Quadrupole polarizabilities of the pion in the
Nambu–Jona-Lasinio model*

B. Hiller¹, W. Broniowski²,³, A. A. Osipov¹,⁴, A. H. Blin¹

¹Centro de Física Computacional, Departamento de Física da Universidade de Coimbra, 3004-516 Coimbra, Portugal  
²The Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, PL-31342 Cracow, Poland  
³Institute of Physics, Świętokrzyska Academy, PL-25406 Kielce, Poland  
⁴Dzhelepov Laboratory of Nuclear Problems, JINR 141980 Dubna, Russia

Abstract

The electromagnetic dipole and quadrupole polarizabilities of the neutral and charged pions are calculated in the Nambu–Jona-Lasinio model. Our results agree with the recent experimental analysis of these quantities based on Dispersion Sum Rules. Comparison is made with the results from the Chiral Perturbation Theory.

Keywords: pion polarizabilities, chiral quark models, Nambu–Jona-Lasinio model, Chiral Perturbation Theory.

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The obtainment of the pion structure parameters, in particular its electric and magnetic polarizabilities [1], has challenged the experimental and theoretical community since the early sixties [2,3] and today remains a field of intense activity (see e.g. [4]). Indeed, on the experimental side we expect in the future more precise measurements of the pion polarizabilities by the COMPASS collaboration at CERN [5], which probably will help to resolve the discrepancy between the dispersion sum rule (DSR) and the chiral perturbation theory (χPT) for the difference of the dipole polarizabilities $(\alpha_1 - \beta_1)_{\pi^\pm}$ [6,7]. On the theoretical side there is also growing interest in the determination of the

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higher order structure characteristics – the quadrupole polarizabilities of the pion. It has been reported that the DSR values of the quadrupole polarizabilities $(\alpha_2 \pm \beta_2)_\pi^\pm$ and $(\alpha_2 + \beta_2)_\pi^0$ disagree with the present two-loop $\chi$PT calculations \cite{11,12}. We contribute to this study by calculating the pion electromagnetic polarizabilities within the Nambu–Jona-Lasinio model (NJL) \cite{13}. To our knowledge, this is the first dynamical calculation for the quadrupole polarizabilities. The NJL model takes into account the quark-antiquark structure of the pion explicitly, providing an example of dynamical chiral symmetry breaking in a system with nonlinear four-quark interactions. In Ref. \cite{14} the lowest order (dipole) polarizabilities have been computed. The alternative approach within the large-distance expansion of the extended NJL model has been used in \cite{15}, and for $\gamma\gamma \rightarrow \pi^0\pi^0$ mode in \cite{16,17,18}. Here we extend the study of Ref. \cite{14} to the quadrupole case, and find a very reasonable agreement with the experimental data. For instance, with the empirical values $m_{\pi^0} = 136, f_\pi = 93.1$ MeV, and with the quark mass $M = 300$ MeV, we obtain the value $(\alpha_2 + \beta_2)_\pi^0 = -0.144 \cdot 10^{-4} \text{fm}^5$, which agrees within the error bars with the value from DSR, $(\alpha_2 + \beta_2)_\pi^0 = -0.171 \pm 0.067 \cdot 10^{-4} \text{fm}^5$ \cite{8}. This is an example of the general behavior found here: the results of the NJL calculations of the dipole and quadrupole polarizabilities are in a good agreement with the DSR values.

Our calculations at the leading-$N_c$ order are done according to the Feynman diagrams of Fig. 1. The analytic expressions for the $A$ and $B$ amplitudes, defined below, are derived with the method presented in detail in Ref. \cite{14}. It is also necessary to include the $1/N_c$-suppressed one-pion-loop contribution, as discussed below. The amplitudes are functions of the Mandelstam variables related to the $\gamma(p_1, \epsilon_1) + \gamma(p_2, \epsilon_2) \rightarrow \pi^a(p_3) + \pi^b(p_4)$ reaction with the on-shell pions and photons. The amplitude

$$T(p_1, p_2, p_3) = e^2 \epsilon_1^\mu \epsilon_2^\nu T_{\mu\nu}, \quad T_{\mu\nu} = A(s, t, u)\mathcal{L}_1^{\mu\nu} + B(s, t, u)\mathcal{L}_2^{\mu\nu}$$

is given in terms of the independent Lorentz tensors.
\begin{align*}
\mathcal{L}_1^{\mu\nu} &= p_1^\mu p_1^\nu - \frac{1}{2} s g^{\mu\nu}, \\
\mathcal{L}_2^{\mu\nu} &= -\left(\frac{1}{2} u_1 t_1 g^{\mu\nu} + t_1 p_2^\mu p_3^\nu + u_1 p_3^\mu p_1^\nu + s p_3^\mu p_3^\nu\right), \quad (2)
\end{align*}

where we have disregarded the terms that vanish upon the conditions \(\epsilon_1 \cdot p_1 = \epsilon_2 \cdot p_2 = 0\). We have introduced the notation \(\xi_1 = \xi - m_\pi^2\), \(\xi = s, t, u\). With the scalar quantities \(A\) and \(B\) one obtains the amplitudes

\begin{align*}
H_{++} &= -(A + m_\pi^2 B) \\
H_{+-} &= (\frac{m_\pi^2}{s} - m_\pi^2) B
\end{align*}

for the equal-helicity and helicity-flipped photons. The general expression for the polarizabilities are conventionally obtained in the \(t\)-channel. The superscripts \(i = N, C\) denote the neutral and charged pions, respectively. The dipole, \(\alpha_1, \beta_1\), and quadrupole, \(\alpha_2, \beta_2\), polarizabilities are by definition extracted from the first two coefficients of the Taylor expansion of the amplitudes around \(s = 0\) with \(u = t = m_\pi^2\). \([19]\),

\begin{align*}
\frac{\alpha A^i(s, t, u)}{2m_\pi} &= \frac{\alpha}{2m_\pi} \left(A^i(0, m_\pi^2, m_\pi^2) + s \frac{d}{ds} A^i(0, m_\pi^2, m_\pi^2) + \ldots\right) \\
&= \beta_1^i + \frac{s}{12} \beta_2^i + \ldots, \quad (3)
\end{align*}

\begin{align*}
-\alpha m_\pi B^i(s, t, u) &= -\alpha m_\pi \left(B^i(0, m_\pi^2, m_\pi^2) + s \frac{d}{ds} B^i(0, m_\pi^2, m_\pi^2) + \ldots\right) \\
&= (\alpha_1 + \beta_1)^i + \frac{s}{12} (\alpha_2 + \beta_2)^i + \ldots, \quad (4)
\end{align*}

with \(\alpha \simeq 1/137\) denoting the QED fine structure constant. The Born term, arising in the case of the charged pion, is removed from the amplitudes. The NJL Lagrangian used in this work contains pseudoscalar isovector and scalar isoscalar four-quark interactions and is minimally coupled to the electromagnetic field. Since we do not take into account explicit vector meson couplings, the value of the quark weak coupling constant is \(g_A = 1\).

The diagrams of Fig. 1 provide polarizabilities which scale as \(N_c^0\). Besides the quark one loop diagrams, it is expected that the pion loops will have important contributions, mainly in the cases where the tree-level results are absent (in the NJL model the chiral counting of meson tree-level results are classified in Refs. \([14,20]\)). Although formally the pion-loop contributions to polarizabilities are at a suppressed level of \(1/N_c\), the small value of the pion mass entering the chiral logarithms enhances them. It is out of the scope of the present work to calculate the pion-loop contributions self-consistently within the NJL model, which is an involved task even for the basic pion quantities \([21,22]\). Instead,

\[\text{This affects directly the difference of polarizabilities } (\alpha_1 - \beta_1)^C \text{ which is proportional to the difference of the low-energy constants } \tilde{l}_6 - \tilde{l}_5 \text{ of } \chi\PT, \text{ related to the } \pi \to e\nu\gamma \text{ decay. We stress, however, that the expression for } (\alpha_1 - \beta_1)^C \text{ evaluated at the leading order of the chiral expansion in the NJL model is formally identical to the leading order } \chi\PT \text{ result } [14].\]
we shall include the lowest model-independent pion-loop diagram at the $p^4$ order, calculated within $\chi$PT in Refs. [23,24,25], and known to be the only non-vanishing contribution to the amplitude $A$ at this order in the neutral channel. The pion-loop amplitudes are

$$A_{\pi l}^N = -4 \frac{s - m^2}{s f^2_\pi} \overline{G}_\pi(s), \quad A_{\pi l}^C = -2 \frac{1}{f^2_\pi} \overline{G}_\pi(s),$$

where

$$\overline{G}_\pi(s) = \frac{1}{16\pi^2} \sum_{n=1}^{\infty} \left( \frac{s}{m^2_\pi} \right)^n \frac{(n!)^2}{(n+1)(2n+1)!}.$$  

(6)

The pion loop in the charged mode contributes only to the quadrupole polarizabilities, as it starts out with a term linear in $s$. It has half the strength of the neutral quadrupole case.

The pion loop as well as the $\sigma$-exchange diagram of Fig. 1 contribute only to the amplitude $A$. Regarding the amplitude $B$ for the neutral (charged) mode, only the quark box (quark box + pion exchange) diagrams contribute in that case, starting from the $p^6$ order for the dipole polarizabilities and from the $p^8$ order for the quadrupole polarizabilities. Thus the combinations $(\alpha_j + \beta_j)^i$, $(j = 1, 2)$, to which the $B$ amplitude leads, provide a genuine test of the dynamical predictions of the NJL model at leading order in $1/N_c$, as they are insensitive to the lowest-order $\chi$PT corrections.

All quark one-loop integrals are regularized using the Pauli-Villars prescription with one regulator $\Lambda$ and two subtractions [26] (in the context of the NJL model see also [27,28]),

$$[f(M^2)]_{PV} = f(M^2) - f(M^2 + \Lambda^2) + \Lambda^2 \frac{\partial f(M^2 + \Lambda^2)}{\partial \Lambda^2}.$$  

(7)

This procedure is consistent with the requirements of gauge invariance. Here $M$ denotes the constituent quark mass, large due to the spontaneous breaking of the chiral symmetry.

It is possible to obtain the results for the quark diagrams in simple analytic forms. The expressions are rather lengthy, so we only show a typical result,

$$\left( \beta^N_1 \right)_{box} = \frac{5\alpha N c g^2}{27\pi^2 m_\pi Z_\pi} \left[ \frac{1}{4M^2 - m^2_\pi} \left( 1 + \frac{m_\pi \arctan \left( \frac{m_\pi}{\sqrt{4M^2 - m^2_\pi}} \right)}{\sqrt{4M^2 - m^2_\pi}} \right) \right]_{PV}.  \quad (8)$$
Table 1
The NJL model parameters for the charged and neutral channels, with the input marked by *. In all cases $f^*_\pi = 93.1$ MeV.

| $M^*$ [MeV] | $m^*_\pi$ [MeV] | $m$ [MeV] | $G$ [GeV$^{-2}$] | $\Lambda$ [MeV] |
|-----------|-----------------|-----------|-----------------|----------------|
| 250       | 139             | 5.8       | 8.49            | 964            |
| 250       | 136             | 5.6       | 8.52            | 963            |
| 300       | 139             | 7.5       | 13.1            | 827            |
| 300       | 136             | 7.2       | 13.1            | 827            |
| 350       | 139             | 8.4       | 17.2            | 767            |
| 350       | 136             | 8.1       | 17.3            | 765            |

The factors $g_\pi$ and $Z_\pi$ are the $\pi\bar{q}q$ coupling and the pion wave function normalization, respectively [14,29]. In the case of the box (box + pion exchange) diagrams one is dealing with strictly finite integrals, which remain stable upon the removal of the regulator, i.e. $\lim_{\Lambda \to \infty} [f(M^2)]_{PV} = f(M^2)$. On the contrary, the factors $g_\pi$ and $Z_\pi$ the regularization is essential.

In Table 1 we collect the model parameters, obtained by fitting the physical pion mass and the weak decay constant. The parameters of the model are the four-quark coupling constant $G$, the cutoff $\Lambda$, and the current quark mass $m$. These are traded for $f_\pi = 93.1$ MeV, $m_\pi = 139$ MeV (charged mode) or $m_\pi = 136$ MeV (neutral mode), and the constituent quark mass, $M$.

Our results are displayed in Tables 2-4, where we show the NJL model predictions for three different values of $M$. In Table 2 we collect also the results of the dispersion relations (DR) fit to the Crystal Ball data for the process $\gamma\gamma \rightarrow \pi^0\pi^0$ [30,31] (for which the dipole polarizabilities have been taken from [32]); the DSR results of Fil’kov and Kashevarov [8], and the $\chi$PT predictions taken from [11,33]. In Table 3 we include the values of the dipole and quadrupole polarizabilities of the charged pion obtained as a result of the DR fit [9] to the available experimental data for the total cross section in the reaction $\gamma\gamma \rightarrow \pi^+\pi^-$ [34,35,36,37,38,39] in the energy region from the threshold up to 2.5 GeV. These results are in conformity with the experiments for $\pi^-Z \rightarrow \gamma\pi^-Z$ at Serpukhov [40,41], $\gamma p \rightarrow \gamma\pi^+n$ at the Lebedev Phys. Inst. [42], and at MAMI [43]. The $\chi$PT predictions are taken from [12].

In Table 4 we present the anatomy of our result for the case $M = 300$ MeV. We display separately the several gauge invariant contributions to the polarizabilities: the box (for neutral polarizabilities), box + pion exchange diagram (for the charged polarizabilities), the $\sigma$ exchange, and the pion loop (5). The pion exchange diagram arises only for the charged channel and builds together with the box a gauge invariant amplitude.
Table 2
The dipole (in units of $10^{-4}$ fm$^3$) and quadrupole (in units of $10^{-4}$ fm$^5$) neutral pion polarizabilities. The first three rows show our NJL model predictions at various values of the quark mass, $M$.

|         | $(\alpha_1 + \beta_1)_{\pi^0}$ | $(\alpha_1 - \beta_1)_{\pi^0}$ | $(\alpha_2 + \beta_2)_{\pi^0}$ | $(\alpha_2 - \beta_2)_{\pi^0}$ |
|---------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| $M = 250$ MeV | 1.13                            | -2.05                            | -0.33                            | 46.3                            |
| $M = 300$ MeV | 0.73                            | -1.56                            | -0.14                            | 36.1                            |
| $M = 350$ MeV | 0.50                            | -1.32                            | -0.07                            | 30.6                            |
| DR fit [8]     | 0.98 ± 0.03                      | -1.6 ± 2.2                       | -0.181 ± 0.004                   | 39.70 ± 0.02                     |
| DSR [8]        | 0.802 ± 0.035                    | -3.49 ± 2.13                     | -0.171 ± 0.067                   | 39.72 ± 8.01                     |
| $\chi$PT [33,11] | 1.1 ± 0.3                       | -1.9 ± 0.2                       | 0.037 ± 0.003                    | 37.6 ± 3.3                      |

Table 3
Same as in Table 2 for the dipole and quadrupole charged pion polarizabilities.

|         | $(\alpha_1 + \beta_1)_{\pi^\pm}$ | $(\alpha_1 - \beta_1)_{\pi^\pm}$ | $(\alpha_2 + \beta_2)_{\pi^\pm}$ | $(\alpha_2 - \beta_2)_{\pi^\pm}$ |
|---------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| $M = 250$ MeV | 0.28                            | 10.4                             | 0.46                             | 23.8                            |
| $M = 300$ MeV | 0.19                            | 9.4                              | 0.20                             | 17.5                            |
| $M = 350$ MeV | 0.13                            | 8.3                              | 0.10                             | 14.2                            |
| DR fit [9]     | 0.18$^{+0.11}_{-0.02}$           | 13.0$^{+2.6}_{-1.9}$             | 0.133 ± 0.015                    | 25.0$^{+0.8}_{-0.3}$             |
| DSR [9]        | 0.166 ± 0.024                    | 13.60 ± 2.15                     | 0.121 ± 0.064                    | 25.75 ± 7.03                     |
| $\chi$PT [33,12] | 0.16 [0.16]                     | 5.7 ± 1.0 [5.5]                  | -0.001 [−0.001]                  | 16.2 [21.6]                     |

Table 4
Contribution of various diagrams to the NJL result for the case $M = 300$ MeV. Units are the same as in Table 2.

|         | box + $\pi$-exchange | $\sigma$-exchange | pion-loop | total  |
|---------|----------------------|-------------------|-----------|--------|
| $(\alpha_1 + \beta_1)_{\pi^0}$ | 0.73 | 0 | 0 | 0.73 |
| $(\alpha_1 - \beta_1)_{\pi^0}$ | -11.13 | 10.57 | -1.0 | -1.56 |
| $(\alpha_2 + \beta_2)_{\pi^0}$ | -0.144 | 0 | 0 | -0.144 |
| $(\alpha_2 - \beta_2)_{\pi^0}$ | 5.09 | 9.07 | 21.97 | 36.13 |
| $(\alpha_1 + \beta_1)_{\pi^\pm}$ | 0.189 | 0 | 0 | 0.189 |
| $(\alpha_1 - \beta_1)_{\pi^\pm}$ | -0.977 | 10.36 | 0 | 9.39 |
| $(\alpha_2 + \beta_2)_{\pi^\pm}$ | 0.198 | 0 | 0 | 0.198 |
| $(\alpha_2 - \beta_2)_{\pi^\pm}$ | -1.63 | 8.87 | 10.29 | 17.54 |

We observe a dependence on the input choice of the constituent quark mass, which affects the polarizabilities more severely in the quadrupole than in the
dipole case. Let us first consider the sum of the polarizabilities, which involves only the box contributions. Comparing the sets with \( M = 250 \text{ MeV} \) and \( M = 350 \text{ MeV} \), the box gets reduced in magnitude by about a factor of 2.2 in the dipole case and by about a factor of 4.6 in the quadrupole case, both in the neutral and charged channels. The faster change in the quadrupole case can be understood with a crude estimate: the ratio of the leading-order term of the dipole to the quadrupole in the expansion around \( m_\pi = 0 \) is \( \sim M^2 \). This gives the suppression factor

\[
\frac{(\alpha_2 + \beta_2)_{M=250 \text{ MeV}}}{(\alpha_2 + \beta_2)_{M=350 \text{ MeV}}} \sim \frac{M_{M=350 \text{ MeV}}^2}{M_{M=250 \text{ MeV}}^2} \sim 2. \tag{9}
\]

The same happens in the charged mode. The data lies halfway between the model values for \( M = 250 \text{ MeV} \) and 350 MeV. The best agreement with respect to the DR and DSR data is obtained for the set with \( M = 300 \text{ MeV} \), for which we get an overall good description.

We stress that the values (including the overall signs) of the sums \((\alpha_2 + \beta_2)_{\pi^0, \pi^\pm}\) are totally determined by the gauge-invariant quark box or the box + pion exchange contribution. This is a straightforward and the most transparent result of the presented NJL-model calculation. Moreover, the main part of the box contribution comes from the first non-vanishing \( p^8 \)-order term in the chiral expansion. Based on this fact we expect that the contact term of the \( p^8 \) 3-loop calculation in \( \chi P T \) may also play an important role in reversing the signs of the 2-loop order results for these quantities.

Let us comment on the channels involving the difference of the electric and magnetic polarizabilities. i) \((\alpha_1 - \beta_1)_{\pi^0}\): here the box contribution is largely canceled by the scalar exchange. At the \( p^4 \)-order of the chiral counting they cancel exactly [13]. The higher-order contributions are quark-mass dependent, decreasing as the constituent quark mass increases. The convergence rate is slow, at \( p^6 \)-order one reaches only about 50% of the full sum. ii) \((\alpha_1 - \beta_1)_{\pi^\pm}\): contrary to the neutral channel, the size of the \( \sigma \)-exchange diagram for this combination is about an order of magnitude larger than the box + pion exchange diagram, and it becomes the most important contribution. The pion loops are absent. iii) \((\alpha_2 - \beta_2)_{\pi^\pm}\): the pattern observed in ii) repeats itself for the quadrupole polarizabilities. However in this case the subleading in the \( 1/N_c \) counting pion-loop diagram has the same magnitude as the \( \sigma \)-exchange term.

In conclusion, we highlight our main results: the NJL model at the leading order of the \( 1/N_c \) counting yields the right sign and magnitude for the quadrupole polarizabilities of the pion, \((\alpha_2 + \beta_2)_{\pi^0, \pi^\pm}\), being in conformity with the DR analysis of the data and the DSR predictions. The sign is stable when the model parameters are changed. The magnitude depends on the
value chosen for the unobservable constituent quark mass, but the best overall fit to the other empirical data, typically yielding \( M \sim 300 \text{ MeV} \), also yields the optimum values for the polarizabilities. We have also obtained the convergence rate for several combinations of the dipole and quadrupole polarizabilities, comparing the \( p^8 \) chiral order to the full result. We have discussed the sensitivity of the different polarizability combinations to the inclusion of the one-pion-loop contribution that is non-vanishing at the \( p^4 \) level of the chiral counting. The relative contribution of each gauge-invariant combination to the polarizabilities has been evaluated and discussed.

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