CERN-SPSC-2004-026
SPSC/I-228
21 September 2004

Letter of Intent to the CERN SPSC for AD Physics Starting in 2006

the ALPHA Collaboration
Antihydrogen Laser PHysics Apparatus

Introduction:

The ALPHA collaboration is a recently formed association of eight institutes. Five of the institutes, Swansea, Tokyo, RIKEN, Aarhus, and Rio de Janeiro, are founding members of ATHENA and/or ASACUSA. Three new institutes, Berkeley, TRIUMF and Liverpool, bring new capabilities to the Antiproton Decelerator (AD) physics program. The purpose of this new collaboration is to achieve the goal of trapping neutral antihydrogen atoms and to subject them to precise spectroscopic measurements as tests of fundamental symmetries. We intend to be ready with a new antihydrogen apparatus when the AD beam returns in 2006. The following is a brief description of our intentions; we will submit a detailed proposal at the SPSC's convenience.

Physics Goals

The production of cold antihydrogen atoms by ATHENA [1] and ATRAP [2] in 2002 was a significant milestone in antimatter physics, but much work is yet to be done. The ALPHA collaboration remains committed to the original vision of the AD physics program: precision comparison of the spectra of hydrogen and antihydrogen in order to test CPT invariance. It is our view that the long-term prospects for antihydrogen physics, and the potential to compete with other CPT tests, depend crucially on the ability to stably trap neutral anti-atoms. We are developing a detailed physics plan that seeks to demonstrate trapping within a time scale of about five years. At the same time our current laser capabilities will be upgraded so that we will be ready to begin resonant laser interaction with trapped antihydrogen atoms as soon as sufficient quantities can be trapped. We will initially concentrate on the 1s-2s transition, since this offers the highest possible precision, and the laser technology is available. However, once antihydrogen has been trapped, other spectroscopic studies and laser manipulations of neutral anti-atoms can be implemented. In the following we outline our strategy for obtaining trapped, cold antihydrogen.

Trapping Anti-atoms

As this is the subject of considerable importance for the future, we briefly review the techniques available. Roughly speaking, three general methods of trapping particles are commonly employed. In the first, the relevant species is "born" trapped. For example, ionizing neutral atoms while they drift in a combination of electromagnetic fields is a common way of loading *ion* traps. In the second method, one applies a dissipative force to free particles so that they lose energy and fall into a trapping potential. This is the case, for example, for laser slowed and cooled neutral atoms in magneto-optical traps, and for the ATHENA positron accumulator, in which positrons lose energy by collisions with nitrogen gas molecules. The third method involves rapidly varying time-dependent potentials to dynamically trap particles after they are injected into a region containing guiding fields. This last technique is used by all three AD experiments to trap antiprotons, and is the time-honored way of loading accelerators or storage rings.

Both the ATHENA and ATRAP proposals envisioned that antihydrogen atoms could be "born" trapped. In this scheme, a magnetic trap for neutral atoms would be superimposed on the Penning-Malmberg fields used to confine and mix the constituent positrons and antiprotons. The magnetic trap configuration for neutrals is the so-called Ioffe-Pritchard geometry (Fig. 1), successfully developed for experiments with Bose-Einstein condensation of hydrogen [3]. The trap consists of a combination of quadrupole and magnetic mirror coils to provide a B-field that has a minimum at the trap center. The atoms interact with the trap fields through their magnetic moments,

$$U = -\vec{\mu} \bullet \vec{B}$$

being the potential energy of an atom with magnetic moment $\boldsymbol{\mu}$ in magnetic field $\boldsymbol{B}$. For hydrogen atoms in the ground state, the hyperfine quantum states can be classified as strong- or weak-field seekers, depending on their orientation. A rough rule of thumb is that the well depth of such a trap is about 0.7 K/T for ground state atoms. Atoms that are produced in higher n-states, as observed in ATRAP [2], could have larger magnetic moments and be easier to trap initially.

The minimum-B configuration traps low-field seekers. Zeroes in the field are to be avoided in order to prevent flipping of the magnetic moment's orientation, turning low-field seekers into high-field seekers and leading to particle loss. The quadrupole is desirable both for its simplicity and for its linear gradient, which can provide strong localization of the anti-atoms about the trapping axis – the latter being an important consideration for maximizing overlap of a laser beam with the trapped sample.

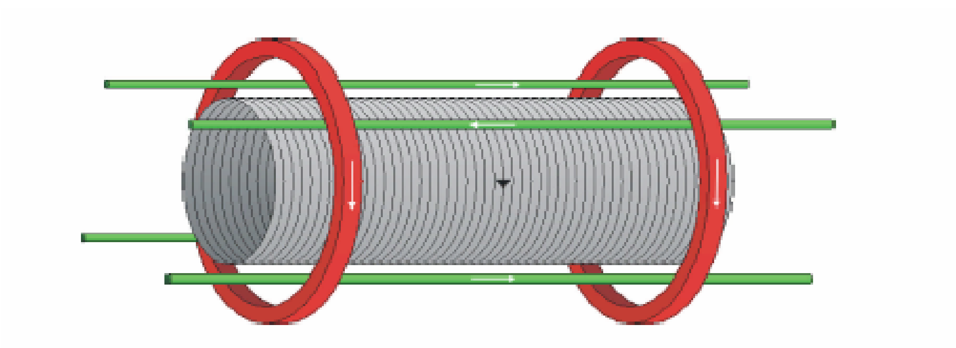

Figure 1. Schematic of the Ioffe-Pritchard trap, illustrating the quadrupole winding and the mirror coils. A solenoidal winding is also shown. In practice, the solenoidal winding will surround the other two.

ATHENA and ATRAP have produced antihydrogen by launching antiprotons into a positron plasma. Antihydrogen could thus be "born" trapped if the temperature of produced anti-atoms is low enough for them to be confined in such a superposed magnetic well. A serious concern, originally raised by a member of our collaboration, is a possible adverse effect on the stability of the charged particle plasmas due to the applied quadrupole magnetic field [4]. At present this is an open issue, with some suggestions that stable single particle orbits may exist [5], but that plasmas, in which particles interact, should be unstable [6]. Experiments have yet to explore the strengths of transverse confinement fields necessary for trapping antihydrogen of even one Kelvin. The mirror fields are thought to be more benign, since they are azimuthally symmetric and need not overlap the mixing region excessively.

As we intend to design and construct a new apparatus for producing and trapping antihydrogen atoms, and to perform the first bound-bound spectroscopy of antihydrogen, our first priority is to experimentally test the robustness of trapped plasmas subjected to quadrupole magnetic fields. Below we discuss the critical steps towards trapping of neutral anti-atoms.

Work at Berkeley

We have begun to experimentally address the question of plasma stability in a quadrupole field. We have procured a variable field, superconducting quadrupole magnet and installed it in a superconducting solenoid at Berkeley. The quadrupole has a maximum field gradient of 40 T/m and the solenoid has a maximum field of 8 T. We are currently studying the effect of various quadrupole field strengths on cold electron plasmas, and we are able to cover a wide range of field combinations of interest in future trapping experiments. Of interest is the effect of such fields on the storage lifetime of cold plasmas. In particular, we hope to establish scaling laws (in field and field gradient) that allow us to predict general behavior. We expect to definitively answer the question of stability by the early autumn of 2004.

If the quadrupole tests indicate that the constituent plasmas can survive the strong, asymmetric fields needed to trap antihydrogen, we will incorporate a Ioffe-Pritchard trap into a new apparatus for producing and trapping anti-atoms. If the necessary quadrupole field destroys the charged particle plasmas, we will fabricate and test a higher-order multipole magnet (also superconducting) [6] for the transverse confinement. (In this case our variable-field quadrupole can be used to determine the maximum acceptable quadrupole field error such a multipole can generate.) A multipole field could in principle confine antihydrogen atoms at larger radius without adversely affecting the trapped charged particles close to the axis. In the extreme, a higher order multipole could be used for the initial trapping of neutrals, and then a high gradient quadrupole could be ramped up to more tightly confine the anti-atoms, for example to increase their spatial overlap with a laser beam.

We are confident that our strategy will lead to successful trapping of antihydrogen atoms, and that the time scale for making the necessary measurements, design decisions, procurements, etc., is consistent with the desire to begin physics with a new apparatus in mid-2006. Access to antiprotons from the AD at the earliest possible time is essential to progress in the field, as many of the important physical details of antihydrogen formation cannot be studied offline.

Work at CERN during the AD Shutdown

The ALPHA collaboration has a permanent presence at CERN of at least six scientists. During the AD shutdown, we intend to continue R&D at CERN in support of antihydrogen physics.

Positron physics

We will continue to develop our state-of-the-art positron source, currently used in ATHENA. A factor of four improvement in accumulation rate is expected with a new radioactive source and other changes. The transfer efficiency to the high field antihydrogen formation region should be improved from the current 30% in ATHENA to 100%. These improvements will result in an effective positron accumulation rate into the mixing region of about 10^6 s^{-1}.

We will also investigate alternative injection geometries, in order to improve laser access to the future apparatus. At the earliest possible date, the quadrupole or multipole magnet will be tested with transferred and trapped positrons at CERN.

Charged Particle Trap, Vacuum, and Cryogenic Research

Building on lessons learned from ATHENA, ATRAP, and ASACUSA, we are considering new trap and system fabrication techniques that will improve the electrical, cryogenic and vacuum performance of the new apparatus, while at the same time allowing access for detectors and multipole magnetic fields. Prototyping work and testing will be carried out at CERN beginning in the autumn of 2004. Likewise, a new and more reliable trap control system is already under development. We are confident of making large improvements in the reliability and efficiency of the apparatus, as compared to the current state-of-the-art antihydrogen apparatus (ATHENA).

Laser Development

Building on work performed for ATHENA, we will continue to develop our laser capabilities at CERN. The laser and frequency-doubling chain for producing 243 nm light for the 1s-2s two-photon excitation exists. During the shutdown of the AD, we will complete the frequency stabilization of this laser to a level of a few kHz and complete construction on a source of atomic hydrogen for use in optimizing this laser.

Members of the ALPHA collaboration have procured a high-power (50 W) CO_2 laser system to try to demonstrate stimulated formation of antihydrogen in the ATHENA apparatus. The main purpose of this experiment is to try to produce antihydrogen in a well-defined, tightly bound (n=11) quantum state. In addition, this technique can provide a direct measurement of the positron temperature, as well as an opportunity to do the first bound-bound spectroscopy of antihydrogen without trapping the neutrals. The work will carry over to the ALPHA apparatus, and several improvements are envisioned for the system if it shows promise in ATHENA. For example, an optical resonant cavity providing a power build-up factor of 10 has been designed. The benefits of the stimulated production mechanism for anti-atom trapping and subsequent spectroscopy are apparent. Refinement of this experiment will be an immediate priority for us at the 2006 start-up of the AD.

Hydrogen and Laser Work in Rio de Janeiro

In parallel with the CERN and Berkeley efforts, the Rio group is developing essential components for spectroscopy of antihydrogen and of hydrogen.

Hydrogen Reference Cell

The most promising technology for ultra-high precision spectroscopy of hydrogen relies on trapped species cooled by forced evaporative cooling. The Rio group is currently constructing a hydrogen reference cell that uses the buffer gas cooling method [7] for the initial cooling. This cell will trap hydrogen atoms at 1.3 K in a Ioffe-Pritchard geometry. The atoms can then be evaporatively cooled to sub-Kelvin temperatures and their spectra measured with extremely high precision. This device will serve as a spectroscopic standard of comparison for measurements of antihydrogen, eliminating the need for an absolute frequency measurement for the first experiments. In the long term it will be desirable to do hydrogen spectroscopy in the magnetic environment of the antihydrogen trap. Many of the techniques being developed in Rio will also be applicable to this situation.

High Power, Quasi-CW Laser for Antihydrogen Spectroscopy

We are also conducting R&D on a new laser system for antihydrogen spectroscopy. The system consists of a high-power laser diode capable of producing pulses of 10's of watts for several microseconds. The diode is injection seeded by a stabilized Titanium-Saphire laser at 972 nm. This wavelength can then be doubled twice in external cavities to produce 243 nm light for exciting the 1s-2s transition. We believe that this system could be very useful for the first resonant laser interactions with trapped antihydrogen.

Towards a New Apparatus

As discussed above, we intend to build a new apparatus that is ready to produce antihydrogen, and has an appropriate trapping field for neutrals, when the AD beam returns in mid-2006. Many of the details of the design depend on the results of issues currently under theoretical and experimental investigation within the collaboration. Our general philosophy is to make efficient trapping of the produced anti-atoms the first design and investment priority. Initially, we will rely on the only proven method of producing low-energy antihydrogen: merged, cryogenic plasmas of positrons and antiprotons.

Detection of Annihilations

The demands on a detector for antihydrogen annihilation will be quite different in the second phase of AD physics. Ideally, the detector must be able to confirm production of antihydrogen with and without the neutral trapping fields present. Confirmation of antihydrogen trapping implies being able to detect the annihilation of neutrals released from the trap. A major challenge is integration of the detector into an apparatus that also contains a multipole magnet. An ATHENA-type annihilation detector for both antiprotons and positrons may not be feasible in a new apparatus.

While it is highly desirable to retain the capability for position sensitive detection of antiproton annihilations (vertex detection), the added material and the strong fields from the multipole may make this very difficult. We have begun Monte Carlo (GEANT4) simulations to address these issues. The issue of space in the bore of the solenoid magnet is also critical. We are considering large-bore (~30 cm) magnets that could accommodate a coaxial Penning trap, multipole magnet, and detector. As stated above, considerations favoring the neutral trapping will drive the design.

The ATRAP field ionization technique, together with high solid angle detection of charged pions, should suffice for the start up phase, in which the key goals will be demonstrating antihydrogen production first without and then with the multipole energized. With the mirror coils off, antihydrogen can drift axially out of the trapping region. With the mirror coils energized, trapping can be attempted. It will probably be desirable that at least one of the mirror coils be capable of fast ramping.

Design and Development Timetable

As noted above, we intend to have a definitive answer to the quadrupole/multipole issue in the early autumn of 2004. We will then prepare a detailed design for the new apparatus by the end of 2004. The appropriate multipole magnet can be delivered within six months. If necessary, a new superconducting solenoid magnet will be procured, to be delivered by the end of 2005. The longest lead-time item in the new apparatus is an eventual position sensitive detector, but it is impossible to design this until the magnetic field configuration to be employed is specified. We are confident of having an apparatus that will be ready to produce antihydrogen in mid-2006.

Collaboration Capabilities

The five ALPHA institutes currently active in the AD physics program have extensive experience in all aspects of antiproton and antihydrogen physics. These institutes have long constituted a vital, active, onsite presence in the ATHENA experiment. In addition to being involved in all aspects of the ATHENA physics program, these institutes have contributed the following expertise and hardware to ATHENA:

Swansea: the ATHENA positron accumulator, positron transfer, technical coordination, plasma diagnostics and control, CO_2 laser system

Aarhus: ATHENA laser laboratory, 1s-2s laser system, technical and physics coordination, CO_2 laser system

Tokyo: external detection, trigger system, data sequencing and acquisition, CO_2 laser physics and laser system, control programming, plasma diagnostics

RIKEN: external detection, trigger system, data acquisition, CO_2 laser system

(In addition to their ATHENA activities, Tokyo and Riken are the leading institutes in the ASACUSA collaboration.)

Rio: hydrogen trapping and spectroscopy, led the MIT experiment for cold hydrogen trapping and spectroscopy, laser development for precision spectroscopy

The three new institutes in ALPHA have capabilities to supplement those listed above.

Liverpool: state-of-the art silicon detector production facility, extensive experience in all forms of detection for nuclear and particle physics, readout electronics, etc. Liverpool will lead detector development for ALPHA.

Berkeley: non-neutral plasma physics, both experimental and theoretical; simulation, laboratory for parallel studies of trapped plasmas

TRIUMF: (this group is lead by a former ATHENA physicist) facilities for design and fabrication for all forms of detection system, extensive experience in AD physics program (see Tokyo and Riken above), expertise in DAQ, On-line, Off-line software and GEANT simulations.

With the above capabilities and the institutes' record of securing funding, we are confident of developing and constructing a competitive apparatus for the next phase of AD physics.

References

[1] M. Amoretti *et al*., *Nature* **419**, 456 (2002).
[2] G. Gabrielse *et al*., *Phys. Rev. Lett*. **89**, 213401 (2002).
[3] D.G. Fried *et al.*, *Phys. Rev. Lett.* **81**, 3811–3814 (1998).
[4] E. Gilson and J. Fajans, *Phys. Rev. Lett.,* **90**: 015001, (2003).
[5] T. Squires *et al., Phys. Rev. Lett.,* **86,** 5266, (2001).
[6] J. Fajans and A. Schmidt, NIMA 521, 318-325 (2004).
[7] J.M. Doyle, B. Friedrich, J. Kim and D. Patterson, Phys. Rev. A 52, R2515 (1995); D. Silveira, O. Pereira, M. Veloso, C.L. Cesar, Braz. J. Phys. 31, 203-210 (2001).

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