THE QCD PHASE DIAGRAM, EQUATION OF STATE,
AND HEAVY ION COLLISIONS

E. Shuryak
State University of New York,
Stony Brook NY 11790 *

After some historic remarks and a brief summary of recent theoretical news about the QCD phases, we turn to the issue of \textit{freeze–out} in heavy ion collisions. We argue that the chemical freeze-out line should actually consist of two crossing lines of different nature. We also consider some inelastic reactions which occur \textit{after} chemical freeze-out, emphasizing the role of overpopulation of pions. The \textit{hydrodynamics} (with or without hadronic afterburner) explains SPS/RHIC data on radial and elliptic flow in unexpected details, for different particles, collision energies, and impact parameters. Apart of Equation of State (EoS), it has basically no free parameters. The EoS which describe these data best agrees quite well with the lattice predictions, with the QGP latent heat $\Delta \epsilon \approx 800 \text{MeV/fm}^3$. Other phenomena at RHIC, such as “jet quenching” and huge ellipticity at large $p_t$, also point toward very rapid entropy production. Its mechanism remains an outstanding open problem: at the end we discuss recent application of the instanton/sphaleron mechanism. The $gg$ collisions with $\sqrt{s} = 2 - 3 \text{GeV}$ may result not in mini-jets but rather in production of sphaleron-like gluomagnetic clusters, which are classically unstable and promptly decay into several gluons and quarks, in spherical mini-Bangs.

1. Introduction: the beginning of our field

Since I happen to present the last talk at this conference, let me start with some historic remarks, on the early days of our field in general and the role of Helmut Satz in particular. I know Helmut longer than the topic of conference, “Statistical QCD”, existed: we first met I think in 1975 in Dubna, a year after my Ph.D. 2 Already then I have been strongly influenced by his general style, which I would characterize as “forceful but kind”. (At this meeting he has demonstrated the same qualities once again, as the chairman of the last session, saving myself from a cascade of difficult questions after this talk.)

Speaking of our field, let me define it as the intercept of (i) the theory of hot/dense matter \textit{different} from the usual hadronic matter (such as nuclear matter); with (ii) the phenomenology of high energy heavy ion collisions 3. Of course the first use of thermodynamics for hadronic collisions was suggested 50 years ago by Fermi 4. Soon after

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2 Very characteristically, I could not find any material from that time, by Helmut had made and kept very nice photos: thanks Helmut once again.

3 There are also phenomenology of neutron stars and cosmological applications: but they are still struggling to be in the mainstream.
Landau argued that hydrodynamics should also be applicable, provided the system is macroscopically large, its size $L$ is much larger than a micro scale $l$, the mean free path. (Below I will return to the fundamental question of our field, whether the system created in heavy ion collisions does or does not satisfy this criterium.) When the first hadronic resonance, $\Delta$, has just been discovered, Landau and S.Z.Belenkij promptly introduced the “resonance gas”, supported by the Beth-Ulenbeck result for the second virial coefficient. Hagedorn in 1960’s developed this idea into dual bootstrap approach for resonances, and introduced his famous limited $T$. As it was understood later, it is indeed a maximal $T$ in a hadronic phase in which there is confinement and QCD strings. It was very important that from the start Hagedorn and others made practical applications of the statistical model to various hadronic reactions.

Of course in the early 70’s, when QCD has been discovered, its ideas were soon applied to hot/dense matter. Based on asymptotic freedom, Collins and Perry suggested that the high $T$ and/or density matter should be close to the ideal gas. The first perturbative corrections were evaluated. The part of gluonic polarization tensor due to high $T$ (unlike that due to virtual gluonic loops) screens the charge: thus the name of this new phase, Quark-Gluon Plasma (QGP). Its excitations are quasiparticles similar to “plasmons” etc of the usual plasma. Furthermore, it was found that static magnetic field is not screened: thus the infrared divergences and other non-perturbative phenomena survive in the magnetic sector. First resummations of (what was later called) Hot Thermal Loops into a plasmon term have also been done by the end of 1970’s. (Its consistent application to many other problems have been worked out by Braaten, Pisarski and others a decade later.) My other paper addressed such practical questions as new flavor, photon and dilepton production from QGP, as well as the first take on the $J/\psi$ suppression by gluon excitation similar to photoeffect.

By the end of 70’s Helmut was the first to realize that in order for this field to be shaped one has to take it all together: he called the first Quark Matter conference - the famous Bielefeld meeting of 1980 (soon reinforced by the next one in 1982) - which have defined the field and created our community.

Since at the time I still was, so to say, in a confined phase, I could not attend these meetings. As I also felt that something should be done at that moment, I wrote the first review article in which available theory results were combined with potential applications to high energy collisions.

2. The QCD phase diagram, version 2001

Let me start with general remarks about the phases of QCD. Basically, starting from the hadronic phase there are three directions to go: (i) High $T$ leading to QGP, the perturbative phase without any condensates. (ii) High density direction, which leads us to the confinement phase with confinement and $T$. (iii) High strangeness direction, which leads us to the QGP phase with confinement and $T$. (iv) The freeze-out happens at fixed desnity, not volume. Both of them have surfaced now again.

I also studied some of them as part of my Ph.D. in early 1970’s, and concluded that for reactions like low energy $pp \rightarrow n\pi$ the thermodynamics indeed works remarkably well, provided (i) one uses microcanonical approach for strangeness etc; (ii) the freeze-out happens at fixed desnity, not volume. Both of them have surfaced now again.

Of course, the famous 1986 paper by Matsui and Satz have superseeded it, by showing that in sufficiently hot QGP the $J/\psi$ is not even bound. However later, Satz, Kharzeev and others have also worked out gluonic excitation to continuum.
to very rich world dominated by quark pairing providing a set of Color Superconducting phases, with broken color group, sometimes with broken chiral symmetry or even broken parity. (iii) Increasing number of light quarks $N_f$ which brings another strange conformal world, without condensates but with the infrared fixed point. Very few studies have been done, on the lattice \[10\] and with instantons (see \[11\]): both have indicated that the critical $N_f$ can be as low as 7 or 5.

All this large variety of phases (including of course the hadronic phase we live in) and their boundaries can be understood with remarkably small set of dynamical tools. Basically, if one is interested in asymptotically large $T, \mu$, the one-gluon exchange should be used. If not, the \textit{instanton-induced} t’Hooft Lagrangian is enough. It generates attraction in three different channels: (i) \textit{quark-antiquark}, leading to chiral symmetry breaking; (ii) \textit{quark-quark} channel leading to color superconductivity; and (iii) attraction between \textit{instanton and anti-instanton}, mediated by light quarks, which leads to their pairing in QGP and conformal phase. The competition of these three attractions defines the phase boundaries.

Let me now make a quick update on recent news, starting with the T direction. Important work by the Bielefeld group (see Laermann, this proceedings) have fixed the critical mass of the quark, in the case when it is the same for 3 flavors. Its value indicate that in QCD we would nearly certainly have a cross-over, not the first order transition.

Addressing the fate of this cross-over line along the $\mu$ direction, Fodor and Katz \[12\] have found the first numerical evidences that the location of the critical endpoint $E$ is at $T \approx 160 \, \text{MeV}, \mu_B \approx 700 \, \text{MeV}$, see fig.1(a).

Going further to the high density we find intense theoretical activity. The main news is the “stress” which is provided by the non-zero strange quark mass on the Color-Flavor-Locked (CFL) phase leads to spontaneous breaking of the $P − parity$, with the non-zero \textit{kaon condensate}, as first shown by Bedaque and Schafer \[13\]. More details on the resulting phase diagram in the plane of chemical potentials for baryon and electric charge has been provided by Kaplan ad Reddy \[14\]: the most surprising feature is that the recovery of pure CFL phase happens only at extremely high density, at $\mu_b$ of the order of millions of GeV. (One will find details on it in T.Schafer’s talk in this proceedings.)

The second time in this field there were two papers from the Stony Brook and the (now) MIT teams, submitted to hep-ph on the same day\[6\]: both are the first attempts to “try the ice” by looking into possible \textit{crystalline phases of quark matter}. This time however the content of the papers are rather different. Rapp, Zahed and myself \[24\] have looked at frozen $\bar{q}q$ (or sigma) field with non-zero momentum: a phenomenon similar to the so called Pierls instability in 1d and Overhauser spin waves in 2d. We found that given very strong pairing force, it may well compete with the 2-flavor Color Superconductivity at $\mu_b \sim 1200 \, \text{MeV}$.

Alford, Bowers and Rajagopal \[25\] have considered a different crystal, in which $qq$ (or diquark) condensate has the non-zero momentum: it is similar to the so called LOFF phase proposed (but not observed yet) for ordinary superconductors. Its tentative place is a narrow region along the border between 2- and 3-flavor-like superconducting phases.

There are multiple works on unusual properties of excitations. Let me single out two

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6The first time, in 1998, those were papers by Alford,Rajagopal and Wilczek, and Rapp,Schafer, Shuryak and Velkovky, which have revived this field.
nice papers by Son, Stephanov and Zhitnitsky \cite{15} who have addressed the $\eta'$ and instantons at very high $\mu$. They have shown this to be the first example of relatively simple “instanton liquid”, in this case a 4-d dilute Coulomb plasma with the $\eta'$ being the exchange field which gets massive due to the Debye mechanism. They have also shown that in this phase there can exist metastable domain walls made of the $\eta'$ field: maybe bubbles made of such membranes can occasionally be produced in heavy ion collisions.

3. Heavy ion collisions

3.1. Physics of the freeze-out

As shown in several talks at this conference, statistical description of particle composition which worked well before also does so at RHIC. The only new number to know is $\mu_b \approx 45\,\text{MeV}$: the resulting predictions agree with measured particle ratios quite well.

However, \textit{Does the success of statistical description imply that we deal with macroscopically large systems?} Not really: the same thermal models provide nearly equally good description of hadronic yields from very low energy reactions like $\bar{p}p$ annihilation at rest to high energy $e^+e^-$ annihilation into hadrons. In the latter case we are quite sure the system is rather dilute: and thus excellent predictions of the thermal model here remains (a long standing) puzzle.

Fitting the matter composition from particular data set, one gets a point at the $T - \mu_b$ diagram. \textbf{What kind of pattern one should eventually see when many such points are collected?} Cleymans and Redlich \cite{16} have suggested a smooth chemical freeze-out line at $T - \mu_b$ plane: they have empirically shown that it is nearly a \textit{semi-circle} approximately correspondnf to energy per particle $E/N$ about 1 GeV. However I would suggest a different picture (see Fig. 1(a)), namely \textit{two crossing lines}, (i) the QGP phase boundary; and (ii) chemical freeze-out line defined by hadronic rates. Their nature is quite different: the first is a place of rapid changes in thermodynamics, the second is of kinetic nature and depends on things like expansion rate, and is in principle different for different nuclei and impact parameters. Although at the phase diagram it looks like two lines are nearly parallel and their crossing would be difficult to detect, it looks more promising in other observables. Strangeness content is one of them: see the $K^+/\pi^+$ ratio in Fig.1(b), in which the change of behavior is really striking. My prediction is that instead of a round maximum shown (corresponding to this semi-circle), we should see instead a peak sue to the crossing of two lines\textsuperscript{7}. Taking more data around the maximum, which we may call “the strangest point” marked S in Fig.1(a) is therefore very interesting and directly linked to the QGP phase boundary.

What happens \textit{after chemical freeze-out} is still hotly debated. As emphasized by Rafelski, in spite of baryon-rich environment at SPS, the anti-hyperon production is not strongly suppressed by annihilation, and their spectra show the same shape as hyperon’s, even a small $p_t$. The same is true for $\bar{p}$ as well. Logically speaking, there are two options: (i) either there is no interaction after chemical freeze-out (as Rafelski argued); or (ii) there exist back reactions, compensating for the annihilated anti-baryons. Rapp and myself as well as C.Greiner \cite{17} have shown that (contrary to disbelief of many) the rates of those\textsuperscript{7}In a particular model similar behavior but with \textit{two} discontinuities has been demonstrated previously by M.Gazdzicki et al, hep-ph/0006236.
are quite sufficient to nearly completely compensate the annihilation. The key element here is the well \textit{pion overpopulation} phenomenon: after chemical equilibration point (at which $\mu_\pi$ is set to zero), the number of pions is conserved while $T$ goes down: it means that $\mu_\pi$ grows, reaching about 70 MeV. Since annihilation $\bar{\text{n}}\pi \rightarrow n\pi$ include $n \approx 6$ pions, the inverse rate gets a big help from $\exp(n\mu_\pi/T)$ factor. “Life after chemical freeze-out” has been recently studied by Derek Teaney \cite{30}, as part of hydro studies to be discussed below. Incorporating non-zero $\mu$’s for \textit{all} species, he calculated the thermodynamics of the resulting chemically non-equilibrium resonance gas. (As above for pions, particle numbers per entropy are kept the same as at the chemical freeze-out point.) It turns out $p(\epsilon)$ (and thus hydro) hardly change, but $\epsilon(T)$ (and thus spectra) did changed quite a lot. Remarkably, new EoS of the resonance gas seem to match that of RQMD: if it is used for description of the hadronic phase, the results no longer depend on where transition from hydro to RQMD takes place.

3.2. Heavy ion collisions: flows and EoS

According to Landau, a decisive test of the macroscopic behavior is \textit{hydrodynamical} flows. \textit{Is this criterium satisfied by elementary pp or $e^+e^-$ collisions?} With appearance of the first multiparticle production data from accelerators in 1970’s, the answer seemed affirmative at first \cite{18},\cite{19}, but more accurate $\pi, K, p$ spectra from ISR had shown \cite{20} that in this case there is no sign of transverse expansion\cite{20} of matter. Beccatini at this\footnote{It has been argued in \cite{20} that the vacuum pressure may balance transverse pressure: the suggested picture resembled rather a string-like model than a hydro explosion.}
conference have shown fits to more modern high energy data, which indicate something like transverse flow, but with the velocity only $v_t \sim 0.2$ or so, much less than hydro predicts (and the RHIC data show), $v_t \sim 0.6$.

Early BEVALAC data have displayed collective phenomena such as directed flow and "squeeze-out", and hydro description had been attempted \cite{21}. Eventually however, it has been also concluded that at such energies ($E \sim 1\text{AGeV}$) the NN mean free path $l_{m.f.p.} \sim 1.5\text{fm}$ is not small enough compared to nuclear size $L \sim 6\text{fm}$ to justify it. Hadronic cascade models took the lead from that time on, and (such as event generators RQMD we use) have provided good description of AGS and SPS data. At AGS and even more so at SPS, much stronger collective expansion effects have been observed. At SPS the mean transverse velocity $v_t$ reached by matter is about 1/2. Although it has been successfully described hydrodynamically \cite{22}, these works did not shed much light at the EoS of very dense matter because at AGS/SPS conditions most of the acceleration happens at late times, in hadronic matter driven by relativistic pions. So, its hydro description is just "dual" to hadronic cascades.

The decisive shift occured when non-central collisions at high energies have been studied experimentally at SPS and RHIC, and theoretically, by our group \cite{29}, as well as by U.Heinz and collaborators \cite{27}. Based on these works and RHIC data, we can now see that we are finally approaching the macroscopic regime. \textit{Finally, we got a Bang, not fizzle.}

I would concentrate here on our last paper from the set \cite{29}, in which systematic study of radial and elliptic flow has been made, with detailed predictions of their energy, centrality and $p_t$ dependence as a function of EoS (the \textit{only} input for hydro). Our Hydro-to-Hadrons (H2H) model uses hydro in QGP and "mixed" phases, but switch to hadronic cascade (RQMD) in the hadronic phase. Thus, in contrast to others, we have \textit{differential freeze-out} of different species, which is very important aspect of the calculation. Its comparison with large set of SPS and RHIC data looks to me very convincing: the model describes radial and elliptic flows in great details. Of course, only few examples can be given here: I selected 2 cases in which the model was not anticipated to work, and surprised us.

One is "crossing" of $\pi^-$ and $\bar{p}$ spectra at $p_T \approx 2.0\text{GeV}$ shown in Fig.3. As shown in the l.h.s., even schematic hydro/thermal model with appropriate transverse velocity $v_t \sim 0.6$ explains it. The r.h.s. shows our predictions (both data and model have absolute normalizations: no free parameters). What is unusual about it is that hydro/thermal description seem to work even at the largest measured $p_t$: so far, no power-like tail due to hard processes is seen\textsuperscript{9}.

Let me now jump to Fig.3(a) which shows the impact parameter dependence of elliptic flow. First note that at SPS the difference between theory and data is substantial, especially at more peripheral collisions. However, this difference completely disappears\textsuperscript{10} at RHIC, where even very peripheral collisions demonstrate large elliptic flow. Another important feature of elliptic flow, also well reproduced by hydro Fig.3(b), is its strong growth with the transverse momentum.

\textsuperscript{9}One more argument that it is not jet fragmentation of any kind is this very point that they would lead to the $\bar{p}/\pi^-$ ratio much less than 1.

\textsuperscript{10}If STAR data were compared with pure hydro results, e.g. reported by U.Heinz et al, they are also below. However, "viscosity" of hadronic matter at freeze-out, taken care of by RQMD in our model, naturally explains this difference.
Figure 2. A comparison of \( \pi^- \) and \( \bar{p} \) spectra. (a) shows a simple thermal model with parameters discussed in the text. (b) shows an absolutely normalized comparison of model and PHENIX spectra.

Last but not least: combining all these hydro results, we were able to show that the whole body of data (i) cannot be described by EoS without the QCD phase transition; and that (ii) it is best described by EoS in which the jump in energy density (“latent heat”) is about \( \Delta \epsilon \approx 800 \text{MeV}/\text{fm}^3 \), or \( \Delta \epsilon/T_c \approx 8 - 10 \). This happen to be in excellent agreement with the lattice results, which the Beilefeld group and others have predicted for years.

4. How QGP happened to be produced so quickly at RHIC?

Heavy ion physics entered a new era when Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory have taken first data in summer 2000. These data (see e.g. [13]) have shown that heavy ion collisions (AA) at highest energies significantly differ both from the hh collisions and the AA collisions at lower (SPS/AGS) energies. Already the very first multiplicity measurements by PHOBOS collaboration have shown that particle production per participant nucleon is no longer constant, as was the case at lower (SPS/AGS) energies, but grows more rapidly. Long-anticipated semi-hard processes have shown up.

If they are perturbative “mini-jets”, cut at scale \( p_t > 1.5 - 2 \text{ GeV} \), the predicted mini-jet multiplicity is expected to be \( dN_g/dy \sim 200 \) for central AuAu collisions at \( \sqrt{s} = 130 \text{ AGeV} \). However, other RHIC data have provided serious arguments against the mini-jet scenario. Those are: (i) Strong collective phenomena such as flows desribed above (ii) Jet quenching: Spectra of hadrons at large \( p_t \), especially the \( \pi^0 \) spectra from PHENIX,
agree well with HIJING for peripheral collisions, but show much smaller yields for central ones. Counting from expected Cronin effect (which in pA collisions is about factor 2) we see a suppression of about order of magnitude. It has not been the case at SPS and it can only happen if the outgoing high-\(p_t\) jets propagate through dense matter, with \(dn_g/dy \sim 1000\). (iii) Furthermore, this estimate is also supported by STAR data on elliptic asymmetry parameter \(v_2(p_t)\) at large transverse momenta \(p_t > 2\, GeV\), see [23]. Note also that the result is consistent with the maximal possible value evaluated from the final entropy at freeze-out, \((dN/dy)_{\pi} \sim 1000\).

In summary, these data are quite consistent with the Quark-Gluon Plasma (QGP) (or Little Bang) scenario in which entropy is produced promptly and subsequent expansion is close to adiabatic expansion of equilibrated hot medium.

How this happened remains an outstanding question. One option is significant reduction of the pQCD cut-off relative to \(1.5 - 2\, GeV\) expected from pp. The other is the subject of the next section.

5. The instanton/sphaleron mechanism of entropy production at RHIC

In spite of significant progress related to instanton-induced effects in QCD vacuum and hadrons (see e.g. review [11]), very little has so far been made toward understanding high energy processes. This is mostly because it is difficult to translate many of our non-perturbative tools to Minkowski space.

The non-perturbative fields in the QCD vacuum (and inside hadrons) are not some shapeless objects, with typical size \(\sim 1\, fm^{-1} \sim 1/\Lambda_{QCD}\), as was assumed in the 70’s.
Instead it is concentrated in small − size instantons, with size \( r \sim 1/3 \text{fm} \), which also generate “constituent quarks” of similar size. When hadrons are boosted to high energies, they become thin disks: and substructure just mentioned makes their partons to be correlated in the transverse plane. Furthermore, what is a part of hadronic wave function in one reference frame, becomes the parton-parton interaction in another. This consideration alone implies importance of the instanton-induced high energy scattering.

We cannot describe here long history of the so called soft pomeron, starting from Pomeronchuck and Gribov in 1960’s. Phenomenologically it is still in very good shape. where a supercritical pole with the intercept \( \Delta \sim 0.08 \). Perturbative BFKL gluon ladder gives the pQCD version of high energy behavior, with a supercritical pole with the intercept \( \Delta \sim 1/2 \): it seem to work for hard processes, with large \( Q \).

For long time people have constructed multi-peripheral models with ladders made of hadrons. Recent story started with Kharzeev and Levin \[35\] who kept t-channel gluons but tried to substitute the gluonic “rungs” of the BFKL ladder by those with a pair of pions, or sigma meson, to improve it. They used the \( gg-\pi\pi \) non-perturbative vertices known from the low energy theorem. Their estimated value for \( \Delta \) was close to \( \Delta_{\text{phen}} \). Introducing instantons into the problem, I re-analyzed \[36\] the contribution of the colorless scalar channel generated by operator \( G_{\mu\nu}^2 \), using the \( gg-\pi\pi \) and \( gg-\text{scalar} - \text{glueball} \) couplings determined previously from the calculation of appropriate Euclidean correlators, see \[11\]. The result turns out to reduce thos of the KL paper, with \( \Delta \approx 0.05 \) only, and pions and glueball contributions being roughly equal.

The next important step has been done by two groups, Kharzeev, Kovchegov and Levin \[37\] and M.Nowak, I. Zahed and myself \[34\]. These works considered inelastic processes, with multi-gluon production. Basically, instead of the glueball peak at \( M \sim 1.7 \text{GeV} \) in the cross section \( \sigma_{gg\rightarrow\text{any}}(s) \) in the colorless scalar channel, these authors argue that a particular colored object is produced, the sphaleron. The cross section as a function of the mass is also believed to have a peak, around 2.5-3 GeV, with a width given by classical instability of this configuration. So, in a way, it is a resonance, although not a hadron due to non-zero color.

Hard processes, involving scales \( Q^2 \gg Q_0^2 \sim 1 \text{GeV}^2 \) are adequately described by pQCD: the result of parton collisions is their re-scattering, see fig.4(a). The multiple production of \( N \) partons is suppressed in pQCD by extra powers of \( \alpha_s(Q^2) \). It is however not true at the semi-hard scale \( Q^2 \sim Q_0^2 \) because here non-perturbative effects \( \sim \exp[\text{const}/\alpha_s(Q_0^2)] \) become comparable or dominant. Specifically for instantons, the so called instanton diluteness parameter \( n \rho^4 \sim (1/3)^4 \sim 0.01 \), were \( n \) (taken from the phenomenology and/or lattice studies \[11\]) is the resulting instanton density in Euclidean space-time, including all interactions and condensates in the vacuum. Compared to \( (\alpha_s(Q_0)/\pi)^n \) one may expect it to dominate over pQCD for processes in the order \( n > 2 \). And the non-perturbative phenomena like instanton-induced production indeed are multi-gluon ones, see fig.4(b).

Note that not necessarily one pair of gluons collides (the figure depict \( 3\times3 \) as an example), also several gluons are produced in one act. This happens because of the large field strength of the instanton \( A_{\mu}^{\text{inst}} \sim 1/g \), which makes processes with any number of gluons

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\[^{11}\text{For comparison, in electroweak theory it is about } 10^{-80} \text{ or so.}\]
Figure 4. The lhs of the figure compares (a) A typical inelastic perturbative process (two t-channel gluons collide, producing a pair of gluons) to (b) non-perturbative inelastic process, incorporating collisions of few t-channel gluons with the instanton (the shaded circle), resulting in multi-gluon production. The rhs side of the figure shows the same process in a quantum mechanical way. The energy of Yang-Mills field versus the Chern-Simons number $N_{cs}$ is a periodic function, with zeros at integer points. The instanton (shown by the lowest dashed line) is a transition between such points. However if some nonzero energy is deposited into the process during transition, the virtual path (the dashed line) leads to a turning points, from which starts the real time motion outside the barrier (shown by horizontal solid lines). The maximal cross section corresponds to the transition to the top of the barrier, called the sphaleron.

of the same orders in $g$.

Furthermore, the intermediate stage of the process (shown by the horizontal dashed lines) indicate coherence of the outgoing gluons: they are first produce in the form of specific gluomagnetic field configuration, the turning points, which I study right now. Before we outline results of the specific calculations, let me emphasize the basic quantum mechanics of the process (see the right-hand side of Fig.1). Instantons are classical solutions describing tunneling from one classical vacuum (in which $G_{\mu\nu} = 0$ and the $A_\mu$ is pure gauge) to another: naturally the energy is zero on it. However if during tunneling some energy is deposited into classical field, from two or more colliding gluons, after the system appears from under the barrier it may propagate in real time. Schematic example of that is shown in the right hand side of fig.1 for three cases, with deposited energy ranging from zero (the original instanton) to that of the barrier maximum.

The top point is known as sphaleron configuration, first found in the electroweak theory. Intensive studies of the instanton-induced processes also were done in this context in early 1990’s, driven basically by possible observability of baryon number violating processes in electroweak theory. The so called “holy grail function” showed that processes with multiple quanta production indeed lead to growing cross section, reaching its maximum at the sphaleron mass and then decreasing. However, since in electroweak theory the maximal cross section has been found to be still very far from observability,

12Which means “ready to fall” in Greek.
the interest to this direction have mostly disappeared around 1993 or so.

The results obtained so far are in reasonable agreement with data, and explain few qualitative points: (i) The pomeron intercept is small ($\Delta_{\text{phen}} \approx 0.08$ because it is proportional the \textit{first} power of the instanton diluteness parameter ($n\rho^4$). (ii) This mechanism also explains \textit{small size} of the Pomeron, (as seen e.g. from the Pomeron slope $\alpha'(0) \approx 1/(2 \text{GeV})^2$): the reason is small instanton size. (iii) Byproduct: at classical level \textit{no odderon} appears. This is related to non-trivial property of instantons/sphalerons: they are always in some SU(2) subgroup of SU(3); and in SU(2) there is no real distinction between quark and anti-quark.

In my recent paper \cite{39} it was suggested that the instanton/sphaleron mechanism may be a way toward the solution of this “early entropy” puzzle. In a way, high entropy may come directly from “sublimation” of strong vacuum gluon fields and of the vacuum quark condensate.

Assuming it to be the dominant process behind the logarithmic growth of the pp cross section, I estimated the probability of the sphaleron production directly from data. Although the cross section of prompt production is \textit{surprisingly small} in mean parton-parton collision, two orders of magnitude below geometric cross section $\pi\rho^2$, the total number of parton-parton collisions in \textit{central} AA collision is so huge that the number of “promptly-produced objects” (mini-jet pairs or sphalerons) in AA collisions per unit rapidity is estimated \cite{39} \[ \frac{dN_{\text{prompt}}}{dy} \sim 100. \]

Although this number is similar to estimated mini-jet production events, this scenario provides significantly larger amount of the entropy produced. Indeed, the mini-jets are just plane waves: they are classically stable and weakly interacting. The sphalerons are kind of resonances existing already at the classical level. They explode into spherical expanding shells of strong field, which rapidly sweep the whole volume and may convert it into Quark-Gluon Plasma\footnote{In heavy ion case partons produced do not hadronize immediately, as is the case for hh collisions.}. Each QCD “turning point” cluster decays into several gluons plus (with some probability) up to the whole $\bar{u}u \bar{d}d \bar{s}s$ set of quarks \footnote{In heavy ion case partons produced do not hadronize immediately, as is the case for hh collisions.}. Key signature of these decays may then be a deviation from the “hot glue scenario”: $\bar{u}u \bar{d}d \bar{s}s$ should be there much earlier than it is possible due to pQCD effects.

6. Conclusions

Let me try to summarize the status of our field, which is a 21-year old youngster, full of life and experimentation, open to whatever those will bring. This makes this field rather unique among other fields in high energy and nuclear physics. Helmut and other “old-timers” have all reasons to be proud of it. In particular:

(i) We finally have excellent dedicated machine, RHIC, and look forward for other observables and for the LHC era for a decade to come.
(ii) The field is growing well. It has enough open questions to provide challenges/ attract many 1-st rate young theorists.
(iii) Our understanding of the QCD phase diagram has grown enormously. All kind of symmetries – \textit{color, flavor,translations and even parity} – can be broken under appropriate conditions.
(iv) Amazingly, the Optimists were right: only factor 2 in multiplicity (from SPS to RHIC)
made a lot of difference! It is a Bang, not a (so often predicted) fizzle. And yes, we do see the “QGP push”. We seem to finally approach the macroscopic limit: hydro works, jets are quenched, ellipticity is very large, even at large $p_t$. The EoS is being determined. Remarkably, it seems to confirm quantitatively the values of $T_c$ and $\Delta \epsilon$ what lattice had predicted all along.

Outlook: Yes, there are many questions left open: but those are being addressed as we speak. One outstanding question discussed above is how so large entropy has been generated so quickly. The other problem I did not mentioned is what exactly is the shape of the freezeout surface, in view of current HBT data.

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