E_{T} AND \pi^{0} SPECTRA FROM αα, dd, and pp INTERACTIONS

AT \sqrt{s_{NN}} = 31 \text{ GEV AT THE CERN ISR}


Presented by

Michael J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973, USA

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Inclusive Single Particle Production

Inclusive single particle production at large transverse momentum, \( P_T \), from heavy nuclear targets was first studied by Cronin and collaborators \(^2\) at Fermilab in the period 1973-1977, basically because of the unavailability of liquid hydrogen targets. They measured the invariant cross section \( \sigma/dP_T \), for inclusive \( \pi^\pm K^\pm p,p \) production near 90° from the interaction of 200 to 400 GeV/c protons with an assortment of nuclear targets and found that the atomic weight dependence at fixed \( P_T \) could be represented by a power law: \(^3\)

\[
\frac{\sigma_{DA}(P_T)}{\sigma_{pp}(P_T)} = A^\alpha(P_T)
\]

The exponent \( \alpha(P_T) \) varied with \( P_T \), the particle produced and the nucleon-nucleon center-of-mass energy, \( \sqrt{s_{NN}} \), and reached values in excess of \( \alpha(P_T) = 1 \). This was dubbed the "Anomalous Nuclear Enhancement." For \( \pi^\pm \) production, \( \alpha(P_T) \) increased with \( P_T \), reaching a maximum value at \( P_T = 4.6 \) GeV/c which varied between \( \alpha = 1.18 \) at \( \sqrt{s_{NN}} = 19.4 \) GeV and \( \alpha = 1.13 \) at \( \sqrt{s_{NN}} = 27.4 \) GeV.

The next step in the study of the collisions of nuclei at high energy occurred at the CERN ISR in 1980, with runs on \( \alpha \alpha \) and \( p\alpha \) interactions at nucleon-nucleon center-of-mass energies of \( \sqrt{s_{NN}} = 31 \) GeV for \( \alpha \alpha \) and \( \sqrt{s_{NN}} = 44 \) GeV for \( p\alpha \). Several experiments took data on inclusive single particle production. \(^4\) The conclusion was that the anomalous enhancement died away for \( p\alpha \) collisions, \( \alpha \lesssim 1 \) at \( \sqrt{s_{NN}} = 44 \) GeV, but came on even stronger for \( \alpha \alpha \) collisions at \( \sqrt{s_{NN}} = 31 \) GeV. The ratio of the cross section for inclusive production of a \( \pi^\pm \) at a given \( P_T \) in \( \alpha \alpha \) and \( pp \) collisions varied from a value of \( \sqrt{s}_{18} \) in the range of \( 3 \leq P_T \leq 4 \) GeV/c to \( \sqrt{s}_{24} \) to 30 in the range of \( 4 \leq P_T \leq 5 \) GeV/c to \( \sqrt{s}_{30} \) to 40 in the range of \( 5 \leq P_T \leq 7 \) GeV/c. The best quoted error \(^5\) on this ratio was \( \sqrt{s}_{20} \).
at $P_T \cong 6$ GeV/c. It is expected that the error will be reduced by a factor of 3 when results from the 1983 ISR run become available. If the ratio of the cross sections is assumed to obey a power law $\left(A_1 A_2 \right)^{\alpha(P_T)}$, then values of $\alpha$ as high as 1.32 ± 0.05 have been observed for inclusive pion production at $P_T \cong 6$ GeV/c in $\alpha\alpha$ collisions. The present situation is more thoroughly described in Martin Faessler's review article. One conclusion that I draw from these results is that $pA$ collisions are different from $AA$ collisions. For a somewhat different point of view, see Sherman Frankel's presentation to this conference.

Other Results Previous to 1984

In the period 1980 to 1983, some additional data became available. Among the most noteworthy were the results from the Multiparticle Spectrometer Group at Fermilab who presented the first measurement of transverse energy, $E_T$, emission in the central region of $pA$ collisions. In this type measurement, the transverse energy, $E_T = E \sin \theta$, is summed over all the particles emitted on an event into a fixed but large solid angle, typically $\Delta \phi = 2\pi$, $\Delta y = \pm 1$, where $y$ is the rapidity measured in the c.m. system. A frequency distribution, or spectrum of $E_T$ over all events is then computed. The $E_T$ spectrum covered the range $1 \leq E_T \leq 21$ GeV for proton collisions on several nuclei from hydrogen to lead, at $\sqrt{s_{NN}} = 27.4$ GeV, and showed that the parameterization $A^\alpha$ was still reasonable. However, the exponent $\alpha$ had risen to values as high as $\alpha = 2.0$. The A.F.S. Group at CERN also presented a charged $E_T$ spectrum, reconstructed from charged particles observed on minimum bias triggers from the 1980 $\alpha\alpha$ and $pA$ runs at the ISR. The spectrum falls 4 orders of magnitude over the charged $E_T$ range from 0 to 12 GeV.

$E_T^\alpha$ Results from the 1983 CERN ISR Run

This brings us to August 1983, when the second (and final) light ion run took place at the CERN ISR. This run was a considerable improvement over the 1980 run, with $\alpha\alpha$, $pA$, $dA$ and $pp$ collisions all studied at $\sqrt{s_{NN}} = 31$ GeV. The $\alpha\alpha$ luminosity achieved at the low-$\beta$ intersection $I-1$ was $1.0 \times 10^{30}$ cm$^{-2}$ s$^{-1}$. The integrated luminosity was a factor of 16 higher than the 1980 run (Table I).
Table I.

<table>
<thead>
<tr>
<th>Process</th>
<th>Integrated Luminosity (cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha\alpha)</td>
<td>(1.0 \times 10^{35})</td>
</tr>
<tr>
<td>(dd)</td>
<td>(4.2 \times 10^{35})</td>
</tr>
<tr>
<td>(pp)</td>
<td>(5.3 \times 10^{35})</td>
</tr>
</tbody>
</table>

Preliminary results from this run were already presented at the 1983 Quark Matter Conference. I shall now present the final results for the total neutral energy spectrum, \(E_{\text{TOT}}^0\), for \(pp\), \(dd\) and \(\alpha\alpha\) collisions at \(\sqrt{s_{\text{NN}}} = 31\) GeV as measured by the BCMOR collaboration, ISR experiment R110.

In this experiment, the total neutral energy emitted in the central region was measured using an electromagnetic shower counter which detected, but did not separately resolve, the photons from the decays of \(\pi^0\) and \(\eta^0\) particles (\(\pi^0 + \gamma\gamma\), \(\eta^0 + \gamma\gamma\)). The apparatus, Figure 1, consisted of a superconducting solenoid with a field of 1.4 Tesla inside of which were placed a barrel of 32 scintillation counters (A), a system of cylindrical drift chambers with 3 dimensional coordinate readout (DCM1–5) 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. The total thickness of the coil and cryostat was 1.0 radia-
tion length, mostly aluminum, so that γ rays could penetrate without
having their energies significantly degraded. The center-of-mass accept-
ance in which the neutral energy was detected covered 90% of θm in azi-
muth with an average rapidity acceptance inside this region of δy = ±0.9.

Each shower counter module was 1.5 m long, subtended 50° in azimuth
and ±1.1 units of rapidity centered on y = 0, and was segmented azimuth-
ally into eight counters. Each counter was a total of 14 radiation
lengths thick which was subdivided in depth into front and back compart-
ments (1:3) which were independently viewed by photomultipliers at both
ends. The lead-glass modules each consisted of a front array of 34
blocks, 4 radiation lengths thick, and a back array of 168 blocks, 15 ×
15 cm by 17 radiation lengths thick, arranged in a stack 12 blocks high
by 14 wide. The angular acceptance of each lead glass module was 57° in
azimuth and ±0.7 units of rapidity. The r.m.s. energy resolution, ΔE/E,
of the lead glass was (4.3/\sqrt{E} + 2)% and that of the shower counters
was (16/\sqrt{E})%, with E in GeV. Charged particles were measured over the
full azimuth in the c.m. rapidity interval |y|<1.2 using the drift cham-
 bers. The spatial resolution was about 350 µm, yielding a momentum reso-
 lution of ΔP_T/P_T = (7%)P_T, with P_T in GeV/c. Further details of the ap-
 paratus can be found elsewhere.\textsuperscript{11,12}

The apparatus was triggered by summing all the energy in the lead
glass and shower counters, with the total required to be above a thresh-
old. In order to cover the wide dynamic range, nominal thresholds of 1,
5, 10, 15, 20 and 25 GeV were used. The threshold was applied again in
the off-line analysis, using more accurate calibration information.

The following selection criteria were applied to the events:
(i) If more than one distinct time cluster were found during the ap-
 paratus 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. Criteria (ii) and (iii) removed a small contamination due to
cosmic ray and beam-gas interactions.

The longitudinal (along the beam axis) position of the energy depo-
sition in the shower counters was calculated from the time difference or
energy ratio of the photomultiplier signals at each end. The energy
c and transverse energy (\epsilon_T = \epsilon \sin θ) in the N-N CM system were calcu-
lated 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 \epsilon_{TOT} = \sum_i \epsilon_i or transverse neutral
energy $E_T = E_{T,1}$. The energy deposited by charged tracks in the shower counters was estimated and subtracted from $E_{TOT}^0$ and $E_T^0$ for each event. Then a frequency distribution of the number of events per GeV of $E_{TOT}^0$ and $E_T^0$ was made and divided by the integrated luminosity $L$ to obtain the spectra $(1/L)(dN/dE_{TOT}^0)$ and $(1/L)(dN/dE_T^0)$, as shown in Fig. 2. The data cover 10 orders of magnitude.

Only the statistical errors are shown in Figure 2. Due to the charged track energy correction there is also a systematic error in the $\alpha\alpha$ data for $E_{TOT}^0 > 6$ GeV and the pp data for $E_{TOT}^0 > 3$ GeV by which the $\alpha\alpha$ and pp data can be displaced together in $E_{TOT}^0$ by $\pm 0.45$ GeV and $\pm 0.25$ GeV, respectively. The systematic error in the slope, or logarithmic derivative, of the $\alpha\alpha$, $dd$ and pp data due to this correction is less than 1%. Other systematic errors in the data of Fig. 2 include an overall uncertainty on the $E_{TOT}^0$ scale of $\pm 5\%$. The data have not been corrected for resolution smearing or finite bin width, which would be equivalent to an overall energy scale shift of less than 1.8%. In addition, owing to a non-linearity introduced in the shower counter response by multiple hits within the same shower counter, the quoted $E_{TOT}^0$ values are high by 3% at $E_{TOT}^0 = 30$ GeV and 1.5% at $E_{TOT}^0 = 15$ GeV. This effect is three times larger in the $E_T^0$ spectra because multiple hits cause an error in angle as well as energy. Thus, the $E_{TOT}^0$ spectra are used for further analysis, since the systematics are better, and in this detector $<E_{TOT}^0> \approx 1.15 <E_T^0>$.

The pp and $\alpha\alpha$ spectra shown in Fig. 2 both become exponentially decreasing for values of $E_{TOT}^0 > 5$ GeV and 12 GeV, respectively. The logarithmic derivatives are $-1.26 \pm 0.01$ GeV$^{-1}$ for pp and $-0.93 \pm 0.02$ GeV$^{-1}$ for $\alpha\alpha$, including all the systematic corrections mentioned above except for the scale error which introduces a common $\pm 5\%$ uncertainty in the values of the slopes. The ratio of the $\alpha\alpha$ to the pp spectra rises monotonically from a factor of 7 at $E_{TOT}^0 = 1.5$ GeV to $10^5$ at $E_{TOT}^0 > 19$ GeV. Note that the $\alpha\alpha$ data extend beyond the nucleon-nucleon kinematic limit. This indicates the inadequacy of the parameterization $R(\alpha\alpha/pp) = (A_1A_2)^\alpha$ for the $E_{TOT}^0$ spectrum. The exponent $\alpha$ just increases linearly with $E_{TOT}^0$ until 19 GeV, where the pp data run out, and would be undefined beyond the kinematic limit.

It is not really surprising that the parameterization which worked for inclusive single particle production should be inadequate for the description of the total energy spectrum in nucleus-nucleus collisions. Single particle spectra are thought to be the result of a single hard collision of nucleons, and thus are sensitive mainly to successive collision effects as an incident nucleon passes through a nucleus before making a hard collision. By contrast, $E_{TOT}^0$ is the sum over many particles in the detector, so it is directly sensitive to multiple simulta-
neous (or parallel) nucleon-nucleon (N-N) collisions in the interacting nuclei.

Therefore, we attempted to analyze the $E^T_{\text{TOT}}$ spectra of $\alpha\alpha$ and $dd$ interactions as the result of multiple parallel N-N collisions, with each N-N collision producing the observed $E^T_{\text{TOT}}$ spectrum of pp interactions. To do this the pp spectrum was treated as the probability function for the collision of two nucleons:

$$f_1(E) = \frac{1}{\sigma_{\text{pp}}} (\frac{d\sigma}{dE})_{\text{pp}}$$

where $\sigma_{\text{pp}} = \int_0^{E_0} (d\sigma/dE)_{\text{pp}} dE$ and the $f_1(E)$ is the differential probability for the emission of energy $E$ in $dE$ in our detector for a single nucleon-nucleon collision. Then, $f_n(E)dE$, the probability of observing $E$ in $dE$ for $n$ such collisions overlapped, is simply a convolution integral:

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

where $0 \leq E_0 \leq n\sqrt{s_{\text{NN}}}$. Here, $E_0$ represents the energy emitted on $n$ collisions. The first term inside the integral is the probability of emitting energy $E$ on one collision and the second term is the probability of emitting a total of $E_0-E$ on $n-1$ collisions.

It should be noted that all the $n$-collision spectra are normalized to unity; only the shape is determined. They can be renormalized to the probability or cross section for $n$ simultaneous parallel nucleon-nucleon collisions, if this is known from a model. Alternatively, the data can be used to fit for the $n$-collision cross sections $\sigma_n$, $n = 1, 2, \ldots, m$ as parameters:

$$\frac{1}{L} \frac{dN^{\alpha\alpha}}{dE^T_{\text{TOT}}} = \sum_{n=1}^{m} \sigma_n f_n(E^T_{\text{TOT}}) \quad (1)$$

However, it is instructive to plot the individual $f_n(E)$ normalized to the observed pp interaction cross section in our detector:

$$\frac{1}{L} \frac{dN^{\text{pp}}}{dE} = \sigma_{\text{pp}} f_1(E).$$

This is shown in Figure 3 for $n = 1, 2, 4, 5$ collisions.

With this "equal probability" normalization, the $E^0_{\text{TOT}}$ spectrum from two simultaneous pp collisions is an excellent description of the avail-
able dd data and similarly the $E^0_{TOT}$ spectrum from four simultaneous pp collisions fits the $aa$ data over the range $8 \leq E^0_{TOT} \leq 17$ GeV. At higher values of $E^0_{TOT}$ the slope of the $aa$ spectrum is too flat to be explained by this extreme case in which 4 individual nucleon-pairs are simultaneously interacting, or even by 5 simultaneous nucleon-pair collisions. Above 25 GeV, the slope of the $aa$ data, $-0.83 \pm 0.02$ GeV$^{-1}$, is
much flatter than the \(-1.00 \pm 0.01 \text{ GeV}^{-1}\) slope of the 5-collision curve in this \(E_{\text{TOT}}^5\) range.

This analysis can be made more sophisticated by fitting the full \(E_{\text{TOT}}^\phi\) spectrum in \(\alpha\alpha\) collisions to a sum of \(n\)-collision convolutions of the observed pp spectrum, as indicated in Equation (1). This is greatly facilitated by using a gamma distribution to represent the \(N-N\) probability distribution \(f_1(E)\). The pp spectrum in Figure 2 is fit to the function

\[
f_1(E) = \frac{a}{\Gamma(p)} (\alpha E)^{p-1} e^{-\alpha E}
\]

(2)

for the parameters \(p\) and \(a\). It should be noted that \(p>0, \alpha>0, f_1(E)\) is normalized to unity over the range \(0 \leq E \leq \infty\) and that \(\Gamma(p)\) is the gamma function of \(p, = (p-1)!\) if \(p\) is an integer. The function fits the pp data very well with the result:

\[
\alpha = 1.41 \pm 0.01 \text{ GeV}^{-1} \quad p = 2.50 \pm 0.06
\]

\[
\sigma_{\text{pp}}^{\text{in}} = 13.1 \pm 0.3 \text{ mb} \quad \chi^2 = 24.6/15 \text{ d.o.f.}
\]

The energy spectrum produced by \(n\) simultaneous independent \(N-N\) collisions, for \(n = 1, 2, 3, \ldots\), is then simply given by the function:

\[
f_n(E) = \frac{a}{\Gamma(np)} (\alpha E)^{np-1} e^{-\alpha E}
\]

(3)

with the values of \(\alpha\) and \(p\) determined above. All the \(f_n(E)\) remain normalized to unity.

The AFS group\(^{13}\) has successfully used the "Wounded Nucleon Model" to relate the multiplicity distributions of pp, ap and \(\alpha\alpha\) collisions at \(\sqrt{s}_{\text{NN}} = 31 \text{ GeV}\). They predicted the relative cross sections for \(n\) nucleon-nucleon collisions per \(\alpha\alpha\) interaction:

\[
r_n = \frac{\sigma_n}{\sigma_{\alpha\alpha}}
\]

The main distinctive feature\(^{13}\) of the "Wounded Nucleon Model" is that it only counts the number of struck nucleons, and that a nucleon contributes only once to the production of particles no matter how many times (\(\geq 1\)) it is successively struck. These predictions can be applied directly in Equation (1), with Equations (2) and (3) used for \(f_n(E)\), if \(n\) is allowed to take on half-integer as well as integer values. For in-
stance, \( n = 2 \) corresponds to 2 N-N collisions, or 4 wounded nucleons, while \( n = 2 \frac{1}{2} \) corresponds to 5 wounded nucleons.

The results of the fits are shown in Figure 4. The solid line on the pp data is the fit to Equation (2) given above. The solid line on the \( \alpha \alpha \) data is the best fit using the \( n \)-collision probabilities derived by the AFS collaboration\(^{13}\) from their charged multiplicity data. This fits the \( E_{TOT}^T \) spectrum out to 10 GeV.
or about 1/4 orders of magnitude down in cross section. The broken line on the \( \sigma_{\text{in}} \) data allows the \( \sigma_{n}^{\text{n}} \), \( n=1,2,3,4 \), to take on the values which give the best fit to the data. This curve fits the \( E_{\text{TOT}}^{\text{QTR}} \) spectrum out to 20 GeV, or over 4 orders of magnitude. It is instructive to note that the \( r_{n} \) parameters of the best fit are just the original AFS\(^{13}\) \( r_{n} \) parameters, plus the 4-collision curve normalized to \( \sigma_{pp}^{\text{pp}} \) as shown in Figure 3. The more sophisticated analysis specifies the shape of the \( \sigma_{\text{in}} \) spectrum and thus allows the total cross section for neutral energy (plus 2 tracks) in our detector to be determined, \( \sigma_{\text{in}}^{\text{QTR}} = 131 \pm 3 \text{ mb} \). The best fit value for the 4-collision cross section is 13 mb which equals \( \sigma_{pp}^{\text{pp}} \) or \( \sim 10\% \sigma_{\text{in}}^{\text{QTR}} \). The tail above 20 GeV in \( E_{\text{TOT}}^{\text{QTR}} \) is still not explained with this model.

The following conclusions can be drawn from the data and fits shown in Figure 4.

The wounded nucleon fit with conventional parameters\(^{13}\) explains the data out to \( E_{\text{TOT}}^{\text{QTR}} = 10 \text{ GeV} \), about 90% of the \( \sigma_{\text{in}} \) interaction cross section in our detector. This is the domain of the average collision, which may be of interest to cosmoologists or to cosmic ray experiments with limited statistics.

From 10 GeV < \( E_{\text{TOT}}^{\text{QTR}} \) < 20 GeV, the data can be described by the simultaneous parallel collision of all the nucleons in the interacting nuclei, \( 4 \text{ N-N collisions for the } \sigma_{\text{in}} \text{ case, with a cross section approximately equal to the pp interaction cross section. This corresponds to } 10\% \text{ of the } \sigma_{\text{in}} \text{ interaction cross section in our detector. This is the region of "Central Collisions." However it appears that the probability for all the nucleons to interact in an } \sigma_{\text{in}} \text{ collision is much larger than previous estimates.}^{13} \)

Above 20 GeV, there is an unexplained exponential tail at a level of \( 10^{-5} \) of the total interaction cross section. The exponential slope of this tail is too flat to be explained even by the extreme case in which all 4 individual nucleon-pairs simultaneously interact in \( \sigma_{\text{in}} \) collisions. The energy density in this tail rises to values greater than 15 GeV per unit of rapidity,

\[
\frac{dE_{\text{TOT}}^{\text{QTR}}}{dy} > 15 \text{ GeV}.
\]

Using a formula given by McLerran,\(^{14}\) this corresponds to a spatial energy density of over 1 GeV/fm\(^3\), which is beginning to approach the values required for the formation of the quark-gluon plasma.\(^{14}\)

Another necessary condition for plasma formation is that the energy be distributed as lots of soft particles, corresponding to long-distance
phenomena, rather than as high $P_T$ jets which are short-distance effects. Preliminary analysis of the $\alpha\alpha$ and $pp$ data of Figure 2 for the average sphericity, $s$, of the events as a function of $E_T$ is shown in Figure 5. The $pp$ data begin to show a dropoff in mean sphericity above 12 GeV, indicating the beginning of some "jet" contribution to the events. The $\alpha\alpha$ data, with a barely perceptible drop of sphericity out to 26 GeV in $E_T$, show no indication of "jettiness." The scale of "jettiness" has been determined for this detector from $pp$ collisions at $\sqrt{s} = 63$ GeV, where jets are observed for $E_T > 20$ GeV ($pp$ collisions!). A uniform azimuthal and rapidity distribution of energy deposition corresponds to an average sphericity, $<s> \sim 0.53$; while 20% jet contribution lowers $<s>$ to $\sim 0.42$, and 60% jets corresponds to $<s> \sim 0.22$. Thus the $\alpha\alpha$ spectrum at the highest values of $E_T^{TOT}$ may have a jet contribution of at most a few percent. This supports the conclusion that over the entire spectrum the neutral energy observed in the central region of $\alpha\alpha$ interactions at $\sqrt{s_{NN}} = 31$ GeV is caused by the emission of many uniformly distributed and presumably soft particles, with jet emission playing a negligible role. It should also be noted that the existence or non-existence of jets has no bearing on our analysis of the $\alpha\alpha$ spectrum in terms of multiple independent $pp$ collisions, since only simultaneous, or parallel, $pp$ collisions were considered.

![Figure 5](image-url)
REFERENCES


3. Note that I use the generic term \( \sigma(P_T) \) to represent the invariant cross section.


6. S. Frankel, "High \( P_T \) Nuclear Cross Sections," these Proceedings.


14. L. McLerran, these Proceedings.