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A HIGH INTENSITY POSITRON BEAM AT THE BROOKHAVEN REACTOR

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ABSTRACT

We describe a high intensity, low energy positron beam utilizing high specific activity ^{64}Cu sources (870 Ci/g) produced in a reactor with high thermal neutron flux. Fast-to-slow moderation can be performed in a self moderation mode or with a transmission moderator. Slow positron rates up to 1.6×10^8 e^+/s with a half life of 12.8 h are calculated. Up to 1.0×10^8 e^+/s have been observed. New developments including a Ne moderator and an on-line isotope separation process are discussed.

INTRODUCTION

A number of proposed positron experiments require a high intensity slow e^+ beam to attain an acceptable signal to noise ratio.[1] Such a beam could be used for differential cross section measurements of positrons scattering in gases.[2] The 2 γ angular correlation measurements of the Fermi surfaces of metals have begun to be extended to surfaces of solids.[3] The beam has been used as a source for a monoenergetic positronium beam to study the possibility of positronium scattering and diffraction from surfaces.[4] If this proves to be practical, such a new tool would greatly supplement results on neutral atom beams.[5] A high positron count rate would also make feasible rare decay studies, such as the measurement of the single photon decay rate of positrons.[6] The implementation of several stages of remoderation,[7] a technique that recently has been realized for the first time,[8] could provide a microscopic beam usable as a positron microprobe or to study matter-antimatter systems at high densities.[1]

At present two ways to reach these high count rates exist and are being further developed. In one approach the bremsstrahlung of a 100 MeV electron beam of a LINAC hitting a target produces showers of positron-electron pairs.[9] The positrons are moderated to form the low energy beam. Due to the nature of the LINAC, a pulsed beam of positrons is available.

The second method, described here, uses thermal neutrons to produce the positron source ^{64}Cu. A reactor with a high thermal neutron flux such as the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory (BNL) is essential. If available as a single crystal, the copper can be used as the moderator, a combination, that we call a self moderator. Alternately the positrons can be moderated by a thin single crystal film; a tungsten film has been used successfully as such a transmission moderator.[10,11]

The reactor based beam will be discussed in more detail below. Section 2 contains calculations to predict the performance of the beam, given the available neutron flux. Self moderation and transmission moderation are compared. In section 3, advantages and disadvantages of such a beam are presented. The technical realization of such a beam at BNL is described in section 4. Problems that were encountered during beam development are presented in section 5. The present beam performance, as well as improvements planned or under way, are covered. Section 6 provides an outlook, and an appendix contains the detailed self moderator calculations outlined in section 3. Also the possibility of further increasing the count rate by an on-line enrichment of ^{64}Cu is considered.[12] Finally the ongoing implementation of the recently developed neon moderator is discussed.[13]

CALCULATIONS TO PREDICT THE BEAM PERFORMANCE

Production of the Positron Activity

The source of positrons, ^{64}Cu, is used. It is produced in the High Flux Beam Reactor (HFBR) at Brookhaven by means of the thermal neutron reaction ^{63}Cu (n,γ) ^{64}Cu. A flux of $f = 8.3 \times 10^{14}$ n_0/cm^2s of thermal neutrons[14] near the core, along with the relative high cross section of $\sigma = 4.5$ b for this reaction, make reasonable amounts of ^{64}Cu possible. The short half life of ^{64}Cu of $t_{1/2} = 12.8$ h necessitates frequent renewal of the source.

With a production rate $\lambda_p = f\,\sigma$ and decay rate $\lambda_d = \ln 2/t_{1/2}$ after an irradiation of time t the positron activity is

$$A(t) = bp\,\frac{m}{M}\,N_a\lambda_p\left[1 - e^{-\lambda_d t}\right]. \qquad 1$$

This formula holds for the case $\lambda_p << \lambda_d$.

In the equation $b = 19\%$ is the fraction of decays through the positron channel, p the fraction of ^{63}Cu in a sample of mass m, and $M = 63.54$ g/mol the molar weight. N_a is Avogadro's number.

After an irradiation of duration

$$t_m = \frac{1}{\lambda_d}\ln\frac{\lambda_d}{\lambda_p} \qquad 2$$

the maximal activity is reached. Figure 1 shows the activity $A(t)/A(t_m)$ as a function of the irradiation time. For the neutron flux available at the HFBR the 95% of $A(t_m)$ is

reached after ~ 55 hours. Figure 2 shows the dependence of the activity on the neutron flux on a log-log scale. Irradiation times are chosen to maximize the activity in each case.

Performance of Copper as a Moderator

A system of Cu(111) on W(110) with a perfect interface is considered. The efficiency ε, defined as the ratio of slow positrons to fast positrons, of such a moderator with the source as an integral part of the copper layer is made up of several contributions. These are the efficiencies resulting from a single crystal of copper on a

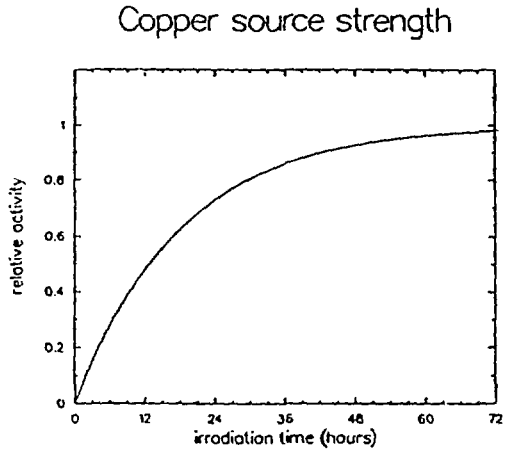

Fig. 1. Fraction of the maximum activity of a copper sample, as a function of the irradiation time in the reactor. The thermal neutron flux is $8.3 \times 10^{14} n_0/cm^2 s$.

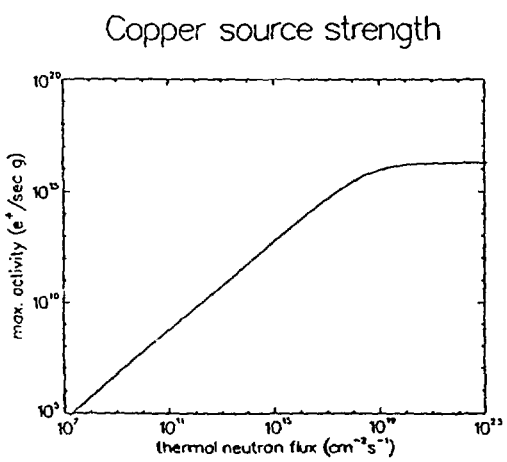

Fig. 2. Maximum positron activity of a sample that can be reached depending on the thermal neutron flux. 99% enriched ^{63}Cu is used

tungsten substrate, the backscattering effect of the tungsten, and the moderation capability of the tungsten crystal.

These contributions are calculated in the appendix and are shown in figure 3. When the Cu layer is on the order of 10^3 nm thick or more only the contribution of the Cu layer itself remains significant. ε_s can be approximated by

$$\varepsilon_s(d) \approx \frac{1}{2} Y_0 \frac{L_+}{d}\left[L_+\alpha \ln\frac{1+L_+\alpha}{1-L_+\alpha} + \int_0^1 dt\, \frac{t}{t-L_+\alpha}\left(1-e^{-\alpha d/t}\right)\right]. \qquad 3$$

The fraction diffusing back from the W substrate is

$$\varepsilon_w(d) = \frac{1}{2} Y_0 \frac{L_+}{d}(1-f)\,\frac{L_w\alpha_w}{L_+\alpha}\,\frac{1}{\cosh d/L_+}\int_0^1 dt\,\frac{t}{t+L_w\alpha_w}\left(1-e^{-\alpha d/t}\right). \qquad 4$$

Here d is the thickness of the copper layer, α and α_w are the products of mass absorption coefficient and density ρ of copper and tungsten respectively,[7,12] f is the backscatter fraction for positrons from the β^+-spectrum off the W-Cu interface, L_+ and L_w are the diffusion lengths for positrons in copper and tungsten, and Y_0 is the branching ratio [Y_0=0.55 for Cu(111) + S].

Performance with a W(100) Transmission Moderator

An alternative to self moderation is the recently developed transmission moderator.[10,11] It consists of a thin ($<10^3$ nm) single crystal of tungsten. Its moderation

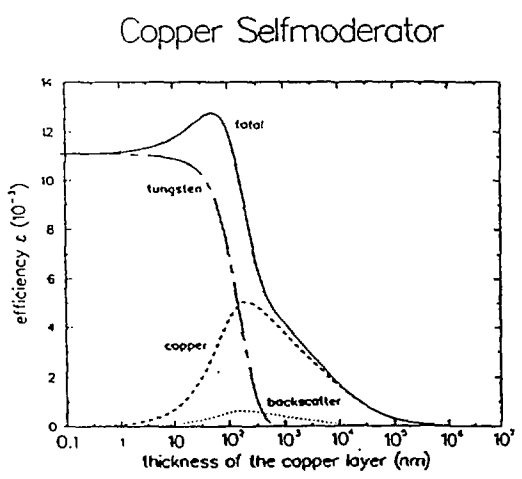

Fig. 3. The various contributions to the efficiency ε of the reactor positron source. _ _ _: the single crystal Cu layer, ...: the fraction due to backscattering off the interface, _ _ _ _: the W substrate, and _____: the total efficiency.

efficiency is theoretically estimated to be $\varepsilon_0 = 4 \times 10^{-3}$ (emitted slow positrons per fast positrons hitting the crystal).[10] Due to self absorption of fast positrons in the source, its activity is reduced by a factor s.

$$s(d) = \frac{1}{\alpha d} \int_0^1 dt \quad t \left[1 - e^{-\alpha d/t}\right] . \qquad 5$$

Further losses depend on the source-moderator geometry factor G. G is at most 0.5 since only one side of the source faces the moderator. The absolute efficiency with this type of moderation would then be

$$\varepsilon_t(d) = Gs(d)\varepsilon_0 . \qquad 6$$

Expected Performance of the Reactor Beam

For a discussion of a self moderator, the efficiency as the fraction of the available activity that contributes to the beam is not very useful. With growing thickness of the crystal the efficiency will decrease but this will be more than compensated by the larger amount of available activity.

In the appendix the product

$$E = \varepsilon d \qquad 7$$

is introduced. Figure 4 shows the various components of E again as a function of the thickness of the Cu layer and constant specific activity. Beyond a 10^5 nm thick copper film significant gains in E are no longer possible. At this thickness only the copper contribution is significant. The source-transmission moderator geometry and the value ε_0 determine which type of moderation is superior. The efficiency of a tungsten single crystal foil was estimated in reference 10 to be $\varepsilon_0 = 4 \times 10^{-3}$ for a 10^3 nm thick crystal. In figure 5 the performances of both moderators are shown, G is assumed to be 0.25. It should be noted that the best reported efficiency for a transmission moderator is 5×10^{-4}.

These values present an upper limit. The thermal neutron flux decreases during a reactor cycle (at BNL about 5%). The capsule absorbs neutrons (<5%). The beam becomes operational about 2 hours after the new source is removed from the reactor, in which time the copper has decayed to about 90% of its original strength.

A typical source of 100 mg is irradiated for 48 hours. A 10^5 nm thick copper crystal of about 1 cm^2 area is produced. It has a positron-activity of A = 14.9 Ci of positrons. Self moderation is calculated to deliver a beam of A = 4.3 $mCie^+/s$ = 1.6×10^8 e^+/s and a transmission moderator A = 2.5 $mCie^+$ = $9.3 \times 10^7 e^+/s$ with $\varepsilon_t = 10^{-3}$.

DISCUSSION OF THE HFBR BEAM

The high positron activity of the source material is achieved by utilizing the reactor's high thermal neutron flux of $8.3 \times 10^{14} n_0/cm^2 s$. A (n,γ) reaction converts

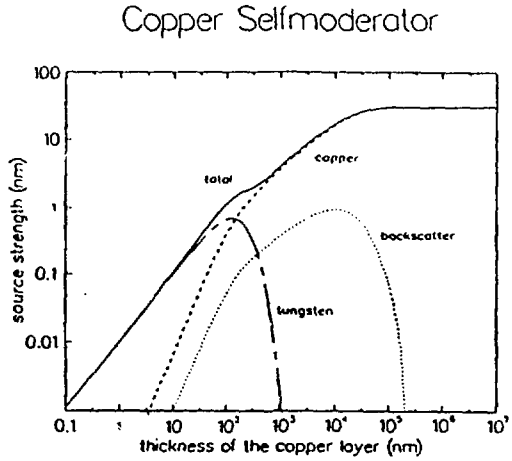

Fig. 4. The source strength on a logarithmic scale as a function of the thickness of the copper layer. The same symbols as in fig. 3 are used.

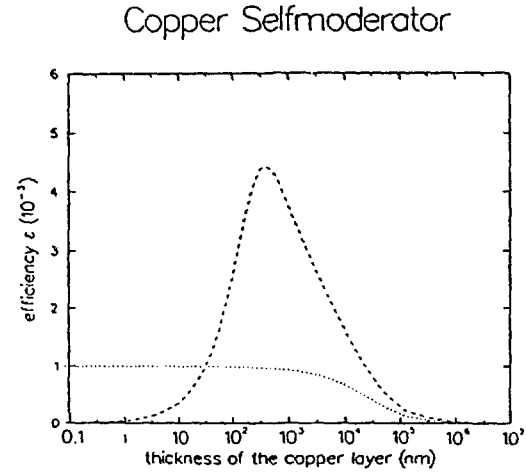

Fig. 5. Comparison of the efficiency ε of a self moderating film of Cu (dashes) and a transmission moderator when located in front of the Cu film (dots).

^{63}Cu into the 12.8 h half life positron emitter ^{64}Cu. The fraction of 69.1% of usable ^{63}Cu occurring in natural copper is usually increased to about 99% in enriched copper. Thus positron activities of 166 Cie^{+}/g can be achieved with 48 hour irradiations. After irradiation, the copper is transferred into the vacuum system, and evaporated onto a W(110) crystal surface. On this surface the epitaxial growth of single crystal copper in the (111) direction is preferred.[16] Cu (111) is the most suitable orientation if used as a moderator.[17] In this case the copper will be the source as well as the moderator.

Periodic irradiation, of sources does not interrupt or disturb work performed by other reactor users. The only interference with a steady supply of new sources are infrequent sample irradiations by other users of this high flux reactor port. In such cases a port with a somewhat lower neutron flux can be used. In contrast most LINACs cannot support the positron beam facility and other experiments simultaneously.

The short half life of the source is advantageous when maintenance work has to be done in the source chamber. In addition to the source material, only a few radioactive isotopes are produced. By using high purity copper, the radioactivity of impurities is kept more than six orders of magnitude below that of the ^{64}Cu isotope. At a LINAC the bremsstrahlung causes a high background radiation and activates material in the vicinity of the positron source. While positrons from pair production are unpolarized, a beam of polarized positrons is possible when they originate in β^+-decays as in ^{64}Cu.

The reactor-based beam operates in a pseudo DC mode that avoids the problem of pileup of signals during the short bursts of positrons in a pulsed beam. A pulsed beam is advantageous for time of flight experiments.

THE TECHNICAL REALIZATION

The Reactor Division routinely irradiates samples for all kinds of research. They have chosen aluminum capsules as containers that are inserted through thimbles into the reactor core at the end of long aluminum tubes. The apparatus to transfer the copper pellet from the reactor into the UHV system was based on this design. The copper sources produced by the reactor cannot be handled directly. The radiation level is high enough to require a remote control system for the transfer of sources into the vacuum chamber. The chamber must be shielded. A concrete house, referred to as the blockhouse, has been constructed around the source chamber. It is capable of protecting against up to 10kCi sources.

The capsule is held in a lead pig for about one hour to let the short-lived isotopes decay. It is cut off the *Al* tube and drops from the lead container on top of the blockhouse, through a drying chamber into a shear mechanism, where the source pellet is removed. In the drying chamber the small amounts of tritium contaminated cooling water from the reactor thimble on the capsule are evaporated and blown through filters in the reactors decontamination facility. Passing an airlock, the copper pellet reaches the crucible, where it is evaporated onto a tungsten crystal and forms the positron source.

In the shear the capsule is broken open to release the source pellet. The shearing process tears flakes off the capsule wall, which can fall into the crucible along with the pellet. These would poison the moderator crystal and greatly reduce the positron intensity of the beam. To prevent this, the part of the capsule that is sheared is made of high purity copper. The empty capsule and the plug are dumped into a lead pig inside the blockhouse.

As it drops out of the airlock, the copper pellet is guided through a tube into an alumina crucible. The copper is evaporated onto a W(110) crystal, which induces the crystalline growth of Cu(111). Annealing and a subsequent H_2S treatment increase the moderator efficiency of the copper. Depending on the initial evaporation, annealing improves the moderator performance by one order of magnitude while the sulfur treatment may gain another 20%. An x-ray study of a copper film verified the Cu(111)

structure. By resistive heating of the tungsten crystal, the copper can be evaporated onto a dump after it has decayed and the tungsten crystal is ready for a new source. After several source cycles the dump is replaced to keep the accumulation of radioactive material low.

An overview of the beam line is shown in figure 6. In the "run" position the copper-coated tungsten faces the beam line. The crystal can be electrically floated to give the beam its transport energy. An accelerator tube in front of this crystal position improves the geometry of the electric field. Here a tungsten single crystal transmission moderator of about 10^3 nm thickness can be rotated into place. A location close to the source is important to improve the geometry on which the efficiency depends to a large extent.

The slow positrons are transported by a magnetic guiding field.[18,19] Two sets of $\vec{E} \times \vec{B}$ plates guide the beam around a γ-ray shield and energy filter the positrons. The positrons can be guided to one of two experimental areas. A set of apertures on one line permits a continuous acceleration up to 16 keV. The other line is equipped with diffusion pumps and a large turbo pump to differentially pump a gas cell where a positronium (Ps) beam is produced.

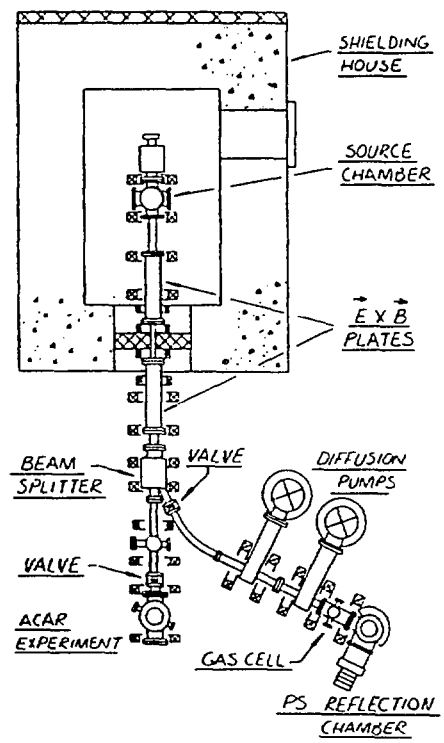

Fig. 6. Top view of the positron beam at the Brookhaven Reactor. Slow positrons are extracted from the source chamber and magnetically guided through two $\vec{E} \times \vec{B}$-regions out of the blockhouse. In the splitter the positrons can be directed to two experimental areas, the ACAR chamber or the Ps-beam line (PS). Shut off valves permit a separation from the main beam line.

As the source material, both spectroscopic pure copper metal (69.1% of usable ^{63}Cu) or isotopic ^{63}Cu oxide (about 99% of ^{63}Cu) from Oak Ridge National Laboratory (ORNL) can be utilized. The isotopic copper oxide is first reduced to metal. Care must be taken to keep the copper free of impurities that would inhibit its use as a good self moderator.

PROBLEMS, IMPROVEMENTS AND RESULTS

Iron and cobalt impurities in the capsule material caused higher than expected radiation levels, owing to neutron induced activation. Higher purity aluminum is now used as the capsule material. The capsule walls are kept thin to accumulate less radioactive waste.

Impurities and dirt that were transferred with the copper poisoned the moderator. Capsules now have a copper piece where they are sheared. Much of the copper was lost during evaporations from an open wire basket. Now an outgassed alumina insert in the wire basket increases the copper yield on the tungsten. Also, the contamination of the vacuum chamber with copper is greatly reduced.

Of prime concern are impurities that are already contained in the source material. An analysis of the γ-ray spectrum of an irradiated pellet showed lines of several metals. Only high grade spectroscopic copper or carefully enriched and reduced material can be used. ^{64}Cu also decays to ^{64}Zn via a β^--decay. Some of this ^{64}Zn will be converted to ^{65}Zn which emits a 1.115 MeV γ-ray during its decay with a halflive of 245 days. Although the activity of impurities is below 1mCi/g of copper they accumulate to significant amounts due to the longer half lives. For this reason, the copper dump is changed periodically. The evaporation procedure is still being refined to produce copper films with a better crystal structure and fewer defects.

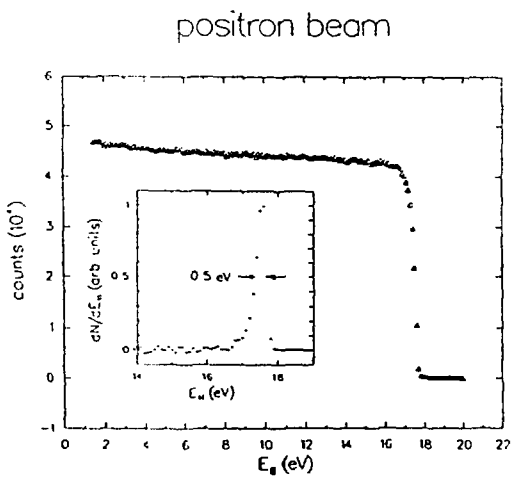

Fig. 7. Retarding potential measurement of the longitudinal energy spread of the positron beam at 18 eV energy. The retarding potential was applied on the gas cell at the end of the Ps-beam line.

Count rates up to 1×10^8 e^+/s have been reached using the self moderation mode. The transmission moderator produced lower rates and it was dismantled as the source evaporation became more reliable. In the gas cell, after the curve in the beam line, the FWHM of the energy spread of the beam was measured to be on the order of 0.5 eV (see figure 7).

OUTLOOK

In order to make measurements and estimates of the conversion efficiency of the moderator possible, a surface barrier detector will be installed to count fast β-particles coming off the source. A neon moderator will be tested and will finally replace the copper self moderator. The implementation is discussed in the appendix.

The possibility of mass-separation of ^{64}Cu from the much more abundant but inactive ^{63}Cu is being investigated. About 2.4×10^{-4} of the copper atoms are ^{64}Cu after a 48 hour irradiation. An improvement of this ratio by a mass separation during the evaporation will increase the specific activity. The source crystal could be made thinner. A higher efficiency ε (see fig. 3) will result in a higher count rate of positrons in the beam. This also will be discussed in the appendix.

A hybrid guiding system is envisioned for a second generation system. The positrons are extracted electrostatically from the source region. For longer distances a magnetic guiding field is planned, which returns to an electrostatic system at the experimental area if required. The source chamber could be floated up to 100 keV. Finally several beam switches are planned to make this beam a multi-user facility.

APPENDIX

The calculation of the efficiency of a self moderator provides the expressions used in section 3. More detailed estimates about the planned neon moderator are presented in the following part. An estimate of possible improvements of the self moderator by incorporating an on-line separation system of ^{64}Cu into the system concludes the appendix.

The self moderator

Positrons originating in β^+-decays of the ^{64}Cu thermalize rapidly and diffuse throughout the crystal. Either they annihilate with electrons or reach the surface. If they do not fall into a surface state or pick up an electron and form Ps they are expelled into the vacuum due to the negative workfunction of the crystal. Modifications to this part result from the fact that the source material is not a free standing foil. The substrate - W(110) in this case - causes a change in the boundary conditions at the interface side. A fraction f of fast positrons will be reflected back into the copper layer. The remaining positrons penetrate the interface and thermalize in the tungsten. They all diffuse throughout the material and have a finite probability of returning to the surface where they can contribute to the positron beam. Since the workfunction of tungsten is more negative than the workfunction for copper this junction acts like a diode which tends to push the thermal positrons out of the tungsten.

The average time for positrons to thermalize (<10 ps) is very short compared to the half life of the source. Consequently the steady state solution of the diffusion equation adequately describes the situation. In addition the large area of the source moderator in relation to its thickness permits a one dimensional calculation. A perfect interface is assumed in this derivation. Further the possibility of positrons scattering

out of the source while they thermalize parallel to and near the surface is neglected. These assumptions tend to overestimate the resulting ε.

From the exponential implantation profile of a source far removed from the moderator the profile for a source moderator can be calculated. Figure 8 illustrates how the reduction to one dimension has been performed. The exponential profile leads to the source moderator profile

$$p_s(x) = \frac{1}{d}\int_0^1 dt \left[1 - e^{-\frac{1}{2}\alpha d/t} \cosh \frac{\alpha(d/2 - x)}{t}\right]; \; t \equiv \cos\theta \; . \qquad 8a$$

Alpha can be calculated from the empirical formula[15]

$$\alpha = C\,\rho Z^{0.25}/\bar{E}^{1.58}; \; C = 1.1 cm^2/_g MeV^{1.58} \; . \qquad . 9$$

d is the thickness of the crystal. ρ is the density, Z the atomic number and $\bar{E}$ the mean energy of the β^+-spectrum ($\bar{E}$ = 0.2 MeV for copper). Similarly the contributions to the implantation profile due to the back reflection $p_f(x)$, and the implantation into the tungsten $p_w(x)$ are calculated. Figure 9 shows the various implantation profiles.

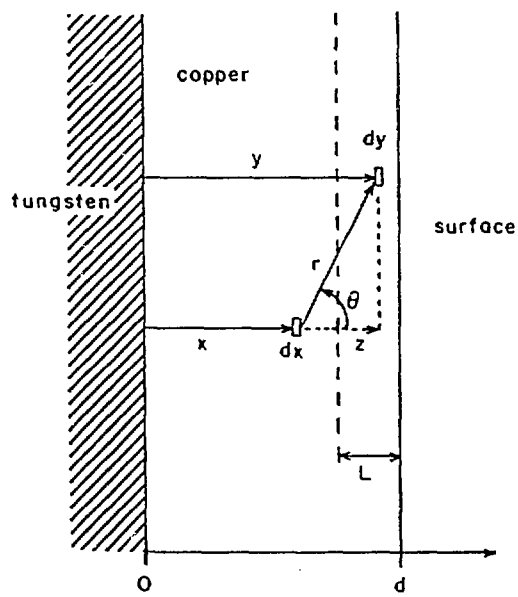

Fig. 8. Schematic to illustrate the calculation of the 1-dimensional implantation profiles. The positrons created at dx stop after a flight path r in the direction θ at dy. Integration across the source yields the implantation profile. The source area is assumed to be large compared to its thickness.

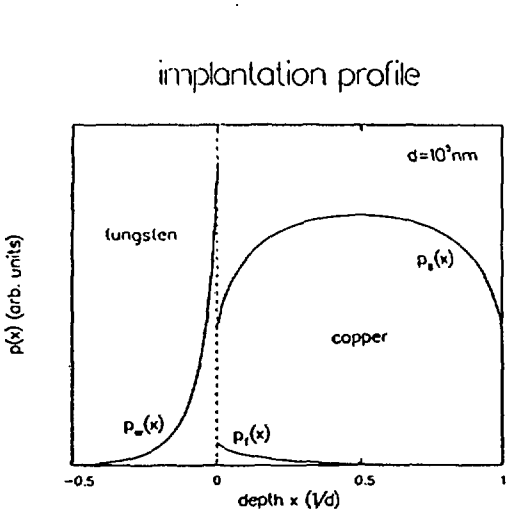

Fig. 9. The contributions to the implantation profile of the Cu self moderator on a single crystal W substrate. Shown are the profile from the self moderating source $p_S(x)$, the fraction due to backscattering $p_f(x)$, and the implantation into the W substrate $p_w(x)$. The Cu layer is 10^3nm thick.

$$p_f(x) = \frac{1}{2d} f \int_0^1 dt \left(1 - e^{-\alpha d/t}\right) e^{-\alpha x/t} \qquad 8b$$

$$p_w(x) = \frac{1}{2d} (1 - f) \frac{\alpha_w}{\alpha} \int_0^1 dt \left(1 - e^{-\alpha d/t}\right) e^{+\alpha_w x/t} \qquad 8c$$

The implantation profiles are used in the diffusion equation for a steady state. The density n(x) of positrons vanishes at the copper surface and deep in the tungsten. The flux j(x) is continuous at the interface.

The fraction Y_0 is emitted as slow positrons. Y_0 and j(d) form the efficiency of the self moderator $\varepsilon(d)$. The various contributions amount to

$$\varepsilon_s(d) = \frac{1}{2} Y_0 \frac{L_+}{d} \left[L_+\alpha \int_0^1 dt \frac{t}{t^2 - L_+^2\alpha^2} \left(1 - e^{-\alpha d/t}\right) \right.$$

$$+ \tanh \frac{d}{L_+} \left(L_+\alpha \ln \frac{1 + L_+\alpha}{1 - L_+\alpha} + \int_0^1 dt \frac{t^2}{t^2 - L_+^2\alpha^2} \left(1 - e^{-\alpha d/t}\right) \right) \qquad 10a$$

$$\left. + \frac{1}{\cosh \frac{d}{L_+}} L_+\alpha \int_0^1 dt \frac{t}{t^2 - L_+^2\alpha^2} \left(1 - e^{-\alpha d/t}\right) \right]$$

$$\varepsilon_f(d) = \frac{1}{2} Y_0 \frac{L_+}{d} f \left[L_+\alpha \int_0^1 dt \, \frac{t}{t^2 - L_+^2\alpha^2} \left(1 - e^{-\alpha d/t}\right) \; e^{-\alpha d/t} \right.$$

$$+ \tanh \frac{d}{L_+} \int_0^1 dt \, \frac{t^2}{t^2 - L_+^2\alpha^2} \left(1 - e^{-\alpha d/t}\right) \; e^{-\alpha d/t} \qquad 10b$$

$$\left. - \frac{1}{\cosh \frac{d}{L_+}} L_+\alpha \int_0^1 dt \, \frac{t}{t^2 - L_+^2\alpha^2} \left(1 - e^{-\alpha d/t}\right) \right]$$

$$\varepsilon_w(d) = \frac{1}{2} Y_0 \frac{L_+}{d} (1 - f) \frac{L_w\alpha_w}{L_+\alpha} \frac{1}{\cosh \frac{d}{L_+}} \int_0^1 dt \, \frac{t}{t + L_w\alpha_w} \left(1 - e^{-\alpha d/t}\right) \qquad 10c$$

Figure 3 shows the efficiency of a crystal depending on its thickness d. For copper $Y_0 = 0.55$ and $f = 0.17$ was estimated for the Cu-W interface.[20] With growing thickness $\varepsilon(d)$ decreases. On the other hand this is more than compensated by the larger amount of source activity. In the case of a source moderator the product E(d) of efficiency and thickness describes the situation better.

$$E(d) = d\varepsilon(d) \qquad 7$$

The absolute source strength is the product of the specific source activity, the source area, and E(d). Figure 4 shows the various parts of E on a logarithmic scale versus the thickness of the copper layer. At about 10^5 nm E levels off. Additional amounts of copper do not improve the source strength unless the area is increased.

For d of about an order of magnitude larger than $L_+ = 110$ nm

$$\tanh \frac{d}{L_+} = 1; \; \cosh \frac{d}{L_+} < 10^{-4} .$$

which simplifies equations (10) and (7) to

$$E(d) = \frac{1}{2} Y_0 L_+ \left[L_+\alpha \ln \frac{1 + L_+\alpha}{1 - L_+\alpha} + \int_0^1 dt \, \frac{t}{t - L_+\alpha} \left(1 - e^{-\alpha d/t}\right) \right]. \qquad 11$$

The Neon moderator

As mentioned by Mills and Gullikson rare gas solids and solid neon in particular, can be used as positron moderators.[13] They report a high yield (Y_0=0.7) and a large diffusion length ($L_+ \approx 10^3$nm) for solid neon. A moderation efficiency $\varepsilon = 7 \times 10^{-3}$ measured by them is higher then any previously known moderator. Neon was condensated onto a cylindrical source geometry to take advantage of the large reflection coefficient of Ne for slow positrons.

The first neon moderated beam[21] performed at the high initial level over a period much larger than the half life of ^{64}Cu. With the cylindrical source geometry self absorption of a ^{64}Cu source can be reduced. The larger surface area of the cylinder permits a thinner copper layer without increasing the beam cross section. The efficiency of a copper source-neon moderator combination was estimated using the same approach as for the efficiency calculation for a self moderator presented in this paper. A 3000 nm thick layer of Ne on a 1.6×10^4nm thick Cu source result in an efficiency ε=0.64%. A 100 mg source of enriched ^{63}Cu irradiated for two days and evaporated onto a 7 cm^2 area of a cup (1 cm diam.; 2 cm high) would yield close to 4×10^9/sec slow positrons.

The reported energy spread of 0.58eV for neon moderators is acceptable. Some advantages of the neon moderator are as follows: 1) no single crystal copper is necessary; 2) no spectroscopically pure material is required; 3) the copper does not have to be removed prior to a new source evaporation. The cup itself can be replaced after several months. The design of a liquid He cooling system inside a LN_2 cooled thermal shield to achieve a temperature of 6K appears to be straight forward. Possible disadvantages are that the base pressure of the vacuum system should be in the 10^{-10}torr range to prevent contamintion and the excellent properties of the neon moderator may be affected by the high radiation level of the source. A neon moderator for the reactor beam will be installed in the near future.

On-line Isotope Separation

The plan is to vaporize the copper and then selectively ionize the ^{64}Cu atoms and only collect these on the tungsten substrate. The ionization could be carried out by means of tunable dye lasers. This method would take advantage of the different hyperfine structure splitting of the atomic energy levels of the various copper isotopes.[12]

At about 200 nm thickness the efficiency of a self moderator peaks. (see fig 3) A reasonable compromise between source size and positron rate is a layer of this thickness. A present about 1 in 4000 ^{63}Cu atoms will be converted to ^{64}Cu during one irradiation. The proposed separation process enhances the ratio of ^{64}Cu to ^{63}Cu by a factor of 1000. Then up to 24% of the source will be active. The total efficiency at 200 nm thickness is about 5×10^{-3} and the result would be a beam of 1×10^{10} e^+/s with a 1 cm^2 source area. To achieve this it would be necessary to irradiate ≈280 mg of isotopic copper for 3 days.

The separation requires some time. A rate of 10^{-8}g ^{64}Cu/min was estimated. Then evaporation times of 2 – 3 hours are necessary. On the other hand the area of the source could be reduced without losses in brightness and within a shorter irradiation time on the order of an hour. A beam of several mm^2 size and $10^8 e^+$/s seems to be realistic.

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