Azimuthal Correlations in the Target Fragmentation Region
of High Energy Nuclear Collisions

T.C. Awes[e], D. Bock[d], R. Bock[a], G. Clewing[d], S. Garpman[c], R. Glasow[d],
H.Å. Gustafsson[c], H.H. Gutbrod[a], G. Hölker[d], P. Jacobs[b], K.H. Kampert[d,1], B.W. Kolb[a],
Th. Lister[d], H. Löhner[h], I. Lund[h], F.E. Obenshain[e], A. Oskarsson[c], I. Otterlund[c],
T. Peitzmann[d], F. Plasil[e], A.M. Poskanzer[b], M. Purschke[a], H.G. Ritter[b], R. Santo[d],
H.R. Schmidt[a], T. Siemiarczuk[a,2], S.P. Sørensen[e,i], K. Steffens[d], P. Steinhaeuser[a,1],
E. Stenlund[c], D. Stüken[d], and G.R. Young[e]

WA80 Collaboration

a.   Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany
b.   Lawrence Berkeley Laboratory, Berkeley, California 94720, USA
c.   University of Lund, S-22362 Lund, Sweden
d.   University of Münster, D-48149 Münster, Germany
e.   Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
h.   KVI, University of Groningen, NL-9747 AA Groningen, Netherlands
i.   University of Tennessee, Knoxville, Tennessee 37996, USA

Abstract

Results on the target mass dependence of proton and pion pseudorapidity distributions and of their azimuthal correlations in the target rapidity range $-1.73 \leq \eta \leq 1.32$ are presented. The data have been taken with the Plastic-Ball detector set-up for 4.9 GeV p + Au collisions at the Berkeley BEVALAC and for 200 $A \cdot \mathrm{GeV}/c$ p-, O-, and S-induced reactions on different nuclei at the CERN-SPS. The yield of protons at backward rapidities is found to be proportional to the target mass. Although protons show a typical "back-to-back" correlations, a "side-by-side" correlation is observed for positive pions, which increases both with target mass and with impact parameter of a collision. The data can consistently be described by assuming strong rescattering phenomena including pion absorption effects in the entire excited target nucleus.

The investigation of pion and baryon spectra and collective flow phenomena at relativistic energies is a well established field of nuclear research [1-3]. It has been addressed theoretically more than 20 years ago [4,5] and was investigated for the first time at the BEVALAC more than 10 years ago [6]. Recently, the study of the *interaction* of these particle species among themselves within the nuclear medium and the possible formation of Δ-matter has gained renewed attraction [7-12]. At relativistic energies, i.e. at bombarding energies around 1 A·GeV, the most important process involving nucleons *and* pions is the excitation of the $\Delta(1232)$ resonance. As the fate of a pion produced at these beam energies is governed by the reactions $\pi NN \rightarrow \Delta N \rightarrow NN$ and $\pi N \rightarrow \Delta \rightarrow \pi N$, one obviously should focus onto observables, where pion absorption and rescattering plays a role. Observables influenced by these processes should be the pion abundance itself as well as their energy and azimuthal distributions with respect to the reaction plane. The collision geometry of heavy-ion reactions delivers a "gauge": once the reaction plane is known, one can find regions (in 3-dimensional coordinate space) where pions can escape the reaction zone with either minimal or maximal reinteraction in baryonic spectator matter [13].

In this letter we shall present results from proton-nucleus and nucleus-nucleus reactions both at relativistic (4.9 GeV) as well as at ultrarelativistic energies (200 A·GeV/c). It has been shown [14] that the target fragmentation region at ultrarelativistic energies features similar characteristics as the central rapidity zone at relativistic energies, i.e. by restricting the investigation to $y \lesssim 0$ one can expect to cover the resonance regime as discussed above. We shall investigate azimuthal correlations both for positive pions and protons and study their dependence on the geometry of the reaction system.

The data were taken employing the Plastic Ball detector [15] at the Berkeley BEVALAC and at the CERN-SPS in the WA80 experiment. The Plastic Ball is a modular, azimuthally symmetric array of ΔE-E telescopes covering the polar range from $160°$ to $30°$ in the laboratory. Full particle identification is achieved for particles stopped in the E counter, thus limiting the energy range of accepted light baryons to $40 \text{ MeV} \leq E_{\text{kin}}/A \leq 240 \text{ MeV}$ and of positive pions to $20 \text{ MeV} \leq E_{\text{kin}}^{\pi} \leq 120 \text{ MeV}$. The pseudorapidity coverage of $-1.73 \leq \eta \leq 1.32$ is ideally suited to study the target fragmentation region at ultrarelativistic energies. If not mentioned differently, the data were analyzed under minimum bias trigger conditions.

An investigation of the target mass dependence of the proton, deuteron, and pion yields is depicted in Fig. 1 for $200 \text{ GeV}/c$ p + A reactions ($A \equiv$ C, Al, Cu, Ag, Au). The individual yields have been parameterized as $dN/d\eta(A) \propto A^{\alpha(\eta)}$ and the exponent α is plotted as a function of η . The backward protons (Fig. 1a) show a clear trend towards a value of $\alpha = 1$, while backward deuterons even exceed $\alpha = 1$. A previous analysis accepting *all* charged particles has provided very similar results
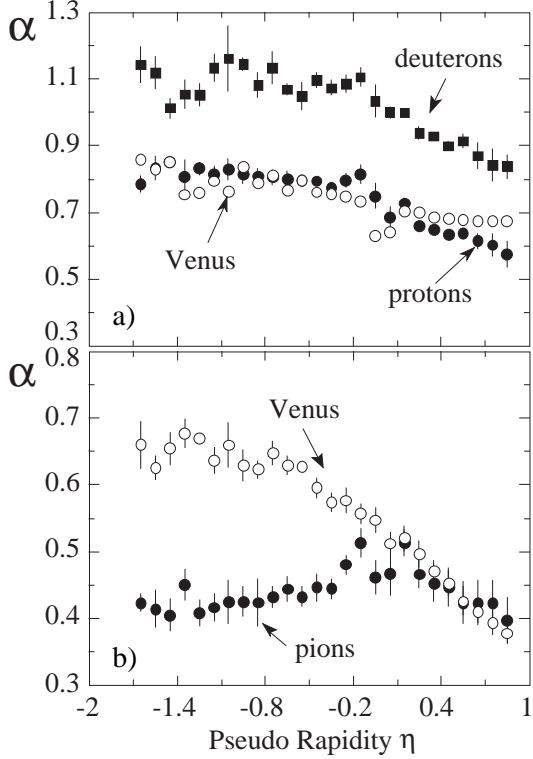
Figure 1: (a): Target mass dependence of protons (filled circles) and deuterons (filled squares) as a function of η for $p+A$ reactions at $200\,\mathrm{GeV}/c$ incident momentum. The target dependence is parameterized as $dN/d\eta \propto A^{\alpha(\eta)}$. The open circles show the result of VENUS simulations filtered to the experimental acceptance.
(b): Same as in (a) but for positive pions (filled circles). The open circles show again the result of VENUS simulations.

[16].

The stronger target mass dependence of deuteron production is qualitatively under-

stood within the coalescence picture, where $\rho_d \propto \rho_p \cdot \rho_n$ [17]. Based on the experimental observation of $\rho_p \propto A$, and assuming

$\rho_p \approx \rho_n$, a dependence of deuteron production $\rho_d \propto A^2$ is inferred, i.e. the *average A*-dependence of deuteron production scales with A^{α} with $\alpha > 1$.

In any event, the observed A-dependence of baryons is a clear indication of an homogeneous excitation of the entire target nucleus. The experimental findings for baryons are well reproduced by VENUS 4.12 simulations. VENUS [18] is a string model which treats rescattering of secondary particles in a rather simplistic way: as two objects approach each other below a critical distance they fuse with subsequent isotropic decay. This corresponds, for the case of NN interactions, to elastic NN scattering.

The situation is quite different for pions as shown in Fig. 1b. Here α stays at about 0.4 for all values of α, while, in contrast, the simulated pion yields from VENUS exhibit an increasing value of α for decreasing values of η. This behavior might be taken as an indication that the large resonance cross section (which is not taken into account in VENUS) plays an important role to decrease the pion yield via absorption as the target mass increases.

More information about possible absorption and rescattering effects can be obtained from azimuthal particle correlations. To search for such kind of effects between protons or between pions in the target rapidity range, a correlation function $C(\Delta\varphi)$ is constructed as follows:

$$C(\Delta\varphi) \equiv \frac{dN}{d(\Delta\varphi)} \; ; \; \text{where}$$

$$\Delta\varphi = \arccos\left(\frac{\vec{Q}_{\mathrm{back}} \cdot \vec{Q}_{\mathrm{forw}}}{|\vec{Q}_{\mathrm{back}}| \cdot |\vec{Q}_{\mathrm{forw}}|}\right) \; \text{with}$$

$$\vec{Q}_{\text{back}} \equiv \sum_{y < y_0} \vec{p}_\perp^{\,i} \ \ \text{and} \ \ \vec{Q}_{\text{forw}} \equiv \sum_{y \geq y_0} \vec{p}_\perp^{\,i}$$

The value of y_0 is chosen as 0.2. This is guided by the experimental fact that the target rapidity distribution of protons peaks at this value [19] and follows the idea of a target "fireball" moving with a rapidity y_0. The influence of the actually chosen value of y_0 to the experimental results, furthermore, has been checked by varying y_0 in a reasonable range $0.1 \leq y_0 \leq 0.3$. Within these limits no significant change of the correlation function has been observed.

Essentially, $C(\Delta\varphi)$ measures whether the particles in the backward and forward hemispheres of the target fireball are preferentially emitted "back-to-back" ($\Delta\varphi = 180°$) or "side-by-side" ($\Delta\varphi = 0°$), meaning on the opposite or on the same side of the reaction plane, respectively.

Figure 2 shows the experimental correlation function $C(\Delta\varphi)$ under minimum trigger bias conditions for $4.9\,\text{GeV}$ (top) and $200\,\text{GeV}/c$ (bottom) protons impinging on a Au target. The lefthand and righthand figures present $C(\Delta\varphi)$ for protons and positive pions, respectively.

Both, for protons and for pions a clear correlation is observed, but of opposite direction. To quantify these experimental results, the data were fitted by $C(\Delta\varphi) \propto 1 + \xi\cos(\Delta\varphi)$ and the strength of the correlation is defined as

$$\zeta \equiv \frac{C(0°)}{C(180°)} = \frac{1 + \xi}{1 - \xi}.$$

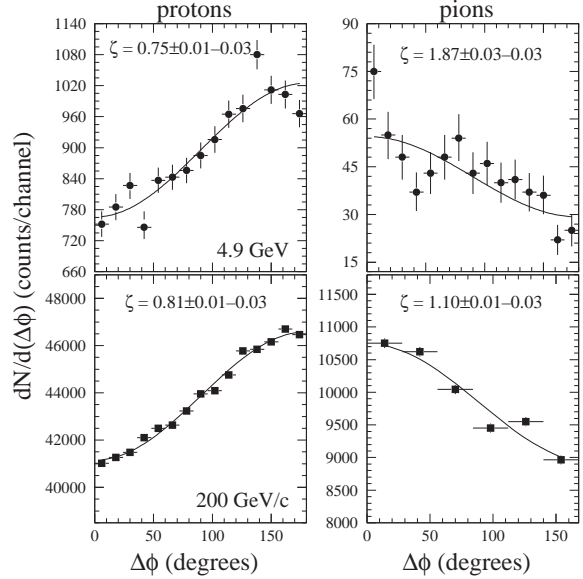As can be seen, one observes $\zeta < 1$ for protons and $\zeta > 1$ for pions, meaning that

Figure 2: The correlation function $C(\Delta\varphi)$ as described in the text for $\text{p} + \text{Au}$ collisions at 4.9 GeV (top) and 200 GeV/c (bottom). The lefthand and righthand panels present $C(\Delta\varphi)$ for protons and positive pions, respectively.

protons are preferentially emitted back-to-back, while pions are emitted side-by-side with respect to y_0. Detector asymmetries, which might cause an artificial side-by-side correlation, have been studied carefully by investigating the azimuthal distributions of $\vec{Q}_{\text{back}}$ and $\vec{Q}_{\text{forw}}$ individually. The observed maximum deviations from azimuthal symmetry allow to set a limit to the influence of the correlation function by $+0.03$ at most. This error is indicated in the values of ζ.

The back-to-back emission of protons can be understood as resulting from (local) transverse momentum conservation. This interpretation is supported also by results

from string models like VENUS. On the other hand, the side-by-side correlation of pions can naturally be explained based on the picture that pions, which are created in a $b \neq 0$ fm collision either suffer rescattering or even complete absorption in the target spectator matter. Both processes will result in a relative depletion of pions in the geometrical direction of the target spectator matter and hence will cause an azimuthal side-by-side correlation as observed in the experimental data. While for a $b \approx 0$ fm collision the emission directions of pions with respect to the reaction plane are expected to become azimuthally symmetric, the azimuthal distributions are expected to become more and more asymmetric as the impact parameter increases.

This hypothesis is clearly supported by the observed target mass and the impact parameter dependence of the correlation. The latter dependence has been determined both for p-induced and for heavy-ion induced reactions by applying cuts to the transverse energy measured event-by-event with the MId-RApidity Calorimeter (MIRAC) [20]. In all systems, a plateau in $dE_T/d\eta$ as a function of E_T is observed with a steep fall-off towards higher transverse energies. To select two regions of impact parameters, the events were divided into two bins with E_T smaller and larger than $2/3 \cdot E_T^{\max}$. These events are denoted as "peripheral" and "central", respectively. More stringent cuts on E_T, i.e. on the impact parameter or on the violence of the collision, were found to result in intolerable large statistical uncertainties of the extracted asymmetry parameter ζ. These uncertainties were on the
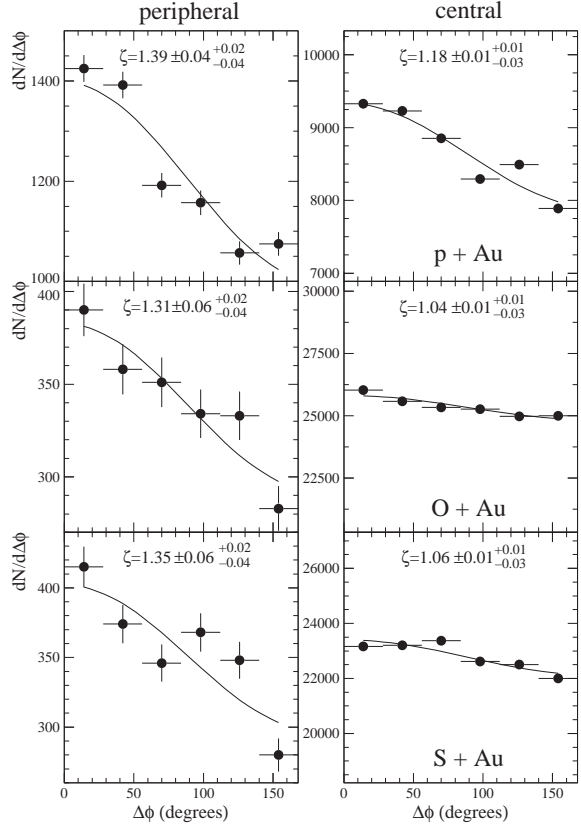

Figure 3: The correlation function $C(\Delta\rho)$ for positive pions from $\mathrm{p+Au}$ (top) and $\mathrm{O+Au}$ (middle), and $\mathrm{S+Au}$ (bottom) reactions at 200 GeV/c taken under minimum bias conditions. The lefthand and righthand panels are selections of peripheral and central events, respectively.

one hand caused by the low multiplicity of pions in the target rapidity region (low E_T) and on the other hand by the small number of events passing the software cut at high E_T.

Figure 3 shows the correlation function for positive pions from $\mathrm{p+Au}$, $\mathrm{O+Au}$, and $\mathrm{S+Au}$ reactions both for peripheral and central collisions, respectively. The corre-

lation function or, equivalently, the corre-
lation
strength parameter clearly shows a behav-
ior as one would expect from the rescat-
tering and absorption picture in spectator
matter: the strength of the correlation is
enhanced for peripheral collisions and al-
most vanishes for central $O + Au$ and $S + Au$
collisions. Furthermore, the azimuthal asym-
metry appears to be stronger for p-induced
reactions than for O- and S-induced reac-
tions. Both variations can be interpreted
by the different amounts of spectator mat-
ter available for secondary interactions. The
systematic error of the asymmetry param-
eter ζ is in peripheral collisions mainly caused
by relative uncertainties in selecting the
same 'violence' of the collision for different
reaction systems by applying software trig-
ger cuts to the associated transverse en-
ergy E_T, and is in central collisions dom-
inated by azimuthal asymmetries in the
detector response itself (see above). The
residual azimuthal correlation observed in
central $O + Au$ and $S + Au$ reactions can
thus to a large extend be explained by de-
tector asymmetries.

The dependence of the correlation co-
efficients on the target mass in minimum
bias data is summarized in Fig. 4 for pro-
tons and positive pions. The curves through
the data points are to guide the eye. Again,
we stress the interpretation within the ge-
ometrical absorption picture: as the tar-
get mass increases the side-by-side asym-
metry increases for the pions due to the
increasing amount of matter in their path.
In contrast, the back-to-back asymmetry
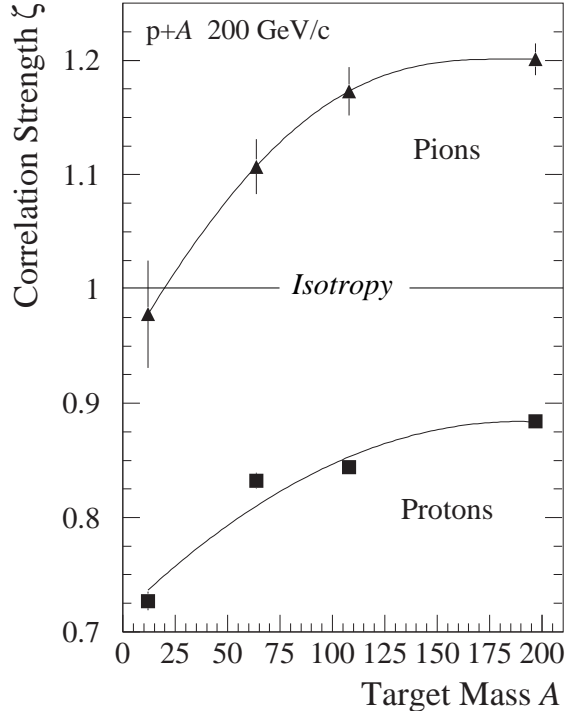of protons tends to vanish. This is also

Figure 4: Target mass dependence of the cor-
relation strength parameter ζ for both π^+ and
protons from minimum bias proton induced
reactions at 200 GeV/c. Only statistical er-
rors are shown. The curves are to guide the
eye.

expected, because correlations due to mo-
mentum conservation, as discussed above,
become weaker for higher event multiplic-
ities, i.e. for heavier system.

The observations presented in this Let-
ter are consistent with a recent investiga-
tion of charged pion flow [10] in symmetric
heavy-ion collisions at SIS energies. Here,
anisotropic pion flow relative to the reac-
tion plane was found ("pion squeeze-out")
and absorption of pions in the reaction plane
was conjectured to be the cause for the

anisotropy. Due to the different reaction geometry in symmetric systems, the spectator matter located in the reaction plane causes a stronger absorption and rescattering of pions in plane than out of plane.

Another investigation of large angle two-particle correlations, carried out at the 3.6 A·GeV C-beam in Dubna [21] showed a back-to-back pion correlation for a light target (Al), no correlation for a medium target (Cu), and a side-by-side correlation for a heavy target (Pb). For protons and deuterons, a back-to-back correlation was observed for all targets. Again, these results appear to be consistent with our observed proton and pion azimuthal correlations and with the variation of the pion correlation when going from a C to a Au target.

In summary, we have found conclusive experimental evidence for pion absorption and rescattering at target rapidities in ultrarelativistic proton-nucleus and nucleus-nucleus collisions. We observe both an impact parameter dependence and a target mass dependence of the strength of the azimuthal correlation function. The data are consistent with the geometrical picture of pions suffering secondary interactions while traveling through target spectator matter and thereby heating up the entire target nucleus. The latter argument is supported both by the observed linear rise of the target rapidity proton multiplicity with target mass A, as well as by two-proton correlations [22] where the extracted source sizes show a dependence on the target mass similar to $\propto A^{1/3}$ and are close to the nuclei radii.

[1] Now at University of Karlsruhe, Germany

[2] Institute for Nuclear Studies, Warsaw, Poland

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