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Charming, equilibrated, and not at all strange: My memories of Jean Letessier and his work

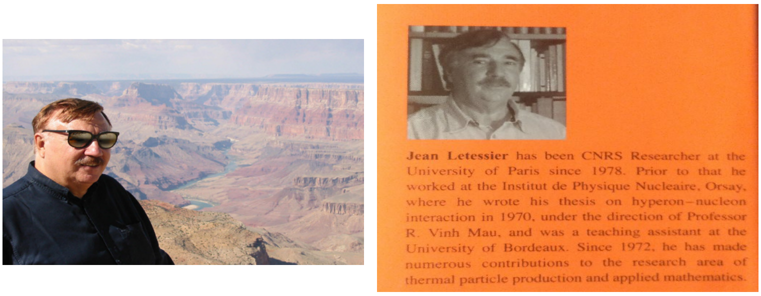
Giorgio Torrieri[1,*]

[1]IFGW,Unicamp

Abstract. This is a tribute to Jean Letessier, some memories of my PhD research in collaboration with him, a summary of the results we have achieved, and some personal thoughts as to the significance of these results to the field of heavy ion physics as well as the future of our field.

Theoretical physics has developed a cult of "assertiveness". To be noticed, you must be loud, confident, and willing to tell the whole seminar room or conference hall that you are correct and the rest of us do not have a clue. We all know, deep down, that the correlation of competence and arrogance is spurious, but somehow we always end up believing it is not.

Jean Letessier is a primary counter-example going against this prejudice. One would generally not notice him engaging in this behavior. And yet brilliant and competent he certainly was, without any doubt. His untimely departure means the loss of one of the pioneers of our field.



Jean Letessier has been CNRS Researcher at the University of Paris since 1978. Prior to that he worked at the Institut de Physique Nucleaire, Orsay, where he wrote his thesis on hyperon–nucleon interaction in 1970, under the direction of Professor R. Vinh Mau, and was a teaching assistant at the University of Bordeaux. Since 1972, he has made numerous contributions to the research area of thermal particle production and applied mathematics.

Figure 1. Jean Letessier, 1938-2020

I[1] met Jean soon after I started my PhD, under the supervision of Johann Rafelski [1]. I got to extensively appreciate Jean's brilliance, competency and helpfulness as I spent years studying how to make a sold link between the relativistic statistical mechanics of quark-gluon plasma and oodles of experimental data haphazardly organized in literature and electronic data-bases, via the subtlety of fitting algorithms.

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[*] e-mail: torrieri@ifi.unicamp.br

[1] This, and the references in this work, are meant to be a personal memory, not a comprehensive overview of the field. The reader is advised to go to look through the talks and proceedings of [3] for such a thorough list of perspectives

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The topic, strangeness enhancement in heavy ion collisions, is one of the pillars of the phenomenology of the quark-gluon plasma phase transition, mainly because of it's spectacular experimental confirmation [2, 3].

Yet, the physical interpretation of this phenomenon was and to a point still is up for grabs. Jean and Johann Rafelski made the important realization that, because of the proximity of the mass of the strange quark to Λ_{QCD} strangeness equilibration could function as a "clock", measuring the degree of chemical equilibration and the global properties of the quark-gluon plasma. This is both because in a Quark-Gluon plasma strangeness would equilibrate *faster* and because strangeness content would be *greater* than in the corresponding hadronic phase. A hadronization via quark coalescence would enhance both effects on the yield of multi-strange particles.

While fast equilibration is generally accepted within the field, most of the heavy ion community believed, and still does, that strangeness content in the quark-gluon plasma relative to a hadron gas is largely irrelevant to freeze-out dynamics because the system remains in chemical equilibrium, $\mu_{q,s} = -\mu_{q,s}$, throughout the hadronization phase transition. Considering that the chemical equilibrium is maintained if and only if

$$\frac{\chi_{q,s}}{T\rho_{q,s}} \times \frac{d\rho_{q,s}}{d\tau} \times \tau_{q,s} \ll 1 \tag{1}$$

Here, the first factor is the susceptibility χ relative to density ρ, the second the hydrodynamic expansion speed and the third is the chemical equilibration time.

considering $\chi_{q,s}$ and bulk viscosity [4] jump over the phase transition [2] and we do not know the behavior of the equilibration time $\tau_{q,s}$, it could just be that the system at freeze-out is in thermal equilibrium but maintains the chemical content of the quark gluon plasma phase. In [2], a particular scenario was proposed where this was realized via an explosive hadronization from a super-cooled plasma phase. While super-cooling necessitates a first order phase transition, other mechanisms, such as jumps in bulk viscosity [4], could produce the same result within a cross-over.

These non-equilibrium effects could be parametrized by phase-space factors γ_i ($i = q$ for light quarks, s for strange ones), with the effective chemical potential μ

$$\mu_{i,\bar{i}} \to \pm\mu_i \ln(\gamma_i) \tag{2}$$

and, if freeze-out is fast, we would expect $\gamma_q \simeq 1.5$ and $\gamma_s \simeq 1.5 - 2$.

This was the theory. One needed considerable computational efforts to, on one side, see what the properties of the quark gluon plasma would say about $\gamma_{q,s}$, on te other try to infer $\gamma_{q,s}$ from experimental data. Jean Letessier was the undisputed leader in the first effort, and one of the primary participants of the second one, which also formed the bulk of my thesis work.

The bulk of our effort was to write a now well-known computer code [5–7] capable of inferring chemical parameters from experimental data. The results were intriguing but inconclusive: The fits [8, 9] pointed to *exactly* the parameter space required by the arguments in [2]: Above a thershold in energy and system size, associated with the onset of nearly equilibrated deconfinement, freeze-out temperature drops to $\sim 140 MeV$ and $\gamma_{q,s} \geq 1.5$. Below this thershold, $T \sim 170$ MeV and $\gamma_{q,s} \leq 1$, reflecting a "hot" but under-equilibrated system that just "hadronizes" without significant partonic dynamics. Note that the enhancement of the ϕ meson from small to large systems [8] can be interpreted as to mean that strangeness enhancement is driven by chemical phase space γ_s^2, rather than kinematic conservation laws ("canonical suppression" [2]).

However, the statistical significance of $\gamma_{q,s} > 1$ was not enough to make this into a fully experimentally-supported statement. Since the difference between equilibrium and non-equilibrium goes with quark number, the penta-quark was the ideal candidate to look for phase space enhancement [11]. Unfortunately, it turned out to be a spurious state.

Of course we did not give up. An interesting opportunity was provided by the experimental study, in heavy ion collisions, of short-lived hadronic resonances, such as

$$Y^* = \Lambda(1520), K^*(892), \Sigma^*(1385), \Xi^*(1530), \Delta(1232), \rho, ...$$

and others. These have the same quark composition as the corresponding stable hadrons

$$Y = \Lambda, K, \Xi, p, \pi, ...$$

, but a larger mass. Hence, if freeze-out temperature is lower than the one expected for chemical freeze-out, as expected if the plasma is over-equilibrated [2], one would expect that their abundance, measurable via ratios such as Y^*/Y , is depleted. Of course, a long hadronic lifetime out of chemical equilibrium can also deplete such resonances, so more than one particle is necessary [12]. It is fair to say that the effect of rescattering, regeneration and lack of chemical equilibrium still has to be conclusively disentangled.

The next step was to examine particle fluctuations. Bose-Einstein statistics, which enhance mesonic and baryonic yields, enhance even more fluctuations of π mesons, whose mass is comparable to freeze-out temperature. The lower freeze-out temperature associated with over-equilibrated freeze-out provides a further boost to this enhancement by eliminating correlations due to resonances. Centrality fluctuations can be eliminated by considering fluctuations of particle ratios, preferably ratios where numerator and denominator are correlated by resonance decays, such as K/π (which probes the presence, at freeze-out,of K^*),p/π (which probes the Δ) and Λ/π (which probles Σ^*). Efforts in such a comprehensive analysis are on-going [6], but, to our knowledge, the model in [6], in the over-equilibrated regime, is the only one that can describe both yields and event-by-event fluctuations with a single set of parameters.

This physical picture, where chemical composition, analyzed via the non-equilibrium ansatz, provides clues to the dynamics and global properties of the hot quark-gluon plasma stage, also gives a special role to the charm quark. This quark is certainly and unquestionably out of equilibrium. It is dominantly produced within the initial hard scatterings, and then it's current is well-described by a conservation law equation driven by collective flow u_μ

$$\partial_\mu \left(\rho_c u^\mu\right) = 0 \quad , \quad \rho_c \equiv \gamma_c F\left[g, m, T\right] \tag{3}$$

where F is the relativistic Boltzmann factor, in terms of the spin degeneracty g and mass of the hadron m and the modified Bessel function $K_2(x)$

$$F\left[g, m, T\right] = \frac{4\pi g}{(2\pi)^2} m^2 T K_2\left(\frac{m}{T}\right) \tag{4}$$

In an equilibrated quark-gluon plasma, even at LHC energies, ρ_c would be thoroughly nengligible w.r.t. $\rho_{q,s}$. Unlike strangeness and light-quark abundance, that depend respectively on the strangeness susceptibility and entropy content of the quark-gluon plasma phase, γ_c is sensitive to $N_{coll}\sigma_{pp\to cX}$, due to the fact that after the initial production charm quarks are effectively conserved.

Charmed hadrons from a quark-gluon plasma will however be created via a coalescence type process, and hence will, just as light and strange quarks, directly be sensitive to the

Table 1. The regimes of interest of heavy ion physics. See [2] for details

$(R\sqrt{s})$ $\sqrt{s}/\Lambda_{QCD}$	$\ll 1$	~ 1	$\gg 1$
$\ll 1$	"Hadrons"	transport	"Gas"
~ 1	Regge?	String gas?	Hagedorn? Criticality?
$\gg 1$	"Partons"	"Glasma"?	QGP

charm composition.

$$n_i = \gamma_q^{q_i}\gamma_s^{s_i}\gamma_c^{c_i}\exp\left[\frac{\sum_{k=q,s,c}(k-\bar{k})\mu_k}{T}\right]F(g_i, m_i, T) \tag{5}$$

At LHC energies this will lead to a dramatic enhancement of charm and multi-charm baryons and mesons, by the same coalescence mechanism of strangeness enhancement described in [2], with the effect being quantifiable according to the publically available computer code in [7].

As a scientific conclusion, we are at the dawn of not one but two new eras: On the one hand, the increased luminosity of the LHC will allow experimentalists to look for multiply heavy baryon and meson states: $\Lambda_c, \Xi_c, B_s, csq$ states etc. etc. etc. as well as possible tetra and pentaquark states. This will be done both for "large" AA systems and for "small" pA and pp systems. On the other, low energy accellerators such as FAIR and NICA will explore the onset of deconfinement by looking for rare probes (ϕ,multi-strange states, D-mesons, J/Ψ) at low energy A-A collisions.

The variety of experimental data we will obtain should allow us to perform conclusively a thorough scan,with light, strange and charmed hadrons, of the relevant regimes (in system size R and energy $\sqrt{s}$ and intrinsic QCD scale $\Lambda_{QCD} \sim T_c \sim m_s$) to probe the onset of deconfinement (table 1) The systems shown in the table are all qualitatively different, requiring their own effective theory. "Hadron" refers to a small hadronic system, best studied by effective theory in the scattering regime. "Gas" refers to an out-of-equilibrium hadron gas, amenable to either hadronic transport simulations or thermal effective field theory. Partons would be an out of equilibrium, hadronizing burst of partons while QGP is the "holy grail", a deconfined system where statistical mechanics applies. The boundaries of these regimes are, respectively, equilibration and deconfinement. In the middle, non-trivial and fundamentally not understood critical phenomena, such as a Hagedorn/stringy regime and critical dynamics, could lurk [2].

Despite the enormous amount of results obtained, papers published, workshops and so on these boundaries have as yet to be firmly established. The tools of analysis of particle abundances outside of chemical equilibrium, pioneered by Jean and Jan, could be instrumental in achieving this mapping. Conclusively established jumps in $T, \gamma_{q,s,c}$, might be instrumental in identifying and characterizing transition regimes, as well as pointing out where, in energy and system size, could these transitions occur.

As Jean left this world, our field entered into a phase where the questions he spent a good part of his professional life investigating could be experimentally answered, by the methods he helped develop.

Collaborating with Jean Letessier was an absolute joy. His quiet demeanor provided a counter-balance to J.Rafelski's exuberance. One would however be gravely mistaken to confuse his quiet demanour with lack of involvement. Every result mentioned in this review would not exist without his contribution. Our field will miss him, and his friends and collegues will sorely miss his company. On a personal level, I cherish his helpfulness while I struggled with understanding the computational and statistical aspects of performing the analyses that went into the core of my thesis work. PhD work is often professionally lonely and daunting, and finding someone who will readily and meaningfully ask questions can make all the difference on a doctoral career. R.I.P. Jean and thanks for your collaboration, help and friendship.

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