Fermi National Accelerator Laboratory

FERMILAB-Pub-93/002

E789

Test of Principle of an Optical Trigger for Beauty

D.M. Kaplan, M. Apolinski and W. Luebke

Physics Department, Northern Illinois University
DeKalb, Illinois 60115

S.W.L. Kwan

Particle Detector Group, Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

January 1993

Submitted to *Nuclear Instruments and Methods*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

TEST OF PRINCIPLE OF AN OPTICAL TRIGGER FOR BEAUTY

D. M. KAPLAN, M. APOLINSKI,[a] and W. LUEBKE
Physics Department, Northern Illinois University, DeKalb, IL 60115, USA

S. W. L. KWAN
Particle Detector Group, Fermilab, Batavia, IL 60510, USA

We have carried out a test of the principle of the Optical Trigger for Beauty proposed by Charpak, Giomataris, and Lederman. We measure the production and trapping by total internal reflection of Cherenkov light produced in a flat crystal of MgF_2 by the passage of high-energy muons. Using an array of drift tubes to measure the trajectories of the muons, we observe a threshold in the production of trapped Cherenkov light as a function of muon incident angle. The shape of the threshold curve is consistent with that expected from a simple optical calculation. An angle-independent component of trapped Cherenkov light, apparently due to delta rays, is also observed. We discuss prospects for a practical device.

1. Introduction

The production of beauty quarks in the collisions of hadrons is a small fraction of the total interaction cross section; for example, in 800-GeV proton-nucleon collisions, $b\bar{b}$ events are expected to occur of order once per million interactions [1]. On the other hand, intense beams of hadrons can be made to interact in solid targets, giving the potential to produce $\sim 10^9$ beauty events per year of running.* To take advantage of this potential, a powerful triggering technique is needed to select beauty-decay events while suppressing the background of "minimum-bias" events which constitute the bulk of the total interaction cross section. Such a trigger will need to exploit characteristics of beauty production and decay which distinguish this process from the background. Beauty decays can be distinguished by (among other characteristics) their high charged multiplicity (5 on average [2]); in addition, due to the long b-quark lifetime (1.4×10^{-12} s [3]) and its dominant cascade decay to charm, many of the decay particles have large impact parameters ($\gtrsim 500\,\mu$m) relative to the primary interaction point.

* e.g. 10^7 seconds of beam at 10^8 interactions/s; cf. reference [9].

2. Optical trigger

Charpak, Giomataris, and Lederman [4] have proposed a trigger device (the "Optical Trigger for Beauty") to take advantage of these characteristics. The proposed device consists of a thin spherical shell of transparent crystal focussed on a point target. In the simplest version, the crystal is chosen to have refractive index just below $\sqrt{2}$. Any particle originating in the target impinges on the crystal at normal incidence, whereas a particle from a decay downstream of the target in general has non-zero impact parameter at the target and impinges on the crystal at an angle which is correlated with its impact parameter. By virtue of the crystal's curvature, Cherenkov light emitted within the crystal by particles originating in the target escapes through the convex face of the crystal; in contrast, particles whose tracks have sufficiently large impact parameters at the target emit Cherenkov light a portion of which is trapped within the crystal by total internal reflection. The trapped light emerges at the edge of the crystal, where it can be detected by a suitable photodetector.

Given the substantial probability per interaction to produce a K_s^0 or hyperon, one might expect an impact-parameter trigger to reject only a small fraction of interactions. However, the crystal can be placed a few beauty decay lengths downstream of the target, upstream of most strange-particle decays; in addition, the light-collection optics can be arranged to suppress sensitivity at the larger impact parameters ($>$ a few mm) characteristic of strange-particle decay. The device should thus produce little or no signal for minimum-bias events, but a large signal for beauty decays occurring downstream of the target. Its efficiency for charm should be considerable, although (due to charm's smaller average lifetime and decay multiplicity) less than that for beauty; however, at trigger level charm is not an important background, as it is produced only $\sim 10^{-3}$ per interaction [5].

3. Test of principle of optical trigger

The device relies on the sharp angular dependence of totally-internally-reflected Cherenkov light. The needed performance could be compromised if there is a significant contribution due to scintillation in the crystal, delta rays, or nuclear interactions. We have carried out a test to assess the importance of the first two of these effects.

3.1 Apparatus description

Because of its good mechanical properties, transparency, and radiation hardness, and because it has refractive index close to $\sqrt{2}$ while not exceeding that value in visible wavelengths, we chose MgF_2 for our test. Our apparatus is shown in Figure 1. A flat, rectangular crystal of MgF_2 of dimensions $2.5 \times 3.2 \times 0.2\,\text{cm}^3$ was placed in the muon flux downstream of an operating experiment (Fermilab Experiment 789) in December 1991 during the final days of the fixed-target run. The crystal was held in place against a Hamamatsu R1828-01 photomultiplier tube by a lucite cookie (Figure 2). Silicone optical grease (GE VISC-600M) between the crystal's edge and the photomultiplier-tube's entrance window minimized light losses due to reflection. To allow room for excess grease, the cookie was relieved to a depth of 4.8 mm around the crystal as shown in Figure 2. An aluminum cap surrounding the crystal and cookie fit snugly over the phototube's magnetic shield and excluded ambient light. Two holes of 1-cm diameter bored in the cap and covered with black plastic tape minimized the material in the muons' path.

The tracks of muons passing through the crystal were measured using a telescope of eight small drift tubes arrayed in 60° stereo on either side of the crystal [6]. The drift tubes provided position measurement to $< 150\,\mu\text{m}$ (RMS) and angular resolution $< 1\,\text{mr}$. The photomultiplier-tube assembly was mounted, with the tube pointing downward, on a pivot, so that its vertical angle with respect to the drift-tube telescope could be varied manually via a screw adjustment. The trigger required coincident pulses in two $2.5 \times 2.5\,\text{cm}^2$ scintillation counters surrounding the telescope, and also in a $30 \times 30\,\text{cm}^2$ counter placed downstream of 4.6 m of shielding concrete, thus ensuring a minimum muon energy of 2 GeV and minimizing effects due to multiple scattering.

3.2 Data acquisition and analysis

For each muon triggering data acquisition, the pulse area from the photomultiplier tube was digitized using one channel of a LeCroy 2249W ADC, and read out along with the eight drift times, which were digitized by a LeCroy 2229 eight-channel TDC whose "start" signal was derived from the scintillator coincidence. The data were recorded on the hard disk of an IBM PC and subsequently transferred to a VAX system for off-line analysis. In the off-line reconstruction, the drift-direction ambiguities in the eight drift tubes led to 256 hypotheses for each muon track; the hypothesis giving the smallest χ^2 was chosen.

3.3 Angular dependence of pulse area

Initially, large light output was observed independent of the muon incident angle. Two mechanisms were hypothesized to account for this: 1) some light refracted out of the crystal could still impinge on the cookie and enter the phototube, and 2) some light incident on the edges of the crystal, which were unpolished, could be reflected back towards the phototube. To absorb the refracted light, we wrapped the crystal with black paper and covered the exposed face of the cookie with black plastic tape. To absorb light incident on the crystal's edges, we blackened with indelible ink all edges except the one contacting the phototube. Following these improvements, a strong angular dependence was observed, as shown in Figure 3a: in the threshold region, the pulse area is seen to increase by a factor of 10 over $\approx 40\,\mathrm{mr}$.* The figure represents data taken at three overlapping settings of the phototube vertical-angle adjustment; each setting covered a range of $\approx 20\,\mathrm{mr}$.

In the planar crystal employed here, Cherenkov-light trapping depends on horizontal (θ_x) as well as vertical angle of incidence (θ_y). The observed dependence on θ_x is shown in Figure 4. To isolate the dependence on θ_y, the data of Figure 3 are restricted to the range $0 < \theta_x < -0.012$, over which the variation of pulse area with θ_x is small.

A simple optical calculation explains the observed effect. For each incident angle θ_y, the light intensity at the phototube is proportional to the range of azimuth ($\Delta\phi$) over which Cherenkov light is trapped. For $\theta_x = 0$, it can be shown that $\cos(\Delta\phi/2)$ is a solution of the quadratic equation

$$[-(n^2-1)\,\sin^2\theta_y]\cos^2\frac{\Delta\phi}{2} + [2\frac{\sqrt{n^2-1}}{n^2}\sin\theta_y\cos\theta_y]\cos\frac{\Delta\phi}{2} + [n^2-1-\cos^2\theta_y] = 0\,,$$

where n is the (wavelength-dependent) index of refraction of the medium. Figure 3b shows $\Delta\phi/2\pi$ for a range of wavelengths. At any given wavelength the threshold in angle is quite sharp: as the threshold is crossed from below, Cherenkov light becomes trapped over a rapidly increasing range in azimuth. Once the azimuth range for trapping matches the dimension of the end of the crystal, the light intensity at the

---

* No attempt was made to align the crystal absolutely with respect to the drift tubes, hence the zero of angle in Figures 3a and 4 is arbitrary.

phototube reaches a plateau beyond which no further increase is possible (assuming light incident on the crystal's other edges is totally absorbed).

The phototube is sensitive over a wavelength range of approximately 300 to 700 nm, over which the refractive index of MgF_2 varies significantly [7] (see Figure 5). Upon integration over the full wavelength range a rather gradual angular dependence results, similar to that which we observe. This is shown by the solid curve in Figure 3b, which represents the superposition of the individual curves for each wavelength weighted by the spectral response of the phototube [8] and the Cherenkov emission spectrum and averaged over the fiducial region. The solid curve in Figure 3a represents a best fit of this wavelength-integrated curve to the observed data, in which the zero of θ_y and the gain and offset of the pulse area are all allowed to vary. The slight disagreement of the calculated threshold shape with the observed data most likely reflects some variation with respect to nominal of the phototube's spectral response, for which only a "typical" specification was available.

3.4 Position-dependence of pulse area

Figure 6 shows the dependence of pulse area on the vertical distance from the phototube of the muon's point of incidence; superimposed is the expected dependence. This dependence arises simply from the geometry of light collection: the range in azimuth over which Cherenkov light is collected increases with decreasing distance.

3.5 Contribution from delta rays

In both angular and position dependence, the agreement of the calculation with the experimental data is reasonably good, provided an approximately angle-independent background level of light, equal to $\approx 10\%$ of the "plateau" value observed at large incident angles, is added to the predicted curve. To investigate the origin of this background light, we illuminated the crystal with an α source and an X-ray source. No fluorescence or scintillation was observed. We conclude that the background light represents the contribution due to delta rays.

3.6 Number of photoelectrons expected and observed

The number of photoelectrons expected, N_e, can be estimated as follows:

$$N_e = \alpha\, L\, \Delta\phi \int_{\lambda_{\rm min}}^{\lambda_{\rm max}} QE(\lambda)\, \sin^2\theta_{\rm Ch}(\lambda)\, \frac{d\lambda}{\lambda^2}\,,$$

where α is the fine-structure constant, L the crystal thickness, $\Delta\phi$ the azimuthal angle subtended by the end of the crystal at the point of muon incidence, QE the quantum efficiency of the phototube, and λ the wavelength; $\theta_{\rm Ch}$ is the Cherenkov angle, given by $\cos\theta_{\rm Ch} = 1/n\beta$, where n is the refractive index of the crystal and βc the velocity of the muon. We take $QE(\lambda)$ from the manufacturer's specification [8]; weighted by the Cherenkov emission spectrum, its average value is 15% in the interval 300 to 700 nm. We evaluate $\Delta\phi$ event by event; its average value is 1.014 ± 0.005. Performing the integration numerically, we find $N_e = 2.0$.

After the data were taken, the phototube and ADC were taken to a test bench for calibration. A deuterium lamp whose spectrum approximated that of Cherenkov light was used to illuminate the phototube. We find a calibration of 92.3 ± 4.3 counts/p.e. and a mean of 1.9 ± 0.1 p.e. in the "plateau" region of Figure 3a ($\theta_y > 0.016$). Of this, 90% or 1.7 ± 0.1 p.e. should be due to muon-induced trapped Cherenkov light (in reasonable agreement with the value calculated above), and the remainder delta-ray induced. (No correction has been made for possible transmission losses in the MgF_2 and optical grease or for reflection losses at the phototube entrance window.)

4. Summary of main results

We have observed a threshold in the production of trapped Cherenkov light as a function of muon incident angle. The shape of the threshold curve is consistent with that expected from a simple optical calculation, as is the observed dependence of light intensity on distance from the phototube. An angle-independent component of trapped Cherenkov light is attributed to delta rays and amounts to $\approx 10\%$ of the plateau value observed at large incident angle.

5. Future prospects

In collaboration with Charpak *et al.*, we are pursuing the further development of this technique. We hope to employ it in a future experiment at Fermilab [9]. Our goal is a factor > 10 suppression of minimum-bias events, while retaining $\gtrsim$30% efficiency* for B-decay events. Since the device is intrinsically fast, it can be used as a low-level trigger, easing the bandwidth requirements of subsequent stages of triggering and data acquisition.

Background suppression by more than an order of magnitude appears to be achievable in principle but depends on overcoming two effects: 1) the dispersion-induced spread in angular threshold and 2) the contribution due to delta rays. Dispersion might be overcome either by limiting sharply the range of sensitive wavelength or by the use of an "achromatic couple" [10], consisting of a spherical shell of one material clad with another material (e.g. sapphire clad with quartz), rather than a single material operating in air or vacuum as discussed above. As discussed below, the delta-ray contribution can be suppressed substantially by employing suitable light-collection optics.

While the average number of photoelectrons observed in this test is small, due to the high beauty decay multiplicity a typical $b\bar{b}$ event might be expected to produce up to 10 times that number. Of course, since low-multiplicity B decays such as $B^0 \to \pi^+\pi^-$ are of particular interest [11], the trigger needs to be efficient even when the large-impact-parameter charged multiplicity is as small as 4 or 5. In addition, a practical device will need to have a central hole to allow the uninteracted beam to pass through, further reducing the detectible multiplicity. Also, trapped Cherenkov light is emitted only within a thin layer of crystal (of thickness $\sim$ the impact parameter [4,12]) near the exit surface. Thus for the $\approx 500\,\mu$m impact parameters typical of beauty decay, only $\approx$1/4 of a 2-mm-thick crystal will produce trapped light.

To increase the level of signal, we intend to pursue three ideas: 1) a multilayer structure of several concentric crystal shells can substantially increase the light yield for impact parameters near threshold [12]; 2) sapphire clad with quartz, in addition to its achromaticity, will yield 40% more Cherenkov photons than MgF_2 due to sapphire's higher refractive index [12]; and 3) a solid-state detector, such as the visible-light photon counter (VLPC) [13], can provide a factor 3 to 4 increase in quantum efficiency. Other possible photodetectors are also being considered.

Use of the pixel information provided by VLPCs might lead to improved background rejection, both on- and off-line. The exit angle of trapped photons at the edge

* While this efficiency may seem undesirably small, beauty events failing the optical trigger are unlikely to be recoverable off-line: such events have small impact parameters and are difficult to distinguish from background.

of the crystal is correlated with the impact parameter of the particle which emitted them. Light-collection optics which preserve exit-angle information have been demonstrated by Charpak *et al.* [10,14]; this information can be employed to suppress the delta-ray contribution substantially, since light due to delta rays emerges over a much wider angular range than that from beauty decays.

If the exit angle of each photon can be read out, this information could supplement track information reconstructed from vertex silicon-strip detectors. Unlike reconstructed tracks, which suffer from pattern-recognition ambiguities (leading to "ghost tracks") whenever there is a high local density of hit strips, the optical information in principle directly reflects actual particle trajectories. The processes which degrade the optical information (such as dispersion and photodetector noise) are unlikely to correlate with ghost tracks in the silicon. Thus the optical information can potentially be used off-line to reject backgrounds remaining after vertex-track reconstruction. On-line, information about the number of distinct impact parameters might be derivable by a suitable trigger processor, which could be used to improve still further the rejection against delta rays and low-multiplicity strangeness decays. These ideas are currently undergoing simulation.

Acknowledgements

We thank D. F. Anderson, C. N. Brown, and L. M. Lederman for useful advice, and K. Gray for assembling the trigger counters and the crystal mount. This work was supported in part by the U. S. Department of Energy, under contract DE-FG02-91ER40641.

References

[a] Present address: Physics Department, Louisiana State University, Baton Rouge, LA 70803, USA.

[1] E. L. Berger, "Heavy Flavor Production," Argonne preprint ANL-HEP-CP-88-26 (1988).

[2] B. Gittelman and S. Stone, in *High Energy Electron-Positron Physics*, A. Ali and P. Söding, *eds.*, World Scientific, Singapore (1988), 273.

[3] V. Sharma, "Review of B Lifetimes from LEP," talk given at the 1992 Annual Meeting of the APS Division of Particles and Fields, Batavia, IL, USA, November 10-14, 1992.

[4] G. Charpak, Y. Giomataris, and L. M. Lederman, Nucl. Instr. & Meth. A306 (1991) 439.

[5] R. Ammar *et al.*, Phys. Lett. 178B (1986) 124; K. Kodama *et al.*, Phys. Lett. 263B (1991) 573.

[6] D. M. Kaplan *et al.*, "A Simple Drift-Tube Telescope for Detector Tests," to be submitted to Nucl. Instr. & Meth.

[7] *Handbook of Optics*, W. G. Driscoll, *ed.*, McGraw-Hill, New York, NY (1978), 7-95.

[8] Hamamatsu Technical Data Sheet, Photomultiplier Tube R1828-01 (1983).

[9] "Letter of Intent for a High-Sensitivity Study of Rare Low-Multiplicity Beauty Decays," Fermilab Proposal 865, D. M. Kaplan, spokesman (1992).

[10] Y. Giomataris, seminar presented at the "Second Workshop on B Physics at Hadron Machines," SSC Laboratory, August 13-14, 1992.

[11] I. I. Bigi and B. Stech, in *Proceedings of the Workshop on High Sensitivity Beauty Physics at Fermilab*, A. J. Slaughter, N. Lockyer, and M. Schmidt, *eds.*, Fermilab (1988), 239.

[12] G. Charpak *et al.*, "Study of an Optical Trigger to be used for Beauty Search in Fixed Target Mode at the LHC," CERN proposal 91-32, DRDC/30 (1991).

[13] M. Atac *et al.*, Nucl. Instr. & Meth. A320 (1992) 155.

[14] G. Charpak *et al.*, "Experimental Study of an Impact-Parameter Optical Discriminator," to be submitted to Nucl Instr. & Meth.

Figure captions

FIGURE 1. Schematic diagram of apparatus (cross-section at $x = 0$); the shielding concrete and downstream trigger scintillation counter are not shown.

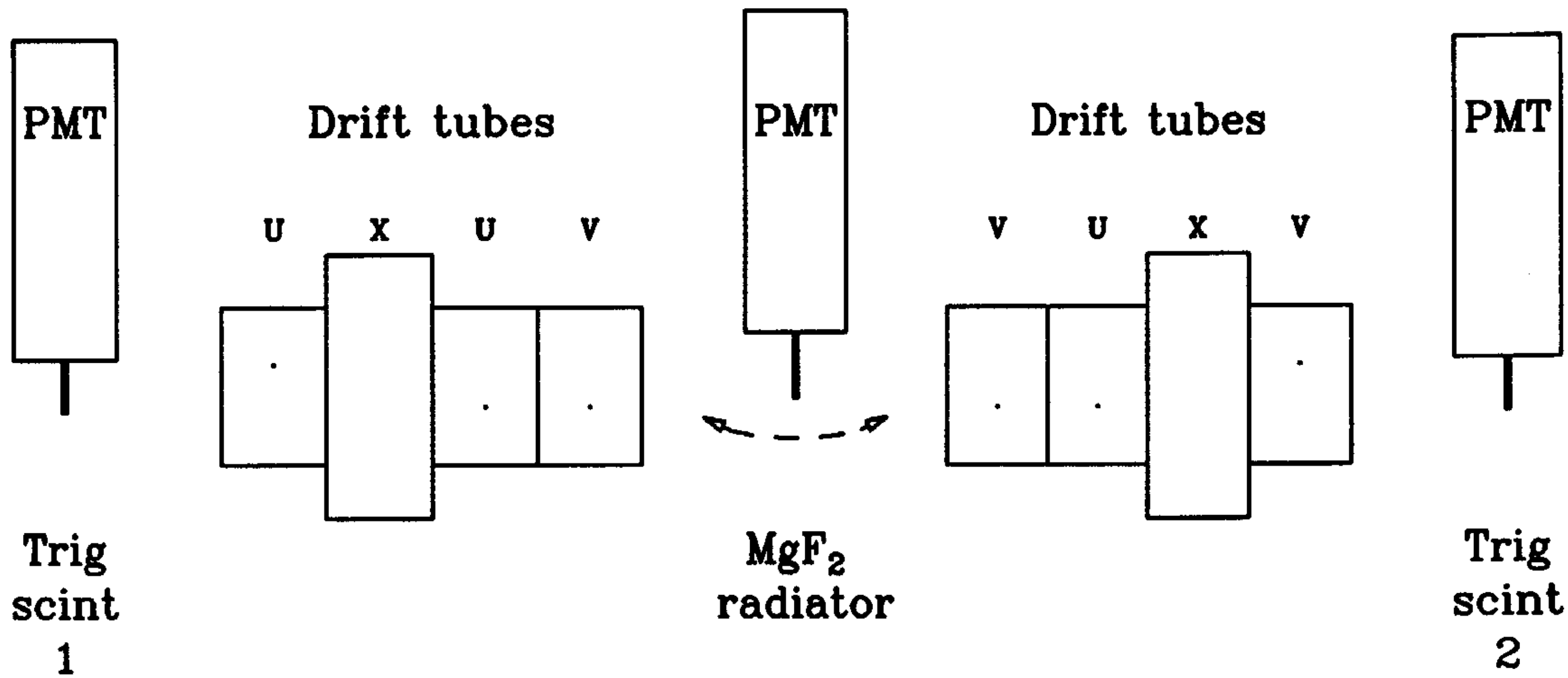
FIGURE 2. Lucite cookie used to mount the MgF_2 crystal (all dimensions in mm).

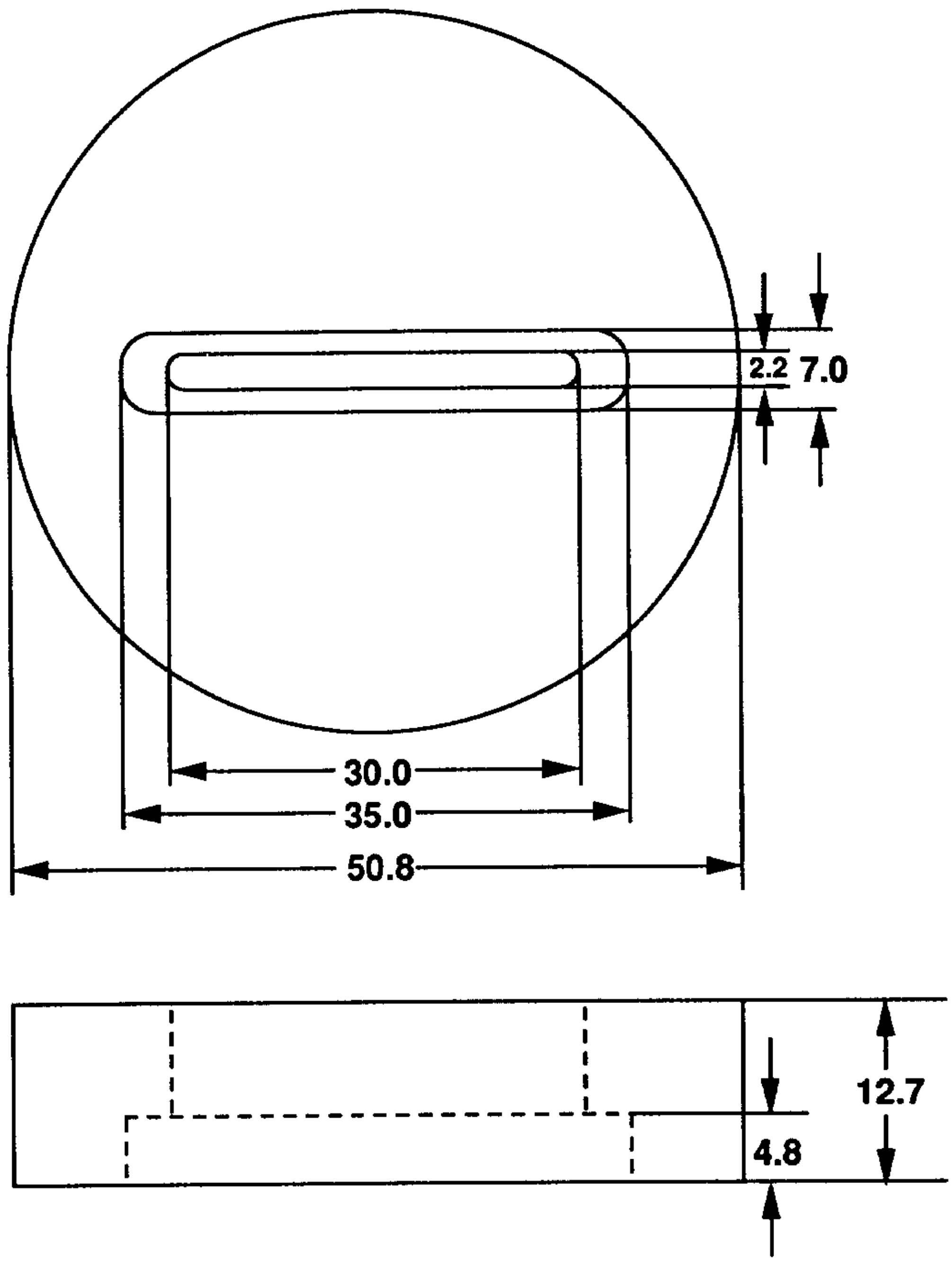
FIGURE 3. a) Observed pulse area (arbitrary units) vs. muon vertical incident angle θ_y (arbitrary zero) for $-0.012 < \theta_x < 0$; curve is result of calculation described in text. b) Dashed curves: calculated threshold behavior at wavelengths from 300 to 800 nm; solid curve is integrated over wavelength taking into account Cherenkov emission spectrum, phototube spectral response, dispersion in MgF_2, and variation of point of muon incidence over face of crystal.

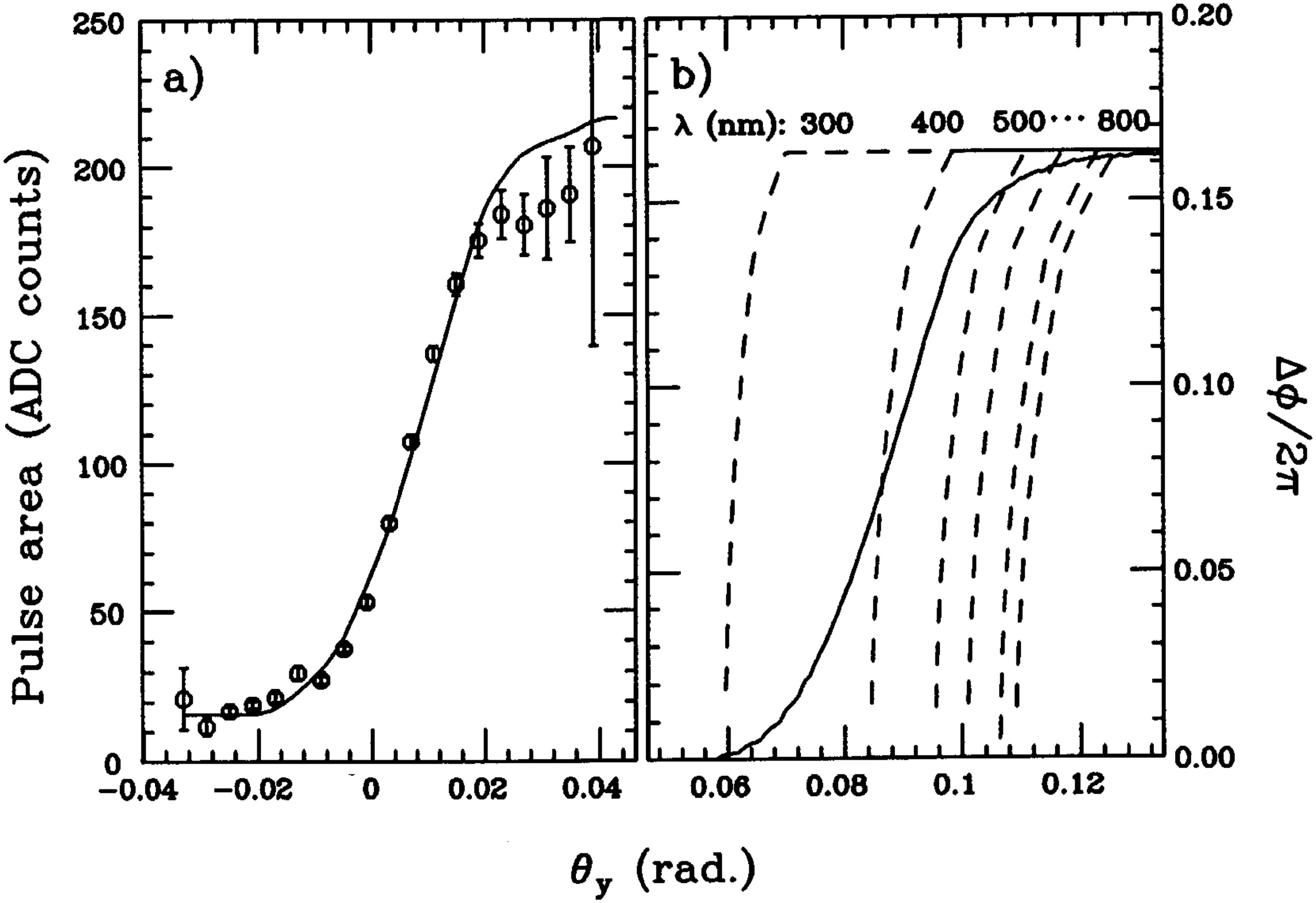
FIGURE 4. Observed pulse area (arbitrary units) vs. muon horizontal incident angle θ_x (arbitrary zero).

FIGURE 5. Refractive index of MgF_2 (ordinary ray) vs. wavelength λ (from reference [7]).

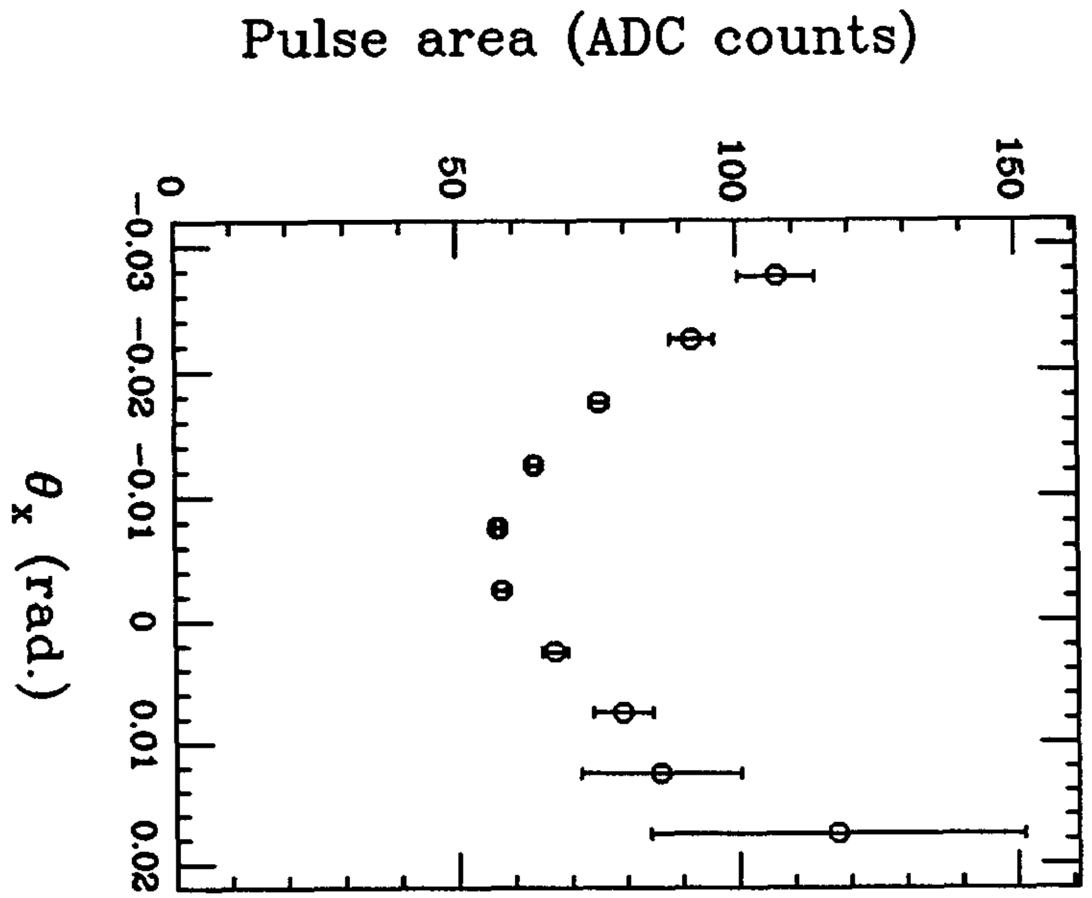
FIGURE 6. Pulse area (arbitrary units) vs. distance from phototube for the interval $\theta_y > 0.016, -0.012 < \theta_x < 0$.

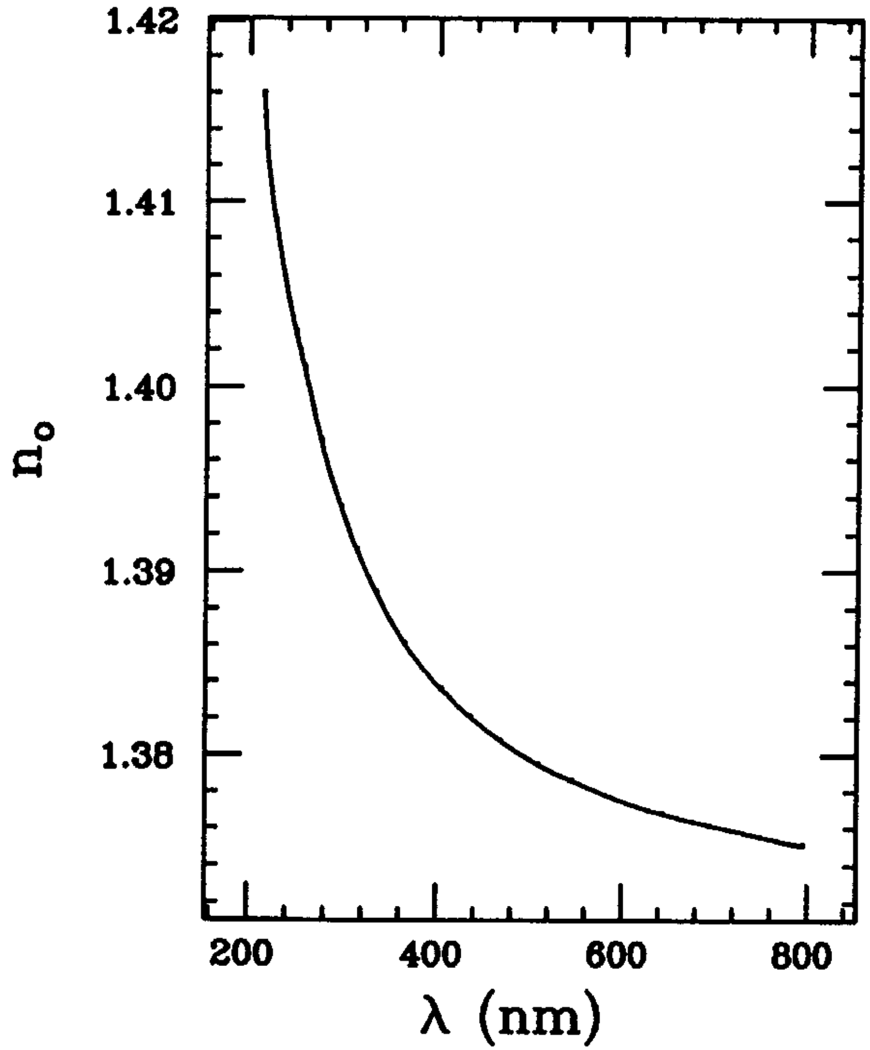

PMT
Drift tubes
U X U V
PMT
Drift tubes
V U X V
PMT
Trig scint 1
MgF2 radiator
Trig scint 2


2.2
7.0
30.0
35.0
50.8
12.7
4.8

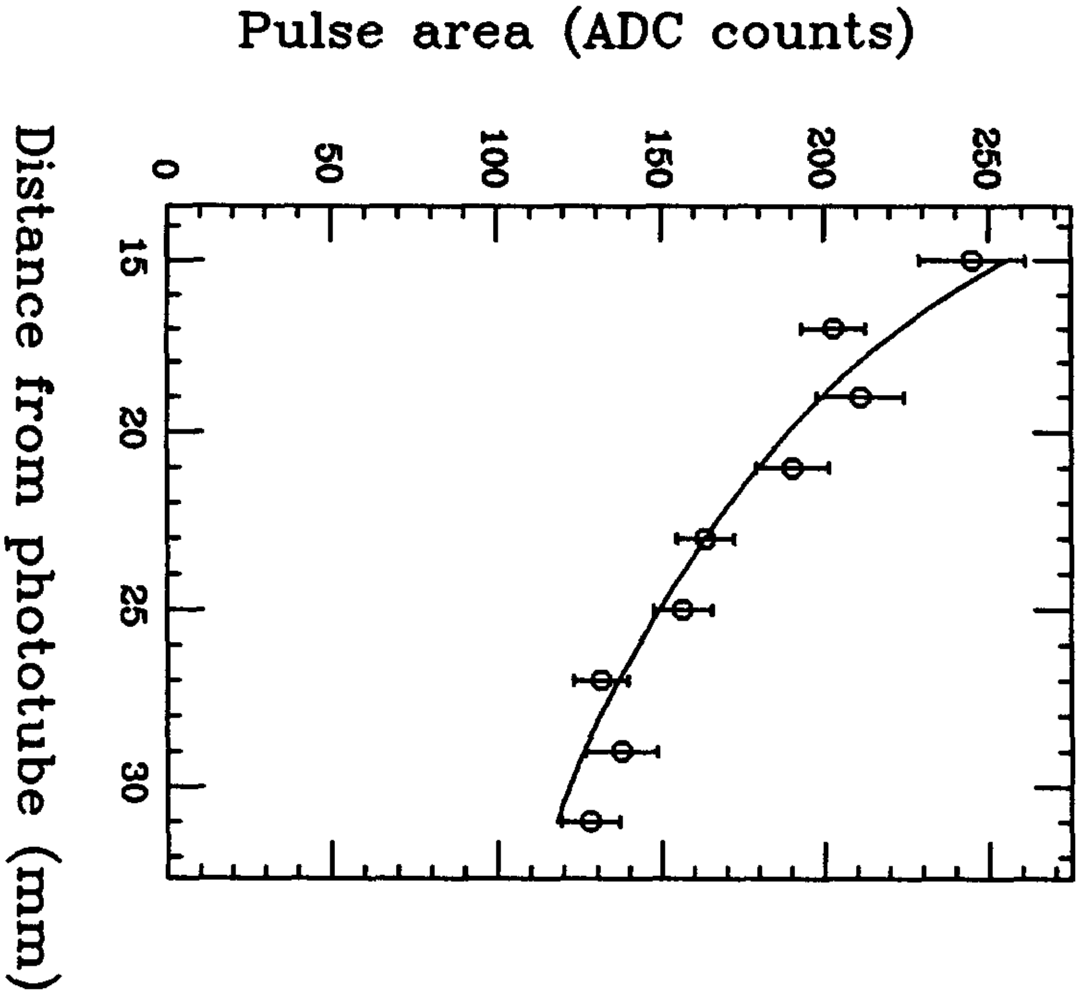


Pulse area (ADC counts)
250
200
150
100
50
0
a)
−0.04
−0.02
0
0.02
0.04
b)
λ (nm): 300
400
500 ··· 800
0.06
0.08
0.1
0.12
0.20
0.15
0.10
0.05
0.00
Δϕ/2π
θy (rad.)


Pulse area (ADC counts)
0
50
100
150
θx (rad.)
−0.03
−0.02
−0.01
0
0.01
0.02



1.42
1.41
1.40
1.39
1.38
n_o
200
400
600
800
λ (nm)



Pulse area (ADC counts)
Distance from phototube (mm)
0
50
100
150
200
250
15
20
25
30