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THE LIVERMORE LINAC

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LOW ENERGY POSITRON PRODUCTION AT THE LIVERMORE LINAC*

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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 results of some of these experiments are given and 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 for low-energy positrons has 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.

Introduction

Beams of mono-energetic positrons from eV to keV energies, often called slow positrons, have been used to study a wide variety of positron, surface, and defect phenomena. These beams have been produced mainly from higher-energy positrons emitted by radioactive isotopes in beta decay. The energetic positrons are thermalized in a moderating material that has a negative work function for positrons. They are then expelled from the moderator with an energy equal to the negative work function, typically 1-2 eV. This results in beams with intensities as high as 8×10^8 positrons per second in currently operating experiments.¹

Experiments in many diverse fields of physics have been performed using slow positrons from radioactive sources. In atomic physics the total cross sections for positrons scattered from noble gases have been measured and significant differences have been observed between the data from electrons and positrons at the same energies.² Electron-positron cross section differences are largest for low energy scattering and tend to disappear at a few hundred eV.

Other basic atomic physics experiments have been performed on positronium atoms. These systems are produced in a vacuum by shining low energy positrons on a clean metallic surface. The positronium atom is the bound state of an electron and a positron with properties analogous to those of a hydrogen atom. This system is of particular interest as there are only electromagnetic forces binding positronium making it a good testing ground for quantum electrodynamic theory. Basic measurements on positronium include the fine splitting of the ground state, the de-excitation of the 2S singlet first excited state, the hyper-fine structure splitting of the 2S-2P first excited states and most recently, the two photon excitation of the first excited 2S triplet state.^{3,4} The two photon experiment was accomplished using a tunable dye laser and a bunched, slow-positron beam and is expected to yield highly accurate measurements of the energies of the states of positronium.

Studies of the positron interaction at or near

the surface of a sample have produced a growing data base for use in solid state physics and materials science.⁵ It is now established that the positron loses energy quickly upon entering the material and then diffuses until it either annihilates or leaves the material through the surface. Those positrons reaching the surface may leave directly as slow positrons or they can bind to an electron and form positronium. Some of the positrons are trapped by the image charge potential at the surface and will detrapp, forming positronium, only at elevated temperatures.

A sensitive tool for the analysis of both surface and bulk material properties is based on the measurement of either the re-emitted positron or positronium fraction as the incident positron energy is varied. These data can be related to the diffusion length of the positron in the material if the stopping distribution of the positrons is known. An associated parameter, E_g , the energy at which one half of the incident positrons are re-emitted is usually quoted. Large variations in E_g are observed with changes in the materials surface or bulk properties. Properties that can be studied by observing variations in E_g include, the order, phase conditions, defect levels and surface cleanliness of a material.

Positron beams can also be used in experiments analogous to those done with electrons. In general the results of these experiments differ from the electron experiments due to the positive charge and the lack of exchange in the positron interaction with electrons. Low energy positron diffraction has been observed from clean metal surfaces.⁶ There have also been measurements of discrete energy loss in positron inelastic scattering from metals.⁷ In both of these measurements the positron results complement those obtained with electrons.

Positron beams have only been used with one of the three basic measurements, positron lifetime, doppler broadening profile and angular correlations. These measurements are used routinely in materials analysis with radioactive sources. The only one of these used with a beam, the doppler broadening measurement, has been performed as a function of positron beam energy to obtain profiles of damage in the near surface regions.⁸ The other measurements, the positron lifetime and the positron annihilation gamma angular correlation measurement, have not been performed due to lack of positron beam intensity.

There is a strong incentive to add positron lifetime and angular correlation experiments to those done with positron beams. The lifetime experiment can be used to identify defects by their characteristic lifetimes. This sensitivity can be used to profile defects near the surface and to study surface traps. The annihilation radiation angular correlation measurement done in two dimensions is extremely rich in information on the momentum distribution of the electrons in a material. The angular correlation measurement performed with positrons deposited near the surface would provide data on the spatial asymmetries in the momentum distribution of the surface electrons. Each of these, the lifetime and the angular correlation measurements would provide

unique data on surface properties.

A linac electron beam can be used to produce energetic positron beams that are both intense and pulsed, thus opening the possibility that lifetime or angular correlation measurements might be attempted. 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 slow positrons. Slow positrons produced with this technique have been used in the past, but the beams were of low intensity.¹⁴

We have studied the efficiency of slow positron production for several electron beam energies and converter-moderator geometries. The optimum electron-positron converter thickness has been identified and the slow-positron yield determined for electron energies from 60 to 120 MeV. Several moderator geometries were tried, including a flat plate and a series of vanes.

Experimental Details

A conventional bent solenoid slow-positron transport system, similar to those described in Refs. 10 and 11, 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 the Yale apparatus the positron transport efficiency is unmeasured but the transmission of thermal electrons is 86%. With this apparatus we used both NaI detectors and 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 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. With the channel plate in the Yale transport we measured the positron beam spot 8 mm in diameter and 24 nsec wide at 200 eV transportation energy.

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 that close coupling between the electron-positron converter and moderator resulted in the highest slow-positron yield. This is expected, since the positrons emerging from the converter have a high

angular divergence. The moderator geometry was fixed while the tantalum electron-positron converter was tested in various configurations. The best geometry found for the moderator consisted of tungsten foils arranged as a series of vanes with the front edges facing the transport system.¹² The best yield was obtained with the moderator and converter arranged as shown in figure 1. A similar arrangement, substituting a flat plate for the vanes in the same moderator-converter geometry, produced fewer slow positrons. The intensity reduction was roughly the same as the reduction in surface area of the plate compared to the vanes.

Figure 1. Electron-positron converter and positron moderator assembly in the best-case geometry. Positrons accelerated through the aperture were transported to a detector by the field of the surrounding solenoid.

Tungsten was chosen from among the known moderator materials 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. Copper moderators also have a high positron yield, but must be prepared and stored in a high vacuum.¹

The positron yield was measured for different electron-positron converter thicknesses. These measurements were made in the best-yield geometry described above. The results for 100 MeV electrons are shown in figure 2. The yield increases as the thickness increases up to the median range of the electron. This thickness is equivalent to three radiation lengths for electrons in tantalum. Thus about 95 percent of the energy in the original electron beam has been converted into other forms of energy, including positrons.

The positron yield was also measured for different electron energies (figure 3). The positron yield steadily increased with increasing energy from 60 to 120 MeV. This results from several effects, dominated by the increase in total energy available from each electron at higher electron energies. There is also an increase in the fraction of the electron energy available for pair production. The separation of these effects is evident in the data since the yield of positrons for a thin converter scales as the beam power while the thick converter yield at high electron energy is greater than predicted from power scaling from low electron energy.

Figure 2. Positron yield from 100 MeV electrons for several electron-positron converter thicknesses. The moderator was kept the same for all these data.

Figure 3. Positron yield as a function of electron energy, measured for two positron-electron converter thicknesses. The solid lines are proportional to beam power, normalized to the lowest energy data.

The highest efficiency measured was 1.5×10^{-6} slow positrons per incident electron. This efficiency is high enough that with the beam from the Lawrence Livermore National Laboratory Linac, slow-positron beams of 0.5 namp average current are possible. With short pulse duration, beams with 6×10^6 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

Slow-positron beams from a linac have some special properties which are the result of the properties of the linac electron beam. Since the electron beam 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 linac the electron beam has micropulse durations of a few psec with several micropulses in a burst constituting the overall pulse width. Thus with proper bunching it is possible to have positron pulses that are short enough to use in lifetime experiments. Bunching can also be used to compensate for the energy dispersion of the slow positrons by using a time varying voltage in the

slow-positron transport system to retard the faster positrons and accelerate the slower ones. Consequently very good time definition or very good energy definition can be obtained in intense slow-positron beams.

With intense, pulsed slow-positron beams it will be possible to perform lifetime and angular correlation measurements, improved determinations of positronium characteristics, 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 with a short positron-pulse, positron lifetime, doppler broadening and other measurements can be made on samples during rapidly changing conditions to study transient effects.

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 confinement 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. 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 to bulk measurements.

The atomic physics beam line has been constructed at Yale and is in final development at Livermore. Portions of the materials science beam line are designed and a prototype of the positron production part of the transport has been constructed and is ready for testing.

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