Learning Hydrodynamics with Yogiro Hama

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Received on 29 September, 2006

As part of the celebration of his 70th birthday, I review the works done in collaboration with Prof. Yogiro Hama and try to recover the history of some of his ideas concerning the formation of a fluid in high energy hadronic collisions, its expansion and dissociation. I show how these ideas evolved and how they are relevant for understanding the present experimental data.

Keywords: Relativistic hydrodynamics; Multiparticle production; High energy hadronic collisions

I. THE BEGINING OF THE FIELD

A complete history of relativistic hydrodynamics is yet to be written. Some partial accounts can be found in [1, 2]. Here, I just want to remember some seminal works which started this field, which might be called hydrodynamics applied to multiparticle production in high energy hadronic collisions. In his pioneering work of 1953 [3] Landau developed several aspects of hydrodynamics and prepaired the formalism for future phenomenological applications. In the following year Khalatnikov [4] found the analytical solution of the one dimensional problem. These brilliant works went forgotten for many years. When remembered, they were regarded with suspition, if not with a frank opposition. About twenty years later, Carruthers used Landau hydrodynamics to study the, at that time, new data from the CERN ISR proton - proton collisions [5]. The phenomenological success of this approach renewed the interest on hydrodynamics and, in particular, motivated the search for the three-dimensional solution of the Landau model. This first success of hydrodynamics found also opponents, for whom this type of collective treatment of a microscopic problem was, at best, a parametrization of data, which was successful only because it was an implementation of energy-momentum conservation applied to a system whose dynamics was dominated by phase space. Still according to these opponents, there was no chance that hydrodynamics would describe a real system because there was no fluid! The number of produced particles was too small and the lifetime of the system was so short that no thermal equilibrium would ever be achieved.

It was in this period of phenomenological success but theoretical discredit, that Yogiro got interested in this subject.

II. THE FIRST WORKS

In his first contribution to the field, Yogiro [6, 7] computed the transverse momentum distribution of charged particles produced in p-p collisions, measured by different collaborations working at CERN [8]. He adopted the simple extension of the one - dimensional solution of the Landau model advanced in [5], assuming that the transverse rapidity of fluid followed a gaussian distribution, in the same way as the (longitudinal) rapidity. He improved the existing formalism introducing an energy dependent width of the transverse rapidity distribution and, most important, taking into account the local thermal motion of the final particles. With his model, Yogiro was able to fit the measured p_T spectra up to values considered large, where many people expected to see the effect of the jets arising from parton-parton collisions and computed with perturbative QCD. He concluded that “there is no evidence of the necessity of the hard scattering mechanism, although this is not otherwise excluded”. He did not believe that we were observing partonic degrees of freedom, but rather a fluid made of pions.

In his next work [9], Yogiro introduced the leading particle effect in the hydrodynamical model. In the original model the colliding particles would come to a complete stopping. However, in the early seventies it was discovered that in nucleon-nucleon collisions, almost always at least one of the incoming particles survives, keeping its charge and baryon number and having a large fraction of the incoming momentum, in a remarkable and unexpected ”transparency”. This is the so called leading particle (LP). Due to his previous experience with high energy hadronic scattering, Yogiro thought of LP production as a kind of diffractive process and, as such, dominated by events in which one LP is formed together with one excited cluster, which gives origin to the bulk of produced particles. In [9] he improved the previous analises of data, including the rapidity distributions, multiplicity distributions and the average multiplicity as a function of the reaction energy.

During those years, Fred Pottag was a student at IFUSP, working on his MsC and later on his PhD, always under Yogiro supervision. In 1981 they finished a work [10] improving the calculations published in [9] in two ways: taking into account the transverse expansion with a phenomenological parameter and replacing the previous convolution formula by the Cooper - Frye formula [11]. With the new formula for the invariant momentum distribution they computed again the pseudo-rapidity and Feynman x distributions of the produced particles. The use of the Cooper - Fryed formula was necessary because, in contrast to the convolution formula, it correctly enforced energy-momentum conservation during the freeze-out. From the quantitative point of view it brought only minor changes to the results obtained in [9].

Apart from the calculations and results, in [10] we can find an interesting argumentation defending the dominance of the one leading particle events over the two leading particles ones. The text also made explicit the concern regarding the origin of these LP's, which was attributed to some diffractive mechanism. The full understanding of the initial stage of the collisions demanded a quantum description. The quantum nature of the process would also imply fluctuations in the initial conditions for the hydrodynamical evolution of the fluid, as for example, a distribution (instead of a single constant value) for the invariant mass of the fireball. This last point would turn out to be very important and today we can see the effect of these fluctuations in the experimental data.

After that, Fred and Yogiro embarked in the ambitious project of finding a three dimensional solution of the hydrodynamical equations. The approach to the problem was still largely analytical. The method of characteristics was employed to minimize the numerical work, which was nevertheless very heavy [12].

A turning point in the history of hydrodynamics was the 1983 Bjorken paper [13], where he applied the boost - invariant solution of hydrodynamics [14] to relativistic nucleus - nucleus collisions. Although based on the unrealistic assumption of a flat rapidity distribution of the produced particles (the rapidity plateau), his solution of the hydrodynamical equations was remarkably simple and appealing. Most of all, he gave legitimacy to the method, which finally went to the mainstream, specially as a tool to analyze the forthcoming nucleus-nucleus collisions data from the CERN-SPS.

III. WORKING TOGETHER

In this period of changes and great expectations I joined Yogiro in his enterprise. In my MsC work we came back to his model [6, 7, 9] applying it to explain the growth of the average transverse momentum $< p_T >$ as a function of the charged particle multiplicity observed in $p-\overline{p}$ collisions at CERN, both at the ISR ($\sqrt{s} = 63$ GeV) and at the SppS collider ($\sqrt{s} = 540$ GeV). This growth was not expected in the string description of these collisions. Some authors invoked the onset of the perturbative QCD dynamics and the increase of semihard parton-parton collisions, the so called mini-jets, as a possible explanation of this behavior. In hydrodynamics this correlation was quite natural, since higher energies allow for hydrodynamical clusters with larger masses, which, live longer and therefore have more time to expand and get accelerated in the transverse direction. The fluid motion is transmitted to the final particles, which are, at the same time more numerous (because of the larger mass) and move with a larger p_T (because of the longer lasting acceleration). In the comparison with data, apart from fixing some parameters related to the hydrodynamical model, we had to be more specific on the production mechanism, having to fix the fraction of events with "single diffraction" (SD) and events with "double diffraction" (DD), where both of the incoming particles are excited and give origin to two thermalized systems, which expand as fluids. SD events generate smaller multiplicities and larger $< p_T >$ than the DD ones with equivalent mass. The detailed comparison suggested that a mixture of both event types, with a slight dominance of the DD events, was required to explain the data [15].

A more stringent test of the excitation mechanism (SD versus DD) was the understanding of the measured forward-backward correlation measured in the same type of collision. Our analysys suggested that half of the events were SD and half DD. This proportion indicated that standard diffractive dissociation (i.e., with Pomeron exchange) could not be the excitation mechanism. If it were, DD events would have been much less frequent. Our results also suggested that the events should be more symmetrical [16]. This feature would later be at the basis of the Van Hove - Pokorski picture of hadron - hadron collisions, according to which, there were always two leading particles and a central cluster, which would generate the bulk of the produced particles [17]. This picture would finally become the Interacting Gluon Model (IGM) [18].

After finishing my MsC I went to Marburg, where I first tried, without much success, to improve Fred's work on the three dimensional solution of hydrodynamics. On the other hand, the partonic description of the initial stage of the collisions, where energy deposition was understood as "gluon stripping" revealed itself very fruitful. One of the main results was an invariant mass distribution, the function already mentioned in [10], expressed in terms of initial gluon distributions and partonic cross sections.

While I was in Germany, Yogiro dedicated himself to the PhD project of Sandra Padula: the study of the effects of hydrodynamical expansion on the HBT interferometry formalism. This project would result in one of his most famous papers.

What is left from those works? The fact that a hydrodynamical model can explain certain features of proton - antiproton collisions is not enough to say that a real fluid is formed during these collisions. Nevertheless, working with this hypothesis allowed us to develop an intuition that would be useful for the hydrodynamical study of nucleus - nucleus collisions, where it is likely that we reach thermal equilibrium and create a hadronic fluid in the laboratory. We were convinced that the fireball production mechanism would be such that it would be formed "in the middle" from the debris of projectile and target and it would be made mostly from gluons. Our model, combining leading particle production with hydrodynamical expansion and local thermal distribution, would turn out to be useful in the near future, as I will describe in the next section, and even in our days [19].

IV. WORKING TOGETHER TEN YEARS LATER

In the begining of the nineties we were again together studying transverse momentum distributions with his hydrodynamical model. At this point in time, we had new data from the Fermilab - Tevatron and a wide scan in energy ($\sqrt{s}$), ranging from a few tens GeV up to almost two TeV became possible. At first we were interested, as ten years before, in the growth of the average transverse momentum. We wanted to fit the data, extract the parameters of the model and determine their dependence on the reaction energy. Yogiro thought that the average transverse velocity should increase with energy and, at the same time, the dissociation temperature should decrease with the energy. In fact, these two parameters are strongly correlated and it is difficult to isolate their individual behavior. We can, for example, obtain a broader transverse momentum distribution either increasing the dissociation temperature or increasing the collective flow transverse velocity. We tried to disentangle these two effects by simultaneously fitting p_T distributions of different particle species. In our case we considered spectra of pions and kaons. While I fitted the spectra, Yogiro went back to the original Landau formulas and found that, with some approximations, the behavior of the dissociation temperature with the energy could be extracted from the hydrodynamical model. The fit supported the theoretical estimates. In [20] we published our conclusions, saying that that T_d should decrease slowly with $\sqrt{s}$.

The interpretation of this result is the following: increasing the reaction energy we form clusters of higher masses, which are also hotter and denser. In order to escape, a particle inside the fireball has to traverse more and denser matter (at higher $\sqrt{s}$). Escaping becomes possible only when the system has sufficiently expanded and cooled, so that the density is smaller. It is not enough to cool down always to the same dissociation temperature. At a higher $\sqrt{s}$, to compensate for the increase of the matter to be traversed, the system has to cool to a lower T_d.

It might seem that this argument is based on a non-relativistic picture of the escaping process, since it uses the notion of "path traversed to escape" implying that a escaping particle has always to cross the frontier of the fluid. This is the case when we deal with a fast moving particle trapped in a slow moving fluid. Since this is not the most frequent situation in high energy hadronic collisions, one might ask how escaping takes place when the escaping particle is not so fast and the fluid around it is in fast expansion. This case is similar to what we find in cosmology, where the particle does not really cross any outer frontier. It is rather "the rest of the universe that goes away", leaving the particle alone and free. In this situation we have to forget about the frontier and use a local freeze-out criterion, similar to the particle decoupling condition used in cosmology. This was done in [21] where the approximate solution of the Landau model was replaced by Bjorken hydrodynamics. We found the same result, i.e., T_d falling with increasing $\sqrt{s}$. This behavior was found again in detailed numerical simulations of the hydrodynamical expansion, carried out with the HYLANDER [22] code and more recently with the SPheRio code [2].

The discussion prompted by the T_d dependence on the energy became a discussion on the freeze-out mechanism, which led Yogiro, Frederique Grassi and Takeshi Kodama to formulate the concept of continuous emission [23].

In paralell with the continuous emission project, Yogiro went on working on the initial conditions and the effect of fluctuations. This was the subject of the PhD work of Samya Paiva and generated a series of publications [24].

Recently, Xu and Kaneta [25] analyzing the p_T spectra measured by the STAR collaboration in $Au-Au$ collisions at RHIC, extracted the freeze-out temperature and found that T_d falls very slowly with the energy, giving support to the conjecture advanced in [20].

In [20] there was also a prediction of how the dissociation temperature would fall with increasing atomic number: $T_d \simeq A^{-1/6}$. In recent years many collaborations developed the technique of selecting events according to their centrality. In practice this allows for a scan of several effective atomic numbers. Extracting the freeze-out parameters from p_T distributions measured at different centralities, Molnar [26] could determine the N_{part} dependence of T_d, which should have the same qualitative features of the A dependence. He finds a T_d falling with N_{part} with a behavior very similar (even quantitatively!) to the one predicted in [20]. This behavior was not yet fully understood and certainly a detailed calculation with SPheRIO would be welcome.

V. FROM PARADOX TO PARADIGM

In 2005, after a series of extensive measurements of elliptic flow and, in particular, of the coefficient v_2 associated to it, a consensus was reached: the best way to understand the results was the with hydrodynamics [27, 28]. We can clearly observe a change in the conferences and in the papers. Hydrodynamics was never taken so seriously before. The nature of the questions changed from "Is it possible that initial partons reach thermal equilibrium?" to "How do they reach equilibrium?" As it is always the case in the history of physics, there are other opinions too. However, this change in attitude towards hydrodynamics can probably be called a change of paradigm.

A three - dimensional solution of the hydrodynamical equations, valid for non-central collisions, to be used with non-smooth initial conditions, able to incorporate event-by event fluctuations and with continuous particle emission: the work of a life! In 2005, as a recognition of his work on hydrodynamics, Yogiro was invited to give a plenary talk at "Quark Matter", the central meeting in this field.

In the next year the Large Hadron Collider will start taking data and in a few years it will be running with heavy ions. Hotter, denser, larger and longer living systems will be formed. There is certainly a future for hydrodynamics, a future to which Yogiro's contribution will have been influential.

VI. FINAL WORDS

Writing these lines led me to review many formulas, many figures and read many papers. I went through all this material with a very unusual look, with a certain detachment for the results, with a special interest in the introductions and side comments and, above all, a strong sympathy for Yogiro's continuous efforts along the same direction. I could see an intelectual trajectory, a balance between changing and conserving ideas. I could observe his long standing, and in the end very fruitful, concern with fluctuating initial conditions and with the dissociation dynamics. I could remember his notorious talent for difficult analytical calculations. His insistence on certain subjects and on certain approaches revealed a scientific personality not susceptible to the “moving fashion”. This strength of belief made him bet on hydrodynamics and some times face a harsh opposition. In short, I could see a career, which is beautiful... and seems far from over!

Acknowledgments

This work was partially financed by the Brazilian funding agencies CNPq and FAPESP under the contract 04/10619-9.

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