Positron-beam-brightness enhancement: Low-energy positron diffraction and other applications

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The implementation and application of the first brightness-enhanced slow positron beam is described. The general concept of brightness enhancement by positron remoderation and the importance of such a technique for improving the phase-space parameters (beam diameter D and angular divergence θ) of positron beams is reviewed. A theoretical brightness gain per remoderation stage of 180 is derived, corresponding to a reduction in D by a factor of 26. Fundamental difficulties in achieving these gains such as those due to lens aberrations and limitations inherent in our particular "backscattering" remoderation technique are described. Details of the construction and performance of a brightness-enhanced electrostatically focused beam are given. This beam achieves a diameter reduction of a factor of 10 per stage. With the use of two stages of remoderation it produces a beam on target with D and θ values of approximately 1 mm and 1°, and an energy width of 0.07 eV at a beam energy of 100 eV. The beam energy is tunable over the range 20—500 eV. These parameters are consistent with those found in standard low-energy electron diffraction beams. Using this new positron beam the first multiple-spot, low-energy positron diffraction pattern has been obtained. A W(110) crystal was used and an electron diffraction pattern was also acquired under identical conditions for comparison. A discussion of the potential uses of brightness-enhanced beams in diffraction studies and a variety of other solid-state and atomic physics measurements is given. Finally, future prospects for brightness-enhanced positron beams themselves including timing techniques, spin polarization, and microprobe development are considered.

INTRODUCTION

As low-energy positron experiments become more sophisticated there are greater demands on the phase-space characteristics of the positron beams themselves. In many of these experiments the intensity and energy width of the beam are no longer of sole importance. In a growing number of surface and atomic physics experiments it is important to restrict the beam diameter D and angular spread θ. For example, it is important for low-energy positron diffraction[1] (LEPD) to reduce the product θD to about 1 mm deg (i.e., comparable to LEED electron beams). Simply aperturing the beam down to achieve the desired θD limitation results in an unacceptably low positron intensity. Thus we have resorted to a technique of *brightness enhancement* first discussed by Mills[2] and by Canter and Mills.[3] In this paper we report the implementation of the first brightness-enhanced, electrostatically focused positron beam with $\theta D \lesssim 1$ mm deg over the energy range 100—500 eV. In addition we will describe several experiments in surface physics and atomic physics that have become feasible as a result of this improvement in beam brightness. In particular we will display the first multiple-spot, low-energy positron diffraction pattern, a pattern obtained using the brightness-enhanced beam.

A typical laboratory beam of low-energy positrons begins with a radioactive source (such as ^{58}Co or ^{22}Na) irradiating a well-annealed, metal single-crystal moderator as depicted schematically in the corner of Fig. 1. A small fraction (of order 10^{-3}) of the incident high-energy (several hundred keV) beta particles thermalize within a positron diffusion length of the surface and are reemitted from the surface of the moderator due to the negative work function that many metals have for positrons. These low-energy (0—3 eV) positrons are then accelerated to several keV and focused into a beam. With use of radioactive sources less than 0.5 Ci a beam of this type produces an intensity I, of $I = 1-3\times10^6$ positrons per second. Unfortunately the optical brightness of this beam, $R = I/(\theta^2 D^2 E)$, is (1) relatively low because of the large size of the moderator ($D \approx 10$ mm); and (2) will remain low despite clever focusing schemes since Liouville's theorem states that $(\sin^2\theta)D^2E \approx \theta^2 D^2 E$ is a constant when the beam is only acted on by conservative forces. We show later that the θD product of a typical beam is at least 20 times too large for such experiments as

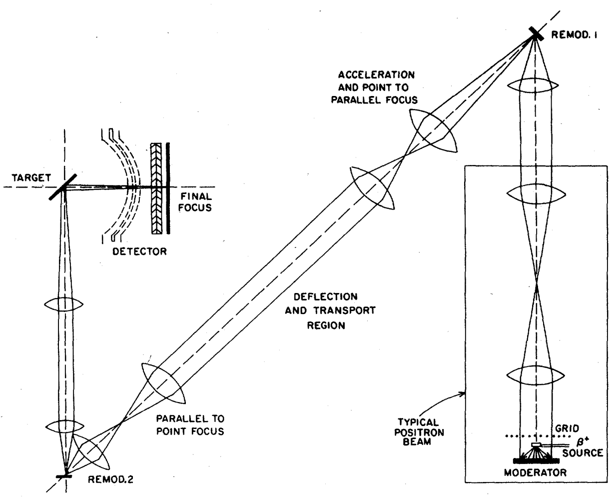

FIG. 1. Schematic drawing of the major components of the brightness-enhanced beam. Shown are a "typical" non-brightness-enhanced beam and the elements necessary for two stages of remoderation. Also indicated are the components required for LEPD and positron-surface scattering measurements.

LEPD. It is for this reason that brightness enhancement plays an important role.

GENERAL FEATURES OF BRIGHTNESS ENHANCEMENT

The general technique that has been proposed for positron beam brightness enhancement[2,3] involves the focusing of the beam down to the smallest possible spot on a second moderator (or remoderator). The remoderator performs the same function as the initial beta-particle moderator except that the few keV positrons now penetrate only distances of order 10^2 Å below the surface. Since positron thermal diffusion lengths are around 10^3 Å, virtually all the incident positrons can diffuse back to the surface where 20—30% are reemitted from the small beam spot in the near-normal direction with an energy equal to the negative work function of the remoderator crystal. Thus with only a modest loss of intensity the beam brightness, R, can be greatly increased due to the loss of energy by the thermalizing positrons. We note that Liouville's phase-space theorem does not apply to the nonconservative processes (ionization, electron-hole pair excitation, plasmon production, etc.) that cause the energy loss in the moderators. With each successive remoderation the beam diameter is reduced until the desired θD product is achieved. We have implemented a brightness-enhanced beam employing two remoderators as shown in Fig. 1. Before discussing in detail the design and performance of this new beam we note first several general features of the brightness-enhancement technique.

In order to quantify the brightness gain that can be obtained from a remoderator, we must know the phase-space parameters of reemitted positrons. Recently Fischer[4] has performed the first high-resolution measurements of the reemitted positron energy spectrum for several typical remoderator crystals (Ni, W, and Cu; clean and with various adsorbates). He finds that most of the positrons are emitted with a kinetic energy characteristic of the positron work function, ϕ_+, for that particular crystal and surface condition, and with an energy width [full width at half maximum (FWHM)] that is ≈ 70 meV, independent of ϕ_+. This result is consistent with the emission of thermalized positrons from the bulk of the room-temperature crystal. The emission angle (full angular spread) θ_e, for a flat remoderator (i.e., free of facets and steps) with work function ϕ_+ (in eV), is then

$$\theta_e = 2\left[\frac{0.035}{\phi_+}\right]^{1/2} \text{rad} = \frac{20}{\phi_+^{1/2}} \text{deg} . \tag{1}$$

In typical moderator crystals of Ni and W, this yields θ_e values of roughly 17° and 12°, respectively, corresponding to ϕ_+ values of 1.5 and 3.0 eV.

In order to produce a small-diameter beam spot on a remoderator, we would like to design the final lens with as short a focal length as possible. Unfortunately, as we increase the angular spread of the final beam in an effort to reduce the diameter, aberrations in the lenses become significant. This generally limits the angular spreads that can be permitted to values less than the intrinsic 10°—20° angles of the reemitted positrons. This effect is a fundamental limitation on the brightness gain attainable for a given choice of lens type. As the diameter we seek becomes smaller and smaller, the limitation becomes ever more severe.

Another constraint on the brightness gain we can achieve from one remoderator is due to the use of reflection-type remoderators. Because the strong fields required for short-focal-length lenses would greatly distort the trajectories of the much less energetic reemitted positrons, we must carefully isolate the strong lens fields from the region near the crystal by use of shielding grids. This problem limits our freedom in choosing final lens geometries for minimum aberrations. If high-efficiency transmission-type remoderators[5] can be perfected, this latter problem would be greatly alleviated

Because of these difficulties, one cannot easily predict the maximum gain in brightness obtainable from a remoderator at a given implantation energy. We take as figures of merit the brightness and diameter gains for an aberration-free system. These are given by

$$G_B = EF(\theta/20)^2 , \tag{2a}$$

$$G_D = E^{1/2}(\theta/20) , \tag{2b}$$

respectively, where E and θ are the incident energy and angle in eV and degrees, and F is the fraction of positrons which are reemitted. For $E = 2$ keV, $\theta = 12°$, and $F = 25\%$, we find $G_B = 180$ and $G_D = 26$. In actual practice, we have obtained brightness gains closer to 30 with corresponding reductions in diameter on the order of 10 for a single remoderation stage. Improved final-stage lens designs may, in the future, reduce the aberrations in this element, thereby moving these values closer to the figure of merit numbers above.

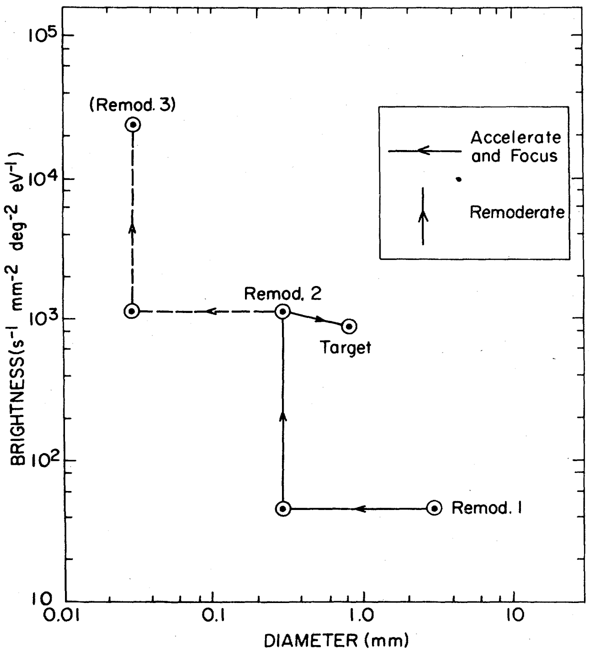

FIG. 2. Plot of beam brightness vs beam diameter for one stage of brightness enhancement. The two major steps in a brightness-enhancement stage are indicated by horizontal and vertical lines. Also shown are the brightness and diameter of the beam used for LEPD ("Target") and what might be obtained after another remoderation stage ("Remod.3").

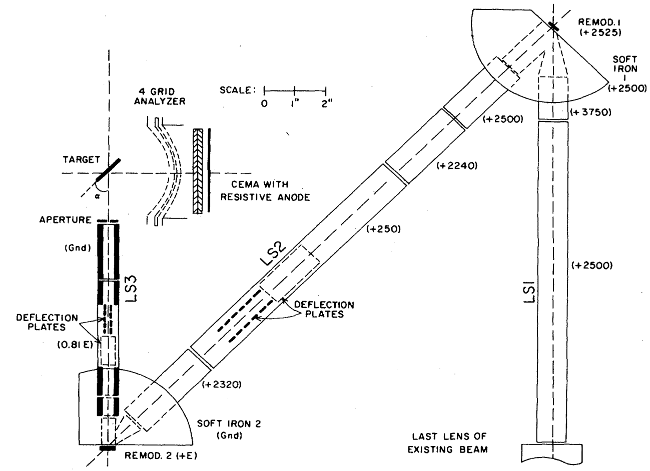

FIG. 3. Scale drawing of the beam optical elements in the brightness-enhanced beam. Shown are major lens elements and deflection plates as well as the soft iron final lens structures; not shown are additional magnetic shielding and support elements. Lens voltages are measured with respect to ground.

In Fig. 2 we illustrate schematically the gains in brightness and diameter obtained by one of our remoderator stages. In addition we indicate the characteristics of the final LEPD beam obtained from our second remoderator as well as a prediction of what might have been obtained had a third remoderator stage been inserted at this point. We shall return to these last two points shortly.

DETAILED DISCUSSION OF THE NEW BEAM

The beam, shown schematically in Fig. 1 and in greater detail in Fig. 3, is of ultrahigh-vacuum design throughout and has a base pressure of $\approx 1\times 10^{-10}$ Torr. It consists of three basic lens sections. They are designed for beta moderation and initial beam formation, brightness enhancement, and delivery to the target of a beam with desired phase-space characteristics, respectively. Lens section 1 (LS1) consists mainly of the electrostatic beam that has been used for several years at Brookhaven.[6] A reflection moderator of W(111) is used to produce low-energy positrons from a 1×3-mm Co^{58} positron source electroplated onto a copper-plated single-crystal tungsten needle. The emitted positrons, produced with a conversion efficiency of roughly 1×10^{-3}, are accelerated to 2 keV [the W(111) moderator being at $+4.5$ kV with respect to ground] and projected some 2 m to extract the beam from the background of high-energy beta particles and γ radiation from the source. We added to this existing beam a final triplet of lenses designed to produce a 3-mm beam diameter on the first remoderator, RM1. A smaller beam spot was not possible due to the poor phase-space characteristics of the existing emitted beam, these being due to distortion of the electric field in the source-moderator region of that beam. With the future implementation of thin transmission moderators,[5] a further reduction in diameter on RM1 of five or more could possibly be realized. By replacing RM1 with a channel electron multipler array (CEMA) coupled to a phosphor screen, we have directly measured the beam diameter at this point. With a movable foil shutter in front of the CEMA we find that two-thirds of all the positrons striking RM1 are in the 3-mm spot. The overall moderation and transmission efficiency into this spot is found to be 3×10^{-4}. (We note that poorly-focused positrons outside the 3-mm spot on RM1 will not be transmitted through the remaining lens sections and thus will not contribute to our final beam.)

Lens section 2 (LS2) is responsible for brightness enhancement by producing a beam-spot diameter on RM2 that is designed to be 15 times smaller than that on RM1. The reemission region around RM1 is basically free of the fringing electric fields found around the initial moderator and radioactive source; thus the phase-space volume of the beam emitted from this remoderator is relatively undistorted. The last strong focusing lens of LS1 and the first lens of LS2 are machined in a block of soft, high-purity, iron as shown in Fig. 4 and held at a potential of -25 V with respect to RM1 ($+2500$ with respect to ground). The strong focusing lens which delivers the 2-keV beam onto RM1 at a 45° angle to the surface normal is tapered with its small end covered with high-transmission W mesh to reduce field penetration into the first LS2 lens where the beam energy is only 25 eV. All of the lens tubes of LS2 (as well as the final triplet of LS1) are made of 2.5-cm-diam type-304 stainless steel and are

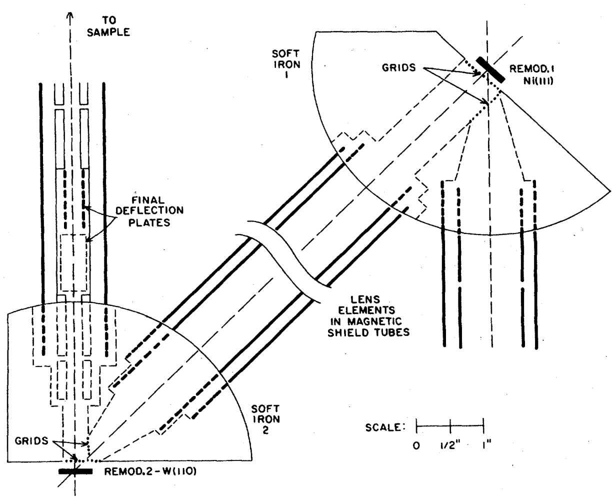

FIG. 4. Expanded scale drawing of the details of the soft iron blocks incorporating the final lens elements before each remoderator and the initial lens elements thereafter. All relevant lens elements and magnetic shield tubes are shown. The location of grids separating the final and initial lens regions at each remoderator are indicated.

held concentrically in a μ-metal tube of 3.8-cm diameter using rings of "Macor" ceramic. (The Macor rings also maintain a 1-mm separation between lens tubes.) Thus, with the iron junction blocks at RM1 and RM2, the beam is completely magnetically shielded. RM1 is mounted on a rotating feedthrough and thus two different remoderating crystals can be separately used and an electron multiplier can also be rotated into position to monitor the beam intensity. Since we found that a W(111) crystal was a very poor remoderator (perhaps due to faceting[7]) we have routinely used a Ni(111) crystal as RM1. [A W(110) crystal, which does not suffer from the faceting problem, would have been an equally suitable choice.] The Ni crystal is cleaned by heating to 1000 °C for several minutes. The reemission efficiency for the incident 2-keV positrons is measured to be about 25%.

The optical design for the second lens section (see Figs. 1 and 3) consists of a point-to-parallel focusing lens triplet 28 cm long, a 10-cm drift region with horizontal and vertical parallel plate deflectors, and a parallel-to-point strong focusing lens triplet, 14 cm in length. The first triplet successively accelerates the beam through energies of 25 eV, 285 eV, and 2.25 keV while providing a nearly parallel beam for transport through the deflection plates. The final triplet of lenses with beam energies of 2.25 keV, 205 eV, and 2.5 keV strongly focuses the beam onto RM2 with a diameter calculated to be 0.2 mm exclusive of aberrations.

A soft iron junction block is again used with a tapered and grided lens to prevent field penetration into the reemission region around RM2 (see Fig. 4). With RM2 replaced with a CEMA and phosphor screen, we find the beam-spot diameter to be too small to measure easily; we estimate a rough upper limit to be $D \leq 0.3$ mm. We find, as expected, that our CEMA counting rate (after accounting for detector efficiencies) is consistent with virtually 100% transmission of the beam through LS2 for those positrons reemitted from the 3-mm spot on RM1. Thus our total conversion efficiency for transport of the beam onto RM2 is approximately 8×10^{-5}.

The purpose of lens section 3 (LS3) is to deliver the doubly remoderated beam to the target with the desired D and θ values of roughly 1 mm$\times$1° at 100 eV. For the present design the beam energy can be varied over an energy range of 20—500 eV. This is accomplished by holding the iron junction block at ground while positively biasing RM2 to the desired voltage corresponding to the final beam energy. This has the advantage that no retuning of LS1 or LS2 is required when sweeping the energy of the output beam. The design has two disadvantages: the incident 2.5-keV positrons encounter a retarding potential of up to 500 V before striking RM2; and the reemitted positrons are accelerated in rather large electric fields which can alter their trajectories in the vicinity of the high transmission grid that covers the entrance to the iron junction block. However, at the low energies required for LEPD, these effects are minimized and the advantages of simple tuning and easy energy control outweigh the disadvantages. To further facilitate the tuning of LS3 the lens voltages and deflection plates are derived from a resistor chain so that all voltages scale with the beam energy E, and thus automated sweeping of the energy is easily accomplished by supplying only a single sweep voltage. Our present lens configuration consists of a triplet of lenses with beam energies E, $1.8E$, and E. They are 6 mm in diameter, stainless steel, magnetically shielded, and incorporate crossed parallel plate deflectors in the higher-energy section. RM2 is a W(110) single crystal that has been heated briefly to 1300 °C and then exposed to 10^2 L (1 L$=10^{-6}$ Torr sec) of O_2 while heating to 850 °C. We estimate the remoderation efficiency of RM2 to be about 25% since our measured overall conversion efficiency of the beam as delivered to the target is 2×10^{-5}. (There is a slight loss in beam due to less than 100% transmission of LS3 as is seen in Fig. 2.) Thus, with our 500 mCi source of ^{58}Co, 5×10^4 positrons/sec at an energy of 20—500 eV can be directed at the target.

Positrons scattered from a target (or the straight through beam with the target retracted) are detected with a 7-cm-diam channel electron multiplier array coupled to a Gear sheet position encoder.[8] This detector, with about 25% detection efficiency for either electrons or positrons at several hundred eV, provides two-dimensional position information with a spatial resolution of <0.5 mm FWHM. Together with four hemispherical grids (identical with usual 4-grid LEED configurations) in front of the CEMA, this position sensitive detector is well suited for positron diffraction experiments. The entire analyzer is mounted in a rotating cradle which allows it to be turned through 90° from the vertical positron shown in Fig. 3 to a horizontal position where the direct beam or forward scattered particles can be detected.

APPLICATION TO LEPD

The diffraction of a low-energy positron beam (without brightness enhancement) has been investigated in the last

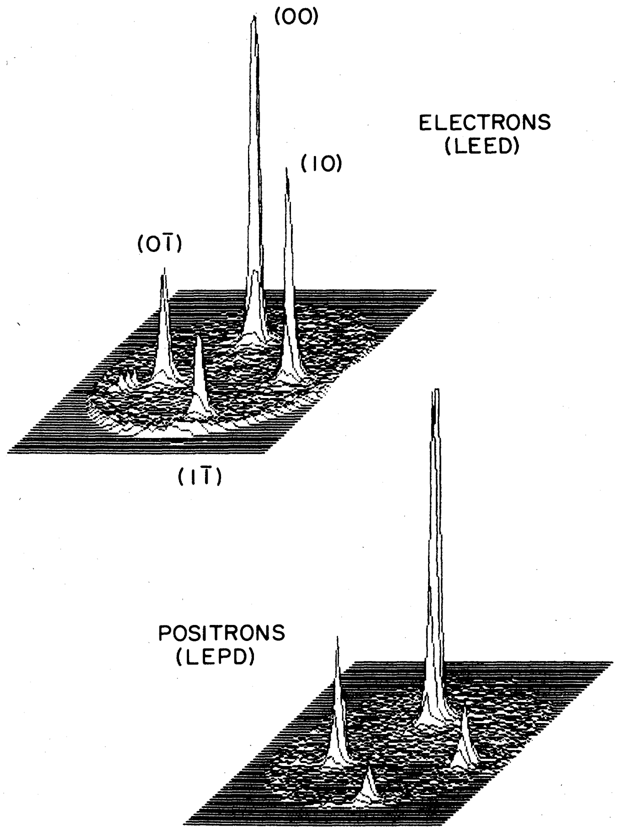

FIG. 5. Isometric plots of low-energy diffraction results for electrons and positrons on W(110). The specular and three diffracted spots are shown in each case. The plots are normalized to give equal heights of the specular spots; absolute scattering probabilities into the specular are 1% and 2% for electrons and positrons, respectively. Beam energy was 250 eV and beam orientation was along the [$\bar{1}$10] bulk direction at $\alpha = 20°$ from the surface plane.

several years by Weiss *et al.*[9] As a demonstration of the performance of our brightness-enhanced beam we have acquired the first multiple-spot positron diffraction pattern ever taken (see Fig. 5). Our system is designed for off-normal incidence diffraction where the incident beam angle with respect to the target surface, α, can be varied from 0° (glancing incidence) to 45°. The pattern shown in Fig. 5 was acquired at $\alpha = 20°$ for a W(110) target oriented so that the scattering plane includes the [$\bar{1}$10] bulk direction which is also in the surface plane. For comparison we acquired an electron diffraction pattern under identical conditions by simply rotating an electron gun into the RM2 position. This gun was designed to mimic the optical emittance of positrons reemitted from RM2. The two diffraction patterns have been normalized so that the specular peaks (the largest peak in each pattern) have the same height. To minimize the uncorrelated background in these spectra, a simple beam-on minus beam-off modulation scheme was employed. We note several features concerning these data.

(1) The peaks are well resolved with FWHM values of around 2.5 mm consistent with the peak widths that would be obtained from a commercial LEED gun at 20° incidence.

(2) Well-resolved peaks can be easily integrated to yield absolute scattering probabilities since we also know the incident beam intensity. Doing so for the specular beams yields 1% and 2%, respectively, for electrons and positrons.

(3) Although the peak positions for electrons and positrons are the same, as expected from kinematics, the intensity-versus-voltage (I-V) characteristics may be very different for the two (see also Ref. 9). The reversal in left-right peak-height asymmetry in the figure is most likely a manifestation of (I-V) differences.

CONCLUSION

We have demonstrated that positron beam brightness enhancement techniques can be straightforwardly implemented to generate a beam with $\theta D < 1$ mm deg at $E \geq 100$ eV. We have investigated several remoderator crystals and have found W(110) and Ni(111) to be equally acceptable while W(111) is unacceptable. Although our beam is of UHV construction which is suitable for surface physics, the brightness-enhancement technique will work in modest vacuum of 10^{-6} Torr [in which W(110) would be the preferred remoderator material]. This feature should make it easier to implement brightness enhancement in several atomic physics applications involving gas targets or on existing non-UHV positron beams without expensive vacuum system modifications.

We have utilized this new beam, together with a position-sensitive CEMA detector system, to produce low-energy positron diffraction patterns. In addition to LEPD we are now performing glancing angle positron and electron scattering experiments where a well-collimated beam of small diameter is essential. Such experiments explore differences and similarities in shape of the surface potentials for positrons and electrons. At somewhat higher energies (>1 keV) where electron-positron correlation is effectively eliminated it has been suggested[10] that positrons could probe the purely electrostatic contribution to the surface potential. In addition glancing angle positron scattering may allow one to produce a "beam" of fast (10—100 eV) positronium (Ps) by electron capture at the surface. By tuning the energy of the incident positron beam the energy of the positronium formed may be controllable to some extent. This positronium beam, if successful, could then be used in the future for Ps-atom cross-section measurements as well as in Ps-surface scattering experiments. A variety of other experiments could, with certain modifications to the beam, benefit directly from its small diameter and angular divergence. Positron energy-loss measurements[11] could be improved due to enhancement of either count rate or energy resolution by use of a brightness-enhancement stage. Similarly, time resolutions in positron surface lifetime measurements could be reduced.[12] Measurements of positron-atom differential cross sections using crossed beams, a topic of considerable recent interest,[13] might take advantage of the excellent energy (70 meV) and angular (1°) resolution of the beam, particularly when low scattering energies are required.

We note briefly some future improvements that might be made in brightness-enhanced positron beams. We have already mentioned that a thin transmission moderator in place of the present backscattering moderator might yield a factor of 5 reduction in the beam diameter on RM1. Certainly one could extend this idea to the remoderators if very thin single-crystal foils (less than 1000 Å thick) can be produced. This would permit simpler geometry at the remoderators, remove the need for grids, and might permit lens configurations with smaller aberration coefficients than in the present design. With either type of remoderator, cooling below room temperature would reduce both the energy and angular spreads of the reemitted positrons below the figures quoted here.[4] In addition, it should be possible to detect a secondary electron emitted from a remoderator when a positron arrives, thereby providing a start signal for timing experiments.[14] A timed, brightness-enhanced beam would be very useful for time-of-flight energy measurements as well as Ps decay-rate studies. It should also be noted that if a spin-polarized beam of positrons[15] is used as the input to a remoderator, there would be very little loss of polarization in the brightness-enhancement stage since the spin is virtually unaffected by the moderation process.[15] Thus experiments employing polarized beams, such as surface magnetism measurements,[16] need not be excluded from any benefits of brightness enhancement.

Finally, we should mention the further gains in brightness and beam diameter that might be obtained if one were to add a third stage of remoderation identical to RM1 and RM2 (see Fig. 2). Although aberrations are an increasingly severe problem as diameters are reduced, we feel that a spot diameter of 30 μm on RM3 is feasible with carefully designed lenses not radically different from those now employed. Beyond this diameter, new approaches may be necessary. It is important to stress that the energy of the positrons reemitted from RM3 at this 30-μm diameter would be only ϕ_+. At more typical beam energies of several keV, further reductions in diameter might be possible. Clearly a beam of diameter $<30\ \mu$m and divergence of order 1° would be a powerful tool for a large variety of experiments in its own right. Moreover such a beam (especially if coupled with some sort of higher flux positron source to improve final beam rates) could be an ideal first stage for a positron microprobe or positron microscope at beam energies in the 50—100-keV range. Clearly an apparatus of this sort would open many new avenues in the use of positrons as probes in the study of condensed-matter physics.

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