PROPORTIONAL QUANTAMETER FOR THE 15-FOOT BUBBLE CHAMBER

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ABSTRACT

The performance of a proportional quantameter to detect and measure the energy of the neutral pions produced by neutrino interactions in the 15-foot bubble chamber is evaluated. The total energy is determined from the sum of a number of wire outputs, while spatial resolution is obtained by reading out other wire planes individually.

INTRODUCTION

Since the neutrino energy spectrum is broad, measurement of the νp and νd total cross sections requires that the full energy of each interaction be determined. Essentially, there are four components: charged hadrons, charged leptons, neutrons, and neutral pions. The charged component can be found with high precision (±3%) from track curvature in the 15-foot H_2, D_2 bubble chamber, although additional equipment is required to identify leptons, particularly muons, with good efficiency. The neutron component may be small for most interactions and can probably be determined with an external hadrometer to sufficient accuracy that the uncertainty in the total energy is not dominated by this source. The most efficient method for measuring the photon energy from neutral pion decay appears to be the lead-plate quantameter: the purpose of this note is to estimate the resolution and precision of this type of detector, thereby emphasizing the importance of allowing for such a device in the bubble-chamber design.

Typically, half the energy in a neutrino interaction appears in the form of charged leptons. Perhaps one-third of the total hadron energy appears in the form of neutral pions, which therefore account for one-sixth of the total neutrino energy. The fraction is large enough so that neutral pions must be detected with good conversion efficiency in any total cross-section experiment; it is small enough so that even a modest accuracy (±10% of the neutral-pion component) would imply that the dominant error results from track curvature. It may therefore be possible to determine the total neutrino energy to ±3% in the hybrid H_2, D_2 bubble chamber, while an estimate of ±5% has been given in a NAL proposal.[1] Corresponding estimates for the neon bubble chamber range as high as ±20%.[2]

Parallel-plate ionization calorimeters, such as the quantameters[3] widely used in monitoring photon beams, have several intrinsic properties that are essential in determining the neutral-pion energy accurately. First, the response depends only upon the relative ionization in the gas gaps as compared to the ionization in the plates; tolerances of 1% or less in these parameters can be met and insure a uniform response to the same level. Second, since the ratio of gap to plate is independent of track angle in a parallel-plate chamber, such a device is intrinsically isotropic. Third, the output of an ionization calorimeter is linear in the energy absorbed over a wide range. Fourth, an ion chamber is operated as a one-parameter device; there is one high-voltage setting and one output signal proportional to the total energy deposited in the chamber as sampled periodically via the ionization in the gas gaps. This last feature greatly simplifies the operation of the calorimeter and results in a highly reproducible instrument.

In the case of electromagnetic showers, virtually all of the energy appears ultimately in the form of ions, which are sampled directly in the ionization calorimeter thereby avoiding such questions as the response of scintillation or Cerenkov counters using phototubes. The SLAC quantameter,[4] for example, has been shown to be linear in energy to ±0.2% from 1 GeV to 14 GeV, the highest energy at which linearity was tested. The response for incident electrons or positrons[5] was found to be the same to about ±0.3%, and the reproducibility over long periods of time is also on this level. The SLAC quantameter has been calibrated with a Faraday cup so that it can be used as an absolute monitor to a few tenths of one percent. One simply fills the chamber with a standard gas and sets the high voltage.

The precision, linearity, and reproducibility of ionization quantameters under very favorable circumstances are clearly excellent. The performance of a large proportional quantameter in detecting the electromagnetic energy in a single neutrino-induced event from the bubble chamber can be estimated by considering those factors which cause the response to deteriorate, as compared with ordinary quantameters used in beam monitoring. The analysis below indicates that a statistical uncertainty of ±3% (1000 tracks for 10-GeV neutral-pion energy) results from shower sampling every one-half radiation length, while sampling every radiation length would give ±4%. When systematic effects are taken into account, the overall accuracy should be better than ±6% for 10-GeV neutral-pion energy or about ±1% of the total neutrino energy in a 60-GeV event. Unlike the neon bubble chamber, which has a radius of about three radiation lengths, the quantameter improves with energy, the accuracy varying roughly as $1/\sqrt{E_{\pi^0}}$.

SHOWER STATISTICS

The gain of the SLAC quantameter with 1-atm argon-CO_2 filling is about 4000 ions per GeV incident.[4] The copper plates are 0.963 cm = 0.72 radiation lengths thick with an average gas gap of 0.476 cm. An output of about 40 ions/track would result from a single minimum ionizing particle passing through such a gap, indicating that the number of tracks sampled is of order 100/GeV. For a total π^0 energy of 10 GeV, 1000 tracks would be expected, yielding a statistical uncertainty of about ±3%. Monte Carlo calculations for electron-photon showers in lead[6] predict about 600 electrons above 1.5 MeV for a 6-GeV shower sampled at intervals of one-half radiation length. This is equivalent to 1000 electrons at 10 GeV, consistent with the first estimate. (The quantameter plates are somewhat thicker than one-half radiation length, but particles of less than 1.5 MeV are detected.)

SHOWER SAMPLING AFTER TWO RADIATION LENGTHS

A recent 15-foot bubble-chamber design specifies a thin exit wall of one-half inch steel, equivalent to about 0.7 radiation lengths. The front wall of the reentrant tank would be of comparable thickness. Photons originating at the center of the bubble chamber will pass through about 0.3 radiation lengths of liquid hydrogen so that the total thickness before entering the quantameter is about 1.7 radiation lengths. This may be considered as the first plate of the quantameter, which would begin with a thin window followed by a sensitive gas gap. Since photon cascades are displaced in the direction of the shower axis by about one radiation length with respect to electron cascades,[6] photon-shower sampling beginning after two radiation lengths should be excellent.

Quantitatively, only about 0.5% of the total ionization in a photon shower at 6 GeV occurs in the first radiation length, while at 1 GeV the value is the same to 0.2%. Less than 4% of the ionization occurs in the first two radiation lengths, the difference in 1 and 6 GeV being less than 1%. The shower multiplicities versus thickness in lead for these two energies are shown in Fig. 1 to illustrate this point.[6] Since the quantameter will be calibrated, only the linearity is in question: this appears to be of order 1% for photons above 1 GeV, even if sampling begins after two radiation lengths. Clearly, it makes negligible difference if 10 GeV reaches the quantameter as two photons or a dozen. In fact, the thickness after which sampling begins can be varied from zero to two radiation lengths without affecting the quantameter output by more than 4%.

SHOWER PENETRATION

The shower penetration in percent depends on the incident photon energy and could affect the energy linearity if the quantameter is too thin. About 7% of the ionization in a 6-GeV photon shower occurs after 15 radiation lengths, while less than 2%

appears after 20 radiation lengths.[6] In ionization quantameters,[3] the spacing of the last gas gap is usually made large enough to "compensate" for shower penetration, reducing this loss by perhaps one order of magnitude. Compensation is also possible in the proportional quantameter: for example, the gain of the last gap can be increased so that the signal from this gap is proportional to the penetrating ionization rather than simply the ionization of one gap at the particular thickness in radiation lengths. In any case, it is straightforward to design a quantameter for which shower penetration alters the energy linearity by less than 1%. The back-scattered energy from a 6-GeV photon cascade in lead is about 0.12% of the total.[6]

SHOWER DATA

Before considering other systematic effects peculiar to the hybrid application, it is useful to compare the estimates of intrinsic quantameter performance with existing data. An energy resolution of ±19% (hwhm) has been obtained at 200 MeV by counting sparks in a lead-plate chamber with plates 0.15 radiation length thick.[7] Scaling to one radiation length and 10 GeV would give

$$19\% \Big/ \left(\frac{10\ \mathrm{GeV}}{200\ \mathrm{MeV}} \times \frac{0.15\ \mathrm{r.}\ \ell.}{1.0\ \mathrm{r.}\ \ell.} \right)^{\frac{1}{2}} = \pm 7\%,$$

as compared with the statistical limit of ±4%. The scaling is pessimistic for two reasons: (1) tracks observed in a photon shower at intervals of 0.15 radiation lengths are not independent in a statistical sense, and (2) spark counting is less efficient than a direct ionization measurement.

Backenstoss et al.,[8] have measured the resolution of a lead-scintillator shower counter consisting of 20 lead plates each 0.8 radiation lengths thick. Their result at 10 GeV is ±4.9%, which scales to ±5.4% at one radiation length. This value is more applicable to the quantameter configuration than that obtained by scaling track-counting results, but it is still somewhat pessimistic since it involves phototube resolution, light attenuation in plastic scintillator, etc.

Hofstadter and Hughes have studied the resolution in a Pb-NaI array as a function of the thickness of lead.[9] Their results for incident electrons at 8 GeV are shown in Fig. 2. The resolution is observed to vary from ±1% (hwhm) with no lead to ±6% with 0.75 inches, about three radiation lengths, in front of each successive crystal. Since the NaI crystals are 7 inches = 7 radiation lengths thick, the results are not directly applicable to the thin gas gaps of a proportional quantameter. They do, however, illustrate that even very crude sampling of an electromagnetic shower at high energy can yield excellent resolution.

MAGNETIC FIELD

Electrons and positrons from photon conversion in the 0.7-radiation length exit wall of the bubble chamber must pass through a magnetic field of 30 kG before reaching the quantameter. Since the H_2, D_2 container is spherical and the reentrant quantameter tank cylindrical, as presently envisioned, the distance traveled in the magnetic field depends upon where conversion occurs. A reasonable approximation is

$$s = 5 \text{ cm} + 200\,(1 - \cos\theta)\text{ cm},$$

where s is the separation, 5 cm is assumed to be the separation in the median plane, 200 cm is the approximate radius of the bubble chamber, and θ is the angle between the median plane and a line from the center of the bubble chamber to the place on the one-half-inch steel wall where photon conversion occurs. A track with radius equal to the separation will just miss the quantameter. The momentum cutoff for detection is then given by

$$\begin{aligned} p(\text{GeV}/c) &= 0.03\, B(\text{kG})\, \rho(\text{m}) \\ &\approx 0.01\, s\ (\text{cm}). \end{aligned}$$

Values of s and p are plotted versus the height above the median plane of the bubble chamber in Fig. 3 (a).

Assuming the distribution function for the fraction of the total energy given to an electron or positron is constant, energy losses occur in $2\,(p/p_0)$ of the conversions, where p_0 is the incident photon energy. The mean energy carried away when a particle is lost is $(p/p_0)/2$ so that the average for all photon conversions is $(p/p_0)^2$. The average energy loss in percent, computed in this way, is plotted versus the height above the median plane in Fig. 3 (b) for several photon energies. This model, while exceedingly crude, suggests that measurements of the total π^0 energy can be made with accuracy of a few percent or better over most of the quantameter area when the total energy is above a few GeV. The losses in the median plane are small even at quite low photon energies, and this property could be extended to the entire quantameter by matching bubble-chamber and quantameter geometries, either making the back of the bubble chamber cylindrical or making the quantameter locally spherical. Nine modules 1 m square in a 3 m × 3 m array would approximate a spherical surface nicely if a reentrant tank of suitable shape were made to contain them.

INCIDENT CHARGED LEPTONS

Muons penetrating the quantameter would contribute to the total ionization about one track per gap. For 20 radiation lengths and 40 gaps, this amounts to about 40 tracks/1000 tracks = 4% of the signal from a 10-GeV neutral-pion shower. A correction of this magnitude is straightforward once the penetrating muon has been identified, for example, by a hadrometer in the hybrid system.

Electrons or positrons entering the quantameter will be detected with exactly the same response as incident photons. If the electrons arise from conversion of π^o photons in the bubble chamber or steel vacuum tank, the resulting signal should be combined directly with that due to π^o photons, a case already discussed. Electrons from an electron-neutrino ν_e vertex can be identified by associating a shower in the quantameter with a charged track in the bubble chamber: spatial resolution in the quantameter is required. The energy of the identified electron can be determined from track curvature in the bubble chamber and can be subtracted from the total quantameter signal, leaving the neutral pion component intact. Dalitz decays are rare and yield pairs of electrons which can be identified in the quantameter and retained in the neutral pion signal.

NEUTRONS AND INCIDENT CHARGED HADRONS

Corrections of order 4% per hadron can be made to the quantameter signal for charged hadrons that penetrate without interacting. No correction is necessary for neutrons that do not interact. For interacting hadrons, the correction may be comparable with the neutral pion signal, and it can only be made by analyzing each event in detail, taking into account the incident hadron energy, the penetrating hadron energy (determined, for example, by a hadrometer), and the spatial information provided by the wire readout of the proportional quantameter.

A thickness of 15-20 radiation lengths of lead is equivalent to about one collision length for strongly interacting particles. Perhaps a third of the energy in each collision goes into neutral pions[10] which shower and are detected with good efficiency by the quantameter unless the interaction occurs in the last few radiation lengths. Depending upon the event configuration, it may be necessary to determine the neutral pion component from the neutrino vertex by track counting rather than by measuring the total quantameter signal. Since the sum of the π^o and interacting-hadron energies is measured absolutely by the quantameter, only the relative numbers of tracks in various showers is required. An accuracy approaching the statistical limit might still be possible in this case, but the analysis would become more complex. A modular quantameter design would substantially reduce the probability for more than one shower signal to occur in a single readout.

SHOWER POINTING ERROR

Experimental data on the accuracy with which the direction of a photon shower can be determined are shown in Fig. 4.[11] The results suggest that the pointing error improves slowly after 1 GeV, while the variation with plate thickness may be $t^{1/2}$. The result, scaled to a plate thickness of one radiation length, is a pointing error of about ±10° (hwhm). This should be sufficient to associate individual showers detected in the quantameter with particular events seen in the bubble chamber when more than one event occurs during an expansion. It would also exclude photons from interactions in the coils upstream of the bubble chamber in most cases and would permit pairs or single electrons and positrons to be associated with photons converting in the one-half-inch steel wall of the bubble chamber.

PROPORTIONAL READOUT

The primary ionization from a single electromagnetic shower at 10 GeV is not sufficient to produce a practical signal across the high capacitance of a large parallel-plate quantameter. In the proportional chamber[12] several orders of magnitude additional amplification can be obtained through avalanche formation in the high electric field surrounding wires 20-50μ in diameter and spaced 1-3 mm apart. In the proportional quantameter[1] shower formation and avalanche multiplication combine to yield a signal across the full capacity of one gap or of one chamber that is comparable with the single-avalanche signal across the capacity of one wire. Furthermore, since a small number of signals are involved in a total-energy measurement, high quality amplifiers can be used to preserve the output linearity and stability. The performance of a proportional quantameter, as compared with an ionization quantameter, appears, therefore, to be limited mainly by such considerations as the wire uniformity, the characteristics of avalanche formation, and the time distribution and time interval sampled. Each of these effects should be greatly reduced in the statistical average over 1000 tracks. A rough guess is that collection times of several tens of nanoseconds would be sufficient to permit reproducibility, uniformity, and energy linearity approaching the statistical limit (±4% for one radiation-length plates at 10 GeV).

DISCUSSION

It appears that a lead-plate proportional quantameter of 15-20 radiation lengths thickness and a similar number of gaps could be used to determine the neutral-pion energy from individual neutrino interactions in the 15-foot bubble chamber with an accuracy well under ±10%. Certain classes of events, particularly those in which hadrons interact in the quantameter, would require detailed analysis, including shower-track counting, before this level could be reached. Since on the average, only one-sixth of the energy in a neutrino interaction is expected to go into neutral pions, an uncertainty as large as ±10% in this component would contribute a smaller error to the measurement of total neutrino energy than results from track curvature in the H_2, D_2 bubble chamber, ±3%. In this sense, it seems clear that a lead-plate proportional quantameter would be highly useful, even if its resolution is several times worse than presently seems feasible.

REFERENCES

[1] M. L. Stevenson et al., Proposal for a High-Energy Neutrino Experiment in the NAL 30 m^3 H_2, D_2 Bubble Chamber, National Accelerator Laboratory Proposal 9, 1970.

[2] C. Baltay, R. B. Palmer, and N. P. Samios, Search for the Intermediate Boson, Lepton Pair Production, and a Study of Deeply Inelastic Reactions Utilizing High Energy Neutrino Interactions in Liquid Neon, National Accelerator Laboratory Proposal 53, 1970.

[3] R. R. Wilson, Nucl. Instr. 1, 101 (1957).

[4] D. Yount, Nucl. Instr. and Methods 52, 1 (1967).

[5] D. Yount, Symposium on Beam Intensity Measurement, V. W. Hatton, Editor (Daresbury, England, April 22-26, 1968, pp. 75-96) (See DNPL/R-1).

[6] H. Nagel, Zeitschrift fur Physik, 186, 319 (1965); U. Völkel, DESY Report 65/6, July, 1965.

[7] R. Cence, private communication, July, 1970.

[8] G. Backenstoss, B. D. Hyams, G. Knop, and U. Stierlin, Nucl. Instr. and Methods 21, 155 (1963).

[9] E. B. Hughes, Observations on the Total Absorption of Electrons and Pions in Matter at GeV Energies, Stanford University Report HEPL 603, June, 1969.

[10] V. S. Murzin, Progress in Elementary Particle and Cosmic Ray Physics (North-Holland Publishing Company, Amsterdam, The Netherlands, 1967), Vol. IX, p. 245.

[11] V. Peterson, private communication, July, 1970.

[12] G. Charpak, D. Rahm, and H. Steiner, Nucl. Instr. and Methods 80, 13 (1970).

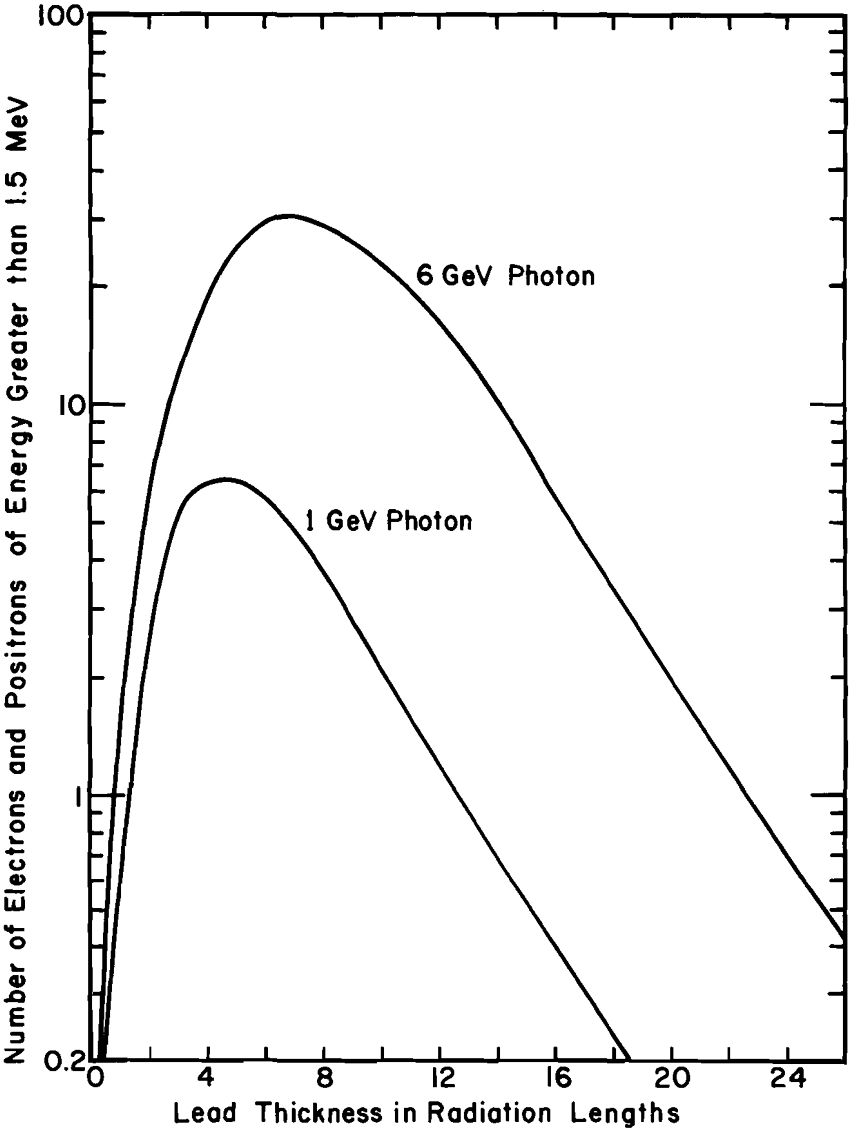

Fig. 1. Electromagnetic showers.

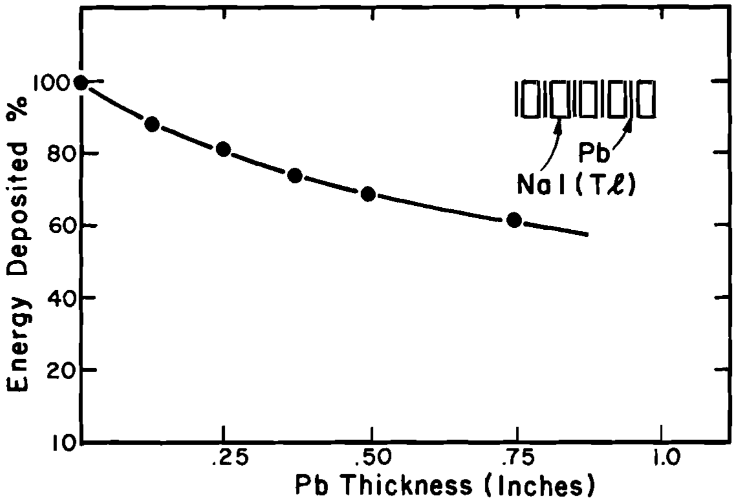

Fig. 2(a). Energy deposited in NaI (Tℓ) vs Pb thickness.

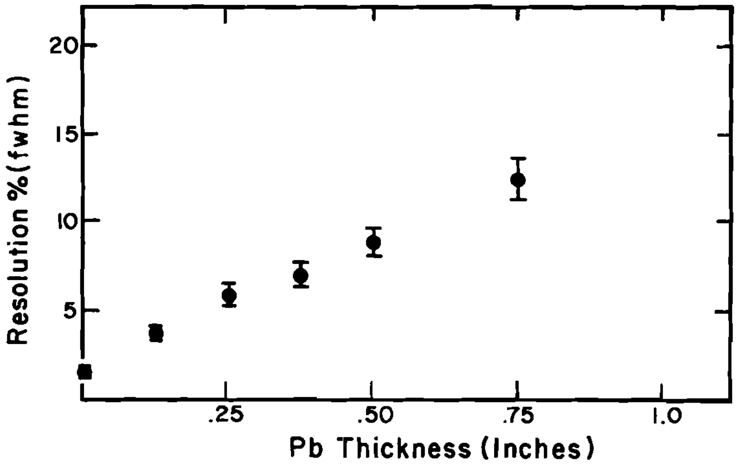

Fig. 2(b). Electron resolution vs Pb thickness.

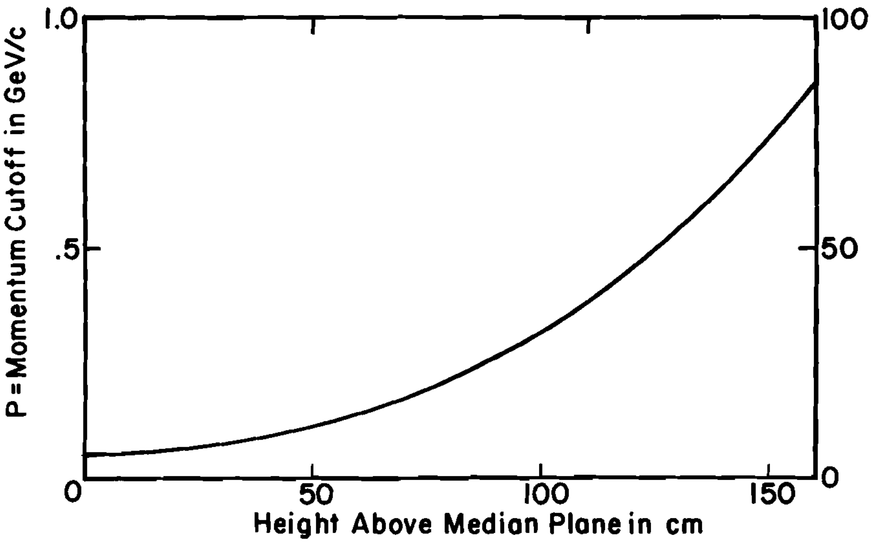

Fig. 3(a). Cutoff momentum vs height above the median plane.

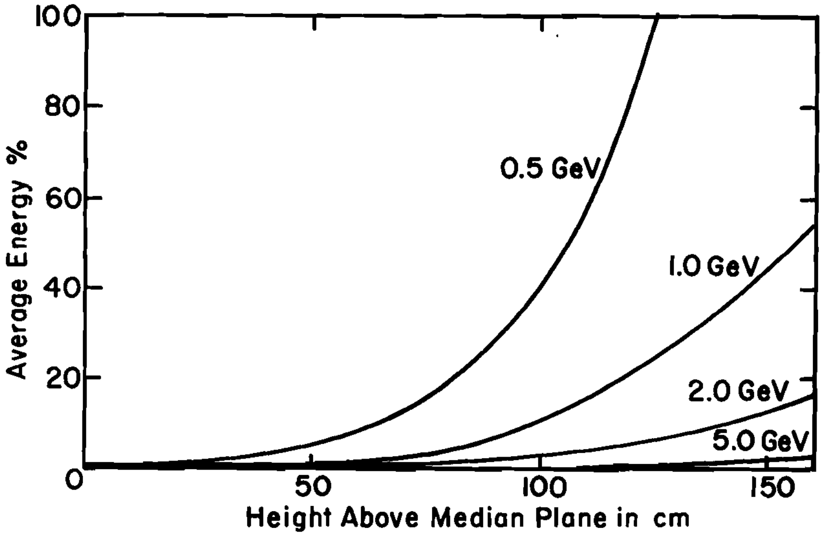

Fig. 3(b). Average energy loss vs height above the median plane.

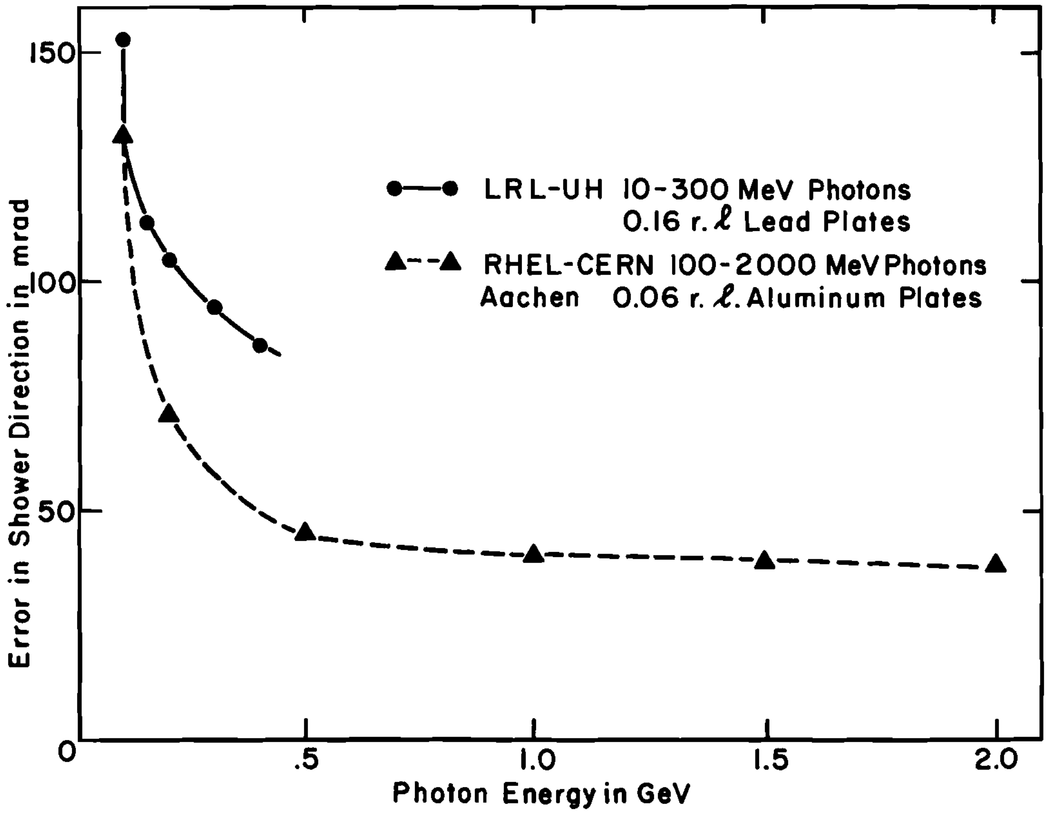

Fig. 4. Shower pointing error.