First indications of the existence of a 38 MeV light scalar boson.

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We present evidence for the existence of a light scalar particle that most probably couples exclusively to gluons and quarks. Theoretical and phenomenological arguments are presented to support the existence of a light scalar boson for confinement and quark-pair creation. Previously observed interference effects allow to set a narrow window for the scalar’s mass and also for its flavor-mass-dependent coupling to quarks. Here, in order to find a direct signal indicating its production, we study published BABAR data on leptonic bottomonium decays, viz. the reactions $e^+e^- \to \pi^+\pi^-\Upsilon(1,2\,S_1)$ and $e^+e^-\to\pi^+\pi^-e^+e^-$ (and $\pi^+\pi^-\mu^+\mu^-$). We observe a clear excess signal in the invariant-mass projections of $e^+e^-$ and $\mu^+\mu^-$, which may be due to the emission of a so far unobserved scalar particle with a mass of about 38 MeV. In the process of our analysis, we also find an indication of the existence of a $b\bar{b}g$ hybrid state at about 10.061 GeV. Further signals could be interpreted as replicas with masses two and three times as large as the lightest scalar particle.

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I. INTRODUCTION

In Ref. [1] an $SO(4,2)$ conformally symmetric model was proposed for strong interactions at low energies, based on the observation, published in 1919 by H. Weyl in Ref. [2], that the dynamical equations of gauge theories retain their flat-space-time form when subject to a conformally-flat metrical field, instead of the usual Minkowski background. Confinement of quarks and gluons is then described through the introduction of two scalar fields which spontaneously break the $SO(4,2)$ symmetry down to $SO(3,2)$ and $SO(3) \otimes SO(2)$ symmetry, respectively. Moreover, a symmetric second-order tensor field is defined that serves as the metric for flat space-time, coupling to electromagnetism. Quarks and gluons, which to lowest order do not couple to this tensor field, are confined to an anti-De-Sitter (aDS) universe [3], having a finite radius in the flat space-time. This way, the model describes quarks and gluons that oscillate with a universal frequency, independent of the flavor mass, in a closed universe, as well as photons which freely travel through flat space-time.

The fields in the model of Ref. [1] comprise one real scalar field $\sigma$ and one complex scalar field $\lambda$. Their dynamical equations were solved in Ref. [1] for the case that the respective vacuum expectation values, given by $\sigma_0$ and $\lambda_0$, satisfy the relation

$$|\sigma_0| \gg |\lambda_0| \quad .$$

A solution for $\sigma_0$ of particular interest leads to aDS confinement, via the associated conformally flat metric given by $\sigma_0 \eta_{\mu\nu}$.

The only quadratic term in the Lagrangian of Ref. [1] is proportional to

$$-\sigma^2 \lambda^* \lambda \quad .$$

Hence, under the condition of relation (1), one obtains, after choosing vacuum expectation values, a light $\sigma$ field, associated with confinement, and a very heavy complex $\lambda$ field, associated with electromagnetism. Weak interactions were not contemplated in Ref. [1], but one may read electroweak for electromagnetism. Here, we will study the — supposedly light — mass of the scalar field that gives rise to confinement.

The conformally symmetric model of Ref. [1] in itself does not easily allow for interactions between hadrons, as each hadron is described by a closed universe. Hence, in order to compare the properties of this model with the actually measured cross sections and branching ratios, the model has been further simplified, such that only its main property survives, namely its flavor-independent oscillations. This way the full aDS spectrum is, via light-quark-pair creation, coupled to the channels of two — or more — hadronic decay products for which scattering amplitudes can be measured.

The aDS spectrum reveals itself through the structures observed in hadronic mass distributions. However, as we have shown in the past (see Ref. [4] and references therein), there exists no simple relation between enhancements in the experimental cross sections and the aDS spectrum. It had been studied in parallel, for mesons, in a coupled-channel model in which quarks are confined by a flavor-independent harmonic oscillator [5, 6]. Empirically, based on numerous data on mesonic resonances measured by a large variety of experimental collaborations, it was found [7] that an aDS oscillation frequency of

$$\omega = 190 \quad \text{MeV} \quad (3)$$

agrees well with the observed results for meson-meson scattering and meson-pair production in the light [8], heavy-light [9], and heavy [10] flavor sectors, thus reinforcing the strategy proposed in Ref. [1].
Another ingredient of the model for the description of non-exotic quarkonia, namely the coupling of quark-antiquark components to real and virtual two-meson decay channels \(11\) via \(^3P_0\) quark-pair creation, gives us a clue about the size of the mass of the \(σ\) field. For such a coupling it was found that the average radius \(r_0\) for light-quark-pair creation in quarkonia could be described by an flavor-independent mass scale, given by

\[
M = \frac{1}{2} \omega^2 \mu^2 r_0^2 ,
\]

where \(μ\) is the effective reduced quarkonium mass. In earlier work, the value \(ρ_0 = \sqrt{2m_σr_0} = 0.56\) \(\text{GeV}\) \(\text{fm}\) was used, which results in \(M = 30\) MeV for the corresponding mass scale. However, the quarkonium spectrum is not very sensitive to the precise value of the radius \(r_0\), in contrast with the resonance widths. In more recent work \(12, 13\), slightly larger transition radii have been applied, corresponding to values around 40 MeV for \(M\). Nevertheless, values of 30–40 MeV for the flavor-independent mass \(M\) do not seem to bear any relation to an observed quantity for strong interactions. However, we will next present experimental evidence for the possible existence of a quantum with a mass of about 38 MeV, which in the light of its relation to the \(^3P_0\) mechanism we suppose to mediate quark-pair creation. Moreover, its scalar properties make it a perfect candidate for the quantum associated with the above-discussed scalar field for confinement.

II. INTERFERENCE

In Ref. \(14\), we made notice of an apparent interference effect around the \(D^*_s D^*_s\) threshold in the invariant-mass distribution of \(e^+e^- \rightarrow J/\psi\pi^+\pi^-\) events, which we observed in preliminary radiation data of the BABAR Collaboration \(15\). The effect, with a periodicity of about 74 MeV, could be due to interference between the typical oscillation frequency of 190 MeV of the \(c\bar{c}\) pair and that of the gluon cloud. Later, in Ref. \(19\), we reported evidence for small oscillations in electron-positron and proton-antiproton annihilation data, with a periodicity of 76±2 MeV, independent of the beam energy. The latter observations are summarized in Fig. 4.

Amongst the various scenarios to explain the phenomenon presented in Ref. \(19\), one was rather intriguing, namely the postulated existence of gluonic oscillations, possibly surface oscillations, with a frequency of about 38 MeV. These would then, upon interfering with the universal quarkonia frequency \(ω = 190\) MeV \(3, 6\), lead to the observed oscillations.

In the present work, we are going to further elaborate on the hypothesis that the observed oscillations are caused by slow gluonic oscillations. However, we will find instead that the phenomenon are more likely to be associated with the interquark exchange of a scalar particle with a mass of about 38 MeV. Moreover, from the fact that the observed oscillations are more intense for bottomonium than for light quarks, we assume that the coupling of this light scalar to quarks increases with the mass.

III. SIGNS OF LIGHT SCALAR PARTICLE?

In Ref. \(18\), the BABAR Collaboration presented an analysis of data on \(e^+e^- \rightarrow π^+π^- Υ (1\,2^3S_1) \rightarrow π^+π^- ℓ^+ℓ^- (ℓ = e, μ)\), with the aim to study hadronic transitions between \(b\bar{b}\) excitations and the \(Υ (1\,2^3S_1)\) and \(Υ (2\,2^3S_1)\), based on 347.5 fb\(^{-1}\) of data taken with the BABAR detector at the PEP-II storage rings.

In Ref. \(10\), we reported evidence for the existence of the \(Υ (2\,2^3D_1)\) at about 10.495 GeV, and some indications of the existence of the \(Υ (1\,2^3D_2)\) at about 10.098 GeV, by analyzing the above BABAR data. In the present paper, these data are further analyzed.

The selection procedure for the data is well described by BABAR in Refs. \(18, 20, 21\). In Fig. 2 we study the invariant-mass distribution of muon pairs obtained from the BABAR data set \(18\) for the reaction \(e^+e^- \rightarrow Υ (2\,2^3S_1) \rightarrow π^+π^- Υ (1\,2^3S_1) \rightarrow π^+π^- μ^+μ^-\), and for a bin size equal to 9 MeV.
FIG. 2: Invariant $\mu^+\mu^-$ mass distribution for events identified as stemming from the reaction $e^+e^- \rightarrow \Upsilon (2S) \rightarrow \pi^+\pi^- \Upsilon (1S) \rightarrow \pi^+\pi^- \mu^+\mu^-$. Data (black) are taken from Ref. [13]. The bin size equals 9 MeV. Statistical errors are shown by vertical bars. The vertical line indicates $M_{\mu^+\mu^-} = M_{\Upsilon (1S)}$. The Gaussian distribution (gray, green in online version) and the excess data at the bottom of the figure (black, red in online version) are explained in the text.

Furthermore, we show in Fig. 2 a simple Gaussian distribution (gray histogram, green in online version), with a width of 89 MeV, around the $\Upsilon (1S)$ peak. We observe that, with respect to the Gaussian distribution, there is an excess of data for $M_{\mu^+\mu^-}$ above the $\Upsilon (1S)$ mass, and a deficit of data for $M_{\mu^+\mu^-}$ below. Actually, we have chosen the Gaussian distribution such that the total difference between the data under the Gaussian histogram and the experimental data vanishes. The excess signal is indicated (dark, shaded, histogram, red in online version) at the bottom of Fig. 2.

We observe from Fig. 2 that the excess of data sets out for masses some 40 MeV below the $\Upsilon (1S)$ mass, viz. at about $M_{\mu^+\mu^-} = 9.42$ GeV, and then towards lower $\mu^+\mu^-$ invariant masses, leaving a small signal on top of the increasing background tail, up to about 9.33 GeV. The deficit data exhibit enhancements at about $M_{\mu^+\mu^-} = 9.50, 9.54$ and 9.57 GeV, i.e., 38, 76, and 114 MeV above the $\Upsilon (1S)$ mass, respectively.

In Fig. 3 we have collected excess signals for other reactions, thereby following similar procedures as before. We have selected all reactions with some reasonable statistics from BABAR data, viz. $\Upsilon (3S_1) \rightarrow \pi^+\pi^- \Upsilon (1S) \rightarrow \pi^+\pi^- \mu^+\mu^-$ (Fig. 3a), $\Upsilon (3S_1) \rightarrow \pi^+\pi^- \Upsilon (2S) \rightarrow \pi^+\pi^- \mu^+\mu^-$ (Fig. 3b), and $\pi^+\pi^- \Upsilon (1S) \rightarrow \pi^+\pi^- e^+e^-$ for all available data (Fig. 3c). The data binning has been chosen in order to optimize statistics.

In Fig. 3a, which is 19 MeV binned, we observe two connected enhancements at 38 and 76 MeV below the $\Upsilon (1S)$ mass, and a third one, 38 MeV further downwards. Above the $\Upsilon (1S)$ mass, we observe two connected negative enhancements, 38 and 76 MeV higher up in mass. In Fig. 3b, which is 38 MeV binned, we observe two connected enhancements at 38 and 76 MeV below the $\Upsilon (2S_1)$ mass, and three connected enhancements at 38, 76 and 114 MeV above the $\Upsilon (2S_1)$ mass.

In itself, it is not surprising that an intrinsic asymmetry in mass distributions leads to excess on one side of the center and to a deficit on the other side, with respect to a symmetric distribution. However, we do observe structure in the excess and deficit data. This can be most clearly seen in the excess distribution of the reaction $e^+e^- \rightarrow \pi^+\pi^- \Upsilon (1S) \rightarrow \pi^+\pi^- e^+e^-$ (see Fig. 3a), where we do not opt for an overall vanishing excess, as we did for the other reactions. The excess signal below $M_{e^+e^-} = M_{\Upsilon (1S)}$ is mainly due to Bremsstrahlung, as explained by BABAR in Ref. [15]. Nevertheless, on top of the Bremsstrahlung background one observes something extra in the invariant-mass interval 9.35–9.42 GeV. No doubt, it is an additional signal of hardly more than 1σ. However, it is in roughly the same invariant-mass interval where we find some excess signal in the other three reactions. Moreover, the pronounced deficit at about 9.50 GeV comes out also in the same invariant-mass interval where we find a deficit signal in the other three reactions. The deficit enhancements at around 9.54 and 9.575 GeV are hardly distinguishable from zero, but show up in the expected energy intervals of 76 and 114 MeV above the $\Upsilon (1S)$ mass.

In Ref. [22], the BABAR Collaboration studied evidence for a light scalar boson in 99 $\times$ 10$^{-6}$ $\Upsilon (2S_1)$ and 122 $\times$ 10$^{-6}$ $\Upsilon (3S_1)$ radiative decays, $\Upsilon (2, 3S_1) \rightarrow \gamma A^0$.
→ γµ+µ−, as suggested by extensions of the standard model, in which a light CP-odd Higgs boson A0 naturally couples strongly to b quarks [23,27]. BABAR reported [22] to have found no evidence for such processes in the mass range 0.212 ≤ m_A0 ≤ 9.3 GeV. Furthermore, in Ref. [23] charged-lepton flavor-violating processes were studied by BABAR for similar large amounts of data, while BABAR tested lepton universality in Ref. [21] also for about 107 Υ (1 S1) → ℓ+ℓ− decay events. No significant deviations from the Standard-Model expectations were observed in these experiments.

With such amounts of events, the BABAR Collaboration should be able to confirm or invalidate our observations. Therefore, it was a pleasure for us to find a similar graph for the residual data in their presentation by E. Guido on behalf of the BABAR Collaboration [21]. This result is shown in Fig. 4. Moreover, the analysis in Ref. [21] took all known possible origins of asymmetry into account. Consequently, what is left (see Fig. 4) cannot be explained by known physics.

When we study Fig. 4 in more detail, we observe a clear structure just around and also below 9.42 GeV, exactly as we found above. Furthermore, we see three minima in the data just around and also below 9.50, 9.53, and 9.57 GeV, i.e., 40, 70, and 115 MeV above the Υ (1 S1) mass, respectively. Again, these minima do not have more significance than 2σ, but they are compatible with the values obtained before.

Moreover, Ref. [21] confirms our assumption that for µ+µ− background is small. Also, it states that the, here reported, systematic uncertainties due to the differences between data and simulation in the processes Υ (1 S1) → τ+τ− and Υ (1 S1) → µ+µ− cancel, at least in part, in their ratio. This implies that a similar excess is found in the Υ (1 S1) → τ+τ− decay.

IV. HYPOTHESIS OF A LIGHT SCALAR PARTICLE

When the Υ (1 S1) decays into a lepton pair and an additional light scalar particle, the invariant mass of the lepton pair will be smaller than the Υ (1 S1) mass. Depending on the amount of momentum taken by the light scalar particle, the event will pass through BABAR’s selection procedure.

Let us designate the hypothetical scalar boson by E(38). If we assume its mass to be about 38 MeV, the mentioned lepton pair will have invariant masses that are smaller than the Υ (1 S1) mass by at least 38 MeV. Hence, we will find an excess of events for invariant ℓ+ℓ− masses below about 9.42 GeV, with a spreading comparable to the spreading of the data without E(38) production. This seems to agree with what we observed in Sec. III. Furthermore, when several E(38)’s are produced, such signals will repeat themselves, viz. at 76, 114, ... MeV below the Υ (1 S1) mass, which also seems to agree with what we found in Sec. III.

In order to explain the structures in the deficit signal, we must assume that the E(38) can be loosely bound inside a b̄b state, giving rise to a kind of hybrid. For such a situation, we have two possibilities, viz. either hybrid-to-hybrid transitions Υ′ (3,2 S1) → π+π−Υ (1 S1) (the primes indicate hybrids), or hybrid-to-b̄b transitions Υ′ (3,2 S1) → π+π−Υ (2,1 S1). The events stemming from the former transitions come in the initial-state band, since the mass difference of the two hybrids equals the mass difference of the pure b̄b states. However, the hybrid-to-b̄b events do not end up in the initial-state band of events, since the mass difference is about 38 MeV too large. Hence, the deficit can be due to those events that were expected to come with a higher invariant two-lepton mass, but ended up outside the initial-state band (see Fig. 5). The dips at about 9.50 and 9.57 GeV in Fig. 4 certainly confirm such shapes, whereas the one in the middle is more distorted. Furthermore, the shapes of the three dips suggest that, actually, the higher mass phenomena are rather related to replicas [21] of the E(38) with masses that are two and three times heavier than the E(38), than to signals stemming from the production of two and three E(38)’s.

Hence, we have to search for possible hybrids [38–42]. In Fig. 5 we show the event distribution for the invariant mass ∆M, which is defined [18] by ∆M = Mππµ+µ− − Mµ+µ−, where the latter mass is supposed to be the Υ (1 S1) mass. Thus, a signal with the shape of a narrow Breit-Wigner resonance seems to be visible on the slope of the Υ (2 S1) resonance, though with little more than 2σ relevance. Nevertheless, by coincidence or not, it comes out exactly in the expected place, namely at 38 MeV. Unfortunately, the data [18] do not
have enough statistics to pinpoint possible higher excitations as well. So we cannot relate, to a minimum degree of accuracy, the other observed deficits enhancements to the possible existence of hybrid states.

V. SCALAR GLUEBALL

From the fact that the \( E(38) \) has not been observed before, one must conclude that it probably does not interact — at least to leading order — through electroweak forces, but instead couples exclusively to quarks and gluons. The interference effect we discussed in Sec. II might well be explained by \( E(38) \) exchange between the quarks, which interferes with the natural quark oscillations. Moreover, since the interference effect is smaller for light quarks than for heavier ones, it is likely that their coupling to the \( E(38) \) is proportional to flavor mass, as one expects from theory.

The \( E(38) \) could very well be just a light scalar glueball, albeit much lighter than found in Refs. [32,53,41]. Its low mass precludes decay into hadrons, while the absence of electroweak couplings does not allow it to decay into leptons either, at least to lowest order. It may decay, though, into photons via virtual quark loops, and through photons, eventually, into \( e^+e^- \) pairs. However, the probability for such reactions to occur is extremely remote, since the coupling between the quarks and the light scalar is proportional to the quark mass [1]. In the case of bottom quarks, we found events of the order of or less than one percent of the total. For light quarks, their mass ratio with respect to bottom quarks reduces this rate to \( 10^{-7} \sim 10^{-6} \).

Hadrons will certainly interact with a light scalar ball of glue. For example, a proton struck by such a scalar particle may absorb it and then emit photons, or decay into a neutron and a lepton-neutrino pair. Yet another possibility is that, being closed universes themselves, these scalar particles mainly collide elastically with hadronic matter. In that case, depending on their linear momentum, they may remove light nuclei from atoms. Nevertheless, we do not see such processes happening around us. Therefore, these light scalars are probably not abundantly present near us. However, in the early universe they may have existed, most probably inflated to hadrons under collisions. On the other hand, interactions with hadrons might have been observed in bubble-chamber experiments, where isolated protons could be the result of collisions with a light scalar particle emerging from one of the interaction vertices.

Light Higgs fields have been considered in supersymmetric extensions of the Standard Model [42]. Furthermore, axions, which appear in models motivated by astrophysical observations, are assumed to have Higgs-like couplings [43]. Model predictions for the branching fraction of \( \Upsilon \rightarrow \ell^+\ell^-+\text{Higgs} \) are not yet excluded by the lepton-universality test in \( \Upsilon \rightarrow S \) decays studied by BABAR in Refs. [23,24].

The light scalar glueball we have discussed here seems to correspond to the lowest-order empty-universe solution of Ref. [1] for strong interactions. It has similar properties as the electroweak Higgs, but now for strong interactions. Quarks couple to it with an intensity which is proportional to their mass, in the same way that mass couples to gravity [40]. In the Standard Model [50,53], the Higgs boson and the graviton are the only particles yet to be observed, and no Higgs particle for strong interactions is anticipated. However, N. Törnqvist recently proposed [54,55] the light scalar-meson nonet [8] as the Higgs bosons of strong interactions, while in Ref. [53] he obtained a nonzero pion mass by means of a small breaking of a relative symmetry between the electroweak and the strong interactions. A relation between the lightest scalar-meson nonet and glueballs has often been advocated by P. Minkowski and W. Ochs (see e.g. Ref. [56]). In our view though, the light scalar mesons are dynamically generated through \( q\bar{q} \) pair creation/annihilation, which mixes the quark-antiquark and dimeson sectors [8].

VI. EPILOGUE

In Sec. II we discussed why we expect an additional scalar particle to exist, besides the Higgs boson for the
electroweak sector. Furthermore, we have estimated its mass based on the average radius for $^3P_0$ quark-pair creation, which had been extracted over the past three decades from numerous data on mesonic resonances (see Ref. [4] and references therein). In Sec. [III] we recalled our results on an apparent interference effect in annihilation data, and stressed the possibility that it may stem from some internal oscillation with a frequency of about 38 MeV. In Sec. [III] we showed that missing data in the reactions $e^+e^- \rightarrow \pi^+\pi^- \Upsilon(1^3S_1) \rightarrow \pi^+\pi^- e^+e^-$ and $e^+e^- \rightarrow \pi^+\pi^- \Upsilon(1^3S_1) \rightarrow \pi^+\pi^- \mu^+\mu^-$ exhibit maxima at $M$, $2M$, and $3M$, for $M \approx 38$ MeV.

Each of the results, viz. the interference effect observed in Ref. [14], the small flavor-independent oscillations in electron-positron and proton-antiproton annihilation data, observed in Ref. [14] and summarized in Fig. 4, the excess signals visible in the $\mu^+\mu^-$ mass distributions of $\Upsilon(1^3S_1) \rightarrow \pi^+\pi^- \Upsilon(1^3S_1) \rightarrow \pi^+\pi^- \mu^+\mu^-$ (Fig. 2), in $\Upsilon(3^3S_1) \rightarrow \pi^+\pi^- \Upsilon(1^3S_1) \rightarrow \pi^+\pi^- \mu^+\mu^-$ (Fig. 3), in $\Upsilon(3^3S_1) \rightarrow \pi^+\pi^- \Upsilon(2^3S_1) \rightarrow \pi^+\pi^- \mu^+\mu^-$ (Fig. 3), and in the $e^+e^-$ mass distributions of $e^+e^- \rightarrow \pi^+\pi^- e^+e^-$ (Fig. 3), and finally the resonance signal shown in Fig. 4, is much too small to make firm claims. However, we observe here that all points in the same direction. Indeed, the probability must be close to zero that one accidentally finds the same oscillations in four different sets of data (Refs. [14, 19]) involving different flavors, statistical fluctuations at $\pm38$ MeV in yet another four sets of different data (Figs. 2 and 3), and moreover a resonance-like fluctuation at 38 MeV in a further set of data (Fig. 4). Furthermore, the related mass comes where predicted by our analyses in mesonic spectroscopy (see Ref. [4] and references therein).

In Sec. [V] we discussed that, most probably, the missing signal is due to the emission of an — as yet unobserved — light scalar particle, while part of the excess data corroborates such an interpretation. Since the corresponding particle has all the right properties, we conclude that we found first indications, of the possible existence of a Higgs-like particle, namely the scalar boson related to confinement. Furthermore, the data also suggest the existence of two replicas of the $E(38)$ with masses that are two and three times heavier than the $E(38)$.

In addition, we believe that this 38 MeV boson, which we designate by $E(38)$, consists of a mini-universe filled with glue, thus forming a very light scalar glueball. Furthermore, we have pinpointed the masses of possible $bbg$ hybrids, one of which shows up as an enhancement in the invariant-mass distribution of BABAR data, albeit with a $2\sigma$ significance at most.

Finally, we urge the BABAR Collaboration to inspect their larger data set in order to settle, with higher statistics, the possible existence of the $E(38)$ and the related $bbg$ hybrid spectrum.

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