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OBSERVATION OF DIFFRACTION EFFECTS IN POSITRON CHANNELING

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An experimental investigation of positron channeling was made with a high-angular resolution apparatus, employing positrons of kinetic energy 1 MeV, derived from the Brookhaven National Laboratory Dynamitron. The pattern of transmission through a Si (100) single crystal of thickness 0.245 μm was investigated for a number of major planes. We have observed for the first time, in excellent detail, the fine structure of the channeling pattern expected to arise from the particle diffraction effects, theoretically explainable in terms of the quantum-mechanical many-beam calculations.

THEORETICAL BASIS

The number of bound states a positron could avail in the transverse channeling potential of a single crystal could be estimated, for planar channeling, [1] as

$$n_p \approx (\gamma N d_p^3)^{1/2} Z^{1/2}, \quad (1)$$

with the following representations:

$\gamma \equiv$ the relativistic mass ratio of the positrons

$N \equiv$ the atomic number density of the target
 $d_p \equiv$ the interplanar spacing, and
 $Z \equiv$ the atomic number of the target.

The observed patterns of channeling (peaks or dips) could have widths which are gauged in terms of a theoretical parameter, the Lindhard characteristic angle. For relativistic positrons, this angle is given, for planar channeling, by the equation

$$\psi_p = (4\pi a Z e^2 N d_p / v p)^{1/2} \quad (2)$$

Fig. 1. Illustrative sketch of the apparatus

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v being the speed of the particles, p their momentum and a the Thomas-Fermi scattering length. The latter is given by

$$a = 0.4685/Z^{1/2} \text{ \AA} \quad (3)$$

For values of $n \gg 1$, the classical treatment is adequate. If not, only a quantum mechanical approach can be satisfactory.[2] In such a case, the particle diffraction effects will dominate the channeling pattern which will be featured with a fine structure determined by the Bragg angle. The latter is given as

$$\theta_B = \lambda/2d_p \quad (4)$$

wherein λ represents the positron wavelength. For 1 MeV positrons, the Bragg angle could be $\approx 0.1^\circ$.

EXPERIMENTAL FEATURES

The positron beam produced by the Dynamitron was adapted for a high-resolution experiment by defocussing the beam and limiting the diameter to 1 mm by a slit, which resulted in a divergence less than 0.01° . However, this also reduced the available intensity drastically to approximately 100 e^+ /sec. The low beam

divergence was confirmed through measurements of the diameter at various points along the beam path.

The collimated beam was incident along a fixed horizontal direction (x) in the laboratory on a Si (100) single crystal of thickness, 0.245 μm . The crystal thickness was comparable to and less than one mean free path for inelastic scattering. The mean scattering angle was calculated to be 0.17° for 1-MeV positrons, and the mean scattering number 0.56, indicative of single scattering. It was mounted transverse to the beam in the y - z plane, on a frame attached to a goniometer (Fig. 1). The direction of the transmission beam emerging from the target was defined by a 2 mm x 2 mm aperture formed by two mutually-perpendicular slits each capable of being moved transverse to the beam direction. The positrons were detected by a windowless HPGe detector mounted downstream behind the beam-defining aperture, which allowed for a maximum angle of detection, $\theta_D = 0.038^\circ$. The count rate in the full-energy peak was approximately 30/sec for a random orientation of the crystal. Data was collected for 200-sec periods at angular intervals of 0.025° .

Fig. 2. A channeling scan for the (111) plane at 2° tilt.

Fig. 3. Patterns for the (001) and (011) planes at tilt, 7.3° .

RESULTS

A histogram was first obtained through a series of scans in which the crystal was rotated over wide ranges about the two directions transverse to the beam. This histogram was used to determine the direction of the $\langle 001 \rangle$ axis in the experimental geometry. We obtained well-resolved channeling patterns for three major planes which show the diffraction effects with fine clarity. Invariably, the pattern consisted of a dip with a central peak of relatively subdued prominence (Fig. 2). The diffraction patterns also carried numerous secondary features, which presumably result from a good number of mutually-interfering channeling effects prompted by different planes and axes. The details of each scan were reproduced with consistency in repeated runs at a given crystal orientation. However, the overall pattern could change significantly even for small variations of the tilt angle, θ . For example, when the tilt was altered from 2° to 0.2° , the secondary features of the (111) scan varied substantially, but the width of the (111) profile itself remained more or less unchanged. Fig. 3 represents the scan obtained for $\theta = 7.3^\circ$, covering the (001) and the (011) planes. The two planes

presented distinct features, including different shapes and relative heights of the central peaks.

The primary nature of the pattern as a dip with a central peak can be understood in terms of the point detector geometry of the experiment. The mean scattering number is only 0.56, and the mean scattering angle, 0.17° , considerably less than the typical critical angle of channeling. Thus, under the channeling condition, the envelope of the steered particles is broader than the aperture of detection. Hence, despite an increase in transmission, the detection rate in the primary beam direction can be lower than for a random orientation.

ANALYSIS AND DISCUSSION

It is presently difficult to identify firmly the various secondary features, but the pattern produced by each major plane studied closely could be seen quite distinctly as a substantial dip with a peak in the center. The dip width presented for each major pattern was determined by a nonlinear Gaussian fit passing through the geometric centers of the constituent

Table 1. Theoretical and measured values of the contour widths and Bragg angles for channeling patterns, corrected for the angle of projection. The ratio yields an estimate of the number of bound quantum levels, n_p for the channeling potential, which is compared to the theoretical value based on the continuum model. An accuracy $\pm 20\%$ may be cited for the experimental value of ψ_p . The probable error in the measurement of θ_B is lower, and is quoted as $\pm 10\%$.

Plane	d_p ($\text{\AA}$)	ψ_p		θ_B		n_p	
		Theory	Exp	Calc	Exp	Calc	Exp
(001)	1.36	0.29	0.36°	0.183°	0.200°	≈ 1.5	1.8
(011)	1.92	0.34	0.40°	0.130°	0.130°	≈ 2.5	3.1
(111)	3.13	0.44	0.45°	0.080°	0.080°	≈ 5.1	5.6

wiggles. The deduced width for each planar dip, corrected for the angle of projection, is listed in Table 1. The measurement values are in fair agreement with the corresponding Lindhard characteristic angles, although the former tend to be somewhat larger. The Bragg angle was extracted from the experimental data as the spacing between the wiggles in the planar pattern, and the values agree with the calculated ones (Eq. 4); see Table 1. The experimental values of the Lindhard angle and the Bragg angle could yield an estimate of the total number of bound quantum levels [2] as $n_p = \psi_p / \theta_B$, which could be compared with the theoretical value (Eq. 1). Such a comparison is also provided in Table 1, and there seems to be a good degree of compatibility, although the experimental values all lie on the higher side. The tunneling effects were estimated, based on theory.[1,3] Found to be only a few percent, they are considered to be beyond experimental identification at present.

It is expected that the observed patterns could be explained in detail by a many-beam calculation,[3] with the present

experimental features taken into account. Work in this direction is being undertaken, and preliminary results suggest that the observed structures could be explained at least roughly.[4] It is hoped that a better understanding of the possible effects of interference between adjacent planes and axii in the pattern could be gained from this work.

ACKNOWLEDGMENTS

This work was supported by NSF grant, PHY. 9203873 and DOE Contract, DE.AC02-76CH00016

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