Recombination in Traps

Francis Robicheaux
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Three Body Recombination
Double Charge Transfer
Radiative Recombination

F. Robicheaux, J. Phys. B **41**, 192001 (2008).
Atomic processes in antihydrogen experiments: a theoretical and computational perspective

Support from DOE and NSF

Three Body Recombination References

P. Mansbach and J. Keck, Phys. Rev. **181**, 275 (1969).

M. E. Glinsky and T. M. O'Neil, Phys. Fluids B **3**, 1279 (1991).

F. Robicheaux and J. D. Hanson, Phys. Rev. A **69**, 010701(R) (2004).

E. M. Bass and D. H. E. Dubin, Phys. Plasmas **11**, 1240 (2004).

F. Robicheaux, Phys. Rev. A **73**, 033401 (2006).

F. Robicheaux, J. Phys. B **40**, 271 (2007).

T. Pohl, D. Vrinceanu, and H. R. Sadeghpour, Phys. Rev. Lett. **100**, 223201 (2008).

E. M. Bass and D. H. E. Dubin, Phys. Plasmas **16**, 012101 (2009).

Double Charge Transfer References

E. A. Hessels, D. M. Homan, and M. J. Cavagnero, Phys. Rev. A **57**, 1668 (1998).

C. H. Storry, et al, Phys. Rev. Lett. **93**, 263401 (2004).

M. L. Wall, C. S. Norton, and F. Robicheaux, Phys. Rev. A **72**, 052702 (2005).

P. H. Donnan and F. Robicheaux, New J. Phys. submitted

Radiative Recombination References

M. Horndl et al, Hyp. Int. **146**, 13 (2003)

C. E. Correa, J. R. Correa, and C. A. Ordonez, Phys. Rev. E **72**, 046406 (2005).

F. B. Yousif, et al, Phys. Rev. Lett. **67**, 26 (1991).

M. L. Rogelstad et al, J. Phys. B **30**, 3913 (1997)

M. Amoretti et al, Phys. Rev. Lett. **97**, 213401 (2006).

A. Scrinzi, N. Elander, and A. Wolf, Z. Phys. D **34**, 185(1995).

C. Wesdorp, F. Robicheaux, and L. D. Noordam, Phys. Rev. Lett. **84**, 3799 (2000); Phys. Rev. A **64**, 033414 (2001).

F. Robicheaux, J. Phys. B **41**, 192001 (2008).

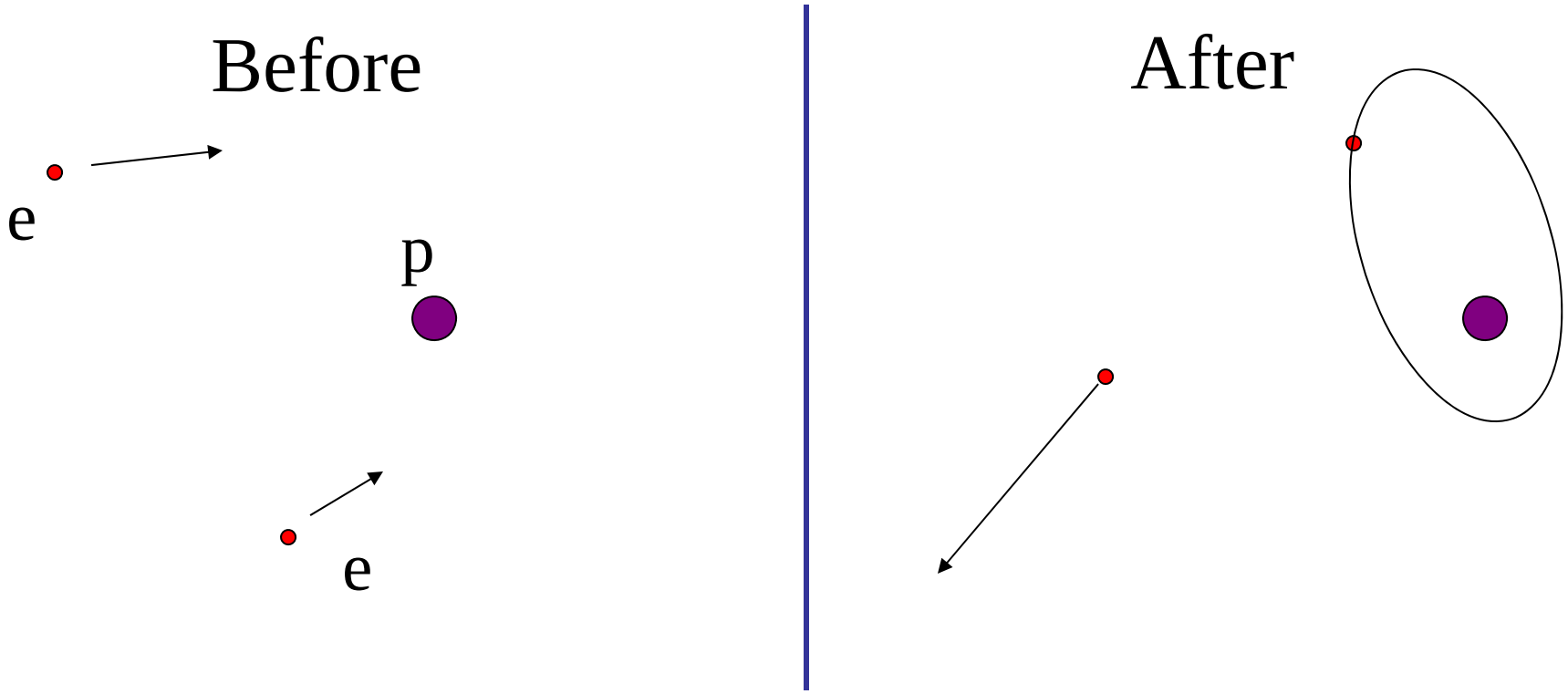
Dielectronic Recombination at higher T!!!!!

PHYSICAL REVIEW VOLUME 181, NUMBER 1 5 MAY 1969

Monte Carlo Trajectory Calculations of Atomic Excitation and Ionization by Thermal Electrons*

Peter Mansbach† and James Keck‡
Avco Everett Research Laboratory, Everett, Massachusetts

(Received 23 December 1968)



No magnetic field

Scaling in Steady State

Important parameters: n = density & T = temperature

Define speed $v = (k_B T/m_e)^{1/2}$ and length scale

$b = k e^2/k_B T$

Rate = $\langle v \sigma \rangle n$

$\sigma = b^2$ Prob (2nd electron in relevant volume)

Prob = $b^3 n$

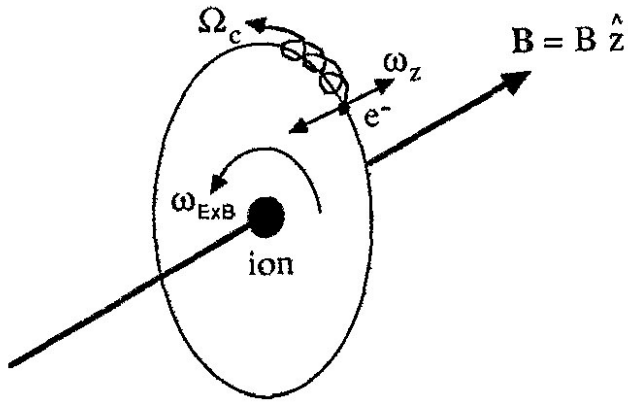
Rate = $C n^2 v b^5 \sim n^2/T^{9/2}$

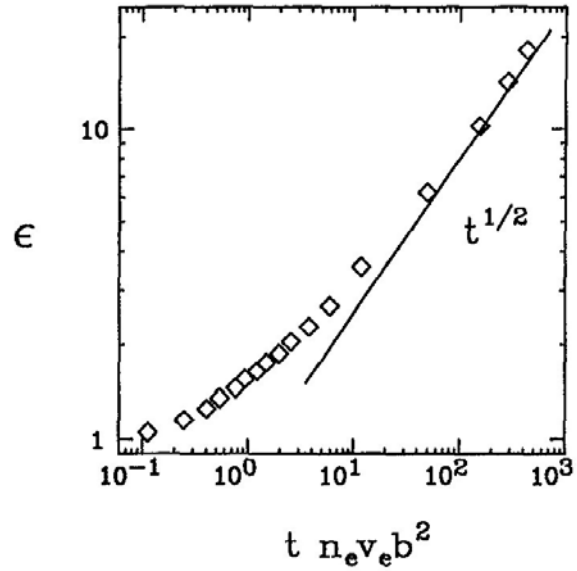
MK value C = 0.76

Guiding center atoms: Three-body recombination in a strongly magnetized plasma

Michael E. Glinsky and Thomas M. O'Neil
University of California at San Diego, La Jolla, California 92093

(Received 10 August 1990; accepted 29 January 1991)





Electrons pinned to field lines => B ~ infinity

GO value C = 0.070

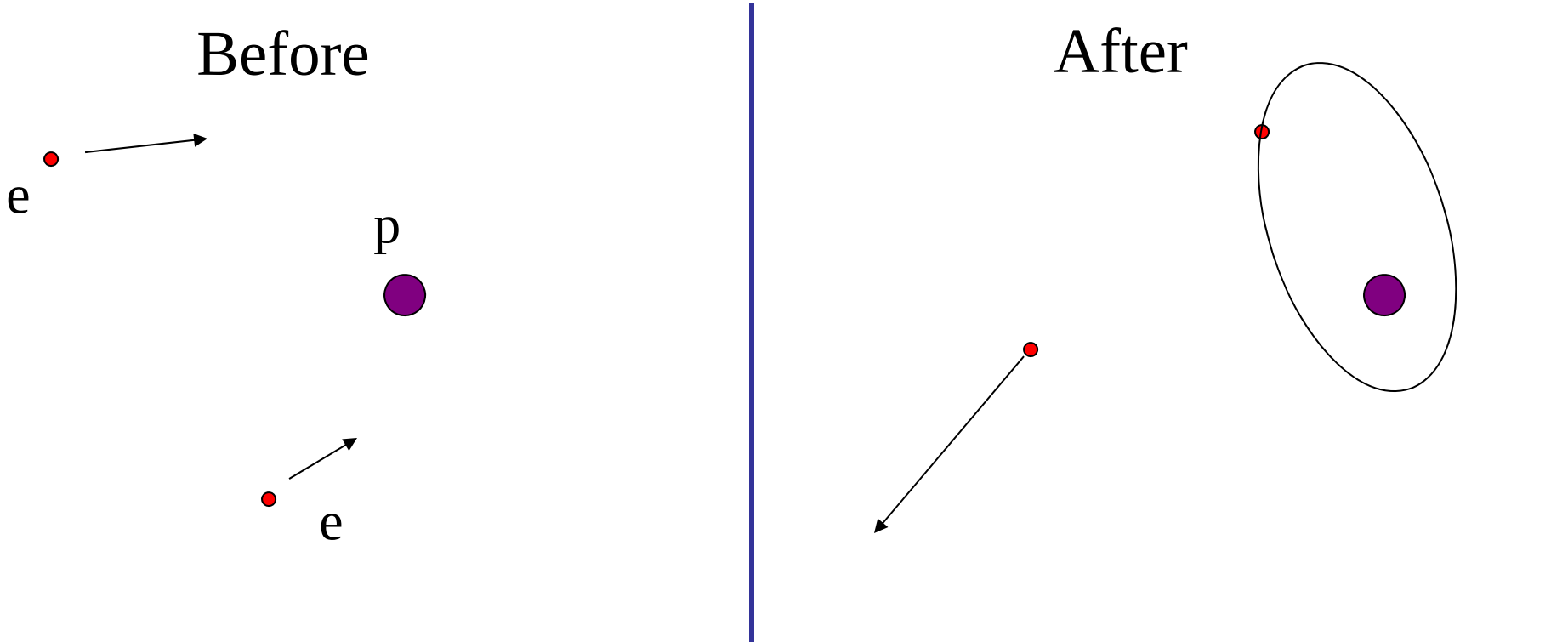
Edge of energy distribution (t when reach ½ steady state)

PHYSICAL REVIEW A **69**, 010701(R) (2004)

Three-body recombination for protons moving in a strong magnetic field

F. Robicheaux* and James D. Hanson
Department of Physics, Auburn University, Auburn, Alabama 36849-5311, USA
(Received 23 July 2003; published 27 January 2004)

Using a classical Monte Carlo method, we have computed the three-body recombination (two free electrons and a proton scattering into one free electron and a hydrogen atom: $e+e+p \rightarrow \mathrm{H}+e$) in strong magnetic fields. The proton is allowed its full motion whereas the motion of the electron is given by the guiding center approximation. We investigate recombination for temperatures and fields similar to those used in recent ex-



Results: Fast H?

Rate = C n^2 v b^5

n = density

v = $(k_B T/m_e)^{1/2}$

b = k $e^2/k_B T$

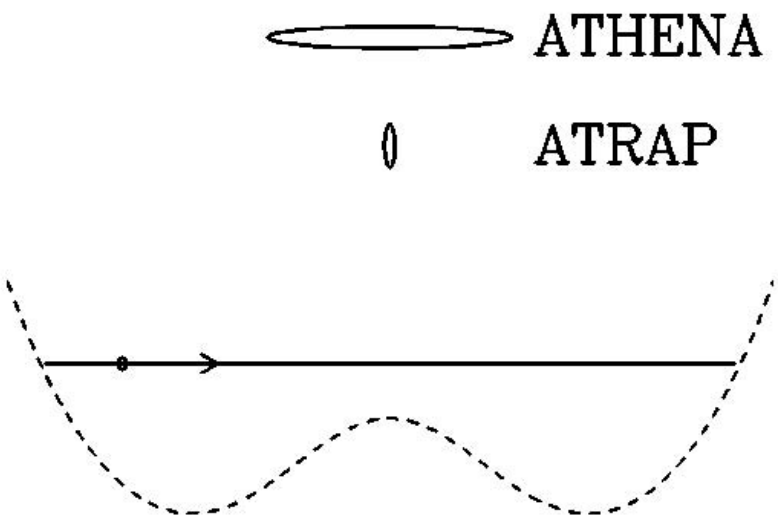
TABLE II. Three-body recombination coefficient as a function of proton speed along the B field. $B = 5.4$ T, $T_e = 4$ K. The speed of the proton is given in units of electron thermal speed $V_0 = \sqrt{2k_B T_e/m_e} = 1.1 \times 10^4$ m/s. The energy of a proton with speed V_z is also given.

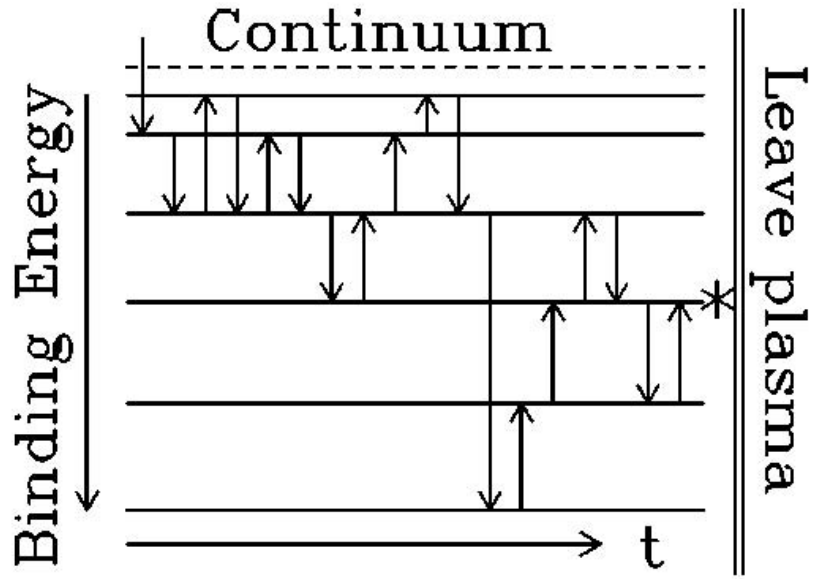
V_z/V_0	C	E (eV)
0.000	0.100	0.00
0.167	0.081	0.04
0.333	0.051	0.14
0.500	0.031	0.32
0.667	0.018	0.56
0.833	0.011	0.88
1.000	0.008	1.27

PHYSICAL REVIEW A **70**, 022510 (2004)

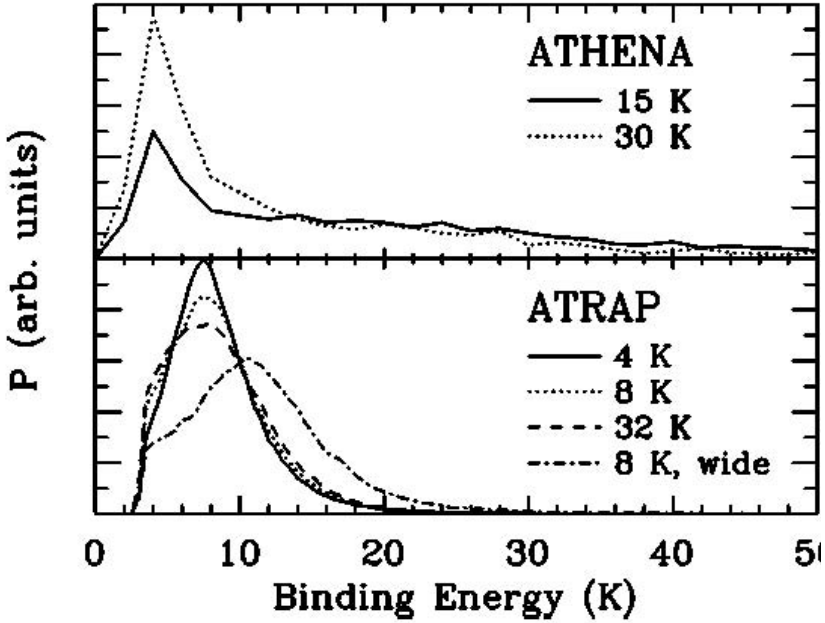
Simulations of antihydrogen formation

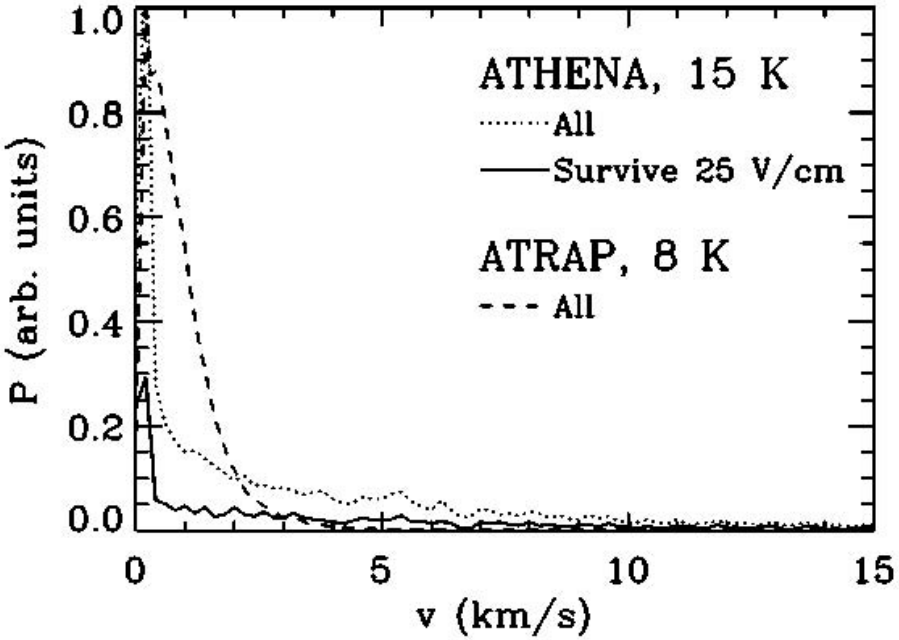
F. Robicheaux*
Department of Physics, Auburn University, Alabama 36849-5311, USA
(Received 31 October 2003; published 20 August 2004)





Results: Small BE & Fast!

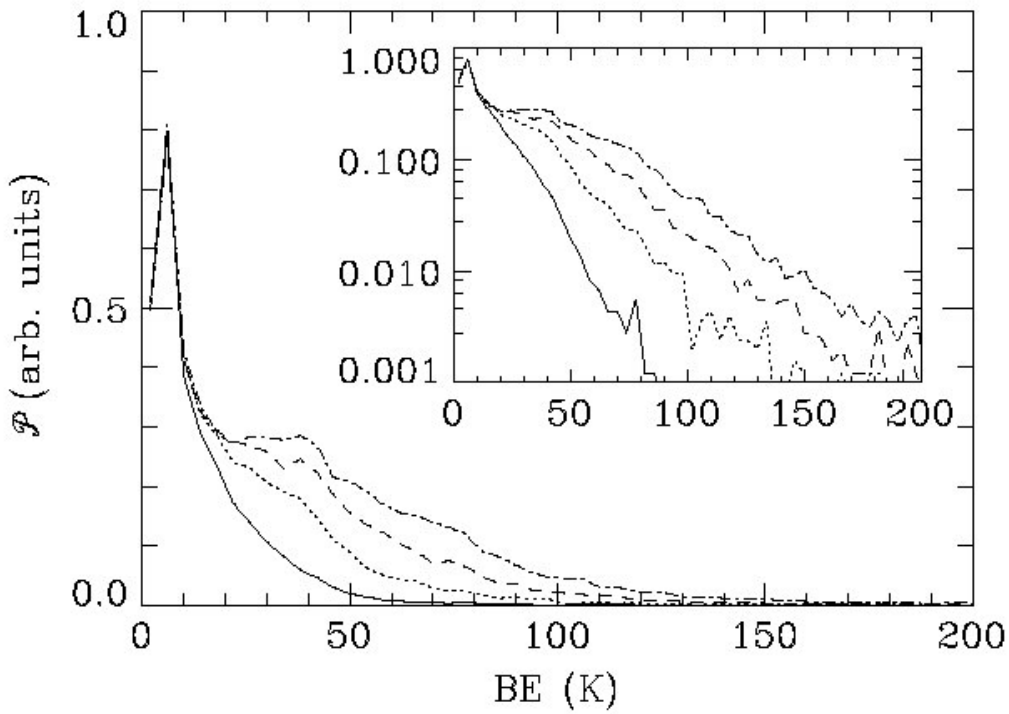




Binding energy much less than expected

Speed of Hbar much larger than thermal (250 m/s) or trap depth (110 m/s).

Evolution of BE



Binding energy distribution after 20, 40, 60, 80 μs after entering 4 K, 1.37 X 10^{-7} cm^{-3} plasma

BE = 100 K => n = 40

1 cm/(100 m/s) = 100 μs

TBR Temperature Surprise?

PHYSICAL REVIEW A **73**, 033401 (2006)

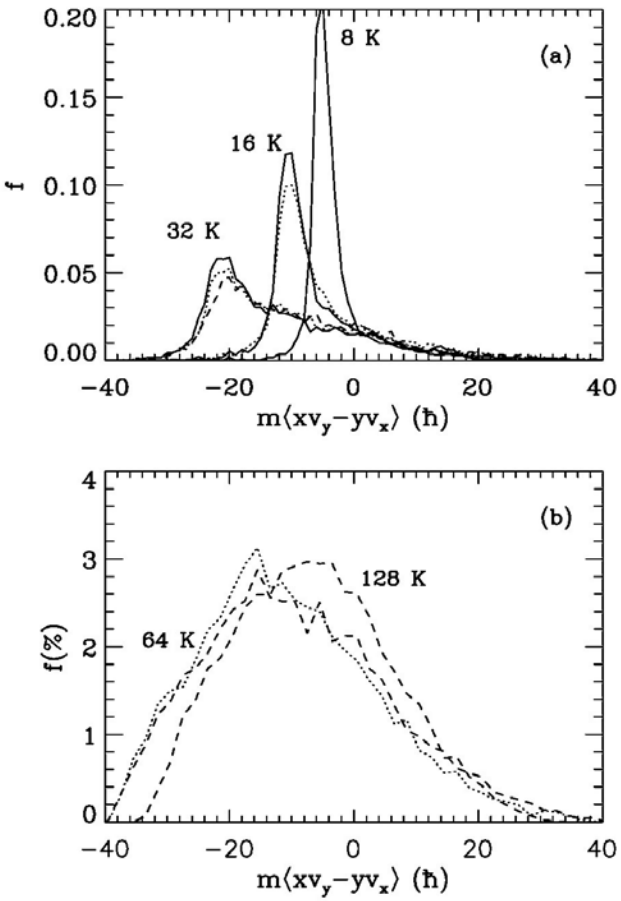
Three-body recombination for electrons in a strong magnetic field: Magnetic moment

F. Robicheaux

Atoms bound by more than 32 K

Fraction with dE/dB > 0 and dE/dB > 10 K/T increases with increasing positron temperature!

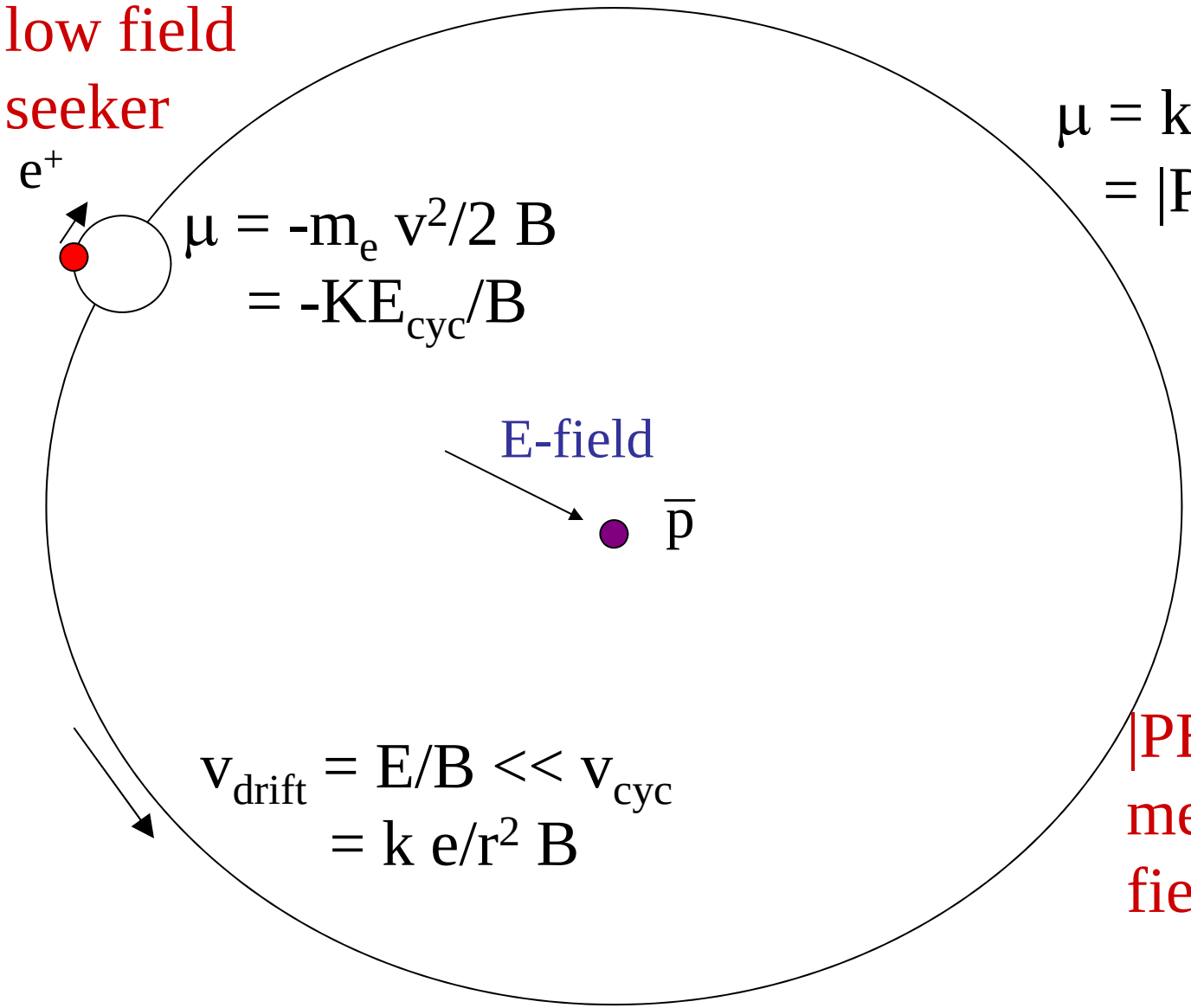
4 K positrons: C = 0.17, f = 0.035
8 K positrons: C = 0.21, f = 0.058
16K positrons: C = 0.25, f = 0.063



Magnetic moment vs T and BE

μ proportional to $m\langle xv_y - yv_x\rangle$

Guiding Center Atom: μ



$\mu = k e^2/2 r B$
$= |PE|/2 B$

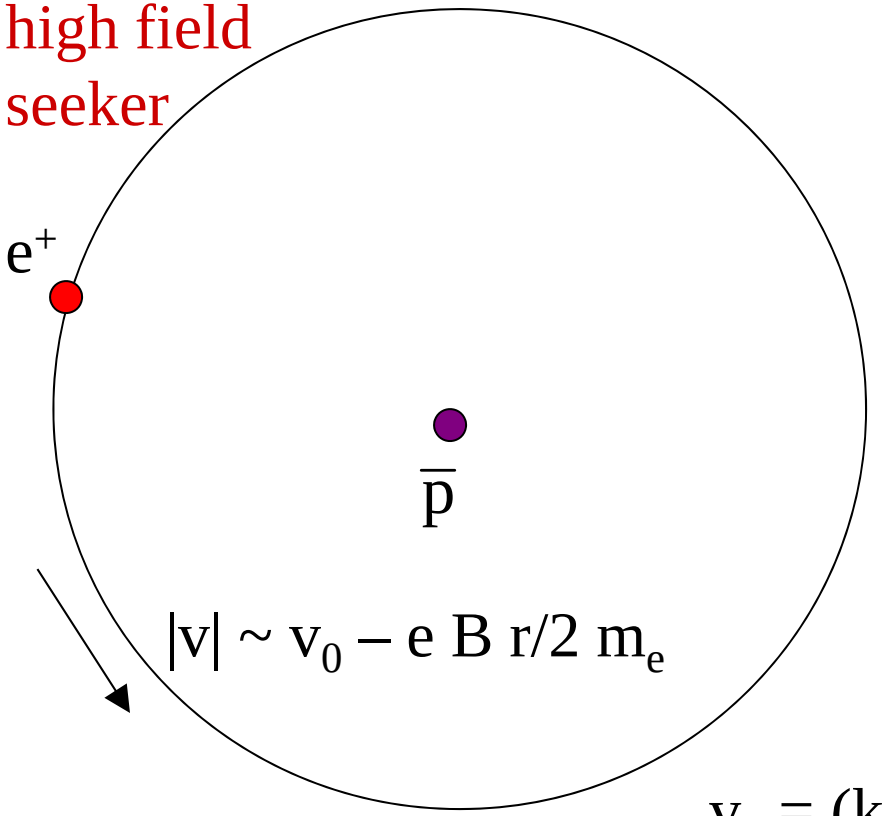
high field seeker

$|PE| < KE_{cyc}$ means GCA low field seeker

High/Low Field Seekers

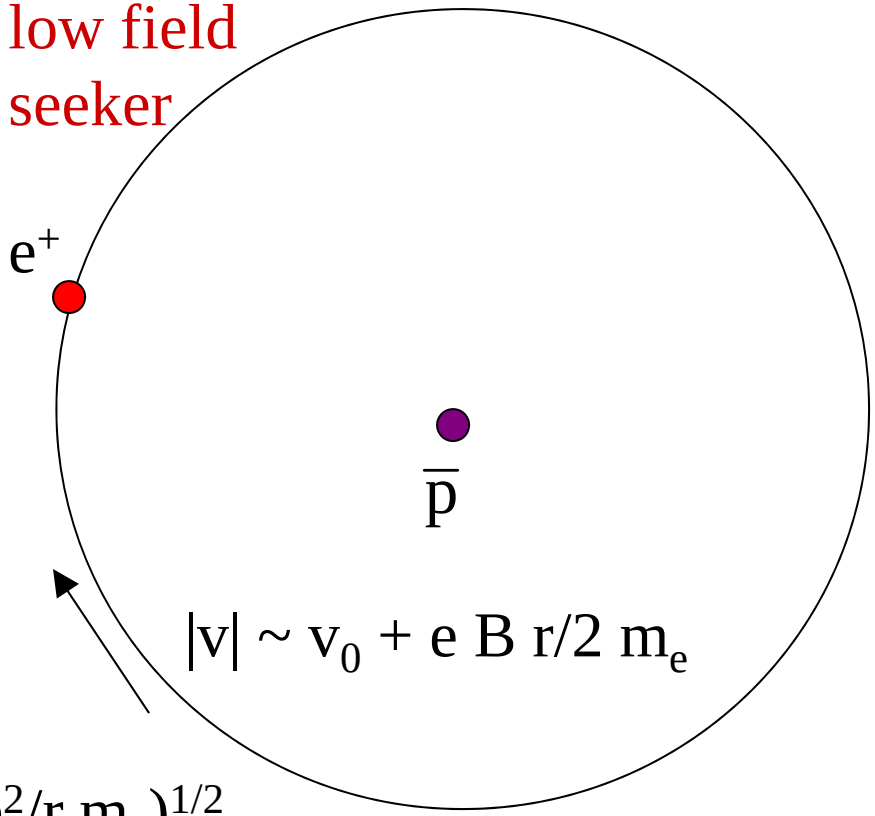
B does not strongly affect μ for more deeply bound states (n < 30).

high field seeker



$|v| \sim v_0 - e\,B\,r/2\,m_e$

low field seeker



$|v| \sim v_0 + e\,B\,r/2\,m_e$

$v_0 = (k\,e^2/r\,m_e)^{1/2}$

$v_0 = 73$ km/s

$e\,B\,r/2\,m_e = 4$ km/s

for n = 30, B = 1 T

$|\,\mu\,| \sim e^2\,(k\,r/m_e)^{1/2}/2$

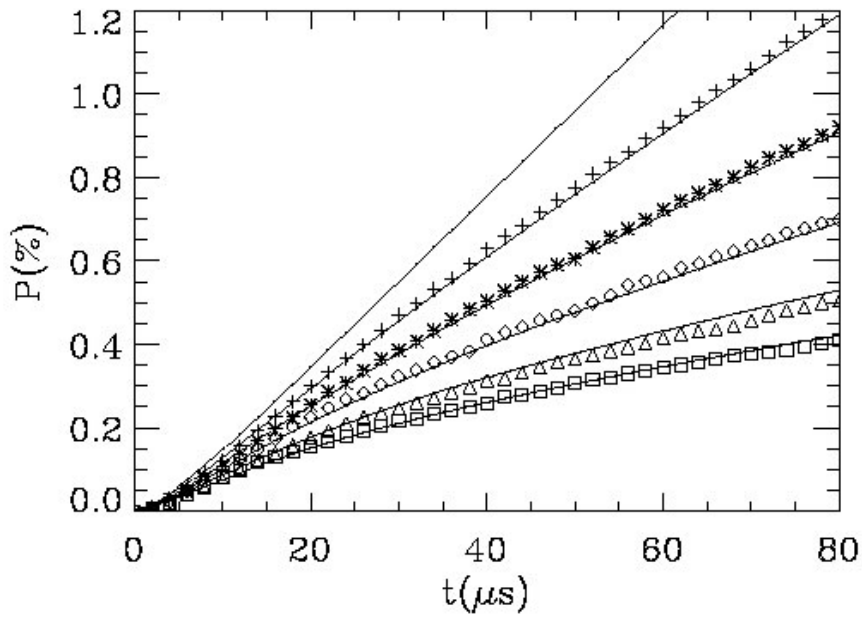
$= e\,|L|\,/2\,m_e$

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. **40** (2007) 271–280 doi:10.1088/0953-4075/40/2/003

Three-body recombination with mixed sign light particles

F Robicheaux



Recombination in 4 K plasma to states bound by > 16 K, for fraction of electrons: 0.0, 0.04, 0.08, 0.12, 0.16, 0.20

Lines from simple model calculation

PHYSICAL REVIEW A VOLUME 57, NUMBER 3 MARCH 1998

Two-stage Rydberg charge exchange: An efficient method for production of antihydrogen

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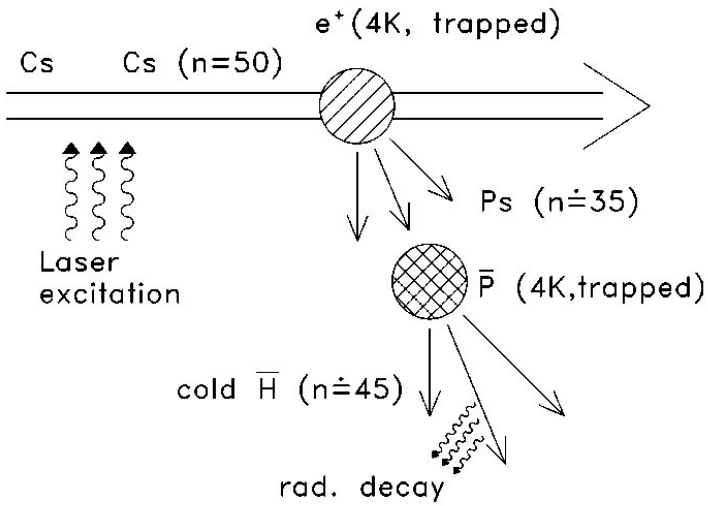
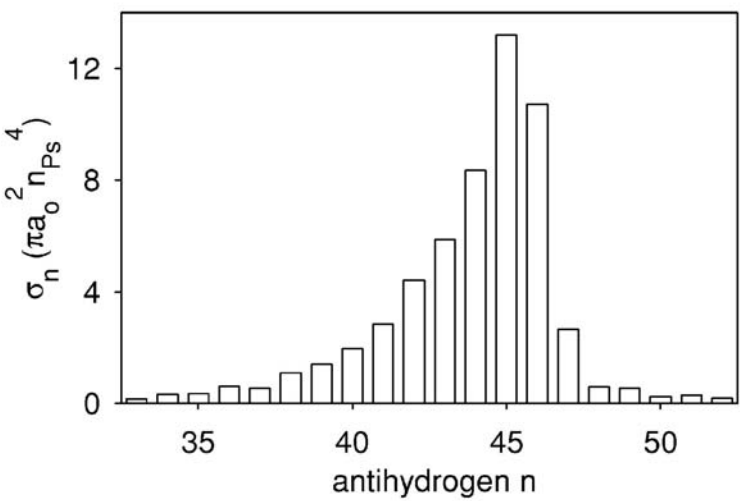
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada M3J 1P3

D. M. Homan and M. J. Cavagnero
Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055
(Received 12 September 1997)



n distribution of antihydrogen



smaller n from conservation of energy

Trends

Number Hbars = $N_{ps}\ N_p\ \sigma/(4\ \pi\ d^2)$

Take $\sigma = 4\ \pi\ (2\ n^2\ a_0)^2$ gives $3.6 \times 10^{-9}\ cm^2$

Guess d = 5 cm for trapping Hbars, gives

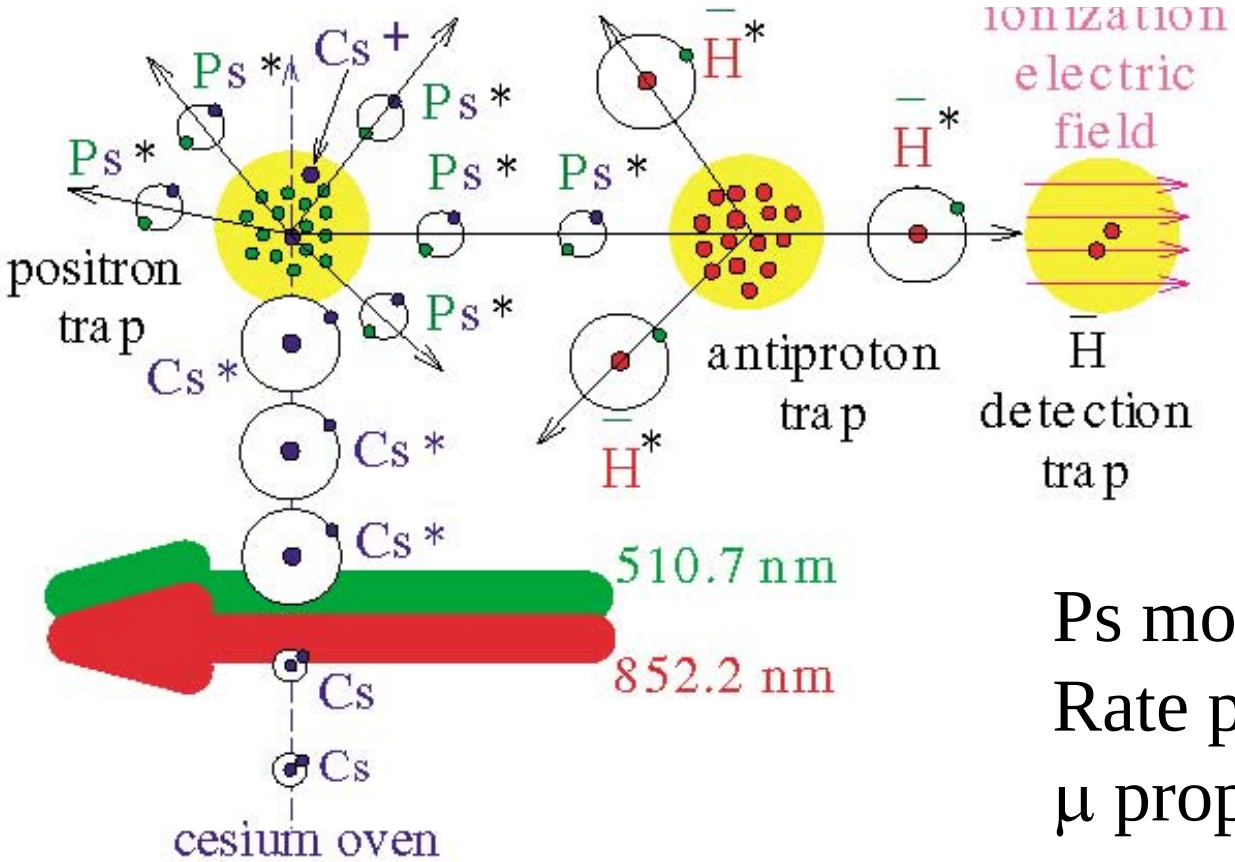
Number Hbars ~ $N_{ps}\ N_p\ 10^{-11}$

PRL 93, 263401 (2004) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2004

First Laser-Controlled Antihydrogen Production

C. H. Storry,[1] A. Speck,[1] D. Le Sage,[1] N. Guise,[1] G. Gabrielse,[1,*] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] H. Pittner,[3] M. Herrmann,[3] J. Walz,[3] T.W. Hänsch,[3,4] D. Comeau,[5] and E. A. Hessels[5]

(ATRAP Collaboration)



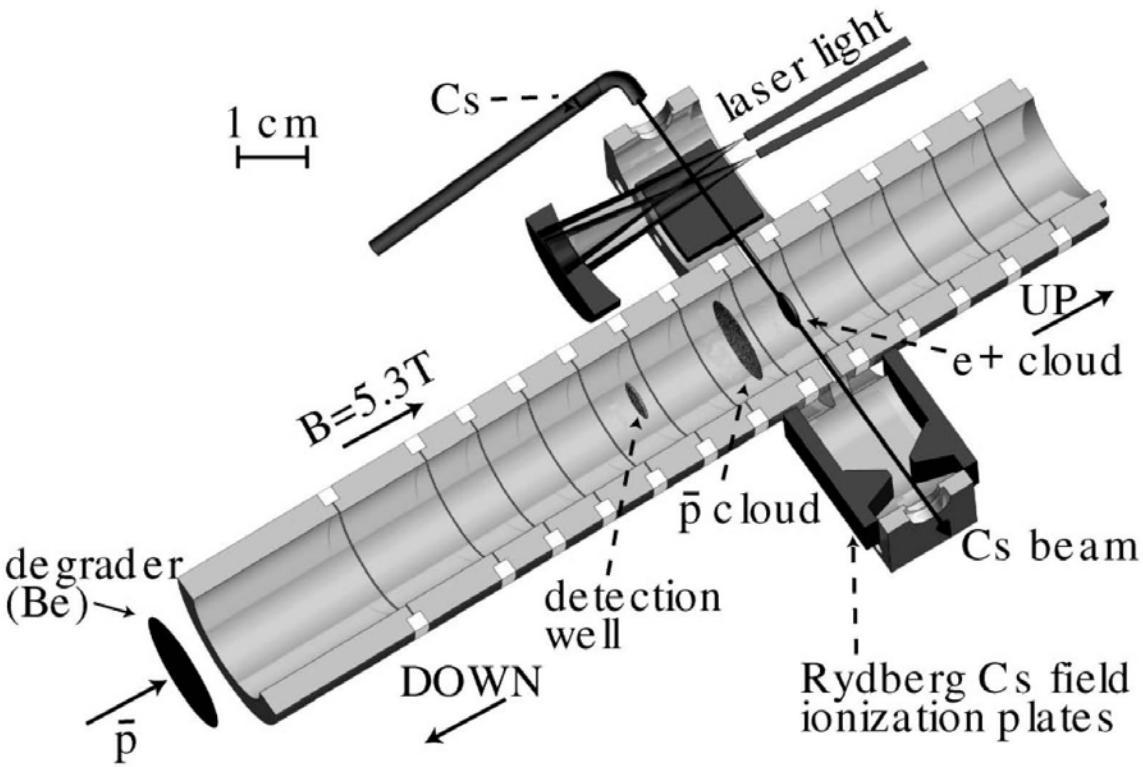
Ps more likely along B

Rate proportional to n^2

μ proportional to n

Results

$14 \pm 4\ \overline{\mathrm{H}}$ detected



"…a formation calculation that includes the crucial role of the magnetic field is needed."

PHYSICAL REVIEW A **72**, 052702 (2005)

Two-stage Rydberg charge exchange in a strong magnetic field

M. L. Wall, C. S. Norton, and F. Robicheaux
Department of Physics, Auburn University, Auburn, Alabama 36849-5311, USA
(Received 21 June 2005; published 4 November 2005)

We have performed calculations of two successive charge transfers from Rydberg states in a strong magnetic field. In the first charge transfer, a positron interacts with a highly excited atom to form positronium. In the second stage, the positronium interacts with an antiproton to give antihydrogen. For many parameters, our

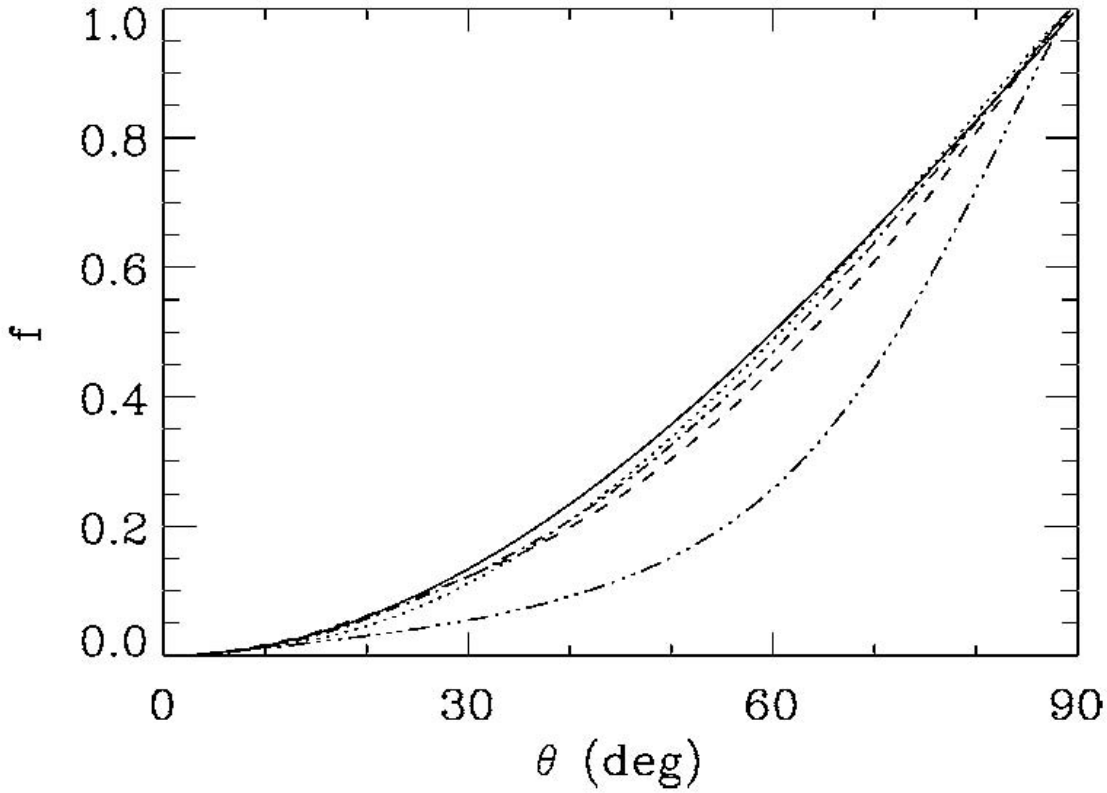
Classical Trajectory Monte Carlo calculation

Small time steps due to large B (cyclotron period = 36 ps Tesla/B)

Two nontrivial results

Angle of emergence, Ps

Fraction of Ps that emerge with angle < θ



Dashed – n=30, 4 T

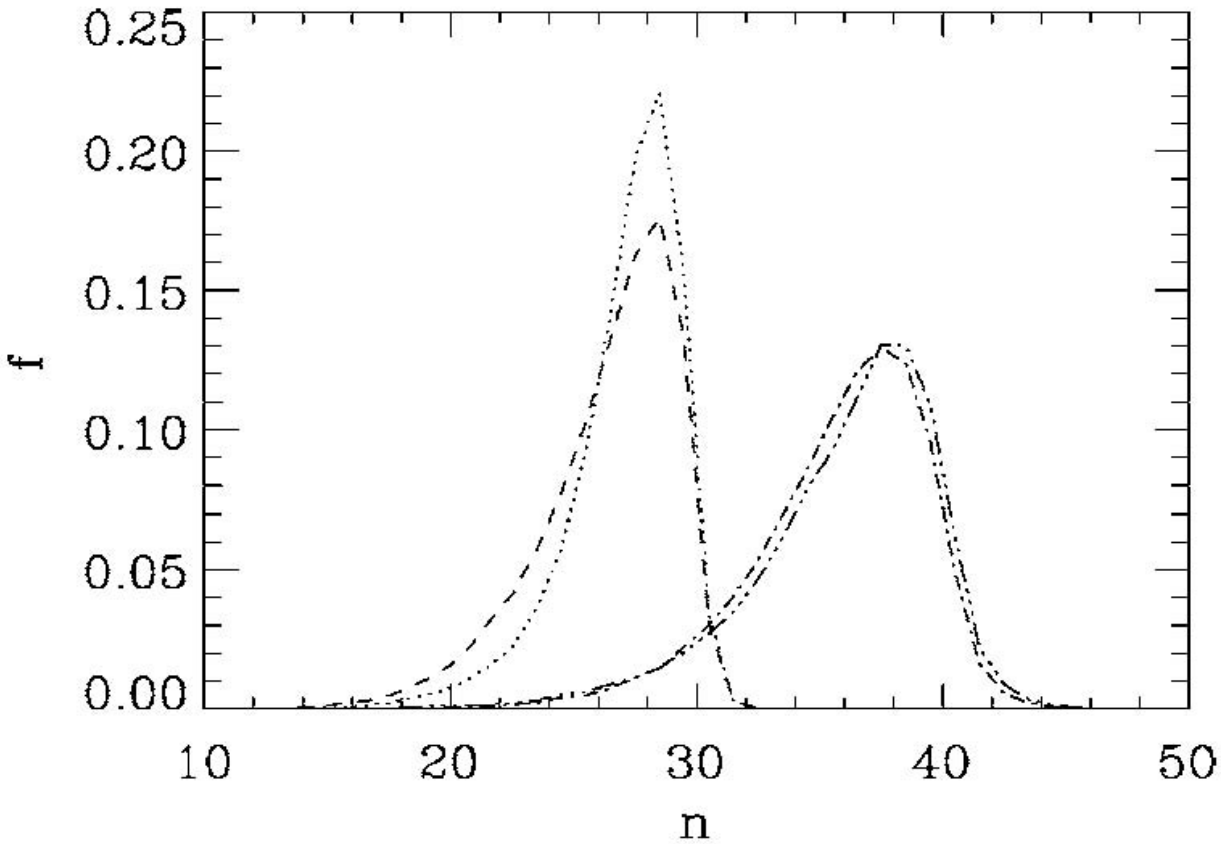
Dotted – n=30, 1 T

Dash-dot – n=40,1 T

Dash-dotdotdot – n=40,4 T

n distribution of anti-H

Fraction of anti-H with principle quantum number = n



Dashed – n=30, 4 T

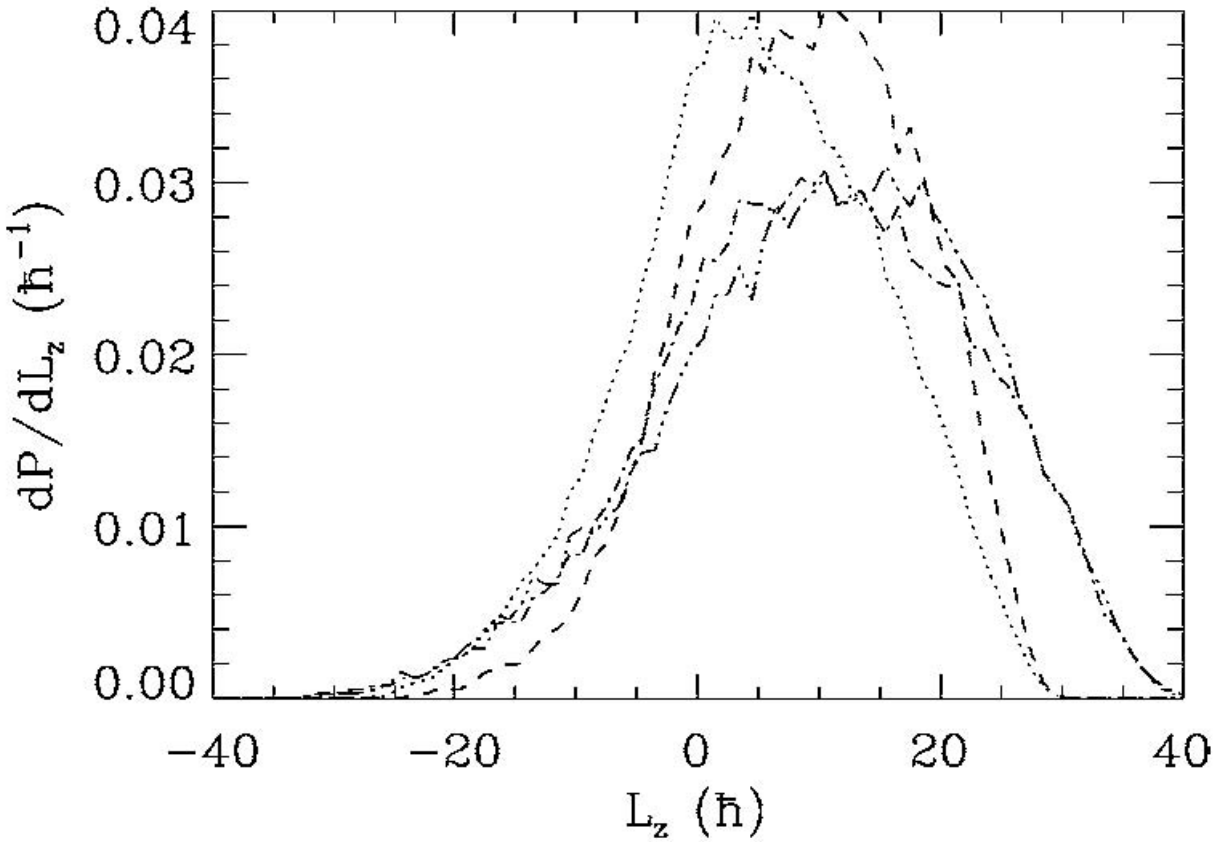
Dotted – n=30, 1 T

Dash-dot – n=40,1 T

Dash-dotdotdot – n=40,4 T

L_z distribution

Fraction of anti-H with $L_z = (rXmv)_z$



Dashed – n=30, 4 T

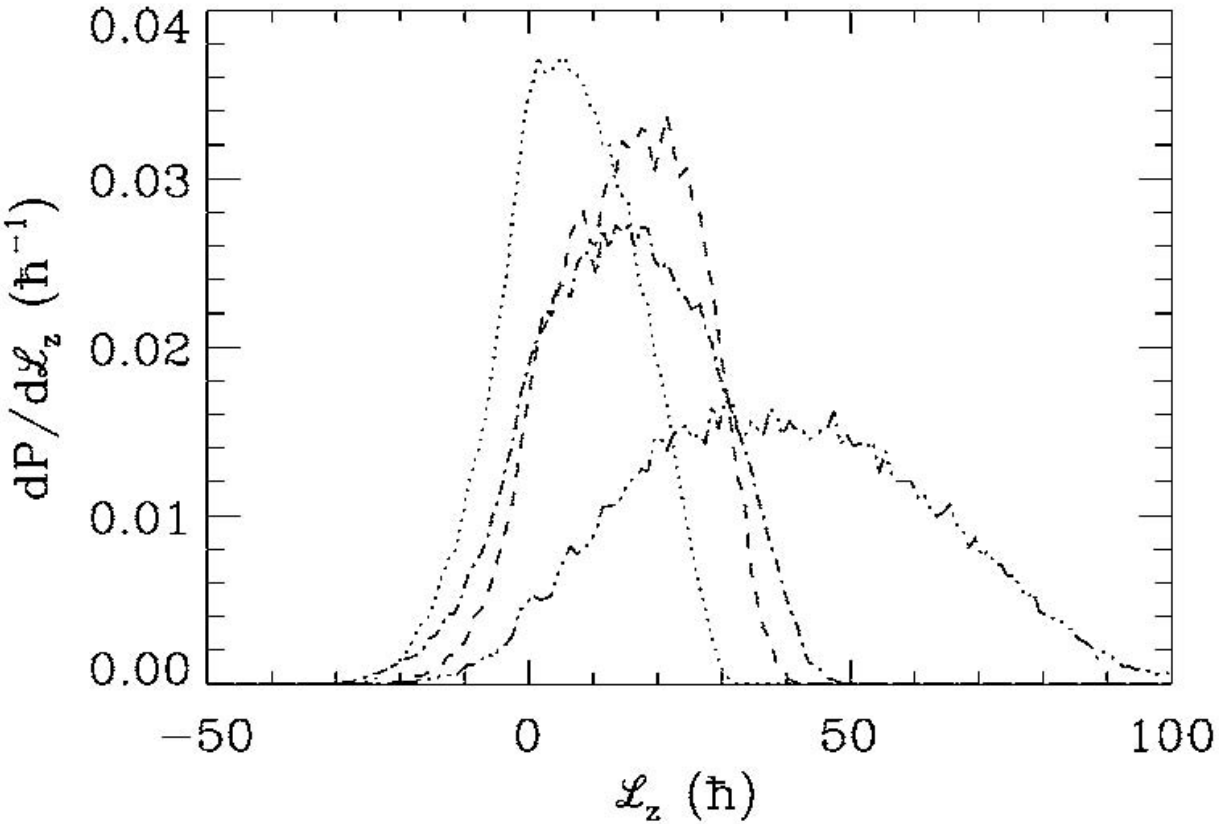
Dotted – n=30, 1 T

Dash-dot – n=40,1 T

Dash-dotdotdot – n=40,4 T

$\mathcal{L}_z$ distribution

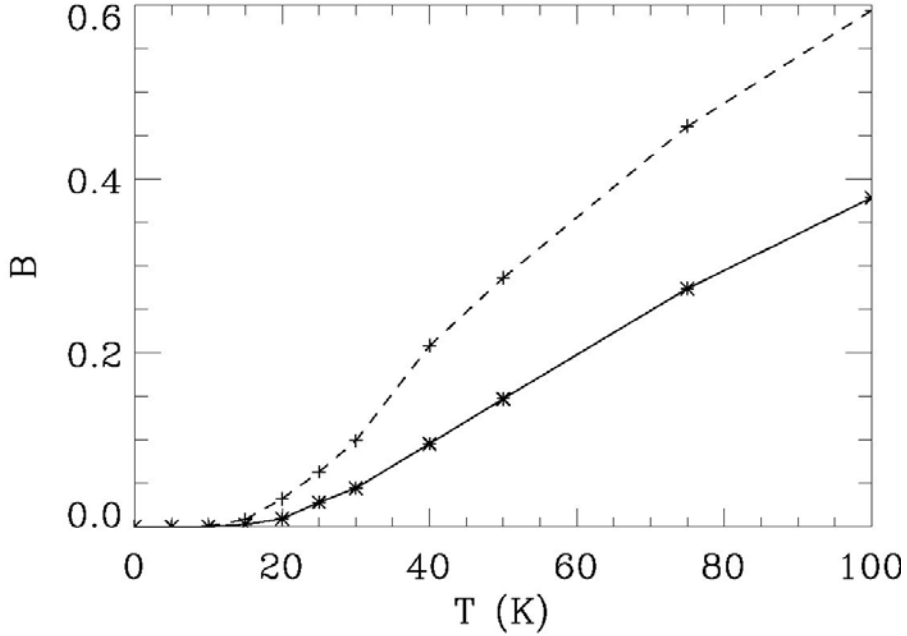
Fraction of anti-H with canonical $\mathcal{L}_z = L_z + qB\rho^2/2$

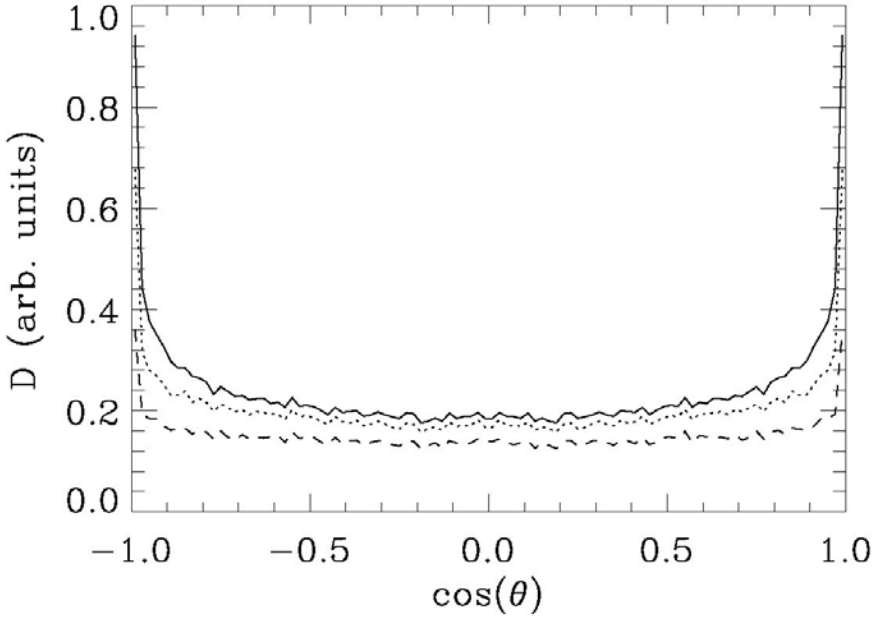


Dashed – n=30, 4 T Dotted – n=30, 1 T

Dash-dot – n=40,1 T Dash-dotdotdot – n=40,4 T

Preliminary Results: High T_e

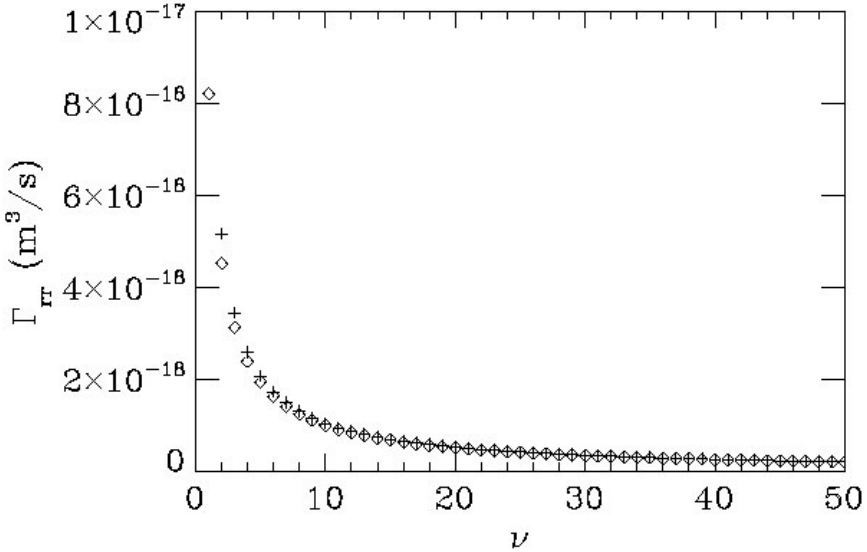




Branching ratio for ionization
solid – n = 40
dashed – evolves

Angular distribution & survive (T_e = 30 K)
0 V/cm – solid
100 V/cm – dotted
200 V/cm – dashed

Radiative Recombination: B=0



Comparison full quantum & Kramers formula for T = 4 K

$\sigma_K = 2.1 \text{ X } 10^{-22} E_0^2/[\nu E (E_0 + \nu^2 E)] \text{ cm}^2$

$\Gamma = \langle v \sigma_K \rangle$

At T = 4 K, $\Gamma = 4.3 \text{ X } 10^{-11} \text{ cm}^3/\text{s}$

Radiative Recombination: B>0

Discussion in F. Robicheaux, J. Phys. B **41**, 192001 (2008).
Rate is increased into smaller BE.
Comparison is h f_{cyc} to k_B T.

At 1 Tesla, T = 4/3 K => not important effect

VOLUME 67, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 1991

Experimental Observation of Laser-Stimulated Radiative Recombination

F. B. Yousif, P. Van der Donk, Z. Kucherovsky, J. Reis, E. Brannen, and J. B. A. Mitchell
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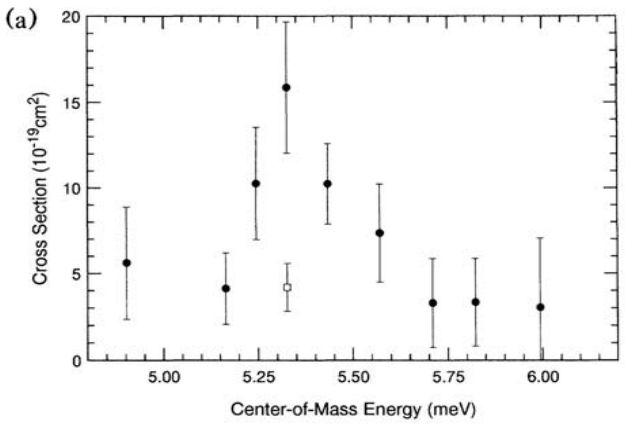
T. J. Morgan
Physics Department, Wesleyan University, Middletown, Connecticut 06457
(Received 13 March 1991)

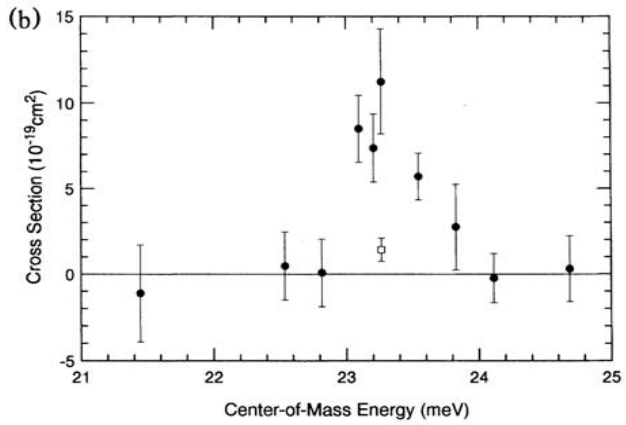
CO_2 laser resonant for threshold to n~10

h f + e^- + H^+ goes to H(nl) + 2 h f

Open symbol: laser off



n = 11



n = 12

J. Phys. B: At. Mol. Opt. Phys. **30** (1997) 3913–3931. Printed in the UK

Stimulated radiative recombination of H^+ and He^+

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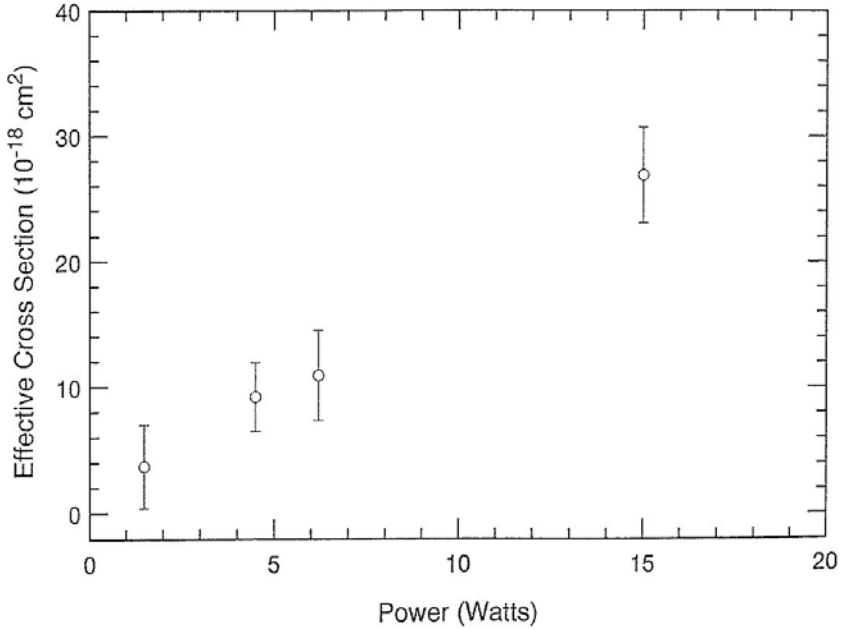
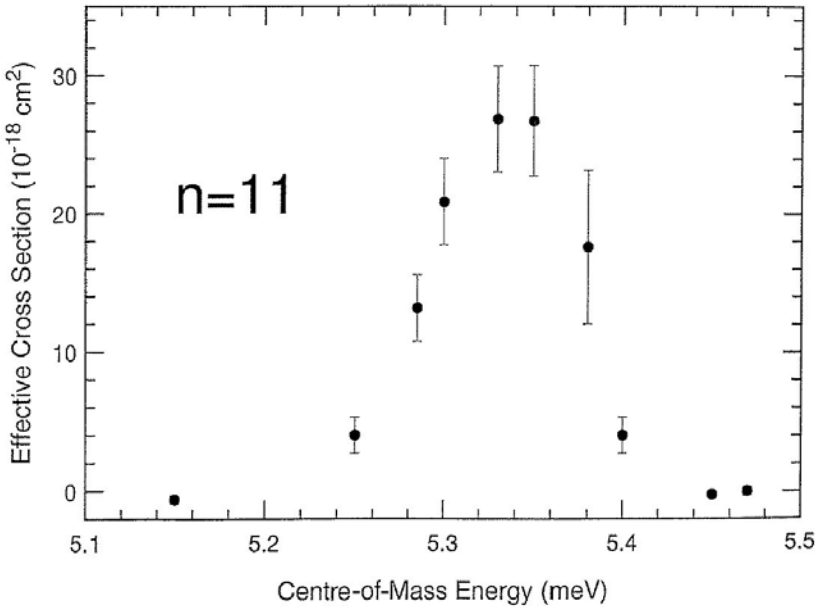
§ Department of Physics, Wesleyan University, Middletown, CT 06459-0155, USA

Received 20 January 1997, in final form 14 May 1997





Search for Laser-Induced Formation of Antihydrogen Atoms

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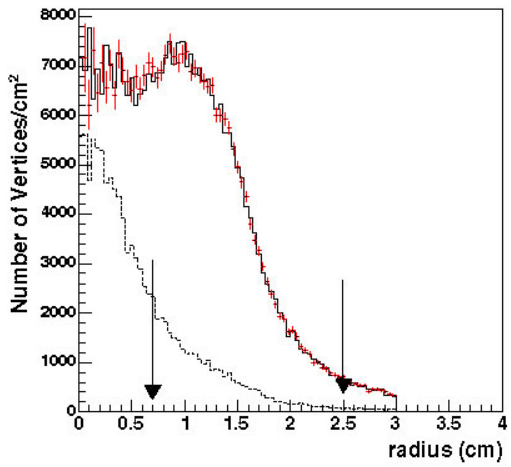
(ATHENA Collaboration)



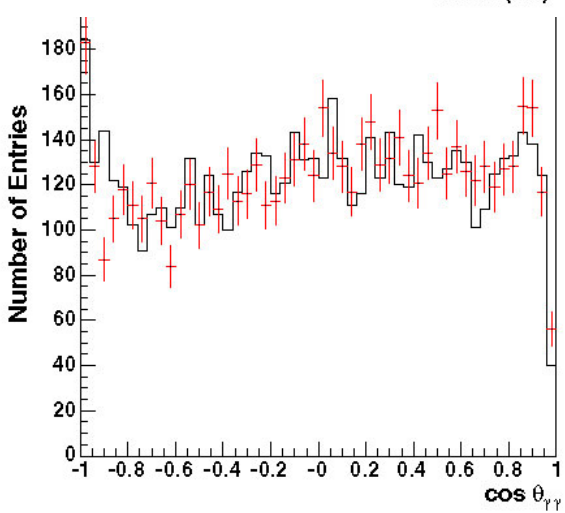


TABLE I. Integrated number of vertices in the arrowed region shown in Fig. 2 for different time windows $[t_1, t_2]$ in seconds.

Run	Vertex quality	Time window (s) [1, 50]	[1, 10]	[10, 50]
Laser on	No	59 496	18 457	41 039
Laser off	No	59 611	18 353	41 258
On-off		−115 ± 345	104 ± 192	−219 ± 287
Laser on	Yes	34 731	10 938	23 793
Laser off	Yes	35 039	10 760	24 279
On-off		−308 ± 434	178 ± 241	−486 ± 219

Random Final Thoughts: TBR

Three body recombination is an important process in several other systems but different forces (and quantum mechanics) gives qualitative differences.

Ultracold gases

H + H + H goes to $H_2(v,J)$ + H in astrophysical gases

Formation of van der Waals molecules