

Brightness Enhancement of Slow Positron Beams

A. P. Mills, Jr.

Bell Laboratories, Murray Hill, NJ 07974, USA

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Abstract. The brightness of slow positron beams can be enhanced significantly by repeated stages of moderation, acceleration and focusing. Presently available data suggest that the source spot area should decrease by 10^{-4} after each stage with only a modest loss of intensity. Beams with very small angular divergence, which could be made with this technique, would be useful for characterizing surfaces by positron diffraction and microscopy. Using such beams it is possible to envision the study of new exotic systems such as the $e^+ - e^-$ plasma and the positronium molecule.

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Slow positron beams, well defined in energy but with rather poor spatial resolution, are presently being used to measure atomic cross sections [1], to form positronium [2] and to observe the interactions of positrons with surfaces [3]. A number of additional interesting areas of study would be possible if reasonable intense positron beams with angular divergence, spot size and energy resolution comparable to those routinely found in electron beams were available. For example, such beams would be useful for low energy positron diffraction [4], positron microscope characterization of surfaces and for the measurement of differential cross sections using intersecting positron and molecular beams. A very intense positron beam which could be focused to a microscopic spot size would also permit the formation and study of new antimatter systems such as the $e^+ - e^-$ plasma, the positronium molecule and possibly anti-hydrogen and muonium. This note presents a discussion of the principles of a novel technique for enhancing the brightness of slow positron sources which could make such experiments practical.

The basic limitation on how well one can focus a particle beam is set by Liouville's theorem, which states that a swarm of particles occupies a constant phase space volume in the presence of conservative forces. As applied to the transverse characteristics of a beam of energy E , Liouville's theorem implies the constancy of $\theta d \sqrt{E}$, where d is the beam's diameter

and θ is its angular divergence. The brightness B of a beam of S particles per second may be defined as

$$B = S(\theta^2 d^2 E)^{-1}. \quad (1)$$

Slow positrons may be obtained from a radioactive source (^{58}Co) by moderating its β^+ spectrum (0–480 keV) using a solid surface which has a negative affinity for positrons [3]. After thermalizing in the solid some of the β -decay positrons diffuse to the surface where a sizeable fraction of them are emitted with a small energy dispersion. When a sulfur-coated Cu(111) surface is used as a moderator [5], one obtains a slow-positron intensity S equal to 0.1% of the radioactive source β^+ activity. The area of the moderator which is emitting slow positrons is of necessity larger than the area of the radio-active source which must be several mm^2 per Curie of activity to ensure that the low-energy end of the β^+ spectrum is not self-absorbed by the source. This large spot-size is a severe limitation on the brightness of the slow-positron beam. For instance, to study positron diffraction from surfaces, one needs a beam divergence $\theta \approx 0.01$ rad, a beam diameter $d \approx 1$ mm, and a beam energy $E \approx 25$ eV. To achieve these specifications in a beam starting with $E = 0.25$ eV, $d = 6$ mm, and $\theta = 1$ rad, its intensity must be sacrificed by a factor of 10^3 .

The main premise of the technique suggested here is the realization that the slow positron moderation process is a way to overcome the limitations dictated

by Liouville's theorem. Starting with a 200 mCi ^{58}Co source ($E \approx 200$ keV, $d \approx 3$ mm, $\theta \approx \pi$, $S \approx 10^9 \text{ s}^{-1}$) with brightness $B \approx 50 e^+ \text{ mm}^{-2} \text{ eV}^{-1} \text{ s}^{-1}$ the moderator described in [5] yields a beam with $B \approx 10^5 e^+ \text{ mm}^{-2} \text{ eV}^{-1} \text{ s}^{-1}$. The three order of magnitude gain in brightness comes about because of the dissipative forces present. This suggests that we might increase the brightness even further by using a second moderating stage. The Cu(111)+S surface has the property that $\sim 50\%$ of positrons which diffuse to the surface are re-emitted as slow positrons. Further, the number of positrons implanted at an energy E which diffuse to the surface varies with energy [6] roughly as $(1 + E/E_0)^{-1}$, where $E_0 \approx 8$ keV for Cu. The primary positron beam ($\theta = 60^\circ$, $d = 6$ mm, $E = 0.25$ eV) could be focussed to a 0.1 mm spot size on a second moderator after accelerating the primary beam to ~ 3 keV. Of the positrons in this second spot, a fraction $(1 + 3/8)^{-1}/2 \approx 1/3$ would be re-emitted as a new slow-positron beam. This beam could be focussed to a 25 eV, 1° , 1 mm beam useful for diffraction studies. The net gain in intensity would be a factor of 300 over the single moderator and the gain in brightness would be a factor of 3000.

The process could be repeated by accelerating the secondary beam to ~ 3 keV and focussing it to a ~ 0.02 mm spot size on a third moderator. The new intensity would be roughly 1/10 of the initial beam and one could form a precision 25 eV, 0.1° , 0.2 mm final beam. It would not be useful to continue this iterative process beyond the point where the spot size approaches the diffusion length of positrons in Cu, $\sim 10^3 \text{ \AA}$, i.e. at the fourth moderator in the example considered above. The positrons from this final spot would have a brightness $B \approx 10^{15} e^+ \text{ mm}^{-2} \text{ eV}^{-1} \text{ s}^{-1}$ and could be focused to a $\sim 10 \text{ \AA}$, 3 kV beam suitable for microscopic examination of surfaces.

The brightness enhancement scheme [7] suggests that it should be possible to make effective use of the large ^{64}Cu β^+ sources which can be made in a reactor, a reasonable neutron flux of $10^{15} n^0 \text{ s}^{-1} \text{ cm}^{-2}$ yielding ~ 6 kCi ^{64}Cu per gram of natural Cu. Since only the outer layers of a source seem to contribute the low energy (10 keV) β^+ particles which are important in producing a beam of thermal positrons [5], the Cu must be spread in a thin layer, say 10 μm , resulting in an activity of about 60 Ci per cm^2 . If the radioactive Cu is evaporated onto a hot mica substrate, an epitaxial Cu(111) crystal results [8] which should serve as its own moderator under suitable ultra high vacuum conditions. It is not out of the question to think of making such a self moderated source with an area of 10^3 cm^2 which could in principle yield $\sim 2 \times 10^{11}$

thermal positrons per second from a 3 mm spot after one stage of brightness enhancement. Such a large current (30 nA) might be useful for pumping a storage ring [9]. For instance, charging a 1 km diameter ring for one hour would result in a ~ 10 A average positron ring current. A nuclear reactor might not be the only way of producing a high intensity positron beam. Other schemes for producing the necessary primary high energy positron flux include Van de Graaff acceleration of protons to produce β^+ active ^{11}C by the reaction [10] $^{11}\text{B}(p, n) ^{11}\text{C}$ and pair production from a bremsstrahlung target in an electron accelerator [11].

A high positron intensity would be very useful for solid state and surface studies, plasma experiments, storage rings, positron microscopes, etc. Further exciting possibilities emerge when we combine the advantages of secondary emission brightness enhancement with positron time bunching [12] which should increase the instantaneous positron flux by 10^5 . One can then envision forming n second bursts of $\sim 10^7$ positrons at thermal energies. The instantaneous current would be low enough to allow such a burst to be implanted into a surface over a microscopic region where the positrons could interact with each other in the solid, forming an interesting matter-antimatter system. The positrons which diffused to the surface might interact with each other while bound in their "image potential" well and could spontaneously be desorbed [13] at low temperatures by the (energetically allowed) formation of positronium molecules or an electron-positron plasma. One may even speculate that it might be feasible to clothe anti-protons etc with positrons to form anti-atoms.

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References

1. T.S.Stein, W.E.Kauppila, V.Pol, J.H.Smart, G.Jesion: Phys. Rev. A **17**, 1600 (1978), and references therein
2. For a recent review see S.Berko, K.F.Canter, A.P.Mills, Jr.: In *Progress in Atomic Spectroscopy*, Part B, ed. by W.Hanle and H.Kleinpoppen (Plenum Press, New York 1979) p. 1427
3. See, for example, A.P.Mills, Jr., P.M.Platzman, B.L.Brown: Phys. Rev. Lett. **41**, 1076 (1978)
4. I.J.Rosenberg, A.H.Weiss, K.F.Canter: Phys. Rev. Lett. **44**, 1139 (1980); A.P.Mills, Jr., P.M.Platzman: To be published
5. A.P.Mills, Jr.: Appl. Phys. Lett. **35**, 427 (1979).
6. A.P.Mills, Jr.: Phys. Rev. Lett. **41**, 1828 (1979)
7. The use of non-conservative forces to overcome the limitations of Liouville's theorem has found application in light collection

- from scintillators by wavelength shifting light pipes. [W.A.Shurcliff: *J. Opt. Soc. Am.* **41**, 209 (1951); R.L.Garwin: *Rev. Sci. Instrum.* **31**, 1010 (1960).] A similar technique for electrons could make use of negative electron affinity GaAs (CsO) surfaces. If a suitable moderator for ultracold neutrons [14] can be found, this would be another field which could benefit from brightness enhancement
8. R.L.Palmer, J.N.Smith, H.Saltsburg, D.R.O'Keefe: *J. Chem. Phys.* **53**, 1666 (1970)
 9. K.G.Lynn: Private communication
 10. T.S.Stein, W.E.Kaupilla, L.O.Roelling: *Phys. Lett.* **51 A**, 327 (1975)
 11. D.G.Costello, D.E.Groce, D.F.Herring, J.W.McGowan: *Phys. Rev.* **B5**, 1433 (1972)
 12. A.P.Mills, Jr., L.N.Pfeiffer: *Phys. Rev. Lett.* **43**, 1961 (1979); A.P.Mills, Jr.: *Appl. Phys.* (to be published)
 13. See A.P.Mills, Jr.: *Solid State Commun.* **31**, 623 (1979), and references therein
 14. A.Steyerl: In *Neutron Physics*, Springer Tracts Mod. Phys. **80** (Springer, Berlin, Heidelberg, New York 1977) pp. 57-130