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Chaotic long orbits of energetic positrons in a dipole magnetic field configuration

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Background and objectives

- In a dipole magnetic field, inward transport and structure formation of particles driven by slow (i.e., comparable to or faster than toroidal precession frequency) fluctuations are widely recognized
- While breakdown of the conservation of $P_\theta \sim \Psi$ is essential for such self-organization processes, there is another non-integrable system realized through the breakdown of μ and J conservation
- We study the behavior of such chaotic high-energy positrons emitted from a Na-22 source in the dipole field and compare numerical results with experiments in the RT-1 device

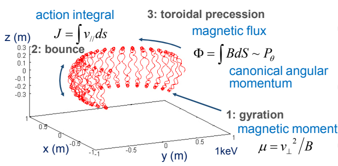
Main results

- In a typical levitated dipole field experiment, such as RT-1, it was shown that considerable ratio of high-energy positrons from radioactive sources have non-integrable chaotic orbits
- These particles make multiple toroidal precessions forming a hollow toroidal cloud, which may be applied for the formation of dense positron cloud in a strong magnetic field region
- Experiments with a small Na-22 source in RT-1 demonstrated the existence of long-lived positrons in the dipole field, showing a good agreement with numerical orbit analysis

References

- Stenson+, Horn-Stanja+, Sato+, invited talks in Tuesday morning
- 1987 Hasegawa, CPPCF **11**, 147.
- 2010 Yoshida+, PRL **104**, 235004.
- 2010 Boxer+, Nat. Phys. **6**, 207.
- 2012 Pedersen+, NJP **14**, 035010.
- 2016 Saitoh+, PRE **94**, 043203; 10th NNP (2012).

Magnetic dipole and scientific applications

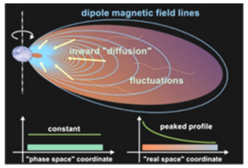


Toroidal trapping configuration:

- most simple and ubiquitous magnetic field configuration in the Universe
- charged particle has three periodic motions and adiabatic invariants
- excellent confinement for non-neutral plasmas due to its axis-symmetry

Inward "diffusion" and self-organization:

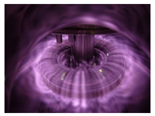
- in general, two constants of motion, H (total energy) and P_θ, meaning the system is non-integrable: particle is not always permanently trapped
- peaked structures are self-organized by slow fluctuation, breaking Ψ conservation
- we study the effects of breakdown of μ and J conservation for high-energy positrons



Fluctuation-induced self-organization of charged particles in a dipole field

Ongoing projects with magnetic dipole:

- RT-1, U. Tokyo, Japan



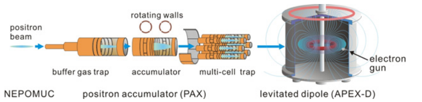
- advanced fusion and innovative trap including anti-matters

2010 Yoshida+, talk of Sato

- APEX, IPP, Germany

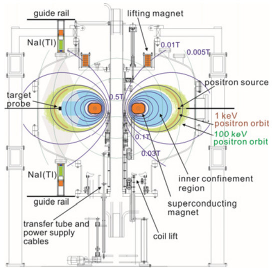
ERC project of T. Sunn Pedersen, currently looking for postdocs

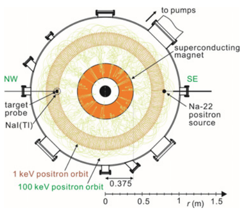
- magnetically-confined electron-positron pair-plasmas



2012 Pedersen+, talk of Stenson and Horn-Stanja

Geometry for the experiment and calculation



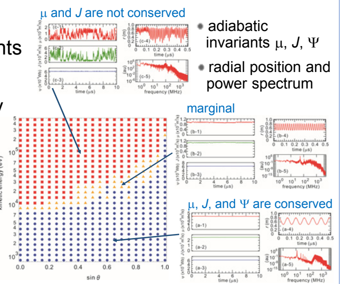


- magnetically levitated high-Tc (Bi-2223) coil
- 250kAT, R25cm 116A x 2160 turns
- positrons are injected from Na-22 located at edge trapping region
- we use the geometry of RT-1 and inject positrons directly from a Na-22 source

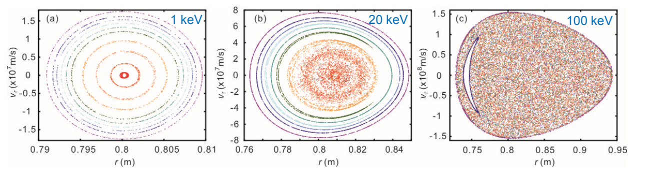
Chaotic orbits of high-energy positrons

Periodic or random behaviors:

- temporal evolutions of adiabatic invariants and radial position for various E_k and θ
- Ψ is always conserved due to symmetry
- above E_k = 20keV, coupling between gyro and bounce motions results in breakdown of μ and J conservation
- two degree of freedom means non-integrable chaotic system (Liouville-Arnold theorem)

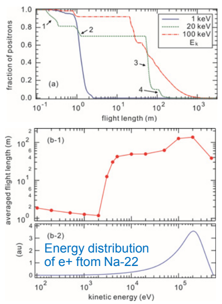


- adiabatic invariants μ, J, Ψ
- radial position and power spectrum



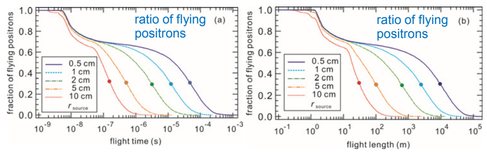
- Poincaré plot confirms chaos, implying long orbit lengths before annihilation

Long flight time of positrons in chaotic motion



Flight length of single particle:

- when motion is periodic, e+ return to the source and are lost just after single gyro/bounce motion
- positrons with chaotic orbits make multiple toroidal circulation with longer flight time



Flight time and length reflecting energy distribution:

$$\frac{dN_1}{dt} = \int \Gamma dS - \frac{N_1}{\tau}$$

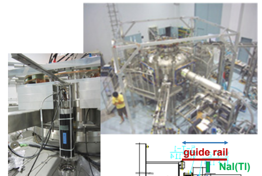
particle balance inside the hollow cloud

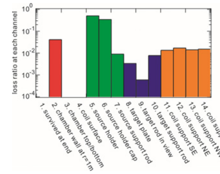
- Na-22 source size (r_{source}) limit the flight time
- with a source of r_{source} = 0.5cm (-> averaged flight time: 50 μs) and100 mCi (3.7 GBq), a hollow could of ~1×10^4 positrons are steadily generated
- if 1% of e+ from the source are transported inward by rotating wall, and assuming 1000 s trapping time, $N_1 \sim 10^{10}$ is expected in strong field region

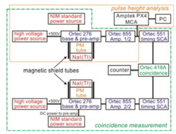
Comparison of calculations and experiments

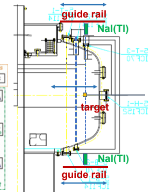
Positron injection and γ-ray measurements:

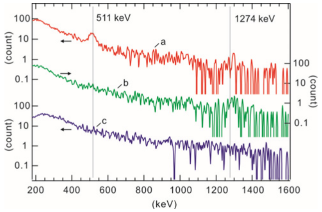
- injection from a 1 MBq (27 μCi) source
- after half, 180°, (or more) toroidal circulation, annihilation γ-rays are observed at a target
- Loss channels were numerically calculated according to the geometry of RT-1











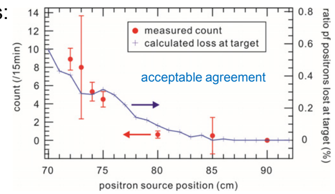
(a) Counts at the target is not observed when (b) the target probe was outside and (c) magnetic field is turned off.

Detection of positrons at the target:

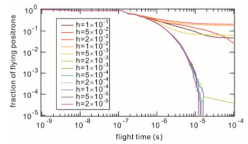
- 511 keV signal at the target, indicating long-lived component of e+ with chaotic orbits make toroidal precession motion before annihilation
- signal source was confirmed by removing the target from the trapping region and turning off the dipole field

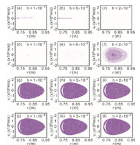
Counts and comparison with calculations:

- coincidence counts at r_{target} = 72cm for various Na-22 source positions
- annihilation rate at the target was also numerically calculated and plotted
- calibration was done by placing 1 MBq Na-22 source on the target probe



Convergence of numerical calculation





Results with various time steps

- the shadowing Lemma predicts that statistical calculations of many orbits converge into a good approximation of a real system
- convergence at $h \sim 1\times10^{-4}$

time step normalized by the cyclotron period