Fermi National Accelerator Laboratory

FERMILAB-Pub-84/45-E
7135.660
(Submitted to Nucl. Instrum. Methods A)

FIRST OPERATION WITH A CRYSTAL SEPTUM TO REPLACE A MAGNET IN A CHARGED PARTICLE BEAM

S. I. Baker, R. A. Carrigan, Jr., and T. E. Toohig
Fermi National Accelerator Laboratory, Batavia, Illinois 60510 USA

W. M. Gibson, I.-J. Kim, F. Sun, C. R. Sun,
V. Tanikella, and R. Wijayawardana
State University of New York, Albany, New York 12222 USA

J. S. Forster, H. Hatton, and I. V. Mitchell
Atomic Energy of Canada Limited Research Company
Chalk River Nuclear Laboratories, Chalk River, Ontario Canada K0J 1J0

E. N. Tsyganov and T. S. Nigmanov
Joint Institute for Nuclear Research, Dubna, Moscow, USSR

V. V. Avdeichikov
V. G. Khlopin Radium Institute, Leningrad, USSR

J. A. Ellison
University of New Mexico, Albuquerque, New Mexico 87131 USA

and

P. Siffert
Centre de Recherches Nucleaires, PHASE, F-67037 Strasbourg, CEDEX, France

April 1984

FIRST OPERATION WITH A CRYSTAL SEPTUM TO REPLACE A MAGNET IN A CHARGED PARTICLE BEAM*

S. I. Baker, R. A. Carrigan, Jr., and T. E. Toohig
Fermi National Accelerator Laboratory
P. O. Box 500, Batavia, Illinois 60510, U.S.A.

W. M. Gibson, I. -J. Kim, F. Sun, C. R. Sun, V. Tanikella,
R. Wijayawardana
State University of New York at Albany
Albany, New York 12222, U.S.A.

J. S. Forster, H. Hatton, I. V. Mitchell
Atomic Energy of Canada Limited Research Company
Chalk River Nuclear Laboratories
Chalk River, Ontario, Canada KOJ 1JO

E. N. Tsyganov, T. S. Nigmanov
Joint Institute for Nuclear Research
Dubna, Moscow, U.S.S.R.

V. V. Avdeichikov
V. G. Khlopin Radium Institute
Leningrad, U.S.S.R.

J. A. Ellison+
University of New Mexico
Albuquerque, New Mexico, 87131, U.S.A.

P. Siffert
Centre de Recherches Nucleaires, PHASE
F-67037 Strasbourg, CEDEX, France

---

* Supported in part by the U. S. Department of Energy under contract ER-78-5-02-5001

+ Supported by the U. S. National Science Foundation grant DMR 8214301

ABSTRACT

Particle channeling in a bent crystal at Fermilab has been used to replace a magnet in a secondary beam. The maximum momentum of particles that could be transmitted to an experimental location was raised from the magnetic septum limit of 225 GeV/c to the full primary beam momentum of 400 GeV/c.

The deflection of a beam of charged particles channeling within the planes of a bent silicon crystal was first observed at Dubna with 8.4 GeV protons [1] and later at CERN at 12 GeV [2]. In more recent experiments at Fermilab [3], the intensity loss of channeled particles was mapped along the crystal bend for particle momenta between 12 and 180 GeV/c. Taken together, these results confirmed the general features of theories [4] of particle loss from planar channeled trajectories in bent crystals. As a consequence of such work, it was suggested [5] that bent single crystals might be used to replace normal beam steering elements. This letter reports a successful replacement of a magnetic septum by a crystal septum.

In the M-Bottom beam at Fermilab the normal septum consists of two 3.05m long dipole magnets operating at 9.6 kGauss at 200 GeV/c and is located 46m from the production target. The beam is deflected 8.9 milliradians downward by the magnetic septum. Following the septum is a bending magnet which deflects the secondary beam back up to the line to the experimental location. Five quadrupole magnets in the beam transport system give two stages of point-to-point focusing and momentum recombination. The vertical beam divergence is 100 microradians FWHM while the momentum spread at 200 GeV/c is 75 GeV/c FWHM. The beam spot at the septum is estimated to be 10 mm high. The maximum beam momentum delivered to the M-Bottom experimental area is 225 GeV/c, a limit set by the septum magnet. Although this beam is not particularly favorable for operation of a crystal septum, it offered a convenient location for a test. Ideally, a septum should have a nearly parallel beam with a small spot size where the crystal is to be installed.

A crystal septum replacement would appear to be most appropriate at momenta above 10 GeV/c, because below that ordinary dechanneling is significant. A critical requirement of this technique is that a crystal plane or axis of the septum lies in the angular extent of the beam. At a particle momentum of 100 GeV/c, the planar channeling critical angle, ψ_p, which determines the angular acceptance of the crystal, is 15 microradians for the (110) plane in silicon; this angle varies as $1/\sqrt{p}$ and is small compared with typical beam divergences (~ 100 microradians). Normally, silicon crystals have been aligned at these momenta by forming a detector in the upstream end of the crystal and then tilting the crystal to line up a plane and minimize the energy loss of individual particles passing through the depleted region. This does not work where the particle flux is high enough to saturate the detector. As an alternate the bending phenomena itself can be used to align the crystal.

For the crystal septum, a silicon single crystal was cut in the form of a rectangular slab, 0.8 mm high, 12 mm wide and 27 mm long, with a (110) plane lying in the major face of the crystal. A surface-barrier detector was fabricated on the upstream end of the crystal. In operation, the crystal was mounted in a four-point, adjustable bending jig with the major face of the slab horizontal. The bend direction was perpendicular to the (110) plane. Figure 1 shows the crystal mounted in this device. The deflection angle, that is the total bend, was first set to 8.9 milliradians using a system of drift chambers in a test stand.

Planar channeling, rather than axial channeling, was chosen for bending. While the critical angle for axial channeling is larger, axial channeling feeds particles into several crystal planes, which bend particles in different directions and through different total bend angles [2].

For planar channeling, approximately 10% of the beam was within the critical angle. Also, the area of the end face of the crystal determined the fraction of the beam that could be steered. About 1% of the total beam arriving at the crystal septum location could satisfy these two conditions. Other factors caused the transmission to be degraded; for example, surface effects, normal dechanneling and bending dechanneling.

For operation as a septum, the crystal was installed between the two elements of the magnetic septum in the beam. In that position the particle energy-loss spectrum in the crystal displayed the expected Landau peak, but it was superimposed on a large background, presumably from low energy particles generated by neutrons in the target gallery. It was therefore impossible to align the crystal by the energy-loss technique. Instead, a technique suggested by I.J. Kim was adopted in which the flux through the M-Bottom beam line itself was used to align the crystal. The beam trim elements were first tuned with the magnetic septum so that particles were transmitted to the experimental area. The magnetic septum was then switched off and the bent crystal substituted. The bent crystal was rotated until the deflected beam was observed at the experimental location. Fig. 2 shows typical data; the width of the distribution is determined by the angular divergence of the beam. With the crystal it was possible to obtain a 400 GeV/c beam at the experimental location, essentially doubling the maximum energy of the secondary beam. This is the highest energy yet at which channeling effects have been observed.

The fraction of initially channeled particles that was transmitted completely through the bent silicon crystal, that is, deflected through the full 8.9 milliradians, was measured to be 10% at 200 GeV/c in the drift chamber test set-up. The dimensions of the beam before the bent crystal were 25 mm by 10 mm (FWHM) and of the crystal front face 0. 8 mm by 12 mm; the beam divergence in the drift chamber test set-up was 100 microradians compared with the total crystal acceptance angle, $2\Psi_{\breve{p}}$ of 30 microradians (all beam angles perpendicular to the bending plane are accepted). Taken together these would give a transmission of 0.1% of the total beam. In principle, the transmission factor can be measured at the septum beam position by comparing the number of particles transmitted to the experimental area using the magnetic septum with the number obtained using the crystal septum. The value obtained with the crystal was 0.03% of the normal beam intensity at 200 GeV/c. This comparison is misleading, however, because the beam line elements were not retuned for the crystal septum measurement.

Fig. 3 shows the momentum acceptance for the magnetic septum and the crystal septum at 200 GeV/c. The momentum acceptance is considerably smaller for the crystal. It should be possible to improve this by proper tuning of the quadrupoles, since in principle the crystal can transmit a large spread in momentum.

Transmission comparisons at 400 GeV/c could not be made as the beam line cannot ordinarily operate with magnetic elements at 400 GeV/c. However, as discussed above, using the crystal septum, about 10,000 particles per spill were taken to the experimental area at 400 GeV/c.

The relative ease of installation and operation of the crystal septum, taken with the fact that other studies [6] have shown little evidence for radiation damage in bent silicon crystals irradiated with high energy beams up to fluences of $10^{17}/cm^2$ suggest that bent crystals may have practical applications. For example, a bent crystal may be well suited for the case in which a low intensity beam is required from a high intensity source. Low intensity diagnostic beams are sometimes needed for storage rings. This possibility has been discussed for sending protons from the Fermilab Booster to the storage ring facilities. The fact that the acceptance angle for channeling is small, resulting in a beam with low angular divergence, may be useful for particular experiments, for example, channeling radiation measurements [7]. Finally, the use of some other material for the septum, such as germanium, which has a larger critical angle because of its larger atomic number, could result in larger transmission factors.

The experimenters would like to thank the Experimental Areas Department at Fermilab and, in particular, R. Schailey, S. Butala and M. Gerardi, for their help with these tests.

References

1. A. F. Elishev et al., Phys. Lett. 88B , 387 (1979).
2. J. Bak et al., Phys. Lett. 93B , 505 (1980).
3. S. I. Baker et al., Phys. Lett. 137B , 129 (1984).

   J. A. Ellison et al., Contributions to the 10th International Conference on Atomic Collisions in Solids, Bad Iburg, Germany (1983), to be published in Nuclear Instruments and Methods.

   S. M. Salman, "Deflection of High Energy Channeled Particles by Elastically Bent Single Silicon Crystals," State University of New York Thesis (1982).
4. J. A. Ellison and S. T. Picraux, Phys. Let. 83A , 271 (1981),

   J. A. Ellison, Nucl. Phys. B206 , 205 (1982),

   H. Kudo, Nucl. Instr. and Meth. 189 , 609 (1981).
5. R. A. Carrigan, Jr., W. M. Gibson, C. R. Sun, and E. N. Tsyganov, Nucl. Instr. and Meth. 194 , 205 (82);

   R. A. Carrigan, Jr., Fermilab, 80/45-Exp, Batavia, (1980).
6. G. H. Wang et al., Nucl. Instr. and Meth. 218 , 669 (1983).
7. V. V. Beloshitsky and F. F. Komarov, Physics Reports 93 , 117 (1982).

Figure Captions

1a. Bending device for the crystal septum. The 0.8 mm thick crystal is visible on the left. The differential screw to adjust the bend is at the bottom. The goniometer motor (not visible) adjusts the crystal attack angle about a horizontal axis. The beam is incident from the left and is bent down.

b. Schematic of a.

2. Crystal alignment curve at 400 GeV/c. The crystal angle is taken relative to the beam direction based on a survey. The width (100 microradians FWHM) is determined by the beam divergence.

3. Relative yield (times 10) vs. momentum for a 200 GeV/c beam using the magnetic septum (closed circles) and the crystal septum (open circles). No attempt was made to provide momentum recombination for the crystal case.

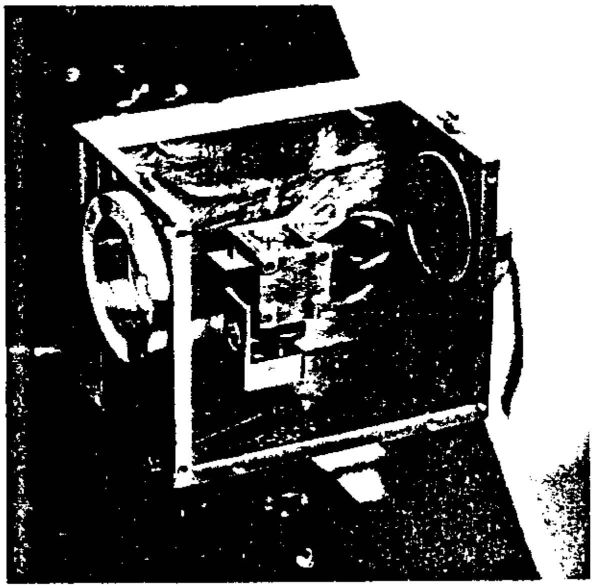

Figure 1a

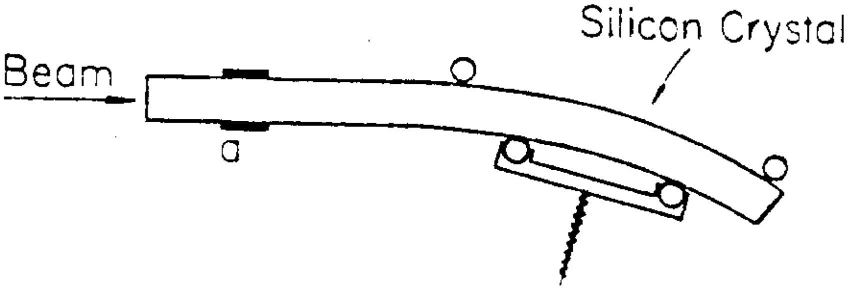

Figure 1b

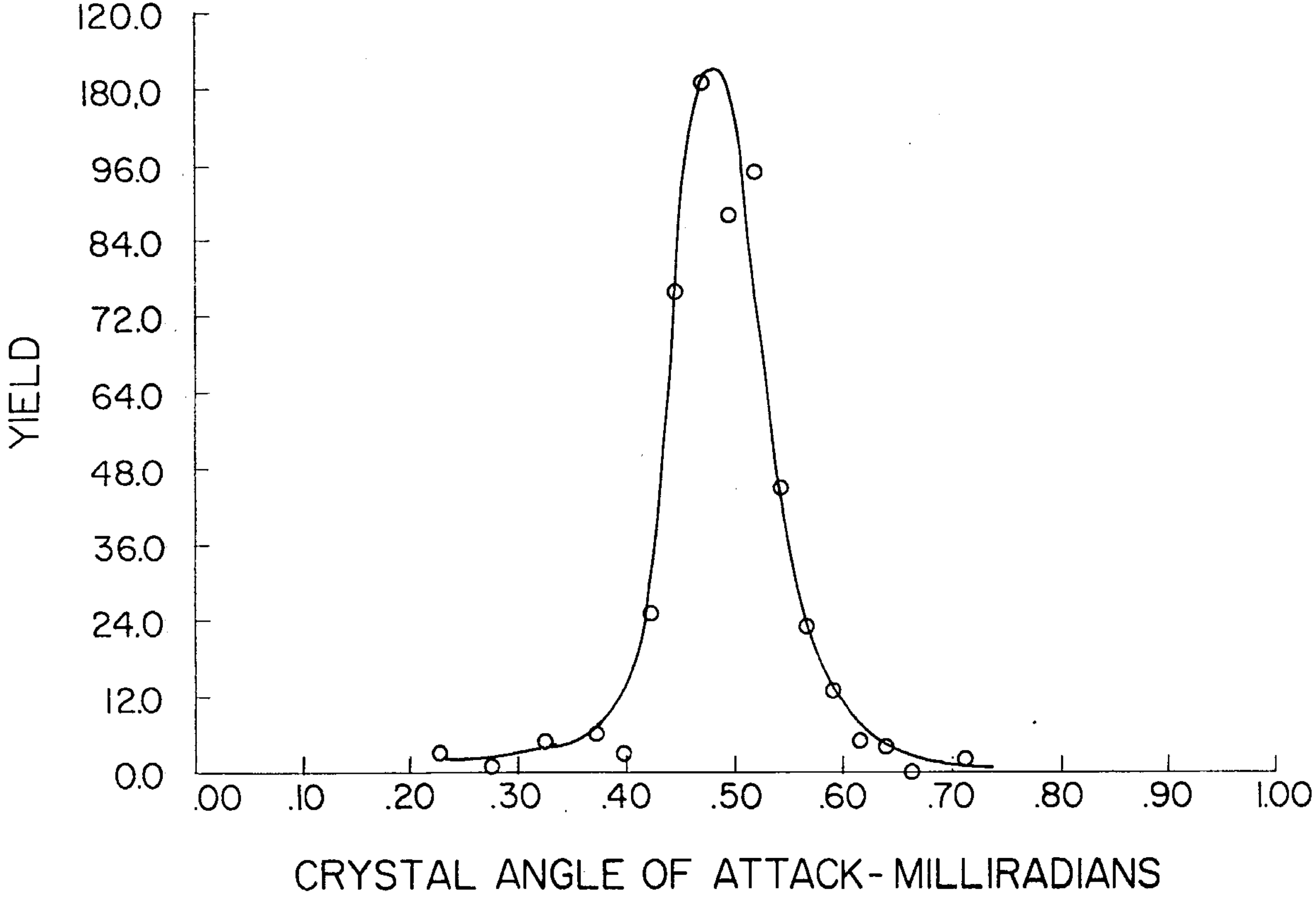
120.0
180.0
96.0
84.0
72.0
64.0
48.0
36.0
24.0
12.0
0.0
YIELD
.00
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
CRYSTAL ANGLE OF ATTACK - MILLIRADIANS

Figure 2

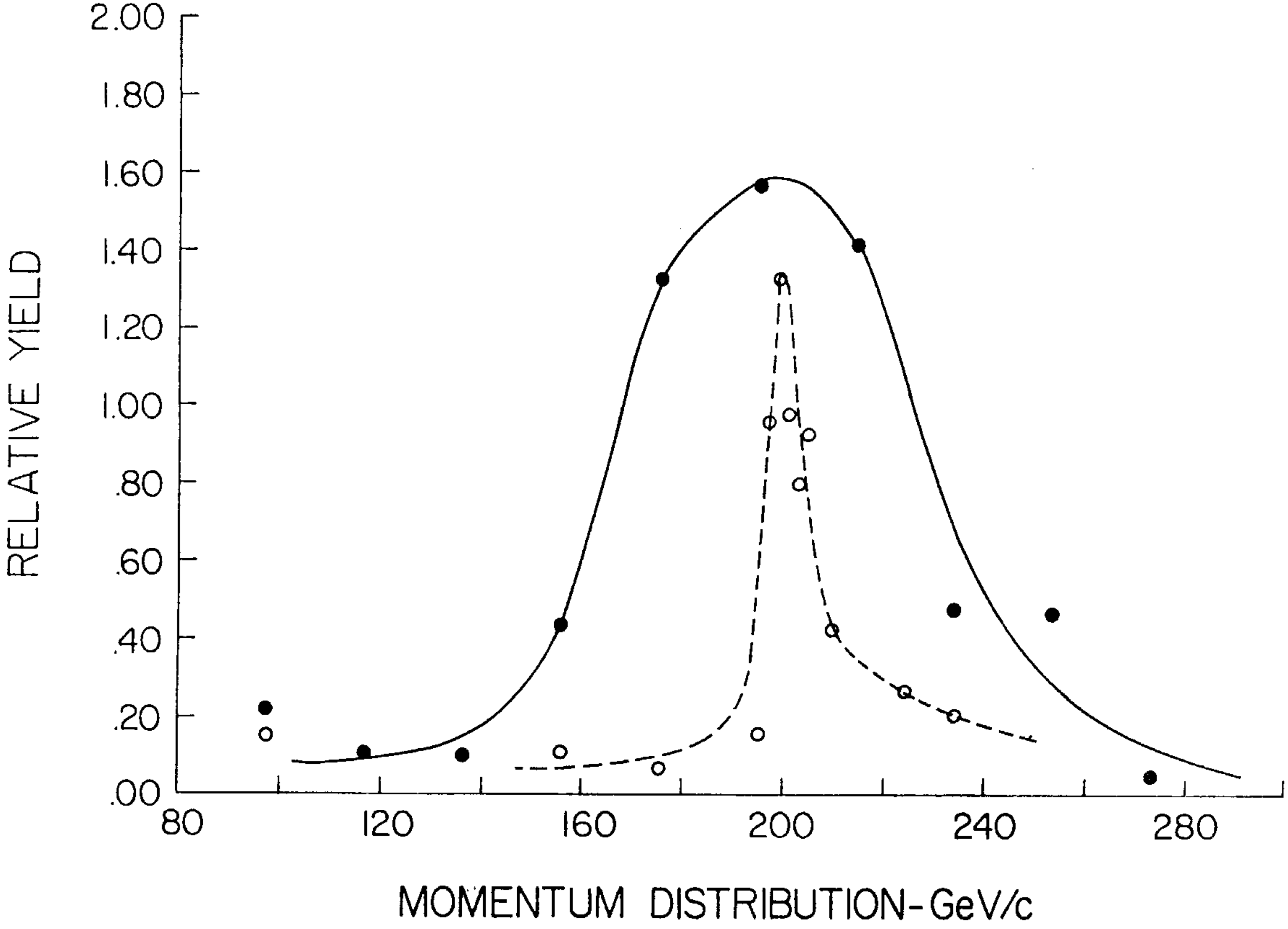
2.00
1.80
1.60
1.40
1.20
1.00
.80
.60
.40
.20
.00
RELATIVE YIELD
80
120
160
200
240
280
MOMENTUM DISTRIBUTION-GeV/c

Figure 3