FORWARD AND TRANSVERSE ENERGY DISTRIBUTIONS IN OXYGEN-INDUCED REACTIONS AT 60 *A* GeV AND 200 *A* GeV

WA80 Collaboration

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Results are presented from reactions of 60 *A* GeV and 200 *A* GeV ^{16}O projectiles with C, Cu, Ag, and Au nuclei. Energy spectra measured at zero degrees and transverse energy distributions in the pseudorapidity range from 2.4 to 5.5 are shown. The average transverse energy per participant is found to be nearly independent of target mass. Estimates of nuclear stopping and of attained energy densities are made.

QCD lattice calculations [1] predict that, at sufficiently high energy densities, hadronic matter undergoes a transition to a new phase of matter, the quark–gluon plasma, in which quarks and gluons are deconfined over a relatively large volume. It has been suggested that collisions between heavy nuclei at ultrarelativistic energies may produce the energy densities, estimated to be greater than 2–3 GeV/fm^3, necessary for this phase transition to occur. An important goal of the first experiments with ultrarelativistic heavy-ion beams at the SPS accelerator at CERN is to investigate the extent to which this suggestion is correct. The primary experimental quantity used for estimating the energy density is the transverse energy, E_T [2–4]. In this paper transverse energy measurements, together with energies measured at zero degrees, are presented. It is shown that, in nucleus–nucleus collisions at ultrarelativistic energies, the transverse energy appears, to first order, to be determined by the number of participating nucleons. Estimates of nuclear stopping and of attained energy densities are also presented.

The experiment was performed with the WA80 experimental arrangement [5,6] at the CERN SPS. The setup includes two calorimeters: the Mid-Rapidity Calorimeter (MIRAC) and the Zero-Degree Calorimeter (ZDC) [7]. MIRAC consists of 30 stacks with each stack subdivided into six 20×20 cm^2 towers. Each tower consists of a lead/scintillator electromagnetic section of 15.6 radiation lengths (0.8 absorption lengths) and an iron/scintillator hadronic section of 6.1 absorption lengths. MIRAC is organized into five groups of six stacks, called six-

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packs, each with dimensions of 1.3×1.2 m^2. Four of the six-packs are arranged in a wall around the beam axis at a distance of 6.5 m from the target and with a 7.5×7.5 cm^2 hole in the center to allow the beam to reach the ZDC. The MIRAC wall has full azimuthal coverage in pseudorapidity, η, from 2.4 to 5.5 with partial coverage extending down to 2.0. The fifth six-pack of MIRAC is placed next to the MIRAC wall, where it covers approximately 10% of the azimuthal angles in the pseudorapidity interval from 1.6 to 2.4. The measured σ/E resolutions of the calorimeter are 14.2% for 10 GeV/c charged pions and 5.1% for 10 GeV/c electrons [7].

The ZDC is a 60×60 cm^2 uranium/scintillator calorimeter divided into an electromagnetic section of 20.5 radiation lengths and a hadronic section of 9.6 absorption lengths. The ZDC is located 11 m from the target and measures the energy of particles that pass through the beam hole in MIRAC. This hole has an inscribed cone angle of 0.3°, corresponding to $\eta > 6.0$. The ZDC is both a key component of the trigger system and an important measuring device from which the total energy of projectile spectators and/or of the leading particles is obtained. The resolution of the ZDC is 2.5% at 3.2 TeV and 4.5% at 0.96 TeV.

All data presented in this paper were obtained under the minimum bias condition. This condition is defined by the requirements that: (a) less than 88% of the full projectile energy is measured by the ZDC; and (b) at least one charged particle is recorded by the multiplicity arrays in the interval $1.3 < \eta < 4.4$. Systematic errors on the absolute cross sections are estimated to be less than 5%.

An important aspect of high energy nucleus–nucleus collisions is the nuclear collision geometry [4], as determined by the relative sizes of the target and projectile nuclei, the overlap volume in the collision, and the impact parameter. As a consequence, simple geometrical considerations can be used as a key for a qualitative understanding of the ZDC energy spectra shown in fig. 1. At 200 A GeV, the ^{16}O + ^{12}C reaction has essentially no cross section for events depositing a small amount energy in the ZDC because, in a simple participant spectator picture, even in the most central collisions, several projectile spectator nucleons, each with an energy of 200 GeV, proceed in the beam direction. In contrast to this, a

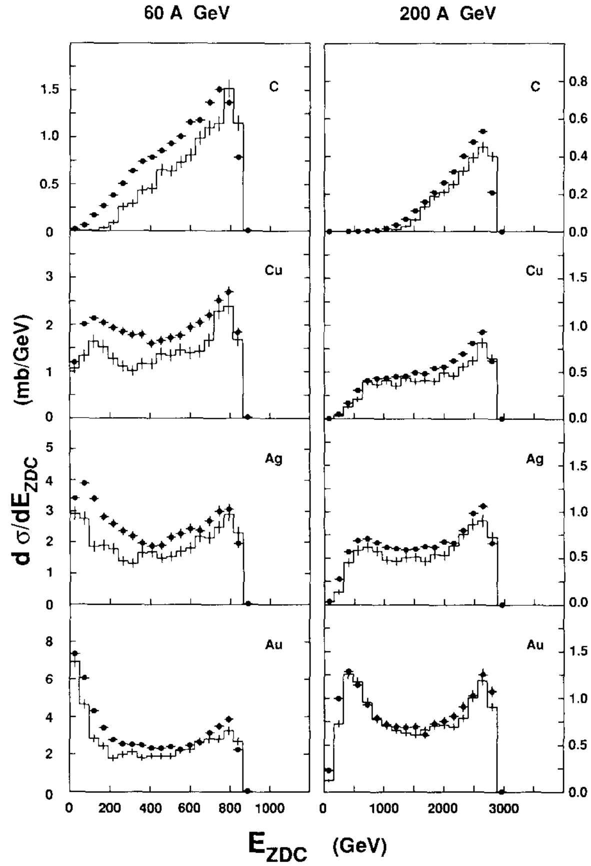

Fig. 1. Energy spectra measured in the zero-degree calorimeter (filled circles) in ^{16}O induced reactions. Histograms give the results of the FRITIOF model [8]. The vertical error bars represent statistical errors.

pronounced peak is seen at small ZDC energies in the spectrum from the ^{16}O + ^{197}Au reaction. In this case, events with low ZDC energies result from central collisions in which the oxygen projectile is engulfed by the massive Au nucleus, resulting in the emission of only a few leading particles at angles less than 0.3°. Furthermore, in this case, a wide range of impact parameters gives rise to collisions in which the entire projectile interacts with a nearly constant number of target nucleons, thus producing the peak at low ZDC energies.

In going from 200 A GeV to 60 A GeV the nucleon–nucleon CM rapidity decreases from 3.0 to 2.4. As a consequence, if there is no significant change in the reaction mechanism, the beam hole in MIRAC results in a more restricted ZDC coverage at the lower beam energy, and the measured integrated energy of the reaction products is correspondingly lower. This is clearly seen in the 60 A GeV $^{16}O+^{197}Au$ spectrum, which has an even more pronounced peak at the lowest energies. In the 60 A GeV $^{16}O+^{12}C$ reaction there are many more events with low ZDC energies as compared to the 200 A GeV case. These events may originate from collisions in which the oxygen projectile fragments so violently that one or more of the projectile spectators has a pseudorapidity lower than 6 and is thereby intercepted by MIRAC.

In an effort to isolate characteristic features of nucleus–nucleus collisions (e.g., collective phenomena) from those that may be expected on the basis of nucleon–nucleon or nucleon–nucleus collisions, we compare measured quantities with calculations that reproduce data from nucleon induced reactions and that make predictions from nucleus–nucleus reactions. While several models for this procedure are available, none has as yet been demonstrated to have clear advantages over the others. Consequently, we have chosen to make comparisons with the Lund model for high-energy nucleus–nucleus interactions (FRITIOF) [8]. Effects of detector acceptance and of trigger bias have been included in all FRITIOF calculations shown in this work.

The absolute cross section predictions of the FRITIOF model are shown as histograms in fig. 1. At 200 A GeV, the ZDC energy spectra are well reproduced by the calculation; whereas, at 60 A GeV, FRITIOF underestimates the cross sections, especially for the lighter targets. As discussed above, this discrepancy at 60 A GeV might be caused by projectile spectator fragmention, which is not included in the FRITIOF model. The agreement at 200 A GeV indicates that the model provides a good description of the impact-parameter dependence of the longitudinal momentum transfer.

The transverse energy produced in the reaction is measured on an event-by-event basis in MIRAC. The transverse energy is calculated as $E_T=\sum E_i \sin(\theta_i)$, where E_i and θ_i are the observed energy and the effective angle of each element i of MIRAC, respectively. The estimated systematic error in the transverse energy scale is 10%. Based on measurements of the response of the calorimeter to electrons, pions, and protons of known energies between 2 and

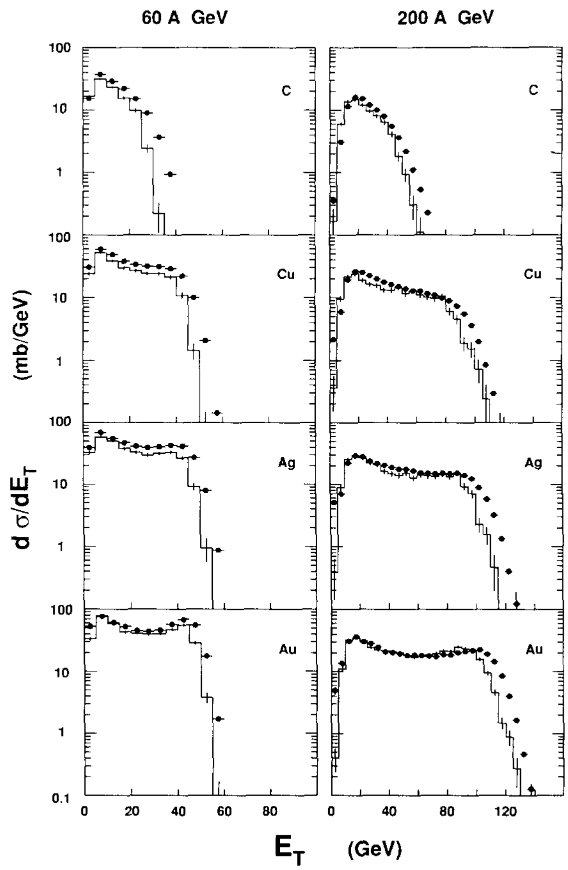

Fig. 2. Transverse energy distributions measured in the pseudorapidity range of $2.4<\eta<5.5$ for 60 A GeV and 200 A GeV ^{16}O projectiles incident on targets of C, Cu, Ag, and Au. The experimental results (filled circles) are presented with their statistical errors. Histograms give the results of the FRITIOF model.

50 GeV, an iterative procedure has been developed by means of which the nonprojective features of the calorimeter response are corrected for. The method is described in detail elsewhere [7,9].

The transverse energy distributions for $2.4<\eta<5.5$ are shown in fig. 2. As in the case of the ZDC spectra, the shapes of the E_T spectra are dominated by effects of the nuclear collision geometry. The spectra for the heaviest nuclei, Ag and Au, show a large "plateau" extending out to 80–100 GeV at 200 A GeV beam energy and to 40–45 GeV at 60 A GeV. The Au spectra have a broad peak at the high-energy end of the plateau. This peak is closely correlated with the low-energy peak in the Au ZDC spectra, as can be seen from the contour plot of $d^2\sigma/dE_T\,dE_{ZDC}$ in

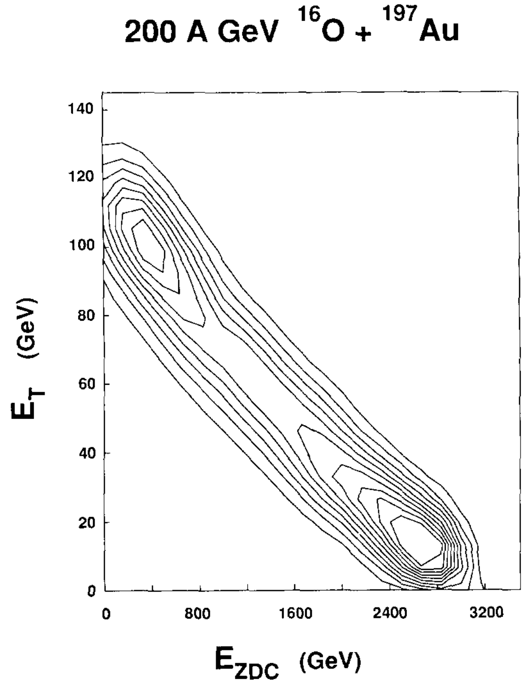

Fig. 3. Yield distributions as a function of the transverse energy (for $2.4 < \eta < 5.5$) and of the energy measured in the zero-degree calorimeter. The distance between the contours corresponds to a factor of two in yield.

fig. 3. This correlation demonstrates that the peak in the E_T distribution, corresponding to low ZDC energies, originates from the most central collisions, in which the entire projectile interacts with a nearly constant number of target nucleons. As the target becomes smaller, the peak and the plateau become less pronounced. For $^{16}O + ^{12}C$, the E_T spectra have shapes similar to those of the E_T spectra measured in proton-induced reactions [10], whereas the heavy target spectra are similar, both in shape and energy scale, to the E_T spectra for 200 A GeV $^{16}O + Pb$ of the NA35 Collaboration [4].

At 60 A GeV, the high-energy tails of the E_T distributions for Cu, Ag, and Au targets almost coincide with one another at a value of approximately 60 GeV. This phenomenon could be caused by "complete stopping" as discussed in ref. [11]. However, at our beam energies, this finding is more likely to be due to a combination of two opposing effects. As the target mass or number of target participants increases, the maximum transverse energy increases. At the same time, however, the rapidity of the effective CM system decreases, leading to decreased coverage by MIRAC. At 60 A GeV these two effects tend to cancel each other; whereas at 200 A GeV the increase E_T dominates over the decreasing coverage, resulting in a net increase of the observed transverse energy. This demonstrates that the precise shapes of the observed E_T spectra are a sensitive function of the pseudorapidity region in which they are measured. Thus, in measurements with coverage of the lower pseudorapidity region, no peak has been seen at high E_T for heavy targets [12]. FRITIOF calculations are consistent with this observation.

The histograms in fig. 2 are the results of FRITIOF calculations. For all targets and projectile energies the model gives a good description of the shapes of the E_T spectra but consistently underestimates the transverse energy scale in the tail region by 10% to 15%.

In view of the importance of the nuclear collision geometry, it is desirable to develop a simple method by means of which the impact parameter and the number of participating nucleons can be determined. An estimate of the number of projectile participants could be obtained from the ZDC with the simple assumption that all of the observed ZDC energy is due to projectile spectators. Similarly, the number of target participants could be estimated on the assumption that all target nucleons lying in the path of the projectile are participants. This relationship between the ZDC energy and the number of projectile participants is not, however, strictly valid in the presence of leading particles or of other reaction products with $\eta > 6.0$. Therefore, two alternative methods have been used to obtain a more accurate estimate of the average number of participating nucleons. First, since the ZDC data are reasonably well described by FRITIOF, the model has been used to establish a relationship between ZDC energies and the number of participants. Second, the average number of participants as a function of ZDC energy was deduced from a sharp sphere nuclear shape model together with the assumption of a monotonic increase of the impact parameter with ZDC energy and by using the relationship between impact parameter and absolute cross section. The results from both methods, shown in fig. 4 for $^{16}O + ^{197}Au$

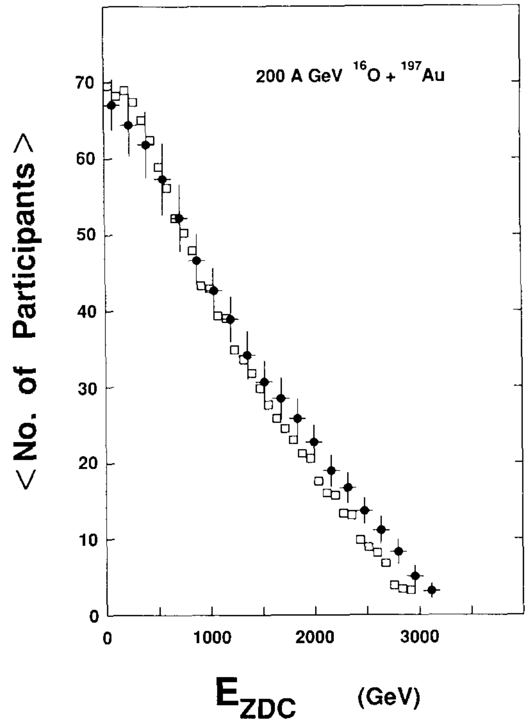

Fig. 4. The average number of participants as a function of the energy measured in the zero-degree calorimeter. The filled circles indicate the results of FRITIOF calculations, and the vertical bars indicate the standard deviations in the distributions of participants at fixed values of ZDC energy. The open squares give the results of a model independent impact parameter analysis (see text for details).

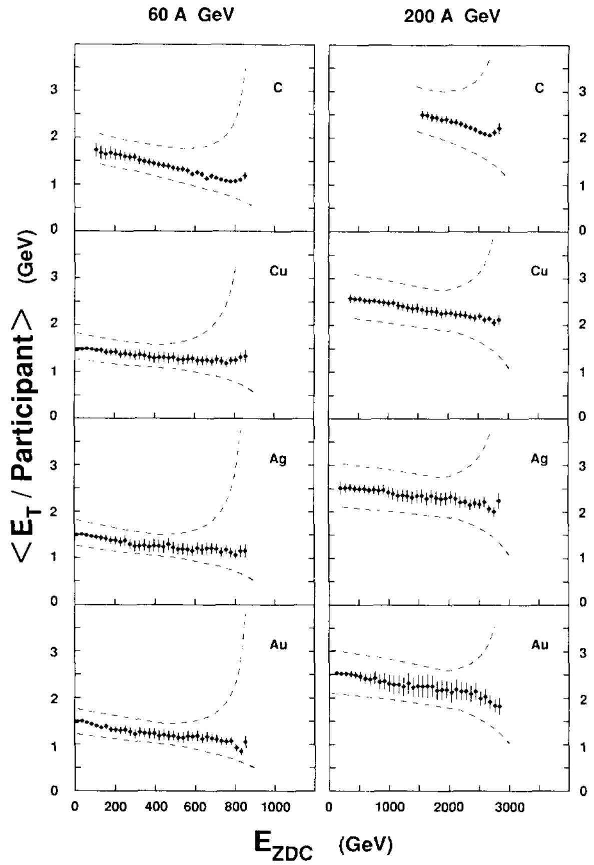

Fig. 5. Average values of E_T/participant as a function of the energy measured in the zero-degree calorimeter. The pseudorapidity range used in the E_T determination is $1.6<\eta<5.5$. The dashed lines indicate the estimated systematic error limits.

at 200 A GeV, are seen to be consistent with each other.

With a relationship established between the total number of participants and the ZDC energy, the E_T distributions can be examined as a function of the number of participating nucleons. In fig. 5, the average E_T per participant is shown as a function of the ZDC energy. This $\langle E_T/\text{participant}\rangle$ is calculated using the azimuthal-acceptance-corrected E_T measured in the pseudorapidity interval $1.6<\eta<5.5$ and the average number of participants corresponding to the observed ZDC energy. The striking feature of fig. 5 is that, at a given bombarding energy, the $\langle E_T/\text{participant}\rangle$ remains nearly constant as a function of target mass and decreases only slowly with decreasing collision centrality. Based on the above analysis, the transverse energies in central Pb+Pb collisions at 200 A GeV can be expected to be five to six times larger than those in ^{16}O+^{197}Au collisions. This does not, however, necessarily imply a higher energy density since the volume associated with the transverse energy production will be correspondingly larger.

The degree of nuclear stopping and the attained energy densities are two of the key quantities that relate to the probability of quark–gluon plasma formation. Estimates of these quantities based on our data are given here. Due to difficulties associated with a precise definition of "nuclear stopping", our stopping results are presented in terms of two different ratios, S_{int} and S_{mid}, between measured and theoretical values of transverse energies. The maximum value of the transverse energy, E_T^{max}, can be estimated under the assumptions that: (a) in central

Table 1
Calculation of the "integrated energy stopping" and the "mid-rapidity energy stopping" in central collisions of $^{16}O+^{197}Au$.

E_{beam}	60 A GeV	200 A GeV
N'_{part} (number of target participants)	52.0	52.0
E_{CM} (GeV)	309.2	559.1
$E'_{CM}=E_{CM}-(M^{proj}+M'_{part})c^2$ (GeV)	245.8	495.7
$E_T^{max}=\frac{1}{4}\pi E'_{CM}$ (GeV)	193.1	389.4
$[dE_T(\text{theory})/d\eta]_{max}=\frac{1}{2}E'_{CM}$ (GeV)	122.9	247.9
$E_T^{integrated}$ (GeV)	109(16)	197(30)
$[dE_T(\text{experiment})/d\eta]_{max}$ (GeV)	43(5)	66(7)
$S_{int}=E_T^{integrated}/E_T^{max}$	57(9)%	51(8)%
$S_{mid}=\dfrac{[dE_T(\text{experiment})/d\eta]_{max}}{[dE_T(\text{theory})/d\eta]_{max}}$	35(4)%	27(3)%

collisions all the projectile nucleons react with a cylinder of the target nucleus that has a base area equal to the cross section of the projectile; and (b) all of the available center-of-mass energy, E'_{CM}, is emitted isotropically in the CM system. E'_{CM} is obtained from the CM energy by subtracting the rest mass of the participating baryons. In this simple model $E_T^{max}=\frac{1}{4}\pi E'_{CM}$ and $[dE_T(\text{theory})/d\eta]_{max}=\frac{1}{2}E'_{CM}$. Numerical details of the calculation are indicated in table 1. In the analysis of the experimental data, only central events have been considered by restricting the number of participants to be larger than 24, 45, 50, and 55 for C, Cu, Ag, and Au, respectively. By fitting the experimental $dE_T/d\eta$ distribution in the interval $1.6<\eta<5.5$ with a gaussian distribution, the $E_T^{integrated}$ has been calculated as the integral of the fitted distribution. Likewise, the quantity $[dE_T(\text{experiment})/d\eta]_{max}$ has been taken to be the maximum value of the gaussian. The "integrated energy stopping", S_{int}, is defined as the ratio between $E_T^{integrated}$ and E_T^{max}. This ratio is seen from table 1 to decrease from 57% at 60 A GeV to 51% at 200 A GeV for $^{16}O+^{197}Au$. Probably a more relevant number for the stopping is the "mid-rapidity energy stopping", S_{mid}, defined as the ratio between $[dE_T(\text{experiment})/d\eta]_{max}$ and $[dE_T(\text{theory})/d\eta]_{max}$. The systematics of this quantity is shown in table 2.At 60 A GeV S_{mid} is about $\frac{1}{3}$ and only decreasing to $\frac{1}{4}$ at 200 A GeV. S_{mid} appears to be only very weakly dependent on the target mass. It should be stressed that in the above discussion of nuclear stopping the isotropic source model has only been introduced to estimate the largest possible kinematical limits.

Table 2
"Mid-rapidity energy stopping" for ^{16}O+C, Cu, Ag, and Au at 60 A GeV and 200 A GeV.

	60 A GeV	200 A GeV
C	31(3)%	21(2)%
Cu	32(3)%	26(3)%
Ag	35(4)%	26(3)%
Au	35(4)%	27(3)%

At present, no generally accepted method exists for the determination of the energy density, ε, from experimental results. We estimate ε from the following formula, which is based on the work of Bjorken [2] and which is similar to that used by Burnett et al. [3]:

$$\varepsilon=\frac{1}{\tau_0\pi R^2}\frac{dE_T}{dy}. \tag{1}$$

Here τ_0 was taken to be 1 fm/c, and the sharp-surface electron-scattering value of 3.0 fm was used for R, the radius of ^{16}O [13]. Rapidity was replaced by pseudorapidity, and an interval of $2.4<\eta<4.0$ was used. Values of ε obtained by this prescription are believed to be underestimates of true energy densities attained [14]. Results are shown in fig. 6 for $^{16}O+^{197}Au$. The ε distribution extends to 1.3 GeV/fm^3 at 60 A GeV and as high as 2.7 GeV/fm^3 at 200 A GeV, reaching, in this case, the region of energy densities that are believed to be required for the formation of the quark–gluon plasma. The value of ε at 200 A GeV is similar to an energy density of 2.2

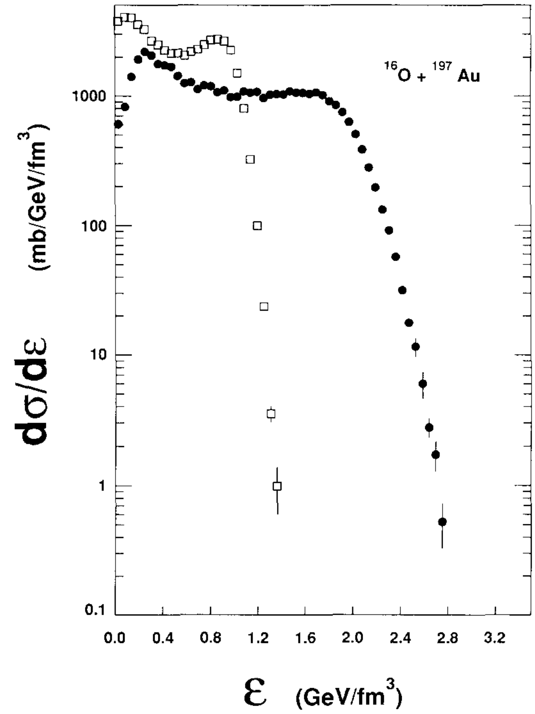

Fig. 6. Energy density distribution for 60 A GeV (open squares) and 200 A GeV (filled circles) $^{16}O + ^{197}Au$ reactions as obtained from eq. (1) (see text for details concerning the calculation of ε).

GeV/fm^3 for average central collisions as measured by the NA35 Collaboration [4].

In summary, results have been presented from reactions of 60 A GeV and 200 A GeV ^{16}O projectiles with various target nuclei. Energy measurements for $\eta > 6.0$ and E_T distributions for $2.4 < \eta < 5.5$ were shown. The importance of the collision geometry was stressed. Average total participant numbers were extracted and used to show that the average transverse energy per participant is nearly independent of target mass at a given bombarding energy. Estimates of stopping and of energy densities have been made. We conclude that conditions required for the formation of the quark–gluon plasma may have been achieved in some of the most central collisions of $^{16}O + ^{197}Au$ at 200 A GeV.

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