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Charged-Particle Distributions in ^{16}O Induced Nuclear Reactions at 60 and 200 A GeV

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Results from ^{16}O induced nuclear interactions with C, Cu, Ag and Au targets at 60 and 200 A GeV are presented. Multiplicity and pseudorapidity-density distributions of charged particles and their dependence on the target mass number are reported. The increase in the particle density with increasing centrality, characterized by the energy flux at zero degrees, is investigated. Comparisons with the Fritiof model reveal systematic differences.

The fixed target nucleus-nucleus physics program at the CERN SPS was launched when the ^{16}O ion-source [1], capable of producing highly charged ions, came into operation. The available energy scale was thereby expanded with nearly two orders of magnitude compared to Berkeley and Dubna energies. The aim of this program is to study the space-time development of hadronic interactions under extreme conditions of energy and baryon densities within the nuclear dimensions. Central nuclear collisions are accompanied by an intense particle production [2]. In such collisions, high energy-densities can be formed over large volumes, and transitions to new phases of matter, e. g. quark-gluon plasma, may occur. As a part of the WA80 [3] experimental

program the multiplicity and the pseudorapidity-density distributions of charged particles are studied in 60 and 200 A GeV ^{16}O induced collisions with various nuclear targets. Characterization of an event is done via the energy flux in the forward direction, $\theta < 0.3^\circ$, which was measured by a Zero-Degree Calorimeter (ZDC) [4] positioned 11 meters downstream from the target. Essentially all the kinetic energy carried by the spectator part of the projectile is deposited in the ZDC, and consequently the energy measured here is strongly correlated to the "centrality" of the event. The data are compared to predictions from the event generator Fritiof [5].

The Multiplicity Detectors

A unique feature of the experiment is the large coverage in pseudorapidity, $\eta = -\ln \tan(\theta/2)$, for charged-particle detection. Between the polar angles 1.7° and 32° , $\eta = 4.2$ to 1.2, the charged particles are measured by large multiplicity arrays consisting of larrocci-type streamer tubes [6]. The streamer tubes are read out through capacitively coupled pads and the position of each "fired" pad is recorded.

The first multiplicity array is placed 2.4 m from the target. In the range $10^\circ < \theta < 32^\circ$, $2.4 > \eta > 1.2$, it has a granular structure of 5600 pads of the sizes 5.2×3.5 and $2.1 \times 5.2 \text{ cm}^2$. Further downstream, at distances of 5.8 and 6.1 m from the target, two other multiplicity arrays are placed. They both cover the angular range $1.7^\circ < \theta < 17^\circ$, $4.2 > \eta > 1.9$, and each of them has 8200 pads of three different sizes, 5.2×3.5 , 2.1×5.2 and $1.0 \times 2.6 \text{ cm}^2$, respectively. All these arrays have an area of about 9 m^2 each. A fourth, somewhat smaller array is placed below the beam axis, at a distance of 2.6 m from the target.

The Plastic Ball detector, consisting of 655 ΔE -E modules, measures all and identifies most of the charged particles in the angular range $30^\circ < \theta < 160^\circ$ [7]. Together, the Plastic Ball and the multiplicity detectors cover 97 % of $4\pi \text{ sr}$.

The detectors are able to measure charged particles which have an energy high enough to penetrate the walls of the vacuum system, the windows of the detectors, and the air in between. For the Plastic Ball detector the thresholds are 11 MeV for protons and approximately 11 A MeV for heavier fragments. For the multiplicity arrays the thresholds are approximately 25 MeV for protons and 14 MeV for pions.

The beam particles were identified in total-reflection Cerenkov counters. Reactions in these counters were vetoed by a halo-detector. Targets of C, Cu, Ag and Au, about 200 mg/cm^2 thick, were used. Data were taken with a minimum-bias trigger which required an energy in the ZDC of less than 0.85 TeV and 2.8 TeV for 60 and 200 A GeV incident energy, respectively, and that at least one charged particle should be recorded in the multiplicity arrays. "Target-in / target-out" trigger ratios were better than 40:1, and the vast majority of the background events were found to have low multiplicities. To a large extent those events were rejected in the off-line analysis.

Corrections to the Data

A charged particle traversing a streamer-tube detector produces a streamer which sometimes can be sensed by more than one pad. The "fired" pads in one detector array were therefore 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 acceptance loss, due to the insensitivity in between the streamer tubes, sets an upper limit of the detection probability for charged particles [6]. In between the readout pads, on the circuit boards, there are also small insensitive areas. The probability of detecting a charged particle, traversing a multiplicity array, has been measured by using the information from three overlapping arrays. The overall detection probability was found to be 85 %. A second method of estimating this quantity, using plastic scintillators on both sides of a detector plane for tagging, gave a similar result. In the analysis, each track was weighted with the inverse detection probability.

In order to separate good tracks from background tracks, hits in the different detector planes were correlated. Background tracks can be due to particles from secondary interactions in air and other materials, or due to albedo particles from the calorimeters in the experimental setup.

The yield of charged particles as a function of polar angle was corrected for the contributions from the following processes:

i) γ -conversion

In order to keep the contribution from γ -conversion low, a 300-500 μm thick aluminum target-chamber and a downstream 500 μm carbon fiber beam-pipe have been employed. The correction is at most 4.4 % at $\theta = 1.7^\circ$ and goes down to 2.4 % at $\theta = 8^\circ$. Note that the electron-positron pair will almost exclusively be assigned to the same hit.

ii) Secondary hadronic interactions

As for γ -conversion, the probability for nuclear interactions of hadrons in the carbon-fiber beam pipe increases with decreasing polar angle. The probability is 2.6 % at $\theta = 1.7^\circ$ and decreases to 1.2 % at $\theta = 8^\circ$. Although the probabilities are quite small, the corrections are still important since each interaction can produce several charged particles, their number depending on the momentum of the incident particle. For calculating the number of charged secondaries emitted in the forward region we used a phenomenological model [8]. We estimate the total contribution from secondary hadronic interactions to be less than 7 % around $\theta = 2.0^\circ$ and then it decreases with polar angle.

iii) Multiple-hits

The probability that two or more particles hit the same detector element depends on the particle density and the detector granularity. The highest multiple-hit probability is found in the angular region of $30\text{--}35^\circ$ and for θ less than 2° . In the case of central oxygen-gold collisions at 200 A GeV these corrections are 40 % and 20 %, respectively. In most regions the corrections are smaller than a few percent.

γ -conversion and secondary hadronic interactions, as well as absorption, in the target are not corrected for. These effects are however small and would change the results with less than 2 % except at $\eta = 0$.

Furthermore we have estimated the contribution to the charged-particle spectra from decaying neutral strange particles into charged decay-products. The Fritiof model predicts a relative contribution of about 7 % to the total charged-particle yield from the processes $\Lambda^0 \rightarrow p\pi^-$ and $K_S^0 \rightarrow \pi^+\pi^-$. Due to the large dimensions of our experimental setup most of these decay products are observed, and consequently, they are included in the data. This fact should be kept in mind when direct comparisons with data from other experiments are made.

Multiplicity and Pseudorapidity Distributions

In Figs. 1a and b we present the charged-particle multiplicity distributions in the range $-1.7 < \eta < 4.2$ for 60 and 200 A GeV ^{16}O interactions with C, Cu, Ag, and Au targets, sampled with the minimum-bias trigger. In the very low multiplicity region a dip occurs which is dominantly a consequence of our trigger conditions. The multiplicity distribution of 200 A GeV $^{16}\text{O} + \text{Au}$ reactions extends to multiplicities of around 500 charged particles, which corresponds to more than 400 produced charged particles.

In order to compare with the Fritiof model [5] we exhibit in Figs. 1c and d the multiplicity distributions for $2.0 < \eta < 4.2$. In this range the contribution from target-nucleus fragmentation, which is not included in Fritiof, is reduced. The minimum-bias trigger conditions were simulated in the model calculations. The comparison with Fritiof shows significant deviations, especially at large multiplicities, for the 200 A GeV data. These findings corroborate those of Ref. [9] where also the transverse energy, E_T , is larger than the Fritiof model predictions, i.e. the excess in E_T is carried by a larger number of produced particles. (See also the inset of Fig. 4.)

In Fig. 2a and b the minimum-bias pseudorapidity-density, $\rho = 1/N_{\text{events}} (\Delta n_{\text{ch}}/\Delta\eta)$, distributions of charged particles for various targets and energies are shown. For all targets and energies the distributions are bell-shaped, and a backward shift of the maximum as the target mass increases is observed. At 60 A GeV the observed peak-shift, as a function of target mass, is about twice as large as for the 200 A GeV data. It should be pointed out that at 60 A GeV the mid-rapidity region is closer to the target fragmentation region which influences the form of the distributions. The dashed curves represent Fritiof model calculations for the different targets. Clearly, a discrepancy in the target fragmentation region is expected due to the fact that neither target fragmentation, nor intranuclear cascading are contained in the model. However, for the 200 A GeV data, a systematic deviation at mid-rapidity still remains. Presently, this deviation is not understood, and new phenomena can not be excluded. Peak-values and positions, both for the data and for the Fritiof model, are given in Table 1. The shift in the peak position, as the target mass changes, is fairly well described by the Fritiof model at 200 A GeV. This shows that such shifts can be produced without invoking any collectivity.

To study the deviations further, Figs. 2c and d show the impact-parameter dependence of the charged-particle distributions in $^{16}\text{O} + \text{Au}$ collisions compared to the Fritiof predictions. For each energy the data have been divided into three samples, characterized by the energy measured by the ZDC. The separations were made at 90 and 270 GeV for 60 A GeV, and at 500 and 1700 GeV for 200 A GeV. Similar features as seen for the different targets are here repeated for the three different

event samples. 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. 3 we show the target mass, A_T , dependence of the charged-particle densities, ρ , for central interactions between ^{16}O and Cu, Ag and Au at 200 A GeV. Here the centrality criterion is that less than 20% of the beam energy is deposited in the ZDC, which corresponds to events where presumably almost all of the oxygen nucleons participate. The densities, ρ , are extracted in η -bins ranging from -1.7 to 4.2. In order to study how the charged-particle density depends on the target mass, we have chosen to use the simple parametrization $\rho \sim A_T^{-\alpha}$. This parametrization gives a fairly good description of the data in all η -regions, but the exponent varies considerably with η . Figure 3 shows $\alpha(\eta)$ as obtained by least-squares fits, exemplified in the inset. The same parametrization is used for the 60 A GeV data and these results are included in Fig. 3. $\alpha(\eta)$ has a maximum around $\eta = 0$ and decreases rapidly with η , indicating that a "global target dependence" is strongly dependent on the considered rapidity region. α being close to one for low values of η might indicate the importance of complete target break-up. The target dependence varies smoothly over the whole η -interval and no regions where $\alpha(\eta)$ is fairly constant are observed. As η approaches 4, the projectile influence is dominant and the particle yield becomes independent of the target mass. The similarity between the two energies suggests that the target influence is essentially independent of the incident energy.

Transverse Energy Per Particle

In Ref. [9] the transverse energy, E_T , distributions measured by the Mid-Rapidity Calorimeter [4] were presented. The inset of Fig. 4 shows the E_T versus the charged-particle multiplicity, n_{ch} , for $^{16}\text{O} + \text{Au}$ at 200 A GeV, both quantities measured in the η -interval 2.4 to 4.0. A linear relationship is seen. In Fig. 4 we show the average E_T / n_{ch} as a function of the energy in the ZDC, at both bombarding energies and for all four targets. (Observe the broken scale on the y-axis.) It should be noted that the contribution from neutral particles is included in the E_T . The E_T / n_{ch} stays fairly constant over the total ZDC energy-range independent of projectile energy and target and has an average value of 550 MeV at both energies. An assumption of equal contributions from negative, positive, and neutral particles lowers this value to 370 MeV per particle. This is in approximate agreement with earlier findings in p-p, p-nucleus and α - α interactions [10].

Particle-Density Fluctuations and Energy Densities

The constant value of the average E_T / n_{ch} shows that an energy-density estimate can be made using a formula with a constant transverse mass, e. g. $\epsilon_0 = (\frac{3}{2}\rho m_T) / (\tau_0 \pi R^2)$ [11]. Here ρ is the charged-particle density, m_T is the transverse mass, τ_0 is the initial formation time, and R is the radius of the transverse reaction zone. For central collisions of oxygen on larger nuclei we have used $m_T = 0.37 \text{ GeV}$, $\tau_0 = 1 \text{ fm}/c$, $R = 1.2 \text{ A}^{1/3} \text{ fm}$, and $A = 16$. In Fig. 5 we show the cross

section for observing a given particle density, ρ_{max} , for the 200 A GeV data. Here ρ_{max} is defined in each event as $\Delta n_{ch}/\Delta\eta$ in the region $2.75 < \eta < 3.25$. The tails of the distributions extend to larger values of ρ_{max} as the target mass increases, and the extreme events have calculated energy densities well above $3 \text{ GeV}/\text{fm}^3$. This is consistent with the findings of Refs. [2,9] where somewhat different methods to estimate energy densities were applied.

Conclusions

We have presented charged-particle distributions as a function of target mass and "centrality" of the collision. Events with more than 450 charged particles have been observed. The Fritiof model underestimates the cross section for the highest multiplicities, particularly at 200 A GeV. The pseudorapidity value where the particle density reaches its maximum is shifted backwards as the target mass increases. This behavior is in qualitative agreement with the Fritiof model. We observe an excess in the particle yield in the central rapidity region, prominent at 200 A GeV, when we compare with the model. For central collisions the target dependence of the particle yield varies strongly with the polar angle. In an $A_T^{-\alpha}$ parametrization of the charged-particle densities, the extracted α -values range from 0.8 to 0, and a comparison with the simple geometrical expectation of $1/3$ is meaningful only if the full angular region is covered. Although the particle yield increases with energy, the influence of the target is almost the same at the two energies. The average transverse energy per charged particle is essentially independent of energy, target mass and "centrality" of the interaction. Particle densities up to 160 charged particles per unit pseudorapidity are reached – a value which has to await theoretical interpretations.

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Table 1. Features of the pseudorapidity distributions from ^{16}O induced interactions, sampled with the minimum-bias trigger, for various targets and energies.

	60 A GeV				200 A GeV			
	Au	Ag	Cu	C	Au	Ag	Cu	C
					Peak height			
Data:	38.8	30.9	25.3	13.6	58.8	51.7	42.6	23.0
Frittof:	32.6	27.0	22.9	11.6	43.5	36.6	30.4	16.8
					Peak position			
Data:	2.00	2.20	2.36	2.78	2.70	2.79	2.91	3.15
Frittof:	2.25	2.34	2.39	2.69	2.75	2.85	2.89	3.21

Statistical errors are $\sim 1\%$ for the peak heights (relative) and 0.1 for the peak positions (absolute).

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Figure Captions

Figure 1 Charged-particle multiplicity distributions for ^{16}O induced reactions with various targets at a) 60 A GeV, b) 200 A GeV, c) 60 A GeV with $\eta > 2$, and d) 200 A GeV, $\eta > 2$. In c) and d) comparisons with the Fritiof model are included.

Figure 2 Pseudorapidity-density distributions of charged particles in interactions between ^{16}O and a) various targets at 60 A GeV, b) various targets at 200 A GeV, c) Au at different "centralities" at 60 A GeV, and d) Au at different "centralities" at 200 A GeV. The statistical errors are smaller than the symbols.

Figure 3 The target dependence of the pseudorapidity densities, parametrized as $\rho \sim A_t^{-\alpha}$, in different regions of η for 160 induced interactions. The large figure shows the extracted α -values for 60 and 200 A GeV, and the inset exemplifies the linear fits to obtain them. In the large figure the points for 60 A GeV are shifted 0.1 units to the right.

Figure 4 E_T per charged particle for interactions between ^{16}O and various targets at 60 and 200 A GeV as a function of E_{ZDC} . The inset shows E_T vs. charged-particle multiplicity for $^{16}\text{O}+\text{Au}$ reactions at 200 A GeV. Statistical errors are exemplified.

Figure 5 Charged-particle density distributions for ^{16}O induced reactions with various targets at 200 A GeV. The upper axis shows the calculated energy density in the region of applicability [11].

Fig. 3

Fig. 4

Fig. 5