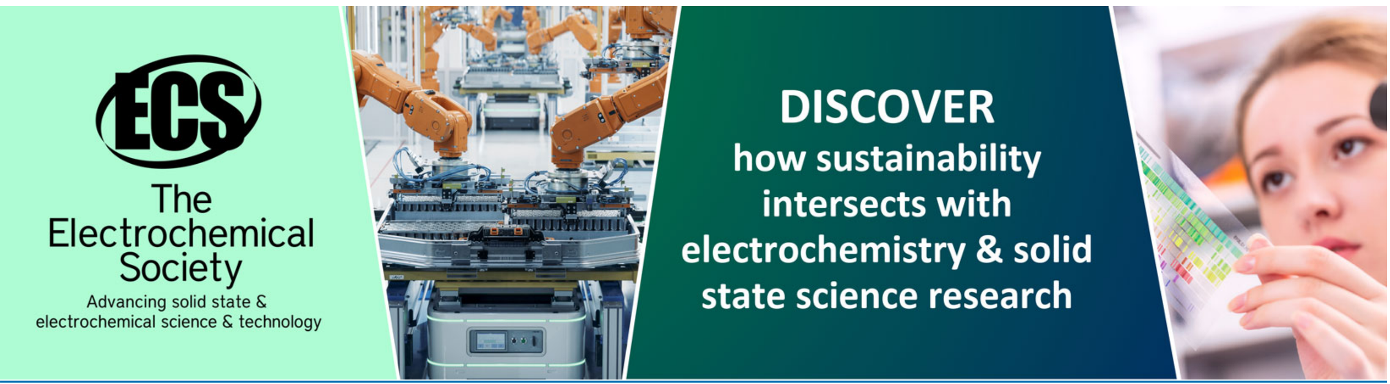
Journal of Physics: Conference Series

Trapped antihydrogen: A new frontier in fundamental physics

To cite this article: N Madsen and The ALPHA Collaboration 2013 *J. Phys.: Conf. Ser.* **443** 012005



Trapped antihydrogen: A new frontier in fundamental physics.

N. Madsen

Department of Physics, College of Science, Swansea University, Swansea SA2 8PP, UK

The ALPHA Collaboration[1]

Abstract. Antihydrogen, the bound state of an antiproton and a positron, has been produced at low energies at CERN since 2002. Antihydrogen is of interest for use in precision tests of nature's fundamental symmetries. The charge conjugation/parity/time reversal (CPT) theorem, a crucial part of the foundation of the standard model of elementary particles and interactions, demands that hydrogen and antihydrogen have the same spectrum. Given the current experimental precision of measurements on the hydrogen atom, subjecting antihydrogen to rigorous spectroscopic examination would constitute a compelling, model-independent test of CPT. Antihydrogen could also be used to study the gravitational behaviour of antimatter.

However, until recently, experiments have produced antihydrogen that was not confined, precluding detailed study of its structure. Experimenters working to trap antihydrogen have faced the challenge of trapping and cooling relativistic antiprotons and using them to make antihydrogen cold enough to be trapped in a magnetic minimum trap with a depth of only 50 μeV. In November 2010 the ALPHA collaboration demonstrated the first trapping of antihydrogen, thus opening the door to precision measurements on anti-atoms which can soon be subjected to many of the same techniques as developed for atoms. The prospect for such measurements improved further with ALPHA's demonstration of 1000 s confinement of the anti-atoms in the summer of 2011 and the recent first detection of resonant quantum interactions in antihydrogen.

1. Introduction

Antihydrogen ($\bar{\mathrm{H}}$), the bound state of an antiproton ($\bar{\mathrm{p}}$) and a positron (e^+) is the simplest anti-atom and also the simplest neutral antimatter system. As such it holds the promise of precise comparisons between matter and antimatter using spectroscopic techniques [1]. Depending on the particular aspect of the (anti)atom investigated, one can study various aspects of the fundamental CPT-theorem which states that all physical laws must be unchanged under the simultaneous application of Charge conjugation, Parity inversion and Time reversal. Antihydrogen, due to its neutrality, furthermore facilitates directly investigating the gravitational interaction of antimatter.

[1] C. Amole, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, A. Capra, C. L. Cesar, M. Charlton, A. Deller, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, C. A. Isaac, S. Jonsell, L. Kurchaninov, J. T. K. McKenna, S. Menary, P. Nolan, K. Olchanski, A. Olin, P. Pusa, F. Robicheaux, E. Sarid, D. M. Silveira, S. Stracka, C. So, R. I. Thompson, D. P. van der Werf & J. S. Wurtele

The first low energy $\bar{\mathrm{H}}$ suitable for scrutiny was made by the ATHENA collaboration working at the CERN Antiproton Decelerator (AD) [2] in 2002 [3]. Following this success, the ALPHA collaboration was started in 2005 with the intermediate goal of trapping $\bar{\mathrm{H}}$ and ultimate goal of performing precision comparisons of H and $\bar{\mathrm{H}}$. ALPHA succeeded in trapping $\bar{\mathrm{H}}$ in 2010 [4] and further in holding on to it for 1000 s in 2011 [5]. These results led to the first detection of a resonant quantum transition in an anti-atom in 2012 [6], thus kicking off the field of $\bar{\mathrm{H}}$ spectroscopy. This paper discusses the challenges that were faced and met to achieve all of these results, and gives a brief glimpse of the future of $\bar{\mathrm{H}}$ physics, in particular in ALPHA.

2. Making cold antihydrogen

Antihydrogen can be formed by merging plasmas of e^+ and $\bar{p}$. To date, this is the most efficient method available, and in a typical experiment in ALPHA the conversion efficiency of $\bar{p}$, the rarest of the two species, is about 30% [4]. The basic scheme is illustrated in Figure 1. All the charged particles used (e^+, electrons (e^-)and $\bar{p}$) are held in a Penning-Malmberg trap where an axial magnetic field ensures transverse confinement and axial electric field ensures axial confinement. A key difficulty, which was identified already in the ATHENA experiment [7], is that one must ensure that the $\bar{p}$ that form $\bar{\mathrm{H}}$ are cold as they possess the bulk of the kinetic energy of the synthesised $\bar{\mathrm{H}}$. This may seem obvious, but in initial experiments the focus was on ensuring that the e^+ were cold, and it was assumed that the $\bar{p}$ would then come to equilibrium with them before forming $\bar{\mathrm{H}}$. However, the key parameter for recombination is the relative velocity, not the temperature, and as the $\bar{p}$ are much more massive than the e^+, they may form $\bar{\mathrm{H}}$ with cold e^+ even with an order of magnitude larger kinetic energy [7].

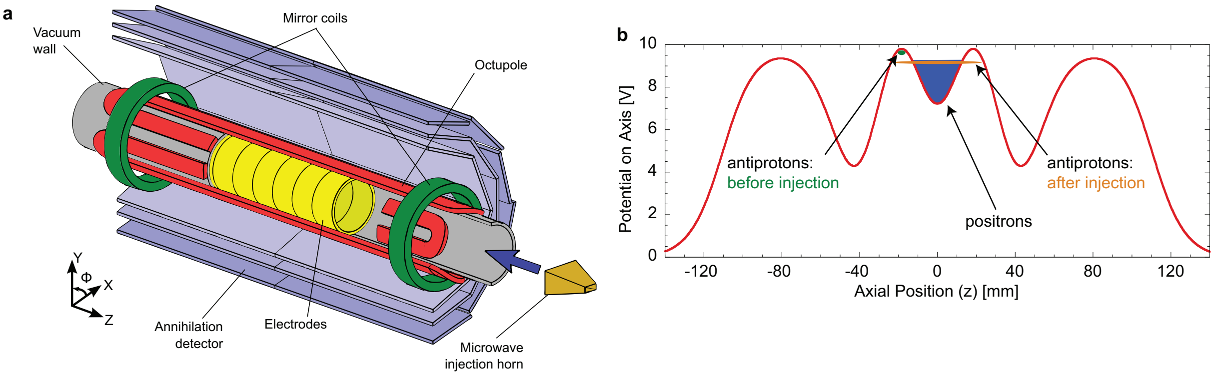


Figure 1. (a) Cut-away, drawing of the $\bar{\mathrm{H}}$ synthesis and trapping region. The super conducting atom-trap magnets, the annihilation detector, and some of the Penning-Malmberg trap electrodes are shown. An external solenoid (not shown) provides a 1-T magnetic field for the Penning-Malmberg trap. (b) The electrical potentials used for merging cold $\bar{p}$ and positrons to make cold $\bar{\mathrm{H}}$. See text for details.

The route taken by ALPHA to improve upon this situation was to (a) work towards making all participating species colder and (b) develop methods to merge the two species without jeopardising the achieved low temperatures.

2.1. Ensuring cold particles for antihydrogen formation

The $\bar{p}$ are delivered by the CERN AD at 5.3 MeV [2] and directed through a thin aluminium foil (~0.2 mm), which ensures that a maximum of particles can be captured dynamically using electric fields switched at ~5 kV [8]. The $\bar{p}$ are then cooled through collisions with an e^- plasma which has been pre-loaded. The e^- plasma cools through emission of cyclotron radiation in the strong axial magnetic field of the Penning-Malmberg trap, cooling towards the temperature of the surroundings which are held at 7 K. In ALPHA, the e^- typically achieve final temperatures of 100-200 K. The neutral trap magnetic fields, to be discussed later, introduce a strong azimuthal asymmetry which is observed to both induce dynamic aperturing and lead to heating of the plasmas [9, 10, 11, 12]. This means that to keep the plasmas cold we must keep them radially small and axially short. The $\bar{p}$ plasma is therefore compressed through the rotating wall (RW) technique [13] which in ALPHA in set to act on the combined e^- $\bar{p}$ plasma, in order to ensure e^- cooling also after compression [14]. The e^- are then released from the mixture by carefully, but quickly pulsing one of the confining electrodes. Using this methodology ALPHA routinely prepares $\bar{p}$ clouds of 40000 particles with a radius of 0.25 mm and a temperature of $\sim$400 K, the e^- ejection process causing some heating. The $\bar{p}$ are then further cooled using evaporative cooling [15] and a typical final $\bar{p}$ cloud consists of 15000 particles with a radius of 0.4 mm and a temperature of 100 K.

The e^+ are accumulated and transferred using well established techniques [16, 17]. These techniques also include the RW compression of the e^+. Using these techniques as well as evaporative cooling of the e^+ ALPHA typically obtains e^+ plasmas with a radius of 0.8 mm containing 1×10^6 e^+ at a density of 5×10^7 cm^{-3} and a temperature of $\sim$40 K.

2.2. Merging antiprotons and positrons

As mentioned above, the traditional technique of launching eV $\bar{p}$ into a cold e^+ plasma generated $\bar{H}$ that is too energetic to be trapped [7]. ALPHA first attempted to solve this issue by merging the plasmas by slowly moving the potentials holding the $\bar{p}$ and e^+ in neighbouring wells [18]. This led to some new loss mechanisms in the neutral trap magnetic fields [19]. However, the technique did not result in trapped $\bar{H}$, so a novel technique using autoresonance [20] to excite the $\bar{p}$ collectively in their well until they enter the e^+ plasma was introduced [21]. This technique makes use of the fact that a anharmonic oscillator will lock to an external drive under certain conditions and by carefully chirping the drive frequency energy can be transferred to the oscillator in a deterministic fashion. To trap $\bar{H}$ ALPHA prepares the $\bar{p}$ and e^+ in neighbouring wells, energises the magnetic trap, evaporatively cools the e^+ and finally merges the two by autoresonantly exciting the $\bar{p}$ into contact with the e^+ (Figure 1b).

3. Trapped antihydrogen and its detection

As there are no readily available means for rapidly cooling the $\bar{H}$ they must be trapped directly after formation. Trapping can be done using the forces exerted by a magnetic field on the magnetic dipole moment of the (anti)atom that arises mainly due to the e^+ spin. The potential energy U of a dipole in a magnetic field $\mathbf{B}$ is given by $U = -\boldsymbol{\mu} \cdot \mathbf{B}$, where $\boldsymbol{\mu}$ is the magnetic dipole moment.

In order to reduce the perturbative influence of the transverse multipole magnetic fields necessary to create the three dimensional minimum of magnetic field strength that forms the atom trap, ALPHA chose to use a transverse octupole rather than a quadrupole configuration common in the atom-trapping community [22].

To trap $\bar{H}$ it is synthesised with the neutral trap energised following the recipe given above. After autoresonant excitation the merged species are held for one second before all charged particles are ejected from the trap. Following this the super conducting neutral trap is de-energised rapidly with an e-folding time of 9 ms by dissipating its stored energy in external resistors. The trap depth is reduced to less than 1% of the full value in about 30 ms [22]. We look for signs of trapped $\bar{H}$ in this time window.

When searching for trapped $\bar{H}$ two potential false signals contribute. The first is from the cosmic rays passing through the apparatus. To deal with this background ALPHA uses a unique annihilation detector constructed with three layers of double-sided silicon strip detectors in a barrel geometry around the core of the apparatus [23]. The detector allows reconstruction of the tracks of the charged pions that appear from $\bar{\text{p}}$ annihilations, and by combining these tracks an annihilation vertex can be found, localising the exact position in space where the $\bar{\text{p}}$ annihilated. Cosmic rays can be distinguished by their very different tracking geometry. Using these techniques we obtain a detection efficiency of $\bar{\text{p}}$ annihilations of 57$\pm$6% with a background rate of 47$\pm$2 mHz. The effective background for detection of trapped $\bar{\text{H}}$ is further reduced by only searching for annihilation signals in the 30 ms window of de-energising the neutral trapping fields. The background fake rate is thus $1.4 \pm 0.1 \times 10^{-3}$ counts per experiment or one event in 700 experiments, thus effectively eliminating this issue [24, 5].

However the annihilation detector detects only $\bar{\text{p}}$ annihilations. In the ATHENA experiment, a similar detector was used, but with the additional capacity of detecting e^+ annihilations [3]. With the added material for the neutral trap magnets e^+ detection was not an option for ALPHA, and instead an extra layer of silicon was added to allow the track curvature to be measured [23]. The second type of false positives is thus bare trapped $\bar{\text{p}}$.

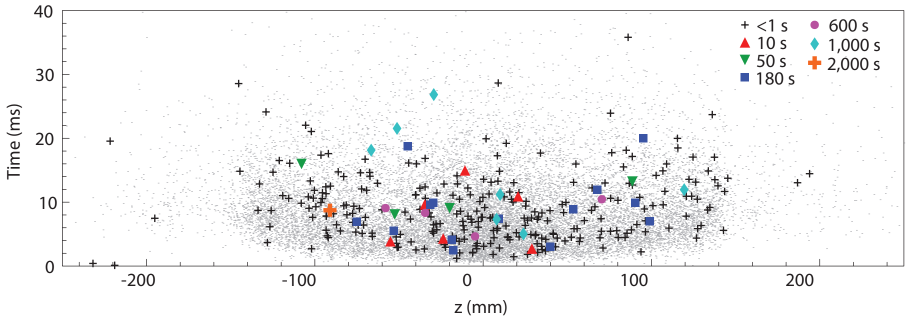


Figure 2. Time and axial z distribution of annihilations on release of $\bar{\text{H}}$ from the neutral trap for different confinement times (see legend) and comparison with simulation (grey dots).

Before de-energising the neutral trap, charged particles are cleared from the trap by a series of electric pulses. Charged particles, in particular $\bar{\text{p}}$, may be trapped on their motional magnetic moment, so-called mirror-trapping. Trapping depends on the relative difference between their transverse (to the magnetic field) and longitudinal velocities. The clearing electric fields applied allow us to eject $\bar{\text{p}}$ with transverse energy less than 20 eV. As most of the manipulating potentials leading up to the $\bar{\text{H}}$ formation are lower than this it is unlikely that any $\bar{\text{p}}$ remain after clearing [25]. However, experimental errors and unforeseen circumstances could lead to a population of energetic $\bar{\text{p}}$ in the trap whose signal could be confused for trapped $\bar{\text{H}}$. To avoid these issues ALPHA applied three controls for fake trapped $\bar{\text{H}}$ signals. The first was to carry out the full $\bar{\text{H}}$ trapping process with all fields and manipulations but while heating the e^+ plasma to 1000 K and thus suppressing the $\bar{\text{H}}$ formation, and therefore any true $\bar{\text{H}}$ trapping signal. The second consisted of applying axial bias fields across the atom trap volume in order to cause any mirror-trapped $\bar{\text{p}}$ still present to be preferentially located either on the left or the right side of the trapping volume. The third and final control was to simulate the release of both $\bar{\text{p}}$ and $\bar{\text{H}}$ atoms from the trapping volume. Due to their different dynamics and energies their behaviour during de-energisation can easily be distinguished with the ALPHA annihilation detector [25]. Figure 2 shows 309 annihilation events recorded in 2010, with most of them taken with a wait time after $\bar{\text{H}}$ synthesis of less than one second. For most of the data presented here, a static electric bias field of 500 V m^{-1} was applied during the confinement and shutdown stages to deflect bare $\bar{\text{p}}$ that may have been mirror-trapped. The bias field ensured that annihilation events could only be produced by neutral $\bar{\text{H}}$. We observed significant signal at holding times of up to 1000 s, sufficient to envisage the first measurements on ground state $\bar{\text{H}}$ [5].

4. Resonant quantum transitions in antihydrogen

Figure 3 shows the Breit-Rabi diagram for the ground state of (anti)hydrogen. For the ground state of hydrogen in a magnetic field, magnetic dipole transitions exist between the low-field seeking (trapped) states with the e^+ spin antiparallel to the local magnetic field ($|c>$ and $|d>$) and the high-field seeking (untrapped) states with the spin parallel. By inducing a spin-flip transition from low to high fields seeking state one may thus eject trapped $\bar{\mathrm{H}}$ from the trap.

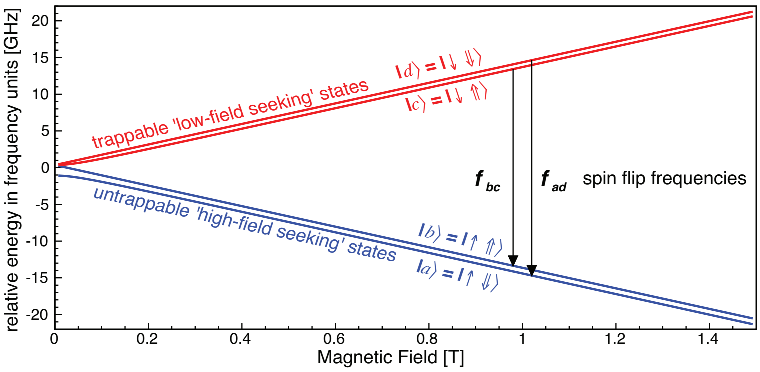


Figure 3. The Breit-Rabi diagram, showing the relative hyperfine energy levels of the ground state of the hydrogen (and $\bar{\mathrm{H}}$, assuming CPT invariance) atom in a magnetic field. In the state vectors shown (for the high-field limit), the single arrow refers to the e^+ spin and the double arrow refers to the $\bar{p}$ spin.

In a series of experiments we illuminated the trapped $\bar{\mathrm{H}}$ with microwave radiation in order to induce such transitions. As the $\bar{p}$ spin state is unknown we illuminated both the (bc) and the (ad) transition frequencies to ensure maximum effect [6]. To ensure frequency overlap with the transitions we swept the transition frequency +10/-5 MHz around the expected frequency of ∼28 GHz. In order to further ensure interaction, we illuminated the two transitions for 15 s each six times repeated, for a total of 180 s of illumination. We made a series of measurements with the microwaves on and off resonance. To ensure against effects of standing waves in the apparatus, we shifted the microwaves on and off resonance by either changing the magnetic field during illumination by 3.5 mT or shift the microwaves by +100 MHz [6].

We searched for an effect of the microwaves in two distinct ways: (a) In so-called disappearance mode, we looked for a suppression of the trapping rate. We observed a clear effect with an decrease in trapping rate of a factor 10.5±2.0 from off to on resonance. (b) In appearance mode, we looked for signal during the microwave illumination. As the standard annihilation discrimination algorithms would result in too high a background from cosmic radiation for this, we refined the analysis to increase the signal to background. We reduced the background by an order of magnitude and the sensitivity by 25%. Figure 4 shows the results, clearly showing a peak in each of the two first 15 s windows where the two transitions are consecutively illuminated. Little to no signal is present when the microwaves are off resonance, with the possible exception of a small signal in the second 15 s period, which would be consistent with resonance with the tail of the lower transition. We thus observed resonant quantum transitions in trapped $\bar{\mathrm{H}}$.

5. Outlook

With trapped $\bar{\mathrm{H}}$, held for up to 1000 s, and the first observation of resonant quantum transitions, the field of $\bar{\mathrm{H}}$ spectroscopy is taking its first steps. As the successful spin-flip measurement demonstrated, long confinement times and sensitive detection makes it feasible to make measurements with only a single anti-atom trapped on average. In the future we envisage

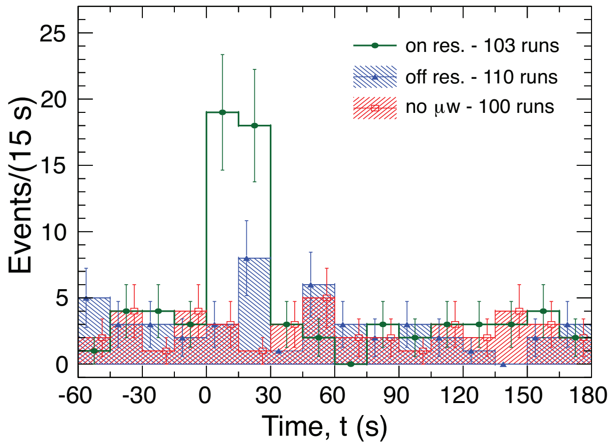


Figure 4. The number of appearance mode annihilation events as a function of time between the end of $\bar{\mathrm{H}}$ production and the trap shutdown. Microwave power is first applied at time t = 0 s. The expected cosmic background per bin per run is 0.026 ± 0.005 events. The error bars are due to counting statistics.

experiments on the $\bar{\mathrm{p}}$ spin-flip transition $|c>$ to $|d>$ which could give new bounds on the $\bar{\mathrm{p}}$ magnetic moment. Furthermore, the ALPHA apparatus is currently being upgraded to allow laser-access and the first laser-spectroscopy of $\bar{\mathrm{H}}$. Finally, trapped $\bar{\mathrm{H}}$ may also serve as a good starting point for measurements of the gravitational influence on $\bar{\mathrm{H}}$, in particular in combination with our unique annihilation position resolution.

References

[1] Madsen N 2010 *Phil. Trans. Roy. Soc. A* **368** 3671
[2] Maury S 1997 *Hyp. Int.* **109** 43
[3] Amoretti M, *et al.*, (ATHENA Collaboration), 2002 *Nature* **419** 456
[4] Andresen G B, *et al.*, (ALPHA Collaboration) 2010 *Nature* **468** 673
[5] Andresen G B, *et al.*, (ALPHA Collaboration) 2011 *Nature Physics* **7** 558
[6] Amole C, *et al.*, (ALPHA Collaboration) 2012 *Nature* **483** 439
[7] Madsen N, *et al.*, (ATHENA Collaboration), 2005 *Phys. Rev. Lett* **94** 033403
[8] Gabrielse G, *et al.*, (TRAP Collaboration) 1989 *Phys. Rev. Lett.* **63** 1360
[9] Fajans J, *et al.* 2005 *Phys. Rev. lett.* **95** 155001
[10] Andresen G B, *et al.*, (ALPHA Collaboration), 2007 *Phys. Rev. Lett.* **98** 23402
[11] Andresen G B, *et al.*, (ALPHA Collaboration), 2008 *Phys. Plas.* **15**, 032107
[12] Fajans J, Madsen N and Robicheaux F, 2008 *Phys. Plas.* **15**, 032108
[13] Huang X-P *et al.* 1997 *Phys. Rev. Lett.* **78** 875
[14] Andresen G B, *et al.*, (ALPHA Collaboration) 2008 *Phys. Rev. Lett.* **100** 203401
[15] Andresen G B, *et al.*, (ALPHA Collaboration) 2010 *Phys. Rev. Lett.* **105** 013003
[16] Surko C M & Greaves R G 2004 *Phys. Plasmas* **11** 2333
[17] Jørgensen L V, *et al.*, (ATHENA Collaboration), 2006 *Phys. Rev. Lett.* **95** 025002
[18] Andresen G B, *et al.*, (ALPHA Collaboration) 2010 *Phys. Lett. B* **685** 141
[19] Andresen G B, *et al.*, (ALPHA Collaboration) 2009 *Phys. Plas.* **16** 100702
[20] Fajans J and Friedland L 2001 *Am. Jour. Phys.* **69** 1096
[21] Andresen G B, *et al.*, (ALPHA Collaboration) 2011 *Phys. Rev. Lett.* **106** 025002
[22] Bertsche W, *et al.*, (ALPHA Collaboration), 2006 *Nucl. Inst. & Meth. A* **566** 746
[23] Andresen G B, *et al.*, (ALPHA Collaboration) 2012 *Nucl. Inst. & Meth. A* **684** 73
[24] Andresen G B, *et al.*, (ALPHA Collaboration) 2011 *Phys. Lett. B* **695** 95
[25] Andresen G B, *et al.*, (ALPHA Collaboration) 2011 *New J. Phys.* **14** 015010