**THE TRANSVERSE ENERGY DISTRIBUTION
IN HADRON-LEAD COLLISIONS**

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ABSTRACT

The transverse energy cross-section $d\sigma/dE_T$ has been measured in the pseudorapidity region $0.6 < \eta < 2.4$ for hadron-lead collisions at 200 GeV/c incident hadron momentum. The E_T distribution extends to 40 GeV, which is twice the kinematic limit for p-p collisions at the same incident beam momentum. The distribution of E_T is found to shift towards low pseudorapidities with increasing total transverse energy.

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1. INTRODUCTION

A previous experiment [1] has reported a large increase in the cross-section for large transverse energy E_T when increasing the mass of the target nucleus. This enhancement was observed in the region of the projectile fragmentation, with a rather limited integrated luminosity. In this paper we present a measurement of the E_T distribution in the target fragmentation region, where, after all, the difference between p-p collisions should be most pronounced. Such a measurement is, of course, closely related to the question of nuclear stopping, an important issue for estimating the beam energy that is necessary to obtain a given energy density in heavy-ion collisions [2].

2. EXPERIMENTAL SET-UP

The experiment (fig. 1) was placed in the H8 beam of the CERN Super Proton Synchrotron (SPS). It was a purely calorimetric detector split into two logical parts: a 'wall' covering the pseudorapidity range 0.6–2.4 in the laboratory frame, and a beam calorimeter measuring the energy in the forward direction. The E_T distribution was measured in the wall only, and the beam calorimeter was used to monitor the total energy of the events. The basic element of both parts was a uranium/copper/scintillator module (stack) [3] previously used by the Axial Field Spectrometer (AFS) at the CERN Intersecting Storage Rings (ISR). The stack is four absorption lengths deep and is segmented into 20×20 cm² towers. Each tower is longitudinally segmented into two parts: a six radiation lengths front part (electromagnetic section = $6X_0$) and a 3.8 absorption lengths back part (hadronic section = 3.8λ). At the time of this measurement the calorimeter had an energy resolution of $\sigma/\sqrt{E} = 0.25$ for electromagnetic showers and $\sigma/\sqrt{E} = 0.50$ for hadronic showers [3, 4]. The front face of the calorimeter wall with the tower granularity indicated is shown in fig. 2, together with the contours of constant pseudorapidity for a target located 1 m in front of the wall. Three beam-defining scintillators, one of which had a cross-section smaller than the target, were placed 20 cm in front of it, and a 20×20 cm² veto counter with a 1 cm² beam hole was placed 1.5 m upstream. A 20×20 cm² interaction counter with a 1 cm² centre hole for the beam, was placed 6 cm downstream of the target. This interaction scintillator covered the same solid angle as the wall, seen from the target. The pretrigger was a coincidence of the beam-defining scintillators and the interaction counter in anticoincidence with the veto counter; this was sensitive to 50% of the inelastic cross-section. Events with an additional beam particle within -70 ns and $+130$ ns from the trigger time were vetoed. The normalization was obtained by scaling to the beam-defining scintillators. A hard-wired on-line summation of E_T was used as a second-level trigger. Each photomultiplier (PM) signal was split by a current divider into two parts: one was sent to a charge-sensitive ADC, and the other was weighted by a resistor and sent to a summation circuit to give an on-line estimate of the total E_T . The values of these (672) weighting resistors were found by using a Monte Carlo method where the E_T produced by an event generator was compared with the simulated response in the wall. The gains of the PMs were equalized by an iterative (computerized) procedure varying the high voltage on each tube so that the current induced by the uranium radioactivity was the same for each PM tube. The real events were interspersed with events taken with random triggers. These random events were also recorded during the bursts and were used to check the pile-up and to correct the zero

level for each individual PM tube on a tape-by-tape basis. They were also used to measure the width of the zero-level noise from the uranium radioactivity, which was found to be 50 MeV per PM in the hadronic section and 10 MeV in the electromagnetic section. The absolute energy scale had already been measured by the AFS Collaboration [3]. The data were recorded with the 200 GeV/c positive beam in the H8 beam line in the SPS North Area. The hadron-lead collision sample is a mixture of p-Pb (60.3%), π^+ -Pb (36.3%), and K^+ -Pb (3.4%).

3. DATA SAMPLE

Data with three different targets were recorded i) a Pb target, 5% of λ thick; ii) a Pb target 1% of λ thick; and iii) an empty target. The total integrated luminosity for the Pb data was $2.36 \times 10^{30} \text{ cm}^{-2}$. From the empty target run the fraction of events not originating from the target was found to vary between 50% and 10% for the 1% Pb target run, and between 10% and 2% for the 5% Pb target run (fig. 3). All the results shown have the contribution from the non-target events subtracted. One possible background source for large E_T is a double interaction in the target, i.e. the leading particle from the first h-Pb collisions interacts with another Pb nucleus in the target. In order to estimate this effect, we took data with two different target thicknesses. However, no difference was found between the E_T distributions from the two different targets over our measured E_T range. A second background source could be two different beam particles arriving at the target too close in time to be recognized by the protection logic, and each interacting with a target nucleus. This source was rejected by monitoring the energy sum in the wall and the beam calorimeters, which should add to the incoming beam energy. Figure 4 shows the distribution of this sum. The events were rejected if this total energy was more than $\pm 3\sigma$ away from the average measured beam energy. A small number of cosmic-ray background events were rejected by a loose requirement of the E_T imbalance ($< 16 \text{ GeV}$). On the average, 7% of the events were rejected by the above-mentioned requirements.

4. MONTE CARLO

One of the main difficulties in analysing the data is to estimate the effect of the final resolution of the calorimeter. It would be rather easy to unfold the measured data and obtain the true distribution if we were handling individual tracks. Since we are dealing with events that have different compositions for the same E_T , the deconvolution has to be done in an iterative way. An event generator was constructed to produce events that resemble the data as closely as possible in energy flow. Events were generated with a flat E_T distribution, and the E_T was divided in rapidity in the same way as was observed in the data. The E_T was divided into individual particles according to a given transverse momentum distribution. The Monte Carlo procedure was done for events having two different average transverse momentum distributions ($\langle p_T \rangle = 350 \text{ MeV/c}$ and 500 MeV/c), and the difference in the result is included in the systematic errors. The produced particles were split into charged and neutral pions; no other particles were considered. Energy and momentum were conserved in the event generator.

The detector was simulated using a shower parametrization [5] for the longitudinal shower development, and a Gaussian distribution for the lateral spread with a FWHM of $\lambda/2$ ($X_0/2$) for

hadronic (electromagnetic) showers. The starting point of the shower was generated according to an exponential distribution with a width of λ for hadronic showers. The energy loss of charged particles between the beginning of the calorimeter and the starting point of the shower was taken into account. The calorimeter response to this dE/dx loss is amplified by the known μ/e ratio [3]. The response to the energy deposition of the hadronic shower is suppressed by the measured asymptotic π/e ratio (0.9). The effect of light attenuation in the calorimeter scintillator (the attenuation length varies between 11 and 15 cm) was also taken into account.

The slope in the E_T distribution of the event generator was put in by statistical weights and changed iteratively so as to agree with the measured distribution unfolded from the detector resolution. The procedure was found to converge after three iterations.

Distortions due to possible non-Gaussian shower profiles, which were not included in the detector simulation program, were investigated separately using the GHEISHA [6] hadronic cascade Monte Carlo, and were found to be small. We investigated separately the variation of the calorimeter response with the increasing fraction of nucleons in the event. A small effect of about 1% was found and the data were subsequently corrected.

Some more details of the analysis procedure can be found in ref. [7].

5. RESULTS

The corrected E_T cross-section is shown in fig. 5 and table 1. We have estimated a 7% systematic error on the E_T scale. This error is composed of: 4% in the energy scale, 1.7% in the μ/e response, 1.7% in e/π , 1% in lateral shower spread, 2.5% in leakage, 2.5% in scintillator attenuation length, 1% from detector alignment, and 3.3% in event generator model-dependence. The distribution extends to 40 GeV, which is twice the p-p kinematic limit. The pretrigger was essentially a multiplicity trigger, and the average multiplicity of the recorded events is significantly higher than the average multiplicity in h-Pb collisions. To give a kinematic argument of what is required to reach the large E_T measured, it should be mentioned that the kinematic limit (i.e. $\sqrt{s}$) at this beam energy is 19.4 GeV for p-p collisions and 38.9 GeV for p-N collisions, where $m_N = 4m_p$. In other words, the effective target mass must be at least 4 GeV/c² in order to explain the large E_T measured. Another way to explain the occurrence of large E_T values is to consider the Fermi momentum of the nucleons inside the Pb nucleus. A Fermi momentum of 1.9 GeV/c would produce an E_T of 40 GeV on the pp interaction level for head-on h-Pb collisions. Although such Fermi momenta occur with low probability, they could produce the observed effect, since the rate of high- E_T events is also relatively low. However, a detailed calculation [8] shows that the E_T distribution cannot be explained by Fermi motion. In fig. 6 our measurements are compared with those of refs. [9–11], which are essentially an extrapolation of the E_T spectra measured in p-p collisions. The band of the ‘Wounded Nuclear Model’ (WNM) prediction in fig. 6 represents our estimated uncertainty in the p-p E_T spectrum, and it is clear that this band overlaps with our data. However, a number of independent p-N collisions, convoluted to give the p-N E_T distribution according to the WNM, would also predict that the rapidity distribution of the E_T flow is invariant with E_T . The pseudorapidity distribution of E_T in fig. 7 shows that this is not the case. On the contrary, the E_T flow shifts more and more to the

backward region when the total E_T is increased, and consequently contradicts the expectation from the WNM. We have added, as a guide-line, the shape of the pseudorapidity distribution for p-p minimum-bias collisions calculated with the Lund model [12]. A further investigation of the data can be found in refs. [8] and [13]. Our findings can be used to estimate the energy density achieved in these large- E_T collisions [14]. Within this model, and assuming $t_0 = 1$ fm/c, an event with $E_T = 40$ GeV in $\Delta\eta = 1.8$ translates into an energy density of approximately 5 GeV/fm^3 . However, we cannot show experimentally that the assumptions used in ref. [14] are fulfilled in our data.

The observation of collisions, occurring with relatively large cross-section and resulting in large E_T , represents the most interesting results of our measurements.

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Table 1Cross-section for transverse energy in $0.6 < \eta < 2.4$ Integrated cross-section = 890 mb = $0.502 \sigma_{\text{in}}$. Systematic error in E_T ($\pm 7\%$).

E_T (GeV)	δE_T (GeV)	$d\sigma/dE_T$ (mb/GeV)	Stat. error	E_T (GeV)	δE_T (GeV)	$d\sigma/dE_T$ (mb/GeV)	Stat. error
4.91	0.15	83.44	3.76	23.11	0.70	2.32	0.0384
5.70	0.17	84.40	3.72	23.90	0.73	1.86	0.0342
6.49	0.20	77.87	3.63	24.70	0.75	1.50	0.0312
7.28	0.22	70.77	3.48	25.49	0.77	1.20	0.0273
				26.28	0.80	0.917	0.02368
8.07	0.24	65.52	3.28	27.07	0.82	0.692	0.0202
8.86	0.27	51.74	3.01				
9.65	0.29	49.90	2.87	27.86	0.85	0.536	0.0176
10.44	0.32	43.46	2.67	28.65	0.87	0.405	0.0152
11.24	0.34	38.99	2.45	29.44	0.89	0.301	0.0130
				30.23	0.92	0.220	0.0111
12.03	0.36	31.20	1.99	31.02	0.94	0.168	0.00969
12.82	0.39	28.96	1.84				
				31.82	0.97	0.107	0.00774
13.61	0.41	24.80	0.696	32.61	0.99	0.0806	0.00670
14.40	0.44	22.48	0.654	33.40	1.01	0.0446	0.00500
15.19	0.46	18.32	0.587	34.19	1.04	0.0443	0.00496
15.99	0.48	16.37	0.550	34.98	1.06	0.0314	0.00423
16.78	0.51	14.18	0.510				
				35.77	1.09	0.0151	0.00293
17.57	0.53	11.69	0.458	36.56	1.11	0.00839	0.00221
18.37	0.56	10.02	0.422	37.35	1.13	0.0106	0.00245
				38.15	1.16	0.00607	0.00186
19.16	0.58	6.64	0.193	38.94	1.18	0.00466	0.00162
19.95	0.61	5.74	0.176	39.73	1.21	0.00304	0.00156
20.74	0.63	4.68	0.156	41.28	1.88	0.00264	0.00096
21.53	0.65	3.64	0.137				
22.32	0.68	3.19	0.126				

Figure captions

- Fig. 1** The experimental set-up.
- Fig. 2** Front face of the wall showing the subdivision of the towers, together with circles of constant pseudorapidity for a target 1 m in front of the wall.
- Fig. 3** Fraction of background events as a function of E_T for the two different target thicknesses.
- Fig. 4** Distribution of total energy measured in the wall and beam calorimeters. The energy is uncorrected for calorimeter response.
- Fig. 5** Cross-section of transverse energy measured in $0.6 < \eta < 2.4$ for 200 GeV/c hadron-lead collisions. The E_T scale has a 7% systematic error.
- Fig. 6** Transverse energy cross-section $d\sigma/dE_T$ compared with some models [9–11]. The hatched band of the WNM represents the uncertainty in $d\sigma/dE_T$ (pp) used as input.
- Fig. 7** Distributions of E_T in pseudorapidity in bins of total E_T . The shaded area shows the combined statistical and systematic error. The dashed lines show the distribution for p-p minimum-bias collisions.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7