

Dynamical chiral symmetry breaking in QED₃

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Abstract: In order to examine how a propagator behaves in non-perturbative theories and how its behavior is influenced by the choice of a covariant gauge, a truncated Dyson-Schwinger equation is used to numerically investigate the properties of fermions and bosons in 3D quantum electrodynamics (QED), and a series of self-consistent solutions for the fermion propagator in the Nambu and Wigner phases are obtained. These numerical solutions show that the propagator behaves very differently in the Landau gauge domain and in the infrared energy region outside it. By using the propagators in the Nambu and Wigner phases under various gauges, it is further investigated how the fermion equivalent pressure difference and fermion condensation change with the gauge parameters. These results indicate that the phase transition described by the CJT equivalent potential and the chiral phase transition described by the chiral condensation are not completely identical.

Key words: propagator; covariant gauge; 3D quantum electrodynamics (QED); equivalent pressure difference; fermion condensation; chiral phase transition

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Gauge fields play a basic role in particle physics. According to theoretical physics, all the physical results should be independent of the gauge parameter. The results show this to be true at every level of approximation in perturbation theory, while this has not been successfully demonstrated in general in the non-perturbative case. Within the framework of strong correlation, the system shows dynamical chiral symmetry breaking (DCSB), where the massless fermion gains a nonzero mass. In addition, all of the information about the system can be obtained from the propagators. Therefore, it is necessary to study the idiographic behavior of propagators and the influence of the covariant gauge on behavior in a non-perturbative theory.

To understand the propagators, we invoke the Dyson-Schwinger (DS) equations for fermion and boson propagators. As is well known, there are two solutions for the

DS equations for the fermion propagator, namely, the Nambu and Wigner solutions. In the chiral limit, the Nambu solution corresponds to the chirally broken phase while the Wigner solution corresponds to the chirally symmetric phase. We believe that the Nambu solution is the solution that is realized in the real world. Several studies^[1-3] have shown that the Nambu solution occurs only with fermion flavors N less than a critical value N_c , but none of them has shown the Wigner solution at $N < N_c$. In this paper, we use a toy non-perturbative model to illustrate the Wigner solution for the fermion propagator. Due to the fundamental nature of the covariant gauge in gauge field theory, we also give both the Nambu and Wigner solutions beyond the Landau gauge to observe the behavior of both the fermion and boson propagators with different gauge parameters.

Due to the simplicity of quantum electrodynamics in $(2+1)$ dimensions (QED₃), one frequently adopts it to gain valuable insight into the general characteristics of a non-perturbative system. This model is chirally symmetric in the absence of a bare fermion mass term, $m_0\bar{\psi}\psi$. The Lagrangian in a general covariant gauge in Euclidean space, ignoring the issues discussed in Ref. [4], can be written as

$$L = \bar{\psi}(\partial + ieA)\psi + \frac{1}{4}F_{\rho\nu}^2 + \frac{1}{2\xi}(\partial_\rho A_\rho)^2 \quad (1)$$

where ξ is the covariant gauge parameter. We use four-component spinors for the fermions, and accordingly, a four-dimensional representation for the γ matrices. QED₃ has many features similar to QCD in $3+1$ dimensions. QED₃ is known to have a phase where the initial chiral symmetry of the theory is spontaneously broken, and it is also known that the fermions are confined to this phase. Moreover, QED₃ is super-renormalizable, and we can, therefore, avoid the ultraviolet divergences that are present in QED₄. These are the basic reasons why QED₃ is regarded as an ideal toy model for non-perturbative theory. QED₃ is a possible candidate for the study of DCSB^[1-13] and confinement^[14-16] within a theory that is structurally much simpler than QCD, while sharing the same basic non-perturbative phenomena. Since the Dyson-Schwinger (DS) equations provide a powerful tool for resolving the propagators in non-perturbative theory, these coupled equations in QED₃ can be used to investigate our problem.

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1 Truncated Dyson-Schwinger Equations for Propagators

From the Lagrangian (1) and DS equations for the fermion propagator, we derive

$$S^{-1}(\mathbf{p}) = S_0^{-1}(\mathbf{p}) + \int \frac{d^3\mathbf{k}}{(2\pi)^3} \gamma_\rho S(k) \Gamma_\nu(\mathbf{p}, \mathbf{k}) D_{\rho\nu}(\mathbf{p} - \mathbf{k}) \quad (2)$$

where $S_0^{-1}(\mathbf{p})$ is the bare inverse propagator for a massless fermion; $\Gamma_\nu(\mathbf{p}, \mathbf{k})$ is the full fermion-photon vertex; and we set $e^2 = 1$. Since the parity of this equation is not broken dynamically, we can decompose it into^[13]

$$S^{-1}(\mathbf{p}) = i\boldsymbol{\gamma} \cdot \mathbf{p} A(p^2) + B(p^2) \quad (3)$$

and obtain a function for wave-renormalization $A(p^2)$,

$$A(p^2) = 1 - \frac{1}{4p^2} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \text{Tr}[i(\boldsymbol{\gamma} \cdot \mathbf{p}) \gamma_\rho S(k) \Gamma_\nu(\mathbf{p}, \mathbf{k}) D_{\rho\nu}(\mathbf{p} - \mathbf{k})] \quad (4)$$

and the fermion self-energy $B(p^2)$,

$$B(p^2) = \frac{1}{4} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \text{Tr}[\gamma_\rho S(\mathbf{k}) \Gamma_\nu(\mathbf{p}, \mathbf{k}) D_{\rho\nu}(\mathbf{p} - \mathbf{k})] \quad (5)$$

In addition, the DS equation satisfied by the polarization tensor for a photon is given by

$$\Pi_{\rho\nu}(q^2) = -N \int \frac{d^3\mathbf{k}}{(2\pi)^3} \text{Tr}[S(\mathbf{k}) \gamma_\rho S(\mathbf{q} + \mathbf{k}) \Gamma_\nu(\mathbf{q} + \mathbf{k}, \mathbf{k})] \quad (6)$$

The corresponding full photon propagator in a covariant gauge is

$$D_{\rho\nu}(\mathbf{q}) = \frac{\delta_{\rho\nu} - \mathbf{q}_\rho \mathbf{q}_\nu / q^2}{q^2 [1 + \Pi(q^2)]} + \xi \frac{\mathbf{q}_\rho \mathbf{q}_\nu}{q^4} \quad (7)$$

with the vacuum polarization $\Pi(q^2)$ defined by

$$\Pi_{\rho\nu}(q^2) = (q^2 \delta_{\rho\nu} - \mathbf{q}_\rho \mathbf{q}_\nu) \Pi(q^2) \quad (8)$$

This vacuum polarization tensor has an ultraviolet divergence which is present only in the longitudinal component and can be removed by applying the projection operator

$$\mathbf{P}_{\rho\nu} = \delta_{\rho\nu} - 3 \frac{\mathbf{q}_\rho \mathbf{q}_\nu}{q^2} \quad (9)$$

to project a finite value of vacuum polarization for it,

$$A(p^2) = 1 + \frac{1}{2p^2} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{A(k^2) [A(p^2) + A(k^2)] [2(1 - \xi'(q^2)) (\mathbf{p}\mathbf{q})(\mathbf{k}\mathbf{q})/q^2 + \xi'(q^2) \mathbf{p}\mathbf{k}]}{q^2 [A^2(k^2)k^2 + B^2(k^2)] [1 + \Pi(q^2)]} \quad (13)$$

$$B(p^2) = \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{B(k^2) [A(p^2) + A(k^2)] (2 + \xi'(q^2))}{2q^2 [A^2(k^2)k^2 + B^2(k^2)] [1 + \Pi(q^2)]} \quad (14)$$

$\Pi(q^2)$ ^[17].

In principle, we can obtain the fermion and boson propagators from these coupled equations. Nevertheless, it is too complex to solve the DS equations because the necessary full fermion-photon vertex $\Gamma_\nu(\mathbf{p}, \mathbf{k})$ is unknown. Although several studies have attempted to resolve this problem, none are completely satisfactory^[4,7-10,18-22].

1.1 The rainbow approximation

The simplest scheme for truncating the DS equation is the rainbow approximation. This structure plays the most dominant role in the full vertex in the high energy region and the full fermion-boson vertex reduces to it in a large momentum limit. Due to the complexity of QCD, many works on hadron physics have adopted this ansatz to analyze low energy behavior. We make use of it, although the tensor destroys the Ward-Takahashi identity (WTI). The pivotal functions for the propagators can then be written as

$$A(p^2) = 1 + \frac{1}{p^2} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{A(k^2) [2(1 - \xi'(q^2)) (\mathbf{p}\mathbf{q})(\mathbf{k}\mathbf{q})/q^2 + \xi'(q^2) \mathbf{p}\mathbf{k}]}{q^2 [A^2(k^2)k^2 + B^2(k^2)] [1 + \Pi(q^2)]} \quad (10)$$

$$B(p^2) = \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{B(k^2) (2 + \xi'(q^2))}{q^2 [A^2(k^2)k^2 + B^2(k^2)] [1 + \Pi(q^2)]} \quad (11)$$

$$\Pi(q^2) = \frac{2N}{q^2} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{A(k^2) A(p^2) [2k^2 - 4(\mathbf{k} \cdot \mathbf{q}) - 6(\mathbf{k} \cdot \mathbf{q})^2/q^2]}{[A^2(k^2)k^2 + B^2(k^2)] [A^2(p^2)p^2 + B^2(p^2)]} \quad (12)$$

where $\mathbf{p} = \mathbf{q} + \mathbf{k}$ and $\xi'(q^2) = \xi[1 + \Pi(q^2)]$.

1.2 Beyond the bare vertex

In this section, by adopting a reasonable approximation for the full vertex function, we obtain the truncated DS equations. For simplicity, we take $\Gamma_\nu^{BC_1}(\mathbf{p}, \mathbf{k}) = \frac{1}{2} [A(p^2) + A(k^2)] \boldsymbol{\gamma}_\nu$, which is selected from the BC-vertex because some previous works have shown that the numerical results of the DS equations employing this ansatz for Γ almost agree with those of the DS equations employing the BC and CP vertex^[18,23-24]. We expect that this form plays a dominant role in the full vertex.

Therefore, we write the truncated DS equations for propagators in a covariant gauge as follows:

$$\Pi(q^2) = \int \frac{d^3k}{(2\pi)^3} \frac{A(k^2)A(p^2)[A(p^2) + A(k^2)][2k^2 - 4(\mathbf{k} \cdot \mathbf{q}) - 6(\mathbf{k} \cdot \mathbf{q})^2/q^2]}{q^2[A^2(k^2)k^2 + B^2(k^2)][A^2(p^2)p^2 + B^2(p^2)]} \quad (15)$$

2 Numerical Results

First, we work within the Landau gauge. From the above DS equations for the fermion propagator, we find that the self-energy function has one trivial solution, i. e., the Wigner solution ($B(p^2) \equiv 0$). In the corresponding phase, the fermion remains massless and chiral symmetry is restored. Setting the original value of $B(p^2) = 0$ and $A(p^2) = 1$, $\Pi(q^2) = 1$ in the rainbow approximation, we iterate the coupled functions to find stable results, and show these in Fig. 1.

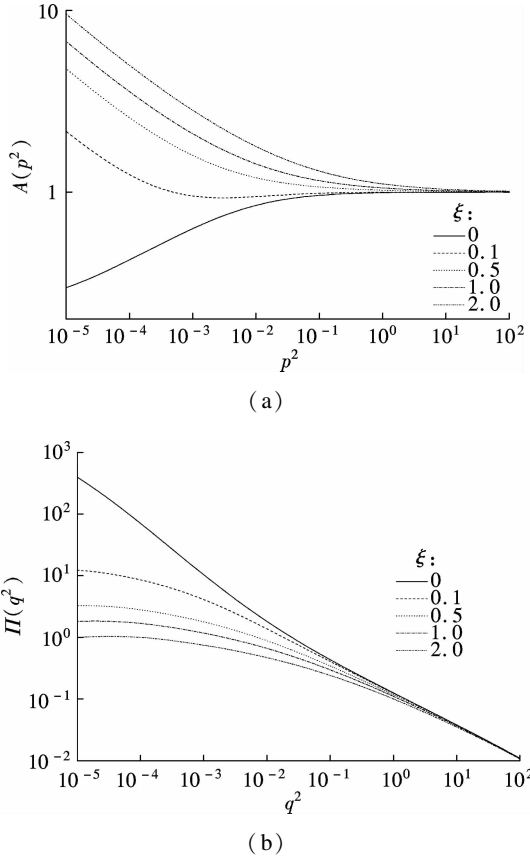


Fig. 1 The gauge dependence in the Wigner phase for the rainbow approximation. (a) $A(p^2)$; (b) $\Pi(q^2)$

The line in Fig. 1 shows that the vector function of the inverse fermion propagator diminishes as $p^2 \rightarrow 0$, while the polarization of the boson reaches infinity as $q^2 \rightarrow 0$. Nevertheless, setting $A(p^2) = 1$ and $\Pi(q^2) = 1$ reduces the single-iteration results at large momenta. This is because QED₃ is asymptotically free and $S(p) \rightarrow S_0(p)$ in the high energy region.

In addition to the Landau gauge, we also give the behavior of the propagators at several values of ξ in Fig. 1. It is shown that the behaviors of both the fermion and boson propagators here are different from those in the Landau gauge, where $A(p^2)$ is divergent in the infrared limit. As ξ is increased, $A(p^2)$ increases more and more

rapidly when p^2 decreases. Correspondingly, $\Pi(q^2)$ gives the opposite trend for ξ and, for a particular value of ξ , is not divergent and remains almost constant in the infrared region.

Moving beyond the rainbow approximation and following the above method, we obtain $A(p^2)$, $\Pi(q^2)$ and show them in Fig. 2. It is shown that, compared with the bare approximation, the truncated scheme changes the value of solutions at a fixed p^2 in the infrared region, but apparently does not change the gauge dependence of the fermion or boson propagator behavior.

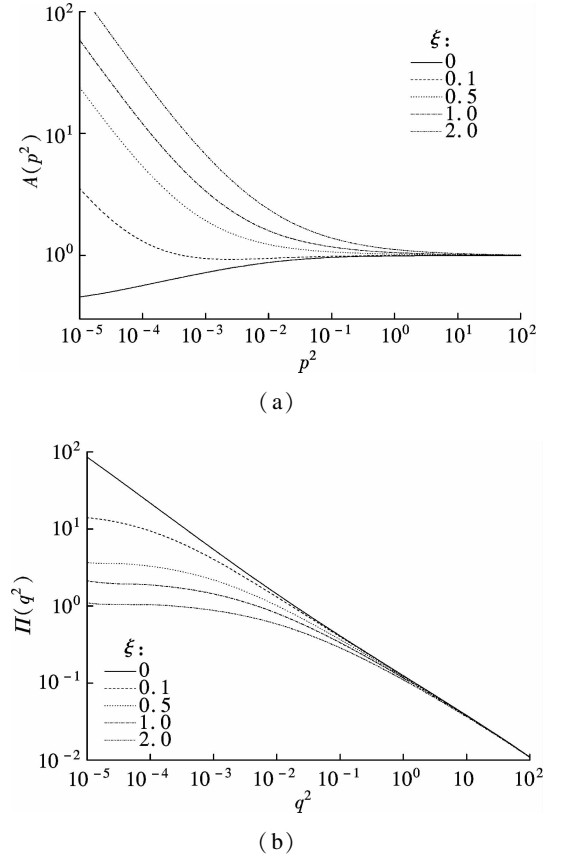


Fig. 2 The gauge dependence in the Wigner phase for BC₁. (a) $A(p^2)$; (b) $\Pi(q^2)$

We next consider the Nambu phase. Eqs. (11) and (14) have nontrivial solutions when $B(p^2) \neq 0$. The original fermion acquires dynamical mass through the non-perturbative effect. We solve the coupled equations numerically for Eqs. (10) to (15) at several values of ξ .

Starting with $A(p^2) \equiv 1$, $B(p^2) \equiv 1$, and $\Pi(q^2) \equiv 1$, we iterate the three coupled equations until all three functions converge to a stable solution. The typical behavior of the three functions A , B , and Π in the Nambu phase are plotted in Fig. 3 in the rainbow approximation and Fig. 4 by application of the BC₁ vertex. For a value of ξ , it is apparent that all three functions are almost constant in the low energy region.

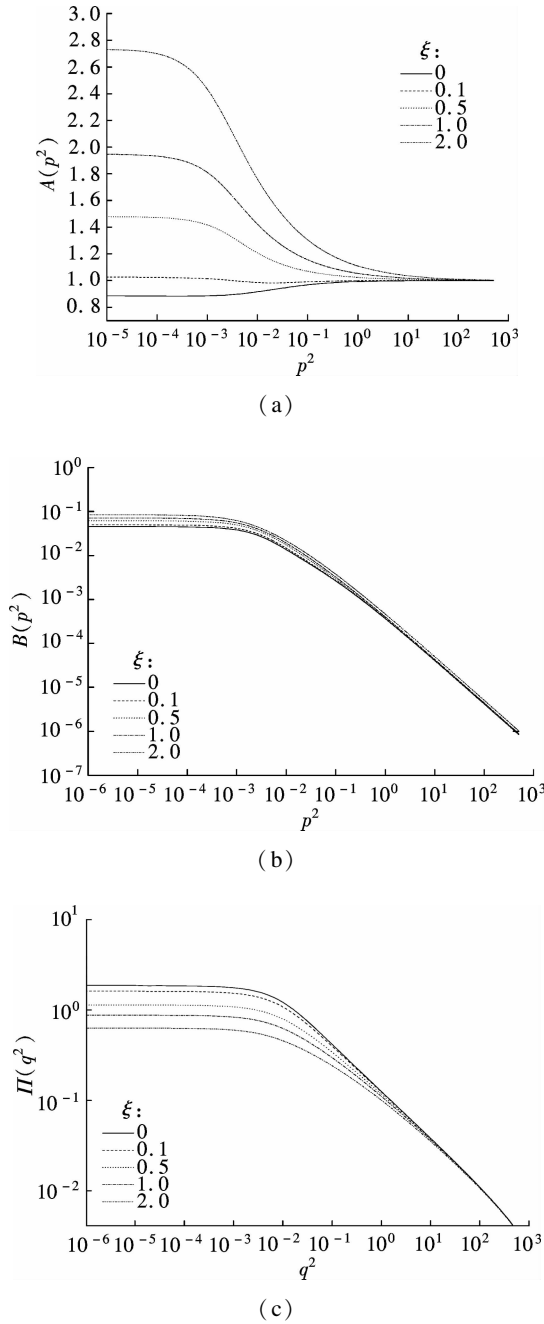


Fig. 3 The typical behavior of A , B , and Π in the Nambu phase at several values of ξ in the rainbow approximation. (a) $A(p^2)$; (b) $B(p^2)$; (c) $\Pi(q^2)$

Within a range of values of ξ , the infrared value of $A(p^2)$ increases with the increase in ξ . Correspondingly, the numerical results show a reversed trend for the infrared value of fermion self-energy and boson polarization with ξ in each truncated scheme for the DS equation. Nevertheless, the behavior of $A(p^2)$ or $\Pi(q^2)$ is independent of ξ in the high energy region. However, compared with the rainbow approximation, $B(p^2)$, which is given beyond the rainbow approximation, appears to depend on ξ . Certainly, for any value of ξ , a different truncated scheme has similar behavior but dissimilar numerical values for the three functions in the infrared region.

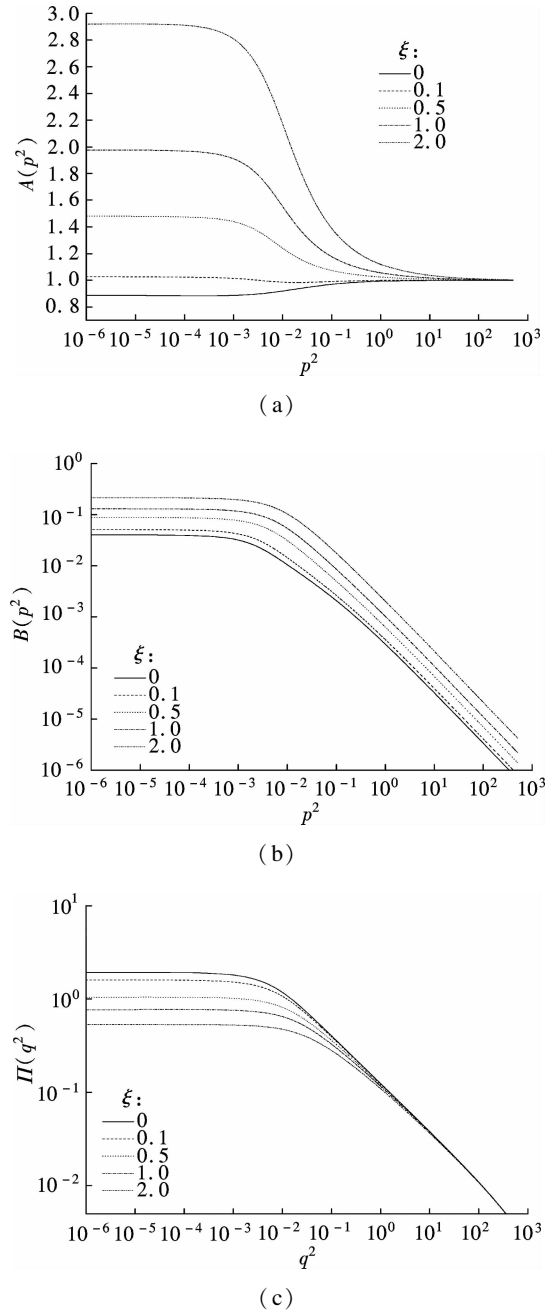


Fig. 4 Gauge dependence of propagators in the Nambu phase for BC_1 . (a) Function $A(p^2)$; (b) Function $B(p^2)$; (c) Function $\Pi(q^2)$

Comparing the two phases, we also find that $A(0) < 1$ in the Nambu phase corresponds to its infrared zero value in the Wigner phase, while $A(0)$ diverges in the Wigner phase when $\Pi(0)$ reaches a finite value in this covariant gauge theory.

3 Physical Phase

The fermion condensate is defined trivially as

$$\langle \bar{\psi}\psi \rangle_\xi = \text{Tr}[S(x \equiv 0)] = \int \frac{d^3p}{(2\pi)^3} \frac{4B(p^2)}{A^2(p^2)p^2 + B^2(p^2)} \quad (16)$$

In principle, this physical value is independent of the gauge parameter^[25-27]. Adopting the above Nambu phase results for the rainbow approximation, we obtain the fermion condensate values and plot them in Fig. 5. We find that the value appears to depend on the gauge parameter consequently.

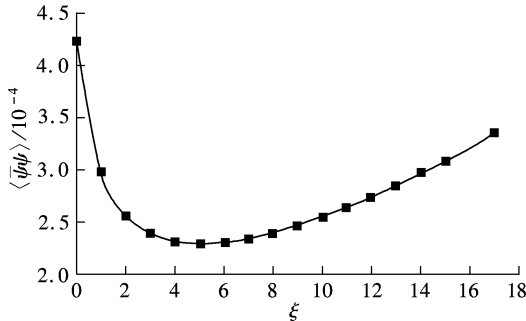


Fig. 5 Gauge dependence of the condensate in the rainbow approximation

It is easily proved that the rainbow approximation destroys the Ward-Takahashi identity. However, although the value in this figure depends on ξ , we see that this condensate is always larger than zero and we learn that the chiral symmetry is broken.

On the other hand, the Wigner solution gives zero fermion condensate and the chiral symmetry is restored. For any ξ , the Nambu and Wigner solutions are obtained from the same DS equations. The solution that is realized in the real world should be determined. We should compare the effective pressure P between the two phases, and the physical one will correspond to the larger P value. The effective pressure is given by^[28]

$$P(\xi) = -\int \frac{d^3p}{(2\pi)^3} \text{Tr} \left\{ \ln[1 - B(p^2)S(p)] + \frac{1}{2} [B(p^2)S(p)] \right\} + \Gamma_2 = -\int \frac{d^3p}{(2\pi)^3} \left\{ \ln \left[\frac{p^2}{A^2(p^2)p^2 + B^2(p^2)} \right] + \frac{B(p^2)}{A^2(p^2)p^2 + B^2(p^2)} \right\} + \Gamma_2 \quad (17)$$

Since the Γ_2 is known only in the rainbow approximation and $\Gamma_2 = 0$, we adopt the first term in the last equation to study the phase transition. To indicate the real phase, we define the order parameter $\Delta = P_N - P_W$.

It is found that with the increase in ξ , Δ decreases and becomes less than 0 when ξ reaches the value $\xi_p = 9.8$ (see Fig. 6).

4 Conclusion

Based on the truncated DS equations applied to the fermion propagator, we have found solutions for both the fermion and boson propagators for several covariant gauges in the Nambu and Wigner phases. Numerical results show that the gauge parameter appears to affect the behavior of the fermion and boson propagators in the low energy region. Apart from the fermion self-energy, the

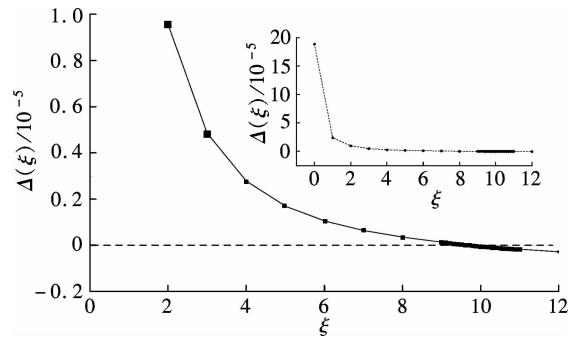


Fig. 6 Order parameter at different ξ values

other two functions are minimally affected in the high energy regions for both phases.

In addition to the Landau gauge, the DS equations also provide the monotonic functions for $A(p^2)$ and $\Pi(q^2)$ at several values of ξ . To the best of current knowledge, beyond the Landau gauge, the solutions for the fermion and boson propagators in the Wigner phase are presented in this paper for the first time. With the increase in ξ , the infrared value of A changes from being zero to a divergent function, while the infrared value of Π reduces to a constant that decreases with ξ but does not completely diminish. We argue that there may be a value of ξ for which the infrared value of A lies between zero and infinity. However, this value of ξ has not been found in the familiar gauge selected.

In addition, the effective potential gives a different result around the chiral phase transition from the condensate, which implies that the two order parameters for the chiral phase transition might be self-inconsistent.

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三维 QED 中的动力学手征对称破缺

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摘要:为了研究非微扰理论中的传播子行为,以及协变规范对其行为的影响,以常用的截断方案下的 Dyson-Schwinger 方程为基础,采用数值联立求解的方法研究了三维量子电动力学(QED)中的费米子和玻色子的行为,并获得了一系列不同规范下费米传播子在 Nambu 和 Wigner 相中的自洽解.对这些数值解的分析表明,远离 Landau 规范的红外区处,传播子行为明显不同于 Landau 规范中的行为.基于 Nambu 和 Wigner 相中的不同规范下的传播子,进一步对等效压力差和费米凝聚随规范参数的变化做了比较,结果表明,采用 CJT 等效势描述的相变与手征凝聚描述的手征相变两者之间不完全自洽.

关键词:传播子;协变规范;三维 QED;等效压力差;费米凝聚;手征相变

中图分类号:O572.24;O413.2