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A COMPARISON OF THE TOTAL NEUTRAL ENERGY SPECTRA OF
 α , dd AND pp INTERACTIONS AT THE ISR

BNL-CERN-Michigan State-Oxford-Rockefeller (BCMOR) Collaboration¹

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A COMPARISON OF THE TOTAL NEUTRAL ENERGY SPECTRA OF
 $\alpha\alpha$, dd AND pp INTERACTIONS AT THE ISR*

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ABSTRACT

The total neutral energy spectra, $E_{TOT}^0 = \sum_i \epsilon_i^0$, have been measured in the central region of $\alpha\alpha$, dd and pp interactions at $\sqrt{s_{NN}} = 31$ GeV with an electromagnetic calorimeter covering 2π in azimuth. The data were collected in the light-ion run at the CERN ISR during August 1983. The cross section ratio of the $\alpha\alpha$ to the pp interactions increases rapidly with E_{TOT}^0 from 7 to 10^5 in the range $1.5 < E_{TOT}^0 < 19$ GeV. The data are compared with a simple model of simultaneous multiple nucleon-nucleon collisions.

INTRODUCTION

In recent years, ultra-relativistic heavy ion collisions ($\sqrt{s_{NN}} \gg \text{Mp}$) have received much attention in connection with observing a possible phase transition between hadron matter and a quark-gluon plasma at high density and/or temperature which would lead to the direct test of QCD.² During August 1983, the second and last light ion data were taken at $\sqrt{s_{NN}} = 31$ GeV at the CERN ISR, providing a unique facility for a detailed comparison between light ion and pp collisions at high energy.

The comparison described in this paper refers to the total neutral energy E_{TOT}^0 spectra,³ mean multiplicity and mean transverse momentum of neutral clusters (mainly π^0 -mesons) in the central region of $\alpha\alpha$, dd and pp interactions.

APPARATUS

The apparatus consisted of a 1.4 T superconducting surrounding a system of cylindrical drift chambers, a barrel of scintillation counters and four modules of lead-scintillator shower counters. The detection of electromagnetic showers was completed by two lead-glass modules located outside the magnet in the azimuthal region not covered by the shower counters.

Each shower counter module was 1.5m long, and subtended 50° in azimuth and ± 1.1 units in rapidity y , and was segmented azimuthally into 8 counters. Each counter was subdivided in depth into a front and a back compartment and had totally 14 radiation lengths thick. The energy deposited in each counter was recorded

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with photomultipliers at both ends. Each lead glass module consisted of a front of 34 blocks with 4 radiation lengths thick and a back array of 168 blocks with 17 radiation lengths thick. The acceptance of each lead glass array was ± 0.6 units in rapidity and 57° in azimuth. Both shower counters and lead glass were initially calibrated in an electron beam at the CERN PS. The apparatus and calibration methods have been described in more detail elsewhere.⁴ The r.m.s. energy resolutions, $\Delta E/E$, of the lead glass and shower counters were $(4.3/\sqrt{E} + 2)\%$ and $(16/\sqrt{E})\%$, respectively with E in GeV. Charged particles were measured over full azimuth and in ± 1.2 units in rapidity using the drift chamber information. The spatial resolution was about $350 \mu\text{m}$, yielding the r.m.s. momentum resolution of $\Delta p_T/p_T = (7 \cdot p_T)\%$ (p_T in GeV/c).

EVENT SELECTION AND DATA REDUCTION

The data analyzed here were taken with a total neutral energy (E_{TOT}°) trigger. The apparatus was triggered when the sum of all energies deposited in the lead glass and the shower counters exceeded some pre-set threshold. In addition the trigger required at least a hit in a 32-element scintillator hodoscope surrounding the intersection region. Data were taken with various trigger thresholds with integrated luminosities of 100 nb^{-1} , 420 nb^{-1} and 580 nb^{-1} for $\alpha\alpha$, dd and pp interactions, respectively.

In the off-line analysis energies were properly calibrated and the threshold was applied again to avoid any trigger inefficiency. For the shower counters the longitudinal (along the beam axis) position of energy deposition was calculated from the time difference or energy ratio between the phototube signals at each end.

The energy (ϵ) and transverse energy ($\epsilon_T = \epsilon \sin\theta$) in the N-N CM system were calculated for each lead-glass block and shower counter, assuming the energy was deposited by massless neutral particles originating at the vertex reconstructed by charged tracks. For each event these energies were summed to give the total neutral energy $E_{\text{TOT}}^\circ = \sum_i \epsilon_i$ or transverse neutral energy $E_T^\circ = \sum_i \epsilon_T^i$. The estimated energy deposited by charged tracksⁱ in the shower counters was subtracted from E_{TOT}° and E_T° .

The events were required to satisfy the following selection criteria: (i) If more than one distinct time cluster were found during the apparatus recording time, the event was rejected as a multiple event. (ii) Events were required to have at least two charged tracks with a vertex within the interaction region. (iii) There must be some energy sharing between the front and back compartments of the lead glass and shower counters. (ii) and (iii) removed a small contamination due to cosmic ray and beam-gas interactions.

Since the pp comparison run was very close in time to the light ion run, most systematic uncertainties were removed by measuring the ratio $\alpha\alpha/pp$. An overall energy scale uncertainty was estimated to be $\pm 5\%$. A correction for multiple hits in the same shower counter has not been made. The E_{TOT}° values would be high by 1.5% and 3.0% at $E_{TOT}^\circ = 15$ GeV and 30 GeV, respectively. This effect would be three times larger in E_T° than E_{TOT}° because multi-hits cause errors in both energy and angle. It should be noted that

$$\langle E_{TOT}^\circ \rangle = 1.15 \langle E_T^\circ \rangle$$

RESULTS

E_{TOT}° Spectra: The number of events per GeV of E_{TOT}° was divided by the integrated luminosity L to give the spectra $1/L \cdot dN/dE_{TOT}^\circ$ as shown in Figure 1. The errors shown in the figure are statistical only. It is noteworthy that there are the $\alpha\alpha$ events beyond the nucleon-nucleon kinematic limit of 31 GeV. The pp data extend to 19 GeV but the dd data are only available in the limited range of 18 to 24 GeV. The E_{TOT}° spectra of $\alpha\alpha$ and pp interactions follow an exponential distribution over seven orders of magnitude for $E_{TOT}^\circ > 5$ and > 12 GeV, respectively. If we fit the data with a form $\sim e^{-\beta E_{TOT}^\circ}$, we find $\beta = 1.26 \pm 0.01 \text{ GeV}^{-1}$ for pp and $0.83 \pm 0.02 \text{ GeV}^{-1}$ for $\alpha\alpha$. The ratio of the $\alpha\alpha$ to the pp spectra increase from a factor of 7 at $E_{TOT}^\circ = 1.5$ GeV to $\sim 10^5$ at $E_{TOT}^\circ = 19$ GeV. The cross section ratios of high energy nucleus-nucleus collisions to the pp collisions are usually parameterized as

$$R(A_1 A_2 / pp) = (A_1 A_2)^\alpha$$

where A_1 and A_2 are the number of nucleon in each nucleus. The exponent α is naively expected to be between 2/3 and 1 depending on the degree of shielding within the nucleus. The values obtained for $R(\alpha\alpha/pp)$ and α are shown in Figure 2. For $E_{TOT}^\circ \leq 3.5$ GeV the exponent α is less than 1 but above this energy it rises almost linearly with E_{TOT}° . The similar results were obtained for the E_T° spectra.

$\langle n^\circ \rangle$ and $\langle p_T^\circ \rangle$ vs. E_T° : The structure of the events was studied by examining the distribution of neutral energy clusters deposited in the lead glass and shower counters. Neutral clusters (mostly π^0 -mesons) were defined as a cluster of energy greater than 300 MeV. In the lead glass a cluster corresponded to at most 4 x 4 adjacent counters in the back array plus the associated front-array blocks. In the shower counters a cluster could extend over at most 3 adjacent counters if the longitudinal positions of these energy depositions were matched within ± 20 cm. The individual γ -rays from π^0 decays were not resolved. The mean multiplicity $\langle n^\circ \rangle$ and the mean p_T $\langle p_T^\circ \rangle$ of neutral clusters are shown as a function of E_T° in Figure 3. $\langle n^\circ \rangle$ and $\langle p_T^\circ \rangle$ appear

Fig. 1. The total neutral energy E_{TOT}^0 spectra for $\alpha\alpha$, dd and pp interactions at $\sqrt{s_{NN}} = 31 \text{ GeV}$ together with curves representing the E_{TOT}^0 spectra produced by 1, 2, 4 and 5 simultaneous N-N collisions as explained in the text.

Fig. 2. $R(\alpha\alpha/pp)$ vs. E_{TOT}^0 .

to rise almost linearly for $E_T^0 \lesssim 10$ GeV for both the $\alpha\alpha$ and pp data. Above this energy $\langle n^0 \rangle$ gets saturating and $\langle p_T^0 \rangle$ rises rapidly for the pp data while $\langle n^0 \rangle$ and $\langle p_T^0 \rangle$ for the $\alpha\alpha$ data still keep rising steadily with E_T^0 . Therefore the $\alpha\alpha$ events at high E_T^0 or E_{TOT}^0 are soft scatterings with many low p_T^0 particles.

DISCUSSION AND CONCLUSION

Since E_{TOT}^0 is the sum over many soft particles in the detector, it is directly sensitive to multiple nucleon-nucleon (N-N) interactions taking place during the same $\alpha\alpha$ collision. Therefore as the first attempt, we tried to interpret the E_{TOT}^0 spectra of $\alpha\alpha$ and dd interactions as the result of (i) multiple parallel N-N collisions, (ii) with each N-N collision producing the observed E_{TOT}^0 spectrum of pp interactions. To do this the pp spectrum was treated as the probability function for the two nucleons:

Fig. 3. Mean multiplicity $\langle n^0 \rangle$ and mean p_T $\langle p_T^0 \rangle$ of neutral clusters as a function of E_T^0 .

$$f_1(E) = \frac{1}{\sigma_{in}^{pp}} \left(\frac{d\sigma}{dE} \right)_{pp}$$

where $\sigma_{in}^{pp} = \int_0^{\sqrt{s}} (d\sigma/dE)_{pp} dE$ and the $f_1(E)$ is the differential probability for the emission of energy E in dE for a single nucleon-nucleon collision. Then, $f_n(E)dE$, the probability of observing E in dE for n -fold collisions is simply a convolution integral:

$$f_n(E_0) = \int_0^{E_0} dE f_1(E) f_{n-1}(E_0 - E)$$

where $0 \leq E_0 \leq n\sqrt{s_{NN}}$. In Figure 1 we plotted the spectra $1/L \cdot$

$(dN^n/dE_{TOT}^0) = \sigma_{in}^{pp} f_n(E_{TOT}^0)$ for $n = 1, 2, 4$ and 5 .

All spectra are normalized to the pp cross section.

The 2-simultaneous N-N collision curve is an excellent representation of the limited available dd data. The 4-simultaneous N-N collision curve fits with the $\alpha\alpha$ data in the range $8 \leq E_{TOT}^0 < 17$ GeV. However the slope of the $\alpha\alpha$ spectrum for $E_{TOT}^0 > 17$ GeV is too flat to be explained by this extreme case of 4 N-N collisions. It should be noted that the cross section used for 4 N-N collisions is about 10% of the observed $\alpha\alpha$ cross section.

In conclusion, the α particle may be too light to produce a quark-gluon plasma at $\sqrt{s_{NN}} = 31$ GeV and multiple parallel N-N collisions do not increase energy densities in space. But the large multiplicity and large yields observed at high E_{TOT}^0 are prerequisites for the formation of the quark-gluon plasma in ultrarelativistic heavy ion collisions.

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