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PROPOSAL TO STUDY CHANNELING AT FERMILAB

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SUMMARY

Channeling, the behavior of charged particles moving through the planes and rows of aligned single crystals, has been studied with great success in connection with many solid state and nuclear processes at low energies. We propose to study channeling at Fermilab energies where the dechanneling lengths are so long that thick single crystals may be used and many different particles, including negative particles other than electrons, are available. Both of these factors permit significant extensions of channeling experiments.

The experimental apparatus will consist of a single crystal and its associated goniometer along with position detectors fore and aft of the goniometer to measure the trajectories of the particles. A goniometer and associated germanium single crystals are available from Bell Laboratory. The system has already been calibrated at Van de Graaff and AGS energies. The high precision drift plane system presently in operation at Fermilab for the kaon form factor experiment (E-456) will be used to measure particle directions before and after the single crystal. Two hundred and fifty hours of beam time are requested. We believe it is desirable to schedule this test of channeling in conjunction with the running of the form factor experiment, in part to provide a calibration of the drift chamber system.

INTRODUCTION

This is a proposal for a parenthetical experiment. It has to do with the steering of charged particles of energy up to 200 GeV by rows or planes of atoms in a single crystal. This steering effect, called particle channeling,[1] has been much studied and is well described theoretically for positive particles at energies up to 50 MeV.[2] (Appendix I contains a discussion of some applications of channeling.) Similar effects are clearly predicted by the theory up to the highest energies. Indeed, the effects should get stronger as the energy is increased since the competing multiple scattering effects scale as E^{-1}, whereas the steering effect (in angular extent) is predicted to scale as $E^{-\frac{1}{2}}$, so that at Fermilab energies, crystals several mm thick may be used.

Recent experimenters at CERN[3,4] and BNL[5] have shown channeling is operative at ~ 1.1 GeV/c and ~ 4 GeV/c respectively. In these experiments, the crystals show increased transmission of particles along the planes and axes of a crystal, leading to peaks in a scatter plot of incident projected angles. The widths of these angular enhancements are directly related to the so-called critical angles for channeling. The axial critical angle for singly charged relativistic positive particles is given by

$$\psi_c = 2\sqrt{\frac{Ze^2}{p\beta cd}} \qquad (1)$$

where d is equal to the spacing of the atoms along the atomic row.

The CERN experiment shows, for positive particles, results about as predicted by the classical theory. (See fig. 1) The CERN experiment has also measured energy deposits in a single crystal as a function of particle incident angle. The experimental agreement is good enough to allow the effect to be applied in some important tests of the theory of energy loss and straggling of positive particles in solids (fig. 2) and to suggest possibly useful applications as a collimating element in ultra-high energy physics. (See Apendix II for a discussion of the energy loss measurements.) The results encourage us to look even higher in energy where competing processes should become even less important, where similar or other applications could be useful and where the limits of the classical theory can be further tested.

For negative particles, the situation is less clear and quite intriguing. The CERN results for 1.1 GeV/c π^- shows a result not predicted by the theory. In the angular distribution of particles transmitted through a crystal, the theory predicts a deep and narrow minimum. The experiment shows a prominent and narrow maximum surrounded by a broad minimum (fig. 3); whereas, the BNL results at 4 GeV/c indicate (with less statistical accuracy) a narrow minimum (fig. 4). Admittedly, the theory is not so well worked out as for positive particles. This is in part due to the paucity of experimental data for negative particles except for low energy electrons (< 1 MeV) where diffraction effects begin to interfere. Such measurements of high energy electrons as exist appear to be in better qualitative agreement with the BNL than the CERN results. Clearly, some additional and systematic experiments are called for.

By measuring the transmission as a function of incident angles at Fermilab energies, we will be able to observe the behavior of channeling at very high energies, extend channeling measurements to several different negative particles, and test the energy dependence of dechanneling lengths at high energies by using crystals of different thicknesses. The experiment will also provide some of the most challenging tests of the developing technologies in very high resolution drift planes and large single crystals.

The proposed experiment represents a diversion for Fermilab intellectually as well as physically. For this we do not apologize. Indeed, we regard this as a strength. We believe, however, that this experiment can be carried out efficiently (perhaps even parasitically) using existing equipment and personnel with a minimum cost or distraction to existing or proposed Fermilab programs. If there is room at Fermilab for such diversion, we elicit serious consideration of this proposal.

CHANNELING MEASUREMENTS

There are two modes for carrying out channeling experiments. One is to use a beam with sufficient divergence so that it includes the entire range of angles of interest (several hundred microradians). Drift chambers can then be used to define the particle direction before and after the crystal and hence to look at the probability for particles to pass through the crystal undeflected as a function of the direction of incidence. This method provides the most convenient and informative survey of the channeling probability, angular extent and other factors. Only a fraction of the particles incident will meet the necessary angular criteria to be channeled.

The other mode which could be used in subsequent measurements of, for example, energy loss or beam collimation makes more efficient use of the beam. It involves use of a parallel beam (preferably with divergence less than the channeling critical angle involved) and precise alignment of the crystal with the incident beam direction. In this mode a large fraction, greater than half, of the particles could be captured into channeling trajectories. A parallel tune of this sort can be implemented with the M1 beam in the Meson Laboratory.

BEAM CONDITIONS

The M1 beam in the Meson Laboratory has a sufficient intensity of all long-lived charged particles with the possible exception of electrons. (Tagged electrons are present at around 0.1% and muons are present at a level of less than one percent at 100 GeV.) We propose to run both positive and negative particles for four different beam momenta, from the highest possible momentum with the beam down to the lowest momentum with the hope of being able to match on to channeling experiments now underway at Brookhaven and planned at CERN. It is estimated that the primary time requirement would be to set up the apparatus and trigger. At present, neither of these seem to be particularly time consuming. We estimate one eight-hour shift is necessary to run each momentum sign, provided the same sign and momentum set are already established. We propose to run with several different single crystal thicknesses at the lowest and highest momenta. This proposal will require 250 hours of beam time.

APPARATUS

For channeling studies, it is important to use crystals of sufficient perfection to observe the desired effects. The small critical angles for channeling encountered at high momenta (expected to be on the order of 70 microradians at 100 GeV/c) put strong restrictions on the amount of mosaic spread which can be tolerated. (Mosaic spread is a term which is used for localized variations in crystal orientation due to slip planes, dislocations and other crystal defects.) Dislocation-free germanium crystals have been chosen as the best available candidates for high energy channeling studies on the basis of anomalous X-ray transmission and lower energy particle channeling measurements. The Brookhaven experiment has been performed with such crystals. They are also expected to be suitable at Fermilab energies.

A special high precision goniometer is available for crystal orientation. This goniometer has a measured precision of 50 microradians in scanning angles and a reproducibility of 170 microradians in setting absolute angles using a remote digital angle encoder and readout and control system. The goniometer has been used in the experiments at Brookhaven and would be moved to Fermilab. Note that in the mode proposed for this experiment, the goniometer is used only to position the crystal initially. The germanium crystals have already been pre-oriented and tested at MeV energies with the Tandem Van de Graaff at Brookhaven and at GeV energies with the AGS.

The foundation of an apparatus for channeling studies exists in the M1 beam in the Meson Laboratory. The apparatus for E-456, kaon form factor, employs low multiple scattering drift planes similar to those developed by Charpak and Sauli for the CERN channeling studies. These planes have spatial resolutions of 60 microns rms.[6] Within the critical angle for channeling there is effectively no multiple scattering by the single crystals so that the planes near the crystal are the sole contribution to multiple scattering in the angle measurement. The measurement system will consist of three high resolution, thin x, y plane pairs - one thirty meters upstream of the single crystal goniometer, one at the single crystal and one twelve meters downstream. The layout for the angle measuring system is shown in Figure 5.

Figure 6 shows the expected half angle at half maximum for axial channeling in the <110> direction in germanium as a function of energy. The curve has been extrapolated from the CERN measurements at 1.35 GeV/c, and as such, is based on an experimental measurement. Note that this angle is smaller than the critical angle given by (1). At 100 GeV/c, the half angle at half maximum is expected to be 35 microradians. Figure 6 also shows the expected resolution for the kaon form factor apparatus with a new drift plane at the center along with the present drift chambers of E-456 for the upstream and downstream measurements. The new center module will have wires with half the diameter used at present and two x and two y measurements rather than four of each. This cuts the radiation length of the center module by five and requires no new technology. For the E-456 plane separation and the new drift plane set in the center, the half angle-half max resolution at 100 GeV/c is 11 microradians. The new center module can be quickly constructed using existing parts that are available in the Dubna group.

Figure 7 illustrates the expected channeling line shape and background at 100 Gev/c extrapolated from the CERN measurements at 1.35 GeV/c. The effect of resolution is also shown. Since the planar channeling angles are expected to be substantially smaller than the axial angles, it is well to strive for high resolution.

The present E-456 system is capable of taking up to 120 events per pulse with drift chambers. Total particle fluxes through the planes can be upwards of a million per pulse. Of course, kaons and antiprotons constitute a minor fraction of these. Statistics comparable to the ones obtained in the recent Aarhus-CERN channeling study near 1 GeV/c (Figures 1, 3) can be achieved in about twenty machine pulses.

The necessary goniometer and single crystals are available now and can be moved to the Laboratory and positioned in place with about a week's notice. We believe the kaon form factor scattering apparatus can be converted quickly and relatively easily. We believe it is important that the channeling run be scheduled in conjunction with the form factor experiment running. In a sense, the form factor running will constitute an excellent calibration of the apparatus for the channeling studies. Note that the angular precision requirements for the kaon form factor are similar to those required for channeling so that successful preparation for one experiment assures satisfactory operation for the other. It is anticipated that there will be no substantial additional requirements on the Laboratory beyond use of the beam and the scattering apparatus. We would prefer that the differential Cerenkov counter system be available for particle identification.

A number of the experimenters on the form factor experiment are participating in this proposal. While this experiment is not the dominant interest of the kaon form factor group, we feel that it constitutes an interesting auxiliary experiment.

Appendix I - Applications of Channeling

The experimental and theoretical development of the understanding of charged particle motion in single crystals, channeling, has been enormous in the last decade. In addition, the channeling effect has also been particularly useful for the study of solid state phenomena with important applications in studies of impurity locations in solids, surface structure and catalysis. In nuclear physics it has provided a means for measuring compound nuclear lifetimes in the range 10^{-14} to 10^{-18} seconds. It is also finding increased use for practical applications such as ion implantation. The possible technological applications for this field appear to be nowhere near exhaustion.

There may be practical applications of channeling to high energy experimentation. Solid state detectors are already used in the Fermilab program. These detectors are now cut so that they are not aligned along channeling directions. If energy loss measurements show significant differences for channeled particles, identification signals for channeled and, therefore, highly collimated particles are available by making the crystal a detector. This situation is discussed in Appendix II. Such detectors might also be used for particle identification. Channeling may also be able to be used to devise low multiple scattering devices in certain applications.

Recently, exotic applications of single crystals for studying short-lived particle interactions and lifetimes have been suggested.[7] Studies of conventional channeling offer the first step in seeing if the necessary single crystal technology can be put into application at Fermilab.

Appendix I (cont.)

Tsyganov[8] has also proposed that single crystals could be used for bending and cooling particle beams. A deformation of a single crystal might be used to deflect channeled particles analogous to the way a light pipe guides light. Particle beams moving along channeled trajectories may lose transverse momentum to the lattice so that the transverse motion is damped. Both possibilities are straightforward to test in the experiment proposed here.

Appendix II - Energy Loss Effects at High Energy

In the recent CERN experiments, the ionization energy deposited in a 1 mm thick germanium crystal by transmitted 1.35 GeV/c protons and positive and negative pions was measured. The crystal was itself a detector made by applying rectifying contacts and totally depleting the crystal through its thickness so that electron-hole pairs produced by the transmitted particles could be swept apart and measured. It was found that channeled protons and positive pions had an energy loss about one-third of that of unchanneled particles. For negative pions, no such reduction in energy loss for channeled particles was observed. An apparent slight and unexpected difference in the energy loss between channeled protons and channeled positive pions is not explained but may be due in part to the fact that the protons are not as relativistic as the pions at ~1 GeV/c. Higher energy measurements will clarify this situation. The observed differences in the channeled and unchanneled particle energy loss form the basis for suggested particle identification and collimation applications in high energy physics experiments.

Basic energy loss processes or energy transfer phenomena are of particular interest at ultra high energy since present theories of electronic energy loss are asymptotic; that is, they are strictly valid only in the high energy limit. In some cases, the predictions of different theories differ qualitatively. For example, a recent and widely accepted theory by Dettman[9] predicts that in the high energy limit, channeled particles will have the same energy loss as unchanneled particles. On the other hand, an even more recent theory of Golovchenko[10] predicts a difference of about a factor of two. The results support the latter theory but other and even higher energy measurements should be made.

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Figure 1

Intensity of 1.35 GeV/c π^+ which have been transmitted through a 1 mm thick germanium crystal with less than 0.35 mrad deflection inside the crystal as a function of incidence direction relative to a <110> crystal axis. The solid line is not a theoretical curve but is in reasonable agreement with the distribution expected from lower energy (<50 MeV) proton transmission measurements. (From Ref. 4)

Figure 2

Energy loss of 1.2 GeV/c protons scattering less than 0.35 mrad in passing through a 1 mm thick germanium crystal for particles incident parallel to a <110> crystal axis (closed points) and incident in a non-channeled (random) direction (open points). After correction for energy transferred to electrons knocked out of the sample without depositing all of their kinetic energy, the energy loss difference between random particles and those incident along the axis is almost a factor of three. (From Ref. 4)

Figure 3

Intensity of 1.1 GeV/c π^- transmitted through a 1 mm thick germanium crystal with less than 0.7 mrad deflection inside the crystal as a function of the incidence direction relative to a <110> crystal axis. (From Ref. 4)

Figure 4

Intensity of 4 GeV/c π^- transmitted through a 1 cm thick germanium crystal as a function of the incidence direction relative to a <110> crystal axis. In this measurement, the statistical accuracy is very much reduced because the experimental arrangement allowed only one incident particle direction to be investigated at one time in contrast to the use of position sensitive proportional counter or drift chamber planes as in the previous figures or in this proposal. (From Ref. 5)

Figure 5

Proposed system for channeling studies using the kaon form factor apparatus.

Figure 6

Axial channeling for germanium and expected resolution for the kaon form factor apparatus.

Figure 7

Line shape expected at 100 GeV/c for axial channeling in germanium for the <110> direction using the kaon form factor apparatus. The channeled line is extrapolated from Reference 4.

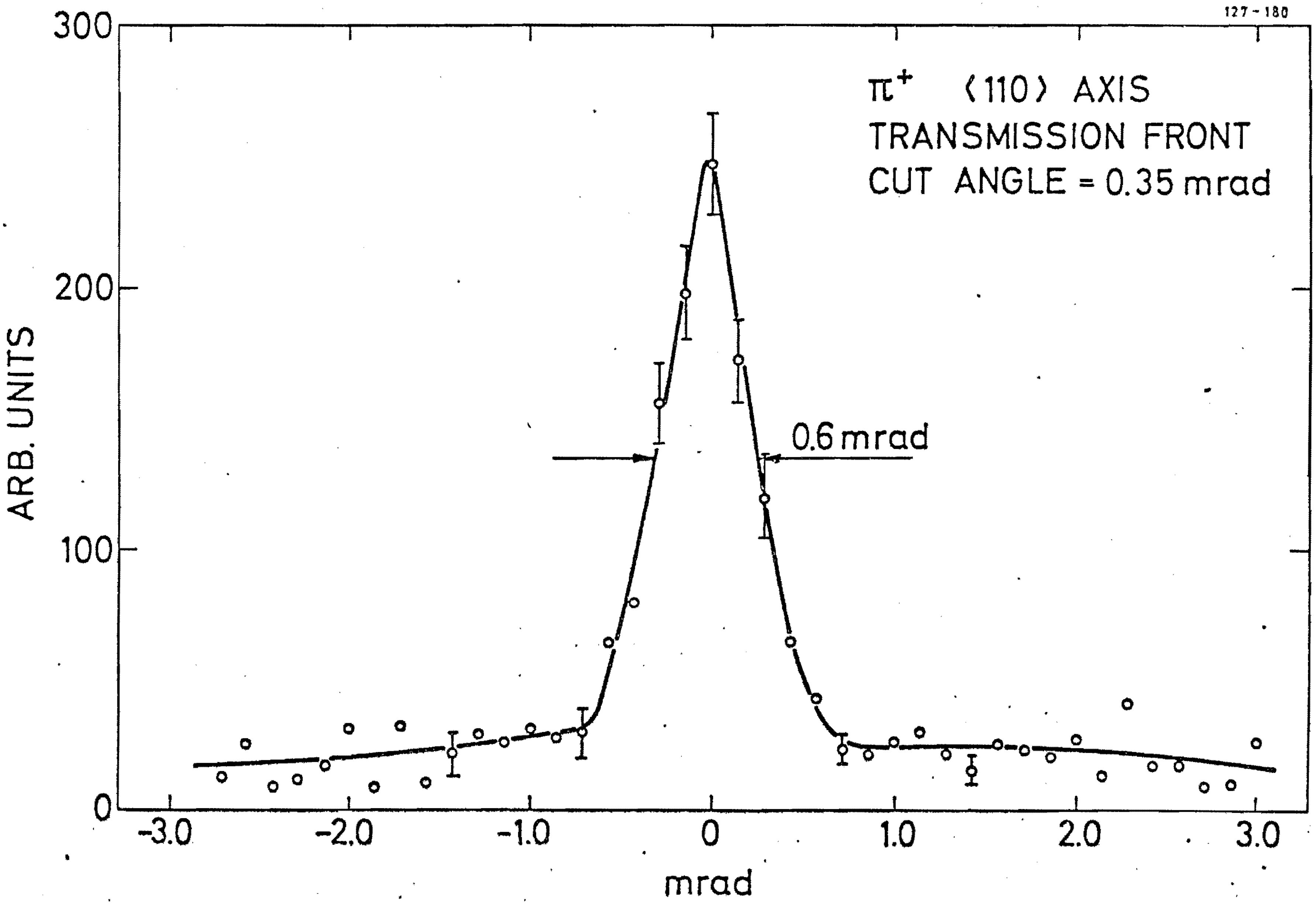


Figure 1 (From Reference 4)

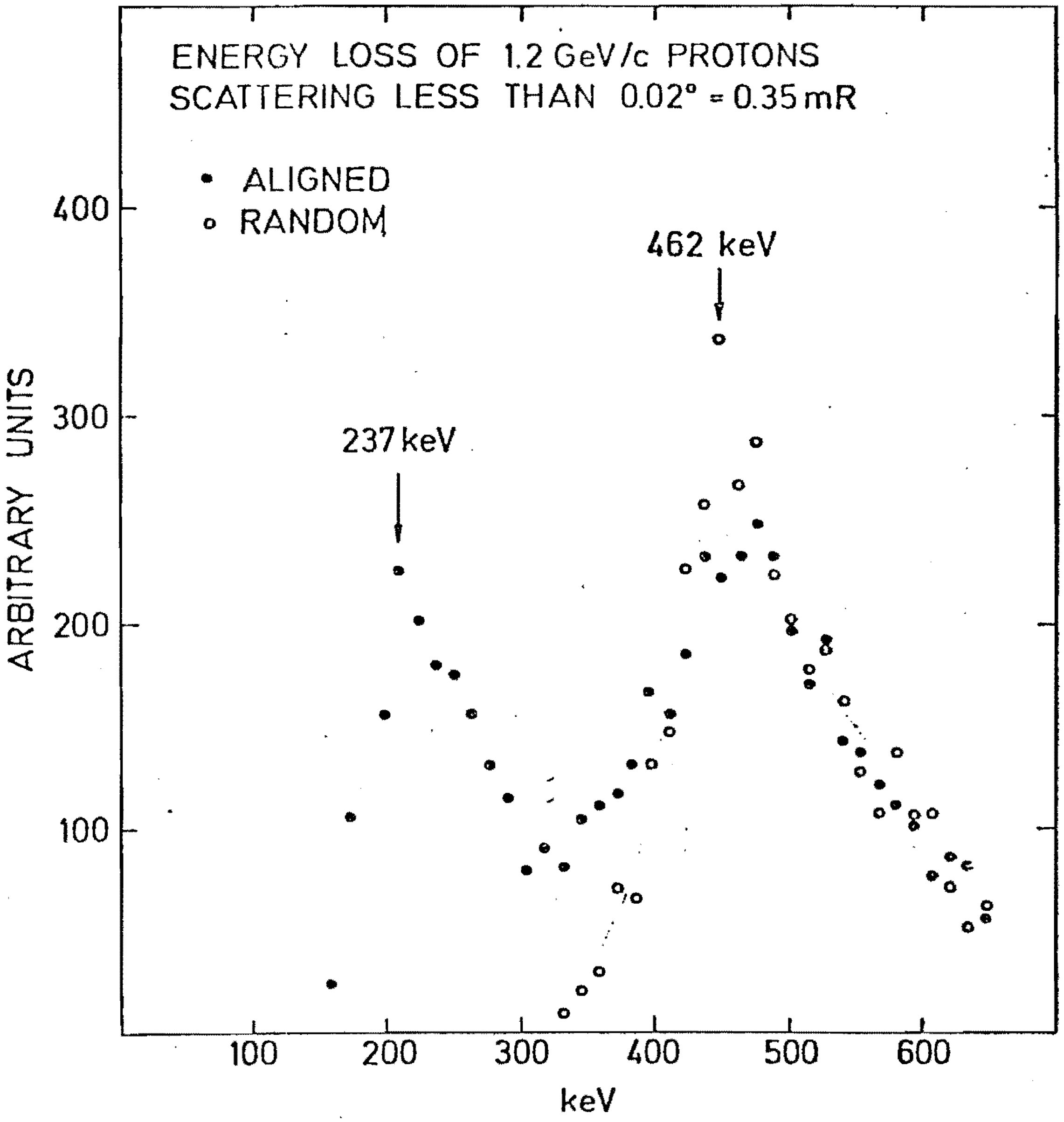


Figure 2 (From Reference 4)

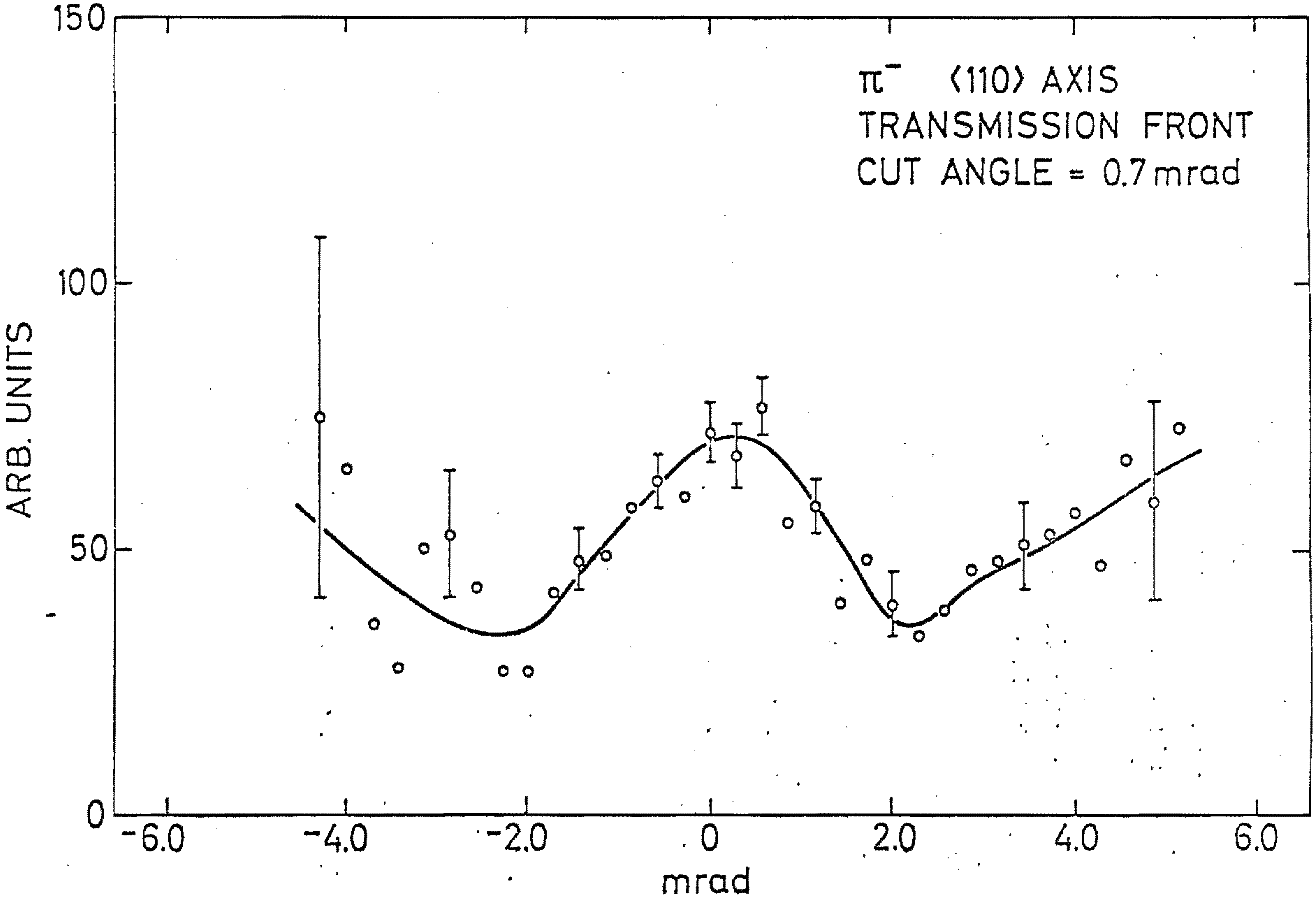


Figure 3 (From Reference 4)

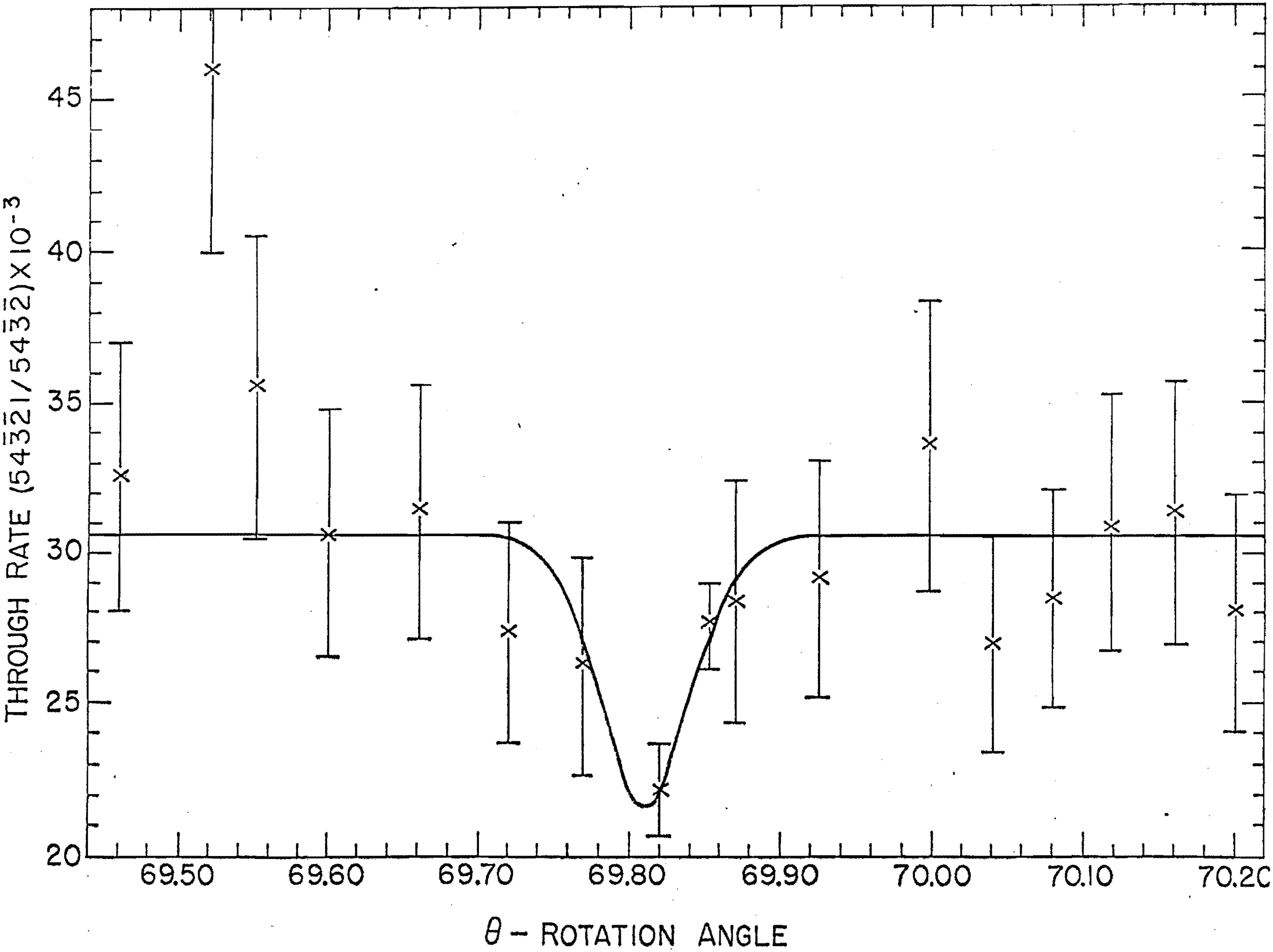
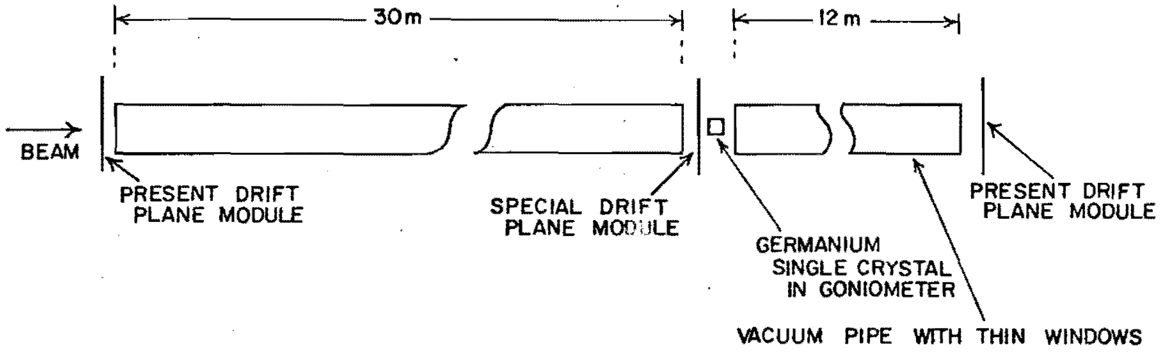

THROUGH RATE $(54\bar{3}\bar{2}1/54\bar{3}\bar{2}) \times 10^{-3}$
45
40
35
30
25
20
69.50
69.60
69.70
69.80
69.90
70.00
70.10
70.2C
θ – ROTATION ANGLE

Figure 4



PROPOSED SYSTEM FOR CHANNELING STUDIES USING THE KAON FORM FACTOR APPARATUS

Figure 5

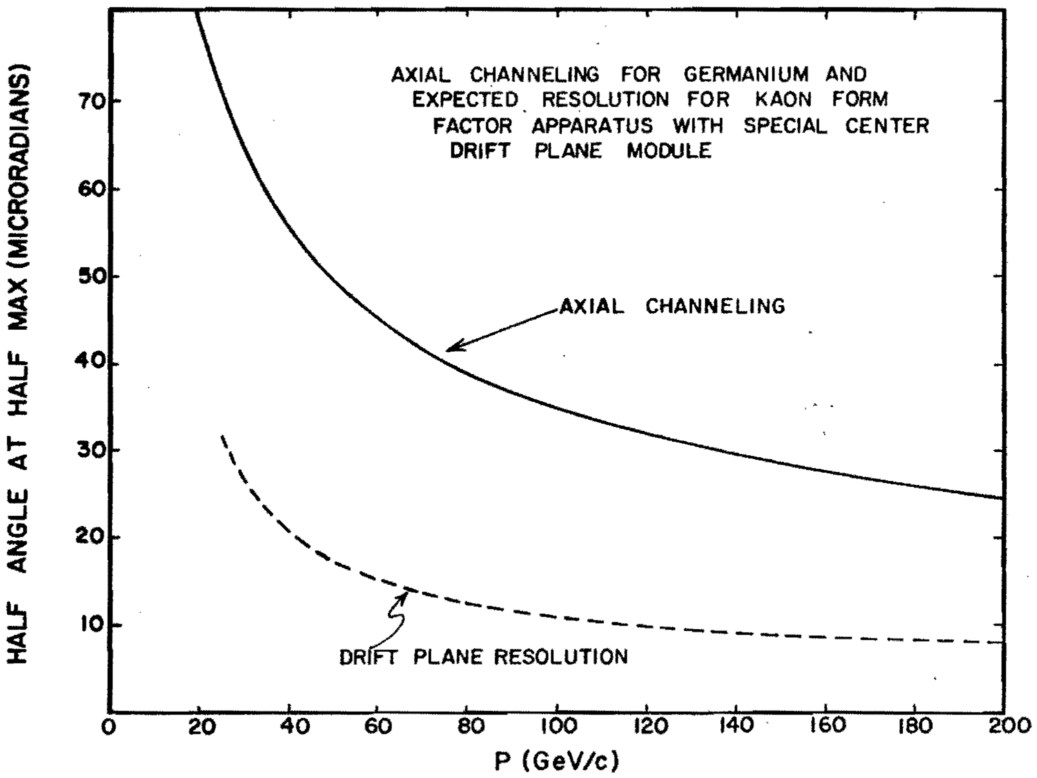

AXIAL CHANNELING FOR GERMANIUM AND EXPECTED RESOLUTION FOR KAON FORM FACTOR APPARATUS WITH SPECIAL CENTER DRIFT PLANE MODULE
AXIAL CHANNELING
DRIFT PLANE RESOLUTION
HALF ANGLE AT HALF MAX (MICRORADIANS)
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
P (GeV/c)

Figure 6

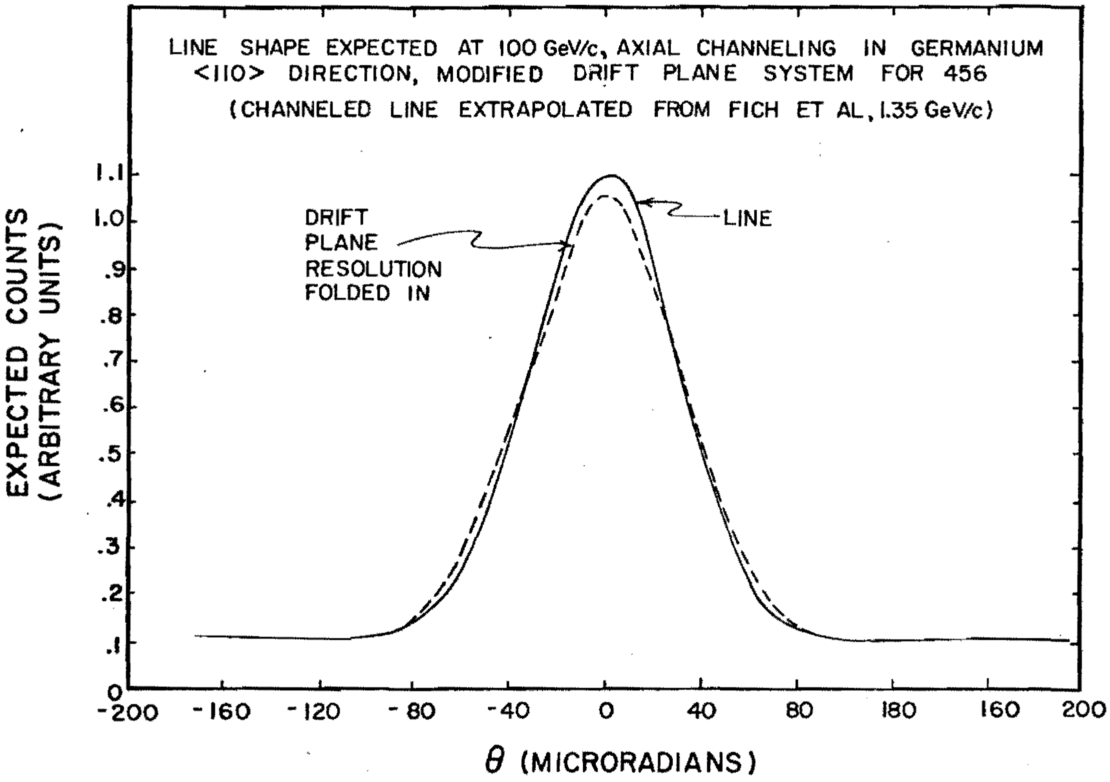

LINE SHAPE EXPECTED AT 100 GeV/c, AXIAL CHANNELING IN GERMANIUM
<110> DIRECTION, MODIFIED DRIFT PLANE SYSTEM FOR 456
(CHANNELED LINE EXTRAPOLATED FROM FICH ET AL, 1.35 GeV/c)
EXPECTED COUNTS (ARBITRARY UNITS)
DRIFT PLANE RESOLUTION FOLDED IN
LINE
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
-200
-160
-120
-80
-40
0
40
80
180
160
200
θ (MICRORADIANS)

Figure 7

Draft

INVESTIGATION OF POSSIBILITY OF BENDING AND COOLING OF BEAMS BY SINGLE CRYSTALS. DESIGN OF NEW TYPE DETECTORS FOR CHARGED PARTICLES

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SUMMARY

The aim of the present experiment is to investigate possible new phenomena in charge particle channeling in a single crystal.

These effects are as follows:

First, as was shown originally in ref. 1, if we bend a crystal, the particle trajectory during planar chanelling should possibly follow the shape of the bent crystal up to a certain critical value of the radius of curvature. Reference 1 shows that in this manner particles can be deflected by approximately four orders more than by means of conventional magnetic fields.

Second, reference 1 suggest that a particle, oscillating between the strings or planes of atoms, could transfer transverse energy to the lattice atoms because these atoms have a finite mass as compared to the channeling particle mass.

Thus, with this process the amplitude of the initial particle oscillation should damp, and the particles which enter the crystal with some angular spread of order of the channeling critical angle, leave it with reduced spread at all. This possible phenomenon in which the particle transverse oscillations damp has been called cooling in reference 1.

Third, a new kind of radiation similar to synchrotron radiation should appear for ultrarelativistic particle channeling. This energy loss per unit length of crystal is proportional to the square of the particle energy. For a beam with fixed energy and different particle types the radiation intensity is proportional to γ^4 as in the case of normal synchrotron radiation. Therefore using this radiation may be possible to devise detectors that are extremely sensitive to particle mass at high energy.

After testing the spectrometer and completing the first stage of research at the High Energy Laboratory, JINR, the experimenters may transport the set-up to IHEP(Serpukhov)for more detailed studies of the process.

With increasing the energy of particles the channeling to background ratio improves and radiation from ultrarelativistic particles sharply increases. For example, in a tungsten crystal 1 mm thick electrons and positrons with an energy of 30-50 GeV captured in the channeling process should radiate almost all their

energy.

The experiment will be carried out in cooperation with scientists of many laboratories such as the Institute of High Energy Physics (Serpukhov), Institute of Nuclear Research (Warsaw) Physical-Technical Institute of the Academy of Sciences of the Ukrainian SSR (Kharkov), Institute of Theoretical and Experimental Physics (Moscow), Polytechnical Institute (Tomsk), the Fermi National Acceleration Laboratory (Batavia, USA) and the State University of New York (Albany, USA).

I. INTRODUCTION

Experimental results show that the process of penetration of charged particles through a single crystal parallel to the crystal planes or axes is markedly different from that into amorphous matter with randomly positiioned atoms. In particular, for positively charged particles, moving along the planes and axes of the crystal, multiple Coulomb scattering is drastically reduced, nuclear interaction turns out to be greatly suppressed, and ionization losses are significantly reduced in most cases. This phenomenon called channeling and observed at low energies, has been described theoretically by Linhard and others/2/. Experiments by a Dubna-Fermilab-Albany-UCLA-Lehigh group have now demonstrated channeling to 250 GeV using the Dubna drift chamber spectrometer/8/. A good review of low energy experiments is given in paper/3/.

In order that a particle may be captured in the process of channeling, the incoming angle of the particle into a crystal should be smaller than a certain angle called the critical angle of channeling. The arytical angle for axial channeling can be written as follows:

$$\psi_c = 2(Z_1 Z_2 e^2 / p\beta cd)^{1/2} ,$$

where d is the distance between adjacent atoms along the direction of motion of the particle, p is the particle momentum.

In the channeling process a positively charged particle moves among the rows of atoms for axial channeling or oscillates in a deep potential wall between the planes of atoms for planar channeling (fig. 1). The maximum curvature of the particle trajectory for planar channeling has been calculated in paper /1/. This paper states that if the electric field is perpendicular to the direction of particle motion, the radius of curvature of the particle trajectory is equal to

$$R = m_o \gamma V^2/eE \qquad (1)$$

where m_o is the rest mass of particle,
γ - the relativistic factor, $\gamma = (1-V^2/C^2)^{-1/2}$
e - the electron charge,
E - is the electric field intensity and
V - the velocity of particle.

For planar channeling an average potential for the plane is given ny the following expression /2/

$$V(\rho) = 2\pi nZe^2a \cdot f(\rho) \quad ,$$

where ρ is the distance from the plane of atoms,
n - the density of atoms per unit area,
Z - the atomic mumber of a lattice atom,
a - the Thomas-Fermi screening radius, and
$f(\rho)$ - the function determined by the atomic screening.

The corresponding intensity of the averaged electric field is equal to

$$E(\rho) = 2\pi nZea \cdot \frac{d}{d\rho}\left\{ f(\rho) \right\} \quad .$$

For the Linhard screening function /2/

$$E(\rho) = 2\pi nZe \left\{ \frac{\rho/a}{\left[(\rho/a)^2 + C^2 \right]^{1/2}} - 1 \right\} \quad ,$$

where $C^2 = 3$.

At distances which are critical from the point of view of penetration through a potential boundary of the atom plane, i.e., when $\rho \approx a$

$$E_c = - \pi nZe \quad . \qquad (2)$$

For a tungsten crystal $E_c = 3 \cdot 10^{10}$ volt/cm. The radius of the maximum curvature of the particle trajectory with an energy of 100 GeV is equal to about 3 cm.

In a bent crystal the surface of the equilibrium potential around which a particle oscillates in the process of channeling does not coincide with the surface equidistant from the planes of the lattice. Instead, the surface will be moved in the direction to one of the atomic planes in such a way that the electrical field is strong enough to create the necessary centripetal acceleration. The motion of particle around this new surface of equilibrium will remain stable up to some critical radius of curvature for the channeled particle. This critical curvature coincides with the maximal curvature of the particle trajectory, defined by the critical electrical intensity (2). Reference 1 states that the bending ability of crystal may turn out to be four orders larger than that for conventional magnets. Of course, the phase space of the particles captured in the process of channeling will be reduced in the case of a bent crystal if there are no processes which lead to decreasing the amplitude of particle oscillations.

The particle motion in a bent crystal is considered in detail in reference/4/.

In theoretical papers the process of channeling is usually treated in an approximation where the process of energy transfer to lattice atoms is neglected. In reference 1 it is shown that this process should lead to self-stabilization of the particle trajectory, i.e., particle oscillations will damp and the particle trajectory will approach the line of the minimum potential between two atomic planes.

According to this paper the distance at which the oscillation amplitude of a single charged particle decreases by a factor of e is about 1 mm for a silicon crystal. The "cooling" rate is inversely proportional to the mass of the lattice atoms so research on the effect for crystals containing hydrogen is of great interest. Due to large accelerations, which a particle great interest.

Due to large accelerations, which a particle undergoes in the process of channeling, radiation similar to synchrotron radiation from electrons in a magnetic field should appear in this process. Perhaps, for the region of ultrarelativistic energies it will be possible to de ign a new type of detectors which could be very sensitive to the particle rest masses.

The energy radiated per unit length by a singly charged particle when its trajectory was radius of curvature r is equal to

$$\Delta E/\Delta l = \frac{2}{3} \cdot \frac{e^2}{r^2} \cdot \beta^3 \cdot \gamma^4 \qquad (3)$$

The average curvature $\overline{K}$ for a trajectory of a particle, captured in the process of channeling at the critical angle is approximately 0.6 K_c, where K_c can be calculated by the formulas (1) and (2).

Calculations show that in a tungsten crystal 1 mm thick positrons with an energy of 5 GeV will radiate about 1 GeV in the process of planar channeling, i.e., about 20% of their energy. In this case the spectrum of radiation extends from visible light up to γ-quanta with an energy of several MeV. Relative energy losses of 50 GeV positrons are larger by an order of magnitude. Losses for channeled electrons are even larger. For TeV energies this radiation becomes intensive enough so that heavy particles may be detected as well. For instance at an energy of 1 TeV in a tungsten crystal 1 cm thick pions lose 69 KeV by this process. As was mentioned above this radiation is very sensitive to the rest mass of the particle (factor γ^4). Therefore, it is hoped that mass-separated detectors may be designed using this radiation. As an illustration, note the intensities of radiation for pions and kaons differ by factor of 150.

It is also of interest to study the processes of channeling for heavy relativistic ions. Specifically, the rate of any "cooling" process will be directly proportional to the charge of the relativistic nucleus. By varying the charge of the incident particle and the mass of the lattice atoms, one can hope to "cool" a beam in rather thin crystalline samples.

II. EXPERIMENTAL SETTING UP

Three main aims of the experiment are as follows:

1. To look for the effect of beam bending in a bent crystal.

2. To search for and to study the cooling effect of beam transverse oscillations if it exist.

3. To do research in to the possibility of design of new particle detectors using synchrotron radiation from channeled particles.

In order to begin these studies, it is first necessary to observe channeling. The first stage of research will be carried out using the extracted beam of the Dubna High Energy Laboratory synchrophasotron.

The particle beam is incident upon a crystal placed in a goniometer. The goniometer permits the crystal to be turned remotely, accuracy of orientation is smaller than the crytical angle. To reduce the angle of multiple scattering in matter the goniometer should be installed to a vacuum pipe.

Moreover, to work at low temperatures, which is necessary in experiments using germanium crystalline detectors, arrangements will be incorporated to permint cooling the crystal in the goniometer to the liquid nitrogen temperature.

Studies will be performed with different single crystals. Silicon and germanium single crystals are the most suitable ones because it is possible to use them as simiconductor detectors. This will permit one to measure the energy lost to the crystal at the same time geoterical measurements are made on the tracks. The sizes of the crystals will be up to 1 cm^2 in the direction perpendicular to the beam and from several millimeters up to a few centrimeters along the beam. So-called "dislocation free" crystals with an admixture of dislocations less than 10^{-9} will be used.

A beam of particles incident on the crystal will be defined by a system of coincidence and anticoincidence counters.

The particle trajectories will be measured by a system of drift chambers. Two blocks of chambers, containing X- and Y-planes will be situated in front of the crystal, and one block after the crystal at the end of the spectrometer. The schematic layout of the experiment is presented in fig. 2. When operating with electron and positron beams, an analyzing magnet will be added to set-up.

Let us consider the method of detecting the channeling effect. One way in which this effect shows itself is by changing the "transparency" of the crystal depending on the particle direction incident on the crystal. "Transparency" can be define as the ratio of the number of particles, having passed through thethe crystal without interaction, to that of particles incident upon the crystal.

One way to search for the channeling effect is to determine of a particle passing through the crastal with a scattering angle smaller than a certain value as a function of the particle incident angle. For example, we can select particles with a scattering angles less than the critical angle of channeling. In the case of channeling sharp peaks are observed in the direction of axes and planes on the wide distribution of the background of random multiple scattering.

After the channling effect has been found we can begin to look for the effect of beam bending by bent single crystal. In other words, we must search for the channeling effect in the case of a bent single crystal. For instance, a silicon crystal 2 x 10 mm^2 in size and 10 mm in length along the beam can be bent at an angle about 10 milliradian so that the chord of bending nearly coincides with the beam direction. Note that in this case the saggita is about 10 microns. If the channeling effect is observed in a bent crystal it is desirable to turn the crystal through an angle of 180° around the beam axis in order to make sure that the direction of outgoing particles changes accordingly.

To investigate the effect of cooling the beam transverse oscillations, it is necessary to compare the angular distribution of incident and outgoing directions for channeled particles. The width of the angular distribution for incident particles should be about the critical angle of channeling. If the width of the angular distribution of outgoing particles is smaller than the value ψ_c , one can conclude that damping of the particle oscillation amplitude takes place in the process of channeling. Measuring the value of this effect versus the thickness of the crystal along the beam, it is possible to determine the "cooling length".

It is interesting to investigate possible "cooling" processes for different multiply charged ions in combination with various kinds of crystals. Possibly in these conditions one can obtain short "cooling length" and there by form parallel beams in the best way.

To study the possibilities of the design of a new-type of detector, sensitive to particle mass, we have to do research using electron and positron beams in an energy region of 2-50 GeV. It is necessary to detect the total energy converted to γ-quanta due to synchrotron nature radiation from channed electrons and positrons.

We can detect this radiation by means of the crystal itself, if it works as a semiconductor detector. Moreover, it is possible to record this radiation using other detectors sensitive to KeV γ-quanta, such as proportional chambers. Energy losses of electrons and positrons can be measured with a total absorption Charenkov counter or with a magnetic spectrometer. Let us consider in more detail the apparatus of the experiment.

Setting up the experiment using the beams of the Dubna and Serpukhov accelerators is similar. The major difference is the distance between the blocks of coordinate detectors. We will consider here only the Dubna experimental set up. The experimental set up at Serpukhov will be dexcribed in detail later.

Trigger system for the spectrometer

The trigger system will include four scintillation counters. Two coincidence counters will be located in front of the first block of drift chambers and have a size of about 5 x 5 cm^2. An anticoincidence counter, placed directly in front of the goniometer containing the crystal, will have a hole smaller than the sensitive area of the crystal. The fourth counter in coincidence will be mounted behind the last drift chamber of the spectrometer.

During the adjastrement of the apparatus and at the initial stage of the experiment the triggering system will consist only of scintillation counters. Drift chambers will be included in trigger system at the next stage of the experiment. A fast processor will compute incoming and outgoing particle angles, scattering angles in the crystal and then send a trigger signal for information readout in the computer.

An important concern will be to find the axial channeling peak since the crystal axis will not initially coincidence with the beam direction. The accuracy in determining the original crystal alighment prior to the experiment may be no better than 1-2 degrees using the X-ray diffraction method. Note that if a crystal is a semiconducting detector, the channeling peak can be found in the experiment using the information on energy loss of particles passing through the crystal.

Figure 3 compares the energy losses in the case of channeling with conventional ionization losses. These data/6/ have been obtained in the CERN experiment at 1.3 GeV. It follows from these data that the energy loss for a channeled particle is roughly half as large as that for a randomly directed particle. Thus, using a threshold discriminator, we can detect the events with low energy losses and make fast scans over a wide region of angles with the goniometer in order to find the channeling effect. Selection of events by energy losses in the semiconductor detector will be included in the trigger logic.

In order to overcome the possibility of the passage of more than one particle through the apparatus during the sensitive time of the drift chambers (400 nsec), the information from one of the scintillation counters will be used to restrict multitrack event detection.

When operating with electrons and positrons in the particle beam, a threshold Cherankov counter and a total-absorption lead-glass counter will be included in the trigger system.

Coordinate detectors

Drift chambers will be used as coordinate detectors, these devices seem to have the best coordinate resolution to data. We plan to use the system of drift chambers made at the High Energy Laboratory for the K-e and π-e scattering experiments at the FNAL accelerator in Batavia. This system successfully operated in the beam and had quite good coordinate resolution and a high reliability. It is interesting to note that this apparatus has already been used in channeling experiments at 35, 100 and 250 GeV/8/.

The construction of the chambers is similar to that of drift chambers with a distributed potential developed at CERN by Charpak and Sauli. Signal wires made of gold plated tungsten 20 microns in diameter are wound with a spacing of 42 mm so that the maximum drift length is 21 mm. We use a gas mixture of Ar + Isobutane + Methylal. With this mixture, the desired linearity can be obtained. In order to have a distributed potential in the drift region, a -3,5 kV power supply is used. The potential for a sense wire is +1.8 kV. The signal enters the input of ah amplifier - discriminator. The amplifiers, developed and made for the K-e, π-e scattering experiments at Fermilab/9/, will be used. The threshold of the amplifiers is about 2 μA. The difference in the delay time for signals with an amplitude from 2 to 20 thresholds is no more than 3 nanoseconds. The average coordinate accuracy is 55 microns (fig. 4). The drift chambers have a right - left ambiguity. For this experiment the size of the sensitive region of the crystal and the part of the beam detected by the trigger counters is smaller than half the distance between the sense wires, so such a problem does not exist.

The chambers are placed in three separate blocks. The first block will consist of four X and four Y-planes, ensuring a coordinate accuracy of about 30 μm for each coordinate. Next, in order to decrease multiple scattering the particles will pass through a vacuum pipe 7 m in length. The central block of the drift chambers will contain two X- and two Y-planes.

The angular resolution of the spectrometer will be set by the multiple scattering in the material of this block. This block will have a fraction radiation length of $3.4\cdot10^{-3}$. The angular resolution of the spectrometer is about 120 microradians at an energy of 10 GeV. This resolution is sufficient to work at the energies of the Dubna accelerator. With increasing energy the ratio of the critical angle to the multiple scattering angle increases as $E^{1/2}$. A rather simple modification of the drift planes will raduce the radiation thickness of the central block down to $4 \cdot 10^{-4}$ radiation lengths. In this case the angular resolution will be about 40 microradians while the angular width of the axial channeling effect will be about 100 microradians.

It might appear that multiple scattering in the central block would restrict observation of the "cooling" effect. In fact, this is not the case. A seoond vacuum pipe will be located just behind the central block The goniometer containing the crystal will be mounted in the head section of the second vacuum pipe. The third block of the drift chambers will be situated after this vacuum pipe. In such a geometry the ability to measure parralel tracks in the outgoing beam is determined by the coordinate resolution of the drift chambers and the distance between them. The distance between the second and thrid blocks of the drift chambers will be 7 m, so that the angular resolution will be about 7 microradians. Such a resolution is quite sufficient to observe the effect of beam "cooling".

Readout system. Computer

The apparatus is made according to CAMAC standards. Information from the CAMAC system will be transfered to the computer. It is planned to use BESM-4 or ES-1040 computers at the first stage of the experiment. In the next stage it is assumed ES-1040 computer will be available from the Serpukhov Scientific-Experimental Division. One of the probabilities also is to use the HP 2100 from UCLA that was used in the form factor experiments. The functions of the on-line programs will include apparatus control, track reconstruction and accumulation of necessary histograms.

"Off-line" data analysis

Off-line data analysis will be carried out by the Dubna CDC-6500 computer. It will take about 100 hours. Note that an off-line analysis program for channeling is already in operation on this computer.

Design resources and the experimental mechanical workshops

In order to carry out the experiment, about 1000 man/hours of mechanical and assembly work is required. In addition, a vacuum casing for mounting the goniometer, vacuum pipes, supports for the drift chambers and the scintillation counters, along with other equipment must be made. This will take about 3000 manhours. To design this equipment, about 5 man-months in the HEL design department are required. The assembling of the equipment and new vacuum tubes for the IHEP stage of experiment will take place at Serpukhov.

Required beam time

It is planned to fulfil the program of research, proposed in the present design, over 1978 and 1979. The assembly of the apparatus and the first stage of research will be performed in 1978. The spectrometer will be transported to Serpukhov at the beginning of 1979. It is unticipated that investigations will be carried out using beams of protons, α-particles, carbon nuclei, electrons and positrons. To perform the program of research at the High Energy Laboratory, about 1000 hours are required at the synchrophasotron. About 500 hours are required at the IHEP beam.

Finances

In order to carry out the experiment, 250 000 roubles are required. These will be divided as follows:

1. Devices and equipment	45 000 roubles

2. Readout, fast and spectrometer electronics	110 000 roubles
3. Materials(electronic components, microcircuits, cables, connectors etc.)	65 000 roubles
4. Gas	30 000 roubles
Total:	250 000 roubles

FIGURE CAPTIONS

Fig. 1. Schemetic of particle motion in the case of planar channeling.

Fig. 2. Experimental layout.

Fig. 3. Ionization loss for 1.3 GeV π^+ mesons for the beam oriented along a crystal axis, and for a random beam.

Fig. 4. Coordinate accuracy of the drift chambers versus the particle distance from the sense wire. These chamber were used in the π-e and K-e scattering experiments at an energy of 250 GeV.

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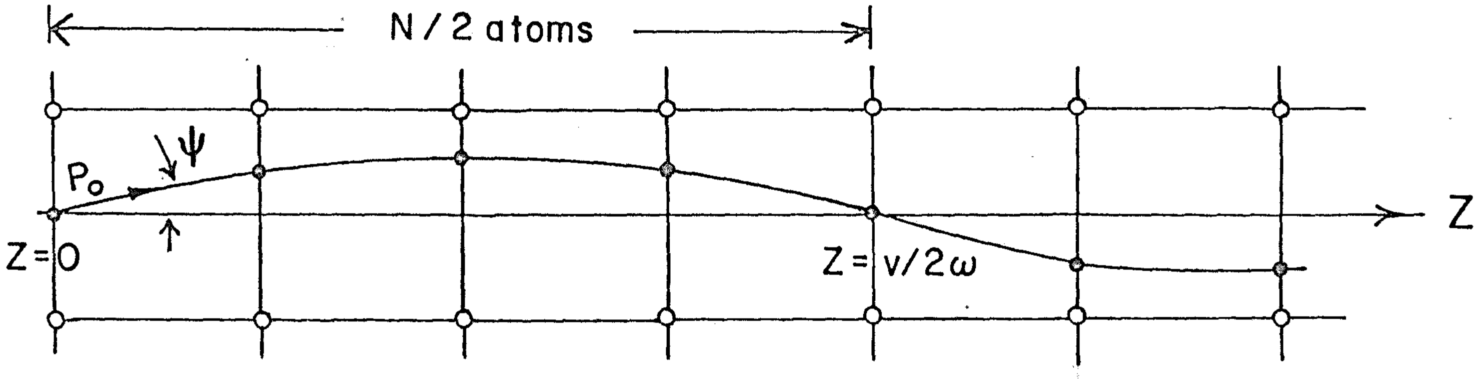

Рис. I

Схема экспериментальной установки

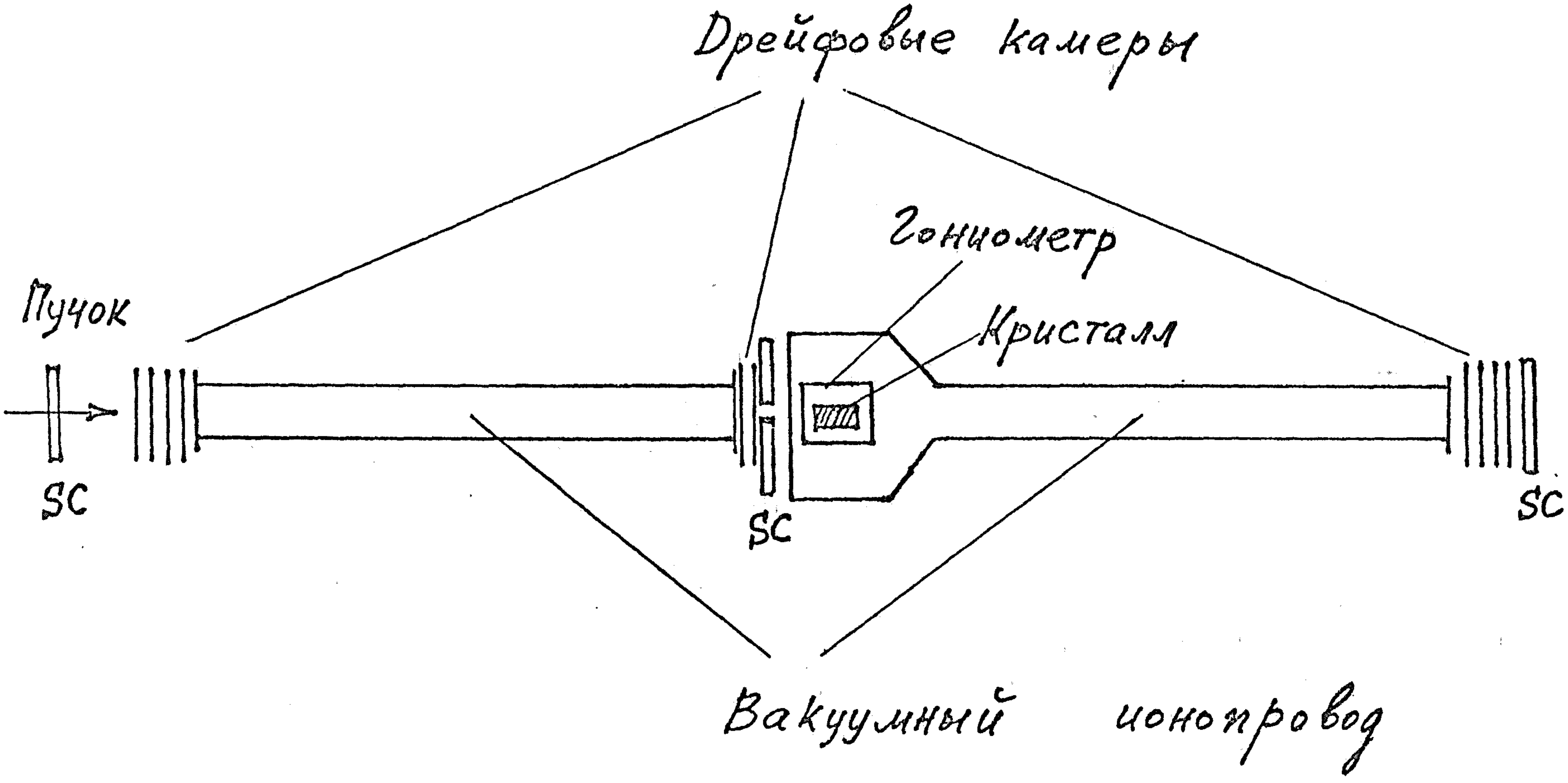

Рис. 2

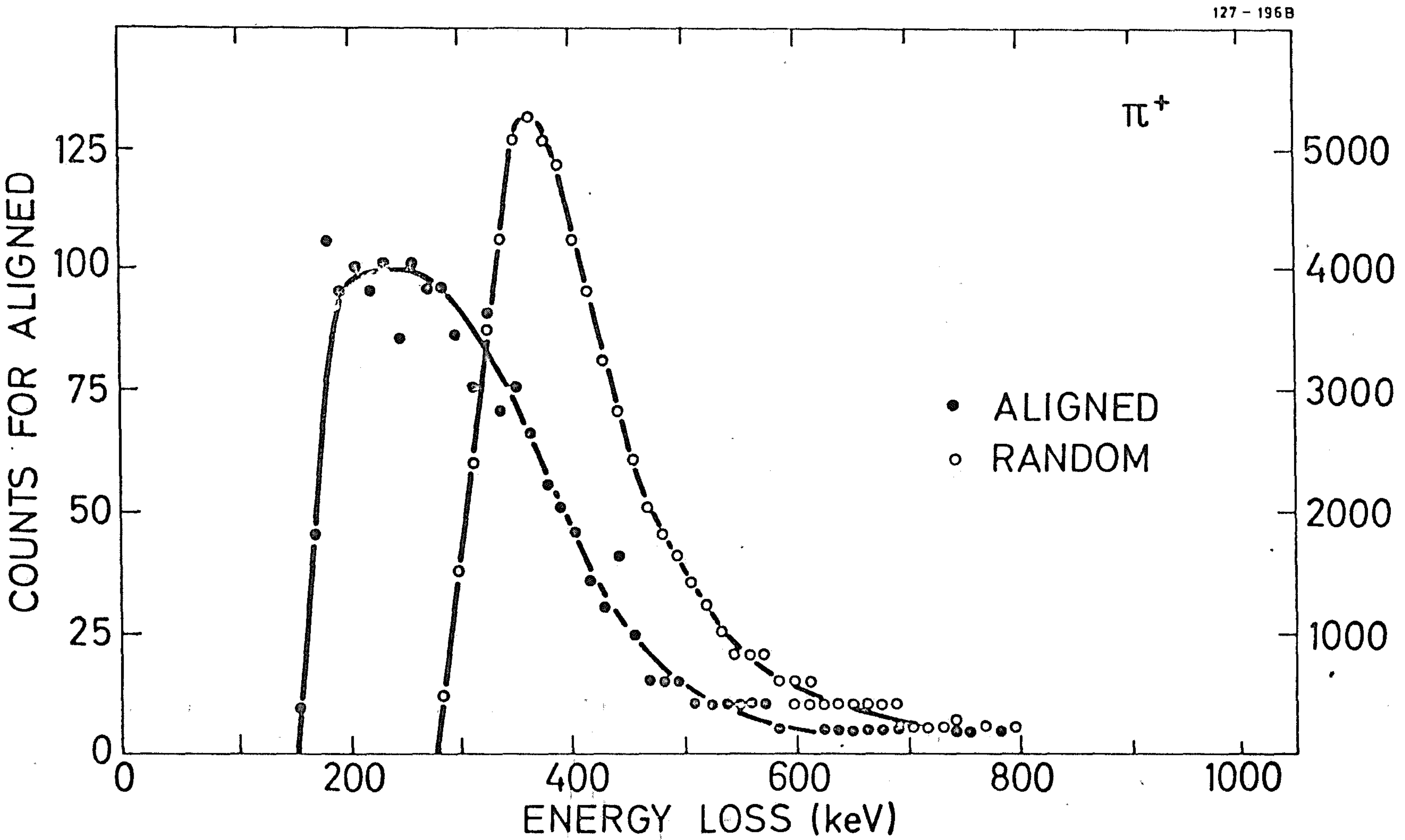
127 - 196B
π⁺
COUNTS FOR ALIGNED
0
25
50
75
100
125
COUNTS FOR RANDOM
1000
2000
3000
4000
5000
● ALIGNED
○ RANDOM
0
200
400
600
800
1000
ENERGY LOSS (keV)

Рис. 3

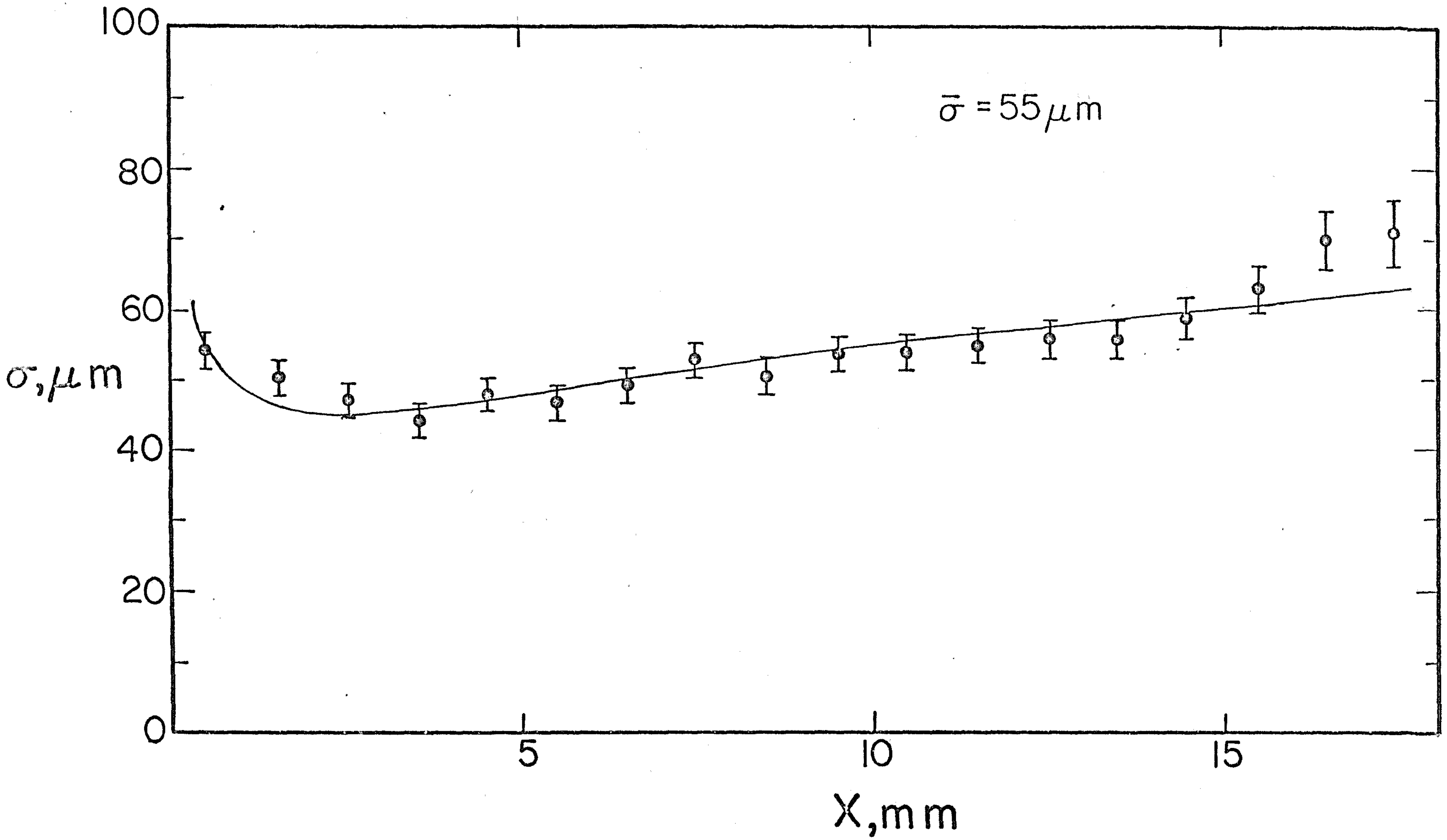

Рис. 4