Observation of a hadronic interference effect in annihilation processes

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We present evidence for small oscillations we observe in $e^+e^-$ and $p\bar{p}$ annihilation data, with a periodicity of $76\pm2$ MeV, independent of the beam energy. We discuss some possible scenarios to explain the phenomenon.

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In Ref. \textsuperscript{1}, we made notice of an apparent interference effect, which we observed in the recent preliminary radiation data of the BABAR Collaboration \textsuperscript{2} (see Fig. 1). The effect, with a periodicity of about 74 MeV, may be due to interference between the typical oscillation frequency of the $c\bar{c}$ pair and that of the gluon cloud. This interference effect is still awaiting confirmation by experiment, which inevitably would require a binning smaller than the 20 MeV of the actual data \textsuperscript{2}.

In the meantime, we observe a very similar effect in rather accurate data on $p\bar{p}\rightarrow J/\psi \pi^+\pi^-$ around the mass of the $X(3872)$ resonance, obtained by the CDF Collaboration \textsuperscript{3} (see Fig. 2). Here, we find that the period equals about 79 MeV. However, we must allow for an uncertainty of roughly 4-5 MeV in the periodicity observed in these data, since CDF estimated their accuracy on the spreading in invariant mass by assuming a width of 1.3 MeV for the $X(3872)$ resonance, whereas their signal width appears to be about 10 MeV.

Such an interference effect can also be observed in data taken by the CMD-2 Collaboration for $e^+e^-\rightarrow \pi^+\pi^-$ \textsuperscript{4} (see Fig. 3), with a periodicity of about 75 MeV and an estimated uncertainty of some 2 MeV.

Finally, data from the BABAR Collaboration for $e^+e^-\rightarrow \Upsilon(2S)\pi^+\pi^-$ \textsuperscript{5} show similar oscillations, with a periodicity of $73\pm3$ MeV (see Fig. 4). However, note that...
the BABAR Collaboration has a very different interpretation of the same data. So it is questionable whether these data can be used in this context. Nevertheless, as this is the only example we are aware of with sufficient statistics for the observation of an oscillation in the $b\bar{b}$ sector, we leave the interpretation as a question open to debate.

All fits have been done using a simple cosine, with argument linearly proportional to the invariant mass and amplitude proportional to the average magnitude of the signal. An exception is the fit to the data of Fig. 2 for which we have used the magnitude of the background signal in the resonance region.

The first striking property of these inferred periodicities is that it is quite constant, independent of the respective process, viz.

\[ e^+e^- \rightarrow J/\psi\pi^+\pi^- , \quad p\bar{p} \rightarrow J/\psi\pi^+\pi^- , \quad e^+e^- \rightarrow \pi^+\pi^- , \quad e^+e^- \rightarrow \Upsilon(2S)\pi^+\pi^- , \]

as well as the flavors involved, namely $n\bar{n}$ ($n = u$ or $d$), $c\bar{c}$, and possibly also $b\bar{b}$. From the observed values and the uncertainty estimates, we feel safe to conclude that the periodicity has a value of 76±2 MeV.

Observables that are independent of flavor must somehow be related to gluons. One such observable is the level spacing for quarkonium spectra (see Ref. [8] and references therein). Here, we seem to have observed a second one.

Furthermore, the effect seems to be quite small, but larger for $e^+e^-$ than for $p\bar{p}$ annihilation, where it easily passes unnoticed (see Fig. 2). In the latter case, the amplitude of the oscillation is just one percent of the total signal, whereas for $e^+e^-$ we find about 10 percent. Anyhow, these numbers must yet be confirmed by further experiments.

Scenarios for an explanation of the phenomenon can be split into two classes: either some process which takes place before annihilation, or interference of two different processes, after annihilation, that lead to the same decay mode. For the former class we have at present no serious candidate, especially because the annihilation mechanisms for $e^+e^-$ and $p\bar{p}$ are very different. However, in the post-annihilation case, involving the formation of $c\bar{c}$ in $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ and $p\bar{p} \rightarrow J/\psi\pi^+\pi^-$, $n\bar{n}$ in $e^+e^- \rightarrow \pi^+\pi^-$, or $b\bar{b}$ in $e^+e^- \rightarrow \Upsilon(2S)\pi^+\pi^-$, we will present here a possible scenario.

For the decay of charmonium into $J/\psi\pi^+\pi^-$, one expects that the reaction is dominated by the transition to a stable charmonium state, $J/\psi$ or $\psi(2S)$, through peripheral emission of a $\sigma$- or $\rho$-like structure which then decays into two pions. But it is also possible that emission takes place from the interior of the charmonium state, close to the $c\bar{c}$ pair. However, the latter reaction is much less probable, as pair creation near the $c\bar{c}$ pair dominantly leads to open-charm decay. For the process $e^+e^- \rightarrow J/\psi\pi^+\pi^-$, this seems a sufficient explanation for the existence of two distinct reactions which might interfere. On the other hand, in $p\bar{p} \rightarrow J/\psi\pi^+\pi^-$, many other reactions may take place, for instance annihilation of just one light $q\bar{q}$ pair and subsequent creation of a $c\bar{c}$ pair, with a rearrangement of the remaining light quarks and antiquarks. Full annihilation of $p\bar{p}$ will probably only take place for a very small fraction of the events. In case our estimates of the amplitudes of the oscillations are correct, we find that full $p\bar{p}$ annihilation only occurs in 1 out of 10 events.

So far charmonium and possibly beautonium, but for the process $e^+e^- \rightarrow \pi^+\pi^-$ we must assume that, after the creation of an initial $n\bar{n}$ pair, the OZI-allowed reaction $n\bar{n} \rightarrow (n\bar{q}) + (q\bar{n})$ (or light) dominates. Nevertheless, non-OZI reactions will also take place. Consequently, also in this case we may expect interference from the two different reactions.

Quantum interference of particles and resonances was recently studied by Ya. Azimov [8]. In his paper he reminds: “Regretfully, the structure of both the rescattering interference and different interference effects in decays is not yet clearly understood. That is why fits to experimental data are still very model-dependent in many cases.” However, in our fits for the present cases, we understand that no model dependence has slipped yet into our observations.

Oscillations have been reported by S. Pacetti [9] in diffractive photoproduction data obtained in the E687 experiment at Fermilab [10], though with a periodicity of about 250 MeV in momentum transfer. The author concludes “We find at least five interfering structures, but to have a clear identification of this (sic) resonances, we need much more precise data.” In Ref. [11], P. Gauron, B. Nicolescu, and O. V. Selyugin demonstrate that the high-precision $dN/d|t|$ in $pp$ data collected by the UA4/2 Collaboration at the CERN SppS Collider at $\sqrt{s} = 541$ GeV [12], shows oscillations at very small momentum transfers. These oscillations seem to be periodic in $\sqrt{s}$, with a periodicity of about 20 MeV. Oscillations of the hadronic amplitude at small transferred momenta are discussed by O. V. Selyugin in Ref. [13], while S. Barshay and P. Hellinger [14] signs for new physics from oscillating behaviour in the amplitude of hadronic diffractive scattering data. They emphasize: “possible signals coming directly from such a new condition of matter, that may be present in current experiments on inelastic processes.” Fourier analysis of oscillations in hadronic amplitudes is performed by J. Kontros and A. Lengyel [15], but the periodicity in $\sqrt{s}$ of their oscillations is two orders of magnitude larger than the oscillations considered in Ref. [11]. Furthermore, in Ref. [16] Y. A. Troyn and collaborators observe oscillations in $\pi^+\pi^-$ from the reaction $np \rightarrow np\pi^+\pi^-$ at $P_n = 5.20$ GeV/c. Unfortunately, the data are not well represented, and so do not allow to extract the periodicity.

For the present observation of a constant periodicity in $\sqrt{s}$, we keep on assuming that it occurs because of two distinct processes, namely peripheral emission and pair...
creation in the deep interior of a meson. In the past, we have shown that the oscillations of quarkonia are independent of flavor and have a frequency $\omega = 190$ MeV (see Ref. 6 and references therein). Upon pair creation in the interior, the signal most probably picks up this frequency. Emission, which we assume to originate from the gluon cloud, would initially keep the gluon frequency. Therefore, if we assume that the periodicity of $76\pm 2$ MeV observed in annihilation processes stems from interference between the two signals, then we are led to frequencies, for gluon oscillations, of either $190 + 2 \times (76 \pm 2) = 342 \pm 4$ MeV or $190 - 2 \times (76 \pm 2) = 38 \pm 4$ MeV. The former value would give rise to radial gluon excitations with level spacings of about 684 MeV, which is in reasonable agreement with the level spacings from the lattice obtained by C. J. Morningstar & M. Peardon in Ref. 17, by Liu & Chuan in Ref. 18, and by E. B. Gregory and collaborators in Ref. 19. An extensive discussion on glueballs can be found in Ref. 20 by E. Klempt and A. Zaitsev.

At first sight, we are inclined to reject the value of $38 \pm 4$ MeV for the frequency of gluon oscillations in mesonic configurations. But from Anti-de-Sitter (AdS) confinement 21, we learn that gluons and quarks all oscillate with the same frequency, which is given by the radius of the AdS system. Hence, neither of the two solutions seems to be acceptable then, because for quarkonia spectra we obtain excellent results with $\omega = 190$ MeV. However, AdS confinement also indicates that the gluon distribution is concentrated towards the surface, much like in the bag model.

This opens up the possibility of surface oscillations, with level spacings that are equal to the oscillation frequency, and which have been solved for the bag model by T. A. DeGrand and C. Rebbi in Ref. 22. Actually, they found frequencies for the lowest-order surface vibrations very comparable to the value $342 \pm 4$ MeV. However, in Ref. 21, H. P. Morsch and collaborators obtained for light baryons, in the range $0.38-0.54$ GeV, and for $b\bar{b}$ quarkonia values even higher than 0.6 GeV, which all seem to be well beyond our result. In Ref. 20, H. R. Fiebig found for the inertia of surface oscillations in light baryons a mass parameter, $\omega$, which, when related by the expressions given in Ref. 23 to the oscillation frequency, gives $\omega = 0.38$ GeV, in reasonable agreement with our value for mesons.

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Before finishing our discussion, let us again come back to the second possible solution for the surface oscillations, namely the much slower ones, with a value of $38 \pm 4$ MeV. Now, for nucleons we observed 24, an average radial level spacing about 12% smaller than that for mesons, and so an equally smaller oscillation frequency. By AdS confinement, this also implies a larger hadron size. So we might assume that surface oscillations for nucleons — and more generally baryons — are of the order of $\omega = 33 \pm 4$ MeV. The lowest surface excitation of a nucleon would then have an excess energy of about $\frac{1}{2} \omega = 16.5$ MeV. For isolated nucleon, the decay width of such excitation could easily be too large to be observed. However, inside the nucleus, where the excitation may jump from one nucleon to another, it might survive a bit longer. Actually, excitations with energies of this order of magnitude have been observed in the distant past 28. Could it be that surface oscillations of the gluon cloud were noticed long before the quark model had even been considered?

In conclusion, constants of nature are extremely important to help master its phenomena. In previous work we found that quarkonia are well described by a frequency of 190 MeV, independent of flavors. Here we seem to have discovered a second constant of strong interactions for quarkonia, namely an interference phenomenon with a constant periodicity of about 76 MeV. For baryons, which have a different color-charge configuration, we suspect this value to be about 12% smaller. Furthermore, we argue that the observed interference patterns in the amplitudes of annihilation processes may be related to the surface oscillations of gluons. From the intriguing fact that the observed periodicities do not depend on the beam energy, we find an additional indication for flavor independence of the quarkonium oscillation frequency.

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