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S. Margetis and the NA49 Collaboration

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Transverse Energy Production in ^{208}Pb+Pb Collisions at 158 GeV per Nucleon

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Abstract

Measurements of forward and transverse energy in 158 GeV per nucleon ^{208}Pb+Pb collisions are presented. A total transverse energy of about 1 TeV is created in central collisions. An energy density of about 3 GeV/fm^3 is estimated for near head-on collisions. Only statistical fluctuations are seen in the ratio of electromagnetic to hadronic transverse energy.

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Collisions of heavy nuclei at high energies serve as a unique tool for studying strongly interacting matter under conditions of extreme density and temperature. The recent acceleration of ^{208}Pb ions in the CERN–SPS to an energy of 158 GeV per projectile nucleon has extended this field of study to a new domain where bulk nuclear matter is excited to such high energy densities that it might undergo a phase transition into a deconfined and/or chirally restored state, as predicted by lattice QCD calculations [1]. If equilibrium is achieved, global observables such as transverse energy production can be related to thermodynamic variables, such as energy and entropy density, commonly used to characterize these collisions. The systematic comparison of such quantities for various collision systems may elucidate the dynamical mechanisms involved and identify observables and conditions under which to search for signals of a possible phase transition. One such observable is the relative production rate of electromagnetic to hadronic energy, which reflects the relative abundance of neutral to charged pions [2]. In this Letter we present and discuss the first data on transverse energy production in ^{208}Pb+Pb collisions, and also make comparison to previously published S+Au and S+S data [3]. We estimate that the energy density in head-on Pb+Pb collisions at this energy reaches about 3 GeV per fm^3, thus surpassing the critical energy density predicted by lattice QCD [1]. The ratio of electromagnetic to hadronic transverse energy, however, is found to exhibit no abnormal fluctuations.

The NA49 experiment is designed to perform inclusive as well as single event measurements of a variety of observables for ^{208}Pb induced reactions at 158 GeV/nucleon laboratory energy. The calorimeter configuration relevant to the data reported here is described in detail in refs. [4,5]. A 'Ring' calorimeter [6] located 6 meters from the 2% interaction length Pb-target covered the pseudorapidity range $2.1 < \eta < 3.4$. It consists of an electromagnetic (EM) lead/scintillator calorimeter of 16 radiation lengths (X_0) and one interaction length (λ_{int}) thick, followed by a hadronic iron/scintillator calorimeter of 6 λ_{int}. It is tube-shaped with inner/outer radii of 28/150 cm, and it is divided into 240 cells, 24 azimuthally (sectors) and 10 radially (rings), with the radial size chosen to cover equal ranges in pseudorapidity. Downstream of the Ring calorimeter, an iron collimator defined the acceptance of a forward

('Veto') calorimeter [6]. Its central hole of 10x10 cm^2 at 11 meters from the target allowed only particles with an emission angle of less than about 0.3^0 ($\approx 5^0$ in the c.m. frame) to reach the Veto calorimeter. This small aperture was designed to cover the projectile spectator region.

The behavior of these calorimeters has been studied in detail in previous experiments (NA5, NA24, NA35) [3]. For the ^{208}Pb beam run the gains of the phototubes in the inner six rings were reduced by up to a factor of three in order to avoid signal overflow [5]. Three sectors (30 cells) were re-calibrated using 30 GeV π^- and e^- beams. The rest were tuned with ^{208}Pb+Pb data by demanding azimuthal symmetry, on the average, for E_T. Data were also taken with the target positioned 10.4 meters upstream from the Ring calorimeter. This allowed a check of the relative calibration of cells in different rings, an estimate of the residual cell non–uniformities, and an extension of the acceptance to higher rapidities [5].

On the average about 95% of the electromagnetic energy, mostly due to photons from neutral pion decays, is contained in the EM part of the calorimeter. However, since the EM part is one λ_{int} thick, a fraction of its response is due to hadron showers. This fraction was estimated for central collisions using an event generator and a GEANT simulation of the calorimeter to be, on the average, 50% of the EM signal. For the evaluation of the electromagnetic and hadronic components in each event these calculated correction factors were applied to the observed electromagnetic and hadronic signals. The effect of the shower spreading over several cells, combined with the non-projective geometry of the calorimeter was estimated through a Monte Carlo study, and the data were also corrected for this effect. The background from non-target interactions was determined by data-taking runs without the Pb-target and found to contribute only at $E_T < 150$ GeV and $E_{VETO} > 22$ TeV. A straightforward subtraction removed it from the E_{VETO} spectrum. The E_T spectrum could not be completely corrected in this range. Details of the calibration and the unfolding procedures can be found in ref. [5]. The systematic error of the absolute value of E_T is estimated to be less than 10%, and of E_T^{EM} and E_T^{HAD} separately less than 15%. The systematic error of the absolute cross section is estimated to be less than 5%.

The forward energy (E_{VETO}) distribution is shown in Fig. 1. We understand the qualitative features of this figure to be governed primarily by the varying collision geometry, which leads to large values of the cross section for large impact parameters, at E_{VETO} values near the full beam energy, followed by a plateau, for partial overlap, and rapidly vanishing cross sections for near head-on collisions characterized by low E_{VETO} values. Predictions of the microscopic hadronic cascade model VENUS [7] (version 4.12) closely reproduce the features of the data, thus underlining the validity of the collision geometry picture. Central, near zero impact parameter collisions, corresponding to the point in the E_{VETO} spectrum where the plateau ends and the steep fall of the cross section begins [3], have a mean energy deposition in the Veto calorimeter ($< E^{B0}_{VETO} >$) of about 6 TeV. Calculations using the VENUS model show that even head-on collisions have 13±2 projectile spectators which deposit about 2 TeV of energy in the Veto. This represents only 30% of the corresponding head-on energy flux in the Veto calorimeter $< E^{B0}_{VETO} > \approx 6$ TeV. The remaining fraction of the Veto energy is due to forward-going non-spectator matter in central Pb+Pb collisions.

The transverse energy (E_T) distribution measured in the acceptance of the Ring calorimeter is also shown in Fig. 1. The shape of the spectrum can again be understood in terms of the collision geometry [3], but here the large impact parameter collisions are at small E_T. The predictions of VENUS are shown as well as the S+Au NA35 data [3], scaled to the present acceptance. For the Pb+Pb data, the low E_T region below 150 GeV is not shown since it is contaminated with non–target interactions [5]. The predictions of the VENUS model agree well with the data indicating proper treatment of the redistribution on the microscopic scale of the initial beam energy into transverse energy.

The symbol ∇ in Fig. 1 indicates the mean E_T value in near head-on collisions, E_T^{B0}, calculated in a geometrical manner described in ref. [3]. We find $E_T^{B0} = 520 \pm 25$ GeV for head-on Pb+Pb collisions, within the pseudorapidity interval $2.1 < \eta < 3.4$.

The differential pseudorapidity distribution of the transverse energy ($dE_T/d\eta$) for central Pb+Pb collisions is shown in Fig. 2. The trigger corresponds to the most central 2% of the total inelastic nuclear cross section. Data from both target positions were combined in

order to obtain maximum pseudorapidity coverage. A peak value of $dE_T/d\eta = 405$ GeV is observed around $\eta = 3$. We would expect a symmetric $dE_T/d\eta$ distribution around $\eta = y_{cm}$ for a symmetric system such as Pb+Pb (y_{cm}^{PbPb}=2.9). This is consistent with Fig. 2.

In the analysis of the data we address primarily two questions. The first concerns the stopping power of interpenetrating nuclear matter: what fraction of the energy available in the center of mass is transformed into excitation in the reaction zone? This leads directly to the second question: what is the energy density in the primordial interaction volume?

Various geometrical and kinematical parameters, together with quantities derived from the data are summarized in Table I for central collisions of the three systems S+S, S+Au and Pb+Pb. The data for the two lighter systems were taken [3] at a slightly higher energy, 200 GeV per nucleon. A systematic comparison with the present Pb results is insightful. In the table, n_{part}^{total} is the total number of participants obtained in the VENUS model for head-on collisions. In the next column $E_T^{4\pi,B0}$/part is the transverse energy per participant in head-on collisions [3] extrapolated to 4π acceptance, using acceptance factors ($\sim$ 2) derived from our calorimeter geometry and VENUS calculations [5]. To determine the degree of stopping in head-on Pb + Pb collisions at this energy from these data, we use a standard approach [3]: 1) isotropically distribute the total centre-of-mass energy (minus the participant baryon rest mass); 2) define E_T^{max} [3] to be the transverse fraction of that energy ($E_T^{max} = (\pi/4) \cdot [\sqrt{s_{TOT}} - m_{part}]$); 3) define the ratio S_R=$E_T^{4\pi,B0}/E_T^{max}$ as the relative stopping. The values of E_T^{max} per participating nucleon and S_R are given in the table. We point out that $\sqrt{s}$ decreases from S + S to S + Au to Pb + Pb. S_R increases with the mass of the colliding system, as intuitively expected, reaching the value (57±6) % for the relative stopping in Pb+Pb. At the lower AGS energy the stopping approaches 100% in central Au+Au collisions [8]. The stopping at the SPS is still very high. There is no indication of significant 'nuclear transparency'.

The last column in Table I is an estimate of the energy density (ε) of the primordial interaction volume, using Bjorken's formula [9] $\varepsilon = (dE_T/d\eta)/(\pi R^2 \tau)$. R is the transverse radius of the participant volume (equal to the radius, $R = 1.12 \cdot A^{1/3}$ fm, of the smaller of

the two nuclei colliding head-on), and τ is the hadronic formation time, which is assumed to be $\tau = 1$ fm, as employed throughout the literature. For the transverse energy density in pseudorapidity space, $dE_T/d\eta$, the midrapidity peak value of Fig.2 ($dE_T/d\eta = 405$ GeV) is used. To maintain consistency with previous systematics of extrapolation to ideal 'head-on' collisions, a correction factor [3] of 1.1 is applied to the peak value of Fig.2. Table I shows an increase in the average density when going from the small, surface dominated S+S reaction volume to the much larger Pb+Pb volume; the Bjorken estimate amounts to $\varepsilon = 3.2$ GeV/fm^3 for Pb+Pb, about 20 times higher than the ground state energy density of nuclear matter (~ 0.16 GeV/fm^3), and in the range where deconfinement is expected [1].

We now turn to the individual components of E_T, namely the electromagnetic (mostly γ's from π^0 decays) and the hadronic transverse energies (mostly $\pi^{\pm}$, p and n). Figure 3 shows the ratio E_T^{EM}/E_T^{HAD} for a sample of central collisions selected by requiring the energy measured by the Veto calorimeter to be less than 7 TeV. A distinctive feature of this distribution is the absence of non–statistical fluctuations of E_T^{EM}/E_T^{HAD} away from the mean on both sides of the distribution. The mean value of the distribution is 0.29, compared to 0.30 in the VENUS calculations. The data can be described by a gaussian function with $\sigma = 0.019$. Simulations of the calorimeter response show that the contamination of the EM signal with hadronic energy leads to a measured sigma which is narrower than the real one [5]. If we unfold the observed width according to simulations we get $\sigma = 0.030$, identical to the VENUS value. Thus, neither the mean value nor the shape and width of the distribution of the ratio of electromagnetic to hadronic transverse energy production reveals unusual physics.

In conclusion, our results for central Pb+Pb collisions using the NA49 calorimeters show that a total transverse energy of 1.4 TeV ($n_{part.}^{total}$ times $E_T^{4\pi,B0}$/part in Table I) is contained in the interaction volume. There is also an increase in nuclear stopping power in going to heavier systems. Using the Bjorken formalism to relate the energy density in momentum space to the the average energy density in the primordial collision volume, we obtain an estimate in excess of 3 GeV/fm^3 for head-on Pb+Pb collisions. We note, however, that

these values are estimates since the applicability of Bjorken's approach might be somewhat restricted at the modest SPS energy and specifically for the light projectile-heavy target collision system S+Au. Nevertheless, it is clear that the SPS Pb beam offers favorable conditions (maximal density, system size and life-time) in the search for the new QCD phase transition which is estimated to occur at about 2 GeV/fm^3. However, no large non-statistical fluctuations are observed in the electromagnetic to hadronic transverse energy fractions measured over about 1.5 units of pseudorapidity, at midrapidity.

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FIGURES

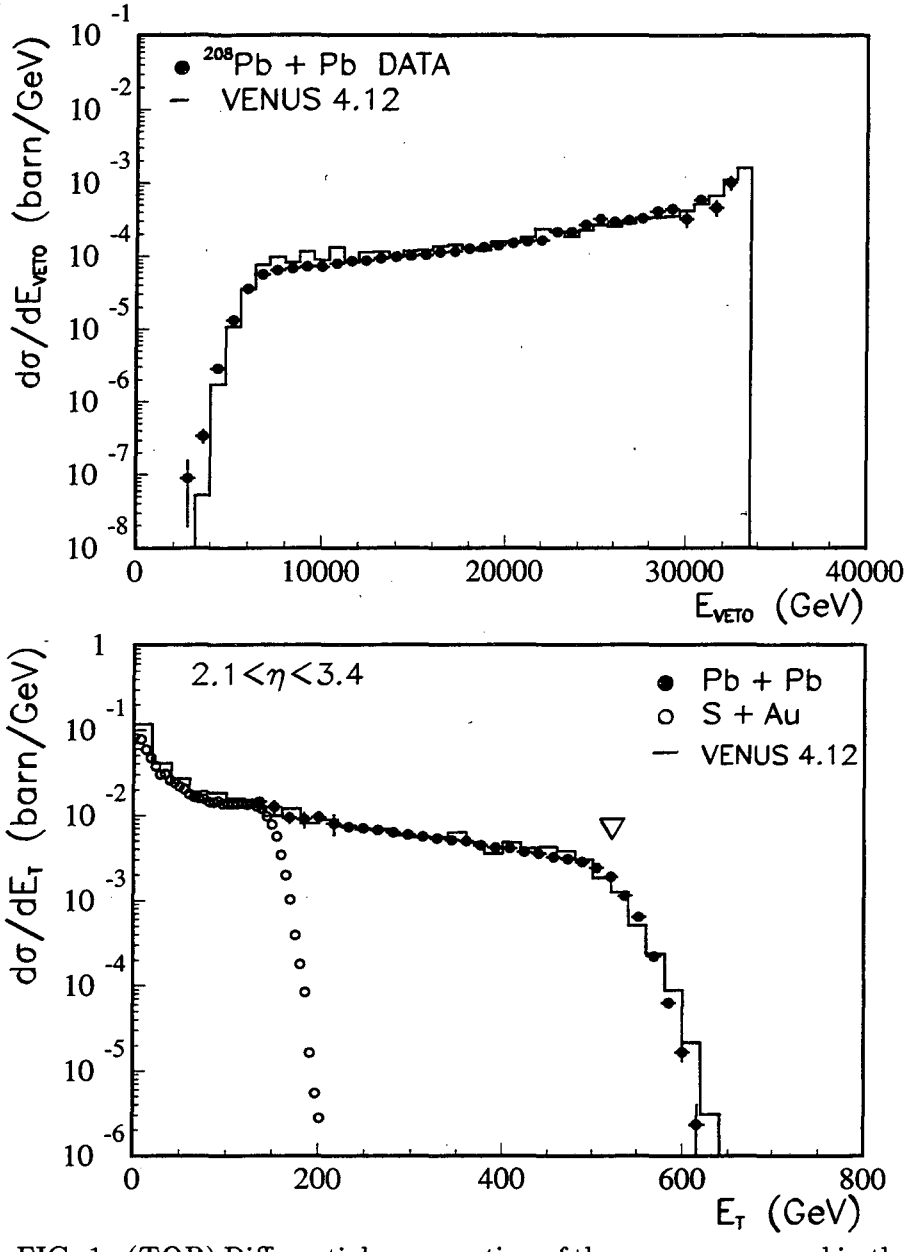

FIG. 1. (TOP) Differential cross section of the energy measured in the Veto calorimeter. Predictions of the VENUS model are also shown. (BOTTOM) Differential cross section of the transverse energy produced in Pb+Pb and S+Au collisions, as measured by the Ring calorimeter in the pseudorapidity range $2.1 < \eta < 3.4$. Results of the VENUS model are also shown. For explanation of the symbol ∇ see text.

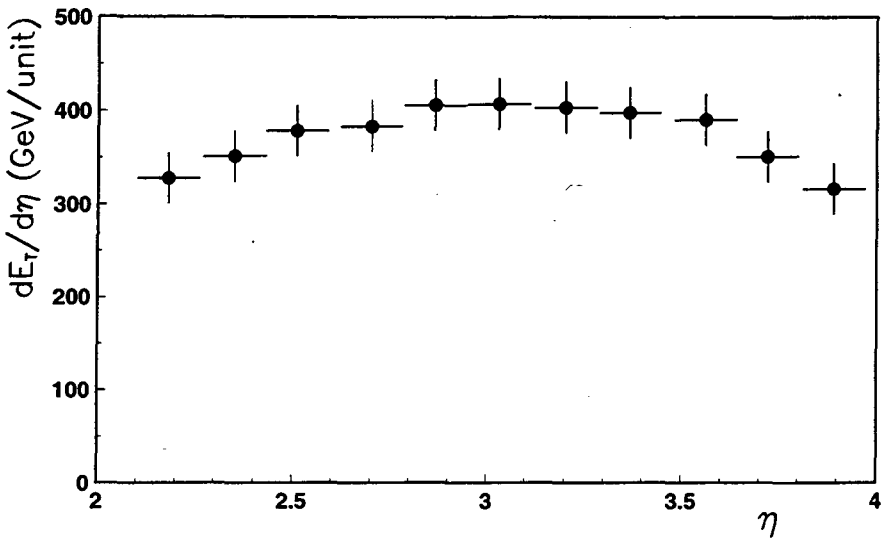

FIG. 2. Pseudorapidity distribution of transverse energy, $dE_T/d\eta$ (per η unit), for central Pb+Pb collisions.

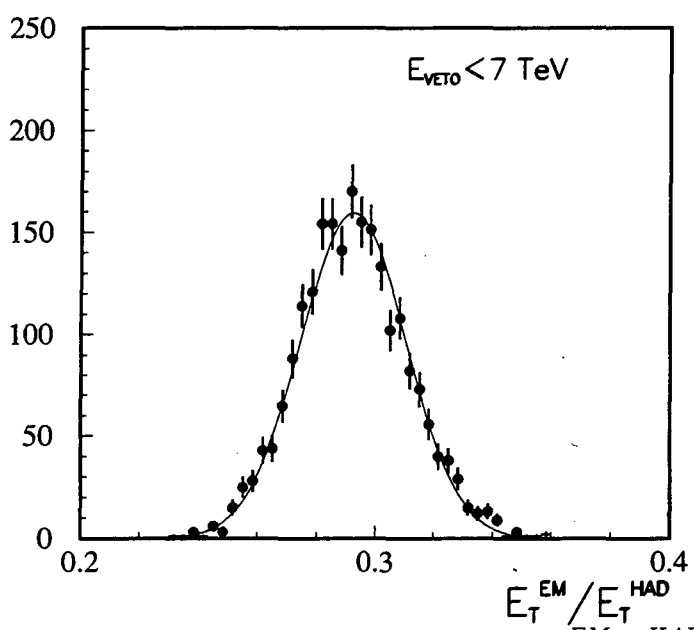

FIG. 3. The distribution of the ratio E_T^{EM}/E_T^{HAD} for central Pb+Pb events with $E_{VETO} < 7$ TeV. The curve is a gaussian fit to the data.

TABLES

TABLE I. Geometric and kinematic parameters, as well as experimental observables. For an explanation of the notation see text. All experimental quantities are dominated by a systematic error estimated to be 10%.

System	E_{LAB}/A (GeV)	$n_{part.}^{total}$	$E_T^{4\pi,B0}$/part. (GeV)	E_T^{max}/part. (GeV)	S_R	ε (GeV/fm^3)
S+S	200	58	3.2	6.9	0.47	1.3
S+Au	200	113	3.2	6.1	0.52	2.6
Pb+Pb	158	390	3.5	6.0	0.57	3.2

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