

Positron transport and cooling with CF<sub>4</sub> in an inhomogeneous magnetic fieldJ. von der Linden<sup>1,\*</sup>, A. Deller<sup>1,2</sup>, S. Nißl<sup>1</sup>, K. Michishio<sup>3</sup>, H. Higaki<sup>4</sup>, and E. V. Stenson<sup>1</sup><sup>1</sup>Max Planck Institute for Plasma Physics, 85748 Garching, Germany<sup>2</sup>Physics Department, University of California San Diego, La Jolla, California 92093, USA<sup>3</sup>National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8568, Japan<sup>4</sup>Graduate School of Advanced Science and Engineering, Hiroshima University, Hiroshima 739-8530, Japan

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We present measurements of positrons ( $e^+$ ) undergoing transport and cooling with molecular CF<sub>4</sub> in the inhomogeneous magnetic field of a dipole trap. The annihilation rate and  $\gamma$ -ray spectra reveal a shift in the primary loss channel from positronium (Ps) formation to collisional cross-field transport. This transition is mediated by molecules cooling  $e^+$  below the charge-exchange threshold for Ps formation. Elucidating the interplay between cooling and annihilation is crucial for optimizing  $e^+$  confinement schemes and refining models of astrophysical  $\gamma$ -ray spectra.

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Positron ( $e^+$ ) annihilation photons originating from the galactic center were first observed  $\sim 50$  years ago [36,43]. Astrophysical  $\gamma$ -rays continue to provide insights into many areas of active research, including the sources and annihilation mechanisms of galactic  $e^+$  [74]. Diffuse 511-keV ( $m_e c^2$ ) sky maps hint that many  $e^+$  escape their sources and propagate vast distances along the interstellar magnetic field. Since their Larmor radius is much smaller than their collisional mean free path, they can be considered magnetically guided [41]. Their diffusion scale length will be influenced by their interactions with atoms, molecules, ions, or electrons before they eventually annihilate [12,34,68]. The transport of  $e^+$  in a molecular gas depends nonlinearly on the interaction energy [16,82]. Ionization dominates at high energies [69], whereas elastic and inelastic scattering are important at lower energies [32,79]. In addition to direct ( $2\gamma$ ) annihilation,  $e^+$  can be lost to positronium (Ps) formation, with a 3:1 ratio of (predominantly)  $3\gamma$ -decaying orthopositronium (oPs) to  $2\gamma$ -decaying parapositronium (pPs) [1,14,60]. Because the self-annihilating Ps atom typically forms via charge exchange [23], energy-resolved  $\gamma$ -ray spectra can provide insight into the makeup of the interstellar medium (ISM) [10,19]. The inconsistency between the observed morphology of 511-keV  $\gamma$ -rays in our galaxy and the expected distribution of  $e^+$  sources is known as the “Positron Puzzle” [73]. The “Positron Puzzle” is not only a problem of identifying positron sources but also a

problem of transport. The observed 511 keV morphology may be a smeared or displaced version of the underlying source distribution [73]. The propagation distance and eventual annihilation channel depend on the energy-loss and scattering processes, on the local ionization and temperature of the ISM, and on the structure of the magnetic field, all of which remain poorly constrained observationally [34,41]. Consequently, accurate models of  $e^+$  transport in the ISM require laboratory constraints on cooling, cross-field diffusion, and the competition between positronium formation and direct annihilation.

When cooling in a gas,  $e^+$  can lose energy and thermalize via a sequence of inelastic and elastic interactions (including  $e^+e^+$  collisions [81]). Positrons experience many of the kinetic phenomena associated with  $e^-$  transport [66]; however, they can also form Ps, which can result in a negative differential conductivity [5,46]. The interdependent behaviors of  $e^+$  in gases can be simulated using Monte Carlo methods or by solving the Boltzmann equation to track phase-space distributions [4,9,31,64]. Despite demand for tests of state-of-the-art  $e^+$  transport models, few experiments have been attempted [16].

Advances with  $e^+$  trapping provide opportunities to study collision-driven  $e^+$  transport in magnetic fields. Intense, pulsed, and energy-tunable  $e^+$  beams can now be generated by combining efficient moderators [50] with accumulation and cooling in Surko traps [80]. Penning-Malmberg traps have been the main focus of  $e^+$  cooling studies [3,45,55], motivated by the needs of  $e^+$  scattering [56] and antihydrogen experiments [24]. However, recent efforts to trap positron-electron pair plasma [77] have led to the development of alternative confinement devices, including radio-frequency traps [28,48], magnetic mirrors [37,84], and supported [39] or levitated dipoles [13,21]. Magnetic fields affect transport by introducing anisotropy with respect to the field direction, whereas electric fields alter the distribution of kinetic and potential energy. Moreover, inhomogeneous magnetic fields can give rise to magnetic mirroring and cross-field drifts [25]. The

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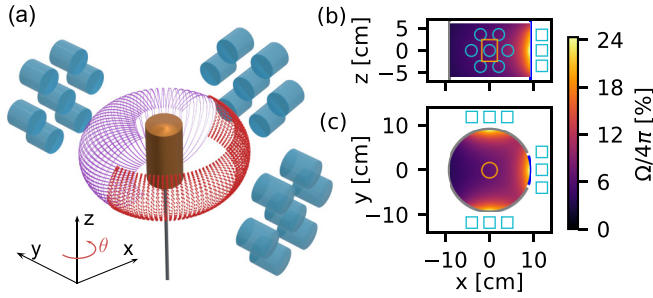


FIG. 1. Magnetic dipole trap and  $\gamma$ -ray detectors. (a) BGO arrangement (light blue) around the permanent magnet (orange). Example orbit of a magnetically (electrostatically) trapped  $e^+$  is shown in red (purple). Solid-angle coverage in (b) the  $y = 0$  and (c)  $z = 0$  planes. Grounded wall electrodes (gray) and the  $S_1$  ejection electrode (blue).

trap geometry, therefore, can have a significant influence on transport [44].

In this Letter, we present time-resolved measurements of the annihilation dynamics of magnetically confined  $e^+$ . Dense bunches of  $e^+$  are accumulated and then injected into a supported dipole trap. The corresponding annihilation spectra exhibit a distinct transition from Ps formation to diffusion-mediated losses. We control this transition by admitting  $\text{CF}_4$  into the trap to cool the  $e^+$  below the charge-exchange threshold. The  $\text{CF}_4$  molecule is of special interest to the  $e^+$  trapping community [20,26] due to the favorable ratio between its low-energy inelastic and annihilation cross sections.

An overview of our confinement procedure is provided below. Details regarding the  $e^+$  source [61], Surko trap [38], dipole trap [70], and drift injection technique [76] are available in the cited works. A bunch of  $10^5$   $e^+$ , with kinetic energies parallel and perpendicular to the magnetic field of  $\langle K_{\parallel} \rangle \sim 7.3$  eV ( $\sigma_{\parallel} = 0.2$  eV) and  $\langle K_{\perp} \rangle \sim 0.1$  eV, is injected into the dipole field of a permanent magnet ( $t = 0$ ) [22]. Kinetic energy is given by  $K = m_e |\vec{u}|^2 / 2$ , where  $m_e$  is the  $e^+$  mass and  $\vec{u}$  the velocity. The confinement volume extends from the cylindrical magnet case (height of 4.6 cm and diameter of 3.3 cm) to the wall electrodes at  $r = 9$  cm. The magnitude of the magnetic field ranges from  $|\vec{B}| \sim 470$  mT at the poles to  $\sim 3$  mT at the wall. The magnet case is biased to  $V_{\text{mag}} = +8$  V, unless noted otherwise. In the midplane, the injected  $e^+$  distribution has a Gaussian radial profile centered at  $r \sim 5.4$  cm with a standard deviation of  $\sigma_r \sim 0.4$  cm. Annihilation events are recorded using an array of  $\gamma$ -ray detectors and a multichannel digitizer. At  $t = 2.2$  s, any remaining  $e^+$  are ejected by a pulsed electric field. We perform experiments using pressures ranging from ultrahigh vacuum (UHV) conditions ( $P \sim 3 \times 10^{-6}$  Pa up to  $P \sim 10^{-4}$  Pa of  $\text{CF}_4$  (measured using a mass-corrected ion gauge [33]). The UHV conditions are dominated by water,  $\text{H}_2\text{O}$ , and air, i.e., mainly  $\text{N}_2$ .

The detector array consists of 21 photomultiplier tubes and 2.54-cm-diameter bismuth-germanate (BGO) scintillators [85] (Scionix 25B25/1M-HV-E2-BGO-X2). The detectors are arranged in clusters of seven inside reentrant ports at  $r \sim 12$  cm and toroidal angles of  $\theta = 0^\circ$ ,  $90^\circ$ , and  $270^\circ$  (Fig. 1). The solid-angle coverage,  $\Omega/4\pi$ , of all detectors (of only the central detectors in each cluster) varies over the midplane

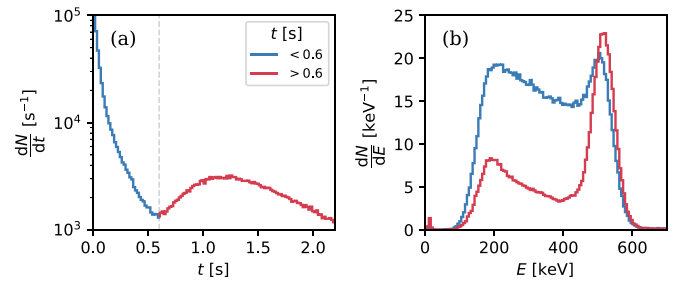


FIG. 2. (a) Count rate and (b) energy spectrum of annihilation  $\gamma$ -rays detected in UHV conditions. Counts associated with events detected before (after)  $t = 0.6$  s are shaded blue (red). Spectra are averages from 50 confinement cycles.

( $z = 0$ ) between 4.4% (0.6%) and 24% (7%). For every  $i$ th  $\gamma$ -ray event, the timestamp,  $t_i$  (8 ns resolution), and energy,  $E_i$  (66 keV resolution), are recorded. Each detector is calibrated by fitting the 511-keV peak.

The  $\gamma$ -ray count rate we observe after injecting  $e^+$  into the dipole trap is shown in Fig. 2(a). Previous studies found that the  $e^+$  population exhibited single or double exponential decay [40,86]. This study increases the counts per cycle from  $\sim 0.1$  to  $10^4$  and timing resolution from  $\sim 25$  ms to 8 ns [39]. Together, these improved statistics and timing resolution reveal that the count rate falls to a minimum at  $t \sim 0.6$  s before rising again. This nonexponential behavior is due to the interplay between the evolving  $e^+$  distribution and the accessible annihilation channels [16]. The energy spectra shown in Fig. 2(b) correspond to the distribution of  $\gamma$ -ray events before (blue) and after (red)  $t = 0.6$  s. The marked change in the ratio of the  $2\gamma$  peak to the  $3\gamma$  continuum suggests that the dominant annihilation mechanism shifts from one that involves Ps formation to one that does not.

The instantaneous decay rate is given by [16]

$$\lambda(t) = -\frac{1}{N_e} \frac{dN_e}{dt} \approx \frac{C(t)}{\sum_i H(t_i - t)}, \quad (1)$$

where  $C(t)$  is the  $\gamma$ -ray count rate determined by binning all timestamps,  $t_i$ , from each confinement cycle. The number of counts detected after  $t$  is calculated using the sum of Heaviside step functions,  $H$ , and is roughly proportional to the remaining number of trapped  $e^+$ . Figure 3(a) shows how the  $e^+$  decay rate changes during confinement for different  $\text{CF}_4$  pressures.

The energy spectra can be related to the Ps fraction,  $F_{\text{Ps}} = N_{\text{Ps}} / (N_D + N_{\text{Ps}})$ , where  $N_{\text{Ps}}$  is the number of Ps decays and  $N_D$  the number of direct decays. The Ps fraction displayed in Fig. 3(b) is calculated by fitting time-binned energy spectra in the range of 230–550 keV to Monte Carlo simulations of the Compton-scattered signal for purely  $2\gamma$  or  $3\gamma$  decay (see Appendix). For all pressures, the spectra are initially dominated by  $3\gamma$  decay. Transitions to  $2\gamma$  decay are correlated with the times of the minimum decay rate, which shift earlier with increasing pressure. It is noteworthy that under UHV conditions,  $F_{\text{Ps}}$  is initially  $< 1$  and subsequently rises. This suggests that oPs quenching may be occurring, perhaps because sufficiently energetic oPs can reach the wall.  $\text{CF}_4$  also reduces the number of counts, coincident pairs, and triple coincidences

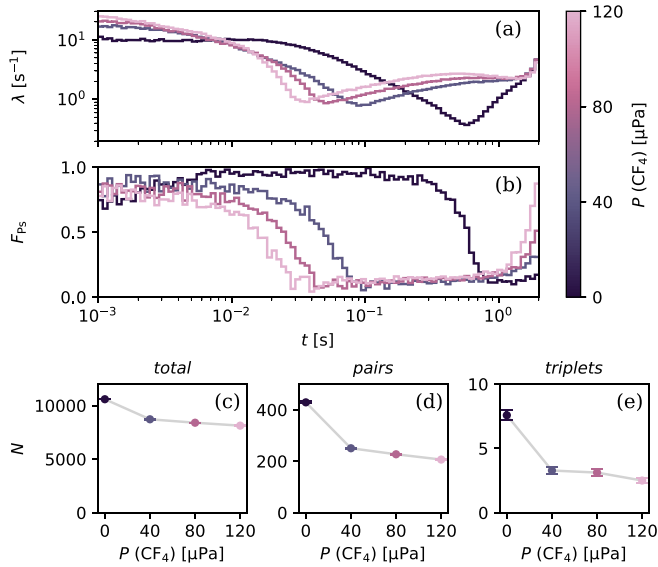


FIG. 3. Annihilation spectra with different CF<sub>4</sub> pressures. Time-dependent (a) decay rate and (b) positronium fraction. The average number of (c) total, (d) coincident, and (e) triplet  $\gamma$ -ray counts over 50 confinement cycles; the error bars represent the standard error of the mean.

[Figs. 3(c)–3(e)] (events are categorized as coincident if their timestamps are within 24 ns [85]). For a constant number of injected  $e^+$ , the number of single, double, and triple  $\gamma$ -ray events should all correlate with the proportion of  $3\gamma$  decays.

Ps formation via charge exchange has a minimum energy requirement of  $E_{\text{ex}} = E_{\text{ion}} - E_{\text{Ps}}$ , where  $E_{\text{ion}}$  is the ionization energy of the target and  $E_{\text{Ps}} = 6.8$  eV is the binding energy of Ps [15,17]. Positrons are injected into the dipole trap with mean kinetic energies of  $K \sim 7$  eV, which is below  $E_{\text{ex}}$  for N<sub>2</sub> (8.8 eV) and CF<sub>4</sub> (9.45 eV), but above the threshold for lower-level contaminants (5.8 eV for H<sub>2</sub>O and 5.2 eV for O<sub>2</sub>). Inelastic collisions with CF<sub>4</sub> molecules rapidly cool the  $e^+$  below these thresholds.

Our observation of predominantly  $2\gamma$  decay at later times [Fig. 3(b)] is consistent with previous confinement studies that attributed delayed losses to collision-driven transport to the wall [39]. Collisions with neutrals allow  $e^+$  to move across field lines with a step size on the order of the Larmor radius,  $r_L = m_e u_{\perp} / e |\vec{B}|$  [49] (where  $u_{\perp}$  is the speed perpendicular to the magnetic field,  $\vec{B}$ ). The expansion time in UHV is consistent with a collision rate on the order of  $\nu \sim 100$  s<sup>−1</sup> [39].

The phase-space dependence of confinement in the magnetic dipole can be leveraged to explicitly measure scattering rates. Trapped orbits consist of three periodic motions: gyration around the magnetic field lines, poloidal bounces between the poles of the magnet, and toroidal drifts around the magnet (counterclockwise from above). Whether an  $e^+$  reflects between the poles due to the electric or magnetic field depends on its pitch angle,  $\alpha = \arctan(\sqrt{K_{\perp}/K_{\parallel}})$ . The guiding-centered drift Hamiltonian is given by [8]

$$E_{\text{gc}} = K_{\parallel} + e\phi + \mu|\vec{B}|, \quad (2)$$

where  $\phi$  is the electric potential. The last term represents the effective potential due to the adiabatically conserved magnetic

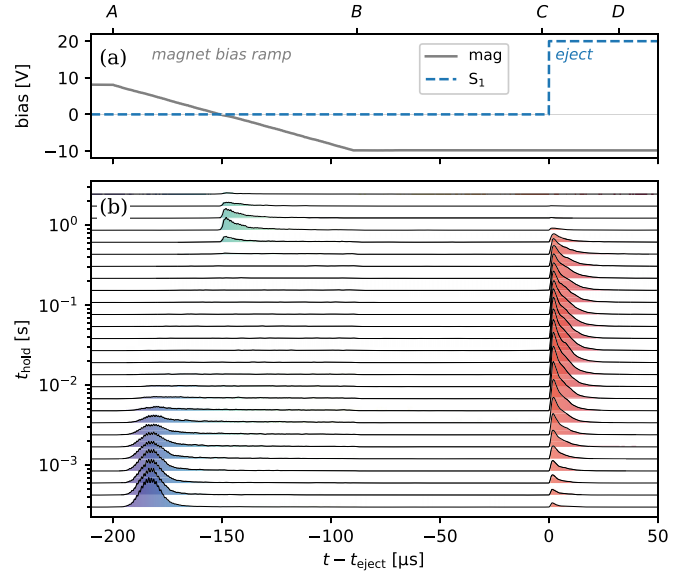


FIG. 4. (a) Magnet case ramp (gray) and  $S_1$  wall segment ejection pulse (dashed blue). The integral bounds used in Eq. (3) are denoted on the top axis. (b) Annihilation signal after different hold times in UHV conditions. The fill color indicates whether annihilation occurs during the ramp (blue and green) or pulsed ejection (red). The signal is smoothed and data in the range  $t > t_{\text{eject}}$  are scaled by the solid-angle correction factor of  $\kappa = 0.5$ .

moment,  $\mu = K_{\perp} / |\vec{B}|$ . The large mirror ratio of the trap allows  $e^+$  from broad regions of phase space to be magnetically confined [e.g., red orbit in Fig. 1(a)]. However,  $e^+$  with negligible  $K_{\perp}$  (i.e.,  $\alpha \sim 0$ ) are in the “loss cone” and only remain trapped because of the electrostatic potential [purple orbit in Fig. 1(a)].

Ramping the bias applied to the magnet case from +8 to −10 V over 100  $\mu$ s selectively ejects  $e^+$ . With the positive bias removed, electrostatically confined  $e^+$  annihilate at the poles of the magnet. When the bias is negative, weakly magnetically trapped  $e^+$  are also pulled into the magnet. Any remaining  $e^+$  are strongly magnetically confined. These can be driven into the wall by switching the 1/8th wall sector,  $S_1$  (blue electrode in Fig. 1), from ground to +20 V [57]. Figure 4(a) illustrates the ejection sequence; the ramp of the magnet bias (gray) commences 200  $\mu$ s before the wall bias (dashed blue) is applied ( $t = t_{\text{eject}}$ ).

Figure 4(b) shows the  $\gamma$ -ray signals during ramped ejection of  $e^+$  in UHV conditions. Each trace represents a different hold time following injection. The signal is the sum of the outputs from the central detectors of each cluster, averaged over nine trap-hold-eject cycles. The photomultiplier tubes are set to low gain to avoid saturation [22]. The shading highlights whether the  $e^+$  are lost during the ramp (blue and green) or during the dump (red). For short hold times,  $t_{\text{hold}} \lesssim 1$  ms, almost all of the signal appears in the positive part of the ramp (blue). This is because the  $e^+$  are injected with low perpendicular energy [27] and are initially electrostatically confined. For  $t_{\text{hold}} > 10$  ms, the annihilation signal is almost entirely in the late ejection window (red). This is because pitch-angle scattering collisions with neutrals result in mirror-trapped  $e^+$  that remain confined even after the magnet bias has ramped to −10 V. After  $t_{\text{hold}} > 1$  s, a signal appears in the negative

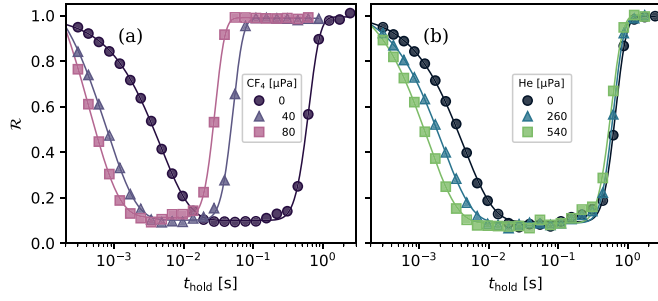


FIG. 5. Fraction of the  $e^+$  annihilation signal during the magnet bias ramp after different hold times for a range of (a)  $\text{CF}_4$  or (b) helium pressures. The solid lines are fits to the measured points.

part of the ramp (green). This population of weakly magnetically trapped  $e^+$  likely arises due to inelastic collisions with neutrals that reduce  $K_\perp$ .

We compute the fraction of the annihilation signal that occurs during the ramp using

$$\mathcal{R} = \frac{\int_A^B \gamma(t) dt}{\int_A^B \gamma(t) dt + \kappa \int_C^D \gamma(t) dt}, \quad (3)$$

where  $\kappa = 0.5$  corrects for the solid-angle coverage at the magnet versus the wall. The integration bounds  $A = t_{\text{eject}} - 200 \mu\text{s}$  and  $B = t_{\text{eject}} - 88 \mu\text{s}$  enclose the magnet ramp, and  $C = t_{\text{eject}} - 3 \mu\text{s}$  and  $D = t_{\text{eject}} + 32 \mu\text{s}$  contain the ejection window. Figure 5(a) shows how the ramp fraction varies with the hold time in UHV conditions, as well as for two different  $\text{CF}_4$  pressures. In all cases, the ramp fraction rapidly decays from  $\mathcal{R} \sim 1$  to 0.1 before returning to  $\mathcal{R} \sim 1$  for longer hold times.

The datasets in Fig. 5 are fit using

$$\mathcal{R}(t) = ae^{-v_\alpha t} + (b - ae^{-v_\alpha t}) \frac{\int_0^{kv_c t} x^{k-1} e^{-x} dx}{\Gamma(k)} + c, \quad (4)$$

where  $a + c \sim 1$  and  $b + c \sim 1$  are the initial and final fractions and  $c \sim 0.1$  is the offset due to the loss cone. The first part of this equation captures the exponential decay of electrostatically trapped  $e^+$  due to pitch-angle scattering at a rate of  $v_\alpha$ . The latter part accounts for the return of the signal to the ramp due to  $e^+$  cooling at a rate of  $v_c$ . This is based on the cumulative distribution function of an Erlang distribution ( $\Gamma$  is the full gamma integral with bounds  $[0, \infty]$ ). That is, Eq. (4) models cooling as a Poisson process, where  $v_i = kv_c$  is the rate of inelastic collisions that must occur  $k$  times before the  $e^+$  can be pulled into the magnet by the negative potential.

As expected, the pitch-angle scattering and cooling rates increased in proportion to the  $\text{CF}_4$  pressure (Table I). In the UHV case, the fit suggests that an average of  $k \sim 10$  inelastic collisions (presumably with residual  $\text{CO}_2$  [30]) typically occur before a magnetically confined  $e^+$  can be dumped onto the magnet. With  $\text{CF}_4$ , this slightly increased to  $k \sim 13$ . The number of required collisions is determined by the initial kinetic energy, the mirror ratio, the electric potential, and the energetically accessible inelastic channels; the strongest of these is associated with the  $v_3$  asymmetric stretch mode, which can extract  $\Delta E \sim 160 \text{ meV}$  per collision. The inhomogeneous fields and the range of energies the  $e^+$  traverse as

TABLE I. Best-fit parameters for the datasets in Fig. 5. Pitch-angle scattering,  $v_\alpha$ , cooling,  $v_c$ , and inelastic collision,  $v_i$ , rates, and the process count,  $k$ .

|               | $P_X$ ( $\mu\text{Pa}$ ) | $v_\alpha$ ( $\text{s}^{-1}$ ) | $v_c$ ( $\text{s}^{-1}$ ) | $k$            | $v_i$ ( $\text{s}^{-1}$ ) |
|---------------|--------------------------|--------------------------------|---------------------------|----------------|---------------------------|
| $\text{CF}_4$ | 0                        | $219 \pm 4$                    | $1.60 \pm 0.01$           | $9.5 \pm 0.6$  | $15 \pm 1$                |
|               | $40 \pm 4$               | $1301 \pm 34$                  | $19.7 \pm 0.1$            | $11.9 \pm 0.8$ | $234 \pm 15$              |
|               | $80 \pm 8$               | $2297 \pm 84$                  | $35.6 \pm 0.3$            | $13 \pm 1$     | $460 \pm 36$              |
| He            | 0                        | $233 \pm 8$                    | $1.50 \pm 0.02$           | $11 \pm 1$     | $17 \pm 2$                |
|               | $260 \pm 30$             | $476 \pm 14$                   | $1.61 \pm 0.02$           | $11 \pm 1$     | $18 \pm 2$                |
|               | $540 \pm 50$             | $768 \pm 32$                   | $1.75 \pm 0.03$           | $9 \pm 1$      | $16 \pm 2$                |

they cool complicate comparison of the cooling rates to established inelastic cross sections [47]. In contrast, pitch-angle scattering is a single-collision process. Assuming an energy-averaged total cross section of  $\sigma = 10^{-15} \text{ cm}^2$  [6,11,52] and a bounce-averaged  $e^+$  speed of  $u = 1.2 \times 10^6 \text{ m s}^{-1}$ , we expect the pitch-angle scattering rate to increase with the  $\text{CF}_4$  pressure according to  $\sigma u / k_B T = 2.9 \times 10^7 \text{ s}^{-1} \text{ Pa}^{-1}$ ; this agrees with our measured scattering sensitivity of  $dv_\alpha/dP = (2.8 \pm 0.3) \times 10^7 \text{ s}^{-1} \text{ Pa}^{-1}$ .

We also perform ramped-ejection measurements with helium, for which all inelastic channels have thresholds well above the  $e^+$  kinetic energy. As shown in Fig. 5(b), the cooling time with helium is comparable to the UHV measurement. The pitch-angle scattering rate, however, did increase due to the additional gas. Our measured scattering sensitivity of  $dv_\alpha/dP = (9.6 \pm 1.1) \times 10^5 \text{ s}^{-1} \text{ Pa}^{-1}$  is triple what we expect for an average cross section of  $\sigma \sim 10^{-17} \text{ cm}^2$  [78]. This discrepancy motivates a thorough characterization of pressure in the confinement volume by sweeping the volume [87] with an ion gauge calibrated to a manometer [89]. If our estimate of the helium pressure is accurate [33], this large discrepancy might be related to the sharp uptick in the elastic cross section at low energies [88].

In summary, we observe transport and cooling of magnetically confined  $e^+$  interacting with  $\text{CF}_4$  molecules over

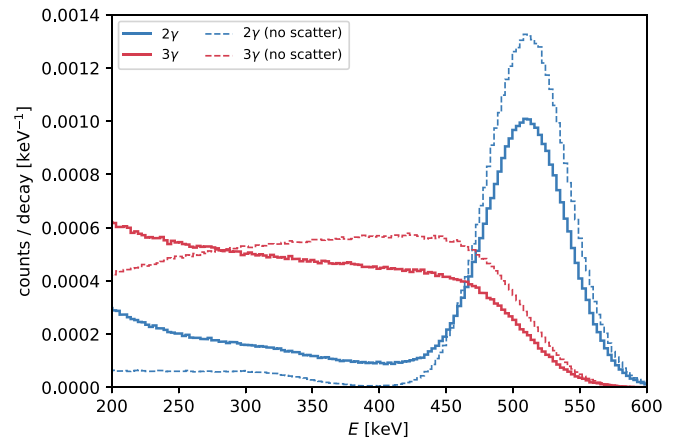


FIG. 6. Simulated energy response of the BGO detectors to  $2\gamma$  and  $3\gamma$  decay. The histograms are normalized to the number of simulated decays. The dashed lines represent simulations that exclude scattering of the  $\gamma$ -rays in the vacuum chamber walls or other solid materials.

multiple timescales. The results highlight the importance of the interplay between the time-varying phase-space distribution and annihilation. Cooling through inelastic collisions mediates a transition in the primary loss mechanism from Ps formation to transport to the wall. Similar processes are thought to populate a reservoir of extremely long-lived, low energy  $e^+$  in the ISM [63]. Earlier experiments lacked the diagnostics to explicitly identify loss channels [39,57]. Notable advances include (1) injection of a dense  $e^+$  bunch instead of a continuous beam [22], (2) implementation of an array of  $\gamma$ -ray detectors with good energy and time resolution [85], and (3) development of a ramped-ejection technique to separate electrostatically and magnetically trapped  $e^+$ .

Experiments with trapped  $e^+$  distributions in various gas mixtures and magnetic fields could provide crucial benchmarks for models of  $e^+$  annihilation in the ISM [10,73], solar flares [18,51,54,71], or biological tissues [53,67,72]. The experiment can be related to astrophysical conditions through the ratio of collisional mean free path,  $\lambda_{\text{mfp}}$ , to Larmor radius  $\eta = \lambda_{\text{mfp}}/r_L = 1/(n_N \sigma r_L)$ , where  $n_N$  is the neutral density and  $\sigma \sim 10^{-16} \text{ cm}^2$  the collisional cross section. A 1 eV positron in an interstellar molecular cloud with a neutral density of  $n = 10^6 \text{ cm}^{-3}$  and a magnetic field of  $B = 10^{-8} \text{ T}$  [35] experiences a normalized collisionality of  $\eta \sim 3 \times 10^6$ ; this is the same order of magnitude as experienced by positrons in the dipole trap with a helium pressure of 500  $\mu\text{Pa}$ . Experimental transport studies can test the completeness of Monte Carlo simulations that are based upon cross sections of the dominant processes [65]. Future studies could build on our methods to characterize the effects of electric fields on transport by varying the magnet bias [4]. Although this work has focused on  $e^+$  collisions with neutrals, our methods could be adapted to study interactions with ions [2,42] or electrons [29,37,62,75]. Long interaction times between collections of positive and negative charges are conceivable with a levitated dipole trap [13]. Combined with time-resolved annihilation spectroscopy, this could facilitate unprecedented studies of transport or recombination losses in low-temperature electron-positron pair plasmas [77].

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**Data availability.** The data that support the findings of this article are openly available [83].

**Appendix: Simulated spectra.** We perform Monte Carlo simulations and ray-tracing calculations with ELWIS (version 26.3.0) [58,59] to estimate the response of the BGO detectors to  $2\gamma$  (direct and pPs) and  $3\gamma$  (oPs) decays. Ten million annihilation events are simulated for each decay channel. The simulations incorporate the layout of the detectors and the geometry of the BGO crystals, as well as  $\gamma$ -ray scattering in the magnet, electrodes, and vacuum chamber walls. The source distribution is a ring with a radius of 5 cm located in the midplane of the trap.  $2\gamma$  decay generates an isotropic distribution of back-to-back pairs of 511-keV photons. The energies of the  $3\gamma$  decay photons are sampled from a linear distribution up to 511 keV [14]. Each triplet is constrained to a total energy of 1022 keV distributed in a single, randomly oriented plane with angles between photons consistent with a net momentum of zero. To account for attenuation and Compton scattering, photons that intersect hard surfaces are probabilistically scattered based on material-appropriate cross sections [7]. The energy deposited in the BGO crystals is folded with the detector resolution (66 keV) to determine the detection signal (if any) of each annihilation event. Figure 6 compares histograms of simulated energy spectra for purely  $2\gamma$  or  $3\gamma$  decay; the dashed lines represent equivalent spectra with the effects of scattering outside of the detectors omitted.

We obtained the positronium fractions,  $F$ , shown in Fig. 3(b) by fitting measured  $\gamma$  spectra,  $f_E$ , with weighted combinations of our simulated spectra  $s_2$  and  $s_3$ :

$$f_E \propto (1 - F)s_2 + F\left(\frac{1}{4}s_2 + \frac{3}{4}s_3\right). \quad (\text{A1})$$

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