Gamma spectra of positronium from charge-exchange with magnetically confined positrons

J. von der Linden*[1], A. Deller[1], S. Nißl[1], H. Saitoh[2], H. Higaki[3], A. Card[1], K. Michishio[4], E. V. Stenson[1]
[1]Max-Planck-Institut für Plasmaphysik, [2]Univeristy of Tokyo, [3]University of Hiroshima, [4]National Institute of Advanced Industrial Science and Technology (AIST)

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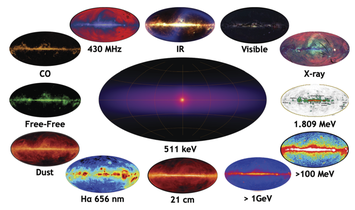
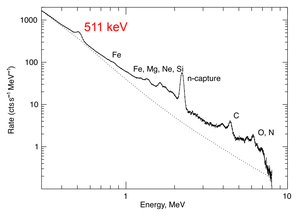
Motivation: interpreting galactic and solar 511keV lines

Skymaps of 511keV compared to other frequencies



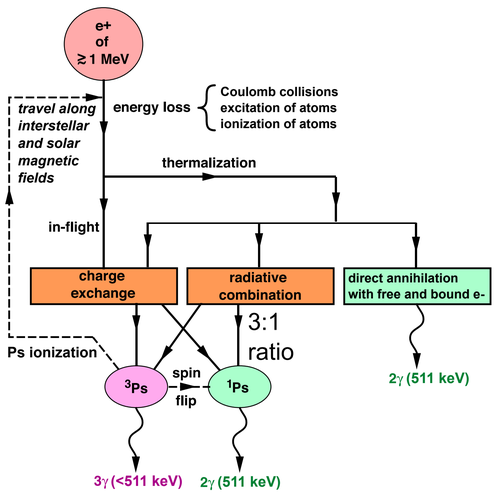
What are the sources of e+ (and their relative contributions)?
Do e+ escape their sources? How much do they diffuse across interstellar field?
In which media do e+ annihilate and how? *figure from Siegert (2023) Astro. Space Sci.*

Gamma spectra of solar flares



Can we relate the ratio of the 2 gamma line and the 3 gamma continuum to the chromospheric media by understanding the contributions of Ps formation, direct annihilation, spin-flip, and Ps ionization? *figure from Murphy (2007) Space Sci. Rev.*

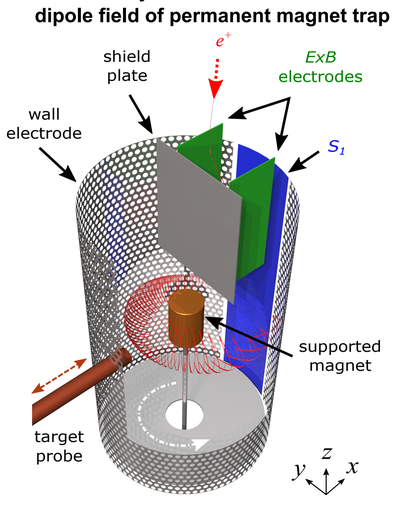
Life of positron in interstellar media and solar chromosphere



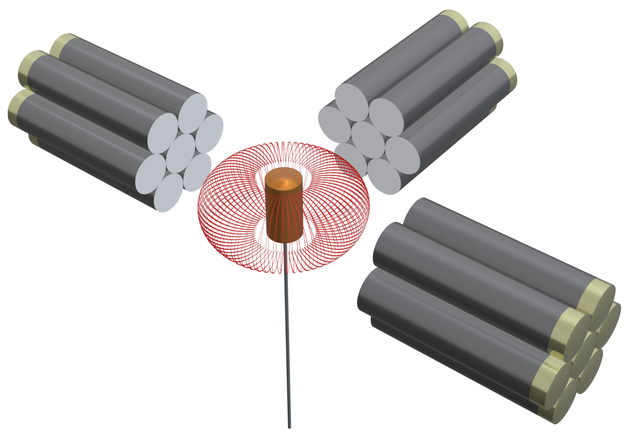
Modified figure from Murphy et al. (2005) Astro.phys. J. Supp.

Diagnose magnetically confined e+ with detector array

ExB drift inject bunch of 10^5 e+ into dipole field of permanent magnet trap



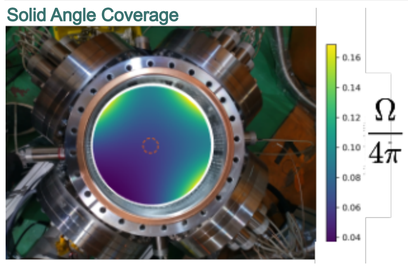
Diagnose with 21 BGO detectors in re-entrant ports at r ~ 12 cm



Deller, von der Linden et al. (2024) Phys. Rev. E

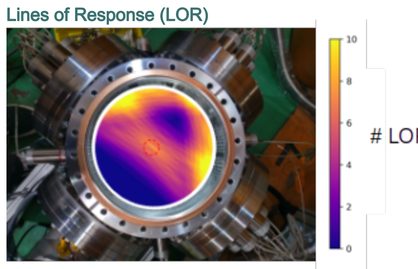
Array of 21 BGO detectors: counts, energy, timing

Solid Angle Coverage



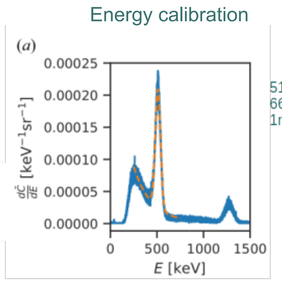
$\frac{\Omega}{4\pi}$

Lines of Response (LOR)



LOR

Energy calibration



511keV FWHM 13%
66keV resolution
1ns time stamping

$\bullet\!\sim\!\sim 2\gamma$

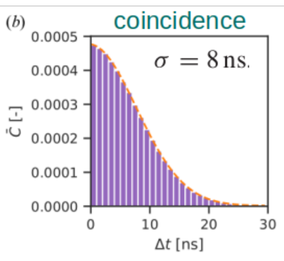
2-γ are 511keV, conserve momentum form Line of Response (LOR)

$\bullet\!\sim\!\sim 3\gamma$

3-γ fill valley below 511keV, conserve momentum lie on plane

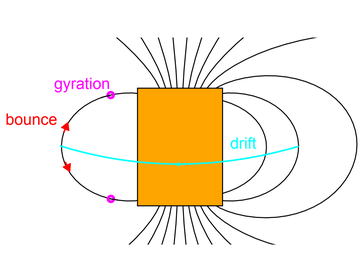
Counts

$$C = \int_{FOV} \underbrace{\Omega(x)}_{\text{solid angle}} \underbrace{\eta(x)}_{\text{efficiency}} \underbrace{f(x)}_{\text{source}} d\vec{x}$$

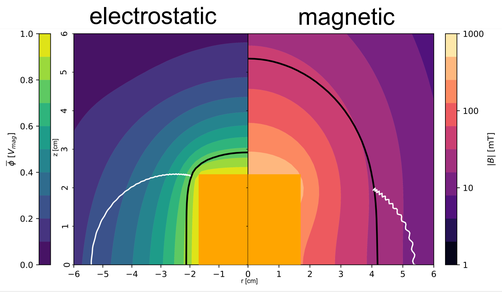


τ_c=3σ=24ns

Permanent magnet trap: confinement through magnetic mirroring and electrostatic reflection



$$E_{gc} = K_{\parallel} + \underbrace{e\phi + \mu B}_{U_{gc}}$$
$$\mu = \frac{E_{\perp}}{B}$$



4 ways to eject for diagnostic purposes

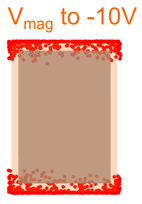
Electrostatic dump

$U_{gc} = e\phi + \mu B$

V_{mag} to 0V

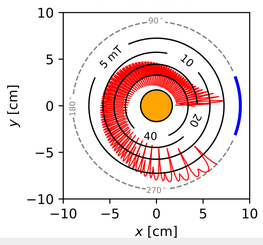
Partial dump of magnetically confined

V_{mag} to -10V



Hard dump

0V to 20V

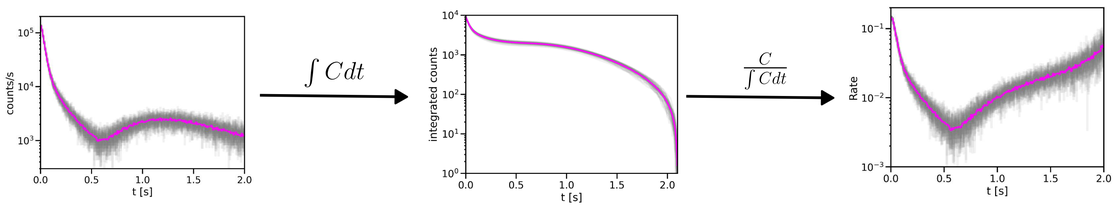


just wait ...

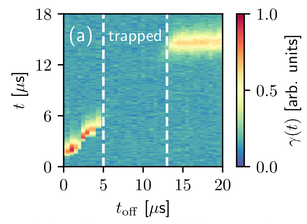
Transport to wall through elastic collisions with neutrals
>100 collisions needed

Horn-Stanja et al. (2018) Phys. Rev. Lett.

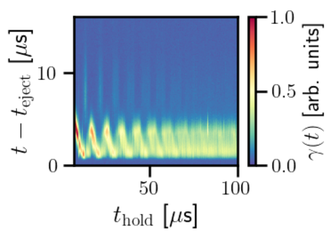
Single-photon counting reveals complex lifetime spectra



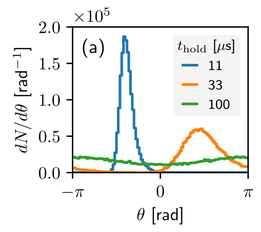
0-100us injection and toroidal expansion



Injection potentials need to be turned off to trap.

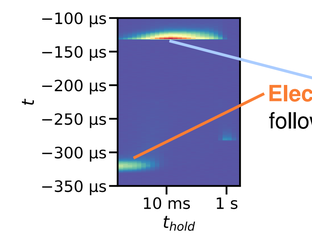


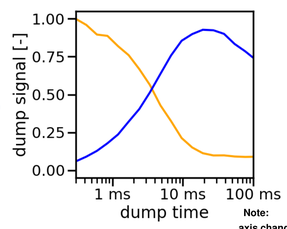
Hard dump vary hold time.

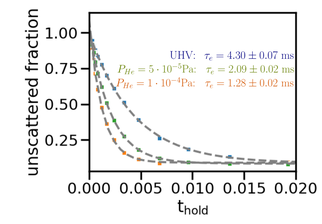


e+ bunch expands toroidally within 100 μs

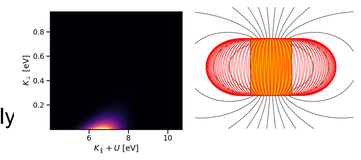
4ms elastic collision time; scattering to magnetic confinement





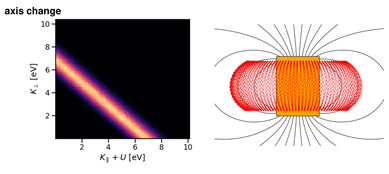


After injection pitch angle is parallel.
e+ are electrostatically confined.



A collision randomly scatters.
After one collision e+ are magnetically confined.

Note: axis change



<600ms: positronium decay following charge-exchange

Positronium decay

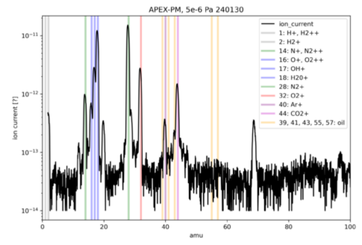
$pPs \rightarrow 2\gamma$

$oPs \rightarrow 3\gamma$ 1:3 ratio

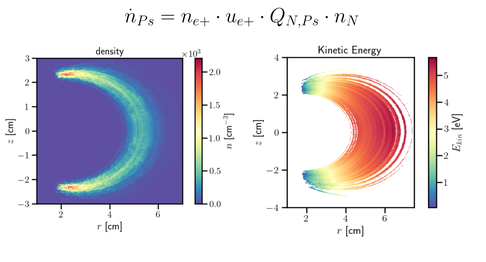
Charge-exchange threshold:

Ionization Potential – Ps ground pot (6.8eV)

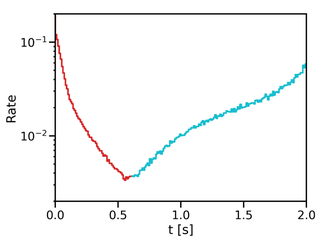
O_2 5.2 eV
H_2O 5.8 eV
CO_2 7.0 eV
N_2 8.8 eV

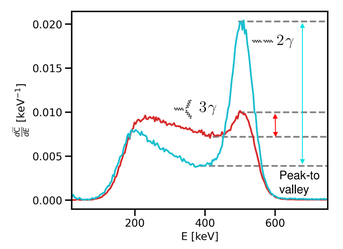


$$\dot{n}_{Ps} = n_{e+} \cdot u_{e+} \cdot Q_{N,Ps} \cdot n_N$$



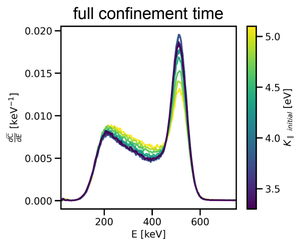
energy spectra suggest positronium decay

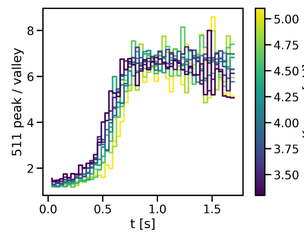


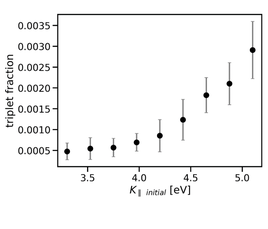


increase kinetic energy by decreasing magnet bias

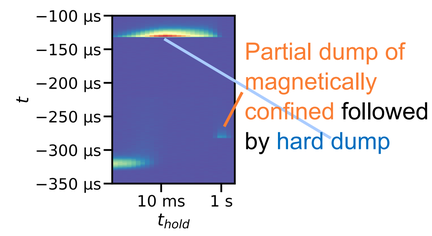
$$E_{gc} = K_{\parallel} + e\phi + \mu B$$

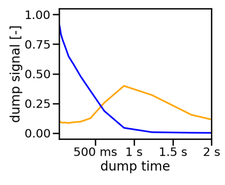


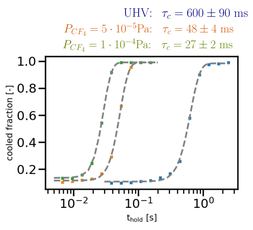


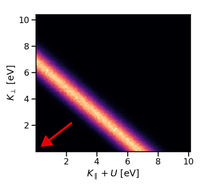


600ms: Cooling time through inelastic collisions





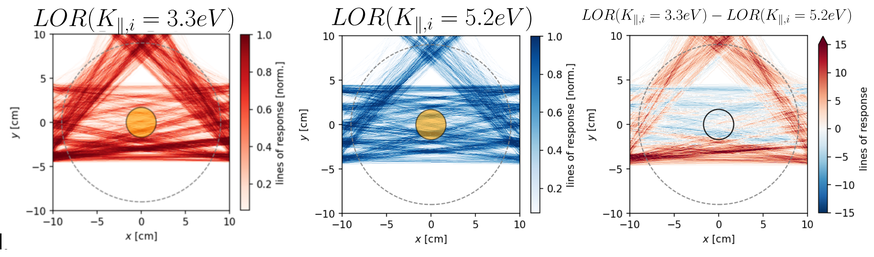




Transport due to elastic collisions to the wall

Charge-exchange depletes hotter e+ and e+ at higher r.
At higher r the kinetic energy is higher.
This results in the valley of losses at t~0.5s.
Charge-exchange is cut off. But the remaining e+ sill need several collisions to reach the wall.

When the magnet bias is higher the kinetic energy is lower so that more e+ are below the charge-exchange threshold, resulting in more annihilation at the wall.



$$U_{gc} = e\phi + \mu B$$

Conclusion

Diagnose magnetically confined e+ with 21-BGO-detector array: dump lifetime, counts, energy, coincidence.
Losses dominated by charge-exchange ('annihilation in-flight') and transport to wall.

Future extensions:
1) transport of positrons across field-lines for varying degrees of adiabaticity (gyro-orbits not small compared to B-field scale length) - relevant to diffusion in ISM.
2) effect of oPs-quenching interactions with free electrons and He-ions on peak-to-valley ratios - relevant to annihilation emission from chromosphere.

Acknowledgments: The APEX collaboration receives/has received support from IPP/MPG; the Helmholtz Association Young Investigator Group program; the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme; the Deutsche Forschungsgemeinschaft (DFG); the Helmholtz Postdoc Programme; the Humboldt Foundation; the UC San Diego Foundation; the United States Department of Energy; the Japan Society for the Promotion of Science (JSPS); and the National Institute for Fusion Science (NIFS).