CERN/EP 86-194
21 November 1986

MULTIPLICITY AND TRANSVERSE ENERGY FLUX

IN $^{16}\text{O} + \text{Pb}$ AT 200 GeV PER NUCLEON

NA35 Collaboration

A. Bamberger⁸⁾, D. Bangert⁴⁾, J. Bartke⁵⁾, H. Bialkowska¹³⁾, R. Bock⁶⁾,
R. Brockmann⁶⁾, C. De Marzo²⁾, M. De Palma²⁾, I. Derado¹¹⁾, V. Eckardt¹¹⁾,
C. Favuzzi²⁾, J. Fendt¹¹⁾, D. Ferenc¹⁴⁾, H. Fessler¹¹⁾, P. Freund¹¹⁾,
M. Gazdzicki^{9,12)}, H.J. Gebauer¹¹⁾, K. Geissler⁴⁾, C. Guerra⁶⁾, J.W. Harris³⁾⁺,
W. Heck⁷⁾, T. Humanic⁶⁾, K. Kadija¹⁴⁾, R. Keidel¹⁰⁾, M. Kowalski⁵⁾,
S. Margetis¹⁾, E. Nappi²⁾, G. Odyniec³⁾, G. Paic¹⁴⁾, A.D. Panagiotou^{1,4)},
A. Petridis¹⁾, J. Pfennig⁷⁾, F. Posa²⁾, K.P. Pretzl¹¹⁾, H.G. Pugh³⁾,
F. Pühlhofer¹⁰⁾, G. Rai³⁾, A. Ranieri²⁾, R. Renfordt⁷⁾, D. Röhrich¹⁰⁾,
K. Runge⁸⁾, A. Sandoval⁶⁾, D. Schall⁹⁾, N. Schmitz¹¹⁾, L.S. Schroeder³⁾,
G. Selvaggi²⁾, P. Seyboth¹¹⁾, J. Seyerlein¹¹⁾, E. Skrzypczak¹²⁾,
P. Spinelli²⁾, R. Stock^{4,7)}, H. Ströbele^{4,6)}, A. Thomas⁷⁾,
M. Tincknell³⁾, L. Teitelbaum³⁾, G. Vesztergombi^{11)*}, D. Vranic^{6,14)},
S. Wenig⁷⁾ and M. Wensveen⁶⁾

ABSTRACT

First results from ultrarelativistic $^{16}\text{O} + \text{Pb}$ collisions at 200 GeV/nucleon are presented. The transverse energy E_T in average central collisions is ≈ 75 GeV for the interval $2.2 \leq y \leq 3.8$. A 16-fold convolution of the inelastic $p + \text{Au}$ transverse energy spectrum, also measured at 200 GeV, reproduces the mean E_T of $^{16}\text{O} + \text{Pb}$. The amount of nuclear stopping power appears to be high.

(Submitted to Physics Letters B)

-
- 1) Physics Department, University of Athens, 157-71 Athens, Greece
 - 2) Dipartimento di Fisica, Università di Bari, and INFN, Bari, Italy
 - 3) Lawrence Berkeley Lab., University of California, Berkeley CA 94720, USA
 - 4) CERN, CH-1211 Geneva 23, Switzerland
 - 5) Institute of Nuclear Physics, PL-30055 Cracow, Poland
 - 6) Gesellschaft für Schwerionenforschung, D-6100 Darmstadt 11, Germany
 - 7) Fachbereich Physik, Universität Frankfurt, D-6000 Frankfurt, Germany
 - 8) Fakultät für Physik, Universität Freiburg, D-7800 Freiburg, Germany
 - 9) Institut für Hochenergiephysik, Universität Heidelberg, D-6900 Heidelberg 1
 - 10) Fachbereich Physik, Universität Marburg, D-3550 Marburg, Germany
 - 11) Max-Planck-Institut für Physik, D-8000 München, Germany
 - 12) Institute of Experimental Physics, University of Warsaw, Warszawa, Poland
 - 13) Institute of Nuclear Studies, PL-00681 Warszawa, Poland
 - 14) Rudjer Boskovic Institute, 41001 Zagreb, Yugoslavia
 - *) On leave of absence from Central Research Inst.f. Physics, Budapest, Hungary
 - +) Alexander v. Humboldt Foundation Fellow

Collisions of nuclei at very high energy should create a finite volume of hadronic matter at high energy density. Recent results from strong interaction lattice gauge theory [1] suggest that, above a critical temperature of approximately 250 MeV, the hadronic state of matter is transformed to a new phase consisting of deconfined quarks and gluons, with an energy density of several GeV/fm^3 , to be compared to that of ground state matter, which is $150 \text{ MeV}/\text{fm}^3$. Such extreme conditions could be reached in central nucleus-nucleus collisions by converting the initial relative c.m. energy into internal excitation of a "fireball" formed at rapidities intermediate between those of target and projectile, provided sufficient beam energy and adequate "stopping power". The stopping power of nuclear matter, which determines the degree to which baryon number and energy density are shifted away from the fragmentation domains towards mid-rapidity, is poorly known. Estimates derived from hadron-nucleus collisions at high energy are controversial [2,3]: the mean rapidity loss of the leading baryon in a proton-nucleus collision is uncertain within the range from $\Delta y \approx 1$ to 2.5. At 200 GeV per nucleon incident energy, attained at the CERN SPS for nuclear beams, the total rapidity gap between target and projectile is $\Delta y = 6.06$. The energy available in the nucleon-nucleon c.m. frame, $\sqrt{s} = 19.4 \text{ GeV}$ per nucleon pair, appears sufficient to create the critical energy density. However, a high degree of nuclear stopping is necessary to concentrate a sufficient fraction of this energy near mid-rapidity.

The aim of the present study, of the $^{16}\text{O} + \text{Pb}$ reaction at 200 GeV/nucleon incident energy, was to focus on a necessary prerequisite of quark matter formation, namely the stopping power. The data were obtained in an accelerator test run in which this experiment, NA35, received 36 hours of external ^{16}O beam. The particle multiplicity and the transverse energy distribution at intermediate rapidity were investigated. The results indicate that a high degree of stopping occurs in central collisions.

The experiment was carried out using a 200 GeV/nucleon ^{16}O beam extracted from the CERN SPS. This energy is reached via a chain of accelerators [4]. A high charge state ECR ion source plus RFQ preaccelerator [5] injects a beam of $^{16}\text{O}(6+)$ into Linac 1. After acceleration to 12 MeV/nucleon and complete stripping, transfer to the PS Booster occurs, and subsequently into the PS at 260 MeV/nucleon. A 10 GeV/nucleon beam is extracted from the PS into the SPS.

Finally, a beam of $\sim 5 \cdot 10^7$ ions/s with 4.4 second extraction and a 14.4 second overall cycle is extracted from the SPS into the external beam transport system. An intensity of $5 \cdot 10^4$ ions/s was used in this experiment.

The NA35 setup [6] consists of a $2 \times 1.2 \times 0.72 \text{ m}^3$ Streamer Chamber in the 1.5 Tesla magnetic field of a superconducting Vertex magnet. Pb and Au targets of 1% interaction length were positioned 13 cm upstream from the Streamer Chamber. Three cameras, each equipped with two-stage magnetically focused image intensifiers of 2000-fold luminous gain, view the Streamer Chamber and record events on 70 mm film. The overall spatial resolution attained in the Streamer Chamber was about 2 mm.

Downstream two large area calorimeters cover the mid rapidity region of $2.5^\circ \leq \theta \leq 12^\circ$. First a highly segmented Photon Position Detector [7] (PPD) of 9.6 radiation lengths thickness measures most of the energy of photons and π^0 's. It is read out by alternating planes of vertical and horizontal proportional tubes with 7.7 mm wire spacing into 3072 ADC channels. Directly behind the PPD there is a Ring Calorimeter [8] of 1.5 m outer and 0.28 m inner radius subdivided into 240 cells. It consists of a 16 radiation lengths lead/scintillator front section and a 6.9 interaction lengths iron/scintillator back section. The total thickness of about 8 interaction lengths fully contains 200 GeV hadronic showers. The internal aperture of the Ring Calorimeter is filled by the Intermediate Calorimeter, covering the angular range of $0.3^\circ \leq \theta \leq 2.5^\circ$. It was only used as a passive absorber in the present experiment. The energy flux in the projectile fragmentation domain $\theta < 0.3^\circ$ is measured by a Veto Calorimeter [8] of 9.9 interaction lengths thickness.

Two triggers were used in the experiment. The first trigger was derived from the energy signal E_{veto} of the Veto Calorimeter. It selected various levels of projectile energy degradation in the collision. These range from "minimum bias", where E_{veto} was just below the incident 3.2 TeV, to "central" where the energy flow into the projectile fragmentation domain was required to be $E_{\text{veto}} \leq 0.5 \text{ TeV}$. The other trigger was obtained from the transverse energy signal E_T^{PPD} derived from the PPD. It selected events in which the total transverse energy of the electromagnetic showers exceeded various levels. On the average 3 events were taken in the chamber per beam spill and, in addition, about 100 events in the calorimeters without accompanying Streamer Chamber information.

A central collision event obtained with the Veto Calorimeter threshold $E \leq 0.5$ TeV is shown in Fig. 1. The charged particle multiplicity from the scan is 267, and the transverse energy recorded in the PPD and Ring calorimeters is 80 GeV. The angular acceptances of the PPD and Ring, as well as that of the Veto Calorimeter, are indicated in the figure. The cross section corresponding to this "violent event" class, with $E_T \geq 80$ GeV, which exhibits no small angle jet of high energy leading fragments, is several hundred mb. Thus, events with high transverse energy are not rare; their cross section corresponds in a geometrical model to impact parameters $b \leq 3$ fm with complete overlap of the ^{16}O ($R = 3$ fm) and the Pb ($R = 7$ fm) nuclei.

Fig. 2 shows the acceptances of the Streamer Chamber, the PPD plus Ring Calorimeters, and the Veto Calorimeter in the p_T versus lab rapidity plane. At transverse momenta below ~ 1 GeV/c, the PPD/Ring acceptance differs for pions and nucleons. The pion acceptance bends away from the midrapidity coverage, $2.2 \leq y \leq 3.8$, at low transverse momenta, $p_T \leq 0.2$ GeV/c, whereas that for baryons shifts downwards at higher p_T . This feature is important for comparing the present data with theoretical models. The Veto Calorimeter covers $y \geq 5$, except at very low transverse momentum for baryons. These acceptances refer to runs without magnetic field, which were used to obtain transverse energy distributions. With field on only the neutral particle acceptance remains unchanged, whereas all charged particles experience a deflection in the horizontal plane, corresponding to an additional apparent transverse energy of about 1 GeV. The proton acceptance of the Veto calorimeter is shifted upwards to $y \geq 5.5$, with no change occurring for neutrons.

The charged particle multiplicity, observed in the Streamer Chamber at lab angles $\theta \leq 60^\circ$ is plotted in Fig. 3 versus the total energy in the Veto Calorimeter. These data were taken with magnetic field on. The multiplicities have been corrected for scanning efficiency, e^+e^- contamination from γ -conversion, secondary particle interactions in the target, and contributions from neutral strange particle decay to charged particles (based on the HIJET [9] prediction for the relative Λ , K_s^0 , and Σ to pion yields). The mean charged particle multiplicity increases with decreasing energy flux in the projectile fragmentation domain, reaching a value of about 260. Also shown is the prediction of the HIJET event simulation code which is based on a model of successive nucleon-nucleon interactions.

Fig. 4(a) shows the differential E_T distribution, as summed from the PPD and Ring Calorimeters^{*)} with the magnet off. The data points with $E_T < 50$ GeV were obtained from events in the calorimeters and accompanying Streamer Chamber pictures. This ensured the inclusion of only valid target interactions. For $E_T > 50$ GeV the fraction of non target interactions was determined from the Streamer Chamber to be < 0.04 . Systematic uncertainties of the E_T -scale and normalization are estimated to be below 10%. The data have not been corrected for the effect of the finite E_T -resolution (approximately 5% at $E_T = 75$ GeV). The HIJET prediction is also shown in Fig. 4(a) for comparison. This distribution is much narrower. The peak near 50 GeV arises in this model from impact parameters $b \leq 4$ fm. The data exhibit the same "central collision" peak at around 75 GeV. Thus, HIJET underpredicts the mid-rapidity $\langle E_T \rangle$ by a factor of approximately 0.66 for central collisions. The total observed cross section for $E_T \geq 75$ GeV is as high as 250 mb, corresponding in a geometric model to $b \leq 3$ fm. At higher E_T the cross section falls near-exponentially. However, the cross section corresponding to $E_T \geq 110$ GeV, i.e. $1.5 \langle E_T \rangle$ of central collisions, is still above 1 mb. This region will be investigated in upcoming higher statistics runs.

Also included in Fig. 4(a) is the 16-fold convolution of the differential E_T distribution for $p + Au$, obtained with a 200 GeV tagged proton beam and the same setup, running with no magnetic field and an interaction trigger requiring $E_{\text{veto}} < 150$ GeV. The E_T distribution in the PPD and Ring Calorimeters for $p + Au$ is shown in Fig. 4(b), along with an analytic fit $d\sigma/dE_T = 0.173 E_T^{2.36} \exp(-0.727 E_T)$ [barn/GeV]. The $p - Au$ cross section corresponding to this trigger mode is 1.3 barn. This amounts to about 70% of the total inelastic cross section, the trigger eliminating the surface interactions ($b > 6$ fm) of the proton, which should not be included in the convolution because we want to compare the resulting E_T spectrum to that of

*) E_T is calculated as the appropriately weighted sum of the energies found in individual PPD channels and Ring Calorimeter cells by the formula

$$E_T^{\text{PPD}} + E_T^{\text{RING}} = \frac{\pi}{4} \frac{1}{d_{\text{PPD wires}}} \sum_i 2 (z_i E_i^z + y_i E_i^y) + \frac{1}{d_{\text{RING cells}}} \sum_i r_i E_i^{\text{cell}}.$$

The factor $\pi/4$ corrects for the effect of the cartesian readout of the PPD, d_{PPD} and d_{RING} are the calorimeters' distances from the target; z_i , y_i and r_i are the distances from the PPD wires and the Ring Calorimeter cells to the beam axis.

small impact parameter $^{16}\text{O} + \text{Pb}$ collisions. In fact, Fig. 4(a) shows that this convolution approximately reproduces both the "central collision" peak position and the slope at high E_T . The small difference between Au and Pb target masses should be negligible. Fig. 4(b) includes the result of a $p + \text{Au}$ HIJET calculation for $b \leq 6$ fm, which does not resemble the data. The inadequacy of this model, with respect to E_T spectra, can thus be traced back to the level of hadron-nucleus collisions.

Tagged pions were also available in the 200 GeV external SPS beam. Within errors, the E_T spectrum for $\pi^+ + \text{Au}$ was found to be identical to $p + \text{Au}$ over the energy range covered here.

The low HIJET prediction for E_T in central collisions observed in Fig. 4(a), in spite of the correct value for the total charged particle multiplicity (Fig. 3), suggests that HIJET must underpredict the mean E_T per particle by a factor of about 0.66. To further investigate this, the number of tracks falling into the PPD and Ring Calorimeter acceptance was determined from the Streamer Chamber, thus establishing the correlation between charged particle number and hadronic transverse energy. The hadronic transverse energy fraction of the summed PPD and Ring Calorimeter E_T was determined by shower simulation. This procedure was carried out for 180 events obtained in a no magnetic field PPD-trigger mode. After corrections for scanning efficiency, e^+e^- contamination, and an additional hadronic E_T fraction due to participant neutrons, the result $\langle E_T/\text{particle} \rangle = 615 \pm 90$ MeV was obtained. The error includes statistics only. The systematic error is of the order of 10%. The above result was obtained for the fraction of events with E_T in the range $60 \leq E_T \leq 80$ GeV, in the central collision peak of Fig. 4(a). The corresponding HIJET prediction for central collisions is $\langle E_T/\text{particle} \rangle = 384 \pm 40$ MeV only, but the mean number of particles in the acceptance agrees with the number obtained from the Streamer Chamber scan. The trigger on high E_T , employed in the data, thus appears to select "hot" events which are absent in HIJET. Note that, in principle, a high total transverse energy at mid-rapidity could just as well arise from a higher multiplicity of particles with a "normal" E_T distribution; this is not observed.

Turning to the implications of the above results for the nuclear stopping power, we note that the value $\langle E_T \rangle = 75$ GeV for central collisions refers to the interval $2.2 \leq y \leq 3.8$ only. For an adjacent acceptance, $0.6 \leq y \leq 2.4$, the E_T distribution of p + Pb at 200 GeV was measured by the CERN NA34 collaboration [10]. Upon applying a similar 16-fold convolution, we find $\langle E_T \rangle = 125$ GeV in that interval for central $^{16}\text{O} + \text{Pb}$ collisions. Assuming that the convolution procedure provides a reasonable estimate for the mean value (as shown in our data) a total E_T of approximately 180 GeV is expected for the domain $0.6 \leq y \leq 3.8$, in the average central collision. For the total volume of the fireball we take that of a cylinder, with the radius of ^{16}O and the length of the diameter of Pb, Lorentz contracted by the appropriate γ_{CM} factor. This simple estimate gives about 60 fm^3 for the interaction volume. Thus, the average transverse energy density should be about 3 GeV/fm^3 . It can be increased:

- (i) by triggering on high E_T events. At the level of a 1mb cross section one expects a 50% increase (c.f. Fig. 4(a));
- (ii) by higher projectile mass. Within the above simple line of argument the total E_T would be expected to be proportional to A_{proj} (from A-fold convolution), and the volume to increase as $A_{\text{proj}}^{2/3}$, the net gain factor increasing as $A_{\text{proj}}^{1/3}$ of the projectile.

Our estimate of about 180 GeV transverse energy in the interval $0.6 \leq y \leq 3.8$ implies a relatively high stopping power. Note that longitudinal energy of about 90 GeV, as appropriate for an isotropic fireball, has to be included in comparing to the total energy in the appropriate c.m. system. This should, for central collisions of $^{16}\text{O} + \text{Pb}$, be that of 16 projectile nucleons striking a cylinder of about 50 target nucleons. Indeed, from the scan of Streamer Chamber events, an excess of about 30 is found for positive over negative tracks in central collisions, to be identified with the number of participating protons. The total energy, formally available in this c.m. frame is 550 GeV, of which we account for about 270 GeV in the acceptance given above. The stopped fraction of the energy thus amounts to about 0.5 of the kinematic limit in average central collisions.

In summary, the first data on $^{16}\text{O} + \text{Pb}$ at 3.2 TeV incident energy show high charged-particle multiplicities, as expected from a superposition of hadron-hadron collisions (HIJET). Central collisions are discernible as events with high E_T , occurring with a cross section that corresponds to the geometrical weight of complete diving of ^{16}O into Pb. The total mid-rapidity transverse energy of central collisions is higher than expected from HIJET. In high E_T events, the mean E_T per particle seems to increase beyond the 0.4 GeV level, typical of hadron-hadron collisions. On the other hand, the high E_T domain of $^{16}\text{O} + \text{Pb}$ is fairly well reproduced by a 16-fold convolution of nonsurface $p + \text{Au}$ collision data. The stopping power implicit in hadron-nucleus collisions thus appears to prevail in central ^{16}O -Pb interactions. This is not too surprising for such a light projectile since one expects the major nuclear medium effect to arise from the heavy target. For light nuclear projectiles the hadron-nucleus process should be the basic ingredient of the dynamics. Its stopping power and E_T distribution do not trivially result from known hadron-hadron physics, as indicated by the failure of HIJET to reproduce either the $p + \text{Au}$ or the $^{16}\text{O} + \text{Pb}$ E_T distribution. Finally, the stopping power of the elementary p -heavy nucleus central collision at 200 GeV appears to be high enough to create a transverse energy density in the average central $^{16}\text{O} + \text{Pb}$ collision of about 3 GeV/fm^3 . This appears sufficient for a comprehensive quark matter search.

The authors wish to acknowledge the extraordinary performance of the accelerator groups at CERN, GSI and LBL, and the generous hospitality of the CERN EP and EF divisions. The enthusiastic support of V. Hermann, E. Keller and M. Yerli is appreciated. We thank Dr. Th. Schouten for his most valuable help in the experiment.

REFERENCES

- [1] J.B. Kogut, Nucl. Phys. A418 (1984) 381c;
H. Satz, ibid. p. 447c.
- [2] D. Barton et al., Phys. Rev. D27 (1983) 2580;
R. Bailey et al., Z. Physik C 29 (1985) 1;
D. Lissauer, Proc. 5. Quark Matter Conf., Asilomar 1986;
to be published in Nucl. Phys. A461.
- [3] W. Busza and A. Goldhaber, Phys. Letters 139B (1984) 235;
S. Date, M. Gyulassy and H. Sumiyoshi, Phys. Rev. D32 (1985) 619;
M. Jezabek and M. Rozanska, Phys. Letters 175B (1986) 206.
- [4] W.C. Middelkoop, CERN preprint SPS/86-15.
- [5] B.H. Wolf et al., GSI Report 86-2.
- [6] A. Sandoval et al., Proc. 5. Quark Matter Conf., Asilomar 1986,
to be published in Nucl. Phys. A461.
- [7] V. Artemiev et al., Nucl. Instr. Meth. 224 (1984) 408.
- [8] C. De Marzo et al., Nucl. Instr. Meth. 217 (1983) 405;
C. De Marzo et al., Phys. Rev. D29 (1984) 363.
- [9] T.W. Ludlam, BNL report 51921 (1985) 373.
- [10] T. Akesson et al., Proc. 23. Int. Conf. High Energy Physics, Berkeley
1986;
A. Franz, PhD Thesis, Univ. Siegen 1986.

FIGURE CAPTIONS

- Fig. 1 Streamer Chamber picture of a central $^{16}\text{O} + \text{Pb}$ collision at 200 GeV/nucleon, together with the angular acceptance of the mid-rapidity calorimeters (PPD and Ring) and the leading fragment calorimeter (Veto).
- Fig. 2 Acceptances of the NA35 detectors for the case of no magnetic field in the Vertex Magnet, shown in the p_T vs. lab rapidity plane. The Streamer Chamber accepts all charged particles with $\theta \leq 60^\circ$. The PPD and Ring Calorimeters accept all particles in mid-rapidity, the exact acceptances depending on the mass of the particles. Here only the acceptances for nucleons (dashed lines) and for pions (shaded area) are shown. For the Veto Calorimeter only the nucleon acceptance is shown. The dark shaded area corresponds to the onset of the acceptance.
- Fig. 3 Mean charged particle multiplicity for lab angles $\theta \leq 60^\circ$ as a function of the total energy observed in the Veto Calorimeter.
- Fig. 4 (a) Midrapidity transverse energy distribution of $^{16}\text{O} + \text{Pb}$. The dashed curve gives the HIJET prediction. The full line is the 16-fold convolution of the E_T distribution for inelastic $p + \text{Au}$ collisions at 200 GeV. The latter data (b) have been measured with the same apparatus. Also shown is the HIJET prediction, and a functional form fitted to the data.

100-1000

Fig.1

FIG. 3

FIG. 4a

FIG. 4b