Showers and resonances: Are we observing the glue?

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Based in pertinent observations, we discuss the properties of the mesonic cloud of gluons. We show that several of the newly discovered charmonium states, which are discovered in suppressed decay modes, are most likely to be the result of depletion by the well-known dominant desintegration modes of charmonium. The thus emerging picture of a structureless gluon cloud is challenged by the present accuracy of experiment.

Although all matter consists of quarks and glue, little is yet known about their interactions. Quarks were never isolated, nor glue balls discovered. It is assumed that quarks are always chaperoned by other quarks, either by one antiquark (meson), or by two quarks (baryon). There exists literature in abundance on possible systems which consist of more quarks and/or antiquarks and glue, but nothing of the kind, besides a handful of candidates, has been discovered yet. Here, we concentrate on charmonium mesons, consisting of a charmed quark (c), a charmed antiquark ($\bar{c}$) and glue.

Before we continue, let us clearly state the model which is in the back of our mind. We imagine charmonium as a c quark glued to a $\bar{c}$ antiquark. The glue, consisting of small particles, called gluons, is by us considered as a sticky substance with the shape of a kind of deformable ball which surrounds the $c\bar{c}$ pair. In Fig. 1 we have depicted that situation. The $c\bar{c}$ pair lives mainly in the deep interior of the meson, where it may freely oscillate [1]. At larger interquark distances the pair is pushed back by the glue, towards the interior.

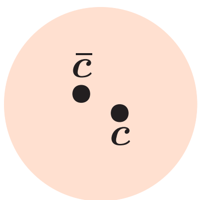

FIG. 1. Artistic representation of a charmonium meson: A $c\bar{c}$ pair surrounded by a sticky substance, called glue.

Such, and similar, systems are studied in international laboratories, like the accelerator centers at CERN (Geneva, Switzerland), SLAC (Stanford, USA), Fermilab (Batavia, USA), KEK (Tsukuba, Japan) and IHEP (Beijing, China). In the most popular process [2] an electron and a positron are first accelerated in opposite directions and then collided head-on (SLAC, IHEP, KEK). In the collision the electron and the positron dump their energy in structures similar to the one represented in Fig. 1. The advantage of electron-positron annihilation is that the system appears dominantly in a specific type of configuration, in the case of $c\bar{c}$ called charmonium, whereas in the processes studied at the other laboratories several different configurations may be formed, which complicates the analysis of the experimental results. The mass M of the resulting charmonium meson can be determined by the use of Einstein's formula $E = Mc^2$ from the total energy E of the accelerated electron-positron pair and the very accurately known value of the light velocity c.

Now, Nature is very friendly with us that it let us study such microscopically small systems of sizes which are about one hundred thousand times smaller than an atom, but it does not let us dispose over such systems for a very long time. Except for a few more stable ones, mesons desintegrate within very short intervals of time of about twenty three orders of magnitude smaller than a second. This phenomenon reflects itself in the intrinsic uncertainty in the mass of a charmonium meson.

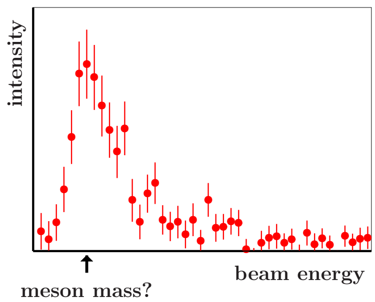

FIG. 2. Enhancement in the intensity of desintegration products as a function of beam energy, indicating the possible existence of a meson with a certain mass.

The existence of a charmonium meson with a certain mass is observed in experiment by varying the total energy of the accelerated electron-positron pair (beam energy). When the energy of the beam nears the mass of a possible charmonium meson, one measures an enhanced intensity of desintegration products at the detectors which surround the place where electrons and positrons collide. In Fig. 2 we show the result of one such measurement. The uncertainty in the mass of the meson results in a mountain-shaped enhancement for the intensity of desintegration products.

Actually, in a recently developed technique, called Initial-State Radiation (ISR) (Belle, BABAR), one studies processes in which, besides a charmonium meson, also a photon is created. The total energy dumped into the meson equals then simply the difference between the beam energy and the energy of the photon. That way, it is not necessary to vary the accelerator energy which results in a more accurate determination of masses.

Let us now return to the system depicted in Fig. 1. After its creation the ball of gluons vibrates, causing locally places of higher mass concentration. When the density is large enough a pair of light quarks can be formed, which may give rise to the formation of a new and light meson-like structure, *e.g.* a σ meson, as shown in Fig. 3a. The σ

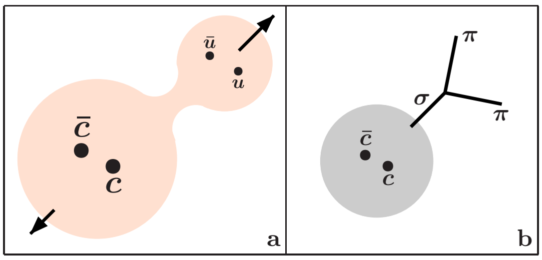

FIG. 3. **a**: Desintegration of charmonium by emission of a sigma meson (σ) which consists of a light quark-antiquark pair ($u\bar{u}$). **b**: Further desintegration of the σ into pions.

meson and the final-state charmonium meson move away from each other due to the surplus in energy, which is converted into kinetic energy. The $c\bar{c}$ meson ends up as one of the more stable lighter charmonium mesons, J/ψ or $\psi(2S)$, whereas the σ meson desintegrates into pions as schematically illustrated in Fig. 3b. We will refer to this and similar processes as *radiation processes*.

But, there exist other, more important, desintegration modes of charmonium, namely, open-charm decays. Those modes are triggered by light-quark-pair creation in between the $c\bar{c}$ pair as depicted in Fig. 4. Open-charm de-

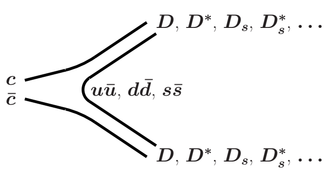

FIG. 4. Breaking up of the $c\bar{c}$ pair into two charmed mesons $D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$, ..., each consisting of one c quark and one light quark u, d or s.

cay into pairs of open-charm mesons, D, D^*, D_s, D_s^*, ..., takes mainly place at energies just a little above the energy equivalent to the sum of the masses of the two open-charm mesons, the so-called *threshold enhancements* [3], or at energies which correspond to *resonances* of the oscillating $c\bar{c}$ pair. The latter energies are of interest for the understanding of the $c\bar{c}$ meson and for understanding strong interactions in general.

Now, when charmonium desintegrates into one mode it cannot desintegrate into the other. Hence, at energies which correspond to threshold enhancements or resonances, out of the millions of $c\bar{c}$ mesons formed in electron-positron annihilation, many more will decay into open charm than via radiation.

At this stage it is useful to consider somebody taking a shower while suddenly another member of the family decides to open a tap in the kitchen, causing the flow of water in the shower to drop significantly. When, moreover, after some communication between the two persons, the one in the kitchen decides to perform a small experiment, by opening and closing rhythmically its tap, the two persons may observe what is depicted in Fig. 5. The peaks

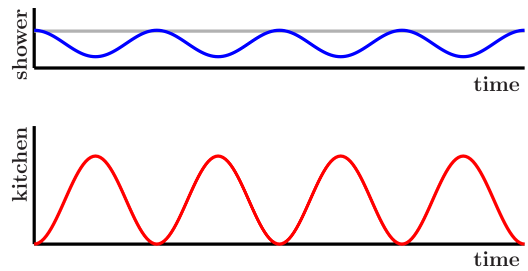

FIG. 5. The upper graph shows as a function of time the intensity of the water flow in the shower, while the lower graph indicates the water flow through the tap in the kitchen. The horizontal line in the upper graph represents the water flow of the shower without interference from the kitchen.

in the lower graph of Fig. 5 indicate when the intensity of the water flow in the kitchen is maximum, whereas at the lowest points of the valleys the tap in the kitchen is closed. At the same time, the water flow in the shower is significantly reduced when the kitchen tap is fully open, whereas its flow is maximum when the kitchen tap is closed, as shown in the upper graph of Fig. 5. Without interference from the kitchen, the flow in the shower is supposed to be constant in time, as is represented by the horizontal curve in the upper graph of Fig. 5.

A very similar phenomenon has been observed [4] for radiation processes of charmonium. Exactly where open-charm decays are expected, the radiation signal is almost depleted. This is very clearly observed for the $\psi(4S)$ $c\bar{c}$ resonance, which peaks at about 4.415 GeV, as is shown in Fig. 6. The radiation data are represented by dots and vertical lines. The latter indicate the experimental uncertainties on the amount of events which are measured within an interval of 20 MeV of beam energy. The observed data show a minimum in the signal, exactly where one expected the $\psi(4S)$ enhancement, indicated by the curve in Fig. 6.

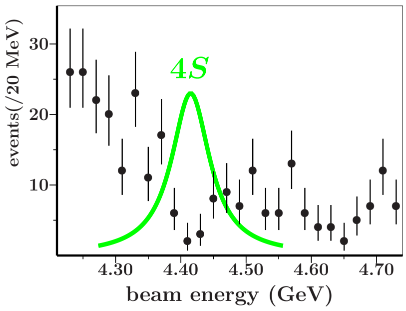

FIG. 6. Exactly where the $\psi(4S)$ resonance is expected (curve), the data (●), taken by the BABAR Collaboration [5], show a clear minimum.

Here, the data are not in function of time, but, in function of the beam energy. However, there is another difference with the shower, namely, we do not know the shape of the radiation signal for the hypothetical case that open-charm decay is forbidden to occur. Unlike the case of the kitchen tap, which can be closed, open-charm decay is not controlled by us. There is just no adult present to terminate the activities in the kitchen. As a consequence, in order to understand the observed radiation signal, we must guess a shape and then reconstruct the experimental data, *e.g.* those taken by the BABAR Collaboration [5]. A possible choice for the shape of the radiation signal when not disturbed by open-charm decay, is depicted in Fig. 7.

We represent in Fig. 7 the presumed shape of how the intensity of radiation varies with beam energy, namely, a broad signal with its central value at about 4.26 GeV and with a width of some 0.75 GeV. We will refer to this shape by $E(4260)$. In the same figure, we show how the various known and even one new open-charm process deplete the $E(4260)$ signal. First, there are the enhancements, in this case dips, of the threshold openings, which occur respectively at 3.73 GeV ($D\bar{D}$), at 3.875 GeV ($D\bar{D}^*$), at 3.936 GeV ($D_s\bar{D}_s$), at 4.02 GeV ($D^*\bar{D}^*$), at 4.08 GeV ($D_s\bar{D}_s^*$), at 4.224 GeV ($D_s^*\bar{D}_s^*$) and at 4.573 GeV ($\Lambda_c\bar{\Lambda}_c$). Then, one has depletion by the three known $c\bar{c}$ resonances $\psi(3S)$, which has its peak at 4.04 GeV, $\psi(2D)$ at 4.16 GeV and $\psi(4S)$ at 4.415 GeV. Finally, we must assume the depletion of a, with this method newly discovered, $\psi(3D)$ resonance at 4.53 GeV.

The resulting curve describes the data very well (see Fig. 7). But, that is, of course, no guarantee that the shape of the $E(4260)$ is indeed correct. For that, many other shapes should be studied. However, there is one more test which can be performed.

The water flow in the kitchen and in the shower are very similar. In particular, the difference between the unperturbed flow, indicated by the horizontal line of the upper graph in Fig. 5, and the actual flow in the shower is minimum when the flow in the kitchen is minimum and maximum when the flow in the kitchen is maximum. In fact, would we make a graph of the difference between the unperturbed and the perturbed flow in the shower and enlarge the resulting graph, it would be identical to the graph for the flow in the kitchen.

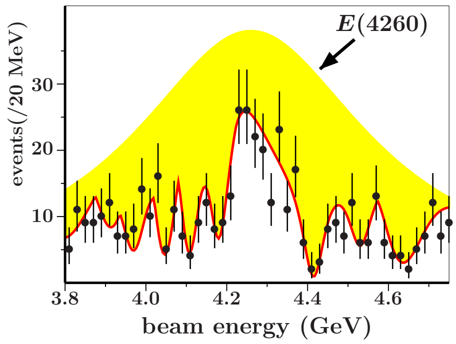

FIG. 7. Study of how the presumed $E(4260)$ signal in $e^+e^- \to \pi^+\pi^- J/\psi$ [5] is depleted by open-charm decays. From left to right: depletion by respectively $D\bar{D}$, $D\bar{D}^*$, $D_s\bar{D}_s$, $D^*\bar{D}^*$, $\psi(3S)$, $D_s\bar{D}_s^*$, $\psi(2D)$, $D_s^*\bar{D}_s^*$, $\psi(4S)$, $\psi(3D)$, and $\Lambda_c\bar{\Lambda}_c$.

For the charmonium meson, we actually dispose of measurements on the kitchen flow, which is open-charm decay. Here, we use quite accurate data on $D^*\bar{D}^*$ decay, which have been obtained by the BABAR Collaboration and are published in Ref. [6]. From Fig. 7 we determine the difference between the $E(4260)$ shape and the measured data. The comparison between the two sets of data, difference and open charm, can only be performed for beam energies from 4.2 GeV to 4.75 GeV, because of uncontrolable differences in phase-space contributions below 4.2 GeV. From the result, which is shown in Fig. 8, we may conclude that, at least for the energy interval from 4.2 GeV to 4.75 GeV it seems to work very well as both signals agree quite accurately.

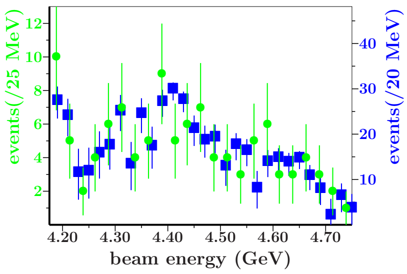

FIG. 8. BaBar data for $e^+e^- \to D^*\bar{D}^*$ [6] (●), and the missing signal in $e^+e^- \to \pi^+\pi^- J/\psi$, [5] (■). The annotations at the vertical axis on the lefthand side refer to the data of Ref. [6], while those on the righthand side concern the data of Ref. [5]. The missing signal is adjusted in magnitude so as to be compared with the $e^+e^- \to D^*\bar{D}^*$ data.

So, since it happens that the shower-kitchen analogy for radiation and open-charm leads to good results, we may wonder what we can learn from it for the interactions between quarks and glue.

To start with, let us compare the charmonium system to the system of a proton surrounded by an electron cloud: the hydrogen atom. The surplus energy of the electron cloud in an excited hydrogen atom is radiated off by the emission of a photon. The resulting spectrum consists of isolated peaks which represent the hydrogen resonance masses. This spectrum is not perturbed by radiation from the proton, because proton excitations need many orders of magnitude larger energies than the few eV's for the excitations of the electron cloud. Moreover, the photon energy itself is by far not enough to produce electron-positron pairs. Radiation and open-charm decay of charmonium have comparable energies, hence interfere noticeably, whereas, furthermore, the radiation energy allows for the creation of pion pairs. Consequently, for charmonium it is complicated to separate peripheral radiation from deep-interior open-charm processes.

Let us also address the shape of the $E(4260)$ enhancement itself. It is well-known that the two-pion amplitude for vanishing total angular momentum is not constant, but peaks at about 1 GeV. This implies that the likelihood for the creation of a pair of pions out of charmonium must have a similar shape, but then for energies for which the total two-pion energy has to be added to the energy taken by the third particle, which is the J/ψ charmonium meson with a mass of 3.1 GeV and with some kinetic energy. Since that explains at least a large part of the shape of the $E(4260)$ enhancement, it leaves us with a rather structureless probability for the creation of a pion pair out of the glue. In particular, we seem to have to conclude that in the interval from 3.8 GeV to 4.75 GeV (see Fig. 7) no gluonic excitations are observed.

Furthermore, we find that open-charm decay is not very much perturbed by radiation, like the water flow in the kitchen would hardly be influenced by activities from the shower. Note, that the rather large discrepancy in signal magnitude between open charm and radiation which we observe in Fig. 8, does not stem from the fact that open charm does not dominate, but from the experimental difficulty to observe the open-charm decay products. Hence, open-charm decay is the dominant process for charmonium. As depicted in Fig. 4, this decay is triggered by light-quark-pair creation in the vicinity of the $c\bar{c}$ pair, with little to no participation of the gluonic cloud. Consequently, we are naturally lead to the picture, as represented in Fig. 1, of a structureless cloud of gluons which confines the $c\bar{c}$ pair to its center.

However, an amorphous gluon cloud without any structure can neither be the final conclusion, since we observed [7], in the new preliminary radiation data of the BABAR Collaboration [8], some indications for an interference effect, possibly between the oscillation frequency of the $c\bar{c}$ pair and that of the gluon cloud, with period of 74 MeV, but with quite some error. That interference effect is awaiting confirmation from experiment, which necessarily needs a smaller binning than the 20 MeV of the actual data [8]. Whether, and how, this is related to oscillations in the gluon cloud, we do not really understand yet.

In conclusion, it seems that important breakthroughs are imminent for our understanding of the interactions between quarks and gluons. But, certainly a lot of experimental and theoretical effort will still be needed to this end.

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