Journal of Physics: Conference Series **505** (2014) 012039 doi:10.1088/1742-6596/505/1/012039

Possibilities with pulsed polarized high density slow positrons

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Abstract. A particularly bright and intense polarized slow positron beam could be formed from isotopically enriched ^{79}Kr produced at a reactor. After moderation with solid Ne, accumulation, compression, and bunching, this type of positron beam would enable a number of experiments including: (1) Long term storage of a neutral polarized electron-positron plasma in a cold box; (2) Pulsed e+ ACAR with a pulsed magnet to measure Fermi surfaces of paramagnetic metals; (3) Single shot measurements of positron annihilation in laser-imploding plasmas; (4) Study of a spin-polarized positronium gas at a density around that of ordinary air to produce a Ps Bose-Einstein condensate at room temperature; (5) High energy polarized positron channelling experiments to study polarized electron spatial wave functions in ferromagnets; and (6) Study of supersonic free expansion spin polarized BEC Ps jets formed from, for example, 10^{11} m=1 triplet Ps atoms created within an open ended 1 μm diameter cylindrical cavity 100 μm in length.

1. Introduction

Positrons are produced with intensities sufficient for multi-user experimentation at nuclear reactors [1, 2, 3, 4] and electron accelerators [5, 6]. Since the positrons are created by pair production from unpolarized photons, the slow positron beams from these sources are unpolarized, i.e. they are produced with no preferential spin orientation. There are many useful and interesting experiments being done with these sources, but one might sometimes wish to use a β^+-decay radioactive source that can produce a beam of polarized positrons [7, 8], for example to examine the state of polarized electrons in a sample [9, 10] and for many other purposes, e.g. [11]. At the present time slow positron beams based on relatively weak (50 mCi) ^{22}Na sources are being used for experiments that require polarized positrons [12]. On the other hand, one may generate an intense polarized slow positron beam starting from positrons pair-produced via backscattering of circularly polarized laser photons [11] from a beam of relativistic electrons [13] or using a radioactive source produced at a reactor [1]. A particularly bright and intense slow positron beam could be formed from isotopically enriched ^{79}Kr produced by neutron activation of ^{78}Kr [14]. In this paper I describe the characteristics of a ^{79}Kr positron source and then briefly discuss some experiments that it would make possible. It is evident that this source could make a valuable addition to the positron facilities at Munich and North Carolina State University [3, 4].

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2. Kr-79 polarized slow positron source

^{79}Kr has a half-life of 35 h and yields a 600 keV end-point energy positron in 6.7% of its decays. ^{79}Kr is produced from stable ^{78}Kr which has a thermal neutron capture cross section of ~6 b and a relative abundance of 0.35%. ^{79}Kr has a thermal neutron cross section of ~27 b [15] which implies that a negligible fraction of any ^{79}Kr produced in a reactor will be destroyed. A flux of 10^{13} thermal neutrons per sec per cm^2 at NCSU (or ~10 times more at Munich) and 1 mole of isotopically pure ^{78}Kr would yield 10^{-5} (or 10^{-4}) moles of ^{79}Kr and 10^{10} (or 10^{11}) slow positrons per second assuming a solid Ne moderator efficiency of 0.5% [16]. If the ^{79}Kr were isotopically pure it could be deposited on a 3 mm (or 10 mm) diameter spot to make a bright polarized slow positron source, assuming the moderation process still works at such high intensities. If not, one could use a single crystal W moderator with some loss of yield [17].

The production of ^{79}Kr is very simple, since one needs only to irradiate ^{78}Kr with thermal neutrons by placing it in a sealed container in a suitable location near the core of a nuclear reactor. A hollow container near a reactor core is filled with ^{78}Kr gas via a long pipe. After one or two days, the gas is pumped out and the ^{79}Kr is separated out by the mass-dependence of the sublimation rates [18] and deposited on a 7 K cryogenic surface with a covering of solid Ne to make a slow positron source. The left over Kr gas is pumped back down the pipe to make the next batch of ^{79}Kr. Unfortunately, the deceptive simplicity does not even hint at the real technical and procedural difficulties associated with making a gaseous Kr positron source.

3. Some experiments enabled by pulsed polarized high density slow positrons

This section discusses some experiments that could be enabled by an intense polarized positron source after moderation [19], accumulation [20], compression [21], and bunching [22]. It is remarkable and fortunate that after all of these processes the positrons remain polarized to the same extent that they were when they stopped in the moderator [12]. In this note I am considering a collection of positrons or Ps atoms to be "dense" when

(a) Ps atoms are interacting with other Ps atoms, either via elastic or inelastic scattering, spin exchanging collisions or Ps_2 molecule formation in the presence of a third body or a surface that permits momentum to be conserved.
(b) The positron gas has a measurable Fermi energy or more than one positron is attaching to the same molecule, for example the case of Ps_2O, i.e. positronic water [23].
(c) Single-shot measurements are being performed which require many positrons at the same time, for example experiments requiring the use of a high power pulsed laser, an exploding target or an exploding magnet.

I am using the word "polarized" in the sense that

(a) The positrons have a significant non-zero average spin angular momentum component along some axis.
(b) The positron interaction with the target is dependent on the positron spin direction.

The following are a few things you might think of doing with dense polarized positrons and positronium that might be classified as explorations of interesting composite systems containing antimatter.

3.1. High density unpolarized triplet Ps at low temperature may resist spin exchange

A spin exchange collision between two very slow triplet Ps atoms yields two singlet atoms which move away from each other, each with a kinetic energy equal to the ground state hyperfine interval which is 0.841 meV = $k_B\times 10$ K. Since this energy must be transferred from the Ps internal degrees of freedom to the center of mass the spin exchange rate matrix element will involve an integral over the final state two-body wave function. If there were no Ps-Ps interaction the rate would then be proportional to the temperature of the Ps gas and would vanish at low enough temperature, making it possible to study a vector Ps Bose-Einstein condensate which would have properties analogous to superfluid ^{3}He. However, since the Ps_2 state exists with a binding energy of 0.435 eV, the free particle final state approximation may not be valid and an improved analysis would be recommended before experimenting on this topic. If an experiment were to be done there would be another problem, how to assemble and cool the Ps more rapidly than the spin exchange quenched triplet lifetime at the higher temperatures. One possibility would be to make the cold Ps in a free expansion jet.

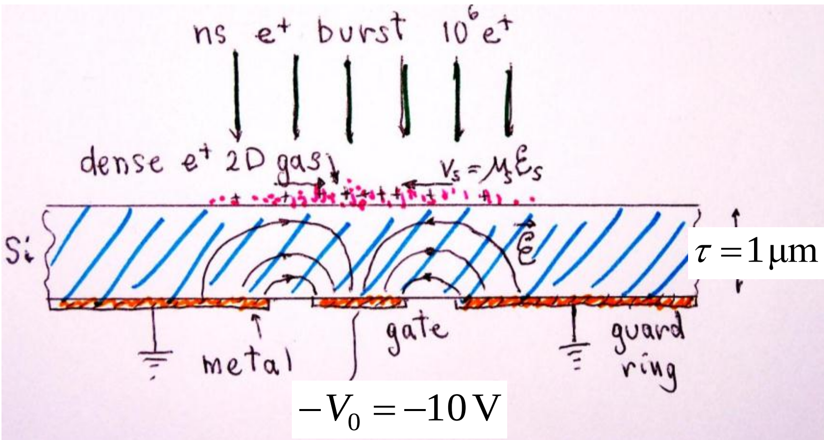

Figure 1. A thin Si sample provided with a back gate and a grounded guard ring to produce an attractive harmonic surface potential for a 2D gas of surface positrons.

3.2. Polarized e+ *on a Si FET*

It has recently been found that Ps is formed via what appears to be a surface-excitonic Ps precursor when a Si(100) surface is bombarded with slow positrons [24]. The yield of Ps emitted into vacuum is enhanced when the Si target is irradiated with laser light [25]. It would be interesting to study the mechanism for these processes in detail by observing the likelihood of polarized positrons forming triplet Ps with spin polarized photo electrons produced in selected surface bands. The use of ps laser pulses could reveal something about the formation dynamics [26]. However if dense pulses of positrons were used and the silicon target were supplied with a back-gating structure as shown in Figure 1, one might be able to make a positron super conductor and cause spontaneous positron emission due to the large positronic Fermi energy. Suppose a 1 ns pulse of 2×10^6 positrons is implanted into a Si sample in a ~ 2 μm diameter spot and about half of them diffuse back to the surface to form a 2D surface positrons gas. The positrons are attracted to the surface region over the gate by a nearly harmonic potential energy

$$V(r) = -V_0 \frac{r^2}{\tau^2}$$

in which their oscillation frequency is approximately

$$\omega_0 = 2\pi f_0 = \sqrt{\frac{2eV_0}{m_+\tau^2}} = 250\,\mathrm{GHz}$$

If the positron surface mobililty is $\mu_+ = 1\ \mathrm{m^2V^{-1}s^{-1}}$, the positron damping rate will be

$$\gamma = \frac{e}{m_+\mu_+} = 10^{11}\,\mathrm{s^{-1}}$$

Finally, if the 10^6 positrons are attracted to a 0.1 μm diameter spot, the positron Fermi energy will be on the order of E_F=10 eV, implying the possibility of spontaneous e+ emission and e+ Cooper pairing.

3.3. Collapse of polarized e+ on a W field emission tip

The possibility that a dense polarized positron gas moving on the surface of a W field emission tip will collect at the tip to make a 4D overdamped BCS superconductor and a very bright polarized e+ source has been discussed before [27].

3.4. Positronium 2D "BEC"

It is believed that positronium can reside on the surface of a quartz single crystal [28] with a binding energy of about 0.15 eV. A pulse of dense polarized positrons would therefore make a 2D Ps gas which would form a 2D BEC-like state at low temperatures (see Figure 2), with properties very similar to those of the cold 2D polariton gas studied by Kasprzak et al. [29].

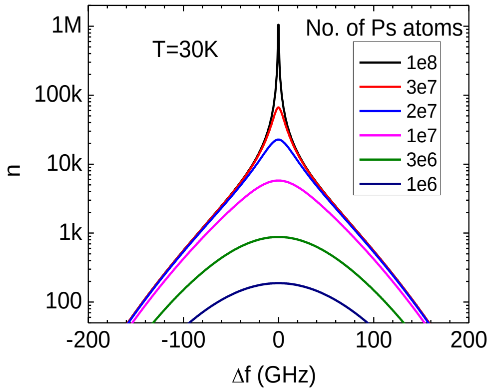

Figure 2. Calculated Doppler distribution of the Ps Lyman-α line at 243 nm for a 2D polarized Ps gas in a 10 μm^2 planar cavity approximating 2D Ps on the surface of quartz. The transition to a 2D BEC (i.e. significant departure from a Maxwell-Boltzmann momentum distribution) is signalled by the appearance of positive curvature in the log of the momentum density.

3.5. Long term storage of a neutral polarized electron-positron plasma

Long term storage of a neutral polarized electron-positron plasma in a cold box [27] could be possible if the walls were coated with solid Ne with perhaps a surface layer of He and the positrons and electrons were both spin polarized so that only triplet collisions would be possible. The Dirac rate is $n\pi r_0^2 c$ so the lifetime of a neutral 100% polarized spin parallel e+ e- plasma is 1 day for density 10^{18} m^{-3} and T=3K. An application of this idea would be for filling a stellarator [30] with a neutral e+e- plasma prior to pulsing the magnetic field.

3.6. Spin-polarized ACAR with a pulsed magnet to measure Fermi surfaces of paramagnetic metals

The theorem of Biasini and Rusz is that one can find the absolute Fermi surface occupancy of a ferromagnetic single crystal with very little distortion by taking the difference between the LCW data for spin up – spin down [31, 32]. An example of the calculated LCW differences between electron spin up and down along two high symmetry directions of a half-metallic ferromagnetic sample is shown in Figure 3. The same technique could be applied to paramagnetic samples which can be significantly polarized in a high magnetic field at low temperature. For example, electrons at the Fermi surface of a paramagnetic metal sample, assuming g=2, have a spin polarization at 4K in B = 10 T:

$$\mathrm{P} = \tanh\{\tfrac{1}{2} g\mu \cdot B/kT\} = \sim 0.9$$

One may envision an experiment using a sample in a 10 T field produced by a ~1 mm diameter pulsed magnet firing at 0.1 Hz and probed via 1 ms pulses containing 10^8 spin polarized positrons. The estimated signal rate in this case would be about 10^4 2γ coincidences per pulse detected without significant pile-up by a LYSO PET camera pair 0.5 m in diameter. Using the Biasini-Rusz technique one would be able to measure the undistorted full 3D Fermi surface of any single crystal metal at low temperature, including not only pure metals but also substitutionally disordered alloys [33, 34] which are not amenable to de Haas-van Alphen Fermi surface measurements except at extremely high magnetic fields [35].

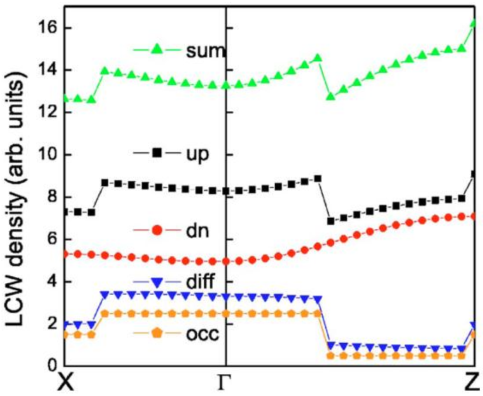

Figure 3. The LCW densities of the up spin, conducting, and down (dn-) spin, insulating, spin-polarized states of CrO_2, together with their sum and difference (diff) along two high-symmetry directions of the Brillouin zone. The occupancy of the up-spin states (occ) is also shown. For the sake of clarity, the occupancy curve is scaled and shifted in the vertical direction. From Ref 32.

3.7. Time-resolved pulsed ACAR for observing the approach to the Ps Bose-Einstein condensate

It has long been hoped that one could produce a spin-polarized positronium gas at a density around that of ordinary air to produce a Ps BEC at room temperature [36, 37]. The Ps BEC would be formed inside a cavity near the surface of a Si wafer as suggested in Figure 4.

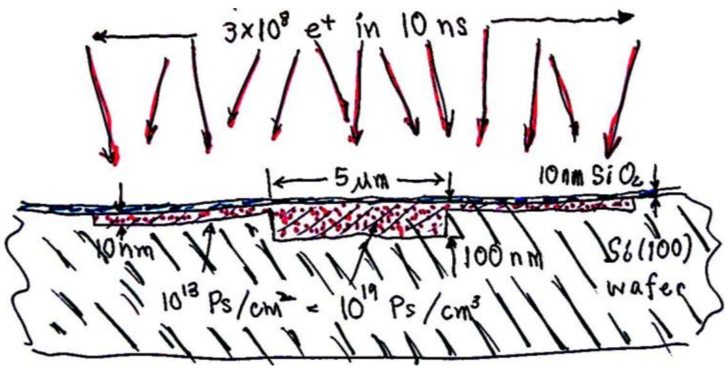

Figure 4. A cavity is formed on the surface of a Si wafer by first forming a depression and then covering it with a thin layer of silica. The design shown here has a top hat structure that might be used to obtain higher densities. The number density hoped for in the drawing is approaching 1 amagat.

The interest would be in obtaining the coldest Ps for spectroscopy, making an atom laser by poking holes in the lid of the cavity, coupling two cavities to obtain Josephson oscillations, observing interesting dynamics in light of the fact that the coherent BEC state is an eigen state of the annihilation operator, and attaining one of the prerequisites for observing stimulated annihilation. The approach to the BEC could be followed using time-resolved angular correlation of annihilation radiation measurements [38, 39].

Acknowledgments

The author is grateful for collaboration with Dr. D. B. Cassidy of University College, London, and with Dr. Adric Jones, Mr. T. H. Hisakado and Prof. H. W. K. Tom of the University of California, Riverside. This work was supported in part by the US NSF grant PHY 1206100.

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