Proposal for TRIUMF Commitment (5YP 2015-2020)

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PROJECT/COMMITMENT TITLE: ALPHA Antihydrogen Symmetry Tests

PROPONENT: Makoto Fujiwara **TRIUMF CONTACT: Art Olin**

PRINCIPAL COLLABORATORS: D. Gill, G. Marshall, J. Lassen, L. Kurchaninov, K. Olchanski (TRIUMF), Hardy, Jones, Madison, Momose (UBC), Thompson (Calgary), Hayden (SFU), Menary (York)

PROJECT DESCRIPTION: ALPHA (Antihydrogen Laser Physics Apparatus) is an international project at CERN, whose goal is to perform fundamental symmetry tests on trapped antihydrogen ($\overline{\mathrm{H}}$), the simplest atomic form of neutral antimatter. ALPHA has made very substantial progress in the present 5 year period; in November 2010, we announced the first stable trapping of $\overline{\mathrm{H}}$ atoms. In June 2011, we reported $\overline{\mathrm{H}}$ confinement for 1000 seconds, extending the initial trapping times by nearly 4 orders of magnitude. Very recently, in March 2012, we succeeded in performing the first spectroscopic measurement of antimatter atoms, via a Canadian-led effort on microwave (μW)-induced hyperfine spectroscopy.

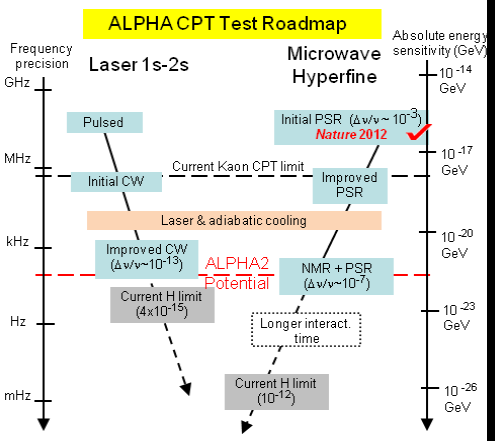
ALPHA is currently undergoing a major upgrade. The new apparatus (ALPHA-2) will be commissioned in 2012 and allow optical access to trapped $\overline{\mathrm{H}}$ for precision laser spectroscopy, as well as improved μW spectroscopy. ALPHA-Canada is making very significant contributions, including the design and the fabrication of the new anti-atom trap cryostat. At the same time, we are working on conceptual design for a new trap to measure the gravitational interaction on antimatter, tentatively named ALPHA-g.

Our primary goals in the period 2015-20 are: (1) full exploitation of the ALPHA-2 apparatus for spectroscopic tests of CPT with increasing precision, and (2) the construction of, and the first measurements with a new gravity experiment apparatus, which will run in parallel to ALPHA-2. Resource requirements for (1) are at the similar level as the present ALPHA operation, while (2) will require engineering support for design/construction of the new ALPHA-g trap (comparable to the current ALPHA-2 trap effort), as well as the construction of a new $\overline{\mathrm{H}}$ annihilation detector (possibly a drift chamber) by the TRIUMF Detector Group. ALPHA-g will be a Canadian-led major initiative requiring a CFI funding. Its timescale is currently under discussion, but as evidenced at a recent workshop held at TRIUMF, there is strong interest among ALPHA members to start the development as soon as possible, because of the competition with newly approved $\overline{\mathrm{H}}$ gravity experiments at CERN (AEGIS, Gbar), as well as the on-going ATRAP experiment. Because we are in a conceptual design stage, the resource and cost requirements below are preliminary, and are based on the "science-driven" scenario, assuming timely availability of the necessary resources.

SCIENTIFIC JUSTIFICATION: Demonstration of stable trapping of $\overline{\mathrm{H}}$ by ALPHA has opened up new exciting opportunities for tests of fundamental symmetries between matter and antimatter. Spectroscopic comparisons of $\overline{\mathrm{H}}$ and H atoms could provide one of the most stringent tests of CPT symmetry. Gravitational symmetry between matter and antimatter, assured by the Weak Equivalence Principle (WEP), could be tested directly for the first time with antimatter. Both CPT and WEP underpin our fundamental understanding of laws of Nature, and hence, any violation would have profound implications.

The CPT theorem guarantees the invariance in any quantum field theory (QFT) of point-like particles in a flat space time, with basic assumptions including Lorentz invariance, locality, unitary and the spin statistics connection. These assumptions may not be valid in quantum gravity, string, and/or extra dimensions theories. The CPT theorem demands that atomic spectra of H and $\overline{\mathrm{H}}$ be identical. The optical 1s-2s transition in atomic H is currently known to 4×10^{-15}, and the ground state hyperfine splitting to the 10^{-12} level. With the ALPHA-2

apparatus, we will perform a series of spectroscopy measurements on $\overline{\mathrm{H}}$ with increasing precision (see figure). One figure of merit for the sensitivity to new physics is the absolute energy scale, and in this respect, laser and μW spectroscopy are complementary.



Gravity is one of the known four fundamental forces in Nature, but it is perhaps least experimentally studied, because of its extreme weakness. While there are a number of indirect arguments against gravitational asymmetry between matter and antimatter (e.g. from the Eötvös-type experiments), no one ever has seen antimatter actually fall in the field of gravity. In a recent review, Lykken et al. concluded: "There is no compelling evidence or theoretical reason to rule out such a difference at the 1% level"

WEP has been tested in various systems: with free neutrons to 10^{-4}, with cold atoms to 10^{-8}, and with bulk matter to the 10^{-13} level. The ultimate goal for antimatter experiments is to match these impressive precisions. Recent long-time confinement of $\overline{\mathrm{H}}$ has opened the path for an important first step. It has now become feasible to observe the effect of gravity on anti-atoms, if, e.g., they are laser-cooled to few mK and held in a vertical trap. A Lyman-alpha laser for cooling is being developed at UBC, and the annihilation detector, to be built by the TRIUMF Detector Group, will be essential for measuring the gravitational sagging of $\overline{\mathrm{H}}$ "gas". Our initial and urgent goal is to directly observe free fall of antimatter as soon as possible, even at order 1 accuracy, while aiming to perform a few % measurement in the longer term.

Additional motivation for the ALPHA-g apparatus is high precision μW spectroscopy on $\overline{\mathrm{H}}$ via NMR (antiproton spin flip) transitions, whose experimental requirements are largely different from those for lasers. However, gravity and NMR have more compatible requirements, including the need for laser cooling and precise monitoring/control of the magnetic field, and hence ALPHA-g will provide a preferred environment for μW as well. Furthermore, two trap operation (ALPHA-2 and -g) will allow development/modifications on one trap while taking physics data with the other, hence will dramatically increase ALPHA's science output.

RELATIONSHIP TO BROADER CANADIAN RESEARCH COMMUNITY: ALPHA is a relatively small international project, but one with very high Canadian impact and visibility. ALPHA-Canada, constituting more than 1/3 of the Collaboration, plays leading roles in numerous aspects of the project. It has grown to be not only the largest, but also the most diverse group in ALPHA. In this process, ALPHA has brought into the TRIUMF community, world-class Canadian university researchers, strengthening the TRIUMF user base. In 2009, U. Calgary joined the TRIUMF consortium as an Associate Member, with ALPHA being one of its main connections with TRIUMF. ALPHA's μW efforts are entirely led by the UBC/SFU/Calgary group. The laser team from Calgary/TRIUMF brings in the expertise for pulsed spectroscopy, while the UBC group consists of leading experts in frequency comb technology, and ultraviolet laser sources, including the Lyman-alpha source for laser cooling. A key feature of ALPHA is the application of subatomic physics techniques – TRIUMF's core expertise – including a particle physics detector and modern analysis techniques (e.g., multivariate analysis). These efforts, led by the York/TRIUMF group, have proven essential for the single-atom detection sensitivity required to unambiguously detect trapping and quantum transitions of $\overline{\mathrm{H}}$. Thus, ALPHA-Canada is very well positioned to exploit fully the science opportunities in the next 5YP period. It is TRIUMF resources and infrastructure that help enable Canadian leadership in this exciting science.

BROADER IMPACTS: A few examples: ALPHA's trapping of $\overline{\mathrm{H}}$ was ranked among top science news of 2010. Of our three recent Nature journal papers, Canadian scientists were lead authors of two, including one featured on the cover of Nature Physics. ALPHA-Canada researchers and students are recognized by prestigious awards, fellowships, and invited lectures. An ALPHA Ph.D. thesis is being published as a book. Public fascination on antimatter is helping to promote TRIUMF and Canadian science through national and international media appearance (e.g. BBC, CBC, Maclean's, many major newspapers). International, interdisciplinary, and hands-on technical experience with ALPHA contributes greatly to training of our students, for careers in both academia and industry.

MAJOR MILESTONES:

Description	Date
ALPHA-2 physics	2015-2020
ALPHA-g conceptual and initial technical design	2013-2014
ALPHA-g CFI application / decision	2013/2014?
ALPHA-g complete technical design / start construction	2015
ALPHG-g complete construction, commissioning, first measurement	2016
ALPHA-g physics	2017-
ALPHA-2/g modifications/upgrade?	2018 if CERN/AD shutdown

RESOURCE REQUIRMENTS:

CASH FLOW REQUIREMENTS						
\YEAR SOURCE \	ONE	TWO	THREE	FOUR	FIVE	TOTAL
TRIUMF	n/a	n/a	n/a	n/a	n/a	n/a
EXTERNAL (int'l)	$1M	$0.5M	$0.1M	$0.1M	$0.1M	$2M (rough)
TOTAL						

TRIUMF NON-CASH RESOURCES in FTE (breakdown available)						
\YEAR RESOURCE\	ONE (2015)	TWO (2016)	THREE (2017)	FOUR (2018)	FIVE (2019)	TOTAL [incl. 2014]
Mech/cryo engineer	1.0	0.5		0.25 if upgrade		2.25 [0.5 in 2014]
Mech/cryo tech	0.2	0.2		0.1 if upgrade		0.5
Electr. engineer (Bishop)	0.12	0.04				0.16
Electr. firmware tech	0.3	0.1				0.4
Detector (Henderson)	0.4	0.2		0.2 if upgrade		1.1 [0.3]
Det. gas system (Openshaw)	0.3	0.1	0.02	0.02	0.02	0.46
Det. tech. (Vincent, Goyette)	1.5	0.5	0.02	0.02	0.02	2.06
Det. electr. (Kurchaninov)	0.1	0.09	0.04	0.04	0.04	0.59 [0.24]
Det. electr. eng. (Constable)	0.4	0.1				0.5
Det. electr. tech (Sorokin)	0.15	0.05				0.2
Det. scintillator (Chan)	0.1	0.1		0.1		0.3
DAQ (Olchanski)	0.12	0.14	0.12	0.12	0.12	0.78 [0.16]
GEANT support (Gumplinger)	0.04					0.12 [0.08]
Design office	0.3	0.1				0.4
Machine shop	1.65	0.5		0.5 if upgrade		2.65

EXTERNAL FUNDING INFORMATION:

ALPHA-g will be a Canadian-led initiative and will require a major CFI through ALPHA-Canada universities (UBC, Calgary, SFU, York) of order of a few million dollars. Possible int'l contribution ($2M) is listed as "cash flow" above.

ONGOING OPERATIONAL REQUIREMENTS:

Similar to the current ALPHA Operation level, included above. Operation for FY2014 also included in total. Operating fund will be provided by NSERC. ALPHA-Canada universities provide substantial infrastructure support.

DECOMMISSIONING REQUIREMENT:

n/a

Accepted: Date: