Title
TRANSVERSE ENERGY AND MULTIPLICITY DISTRIBUTIONS IN COLLISIONS AT 60 AND 200 GEV PER NUCLEON

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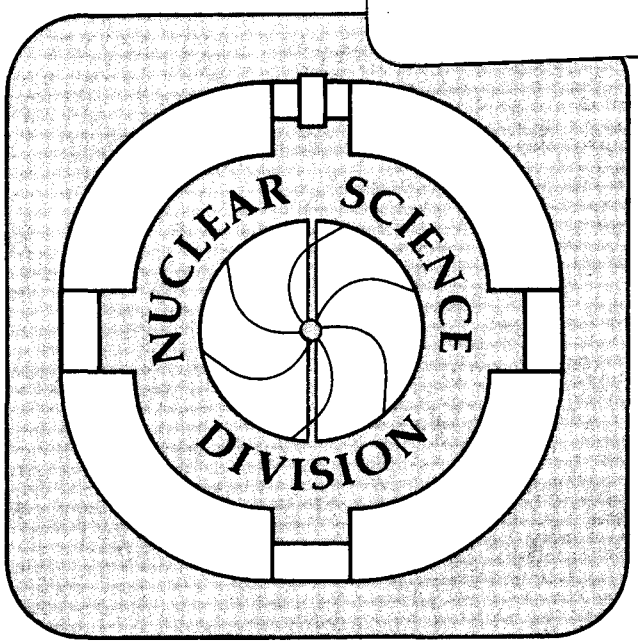

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TRANSVERSE ENERGY AND MULTIPLICITY DISTRIBUTIONS IN COLLISIONS AT 60 AND 200 GEV PER NUCLEON

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Transverse energy and multiplicity distributions from several CERN heavy ion experiments are presented. The large degree of nuclear cascading is shown. Nuclear stopping and the energy density reached in central collisions are discussed.

1. INTRODUCTION

The successful acceleration of light ions at the CERN SPS and at the Brookhaven AGS opened the exiting new field of ultra-relativistic heavy ion collisions for systematic studies. The first results from the different experiments provided a great amount of information about the basic properties of high energy heavy ion reactions and have revealed some puzzling new features.

In this paper the particular aspects of transverse momentum and charged particle production are reviewed. These two quantities are determined by most of the experiments and serve to characterize the events. Large multiplicities and large transverse energies are correlated with violent collisions or with small impact parameters. A careful analysis of those data will lead to a better understanding of the reaction mechanism. In addition, transverse energy and multiplicity measurements allow to make an estimate of the initial energy density reached in the collision. High energy density is an essential condition for the occurrence of the deconfinement phase transition that is predicted by lattice QCD calculations[1,2].

The results of the first round of experiments with oxygen ions at 60 and 200 GeV per nucleon are collected in the proceedings of the Quark Matter 88 conference[1]. Some of these results are repeated here together with new results from the sulphur run at 200 GeV per nucleon. The richness of the data makes it impossible to mention all the relevant data from all the experiments.

The data are compared with model predictions. An overview of the different models and the Monte Carlo codes FRITIOF[3], IRIS[4] and VENUS[5] has been given in a paper by Capella[6]. Their common feature is the assumption that the properties of the nucleus-nucleus collisions can be calculated from a superposition of nucleon-nucleon collisions (independent strings) if the nuclear geometry is treated correctly and if the known physics of N-N collisions is properly taken into account. It is hoped that deviations from the "normal" behaviour predicted by those models will show characteristic properties of nucleus-nucleus collisions, like collective phenomena. However, the definition of "normal" behaviour is far from being final and may require many iterations.

2. FORWARD ENERGY

The amount of energy that the projectile lost in a nuclear reaction is a good indication for the violence of the collision and for the impact parameter. This energy can be determined from the difference between the projectile energy and the energy of the projectile fragments under nearly zero degrees. Figure 1 shows an example of the energy spectra measured under zero degrees

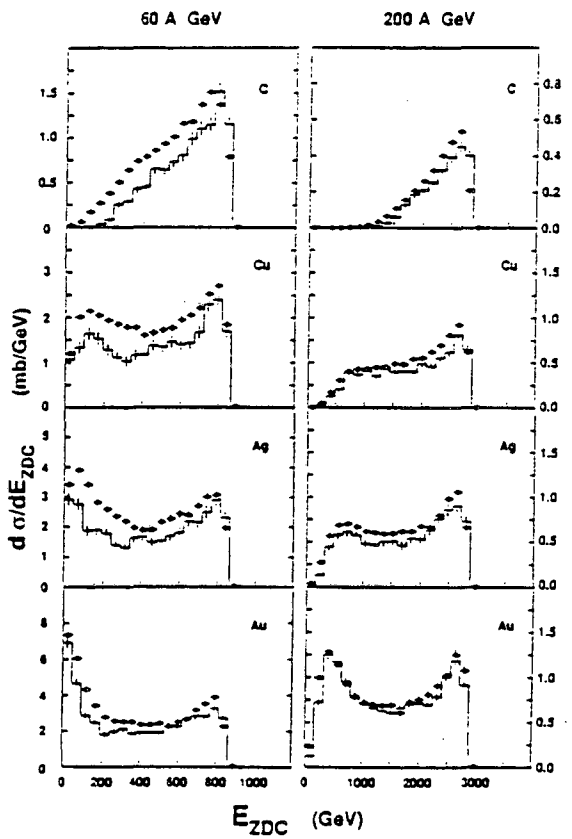

FIGURE 1
Energy spectra measured in the zero degree calorimeter (filled circles) in oxygen induced reactions (WA80). Histograms give the results of the FRITIOF model

by WA80[7] in oxygen induced reactions at 60 and 200 GeV per nucleon. For the carbon targets there is essentially no probability for events with a small energy deposit in the zero degree calorimeter, since the target nucleus is smaller than the projectile and in a simple participant-spectator model there will always be projectile remnants at angles smaller than 0.3 degrees. The probability for small energy deposits at zero degrees increases as the mass of the target nucleus increases. The fact that there is a large cross section for a total overlap between an oxygen projectile and a gold target is manifested by a relative peak at small zero degree energies.

The predictions of the FRITIOF model[3] are shown as histograms in figure 1. The agreement with the data is quite good, especially for the shapes of the distributions. This indicates that this

model provides a good description of the impact parameter dependence of the longitudinal momentum transfer.

3. CORRELATIONS

The longitudinal energy missing under zero degrees has been transformed into transverse energy during the collision. The transverse energy E_T is defined as $E_T = \sum E_i \sin\theta_i$, where E_i is the kinetic energy for baryons, the total energy plus the rest mass for antibaryons and the total energy for all other particles. θ_i is the scattering angle. The correlation between transverse energy and forward energy, measured by WA80[7], is shown in figure 2 for ^{16}O+ Au at 200 GeV

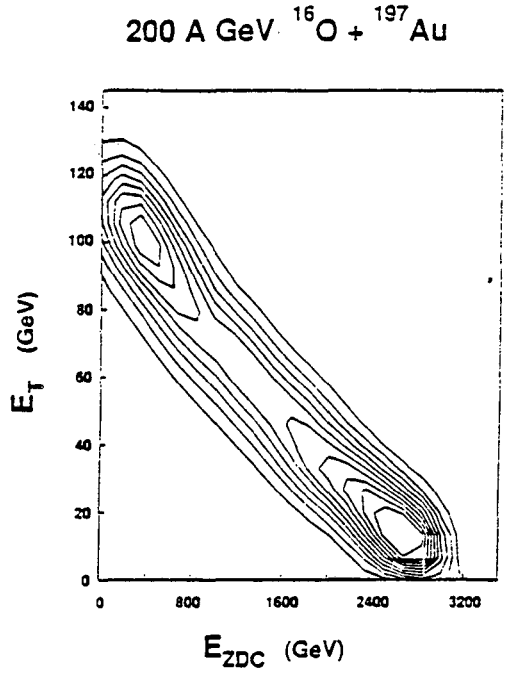

FIGURE 2
Contour plot of the correlation between the forward and the transverse energy (WA80)

per nucleon. The contours indicate that there is a large probability for peripheral collisions (small E_T and forward energy close to the total beam energy of 3.2 TeV) and for central collisions where only a small part of the projectile energy is measured in the forward direction. These findings are in agreement with a geometrical picture of the reaction where a large cross-section can be expected for peripheral collisions and for central collisions where the cross-section for total overlap between the Au target and the ^{16}O projectile is relatively large.

The correlation between E_T and the charged particle multiplicity measured by the WA80 collaboration[8] is shown in figure 3 for oxygen on gold at 200 GeV per nucleon. The strictly linear relationship between the two quantities indicates that charged particles are produced with a mean transverse energy of about 550 MeV. This value changes by not more than 10% as a

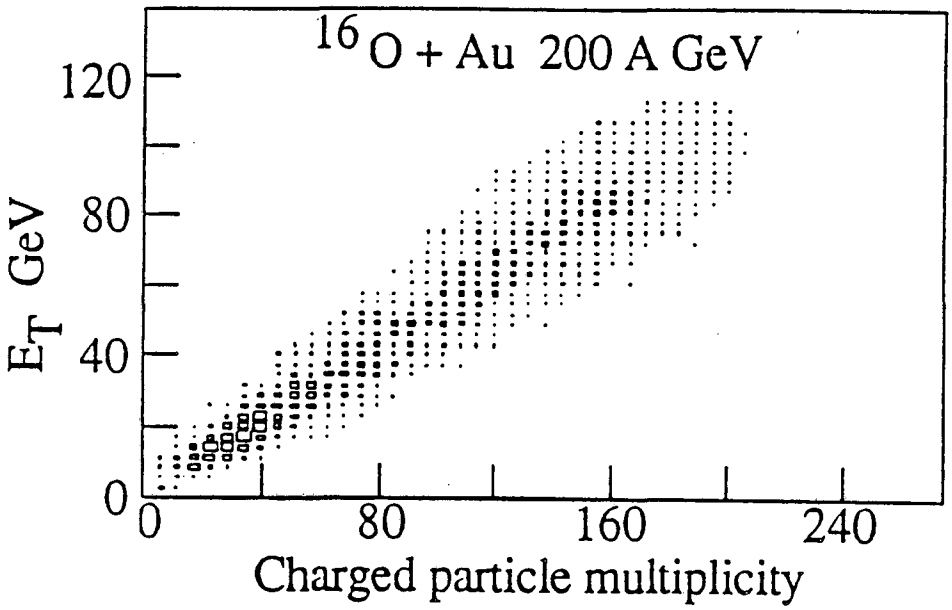

FIGURE 3
Correlation between the charged particle multiplicity and the transverse energy (WA80)

function of impact parameter (E_T)[9] and is the same (within 10%) at 60 and 200 GeV per nucleon for all the different targets[8].

4. TRANSVERSE ENERGY AND MULTIPLICITY

The linear correlation between the mean charged particle multiplicity and the mean transverse energy suggests that both are equally well suited for the characterization of the events and that future experiments need to measure only one of the two quantities provided that this relation holds for all possible selections up to very small cross sections and that fluctuations are not important. In the rest of this paper this equivalence will be further studied and demonstrated.

Transverse energy distributions measured with oxygen induced reactions at 60 and 200 GeV per nucleon by WA80[7] are shown in figure 4 and the corresponding multiplicity distributions[8] in figure 5. The shape of the distributions is determined by the collision geometry as has been nicely demonstrated in ref 10. The transverse energy and the charged particle multiplicity increase with increasing energy and with increasing target mass.

It is interesting to note that the E_T distributions at 60 GeV seem to saturate for the heavier targets (Cu, Ag, Au). At AGS energies this behaviour has been interpreted as a sign for complete stopping[11,12], at the CERN SPS, however, this has been investigated in detail and is an effect of limited acceptance of the calorimeters[13] that cover only the forward hemisphere in the N-N center of mass system.

The histograms in figures 4 and 5 show the FRITIOF predictions. The shape of the spectra is well described, but generally FRITIOF underestimates the magnitude of E_T and of the multiplicity.

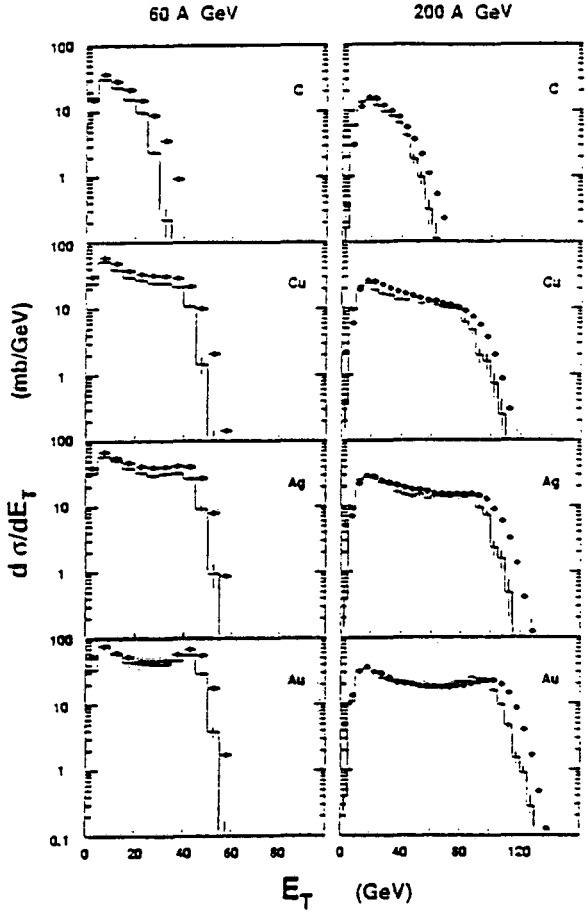

FIGURE 4

Transverse energy distributions in 2.4< η <5.5 for 60 and 200 GeV per nucleon oxygen induced reactions (WA80). The FRITIOF predictions are represented by the histograms

Slightly better agreement with the data has been obtained with the code VENUS[5]. In this work, results on E_T from WA80[7], NA34[10] and NA35[14] are compared with theoretical predictions. Using one single model offers a very convenient test of the consistency between different experiments since all the experiments cover a different range of pseudorapidity with their calorimeters and multiplicity arrays. Of course, all the details of the analysis like unfolding of calorimeter results and square versus spherical boundaries in the η-range have to be taken into account.

Figure 6 shows the projectile mass dependence of E_T as measured by NA34[15]. The E_T values obtained with the ^{32}S projectile are higher than the corresponding values for the ^{16}O beam by about a factor of 1.6. This seems to indicate that the projectile mass dependence scales with $\alpha = 2/3$. The same result has been reported by WA80[16]. The two bands in figure 6 show the predictions by the IRIS model[4]. Again, the data are underpredicted and it seems that the IRIS predictions increase faster with increasing projectile mass than the data.

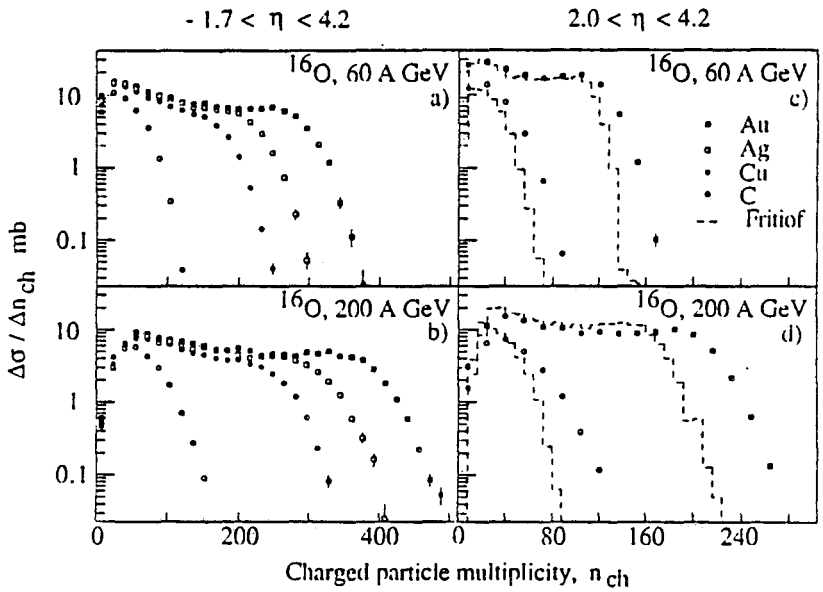

FIGURE 5
Multiplicity distributions for 60 and 200 GeV per nucleon oxygen induced reactions in two different rapidity intervals (WA80). The FRITIOF predictions are represented by the histograms

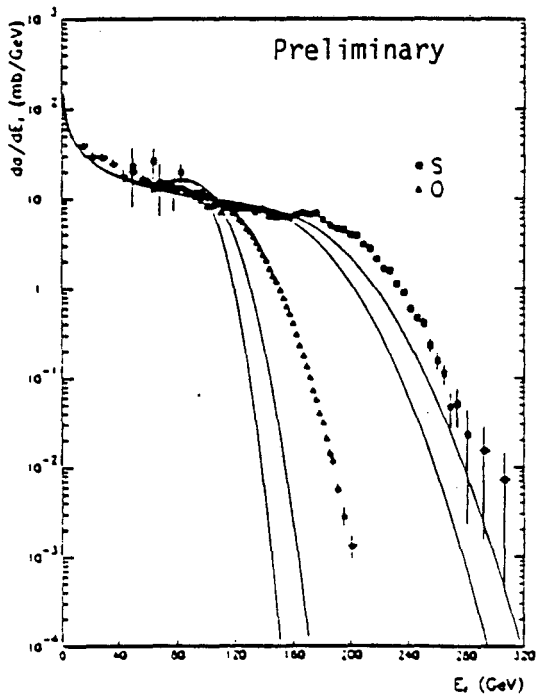

FIGURE 6
Transverse energy differential cross-section, dσ/dE$_T$, in -0.1< η <2.9 for ^{16}O + W and ^{32}S + W at 200 GeV per nucleon (NA34). The bands represent the IRIS predictions

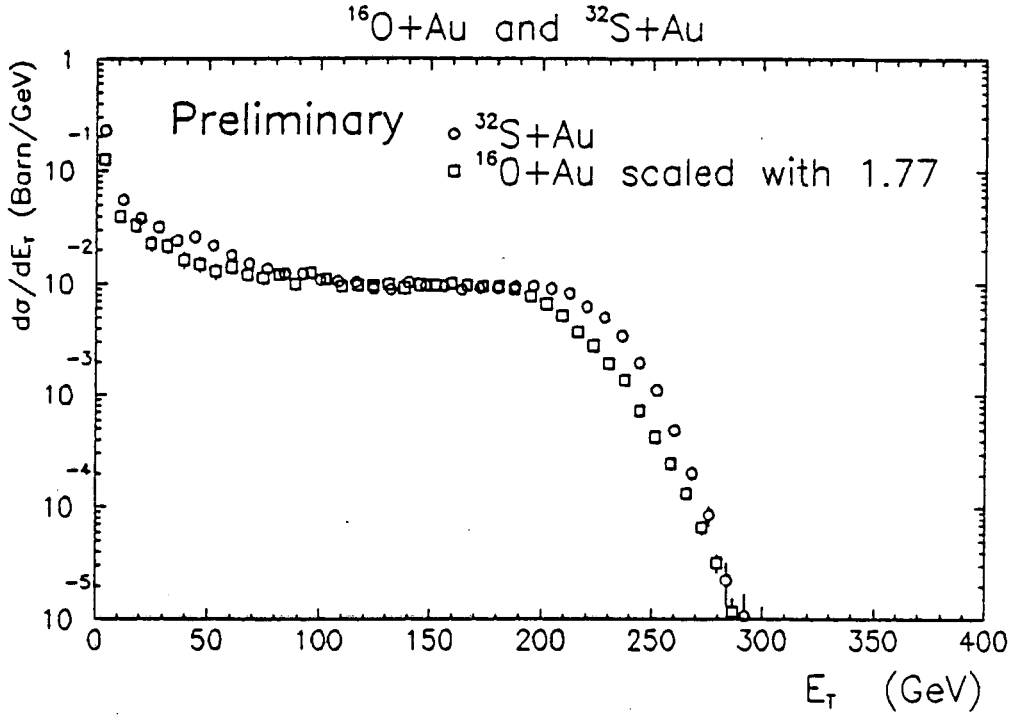

FIGURE 7

Transverse energy differential cross-section, $d\sigma/dE_T$, for ^{32}S + Au and ^{16}O + Au scaled with 1.77 (NA35)

An interesting observation has been made by the NA35 collaboration[17]. As shown in figure 7, the ^{32}S + Au E_T distribution is nearly identical with the ^{16}O + Au distribution scaled by 1.77, that is the ratio of the maximal total energy in the center of mass of the fireball system for the two reactions, without taking into account the change in acceptance. This scaling law holds for the lower mass targets as well. It will be interesting to see if such a law can be established over a larger mass range. A scaling factor of less than two, however, indicates that the simple folding model that explains the E_T distribution of central ^{16}O + Au collisions as a folding of 16 p + Au distributions[14] does not work[18] for ^{32}S + Au, since it uses the wrong collision geometry. It should as well be noted that the scaling factor would be larger than 1.77 if determined at 50% of the plateau value as done for the other experiments.

More detailed information can be obtained from the pseudorapidity dependence of the transverse energy[9] and the multiplicity[8] as shown in figures 8 and 9. The rapidity density increases with increasing energy and target mass. The position of the peak of the multiplicity density distribution shifts from forward of mid-rapidity of the N-N system (η = 3 for 200 GeV) for the carbon target to backward angles as would be expected in a fireball picture. The comparison with model predictions shows that the models underpredict the measured E_T and multiplicity distributions. The deviations are larger near target rapidity and for the heavier targets. Multiplicity

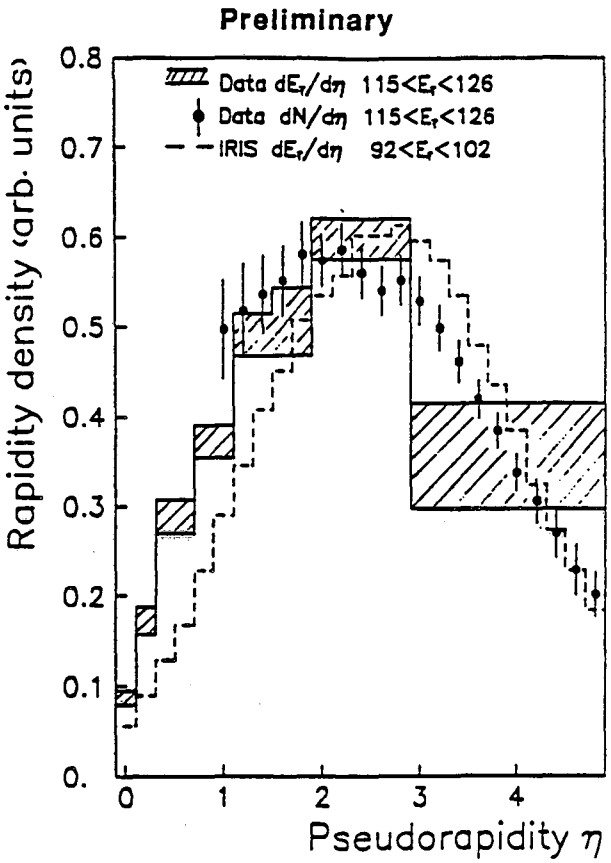

FIGURE 8

Transverse energy distribution $dE_T/d\eta$, multiplicity distribution $dN/d\eta$ and IRIS $dE_T/d\eta$ (NA34)

distributions measured with emulsions[19], however, show good agreement with FRITIOF calculations over the whole rapidity range. Since in the emulsion results only the fast "shower" particles (momenta larger than about 1 GeV/c) are analyzed, one can conclude that the discrepancies between the WA80 results and the FRITIOF calculations near target rapidities are mainly due to target cascading producing relatively slow particles. Target cascading has been observed in p-nucleus reactions[20] and is not included in the models discussed so far.

5. TARGET CASCADING

The target mass dependence of observables like cross sections or multiplicities can be parametrized as A^{α}. The exponent α extracted by WA80 from the multiplicity distributions[8] is shown in figure 10 for ^{16}O induced reactions at 60 and 200 GeV per nucleon as a function of the pseudorapidity η. Over the observed η range α varies dramatically from $\alpha = 0$ near the projectile over $\alpha = 1/6$ near mid-rapidity to $\alpha > 0.8$ at the target rapidity. This indicates that a large fraction of the target is involved in the collision. The reaction products in the target rapidity are measured by the Plastic Ball in the WA80 experiment[21]. Figure 11 shows that up to 50 GeV transverse

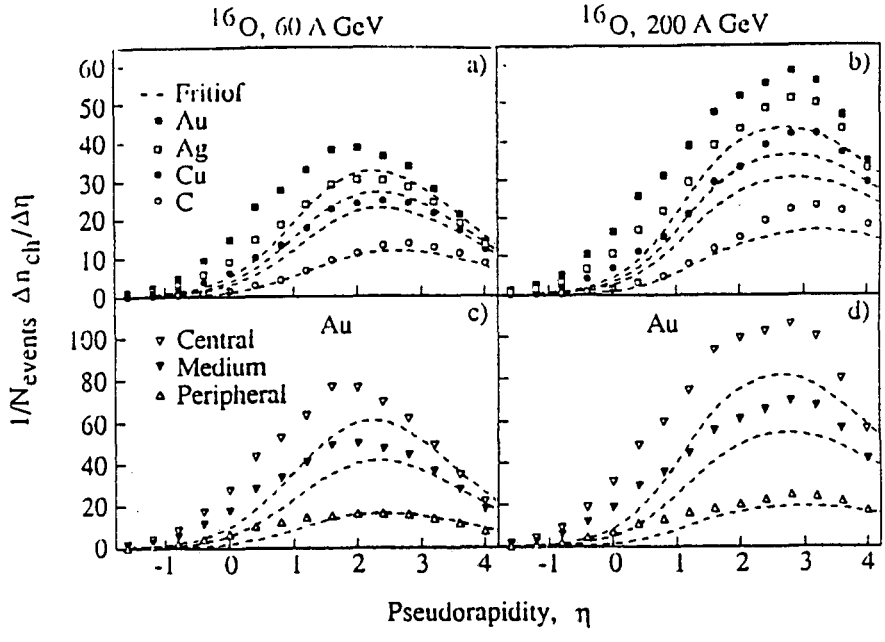

FIGURE 9

Pseudorapidity density distributions dn/dη of charged particles for oxygen induced reactions at 60 and 200 GeV per nucleon. a) and b) are taken with minimum bias trigger and c) and d) for different centrality selections (WA80). The dashed lines represent the FRITIOF predictions

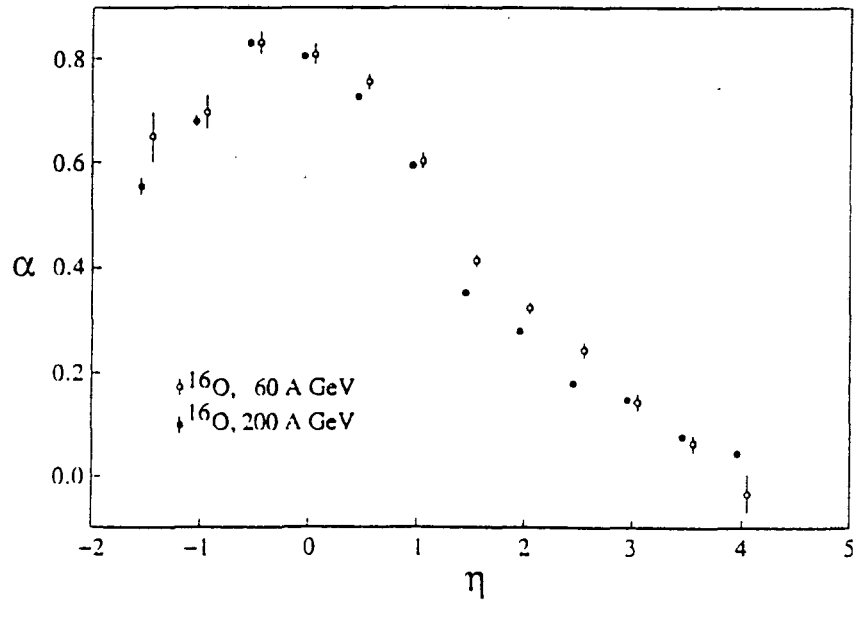

FIGURE 10

Target dependence of the multiplicity density, parametrized as A^{α}, as a function of the pseudorapidity η (WA80)

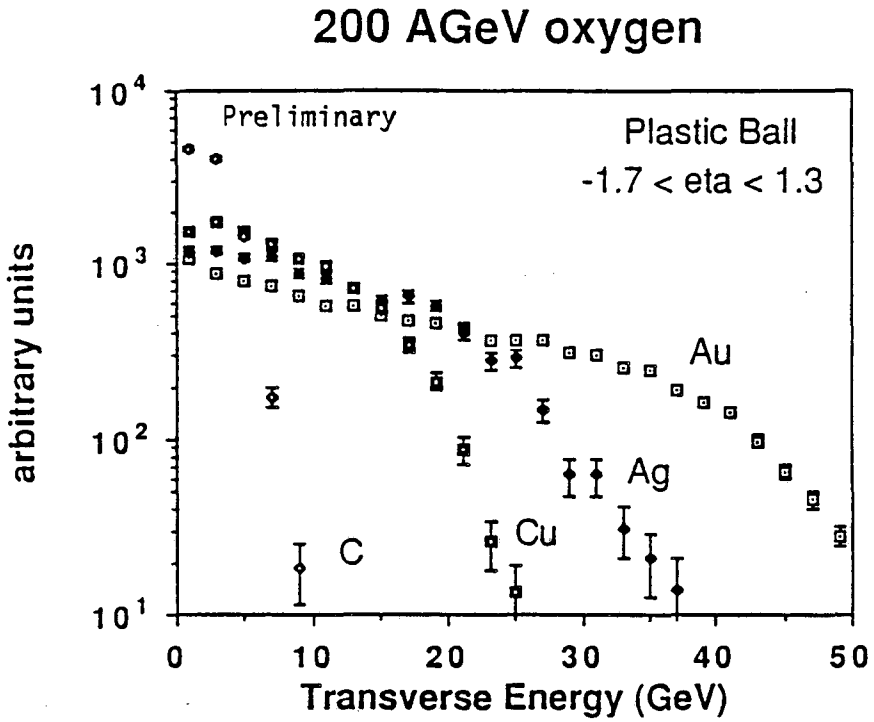

FIGURE 11
Transverse energy distributions $d\sigma/dE_T$ in $-1.7 < \eta < 1.3$ (WA80)

energy are observed in $-1.7 < \eta < 1.3$ for ^{16}O + Au reactions at 200 GeV per nucleon. The scaling factor extracted is $\alpha = 0.7$ in accordance with the behaviour indicated in figure 10. In the same rapidity interval much more than 100 charged particles have been observed[8] for the same reaction as can be seen from the difference between the distributions in figure 5b and 5d.

The degree of target cascading depends on the formation time of the produced hadrons. If those particles are formed very late, they cannot re-interact in the target, a short formation time on the other hand will lead to a large degree of cascading. Thus the target nucleus can be used to measure the hadron formation time in the same way as in p-nucleus collisions[20]. There are presently two approaches to take nuclear cascading into account in the Monte Carlo models[22,23]. By trying to explain the experimental multiplicity and transverse energy distributions or the rapidity distributions of the protons measured in the Plastic Ball[21], a formation time parameter τ can be determined. It will be interesting to see if the distributions measured in the backward direction will be described by those models* and if all the present differences between the independent string models and the data can be attributed to target

* The definition of E_T used in ref. 22 differs from the definition used in the experiments. Consequently, agreement with the experiment is only possible[24] with formation times in the order of 1 fm/c.

cascading or if other phenomena not included in independent nucleon-nucleon interactions will be needed to explain the data.

6. STOPPING AND ENERGY DENSITY

There are two different possibilities to create high energy density at mid-rapidity. At BEVALAC and probably as well at AGS energies we are in the Landau stopping domain where the incoming baryons are stopped and randomly distributed in the center of mass system. At about 30 GeV per nucleon it is estimated[25] that nuclei become transparent and that the rapidity gap between the nucleons widens. This is the Bjorken scaling domain. It is highly probable, that at CERN energies the projectile is no longer fully stopped, but a rigorous proof can only be achieved by measuring the rapidity distribution of the nucleons or the protons. That has not yet been done over the full rapidity range. A crude estimate of the degree of stopping can be obtained by comparing the transverse energy measured in the calorimeters with a maximum energy E_{Tmax}, that is calculated under the assumption of a fireball geometry and that all the available center of mass energy is emitted isotropically. The integrated energy stopping[7] is defined as $S_{int} = E_{Tint}/E_{Tmax}$ where E_{Tint} is calculated as the integral over a Gaussian distribution that fits the measured $dE_T/d\eta$ distribution. The mid-rapidity stopping S_{mid} is defined as the ratio of the measured and calculated $dE_T/d\eta$ values at mid-rapidity (maximum of the distributions). For ^{16}O + Au at 200 GeV per nucleon S_{int} is 51%. This confirms, that we are not in the stopping regime and from the low value of 27% for S_{mid} one can conclude, that the rapidity distribution is rather flat.

There is no direct way to determine the energy density reached in high energy heavy ion collisions. A procedure generally accepted at 200 GeV per nucleon is to use the Bjorken formula[26] that is derived for the case of a large, nearly baryon free central region. The energy density ε is given as a ratio of energy per volume where the energy can be determined via the transverse energy or via the particle-density ρ at mid-rapidity:

$$\varepsilon = \frac{E}{V} = \frac{1}{\tau \pi R^2} \frac{dE_T}{d\eta} = \frac{1}{\tau \pi R^2} \rho \, m_T .$$

This formula contains the proper formation time τ and the radius of the projectile R as parameters. With τ = 1 fm/c and a radius of R = 3 fm for the oxygen projectile energy densities of 2 to 3 GeV/fm^3 have been determined by WA80, NA34 and NA35 from transverse energy distributions and by WA80 from multiplicity distributions for central ^{16}O + Au collisions. This density is well in the region where the deconfinement phase transition might occur[2]. In sulphur induced reactions the transverse energy increases by about a factor of 1.6 (WA80, NA34). When inserted into the Bjorken formula, this factor cancels with the increase in the projectile radius. Therefore about the same energy density is reached in sulphur induced reactions, but of course the volume over witch this density is reached is bigger. The NA35 data, however, show a slight increase in the energy density. Other methods to determine the energy density predict an increase with increasing projectile mass[27]. Given the preliminary nature of all the sulphur data, it is too early to extrapolate to the energy density that can be expected from Pb + Pb collisions.

It has been argued lately, that the parameters put into the Bjorken formula may not be realistic[28]. The formation time could as well be larger than 1 fm/c (e.g. 2 fm/c) and instead of the electromagnetic charge radius of 3 fm an "effective interaction" radius of about 4 fm would be equally justified. Those modifications could lower the energy density considerably.

7. SUMMARY

The first experiments with oxygen and sulphur beams at CERN provided a great wealth of new data. For the average event most of the features of transverse energy and multiplicity production can be described quite well by models based on the assumption of the interaction of independent strings using the correct nuclear collision geometry. Major deviations from those model predictions mainly in the target rapidity region are attributed to the high degree of nuclear cascading. There are attempts to take cascading into account by combining the string models with some form of intranuclear cascade calculations. This should give a better description of the data and should allow to determine the hadron formation time. The occurrence of new phenomena, however, can not yet be excluded.

At CERN energies the projectile is not completely stopped by the target nucleus. Therefore the initial energy density can be estimated by the Bjorken formula, even though there are considerable uncertainties inherent in such a procedure. The initial energy density reached in the reactions ^{16}O + Au and ^{32}S + Au is of the order of 2 to 3 GeV/fm^3. That falls well in the region where lattice QCD calculations predict a deconfinement phase transition.

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