ENERGY AND PARTICLE DENSITIES FROM OXYGEN-INDUCED NUCLEAR REACTIONS

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WA80 Collaboration

S Garpman\textsuperscript{5}, R Albrecht\textsuperscript{1}, T C Awes\textsuperscript{2}, C Baktash\textsuperscript{2}, P Beckmann\textsuperscript{3}, F Berger\textsuperscript{3} R Bock\textsuperscript{1}, G Claesson\textsuperscript{5}, L Dragom\textsuperscript{3}, R L Ferguson\textsuperscript{2}, A Franz\textsuperscript{4}, R Glasow\textsuperscript{3} H A Gustafsson\textsuperscript{5, b}, H H Gutbrod\textsuperscript{1}, J W Johnson\textsuperscript{2}, K H Kampert\textsuperscript{3}, B W Kolb\textsuperscript{1} P Kristiansson\textsuperscript{4}, I Y Lee\textsuperscript{2}, H Lohner\textsuperscript{3}, I Lund\textsuperscript{1}, F E Obenshain\textsuperscript{2}, A Oskarsson\textsuperscript{5}, I Otterlund\textsuperscript{5}, T Peitzmann\textsuperscript{3}, S Persson\textsuperscript{5}, F Plasil\textsuperscript{2}, A M Poskanzer\textsuperscript{4}, M Purschke\textsuperscript{3}, H G Ritter\textsuperscript{4}, R Santo\textsuperscript{3}, H R Schmidt\textsuperscript{1}, T Siemiarczuk\textsuperscript{1, a}, S P Sorensen\textsuperscript{2, c}, E Stenlund\textsuperscript{5}, and G R Young\textsuperscript{2}

\begin{itemize}
\item \textsuperscript{1} Gesellschaft für Schwerionenforschung (GSI), D-6100 Darmstadt, FRG
\item \textsuperscript{2} Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
\item \textsuperscript{3} University of Münster, D-4400 Münster, FRG
\item \textsuperscript{4} Lawrence Berkeley Laboratory, Berkeley, California 94720, USA
\item \textsuperscript{5} Division of Cosmic and Subatomic Physics, LU, S-22362 Lund, Sweden
\item \textsuperscript{a} Institute for Nuclear Studies, PL-00681 Warsaw, Poland
\item \textsuperscript{b} EP-Division, CERN, CH-1211 Geneva, Switzerland
\item \textsuperscript{c} University of Tennessee, Knoxville, Tennessee 37996, USA
\end{itemize}

Abstract  Charged particle multiplicity and pseudo-rapidity distributions observed in $^{16}$O induced nuclear collisions at 60 and 200 A GeV are presented in conjunction with forward and transverse energy distributions. From the measurements estimates of the supreme energy density obtained in central $^{16}$O + $^{197}$Au collisions at 200 A GeV yield a value of about 3 GeV/fm$^3$ seemingly enough to fulfill the presumptions for chiral symmetry restoration. The target mass dependence on the pseudo-rapidity densities is examined using a power law parametrization. The data are also compared to simulations from the Lund model (Fritiof) for nucleus-nucleus collisions.

Introduction  The CERN SPS program of fixed-target nucleus-nucleus collisions initiated when the $^{16}$O ion-source/1/ came into operation. The program offers the unique opportunity to explore the properties of nuclear matter at extremely high densities, $10^{15}$ g/cm$^3$ (about 4 times normal nuclear matter density), and temperatures, T > $10^{12}$ Kelvin (about 100 MeV), where novel, exotic forms of matter may exist. An important but not easily accessible parameter for the yields in the reactions is the impact parameter. Central nuclear collisions are accompanied by an intense particle production/2/ whereas peripheral collisions only yield a few particles. The geometrical aspects of the collision is controllable by measuring the energy flux in the forward direction, $\theta < 0.3^\circ$, by a uranium/scintillator sampling calorimeter positioned 11 meters downstream from the target.

Experimental Set-up  The experimental arrangement of WA80, shown in Fig 1, has been described earlier/3,4/. The charged particles are measured by
huge multiplicity planes (LAM, SAM, MIRAM) consisting of Iarrocci-type streamer tubes and covered with printed circuit cards with pad readout. The multiplicity planes cover the polar angle region $1.7^\circ < \theta < 32^\circ$ (in pseudo-rapidity ($\eta$) it corresponds to $4.2 > \eta > 1.2$) with regions of mutual overlap. For the multiplicity planes the thresholds are approximately $25 \text{ MeV}$ for protons and $14 \text{ MeV}$ for pions. At larger polar angles the Plastic Ball detector measures all and identifies most of the charged particles in the polar angle range $30^\circ < \eta < 160^\circ$. Together, the Plastic Ball and the Multiplicity Walls encompass 97% of $4\pi \text{ sr}$. The calorimeter setup includes the above mentioned Zero-Degree Calorimeter (ZDC) and a Mid-Rapidity Calorimeter (MIRAC). The latter consists of 30 stacks each of which is subdivided into six $20 \times 20 \text{ cm}^2$ 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. Four groups consisting of six stacks (a six-pack) are placed with 90° rotational symmetry around the beam leaving a $7.5 \times 7.5 \text{ cm}^2$ centre hole to allow the beam residues to reach the ZDC. The MIRAC wall has full azimuthal coverage in pseudo-rapidity region $2.4 < \eta < 5.5$ and partial coverage down to 2.0 units. The fifth six-pack is placed on one side adjacent to the MIRAC wall and cover $1.6 < \eta < 2.4$ but in azimuthal angles only about 10%.

**Trigger Conditions** All data presented were taken under a minimum bias condition. The only requirement imposed was that: (i) less than 88% of the full projectile energy was registered in the ZDC; and (ii) at least one charged particle was recorded by the multiplicity planes. Systematic errors on the absolute cross sections are estimated to be less than 5%.

**Data Rate and Beam Line Configuration** A typical beam level was $2 \times 10^6$ ions per beam spill, where the effective spill length was about 3.8 seconds per machine cycle of 14.4 seconds. The $O^{16}$ ions were identified by quartz Cherenkov beam counters before they impinged on targets of C, Cu, Ag and Au ($200 \text{ mg cm}^{-2}$ thickness). Typically the probability for a beam particle to interact with the target is 0.8, 0.3, 0.3, 0.2%, respectively. The vacuum system consists of a 600 micron thick aluminium target-chamber furnished with a 5-cm-diameter carbon-fibre/epoxy beam pipe of 500-micron thickness extending downstreams about 6 metres.
Forward and Transverse Energy Spectra

To start with the forward energy spectra we show in Fig 2, the differential crosssection as a function of $E_{ZDC}$. A general trend in the data for both incident energies is that whereas the lightest target C seem to have a monotonously increasing spectrum as a function of $E_{ZDC}$, the heaviest target Au exhibit a more U-shaped distribution. Since the ZDC spectra mostly reflect the geometrical aspects of the collisions there is reason to believe that this behaviour is due to the small amount of nuclear material traversed in a C nuclei even in a central collisions in comparison to a Au target nuclei.

In going from 60 A GeV to 200 A GeV the nucleon-nucleon CM rapidity changes from 2.4 to 3.0. Provided there is no change in the reaction mechanism it results in a more restricted ZDC coverage at the lower beam energy. In the 60 A Gev data this "coverage effect" would enhance the yield at low $E_{ZDC}$ as compared to the 200 A GeV data. In the comparison with the Lund Model PRITIOF effects of geometrical acceptance and of trigger bias have been included.
The transverse energy $E_T = \sum E_i \sin(\theta_i)$, where $E_i$ and $\theta_i$ are the observed energy and the effective angle of each element $i$ of MTRAC, are shown in Fig. 3. The estimated systematic error in the transverse energy scale is 10%. As in the case of the ZDC spectra, the effects of the nuclear collision geometry dominates the shape of the $E_T$ spectra. The spectra for the heaviest nuclei, Ag and Au, show a large "plateau" extending out to 80-100 GeV at 200 A GeV and to 40-45 GeV at 60 A GeV. The Au spectra exhibits a broad peak at the high-energy end of the plateau. It has been demonstrated/9/ that this peak in the $E_T$ distribution corresponds to low ZDC energies and that it originates from the most central collisions, in which the entire projectile interacts with a fairly constant number of target nucleons. For $^{16}$O+$^{12}$C, the $E_T$ spectra have a shape similar to that measured in proton-induced reactions/10/ whereas the heavy target spectra resembles the $E_T$ spectra for $^{16}$O+Pb of the NA35 Collaboration/2/. For the 60 A GeV data the tails of the $E_T$ distribution more or less coincide at a value of approximately 60 GeV. Since it is expected that an increase of the target mass should increase the maximum transverse energy it might be caused by a cancellation effect due to limited coverage of the calorimeter at this energy. FRITIOF calculations support such a point of view.

At 200 A GeV the tails of the $E_T$ distributions appear to be Gaussian shaped/1,12/ a fact which can be utilized for studying beam and target mass dependence and also provide a suitable frame for extrapolations of eventfractions. Preliminary results from $^{12}$S+Au $E_T$ spectra also fulfill this relation/12/. To estimate the energy density obtained in 60 and 200 A GeV $^{16}$O+Au interactions the Bjorken formula/13/ was used in the form: $\varepsilon = 1/(t_0 R^2) \times dE_T/dy$, with $t_0$ taken to be 1 fm/c and $R = 3.0$ fm for the radius of $^{16}$O. We used pseudo-rapidity instead of rapidity, and an interval of $2.4 < \eta < 4.0$ was used. Values of $\varepsilon$ obtained by this prescription are believed to underestimate the true energy density.

Results are shown in Fig. 4 and one can
observe that the supreme energy density is about 1.3 GeV/fm$^3$ at 60 A GeV and 2.7 GeV/fm$^3$ at 200 A GeV. In the latter case energy densities sufficient for formation of the quark-gluon plasma (QGP) is reached according to common belief. From the calorimeter data it can be concluded that the presumptions for the creation of the plasma may be fulfilled for the utmost central events in 200 A GeV $^{16}$O+$^{197}$Au.

**Charged Multiplicity and Pseudo-Rapidity Distributions** A charged particle traversing a streamer-tube detector produces a streamer which is sensed by an external pad, sometimes by two pads. The "fired" pads in one detector array were filtered through a cluster routine which assigns "fired" pads to clusters, hereafter called hits. Typically, 60% of the hits consist of only one "fired" pad. If more than four adjacent pads "fired", they were assigned to two or more hits. The overall detection probability was found to be 85% by using information from three overlapping arrays and by using plastic scintillator on both sides of a detector plane for tagging. The two methods gave result in concordance. In order to separate good tracks from background tracks that do not emanate from the target, hits in the different detector planes were correlated. These background tracks could be due to secondary interactions in traversed materials or could be albedo particles from the calorimeters. The rejection of background tracks were done by using pairs of detector planes and by projecting hits from the plane adjacent to the target onto the downstream one. Only projected hits inside a correlation radius of 5 to 10 cm (depending on local padsizes) were considered and the one with the smallest deviation from the prediction was used/14/. The spectra have been corrected for $\gamma$-conversion into $e^+e^-$ pair in the material traversed (Al target chamber, carbon fiber beam-pipe and air). The $\gamma$ particles were assumed to be present due to $\pi^0$ decay close to target site. These corrections are small, typically a few percent. Note that $e^+e^-$ pairs will almost always be assigned to the same hit. Observe that no corrections have been employed for the contribution to the charged particle spectra from decaying neutral strange particles into charged decay-products ($\Delta^0 \rightarrow p\pi^-$ and $K^0_s \rightarrow \pi^+\pi^-$). Due to the large dimensions of our experimental setup most of these decay products are observed, and consequently included in the data. The Lund model FRITIOF predicts a relative contribution of about 7% to the total charged-particle yield from these processes.
In Figs. 5a and b the charged-particle multiplicity distributions for 60 and 200 A GeV $^{16}$O interactions with C, Cu, Ag, and Au target is given. The minimum-bias trigger was used and the $\eta$-region is: $-1.7 < \eta < 4.2$. In the very low multiplicity region a dip occurs which is dominantly an artifact of the trigger conditions. Note the resemblance in shape between the multiplicity distributions and the $E_T$ distributions for various targets and incident energies. The multiplicity distribution of 200 A GeV $^{16}$O+Au reactions extends to multiplicities of around 500 charged particles, which corresponds to more than 400 produced charged particles. In order to compare the multiplicity distributions with the Lund Model FRI-TIOF/15/ we restrict in Figs. 5c and 5d the $\eta$-intervall to $2.0 < \eta < 4.2$. The reason for this restriction is that the model can not handle target-nucleus fragmentation. The comparison with the model shows significant deviations, especially at large multiplicities and for the 200 A GeV data. This deficit of the model was also found in the high-$E_T$ tails of the $E_T$-distributions. Observe that the minimum-bias trigger conditions were simulated in the model calculations.
In Fig. 6a and b the pseudo-rapidity distributions of charged particles from $^{16}\text{O}$ amongst various targets at the two incident energies are displayed. The distributions exhibit a broad maximum which shifts backward as the target mass increases. This shift is much more pronounced in the 60 A GeV data than in the 200 A GeV. Note that at 60 A GeV the mid-rapidity region (Y=2.4) is closer to the target fragmentation region which affects the form of the distribution. The dashed curves show the result from Lund Model calculations. In this model the formation time for particles are assumed long which prevents target fragmentation and intranuclear cascading to be taken into account. Note however, that a systematic deviation at mid-rapidity of the 200 A GeV data is present. This deviation is not understood and may leave room for new physics. In Fig. 6c and d we show a comparison with the Lund model for a peripheral, medium and central data sample for $^{16}\text{O}+\text{Au}$ at the two energies. The separation between the samples was done with the energy measured in the ZDC (90 and 270 GeV for 60 A GeV data and 500 and 1700 GeV for 200 A GeV data). For the 200 A GeV data the relative deviations at mid-rapidity are approximately the same for the three samples.
The Target Mass Dependence

In the inset of Fig. 7 we show the target mass, \( A_T \) dependence of the charged particle densities, \( \rho \) for central interactions between \( ^{16}O \) and \( Cu, Ag \) and \( Au \) targets at 200 A GeV. The centrality criteria was that less than 20% of the beam energy is registered in the ZDC, which corresponds to events where most of the \( ^{16}O \) nucleons participate. The densities, \( \rho \), are extracted in \( \eta \)-bins ranging from -1.7 to 4.2. To investigate the target mass dependence we have allotted a power law parametrization \( \rho = A_{\eta}^{\alpha} \). The main Fig. 7 shows the result of least-squares-fit of the parameter \( \alpha \) versus \( \eta \) for both energies. \( \alpha(\eta) \) has a maximum around \( \eta = 0 \) where \( \alpha \) is close to one (volume effect). Observe that \( \alpha \) varies smoothly over the whole \( \eta \)-interval with no region of constancy. The value of \( \alpha \) close to the \( \gamma cm \) 2.4 and 3.0 is small 0.2-0.3 (length effect) and decreases to 0 towards the beam fragmentation region.

Conclusions

We conclude that conditions required for the formation of the quark-gluon plasma may have been achieved in some of the utmost central collisions of \( ^{16}O-^{197}Au \) at 200 A GeV. The importance of the collision geometry for determining the shape of the \( E_T \) spectra and multiplicity spectra have been discussed. The influence of the target mass on the charged particle density is dominant in the target fragmentation region.
and decreases smoothly and is rather weak at the $y_{NN}$ cms system and falls to zero in the projectile fragmentation region.

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