Slow positron beam design notes

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Recent methods of producing high flux (10^5-10^6) s^{-1} slow positron beams are briefly reviewed. Currently, slow positron beams are produced most efficiently using a single crystal Cu(111) + S backscatter geometry moderator for ultra-high vacuum (UHV) conditions and an annealed W-vane converter for non-UHV conditions. The respective fast positron to slow positron conversion efficiencies for the Cu(111) + S and W-vane converters are $(9 \pm 3) \times 10^{-4}$ and $(1.2 \pm 0.2) \times 10^{-4}$. A new figure of merit, the "normalized brightness-per-volt", for converters is introduced which takes into account the transverse energy spread as well as the conversion efficiency. The importance of the normalized-brightness-per-volt in beam design and future methods to improve this figure of merit are discussed.

Les méthodes récentes de production de faisceaux intenses (10^5-10^6) s^{-1} de positrons lents sont brièvement passées en revue. Les procédés courants les plus efficaces utilisent soit un modérateur à monocristal Cu(111) + S, dans des conditions d'ultravide, soit un convertisseur W, dans des conditions de vide moins poussé. Les rendements de conversion des positrons rapides aux positrons lents sont respectivement de $(9 \pm 3) \times 10^{-4}$ et $(1{,}2 \pm 0{,}2) \times 10^{-4}$ pour les deux modes de conversion. On introduit un nouvel indice de qualité, la "brillance par volt normalisée," qui tient compte de l'étalement transversal de l'énergie aussi bien que du rendement de conversion. On discute l'importance de cette "brillance par volt normalisée" pour la conception des faisceaux, ainsi que les méthodes susceptibles d'améliorer cet indice de qualité.

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I. Introduction

The following notes are intended to serve as a brief outline of the considerations involved in slow positron beam design. Reviews of the theoretical and experimental aspects of slow positron production are available elsewhere (1, 2). The type of beams discussed here will be high-flux, isotope-produced, general purpose slow positron beams. Thin-scintillator time-of-flight beams (3, 4) and activated boron converters (5) will not be treated here. A distinction will also be made between slow positron production techniques that are appropriate to ultra-high vacuum (UHV) ($10^{-9}-10^{-11}$ Torr) and non-UHV ($10^{-5}-10^{-9}$ Torr) conditions.

II. Primary positron sources

High activity sources of fast positrons, hereafter referred to as β^+, are presently available in the form of ^{58}Co diffused into a Cu matrix and encapsulated ^{22}Na. Discussion of the relative merits of each source will be made in the context of the particular slow positron converters with which they can be used.

II.A. ^{58}*Co*

The low self absorption sample preparation method (6) is as follows. A 1−2 μm thick Cu spot is electroplated onto a W foil which has been produced by a nonscintering process[1] in order to prevent the Cu from diffusing into the W. The ^{58}Co is then thermally diffused at 950−1000°C for 0.75−1.0 h into the Cu spot. This method of preparation, as well as the conventional method of diffusing ^{58}Co (≈20 μm) into thick Cu foils, can be provided by New England Nuclear (NEN)[2]. The extent to which ^{58}Co diffusion and hence source self-absorption should be avoided depends on which portion of the β^+ energy spectrum is most important for the subsequent emission of slow positrons, hereafter referred to as e^+. The present limitation on the specific activity for ^{58}Co diffused into 1−2 μm Cu on W is 100 mCi/mm^2 which is sufficient for most sub-Curie applications. The maximum suggested bakeout temperature of the ^{58}Co source is 150°C, which is sufficient for use where UHV conditions in the e^+ converter region are necessary.

II.B. ^{22}*Na*

Unlike ^{58}Co diffused into Cu, there is not yet any similar method of diffusing ^{22}Na into a matrix material (having normally acceptable self-absorption limits) in order to contain the ^{22}Na. The presently available com-

[1]Nonporous W foil is obtainable from Materials for Research Corporation, Orangeburge, New York, NY 10962.

[2]New England Nuclear, 601 Treble Cove Rd. N., Billerica, MA 01862. The 20 μm diffusion depth is based on a calculation by F. Sinclair.

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mercial ^{22}Na source assemblies contain the activity in a vacuum tight capsule with a 5–10 μm Ti window covering the source.[3] An electron beam welded Ti window allows the source to be baked to 250°C and thus the source is UHV compatible, barring any pinhole leaks in the window. It is commonly known that ^{22}Na is more economical than ^{58}Co on a cost per β^+ basis. However, in terms of cost per e^+, the issue is not as clear since the bulky capsule (15 mm minimum diameter) prevents ^{22}Na from being used with the highest efficiency e^+ converter discussed in Sect. III.B.

III. Slow positron converters

The most commonly quoted figure of merit for an e^+ converter is the conversion efficiency ϵ defined as the ratio of the extractable e^+ emission rate to the β^+ emission activity of the β^+ source. The less common practice of quoting a conversion efficiency normalized for the fraction of β^+ that is incident on the converter is often misleading since it does not take into account the β^+ source placement restrictions that are inherent in a particular converter design – nor does it accurately represent the e^+ yield as a function of source-converter separation. An additional figure of merit is ΔE, the FWHM of the e^+ energy distribution as measured parallel to the beam axis. Although the Cu(111) + S converter is the best converter to date (6), it requires a UHV environment which is not readily available in many experiments. Thus some discussion of the less efficient W-vane converter, developed at Oakridge National Laboratory (ORNL) by Dale *et al.* (7) is warranted since it is the most efficient non-UHV compatible converter to date.

III.A. W-vane converter

At present, the Brandeis variation (Fig. 1) of the ORNL converter yields $\epsilon = (1.2 \pm 0.2) \times 10^{-4}$ with $\Delta E = (1.5 \pm 0.5)$ eV. The 13 μm Al foil is used for shielding the interior of the converter from electric fields that would otherwise attract the e^+ back towards the grounded source. Replacing the foil with a fine grid or biasing the source to the converter potential should be tried. With the foil present in the Brandeis converter, only a 20% improvement in ϵ was obtained when going from the conventional ^{58}Co source to a low self absorption ^{58}Co source (6) which yields a factor of 4.5 improvement for the backscatter geometry converter discussed in Sect. III.B. Either this discrepancy in ϵ improvement is due to differences in the converter geometries (and the corresponding portions of the β^+ spectrum that they rely on for optimal ϵ) or the Al foil

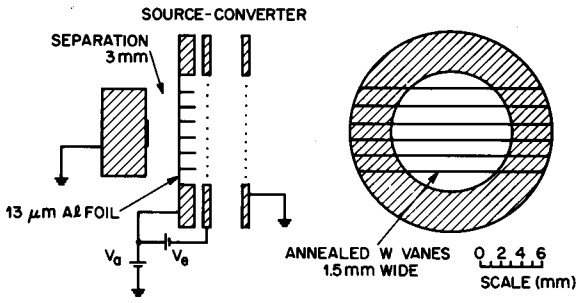

FIG. 1. W-vane converter. V_a = acceleration voltage. V_e = extraction voltage (usally 10 V).

undermines any gain made in avoiding self absorption of low energy β^+. Additional foils in front of a conventionally prepared ^{58}Co source (where there is already significant self absorption of low energy β^+) are not found to produce significantly higher than expected reductions in ϵ (8).

Method of W preparation

A 1.5 mm wide ribbon is cut from a 0.001″ W sheet. After degreasing the ribbon, it is etched in a 1:1:1 mixture of 30% H_2O_2, 1 *M* NaOH and 1 *M* NH_4OH to produce a matte finish (7). The ribbon is then heated after rinsing in distilled H_2O by passing electrical current through it while under vacuum. The optimum annealing condition reported so far by the ORNL group is 2200°C at 5×10^{-8} Torr. As the annealing temperature is reduced and the pressure increased, an increase in ΔE and a decrease in ϵ is observed. At Brandeis, the W is slowly cooled over a 20 min period with the ribbon suspended by both ends in a V position as a result of a relatively sharp bend in the middle of the ribbon with straight sides. Avoiding mechanical strains in the ribbon during annealing may be important. After cooling, the ribbon is removed from the vacuum chamber, cut into short strips and placed into the converter. There is no need for rushing this procedure since the W can be exposed for a day in air without significant loss in e^+ emission efficiency. After a few hours pump-down in the e^+ beam apparatus, the converter is at optimal efficiency with no *in situ* heating or surface treatment necessary. Thus the W-vane converter is a passivated converter which reduces considerably the problems in non-UHV e^+ beam work.

With annealing at 1850°C in 10^{-5} Torr, the Brandeis converter has twice the efficiency observed at ORNL. This improvement in ϵ is presently attributed to the 1.5 mm W-vane width vs. the 3 mm width of the ORNL converter which is otherwise similar to the Brandeis geometry shown in Fig. 1. One disadvantage of the parallel vane geometry is that it unnecessarily increases ΔE. Annealed W-grid converters which have better extraction field geometries have been used but large

[3]A 10 μm window is used by Amersham (2636 S. Clearbrook Drive, Arlington Heights, IL 60005) and a 5 μm window is used by NEN.

values of ϵ have not yet been observed.[4] It should be noted that placing the vanes at 45° with respect to the beam axis reduces ϵ by a factor of 2 and reduces the line-of-sight downstream β^+ background by a much larger amount. This background is easily avoided in large beam transport systems, but if a compact apparatus is needed, the 45° arrangement may be worthwhile. The importance of multiple backscattering of the β^+ versus direct implantation on the first encounter with the converter surface has not been determined. From present evidence, the parallel arrangement of W vanes may be just as important for presenting surfaces of shallow angle β^+ incidence (and hence better stopping within a diffusion length from the surfaces) as they are for taking advantage of multiple backscattering.

Principle of operation

The ORNL group attributes the high ϵ of the W-vane converter to the absence of positron diffusion limiting defects (e.g., grain boundaries) and thick oxide layers which are removed by the high temperature annealing. They estimate the oxide layer after the 2200°C, 5×10^{-8} Torr annealing to be 4 Å thick. Additional oxide layers decrease ϵ and increase ΔE as well as increase the relative height of the lower energy tail observed in the emitted energy spectrum. Using a single-backscattering planar geometry (Sect. III.B) under UHV conditions Wilson and Mills (9) report $\Delta E = 0.3$ eV for clean W(111). Heating the W in 10^{-6} Torr O_2 results in a broad energy distribution with an endpoint energy of 3.9 eV. An optimum coating of oxide, or perhaps carbon, which will passivate the W and at the same time minimize scattering of the ejected e^+, which increases ΔE, has not yet been determined. The ORNL experiments also measured ϵ for a large variety of metals. Although they did not have atomically clean surfaces, they observed a trend between ϵ and positron work function which suggests that the high ϵ for W is also due to its large negative positron work function.

III.B. Cu(111) + S single backscattering converter

Workers at Bell Labs have carried out a systematic investigation of β^+ implantation with subsequent thermalized e^+ diffusion to and escape from clean metal surfaces under UHV conditions. The result is the converter shown in Fig. 2 having $\epsilon = (9 \pm 3) \times 10^{-4}$ with $\Delta E = (0.3 \pm 0.1)$ eV (6).

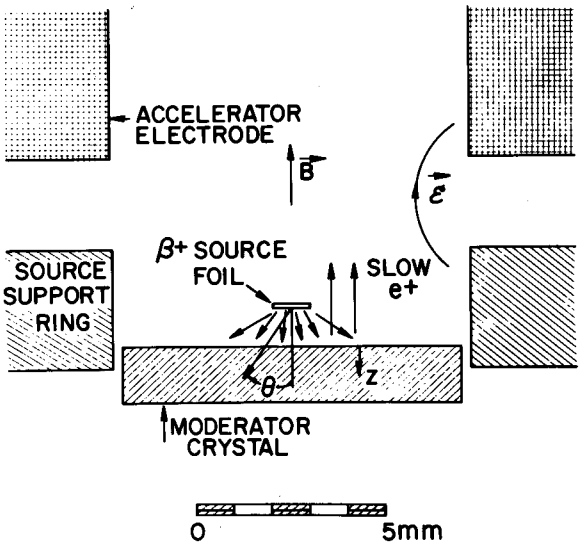

FIG. 2. Geometry of the Cu(111) + S converter and positron source foil. The Cu(111) moderator crystal is mounted by Ta tabs to a Ta disc on the end of a movable Mo plug.

Method of Cu(111) preparation

After spark cutting and chemically polishing (6) the oriented Cu(111) converter specimen, it must be placed in a UHV system for further surface treatment. The surface is then cleaned by argon ion bombardment, followed by annealing at 700°C to repair the surface damage produced by the ion bombardment. The annealing also produces a fractional surface monolayer of S due to diffusion of minute amounts of S contamination from the bulk to the surface. The ion bombardment for Cu cleaning can be avoided if the Cu can be heated to near evaporation temperatures (800–900°C) (10). An additional 30% increase in ϵ is obtained by exposing the Cu(111) converter to H_2S instead of just relying on heating to get S coverage (10). A drawback to this procedure is that it increases ΔE and also accidental overexposure of H_2S could be damaging to the beam system. The Cu(111) + S converter has been reproduced at Brookhaven with ϵ comparable to the Bell Labs results (9).[5] At Brandeis, initial efforts to produce the desired Cu(111) + S surface by heating alone have yielded $\epsilon = (0.3 \pm 0.2) \times 10^{-3}$ with an upper limit on ΔE of 0.6 eV. The large uncertainty in ϵ is due to uncertainties in the Brandeis electrostatic beam system transmission which is partially dependent on the angular distribution of the e^+ from the

[4]At present the parallel vane converter tried by Coleman has yielded more than a factor of 10 over his grid converter. However, final assessment of the grid geometry should be withheld until it is given the identical annealing treatment used for the parallel vane converter (P. G. Coleman, private communication, 1981).

[5]Note that there is a misprint in the abstract of ref. 9: a 300 mCi source gives 2×10^6 e^+/s instead of 2×10^5 e^+/s. Lynn also finds that Ar ion bombardment is necessary for initial Cu(111) cleaning and that heating alone is not adequate.

Cu(111) + S surface. It is important to note that the $\epsilon = 1 \times 10^{-3}$ performance requires that the ^{58}Co source be prepared according to the prescription described in Sect. II.A. Conventional ^{58}Co preparation reduces ϵ by 4.5. At present this converter geometry prevents the use of an encapsulated ^{22}Na source.

Principle of operation

The success of the converter is based on the long diffusion length ($\approx 10^3$ Å) of thermalized e^+ in defect free single crystal Cu and the high emission probability $y = 0.55$ for e^+ reaching the Cu(111) + S surface (6). The importance of the S monolayer may be attributed to its passivating effect on the surface and its role in increasing y by a factor of two over the value for clean Cu(111). The passivation, i.e., the several month stability of the converter in $\approx 10^{-10}$ Torr vacuum, is probably due to a saturation of available adsorption sites.[6] The increase in y with additional S coverage is consistent with a model (based on a physical picture of the e^+ velocity as it escapes the metal without being captured into a surface state or forming Ps) proposed by Murray and Mills (12) which relates y to the positron workfunction ϕ_+, i.e.,

$$[1] \quad y = \exp\left[-\left(-E_0/\phi_+\right)^{1/2}\right]$$

where $E_0 = 0.27$ eV. For $\phi_+ > 0$, y is a complex number and no e^+ emission results. The above expression is a good semi-empirical fit to experimental data for aluminum and copper. However, the β^+ implantation depth, e^+ diffusion length and hence ϵ are material-dependent. Epitaxial growth of an $\approx$1000 Å thick Cu(111) film on a W single crystal substrate has been proposed by Lynn at Brookhaven as a means of taking advantage of the stopping power and high backscattering of W and, at the same time, the narrow energy emission from flat Cu(111). Preliminary indications from measurements at Brookhaven of slow positron reemission resulting from keV positron injection into Cu(111) coated W promises to result in a converter (same geometry as Fig. 2) with $\epsilon \approx 10^{-2}$ and $\Delta E < 0.3$ eV.[7]

IV. Slow positron beam transport

IV.A. Magnetic solenoid

A magnetic solenoid is the simplest way to transport positrons from the converter to a target region which is shielded from the source. An internally baffled solenoid which is bent so as to prevent line-of-sight β^+ or γ background from the source reaching the target is commonly used. The two main considerations in this transport method are uniformity of the axial field and preventing large off-axis drifts in the guiding center of the e^+ cyclotron motion as it follows the curved magnetic field. Denoting $v_\perp$ and $v_\parallel$ as the velocity components perpendicular and parallel to the guiding magnetic field direction, respectively, the need for field uniformity is illustrated by the following constraint (13):

$$[2] \quad \frac{\sin^2\theta}{B} = \text{const.}$$

where B is the field strength and θ is the pitch angle, i.e.,

$$[3] \quad \tan\theta = v_\perp/v_\parallel$$

Increases in B are particularly harmful since the above constraint can lead to the reflection of positrons having sufficiently large pitch angles (14). With some care, however, increasing B can be used to squeeze the beam diameter through small orifices. Ignoring the individual e^+ cyclotron radius, the overall beam diameter is inversely proportional to the square root of the field strength, within the limits of the adiabatic condition that the field changes slowly over the axial distance traveled by the positron during one cyclotron orbit. This same adiabatic condition is necessary for the approximation that the positrons follow the magnetic lines of flux around a curved section. The "first order" deviation of an e^+ with longitudinal energy $E_\parallel$ from following a curved solenoid having a radius of curvature R and a field strength B is obtainable from the approximation

$$[4] \quad v_D(\text{cm/s}) = 2 \times 10^8 \frac{E_\parallel(\text{eV})}{R(\text{cm})B(\text{G})}$$

where v_D is the drift velocity of the cyclotron guiding center away from the lines of flux (15). The direction of v_D is perpendicular to the plane defined by the curved arc of the solenoid. Compensation from this drift is done with external magnet coils or internal electrostatic plates that deflect the beam transversly to the deflection field.

IV.B. Electrostatically focussed beams

Electrostatically focussed e^+ beams are desirable for angle resolved studies of scattered e^+ and ejected secondary e^- as a result of e^+ incident on solid surfaces (16) and individual atoms. Such beams are also convenient for experiments where e^+ polarization is important (17). The general principles of electrostatic focussing are well covered elsewhere (18, 19).[8]

[6] A Ti sublimation pump keeps the H_2O partial pressure orders of magnitude less than the total 10^{-10} Torr pressure. At Brandeis, H_2O was found to be the most likely source of poisoning for the Cu(111) + S converter.

[7] K. G. Lynn, private communication, 1981.

[8] They are also covered by C. E. Kuyatt in his "Lectures on electron optics" given in 1967 (C. E. Kuyatt, Center for Radiation Research, Room C229, RADP, Washington, DC 20234).

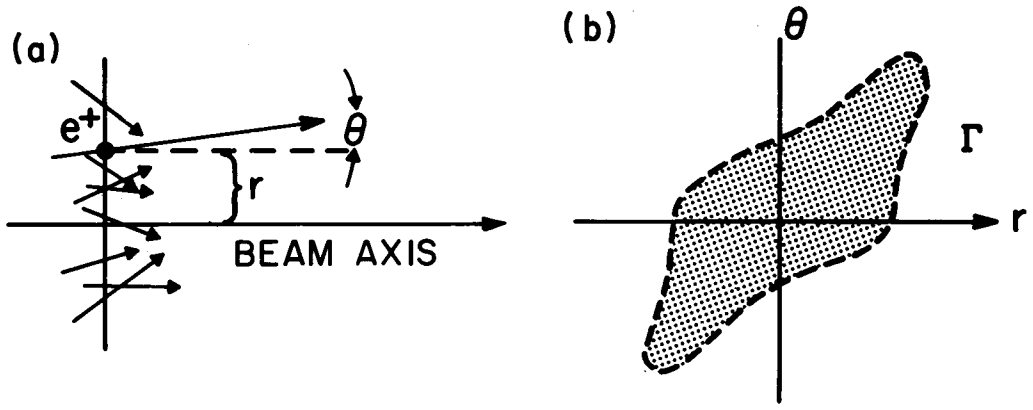

FIG. 3. (*a*) An ensemble of particles in a beam, each particle characterized by its value of r and θ. (*b*) "$r-\theta$" diagram of a typical beam. The ensemble of particles is bounded and occupies an area Γ in $r-\theta$ space.

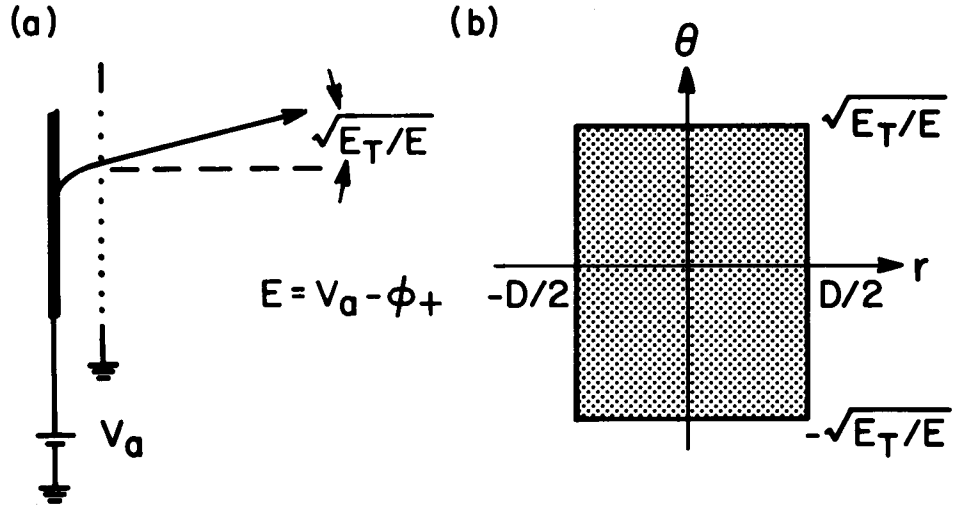

FIG. 4. (*a*) Exit angle for positron emitted with energy E_T perpendicular to the beam axis and accelerated to a forward energy E. (*b*) The corresponding $r-\theta$ diagram assuming uniform and iostropic emission from a converter of diameter D.

Beam characterization with r$-\theta$ *diagrams*

A rotationally symmetric system is assumed. Each e^+ trajectory passing through a particular plane transverse to the beam axis is characterized by its slope θ and height r with respect to the axis, as shown in Fig. 3. The area in $r-\theta$ (or "phase") space occupied by the particles is denoted as Γ. The fundamental limitation on beam focussing is expressed in the following version of Liouville's theorem (20):[9]

$$[5] \quad \Gamma\sqrt{E} = \text{constant}$$

Thus beam diameter can be decreased at the expense of increasing angular divergence, and vice versa. One or both, however, can be decreased by increasing E, the beam kinetic energy along the beam axis, while still conserving the particle flux.

For a uniformly emitting converter of diameter D, illustrated in Fig. 4, the corresponding phase space area for the e^+ being accelerated forward to an energy E is given by

$$[6] \quad \Gamma = 2D\sqrt{E_T/E}$$

where E_T is the endpoint energy for e^+ emission transverse to the beam axis, i.e., along the surface plane of the converter. The corresponding invariant quantity is

$$[7] \quad \Gamma\sqrt{E} = 2D\sqrt{E_T}$$

which is independent of the forward acceleration voltage. It is thus seen that D and E_T play an important role in determining the amount of collimation that can be achieved without resorting to aperturing the beam.

[9] This form is equivalent to the small angle approximation of the Abbe–Helmholtz Sine Law.

Normalized brightness-per-volt

Virtually all angle resolved scattering experiments require good beam collimation as well as a high flux. In this case ϵ is often an inadequate figure of merit for a converter, since it only relates to beam flux. A more appropriate figure of merit usually is

$$[8] \quad r_v = \frac{\epsilon}{4D^2E_T}$$

where r_v is the normalized brightness-per-volt. The normalization is with respect to the primary source β^+ activity A_+, since A_+r_v is the usual brightness-per-volt used to characterize charged particle sources (21). The denominator in the above expression for r_v is seen to be simply the square of the converter's invariant $\Gamma - \sqrt{E}$ product. For the W-vane converter E_T has not been measured directly, but can be estimated from ΔE. Assuming monoenergetic, isotropic e^+ emission from the vanes we can make the approximation $\Delta E \approx E_T$. This is equivalent to attributing a converter's energy spread to surface scattering, which in turn is characterized by an intrinsic transverse energy component. For the W-vane converter we consequently have $r_v = (0.24 \pm 0.11)\ eV^{-1}\ m^{-2}$. Applying the same considerations to the Cu(111) + S converter yields $r_v = (9 \pm 5)\ eV^{-1}\ m^{-2}$, which is nearly 50 times larger than r_v for the W-vane converter. Since the necessary β^+ source activity A_+ needed to obtain an unapertured beam of flux N_+, diameter D_+, angular spread Θ_+ about zero average angle, at an energy E_+ is

$$[9] \quad A_+ = \frac{N_+}{r_v D_+^2 \Theta_+^2 E_+}$$

then a 50 times weaker source can be used with the Cu(111) + S converter to achieve the same flux per unit area per unit solid angle that can be produced with the W-vane converter. An additional constraint on A_+ is that it at least be equal to N_+/ϵ. If A_+ exceeds N_+/ϵ, then the beam must be apertured in order to achieve the desired collimation.

Further improvements in r_v

From the above discussion, it is seen that reducing E_T can be as important as increasing ϵ when designing a converter. On the basis of observing nearly normal reemission of e^+ from flat Cu(111) + S target sample bombarded with few keV e^+, Murray and Mills predict that $E_T \approx kT/2$ should ultimately be possible if all sources of scattering, as the e^+ leaves the surface, can be eliminated (22). Further since ϵ is expected to improve as $T^{-1/4}$ for a defect free single crystal converter (10), then an improvement of r_v by a factor of $(T/300\ K)^{-5/4}$ over the present room temperature value would be feasible as a result of cooling the converter. To prepare a surface to be flat enough on a 100–1000 Å scale, so that the e^+ have only thermal transverse energy, is very difficult. The Cu(111) on W experiments at Brookhaven suggest flatter Cu(111) surfaces, as evidenced by a narrower emission, are produced when grown on W than obtainable by polishing bulk Cu(111) samples. Cooling a converter also requires extra care in preventing gas molecules from covering the converter surface in times comparable to 10^4 s. This is the time for monolayer coverage in 10^{-10} Torr when the sample is at $\leq$150 K where the sticking coefficient of most of the constituent molecules is unity. Without enormous effort, however, a factor of 5 improvement in r_v should be realizable with liquid nitrogen cooling the converter.

A more ambitious method of increasing r_v has been recently proposed (23). Taking the e^+ from a conventional Cu(111) + S converter and accelerating them to a few keV allows one to focus the beam down to a $\approx$0.1 mm diameter with $\approx$15° angular width. If the beam is then focussed onto a thin ($\approx$1000 Å) Cu(111) foil, the e^+ will thermalize in the foil, diffuse to the outer surface, Cu(111) + S, and escape as e^+ with $E = -\phi_+ = 0.8$ eV. In effect, this is a way of reducing D without increasing E_T. Allowing for reconversion losses one expects a 10^3 increase in r_v. The technology that has to be acquired first is producing thin single crystal Cu(111) films that are self supporting (on a grid substrate) and whose surfaces can be subjected to cleaning under UHV conditions. In addition to producing much smaller diameter collimated beams for crossed beam experiments, the reconversion (i.e., "enhanced brightness") would be valuable for recovering the monoenergetic energy distribution of the e^+ that are smeared-out in energy when "time-bunching" with pulsed beams is used (24). With specially shaped pulsing of the e^+ acceleration optics (and some bottling) an increase in r_v by a factor of 10^6 over a 10 ns pulse width might be achievable if the pulsing is combined with the thin film reconversion method, keeping in mind that we are still only speaking of a 10^6 e^+/s average flux from a few hundred mCi ^{58}Co source.

V. Conclusion

In closing, we touch briefly on the subject of ultra high flux slow positron beams. For the ^{58}Co and ^{22}Na sources discussed above, the maximum source strength is in the range of 0.1 to 1 Ci principally because of manufacturing costs. Thus, present generation slow positron beams are limited to fluxes of a few times 10^6 positrons/s. A third isotope, ^{64}Cu, is easily produced in great quantities in a nuclear reactor, although the useful activity per unit area of ^{64}Cu is comparable to that of ^{58}Co because of self absorption constraints on the source thickness. However, when the brightness-

enhancement technique becomes available, we should be able to make use of large area ^{64}Cu sources to form a ~10 Ci strength slow positron beam at a reactor site. Another method of obtaining ultra high flux beams is to use a pulsed LINAC which accelerates a pulse of electrons to produce a γ-flash, via Brehmstrahlung, which in turn leads to pair production in the slow positron moderator (25).[10] In view of these essentially on-hand technologies for producing ultra high flux beams, one can envision a large variety of new positron experiments available for research in the area of solid state physics, atomic collisions, and fundamental quantum electrodynamic tests.

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[10]The first use of this method also produced the first positron beam of sufficient strength for positron–helium scattering cross section measurements (see ref. 25). A more recent version of this method, reported by R. H. Howell at Lawrence Livermore, should produce slow positron yields comparable to a brightness enhanced, reactor activated ^{64}Cu converter.