

Spectrometry of captured highly charged ions produced following antiproton annihilations

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We report the first capture and time-of-flight spectrometry of highly charged ions (HCIs) produced following annihilations of trapped antiprotons in a Penning-Malmberg trap. A multistep nested-trap technique was developed at the AEGIS experiment at CERN to trap and identify the annihilation-linked ions using external scintillators. The successful capture and mass analysis of helium and argon ions confirm the viability of the approach. This proof-of-principle demonstration establishes the foundation for future high-resolution mass spectrometry of recoil-filtered nuclear annihilation fragments. This methodology could enable studies of antiprotonic atom formation and cascade dynamics, allow the in-trap synthesis of radioactive HCIs, and provide a particularly sensitive probe of the neutron-to-proton composition at the outer periphery of the nucleus.

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I. INTRODUCTION

Precise knowledge of the spatial distributions of protons and neutrons in atomic nuclei is central to both nuclear physics and astrophysics. While electromagnetic probes can map charge densities with high precision [1,2], the neutron-rich peripheral region of nuclei remains experimentally challenging to explore. As an example, the neutron skin, given by the difference in neutron to proton root-mean-square radius, is a sensitive link to the nuclear forces [3], and its study allows us to explore the density dependence of the nuclear symmetry energy, which elucidates the properties of neutron stars [4,5]. The ongoing CREX-PREX dilemma [6–9], arising from unexpected tensions in the measured neutron skin thicknesses of ^{48}Ca and ^{208}Pb , further highlights the need for techniques sensitive to the neutron distribution in the peripheral region of nuclei.

In this respect, the antiproton ($\bar{p}$) offers a unique probe, being notoriously sensitive to regions of low hadronic density as a result of its annihilation [10,11]. The antiproton's substantially larger mass—approximately 1836 times that of the electron—together with its identical negative charge, allows it to be bound in a radially localized Rydberg orbit in close proximity to the atomic nucleus, as an antiprotonic atom [10,12–15]. The annihilation on either a proton or neutron results in the release of roughly ~ 1.5 GeV captured by multiple mesons ejected from the annihilation site [16]. If the annihilation occurs in the far periphery, then the mesons may miss the residual nucleus, leaving behind a “cold” nuclear fragment with minimal recoil momentum and one less nucleon [13,17]. The ratio of neutron (n) to proton (p) loss of these nuclear annihilation fragments mirrors the local (n/p) density ratio in an outer peripheral region ~ 3 fm beyond the half-density radius of the nucleus, where the nuclear density is up to 10^3 times lower than the core [18,19]. The study of annihilation fragments following these cold annihilation events offers a sensitive constraint on the neutron skin and the isospin structure of the extreme peripheral region of the nucleus [20].

Historically, the study of antiproton interactions with matter has been performed via beam-on-target (gas, liquid, or solid) experiments [12,21], which has provided valuable data on antiproton ionization and capture cross sections for benchmarking atomic theory [22–26]. Following the antiprotonic atom cascade and annihilation, x-rays, high-energy mesons, and light, energetic annihilation fragments (such as neutrons, protons, deuterons, tritons, and helium nuclei) have all been directly detected [10,16,27–32]. However, the much heavier nuclear fragments have only been studied using radiochemical means through gamma spectroscopy [18,27]. Due to the limitations of this radiochemical approach, the single-nucleon loss annihilation fragment ratios could only be deduced for selected cases with appropriate decay properties [13,19,33,34]. These measurements allowed systematic studies of the neutron skin by constraining models together with x-ray spectroscopy measurements of antiprotonic atoms and electron scattering data [20,35]. However, cases involving nonradioactive annihilation fragments, such as those from ^{208}Pb , had to be interpolated [36], introducing a significant systematic uncertainty for the determination of their neutron skin.

As a result of the technical advancements at the AD-ELENA facility at CERN, the cooling, trapping, and accumulation of millions of antiprotons in Penning-Malmberg traps is now routine [37,38]. This has opened the possibilities for studies of antiprotonic atoms formed in a controlled ultrahigh-vacuum (UHV) environment, as first proposed by Wada and Yamazaki [39]. More recently, the PUMA experiment at CERN is aiming at probing the nuclear periphery of short-lived radioactive nuclei using trapped antiprotons, by measuring the net charge of mesons from the annihilation. This method explores a region ~ 2 – 2.5 fm from the nuclear half-density radius [40]. A complementary approach, conceptually outlined here, aims at the direct capture and time-of-flight (TOF) spectrometry of recoil-filtered cold annihilation fragments. This technique allows for the *in situ* trapping of charged species resulting from the antiproton annihilation, including both nuclear annihilation fragments and ions produced via the ionization of the trap environment. Specifically, the envisioned mass spectrometry of the captured nuclear fragments from cold annihilation events will enable a tool for probing the outer peripheral region ~ 3 fm beyond the half-density radius, while filtering “hot” events where high-energy mesons strongly interact with the residual nucleus, by the fragment recoil energy. Antiproton-based probes of the neutron periphery are known to involve sizable model dependence [17], including assumptions about the annihilation mechanism, fragment survival, and bound-state antiproton overlap with the nuclear matter distribution. This approach could help constrain these model dependencies through simultaneous charge and mass measurements of the recoil-filtered annihilation fragments. The high charge state of these annihilation fragments, resulting from the Meitner-Auger cascade, enables their efficient capture within a Penning-Malmberg trap, as indicated by recent simulations [41]. Beyond their role as nuclear probes, these often-radioactive highly charged ions (HCIs) offer valuable systems for fundamental interactions and metrology [42–47].

In this work, we report the foundation of this technique via a first proof-of-principle study, demonstrating the capture of annihilation-induced ions, a crucial step for the future capture of nuclear annihilation fragments. We demonstrate the procedure by capturing highly charged ions produced from antiproton annihilations occurring on ultralow-density helium and argon gas within a Penning-Malmberg trap. Using the AEGIS experiment at CERN [48], we employed TOF spectrometry to identify the captured ion species. These first results establish the core methodology for producing and trapping radioactive HCIs and outline a path toward the high-resolution spectrometry of cold annihilation fragments, which will give access to observables to study the antiproton annihilation process, and serve as a powerful and complementary tool to probe the outer nuclear periphery.

II. EXPERIMENT

The experiment was conducted in the AD-ELENA antiproton decelerator complex at CERN [37], using the AEGIS Penning-Malmberg traps, seen with cross-sectional view in Fig. 1. The AEGIS experiment is composed of two superconducting solenoid magnets with two connected

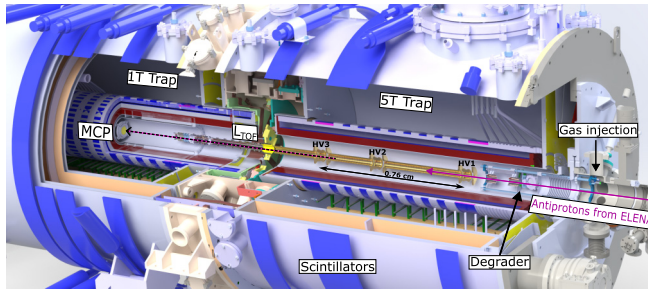


FIG. 1. Overview of the AEgIS experimental setup. Antiprotons decelerated by the AD-ELENA decelerators enter the AEgIS 5 T trap after passing a degrader foil. The antiprotons are trapped in the 5 T trapping region, between the HV1 and HV3 electrodes biased to $V_{HV} = -14$ kV. Buffer gas was injected using a leak valve at the entrance of the 5 T trapping region. Annihilations occurring within the trapping region are detected via ejected mesons using external scintillators shown in blue. Positive ions are captured using a nested-trap potential presented in Fig. 2 and ejected axially to a downstream MCP, placed at a distance of $L_{TOF} = 1.05(1)$ m within the 1 T trapping region for TOF analysis of the charged species.

Penning-Malmberg trapping regions, a 5 T region used for catching and preparing antiprotons and an adjacent 1 T trapping region used for antihydrogen production [48]. In these studies, only the Penning-Malmberg trap electrodes between the high-voltage HV1 and HV3 electrodes were used; all the trap electrodes in the 1 T region were grounded.

Bunches of approximately 8×10^6 antiprotons at 100 keV kinetic energy were delivered from the AD-ELENA decelerator complex every ~ 110 s [49]. These $\bar{p}$ bunches impinged on a 1400-nm-thick Mylar degrader foil held on a flippable mount positioned inside a 5 T superconducting solenoid magnet, inserted during antiproton injection (lasting ~ 10 s). This degrader reduces the $\bar{p}$ energy sufficiently (below ~ 20 keV) for dynamic capture within the 5 T Penning-Malmberg trap. Antiproton capture was achieved by rapidly pulsing (~ 100 ns) the high-voltage (HV1) electrode, to potentials up to -14 kV with the HV3 maintained at -14 kV. Typically, around 3×10^6 antiprotons were captured per cycle. Between HV1 and HV3 electrodes reside 20 cylindrical ring electrodes (3 cm diameter and 1.5–3 cm long) made from gold-plated copper, including the high-voltage electrode HV2, which can be individually biased up to ± 200 V (10 mV resolution) via the AEgIS control system [50,51], allowing for precise manipulation of trapped charged particles. The trap electrodes are maintained at cryogenic temperatures (~ 10 K). The controlled injection of either helium or argon gas (99.9% purity) into the AEgIS trapping region was achieved using an adjustable high-vacuum leak valve connected to a reservoir tuned to a pressure between 10 and 100 mbar. The leak valve was regulated to maintain a pressure reading of 10^{-7} to 10^{-8} mbar at a vacuum gauge located at the entrance to the 5 T trapping region, for the duration of the experimental campaigns. The pressure profile within the trapping volume itself is expected to deviate substantially from this upstream value due to the strong cryogenic pumping by the cold bore and electrodes. The inefficient cryopumping of helium resulted in a helium contamination present during the argon

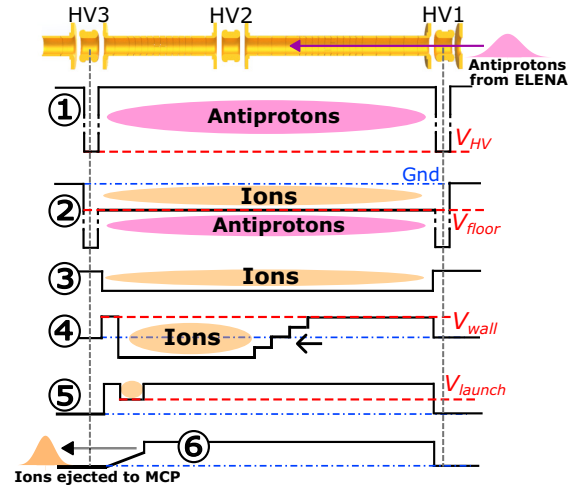


FIG. 2. Overview of the multistep nested-trap procedure, used for the capture and TOF spectrometry of positive ion species formed following antiproton annihilations in the 5 T AEgIS Penning-Malmberg trap. Each step is presented within the main text in chronological order from 1 to 6, showing the applied voltages on the trap electrodes together with the antiproton and ion location within the trap. The 0 V potential of the trap is indicated with a blue dash-dotted line; the red dashed lines indicate relevant voltage settings.

injection campaign. To prevent backstreaming of the injected gas and potential contamination of ELENA, an upstream gate valve was closed and actuated only for brief periods (~ 5 s) synchronized with the injection of the antiproton beam into the AEgIS apparatus.

The experimental cycle proceeded as follows for every captured antiproton bunch arriving from ELENA into the AEgIS trapping region (follow steps presented in Fig. 2):

(1) Antiprotons passing the inserted degrader were captured between the HV1 and HV3 ($V_{HV} = -14$ kV) electrodes. Collisions with the buffer gas cooled the antiprotons, resulting in the ionization of atoms in the trap.

(2) The low-voltage electrodes between HV1 and HV3 were biased to $V_{floor} = -160$ V for helium and -190 V for the argon campaign, forming a nested potential well that allowed for the capture of positive ions within the trap volume. Antiproton annihilations occurring within the trapping region were monitored using external scintillators that detected pions emitted through the vessel, seen in Fig. 1.

(3) After a set antiproton trapping time ($\tau_{\bar{p}}$), the potentials of the HV3 and HV1 electrodes were each ramped down to ground over approximately 15 s sequentially. This process ejected the remaining antiprotons axially, while spilling over any cold positive ions into the central region. Annihilations were simultaneously monitored using the external scintillators, providing a measure of the remaining antiproton number. Positive ions with insufficient axial energy to overcome the potential V_{floor} remained trapped in the central region.

(4) The potential on the low-voltage electrodes was manipulated to axially compress the captured positive ions into a shorter trap (approximately 4 cm long) formed by three adjacent 1.5-cm-long electrodes near the downstream HV3

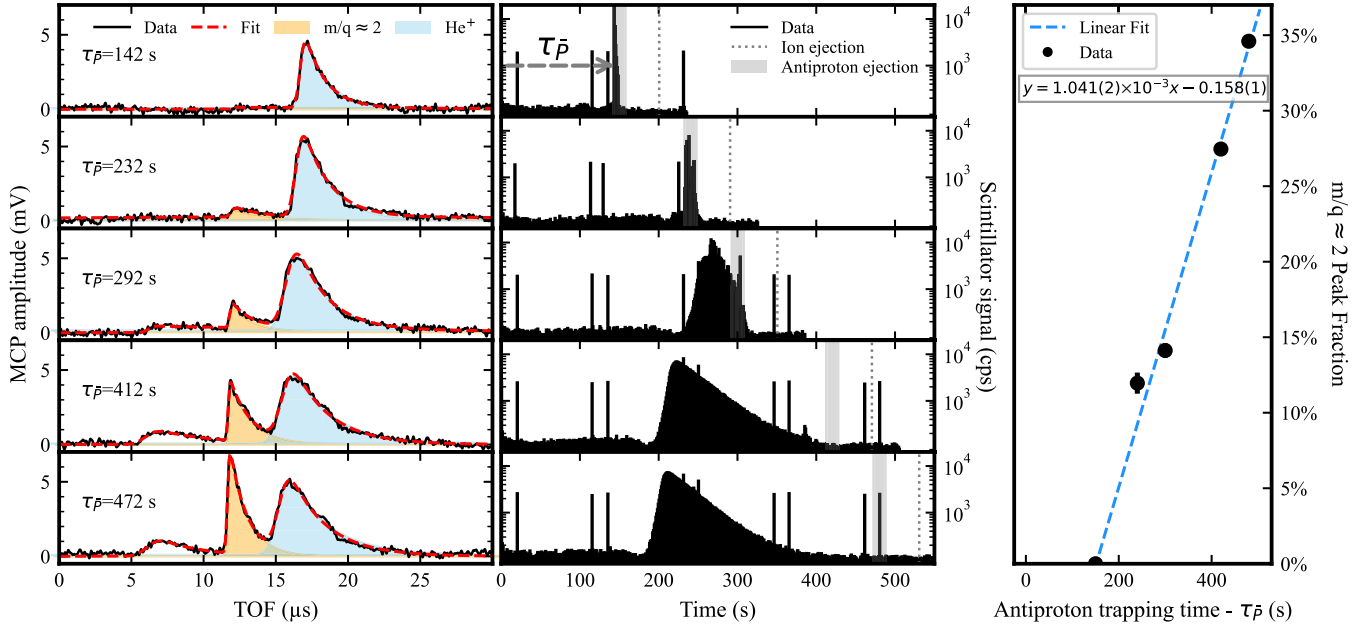


FIG. 3. TOF measurements in helium background, showing MCP signal observed at different antiproton storage times ($\tau_{\bar{p}}$) together with measured annihilation events using external scintillators. Left and center panels: MCP signal vs TOF (left panel) together with corresponding scintillator signal vs time after antiproton capture (center panels). The MCP signal shows peaks identified as He^{1+} ($m/q \approx 4$) and ($m/q \approx 2$) species, the center panels show the scintillator events observed for each measurement, the gray shade shows the release of antiprotons, and the dotted line indicates the ion ejection time. The repeated spikes observed in the scintillator signal are from the AD-cycle background. Right panel: Plot of the integrated fractional intensity of the $m/q \approx 2$ peak with respect to $\tau_{\bar{p}}$, fitted with the linear function shown in the inset.

electrode. Before the compression, a deeper potential well was formed with the set wall voltages $V_{\text{wall}} = 160$ V for helium and 190 V for the argon campaign. This sequence took approximately 20 s.

(5) The floor potential of the shorter trap was raised to a set launch potential V_{launch} over approximately 5 s, evaporatively cooling the trapped ions. For the helium injection campaign, a launch potential of $V_{\text{launch}} = 90$ V with $V_{\text{wall}} = 160$ V was set and a shallower trap with $V_{\text{launch}} = 180$ V and $V_{\text{wall}} = 190$ V was used for the argon campaign, for reducing the energy spread by filtering the ions with energies above ~ 5 eV.

(6) Finally, the downstream wall electrode was rapidly switched (1 ns timescale) to 0 V, ejecting the trapped positive ions axially toward a microchannel plate (MCP) detector located at a distance of $L_{\text{TOF}} = 1.05(1)$ m downstream within the 1 T magnetic field of the trapping region. The front face of the MCP was biased to 0 V. The MCP readout was amplified and recorded using a Teledyne LeCroy HDO6104 oscilloscope, triggered synchronously with the ejection pulse, yielding the captured TOF signal. The scintillator signals were processed using counting modules to monitor annihilation rates and timings throughout each experimental cycle.

To characterize background signals, the complete procedure was performed under good vacuum conditions ($< 10^{-15}$ mbar), with and without trapped antiprotons for each experimental setting. The TOF spectrometry was calibrated using electron-cooled antiprotons trapped using the same electrodes but in a reverse-polarity trap (steps 5 and 6 in Fig. 2). Following this calibration, the procedure was tested with the controlled injection of ultralow-density gases, first

using helium and followed by the helium-argon mixture. A detailed description of the calibration and fitting procedure is presented in the Appendixes.

III. RESULTS

The results of the multistep nested-trap approach tested with helium injection are presented in Fig. 3, revealing the evolution of the TOF spectrum (left panels) and scintillation signal (center panels) with respect to different antiproton trapping times ($\tau_{\bar{p}}$). The antiproton ejection time is indicated with a gray shade for each measurement, with a dotted vertical line indicating the ion ejection time. When antiprotons are released from the trapping region before annihilations are detected, only a single ion peak is observed in the spectrum. As shown in the top-left panel of Fig. 3, this peak at $16.5(4)$ μs corresponds to a species with a mass-to-charge ratio of $m/q = 3.8(2)$ u/e according to the antiproton calibration, which is in agreement with expected He^{+} ions.

The average resolution achieved in these measurements was $M/\Delta M \approx 4$, significantly lower than for the electron-cooled antiprotons that achieved a mass resolution of $M/\Delta M \approx 45$, as presented in the Appendixes. As the antiproton trapping time is increased, annihilations are observed inside the trapping region during the ion capture sequence (center panels in Fig. 3). As a result, a second peak appears at $12.0(2)$ μs corresponding to ion species with $m/q = 2.01(6)$ u/e suggesting the capture of either H_2^{+} , He^{2+} , or HCl fragments, all with $m/q \approx 2$ u/e. Background measurement under good vacuum conditions indicated no detectable MCP signal. A third peak appears around 6 μs that is attributed to ions

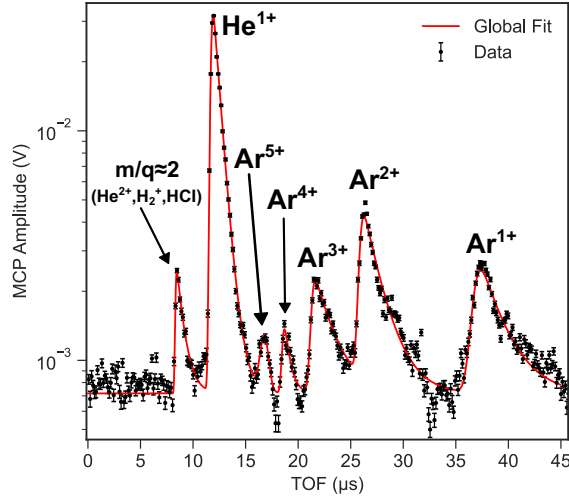


FIG. 4. TOF spectrum of ejected positive ions observed during the argon/helium experiment. Data (points) are shown with the multipoint fit (red line).

not sufficiently cooled before release, which was confirmed by stepwise reducing the trap depth by lowering V_{wall} . The fractional peak intensity of the $m/q \approx 2$ u/e peak versus the antiproton trapping time is seen in the right panel of Fig. 3. A linear increase of the $m/q \approx 2$ u/e ion fraction is seen, directly following the observation of annihilations in the trapping region.

In the following experiment, argon was introduced together with a helium background. Figure 4 shows the acquired TOF spectrum, representing the average sum of four measurements, captured following the complete annihilation of all antiprotons in the trapping region after ~ 150 s trapping time. The fit results are overlaid on the spectrum that exhibits seven distinct peaks, which are presented on a log-lin scale to enhance clarity for the weaker signals. Table I summarizes the identified peaks, their measured TOF, and calculated m/q values using the He^{1+} peak as a calibration reference. In these measurements, an average mass resolving power of $M/\Delta M \approx$

TABLE I. Identified ion peaks from the argon campaign spectrum (Fig. 4). The spectrum was calibrated using TOF of the identified He^{1+} peak; m/q values are given with statistical uncertainties (parentheses). The literature values are taken from Ref. [52].

TOF (μs)	$\frac{m}{q} _{\text{exp}} (\frac{\text{u}}{\text{e}})$	Ion candidate(s)	$\frac{m}{q} _{\text{lit}} (\frac{\text{u}}{\text{e}})$
8.457(30)	2.018(14)	H_2^+	2.015 10
		He^{2+}	2.000 75
		HCl frag. ^a	2.0–2.6
11.911(7)	—	He^{1+}	4.002 60
16.774(75)	7.94(7)	Ar^{5+}	7.991 93
18.698(68)	9.86(7)	Ar^{4+}	9.990 05
21.641(56)	13.21(7)	Ar^{3+}	13.320 25
26.264(29)	19.46(5)	Ar^{2+}	19.980 64
37.378(55)	39.41(12)	Ar^{1+}	39.961 83

^a Assuming the complete stripping of nuclear annihilation fragments with masses greater than ^4He .

5 was achieved, sufficient to distinguish the different charge states in the spectrum. Besides the He^{1+} peak and the signal at $m/q \approx 2$ u/e, several peaks appear at m/q values consistent with argon ions in various charge states, ranging from Ar^{1+} through Ar^{5+} . Higher charge states could not be identified due to the large He^{1+} signal. The TOF values are in reasonable agreement with the literature values shown, although a slight systematic deviation toward higher m/q is observed for the heavier ions. Detailed calibration and fitting procedures are presented in the Appendixes.

IV. DISCUSSION

The presented measurements establish a first demonstration of the capture, cooling, and TOF spectrometry of ions formed following antiproton annihilations in a Penning-Malmberg trap. The demonstrated simultaneous measurement by scintillator tagging with ion yields also shows that external scintillators provide a practical handle to identify annihilation-linked ion production.

In helium buffer gas, the nearly time-independent He^+ yield is consistent with the direct collisional ionization during $\bar{p}$ injection, whereas the growth of the $m/q \approx 2$ u/e peak is a result of a secondary process following the antiproton annihilations occurring within the trapping region, suggesting annihilation-linked ion production. Direct capture of ^4He fragments is excluded, as their recoil energy is far beyond the potential depth of the trap. Antiproton annihilations occurring on heavier elements such as the gold-plated electrodes are expected to result in a large distribution of highly charged nuclear fragments [27]. While a small contribution from directly trapped primary nuclear fragments, especially for the heavier Ar target, cannot be excluded, the current charge-state distribution, together with the absence of an efficient and charge state preserving cooling mechanism for fast HCl fragments, favors secondary ionization as the dominant origin under these conditions. A more likely scenario is that the HCl annihilation fragments or energetic electrons impact ionize the residual gas within the trapping region. Reference data for slow $\bar{p}$ -He and Ar collisions show predominantly He^+ and Ar^{2+} up to ~ 25 keV impact energy [53]. Thus, the observation of Ar^{5+} , which requires a cumulative ionization energy exceeding 200 eV, at $\bar{p}$ energies < 14 keV points to the presence of highly ionizing particles within the trap volume that drive secondary ionization of the buffer gas, which could generate He^{2+} ions. In this scenario the intensity is expected to decrease with increasing charge state, notably Ar^{1+} showed a lower yield than Ar^{2+} . This is explained by m/q normalization and losses of the low- m/q ions by the magnetic bottleneck (5 to 1 T). We note that hydrogen is a well-known impurity in Penning-Malmberg traps, even under UHV conditions [54]; H_2^+ ions could thus also be a possible candidate. However, background measurements running the sequence with He/no- $\bar{p}$ and no-He/ $\bar{p}$ indicated no detectable MCP signal, supporting He^{2+} ions as the most likely candidate. A refined technique with improved mass resolution could easily isolate any contamination during future measurements.

The present buffer-gas environment, used in this work simultaneously as a target for the ion formation and cooling of the species, limits sensitivity to the most interesting

stripped annihilation fragments, HCIs are depleted by charge exchange, and primary fragments may scatter before capture. A direct path forward, to directly isolate the primary nuclear fragments, is to perform measurements without the presence of buffer gas to preserve fragment charge states and kinematics. Refined approaches utilizing $\bar{p}$ -anion mixing would allow the laser-triggered synthesis of antiprotonic atoms and fragments in UHV [41,55], and for species not forming anions, a Rydberg excited atomic beam could be injected on the trapped cold antiproton target, similar to positronium formation [56].

The experiments reported here were constrained by a ~ 190 V well depth set by available voltage supplies and electrode geometries. Furthermore, captured ions were not sufficiently cooled before their ejection from the trap for TOF spectrometry. Enabling positive bias on the HV electrodes will substantially increase capture efficiency of charged species to energies beyond $10 \text{ keV}/q$. This will allow the efficient capture of cold annihilation fragments for nuclear periphery studies, with the estimated complete capture of cold fragments from annihilation on ^{80}Kr and heavier nuclei [41]. We note that the extraction of nuclear structure information from these measurements relies on theoretical descriptions of the antiproton-nucleon/nucleus interactions, which motivate the need for modern theoretical approaches [57–59] to fully interpret future data.

Achieving the mass resolution required for isotopic and isobaric separation will require efficient, nonintrusive cooling of the captured HCIs. Promising options include combined electron/positron cooling [60,61] and sympathetic cooling with laser-cooled ions [62]. Once the fragments are cooled to thermal energies, a TOF resolving power comparable to that obtained with electron-cooled antiprotons ($M/\Delta M \sim 100$) should be reachable at AEGIS, using the demonstrated technique. For example, to identify $A - 1$ fragments of fully stripped ^{80}Kr fragments following annihilation, a minimal mass resolution above $M/\Delta M > 35$ is necessary. To resolve multiple charge states of different isotopes and isobars, multireflection TOF (MR-TOF) mass spectrometry is a promising approach that can reach resolving powers exceeding $M/\Delta M > 10^6$ [63]. As a complementary tool, mass-selective rf techniques could provide in-trap filtration of specific m/q bands [64].

Once implemented, this technique will enable systematic studies of charge-state distributions across different target atoms, thereby constraining antiproton collisional-ionization cross sections and the capture/cascade process, valuable for exotic atom theory [23,24,26,65,66]. Single-nucleon-loss fragment ratios can map the changes in the neutron to proton density at the nuclear periphery along isotopic chains, providing a powerful complement to nuclear charge-radius data [2,67]. These measurements could reveal subtle changes in the neutron skin, constraining the nuclear forces [3] and the equation-of-state of neutron stars [4,5]. This unique probe could potentially also be sensitive to surface α clustering in nuclei [68,69]. In addition, measurements of $A-2$ and higher-order fragment, if captured, could yield valuable benchmarks for intranuclear cascade models [16,41] and multinucleon annihilation processes, such as Pontecorvo reactions [70,71].

V. CONCLUSIONS

This proof-of-principle work establishes a practical approach for studying annihilation-induced ion production within a Penning-Malmberg trap, demonstrating the essential steps for direct capture and TOF spectrometry of nuclear annihilation fragments. Technical developments, such as laser-triggered annihilation in UHV, deeper nested wells, nonintrusive cooling, and high-resolution mass analysis (MR-TOF and/or mass-selective rf), are readily achievable. Once implemented, studies of the charge and mass of recoil-filtered nuclear annihilation fragments will offer unique insight into the life cycle of antiprotonic atoms, while enabling a powerful complementary tool to probe the outer nuclear periphery, with broad implications for atomic, nuclear, particle, and astrophysics. The future availability of transportable antimatter traps [40,72] together with the presented approach could extend this technique to probe the outer nuclear periphery of short-lived nuclei and allow an alternative path for synthesizing radioactive HCIs in facilities without access to large accelerator infrastructure.

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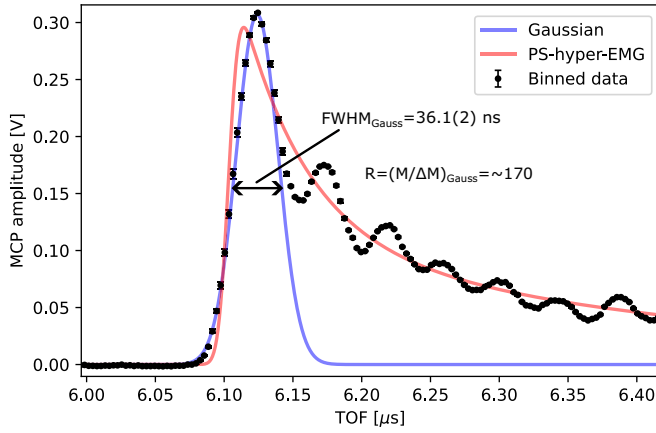


FIG. 5. TOF spectrum of ejected electron-cooled antiprotons ejected from a trap using the electrode bias $V_{\text{launch}} = -180$ V and $V_{\text{wall}} = -190$ V, fitted using PS-hyper-EMG function (red) and the Gaussian core (blue).

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DATA AVAILABILITY

The data that support the findings of this article are openly available [73]; embargo periods may apply.

APPENDIX A: TIME-OF-FLIGHT CALIBRATION AND FITTING PROCEDURE

Antiproton TOF calibration. In order to characterize the TOF spectrometry procedure, electron cooled antiprotons were prepared in a reverse polarity trap and ejected into the MCP (steps 5 and 6 in Fig. 2). Assuming a constant velocity approximation, the TOF (T_{TOF}) of the released ions is given by $T_{\text{TOF}} = L_{\text{eff}}(\frac{1}{2V} \frac{m}{q})^{\frac{1}{2}}$, where L_{eff} is the effective distance traveled assuming constant velocity, m is the mass of the ion, V is the accelerating voltage applied to the ion, and q is the charge. The sample spectrum acquired using $V_{\text{launch}} = -180$ V and $V_{\text{wall}} = -190$ V, presented in Fig. 5, is fitted using a double tailed PS-hyper-EMG distribution [74] and separately using a Gaussian function fitted to the data in a window 60 ns around the peak. A TOF of $t_G = 6.1243(1)$ μs with $\text{FWHM}_G = 36.1(2)$ ns gives a mass resolution of $R = \frac{t_0}{2\Delta t_{\text{FWHM}}} = M/\Delta M \approx 170$ for the Gaussian core where t_0 is the peak centroid and Δt_{FWHM} the full width at half maximum of the fitted function. A mass resolution of $M/\Delta M \approx 45$ was obtained by numerically computing the FWHM of the fitted PS-hyper-EMG to account for the peak asymmetry. This observed asymmetry is partly a result of the spatial distribution of the antiprotons in the trap prior to the release, convoluted with the MCP detector response that had a slight impedance mismatching during the measurement.

Systematic studies were performed under different trap configurations to characterize the TOF ejection measurement for the ion studies.

The centroid μ represents the reference TOF of the antiprotons, which was used to calibrate the TOF spectra of other ions. In order to calibrate the TOF spectrum, the mass-to-

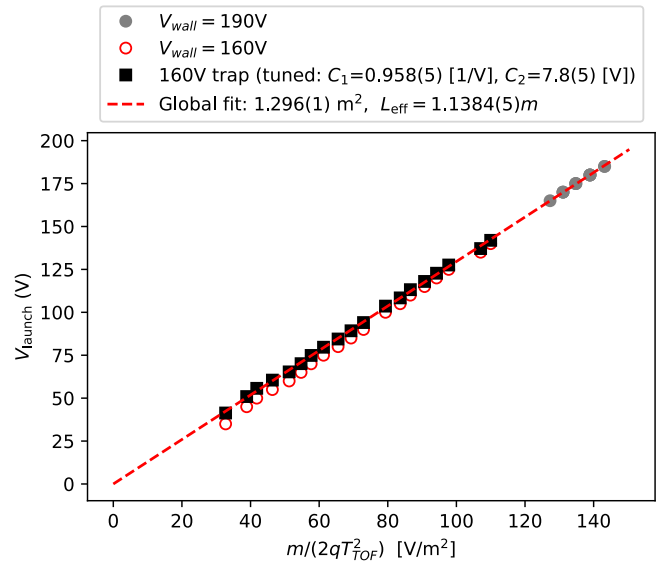


FIG. 6. Calibration of the TOF spectrometer. Launch potentials V_{set} and corrected V_{launch} are plotted against $m/(2qT_{\text{TOF}}^2)$. The 190 V trap shows direct proportionality, while the 160 V trap requires correction using $V_{\text{launch}} = C_1 V_{\text{set}} + C_2$, with $C_1 = 0.958(5)$ and $C_2 = 7.8(5)$ V. The global fit yields $L_{\text{eff}} = 1.1384(5)$ m.

charge ratio m_i/q_i was calculated from

$$\frac{m_i}{q_i} = \left(\frac{T_i}{T_{\text{ref}}} \right)^2 \frac{m_{\text{ref}}}{q_{\text{ref}}}, \quad (\text{A1})$$

where T_i and T_{ref} are the TOFs of the charged particle species of interest and the reference particle, such as the antiproton reference, respectively, where $(\frac{m}{q})_{\bar{p}} = 1.007276$ u/e for the antiproton.

APPENDIX B: TRAP CONFIGURATIONS AND VOLTAGE CALIBRATION

TOF calibration measurements using cold antiprotons were performed with two trap configurations, $V_{\text{wall}} = -190$ V and $V_{\text{wall}} = -160$ V, while varying the applied launch potential V_{launch} on the central electrode. We study the characteristics of the TOF procedure by plotting V_{launch} against $m/(2qT_{\text{TOF}}^2)$ (see Fig. 6). While the measurements performed using $V_{\text{wall}} = -190$ V are in good agreement with the proportionality expected from the constant-velocity assumption, the measurements using $V_{\text{wall}} = -160$ V deviate slightly. This deviation is expected since the set voltage $V_{\text{launch}}^{\text{set}}$ of the deeper trap differs from the actual potential experienced by the charged particles at the trap center, here denoted $V_{\text{launch}}^{\text{real}}$. The true launch potential is therefore parametrized as

$$V_{\text{launch}}^{\text{real}} = C_1 V_{\text{launch}}^{\text{set}} + C_2, \quad (\text{B1})$$

with C_1 and C_2 being calibration constants. These parameters could be determined, including their uncertainties, by minimizing the global χ^2 of the combined datasets relative to the proportional linear relation $V_{\text{launch}}^{\text{real}} = k \frac{m}{2qT_{\text{TOF}}^2}$, where $k = L_{\text{eff}}^2$ is the global fit coefficient. In this procedure, the $V_{\text{wall}} = -190$ V configuration was taken as a fixed reference, while C_1 and C_2 for the $V_{\text{wall}} = -160$ V configuration were varied

until the best agreement with the common fit was obtained. The extracted calibration constants are $C_1 = 0.958(5)$ (1/V) and $C_2 = 7.8(5)$ V.

This correction restores consistency across both configurations and enables a unified determination of the effective flight length. From the global corrected fit, we extract an effective distance of $L_{\text{eff}} = 1.1384(5)$ m, slightly larger than the measured geometric flight path of 1.05(1) m, that can be attributed to the constant-velocity approximation and the trap geometry.

APPENDIX C: ANALYSIS OF THE ARGON/HELIUM TOF SPECTRUM

1. Data preprocessing and ringing removal

The raw TOF data from the four experimental runs were combined to create a single dataset. The resulting signal was binned into 70 ns intervals, and the mean voltage and standard error of the mean were calculated for each bin. As the MCP detector produces negative pulses, the spectrum was inverted to facilitate the analysis of positive peaks.

The intense He^{1+} peak, arriving at approximately 12 μs , induced a significant electronic ringing artifact that manifested as a persistent oscillation across the spectrum. To isolate the smaller ion peaks for analysis, this artifact was modeled and subtracted. The model consisted of a composite function describing both the primary He^{1+} peak and the ringing it produced. The peak itself was modeled with an exponentially modified Gaussian (EMG) distribution, while the ringing was described by a sum of two distinct damped sinusoidal functions of the form

$$V_{\text{ring}}(t) = \sum_{i=1}^2 C_i \exp\left(-\frac{t - t_{0,i}}{\tau_{r,i}}\right) \sin(2\pi f_i(t - t_{0,i}) + \phi_i),$$

where for each component i , C is the amplitude, τ_r is the decay time, f is the frequency, ϕ is the phase, and t_0 is the start time relative to the main peak.

This full composite model was fitted to the binned spectrum using a least-squares algorithm. To ensure the model accurately captured the background artifact without being biased by the other ion peaks, the fit was constrained using time windows containing only the main He^{1+} peak and representative regions of the oscillating background. After obtaining the best-fit parameters, the contribution from the two damped sinusoids was calculated and subtracted from the entire spectrum. The result of this procedure was a “cleaned” spectrum with the ringing artifact removed, which was used for the subsequent multippeak fit and calibration.

2. Multippeak fit and TOF determination

The cleaned spectrum was fitted with a global model consisting of a sum of seven EMG functions, one for each identified ion species, and a constant background. This 29-parameter function was fitted to the data using a weighted least-squares algorithm, where the weights were the inverse square of the propagated standard errors from the binning stage. To ensure conservative error estimates, the resulting

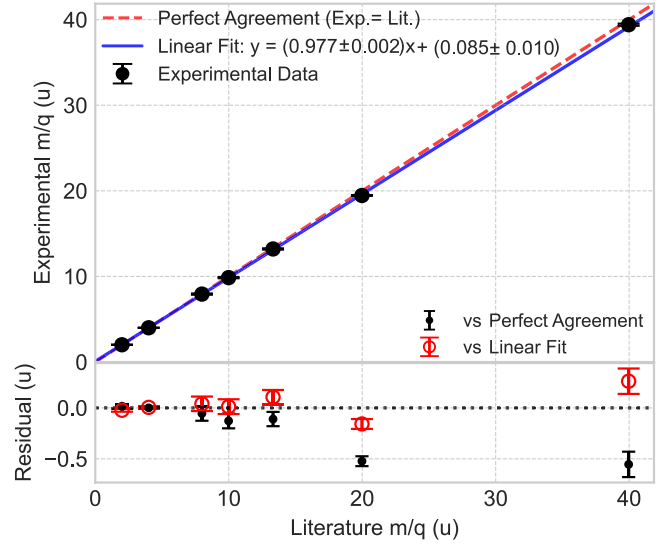


FIG. 7. Calibration of the experimental mass-to-charge (m/q) axis. (Top) Experimental m/q values, determined using a single-point calibration with He^{1+} , are plotted against their literature values (black points). The red dashed line indicates a perfect 1:1 correlation, while the blue solid line shows a weighted linear regression fit to the data, which corrects for systematic instrumental effects. (Bottom) Residuals of the experimental data with respect to the ideal 1:1 line (black points) reveal a clear systematic trend, especially for heavier ions. Residuals with respect to the linear fit (red circles) are scattered around zero, demonstrating the effectiveness of the linear correction.

covariance matrix from the fit was scaled by the reduced chi-squared (χ^2_{ν}) of the fit if this value exceeded unity.

For an asymmetric EMG distribution, the peak maximum (the mode, t_{mode}) is shifted relative to the distribution’s location parameter, μ . Therefore, the final TOF for each ion was determined by numerically calculating the mode of its corresponding fitted EMG function. The uncertainty in this TOF value was calculated by analytically propagating the errors from the relevant parameters (μ , σ , τ) in the scaled covariance matrix.

3. Mass-to-charge calibration and linearity correction

The TOF values were converted to a mass-to-charge (m/q) axis using Eq. (A1), with the precisely determined TOF mode of the He^{1+} peak (T_{ref}) serving as a single-point reference. The statistical uncertainties in the calculated m/q values, as reported in Table I, were derived by propagating the uncertainties from the fitted TOF modes of the ion of interest (δT_i) and the reference ion (δT_{ref}) using the standard formula:

$$\delta\left(\frac{m}{q}\right)_i = 2\left(\frac{m}{q}\right)_i \sqrt{\left(\frac{\delta T_i}{T_i}\right)^2 + \left(\frac{\delta T_{\text{ref}}}{T_{\text{ref}}}\right)^2}.$$

This single-point calibration assumes a perfectly quadratic relationship between TOF and m/q over the full range. However, the data in Table I presented in Fig. 7 show that this approximation works well for ions with m/q values close to the He^{1+} reference, but systematically deviates for the slower ions.

To characterize this deviation, a weighted linear regression was performed on the experimental m/q values versus their known literature values (see Fig. 7). This fit provides a linear

correction that accounts for the observed offset and more accurately calibrate the mass axis across the entire detected range.

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