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Particle-Hole and Delta-Hole Excitation in Nuclear Mater

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A new relativistic method for calculation of particle-hole and Delta-hole excitations of the pion in nuclear matter is proposed. The difference between the usual method and ours is pointed out. The dispersion relation of the pion meson including virtual particle-hole excitations is analyzed. The results are compared numerically with that for the non-relativistic counterpart. The formulas of relativistic Delta-hole excitation induced by pion in nuclear matter are also discussed.

Key words: nuclear matter, π-propagator, particle-hole excitation, Δ-hole excitation, relativistic Lindhard function, π-dispersion relation.

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1. INTRODUCTION

Pion dynamics in nuclear matter, especially its energy-momentum dispersion relation, has been one of the key issues in nuclear physics [1]. In non-relativistic cases, a phenomenological optical potential of pion-nucleus interaction is obtained by studying pion-atom and pion-nucleus scattering. The optical potential is related to the pion self-energy which can be used to analyze the pion dispersion relation and predict a possible existence of pion condensate in nuclear medium. On the other hand, the pion self-energy corresponding to particle-hole and Delta-hole excitation can be also calculated microscopically in a non-relativistic way. Using the theoretical results of the pion self-energy, one can then discover something new and interesting, such as pion condensates, from the dispersion relation

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of pion in nuclear medium [2].

However, as energy increases or particularly in the case of relativistic heavy ion collisions, the relativistic effect in pion dispersion relation becomes so important [3] that the non-relativistic treatment of the problem is inadequate. A relativistic treatment is in abundant demand.

The relativistic many-body theory provides an ideal frame for treating the relativistic effect. In the many-body theory, the propagator of the nucleon can be expressed either by a sum of a Feynman propagator G_F plus density dependence propagator G_D [4] or by a sum of propagators for particle (S_p), hole (S_h) and antiparticle $S^{\bar{p}}$ [5]. The former definition is commonly used in the calculation of pion self-energy. However, for pseudovector πNN coupling and the derivative πNΔ coupling the particle-antiparticle excitation term, which is divergent due to its non-renormalization property [6], is commonly neglected. As pointed out later, this treatment cannot produce a correct expression for particle-hole excitation and also induce a p$\bar{p}$ excitation term which violates the Pauli principle. The correct expressions of the propagators for the particle-hole and particle-antiparticle excitations can be obtained only by use of the decomposition of propagator G into three terms of S_p, S_h and $S_{\bar{p}}$.

This paper is organized as follows. In Section 2, the pion self-energy in nuclear medium will be given by the two ways mentioned above. The numerical results on the pion dispersion relation obtained by use of the πNN pseudovector coupling are compared with that given by the classical approximation. The comparison shows a significant difference between the two treatments. In Section 3, the expression for Δ-h excitations is also derived. Finally, concluding remarks are reserved for Section 4.

2. RELATIVISTIC DESCRIPTION OF PARTICLE-HOLE AND PARTICLE-ANTIPARTICLE EXCITATIONS

The nucleon propagator $G(p)$ in nuclear matter at zero temperature can be expressed in the form

$$G(p) = G_F(p) + G_D(p), \tag{1}$$

$$G_F(p) = \frac{1}{\gamma \cdot p - \tilde{m}_n + i\varepsilon}, \tag{2}$$

$$G_D(p) = \frac{i\pi}{E_p}(\gamma \cdot p + \tilde{m}_n)\delta(p_0 - F_p)n_p, \tag{3}$$

with G_F being the usual Feynman propagator, G_D the nuclear density dependent part of the propagator $G(p)$ in medium, $\tilde{m}_n$ effective mass of nucleon determined by equation of state (EOS) of nuclear matter, $E_p = \sqrt{p^2 + \tilde{m}_n^2}$, the n_p distribution function of nucleon and p_F is the Fermi momentum. For πNN pseudoscalar coupling, the pion self-energy, Π^{PS} can be written as a sum of the Π_F^{PS} and Π_D^{PS}.

$$\Pi_F^{PS}(q) = -\frac{g_{\pi NN}^2}{(2\pi)^3}\int\frac{dp}{E_pE_{p+q}}\left[4E_{p+q} + q^2\left(\frac{1}{E_p + E_{p+q} - q_0 - i\varepsilon} + \frac{1}{E_p + E_{p+q} + q_0 - i\varepsilon}\right)\right], \tag{4}$$

$$\Pi_D^{PS}(q) = \frac{g_{\pi NN}^2}{(2\pi)^3}\int\frac{dp}{E_pE_{p+q}}\left\{(1 - n_p)n_{p+q}q^2\left(\frac{1}{E_p - E_{p+q} - q_0 - i\varepsilon}\right.\right.$$

$$+\frac{1}{E_p - E_{p+q} + q_0 - i\varepsilon}\Big) + n_p\Big[4E_{p+q}$$

$$+ q^2\left(\frac{1}{E_p + E_{p+q} - q_0 - i\varepsilon} + \frac{1}{E_p + E_{p+q} + q_0 - i\varepsilon}\right)\Big]\Big\}, \tag{5}$$

The Π_F^{PS} comes from the contributions of two Feynman propagators which do not vanish when p_F goes to zero but $\Pi_D^{PS}|_{pf\to 0} \to 0$. Therefore, Π_D^{PS} is of explicit density dependence. Since Π_F^{PS} is divergent it is usually neglected. The first term of the Π_D^{PS} contains the factor $(1 - n_p)n_{p+q}$ so that it has the same form as that for particle-hole excitations. Once summing over the second term of Π_D^{PS} and Π_F^{PS}, the factor $(1 - n_p)$ appears. Thus, the resulting term contained the factor naturally denote particle-antiparticle excitation. Obviously, if neglecting the Π_F^{PS} but remaining the second term of Π_D^{PS} the Pauli principle would completely be destroyed.

On the other hand, the nucleon propagator $G(p)$ can be also expressed as a sum of a particle-S_p, hole-S_h and antiparticle-propagator $S_{\bar{p}}$.

$$G(p) = S_p(p) + S_h(p) + S_{\bar{p}}(p), \tag{6}$$

$$S_p(p) = \frac{\tilde{m}_n}{E_p}\frac{(1 - n_p)\Lambda_+(p)}{p_0 - E_p + i\varepsilon}, \tag{7}$$

$$S_h(p) = \frac{\tilde{m}_n}{E_p}\frac{n_p\Lambda_+(p)}{p_0 - E_p - i\varepsilon}, \tag{8}$$

$$S_{\bar{p}}(p) = -\frac{\tilde{m}_n}{E_p}\frac{\Lambda_-(-p)}{p_0 + E_p - i\varepsilon}, \tag{9}$$

where the $\Lambda_\pm$ are the projection operators of particle $(+)$ or antiparticle $(-)$.

$$\Lambda_+(p) = \frac{\gamma_0 E_p - \boldsymbol{\gamma}\cdot\boldsymbol{p} + \tilde{m}_n}{2\tilde{m}_n}, \tag{10}$$

$$\Lambda_-(p) = \frac{-\gamma_0 E_p + \boldsymbol{\gamma}\cdot\boldsymbol{p} + \tilde{m}_n}{2\tilde{m}_n}. \tag{11}$$

with these definitions the pion self-energy in nuclear medium can be easily calculated. The non-vanished parts of the self-energy come from ph excitation, Π_{ph}, and $p\bar{p}$ excitation, $\Pi_{p\bar{p}}$. For the pseudoscalar πNN coupling one gets

$$\Pi^{PS}(q) = \Pi^{PS}_{ph}(q) + \Pi^{PS}_{p\bar{p}}(q), \tag{12}$$

$$\Pi^{PS}_{ph}(q) = \frac{g^2_{\pi NN}}{(2\pi)^3}\int\frac{d\boldsymbol{p}}{E_pE_{p+q}}(1 - n_p)n_{p+q}\Big[2(E_p - E_{p+q})$$

$$+ q^2\left(\frac{1}{E_p - E_{p+q} - q_0 - i\varepsilon} + \frac{1}{E_p - E_{p+q} + q_0 - i\varepsilon}\right)\Big], \tag{13}$$

$$\Pi^{PS}_{p\bar{p}}(q) = -\frac{g^2_{\pi NN}}{(2\pi)^3}\int\frac{d\boldsymbol{p}}{E_pE_{p+q}}(1 - n_p)\Big[-2(E_p + E_{p+q})$$

$$+ q^2\left(\frac{1}{E_p + E_{p+q} - q_0 - i\varepsilon} + \frac{1}{E_p + E_{p+q} + q_0 - i\varepsilon}\right)\Bigg], \tag{14}$$

where $\Pi^{PS}_{p\bar{p}}$ is divergent. Comparing Eqs. (13) and (14) with Eqs. (4) and (5) shows a remarkable difference which means that using the decomposition of G_F and G_D leads to a incorrect description of ph and p$\bar{p}$ excitation processes. Although the sum of Eqs. (13) and (14) is equivalent to the sum of Eqs. (4) and (5), a correct investigation of ph and p$\bar{p}$ excitations must start from Eqs. (6)-(14). Otherwise, one would be misled to some inadequate conclusions.

For pseudovector πNN coupling, the pion self-energy Π^{PV} can be calculated in a similar way to that for ph and p$\bar{p}$ excitations. The resulting expressions read

$$\Pi^{PV}(q) = \Pi^{PV}_{ph}(q) + \Pi^{PV}_{p\bar{p}}(q), \tag{15}$$

$$\Pi^{PV}_{ph}(q) = \frac{2f^2_{\pi NN}}{m^2_\pi}\int\frac{dp}{E_pE_{p+q}}(1-n_p)n_{p+q}\Big\{(E_{p+q}-E_p)[(E_p+E_{p+q})^2$$
$$-q^2] + 2\tilde{m}^2_n q^2\left(\frac{1}{E_p - E_{p+q} - q_0 - i\varepsilon} + \frac{1}{E_p - E_{p+q} + q_0 - i\varepsilon}\right)\Big\}, \tag{16}$$

$$\Pi^{PV}_{p\bar{p}}(q) = \frac{2f^2_{\pi NN}}{m^2_\pi}\int\frac{dp}{E_pE_{p+q}}(1-n_p)\Big\{(E_p+E_{p+q})[(E_p-E_{p+q})^2$$
$$-q^2] - 2\tilde{m}^2_n q^2\left(\frac{1}{E_p + E_{p+q} - q_0 - i\varepsilon} + \frac{1}{E_p + E_{p+q} + q_0 - i\varepsilon}\right)\Big\}, \tag{17}$$

Here the $\Pi^{PV}_{p\bar{p}}$ is also divergent. Strictly speaking, the pseudovector πNN coupling interaction is of non-renormalization. Thus, one needs an adequate method to resolve this difficulty of the divergence. However, due to the spatial limitations of this short paper, we avoid discussing contributions from the p$\bar{p}$ excitations. Under the non-relativistic limit, Eq. (16) reproduces the result of the non-relativistic treatment [7],

$$\Pi^{PV}_{ph}(q) \to \frac{f^2_{\pi NN}}{m^2_\pi} q^2 U_N(q_0, |q|), \tag{18}$$

with $U_N(q_0, |q|)$ being the non-relativistic Lindhard function [7]. The real part of U_N reads

$$\mathrm{Re}U_N(q_0,|q|) = \frac{\tilde{m}_n p_F}{\pi^2}\Bigg\{-1 + \frac{1}{2q_F}\left[1-\left(\frac{\nu}{q_F}-\frac{q_F}{2}\right)^2\right]$$
$$\cdot \ln\left|\frac{\frac{\nu}{q_F}-\frac{q_F}{2}+1}{\frac{\nu}{q_F}-\frac{q_F}{2}-1}\right| - \frac{1}{2q_F}\left[1-\left(\frac{\nu}{q_F}+\frac{q_F}{2}\right)^2\right]$$
$$\cdot \ln\left|\frac{\frac{\nu}{q_F}+\frac{q_F}{2}+1}{\frac{\nu}{q_F}+\frac{q_F}{2}-1}\right|\Bigg\}, \tag{19}$$

where

$$\nu = \frac{q_0 \tilde{m}_n}{p_F^2}, \; q_F = \frac{|\boldsymbol{q}|}{p_F}.$$

The energy-momentum dispersion relation of pion is determined by regularities of pion propagator i.e.,

$$\omega^2 - \boldsymbol{q}^2 - m_\pi^2 - \mathrm{Re}\Pi_{\mathrm{ph}}^{\mathrm{PV}}(\omega, |\boldsymbol{q}|) = 0, \tag{20}$$

The numerical results are shown in Fig. 1. Here we take $\tilde{m}$ to be nucleon mass m_n. $m_\pi = 140$ MeV, $f_{\pi NN} = 0.97$ and nuclear density $\rho = 0.2\ \mathrm{fm}^{-3}$. As can be seen from the figure, in the space-like region the difference between the relativistic and the non-relativistic treatment is negligible. They are all in the shadow region. This means that the mode of acoustic excitation is fully damped. No stable wave exists under this approximation. In the time-like region, as the energy increases the area between the dotted line and dashed line is enlarged. Once $|q| = 2.9\, p_F$ the dashed line enters the space-like region.

Many other important factors need to be considered in the present calculations of the pion dispersion relation. For example, the short range correlation in the NN, NΔ interaction and πNΔ coupling must be included.

3. DELTA-HOLE EXCITATION

Based on the definition of Δ particle propagator, the Feynman propagator S_Δ^μ can be written as a sum of Δ-particle propagator $S_\Delta^{\mu\nu}$ and anti-Δ particle ($\bar{\Delta}$) propagator $S_{\bar{\Delta}}{}^{\mu\nu}$,

$$S_F^{\mu\nu}(p) = S_\Delta^{\mu\nu}(p) + S_{\bar{\Delta}}^{\mu\nu}(p), \tag{21}$$

$$S_\Delta^{\mu\nu}(p) = \frac{m_\Delta}{E_p^\Delta} \frac{\Lambda_+^{\mu\nu}(p)}{p_0 - E_p^\Delta + i\varepsilon}, \tag{22}$$

$$S_{\bar{\Delta}}^{\mu\nu}(p) = -\frac{m_\Delta}{E_p^\Delta} \frac{\Lambda_-^{\mu\nu}(-p)}{p_0 + E_p^\Delta - i\varepsilon}, \tag{23}$$

with $\Lambda_\pm^{\mu\nu}$ being the projection operation of $\Delta(+)$ and $\bar{\Delta}(-)$ particles.

$$\Lambda_+^{\mu\nu}(p) = \frac{\gamma_0 E_p^\Delta - \boldsymbol{\gamma}\cdot\boldsymbol{p} + m_\Delta}{2m_\Delta}\Big[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{2}{3m_\Delta^2} p^\mu p^\nu + \frac{1}{3m_\Delta}(p^\mu\gamma^\nu - p^\nu\gamma^\mu)\Big], \tag{24}$$

$$\Lambda_-^{\mu\nu}(p) = \frac{-\gamma_0 E_p^\Delta + \boldsymbol{\gamma}\cdot\boldsymbol{p} + m_\Delta}{2m_\Delta}\Big[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{2}{3m_\Delta^2} p^\mu p^\nu - \frac{1}{3m_\Delta}(p^\mu\gamma^\nu - p^\nu\gamma^\mu)\Big], \tag{25}$$

where $p^\mu = (E_p^\Delta, \boldsymbol{p})$, $E_p^\Delta = \sqrt{\boldsymbol{p}^2 + m_\Delta^2}$. Substituting Eqs. (22)-(25) into Eq. (21), the resulting $S_F^{\mu\mu}$ can be written in the form

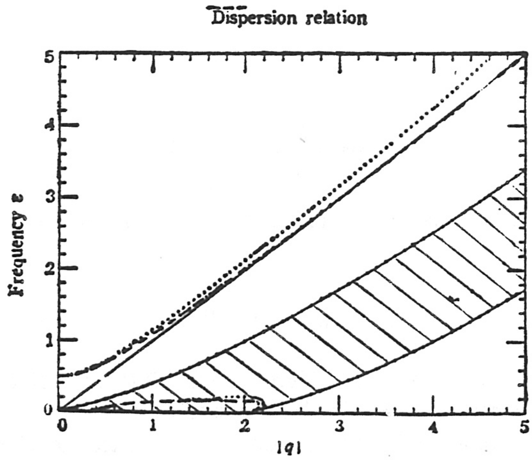

Fig. 1
Pion dispersion relation in nuclear matter. The dotted line stands for the results from the non-relativistic calculation, the dashed line denotes relativistic results. Time and space is separated by the solid line. The shadow region denotes the area where the $\Pi_{\rm ph}^{\rm PV}$ has a non-vanishing imaginary part. The energy ω is presented by the vertical axis and the horizontal axis is momentum $|q|$. Both energy and momentum are measured in Fermi momentum $p_{\rm F}$.

$$S_{\rm F}^{\mu\nu}(p) = S^{\mu\nu}(p) + \cdots, \tag{26}$$

$$S^{\mu\nu}(p) = \frac{1}{\gamma\cdot p - m_\Delta + i\varepsilon}\left[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{2}{3m_\Delta^2}p^\mu p^\nu + \frac{1}{3m_\Delta}(p^\mu\gamma^\nu - p^\nu\gamma^\mu)\right], \tag{27}$$

The remaining parts, "..." in Eq. (26) are convariant, but they do not possess a propagator's form [6-9]. Like the case for vector meson with mass, these parts are usually omitted and only $S^{\mu\nu}$ is retained there. However, if one directly uses the decomposition of $S_{\rm F}^{\mu\nu}$ into $S_\Delta^{\mu\nu}$ and $S_{\bar\Delta}^{\mu\nu}$, not the $S^{\mu\nu}$, to calculate pion self-energy, the uncertainty in the calculations of Eq. (26) is definitely avoided.

The πNΔ coupling interaction $\mathscr{L}_{\pi N\Delta}$ is generally given [6,9] by

$$\mathscr{L}_{\pi N\Delta} = \frac{1}{\sqrt{2}}\frac{f_{\pi N\Delta}}{m_\pi}\bar\psi_\Delta^\mu(g_{\mu\nu} + \xi\gamma_\mu\gamma_\nu)\boldsymbol{T}\cdot\psi\partial^\nu\boldsymbol{\pi} + \text{h.c.}, \tag{28}$$

where the ξ is an arbitrary constant, T isospin matrix [10]. For an energy-shell Δ particle, the term contained ξ has no contribution since the Δ particle satisfied the equation $\bar\psi_\Delta^\mu\gamma_\mu = 0$. Therefore, the ξ term contributes to $\mathscr{L}_{\pi N\Delta}$ only from off-shell Δ-particles.

The pion self-energy $\Pi_{\Delta N}$ via Δ excitation may be evaluated by particle-, hole-, and antiparticle propagators. The $\Pi_{\Delta N}(q)$ consists of three terms excited by Δh, $\bar\Delta$p and $\Delta\bar{\rm p}$ pairs.

$$\Pi_{\Delta N}(q) = \Pi_{\Delta h}(q) + \Pi_{\bar\Delta p}(q) + \Pi_{\Delta\bar p}(q), \tag{29}$$

$$\Pi_{\Delta h}(q) = -\frac{8i}{6}\frac{f_{\pi N\Delta}^2}{m_\pi^2} q^\alpha q^\beta \int \frac{dp}{(2\pi)^4} \mathrm{Tr}[(g_{\alpha\lambda} + \xi\gamma_\alpha\gamma_\lambda) S_\Delta^{\lambda\sigma}(p)(g_{\sigma\beta} + \xi\gamma_\sigma\gamma_\beta) S_h(p+q)] + (q \to -q), \tag{30}$$

$$\Pi_{\bar{\Delta}p(\Delta\bar{p})}(q) = -\frac{8i}{6}\frac{f_{\pi N\Delta}^2}{m_\pi^2} q^\alpha q^\beta \int \frac{dp}{(2\pi)^4} \mathrm{Tr}[(g_{\alpha\lambda} + \xi\gamma_\alpha\gamma_\lambda) S_{\bar{\Delta}(\Delta)}^{\lambda\sigma}(p) \cdot (g_{\sigma\beta} + \xi\gamma_\sigma\gamma_\beta) S_{p(\bar{p})}(p+q)] + (q \to -q), \tag{31}$$

As is seen, the $\Pi_{\Delta h}$ is finite but the $\Pi_{\bar{\Delta}h}$ and $\Pi_{\Delta\bar{p}}$ are divergent. With the same reason as above, we omit the $\bar{\Delta}$p and $\Delta\bar{\text{p}}$ excitations here. After further simplification the $\Pi_{\Delta h}$ can be rewritten as

$$\begin{aligned}\Pi_{\Delta h}(q) = {} & \frac{16 f_{\pi N\Delta}^2}{9 m_\Delta^2 m_\pi^2} \int \frac{dp}{(2\pi)^3} \frac{n_{p+q}}{4E_p^\Delta E_{p+q}} \Big\{ 2(E_p^\Delta - E_{p+q}) \cdot [E_p^\Delta E_{p+q} q_0^2 + q^2 m_\Delta^2 \\ & - (\mathbf{p}\cdot\mathbf{q})^2] - 2E_p^\Delta q_0^2 (m_\Delta^2 - \tilde{m}_n^2 - \bar{q}^2) + [(m_\Delta + m)^2 - q^2] \\ & \cdot \Big[\frac{1}{2}(E_p^\Delta - E_{p+q}) \cdot ((E_p^\Delta + E_{p+q})^2 + q_0^2) - (E_p^\Delta + E_{p+q}) \\ & \cdot (m_\Delta^2 - \tilde{m}_n^2 - q^2) \Big] \Big\} + \frac{f_{\pi N\Delta}^2}{4m_\pi^2} [(m_\Delta + \tilde{m}_n)^2 - q^2] \\ & \cdot \Big[q^2 - \frac{1}{4m_\Delta^2}(m_\Delta^2 - \tilde{m}_n^2 + q^2)^2 \Big] \cdot U_\Delta(q),\end{aligned} \tag{32}$$

where the $U_\Delta(q)$ is referred to the relativistic Lindhard function of Δh excitation [7] and has the form

$$U_\Delta(q) = -\frac{16}{9}\int \frac{dp}{(2\pi)^3} \frac{n_{p+q}}{E_p^\Delta E_{p+q}} \left(\frac{1}{E_p^\Delta - E_{p+q} - q_0 - i\varepsilon} + \frac{1}{E_p^\Delta - E_{p+q} + q_0 - i\varepsilon} \right). \tag{33}$$

Eq. (32) tells us that the $\Pi_{\Delta h}$ here is independent of the constant ξ, in contrast to the result given by $S^{\mu\nu}$ in Eq. (26), which depends on ξ and does not reflect a real Δh excitation since it contains non-Δh excitation part. Eq. (32) produces a good description of pion self-energy from Δh excitations.

In our coming paper, the short range correlation of NN and NΔ interaction will be considered. The pion dispersion relation will be then evaluated in terms of the Ring Approximation of Π_{ph} and $\Pi_{\Delta h}$.

4. SUMMARY AND DISCUSSION

To study pion dispersion relation in nuclear medium, the key issue is to correctly calculate pion self-energy. In Section 2, we pointed out that if pion self-energy is calculated by the decomposition of propagator G into G_F and G_D, one would not get a correct expression of Π_{ph}. Furthermore, if the Π_F is neglected the Π_D contains some terms which violate the Pauli principle. However, on the contrary, the procedure decomposing the total propagator into particle, hole and antiparticle propagators provides a correct, successful method to calculate ph and p$\bar{\text{p}}$ excitation, in which the contribution from individual terms can also be easily studied.

Due to the divergence of $\Pi_{p\bar{p}}$, we have not considered its contribution in the present work. Our numerical calculations show that:

(1) the difference between self-energies produced respectively by the non-relativistic and the relativistic treatments increases as the energy-momentum increases. The acoustic excitation modes in the space-like region appear in the region where the Π_{ph}^{PV} has an non-vanishing imaginary part;

(2) if the PS coupling constant $g_{\pi NN}$ and PV coupling constant $f_{\pi NN}$ are related by equation $f_{\pi NN}/m_\pi = g_{\pi NN}/2m_N$, the PS and PV coupling do not cause any differences but as energy-momentum increases the difference appears remarkably.

The difference $\Pi_{\Delta N}$ calculated by use of the two different decompositions of $S^{\mu\nu}$ or $S_{\Delta}^{\mu\nu}$ plus $S_{\bar{\Delta}}^{\mu\nu}$ has been also pointed out. A correct expression of $\Pi_{\Delta h}$ is initially given here. The Δh excitation and the short range correlation contributing to pion self-energy will be studied in a forthcoming paper.

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