatter.

- **Antihydrogen**… spectroscopy: CPT symmetry test on 1S-2S of $2{\cdot}10^{-12}$ [1]
  probing of the WEP of antimatter: Indirectly known to hold at 10^{-7} g
  Limit on neutral *matter:* relative 10^{-9} $\delta g/g$ [2]; absolute 10^{-5} $\delta g/g$ [3]; WEP 10^{-14} [4]

- **Protonium**… measure g, WEP in purely baryonic system,
  spectroscopy to probe the residual strong force on threshold

- **Antiprotonic deuterium**…
  isospin dependence on g, spectroscopy

- **Muonic antihydrogen**…
  spectroscopy, Lamb shift due to finite size of $\bar{p}$
  Proton-charge-radius-puzzle observed in μp [5]

[1] M. Ahmadi et al., *Nature* **557**, 71 (2018)
[2] H. Mueller et al., *Nature* **463**, 926 (2010)
[3] R. F. C. Vessot et al., *Phys. Rev. Lett.* **45**, 2081 (1980)
[4] S. Baessler et al., *Phys. Rev. Lett.* **83**, 3583 (1999)
[5] A. Antognini et al., *Science* **339**, 417 (2013), r_E=0.84087(39) fm, 7σ different than 2010CODATA

Orders of magnitude

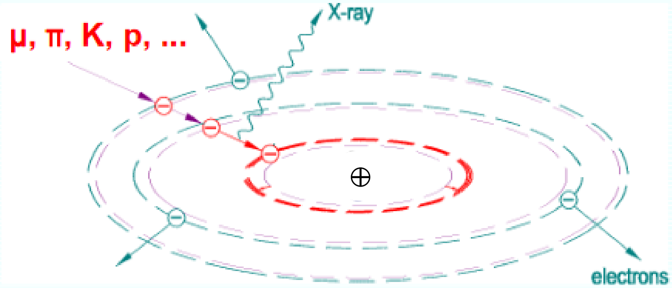
Coulomb bound system $V_{coulomb} = -Ze^2/r$

Binding energies $B_n = -(m_r c^2\alpha^2)(Z^2/2n^2)$

Radii $a_n = (hc/m_r c^2\alpha)(n^2/Z)$

dimension		m [MeV/c²]	$B_{n=1}$ [keV]	r_{Bohr} [fm]
'atomic' dim.	e^-p	0.511	0.0136	$0.5\cdot10^5$
↓	μ^-p	105	2.5	279
	π^-p	140	3.2	216
	$\bar{p}p$	938	12.5	57
'nuclear' dim.	$\langle r_p \rangle$			0.8

capture of a
negatively charged particle
in the Coulomb field of nuclei

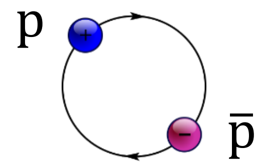


EXOTIC ATOM

D. Gotta et al., *Nucl. Phys. A* **660**, 289 (1999)

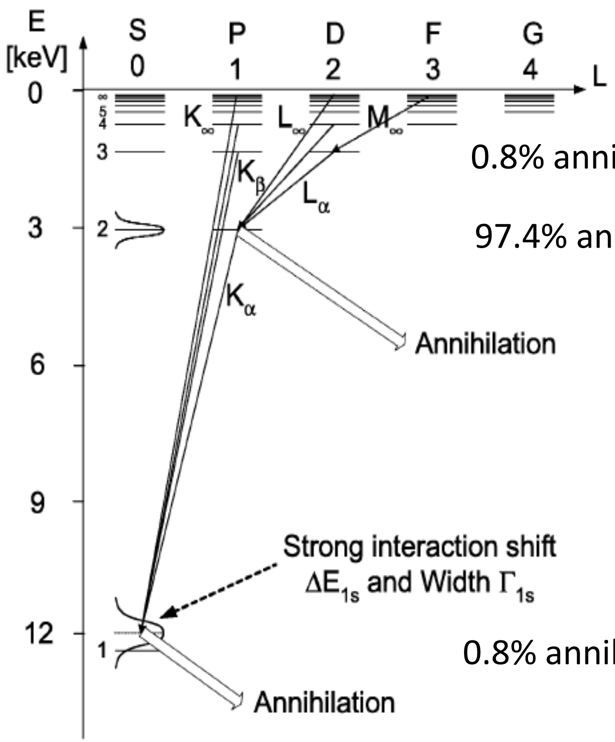
Pn properties

Pn energies & length scales to H: $\frac{m_r^H}{m_r^{Pn}} = 938$



$a_{Bohr}^{Pn} = 57\,\text{fm}$

Pn level scheme

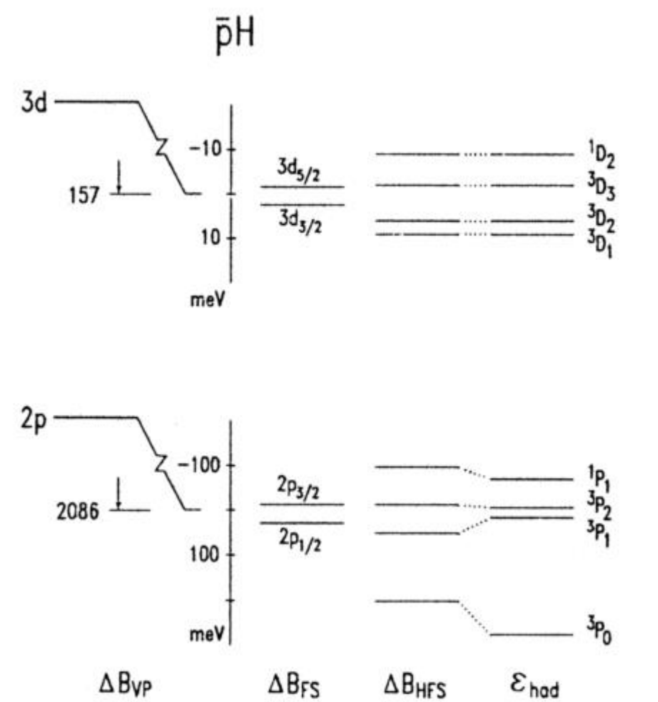


0.8% annihilate

97.4% annihilate

0.8% annihilate

Pn binding energy, hadronic shift of levels

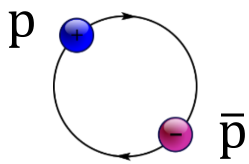


E. Klempt et al., *Physics Rep.* **363**, 116 (2002)

D. Gotta et al., *Nucl. Phys. A* **660**, 289 (1999)

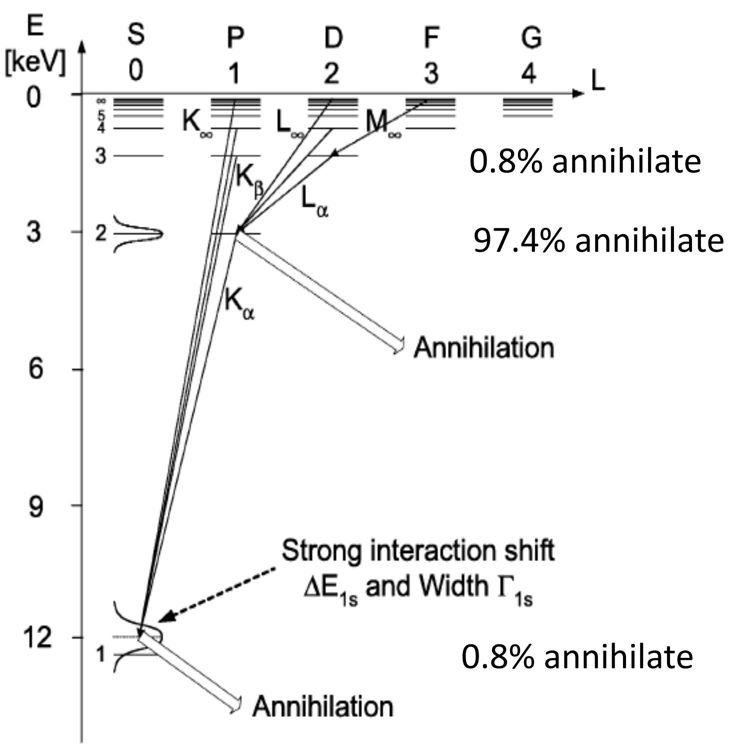
Pn properties

Pn energies & length scales to H: $\frac{m_r^H}{m_r^{Pn}} = 938$



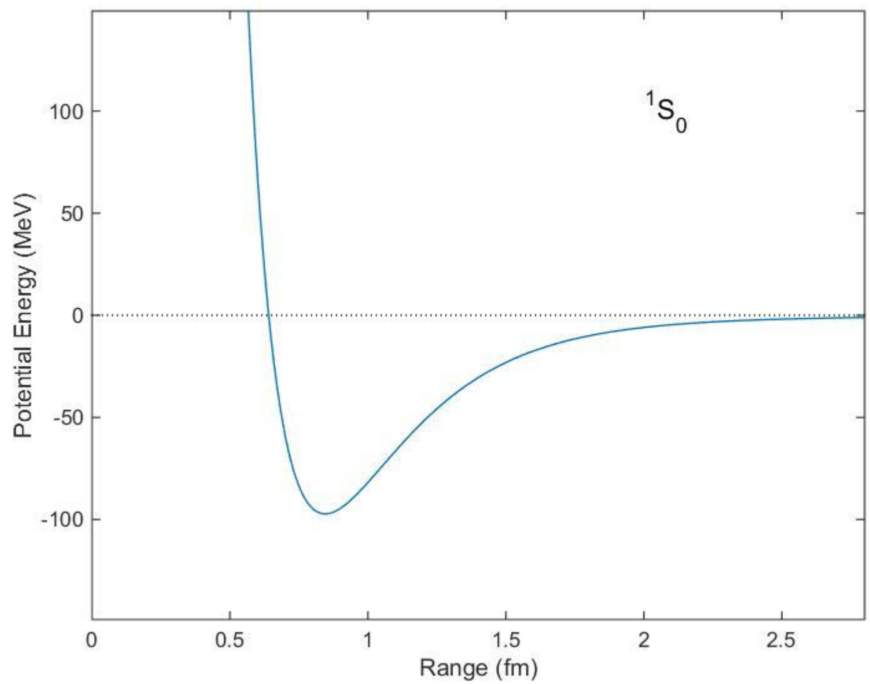
$a_{Bohr}^{Pn} = 57\,\text{fm}$

Pn level scheme



E. Klempt et al., *Physics Rep.* **363**, 116 (2002)

Reid potential corresponding to residual strong force



Cold Pn production via H^- in a Penning trap

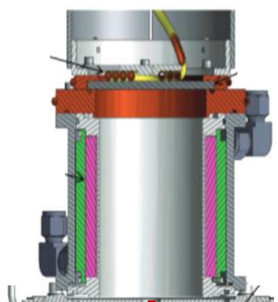
Spectroscopy and g-measurement benefit from colder Pn

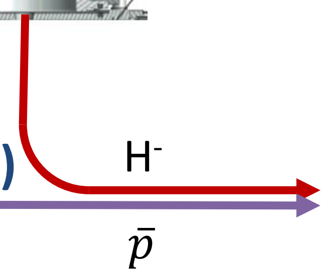
Pn 'traditionally' produced in eV range by injecting $\bar{p}$ into liquid H

→ Penning trap can produce Pn with < 0.1 eV via resonant-charge-exchange

p/H/H^- source

e.g. >1 μA H^- RF cw source:
T. Kalvas et al., AIP Conf. **1655**, 030015 (2015)





Antiproton Decelerator (AD)

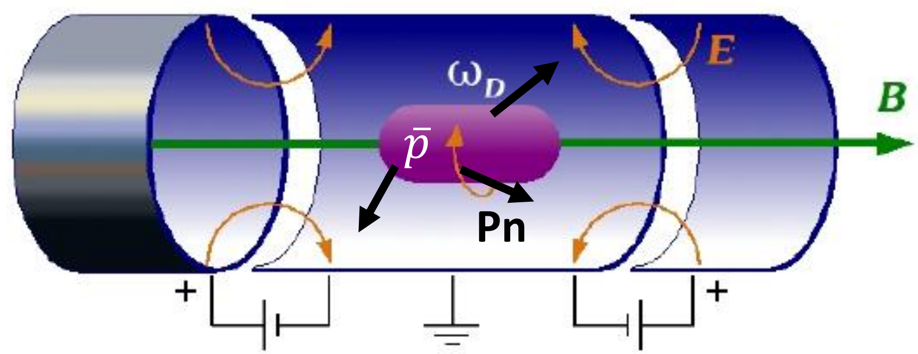
$\bar{p}$ at 5.3 MeV,
Cycle time ~100 s at $>3{\cdot}10^7$ $\bar{p}$,
After degrader foils ~10^5 $\bar{p}$ at 10 keV

M. Hori & J. Walz, *Prog. of Partic. Nucl. Phys.* **72**, 206 (2013)

Penning - Malmberg trap

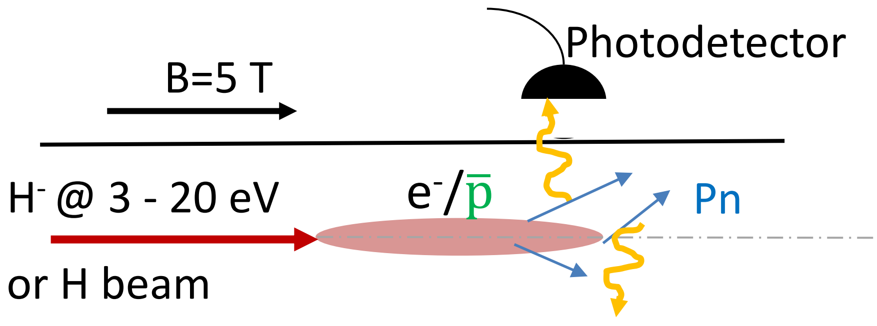
10 keV $\bar{p}$ are trapped and electron-cooled to < 0.1 eV

R. Brusa et al. (AEgIS), *J. Phys.: Conf Ser.* **791**, 012014 (2017)
M. Ahmadi et al. (ALPHA), *Nature Com.* **8**, 681 (2017)
C. Amole et al. (ASACUSA), *Nature Com.* **5**, 3955 (2014)
G. Gabrielse et al. (ATRAP), *Phys. Rev. Lett.* **108**, 113002 (2012)



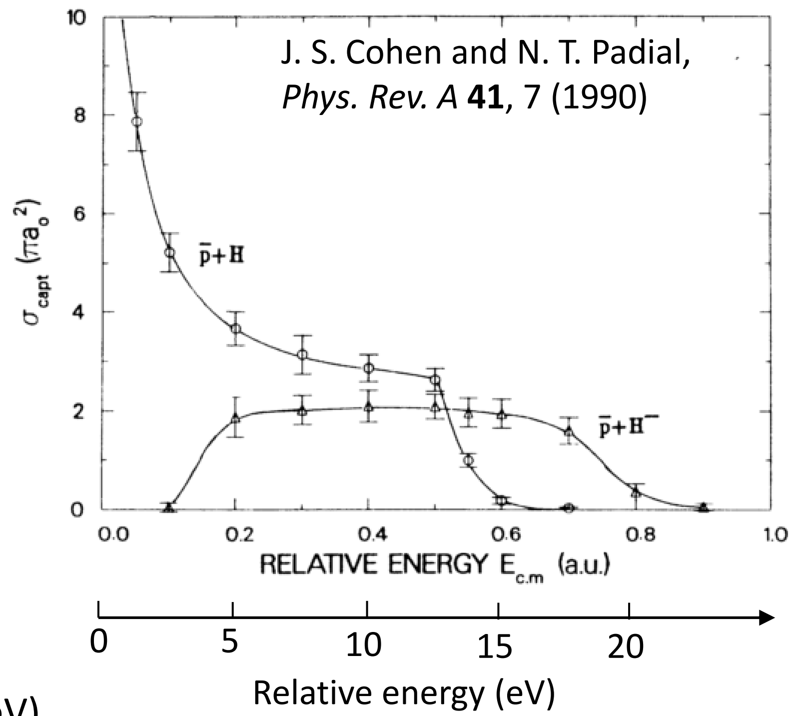
Pn production schemes via H^-

Simplified sketch of Penning trap Pn production via resonant-charge-exchange reaction:



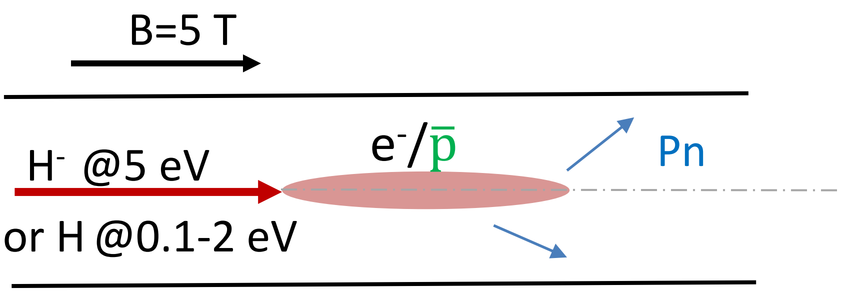
$H^- + \bar{p} \rightarrow Pn + 2e^-$

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



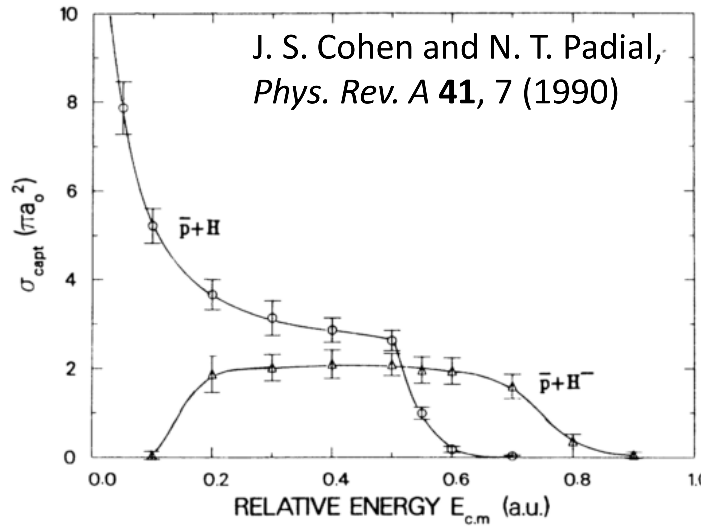
Challenge: Direct H sources can be broad in energy (1 to 2 eV)

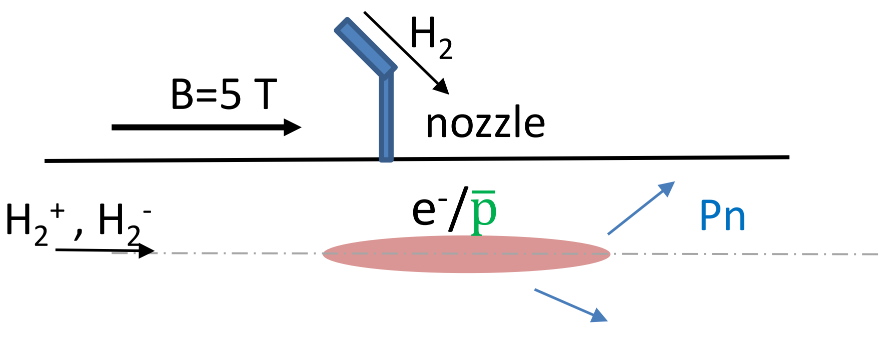
Pn production schemes via H^-, H_2



$H^- + \bar{p} \rightarrow Pn + 2e^-$

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

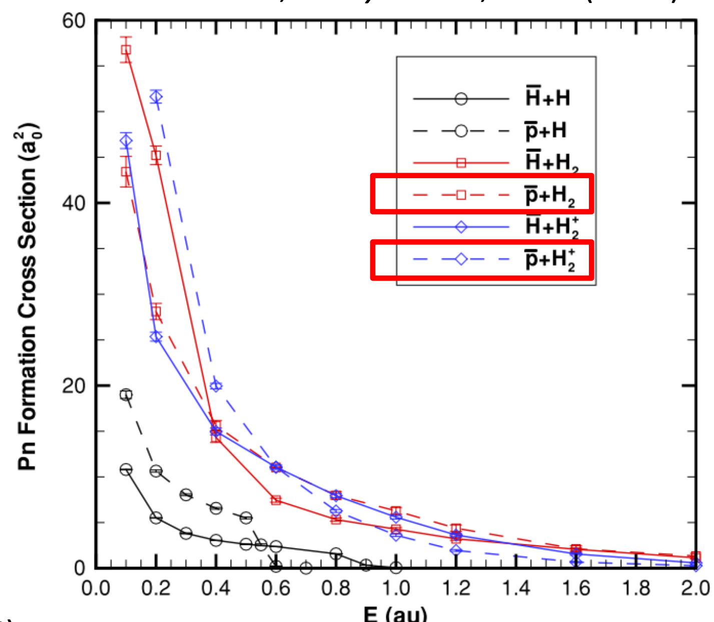




$H_2 + \bar{p} \rightarrow H + Pn + e^-$ $\qquad$ $H_2^- + \bar{p} \rightarrow p + Pn + 2e^-$

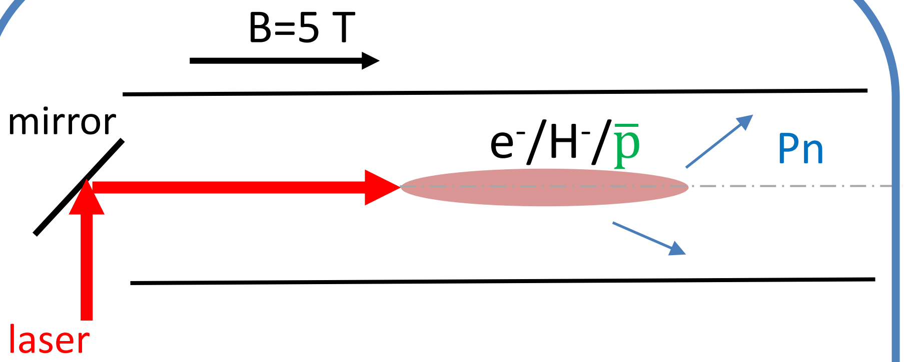
$H_2^+ + \bar{p} \rightarrow Pn + H$ [1]

J. S. Cohen, *J. Phys. B* **39**, 3561 (2006)



[1] ~100 Pn@<1 eV N. Zurlo et al. (ATHENA), *Hyp. Int.* **172**, 97-105 (2006)

Two-step Pn production schemes via H



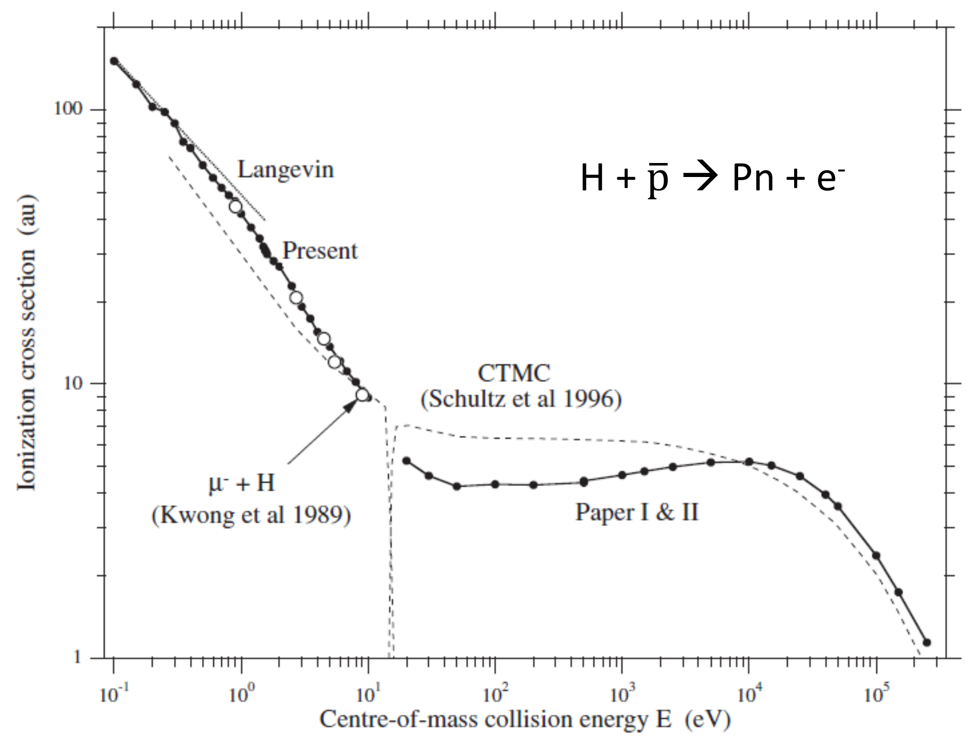
Electron-cooling of H^- and $\bar{p}$

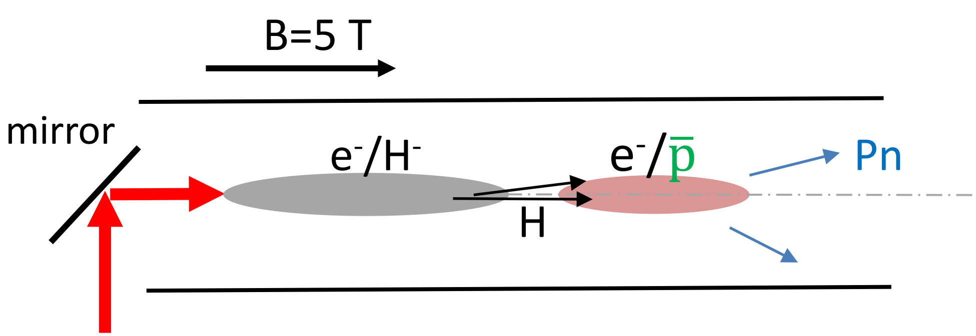
1) $H^- + \gamma \rightarrow H + e^-$ 2) $H + \bar{p} \rightarrow Pn + e^-$

Duty cycle by plasma manipulations: ~ 1 min,
$\bar{p}$ are recyclable and stackable from AD

Suitable scheme to reach <0.1 eV Pn

K. Sakimoto, *J. Phys. B* **34**, 1769 (2001)

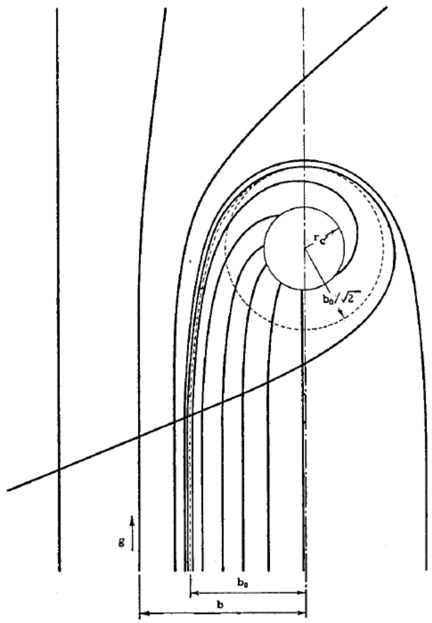




Formation cross section of Pn via H

Classical orbiting / Langevin cross section approximation:

G. Gioumousis et al., *J. Chem. Phys.* **29**, 294 (1958)



Critical impact parameter b_c:

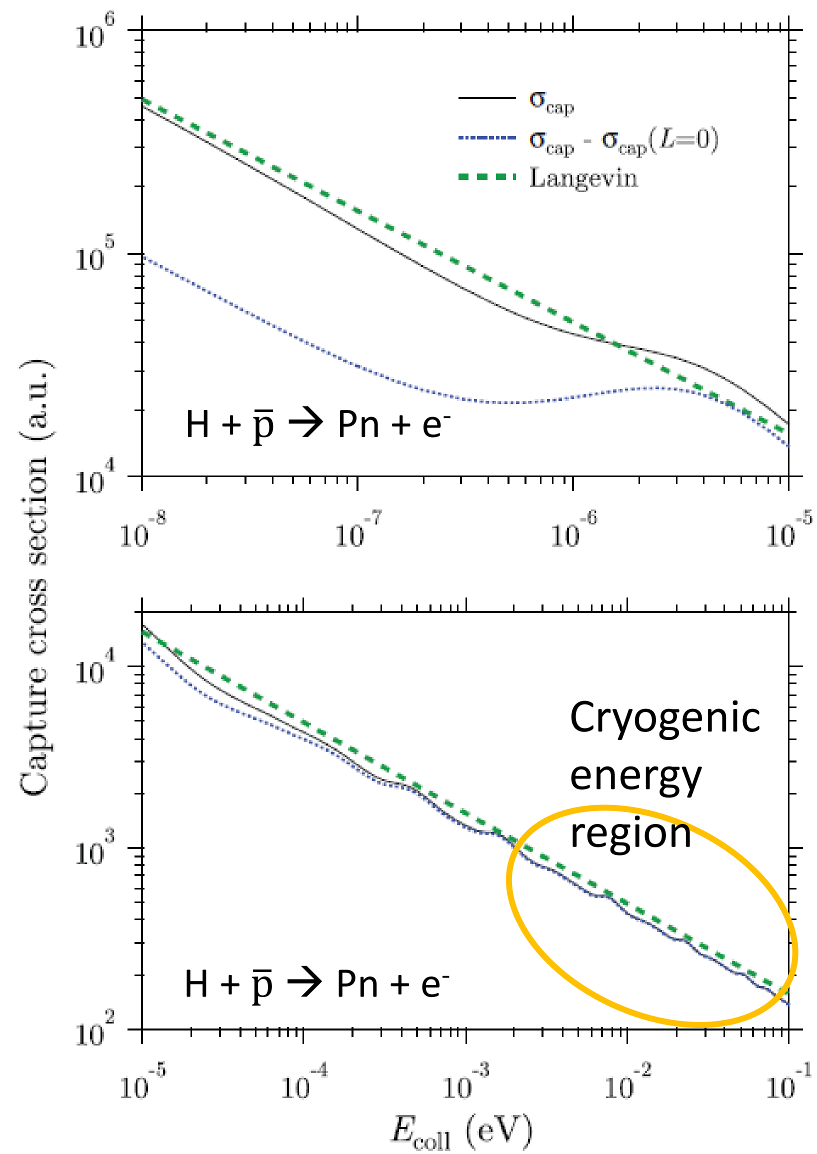
$$\sigma_{Langevin} = \pi\, b_c^{\,2} \qquad b_c = \left(\frac{2\ \alpha(n)\ e^2}{E_{coll}} \right)^{1/4}$$

Polarizability for H(s) increases with n:

$$\alpha^{(S)}(n) = a_0^{\,3} n^4 (2n^2 + 7)/2$$

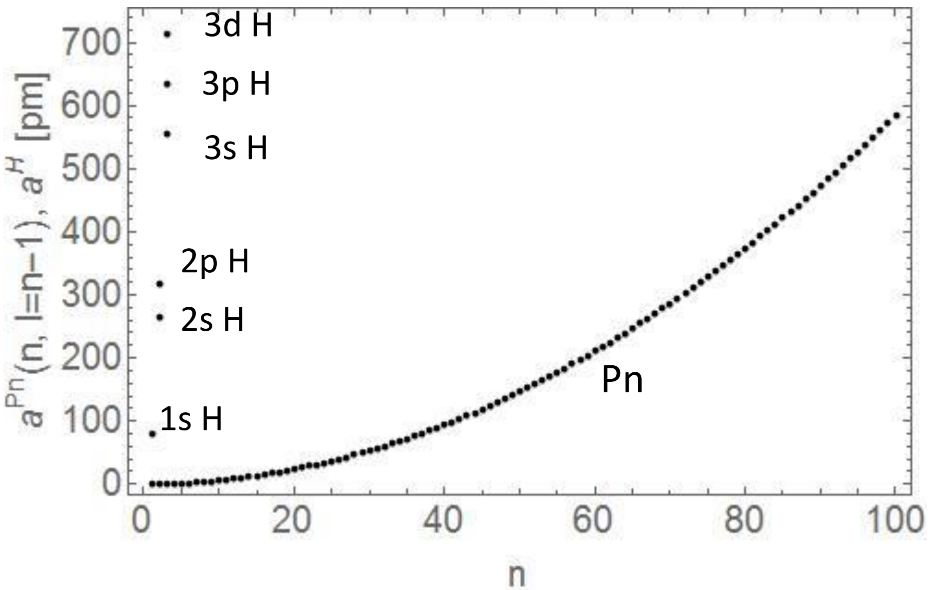
K. McDowell, *J. Chem. Phys.* **65**, 2518 (1976)

K. Sakimoto, *Phys. Rev. A* **88**, 012507 (2013)



Pn production in Rydberg states… two benefits

1) $H^- + \gamma \rightarrow H + e^-$ 2) $H + \bar{p} \rightarrow Pn + e^-$



Pn formation cross section scales with H(n):

$$\sigma_{Langevin} \propto n^3$$

$$e.g.: \sigma_{Pn}(H29p) = 11500 \cdot \sigma_{Pn}(H1s)$$

… similar size of H and Pn
H(2s)→ Pn (n~60)
H(3s)→ Pn (n~100)
H(29s)→ Pn (n~1000)

R. S. Hayano, *Nucl. Phys.* **A655**, 318 (1999)

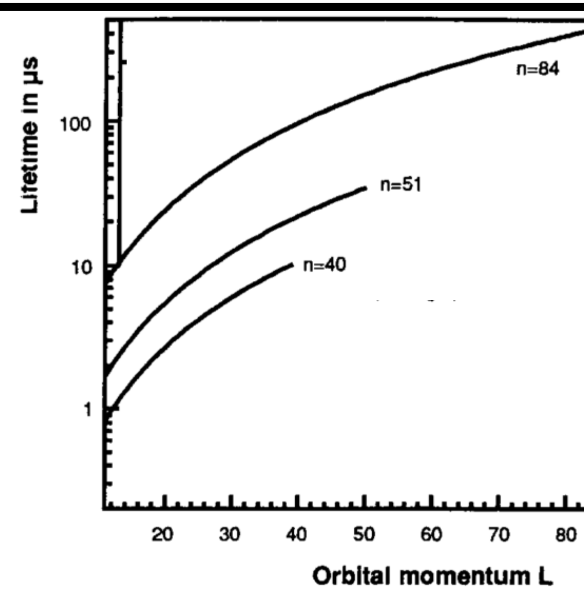
…lifetime before annihilation scales with Pn(n)

$<\tau_{Pn30(from\ H1s)}>$ ~ 2 μs

$<\tau_{Pn60(from\ H2s)}>$ ~ 42 μs

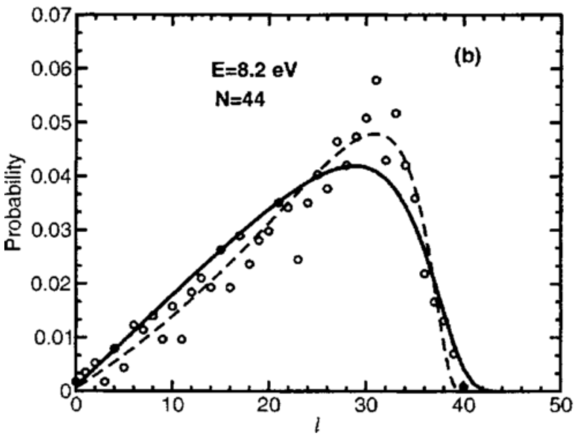
$<\tau_{Pn100(from\ H3s)}>$ ~ 400 μs

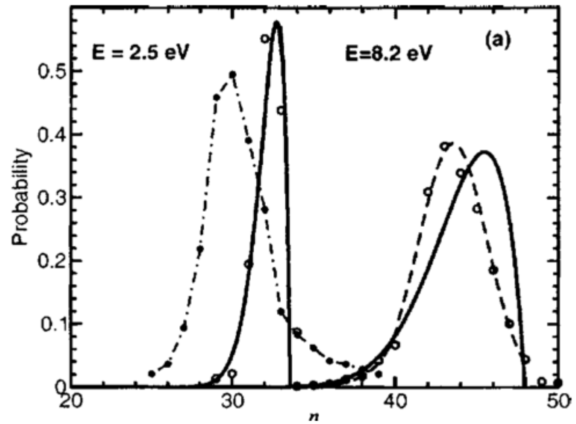
$<\tau_{n=Pn1000(from\ H29s)}>$ ms



Pn production in Rydberg states… two benefits

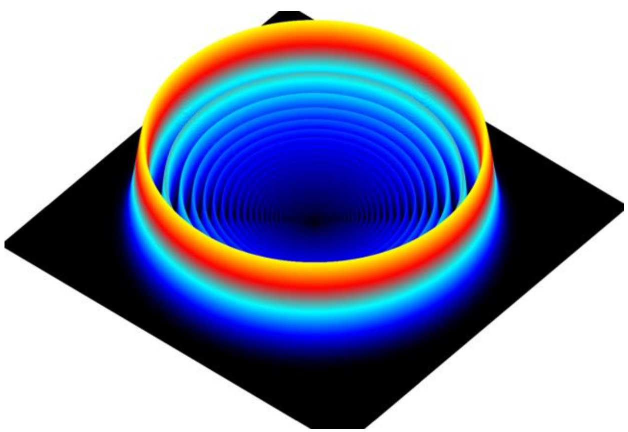
H(1s)→ Pn (n~30) **At low E_{col} , Pn is produced in 'triangular' L and narrow n state distribution**



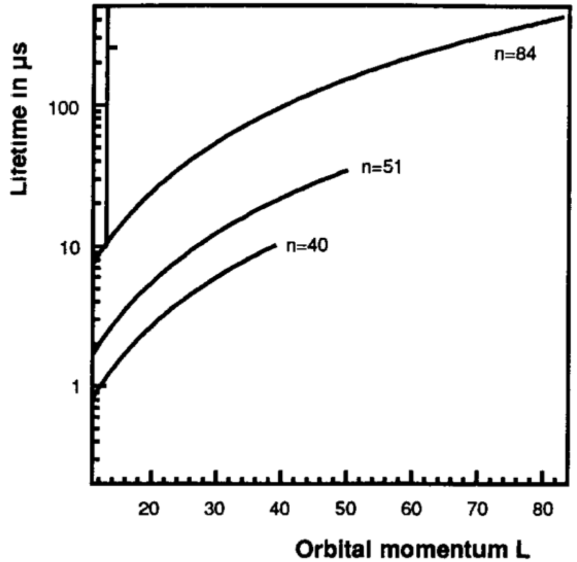


$<\tau_{Pn30(from\ H1s)}> \sim 2\ \mu s$

J. S. Cohen and N. T. Padial, *Phys. Rev. A* **41**, 7 (1990)



Pn in state 30s, by J. Baez (2015)



R. S. Hayano, *Nucl. Phys.* **A655**, 318 (1999)

$H^{-}(1s) \rightarrow H(\text{Rydberg})$

What is the best way to excite H^- to Rydberg H ?

$H^- + \gamma \rightarrow H + e^-$

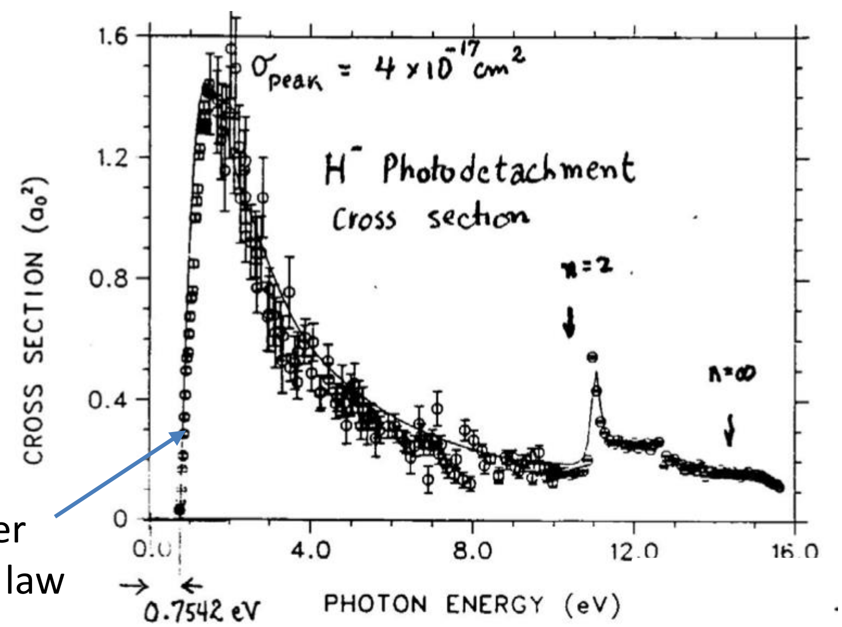
$H + \bar{p} \rightarrow Pn + e^-$

One-photon options:

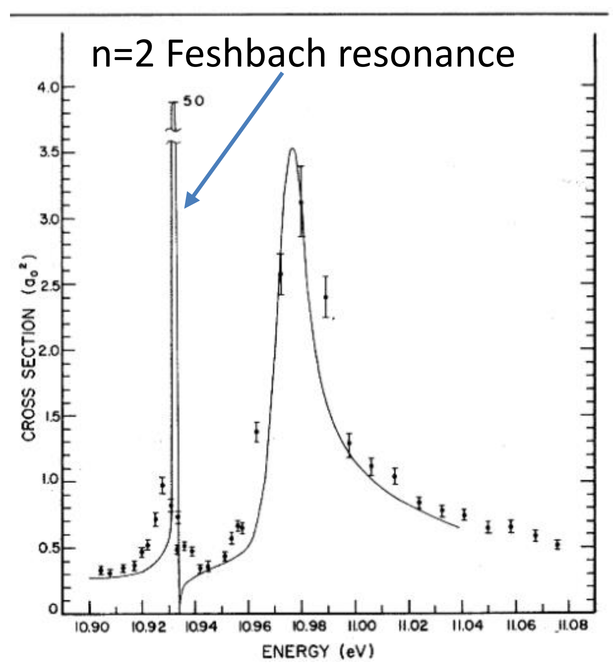
1) 113 nm (photodetachment on Feshbach resonance) + Rydberg laser
2) 1652 nm photodet. on threshold + 121 nm + Rydberg
3) 1064 nm photodetachment + 121 nm + Rydberg laser

Two-photon options:

4) 224 nm (on Feshbach res.) + Rydberg
5) 1652 nm + 242 nm + Rydberg



$e^{3/2}$ Wigner threshold law



H. C. Bryant et al., *Phys. Rev. Let.* **38**, 5 (1977)

$H^-(1s) \rightarrow H(\text{Rydberg})$

What is the best way to excite H^- to Rydberg H ?

$H^- + \gamma \rightarrow H + e^-$

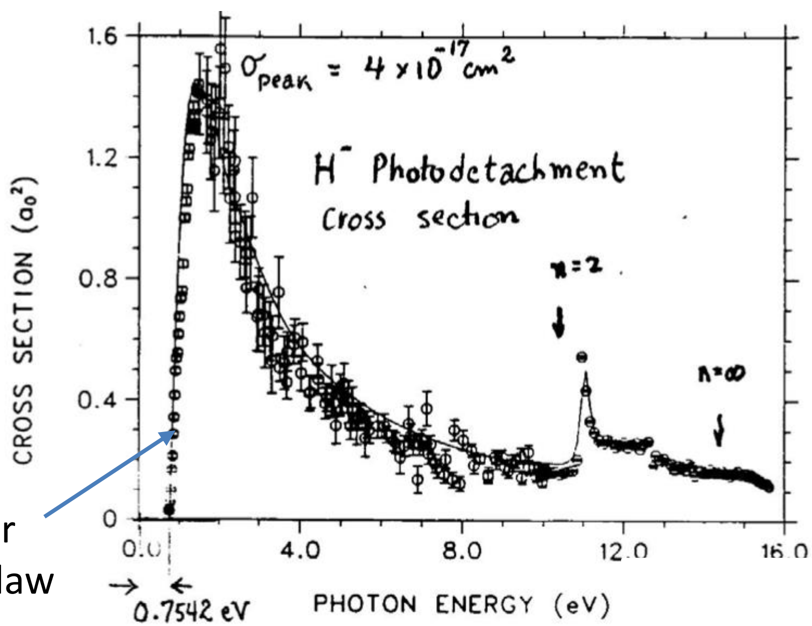
$H + \bar{p} \rightarrow Pn + e^-$

One-photon options:

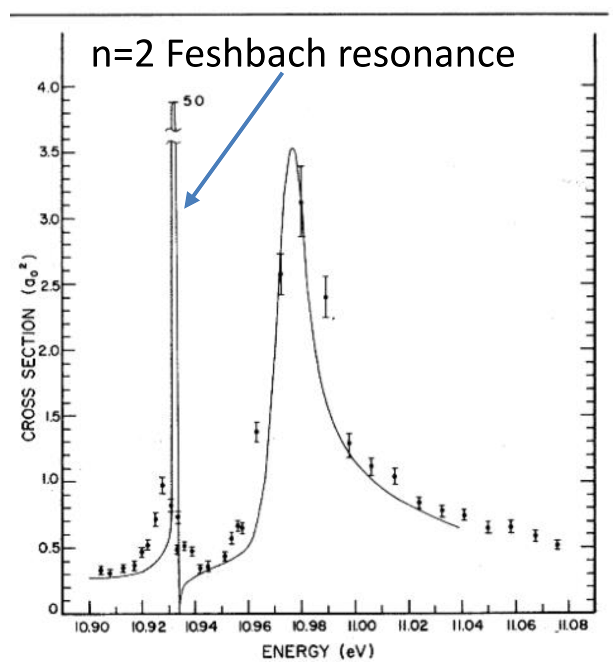
1) 113 nm (photodetachment on Feshbach resonance) + Rydberg laser
2) 1652 nm photodet. on threshold + 121 nm + Rydberg
3) **1064 nm photodetachment + 121 nm + Rydberg laser**

Two-photon options:

4) **224 nm (on Feshbach res.) + Rydberg**
5) 1652 nm + 242 nm + Rydberg



$e^{3/2}$ Wigner threshold law



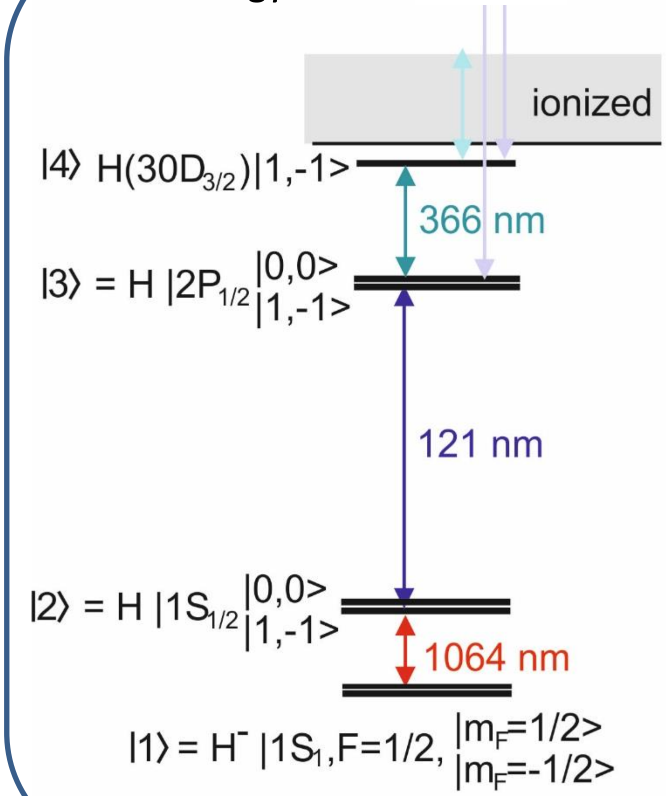
H. C. Bryant et al., *Phys. Rev. Let.* **38**, 5 (1977)

$H^-(1s)$ – H(1s) – H(2p) – H(30d)

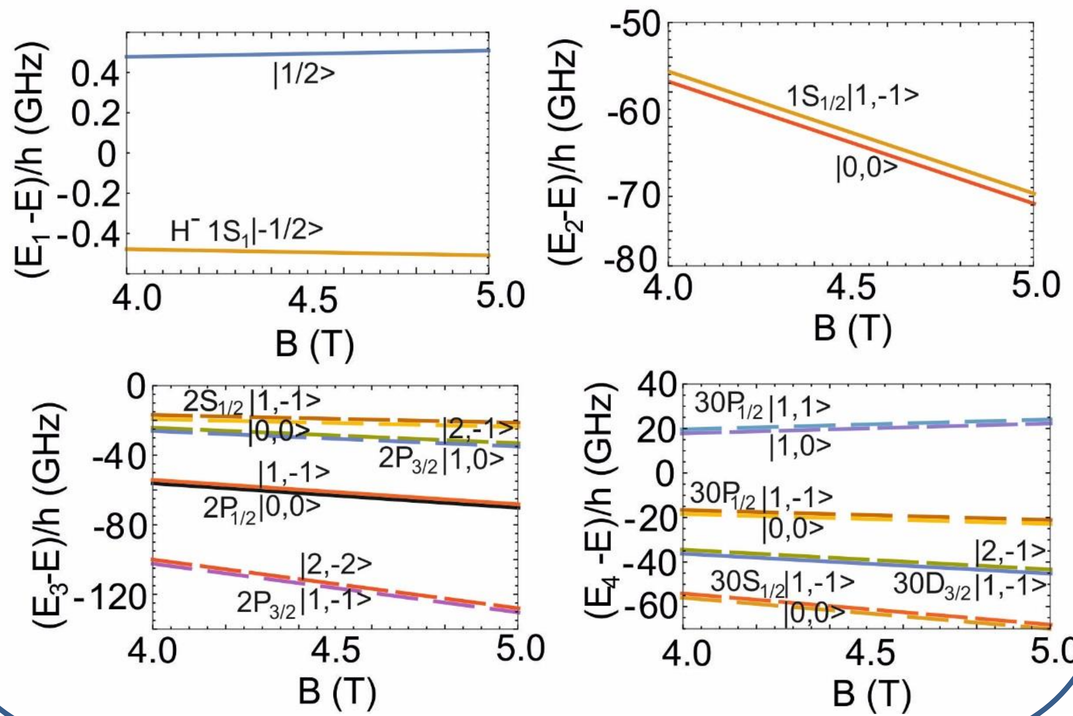
One-photon options:

1064 nm photodetatchment + 121 nm + 366 nm Rydberg laser

Energy levels for H^- and H



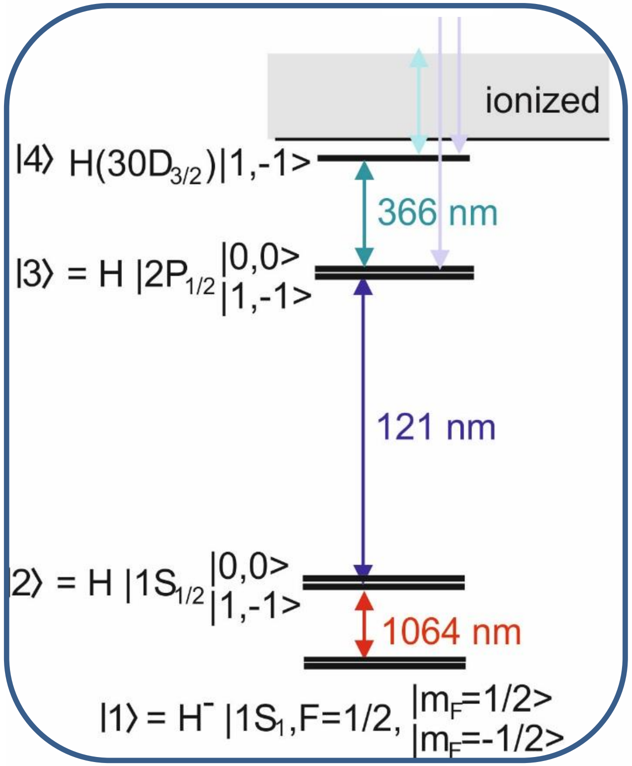
Zeeman shifts in B=5 T Penning trap of relevant 4 states (closest neighbouring states are in dashed lines)

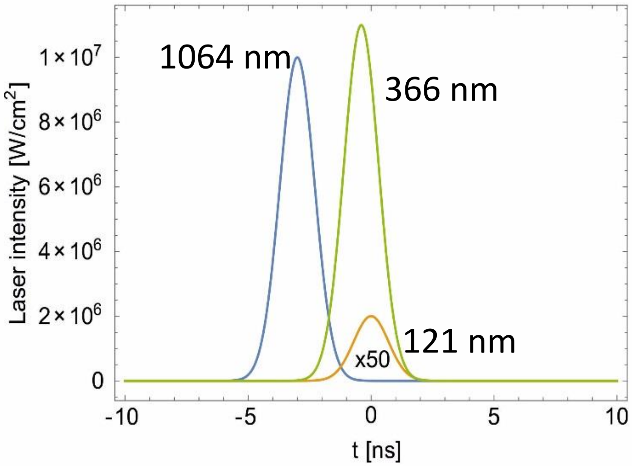


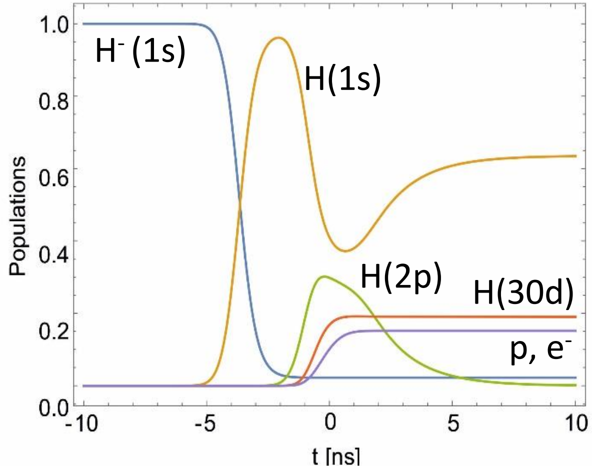
$H^-(1s)$ – H(1s) – H(2p) – H(30d)

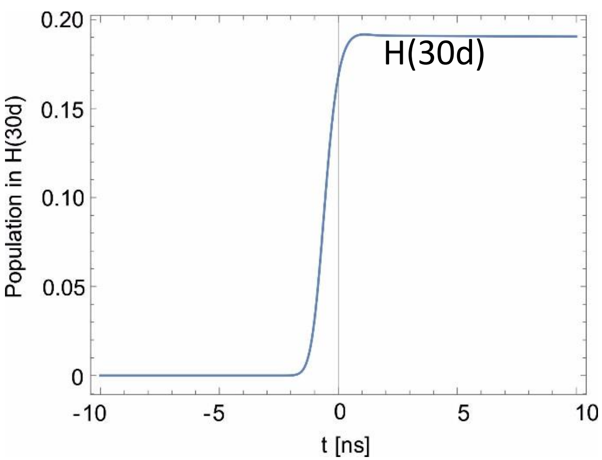
Cross sections are known for H:
σ bound-bound
σ bound-continuum
$\sigma_{H\text{- to }H} = 4\cdot10^{-17}$ cm^2

5-level optical rate equations using parameters:
w_{lasers}= 1 cm^2 ,
P_1= 9 mJ/1 ns, P_2=20 μJ/1 ns, P_3=11 mJ/1 ns
delay times $t_{1\text{-}2}$=-3 ns, $t_{3\text{-}2}$=-0.4 ns









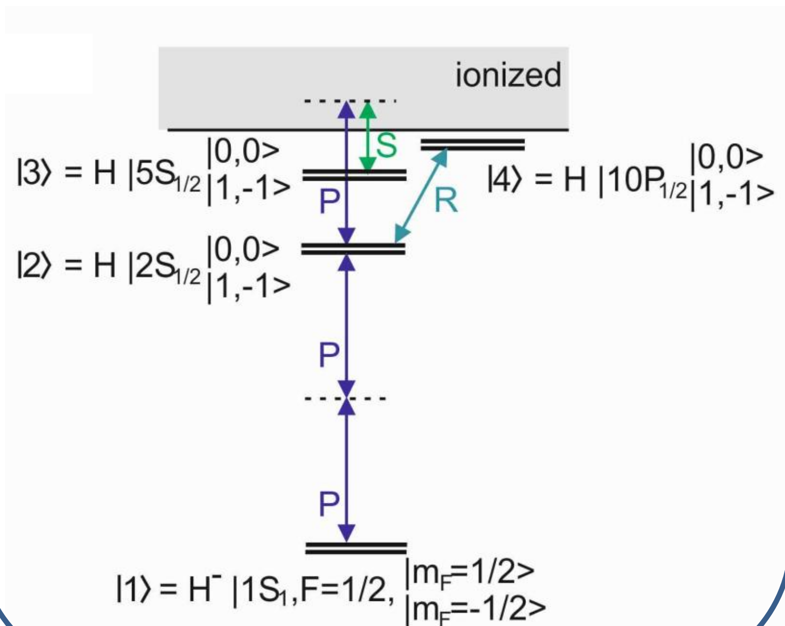
optical rate equations:
Fermi's Golden Rule: *A. Burgees, Astrophys. J.* **141**, 1588 (1965)

H$^-$(1s) – H(2s) – H(10p)

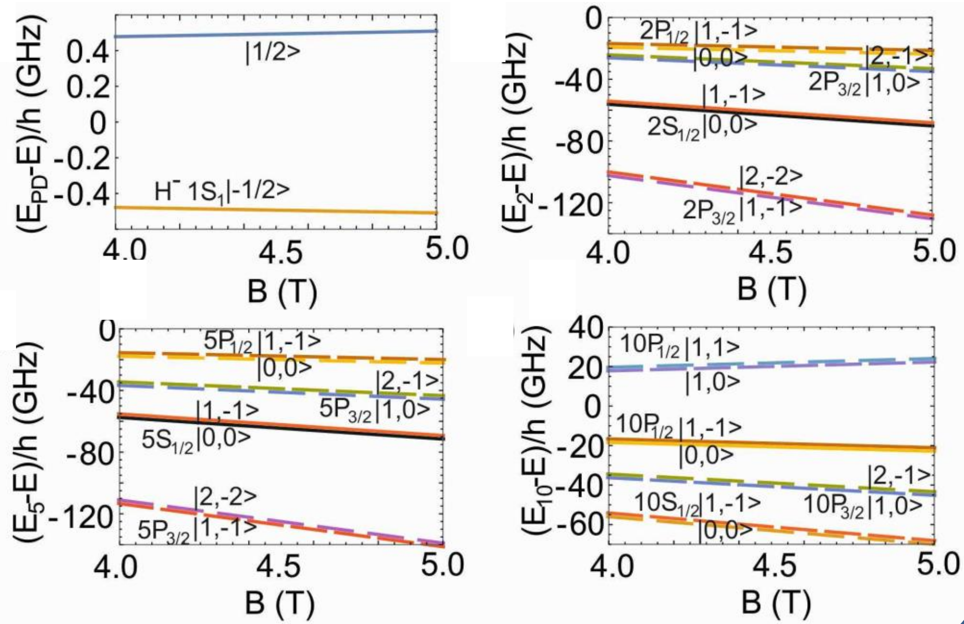
Two-photon options with SCRAP using LICS [1]:

224 nm (Pump) + 462 nm (Stokes) + 379 nm Rydberg laser

Pump (P) and Stokes (S) laser for SCRAP + LICS
Laser R excites to the Rydberg state of H



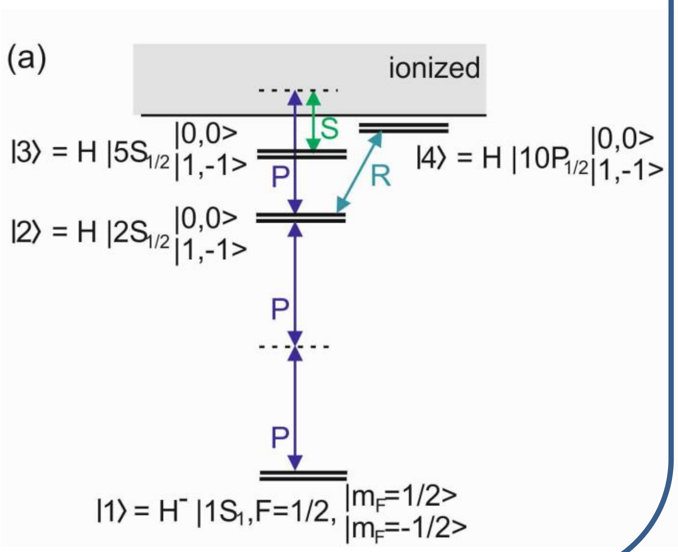
Zeeman shifts in B=5 T Penning trap of relevant 4 states (closest neighbouring states are in dashed lines).



[1] Similar scheme as in e.g.: L. P. Yatsenko et al. *Phys. Rev. A* **71**, 033418 (2005)

$H^-(1s)$ – H(2s) – H(n10p)

Pump (P) and Stokes (S) laser for SCRAP + LICS
Laser R excites to the Rydberg state of H



Calculation for field free solution:

S…. Stark shifts
Ω … Rabi frequencies
Γ …ionization rates

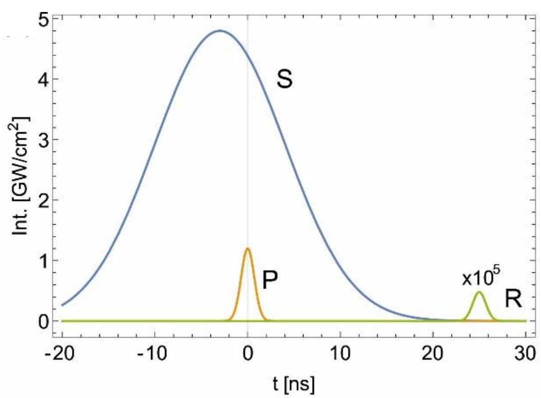
The ionization rates are for field free (B=0)
Estimated with loss-free Feshbach transition

Table 2.1 lists the values for the ionization rates and Stark shifts in units of 1/ns for intensities in GW/cm^{-2} for the relevant levels of Fig.3:

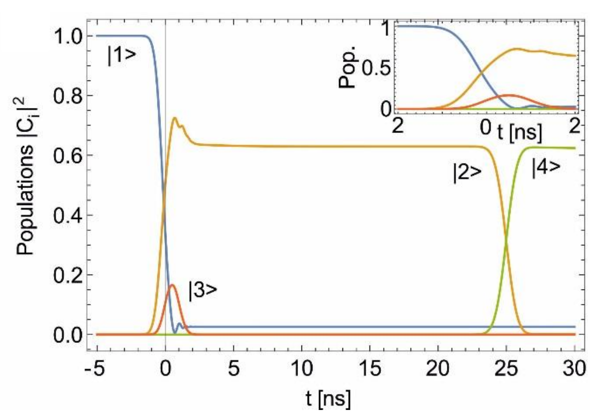
$\Gamma_{2,P}(t) = 2.91\ I_P(t)$	$\Gamma_{2,S}(t) = 0$	$\Gamma_{2,R}(t) = 0$
$\Gamma_{3,P}(t) = 0.18\ I_P(t)$	$\Gamma_{3,S}(t) = 1.98\ I_S(t)$	$\Gamma_{3,R}(t) = 1.04\ I_R(t)$
$\Gamma_{4,P}(t) = 1.29\ I_P(t)$	$\Gamma_{4,S}(t) = 0.14\ I_S(t)$	$\Gamma_{4,R}(t) = 1.58\ I_R(t)$
$S_{1,P}(t) = -1.89\ I_P(t)$	$S_{1,S}(t) = -1.35\ I_S(t)$	$S_{1,R}(t) = -1.19\ I_R(t)$
$S_{2,P}(t) = 4.78\ I_P(t)$	$S_{2,S}(t) = 19.89\ I_S(t)$	$S_{2,R}(t) = 23.32\ I_R(t)$
$S_{3,P}(t) = 3.89\ I_P(t)$	$S_{3,S}(t) = 12.31\ I_S(t)$	$S_{3,R}(t) = 7.84\ I_R(t)$
$S_{4,P}(t) = 1352\ I_P(t)$	$S_{4,S}(t) = 5789\ I_S(t)$	$S_{4,R}(t) = 3875\ I_R(t)$
$\Omega_P(t) = 4.63\ I_P(t)$	$\Omega_{SP}(t) = 20.28\sqrt{I_P(t) I_S(t)}$	$\Omega_R(t) = 1442\sqrt{I_R(t)}$
q=0.5		

Optimization for the laser parameters, table 2.1 shows the intensities in GW/cm^2

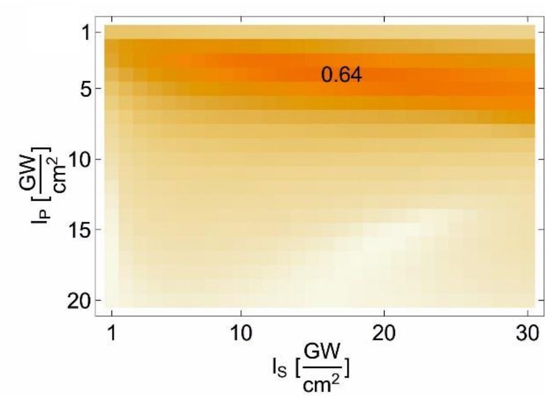
Laser pulse shapes



Level populations



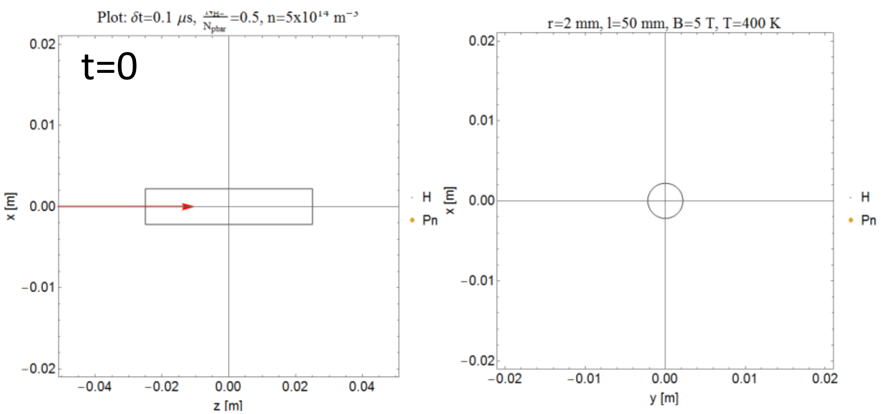
Transfer efficiency vs laser intensities



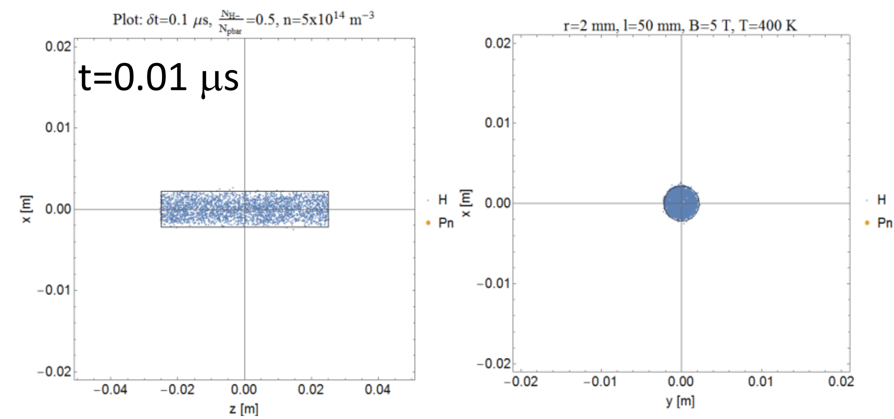
Pn production in a Penning trap

MCMC approach

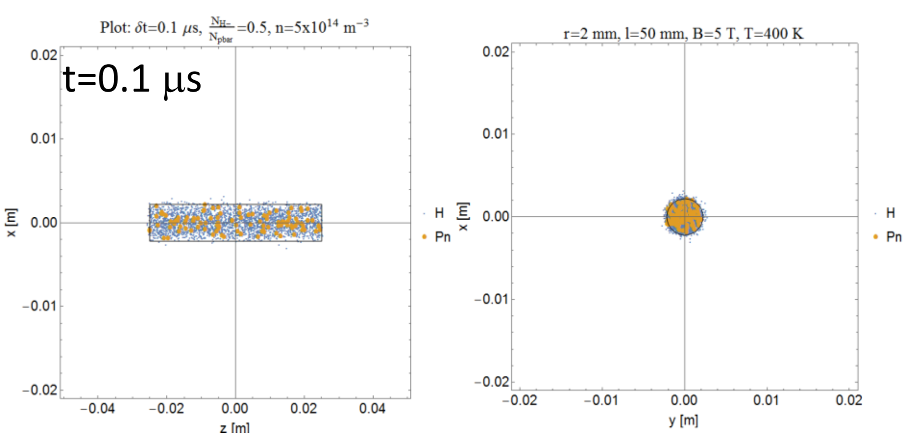
Start with $H^-/\bar{p}$ plasma in trap at thermal equilibrium (density n, temperature T). Interaction with lasers at t=0

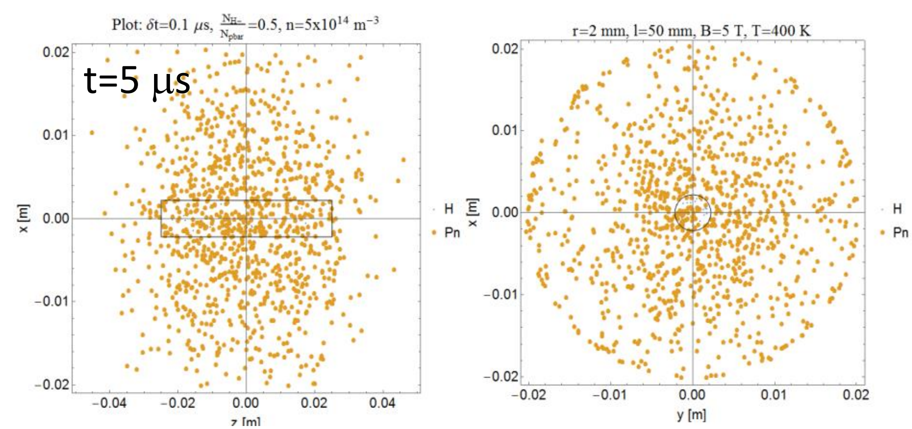


Created number of H*



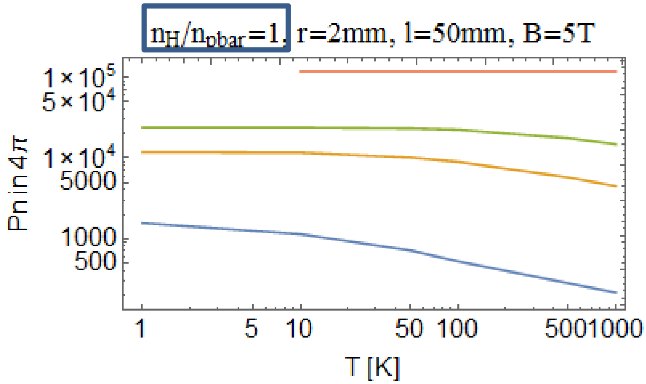
Pn production via resonant charge-exchange. Pn emission pattern determined by B, n, T

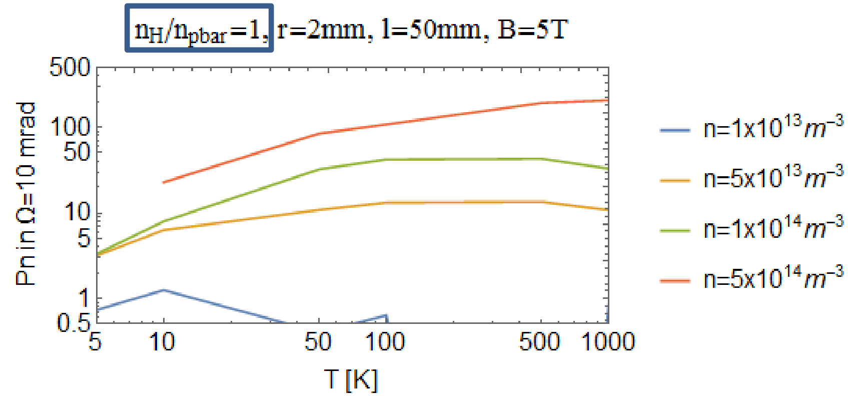


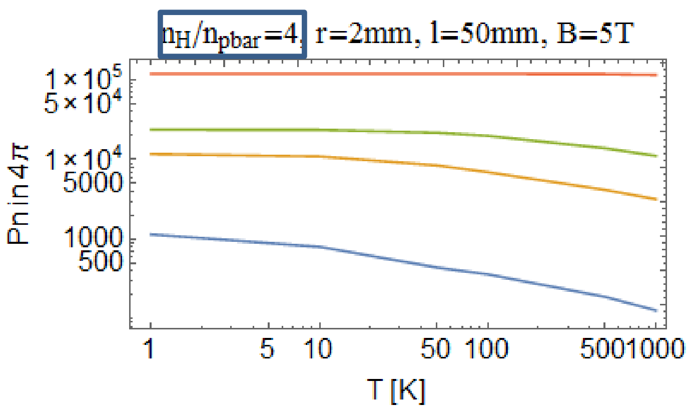


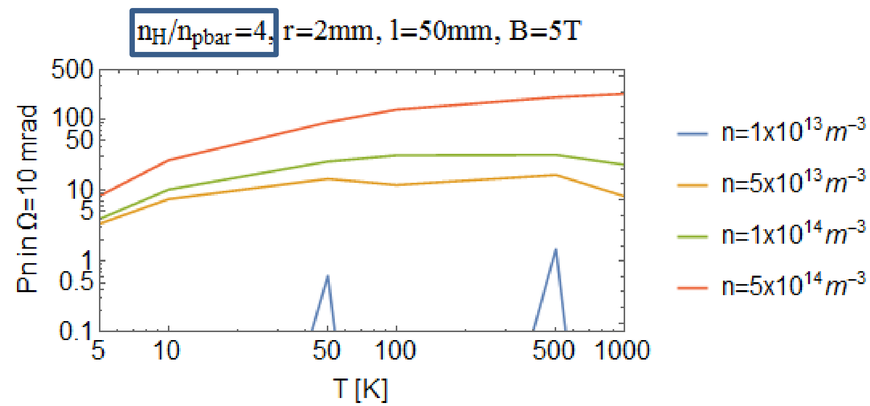
Pn formation – contour scan for Rydberg H(10p)

5 T

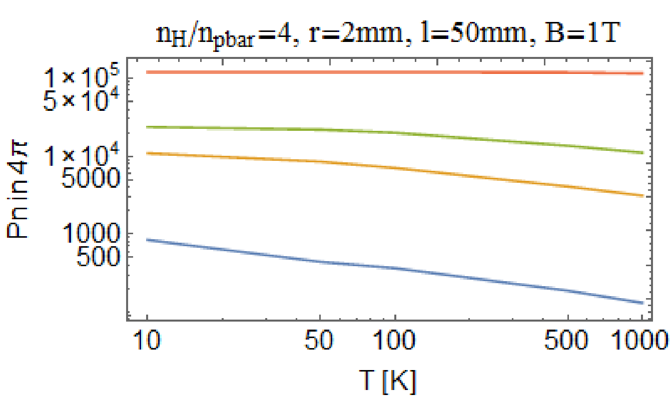


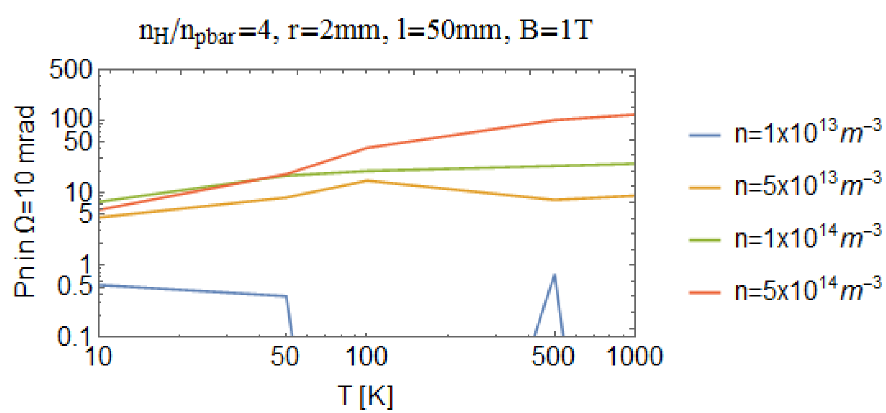






1 T

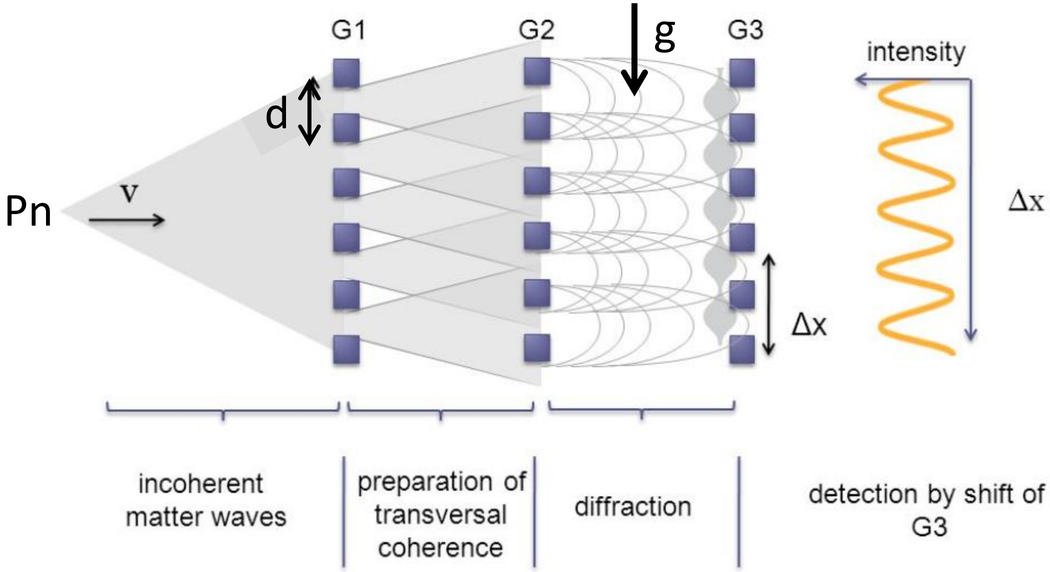




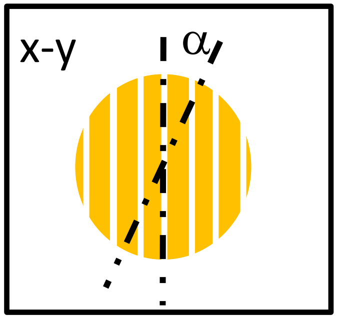
Outlook for gravity measurement of Pn

de Broglie wavelength $\lambda = \frac{h}{m\,v}$

Idea:
g-measurement in an axial rotatable Talbot-Lau atom interferometer



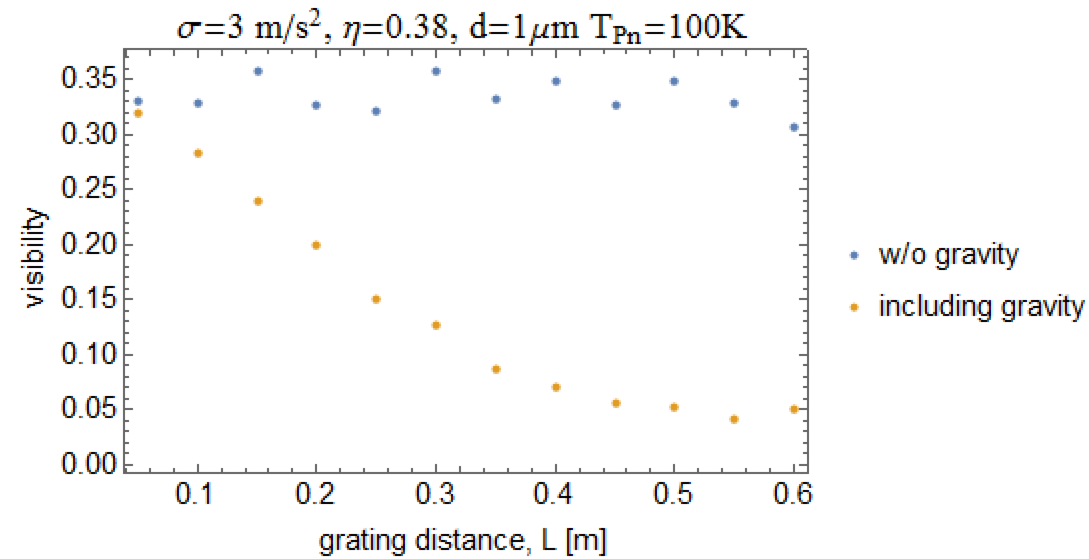
$\alpha = 0^{o} - 30^{o}$ Talbot-Lau layout (is sensitive to 0 and 0.5 g):



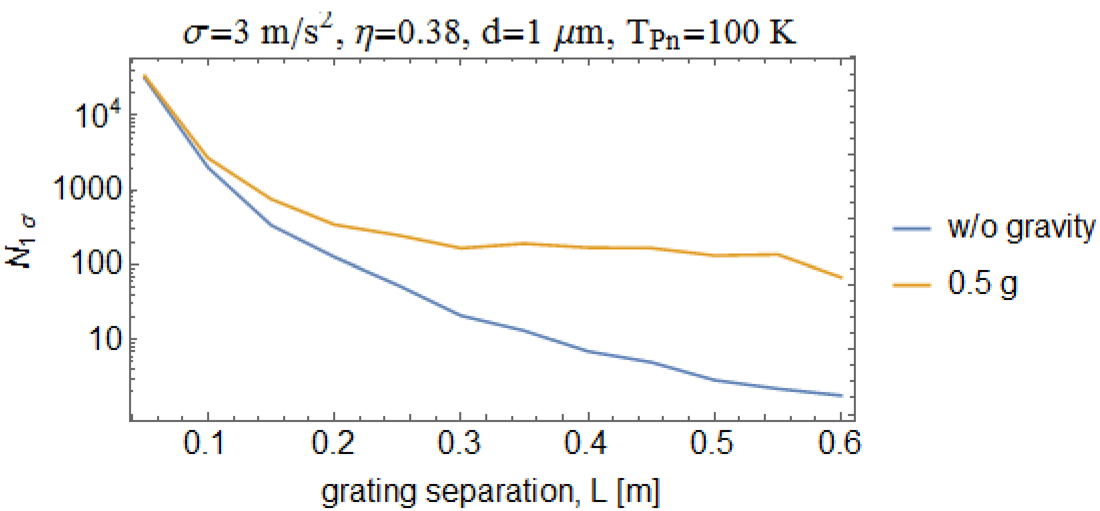
R. Colella et al., *Phys. Rev. Lett.* **34**, 1472 (1975)
M. Oberthaler, *Heidelberg*

H. Mueller et al., *Nature*, **463**, 926 (2010)
S. Baessler et al., *Phys. Rev. Lett.*, **83**, 3583 (1999)

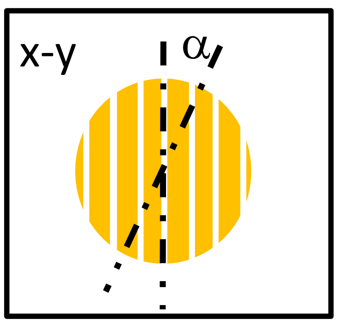
Outlook for gravity measurement of Pn



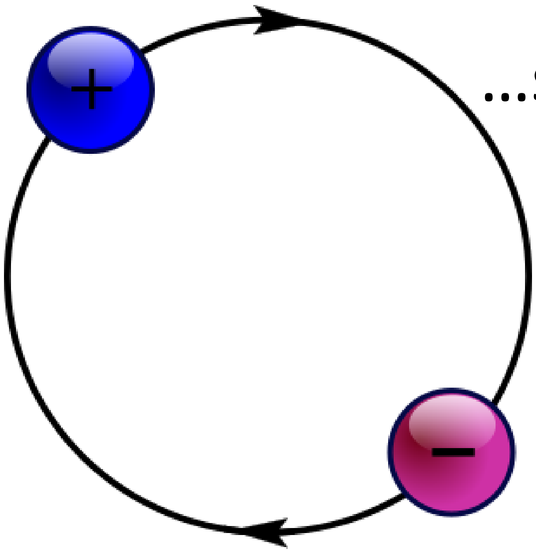
Required detected Pn to reach 1σ g-measurement:



α =0º – 30º Talbot-Lau layout
(is sensitive to 0 and 0.5 g):



R. Colella et al., *Phys. Rev. Lett.* **34**, 1472 (1975)
M. Oberthaler, *Heidelberg*



...stay tuned for precision Pn physics in traps

Special thanks to:

Michael Doser, CERN

Daniel Comparat, Laboratoire Aimé Cotton

Thank you very much for your attention!