Excited hadrons as a signal for quark-gluon plasma formation

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Abstract

At the quark-hadron transition, when quarks get confined to hadrons, certain orbitally excited states, namely those which have excitation energies above the respective \( L = 0 \) states of the same order as the transition temperature \( T_c \), may form easily because of thermal velocities of quarks at the transition temperature. We propose that the ratio of multiplicities of such excited states to the respective \( L = 0 \) states can serve as an almost model independent signal for the quark-gluon plasma formation in relativistic heavy-ion collisions. For example, the ratio \( R^* \) of multiplicities of \( D_{S J}^{\pm}(2317)(J^P = 0^+) \) and \( D_{S}^{\pm}(2112)(J^P = 1^-) \) when plotted with respect to the center of mass energy of the collision \( \sqrt{s} \) (or vs. centrality/number of participants), should show a jump at the value of \( \sqrt{s} \) beyond which the QGP formation occurs. This should happen irrespective of the shape of the overall plot of \( R^* \) vs. \( \sqrt{s} \). Recent data from RHIC on \( \Lambda^*/\Lambda \) vs. \( N_{part} \) for large values of \( N_{part} \) may be indicative of such a behavior, though there are large error bars. We give a list of several other such candidate hadronic states.

PACS numbers: 25.75.-q, 12.38.Mh

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Keywords: quark-hadron transition, quark-gluon plasma, relativistic heavy-ion collisions

I. INTRODUCTION

There are strong reasons to believe that in ultra-relativistic collisions of heavy nuclei, a hot dense region of quark-gluon plasma (QGP) may get created. There is a wealth of data which strongly suggests that this transient QGP state may have been achieved in these experiments [1]. Still a conclusive evidence for the QGP detection is missing. Among many signals which have been proposed for the detection of QGP, probably the suppression of $J/\psi$ had the potential of being the cleanest signal [2]. However, due to various uncertainties involving final state interactions etc. it has not been possible so far to use even this signal to make definitive statements about QGP detection [3]. Most other signals depend more sensitively on the details of plasma evolution as well as on the details of the quark-hadron transition dynamics, and hence the predictions become crucially dependent on underlying models used to describe the dynamics of various stages of the parton system evolution [4].

Ideally one would like to have a signal which depends least on the details such as the order of quark-hadron transition etc. In view of lattice results, which suggest that quark-hadron transition may be a cross-over [5], one would like to only use the single defining property of the quark hadron transition, namely that quarks and gluons are deconfined above the transition temperature $T_c$, while they are confined into hadronic states below $T_c$. (For a smooth cross-over, there may not be a sharp value of $T_c$ at which confinement properties of quarks change abruptly. In such a case, by the transition temperature $T_c$ we will mean a range of temperature near the value $T = T_c$ across which the confinement of quarks significantly changes. If this range is narrow enough then use of a definite value for $T_c$ will still capture the essential physics of our model.) In the following we argue that the ratio $R^*$ of multiplicities of certain specific orbitally excited hadronic states to the respective $L=0$ states, where $L$ is the orbital angular momentum, may provide such a model independent signal for QGP formation in relativistic heavy-ion collisions. (In the following, by orbitally excited state, and orbital excitation energy, we will always mean the $L=1$ orbital excitation above the corresponding $L=0$ state, and the energy splitting of these two levels.) For example, the ratio $R^*$ of multiplicities of $D_{SS}^{*\pm}(2317)(J^P = 0^+)$ and $D_S^{\pm}(2112)(J^P = 1^-)$ when plotted with respect to the center of mass energy of the collision $\sqrt{s}$, or centrality/number of participants ($N_{part}$), should show a jump at the value $\sqrt{s_c}$ of $\sqrt{s}$ (or centrality) beyond which the QGP formation occurs.

It is important to clarify here that we do not discuss how $R^*$ should behave as a function of $\sqrt{s}$ (or, $N_{part}$). That is a separate issue and involves factors like the final state interaction etc. Our only claim is that, whatever be the form of the curve of $R^*$ vs. $\sqrt{s}$ (increasing or decreasing), there should be a jump enhancement at (or near the value) $\sqrt{s_c}$ (or, at some specific value of $N_{part}$) beyond which QGP formation happens. In this context we note that the recent data from RHIC on $\Lambda^*/\Lambda$ shows a strong decrease as a function of $N_{part}$ [6,7]. However, as just mentioned above, this is of no consequence to our model. What is important is to look for any possible jump in this decreasing curve at some specific value of $N_{part}$. We note from ref. [6] that the value of the multiplicity ratio for $\Lambda^*/\Lambda$ for very large $N_{part}$ (beyond 350) may be consistent with a slight increase, though completely within the
error bar, to conclude anything. (This possible increase is less clear in ref. [7], which could be due to different binning.) What is important is that if there is any rapid increase in $R^*$ beyond some $N_{\text{part}}$ then it will be very hard to explain it with existing models where a decrease in the multiplicities of resonances arising from final state interaction in the hadronic medium is naturally expected. (Note that any resonance regeneration should show smooth dependence on $\sqrt{s}$.) As we will see below, our model will naturally account for any such increase.

We give a list of several hadronic states which could provide such a signal for QGP formation in relativistic heavy-ion collisions. We mention that in order that these enhanced multiplicities of orbitally excited states survive up to the hadronic chemical freezeout, the chemical equilibrium should not last for long after the hadronization. This may not be an unreasonable assumption as chemical freezeout temperatures are close to the expected value of the transition temperature [8]. It is also expected that resonances may not achieve chemical equilibrium.

The paper is organized in the following manner. In section II, we describe the physical picture underlying the signal we are proposing. In section III, we discuss the details of the signal and certain special features specific to this signal. In section IV we discuss a rough estimate of the ratio $R^*$ based on a recombination model. In section V we give a list of candidate hadronic states which can be used for this signal. Section VI gives conclusions.

II. PHYSICAL PICTURE OF THE MODEL

We start by trying to form a physical picture of the process of hadron formation at the transition stage. We will restrict our attention to hadrons with not very high $P_T$, so that the hadronization will be expected to be dominated by something like the recombination process, rather than by fragmentation [9,10]. This may cover hadrons starting from very low $P_T$, up to hadrons with $P_T$ as large as few GeV/c, see ref. [9]. (As we will later argue, there are other arguments in our model suggesting that the signal we propose will be more prominent when restricted to low $P_T$ hadrons.) Further, as in certain recombination models [9], at the onset of hadronization, we may think of the effective degrees of freedom to be only (constituent) quarks with gluons essentially not being present as dynamical degrees of freedom. During hadronization, the effects of gluons will be primarily manifested in terms of confining color strings. In our picture the formation of hadrons will be with valence quarks which seems to be a reasonable approximation [9].

In the deconfined plasma, above $T_c$, the color field lines are spread out, and quarks and gluons are quasi-free with the usual Debye screening of color charges. As the transition temperature is approached from above, confinement sets in and color field lines start squeezing in the form of color flux tubes connecting quarks with antiquarks forming mesons, or forming baryons, glueball etc. (We use here the language of color string for the simplicity of physical picture. Basic physics we use is simply that hadrons form by combination of nearby quarks/antiquarks, as in the recombination models [9,10]).

For simplicity, let us first consider a single quark and antiquark with the overall quark-antiquark system being in the color singlet state. Let us further assume a hypothetical situation when the quark and the antiquark do not have any kinetic energy as the system
approaches the transition stage. The color lines will squeeze in the form of a flux tube, connecting the quark with the antiquark thereby forming a meson. If the color field distribution about the line joining the quark and the antiquark was not very asymmetric then the resulting meson should most likely form in a state of zero orbital angular momentum. This is because the color field lines will just squeeze, forming the color flux tube, which will lead to the confining potential for forming the meson. This flux tube, for a symmetric configuration will not have any orbital angular momentum, but may have radial excitations, as it relaxes to the appropriate meson state in a given energy eigenstate. Even in a bag model like picture, initially static quark and antiquark will be attracted to each other, get bound inside the bag with appropriate kinetic energies inside the bag, developing the constituent masses. Again, for isolated pair, and symmetric initial color fields, it seems unlikely that an orbital excitation can result.

Orbitally excited states for this case also can form due to following types of processes. As the quark-antiquark pair, connected by the flux tube (or inside the bag, in the bag picture), relaxes to an appropriate meson state, it can create some other lighter meson by fragmentation (or emit soft gluons if the initial quark and antiquark are not in a color singlet state, as in the Color Octet models [11]), resulting in the generation of orbital angular momentum for the remaining meson. Secondly, most often the initial color field configuration will be asymmetric (time dependent), leading to the formation of color flux tube (or bag) at the transition stage which is of deformed (time dependent) shape. Such a flux tube (bag), while relaxing to the meson state may generate orbital angular momentum. Also, orbital angular momentum can be generated due to the effects of other partons on this quark-antiquark pair.

So far we have made the unrealistic assumption that the quark and the antiquark under consideration had no kinetic energies at the onset of hadronization. Let us now take into account the fact that at a non-zero temperature $T$, quarks and antiquarks will have thermal energies, with average kinetic energy per degree of freedom being about $\frac{1}{2}T$. For relativistic quarks one should talk about the total energy. However, at the onset of hadronization, quarks will develop constituent masses, so even for light quarks, the use of non-relativistic terminology may not be a serious problem, especially as our discussion is mostly qualitative in nature. Let us now consider the binding of such quarks and antiquarks into mesons at $T = T_c$. The flux tube developing between the quark and the antiquark pair, now connects two point particles which have non-zero velocities. Clearly, in this case, for certain fraction (of order one) of cases, the quark and antiquark velocities will end up in the form of non-zero angular momentum of the resulting hadronic state. For example (using a semiclassical, non-relativistic picture), when their velocities are transverse to the flux tube connecting the pair, and are opposite to each other, then the resulting meson state will have non-zero orbital angular momentum. In the bag picture, with appropriate impact parameter, initial velocities will lead to orbital excitation as quarks get confined into hadrons.

Note here that quarks will anyway develop appropriate kinetic energies as they fall into any bound state. Such kinetic energies will result from the color forces binding the quarks into hadronic states. As we mentioned above, this will happen even if quark/antiquark did not have any initial kinetic energies. However, if each quark and antiquark in the entire system has a given (average) definite kinetic energy, then in certain fraction of the cases when these velocities are appropriately oriented, orbital excitation should result. What
we are saying is that it is difficult to form $L = 0$ hadrons when quarks/antiquarks have large initial velocities, just as it is difficult to form orbitally excited hadrons with initially static quarks and antiquarks. $L = 0$ meson can result only for special situations when the momenta of the quark and the antiquark are either parallel, or antiparallel with zero impact parameter. For generic situations, orbital excitation should result. (In the string picture, the string itself may have non-zero orbital angular momentum due to time dependence of the initial color field between the quark and the antiquark, as we mentioned above. However, it is not clear how, or whether, this string angular momentum may be related to thermal energies of partons, gluons in this case. Presumably, there will be no net orbital angular momentum left for the string if many gluons participate during the development of the color flux tube between the quark and the antiquark at the onset of confinement. Any other contributions to string angular momentum should be present even when the system temperature remains below $T_c$, hence it should not affect the qualitative aspects of the signal we are proposing.)

From the above intuitive reasoning, we conclude that thermal velocities of quarks and antiquarks at the hadronization stage can lead to the formation of orbitally excited mesons. In this picture, the thermal kinetic energies of the quark and the antiquark provide the required excitation energy for creating the orbital excitation. Now, in general the kinetic energy available will not be close to the required orbital excitation energy. For example, suppose the separation between the $L = 0$ state and the orbitally excited state is of order 800 MeV or more (as for the orbital excitations of $\pi$ and $\eta$ mesons). Even the combined thermal kinetic energies of quark and the antiquark should not be much larger than about $2-3T_c \approx 500$ MeV (with $T_c \approx 170$ MeV). In such a situation the required orbital angular momentum has to come from other sources as well, as discussed above.

However if one considers those specific mesons for which the orbital excitation energy roughly matches with the combined thermal kinetic energies of the quarks, then the required orbital excitation energy is right away available for creating the excited meson state. As every quark/antiquark has an average kinetic energy of order $T_c$ at the stage when they get confined to hadrons, we conclude that formation of those orbitally excited mesons which have orbital excitation energies of order $\alpha T_c$ should be greatly enhanced. Here the factor $\alpha$ is introduced to parameterize the part of kinetic energy of the quarks that gets converted into the orbital excitation energy of the meson. We are assuming here that a significant part of thermal kinetic energy of quarks survives as quarks develop constituent masses at the onset of confinement, even for light quarks. We again mention that quarks, when they get bound into hadrons, will have appropriate kinetic energies (e.g. in the bag model), which will result from confining color forces. What we are suggesting is that it is possible that a part (characterized by $\alpha$) of initial thermal kinetic energies of quarks, when quark/antiquark velocities are appropriately matched, may end up directly in the form of orbital excitation.

With this, we can have a rough estimate of the range of $\alpha$ by first assuming that it is only one specific velocity component of, say, quark which will give the required orbital excitation energy, when combined with opposite velocity component of roughly similar magnitude of the partner antiquark. Each velocity component will have thermal kinetic energy of about $\frac{1}{2}T_c$ at the transition stage (again, using a non-relativistic picture with quarks which develop constituent masses). Thus the total thermal energy of the quark-antiquark system which can be used to give orbital excitation energy will be about $T_c$. Other velocity components of quark and the antiquark could combine to give higher orbital excitation energy, or could
contribute to radial excitation energy. For example, average kinetic energy of the quark for the degree of freedom transverse to the color string will be about $T_c$. Combined kinetic energy of the quark and antiquark for suitable configuration (with opposite velocities for quark and antiquark) can then become $2T_c$ which can directly translate into the orbital excitation energy. From the above qualitative discussion we expect that the average value of $\alpha$ could be close to 1-2, and in any case should not be larger than 3. The value $\alpha = 3$ corresponds to the case when entire kinetic energy $\frac{3}{2}T_c$ of the quark and of the antiquark ends up in the form of the orbital excitation energy. (of course, these are kinetic energies on the average only.) For the case of baryons, the estimates of $\alpha$ should be appropriately modified by accounting for the thermal kinetic energy of each of the three quarks.

### III. EXCITED HADRONs IN RELATIVISTIC HEAVY ION COLLISIONs

Let us now consider the general situation of a relativistic heavy-ion collision. Let us first consider the situation when the collision process creates a system which thermalizes but does not reach up to the transition temperature $T_c$ so the QGP state is never created. In such a situation the formation of hadrons can be modeled using string fragmentation as the QCD strings break creating secondary hadrons [12]. In this situation there appears no reason to relate the thermal energies (of hadrons) to the orbital excitation energies, at the stage of hadron formation. The production of orbital excitations will mostly result from the transverse momentum created for the quark-antiquark pairs from the breaking of QCD string in the fragmentation model [12]. There will be a distribution of $P_T$ of quarks and antiquarks, with no specific value of $P_T$ preferred. In particular, there is no reason to relate the transverse momentum of quarks/antiquarks at the fragmentation stage to the thermal energies in the resulting hadron system. Thus there is no reason to expect enhancement in the multiplicities of any specific orbitally excited states at some particular value of the temperature of the final hadronic system.

Now consider the situation when the temperature of the system reaches above $T_c$ and deconfined QGP state forms. As the QGP expands and cools, its temperature drops to $T_c$ and partons combine to form hadrons. As we argued above, now specific orbitally excited states, with orbital excitation energies close to $\alpha T_c$ will form with enhanced rate. We should note that the formation of hadrons in a QGP state which is cooling through $T_c$ and the formation of hadrons in collisions where temperature never reaches up to $T_c$ may be of very different nature [9,10]. Therefore one may not be able to compare directly the multiplicities of orbitally excited states between the two cases. However, we can consider the following ratio,

$$R^* \equiv \frac{N(M^*)}{N(M)}.$$

Here $N(M^*)$ and $N(M)$ are the total multiplicities of orbitally excited meson and the corresponding $L = 0$ state meson respectively. For such a ratio, the effects of any possible intrinsic difference between the two types of hadronization may be minimized. Also, to make sure that hadrons which form from hadronization of QGP do not get mixed with hadrons forming in the regions which do not undergo deconfining transition one should confine to
near central rapidity regions. As we have mentioned above, restriction to hadrons with not very high $P_T$ should ensure that only hadrons forming via a recombination type process are being included and not the ones coming from the fragmentation process.

As for other orbitally excited states, for which the orbital excitation energy is very different from the expected range of $\alpha T_c$, for them also the ratio $R^*$ defined above may be somewhat enhanced due to thermal velocities of quarks and antiquarks. However, for them the dominant contribution to the orbital excitation energy must come from sources other than the thermal energy. Those sources will lead to contributions which may become difficult to distinguish from various sources for the case of hadronization when temperature remains below $T_c$. Hence, in those cases the ratio $R^*$ may not show any significant change as the maximum temperature of the system crosses $T_c$.

It is not entirely clear what happens for the states which have excitation energies well below $T_c$. Though, in the particle data table there appear to be no such states, still, conceptually one should discuss this case. If thermal kinetic energy of quarks and antiquarks is very large then during the formation of hadrons the remaining kinetic energy has to be either converted to part of the energy of QCD string, or dissipated away in other modes, e.g. by emission of lighter mesons.

The effects we have discussed above are valid for baryons as well, as the basic physics of orbital excitation coming from the transverse components of thermal velocities of quarks remains the same. It is also possible that the effect we are proposing here may be present even for radially excited states of mesons. However, radial excitations may not be uncommon even when quarks do not have significant thermal velocities. For example, when a quark and an antiquark become joined by the QCD string at the stage of hadronization, then while relaxing to an appropriate meson state, radial excitations can result. It may thus become difficult to disentangle the effect of thermal kinetic energies on radial excitations.

We therefore focus on the orbital excitations of hadrons as the underlying physical picture is simple to analyze.

The physical picture which we are using here for the enhanced formation of specific orbitally excited states is similar to the formation of resonances where the cross-section shows a peak when the center of mass energy equals the energy of the intermediate bound state. The difference here is that we are here focusing primarily on the initial kinetic energy of the quark and antiquark and essentially arguing that the cross-section should show enhancement when the initial kinetic energy is of the same order as the orbital excitation energy of the meson state. Clearly this special treatment of initial thermal kinetic energies of quarks is a very strong assumption, even stronger than the non-relativistic, semiclassical picture underlying the entire discussion. For heavy quarks the non-relativistic treatment is reasonably accurate [13]. Even for light quarks, as the quarks start binding into hadrons the constituent quark mass will start playing the dominant role and the non-relativistic treatment may still capture essential physics. (Velocities of light quarks are about 0.7-0.8 in heavy-light bound states [14].) What remains a gross approximation is the special status of the initial (thermal) kinetic energies of quarks/antiquarks. As we discussed above, quarks and antiquarks, when they get bound into hadrons will develop kinetic energies (e.g. in the bag model), which will result from confining color forces. What we have focused on is that the system undergoing hadronization consists of quarks and antiquarks (as we mentioned earlier, we consider only on the valence quarks/antiquarks in hadron formation), all of which
have roughly same kinetic energies (of order $T_c$). When such rapidly moving quarks and antiquarks get captured into hadrons, then it seems very natural to assume that it will be relatively difficult to form $L = 0$ hadrons and that a part (characterized by $\alpha$) of initial thermal kinetic energies of quarks may end up directly in the form of orbital excitation.

As confinement sets in, and quarks pick up constituent masses, the kinetic energies of quarks will contribute to resulting potential energy of the system, e.g. to the energy of flux tube which connects a quark and an antiquark to form a meson. Kinetic energies of quarks will also get significantly affected as they develop constituent masses due to effects of confinement. Such effects should tend to lower the value of $\alpha$, and clearly all such effects have to be properly accounted for. For example, the spin-orbit interaction energy also may play an important role in determining the value of $\alpha$. In the absence of a detailed picture of confinement, we just parameterize such effects in terms of $\alpha$.

Even with all these ambiguities and crudeness of our arguments, we suggest that there remains the possibility that the thermal velocities of quarks and antiquarks may have a sizable contribution to the orbital excitation of hadrons (and possibly also for radial excitations of hadrons). If this is true then the relative ratios of orbitally excited states $R^*$ (as discussed above) carry a signature of the transition temperature $T_c$ at which all the quarks/antiquarks become bound into hadrons.

The specific signal we propose is the following. One should plot the ratio $R^*$ for various hadronic states as a function of the center of mass energy of the collision, for, say, given colliding nuclei (which determines the initial energy density, and hence the temperature of the resulting system [15]). Alternatively, one can also plot $R^*$ as a function of number of participants $N_{\text{part}}$/centrality for a given center of mass energy. For generic hadronic states, $R^*$ should vary in a certain smooth manner as a function of $\sqrt{s}$ (or, of centrality). For example, if we assume that abundances of hadrons are determined by the thermal equilibrium distribution, as seems to be the case for most hadrons [8,16], then the dominant behavior of the ratio $R^*$ should be given by, $R^*_{\text{thermal}} \sim exp\left[-(E^* - E)/T\right]$ (with appropriate chemical freezeout temperature). Here $E^*$ and $E$ are the energies of the orbitally excited hadron and the $L = 0$ state hadron respectively. We are not writing here the detailed expressions for the multiplicities (including possible factors of the appropriate chemical potentials), as in the thermal models [8]. Also, we do not discuss about the contributions of decays of heavier states to various multiplicities at freezeout. This is because such factors will be present for the ratio $R^*$ even when the system temperature always remains below $T_c$, and hence do not affect the nature of the signal we propose. For our purpose it suffices that $R^*$ is some smooth function of $\sqrt{s}$.

It is important to clarify here that we are mentioning this case of thermal abundances only as an example. We are not arguing for any specific shape of the plot of $R^*$ vs. $\sqrt{s}$ (or, $N_{\text{part}}$). For example, it is very likely that resonances do not chemically equilibrate, so the assumption of thermal distribution for them is inaccurate. Further, the final multiplicities will be severely modified by factors such as final state interactions and loss of signals in the medium, which will be expected to strongly suppress resonances as a function of $\sqrt{s}$ (or centrality), (also by enhancement factors such as resonance regeneration). The overall curve of $R^*$ may very well be decreasing as a function of $\sqrt{s}$ or $N_{\text{part}}$ (as for $\Lambda^*(1520)/\Lambda$, see ref. [6,7]).

Now, at some critical value $\sqrt{s_c}$ of $\sqrt{s}$ at which the temperature of the system reaches
above $T_c$, the above described enhancement of orbitally excited states should become oper-
active due to the formation of QGP state. This should result in an abrupt enhancement in
the value of $R^*$ for those hadrons for which the orbital excitation energy is close to $\alpha T$ at
$T = T_c$, i.e.

$$E^* - E \simeq \alpha T_c. \quad (2)$$

Further, this enhancement should prevail at all higher values of $\sqrt{s}$. Again, note that
if the overall curve of $R^*$ is decreasing as a function of $\sqrt{s}$ then our argument implies that
beyond a critical value $\sqrt{s_c}$ (or centrality), there should be a separate segment of the plot of
$R^*$ with a jump enhancement at $\sqrt{s_c}$. Even for other hadrons for which the orbital excitation
energy is not too close to $\alpha T_c$ at $T = T_c$, there may be some enhancement in the corresponding $R^*$
beyond $\sqrt{s_c}$, with the enhancement decreasing as $E^* - E$ deviates more and more from the
value of $\alpha T_c$. One can also consider the ratio of multiplicity of an orbitally excited hadron
state, say with energy $E^*$, to $L = 0$ state of some different hadron which has the same (or
almost the same) energy. Such a ratio, from thermal models, should not strongly depend on
temperature (assuming other factors like chemical potential to be same for the two states),
and hence on $\sqrt{s}$, apart from the effects of final state interaction in the hadronic medium.
Our model will then predict a sharp change in the value of this ratio at some specific value
$\sqrt{s_c}$ of $\sqrt{s}$. This may have an advantage that departure from a (possibly) roughly constant
value of the ratio at $\sqrt{s_c}$ may be easier to identify. On the other hand, using states of
the same hadron is advantageous in minimizing the effects of details of the parton system
evolution etc.

Note that this requires that the enhanced multiplicities of these specific orbitally ex-
cited states should depart from the thermal distribution. This appears to be the case for
resonances. In any case this possibility does not seem unreasonable to us as, even with
the general success of statistical models, it is clearly a very strong assumption that strictly
all hadronic multiplicities should follow equilibrium distributions. For this to happen, the
hadronic system should last for long enough time (compared to all relevant hadronic inter-
action rates) before the chemical freezeout happens. This does not seem to be the case as
chemical freezeout temperatures do not seem to be much different from the expected value
of the transition temperature [8]. In fact, it has been argued in ref. [8] that, in view of
the short time scale between the hadronization and the chemical freezeout, hadronic multi-
plicities are most likely established during hadronization. As the detailed dynamics of this
process is not understood, it is not clear to us how (or whether) this can lead to a suppression
of the signal we are proposing. It is possible that if there is a large enough contribution to
the multiplicities of certain specific orbitally excited states, as we are proposing, then the
resulting jump in $R^*$ may survive.

We do not know the value of $\alpha$ so one cannot say exactly where this enhancement should
occur. Still at some value of $T$, and hence of $\sqrt{s}$ (or centrality), the enhancement in the
value of $R^*$ as described above should occur. Such an abrupt enhancement will signal the
formation of QGP, and at the same time, the value of $T$ (extracted from the value of $\sqrt{s}$)
[15] will give the value of the transition temperature $T_c$ if we can control the estimate of $\alpha$.
As we argued above we expect $\alpha$ to be roughly in the range of 1-3, with more probable values
being close to 1-2. Thus the value of $\alpha T_c$ can be conservatively estimated to lie somewhere
in the range of 150 - 500 MeV, with a value of about 150-350 MeV being a more probable estimate.

We emphasize here three important aspects of the signal we have proposed. First, a jump in the values of $R^*$ at a common value $\sqrt{s_c}$ of $\sqrt{s}$ (or of centrality), for a set of hadrons, will be a concrete signal that the system has gone through a transient stage of QGP phase. Secondly, from the value of $\sqrt{s_c}$ one can extract the value of $T_c$ depending on the value of $\alpha$, as mentioned above. This determination of $T_c$, in some sense, will be similar in character to the determination of $T_c$ through the value of $\sqrt{s}$ at which the proposed $J/\psi$ suppression [2] takes place due to QGP formation. (Though, note that $J/\psi$ suppression happens at a significantly higher temperature than $T_c$, above about $2T_c$, see ref. [17]. Also, $J/\psi$ suppression is not expected to be sharp at some definite $\sqrt{s}$, it gets smeared because of final state interactions. As there appears no reason to expect such strong smearing in our model, the jump in $R^*$ may be sharper.) Apart from the uncertainties in $\alpha$, this determination of $T_c$ will also depend on the details assumed for the entire collision process which relate the center of mass energy of the collision to the energy density of the plasma, and hence temperature by assuming thermal equilibrium [15]. Various parameters, such as the initial thermalization time, crucially affect these estimates of the temperature. The third feature of our proposed signal is important from this point of view, as here one will have another completely independent determination of the approximate value of $T_c$. This arises from the fact that the specific orbitally excited states of hadrons which will show the jump in corresponding values of $R^*$ are precisely those which have orbital excitation energies of order $\alpha T_c$. For example, the candidate states we have proposed (see below) have been chosen because the expected value of $T_c$ is about 170 MeV. (From this point of view, one should plot $R^*$ vs. $\sqrt{s}$ for all available partner hadronic states, to find out which ones, if any, show a jump in $R^*$.) Of course, as the value of $\alpha$ is uncertain at least by a factor of 2, one will only be able to infer the value of $T_c$ within that factor by looking at the orbital excitation energies of states which show jump in $R^*$. Still, it is important to appreciate that this determination of $T_c$ is completely independent of the determination of $T_c$ through $\sqrt{s_c}$ (or specific centrality) at which the jump in $R^*$ is expected to occur, and is uncertain only by factor $\alpha$. (Of course, for better estimates of $\alpha$ one needs a proper understanding of the hadronization process itself.)

We mention another important effect which naturally happens in our model. In our picture, the thermal kinetic energies of quarks get used up in generating the orbital excitation energies for certain specific hadrons (as given above). Thus, for these hadrons, immediately after formation, there should be little thermal kinetic energy left for the center of mass motion of the hadron. For other hadrons for which the thermal kinetic energies of the constituent quarks does not result in orbital excitation, net kinetic energy of hadron should be significant. Thus, one expects that orbitaly excited states should have low $P_T$, while the $L = 0$ state hadrons should have $P_T$ as consistent with the thermal kinetic energies involved. We will use this fact in the estimation of $R^*$ using a recombination model in the next section. As the kinetic energy of the order of $\alpha T_c$ gets used up in creating the orbital excitation, we expect that, on the average, $P_T$ of the excited states should be determined using kinetic energies which are lower by about $\alpha T_c$ compared to other states. Of course, this difference exists only at the stage of hadronization. If thermal equilibrium of hadrons prevails for any significant time after hadronization, all hadrons will acquire thermal kinetic energies.
However, for certain collisions it is possible that hadronic thermal freezeout happens almost immediately after hadronization [20]. (For example, with large value of $\sqrt{s}$ to allow for QGP formation, but with small nuclei, so that transverse expansion becomes dominant at an early stage.) If that happens then orbitally excited states (or, in general even the radially excited states) should have significantly low $P_T$ compared to other hadrons. (In principle, this effect may be operative for even those orbitally excited states which have significantly larger excitation energies compared to $\alpha T_c$, as part of the orbital excitation energy may still be coming from the thermal kinetic energies of quarks.) These arguments have the important implication that for such collisions (where thermal freezeout happens close to hadronization), the jump in $R^*$ which we have proposed to occur at some critical value of $\sqrt{s}$, should be much more prominent if one restricts to hadrons with low $P_T$.

IV. ESTIMATE OF $R^*$ IN RECOMBINATION MODEL

Some estimate of the ratio $R^*$ can be obtained within the framework of recombination model discussed in ref. [9]. For rough estimates, we first review the non-relativistic estimate of the momentum distribution of the ground state meson $M$ from ref. [9]. Though we have quoted data for $\Lambda$ baryon from RHIC ([6,7]), we will not attempt to calculate $R^*$ for baryons in the recombination model to keep the basic physical arguments simple. After all, recombination models do not capture the physics of development of confining forces (string) between quarks and antiquarks. Therefore, the calculations provided in this section still have to be supplemented with the basic physics of our model, namely, certain situations will be argued to lead to $L = 0$ meson while others leading to $L = 1$ meson.

Spatial wave functions for a (quasi) free quark and antiquark (with momenta $p_1$ and $p_2$), and for a meson (with momentum $P$) formed by this quark-antiquark system are written as,

$$<x|Q, p_1, p_2> \sim e^{i(p_1 . x_1 + p_2 . x_2)}$$
$$<x|M, P> \sim e^{iP . R} \phi_M(y).$$

Here, $R = (x_1 + x_2)/2$ is the center of mass coordinate and $y = x_1 - x_2$ is the relative coordinate. $\phi_M(y)$ is the normalized meson wave function. The relative momentum conjugate to $y$ is $q = (p_1 - p_2)/2$, and the center of mass momentum is $P = p_1 + p_2$.

Meson momentum distribution is then evaluated using the overlap $<Q, p_1, p_2|M, P>$ (see, ref. [9] for details). One gets,

$$\frac{dN_M}{d^3P} = A \int \frac{d^3q}{(2\pi)^3} w(P/2 + q)w(P/2 - q)|\hat{\phi}_M(q)|^2.$$

Here, $w(q)$ gives the parton phase space distribution, $\hat{\phi}_M(q)$ is the meson wave function in momentum space, and $A$ accounts for constant factors like degeneracy and volume etc.

Let us consider the situation when the momenta $p_1$ and $p_2$ of the quark and the antiquark are large (compared to the width of $\hat{\phi}_M(q)$, which will be expected to be of order $\Lambda_{QCD}$). We then consider two situations,

1. $p_1$ and $p_2$ are almost parallel, as discussed in ref. [9]. Then $|q| << |P|$. As we discussed, this situation will correspond to the formation of $L = 0$ meson, with the meson center of mass momentum $P$ being large.
(2) \( \mathbf{p}_1 \) and \( \mathbf{p}_2 \) are almost opposite to each other. Then \( \mathbf{P} \) is small and \( |\mathbf{q}| >> |\mathbf{P}| \). This is the opposite limit of the recombination case discussed in ref. [9], where this situation is not considered as leading to formation of any meson. For example, in ref. [9], it is argued that hadrons with large \( \mathbf{P} \) can result from combining quarks with smaller momenta. We take this to hold true for \( L = 0 \) meson, as mentioned in the case (1) above. However, for \( L = 1 \) hadrons we take the opposite situation where quarks with large momenta combine to give a hadron with small \( \mathbf{P} \). In ref. [9], higher \( L \) states are incorporated by using degeneracy factors, as in the statistical models. In contrast, in our model, almost opposite momenta of quark/antiquark result in an orbitally excited meson, (with appropriate impact parameter between the quark and the antiquark).

Note that with long range confining forces operating between quarks/antiquarks during hadronization, combining even fast moving quark and antiquark (with opposite velocities) to form a meson should not be a problem. We can then incorporate this basic difference to modify the approach of ref. [9] for discussing \( L = 1 \) meson.

We first repeat the main steps of case (1) from ref. [9], and then modify those steps for case (2). For case (1), the meson multiplicity is calculated ([9]) by using the Taylor expansion of \( w(\frac{\mathbf{P}}{2} \pm \mathbf{q}) \) about \( \frac{\mathbf{P}}{2} \) (as \( |\mathbf{q}| << |\mathbf{P}| \)). This gives,

\[
 w(\frac{\mathbf{P}}{2} + \mathbf{q})w(\frac{\mathbf{P}}{2} - \mathbf{q}) = w(\frac{\mathbf{P}}{2})^2 + O(\mathbf{q}^2). \tag{5}
\]

With this, the lowest order contribution to the meson multiplicity can be obtained ([9]) just by using the normalization of the wave function of the meson. One gets,

\[
 \frac{dN_M}{d^3P} = Aw(\frac{\mathbf{P}}{2})^2 = Ae^{-\frac{\mathbf{P}^2}{4mT}}. \tag{6}
\]

Here we have used the non-relativistic distribution for the quarks with mass \( m \) (for simplicity we use same flavor for quark and the antiquark),

\[
 w(\mathbf{P}) \sim e^{-\frac{\mathbf{P}^2}{2mT}}. \tag{7}
\]

Important thing to note in Eq.(6) is that to this order the expression for the meson distribution does not depend on the shape of the meson wave function, which, for the ground state meson can be taken as (in momentum space)

\[
 \hat{\phi}_M(\mathbf{q}) \sim e^{-\frac{\mathbf{q}^2}{2\Lambda_M^2}}. \tag{8}
\]

\( \Lambda_M \) is the width of the wave function, and should be of the order of \( \Lambda_{QCD} \).

Now we consider case(2) and discuss the formation of \( L = 1 \) meson. Since for this case we consider \( |\mathbf{P}| << |\mathbf{q}| \), we Taylor expand \( w(\frac{\mathbf{P}}{2} \pm \mathbf{q}) \) about \( \pm \mathbf{q} \). We get,

\[
 w(\mathbf{q} + \frac{\mathbf{P}}{2})w(-\mathbf{q} + \frac{\mathbf{P}}{2}) = w(\mathbf{q})w(-\mathbf{q}) + O(\mathbf{P}). \tag{9}
\]

Neglecting \( O(\mathbf{P}) \) terms, we get,

\[
 \frac{dN_{M'}}{d^3P} = A' \int \frac{d^3q}{(2\pi)^3} w(\mathbf{q})w(-\mathbf{q})|\hat{\phi}_{M'}(\mathbf{q})|^2. \tag{10}
\]
A′ differs from A in Eq.(4) in the degeneracy factor. It is clear that in this limit (|P| << |q|), the form of the wave function will be important in determining the momentum distribution of the meson M*. Since in this case we are considering formation of L = 1 meson, we use the following form of the wave function for meson M* ([18]),

\[ \hat{\phi}_{M^*}(q) \sim q_x e^{-\frac{q^2}{2\Lambda_M^2}}. \]  

(11)

Note that we use the same width Λ_M as for L = 0 meson. Here, q_x is the x component of q. Using Eq.(7) for w(±q), we get,

\[ \frac{dN_{M^*}}{d^3P} = A' \int \frac{d^3q}{(2\pi)^3} e^{-\frac{q^2}{2m^T}} q_x e^{-\frac{q^2}{2\Lambda_M^2}}. \]  

(12)

Let us define,

\[ q' = q(1 + \frac{\Lambda^2_M}{mT})^{1/2} \equiv qC. \]  

(13)

Then we can write,

\[ \frac{dN_{M^*}}{d^3P} = \frac{A'}{C^5} \int \frac{d^3q'}{(2\pi)^3} q'_x e^{-\frac{q'^2}{2\Lambda_M^2}}. \]  

(14)

The integral is unity due to the normalization of the wavefunction. We thus get,

\[ \frac{dN_{M^*}}{d^3P} = \frac{A'}{C^5}. \]  

(15)

Using this equation and Eq.(6) we get the following expression for the (momentum dependent) ratio \( R^*_P \).

\[ R^*_P = \frac{\kappa e^{\frac{P^2}{4m^T}}}{(1 + \frac{\Lambda_M^2}{mT})^{5/2}}, \]  

(16)

with T here being equal to \( T_c \). Here, \( \kappa \) gives the ratio of the two degeneracy factors. This expression shows a rapid increase for large value of (L = 0) meson momentum. One may consider this increase as coming from the trivial factor of \( e^{-P^2/2mT} \) for the momentum distribution of the L = 0 meson, as the L = 1 meson is taken here to have small momenta. However, it is important to note here that both mesons (L = 0 and L = 1) are considered here as forming from the same quark and antiquark having large momenta \( p_1 \) and \( p_2 \). There is a suppression factor for both, quark, and antiquark, of the form \( e^{-p_i^2/2m^T} \), \( i = 1, 2 \). For L = 0 meson, this leads to large momenta P for the meson, leading to the suppression factor \( e^{-P^2/2m} \). On the other hand, for L = 1 meson, the same suppression factors of the quark and the antiquark are absorbed in the wave function of the meson. This softens the suppression factor from an exponential suppression to a multiplicative factor as in Eq.(16). Note that this expression should eventually breakdown at sufficiently high P. This is because our assumption that a quark and an antiquark of opposite momenta leads to an (orbitally
excited) bound state will not hold true for very large values of quark/antiquark momenta. Even for $L = 0$ meson, as discussed in ref. [9], recombination model is not expected to be applicable for very large values of $P$ (beyond a couple of GeV), as the physics may be dominated by fragmentation in this regime.

We should clarify that we are not claiming here a derivation showing the enhancement of $R^*$ as we have argued in previous sections. For example, one could have very well considered the $L = 0$ meson wave function for case (2), instead of Eq.(11), with similar result as in Eq.(16) with the exponent 5/2 changing to 3/2. (Or, one could have considered other excited states of the meson.) The above estimate of $R^*_P$ has to be supplemented with our basic picture that for a quark and an antiquark with large momenta $p_1$ and $p_2$, $L = 0$ meson is likely to result when the two momenta are almost parallel. On the other hand, if the two momenta are almost opposite to each other, then $L = 1$ meson (or, possibly a radially excited one which we do not discuss) is likely to form because the available thermal kinetic energy may be enough to lead to $L = 1$ excitation (at least for the candidate states we suggest in the next section). The estimate of $R^*$ provided here is, therefore, to be taken as indicative of the extra contribution to the multiplicity of the orbitally excited meson $M^*$ when QGP formation occurs.

V. CANDIDATE HADRONIC STATES FOR THE SIGNAL

Using the particle data table [19], there are several candidate hadrons which have orbitally excited states with excitation energies of order 200-400 MeV above the corresponding $L = 0$ states. We give several such candidates in the following. Other candidate states can be found from ref. [19] with the basic criterion being the relevant range for the orbital excitation energy. Below, each equation gives the hadronic state, along with its partner orbitally excited state.

Mesons :

\[
D_{s}^{*\pm}(J^P = 1^-) \ m = 2112 \text{ MeV} \\
D_{s1}^{*\pm}(J^P = 0^+) \ m = 2317 \text{ MeV} \\
\Delta m = 205 \text{ MeV} \quad (17)
\]

\[
D^{*0}(J^P = 1^-) \ m = 2007 \text{ MeV} \\
D_2^{*0}(J^P = 2^+) \ m = 2459 \text{ MeV} \\
\Delta m = 452 \text{ MeV} \quad (18)
\]

\[
J/\psi(1S)(J^P = 1^-) \ m = 3097 \text{ MeV} \\
\chi_{c0}(1P)(J^P = 0^+) \ m = 3415 \text{ MeV} \\
\Delta m = 318 \text{ MeV} \quad (19)
\]

Baryons :
\[ \Lambda^+_C(J^P = \frac{1}{2}^+) \ m = 2285 \text{ MeV} \]
\[ \Lambda^+_C(J^P = \frac{1}{2}^-) \ m = 2594 \text{ MeV} \]
\[ \Lambda^+_C(J^P = \frac{3}{2}^-) \ m = 2625 \text{ MeV} \]
\[ \Delta m = 309, 340 \text{ MeV} \quad (20) \]

\[ \Lambda(J^P = \frac{1}{2}^+) \ m = 1116 \text{ MeV} \]
\[ \Lambda(J^P = \frac{1}{2}^-) \ m = 1406 \text{ MeV} \]
\[ \Lambda(J^P = \frac{3}{2}^-) \ m = 1519 \text{ MeV} \]
\[ \Delta m = 290, 403 \text{ MeV} \quad (21) \]

\[ \Xi^+_C(J^P = \frac{1}{2}^+) \ m = 2466 \text{ MeV} \]
\[ \Xi^+_C(J^P = \frac{3}{2}^+) \ m = 2647 \text{ MeV} \]
\[ \Xi^+_C(J^P = \frac{1}{2}^-) \ m = 2790 \text{ MeV} \]
\[ \Delta m = 324, 143 \text{ MeV} \quad (22) \]

\[ \Xi^0_C(J^P = \frac{1}{2}^+) \ m = 2472 \text{ MeV} \]
\[ \Xi^0_C(J^P = \frac{3}{2}^+) \ m = 2645 \text{ MeV} \]
\[ \Xi^0_C(J^P = \frac{1}{2}^-) \ m = 2790 \text{ MeV} \]
\[ \Delta m = 318, 145 \text{ MeV} \quad (23) \]

We mention that for some of these states $J^P$ as quoted above are not confirmed, see ref. [19]. The energy differences for the partner states as given above are reasonably close to the expected value of $\alpha T_c$ (with $T_c \simeq 170$ MeV), and hence should be good candidates for evaluation of the ratio $R^*$ as described above. For example, $D^*_{SJ}(2317)(J^P = 0^+)$ and $D^*_{S}(2112)(J^P = 1^-)$ have a mass difference of 205 MeV and hence one may expect that an important fraction of the orbital excitation energy in this case may come from the thermal kinetic energies of quark and antiquark (even with lower estimates of $\alpha$ as mentioned above). In principle one could allow the spin of the $L = 0$ state and the corresponding orbitally excited state to be different. In view of hyperfine contributions one may like to have the same spin for the partner states for the evaluation of the ratio $R^*$. However, such contributions will be present for the formation of these states even below $T_c$, and for hadrons forming at $T_c$.
in our picture it may just affect the value of $\alpha$ without affecting the qualitative aspect of the signal (i.e., a jump in the value of $R^*$ at $\sqrt{s_c}$). We have not addressed here the important issue of experimental observations of all these states mentioned above, and for many of these it may be difficult to have data in relativistic heavy-ion collisions.

Recently, measurements of $\Lambda^*(1520)/\Lambda$ have become available from RHIC as a function of $N_{\text{part}}$ [6,7]. Note that this set is one of the candidates we have listed above (Eq.(21), with $\Lambda^*$ listed at 1519 MeV). The multiplicity ratio $R^*$ for $\Lambda^*/\Lambda$ shows a strong decrease as a function of $N_{\text{part}}$ [6,7]. As discussed above, this overall decrease is of no consequence to our model. However, the value of the multiplicity ratio for very large $N_{\text{part}}$ (beyond 350) may be consistent with a slight increase, though completely within the error bar, to conclude anything definite. We again stress, what is important is that if there is any increase in $R^*$ beyond some $N_{\text{part}}$ then it will be very hard to explain it with existing models where a rapid decrease in the multiplicities of resonances arising from final state interaction in the hadronic medium is naturally expected. Our model will naturally account for any such increase. In fact, the (possible) increase in $R^*$ seems to occur beyond sufficiently large value of $N_{\text{part}} \approx 350$ which may be consistent with QGP formation. We mention that this (possible) rise in $R^*$ for $\Lambda^*/\Lambda$ is more distinct in ref. [6] where $R^*$ is plotted as a function of $N_{\text{part}}$. In ref. [7], the plot is w.r.t. $dN_{\text{ch}}/d\eta$, and the rise does not appear clear (which may be due to different binning). One has to wait for more refined data with a more detailed plot of $R^*$ vs. $N_{\text{part}}$ to see if actually there is a discontinuity in the plot of $R^*$ for $\Lambda^*(1520)/\Lambda$ beyond some value of $N_{\text{part}}$.

It is important to realize here that the abundances of the hadrons may be dependent on QGP formation from other physical considerations also. For example, the suppression of $J/\psi$ and $\chi_{c_i}$ due to Debye screening of color in the QGP state is well discussed in the literature. Further, due to larger radius of $\chi_{c_i}$, the suppression from Debye screening is larger for $\chi_{c_i}$ [17]. Even in the recombination model, one would expect that forming orbitally excited states may be harder due to their larger sizes as the medium is very dense. Clearly such effects will give rise to opposite behavior for the ratio $R^*$ as compared to the effect of thermal kinetic energy of quarks as we have discussed. Final dependence of $R^*$ on $\sqrt{s}$ will result from a combination of the two effects. (Note that similar effects also occur from hadronic final state interaction. However, such hadronic state interaction effects are of no consequence to our model which only predicts a jump in $R^*$ beyond some $\sqrt{s}$, and not the overall shape of the curve of $R^*$. Thus, decrease of $\Lambda^*/\Lambda$ vs. $N_{\text{part}}$ may be naturally expected from such final state interactions, but any possible rapid rise beyond some value of $N_{\text{part}}$ cannot be accommodated in such models.) Though there are detailed estimates [17] of suppression of $J/\psi$ and $\chi_{c_i}$, it is not possible to say which effect will dominate due to lack of definite quantitative estimates for the effect we are proposing. In any case, for hadrons with light quarks, the Debye screening is very effective due to larger sizes of these hadrons (compared to the Debye length), so one only needs to consider their formation from quark/antiquark recombinations at $T_c$. Thus, for these hadrons, the predicted jump in $R^*$ should not be adversely affected by these other considerations.
VI. CONCLUSIONS

In conclusion we have suggested a novel signature for the detection of the transient QGP state formation in relativistic heavy-ion collisions. The basic nature of the signal is almost model independent in the sense that it does not depend on the nature or even the existence of phase transition between the confined and the deconfined state of QCD. Further, details of plasma evolution etc. also may not be of much importance. This is because $R^*$ depends on the ratios of multiplicities of states of a given hadron and presumably the effects of plasma evolution etc. will get minimized in taking the ratio.

We emphasize that though the arguments we have presented are very qualitative and crude, the basic physics underlying these arguments is simple. Main argument we have used is that quarks/antiquarks have thermal velocities at the stage when they all get captured to form bound states at the hadronization stage, i.e. when the temperature of the system is equal to $T_c$. Due to this thermal velocity, when QCD string starts joining, say, a quark with antiquark to form a meson, it is easy to generate orbital motion of quarks in the bound states. Essential part of the argument being that it is difficult to form $L = 0$ hadrons when quarks/antiquarks have large initial velocities, in the same way as it is difficult to form orbitally excited hadrons if quarks/antiquarks did not have any initial velocities. We then further argue that for those hadrons for which the orbital excitation energy is a certain fraction (characterized by $\alpha$) of the thermal kinetic energy of quark/antiquark system at $T = T_c$, the formation of such orbitally excited bound states will be enhanced. Using these arguments we suggest that the ratio of multiplicities of orbitally excited state to the $L = 0$ state of such specific hadrons should show an abrupt increase at a critical value of $\sqrt{s}$ which corresponds to the formation of an intermediate, transient, QGP state. As we mentioned above, alternatively, one can also plot $R^*$ as a function of centrality for a given center of mass energy, with $R^*$ expected to show a jump above certain value of the number of participants.

The signal we have proposed is simple and just requires plotting of the respective ratios $R^*$ (as defined by Eq.(1)) for various hadrons with respect to $\sqrt{s}$. One important feature of this signal is that it predicts a jump in the value of $R^*$, at a common value of $\sqrt{s}$ (for given colliding nuclei), for a whole class of hadronic states which have orbital excitation energy splitting of similar magnitude. Most likely candidate hadrons which have orbital excitation energies roughly in the required range are charmed and strange hadrons. For example, $D^*_{S+} (2317) (J^P = 0^+)$ and $D^*_{S+} (2112) (J^P = 1^-)$ have a mass difference of 205 MeV. Thus, a plot of the ratio of total multiplicities of $D^*_{S+} (2317) (J^P = 0^+)$ and $D^*_{S+} (2112) (J^P = 1^-)$ with increasing $\sqrt{s}$ may contain the information of QGP formation as discussed above. We have given a list of several such candidate hadronic states. We note that the recent data [6,7] on the multiplicity ratio $\Lambda^* (1520)/\Lambda$ from RHIC as a function of $N_{\text{part}}$ may be consistent with our model, with a possible hint of a slight increase beyond $N_{\text{part}} \simeq 350$. One needs to have a more refined data, with more detailed plot for intermediate values of $N_{\text{part}}$ to make any definite conclusions. We have not addressed the issue of experimental observations for various resonances listed in the previous section. It may not be easy to collect enough statistics for many of these candidate states [21,3]. As we mentioned above, the effect we have proposed may be present even for radially excited states of hadrons. However, for radial excitations the effect may not be prominent. We have primarily discussed orbital excitations of hadrons as the basic physics of our arguments is simpler to model for this case. A better
understanding of the underlying physics of quark/antiquark recombination into hadrons is needed before one can make any definitive quantitative predictions regarding this signal.

ACKNOWLEDGEMENTS

We are very grateful to S.A. Bass, D.K. Srivastava, J. Cleymans, and S. Digal for very useful discussions and comments. We also thank S.C. Phatak, B. Rai, A. P. Mishra, R. Ray, and V. S. Kumar for useful discussions.
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