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EXCITATION OF PHYSICAL VACUUM

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Introducing the notion of an «excitation of physical vacuum», we do an attempt to explain some strange experimental facts such as large value of σ-term measured in pion–nucleon low-energy scattering, $\Delta T = 1/2$ rule in kaon two-pion decay modes, the ratio of strange to nonstrange yield in low-energy proton–antiproton annihilation, excess of soft photons in hadron collisions. As a test of our approach we suggest to measure the multiparticle production processes and decays of heavy virtual objects.

Введя понятие «возбужденного физического вакуума», мы предприняли попытку объяснить некоторые странные данные эксперимента, такие как большая величина σ-члена, привлекаемая для описания низкоэнергетического пион-нуклонного рассеяния, правило $\Delta T = 1/2$ в распадах пионов, отношение каналов выхода странных и нестранных мезонов при аннигиляции нуклонов вблизи порога, выход мягких фотонов при столкновении адронов. В качестве теста мы предлагаем измерять процессы с образованием достаточно большого (более четырех) числа пионов, а также исследовать аналогичные моды распада тяжелых виртуальных объектов.

1. MOTIVATION

Motivation of this note is the need to explain some strange experimental facts in particle physics.

One of them is a too large value of strangeness content $y = \langle P|\bar{s}s|P\rangle / \langle P|\bar{u}u + \bar{d}d|P\rangle$ in the nucleon $|P\rangle$ state. This quantity can be expressed with the experimentally measured value of the so-called σ-term:

$$\sigma = \frac{\sigma_0}{1-y}, \tag{1}$$

where $\sigma = 80{-}200$ MeV is the measure of chiral symmetry violation and can be expressed in terms of pion–nucleon scattering lengths; $\sigma_0 \approx 30$ MeV can be calculated in the framework of quark–parton model [1, Chap. 5]. It is difficult to explain too large value of $y > 0.5$.

Another one is the experimental evidence on «too large strangeness» in proton which follows from the experiments with annihilation of proton and antiproton near threshold into mesons [2]. It turns out that in the case that initial particles are in state $^3P_0$ the ratio of kaon production to pion production is of order of unity:

$$\frac{\mathrm{Br}\,(\bar{p}p \to KK)}{\mathrm{Br}\,(\bar{p}p \to \pi\pi)} \approx 1, \tag{2}$$

contrary to the state $^3S_1$ where this ratio is small.

We mention here the problem of understanding an excess of soft photons created at high-energy hadron collisions [3]. There are some uncertainties in model description of high-multiplicity processes [4]. We also mention here the long-standing problem of explanation of $\Delta T = 1/2$ rule in weak kaon decays.

2. PHYSICAL VACUUM EXCITATION

In this note we do an attempt to understand these phenomena in the framework of the model of Physical Vacuum (PV) excitement [5]. We regard PV as a Dirac cellar which can be excited when accepting some amount of energy released during the collision of initial particles (or decay of heavy initial particle). This excited state is a state containing any number of gluons and light (current) quark–antiquark pairs with quantum number of vacuum 0^{++}. We suppose the equal probabilities of presence of quark–antiquark germs of any flavor. The PV excited state is similar to the state of a liquid with the temperature close to the boiling point. When the germs accept sufficient amount of energy, the current quarks turn to the constituent ones and at the hadronization stage reveal themselves as mesons or nucleons. For the case of proton–antiproton annihilation the branching ratio of kaon and pion production is expected to be approximately equal.

For collisions with total energy large enough to produce the charm germs or the ones of beauty, the rates of production of corresponding hadrons (when taking into account the difference of phase volumes) become of the same order. From this point of view the experimental result (2) can be accepted. As for (1) we expect the PV contribution to $y = y_{\rm PV} + y_I$ dominates ($y_{\rm PV} = 0.5$) for the case of proton–antiproton annihilation, whereas the contribution of the intrinsic one ($y_I = 0.15$) is more realistic one. In paper [6] the value of $\sigma \approx 80$ MeV was obtained in the framework of Nambu–Iona-Lazinio model with σ-pole intermediate state.

The mechanism of the meson creation from the region of the excited vacuum state of the size L reminds the process of vapor bubble creation in hot water [7]. When the temperature does not exceed the boiling point $T < T_c$, the bubbles which always exist in a liquid due to fluctuations do not increase. The superficial tension dominates. The situation changes in the boiling point $T = T_c$: the new phase becomes more convenient energetically and the number of the bubbles of size R creation become dominant:

$$n(R) \sim \exp\left(-\Delta W(R)/T\right) \sim \exp\left(-a(T - T_c)R^3\right), \tag{3}$$

with $\Delta W = \Delta E - T\Delta S + P\Delta V$ free energy, $\Delta W = 4\pi/3vR^3(\mu_1(T) - \mu_2(T)) + 4\pi\sigma R^2$, where $\mu_{1,2}$ are the chemical potentials of liquid and gas phases, v and σ are the volume per one molecule and the superficial tension, respectively. It is important to note that the probability of creation of a large bubble (hadron in a gluon liquid) has a resonance form:

$$W \sim \int r^2 \exp\left(-a(T - T_c)r^3\right) dr \sim \frac{1}{|T - T_c|} = \frac{1}{|M - E|}. \tag{4}$$

This expression reminds the Breit–Wigner form and, presumably, can be confirmed taking into account the dynamics of this process. We can conclude that any process with possible PV intermediate state will have some enhancement, which can be associated with intermediate state with quantum numbers $I^G(J^{PC}) = 0^+(0^{++})$, so-called σ meson. The matrix element of process with production of some state X with vacuum quantum numbers will have a form

$$M(ab \to cX) = \frac{1}{s_1 - M_\sigma^2 + i\Gamma_\sigma M_\sigma} M(ab \to c + {\rm PV}) M({\rm PV} \to X) + \ldots, \tag{5}$$

with dots denoting the contributions which do not contain the σ-pole contribution; s_1 is the invariant mass square of the set of particles X.

We remind that in this way the remarkable enhancement of decay amplitudes with $\Delta T = 1/2$ in two-pion modes of kaon decays can be understood [8].

Consider now the phenomenon of soft photon emission at hadron collisions. According to our model, the hot quark–gluon system appears as a result of energy accepted by PV. Germs consisting of the current (light) quark–antiquark pairs of different flavors turn into pairs of constituent (heavy) quarks and gluons which can be considered as almost equilibrium system. Almost real hadrons can be emitted from the boundary of hot vacuum surface as real hadrons. This scenario is similar to the Big Bang one resulting in our Universe creation. In the latter case the equilibrium between electrons, protons and photons breaks at the temperature $T = 3000$ K when the electron–proton recombination and the creation of neutral atoms take place. At this stage photons cease to interact with the matter and start to expand as relic ones. At the contemporary moment we observe the spectrum of relic photons (black body spectrum) [9]:

$$\frac{d\rho}{d\nu} = \frac{8\pi}{c^3} \frac{\nu^2}{\exp{(h\nu/T)} - 1}, \tag{6}$$

where $d\rho/d\nu$ is the spectral spatial density of photons; c and $h\nu$ are the light velocity and the energy of photon, respectively. Maximum of spectral distribution is located at $h\nu_0 = 2.8 k_B T$. The temperature and the density of contemporary relic photons are $T_0 = 3$ K and $480\ \mathrm{cm}^{-3}$, correspondingly.

Massless gluons interacting with quarks similarly to photons have a zero chemical potential and therefore obey the black body emission spectrum. Gluon density at the deconfinement temperature $T_c \approx 200$ MeV can be estimated as

$$\rho_{\mathrm{gl}} = 2.4 \left(\frac{T_c}{T_0}\right)^3 \cdot 10^{-37}\ \mathrm{fm}^{-3} \approx 0.3\ \mathrm{fm}^{-3}. \tag{7}$$

So the number of gluons in the hot vacuum region of size $L = 20$ fm will be of order of a few hundred. What is their fate at the hadronization stage? They cannot be emitted as free particles due to their open color. Besides, they cannot create the colorless glueball state, as well as they are mostly soft. The gluon excess is accepted by the quarks which are now heavy. These hadrons are almost on the mass shell. The energy excess is emitted by means of soft photons.

Dynamics of turning the soft gluons to soft photons is presumably as complicate as the confinement phenomenon one. We will not touch it here.

Averaging over the temperature of the quark–gluon system from the beginning stage $T \gg T_c$ up to $T = T_c$ at the final hadronization stage, one can estimate the soft photon emission spectrum:

$$\frac{dW}{d\nu} \sim \int\limits_0^{T_c^{-1}} d\beta f(\beta) \exp{(-\beta h\nu)} \sim \frac{A}{\nu} f(0). \tag{8}$$

The average energy of gluons can be estimated from the total energy deficits carried by soft photons $\Delta E \sim 10^{-2} E$ and their number estimated above. For the case of proton–antiproton annihilation we estimate $h\nu \sim 1{-}2$ MeV. The spectrum behavior is the same as QED soft photon emission one, but the quantity A can be an order larger than the QED one [10] $A_{\mathrm{QED}} = \alpha/\pi \sim 2.5 \cdot 10^{-3}$.

3. HIGH MULTIPLICITY PROCESS

Let us now consider the manifestation of PV mechanism in high multiplicity processes. For definiteness first consider the decay of particle with rather high mass, such as $\rho \to 4\pi$; $J/\Psi \to 2\pi\mu\bar{\mu}$. Matrix element will have an additional term which corresponds to two pions created by PV and the off-mass shell meson decaying by two-particle channel.

The quantum numbers of the set of pions created from PV coincide with vacuum quantum numbers 0^{++} and, besides, zero total 3-momentum in the rest frame of decaying particle. The last feature is a specific one for the PV excitation mechanism.

It is easy to see that the corresponding contribution to the total width does not contain an interference term of traditional matrix element of n-particle decay and $n-2$ decay matrix element with two pions created by the PV mechanism. Really the kinematics of creation is quite different.

So in general the width will have a form of some finite sum of contributions with two pions, four pions and so on created through the PV excitation channel.

To obtain some definite predictions we must work in the framework of a model (we want it to be called «a corrupt model» (CM)). We suggest that the effective Lagrangian which takes into account PV excitation can be built starting from the usual one L_0 as [11]

$$L_{\text{eff}} = L_0 \left[1 + c_2 \frac{\boldsymbol{\pi}^2}{f_\pi^2} + c_4 \left(\frac{\boldsymbol{\pi}^2}{f_\pi^2} \right)^2 + \ldots \right], \tag{9}$$

with f_π pion decay constant. So the matrix element of decay process of heavy object A to a set of particles a, accompanied by emission of set of $2n$ pions $A(P_A) \to a + 2n\pi$, some of them created through the PV excitation mechanism, will have a form (see Fig. 1)

$$\begin{aligned} \langle A, \text{PV}|L_{\text{eff}}|a, 2n\pi\rangle = M(A \to a + 2n\pi) = \\ = \sum_{k=0}^{n} M_k(A \to a_k + 2k\pi) M_0(a_k \to a + 2(n-k)\pi) + \\ + \sum_{k=0}^{n} M_0(A \to a + \sigma_k + 2(n-k)\pi) M_k(a_k \to 2k\pi), \end{aligned} \tag{10}$$

where $|a_k\rangle, |\sigma_k\rangle$ are the intermediate state with quantum numbers of A and vacuum, respectively.

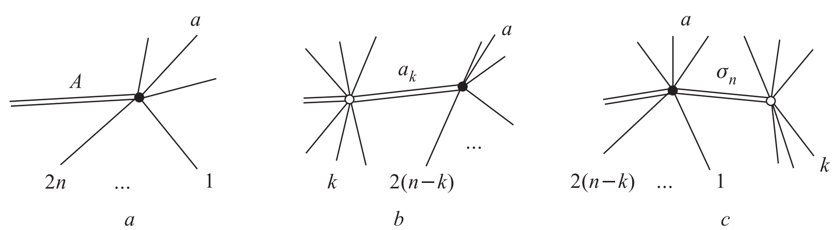

Fig. 1. Contribution to the decay $A \to a + 2n\pi$ matrix element: *a*) without PV excitation; *b*) $2k$ pions created through PV excitation with quantum numbers of A intermediate state; *c*) $2k$ pions created by PV excitation with intermediate-state vacuum quantum numbers

To take into account energy distribution between sets of final-state particles, we will write the phase volume in the form

$$d\Phi_{a,2n\pi} = \delta^4\left(P_A - \sum p_a - \sum_{i=1}^{2n} q_i\right)\Pi\frac{d^3p_a}{2\epsilon_a}\prod_{i=1}^{2n}\frac{d^3q_i}{2\omega_i} =$$
$$= d^4q\delta^4\left(P_A - q - \sum p_a - \sum_{i=1}^{2(n-k)} q_i\right)\prod_{j-1}^{2(n-k)}\frac{d^3q_i}{2\omega_i}\prod\frac{d^3p_a}{2\varepsilon_a}\delta^4\left(q - \sum_{j=1}^{2k} q_i\right)\prod_{j=1}^{2k}\frac{d^3q_j}{2\omega_j}. \quad (11)$$

Keeping in mind the kinematical fact of absence of interference terms of different contributions to the matrix element, we can put the width in the form (we imply the rest frame of decaying particle)

$$\Gamma(A \to a, 2n\pi)(M_A) = \Gamma_0(A \to a, 2n\pi)(M_A) +$$
$$+ \sum_{k=1}^{n}\lambda_k\int\limits_{a(k)}^{b(k)} q_0^3 P_k(q_0)dq_0\left[\frac{\Gamma_0(A \to a + \sigma_k + 2(n-k)\pi)(M_A)}{(q_0^2 - M_{\sigma_k}^2)^2 + M_{\sigma_k}^2\Gamma_{\sigma_k}^2} +\right.$$
$$\left.+ \frac{(1 - q_0/M_A)\Gamma_0(A \to a + 2(n-k)\pi)(M_A - q_0)}{((M_a - q_0)^2 - M_{a_k}^2)^2 + M_{a_k}^2\Gamma_{a_k}^2}\right], \quad (12)$$

with $\Gamma_0(M)$ the width calculated in the framework of standard field theory. Here we denote $a(k) = 2km_\pi$, $b(k) = M_A - m_a - 2(n-k)m_\pi$, and the phase volume of $2k$ particles in the nonrelativistic case [12]

$$\int \delta(q_0 - \sum \omega_i)\delta^3\left(\sum_{i=1}^{2k}\mathbf{q}_i\right)\Pi\frac{d^3q_i}{2\omega_i} = c_k((q_0 - 2km_\pi)/f_\pi)^{3k-5/2} = c_kP_k(q_0). \quad (13)$$

We use the realistic assumption $M(A \to a_k + 2(n-k)\pi) = M(\sigma_k \to 2k\pi) = M_k$. To realize the requirement of zero total 3-momentum of a set of $2k$ pions created through the PV excitation mechanism, we use the (model-dependent) assumption

$$|M_{2k}|^2 = q_0^3\lambda_k c_k^{-1}\delta^3(\mathbf{q}). \quad (14)$$

The quantities M_k, Γ_k and λ_k can be considered as free parameters.

For illustration let us consider 4-particle channel decays of ρ and Ψ':

$$\Gamma(\rho \to 4\pi) = \Gamma_0 + \Delta\Gamma_\rho, \quad (15)$$

where Γ_0 can be found in [13] (and the references therein) and (see Fig. 2)

$$\Delta\Gamma_\rho = \lambda_1\int\limits_{2m_\pi}^{M_\rho - 2m_\pi} q_0^3 dq_0\beta(q_0)\left[\frac{(1 - q_0/M_\rho)\Gamma_{\rho\to 2\pi}(M_\rho - q_0)}{((M_\rho - q_0)^2 - M_\rho^2)^2 + M_\rho^2\Gamma_\rho^2} + \frac{\Gamma_{\rho\to 2\pi+\sigma}(M_\rho)}{(q_0^2 - M_\sigma^2)^2 + M_\sigma^2\Gamma_\sigma^2}\right],$$
$$\beta(q_0) = \sqrt{1 - \frac{4m_\pi^2}{q_0^2}}, \;\; \Gamma_{\rho\to 2\pi}(M) = \frac{Mg_{\rho\pi\pi}^2}{48\pi}\left(1 - \frac{4m_\pi^2}{M^2}\right)^{3/2}. \quad (16)$$

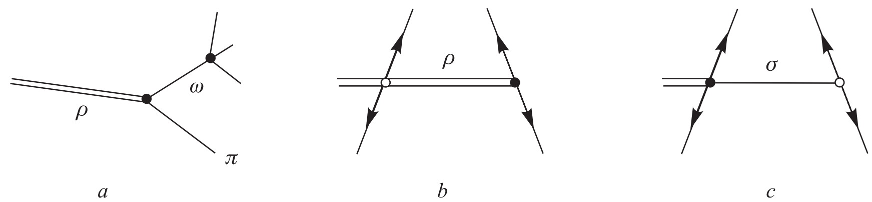

Fig. 2. Feynman diagrams for $\rho \to 4\pi$ decay: *a*) without PV excitation; *b, c*) two-pion production through PV excitation

For $\Psi' \to 2\pi\mu\bar{\mu}$ decay we have $\Gamma = \Gamma_0 + \Delta\Gamma_\Psi$ with (see Fig. 3)

$$\Delta\Gamma_\Psi = \lambda_1 \int\limits_{2m_\pi}^{M_{\Psi'}-2m_\mu} q_0^3 dq_0 \beta(q_0) \times$$

$$\times \left[\frac{(1 - q_0/M_{\Psi'})\Gamma_{J/\Psi \to \mu_+\mu_-}(M_{\Psi'} - q_0)}{((M_{\Psi'} - q_0)^2 - M_{J/\Psi}^2)^2 + M_{J/\Psi}^2 \Gamma_{J/\Psi}^2} + \frac{\Gamma_{\Psi' \to \sigma + \mu_+\mu_-}(M_{\Psi'})}{(q_0^2 - M_\sigma^2)^2 + M_\sigma^2 \Gamma_\sigma^2} \right]. \quad (17)$$

We recall that, besides the possibility of vacuum excitation considered above for energies exceeding the ρ-meson mass, the additional contributions connected with higher meson resonance excitation must be taken into account when describing the e^+e^- annihilation experiments [14].

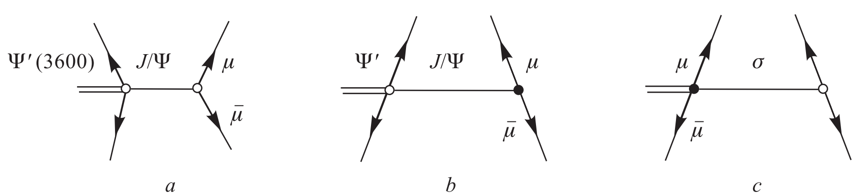

Fig. 3. Feynman diagrams for $\Psi^{'}(3600) \to 2\pi\mu^+\mu^-$ decay: *a*) without PV excitation; *b, c*) two-pion created from PV excitation

The model suggested will give the same result as in the traditional field theory for such processes as $e^+e^- \to \pi^+\pi^-\pi^0$; $K^+K^-\pi^0$; $a\bar{a}\gamma$.

Really in our model in the centre-of-mass frame of the initial electron and positron the sum of 3-momentum of two particles created by vacuum excitation is zero as well as the 3-momentum of the third particle. In this kinematics the PV-matrix element equals zero.

The events with possible groups of the final particles with quantum numbers of vacuum and with the zero 3-momentum in the rest frame of decaying particle can be searched for at proton–proton or nucleus–nucleus colliders with creation of large number of particles and DIS experiments.

DISCUSSION

The idea of PV excitation through energy transfer to Dirac cellar reminds the idea of using tadpoles in the 1960s to explain $SU(3)$-symmetry violation [15], so it is not a new one.

The effective Lagrangian used above to describe multipion production was first suggested by S. Wienberg [11] in the framework of current algebra and further was derived in models with nonlinear realization of symmetry [16].

The PV excitation state $|\sigma_k\rangle$ with quantum numbers of vacuum $J^PC = 0^{++}$ can exist as particle with definite mass and width and, besides, as some object which cannot be interpreted as a definite particle. The situation reminds the pomeron state with quantum numbers $J^{PC} = 1^{++}$ used to describe high-energy hadron–hadron scattering, which cannot be associated with the definite particle.

The dominant role of gluons in creation of jets at hadron collisions was underlined in papers of P. Carruthers and E. V. Shuryak [17].

In a paper of one of the authors (M. K. V.) a reason why the ratio of $K \to 2\pi$ decay matrix elements $M(K_s \to \pi^+\pi^-)/M(K^+ \to \pi^+\pi^0) \sim 50$ was given: really in the neutral kaon decay the intermediate state with vacuum quantum numbers with mass value close to kaon mass was shown to give the dominant contribution [8].

The formulae given above have a rather qualitative meaning.

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