Chapter 3

Positron emission from the moderator

Positron moderators have been developed and studied for more than a decade. They are now used to produce slow, nearly monoenergetic beams of positrons for a variety of applications in atomic and solid state physics. (There is a great deal of literature on this subject. For a review see Ref. [7].) Single crystals of various metals are generally the material of choice for positron moderators.

When a high energy positron from a radioactive decay impacts a solid, it rapidly thermalizes near the surface. The positron lifetime in a solid is typically several microseconds. During this time the positron diffuses randomly over many microns if the material is a well-ordered single crystal. Vacancies, impurities, and other defects in the crystal trap positrons and prevent further diffusion. Those positrons which diffuse to the crystal surface see a positive work-energy function ϕ_+ due to the lattice of positive ions, causing them to be ejected nearly monoenergetically if their thermal energy spread is small compared to ϕ_+ [7,30].

A high-quality moderator is critically important for slowing and trapping large numbers of positrons. The first important factor is that the the moderator efficiency η (the fraction of slow positrons emitted per fast incident positron) be as large as possible; the positron trapping rate is directly proportional to η. The

second factor is that ΔE, the spread of kinetic energies around ϕ_+ with which the positrons are emitted, be as small as possible. (We define ΔE as the spread of kinetic energies along a direction normal to the crystal surface, which in this case corresponds to kinetic energy *parallel* to the magnetic field lines. The positron kinetic energy which is *transverse* to the magnetic field lines is in the form of cyclotron motion and is unimportant for our calculations.) The trapping rate is typically inversely proportional to ΔE, as explained in Chapter 4. It is worth noting that, for all moderators, some fraction of the emitted positrons scatter off surface contaminations or quantum bound surface states; this tends to increase ΔE. Other positrons are ejected in the form of positronium, which reduces the measured efficiency η.

We use a single crystal tungsten (110) moderator because this material has been demonstrated to achieve efficiencies as high as $\eta \approx 10^{-3}$ and energy spreads as small as $\Delta E \leq 65$ meV at temperatures near 4 K [31,32,33]. Tungsten moderators are widely used and considered reliable and relatively easy to use [34,35]. One potential drawback is a measurement [36] indicating that their efficiency η drops dramatically when cooled to 4 K due to quantum reflections of positrons at the surface. However, earlier results [32,33] show a constant or increasing efficiency as the crystal temperature nears 4 K. The disparate results may be due to the different procedures used to prepare the crystal surfaces [34]. Fortunately, we can control the temperature of our crystal using a field emission point array (Section 3.3), allowing us to measure changes in η as a function of temperature and also to heat the crystal should quantum reflections become a problem.

We considered using a copper (111) crystal as a moderator. Copper has the advantage of a much lower annealing temperature compared to tungsten. Unfortunately, the annealing temperature is within 50 degrees of the melting temperature [34,35], requiring an accurate thermometer and a high degree of control over the electron beam heating current. The difficulties in thermometry and temperature control in our 4 K environment, combined with the difficulties of replacing a

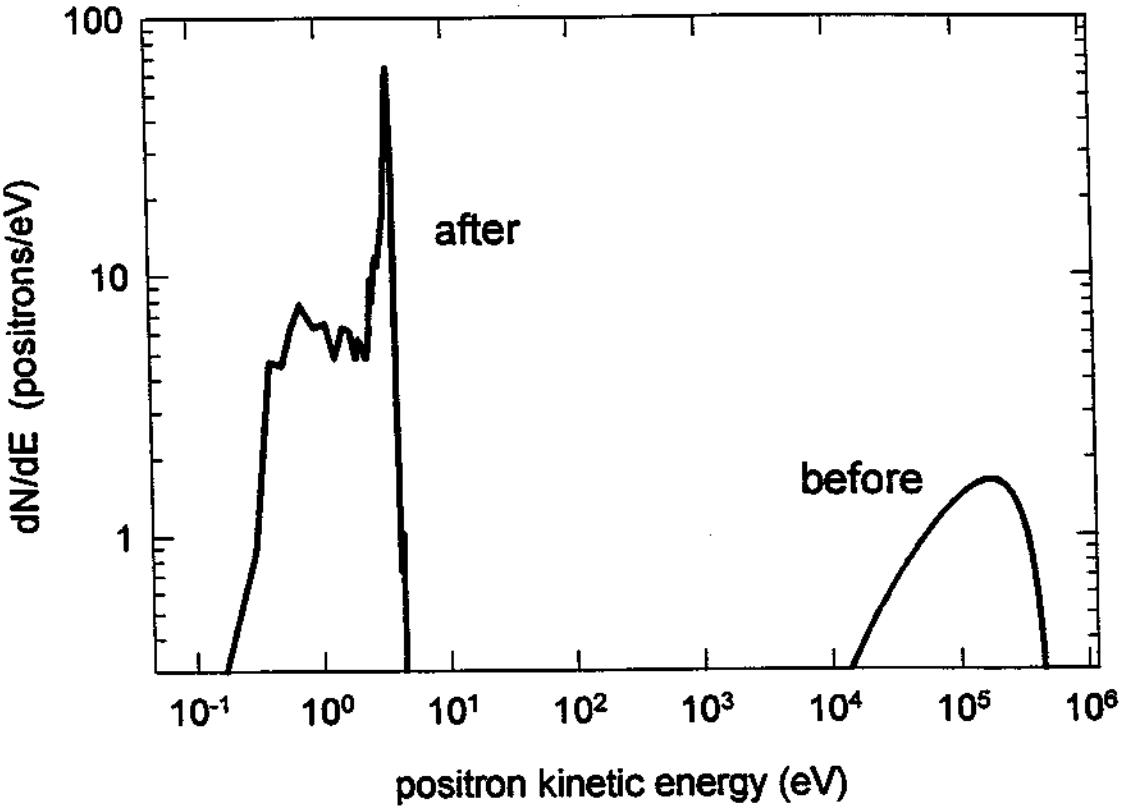

Figure 3.1: Energy distribution of positrons before and after moderation. The area of the "before" curve is normalized to 1. The "after" curve is for $\eta = 10^{-4}$.

crystal should it be damaged, made the tungsten moderator more attractive.

3.1 Positron energy spectrum before and after moderation

The advantages of using a positron moderator are illustrated in Fig. 3.1, which compares the energy distribution of positrons before moderation (as calculated from the Fermi decay theory for ^{22}Na) and after moderation (using the results of Section 3.4 and a conservatively assumed $\eta = 10^{-4}$.) While moderators decrease the number of positrons in the beam by a factor of η, they dramatically increase

the beam brightness dN/dE—that is, the number of positrons per eV of kinetic energy. The positron trapping rate is proportional to dN/dE.

3.2 Initial moderator treatment

We purchased three W (110) crystals from Goodfellows Corporation, each with a diameter of 0.12 inches and a width of 0.08 inches. In addition, each had small holes (less than 0.01 inches diameter) electron-beam drilled through the side. As shown in Fig. 3.2, thin tungsten wires (0.07 mm diameter) through these holes connect the crystal to a molybdenum ring. This mounting scheme—used inside the trap can and also when the crystal is annealed in a separate vacuum chamber—provides a high degree of thermal isolation and helps avoid contamination of the crystal from other materials since only tungsten wires contact the tungsten crystal.

We used three different crystals during the course of the measurements reported in this thesis. The first crystal we used was poorly prepared (described below) and did not function as a moderator. The second and third crystals were prepared more carefully; both moderated positrons with roughly equal efficiencies. (The data in Fig. 3.5 and 3.6 were taken with the second crystal, and the data in Fig. 3.7 with the third.) The second and third crystals were prepared in the following manner: First, their surfaces were mechanically polished for a few minutes with 1 μm Al_2O_3 grit suspended in distilled water on a silk polishing cloth (polishing grit and cloth purchased from Buehler Ltd.) to remove all surface features larger than 1 μm. (After polishing, fine scratches estimated to be slightly under 1 μm deep were visible under a microscope at 30 times magnification.) Next, they were electrochemically etched in a solution of 4–5 NaOH "PELLETEs" (total weight 0.8 grams) per 50 cc of water at a current density of 0.3 A/cm^2, which removes surface material at a rate of $\sim$ 18μm per minute. Care was taken to use only glass or stainless steel in the solution, and the solution was agitated by bubbling

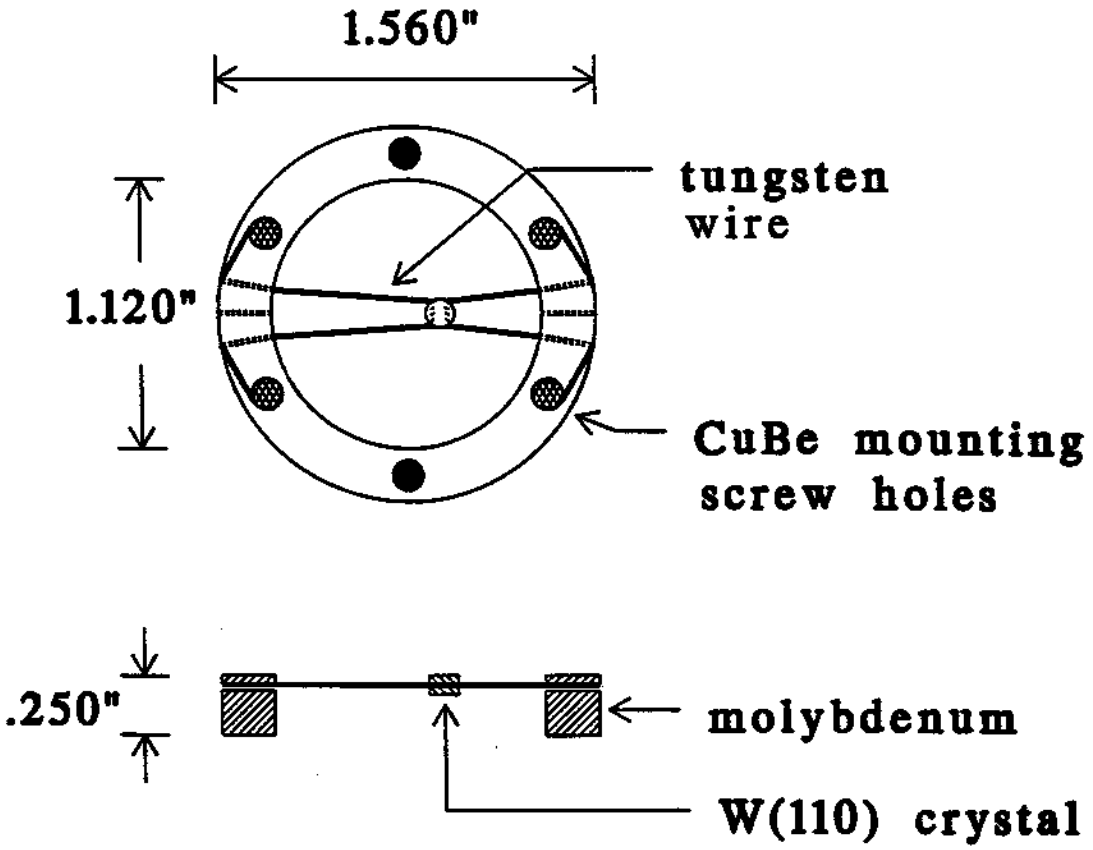

Figure 3.2: Top view and side view of tungsten crystal and mounting jig.

helium gas directly onto the crystal surface during etching. (This removed tiny bubbles which form on the crystal during etching and mar the surface.) An ethanol rinse left no noticeable residue. The second crystal, which had been etched for 12 minutes, had nine or ten "bumps" of an estimated 1 to 3 μm in size scattered over its surface. The third crystal, which had been etched for only 2 minutes, had only one such bump. In both cases, aside from the bumps, the surfaces appeared mirror-like under the microscope, almost uniformly smooth and without polishing scratches.

The crystals were then annealed for 1-2 hours at temperatures estimated in

excess of 2300 K—the second crystal in a vacuum of 4×10^{-7} Torr and the third crystal at 1×10^{-8} Torr. The crystals were heated by electron bombardment from a hot filament which supplied up to 40 mA of electron beam current. The filaments were 0.5 mm diameter thoriated tungsten wire heated by 0–6 Volts, 0–20 amps alternating current and radiated at about 100 Watts when delivering 40 mA beam current. The crystals were biased 1000 Volts positive with respect to the filament and appeared white hot throughout the annealing process. The uncertainty in the annealing temperature is ±200 K due to uncertainty in the crystal emissivity (between 0.1 and 0.2).

After annealing, the second and third crystals were held at 900 K in an atmosphere of 10^{-6} Torr oxygen for three hours. The purpose of this procedure is to remove interstitial carbon—which inevitably contaminates these crystals—from near the surface [34,35,37]. They were given one final heating to 2200 K in high vacuum, then brought up to atmosphere and immediately mounted in the trap can, which was then pumped to $\sim 10^{-7}$ Torr (for about 12 hours) and sealed via its pinch-off tube.

By contrast, the first crystal we installed—which had an efficiency η too low to be measured by our methods—was not etched electrochemically, and we relied upon the supplying company's mechanical polishing of the surface rather than our own. It was annealed for only a few seconds in the trap can at 10^{-6} Torr shortly before pinch-off without any treatment to remove interstitial carbon.

3.3 Heating the moderator "white hot" in a 4 K environment

When the moderator is transfered from the annealing chamber to the trap can, oxygen and other molecules inevitably contaminate the surface. This has two undesirable effects. First, contamination sites trap positrons, preventing re-emission

and lowering η. Second, emitted positrons scatter from these surface molecules. While elastic scattering at the surface does not change the positron's *total* kinetic energy, it preferentially transfers some of that energy from longitudinal (parallel with the magnetic field lines) into transverse (cyclotron) motion, which increases ΔE. It is desirable to clean the crystal's surface *after* it has been installed in the trap can. Once the surface is clean, the ultra-high vacuum in the trap can prevents the surface from being recontaminated.

Electron-bombardment heating is a common means for cleaning and annealing metal crystals. Usually, the electron source is a thoriated tungsten filament operated at up to 100 watts of power; however, it is not convenient to use such a filament in our trap can during normal operating conditions. The large heat load would boil off large amounts of liquid helium, and the local heating would probably raise the background pressure inside the sealed trap can to undesireable levels. There are the additional complicating factors of constructing a filament which can withstand the strong forces it would experience in the 5.9 Tesla magnetic field, and attaching lead wires from the filament to the magnet hat's vacuum feedthroughs which can handle the large current load without also increasing the thermal conduction load from the room temperature hat to the liquid helium dewar.

The Spindt-type field emission point array is an alternative electron beam source more compatible with our sealed, cryogenic environment. We mounted such an array directly underneath the moderator inside the trap can. These devices, produced by SRI International, consist of an array of $\sim 10,000$ field emission points of a type shown in Fig. 3.3 [38]. Field emission points do not generate much heat during operation and so they do not add to the overall heat load on the system. The arrays require only a few milliamps of input current so they do not require high-current leads and do not experience strong forces in the magnetic field. When the cathode is biased to -120 Volts with respect to the gate, the array produces more than 5 mA of electron beam current. These electrons follow the magnetic field lines and strike the moderator, which we biased 600 or 1200 volts positive

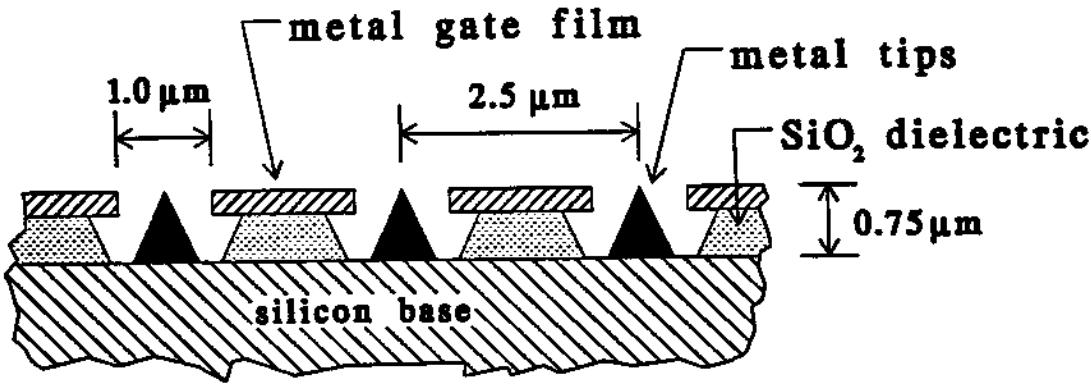

Figure 3.3: Cross section of Spindt-type field emission point array.

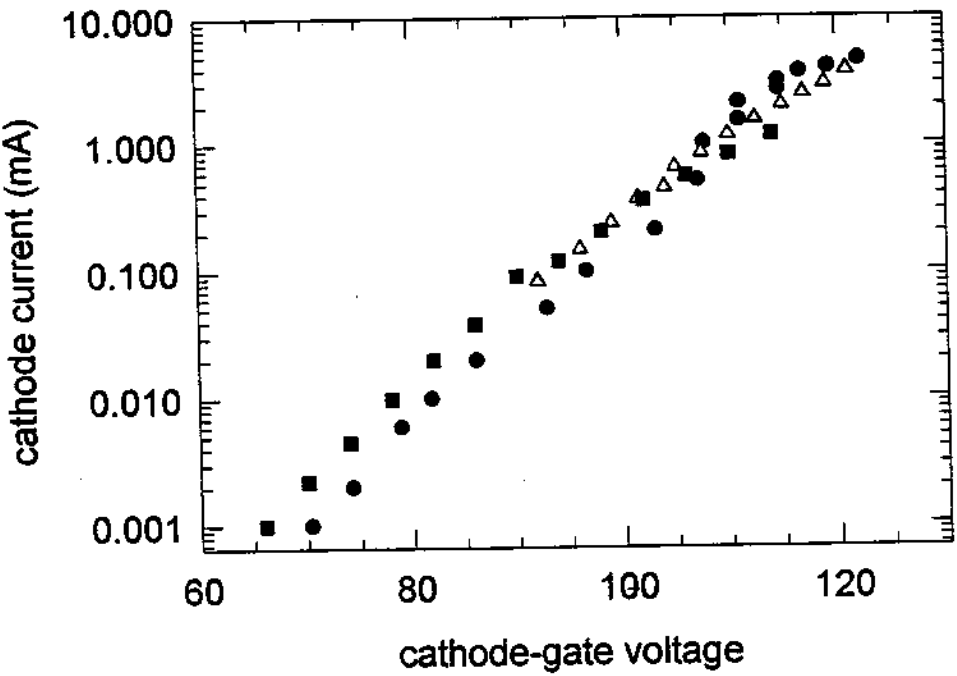

Figure 3.4: Typical voltage-current curve for a Spindt-type field emission point array. Data are shown for three separate runs.

with respect to the array. In this way, we heat the moderator to temperatures exceeding 2000 K for many minutes while the rest of the trap and the trap can walls remain cold, heat sunk to liquid helium, and under high vacuum. The effects of cleaning the crystal in this fashion are shown in the next section. It has been recommended [34] that, when we heat the crystal in this fashion, we cool it slowly ($\leq$ 100 degrees per minute) since rapid cooldown can quench vacancies into the crystal lattice.

Although the manufacturer of the field emission point arrays experiences long-term reliability with these devices when operating under high vacuum at room temperature, the arrays have proven to be less robust in our 5.9 Tesla, 4 K environment than we had initially hoped. Three of them failed during operation thus far. The first was lost when a bias of -200 Volts was mistakenly applied between the cathode and the gate. This caused an electric arc which permanently shorted the cathode to the gate, rendering the device unusable. We now regularly employ resistors in the gate- and cathode-biasing circuits to protect against sudden voltage or current surges. (10 kΩ for the gate, and from 5 kΩ to 2 MΩ for the cathode.) The second array was also destroyed by an electric arc between the cathode and the gate. In this case the device had been operating normally for nearly an hour and had just reached a cathode current of 1 mA when it failed. Since the cathode had operated at 1.6 mA for several minutes some weeks previously, the failure was unexpected. It may have been caused by a local pressure surge due to outgassing of the array as the cathode current increased [38].

In order to minimize this problem, the cathode current on the third array was increased extremely slowly—always keeping the cathode current low enough so that it did not fluctuate more than 1 to 2 percent, requiring at least two full days to increase the cathode current from 1 μA to 1 mA—to give the device plenty of time to outgas. (We believe that fluctuations in the cathode current are indicative of local pressure surges.) During this procedure, the moderator was biased only +50 Volts relative to the array to reduce the heat load on the system and to

reduce the energy with which ions could return to the array. Unfortunately, a new problem developed. The isolation resistance between the cathode and the gate, which initially was more than $10^{10}\Omega$, gradually decreased so that by the fourth day of use the isolation resistance had dropped to nearly $10^5\ \Omega$. Since it appeared at this point that the array would only be useable for a few more hours, we decided to increase the speed with which the cathode current was increased, hoping that the device had already outgassed sufficiently. Unfortunately, it experienced another electric arc (when it reached 1.1 mA) which destroyed the array. We are hopeful that the problem of isolation resistance degradation can be solved by "baking" the array clean before operation—either by increased baking of the trap and trap can under vacuum before it is sealed, or by heating the array *in situ* with a small resistive element while the trap can is sealed at 4 K.

3.4 Moderator performance

The process by which moderated positrons are loaded into the trap is described in Chapter 4; the procedure for counting the trapped positrons is described in Chapter 5. We use those results now to analyze the performance of our moderators.

Figure 3.5 shows the energy-analyzed positron trapping rate as a function of the bias potential applied to the moderator. (This data set was taken with our first working moderator—the second crystal we installed in the trap can.) Before the moderator was cleaned using the field emission point array, positrons emerged with a spread of (longitudinal) energies $\Delta E \approx 3$ eV. After the moderator was heated to ~1600 K for a few minutes and cooled, the energy distribution changed dramatically. The energy spread of the peak became $\Delta E \approx 700$ meV, with a low-energy tail of approximately twice the area of the peak. The loading rate at the peak increased while the overall yield η (propotional to the area under the peak) remained about the same. This result is consistent with moderator performance noted in the literature [31,39]. In particular, oxygen has been shown [37] to increase

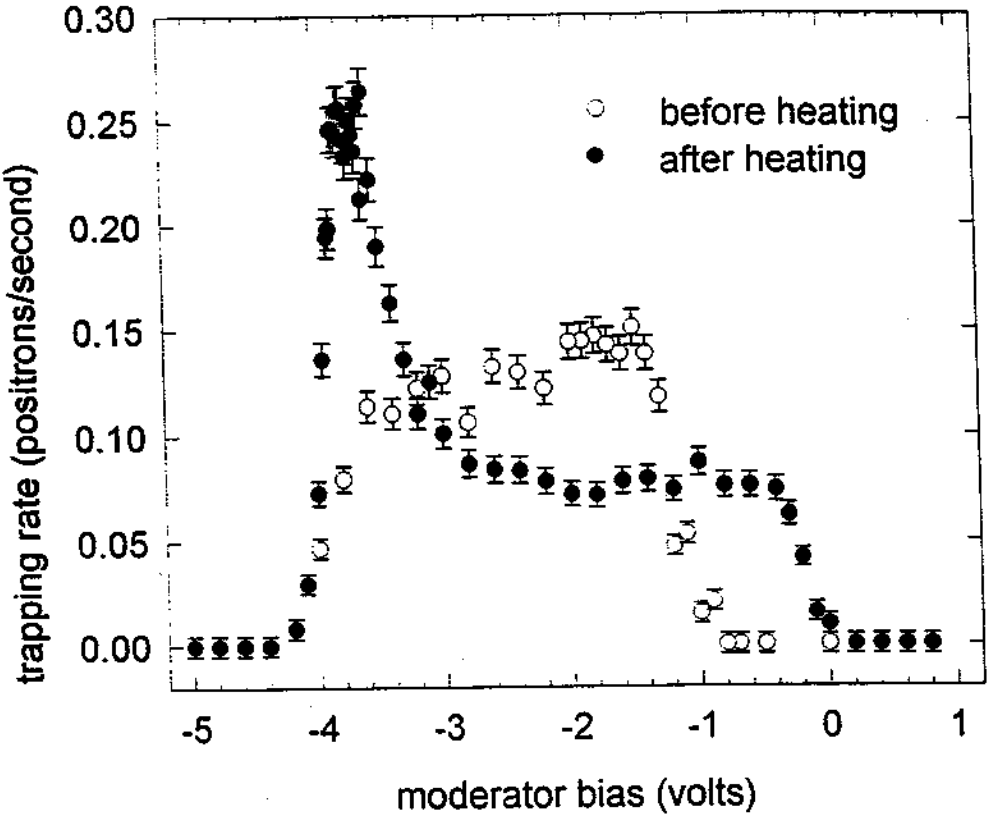

Figure 3.5: Positron loading rate measured before ○ and after • the moderator was cleaned by heating to ~ 1600 K *in situ* for three minutes, while the rest of the trap remained cold and under high vacuum.

ΔE on tungsten moderators unless the crystals are cleaned by heating to at least 1600 K in vacuum.

A clean crystal surface can be recontaminated if the surrounding vacuum is inadequate. Monolayers of contaminants build over time, degrading moderator performance. However, this is not a problem inside our cryogenically cooled trap can. After the first cleaning cycle shown in Fig. 3.5, the moderator and trap remained cold (4 K) for six weeks while other measurements were made. At the end of those six weeks, no change was measured in either η or ΔE.

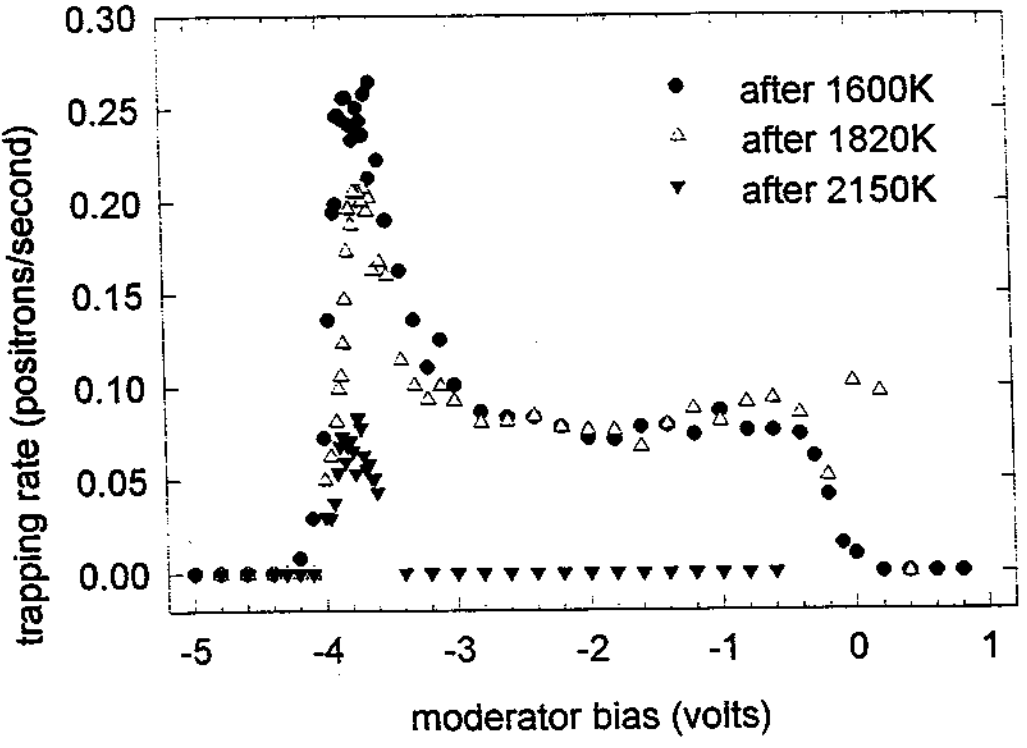

Figure 3.6: Moderator performance (a) after first heating cycle to 1600 K, (b) after second heating cycle to 1820 K, (c) after third heating cycle to 2150 K.

In an effort to improve the performance of this moderator, it was heated a second time, this time to ~1820 K. The results are shown in Fig. 3.6. Little change was noted. The moderator was heated a third time to ~2150 K, after which we experienced a field emission point array failure. This time there was a dramatic and unfortunate change in moderator performance. While the positron emission energy spread decreased to $\Delta E \approx 400$ meV, the overall yield η dropped dramatically. We believe this happened because the moderator cooled too quickly and allowed vacancies in the crystal surface to quench into place. Alternatively, interstitial carbon may have moved from the bulk of the crystal to near the surface. After the data set for Fig. 3.6 was taken, we replaced both the crystal and the

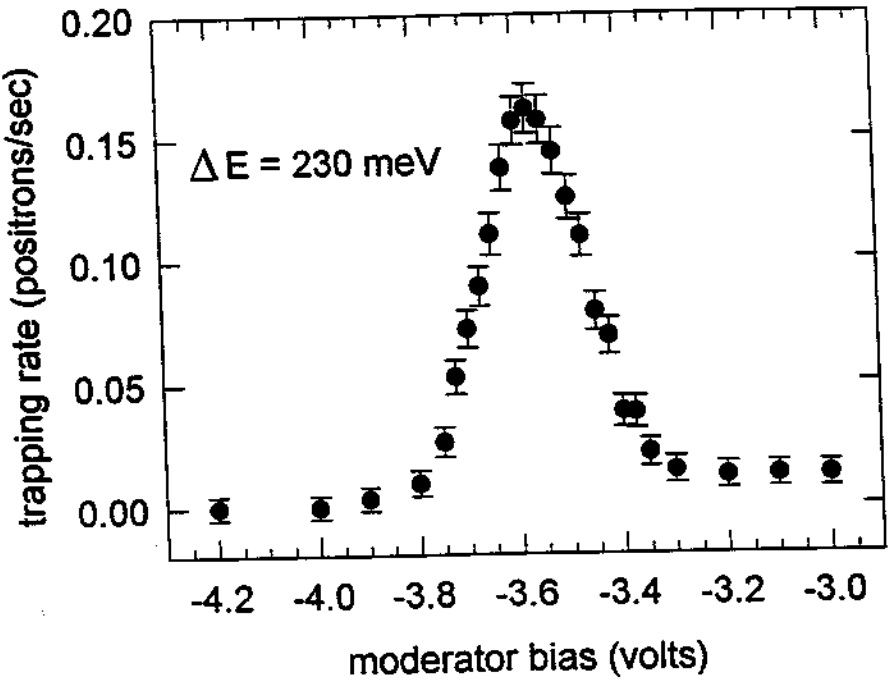

Figure 3.7: Narrowest positron energy distribution achieved to date.

array.

The positron energy distributions in Fig. 3.5 and 3.6 show a low-energy tail from the peak at ϕ_+ to ~ 0 Volts. (The reason the loading rate does not drop to zero precisely at 0 Volts is presumably due to contact potentials.) This is consistent with published moderator behavior [31,33,34,35,37,39], which always shows a low energy tail with an area of at least 50% of the area under the peak.

The third moderator crystal we used also had an initial positron energy spread of $\Delta E \approx 3$ eV before it was cleaned. After the first heating cycle it gave results very similar to Fig. 3.5. After several more heating cycles it produced the narrowest energy spread achieved to date, shown in Fig. 3.7, with $\Delta E = 230$ meV and a maximum loading rate of ~ 0.2 positrons per second. The third field emission point array failure occured after the heating cycle which produced Fig. 3.7. Further

moderator studies are planned, with hopes of achieving narrower energy spreads and higher positron trapping rates, with a new electron beam source.

3.5 Possibilities for improved moderator performance

There are several possibilities which might yield better moderator performance in future experiments [34,35,40]. New tungsten crystals could be purchased from a company which is better able to control the purity of their samples and better able to insure that the surface is cut precisely along the crystal plane. Initial annealing in a much improved vacuum ($< 10^{-9}$ Torr) might prevent contaminating molecules from imbedding in the crystal. There is, however, no published literature of which we are aware which demonstrates this to be a factor.

We have clearly shown that the efficiency of our moderators does not drop dramatically below 10^{-4} at 4 K, as had been suggested [36]. When we obtain a field emission point array or other electron beam source which can operate continuously in our environment, we will use it to heat the crystal continuously, while maintaining the trap electrodes at 4 K, to measure η and ΔE as a function of crystal temperature.