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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Test of a Forward Neutron Calorimeter for the ZEUS experiment at HERA

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Abstract

A Forward Neutron Calorimeter (FNC) for ZEUS is being constructed to detect high energy neutrons produced in the proton direction in ep collisions at HERA. To investigate the feasibility of such studies, a small iron–scintillator sandwich calorimeter was placed on the zero degree line 102 m downstream of the main ZEUS detector. The calorimeter was calibrated by studying proton beam–gas interactions during the HERA acceleration cycle. The design and construction of the calorimeter are described and the results of the test studies presented.

1. Introduction

It has recently been argued that the detection of nucleon charge exchange reactions in ep collisions at HERA will open new opportunities in the study of hadron structure [1,2]. In particular, virtual electron–pion and photon–pion scattering can be investigated by detecting neutrons produced with low momentum transfers. These neutrons have high energies ($\geq$ 300 GeV) and very small scattering angles ($\leq$ 1 mrad). A measurement of the energy and production angle of the neutron, together with complementary measurements of the scattered electron and other produced hadrons will completely determine the event kinematics.

To study the feasibility of this experiment, a small test calorimeter was constructed and installed near ZEUS [3] in the HERA tunnel at DESY. The calorimeter was tested by studying neutrons produced by interactions of the proton beam with residual gas molecules inside the vacuum pipe. Using the HERA acceleration cycle the energy spectra of the produced neutrons were measured at different proton beam energies. The calorimeter was calibrated by studying how the neutron spectrum changed with beam energy. In this paper we describe those aspects of HERA relevant to the design, construction and installation of the calorimeter. We describe the calorimeter and the experimental setup and present results from the test and calibration studies.

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2. The proton beam line at HERA

At HERA there are two separate accelerators in the same tunnel. The electron machine lies in a plane and the proton machine is installed above it. At four interaction regions the proton beam is brought down to the level of the electron beam and ep collisions occur at zero crossing angle. After leaving the interaction region the proton beam is steered to its nominal orbit. Between 36 and 49 m downstream of the collision point it is moved horizontally to an orbit 15.79 mm away from the neutral line, the straight extension from the collision region of the beam line. Then it is bent upwards through an angle of 5.7 mrad by three dipoles located between 65 and 80 m. The ZEUS experiment uses these dipoles as a momentum analyzer for its Leading Proton Spectrometer (LPS) [4]. Small angle neutrons which are not obscured by the beam line elements exit the vacuum pipe downstream of the dipoles between 85 and 100 m from the interaction point. From 80 to 120 m, where the cold section containing the superconducting magnets of the proton beam begins, there are no proton beam elements; however, Stations 5 and 6 of the LPS (silicon strip detectors near the proton beam) are located at 81 and 90 m, respectively. In addition, every few meters a vacuum pump is mounted beneath the proton beam pipe.

In order that the separation of the proton beam and the scattered neutrons be as large as possible the calorimeter had to be installed as far downstream as possible. Beyond 100 m the beam pipe has a diameter of only 73 mm; however, it is surrounded by insulation which increases its

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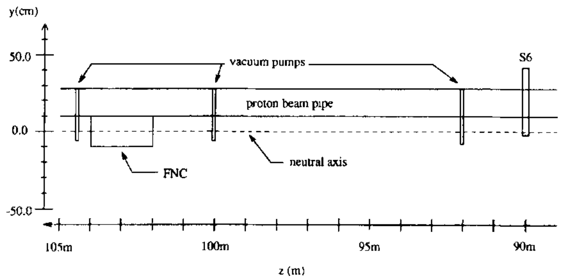

Fig. 1. An elevation view schematic of the HERA proton beam line in the vicinity of 100 m from the ZEUS IP. The dashed line shows the trajectory of the neutrons along the neutral axis. Station 6 of the Leading Proton Spectrometer is shown at 90 m.

effective diameter to approximately 160 mm. At this location the electron beam rf cavities encroach to within 600 mm of the center of the proton beam. Also, the neutral line is just 170 mm below the center of the proton beam pipe. Because of the presence of the beam pipe and the electron rf cavities, the test calorimeter is severely limited in transverse size. In the longitudinal direction, vacuum pumps limit the length of the calorimeter to 3 m.

Within these constraints a calorimeter was positioned at 102 m, centered on the neutral line as shown in Fig. 1. Due to the beam pipe wall, vacuum pumps, and the mechanics of the last LPS station a considerable amount of material ($\sim$ 1–2 interaction lengths) is present in front of the calorimeter.

The angular acceptance for produced neutrons is determined by the apertures of the proton beamline elements. To reach the calorimeter, forward neutrons must remain within the beam pipe until they pass the last vertical bending magnet before the cold section. To study the angular acceptance, a Monte Carlo program was written which tracked neutrons produced at the interaction point with random horizontal and vertical dips through the HERA proton beamline apertures. Fig. 2 shows a scatter plot of the projected angles of neutrons that reach the calorimeter. In the figure Θ_H is the direction away from the center of the tunnel, and Θ_V is up. At the calorimeter the neutron spot is about 35 mm in radius, and is centered at approximately (25, 25) mm, due to the aperture limitations caused by the horizontal jog of the proton beam followed by its vertical bend. Although the angular acceptance is small, the distribution of the neutrons peaks strongly at very small angles and the flux is expected to be large.

3. Design and construction of the calorimeter

The Forward Neutron Calorimeter (FNC) should be capable of measuring neutrons with energies up to the HERA proton beam energy of 820 GeV. Since the incident energies are so large, a crude sampling calorimeter can, in principle, give a good energy measurement. We expect that the resolution function for the energy is given by a sum in quadrature,

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus b, \tag{1}$$

consisting of a sampling term with constant a and a constant term b. Then even if a is as large as 200%, sampling fluctuations will contribute no more than 10% to the resolution for energies above 400 GeV. Therefore good energy resolution can be obtained provided b is small.

It is important that the calorimeter be of sufficient length to contain the shower longitudinally. This ensures a linear response of the calorimeter and helps keep the magnitude of b under control. Transverse containment is less important, but leakage out the sides will degrade a. At high energies another important contribution to b comes from fluctuations of hadronic energy in the shower into electromagnetic energy through neutral pion production. As a result, the response of the calorimeter to electrons and photons should be as close as possible to its response to hadrons, a property referred to as compensation. These design considerations were coupled to the need that the calorimeter be inexpensive, be completed quickly to meet installation deadlines, and be assembled in situ in the HERA tunnel.

Calorimeter tests have shown that a sampling cell of 100 mm iron and 5 mm scintillator can provide a resolution of $120\%/\sqrt{E}$ [5]. Additional studies [6] have shown that this calorimeter compensates. Our calorimeter was constructed of 15 sampling layers, each consisting of 100 mm of iron followed by two layers of 2.6 mm thick scintillator tiles, giving a sampling fraction of 0.8%. The transverse size was 200×200 mm^2, which, though limited, was well matched to the beam line configuration. The

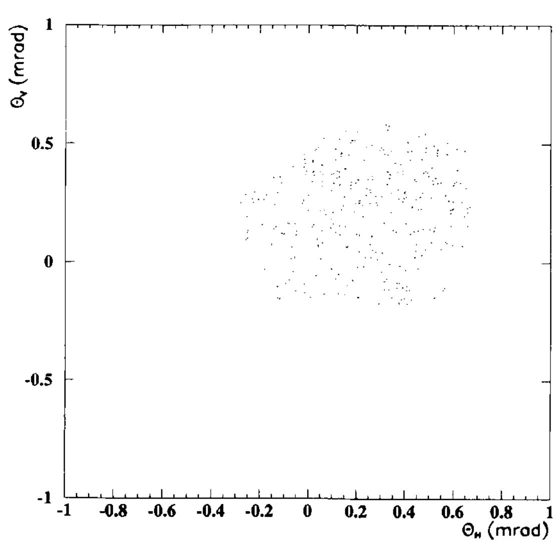

Fig. 2. The angular acceptance of a zero degree neutron calorimeter as determined by the apertures of the proton beamline elements.

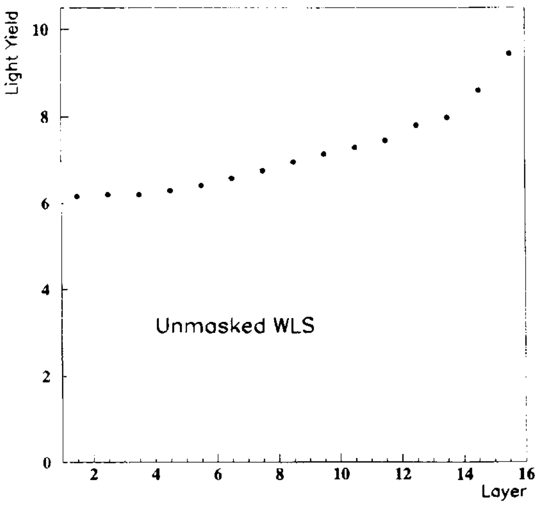

Fig. 3. The light collected by unmasked WLS as a function of layer. The layer separation is 108 mm.

total depth, about 9 interaction lengths, is sufficient to contain 95% of an 800 GeV shower [7]; so we expect its energy response to be linear. The energy resolution is degraded in comparison to $120\%/\sqrt{E}$ since the transverse size is only about 1.5 interaction lengths.

The readout of the scintillator light was accomplished with wavelength shifter light-guides (WLS) mounted on the right and left sides of the calorimeter. They consist of flat 2 mm thick plates of doped (Kuraray Y7, 30 ppm) acrylic, which absorbs the blue scintillation light and converts it to green. At one end, the plastic was slit and formed into an adiabatic light guide. The WLS light guides are connected to Hamamatsu R580-12 photomultipliers powered by resistive bases. An optical fiber was laid from the ZEUS main calorimeter laser station to the position of the neutron calorimeter in the tunnel, where an optical fanout distributed the light to each PMT. The pulses from the laser light were used for timing studies.

In order to ensure uniformity of light collection, masks were provided both for the scintillator and the WLS. Each double layer of scintillator was wrapped in Tyvek, a highly reflective white paper, printed with a black pattern designed to reduce attenuation length effects in the scintillator. The attenuation length of the WLS was measured (Fig. 3) and it was found that there was a 40% difference in light transmission from front to back. For each scintillator layer, a transmission mask was produced. Clear plastic overhead transparencies were printed with black dots of radius 0.6 mm randomly placed to reduce the amount of light reaching the WLS. Completely clear plastic transmitted about 86% of the scintillator light and the fraction could be reduced from this value by increasing the density of black dots. These masks were then inserted between the WLS and the edge of each scintillator.

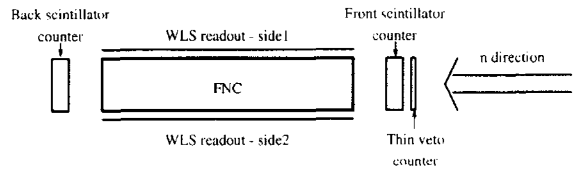

Fig. 4. The setup of the forward neutron calorimeter (FNC) and trigger counters in the HERA tunnel at $z = 102$ m. The interaction point is at $z = 0$.

The FNC rested on an aluminum table. Scintillation trigger counters were also installed in front and back as shown in Fig. 4. A 16th iron block was placed after the last calorimeter layer to act as an absorber for the rear counter.

3.1. Monte Carlo studies of the FNC

The expected response of the FNC to high energy neutrons was studied using the GEANT package [8]. Iron–scintillator calorimeters have been the subject of extensive beam studies at CERN and at Fermilab, and Monte Carlo calculations show fair agreement with experimental results (see, e.g. [5]).

The simulated response for our calorimeter is shown in Fig. 5. Despite the large transverse leakage, the response is predicted be to quite linear, but the energy resolution of the calorimeter is expected to be substantially degraded. The simulated energy resolution can be parameterized as

$$\left(\frac{\delta E}{E}\right)_{\mathrm{MC}} = \frac{173\%}{\sqrt{E}} \oplus 6\%. \qquad (2)$$

These studies also indicate that our 200×200 mm^2 calorimeter sees only 80% of the energy seen by a corresponding 500×500 mm^2 sized calorimeter. (This agrees with SPACAL [9] transverse profile measurements, al-

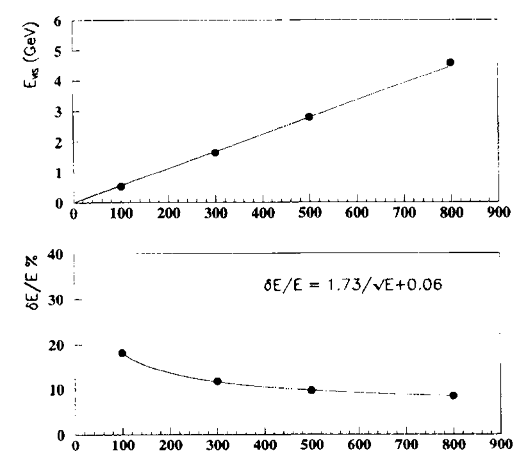

Fig. 5. The response and resolution of the neutron calorimeter as a function of energy, as given by a GEANT simulation.

though for lead, not iron.) In addition, the ratio of the response for electrons to the response for neutrons (e/h), averaged over energies, is degraded to 1.3 from the value $e/h \approx 1$ that would be expected for a calorimeter of this granularity, but having no lateral leakage.

4. ^{60}Co source scans

For quality control, and as a calibration study, the calorimeter was scanned with a 2 mCi source (^{60}Co) using the techniques and setup developed for the ZEUS main calorimeter [10]. With the high voltages of the calorimeter PMTs set at their nominal value of 1300 V to give the required gain (this could be calculated using the results from the ZEUS main calorimeter [11] which uses the same optical components and PMTs), the calorimeter was scanned with the source along the middle of the right and left sides. The source tube travelled in a brass guide tube fastened outside the WLS.

Fig. 6 shows the response of the right PMT during the scan of the right side of the calorimeter. Layer 15 is located at about 25 mm and layer 1 at 1550 mm. The inset zooms in on the region of layer 15 (a typical layer). A clear 'flat top' of 8 mm width, the spacing between iron blocks, is visible. The average value of the flat top was taken as a measure of the calorimeter response at each layer.

The scan shows that transmission filters did not completely remove the effect of the attenuation of the WLS, although it was significantly reduced. The ratio of the average responses on each side as a function of layer shows no evidence for a layer dependent relative gain (Fig. 7) and is flat to within an rms deviation of 4%. From this

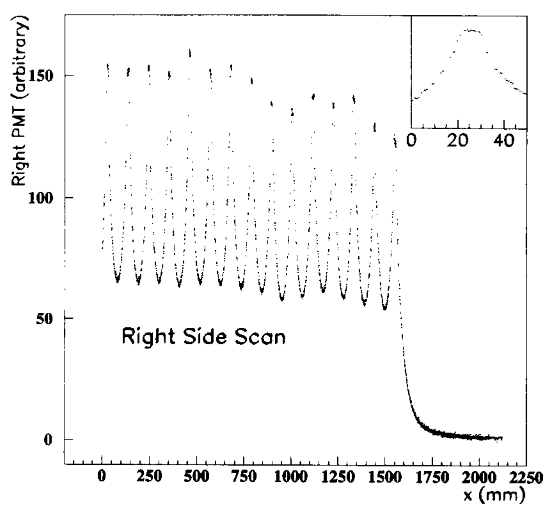

Fig. 6. The response of the right PMT to a ^{60}Co scan down the middle of the right side. The inset shows the region near layer 15. Note that x increases away from the PMT end.

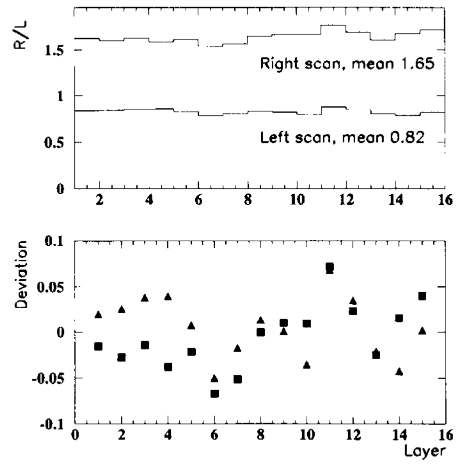

Fig. 7. The ratio of the response of the right and the left PMT by layer for ^{60}Co scans along the middle of the WLS. Also shown are the deviations from the mean for right (■) and left (▲) scans.

data the response, g, of the right PMT relative to the left PMT can be estimated from the relation

$$g^2 = \left\langle \frac{R}{L} \right\rangle_{\text{Right}} \left\langle \frac{R}{L} \right\rangle_{\text{Left}} \tag{3}$$

where $R(L)$ is the response of the right (left) phototube. The subscript denotes the source side. This method gives 1.16 for g; the simple ratio $R_{\text{right}}/L_{\text{left}}$ gives 1.17.

The source data can also be used to determine the scintillator's effective attenuation length, λ_S, since the the transmission, T, is given by

$$T^2 = e^{-2D/\lambda_S} = \langle L/R \rangle_{\text{Right}} \langle R/L \rangle_{\text{Left}}, \tag{4}$$

where D is the horizontal length of the scintillator tiles. From this we find an average attenuation length of 520 mm. It should be noted, though, that for the ZEUS uranium calorimeter the effective attenuation length determined in this manner is only about 60% that determined by electron scans. From λ_S we can estimate the horizontal offset, Δx, of the impact point of a neutron from the center of the calorimeter by

$$\Delta x = \frac{\lambda_S}{2} \ln(R/L) \approx \lambda_S \frac{(R-L)}{(R+L)}. \tag{5}$$

where, in this last equation, R and L are corrected for the relative gain of the PMTs.

5. Operation and calibration of the calorimeter

Starting in April 1993 the FNC was operated as a stand-alone device, independent of the ZEUS trigger and readout. Data were recorded on the occurrence of coincidences in the front and rear counters or on a large energy deposit in the calorimeter. The data consisted of the charge collected from each of the five photomultiplier tubes, digitized by a LeCroy 2249W eleven bit ADC. In addition the beam energy and current were recorded from a data base which was updated by HERA every 30 seconds. From August 1993 the readout was integrated into the full ZEUS data acquisition system through the main calorimeter electronics [11].

5.1. Counting rates during HERA operation

During the running period with the ZEUS detector, the FNC trigger rate was recorded in the data stream. A trigger occurred on a coincidence of the two FNC calorimeter channels with an energy threshold of 100 GeV. The rate depended strongly on the beam conditions. Under good beam conditions it lay between 50 and 250 Hz; however, values as high as 1 MHz were also recorded. Reasons for these high rates include adjustments of the position of the LPS silicon strip detectors in front of the FNC, misalignment of the proton beam orbit, and special HERA tests, such as the insertion of a wire target into the proton beam. The proton beam current averaged 11.4 mA over the running period. The protons occupied 90 bunches out of the 220 HERA rf buckets, which are separated by 96 ns. Taking this into account, the FNC occupancy was 3.5×10^{-5} at the trigger rate of 150 Hz. Thus at full luminosity of 160 mA of protons in 210 bunches the occupancy expected is 2.1×10^{-4}.

5.2. Calibration using beam–gas interactions

For complete calibration and understanding, the calorimeter should be placed in a test beam with energies up to 800 GeV. This being unavailable, the possibility of calibrating the FNC in situ, using beam–gas interactions and beam halo muons is extremely important. The study of beam–gas interactions has the additional benefit of allowing changes or drifts in calibration to be monitored continually, even during data taking.

Protons are injected into the HERA ring with an energy of 40 GeV. When injection is complete the beam energy is increased slowly to 820 GeV in several stages. At 70 GeV the beam optics are changed from injection to luminosity. The beam optics are also readjusted at 300, 482, and 677 GeV. At each of these energies between 40 and 820 GeV there is a slight pause in the beam acceleration while new machine parameters are set up. This injection and acceleration cycle makes possible the study of the response of the calorimeter to neutrons produced in beam–gas interactions of known incident energy.

Data were taken during proton acceleration ramps. In order to eliminate neutrons which interacted upstream of the FNC, events were selected by requiring a signal consistent with pedestal in the counters in front of the calorimeter.

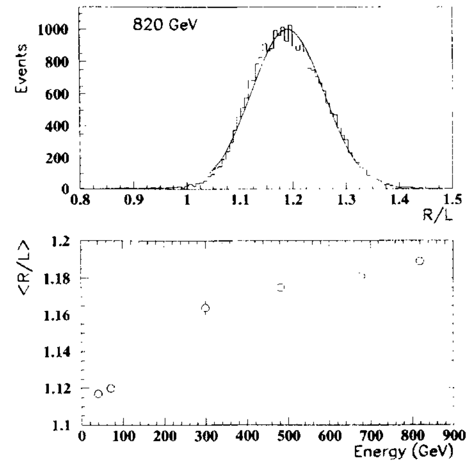

Fig. 8. The distribution of the ratio of the right to left calorimeter channels after pedestal subtraction for 820 GeV data. Also shown is the variation of the mean of the ratio as a function of proton beam energy.

Since the entry point of the neutrons is approximately centered on the face of the calorimeter, the relative gain of the two calorimeter channels can be determined by taking the mean of their ratio. The distribution of the ratio of the right channel to the left channel (R/L) after pedestal subtraction is shown in Fig. 8 for 820 GeV data. The distribution is approximately Gaussian with a mean value of 1.19. The positional spread of impact point of the neutrons on the face of the calorimeter gives the dominant contribution to the width. As shown in the same figure, during a ramp of the proton beam the R/L ratio varies. This variation is consistent with the (10–20) mm horizontal shift of the proton beam expected in the change from injection to luminosity optics. Other explanations, such as calorimeter inhomogeneities and saturation of the left PMT can be ruled out: inhomogeneities by ^{60}Co scans, saturation by the linearity of the energy response (see below).

Once the relative gain of the right and left readout channels is known, the neutron spectra are obtained by accepting only those events in which the neutron shower is centered in the calorimeter, $(R-L)/(R+L) < 0.1$ after pedestal subtraction and correction for relative gain. The spectra are shown in Fig. 9. Noteworthy is the marked change in shape between the low and high energy data. The high energy data (≥ 300 GeV) show a broad, but clear peak near the kinematic end point. This peak is expected from Triple Regge Theory [12,13], which also predicts its energy. The high energy spectra are also in good qualitative agreement with ISR data [14]. At 820 GeV the end point occurs at approximately channel 3200 corresponding to 800 pC of charge implying 1 pC/GeV. This is close to our expectation since the ZEUS main calorimeter with similar photomultiplier tube gain receives about 10 pC/GeV with a sampling fraction 10 times larger than FNC.

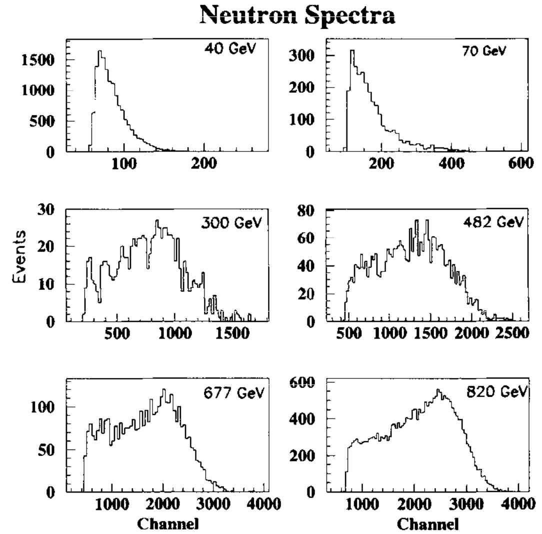

Fig. 9. The neutron spectra for each energy stage of a proton ramp. Shown is the sum $(R+L)$ after pedestal subtraction and correction for relative gain R/L. Only those events which satisfy the containment condition $(R-L)/(R+L)<0.1$ are plotted.

We have used two methods of determining the absolute energy scale: either through a measurement of the kinematic end point, or by measuring the peak position. The first method depends on no inherent physics other than energy momentum conservation, but the determination of the end points is difficult and subjective. On the other hand, the measurement of the peak position is much easier, but the resulting energy scale depends on the theoretical value of the peak position.

The kinematic end points were determined visually by plotting the neutron spectra on logarithmic scales. Fig. 10 shows the variation of the end point with beam energy. The response of the calorimeter is linear to within errors, so the absolute energy scale can be determined by fitting the response to a straight line. This procedure yields an energy scale of 4.7 channels/GeV. Because of the subjectivity of the method it is difficult to estimate errors. In addition, the method is likely to lead to biased estimates of the end point, since high fluctuations in measured energy can easily lead to an overestimate of the end point.

A less subjective determination of the energy scale uses a measurement of the peak position. The neutron spectra in the region of the peak are first fit to a polynomial. The position of the maximum is then calculated from the fit parameters. The dependence of the peak position with beam energy is shown in Fig. 10. The observed linear behavior of the data is consistent both with a linear response of the calorimeter and with the scaling with beam energy of the neutron energy spectrum (that is, the spectrum is only a function of $E_{\mathrm{neutron}}/E_{\mathrm{beam}}$).

The expected neutron energy distribution is determined by a Monte Carlo calculation [1] in which it is assumed that the inclusive neutron cross section is given by the product of the pion–nucleon total cross section and a factor representing the flux of virtual pions in the proton. The parametrization of Donnachie and Landshoff [15] was used for $\sigma_{\pi p}$. The distribution observed in the neutron calorimeter is insensitive to the composition of the residual gas in the vacuum pipe since the variation of $\sigma_{\pi p}/\sigma_{\pi n}$ with energy is slight; however, there is a dependence on the variation of the gas pressure along the beam line since the geometrical acceptance of the calorimeter depends markedly on the distance between the interaction and the calorimeter. Since the gas pressure is highest in the interaction region, we assumed that beam–gas interactions came

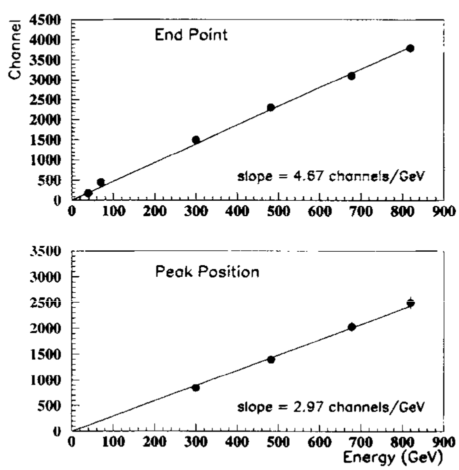

Fig. 10. The variation of the kinematic end point and the peak position of the neutron spectra as a function of the proton energy.

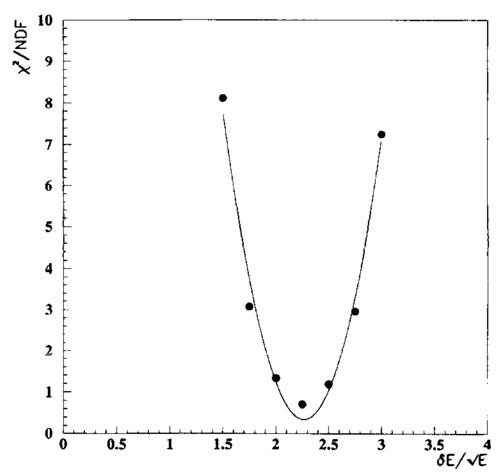

Fig. 11. The variation of the reduced χ^2 for a comparison of the expected to observed neutron distribution at 820 GeV as a function of $\delta E/\sqrt{E}$. Superimposed is the result of a quadratic fit. The minimum is at $\delta E/\sqrt{E}=230\%$.

predominantly from the region $-30 < z < 30$ m centered on the interaction point, and that the gas pressure was uniform throughout. The predicted peak position is then determined in exactly the same manner as the peak position of the data. This procedure gives 1.31 as the ratio of the kinematic end point to the peak position. From this value and the fitted slope from Fig. 10 we obtain an energy scale of 3.9 channels/GeV. By assuming linearity and using just the 820 GeV data we find 4.0 channels/GeV. The statistical errors resulting from the fitting procedure are small, less than 1%; however, the energy scale depends on knowing the absolute position of the peak. This introduces a systematic error which arises from uncertainties in our a priori knowledge of the neutron spectrum and which, as a result, is difficult to estimate. A conservative estimate takes the discrepancy between the two methods, but that ignores the excellent agreement between theory and experiment found at Fermilab and CERN [1].

A comparison of the observed neutron spectrum at 820 GeV and the predicted spectrum can also be used to determine the energy resolution of the calorimeter. We fix the constant term b in Eq. (1) to zero. The expected distribution is smeared for an assumed value of a. After normalizing the two distributions, observed and expected, to the same height at the peak position, a χ^2 is calculated for $E > E_{peak}$. Fig. 11 shows a plot of the reduced χ^2 as a function of a. The minimum value occurs for $a = 230\%$. If we set $b = 6\%$, we find 192% for the sampling term. All resolution functions give an excellent fit to the data, the Monte Carlo result being marginally best. Fig. 12 shows the observed neutron spectrum at 820 GeV compared to the Monte Carlo prediction.

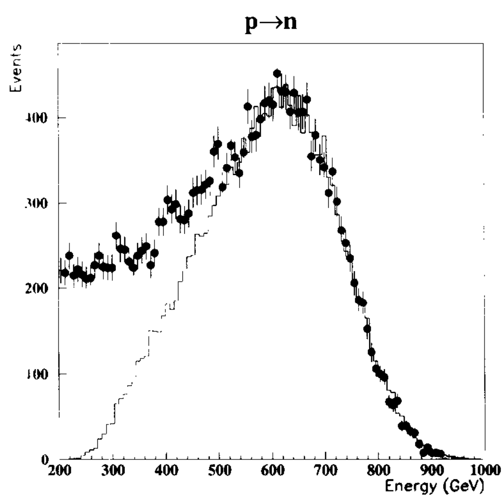

Fig. 12. The observed neutron spectrum at 820 GeV. Superimposed is the expected neutron spectrum obtained under the following assumptions: (i) the transition p → n is given by Triple Regge theory [1], (ii) $\sigma_{\pi p}$ is parameterized by [15], (iii) beam–gas interactions occur uniformly between −30 and 30 m, and (iv) the energy resolution of the calorimeter is given by Eq. (2).

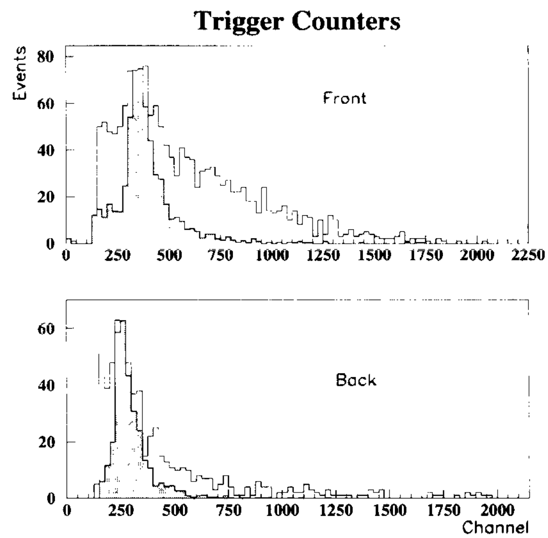

Fig. 13. The pulse height distributions in the front and back counters for the beam halo muon trigger after cuts. The dark spectra superimposed are those for cosmic ray muons after normalization to the spectra of the beam halo muons.

5.3. Beam halo muons

Beam halo muons were identified using the front and rear scintillation counters. The counters were tested with cosmic rays before installation in order to set the gain of the photomultiplier tubes and to determine the position of the muon peak.

The beam halo muon trigger consisted of a coincidence between the front and rear counters, with thresholds set below the minimum ionizing levels. Data were taken with an 820 GeV proton beam. Fig. 13 shows the pulse height distribution for each trigger counter after using all other channels to select muons. Both show a peak at the expected position for muons. Before any cuts, the peak for the front counter sits on a large, slowly varying, background distribution. Since the energy deposited in the calorimeter is very small, the background is consistent with accompanying soft particles whose energy is mainly absorbed in the first absorber layer.

Fig. 14 shows the distribution of pulse heights in the calorimeter after cuts on the muon peaks in the counters. They have been fit to Landau functions which are shown superimposed in the figure. The ratio of peak positions gives 1.14 for the relative gain of the two calorimeter channels consistent with the source scan. The muon peak at 8 channels corresponds to an apparent energy of 2 GeV. For a muon passing through 15 layers of 5 mm of scintillator we expect a signal corresponding to 1.9 GeV for this

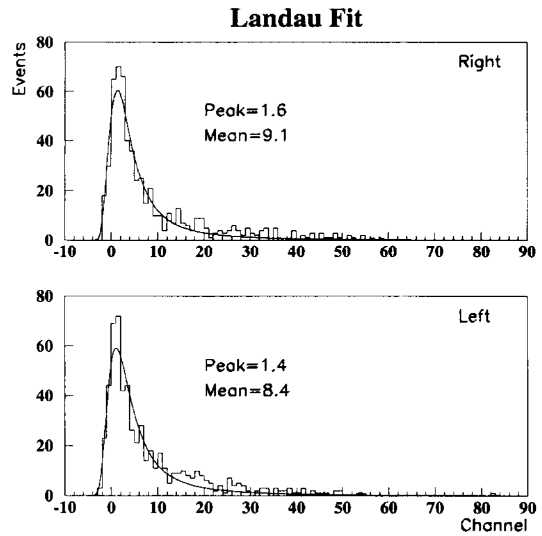

Fig. 14. The calorimeter pulse height distribution for beam halo muons after pedestal subtraction. Superimposed is a fit of the Landau distribution to the data.

calorimeter since its sampling fraction for minimum ionizing particles is just 0.8%.

6. Summary

A Forward Neutron Calorimeter will allow ZEUS to access a large amount of interesting physics, for example, the measurement of the pion's deep inelastic structure function. With the tests reported here it has been shown that the installation of a calorimeter in the HERA tunnel is feasible and that beam–gas interactions will provide an important calibration and monitoring tool. We are now preparing a full sized lead–scintillator calorimeter which will be installed in the ZEUS experiment in the HERA winter shutdown of 1994–1995 [2]. In addition, we are planning to make measurements at CERN which will improve our knowledge of the leading neutron spectrum in proton–nucleon collisions. These will help us understand the systematic errors which result from using beam–gas interactions at HERA to determine the absolute energy scale of the FNC.

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