Scintillating Glass Fiber-Optic Targets

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I. Physics Overview

A large amount of effort by the high energy physics community in recent years has been focussed on the study of charm particles. An effort of similar magnitude to study beauty particles is expected in the future. Although most of the available information about charm spectroscopy comes from experiments at e^+e^- colliding beam facilities and essentially all of the current information on beauty particles comes from this source, nevertheless, it is very likely that the definitive measurements of lifetimes for beauty states will be performed at fixed target machines, where one has substantial Lorentz boosts for these particles and where one can view the particle decays directly in a target. In contrast, typical heavy-particle momenta are very low at colliders (1-2 GeV/c), and, as a consequence, lifetime measurements are limited ultimately by the multiple-scattering of outgoing secondary particles in the walls of the beam pipe. Second, it is of course essential to study both electromagnetic and hadronic production mechanisms for the B-system.

Recent results from fixed-target experiments designed to study charm particles have demonstrated the tremendous value of a high-resolution visible target for this purpose. Early spectrometer experiments without such a target have made obvious the severe problems existing when the particles associated with the charm particle decay cannot be clearly selected and all combinations of secondaries must be considered. These combinatorial problems are bound to be much more severe and are likely to be insurmountable with the higher multiplicities of secondaries expected in beauty experiments at the Tevatron. However, visible targets such as the emulsions and bubble chambers now in use or under consideration have their own limitations. They tend not to be triggerable so that they suffer from serious limitations on beam intensity or total beam and they yield data samples in which the fraction of events involving charm is small and in which the fraction of beauty events might be expected to be infinitesimal.

Our current knowledge of charm and beauty production allows us to outline the formidable challenges that experiments must face and to summarize the requirements which must be satisfied if these challenges are to be met successfully.

A beauty search experiment must cope with the following:

1. The total cross section for $B\bar{B}$ production is estimated to be of order $\sim 10^{-6}$ of the inelastic pp cross section, and of order $\sim 10^{-4}$ of the γp cross section. This suggests that event samples are going to be small, even with substantial running times.
2. The hadronic weak decays of B mesons are known to involve many secondaries (from measurements at CESR). Although semi-leptonic decays appear to contain a lower average particle multiplicity, the demands on spectrometer acceptance and efficiency are severe if one expects to reconstruct even a few decays completely.
3. The branching ratios for B decays into any given mode are expected to be very small ($\leq 1\%$). This suggests that brute-force searches for bumps in mass spectra are almost certainly doomed.
4. The current best estimates for lifetimes for B particles fall in the range: 10^{-14} sec $< \tau < 10^{-12}$ sec. Hence one needs vertex detection capable of addressing lifetimes substantially below those for charm particles.

To counter these difficulties, a fixed-target experiment to study beauty production must exploit the following:

1. Use of the highest energy beams available, to obtain a more favorable beauty production cross section.
2. Use of a specialized trigger to reject unwanted events.
3. Use of an open-geometry spectrometer with precision tracking, hadron identification, and calorimetry for lepton and photon detection. The acceptance must be made as large as possible consistent with trigger requirements and high event-rate capability.
4. Use of an active target system in order to identify decay vertices for rare particle decays. This target must be capable of identifying lifetimes $\tau \gtrsim 10^{-14}$ sec. In fact, the active target is essential not only for lifetime measurements, but also for identifying individual particle states and specific decay modes. Without it, combinatorial backgrounds would pre-

vent any hope of spectroscopic analysis.

While we think that elements 1-3 of the above list are presently realizable, element 4 is still problematic. We believe that most visible target schemes currently being used to observe charm decays will be unable to meet the more stringent requirements of a fixed-target beauty production experiment. Therefore our approach has been to develop a triggerable, high-resolution active target.

We list the basic requirements that this vertex detector must satisfy, in order to be an effective device in a beauty search experiment:

R1. The device must be capable of detecting impact parameters of order $\lesssim 3\mu$ ($\tau \gtrsim 10^{-14}$ sec). One must detect $\gtrsim 10$ hits/mm of path length for minimum-ionizing particles with a resolution/point of $\sigma \lesssim 10\,\mu$ in order to overcome multiple scattering effects.

R2. The target should have a fast response time in order to be suitable for relatively high beam rates.

R3. The target should be triggerable to minimize the amount of data which must be analyzed.

R4. The target should have as long a radiation length as possible to minimize gamma conversions and the effects of multiple-scattering of charged tracks.

We describe below our recent experience with the use of scintillation active targets.

II. Status of Active Target Development

During a recent charm search experiment at Fermilab (E-515)[1] in which several of us were participants, we tested an active target device, a scintillation camera[2] built by D. Potter, in conjunction with the spectrometer system. Figs. 1 and 2 indicate the experimental layout of E-515 and a schematic of the target device. The reaction under investigation was:

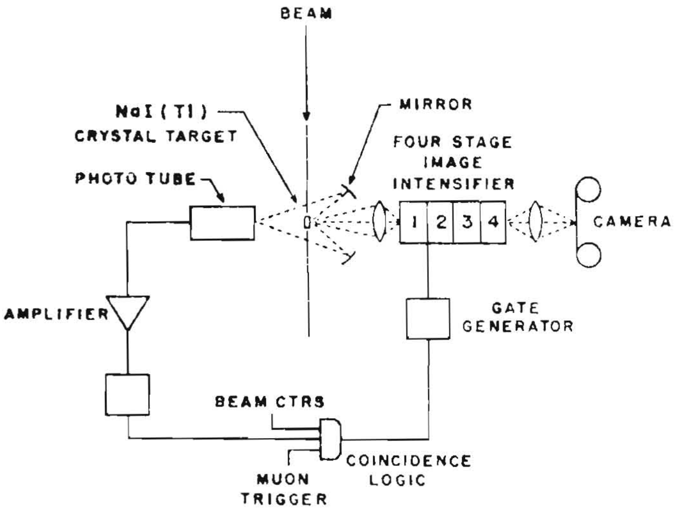

Fig. 2. SCINTILLATION CAMERA SCHEMATIC

$$\begin{pmatrix}\pi^-\\ p\end{pmatrix} + \mathrm{TGT} \rightarrow C_1 + \overline{C}_2 + X$$

$$\overline{C}_2 \rightarrow \mu^-,\ e^-,\ K^+\pi^-,\ \ldots$$

$$C_1 \rightarrow \mu^+$$

The experimental strategy was to trigger on a prompt muon from the semileptonic decay of one of the charm particles (C_1 or $\overline{C}_2$) in an upward arm ($\theta \geq 40$ mr vertically) and to examine the decay of the associated state with open geometry (-80 mr $\leq \theta \leq 40$ mr vertically). The target itself was a small NaI crystal, a disk 1.8 cm in diameter and 1.8 mm thick. Scintillation light produced along beam tracks and charged secondaries from interactions in the crystal was imaged optically onto a commercially available four-stage image intensifier. The photo-image of the tracks was stored on the seond stage phosphor until a trigger signal gated the image onto film. Roughly 50 K pictures were recorded with this device (Fig. 3 shows two examples of charm candidates). The film

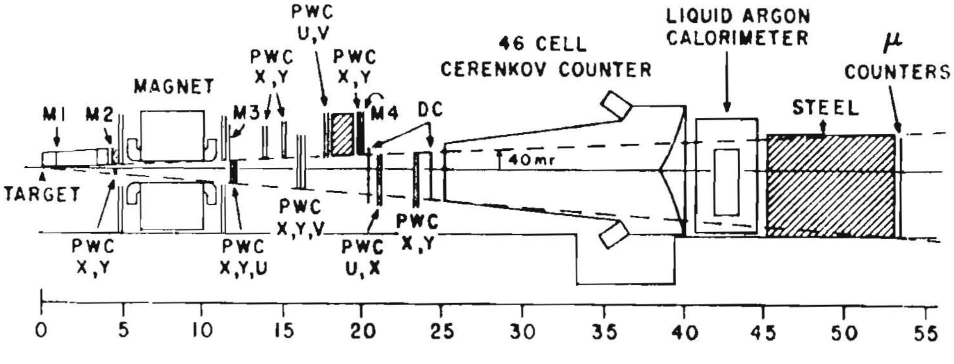

Fig. 1. E515 ELEVATION VIEW

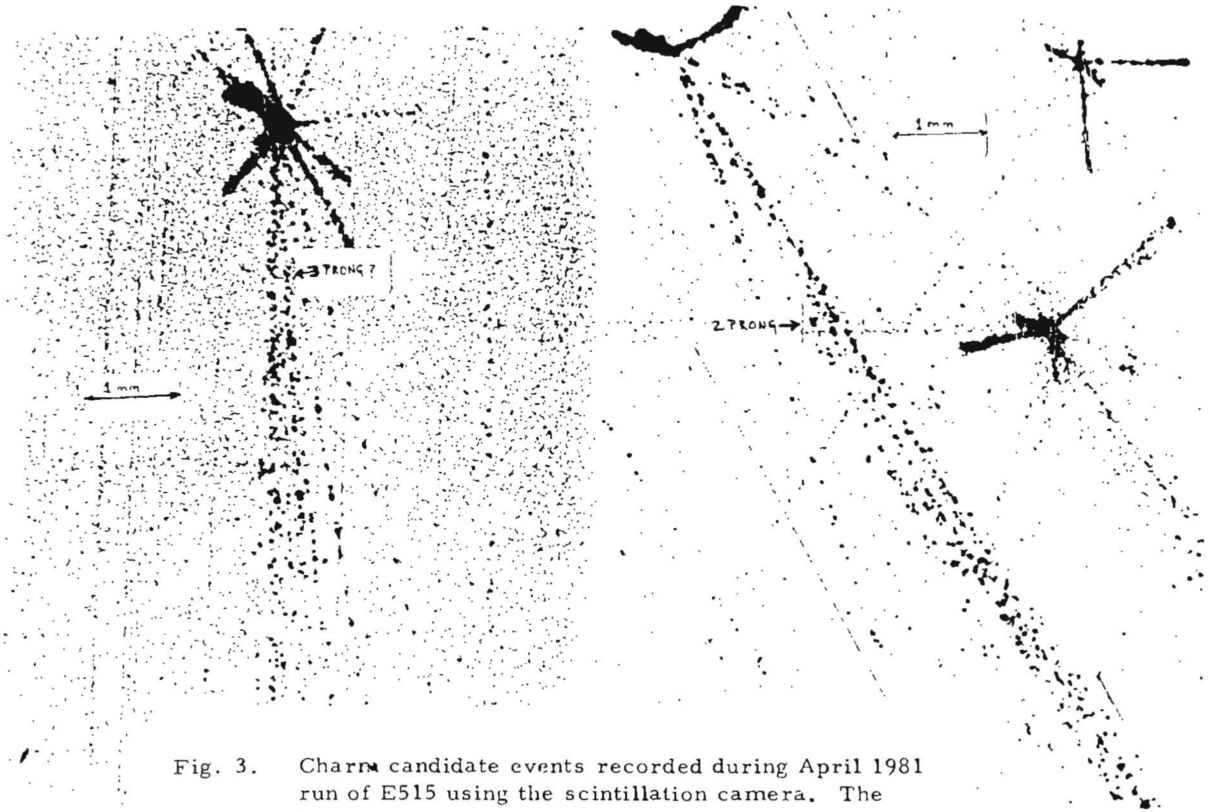

Fig. 3. Charm candidate events recorded during April 1981 run of E515 using the scintillation camera. The beam is incident from the top. Dark prongs are nuclear breakup. Sight in the plane of the paper to see topology better. (This fourth generation reproduction of the originals does not do justice to the data film.)

is presently being measured and analyzed at Notre Dame and Rutgers to look for charm particle decays.

Based on our experience to date, we find that the existing scintillation camera and NaI target are inappropriate for use in the study of the beauty system for several reasons. First, the short radiation length of NaI (2.59 cm) compounds multiple-scattering problems for charged tracks and leads to many gamma conversions which make analysis of the events much more difficult. Second, the density of detected hits per unit path length for minimum-ionizing particles (2-3/mm) is too low for consistent recognition of impact parameters below 30 μ. Thus mean lifetimes $\tau \lesssim 10^{-13}$ sec cannot be studied with this system. Hence this NaI target system fails to satisfy requirements R1 and R4 for a satisfactory vertex detector for beauty as defined in Section I of this paper. Satisfaction of R1 would be exceedingly difficult with any system using a NaI crystal because of the optics problems in collecting a sufficient fraction of the produced photons and the limitations of quantum efficiency for detection systems. The use of NaI or any compound with a short radiation length is inherently in conflict with R4.

Thus we have had to examine other techniques and other materials for construction of an active target for vertex detection. A most promising and potentially very exciting prospect has been the use of a fiber-optic plate composed of scintillating glass fibers as the target. We were able to obtain such a plate in May, 1982 from A. Rogers who has been developing these devices for their medical applications. A schematic of this fiber-optic plate is shown in Fig. 4. It consists of 4 mm long cladded-glass fibers spaced on 25 μ centers.[3] The active element (scintillant) in this glass is Tb_2O_3.

We have made tests using this fiber-optic target and have been successful in obtaining images of 200 MeV/c π^+ mesons on film using the following techniques. As indicated in Fig. 5, we optically greased the scintillating-glass target (which was of dimensions 2 cm x 2 cm x 4 mm) onto the input plate of a commercially available 3-stage, electrostatically-focussed image intensifier which served to amplify the light to a level sufficient for recording onto film. The input and output plates of the image intensifier were non-scintillating fiber-optic plates composed of 5.5 μ fibers. Fast 35 mm film was pressed up against the output plate of the image intensifier to record the amplified light. The device was placed in the test beam at the Argonne IPNS accelerator, which delivered π^+ mesons to the target material. The beam was incident normal to the fiber axes. Sample pictures taken in August, 1982 are shown in Figs.6-8.

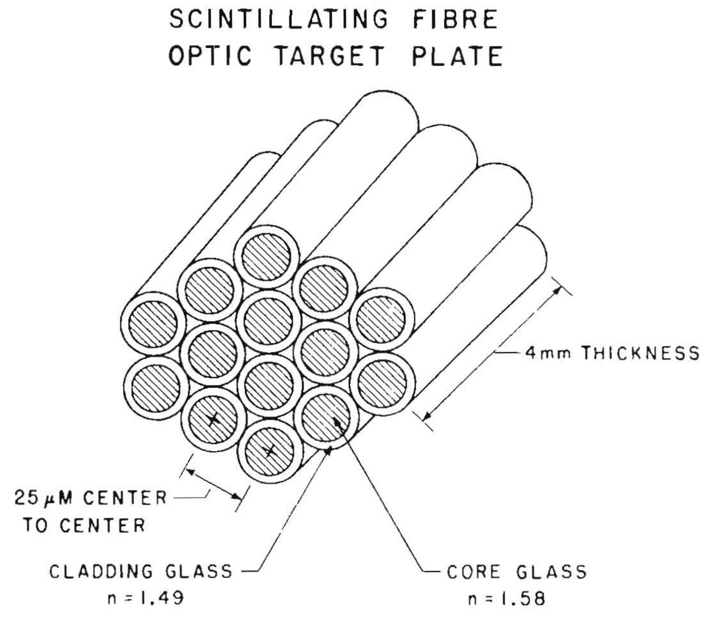

Fig. 4. Schematic of the Tb_2O_3 glass, fiber-optic target.

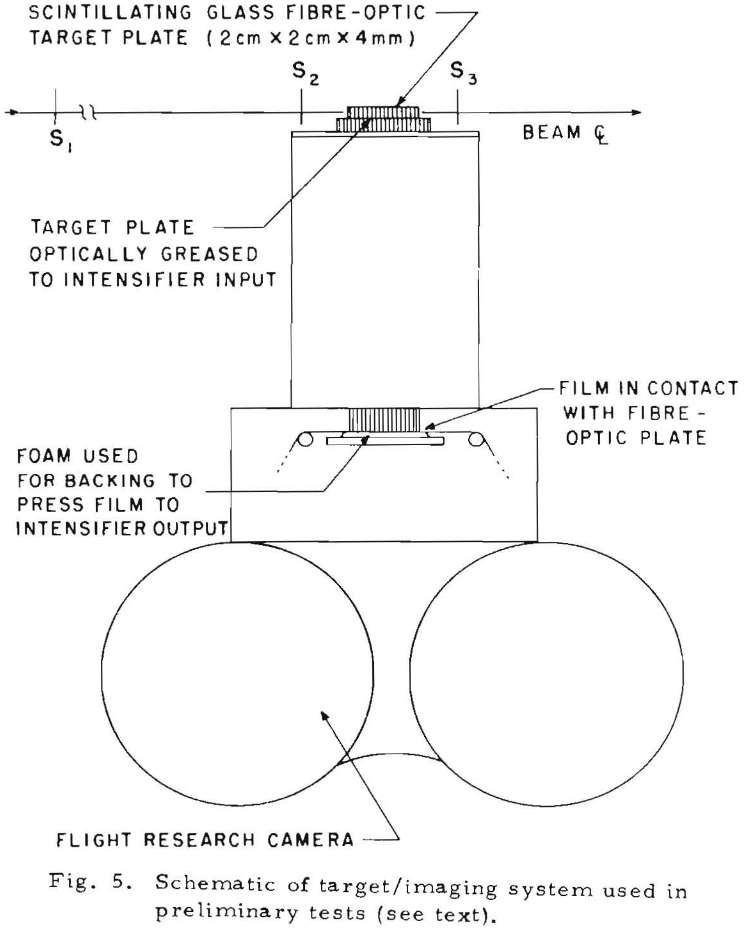

Fig. 5. Schematic of target/imaging system used in preliminary tests (see text).

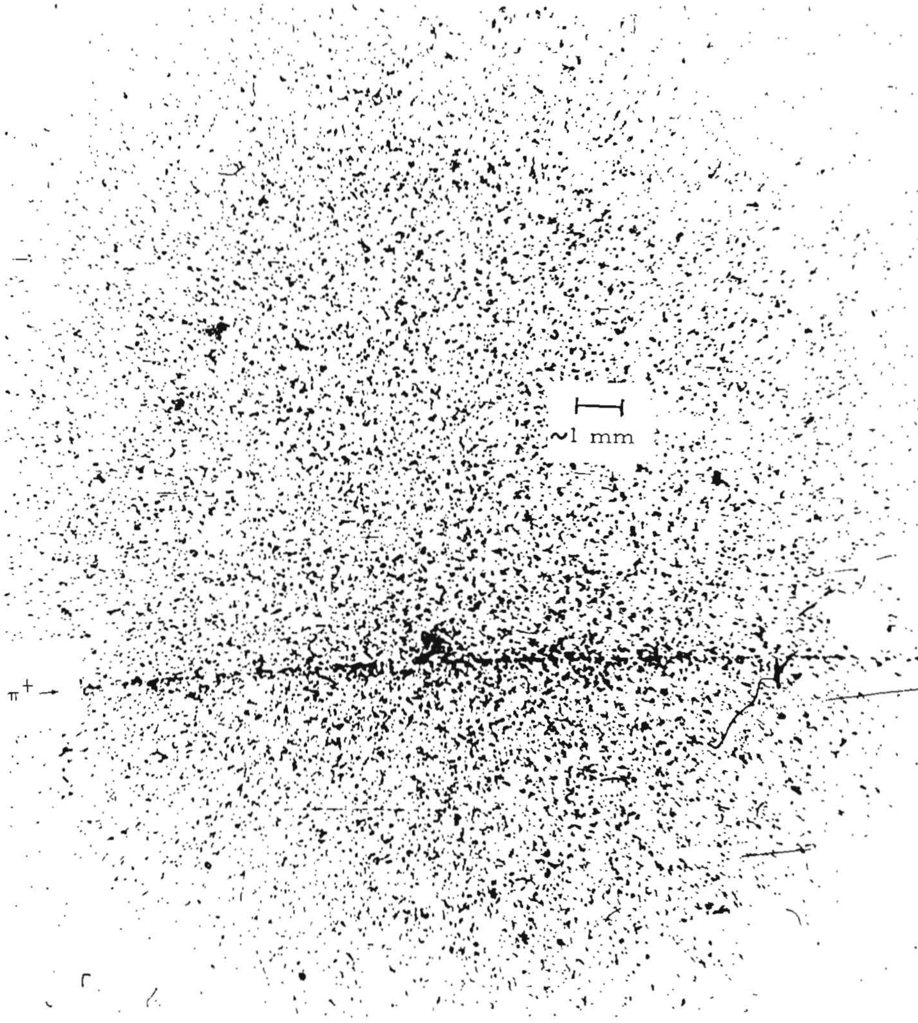

Fig. 6. Track of a 200 MeV/c π^+ meson detected in the Tb_2O_3 glass. Spotty background is the integrated dark current of the ungated image intensifier. Exposure time was 1 second.

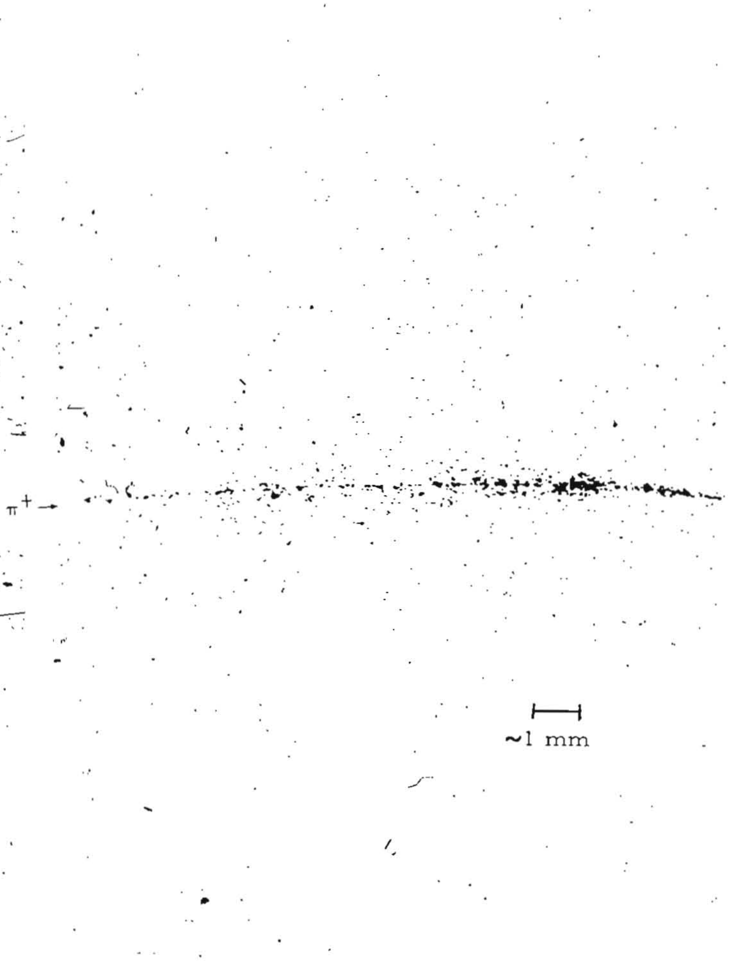

Fig. 7. Track of a 200 MeV/c π^+ meson detected in the Tb_2O_3 glass. Integrated dark current is reduced relative to Fig. 6 because of shorter exposure time, ~ 1/30 sec.

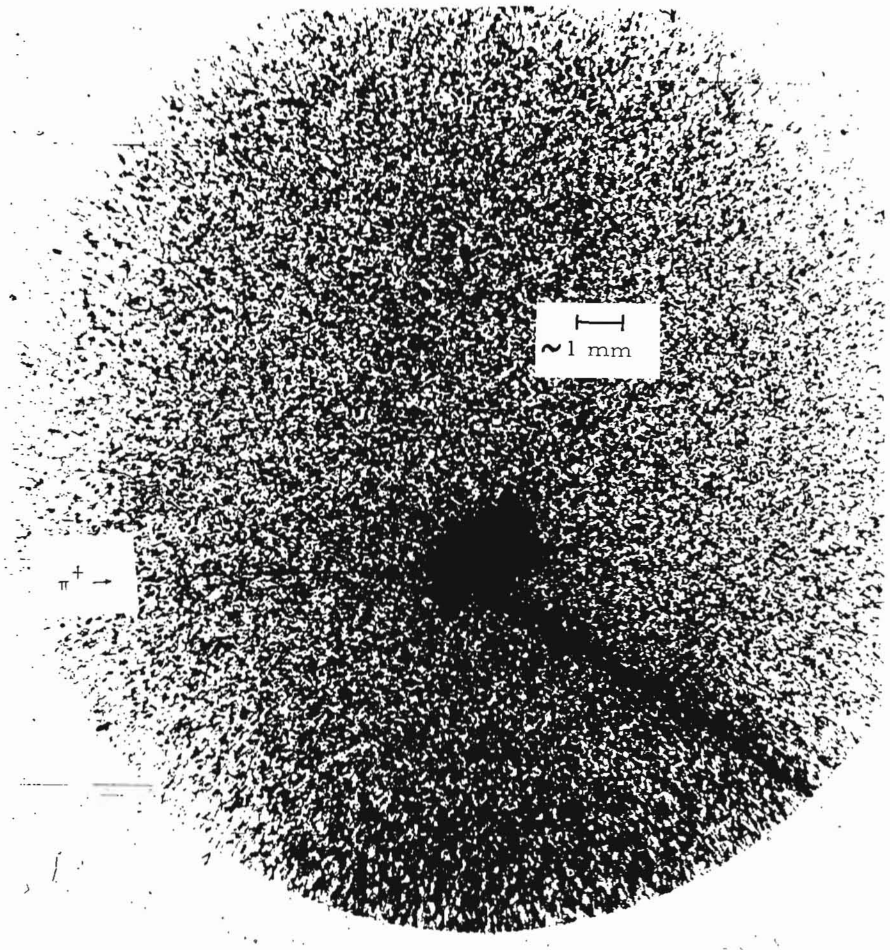

Fig. 8. A nuclear interaction in the Tb_2O_3 glass produced by an incoming 200 MeV/c π^+ meson. Region of total darkening is an artifact of photographic reproduction - the original film shows a short, stopping track of fairly narrow width.

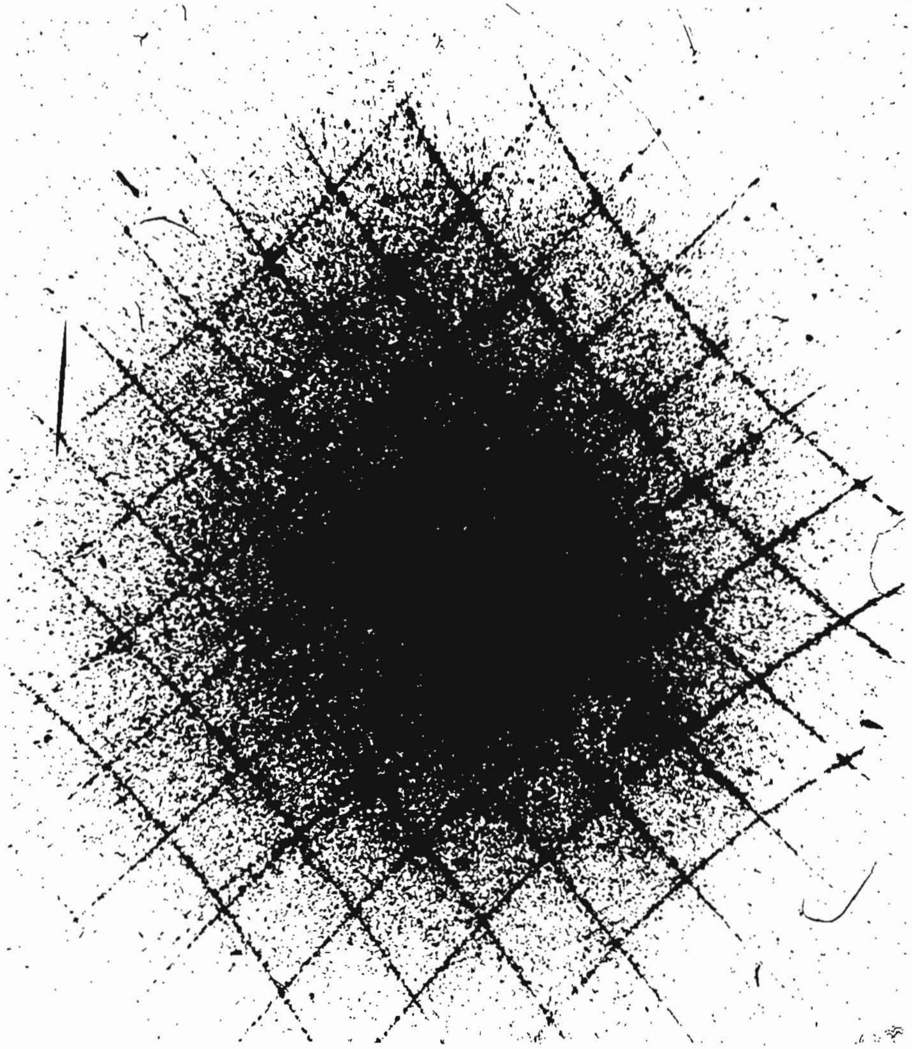

Fig. 9. Pin cushion distortion of the image intensifier system. A cartesian grid of 2.0 mm spacing was placed on the input plate of the image intensifier and illumination was provided by an LED.

These show clear tracks and, in one instance (Fig. 8), a nuclear interaction.

Some general comments on these pictures are in order:

1. There is a very spotty background in each frame. This is due to the dark current of the ungated image intensifier. In an actual experiment one would use a gated tube and this effect would be eliminated.
2. The particle tracks are actually straight in real space, but the electrostatic focussing of the image intensifier generates a pin-cushion distortion which makes the tracks look curved. To see this effect directly, we have photographed a Cartesian grid which was placed on the input faceplate of the intensifier. The grid photograph is reproduced in Fig. 9 and indicates the character of the distortion. The grid spacing is 2 mm. Distortions can be removed in the process of analyzing measurements of the photographed tracks.
3. The diameter of the output face of the intensifier is 25 mm; this is the maximum detectable track length in this test configuration.

Based on these photographs and others, we conclude that a target composed of scintillating glass fibers can in fact be used to record particle tracks, and that, with the Tb_2O_3 scintillating glass, about 7 hits/mm can be detected along the path of a minimum ionizing particle using a matched image intensifier. The dot size in these tests was $\sim 50\,\mu$ which is quite reasonable considering our relatively inexpensive test arrangement. This "existence proof" suggests that the technique has excellent prospects.

However it should be noted that the Tb_2O_3 glass itself has a number of drawbacks which limit its applicability as an active target for high energy physics experiments.

1. The time constant for the scintillation transitions is of order ~ 10 msec, which is much too long to be useful in high beam rate conditions (although it is potentially useful in other applications). Thus the terbium glass fails requirement R2, specified in Section I.
2. Although the radiation length of the Tb_2O_3 glass is twice that of NaI, the glass does contain some additional heavy elements so that gamma conversions and multiple scattering are still a potential problem. Hence requirement R4 is not met to our satisfaction.
3. The scintillation light produced peaks at 5500 Å, which is not a wavelength optimized to the best photocathode materials. An extended-red photocathode had to be used in the tests.

To overcome these problems, we are developing a new glass containing Ce_2O_3 as the scintillant and which contains no elements heavier than calcium except for cerium. This glass has several nice features:

1. The time constant for the scintillation transitions is of order 80 nsec, which is ~ 2.5 times faster than NaI.
2. The scintillation light is produced near 4000 Å, which is well matched to the best photocathodes (D-type).[4]
3. Because the glass was selected to avoid heavy-element content, the radiation length is anticipated to be roughly 5 times that of NaI.

As of this writing, the Ce_2O_3 glass has been produced, and it will be drawn with the appropriate cladding material to fabricate fiber-optic target plates. The aim will be to produce target plates containing fibers spaced on 6μ centers, with a target volume of 1 inch^3.

In Table I we present a comparison of the performance of NaI and Tb_2O_3 glass targets based on actual measurements, and we include estimates for the Ce_2O_3 glass target. The higher hit density anticipated for Ce_2O_3 results from two factors: 1) The blue scintillation light improves image-intensifier quantum efficiency by roughly a factor of two; 2) We have reason to believe that cerium is a better scintillator than terbium. This could increase the observed hit density still further. The better spatial resolution for Ce_2O_3 is derived from the smaller fiber spacing ($6\,\mu$) which is planned and the assumed use of an improved image intensifier.

TABLE I

Comparison of Various Target Materials*

	NaI	Tb_2O_3	Ce_2O_3
Spatial Resolution (μm)	20	< 50	$\lesssim 10$
Density of Track (hits/mm)	2-3	~ 7	~ 15
Triggerable During Tests	yes	no†	yes
Scintillation Time Constant	200 ns	10 ms	80 ns
Radiation Length Relative to NaI	1	~ 2	$\lesssim 5$

*Results for NaI and Tb_2O_3 are based on measurements, Ce_2O_3 values are estimates. See text.

†The Tb_2O_3 target can be used in a triggerable arrangment, of course. This was unavailable during the initial test run for which the target parameters were recorded.

Given the characteristics expected for the Ce_2O_3 glass listed in Table I, there appears to be no reason why it should not be acceptable material for the fabrication of a useful experimental target. First, however, these properties must be definitely established in tests.

With the Ce_2O_3 target and a new gated imaging system, we will address the following questions which we feel are fundamental; hit density/mm of track length; light-sharing across fiber boundaries; spatial resolution; radiation-length effects; high-contrast behavior of the intensifier for slow nuclear tracks; fast gating and gating efficiency; and vacuum film handling. This program is being actively pursued

ACKNOWLEDGEMENT

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1. E-515, Charm search with a prompt muon trigger. Northwestern, Carnegie-Mellon, Fermilab, Notre Dame Rutgers Collaboration.

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3. With a core glass index $n = 1.58$ and a cladding index of $n = 1.49$, approximately 10% of the scintillation light produced in a fiber is trapped by internal reflection. This can all be collected if one views the fibers from one direction with the away side aluminized.

4. A.R. Swopart, Nucl. Inst. and Meth. <u>140</u>, 19-28 (1977).