Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Instruments and Methods in Physics Research B 247 (2006) 133–137

NIM B
Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

Progress with cold antihydrogen

M. Amoretti [a], C. Amsler [b], G. Bonomi [c], P.D. Bowe [d], C. Canali [a,e], C. Carraro [a,e], C.L. Cesar [f], M. Charlton [g,*], M. Doser [c], A. Fontana [h,i], M.C. Fujiwara [j,k], R. Funakoshi [j], P. Genova [h,i], J.S. Hangst [d], R.S. Hayano [j], I. Johnson [b], L.V. Jørgensen [g], A. Kellerbauer [c], V. Lagomarsino [a,e], R. Landua [c], E. Lodi Rizzini [h,l], M. Macrí [a], N. Madsen [d], G. Manuzio [a,e], D. Mitchard [g], P. Montagna [h,i], H. Pruys [b], C. Regenfus [b], A. Rotondi [h,i], G. Testera [a], A. Variola [a], L. Venturelli [h,l], D.P. van der Werf [g], Y. Yamazaki [k], N. Zurlo [h,l]

ATHENA Collaboration

[a] *Istituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italy*
[b] *Physik-Institut, Zürich University, 8057 Zürich, Switzerland*
[c] *Department of Physics, CERN, 1211 Geneva 23, Switzerland*
[d] *Department of Physics and Astronomy, University of Aarhus, 8000 Aarhus C, Denmark*
[e] *Dipartimento di Fisica, Università di Genova, 16146 Genova, Italy*
[f] *Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21945-970, Brazil*
[g] *Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK*
[h] *Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, 27100 Pavia, Italy*
[i] *Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, 27100 Pavia, Italy*
[j] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[k] *Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan*
[l] *Dipartimento di Chimica e Fisica per l'Ingegneria e per i Materiali, Università di Brescia, 25123 Brescia, Italy*

Abstract

The creation of cold antihydrogen by the ATHENA and ATRAP collaborations, working at CERN's unique Antiproton Decelerator (AD) facility, has ushered in a new era in atomic physics. This contribution will briefly review recent results from the ATHENA experiment. These include discussions of antiproton slowing down in a cold positron gas during antihydrogen formation, information derived on the dependence of the antihydrogen formation rate upon the temperature of the stored positron plasma and, finally, upon the spatial distribution of the emitted anti-atoms. We will discuss the implications of these studies for the major outstanding goal of trapping samples of antihydrogen for precise spectroscopic comparisons with hydrogen. The physics motivations for undertaking these challenging experiments will be briefly recalled.

PACS: 36.10.−k; 34.8.DLx; 52.20.Hv

Keywords: Antihydrogen; Antiprotons; Positrons; Penning trap

---

1. Introduction and motivations

The creation of low energy antihydrogen [1,2] is a landmark in atomic physics research. This achievement has

---

[*] Corresponding author. Tel.: +44 1792 295849; fax: +44 1792 295324.
E-mail address: M.Charlton@swansea.ac.uk (M. Charlton).

0168-583X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2006.01.060

spawned an explosion of theoretical activity in cognate areas of atomic and plasma physics, fuelled by further experimental advances by the ATHENA [3–7] and ATRAP [8–10] collaborations. Reviews of some of this work have been given elsewhere recently [11,12].

The main physics motivations for antihydrogen production lie in the promise for tests of CPT symmetry and antimatter gravity. CPT is a theorem in local quantum field theory in which the three quantum mechanical transformations of C (charge conjugation), P (parity) and T (time reversal) are combined. There are no known violations of this symmetry (see e.g. [13] for a summary of limits), but expectations are that modern theories of particle physics, that treat particles as extended objects rather than points, may contain CPT violation (see e.g. [11] and references therein). In this respect, precise hydrogen–antihydrogen comparisons may provide an important testing ground for new physics.

Gravity remains the "odd one out" in terms of Grand Unification. Indeed, as is well known, there is currently no acceptable quantum theory of gravity. In addition, we have no information on the gravitational interaction of antimatter. For instance, all we can glean from CPT is that antihydrogen will fall as fast towards a hypothetical anti-Earth as hydrogen does towards Earth. Given the current state of affairs either quantum mechanics or general relativity (or both of them) are incomplete. At the very least this makes gravity on antimatter an interesting phenomenon to study.

2. Experimental details

The ATHENA antihydrogen apparatus has been described in detail elsewhere [14]. The apparatus has three essential parts: a positron beam, accumulator and transfer section; an antiproton catching trap and associated Penning traps to promote antihydrogen formation; an antihydrogen annihilation detector. We briefly describe these here.

Low energy positron beams (see e.g. [15,16] and this volume) are now a standard feature in many physics laboratories. ATHENA used a solid neon moderator-based positron beam, derived from a ^{22}Na source, coupled to a buffer gas-cooled Penning–Malmberg trap [17–20]. In excess of 100 million positrons were accumulated in this apparatus, in about 3 min, and then transferred efficiently [21] to the antiproton apparatus. Further manipulation of the positron plasma in the 3 T magnetic field, cryogenic environment (15 K), of the antiproton traps could be undertaken using the rotating electric field technique [21–23]. Typically around 80 million positrons at a density of about 2×10^8 cm^{-3} were used for antihydrogen formation. The temperature of the positron cloud could be raised by applying a radio frequency signal to one of the trap electrodes surrounding the plasma. The temperature change was monitored non-destructively using a specially developed technique based upon the excitation and detection of plasma mode frequencies [24,25].

Antiprotons were captured and cooled using the well-documented procedure developed at CERN by Gabrielse and co-workers [26,27] and applied to form large antiproton clouds by the PS200T collaboration [28,29]. A 100 ns wide burst of about 2×10^7 antiprotons was ejected from the AD about every 100 s or so at a kinetic energy just above 5 MeV. About 1 in a 1000 of these could be dynamically captured in a 5 kV deep catching trap following energy degradation on passing through a carefully optimized thin foil. Once held in the 3 T Penning trap, the antiprotons were further cooled by interaction with a pre-loaded cloud of about 10^8–10^9 electrons, which self-cool in the strong field to the ambient temperature of 15 K. After about 10 s the antiprotons, which Coulomb couple efficiently to the electron cloud as they pass to-and-fro through it, reach thermal equilibrium with the electrons and occupy a small harmonic trap. The electrons can easily be removed by the application of short voltage pulses to leave about 10^4 antiprotons for release into the positron plasma.

Both the ATRAP and ATHENA collaborations have applied the nested Penning trap approach [30] to promote antihydrogen formation, and the system used by ATHENA is illustrated in Fig. 1. Here the axial electric potential, provided by the voltages applied to the

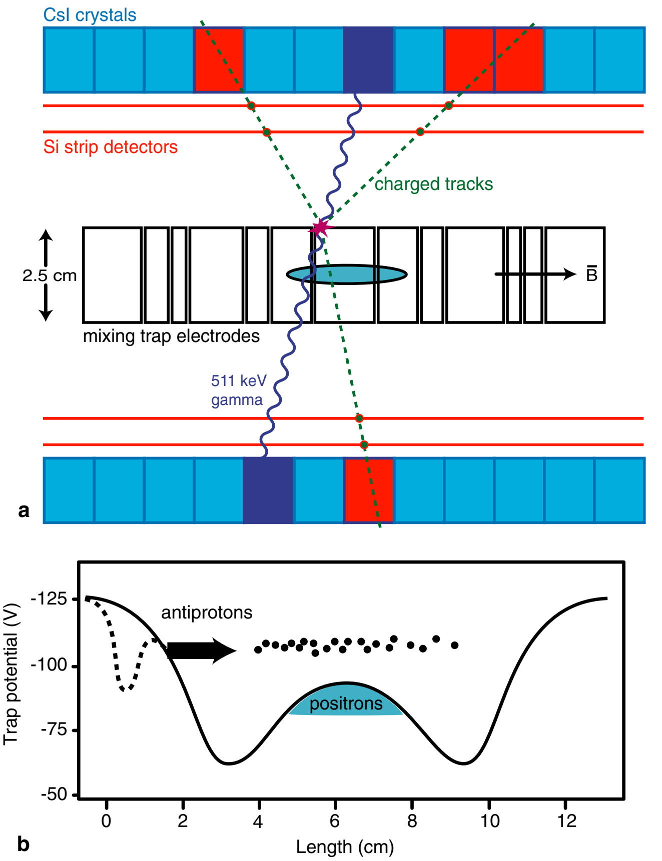

Fig. 1. (a) Schematic illustration of the ATHENA nested well apparatus with pion and γ-ray detectors included. (b) On-axis nested well potential showing the antiproton well (dashed line) before mixing.

cylindrically symmetric electrode system, was used to simultaneously confine the positrons and antiprotons. The nested well voltages used (Fig. 1(b)) meant that the antiprotons entered the positron cloud at a kinetic energy of about 30 eV, whereupon cooling occurred and antihydrogen formation ensued [5].

ATHENA used the annihilation of antihydrogen to generate their anti-atom signature. Once formed, any antihydrogen that survives the electric fields of the plasma, and collision processes therein, will migrate out of the charged particle traps. Most antihydrogen atoms drift to the electrode walls of the traps in the immediate vicinity of their point of creation and annihilate on contact. Put simply, such events produced a few charged pions from the annihilation of the antiproton and a pair of back-to-back 511 keV γ-rays following the annihilation of the positron (see Fig. 1(a)). A purpose-built detector [14,31] able to locate the antiproton vertex (i.e. the point of annihilation) was deployed, and the demand made that this event be accompanied by the characteristic γ-ray signal emanating from the same point at the same time. Later, ATHENA found that other, less stringent, proxies could be used to pinpoint antihydrogen via a capability to spatially distinguish between annihilations due to antihydrogen and those from bare antiprotons [3,4]. In essence the ATHENA detection technique was a global technique in the sense that all emitted antihydrogen could be detected, more-or-less independently of its binding energy.

3. Physics with cold antihydrogen

In this section we summarize some of the physics output from the results of the ATHENA collaboration. Salient results from ATRAP have been described elsewhere [12].

ATHENA has made the most complete study to date of cooling of antiprotons immersed in a positron plasma, correlated with antihydrogen formation [5]. By analyzing the time-dependence of the energy distribution of the antiproton swarm once it had been released from its holding well (see Fig. 1), and comparing changes in this distribution with the behaviour of the antihydrogen signal, a number of important conclusions were forthcoming. (Note that in this work the positron plasma typically had a radius of 3 mm, a length of 30 mm and a density of just over 10^8 cm^{-3} [24,25].) When the positrons are cold (typically 15 K) the antiprotons which have good physical overlap with the positron plasma cool within about 10–20 ms to energies where antihydrogen formation proceeds efficiently; see the inset of Fig. 2. On a longer timescale (>1 s) a slower cooling of antiprotons occurs leading to a continued, though diminishing, production of antihydrogen. This behaviour is most likely associated, as detailed in [5], with the cooling of antiprotons initially radially separated from the antiproton cloud. This is probably caused by the slow radial expansion of the positron plasma. A further effect is observed after about 500 ms when some of the antiprotons become axially separated from the positrons and occupy the lateral wells on either side of the plasma. (Note that this is not evident in the integrated data presented in Fig. 2.) This is thought to be due to field ionization of Rydberg antihydrogen at the longitudinal extremes of the nested potential; see [5] for further details and discussion.

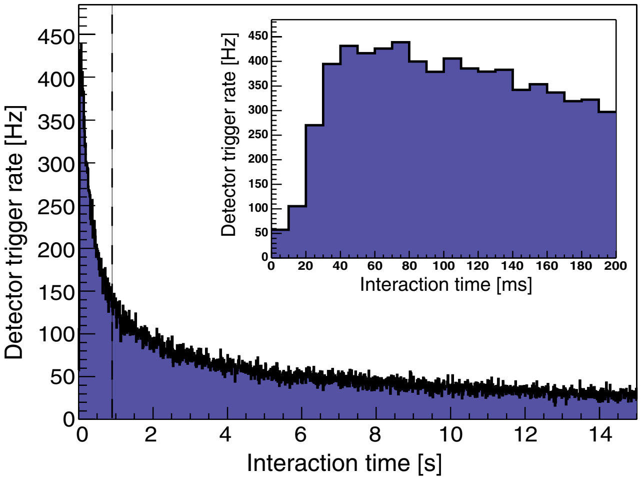

Fig. 2. Antihydrogen formation rates from ATHENA; see text.

Given the capability of ATHENA to manipulate the temperature of their positron plasma, T_e, and to record the change in temperature [24,25], a study of the rate of antihydrogen production versus T_e was undertaken [7]. This was motivated by a desire to try to isolate the mechanism(s) responsible for antihydrogen formation, since it is well known (see e.g. [11] and references therein) that the two main reactions have quite distinct dependencies upon T_e. Direct radiative capture, which is expected to lead to more tightly bound antihydrogen atoms, should vary as $T_e^{-0.63}$. By contrast the three-body reaction (two positrons, plus an antiproton), which predominantly populates high-lying states, should display a steep $T_e^{-4.5}$ behaviour and dominate at low temperatures.

Antihydrogen production rates have been derived by ATHENA using three different proxies [7], and two of these are shown in Fig. 3. The sharp increase at low temperatures expected for the three-body reaction was not observed in any of the data and a fit to the trigger rate data yielded a power law of $T_e^{-0.7\pm0.2}$ [7]. The apparent accord with the prediction for radiative combination is, however, shattered when the absolute rate of antihydrogen formation in ATHENA (see Fig. 2) is compared with expectations, which turn out to be about an order of magnitude lower [7]. This puzzle needs to be resolved, but clues lie, as pointed out by Robicheaux [32], in the nature of the experiments wherein the antiprotons pass in and out of the positron plasma such that the three-body process is periodically arrested. The characteristic $T_e^{-4.5}$ behaviour is that expected for an antiproton in thermal equilibrium with a positron plasma of infinite extent – clearly this situation is not mirrored experimentally. Further experimental and theoretical work, particularly on the behaviour of very

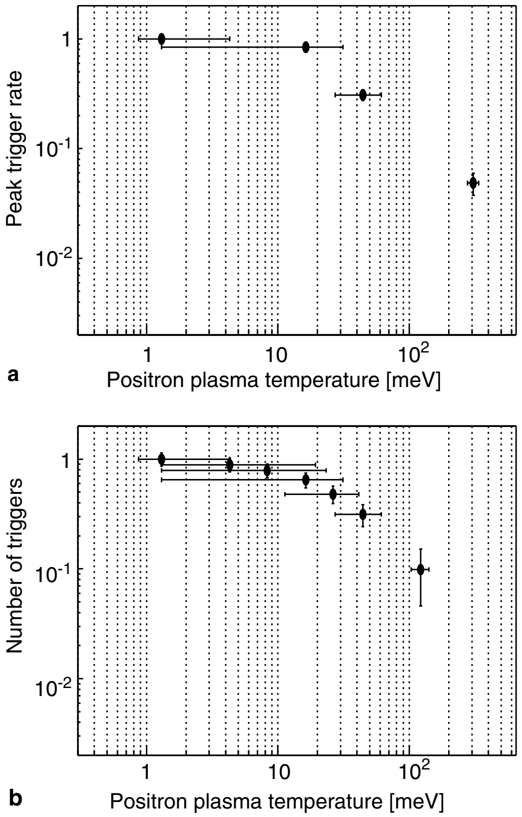

Fig. 3. Dependence of antihydrogen production on the positron plasma temperature as derived by ATHENA using (a) their peak trigger rates and (b) the total number of detector triggers [7]. Both measures are normalized to unity at 15 K (just above 1 meV).

weakly bound antihydrogen atoms [33] in the strong prevailing magnetic and electric fields, is anticipated.

ATHENA has recently published a study of the spatial distribution of cold antihydrogen formation [6]. By utilizing the position sensitivity of their detector and carefully sifting antihydrogen events from those due to antiproton annihilations on the trap electrodes (see also [3]) it proved possible to extract the axial antihydrogen distribution. It was found that the distribution is independent of T_e and is axially enhanced. This has indicated that antihydrogen is formed before the antiprotons reach thermal equilibrium with the positron plasma. (Note that the thermal equilibrium state of the antiprotons involves them co-rotating with the positron cloud due to the $\mathbf{E}\times\mathbf{B}$ drift motion.) Fig. 4 shows a comparison of the axial distribution found when the positrons and antiprotons were "cold mixed" (i.e. the positron cloud was kept at the ambient of 15 K) with various calculated distributions. By assuming that the transverse (to the axis of the Penning traps) temperature of the antiprotons is 15 K, the experimental data could be fit yielding a lower limit on the axial temperature of the antihydrogen of 150 K. However, upon inspection of Fig. 4 and noting the discussion in [6], it is clear that it is not possible to uniquely isolate the antihydrogen temperature.

Despite this, it is notable that the ATHENA study [6] is in broad accord with results from ATRAP [9] which produced a first measurement of the velocity of antihydrogen atoms emitted along the axis of their Penning trap. It is not appropriate here to go into experimental details however Gabrielse et al. [9] derived an antihydrogen kinetic energy of around 200 meV for the weakly bound states detectable using their field ionization technique [2]. Together, the ATHENA and ATRAP studies have serious retrograde implications for prospects for antihydrogen trapping (Section 4).

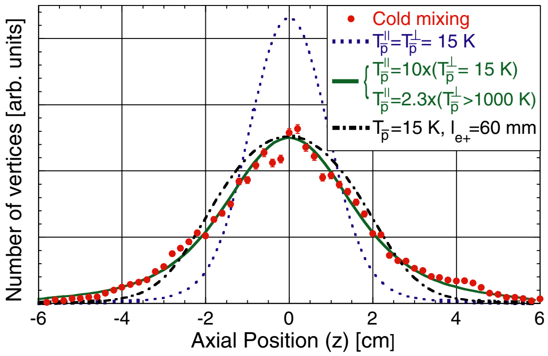

Fig. 4. The measured axial distribution for cold mixing compared to a number of calculations. The poor fit with the antiproton temperature held at 15 K (dotted line) both parallel to, and perpendicular to, the axis of the trap is notable. Holding these temperatures at 15 K and un-physically lengthening the positron plasma does not adequately fit the data (broken line), which can only be reproduced by admitting antihydrogen formation by epithermal antiprotons (solid line).

4. Conclusions and outlook

It is clear that to perform spectroscopy on antihydrogen to rival current precisions with hydrogen (around 1 part in 10^{14} [34]) a trapped ensemble of anti-atoms will need to be created. If gravity measurements on antihydrogen are to be contemplated very low temperatures for the anti-atom ($\approx$ mK) are necessary. How to achieve the latter is by no means clear (though some interesting, but very challenging, suggestions are beginning to emerge; see e.g. [35]), but it is likely that trapped antihydrogen will be involved.

Thus, a major challenge for the future of the field is to trap antihydrogen. This will probably involve a magnetic gradient device employing a quadrupole [36] or higher-order pole configuration. A central question here is compatibility of the inherent magnet gradients of the neutral trapping fields with the stability of the charged particle clouds and plasmas [37–40]: work and debate are ongoing.

However, assuming these problems will be solved, it is still unclear which production technique will produce the highest yield of trappable antihydrogen. Current technology means that trap depths are likely to be limited to around 1 K. There are manifest uncertainties in the nested trap scenario regarding velocity- and state-distributions on production (Section 3) and whether any relaxation towards lower speeds/states is occurring. Nonetheless, this method is efficient and can likely be refined. Alternative techniques involving antiproton–positronium interactions are, once again, also attracting attention [41–45]. Indeed, the double-charge exchange reaction sequence proposed by Hessels et al. [44] (which involves producing Rydberg positronium atoms and allowing them to interact with cold, trapped antiprotons, resulting in creation of Rydberg antihydrogen states) has already been demonstrated in a proof-of-principle investigation by ATRAP [45]. Although the velocity and state-distributions of the Rydberg antihydrogen are not yet known from experiment, the potential benefits of using Rydberg positronium for antihydrogen production in terms of reaction rates, the control over the states produced and the near-absence of recoil were pointed out a while ago [42,43].

To date, experiments with antihydrogen have shown that, whilst it is relatively straightforward to produce the anti-atom once the conditions for positron and antiproton trapping have been optimized, there are still mysteries and lack of knowledge concerning many factors underlying the production mechanism(s) and the outgoing antihydrogen. Early indications from ATHENA and ATRAP [6,9] are that further effort will need to be expended if significant trappable populations of antihydrogen are to be achieved. Nevertheless, work is ongoing aimed at creating the conditions for trapping which we can hope to see implemented at the AD in the not-too-distant future.

Acknowledgements

The ATHENA work was supported by CNPq, FAPERJ, CCMN/UFRJ (Brazil), INFN (Italy), MEXT (Japan), SNF (Switzerland), SNF (Denmark) and EPSRC (UK). The collaboration is also grateful for the excellent support provided by CERN via the AD facility. The corresponding author would like to thank his co-authors in [11] for many years of fruitful interaction.

References

[1] M. Amoretti et al., Nature 419 (2002) 456.
[2] G. Gabrielse et al., Phys. Rev. Lett. 89 (2002) 213401.
[3] M.C. Fujiwara et al., Phys. Rev. Lett. 92 (2004) 065005.
[4] M. Amoretti et al., Phys. Lett. B 578 (2004) 23.
[5] M. Amoretti et al., Phys. Lett. B 590 (2004) 133.
[6] N. Madsen et al., Phys. Rev. Lett. 94 (2005) 033403.
[7] M. Amoretti et al., Phys. Lett. B 583 (2004) 59.
[8] G. Gabrielse et al., Phys. Rev. Lett. 89 (2002) 233401.
[9] G. Gabrielse et al., Phys. Rev. Lett. 93 (2004) 073401.
[10] G. Gabrielse et al., First evidence for atoms of antihydrogen too deeply bound to be guiding centre atoms, submitted for publication.
[11] M.H. Holzscheiter, M. Charlton, M.M. Nieto, Phys. Rep. 402 (2004) 1.
[12] G. Gabrielse, Adv. At. Mol. Phys. 50 (2005) 155.
[13] Particle Data Group, Phys. Lett. B 592 (2004) 84.
[14] M. Amoretti et al., Nucl. Instr. and Meth. A 518 (2004) 679.
[15] A.P. Mills Jr., in: A. Dupasquier, W. Brandt (Eds.), Positron Solid State Physics, Proc. Int. School of Physics "Enrico Fermi" (Course CXXV) IOS-Holland, 1983, p. 432.
[16] P.J. Schultz, K.G. Lynn, Rev. Mod. Phys. 60 (1988) 701.
[17] L.V. Jørgensen et al., in: F. Anderegg, L. Schweikhard, C.F. Driscoll (Eds.), Non-neutral Plasma Physics IV, AIP Conf. Proc., Vol. 606, 2002, p. 35.
[18] D.P. van der Werf et al., Appl. Surf. Sci. 194 (2002) 312.
[19] T.J. Murphy, C.M. Surko, Phys. Rev. A 46 (1992) 5696.
[20] C.M. Surko, R.G. Greaves, Phys. Plasmas 11 (2004) 2333.
[21] L.V. Jørgensen et al., Phys. Rev. Lett. 95 (2005) 025002.
[22] F. Anderegg, E.M. Hollmann, C.F. Driscoll, Phys. Rev. Lett. 81 (1998) 4875.
[23] R.G. Greaves, C.M. Surko, Phys. Rev. Lett. 85 (2000) 1883.
[24] M. Amoretti et al., Phys. Rev. Lett. 91 (2003) 055001.
[25] M. Amoretti et al., Phys. Plasmas 10 (2003) 3056.
[26] G. Gabrielse et al., Phys. Rev. Lett. 57 (1986) 2504.
[27] G. Gabrielse et al., Phys. Rev. Lett. 63 (1989) 1360.
[28] X. Feng et al., Hyperfine Interact. 100 (1996) 103.
[29] M.H. Holzscheiter et al., Phys. Lett. A 214 (1996) 279.
[30] G. Gabrielse et al., Phys. Lett. A 129 (1988) 38.
[31] C. Regenfus, Nucl. Instr. and Meth. A 501 (2003) 65.
[32] F. Robicheaux, Phys. Rev. A 70 (2004) 022510.
[33] S.G. Kuzmin, T.M. O'Niel, M. Glinsky, Phys. Plasmas 11 (2004) 2382.
[34] M. Niering et al., Phys. Rev. Lett. 84 (2000) 5496.
[35] J. Walz, T.W. Hänsch, Gen. Relat. Gravit. 36 (2004) 561.
[36] D.E. Pritchard, Phys. Rev. Lett. 51 (1983) 1336.
[37] E.P. Gilson, J. Fajans, Phys. Rev. Lett. 90 (2003) 015001.
[38] J. Fajans, A. Schmidt, Nucl. Instr. and Meth. A 521 (2004) 318.
[39] J. Fajans et al., Phys. Rev. Lett. 95 (2005) 155001.
[40] T.M. Squires, P. Yelsey, G. Gabrielse, Phys. Rev. Lett. 86 (2001) 5266.
[41] J.W. Humberston et al., J. Phys. B: At. Mol. Phys. 20 (1987) L25.
[42] M. Charlton, Phys. Lett. A 143 (1990) 143.
[43] B.I. Deutch et al., Hyperfine Interact. 76 (1993) 153.
[44] E.A. Hessels, D.M. Homan, M.J. Cavagnero, Phys. Rev. A 57 (1998) 1668.
[45] C.H. Storry et al., Phys. Rev. Lett. 93 (2004) 263401.