A Study of Defects in Platinum Using Positron Annihilation

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A STUDY OF DEFECTS IN PLATINUM USING POSITRON ANNIHILATION

by

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INTRODUCTION

Pure metals that have been annealed at high temperature have a definite periodic arrangement of the atoms. However, imperfections or defects in the lattice structure are still to be found in the metal or may be produced by external means. These imperfections may be divided into three main types: static imperfections, excitation states of the crystal, and transient imperfections. Static imperfections include dislocations, vacancies, interstitial atoms, an extra valence electron at a lattice site, or a missing electron at a lattice site (hole). The excitation states of a crystal are considered imperfections only in the sense that they produce some deviation from perfect symmetry. Transient imperfections include photons, energetic charged particles and energetic uncharged particles; these are often used as experimental tools.

In this thesis it is the vacancy defect that is of interest. A vacancy is a lattice site which is not occupied. Vacancies can be produced in a sample by heating, quenching, plastic deformation (a form of cold working), and irradiation by energetic particles. Vacancy defects are also known as Schottky defects. The combination of a vacancy and a corresponding interstitial atom taken as a pair is known as a Frenkel defect.
Several groups have worked in the area of positron annihilation in vacancy enriched metals. I. K. MacKenzie et al. have studied the temperature dependence of the mean lives of positrons in the metals aluminum, cadmium, indium, and zinc. Results indicate a dependence which can be linked to the equilibrium density of point defects. S. Berko and J. C. Erskine have studied deformed aluminum samples; they found a dependence of the angular correlation curves on the type of treatment given to the samples. Recent studies of deformed metal samples by Russian workers have shown significant differences between the angular correlation results for deformed and annealed undamaged samples. In particular the normalized angular correlation results have shown a narrowing of the angular distribution for the deformed sample compared to the annealed undamaged sample.

Previous research indicates that there is a relationship between positron annihilation results and vacancy or defect concentration in a metal. Of particular interest in this thesis is the study of positron annihilation in pure (99.95%) platinum metal samples. It was desired to determine if there is any dependence upon the defect concentration in irradiated and plastically deformed metal samples. Platinum is an excellent metal for study, since large concentrations of defects due to irradiation can be maintained at room temperature in the sample.
EXPERIMENTAL METHOD

The Positron Annihilation Technique

The positron is a stable particle as long as it does not encounter an electron. However, a positron passing through matter will eventually annihilate with an electron. The annihilation normally occurs when the positron has slowed down to thermal velocities. In a solid metal the slowing process is usually complete after a time of the order of $10^{-12}$ seconds. When the annihilation occurs two or more photons must be emitted in order to conserve momentum. The emitting of three photons is a rare event since the annihilation cross section for three photon emission is considerably smaller than the two photon cross section. Therefore, the most common event is the emission of two photons in opposite directions in order to conserve momentum. Figure one is a two dimensional representation of the two photon annihilation process. The annihilating pair have a total momentum $P$ and the annihilation photons have momentum $p_1$ and $p_2$. Conservation of momentum in the $z$-direction requires that

$$ (p_1 + p_2) = P \sin(B) = p_z \quad (1). $$

Conservation of energy in the annihilation process implies that

$$ (p_1 + p_2)c = 2 mc^2 \quad (2), $$

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Figure 1. Momentum diagram of the annihilation process

\( p_1 \) and \( p_2 \) --- Momentum of the annihilation photons.

\( P \) --- Momentum of the center of mass of the annihilating positron and electron.

\( A/2 \) --- Angle between \( p_1 \) or \( p_2 \) and the x-axis.

\( B \) --- Angle between \( P \) and the x-axis.
where \( m \) is the rest mass of an electron (or positron) and \( c \) is the speed of light. Combination of (1) and (2) yields that the angle \( A \) is proportional to \( p_z \) or

\[
\sin(A/2) \sim A/2 = p_z / 2mc \quad \text{or} \quad p_z = mcA,
\]

where \( A \) is the deviation from \( 180^\circ \) and use of the small angle approximation has been made.

For the free electron with no momentum component in the \( z \)-direction, the angle \( A \) is zero and the two annihilation photons are emitted in directions \( 180^\circ \) apart. If the center of mass of the annihilating pair moves with a \( z \)-component of momentum which is not zero, then the angle \( A \) is no longer zero. The \( z \)-component is the only one of interest, since the conventional long slit geometry was used with the \( z \)-axis perpendicular to the surface of the sample. For low velocity positrons the deviation from \( 180^\circ \) is no greater than \( 1^\circ \). Therefore the small angle approximation is an acceptable one.

The electrons in any metal are moving about in all directions in the lattice structure. This means that the electrons also possess various components of momentum in the \( z \)-direction. The positrons in annihilating with the electrons produce a distribution of photons at various angles around the \( 180^\circ \) position. This distribution is generally referred to as an angular correlation distribution and corresponds to the momentum distribution of the electrons in the metal. The positron and electron wave functions \( \Psi \).
and $\mathcal{V}(\mathbf{k})$ determine the actual shape of the angular correlation distribution. The wave functions determine the probability that two photons, with total momentum $\mathbf{p} = n\mathbf{k}$, will result from an annihilation event. The probability is proportional to the square of the modulus of the Fourier transform of the wave function product

$$p(\mathbf{k}) \propto \mathcal{V}^{*}(\mathbf{k}) \mathcal{V}(\mathbf{k}) \exp(-\mathbf{k} \cdot \mathbf{r}) d^3r \right|^2$$

The angular correlation distribution, $I(\mathcal{R})$, is given by

$$I(\mathcal{R}) \propto \int\int p(\mathbf{k}) d_kx d_ky$$

The $I(\mathcal{R})$ distribution can be determined experimentally by an appropriate procedure.

**Experimental Apparatus**

**The mechanical equipment**

The basic equipment used to obtain angular correlation results was rather simple and is shown in figure two. It consisted of two detector assemblies situated on opposite sides of a sample chamber. The detector assemblies were mounted on aluminum mounting blocks and were positioned fifty one inches from the center of the sample chamber. One of the two detector assemblies moved up and down through an angle of approximately two degrees. Within the sample chamber were located a source and a sample to be studied. The entire system was mounted and positioned on a frame made from angle iron.

The detectors were cylindrical scintillation counters six inches long which were shielded by lead in order to
reduce the random background count. Located in front of each detector were two lead blocks (detector slit) whose separation could be adjusted. The lead blocks were three inches thick and provided a collimated beam for the detector. The separation was adjustable so that the angular resolution could be changed. However, throughout the experiment the angular resolution was kept constant at one milliradian.

One detector was fixed in position and the other mounted on an aluminum mounting block which moved along a circular arc. The relative height and level of each detector could be changed by adjusting three brass bolts. The aluminum mounting block on which the movable detector rested was positioned atop a threaded shaft. Then as a motor turned the shaft, it moved the detector to the desired position.

The sample chamber was constructed from lead blocks approximately two inches thick. Therefore, five inches of lead shielded the detectors from the source. Slits were cut in the sides of the sample chamber facing the detectors to provide collimated beams. Also, additional collimation was provided by lead slits one foot from each side of the sample chamber. A part of the sample chamber was a means of supporting and positioning the source above the sample. The means of support was a rod supported from above and centered with respect to the
Detector slit

Additional collimation slit

Slit in the sample chamber

Rod to support source

Threaded shaft

Detector assembly (stationary)
Sample chamber
Detector assembly (movable)

- --- Lead shielding
- --- Aluminum mounting block
- --- Lead collimation slits

Figure 2. Diagram of the mechanical equipment (side view).
sample chamber. The source was screwed onto the bottom of the rod which in turn could be screwed up and down. The Na\textsuperscript{22} source was positioned inside a steel cylinder whose bottom opening was covered by a stainless steel foil. The thin (.00025 inch) foil covered the bottom opening and helped to protect and isolate the 2.5 mc source. The steel cylinder screwed on the rod and was positioned approximately half an inch above the sample.

Before attempting to use the detector assemblies and sample chamber as a unit, they had to be aligned. This was best accomplished by positioning the detector assemblies at the 180° position and passing a laser beam through the slits. To do this, one of the detectors had to be removed in order to pass the laser beam through the back side of the detector slit. Now the aluminum mounting plates were raised and lowered until the laser beam passed through all slits properly. "Properly" in this case meant through the centers of the slits in the sample chamber and directly through the detector slits. With the slits properly aligned, the mechanical equipment was ready to use.

The electronic equipment

The electronic equipment used in the research was transistorized equipment. The electronics was purchased from the Hamner Electronics Co. Inc. in Princeton, New Jersey and the Ortec Co. in Oak Ridge, Tennessee. Basically, it was made up of modules plugged into one power supply unit. All
equipment was powered by a line voltage which was regulated by a Sorenson voltage regulator. Basic organization was that of a typical two-gamma coincidence system. The coincidence circuit had a resolving time of 100 nanoseconds. Figure three is a block diagram of the electronics. An automatic control unit timed and controlled the experiment.
Figure 3. Block diagram of the electronics.
SAMPLE PREPARATION

Defect Production in Metals

As stated in the introduction, defects can be produced by heating, quenching, plastic deformation or irradiation of metal samples. Heating and quenching of metal samples are closely related procedures. It is a well known fact that heating metal samples causes an increase in the vacancy concentration. The concentration of vacancies at a given absolute temperature $T$ is given by

$$\frac{n}{N} = A \exp(-\frac{\phi_v}{kT})$$

where $n$ is the number of vacancies, $N$ is the total number of lattice sites, $A$ is a proportionality constant dependent on the thermal entropy change, and $\phi_v$ is the energy of formation of one vacancy. For typical metals with close packed structures, the value of $n/N$ is of the order of $10^{-3}$ to $10^{-4}$. Quenching is just a rapid cooling of heated metal samples to a temperature below that of the migration temperature for vacancies. Quenching maintains the increased concentration of vacancies in the metal samples. Therefore, by careful control, vacancy concentrations of varying magnitude can be produced in metals. Studies of quenched platinum samples have been done by Bauer and Goeppinger. They studied resistivity changes in irradiated samples of pre-quenched and unquenched platinum samples. Bauer and Goeppinger observed a difference.
in recovery for the two types of samples, where recovery refers to the removal of damage present in the samples.

Two non-thermal means of producing defects are plastic deformation and electron irradiation. Plastic deformation can occur by either translational slip or twinning.\textsuperscript{11} Translational slip is a process whereby one part of a crystal slides as a unit across an adjacent part. Twinning takes place when a small amount of displacement occurs successively on each of many neighboring crystallographic planes. Because platinum has a face-centered cubic structure, the most common mode of plastic deformation is translational slip.

Plastic deformation\textsuperscript{12} produces vacancies, interstitials, and dislocations in a metal. In general, plastic deformation causes a very complex type of damage to a metal. As stated in the introduction, plastic deformation produces significant changes in the angular correlation results.

Irradiation by energetic electrons produces large numbers of Frenkel pairs. Irradiation allows high concentrations of vacancies to be produced in metal samples. This is due to the fact that interstitial type defects and small interstitial clusters are more mobile than single vacancies.\textsuperscript{12} The interstitial type defect in being more mobile becomes trapped at sinks within the sample. Through careful control of the irradiation process, the free
interstitial type defects can be removed without complete removal of the vacancies.

The process of irradiation by energetic electrons produces displacement of atoms by direct interaction through the Coulomb potential. It is known that a certain minimum energy $E_d$ is required to displace an atom in a lattice. For most solids this energy averages about 25 ev.\textsuperscript{13} Therefore, if the electrons interacting with the atoms in a lattice impart an energy $E_p \geq E_d$ to an atom, it can be displaced. A complicating feature of the process is that the displaced atoms, if energetic enough, are also able to displace other atoms. Electron energies used for the irradiation are in the Mev range and, therefore, a relativistic calculation of the maximum energy given to an atom in the lattice must be made. It can be shown\textsuperscript{13} that

$$T = \frac{2E}{Mc^2}(E - 2mc^2)$$

where $m$ is the rest mass of the electron, $M$ is the rest mass of the atom and $E$ is the kinetic energy of the electron. For additional explanation of the irradiation process see reference \textsuperscript{13}, pages 26 - 33.

In order to produce the simplest type of damage possible, each displacement reaction must involve only the formation of Frenkel pairs. The amount of damage produced\textsuperscript{14} can be determined by observing the resistivity changes of the sample. The observed changes in the resistivity are caused
by the introduction of scattering centers for conduction electrons in the sample.

Annealing of Damaged Samples

Defects produced in a solid can be removed by selective annealing. This is due to the fact that defects are capable of moving if the temperature is sufficiently high. Thus, the damage is altered and eventually will be annealed out. The process is commonly known as "recovery" or "annealing". Platinum metal has four definite stages of recovery. In the temperature range associated with each recovery stage, changes are taking place in the metal. Frenkel pairs are annihilating each other, defects are migrating and becoming trapped at sinks within the sample, and clustering of defects is taking place. Dislocations are not removed in the temperature range associated with recovery. Samples have to be annealed at higher temperatures before dislocations can be removed. For platinum the recovery stages are Stage I (4°K to 35°K), Stage II (35°K to 240°K), Stage III (240°K to 300°K) and Stage IV (400°K to 750°K). The details and mechanism of the recovery process for platinum are rather involved. Several articles are available giving a more complete discussion of the recovery process in platinum.
Preparation of Platinum Samples

All samples were pure platinum metal (99.95%) and were prepared by Dr. C. Lewis Snead at Brookhaven National Laboratory, Upton, Long Island, New York. The irradiated samples were prepared by using the Dynamitron located there to accelerate electrons to energies of 2.5 Mev. One sample was plastically deformed 8%. Prior to being irradiated or deformed, all samples were annealed at 1150°C to remove any damage that may have been present initially. Irradiated, plastically deformed, and annealed undamaged samples were studied in the experiment. Dr. Snead's estimate of the defect concentration in the irradiated sample can be found in Appendix I.\textsuperscript{19}

An additional procedure used in preparing samples was that of annealing samples at high temperature for two hours. The temperatures were obtained by using an oven accurately calibrated for precise maintainance of any desired temperature. The irradiated sample was annealed at 100°C for 24 hours, 250°C for 2 hours, and 400°C for 2 hours. The deformed sample was annealed only once at 400°C for two hours.
EXPERIMENTAL PROCEDURES

Sample Placement

The sample had to be positioned at the correct height and centered with respect to the slits in the sample chamber. The positioning could be checked by using a mirror and looking through one slit to the other slit. If the sample were centered with respect to the top, bottom and sides of the slits, it was positioned correctly. The sample chamber floor was designed to make this as easy as possible. A cylinder of aluminum slipped into a holder which automatically centered the sample within the sample chamber. In the top of the cylinder was drilled a hole into which a special mount screwed. The sample was glued onto the special mount which was then screwed into the aluminum cylinder. With the sample properly glued on, it was necessary only to adjust the height. When the proper height was obtained, a nut was tightened which locked the special mount rigidly in place. Then the aluminum cylinder was slipped into the holder and turned clockwise or counter clockwise until the sample was centered properly.

Data Processing

Obtaining and recording data

With the sample in place, counts were taken for a certain interval of time. Ten minutes was the time interval
used throughout the entire experiment. For the experi-
ment, the movable detector moved through a range of
approximately two degrees or one degree each side of the
horizontal position. The two degree range was covered
in thirtyfive steps of one milliradian each. After count-
ing for ten minutes, the system would print out the re-
sults and move the detector to the next position. With
this completed, the scaler was reset and another count
at the new position was made. A suitable arrangement of
relays and switches made it possible to move through the
two degree range automatically and then repeat the process
all over again.

The experimental procedure was one of allowing the
equipment to operate until enough data had been obtained.
Generally it was desired to have at least 20,000 counts
in the peak of the distribution. This necessitated
allowing the equipment to operate three to eight days
for each sample studied. With the experimental runs
complete, it was necessary to reduce the data to more
usable form.

Data reduction and plotting

Experimental results from several different runs had
to be added together in order to accumulate 20,000 counts
in the peak. This was accomplished by first grouping the
numbers from corresponding positions of the 35 interval
breakdown. The next step was to add all numbers from
corresponding positions together. With this completed the data was punched on I.B.M. cards. This was necessary since the data was to be reduced by an I.B.M. 1620 Computer. The computer calculated the centroid of the angular distribution curves and normalized the curves to a given area (100,000 units). The computer program and a brief description of it can be found in Appendix II.

With the data properly reduced, it was very easy to check the results for any error, experimental or arithmetic. The curves were angular correlation curves and should fold about the zero degree position and line up. All results were normalized to the same area and could be compared directly with each other.
RESULTS

Initial interest centered in studying three radiation damaged samples. Later interest centered in studying only the most damaged sample of these three and one plastically deformed sample. The three samples were given a varying amount of radiation-produced damage. It was specifically desired to compare the angular correlation results for the irradiated samples both with each other and with an annealed undamaged sample. Experimental results are in the form of normalized coincidence counts as a function of angular position. For purposes of comparison, the two portions of the angular correlation curve have been folded about the maximum onto each other. Normalization is to 100,000 units of area under the curve and is the same for all experimental results.

Figure four is the angular correlation curve for the most damaged sample. Examination of Figure four reveals that something is wrong in that the angular correlation curve is asymmetric. There is a large and significant difference particularly in the region of the peak. The circle data points are from an angular position below the center of the sample. The difference between the two portions of the correlation curve represents a loss in the counting rate. Absorption of photons associated with the positron annihilation events has occurred. The sample was thick
(10 mm x 5 mm x 1 mm) and absorption was a definite factor. Calculations using the absorption coefficient of platinum for 0.5 Mev photons revealed a 60 to 70 percent absorption of photons. This was based on an assumed path length through the sample of 5 mm. The absorption becomes more noticeable close to the center of the correlation curve. Since absorption destroys both the normalization and centering of the correlation curve, it had to be reduced before any meaningful results could be obtained using the thick samples.

Observing that the absorption would be very sensitive to any variation in the sample positioning gave one a place to start. It was decided that some information could be gained by varying the angle of the sample relative to the line joining the two detectors. This was done and the results indicated that by tipping the sample at an angle of 10° the effect of sample absorption could be reduced. This is well demonstrated by the result in Figure five. Figure five is a plot of the total number of photons counted (no coincidence required) in one minute at positions 6 through 31 for the movable detector. Position 17 corresponds to the center of the correlation curve or an angle of zero milliradians of Figure four. The total count remains relatively constant across the angular path of the movable detector. Therefore, thick samples could be used if they were mounted by being tipped ten degrees. For future work
it would be more satisfactory to use samples that are thin (15 mm \times 3 \text{ mm} \times .3 \text{ mm}). This would greatly reduce the problem of absorption.

With the absorption problem solved, it was decided to anneal the most damaged sample at three different temperatures. The annealing removed the damage from the sample. Figures six through eight are the angular correlation results for the sample annealed at 100^\circ\text{C} for 24 hours, 250^\circ\text{C} for 2 hours, and 400^\circ\text{C} for 2 hours. Thin plastically deformed samples were also prepared and Figure nine is the result for the most deformed sample. Figure ten is the result obtained after annealing the deformed sample at 400^\circ\text{C} for 2 hours.

For purposes of comparison, Figures six through ten have the result for an annealed undamaged sample plotted. The sample was made thinner and also mounted tipped. The degree of agreement between the two portions of the curve for the thin sample demonstrates that the absorption has been greatly reduced.
Figure 4. Angular correlation results for annealed (100°C) irradiated polycrystalline platinum.

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Figure 5. Plot of total number of photons arriving at the movable detector versus position.

Two standard deviations
Figure 6. Angular correlation results for unirradiated and for annealed (100°C) irradiated polycrystalline platinum.
Figure 7. Angular correlation results for unirradiated and for annealed (250°C) irradiated polycrystalline platinum.
Figure 8. Angular correlation results for unirradiated and for annealed (400°C) irradiated polycrystalline platinum.
Figure 9. Angular correlation results for undeformed and for plastically deformed polycrystalline platinum.
Figure 10. Angular correlation results for undeformed and for annealed (400°C) plastically deformed polycrystalline platinum.
CONCLUSIONS

Examination of the angular correlation curves for the annealed irradiated sample (Figures six through eight) reveals an interesting change. When compared to an annealed undamaged sample, a shifting of the angular distribution is observed. Examination of Figure six reveals that a shift of the peak upward and narrowing of the angular correlation curve for the irradiated sample has occurred. Figure six is the experimental curve for the sample when it had the highest defect concentration. Subsequent anneals (Figures seven and eight) served only to remove the defects and correspondingly removed the shift of the peak upward and narrowing of the correlation curve. An additional observation can be made in that after annealing at 400°C (Figure eight) no appreciable variation can be observed between the two angular correlation curves. Tipping the sample did not solve the absorption problem completely and a small discrepancy is still observed in the peak. It appears that whatever was produced by the irradiation process has been removed. It was estimated that initially one lattice site in a thousand was vacant in the sample. Therefore, it would appear that the removal of vacancies during annealing was responsible for the changes in Figure six through eight.
The research of J. J. Jackson revealed that vacancies do not move appreciably until samples are annealed at temperatures over 100°C. This is in good agreement with the changes observed in Figures six through eight. Annealing at 250°C removed much of the damage and annealing at 400°C appears to have removed the damage completely.

The experimental results (Figures six through eight) agree qualitatively with the research of Dekhtyar et al. and Berko and Erskine. They also observed a shift in the peak upward and a narrowing of the angular correlation curve for samples with increased concentrations of defects. A. T. Stewart and S. M. Kim have studied positron annihilation in quenched and annealed undamaged aluminum samples at liquid nitrogen temperature (78°K). Equal numbers of dislocations were present in the samples and quenching could only have produced an increase in the vacancy concentration. Considerable shifting of the peak upward, narrowing of the curve and smearing near the Fermi momentum were observed by these workers. It would be reasonable to assume that vacancies were responsible for the observed changes in the angular correlation results.

A possible explanation of the observed shift for the irradiated sample is that a vacancy is a center of negative charge and attracts positrons. The attraction increases the likelihood of annihilation with the greater concentration of conduction electrons at a vacancy in the lattice.
Contributions to the peak of the angular correlation curve are primarily from annihilations with conduction electrons. Therefore, the shift upward is caused by an increased probability of annihilations with conduction electrons in the region of a vacancy.

Examination of the angular correlation curves for plastically deformed platinum (Figures nine and ten) reveals a shift similar to the one observed in Figures six through eight. However, a difference does exist in that the deformed sample did not recover completely after being annealed at 400°C. In comparison to the annealed undamaged sample, the distribution is still narrowed and the peak shifted upward. Previous work indicated that the irradiated sample recovered rather completely after being annealed at 400°C. It is known that dislocations are produced by the process of plastic deformation. Dislocations are removed only at temperatures considerably above the temperatures at which recovery takes place. Therefore, it is possible for large numbers of dislocations to remain in the sample after annealing at 400°C. The vacancies present in the deformed sample should have been removed by the 400°C anneal. It would appear that dislocations also produce a shift in the angular correlation curve similar to the shift associated with vacancies. Additional research involving plastically deformed samples could prove interesting.
The main conclusions that can be made from the results are:

1. Increased defect concentrations in platinum cause a narrowing of the angular correlation curve and a shifting of the peak upward.

2. Recovery for irradiated platinum samples and for deformed platinum samples is similar.

3. Recovery in deformed platinum is not complete after annealing at 400°C. The incomplete recovery perhaps is caused by the presence of large numbers of dislocations or some interaction between Frenkel defects and dislocations.
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APPENDIX I

Calculation of Defect Concentration

It can be shown that the defect concentration for the sample studied is given by the following formula:

\[
\text{concentration} = \frac{\Delta \psi}{(\text{AREA}) \times 1.6 \times 10^{-19} \times \Delta \rho \times 100\% \times (\Delta \rho)_{90^\circ K}}.
\]

The \(\Delta \psi\) is a measure of the total number of electrons passing through the sample. It is determined through the use of a Faraday cup and suitable arrangement of a capacitor and a counter. \(\Delta \rho\) is the contribution to the resistivity of the sample by a single Frenkel pair. For platinum this number is of the order \(\Delta \rho = 6.5 \times 10^{-6}\ \text{cm}\%\).

\(\left(\frac{\Delta \rho}{\Delta \psi}\right)_{90^\circ K}\) is a measure of the slope of a given curve and is determined by interpolation of experimental data. For 2.5 Mev electrons it has the value \(3.3 \times 10^{-26}\ \text{cm}^2/\text{elec/cm}^2\).

For the sample studied, one has

\[
\frac{1}{1.6 \times 10^{-19} \times (\text{AREA})} \times \Delta \psi = 1.637 \times 10^{+19} \ \text{elec/cm}^2
\]

concentration = \(1.637 \times 10^{+19} \times (3.3 \times 10^{-26}) / (6.5 \times 10^{-6})(100)\)

\[= 8.3 \times 10^{-4} \approx 10^{-3}.
\]

So the concentration of vacancies is one part in \(10^3\), that is, one in a thousand lattice sites is vacant.
APPENDIX II

Computer Program

The program was written to reduce angular correlation data obtained in experimental research. This was essential in order to produce results that could be compared quickly and easily. Experimental data was in the form of counting rates taken from an angular distribution curve. The program was written so that counts from 50 different positions on the angular distribution curve could be processed. The program was divided into five parts: (1) reading in the data, (2) calculation of the centroid of the distribution, (3) calculation of a first derivative for the distribution and normalizing it, (4) calculation of abscissa coordinates for the first derivative and (5) normalizing the angular distribution curve to a given area. In the research only parts 1, 2, and 5 were needed.

LISTING OF THE PROGRAM

DIMENSION Y(50), DM(50), ERR(50), YNOR(50),
DNOR(50), ERN(50), YR(50)

500 READ 36, N, ACON, DECAY

DO 101 J = 1,50

Y(J) = 0.

101 YR(J) = Y(J)

PUNCH 38, N, ACON, DECAY

37
DO 1 J = 1,N
READ 37, Y(J)
YR(J) = Y(J)
JJ = J - 1
1 Y(J) = Y(J) * ((DECAY)**JJ)
DO 2 I = 1,50,5
PUNCH 39, YR(I), YR(I+1), YR(I+2), YR(I+3), YR(I+4)
IF((I-4) - N) 2, 102, 102
2 CONTINUE
102 YMAX = 0.
DO 3 J = 1,N
IF(YMAX-Y(J)) 4, 3, 3
4 INDYO = J
YMAX = Y(J)
3 CONTINUE
PUNCH 40, INDYO, YMAX
MRVAL = N - INDYO
LVAL = INDYO - 1
MDIFF = MRVAL - LVAL
MRST = INDYO + 1
LFIN = INDYO - 1
MRFI = N
LSTAT = 1
IF(MDIFF) 6, 7, 8
6 LSTAT = 1 + (-1)*MDIFF
GO TO 7
MRFI = N - MDIFF

PUNCH 41, MRST, MRFI, LSTAT, LFIN, MDIFF

YPLUS = 0.

YMIN = 0.

DO 9 J = MRST, MRFI

9 YPLUS = YPLUS + Y(J)

YPLU = YPLUS - Y(MRFI)

DO 10 K = LSTAT, LFIN

10 YMIN = YMIN + Y(K)

YMMIN = YMIN - Y(LSTAT)

SPLUS = YPLUS - YMAX - YMMIN

SMIN = YPLU + YMAX - YMIN

XCORR = 0.

IF(SPLUS - SMIN) 5, 100, 5

5 XCORR = (SPLUS + SMIN)/(2.*(SMIN - SPLUS))

PUNCH 42, YPLUS, YPLU, YMIN, YMMIN, XCORR

IND = N - 1

DO J = 1,IND

DM(J) = ABSF(Y(J+1) - Y(J))

ERR(J) = SQRT(Y(J+1) - Y(J))

PUNCH 43, DM(J), ERR(J)

IF(XCORR) 14, 20, 15

14 XA = ABSF(XCORR)

IF(XA - .5) 16, 16, 17

16 DL = .5 - XA

SLOPL = 0. - DL
SLOPR = 1. + SLOPL
GO TO 21
17 DR = XA - .5
SLOPR = 0. + DR
SLOPL = SLOPR - 1.
GO TO 21
15 IF(XCORR - .5 ) 18, 18, 19
18 DR = .5 - XCORR
SLOPR = 0. + DR
SLOPL = SLOPR -1.
GO TO 21
19 DL = XCORR - .5
SLOPL = 0. - DL
SLOPR = 1. + SLOPL
GO TO 21
20 SLOPR = .5
SLOPL = .5
21 PUNCH 44, SLOPL, SLOPR
ISIM = 1
LSIM = N
LOM = N
22 IF(LOM) 23, 24, 25
25 LOM = LOM - 2
GO TO 22
24 PUNCH 45
MSIM = MDIFF
IF(MSIM) 26, 27, 28

26 ISIM = 2
GO TO 23

28 LSIM = N - 1

23 SUMS = Y(ISIM) + Y(LSIM)
ISIM = ISIM + 1
DO 29 J = ISIM, LSIM, 2

29 SUMS = 4.*Y(J) - SUMS
ISIM = ISIM - 1
LSIM = LSIM - 1
DO 30 K = ISIM, LSIM, 2

30 SUMS = SUMS + 2.*Y(K)
AREA = SUMS/3.
FACT = ACON/AREA
PUNCH 46, AREA, FACT
DO 31 J = 1,N
YNOR(J) = FACT*Y(J)

31 PUNCH 47, Y(J), YNOR(J)

DMAX = 0.
DO 32 J = 1, IND
IF(DMAX - DM(J)) 33, 32, 32
DMAX = DM(J)

32 CONTINUE

FN = 2./DMAX
PUNCH 48, DMAX, FN
DO 35 J = 1, IND
DNOR(J) = FN*DM(J)
ERN(J) = FN*ERR(J)

35 PUNCH 49, DM(J), DNOR(J), ERN(J)

27 GO TO 500

36 FORMAT(12,F7.3,F12.9)

37 FORMAT(F12.2)

38 FORMAT(I2,F7.3,F12.9)

39 FORMAT(5F12.2)

40 FORMAT(6HINDYO=I2,3X5HMAX=F12.2)

41 FORMAT(I2,3XI2,3XI2,3XI2,3XI2)

42 FORMAT(4(F12.2,3X),6HXCORR=F7.3)

43 FORMAT(6HDM( )=F12.2,3X7HERR( )=F14.8)

44 FORMAT(17HFIRST SLOPE LEFT=F7.3,3X18HFIRST SLOPE RIGHT=F7.3)

45 FORMAT(9HN IS EVEN)

46 FORMAT(5HAREA=F14.2,3X5HFACT=F14.8)

47 FORMAT(5HY( )=F12.2,3X8HYN)R( )=F12.8)

48 FORMAT(5HDMAX=F12.2,3X3HFN=F14.8)

49 FORMAT(6HDM( )=F12.2,3X8HDNOR( )=F12.6,3X7HERN( )=F14.8)

END