UCRL- 89212
PREPRINT
Conf-830740--1

UCRL--89212

DE83 012941

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R. H. Howell and R. A. Alvarez
University of California
Lawrence Livermore National Laboratory
Livermore, CA 94550

K. A. Woodle, S. Dhawan, P. O. Egan
V. W. Hughes, and M. W. Ritter
Yale University
Gibbs Laboratory
New Haven, CT 06520

This paper was prepared for submittal to
NATO Advanced Research Workshop on
Positron Scattering in Gases
July 19-23, 1983

May 1983

Lawrence
Livermore
National
Laboratory

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SUMMARY

Beams of monoenergetic positrons with energies of a few eV to many keV have been used in experiments in atomic physics, solid-state physics and materials science. The production of positron beams from a new source, an electron linac, is described.

Intense, pulsed beams of low-energy positrons have been produced by a high-energy beam from an electron linac. The production efficiency, moderator geometry, beam spot size and other positron beam parameters have been determined for electrons with energies from 60 to 120 MeV. Low-energy positron beams produced with a high-energy electron linac can be of much higher intensity than those beams currently derived from radioactive sources. These higher intensity beams will make possible positron experiments previously infeasible.

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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INTRODUCTION

Since the introduction of experiments using beams of mono-energetic positrons there has been a continuing effort to increase the intensity of these positron sources for both pulsed and continuous beams. These efforts have centered mainly around the improvement in the conversion of energetic positrons from radioactive sources to mono-energetic, low-energy positrons by improving the moderator material characteristics. This effort has led to higher beam intensity through improved moderator efficiency and a clearer understanding of the production of low energy positrons by a process of diffusion to the moderator surface and expulsion by the negative positron work function. The efficiency of the moderation process has been improved to such an extent that theoretical limits have been approched. Any further large increases in positron beam intensity must come from the use of more intense sources.

To provide a more intense source of positrons through radioactive decay requires the use of sources with short half lives. The limit of the positron intensity from the usual sources of positrons, ^{22}Na or ^{58}Co, results from the inability of the positrons from the back of the source to penetrate the source material and escape the source configuration. The overburden of material is lower in sources that have short half lives, ^{11}C or ^{64}Cu but these sources must be continually renewed by irradiation with an accelerator[1] or reactor.[2]

Intense sources of high energy positrons can be obtained by pair production in the bremsstrahlung field that results from hitting a radiator-converter with the electron beam. Positrons are produced in electron-positron showers resulting from repeated cycles of pair-production and bremsstrahlung radiation. The positrons can be moderated and emitted as low energy positrons in much the same way as in the radioactive source systems. Low energy positron beams produced by this technique have been used at other laboratories, but the beams were of low intensity.[3,4] More recently work at Livermore[5] has demonstrated that intense beams of low energy positrons can be derived from linac electron beams.

In the Livermore experiments the important parameters of the production of low energy positrons from high energy electrons have been identified and operating ranges established: The geometry of the electron radiator-convertor and positron moderator was studied, and the optimum radiator-convertor thickness was determined for both tungsten and tantalum convertors. The variation in positron production with primary electron beam energy was measured. The size of the positron emitting region on the moderator was determined for several incident primary beam angles. Some of the potential problems in routine production of intense beams were identified.

It was found that the most important parameter affecting low-energy positron production is the geometry of the radiator-converter and moderator. The best results were obtained with the closest coupling possible between these two elements. The optimum thickness of the radiator-converter is the same number of radiation lengths for the materials studied and the overall positron production was dominated by the power deposited in the radiator-converter regardless of electron beam energy for energies above 60 MeV.

EXPERIMENTAL DETAILS

The initial Livermore experiments were performed with a conventional bent solenoid slow-positron transport system, similar to those described in Refs. 6 and 7. This apparatus was used to measure the slow-positron production efficiency. The electron beam passed through thin stainless steel windows to reach the position of the electron-positron converter. The converter-moderator assembly was withdrawn to tune the electron beam. A bias between the moderator and an aperture accelerated the slow positrons to energies between 10 and 100 eV. This transport system had 50 percent transmission 1 cm off the central axis.

Initially, positrons were detected by a 1 cm diameter channel electron multiplier (CEM) positioned on the solenoid axis. The CEM was run in a single particle counting mode. Thus multiple positrons in a beam pulse were indistinguishable from single positrons. To measure the electron-beam-to-slow-positron conversion efficiency accurately, it was necessary to restrict the electron beam current so that the positron counting rate in the CEM was about 30 percent of the beam repetition rate of 1440 sec^{-1}.

A second system constructed at Yale allowed us to transport the slow positrons out of the accelerator cave and away from most of the beam-induced background. In this apparatus the positron transport efficiency is unmeasured but the transmission of thermal electrons is 86%. In the low background experimental area we used both NaI detectors and micro-channel plate detectors to measure the positron production rates with electron beam peak currents near the maximum available from the linac. Observations of both the output current trace of the micro-channel plate and the annihilation radiation counting rate in the NaI detectors placed far from the slow positron beam stop demonstrated that slow positron production was proportional to the beam current for all beam levels available at our linac.

A third positron transport system was constructed as a prototype of the positron production part of a permanently available low energy positron beam line dedicated to materials science experiments, Fig. 1. In the prototype system we could accurately determine the size and shape of the positron emitting beam spot by observing the optical output of a micro-channel plate. From the electrical output of the micro-channel plate we measured positron production efficiency and the distribution of the positron time of flight.

A new feature of the prototype transport system was that the radiator-convertor was outside the vacuum system and the moderator inside. Vacuum was maintained by a thin aluminium window. The transport system also has the capability of extracting and transporting the positrons using purely electrostatic elements or magnetic elements or a combination of both. By adjusting the fields in the prototype system it was possible to reduce the size of the spot on the micro-channel plate to less than 1/4 of the size of the positron emitting spot on the moderator.

In all transport systems the energy of the positrons was measured by the time of flight. The agreement between the energy measured by time of flight and the acceleration voltage uniquely identified the slow positrons. There was also a prompt signal produced by the intense bremsstrahlung flash from the primary linac beam. The prompt signal served as a convenient time mark for the time-of-flight determinations.

RESULTS

We found in all cases that close coupling between the electron radiator-converter and positron moderator resulted in the highest slow-positron yield. This is expected, since the positrons emerging from the converter have a high angular divergence. The best materials for radiator-converters have the combination of high density, high atomic number, high melting point and low residual radioactivity after use. For the radiator-converter we have used either tungsten or tantalum at different times and found that the positron yield is not sensitive to which of these materials were used. Both of these materials have all of the desirable characteristic except that they have high levels of residual radioactivity.

For the positron moderator tungsten was chosen from among the materials known to have high negative work functions for positrons because of its high positron yield, ease of preparation, and resistance to degradation in air. The higher atomic number of tungsten gives it a higher stopping efficiency for energetic positrons and a lower susceptability to radiation damage by positrons or electrons that have only a few MeV of energy.

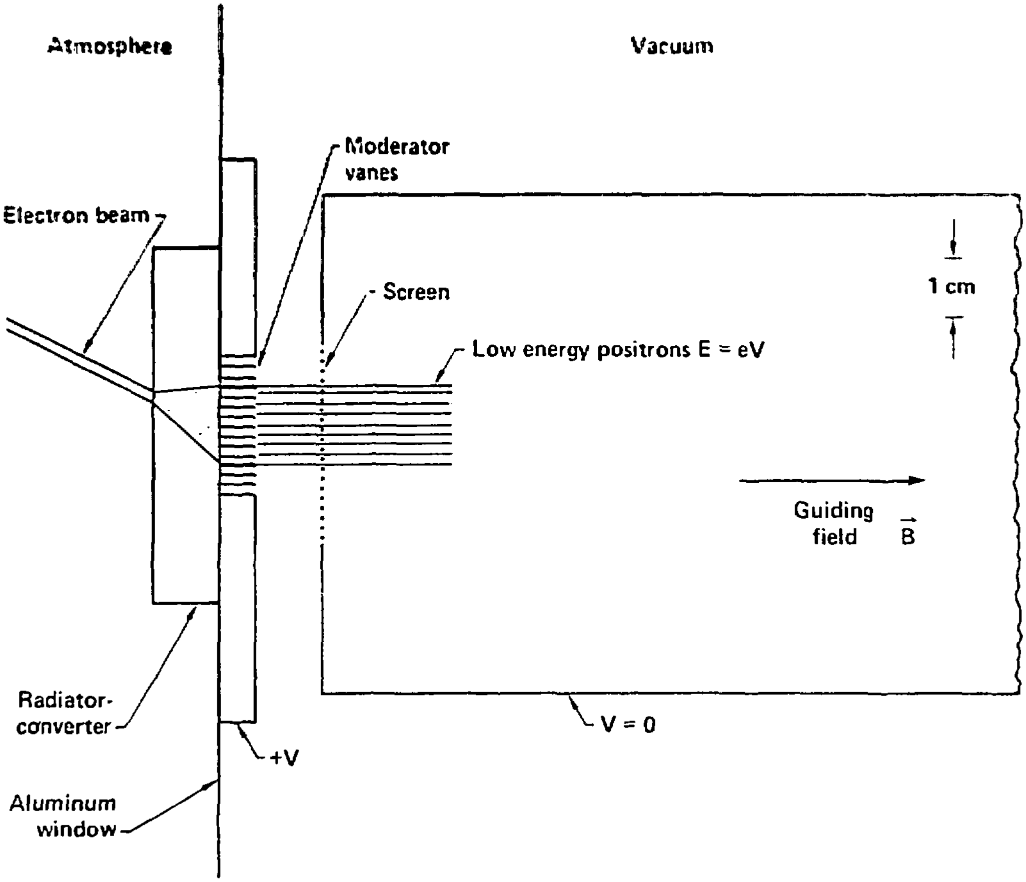

Fig. 1. Front end geometry of the prototype system designed to study design features for the permanent beam line being installed at Livermore. Problems of shielding from residual radiation and removal of heat are simplified by keeping the radiator-converter in air. Positrons were detected with a micro-channel plate 1.5 m from the moderator.

The moderator material was prepared as described in Ref. 8 and then stored and transferred in air to the experimental apparatus. Copper moderators also have a high positron yield, but must be prepared and stored in a high vacuum[9] and may not be as radiation resistant as tungsten.

The best geometry found for the moderator and transport consists of tungsten foils arranged as a series of vanes with the front edges facing the transport system and the surface of the vane parallel to the magnetic guiding field in the transport. Several other geometries for the moderator were tried including flat plates with the plate surface perpendicular to the guiding field and a series of wires arranged in a grid. Comparing these geometries, we found that the low energy positron yield was the highest with the vanes and was lower in the other geometries by about the same amount as the reduction in surface area of the moderators.

In Ref. 5 the positron yield is reported for different electron radiator-converter thicknesses; the best yield was found at three radiation lengths for electrons in tantalum. Similar measurements, shown in Fig. 1, were made with 100 MeV electrons and a tungsten radiator-convertor in the prototype transport system. The maximum low energy positron production is still found at a thickness corresponding to three radiation lengths in the material. Thus about 95 percent of the energy in the original electron beam has been converted into other forms of energy, including positrons.

The size of the positron emitting region of the moderator could be determined in the prototype transport system by observing the positron spot on the micro-channel plate. These measurements were done for a flat plate tungsten radiator-convertor, three radiation lengths thick, with the moderator vanes placed directly against the downstream side of the plate. The edge of the vanes was clearly visible in the positron beam spot so the vane spacing provided a length calibration. An electron beam about 2 mm in diameter was incident on the plate at either 40° or 15°. For both electron beam angles the size of the positron emitting region of the moderator was roughly 1 cm.

The highest efficiency to date was measured in the prototype transport system by reducing the electron beam intensity and counting single positron events in the micro-channel plate. The value is 2.0×10^{-6} slow positrons per incident electron. This efficiency is high enough that with the beam from the Lawrence Livermore National Laboratory S-band Linac, slow-positron beams of 0.5 namp average current are possible. With short pulse duration, beams with 8×10^{5} slow positrons per pulse can be produced in pulses shorter than 20 nsec repeated 1440 times a second. These beams are several orders of magnitude more intense than those from existing radioactive sources.

DISCUSSION

Production of positron beams with an electron linac results in special properties and problems due to the properties of the linac electron beam. Since the electron beam in most linacs is pulsed the positron beam will be pulsed as well. The time width of the positron pulse will depend on the width of the electron beam pulse, the lifetime of the positrons in the moderator and the qualities of the positron transport. In a typical rf linac the electron beam has a time structure consisting of a train of micropulses each about 10^{-11} s in duration separated by the rf period. The pulse train may have any length from a nanosecond to several microseconds. Thus with proper bunching it is possible to have positron pulses that are short enough to use in short lifetime experiments. Bunching techniques can also be used to compensate for the energy dispersion of the slow positrons and so very good time definition or very good energy definition can be obtained in intense slow-positron beams.

With intense, pulsed slow-positron beams we can perform time-of-flight energy analysis of scattering from gasses and time-of-flight measurements of positrons and positronium scattered or diffracted in a wide variety of conditions. Also we can perform new materials-science measurements including two-dimensional angular correlation measurements, and with a short positron pulse, positron lifetimes. These and other materials measurements such as Doppler broadening can be made on samples during rapidly changing conditions to study transient effects.

There are two practical problems with producing high intensity low energy positron beams with an electron linac: First is the need to dissipate large amounts of power in the radiator-convertor and also in the surronding apparatus. The LLNL linac produces 10 kw in the mode that has a high rate of short pulses and nearly 40 kw in the mode that has a low rate of longer pulses. In the production of low energy positrons a large fraction of the linac power will be deposited in the radiator-convertor in the form of heat which must then be carried off. Second is the high levels of radioactivity that will be present during and after the positron production. Materials used in the construction of a low energy positron system must be choosen with radiation hardness and residual activation characteristics in mind. Organic materials degrade quickly when near the linac beam, and steel and many other metals remain radioactive for relatively long times after irradiation.

There are also problems in setting up experiments with linac positrons. The intense bremsstrahlung produced during positron production must be shielded for many experiments. Also when using pulsed sources the performance is often limited by detection systems that cannot accomodate multiple events in one beam pulse. In this case the intensity of the source must be low enough that the detector will not respond at every pulse. If this condition is not met then the counting rate in the detector is just the source pulse rate and the detector will respond preferentially to the early events leading to a distortion of the data. In general the source intensity must be limited so that about 30% of the source pulses result in detector responses. There is a solution to this problem when the detector is capable of responding separately to several events during a single beam pulse. In that case the source strength is not limited by the pulse rate.

At the Livermore linac there are two beam lines under development for the transport of slow positrons. Both of these will be based on the use of long solenoids for magnetic transport of the low-energy positrons. One of these will be dedicated to positronium atomic physics experiments in a collaboration with groups at Yale and Stanford. The second transport will be for general use in solid state physics and materials science experiments. Eventually the materials science beam will have several useful features including a bunching system for lifetime experiments and sufficient energy range to cover both surface and bulk measurements.

The atomic physics beam line has been constructed at Yale and is in final development at Livermore. The permanent materials science beam line has been designed and the basic system is under construction. The prototype of the positron production part of the transport has been used in tests and is now free for use in new experiments.

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