Technical Report
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1 GBAR Overview

This summer I assisted the GBAR experiment with several aspects of the laser system used for the excitation of positronium. Positronium is an exotic type of atom comprised of an electron and a positron (the anti-particle of the electron). GBAR (Gravitational Behavior of Antihydrogen at Rest) [1] aims precisely determine how antimatter moves due to the Earth's gravity. At it's core, the premise of this measurement is simple enough that it be described by basic kinematics: A neutral anti-particle is dropped from a known height into free fall, after some known time a signal is detected when it annihilates at one end of a free fall chamber. You may then ask what the gravitational strength of the pull on that particle must have been to have seen a signal at that time.

GBAR needs to produce positive antihydrogen (an antiproton and two positrons) to reach the low energies desired for free fall, at which point the extra positron must be photo-detached so that we measured the free-fall of a low-energy, neutral antihydrogen atom. However, producing antihydrogen is difficult and generating positive antihydrogen has not yet been done. GBAR aims to overcome this using excited positronium as a positron source. Achieving μK cooling of positive antihydrogen is a novel technique that will open new doors for ultracold antimatter physics. The GBAR experiment will test CPT, the weak equivalence principle for antimatter, and could confirm or deny the existence of repulsive gravity (anti-gravity) while developing novel techniques for probing antimatter. Overcoming these challenges opens new doors in antimatter physics and will directly confirm or deny fundamental principles of physics.

2 Laser Control + Positronium Excitation

Producing excited positronium is a critical aspect of creating positive antihydrogen. For the main free-fall experiment, the antihydrogen must be neutral. However, this antihydrogen must be steered and cooled, something that is best done with a charged particle. Additionally, sympathetic cooling must be employed to reach the μK temperatures required for this experiment. This is most effectively employed when cooling positively charged ions. Positively charged antihydrogen would provide these conditions, thus a double-capture of positrons by an antiproton must be accomplished. The positronium atom has been selected as the positron donor because it possesses a larger cross-section than that of a bare positron beam. Additionally, we may exchange all antiparticles in our system for particles in the experiment for practice without changing anything. This is ideal for testing purposes because protons are much more easily accessible than antiprotons during the current Long Shutdown (LS2).

The cross section of this double-capture process has been extensively computed [2] and it has been found that this process is much more efficient with positronium excited to the 3D state. A laser that excites this transition (a two-photon transition at 410 nm) was constructed by my advisor Dr. Comini for this purpose. This laser system produces 10 mJ pulses at 10 Hz for a 10 mm long by 1 mm wide positronium pulse target, so as to excite each square millimeter of the target using 1 mJ. My work this summer has focused on integrating many aspects of this system with the experiment: implementing remote controls, calibrating equipment, and preparing the beam for transport into the reaction chamber.

This project always provided new and challenging learning experiences. While my experiences in atomic and molecular optics certainly assisted some of the learning curve, there was always a new technical challenge to overcome through patience, trial, and error. I grew greatly this summer with core experimental physics skills, particularly front-end and back-end instrument communication. The first quarter of my time here primarily involved developing a library and GUI to remotely control the pulsed laser in our system, teaching me much about serial communication and how we fundamentally communicate with our machines. Furthermore, I learned to integrate many instruments using different communication standards on different computer systems, centralizing this information and automating the process to monitor them. One of my central goals for the summer was to be able to combine these libraries and control these instruments remotely from the GBAR control room, something I've successfully tested in my final week here.

One large focus for my work this summer, with respect to developing libraries for these instruments, has been to provide a platform from which others can build off from where I left off in the future. There may be new laser systems introduced in the future, or new instrumentation that would needed to be implemented. Recognizing this, I have take great care to documented my work and improve code-readability. All of the work has been nearly organized on our collaboration's GitLab server so it and all of my notes are easily accessible to the entire collaboration.

Implementing automatic monitoring and diagnostics has been another major focus of my work. During data collection, constant checks must be run to verify that all systems related to the laser are behaving as they should. This includes checks on the stability in time of laser frequencies, verifying that all instruments are communicating properly, and confirmation of the presence of a well-aligned beam. Even before data collection, it's always good to confirm that instruments are behaving and would be ready to perform all necessary functions. Considering this, I've implemented a diagnostic checklist the code steps through slowly, verifying in further detail than the basic monitor that all systems are working. One aspect of this work I wish I could have developed more completely is a flushed-out user interface for reporting diagnostic statuses. Due to technical issues with remote communication this was not feasible without losing many weeks of productivity. I have left some of the groundwork behind for a future undertaking, but this was not a main priority. Another aspect I would still like to develop is a logger that flags and reports negative system checks, depending on the time available in the final week I may begin this.

Essentially all of this work was done in Python, an environment that should be easy enough for others to work with in the future. The libraries and scripts are mostly straightforward, so they should be easily readable and understood. However, I've considered those who will just need to use the libraries and not extensively study them. I've written a brief users manual that steps them through the process of connecting to the devices and communicating with them, listing most major functionalities and then pointing them to the libraries if they would like to do more sophisticated things. Recently, we were successfully able to test remote control of the laser hut systems from the GBAR control room, this was an important capstone in my project and was incredibly gratifying.

3 Beam Transport

Breaking away from the computational aspects of my project, transport of the 410 nm beam from the laser hut to the reaction chamber has been another major focus for me. This has developed more slowly, simply due to the arrival of necessary parts. However, significant progress has been made in the last weeks. There are two parts of this: First, the optics must be put in place that direct the beam from the laser hut vertically down several meters to the reaction chamber. Second, this beam must be very well stabilized. The latter is greatly complicated by the fact that the laser hut and reaction chamber do not move together, so if one shakes the other might hold still or shake the other direction. This is not acceptable when a beam needs to be directed through a $1\,\mathrm{mm}^2$ target where the positronium is confined.

Recently, we installed a laser safety box at the bottom of the beam pipe that directs the light from the hut to the experimental zone. Inside of this box is an optical breadboard to that we will soon migrate some of the final optics in the path to the reaction chamber. Once these are installed, we will also position a position sensitive photodiode to track the position of the beam. This photodiode will report when the beam is misaligned and will send a correcting signal to piezos connected to mirrors. Over the summer, we have been calibrating these photodiodes with a test bench simulating experimental conditions. Now were are prepared to move this system to the real experiment and implement automatic beam stabilization. This should effectively counteract the relative motion of the laser hut and the reaction chamber, allowing us to precisely direct the beam to the positronium target.

4 Concluding Remarks

Over the last two months I've implemented a powerful remote control system that is hopefully versatile enough that GBAR will not only be able to use it but also expand on it as the experiment progresses. It's been an incredibly exciting opportunity to contribute to this project, aside from its ambitious and captivating science goals, this work provided so many unique challenges that developed my skills in experimental physics research. I'd like to thank the GBAR collaboration for welcoming me into their community and giving me the chance to work on this project, and to CERN, the Summer Student Program, the University of Michigan, and the National Science Foundation for the colossal effort to make this program possible.

References

[1] GBAR Collaboration. (2011); Proposal to measure the Gravitational Behaviour of Antihydrogen at Rest; CERN-SPSC-2011-029 / SPSC-P-342

[2] Comini, Pauline. (2014); Étude de la formation d'antihydrogène neutre et ionisé dans les collisions antiproton positronium Study of the antihydrogen atom and ion formation in the collisions antiproton positronium; 10.13140/2.1.4519.7605.