MASTER

**THE CHANNELING OF POSITIVE AND NEGATIVE
PIONS IN A SILICON CRYSTAL**

CONF-770951-15

D.S. Gemmell, R.E. Holland, W.J. Pietsch,
A.J. Ratkowski, J.P. Schiffer, T.P. Wargler,
J.N. Worthington and B. Zeidman

Prepared for
7th International Conference on
Atomic Collisions
Moscow State University
Moscow USSR
September 19-23, 1977

U of C-ANA-USAERDA

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

**operated under contract W-31-109-Eng-38 for the
U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

The Channeling of Positive and Negative Pions in a Silicon Crystal

D.S. Gemmell, R.E. Holland, W.J. Pietsch,[#]
A.J. Ratkowski, J.P. Schiffer, T.P. Wangler,
J.N. Worthington and B. Zeidman,

Argonne National Laboratory, Argonne, Illinois 60439^{*}

and

C.L. Morris and H.A. Thiessen

Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

ABSTRACT

The channeling characteristics for 70.5-MeV and 255-MeV π^+ and π^- traversing a 120- μ thick silicon crystal have been measured. The energy loss for channeled π^+ is about 2/3 that obtained for "random" incidence, while that for channeled π^- is slightly ($\sim 10\%$) higher. For both π^+ and π^- strong steering effects are observed under axial channeling conditions. Similar steering effects are seen in planar channeling for π^+ but not for π^- . The results suggest there is a high probability for π^- to be captured into classical trajectories that spiral around the rows of atoms in the crystal.

[#] On leave of absence from the University of Cologne, West Germany.

^{*} Work supported by the U.S. ERDA, Division of Physical Research.

Most channeling experiments have thus far been performed with positively charged projectiles having masses greater than or equal to that of the proton. Channeling phenomena observed with these positive ions can be well described in terms of classical projectile trajectories. This classical behaviour is primarily a consequence of the large projectile mass (there is then a large number of quantum states available to be populated in the potential well that governs the channeled motion¹). There is no fundamental reason why the channeling characteristics observed for positive projectiles should be of any greater physical interest than those for negative projectiles. It is, in fact, a matter of interest to compare channeling effects for classically behaving beams that differ only in the sign of their electric charge. Experiments comparing effects seen with electron and positron beams¹ have suffered from the disadvantages that at low bombarding energies diffraction phenomena dominate and render interpretation difficult, while at high energies (where the relativistic increase in mass leads to a more classical behaviour) the angular widths of the channeling anomalies become prohibitively small from a practical standpoint.

The desirability of employing more massive negative projectiles leads in a natural way to the use of secondary beams from high-energy accelerators. Recently Allen et al² reported an angular anomaly in the fraction of 4-GeV/c π^- transmitted through a 1-cm thick Ge crystal under axial channeling conditions. With the intense secondary beams now available from the so-called "meson factories", a new class of channeling experiments with

classically behaving projectiles becomes feasible. The qualities of these beams are such that they can be severely collimated to meet the stringent requirements for channeling while still giving useful intensities. Furthermore, the beam energies can be made low enough that the angular widths for channeling become large compared with the beam divergence. We report here on the first measurements with such beams - a comparison of the channeling characteristics for 70.5-MeV and 255-MeV π^+ and π^- in a silicon crystal.

The pion beam at the EPICS channel³ of the Los Alamos Meson Facility was collimated by sets of adjustable stainless-steel clad uranium jaws inserted at several locations between the EPICS bending magnets. This collimation reduced the pion intensity available at the target position by about a factor of 10^5 . Before performing the actual channeling measurements the size and the dispersion of the pion beam were measured with an arrangement containing a remotely adjustable slotted scintillator and a helical-wire proportional counter located 3.5 m downstream. Using the scintillator as a veto counter permitted accurate determination of individual trajectories for pions passing through the 1-mm wide slot. The size of the beam spot at the target position was measured to be 5 x 5 mm. The vertical dispersion was 0.57 mrad/mm and there was no detectable horizontal dispersion. At any point in the beam spot the angular divergence was less than 0.5 mrad. These figures are in excellent agreement with previously calculated values based on the expected beam-optical properties of the EPICS channel³. The π^+ count rate was typically a few hundred per second and that for π^- was about

a factor of four lower. Throughout these and subsequent measurements the beam-spot size and stability were monitored with four adjustable scintillators located 80 cm upstream from the target position. Contaminant beam particles were relatively few because of the tight collimation and magnetic selection. Those that did reach the target position were completely rejected by time-of-flight and pulse-height techniques.

The channeling target crystal was a 120- μm -thick silicon surface barrier counter⁴ that functioned also as an energy-loss detector. This detector was operated under conditions of total depletion and had entrance and exit surfaces that were flat and coplanar to within $\pm 1\mu\text{m}$. The active diameter of the detector was 16 mm. The crystal was cut with the $\langle 110 \rangle$ axis normal to the planar surfaces. The electrode coatings were 20 $\mu\text{g}/\text{cm}^2$ Al on the entrance surface and 20 $\mu\text{g}/\text{cm}^2$ Au on the exit surface. The detector was cooled to 6°C and was held in a 3-axis goniometer remotely controlled by an on-line computer. The channeling measurements consisted of determining the energy losses and the scattering trajectories for transmitted pions as functions of the incidence angle with respect to the $\langle 110 \rangle$ axis and the (110) and (111) planes of the Si target crystal. The incidence positions and the scattering directions were determined with helical-wire proportional chambers having spatial resolutions of 0.3 mm.

For π^+ at both bombarding energies, going from "random" to "aligned" incidence resulted in a reduction in energy loss.

The most probable energy loss for axial alignment was about 2/3 of that for random. For both planar alignments the corresponding factor was about 3/4. (The axial result is consistent with the recent measurements of Fich et al⁵ for 1.35-GeV/c π^+ in Ge.) For π^- , alignment was found to produce a slight ($\sim 10\%$) increase in the energy loss. Fig. 1 illustrates the sharply differing behaviours of the energy losses for 70.5-MeV π^+ and π^- under conditions of $\langle 110 \rangle$ axial alignment.

The energy-loss spectra⁶ for π^+ were able to be decomposed into "channeled" and "random" fractions [Fig. 1(a)]. (This separation could not be done in any meaningful way for π^-). The angular variation of the "channeled" component for π^+ showed a sharp peak (see the insert in Fig. 1) with a width (fwhm) markedly less than twice the expected channeling critical angle.⁷ This angular behaviour together with the reduction in energy loss for channeled π^+ is completely in accord with the channeling behaviour observed for low-energy positive ions.¹

Although alignment has little effect on the π^- energy-loss, there is a surprisingly large steering effect observable in the scattering angles measured near axial alignment conditions. In fact, the effects are of about the same magnitude as those expected and seen for positively charged projectiles. Fig. 2 demonstrates this for 255-MeV π^+ and π^- . The angular extents of the anomalies correspond fairly well with the values calculated for π^+ .⁷ Similar effects are seen in planar channeling of π^+ , but are totally absent in the planar case for π^- .

These results may be understood from the expectation that whereas for classical positive-particle channeling the trajectories lie

between the rows or planes of target atoms, negative projectiles can readily establish trajectories that spiral in classical orbits around rows of atoms.⁹ Such trajectories can be expected to persist stably for relatively long times because of the sharply reduced nuclear multiple scattering. The corresponding type of trajectory for planar alignment would have to oscillate to and fro through the planes of target atoms. This would result in greatly enhanced nuclear multiple scattering which would rapidly destroy the guided motion. This may account for the absence of observable planar steering effects in the present experiments. A rough estimate of the angular width associated with the spiral motion can be made by equating the centrifugal force with the force attracting a negative particle to a line of charge. This gives $\theta_S \sim (2Z_1Z_2e^2/pvd)^{1/2}$, where $-Z_1e$ is the projectile charge, Z_2e is the nuclear charge of the crystal atoms, d is the internuclear spacing along the row of atoms and p and v are the projectile's momentum and velocity. In magnitude θ_S is close to the value of $\psi_{1/2}$ quoted in ref. 7. The near equality of the widths of the axial angular anomalies for π^+ and π^- tends to confirm this interpretation. The small effect of the spiral motion on the stopping power for π^- suggests that the average electron density sampled by these trajectories is slightly higher than that for the whole crystal. This is in sharp contrast with the positive particle case, where the trajectories sample greatly reduced electron densities.

To summarize, we report here on the first investigation of channeling phenomena observed for beams of classically behaving

projectiles that differ only in the sign of their electric charge. For π^+ , we see the expected extrapolation to higher energies of results previously found for low-energy positive ions. For π^- , we find no readily observable effects in planar alignment, but find evidence under axial alignment conditions for a spiralling trajectory that while affecting the stopping power only slightly, manifests itself in steering effects comparable to those seen for π^+ .

We gratefully acknowledge the help of T.H. Braid, J. -C. Poizat and J. Remillieux in the early phases of this investigation and to the staff at LAMPF for their help in achieving the high quality beam required for these measurements.

REFERENCES

- ¹For reviews of this and other aspects of channeling, see D.S. Gemmell, Rev. Mod. Phys. 46, 129 (1974) and "Channeling; theory, observation and applications" Ed. D.V. Morgan, John Wiley, NY (1973).
- ²D. Allen, D. Gockley, G. Lazo, W. Gibson, H. Wegner and A. Kanofsky, Lett. Nuov. Cim. 15, 529 (1976).
- ³"A Proposal for EPICS: A High Resolution Pion Beam and Spectrometer Facility for Nuclear Structure Research at LAMPF," compiled by H. A. Thiessen and S. Sobottka, Los Alamos Scientific Laboratory report LA-4534-MS (1970).
- ⁴Supplied by ORTEC Inc. Oak Ridge, Tennessee.
- ⁵O. Fich, J.A. Golovchenko, K.O. Nielsen, E. Uggerhøj, C. Vraast-Thomsen, G. Charpak, S. Majewski, F. Sauli and J.P. Ponpon, Phys. Rev. Lett. 36, 1245 (1976).
- ⁶Strictly speaking, the energy spectra measured in the Si counter are not exactly equivalent to the pion energy-loss spectra because some energy (eg. part of that carried by very fast electrons) escapes the detector (see, for example, the discussion in ref. 5). These considerations do not substantially alter the nature of the results reported here.
- ⁷Using an expression due to Barrett⁸ that fits a great variety of low-energy positive-ion channeling data, and making the appropriate relativistic corrections,¹ one calculates expected values of the fwhm of the channeling angular anomaly in the scattering of π^+ to be $2\psi_{1/2} = 2.3$ and 1.4 mrad. at 70.5 and 255 MeV, respectively.
- ⁸J.H. Barrett, Phys. Rev. B3, 1527 (1971).
- ⁹This idea has been suggested previously by Kumm et al¹⁰ to explain features seen in electron channeling.
- ¹⁰K. Kumm, F. Bell, R. Sizmann, H.J. Kreiner and D. Harder, Radiat. Eff. 12, 53 (1972).

FIGURE CAPTIONS

Fig. 1 (a),(b) Energy-loss spectra for 70.5-MeV π^+ and π^- , respectively, obtained for "random" incidence and for an incidence direction aligned with the $\langle 110 \rangle$ crystal axis. The "aligned" spectrum in (a) is decomposed into "channeled" and "random" components. The insert shows the dependence of the "channeled" component of (a) on the incidence angle with respect to the $\langle 110 \rangle$ crystal axis.

Fig. 2 (a) Deflection of the centroid of the angular distribution for transmitted pions and (b) the fwhm for this distribution. Both are plotted for 255-MeV π^+ (open circles) and π^- (closed circles) as functions of the angle between the incidence direction and the $\langle 110 \rangle$ crystal axis.

(a) π^+

(b) π^-

(b) π^-

RANDOM

ALIGNED