Final report for NKFIH Project K103917:

Antimatter studies at the Antiproton Decelerator of CERN

Executive Summary

Our main subject was the theoretical and experimental study of symmetries in particle physics, with special emphasis on the mysterious disappearance of antiparticles after the Big Bang. Our experiments were oriented to compare the properties of protons and antiprotons at the Antiproton Decelerator of CERN (also called Antimatter Factory), the only facility where such studies can be performed, within the framework of the ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) Collaboration. To measure the mass of the antiproton using laser spectroscopy on antiprotonic helium atoms the precision of the results is limited by the thermal motion of the helium gas of the target. We have built a special target with a cooling system which went down to the temperature of 1.5 K and it provided the same precision with single-photon resonances (Science, 2017) which was previously achieved by us by two-photon spectroscopy. We have also set up an apparatus to study laser spectroscopy on antiprotonic atoms produced in superfluid helium and possibly observed the effect of the phase transition. As a technical contribution we participated in developing and building the ELENA ring for the post-deceleration of antiprotons of the Antiproton Decelerator. *Dániel Barna, Dezső Horváth and Péter Zalán* (Wigner RCP, Budapest) participated on behalf of our group in this work.

There were two lines of theoretical studies connected to this main topic: studies of symmetry effects in quantum theory and calculations of charged particle impact, scattering and ionization in gases and solids. The time symmetry of large quantum systems can be violated by inevitable entanglement with the rest of the universe or by new physics of spontaneous decoherence. The mathematical structure of corresponding non-unitary quantum dynamics as well as possible experimental tests have been investigated by *Lajos Diósi* (Wigner RCP, Budapest). Ionization and scattering of charged particles was the main subject of theoretical calculations done by *Sándor Borbély, László Nagy* (Babes-Bolyai University, Cluj-Napoca) and *Károly Tőkési* (Atomki Institute of Nuclear Research) using the classical trajectory Monte Carlo method. We have provided reference data for the single and double total ionization cross sections for a wide range of antiproton impact energies (3keV - 1MeV).

With the support of the grant we have organized the "International Conference on Precision Physics and Fundamental Physical Constants (FFK-2015)", Budapest, 12-16 October 2015. The main subject of the conference was testing symmetry principles, and several participants of our group presented talks at it, see the programme at https://indico.cern.ch/e/ffk2015. We have published 30 papers in peer-reviewed journals, 31 conference papers, 4 books and gave many invited conference talks acknowledging this grant. In the detailed report below we list the most important, explicitely cited publications only, in the *Publications* part of the report you can find all 69 of our publications connected to this project.

Detailed report

1. *Measuring the mass and magnetic moment of the antiproton (Dániel Barna, Péter Zalán and Dezső Horváth, Wigner RCP)*

The method of this measurement was first established at the Low Energy Antiproton Ring (LEAR) of CERN in the middle 90's and later developed at the Antiproton Decelerator [1-3]. Slow antiprotons are stopped in gaseous or liquid helium where with about 3% probability they will be trapped in a metastable atomic orbit. One can use resonant laser pulses to drive them over to unstable states where they immediately annihilate with the nucleus thereby signalising the correct laser frequency (Fig. 1).

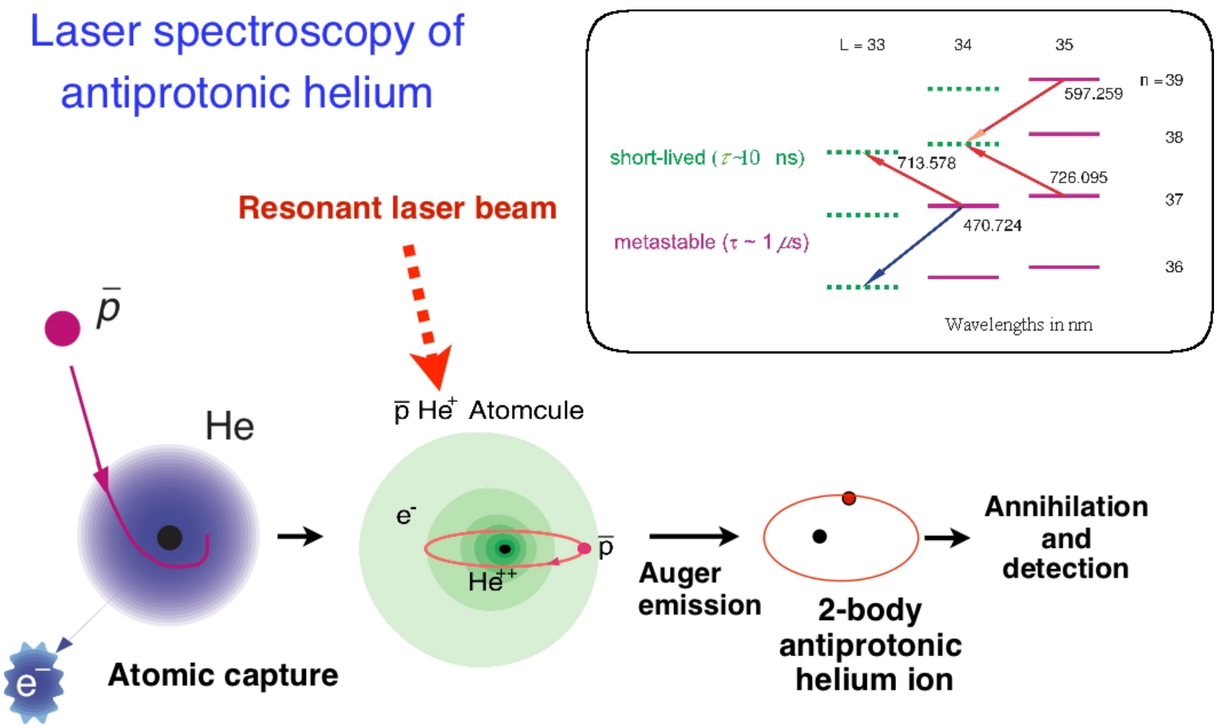

Figure 1: Principle of laser spectroscopy [1]. An antiproton captured in a metastable orbit in a helium atom is forced to annihilate when a laser pulse of the resonant frequencey transfers it to a short-lived state.

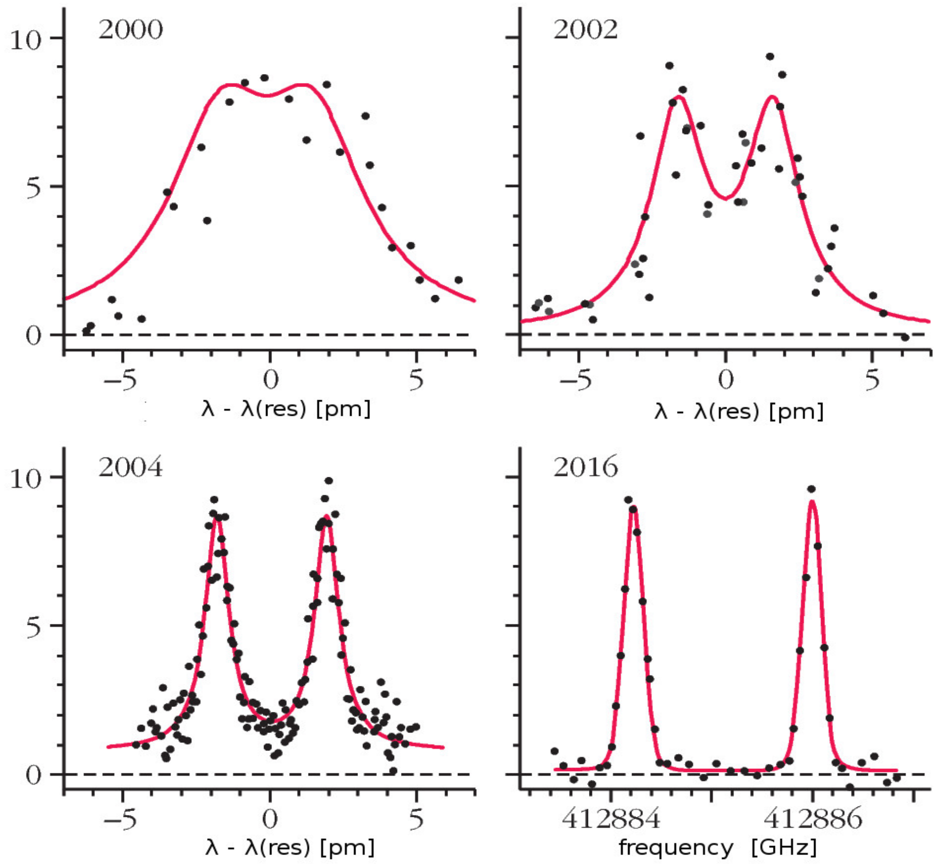

Fig. 2. The development of laser resolution demonstrated on the (N=37,L=35) → (38,34) split antiprotonic transition. The last situation was achieved by the two-photon method [2,3] in 2014.

Fig. 2 shows the development of the spectroscopy resolution on a split state: note that each order of magnitude gain in resolution needed several years of work to achieve. During this grant period we have constructed a new cooling system with which the exotic atoms could be cooled in collisions with the low-pressure buffer gas down to 1.5 -1.8 K. As previously we could make measurements at 5.5 - 6.1 K only, this change meant a factor of 3 - 4 improvement. The construction work was made by Masaki Hori, Anna Sótér and Dániel Barna (Fig.3). The result was published in **Science** [4] as the first case of super-cooled exotic atoms. The next step will be two-photon spectroscopy on the super-cooled antiprotonic helium, with that our determination of the antiproton mass will reach in precision that of the proton mass. Our result (assuming the validity of CPT invariance) is already used to decrease the uncertainty of the value of the proton mass, which is very important in all biochemical calculations.

Thus our measurements confirm CPT invariance as the antiproton mass agrees with the proton mass on the level of 10^{-9} [2-4].

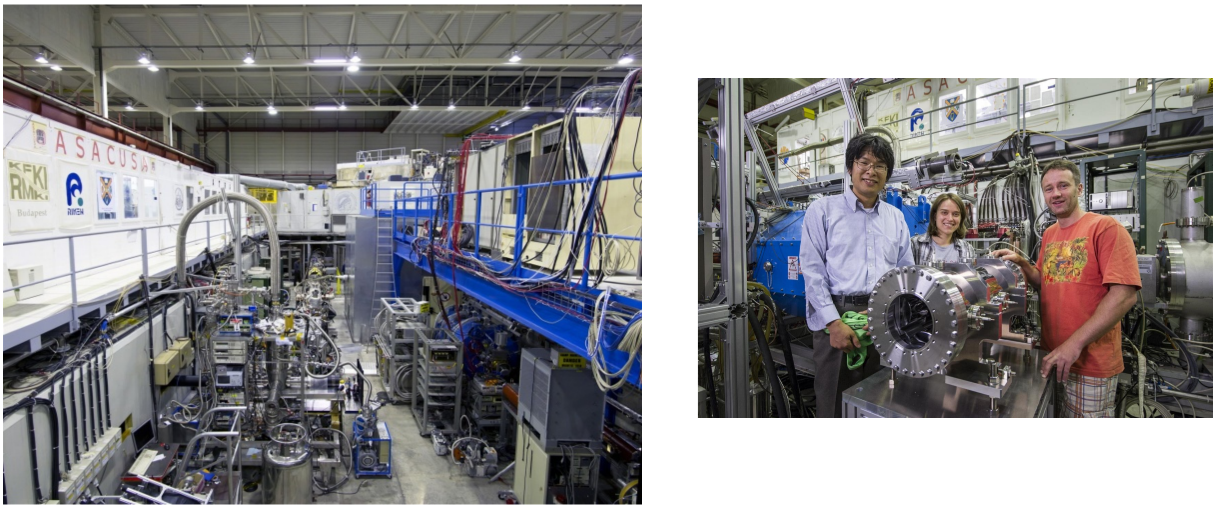

Fig. 3. Left: The spectroscopy setup [4] with the pipe of the new cooling system behind the concrete wall. Right: Masaki Hori, Anna Sótér and Dániel Barna, the constructors of the setup.

In this period we have finished the measurements of the magnetic moment of antiprotonic helium by studying the hyperfine splitting (Fig. 1) in ^{3}He. The principle of the measurement is explained in Fig. 4. The results fully agree with the calculations made assuming the proton mass and magnetic moment for the antiproton thereby confirming CPT invariance [5].

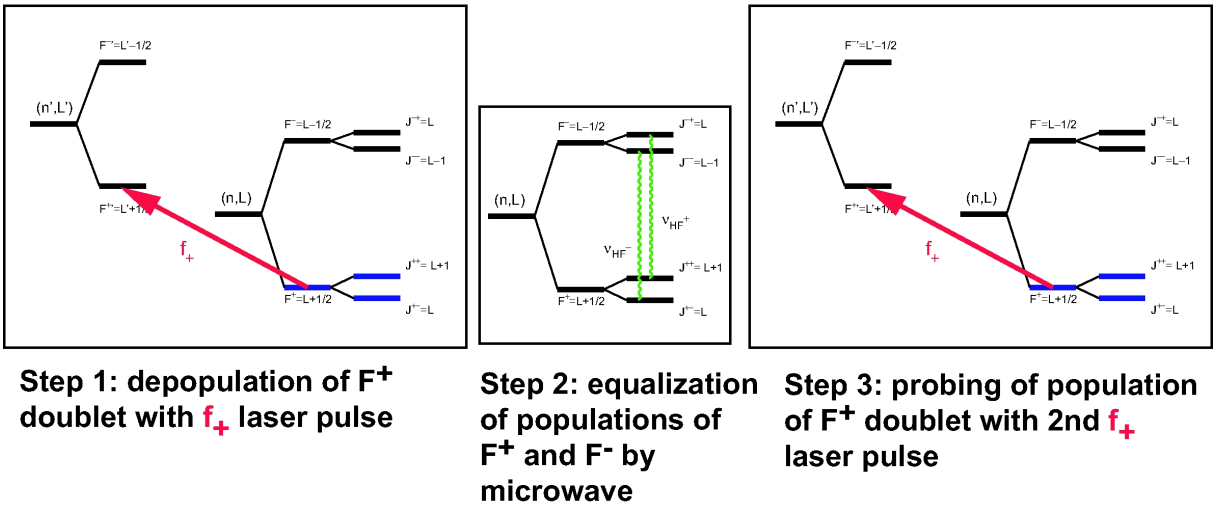

Fig. 4. The principle of measuring the magnetic moment of the antiproton using the laser-microwave-laser triple resonance method on antiprotonic helium [5].

Our last spectrocopic result is the measurement of transitional laser spectra of antiprotonic helium in superfluid helium liquid. We have a preliminary observation of narrowing the spectral lines in the phase transition. It is not published yet, the paper [6] is in preparation, but the data collection is finished.

Following our proposal we have contributed to the technical development of the spectroscopic method in three ways.

- We developed a new kind of detector to detect the annihilation photons [6]. That was later used not only in our work, but also by a Genova group which studied antiproton absorption and nuclear reactions in metals.
- Dániel Barna participated in the development of the ELENA storage ring at the Antiproton Decelerator, mostly by designing the electromagnetic beam transportation lines [8].
- We started to design and build a two-tone Paul-trap to simultaneously confine antiprotons and positrons in the same volume, but it was abandoned due to lack of manpower.

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2. *Theoretical studies of symmetries in quantum systems*
(Lajos Diósi, Wigner RCP)

Extreme high precision tests of low energy phenomena are so demanding that quantum foundational limitations of detection and control may become a challenge. We have theoretically investigated various forms and contexts of quantum and/or environmental noise and disturbances[1-7]. They may technically deteriorate the performance of detection and control [4], but they may also contribute to mathematical consistency of our models [3]. We extended the time-reversal invariant theory of quantum detection for sequential detections [5].

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3. *Theoretical calculations of ionization processes*
(Sándor Borbély and Ladislau Nagy, Babes-Bolyai University, Cluj-Napoca, and Károly Tőkési, Atomki, Debrecen)

Theoretical calculations were performed for ionization processes at the impact of antiprotons, other charged particles, atoms and photons on various atoms. These studies were partially related to the antimatter studies. The calculation methods included included the numerical solution of the time-dependent Schrodinger equation, the classical trajectory Monte Carlo method and the three-dimensional semiclassical trajectory Monte Carlo method. Because of length limitation the topics are just listed here, the details are in the quoted publications.

- Ionization of atoms with XUV and EUV laser pulses [1-3]
- Ionization of atoms with slow protons and antiprotons [4-5]
- Energy loss and ionization of electrons and positrons in atomic systems [6-7]
- Transmission and guiding of charged particles, electrons, positron and hydrogen ions through microcapillaries [8-9]
- Collisions of electrons and positrons on solid surfaces [10-12]

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4. *Studies of broken symmetries (D. Horváth)*

These studies were originally triggered by the CPT-tests, but went out of the scope of previous topics.

- Broken symmetries in physics: search for Higgs-bosons and supersymmetry [1-3]
- The failed discovery of superluminal neutrinos started us thinking about how to measure the neutrino masses [4-5].

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