Hadronic Observables: Theoretical Highlights

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I present highlights from the parallel sessions on the theory of hadronic observables in $e^+e^-$, hadronic and nuclear reactions.

1. OVERVIEW

The parallel talks which I will cover can be assigned to one or several of the following three subject areas:

1. Thermalization, flow, and source sizes;
2. Chiral dynamics and disoriented chiral condensates (DCC’s);
3. New developments for transport models and event generators.

Rather than commenting on individual talks in any detail, I will use these headings to classify the highlights presented at this conference. Before discussing individual results, however, I will make some general remarks on thermalization, flow and hadronic freeze-out in high energy reactions which, from the discussions at the conference inside and outside the lecture halls, I find appropriate and, hopefully, clarifying. For lack of space I omit references to talks given at this conference which can be found elsewhere in the proceedings, mentioning only the names of the speakers.

2. THERMALIZATION, FLOW, AND FREEZE-OUT

“Thermal” behaviour can arise in many conceptually different ways. In each case the “temperature” parameter $T$ has a different meaning. To avoid confusion it is therefore essential to keep the different concepts of “thermalization” separate and to be very specific about which concept one refers to in a given situation.

For us the two most important variants of “thermal” behaviour are the following:

1. The statistical occupation of hadronic phase space with minimum information. The “information” in this case is provided by external constraints on the total available energy $E$, baryon number $B$, strangeness $S$ and, possibly, a constraint $\lambda_s$ on the fraction of strange hadrons. This leads to “thermal” behaviour via the Maximum Entropy Principle in which the “temperature” $T$ and “fugacities” $e^{\mu_b/T}$, $e^{\mu_s/T}$ (which in the canonical approach are replaced by so-called “chemical factors” [1, 2]) arise as Lagrange multipliers to implement the constraints. Examples are nucleon emission from an evaporating compound nucleus in low-energy nuclear physics and hadronization in $e^+e^-$, $pp$ and $p\bar{p}$ collisions (hadron yields [1, 2] and $m_\perp$-spectra [3]). The number of parameters to fit the data in such a situation

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is equal to the number of “conserved quantities” (constraints), and it reflects directly
the information content of the fitted observable(s). This type of “thermal” behaviour
requires no rescattering and no interactions among the hadrons, there is no pressure and
no collective flow in the hadronic final state and, in fact, the concept of local equilibrium
can not be applied. In other words, this type of “thermal” behaviour is not what we are
interested in in heavy ion collisions, except as a baseline against which to differentiate
interesting phenomena.

(2) Thermalization of a non-equilibrium initial state by kinetic equilibration (rescat-
tering). This does require (strong!) interactions among the hadrons. Here one must
differentiate between thermal equilibration (reflected in the shape of the momentum spe-
tra), which defines the temperature $T$, and chemical equilibration (reflected in the particle
yields and ratios) which defines the chemical potentials in a grand canonical description.
The first is driven by the total hadron-hadron cross section while the second relies on
usually much smaller inelastic cross sections and thus happens more slowly. This type of
equilibrium is accompanied by pressure which drives collective flow (radial expansion into
the vacuum as well as directed flow in non-central collisions). In heavy ion collisions it is
realized at most locally, in the form of local thermal and/or chemical equilibrium – due to
the absence of confining walls there is never global equilibrium. This type of “thermal”
behaviour is what we are searching for in heavy ion collisions.

I stress that flow is an unavoidable consequence of this type of equilibration. Thermal
fits without flow to hadron spectra are not consistent with the kinetic thermalization
hypothesis. Flow contains information; it is described by three additional fit parameters
$v(x)$. This information is related to the pressure history in the early stages of the collision
and thereby (somewhat indirectly) to the equation of state of the hot matter.

Most thermal fits work with global parameters $T$ and $\mu$ which, at first sight, appears
inconsistent with what I just said. But here the role of freeze-out becomes important:
freeze-out cuts off the hydrodynamical evolution of the thermalized region via a kinetic
freeze-out criterium \[4\] which involves the particle densities, cross sections and expansion
rate. In practice freeze-out may occur at nearly the same temperature everywhere \[4\].

Clearly a thermal fit to hadron production data (if it works) is not the end, but rather
the beginning of our understanding. One must still check the dynamical consistency
of the fit parameters $T_f, \mu_f, v_f$: can one find equations of state and initial conditions which
yield such freeze-out parameters? Which dynamical models can be excluded?

2.1. Chemical equilibrium analysis of $e^+e^−, pp$, and $AA$ collisions

In spite of what I said about case (1) above, a “thermal” analysis of hadron yields
in elementary collisions is still interesting. The interest arises a posteriori from the ob-
served universality of the fit parameters, namely a universal “hadronization” or “chemical
freeze-out” temperature $T_{\text{chem}} = T_{\text{had}} \approx 170$ MeV (numerically equal to the old Hagedorn
temperature $T_H$ and consistent with the inverse slope parameter of the $m_T$-spectra in $pp$
collisions \[3\]) and a universal strangeness fraction $\lambda_s \approx 0.2-0.25$, almost independent of
$\sqrt{s}$ \[1, 2, 5\]. This is most easily understood \[2\] in terms of a universal critical energy
density $\epsilon_{\text{crit}}$ for hadronization, which, via the Maximum Entropy Principle, is parametrized
by a universal “hadronization temperature” $T_{\text{had}}$ and which, according to Hagedorn, char-
acterizes the upper limit of hadronic phase space. Supporting evidence comes from the
observed increase with $\sqrt{s}$ of the fitted fireball volume $V_f$ (which accomodates the increasing multiplicities and widths of the rapidity distributions). Although higher collision energies result in larger initial energy densities $\epsilon_0$, the collision zone subsequently undergoes more (mostly longitudinal, not necessarily hydrodynamical) expansion until $\epsilon_{\text{crit}}$ is reached and hadron formation can proceed. The systematics of the data can only be understood if hadron formation at $\epsilon>\epsilon_{\text{crit}}$ (i.e. $T>T_H$ for the corresponding Lagrange multipliers) is impossible. With this interpretation, the chemical analysis of $e^+e^-$, $pp$ and $p\bar{p}$ collisions does provide one point in the $T$-$\mu_B$ phase diagram (see Fig.1). – The only “childhood memory” of the collision system is reflected in the low value of $\lambda_s$, indicating suppressed strange quark production (relative to $u$ and $d$ quarks) in the early pre-hadronic stages of the collision.

![Diagram](Fig.1) Compilation of freezeout points from SIS to SPS energies. Filled symbols: chemical freeze-out points from hadron abundances. Open symbols: thermal freeze-out points from momentum spectra and two-particle correlations. (For each system, chemical and thermal freeze-out were assumed to occur at the same value $\mu_B/T$.) The chemical freeze-out point from $e^+e^-$ collisions [1] has been included while those from $pp$ and $p\bar{p}$ collisions [2] were omitted for clarity. (Generalization of the figure presented by Braun-Munzinger and Metag to whom I am grateful for help.)

In this light the observation [3] of a chemical freeze-out temperature $T_{\text{chem}} \approx T_H \approx 170$ MeV in heavy ion collisions at the SPS (Fig.1) is not really interesting. It suggests not only to the sceptic that in heavy ion collisions hadronization occurs via the same statistical hadronic phase space occupation process as in $pp$ collisions. What is interesting, however, is the observation (Becattini) that the strangeness fraction $\lambda_s \approx 0.4–0.45$ in $AA$ collisions...
is about a factor 2 larger than in \( e^+ e^- \) and \( pp \) collisions. If \( pp \) and \( AA \) collisions hadronize via the same mechanism, and in \( AA \) collisions the Maximum Entropy particle yields fixed at \( T_{\text{had}} \) are not modified by inelastic hadronic final state rescattering, this increase in \( \lambda_s \) must reflect a difference in the properties of the prehadronic state! In nuclear collisions the prehadronic stage allows for more strangeness production, most likely due to a longer lifetime before hadronization.

Sollfrank showed that \( \lambda_s = 0.45 \) corresponds to a strangeness saturation coefficient \( \gamma_s \approx 0.7 \), and that the factor 2 rise of \( \lambda_s \) in \( AA \) collisions cannot be explained by the removal of canonical constraints on strangeness production in the small \( e^+ e^- \) and \( pp \) collision volumes. He also argued that a strangeness saturation of \( \gamma_s \approx 0.7 \) in the hadronic final state may be the upper limit reachable in heavy ion collisions because the corresponding strangeness fraction agrees with that in a fully equilibrated QGP at \( T_{\text{had}} \approx 170 \) MeV. If both strangeness and entropy are conserved or increase similarly during hadronization, \( \gamma_s \approx 0.7 \) in the Maximum Entropy particle yield of the final state hadrons would be a universal consequence of a fully thermally and chemically equilibrated QGP before hadronization (and the SPS data would be consistent with such a state)!

According to Fig. 1 chemical freeze-out at the SPS (and also at the AGS?) appears to occur right at the critical line, i.e. at hadronization, whereas the SIS data indicate much lower chemical freeze-out temperatures (Metag). The origin of this is not yet clear but likely due to longer lifetimes of the reaction zone, especially at lower beam energies, allowing for chemical equilibration by inelastic hadronic reactions.

### 2.2. Thermal equilibrium and flow

The other interesting observation in the hadronic sector of nuclear collisions is that of collective flow (radial expansion flow, directed and elliptical flow). It is usually extracted from the shape of the single-particle momentum distributions. Radial flow, for example, leads to a flattening of the \( m_\perp \)-spectra. For the analysis one must distinguish two domains. In the relativistic domain \( p_\perp \gg m_0 \) the inverse slope \( T_{\text{app}} \) of all particle species is the same and given by the blueshift formula \( T_{\text{app}} = T_f \sqrt{\frac{1+\langle v_\perp \rangle}{1-\langle v_\perp \rangle}} \). This formula does not allow to disentangle the average radial flow velocity \( \langle v_\perp \rangle \) and freeze-out temperature \( T_f \). In the non-relativistic domain \( p_\perp \ll m_0 \) the inverse slope is given approximately by \( T_{\text{app}} = T_f + m_0 \langle v_\perp^2 \rangle \), and the rest mass dependence of the “apparent temperature” (inverse slope) allows to determine \( T_f \) and \( \langle v_\perp^2 \rangle \) separately. (In \( pp \) collisions no \( m_0 \)-dependence of \( T_{\text{app}} \) is seen.) Plots of \( T_{\text{app}} \) against \( m_0 \) were shown in many talks at this conference, showing that the data follow very nicely this systematics, from SIS to SPS energies (open symbols in Fig. 1). Notable (but not understood) exceptions were the \( \Xi^0 \)- and \( \Omega^- \)-spectra of WA97 (Králik) which are steeper than expected from this formula.

### 2.3. Rescattering – yes or no?

In his overview of the beam energy dependence of flow phenomena Ollitrault showed that all three types of flow phenomena appear in the data simultaneously, pointing to rescattering among the secondary hadrons as a common origin. The difference between the chemical and thermal freeze-out points in Fig. 1 suggests significant elastic rescattering between hadronization and decoupling, causing expansion and cooling of the momentum distributions. (Elastic collisions include resonance channels like \( \pi + N \rightarrow \Delta \rightarrow \pi + N \) which do not change particle abundances.) While present SPS data are consistent with a common
chemical freeze-out temperature in small (S+S) and large (Pb+Pb) collision systems (suggesting that particle abundances decouple directly after hadronization), thermal freeze-out seems to happen at lower temperature in Pb+Pb (120-130 MeV) than in S+S (140-150 MeV). This is consistent with hydrodynamical simulations (Shuryak) which show that larger systems live longer, develop more collectivity and cool down further before breaking apart. Low thermal freeze-out and large transverse flow in Pb+Pb are confirmed directly by HBT analyses.

I find the evidence presented at this meeting for the presence of all 3 types of collective flow at AGS and SPS energies convincing. Still, it is gratifying that the alternative view, namely that the nuclear broadening of the $p_\perp$-spectra can be understood without flow in terms of initial state scattering only [8], can be rejected by independent methods

While hadronic single-particle spectra were shown to have limited discriminating power [9], initial and final state rescattering effects can be clearly differentiated by studying two-particle HBT correlations and event-by-event fluctuations. An HBT analysis [10] of the models presented in [8] showed that they cannot account for the observed transverse expansion of the reaction zone, giving an $R_\perp$ which is factor 2 too small compared to the data, nor for the radial flow reflected in the observed significant $M_\perp$-dependence of $R_\perp$, nor the observed growth of $R_\parallel$ with $A$ which reflects the longer total reaction times until freeze-out in the larger nuclear collision systems. A study of event-by-event fluctuations of the average $\langle p_\perp \rangle$ for pions [11] shows that initial state scattering effects generically increase those fluctuations while the data show a strong decrease from $pp$ to Pb+Pb, consistent with URQMD rescattering simulations presented by Bleicher. Thus strong (elastic) rescattering is required by the HBT and fluctuation data.

2.4. The power of HBT

Pratt, Wiedemann and Schmidt-Sørensen discussed the usefulness of two- and three-particle correlations, in conjunction with single-particle spectra, for a direct reconstruction of the geometry and dynamical state of the reaction zone at freeze-out. The slopes of both the single-particle $m_\perp$-spectra and the function $R_\perp(M_\perp)$ (the transverse HBT radius) are given by combinations of $T_f$ and $v_f$, the temperature and transverse flow velocity at freeze-out. But since the two combinations are essentially orthogonal on each other in the $T_f$-$v_f$ plane, together they allow to separate thermal from collective motion (Wiedemann, Roland). For central Pb+Pb collisions at the SPS the average transverse flow velocity extracted in this way is large, $\langle v_\perp \rangle \simeq 0.5c$, while the thermal freeze-out temperature is low, $T_f \simeq 120-130$ MeV. The large transverse flow is accompanied by a large transverse expansion: the pion source at freeze-out is more than twice as large as the colliding Pb nuclei. This is quantitatively confirmed by an analysis of Coulomb effects of the fireball on the shape of the charged pion spectra at small $p_T$ (Heiselberg). The source expands rapidly longitudinally, with a nearly boost-invariant longitudinal velocity profile, for about 9 fm/c before the pions decouple and are emitted over a period of about 2-3 fm/c (Wiedemann).

The pion-emitting source seems to be “transparent” rather than opaque, emitting pions from everywhere, not only from a thin surface layer. Opacity leads to a smaller outward

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2Please note that initial and final state scattering effects on the spectra are not additive; if strong enough, both effects together dissolve into collective flow. It is therefore not correct to “subtract” initial state scattering effects from the slope parameters in order to isolate the flow contribution.
than sideward HBT radius at low transverse pair momenta (Heiselberg) or a negative “temporal” radius parameter in the YKP parametrization [12]. This is excluded by the NA49 data [13], while NA44 data may still allow for $R_{\text{out}}^2 < R_{\text{side}}^2$ at low $K_{\perp}$ (Heiselberg); this requires clarification.

These studies bring us close to a quantitative characterization of the final state in heavy ion collisions in phase-space, including its geometric and dynamical space-time structure. This can be used for a strongly constrained extrapolation backward in time. In [14] I presented a semi-quantitative attempt to do so, going as far back in time as necessary to shrink the reaction zone to its initial size before transverse expansion (about 1.5 fm/c after impact). Using energy conservation I estimate an initial energy density of about $\epsilon_0 \approx 2$ GeV/fm$^3 \geq 2\epsilon_{\text{crit}}$. This again points towards a non-hadronic initial state, with enough local equilibration to drive transverse collective expansion by thermodynamic pressure.

Schmidt-Sørensen presented the first serious attempt to extract a true 3-pion correlation signal from heavy-ion collisions. For chaotic sources the normalized true 3-pion correlator $r_3$ can be written as $2 \cos \Phi$ where $\Phi$ is the sum of phases of the three 2-body exchange amplitudes and a function of the relative momenta $q$. $r_3(q=0)$ measures the degree of chaoticity of the source, and its $q$-dependence measures the source asymmetry around its center [15]. Within the (large) statistical error bars the data of Schmidt-Sørensen can be fit by the functional form $2 \cos \Phi(q)$, consistent with a completely chaotic source.

3. CHIRAL DYNAMICS AND DISORIENTED CHIRAL CONDENSATES

The search for DCC’s continues to motivate theoretical work to predict their evolution and experimental signatures. Most existing work concentrates on the dynamics of the chiral field itself, neglecting interactions with other types of hadrons in the reaction zone, e.g. baryons. One usually tries to solve directly the relativistic field equations for the chiral field, but such an approach becomes impractical once interactions with other fields are included. These are more easily implemented in terms of semiclassical transport models for test particles or wavepackets.

M. Bleicher showed a URQMD simulation for Pb+Pb collisions at the SPS in which a DCC was put in by hand late in the reaction and seen to be destroyed by subsequent collisions with other hadrons on a very short time scale of order 1-2 fm/c. While this sounds troublesome (and may be correct) the treatment is not quite consistent: the DCC itself is not allowed to evolve (and possibly regenerate) since its dynamics cannot be handled within the existing transport approach.

This problem was addressed by J. Randrup who presented an implementation of the linear $\sigma$ model in form of a transport code with particles and mean fields. The relativistic field equations are split into equations for the mean field and the fluctuations. The latter is Wigner transformed into a transport equation. Neglecting collisions among the quantum fluctuations, it takes the form of a generalized Vlasov equation. The numerical simulation of this set of equations was shown to agree well with a direct solution of the initial field equations. This new technical tool for solving the chiral dynamics can now be merged with other transport codes such that the question raised by Bleicher can be addressed more quantitatively.

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3 Whether the observed transverse flow is created before or after hadronization cannot be decided yet.
V. Koch argued that the destruction of a DCC by collisions with thermal pions is not all bad because on the way out the DCC contributes to the low-mass dilepton spectrum. (This picks out the charged pion component of the DCC via the process \( \pi^+\pi^- \rightarrow l^+l^- \).) He showed mean-field simulations with up to a factor 100 enhancement in the dielectron spectrum at low \( p_T \) but a more realistic estimate for the magnitude of the effect would require the inclusion of collisions.

M. Asakawa said that he was not worried about the failure by WA98 and others to see any DCC signals because he believes that central heavy ion collisions are the wrong place to look for DCC’s! Not only threaten the large multiplicity densities in central collisions to destroy the DCC’s by collisions, but also the spontaneous domain growth may happen too slowly. Following a suggestion by Minakata and Müller [16], he proposed instead collisions at non-zero impact parameter because then the DCC’s can be driven by the magnetic field generated by the charge current of the two colliding nuclei. The latter couples to the neutral component of the chiral field via the anomaly \( E \cdot B \) which mediates the transition \( 2\gamma \rightarrow \pi^0 \) and spawns DCC’s by giving them an initial kick. Quantitative predictions based on this nice idea are not easy due to uncertainties in the initial conditions, but his results looked quite promising.

4. NEW DEVELOPMENTS FOR TRANSPORT MODELS

A common problem for transport models of the phase-space evolution in high-energy heavy-ion collisions is to get the correct nuclear stopping power, i.e. the amount of energy degradation experienced by projectile baryons when passing through a nuclear target. A particular difficulty is the extra rapidity loss connected with the conversion of a projectile nucleon into a leading hyperon via associated strangeness production. \( pA \) data indicate stronger stopping for leading \( \Lambda \)'s than for protons, causing an extra shift of strangeness production towards target rapidities which cannot be explained in terms of normal baryon stopping. The existing versions of HIJING and VENUS do not reproduce this behaviour [17]. The same effect may be responsible for the more central strangeness production in \( Pb+Pb \) than \( S+S \) collisions, in particular for the much more centrally peaked \( \Lambda \) rapidity distribution shown by G. Roland which is presently not understood.

The baryon stopping problem was addressed by K. Geiger, Y. Nara, and S.E. Vance. Geiger presented results from his code VNI which consists of a perturbative partonic cascade followed by cluster hadronization. Nara implemented rescattering effects among produced hadrons into HIJING. Vance modified HIJING by including, with 25% relative probability, a new process which breaks up the leading diquarks from a nucleon-nucleon collision, creating a “baryon junction”. After string breaking these junctions create baryons near midrapidity. All three suggestions lead to enhanced baryon stopping and higher net baryon density near midrapidity. There are differences in detail which need to be sorted out. No systematic investigation of the different shapes of proton and \( \Lambda \) rapidity distributions was presented yet which thus remains an open question.

5. CONCLUDING REMARKS

The present generation of experiments has come a long way towards the goal of measuring as many different experimental observables simultaneously as possible and correlating
them with each other. Hence the times are over when theorists could get away with trying to explain single pieces of data. We must now begin to adopt a global view of the reaction. The present data allow to combine a variety of different signatures in a controlled way and thereby test theoretical models in many corners simultaneously. In this way we can begin to eliminate models. Natural selection must be permitted to work, leaving only the most successful theories in the competition. How else are we going to find out the truth in this complex field?

In the hadronic domain the HBT analysis of two- and three-particle correlations has been established at this meeting as a powerful and quite practical new tool for our understanding of heavy-ion dynamics. I am sure that it will now rapidly show its full potential, including the interesting generalization of the method to unlike particle correlations [18].

A new and quite promising field where clearly much more theoretical guidance is required is event-by-event physics. The NA49 data [13] show that, on the $10^{-3}$ level, all Pb+Pb collisions are alike. The obvious conclusion is that if QGP is made in Pb+Pb collisions at the SPS, it is made in every collision! On the other hand, not seeing any qualitative structures in the fluctuation spectra makes their analysis more difficult than originally thought; a quantitative understanding of their widths is required. Theorists are just beginning to take up that challenge, and no final results were reported yet at this meeting.

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