## Scalar Glueball as the "Color-Singlet Monopole" in the DGL Theory

Y. Koma*, H. Suganuma and H. Toki

*Research Center for Nuclear Physics, Osaka University*

Recent studies of the lattice QCD in the maximally abelian (MA) gauge suggests that the QCD-vacuum can be regarded as the dual superconductor[1], which is well-described by the dual Ginzburg-Landau (DGL) theory[2]. In this vacuum, as a result of the dual Higgs mechanism, monopole condensation $\langle 0|\chi_\alpha|0\rangle = v$ is occurred and the color-electric field between the quarks is forced to form the flux-tube configuration due to the dual Meissner effect. The color confinement is understood in consequence of the flux-tube formation since it earns constant energy per unit length, which leads the linear inter-quark potential. Then, the various hadronic objects are understood as the flux-tube excitations intuitively. The flux-tube ring that we have studied as the glueball is one of the application of this flux-tube picture of the hadrons [3, 4].

In this report, we consider another aspect of the scalar glueball in the DGL theory which is closely related to the dual Higgs mechanism. Taking monopole condensation into account, the monopole field can be defined as

$$\chi_\alpha \equiv \left( v + \frac{1}{\sqrt{2}} \tilde{\chi}_\alpha \right) e^{i\eta_\alpha / v}, \tag{1}$$

where $\tilde{\chi}_\alpha$ and $\eta_\alpha$ are real variables denoting the magnitude of the vacuum fluctuation and the phase, respectively. Here, $\alpha$=1, 2, 3 labels the color-magnetic charge of the monopole field, red(R), blue(B) and green(G). Since the origin of the monopole field is the off-diagonal gluon field in the MA-gauge in QCD, this new field $\tilde{\chi}_\alpha$ would present the scalar gluonic excitation corresponding to the dual Higgs particle. Especially, the Weyl symmetric field defined by $\tilde{\chi}^{(0)} \equiv (\tilde{\chi}_1 + \tilde{\chi}_2 + \tilde{\chi}_3)/\sqrt{3}$ is the color-singlet field, so it can be identified with the scalar glueball. Although the relation between the flux-tube ring is not clear, it can be considered as one of the feature of the scalar glueball. Therefore, the study of the color-singlet monopole may tell us the properties of the scalar glueball.

Here, we concentrate on the calculation of the $\tilde{\chi}^{(0)} q\bar{q}$ vertex function, which plays an important role to understand how the scalar glueball interacts with the quarks. We rewrite the DGL lagrangian in terms of the color-singlet monopole $\tilde{\chi}^{(0)}$, and obtain

$$\begin{aligned} \mathcal{L}_{\rm DGL} \;=\; & -\frac{1}{4}\left(\partial_\mu \vec{B}_\nu - \partial_\nu \vec{B}_\mu\right)^2 + \frac{1}{2} m_B^2 \vec{B}_\mu^2 \\ & + \bar{q}\,(i\partial\!\!\!/ - m_q)\, q \\ & + \frac{1}{2}(\partial_\mu \tilde{\chi}^{(0)})^2 - \frac{1}{2} m_\chi^2 \tilde{\chi}^{(0)\,2} \\ & + \sqrt{\frac{3}{2}} g^2 v \tilde{\chi}^{(0)} \vec{B}_\mu^2 - \varepsilon^{\mu\nu\alpha\beta} \partial_\mu \vec{B}_\nu n_\alpha \frac{1}{n\cdot\partial} \vec{j}_\beta + \cdots . \end{aligned} \tag{2}$$

Here, we find that the dual gauge field $\vec{B}_\mu$ and the monopole field $\tilde{\chi}^{(0)}$ acquire the mass $m_B \equiv \sqrt{3} g v$=0.5 GeV, $m_\chi \equiv 2\sqrt{\lambda} v$=1.6 GeV, thus, they behave as the massive vector field and real scalar field, respectively. Since the interaction lagrangian is quite complicated, we write

*e-mail: koma@rcnp.osaka-u.ac.jp

only two terms giving the lowest diagram as shown in Fig.1. The vertex function is given by

$$
\begin{aligned}
\Gamma_{\tilde{\chi}^{(0)}q\bar{q}} = {} & \frac{1}{(2\pi)^4}\int d^4p\cdot 2i\sqrt{\frac{3}{2}}g^2 v\delta^{ij}g^{\rho_1\rho_2} \\
& \times i\delta^{ik}\frac{-g_{\rho_1\nu_2}+(k-p)_{\rho_1}(k-p)_{\nu_2}/m_B^2}{(k-p)^2-m_B^2+i\epsilon}\left(\varepsilon^{\mu_2\nu_2\alpha_2\beta_2}(k-p)_{\mu_2}n_{\alpha_2}\frac{e}{n\cdot(k-p)}\gamma_{\beta_2}H^k\right) \\
& \times i\delta^{jl}\frac{-g_{\rho_2\nu_3}+p_{\rho_2}p_{\nu_3}/m_B^2}{p^2-m_B^2+i\epsilon}\left(\varepsilon^{\mu_3\nu_3\alpha_3\beta_3}p_{\mu_3}n_{\alpha_3}\frac{e}{n\cdot p}\gamma_{\beta_3}H^l\right) i\frac{(\not{p}-\not{q})+m_q}{(p-q)^2-m_q^2+i\epsilon}, \qquad (3)
\end{aligned}
$$

which includes various channels, scalar, vector, tensor, and so on. Each channel is extracted by using the traceless of $\gamma$-matrix. It is interesting to note that this vertex function contains the 1-loop integral which consists of the propagator of the massive vector boson, so one may expect it includes the ultra-violet divergence. Thanks to the $\varepsilon$-tensor in the $\vec{B}_\mu q\bar{q}$ vertex, however, all such divergent terms disappear.

We show the typical behavior of the vertex function in the scalar channel, $\Gamma_S \equiv \mathrm{tr}[\Gamma_{\tilde{\chi}^{(0)}q\bar{q}}]$, as a function of the coupled quark momentum in Fig.2. Here, we have set $p\cdot q=0$ for simplicity. We find that the heavy quark (c$\sim$1.6 GeV) interacts with the scalar glueball about four times stronger than the light quarks (u,d,s$\sim$0.3-0.5 GeV). It seems to indicate the flavor dependence of the interaction of the scalar glueball. Although we must also consider other channel contributions, it is interesting to investigate how this interaction property reflects on the scalar glueball decay into the two pseudo-scalar mesons and the glueball-quarkonium mixing states.

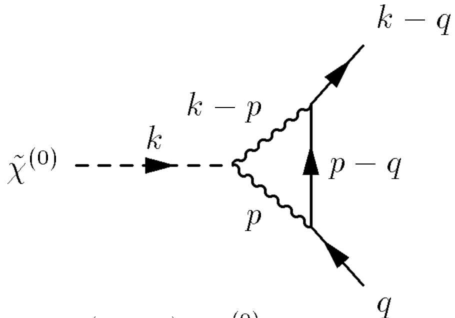
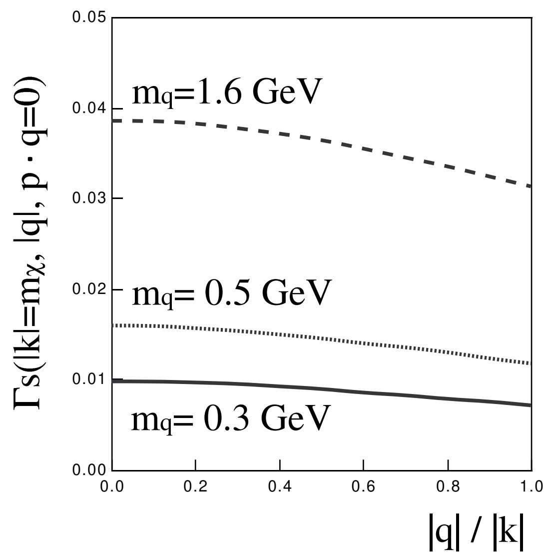



Fig.1(upper) : $\tilde{\chi}^{(0)}q\bar{q}$ vertex

Fig.2(right) : The vertex function in the scalar channel as a function of coupled quark momentum.




## References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