Studies of the formation of slow positrons in MgO-coated moderators

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Studies have been made of the production of slow (~1 eV) positrons by high-energy positrons from a radioactive source. Moderators consisting of thin metallic foils coated with MgO smoke were used in the transmission mode. The thinnest foils gave the largest fluxes of slow positrons. A double moderator, consisting of a MgO-coated grid following the MgO-coated thin foil, gave a flux almost double that of either the foil or grid alone. The positron beam machine used is described. It has electrostatic optics for the collection, analysis, and transmission of the slow positrons.

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I. INTRODUCTION

Since the discovery[1] in 1968 that low-energy (slow) essentially monoenergetic positrons (~1 eV) are emitted from metal surfaces which have high-energy positrons incident on them, several positron beam machines have been built and used in a variety of experiments. These experiments have included the first direct measurement of the vacuum decay rate of ortho-positronium,[2] the first observation of the $n = 2$ state of positronium,[3] studies of the scattering of low-energy positrons with a variety of gases,[1,4-6] and the study of the positron emission itself.[7,8]

The major limitation in these experiments has been the low intensity of the beam. The conversion process by which the energy of the positrons is reduced from several hundred keV to 1 eV and then emitted is very inefficient. Between 10^4 and 10^7 fast positrons are needed for each slow positron emitted. The yield seems to be a sensitive function of the metal[8,9] used and the condition of its surface. In 1971[10] it was found that a coating of MgO fumed on the metal greatly increases the yield. Despite the importance of this advance, no systematic study of the MgO-coated moderator has yet been published. The present paper reports a series of experiments on MgO-coated moderators, concentrating on combinations of foil and grid moderators. There is no well-established theory of the moderation-emission process in MgO. It is hoped that these results will help to provide the groundwork needed to formulate the theory of this process.

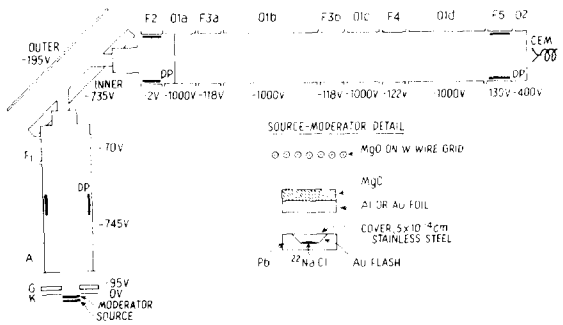

FIG. 1. Schematic of positron beam machine. The name and voltage on the lens elements are shown. Further details are in Table I. The insert shows the source moderator configuration, here using the sealed ^{22}Na source and the double moderator.

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II. POSITRON BEAM DESCRIPTION

A positron beam generator consists of a radioactive source, moderator, and entrance optics to collect the low-energy positrons into a beam, energy analysis to remove the

TABLE I. Lens Specifications. Figure 1 shows the placement of the lenses.

Symbol	Lens name	Diameter (mm)	Length (mm)	Voltage
K	Cathode	9.5 hole	5.6 spacing to grid	0
G	Grid	9.5 hole 6 thick	11 spacing to anode	− 95
A	Anode	9.5 hole 26 tube	114	− 745
D.P.	Anode deflection plates	24	25	...
F1	Focus 1	26	24	− 70
Inner	Analyzer inner cylinder	26, 13 tube 3 hole 19 rod	32	− 735
Outer	Analyzer outer cylinder	52		− 195
F2	Focus 2	26	24	− 2
D.P.	Focus 2 deflection plates	24	24	...
O1a	Output 1*a*	26 3 hole	32	− 1000
F3a	Focus 3*a*	26	26	− 118
O1b	Output 1*b*	26	100	− 1000
F3b	Focus 3*b*	26	26	− 118
O1c	Output 1*c*	26	36	− 1000
F4	Focus 4	26	26	− 122
O1d	Output 1*d*	26	80	− 1000
F5	Focus 5	26	26	− 130
D.P.	Deflection plates	24	25	...
O2	Output 2	26 3 hole	13	− 400

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unmoderated high-energy positrons and gamma rays from the source, a transport system to carry the beam to the experimental region, and a detector. The present beam was designed to be used on studies of the polarization of the positron beam and the measurement of positronium lifetimes. Thus, high efficiency with minimal energy resolution was desired, to be achieved without the use of magnetic fields for collection or analysis. The details are shown in Fig. 1.

The source was either ^{22}Na or ^{58}Co. The ^{22}Na source was 10 mCi in activity, consisting of NaCl deposited in a depression in a Au-flashed lead pellet. A 5×10^{-4}-cm-thick stainless steel foil sealed the source. The ^{58}Co sources (38, 50, and 150 mCi) were electrodeposited on thin (0.012 mm) copper foils, annealed, and coated with Krylon spray. A lead backing sheet increased the slow positron flux by 30% by backscattering high-energy positrons. A variety of moderators, described later, have been used. These were placed between the source and the entrance optics.

The entrance optics consisted of a triode "electron gun" followed by a three-element lens. The gun was composed of aperture lenses. All remaining lenses were cylindrical tube lenses, made of commercial copper tubing. The triode gun was based on the design described by Soa,[11] but it has been found that the grid voltage must be much higher than prescribed by Soa. Computer simulation[12] of the particle trajectories in the gun showed that with low grid voltages the lens is extremely sensitive to variations in the initial energy of the particles. Even though the positrons are emitted with an energy spread of no more than 1 eV, the energy sensitivity of the gun prevented formation of an achromatic focus. At the grid voltage used the gun produces a diverging beam, with 745 eV energy, which is coverged by the three-element lens to pass through a 3-mm-diam hole at the entrance of the energy analyzer.

A cylindrical mirror analyzer[13] with slits (circular holes) on the axis was used. A compact model (inner cylinder 19-mm diameter, outer cylinder 52-mm diameter, length 100 mm) was built of copper rod and tubing. Four logarithmically spaced guard wires at the appropriate potentials were used to reduce fringing fields at the edges of the analyzer semicylinders. The analyzer bent the beam through 84.6°, an angle which allows a second-order focus at the output hole. At a central energy (E_0) of 750 eV the measured energy width (FWHM) of the analyzer was 0.05 E_0, in good agreement with theory.

The output of the analyzer went into a series of lenses designed to carry the beam to a target area far enough away from the source to allow efficient shielding from the source gamma rays. The first lens had three elements and a short focal length $F = D$, where D is the lens diameter. The central element had deflection plates to bend the beam through the additional 5.4° so that the total beam deflection was 90°. The second lens was a five-element lens with its first image at infinity, and its second in the middle of the last element. A second identical five-element lens was used to make the total beam transport 50 cm. A set of deflection plates at the final low-voltage lens was used to center the beam on a 3-mm-diam aperature. Behind the aperture was a Channeltron electron multiplier to detect the positrons.

The transmission of the beam was determined, but the collection efficiency and transmission of the entrance optics was extremely difficult to measure. The radioactive source caused a high background in any particle detector, and use of an electron filament in place of the source could cause systematic errors because of the difference in emission area, angle, and energy distribution. These difficulties were not present in later elements of the beam. The transmission of the analyzer alone was (90 ± 10)%. The output lenses transmitted (90 ± 5)% of the positrons incident on them through the final 3-mm-diam hole at 400 eV energy. In the original version[14] of this beam there was a second identical energy analyzer. It was found, however, that only 30% of the beam could be refocused well enough to pass through the second analyzer, presumably due to aberrations in the analyzers and the lenses. A second change made in the beam was the use of short focal length lenses in the output section. This change allowed the beam to be brought to a focus at a 3-mm-diam hole. The best flux obtained was 1800/sec from the sealed 10 mCi ^{22}Na source.

The vacuum system maintained pressures near 10^{-7} Torr using a 240 l/sec Vac Ion pump with a brass and aluminum chamber sealed with Viton O-rings. A magnetic shield was constructed out of 0.8-mm-thick Moly Permalloy to fit within the chamber. Once it was annealed and degaussed, it reduced the Earth's magnetic field to 25×10^{-7} T or less. The lenses were made of copper tubing, with a 26-mm inside diameter. They rested on an aluminum lens bench using tubular glass ceramic beads as insulators. The analyzer used machinable glass-ceramic (Corning Glass Works' MACOR) supports. Other insulators were Teflon and mylar. Reasonably clean vacuum practice was observed, but no attempt was made to reach ultrahigh vacuum conditions. The lens potentials came from a series of voltage dividers powered by a 1-kV 30-mA power supply. Voltage divider chains were made of fixed resistors and 10-turn potentiometers, having current limiting resistors between the wiper blade and the lens. Shielded cables were used between the potentiometer box and the glass-kovar vacuum feedthroughs. The deflection-plate potentials were supplied by 45-V batteries floating at the lens voltage. Each set of four plates had two batteries: one potentiometer for adjustment of the average voltage, and two to adjust the potential differences between pairs of opposing plates.

III. TESTS OF MODERATORS

The moderator accepts positrons with energies up to the endpoint energy of the source, about 500 keV, and emits a few positrons with energies in a narrow range near 1 eV. The output energy distribution has been measured by several authors.[4,5,7,9,10] Mills[8] has shown that the yield, y of slow positrons reflected (from clean aluminum) depends on the energy of the incoming positron E as

$$y = y_0 E_0 (E + E_0)^{-1},$$

where $E_0 = 720$ eV and $y_0 = 0.39$. This relationship, tested in the range 200 eV $\leqslant E \leqslant 3$ keV, predicts that most of the slow positrons come from positrons originally at the low end of the incoming spectrum. However, self absorption and the

positron-nucleus repulsion remove all but a negligible fraction of positrons from this end of the beta spectrum. Measurements of the yield by higher energy positrons are needed.

Moderators work either in the backscattering mode, where the positrons enter and leave the same surface, or in the transmission mode, where the emitting surface faces away from the source. In addition, one commonly used moderator[6] is of the venetian blind geometry and may involve double backscattering.

The most commonly accepted model of the moderation-emission process is that the positrons lose energy by scattering in the metal, are thermalized, then diffuse to the surface where some escape with an energy characteristic of the metal and surface. The scattering process probably involves both multiple small-angle scattering, mainly with electrons, and single large momentum transfer events, mainly with electrons, and single large momentum transfer events, mainly with nuclei. The escape process is not well understood. One theory suggests that there is a positron work function, which imparts a positive energy to the positron expelled from the surface of some metals.[15] Recent work by Mills, *et al.* (private communication), shows satisfactory agreement with theory for several metals. Another theory,[6] noting the high slow positron yield from surfaces on which positronium is efficiently formed, suggests that electric fields on the surface of the MgO grains dissociate positronium (probably in an excited state), releasing the positron.

The present series of tests were conducted more to explore moderator designs which produce a high yield than to make a critical test of either theory. Probably a great deal of information must be learned about the process before a conclusive test can be made.

The first moderators tested were of the venetian blind geometry.[10] A set of four vanes were cut from 2.5×10^{-3}-cm-thick gold sheets and were annealed in a flame. The 1.5-mm-wide vanes, 1 cm in length, were spaced 1 mm apart. A ^{58}Co source of 46 mCi strength was used with the earlier beam configuration.[14] With MgO formed by burning a Mg ribbon in air, 50 ± 5 counts/sec were recorded. Since it is likely that at the high temperature at which Mg burns there is some Mg_3N_2 contamination, the ribbon was burned in oxygen which had been collected over water. In several trials

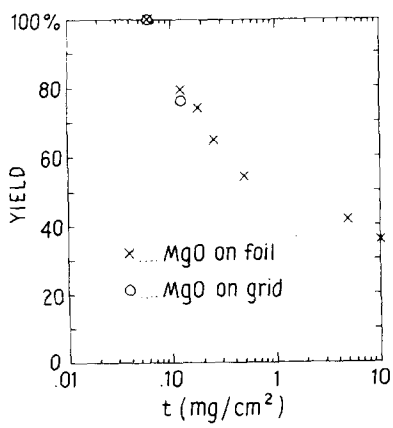

FIG. 2. Yield-vs-metal foil thickness for aluminum. Yields are given with respect to the flux obtained using the minimum foil thickness (one leaf).

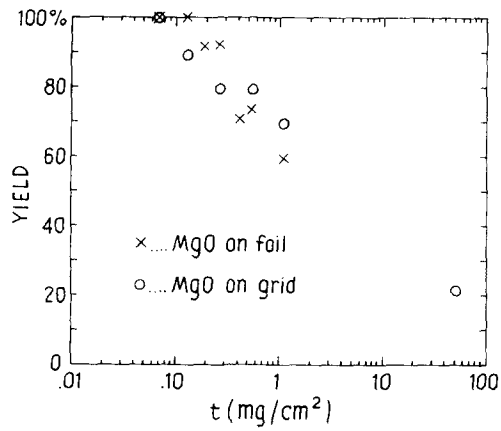

FIG. 3. Yield-vs-metal foil thickness for gold. Yields are given with respect to the flux obtained using the minimum foil thickness (one leaf).

the yield varied from 55 to 72 c/s. Thus, there is an increase in slow positron yield when the MgO is burned in O_2. The influence of the atomic mumber of the backscatterer was tested by using vanes made of copper. MgO burned in O_2 gave 48 ± 4 c/s, somewhat smaller than the yield from gold vanes. The bare copper surface was heated until coated with a thick black oxide. Only 15 ± 3 c/s of positrons were found. Thus, not all metallic oxides are efficient slow positron emitters.

Analysis of the results of Canter *et al.*[10] seemed to indicate that the venetian blinds were effective moderators because the positrons had a significant chance of undergoing several collisions. This is reasonable because those positrons backscattered with an energy of a few kilovolts could strike the second vane and thermalize near the surface, having an increased escape probability. This reasoning prompted the design of an optically dense chevron-shaped moderator, made of gold vanes and covered with MgO burned in O_2. Only 21 ± 2 c/s were observed, considerably below the number from a sample venetian blind. Evidently several collisions are not the only key to efficient slow positron production.

One of the problems with the venetian blinds in the present beam was apparently the large size of each vane (1 mm) compared with the effective entrance aperture of the beam (3-4 mm). Attempts at making significantly smaller vanes failed. This, together with the need for a sample geometry for the proposed polarization experiment,[14] prompted a return to the transmission geometry which had been used in the first slow beam,[1] but was generally discarded after backscattering geometry showed higher yields. Pendyala,[16] showed that gold films evaporated on mica had slow positron yields which peaked at 200-300 nm of Au. To avoid difficulties associated with metallic surfaces in the present vanes in the 10^{-7} Torr vacuum, MgO was always used as the emission surface. The MgO, burned in air, was 2-5 mg/cm^2 thick, thick enough to thermalize positrons with energies up to 50 keV. The MgO was backed with a metallic foil of variable thickness.

Three types of foils were studied, mylar with an evaporated gold surface, aluminum, and gold. In each experimen-

TABLE II. Beam flux (in counts/sec) for various combinations of foil, MgO, and MgO-coated grid. Source, foil, and grid arrangement is shown in Fig. 1 (insert).

Foil		Grid alone	Grid plus foil	Foil with MgO	Grid plus foil with MgO
Au	68 $\mu g/cm^2$	980	790	810	1500
	49 mg/cm^2	980	220	220	220
Al	62 $\mu g/cm^2$	1040	770	720	1140
	14 mg/cm^2	1040	390	270	550

tal series, MgO was fumed on a foil and additional uncoated foils were stacked between the source and the coated foil to test the effect of foil thickness. Results are discussed separately:

(1) Evaporated Au on mylar: There were two foils available which had gold of 100 and 150 nm thickness (0.2 and 0.3 mg/cm^2, respectively) on 0.53×10^{-3}-cm (0.5 mg/cm^2) thick mylar. The original beam configuration was used with the 10-mCi ^{22}Na source. The thinner foil gave the higher yield, and the yields dropped uniformly as more foils were added. The difficulty in separating the effects of the plastic and gold in these experiments lead to the use of metal foils.

(2) Aluminum: From 1 to 16 stacked aluminum foils of 68 $\mu g/cm^2$ each were used. For still thicker foils, commercial grade rolled aluminum from 1.7×10^{-3} to 5.1×10^{-3} cm was used. The results are shown in Fig. 2. Again there was no indication of a peak in yield, but only a secular decrease with increasing thickness.

(3) Gold: Commercial hammered gold leaf (23 carats) was used. Each leaf was 63 $\mu g/cm^2$, or about 35 nm thick. Up to 16 leaves were stacked. The results are shown in Fig. 3. There is no peak, but the reduction in beam flux was less than for aluminum, and the flux was almost constant out to 240 $\mu g/cm^2$ thickness.

(4) The results of (2) and (3) above suggested that peak positron flux may be obtained by using a self supporting MgO film. As a practical substitute, a knitted tungsten grid made of 2.5×10^{-3}-cm-diam wires was used.[17] MgO was fumed on this grid, building up the same thickness used on the foils. Because of the refractory nature of the grid, it could be coated in the hotter part of the flume, where the MgO builds up more quickly. Positron beam flux was between 900 and 1200 cps, depending on the thickness of MgO. The maximum flux was for an intermediate thickness, about 20×10^{-3} cm. At this thickness, the grid had about 50% of the open area covered. This flux is about equal in intensity to that obtained using either one aluminum or one gold leaf.

(5) Al and Au foils were placed between the source and the grid. The decrease in flux was the same as when the MgO was coated directly on the foil. (See Figs. 2 and 3) This suggests that the MgO-metal interface is not important in the formation of slow positrons.

(6) A double moderator was constructed by placing a metallic foil coated with MgO between the source and the MgO-coated grid. This combination increased the flux by up to a factor of 2. The enhancement, predicted by Donnalley,[18] is probably due to some high-energy positrons which pass through the foil and MgO, but then strike the MgO on the grid and are moderated and emitted. At the same time, many of the slow positrons from the foil-MgO can pass through open areas of the grid. The electric fields in the collecting lens undoubtedly improve this extraction process. The yield is reduced when the MgO coating on the grid reduces the open area to much lesss than 50% of the total.

The series of tests decribed in Table II were done to compare grid alone, grid plus metal, metal coated with MgO alone, and grid plus MgO-coated metal. For thin Al and Au there is little difference whether the MgO is on the foil or on the grid, and in both cases the double moderator gives the largest flux. For thick aluminum, with MgO on the grid, there is a somewhat greater flux, but the double moderator has a still higher yield. Note that positrons must have at least 100 keV in energy to penetrate this aluminum foil. The thick gold, however, shows no larger yield for the double moderator.

(7) The effect of metallic defects on slow positron flux was seen in two ways. The thick gold foils were formed by rolling a 0.13-mm gold sheet. A foil rolled to 0.025 mm placed behind a MgO-coated grid gave 150 c/s. After annealing in a flame the same foil gave 250 c/s. It is likely that rolling creates defects in the metal where positrons are trapped and annihilate. A double moderator was used over a period of 60 days, during which the flux gradually dropped from 1400 to 900/sec. Replacing the MgO-coated grid made no change in the flux, but replacing the foil and its coating increased the flux to its original value. It is likely that the 10-mCi source caused radiation-induced defects in the gold leaf which trapped some moderated positrons. No other type of foil was used over a long enough period of time for such an effect to develop.

IV. CONCLUSIONS

The double moderator is an important advance in the slow positron art. The best beam flux found was 1800 cps for a 10-mCi ^{22}Na sealed source. This is 5.4×10^{-6} slow positrons per source positron decay. Using the identical double moderator with a ^{58}Co source gave an additional factor of 2 increase in beam, with up to 1.1×10^{-5} slow positron per source positron emitted. The difference is what could be expected from the attenuation of the stainless steel ^{22}Na source cover. While this conversion efficiency is not as high as reported by other workers, it is known that the entrance optics was not very efficient. Higher fluxes are expected from a redesigned beam.

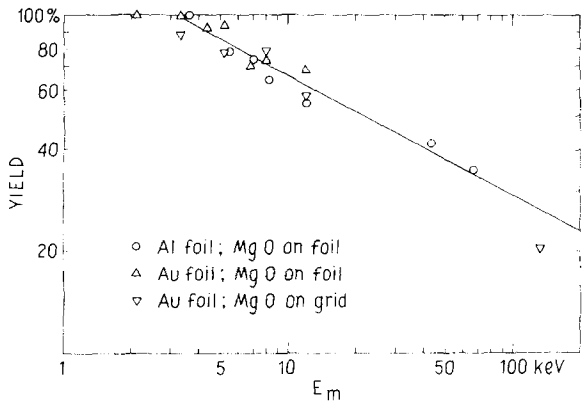

FIG. 4. Yield plotted versus the energy which electrons would need to have a range equal to the thickness of the foil. Positron energies are likely to be similar.

Figure 4 shows on a log-log plot the relative yield as a function of the energy of an electron which would have a range equal to the thickness of the foil. Electron ranges[19] were used because positron ranges are not available, but the two could be expected to have a relatively constant ratio. The yields are relative to the beam flux obtained either with a grid alone or a single coated foil, depending on run. This graph should be considered as an interesting speculation because it unifies data from aluminum and gold, metals having very different Z and A. It suggests that even though positrons from low input energies are most efficiently moderated, those with energies up to 100 keV can be moderated with efficiencies reduced by a factor of 3 or less.

These conclusions are consistent with the results of Mills,[8] who measured the production of slow positrons by positrons with energy up to 3 keV incident on thick, clean, metal surfaces. Measurements of the polarization of the slow positrons,[20] now underway, should help to clarify the energy region from which the slow positrons are produced, as well as the process of emission from the MgO grains.

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