Submitted to Physics Letters

LNF-91/074 (P)
4 Novembre 1991

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INFN - Laboratori Nazionali di Frascati
Servizio Documentazione

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Chiral Symmetry and Pion Polarizabilities

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ABSTRACT

We use chiral perturbation theory including 1-loop contributions to derive formulae needed to deduce pion polarizabilities from $\gamma\pi \to \gamma\pi$ and $\gamma\gamma \to \pi\pi$ data. We deduce for the first time values for the $\pi^{\pm}$ and π^0 polarizabilities from $\pi\pi$ production data, and compare these new results to chiral symmetry predictions.

Hadron electric (α) and magnetic (β) intrinsic polarizabilities [1, 2, 3, 4, 5] characterize the induced transient dipole moments of hadrons subjected to external electromagnetic fields. They probe the rigidity of the internal structure of baryons and mesons, being induced by the rearrangement of the hadron constituents driven by the presence of the photon fields during gamma-hadron Compton scattering. The Compton scattering data determine the Compton polarizabilities $\bar{\alpha}$ and $\bar{\beta}$, expressed in this work in Gaussian units of 10^{-43} cm^3. Petrun'kin [1] gives:

$$\bar{\alpha} = 2\sum \frac{|\langle 0|\vec{d}_z|n\rangle|^2}{E_n - E_0} + \frac{1}{3}\frac{e^2}{M}\langle r^2\rangle = \alpha + \Delta\alpha; \tag{1}$$

where the first and second terms give the intrinsic α, and center of mass oscillation contributions, respectively. The sums are over all E1 excitations of the target hadron. Here $\vec{d} = \sum e_k \vec{r_k}$ is the electric dipole operator, and $\langle r^2\rangle$ is the mean square charge radius of the hadron. All theories and data for pion polarizabilities presented in this work (except sum rule results) are based on the accepted constraint for pions [6], $\bar{\alpha}_\pi + \bar{\beta}_\pi = 0$.

Recently, pion polarizabilty calculations were carried out by Bernard, Hiller, and Weise [7] emphasizing vector meson dominance diagrams, and by Bernard and Vautherin [8] within generalized SU(3) models. They find values for $\bar{\alpha}_\pi$ ranging from $\sim 7 - 14$. Since the classical term $\Delta\alpha \sim 15.1$ is large and positive, these calculations imply that the intrinsic polarizability must be negative [6]. That is possible due to negative energy intermediate states from quark sea components [9] in the pion wave function and from disconnected diagrams [6] arising when a γ-ray (or ρ meson) dissociates into particle-antiparticle pairs. Holstein [6] shows from a different point of view that a large negative intrinsic polarizability can be associated with vector meson contributions and that meson exchange via an axial meson pole diagram effectively provides the main contribution ($\bar{\alpha}_\pi = 2.6$) to the polarizability.

Another theoretical approach is based on the s-channel ($\gamma + \pi \rightarrow \gamma + \pi$) and t-channel ($\gamma + \gamma \rightarrow \pi + \pi$) dispersion sum rules [1, 10]. For charged pions, they give:

$$\bar{\alpha}_\pi + \bar{\beta}_\pi = 0.39 \pm 0.04, \quad \bar{\alpha}_\pi - \bar{\beta}_\pi \sim 10.8; \tag{2}$$

implying $\bar{\alpha}_\pi \approx$ 5.6 and $\bar{\beta}_\pi \approx$ -5.2. For the neutral pion,

$$\bar{\alpha}_{\pi 0} + \bar{\beta}_{\pi 0} = 1.04 \pm 0.07, \quad \bar{\alpha}_{\pi 0} - \bar{\beta}_{\pi 0} \sim -10.0; \tag{3}$$

implying $\bar{\alpha}_{\pi 0} \approx$ -4.5 and $\bar{\beta}_{\pi 0} \approx$ 5.5. These sum rule values should be considered model-dependent theoretical estimates because of the difficulties in evaluating the high-energy asymptotic contributions. There are very large (unstated) uncertainties for the difference sum rule results.

For the γ-π interaction at low energy, chiral perturbation theory (χPT) provides a rigorous way to make predictions; because it stems directly from QCD and relies only on the solid assumptions of spontaneously broken $SU(3)_L \times SU(3)_R$ chiral symmetry, Lorentz invariance and low momentum transfer. Unitarity is achieved by adding pion loop corrections to lowest order, and the resulting infinite divergences are absorbed into physical (renormalized) coupling constants L_i^r (tree-level coefficients in $L^{(4)}$, see Refs. [11, 12]). With a perturbative expansion of the effective Lagrangian limited to terms quartic in the momenta and quark masses ($O(p^4)$), the method establishes relationships between different processes in terms of the L_i^r. For example, the radiative pion beta decay and electric pion polarizability are expressed as [12]:

$$h_A/h_V = 32\pi^2(L_9^r + L_{10}^r), \tag{4}$$

$$\bar{\alpha}_\pi = \frac{4\alpha_f}{m_\pi F_\pi^2}(L_9^r + L_{10}^r); \tag{5}$$

where F_π = 93.1 MeV [13] is the pion decay constant, h_A and h_V are the axial vector and vector coupling constants in the decay, and α_f is the fine structure constant. Recently a new value F_π = 92.4 MeV was claimed [14] but here we use the standard value. The experimental ratio [13], $h_A/h_V = 0.46 \pm 0.02$, leads to $\bar{\alpha}_\pi = -\bar{\beta}_\pi = 2.7 \pm 0.1$, where the error is due only to the uncertainty in the h_A/h_V measurement.

For the pion polarizability, the $\gamma - \pi^-$ scattering was measured [15, 16] at Serpukov with 40 GeV pions via radiative pion scattering in the nuclear Coulomb field (π^- + Z $\rightarrow$ π^- + Z + gamma) where the incident pion Compton scatters from a virtual photon in the Coulomb field of a nucleus of atomic number Z and the final state gamma ray and pion are detected in coincidence. This reaction is an example of the well tested [17] Primakoff formalism. It is equivalent to $\gamma + \pi^- \rightarrow \gamma + \pi^-$ scattering for laboratory γ-ray energies in the range 60-600 MeV incident on a target π^- at rest. The experiment yielded:

$$\bar{\alpha}_\pi = -\bar{\beta}_\pi = 6.8 \pm 1.4_{stat} \pm 1.2_{syst}. \tag{6}$$

The pion electric polarizability was also determined in a Lebedev radiative pion photoproduction experiment [18], $\gamma p \rightarrow \gamma\pi^+ n$, in which the incident γ-ray scatters form a virtual pion. The quoted result, $\bar{\alpha}_\pi = 20 \pm 12$, does not include experimental and theoretical systematic uncertanties.

Independent information on the pion polarizabilities can be obtained also from the reaction $\gamma\gamma \rightarrow \pi^+\pi^-$ which is related to the Compton scattering by crossing symmetry. The cross section for the $\gamma\gamma \rightarrow \pi^+\pi^-$ process is calculated in χPT with the inclusion of pion and kaon loops at the $L^{(4)}$-level. Transforming the equations of Ref. [19], we obtain:

$$(\frac{d\sigma}{d\Omega})^{\chi PT}_{\gamma\gamma\to\pi^+\pi^-} = \frac{\alpha_f^2}{2s}\frac{\beta_v}{2}[| \tilde{B}_1 + \frac{m_\pi}{2\alpha_f}\bar{\alpha}^*_\pi(s)s |^2 + | \tilde{B}_2 + \frac{m_\pi}{2\alpha_f}\bar{\alpha}^*_\pi(s)s |^2]. \tag{7}$$

Using crossing symmetry (i.e., exchanging s and t variables in the scattering amplitude), we have :

$$(\frac{d\sigma}{d\Omega})^{\chi PT}_{\gamma\pi\to\gamma\pi} = \frac{\alpha_f^2}{2s}[| B_1 + \frac{m_\pi}{2\alpha_f}\bar{\alpha}^*_\pi(t)t |^2 + | B_2 + \frac{m_\pi}{2\alpha_f}\bar{\alpha}^*_\pi(t)t |^2] \tag{8}$$

Here, s, t, u are the usual Mandelstam variables, and β_v is the velocity of the final pions in the CM-system. We do not here consider the claimed [20] low mass isospin zero resonances in the $\pi\pi$ system. We have :

$$B_1 = \tilde{B}_1 = 1, B_2 = -1 + \frac{t}{G(s,u)}, \tilde{B}_2 = -1 + \frac{s}{G(t,u)}, G(x,u) = \frac{(x-m_\pi^2)(u-m_\pi^2)}{2m_\pi^2}. \tag{9}$$

The "effective polarizability" $\bar{\alpha}^*_\pi$ is given by:

$$\bar{\alpha}^*_\pi(x) = \bar{\alpha}_\pi + \frac{2\alpha_f}{m_\pi}\frac{L(x)}{x} = \bar{\alpha}_\pi + \delta\bar{\alpha}_\pi(x). \tag{10}$$

The complex L-term represents the 1-loop contributions with vertices in $L^{(2)}$ and is given [19] by:

$$L(x) = -\frac{1}{32\pi^2 F_\pi^2}[\frac{3}{2}x + m_\pi^2 ln^2 Q_\pi(x) + \frac{1}{2}m_K^2 ln^2 Q_K(x)], \tag{11}$$

where

$$Q_i(x) = \frac{(x-4m_i^2)^{1/2} + x^{1/2}}{(x-4m_i^2)^{1/2} - x^{1/2}}, \quad i = \pi, K \tag{12}$$

The effective polarizability $\bar{\alpha}^*_\pi$(x) is a real quantity in Compton scattering (x=t≤0) and a complex quantity in the $\gamma\gamma \to \pi\pi$ reaction (x = s $\geq 4m_\pi^2$).

In the limit of a structureless pion ($\bar{\alpha}_\pi = \bar{\beta}_\pi = 0$), Eq. (8) reduces to the Born cross section given by:

$$(\frac{d\sigma}{d\Omega})^{Born}_{\gamma\pi\to\gamma\pi} = \frac{\alpha_f^2}{2s}[| B_1 |^2 + | B_2 |^2]. \tag{13}$$

The chiral Compton cross section formula differs from that used in previous studies by the presence of the extra energy dependent loop term $\delta\bar{\alpha}_\pi$(x). These results are based on an expansion in quark masses and momenta and within the framework of a 1-loop approximation are expected to be reliable up to s, t values of order $10m_\pi^2$. In the vicinity of t = 0, the series expansion of $\delta\bar{\alpha}_\pi$(t) is:

$$\delta\bar{\alpha}_\pi(t) \approx \frac{\alpha_f}{m_\pi}\frac{1}{192\pi^2 F_\pi^2}[1 + \frac{1}{2}(\frac{m_\pi}{m_K})^2]\frac{t}{m_\pi^2} \approx 0.257\frac{t}{m_\pi^2}. \tag{14}$$

Therefore, only for forward angle Compton scattering (θ = 0, t=0) can the loop term $\delta\bar{\alpha}_\pi$ be ignored. The expression for $\delta\bar{\alpha}_\pi$ indicates that the first order correction to the polarizability in Compton scattering (t $\leq$ 0) due to the loop-correction is negative. This has the consequence that experimental values of $\bar{\alpha}_\pi$ obtained ignoring $\delta\bar{\alpha}_\pi$, should be increased. The effect depends upon the momentum transfer and would increase the Lebedev polarizability by 5%. For the Serpukov experiment, some 1-loop contributions were considered [21]. The shift in the measured value of the Serpukov polarizability was estimated to be 0.7 $\pm$ 0.3, close in percentage terms with our own result.

Further insights into this problem can be obtained from the process $\gamma\gamma \to \pi^0\pi^0$. Since only neutral particles are involved in this case, the Born term vanishes (B_1 = B_2 = 0) and therefore, at the lowest level O(p^4), this cross section can only be generated by finite 1-loop graphs and hence provides a unique testing ground for the loop structure of χPT.

By using the expressions given in Refs. [19, 22] one can write the chiral cross sections for $\gamma\pi^0 \to \gamma\pi^0$ and $\gamma\gamma \to \pi^0\pi^0$ in the usual way:

$$(\frac{d\sigma}{d\Omega})^{\chi PT}_{\gamma\pi 0\to\gamma\pi 0} = \frac{m_\pi^2}{4s} \mid \bar{\alpha}^*_{\pi 0}(t) \mid^2 t^2, \tag{15}$$

$$(\frac{d\sigma}{d\Omega})^{\chi PT}_{\gamma\gamma\to\pi^0\pi^0} = \frac{1}{2}\frac{m_\pi^2}{4}\frac{\beta_v}{2} \mid \bar{\alpha}^*_{\pi 0}(s) \mid^2 s \tag{16}$$

Here the effective polarizability of the π^0 is given by:

$$\bar{\alpha}^*_{\pi 0}(x) = \frac{\alpha_f}{32\pi^2 m_{\pi 0} F_\pi^2}[4(\frac{m_\pi^2}{x} - 1)(1 + \frac{m_\pi^2}{x} ln^2 Q_\pi(x)) - (1 + \frac{m_K^2}{x} ln^2 Q_K(x))], \tag{17}$$

This loop-function, shown in Fig.1, is a real quantity in Compton scattering (x = t $\leq$ 0) and a complex quantity in the $\gamma\gamma \to \pi^0\pi^0$ process (x = s $\geq 4m_{\pi 0}^2$), in complete analogy to the case of the charged pion. The conventional polarizability value for a Compton scattering experiment near t = 0 is:

$$\bar{\alpha}^*_{\pi 0} \approx \bar{\alpha}_{\pi 0}(1 - \frac{13}{15}\frac{t}{m_\pi^2} - \frac{1}{4}\frac{t}{m_K^2}), \tag{18}$$

where

$$\bar{\alpha}_{\pi 0} = -\bar{\beta}_{\pi 0} = -\frac{\alpha_f}{96\pi^2 m_{\pi 0} F_\pi^2} = -0.49. \tag{19}$$

Eq. (18) corrects a numerical error in the coefficient of the (t/m_π^2)-term given in Eq. (67) of Ref. [6]. Eq. (19) is the parameter-free prediction for the π^0 polarizability obtained at O(p^4) in χPT. In the threshold region for the production channel, Fig. 1 shows that $\bar{\alpha}^*_{\pi^0}$ increases very slowly from its value calculated at s = $4m_\pi^2$ (above the physical threshold at s = $4m_{\pi^0}^2$):

$$\bar{\alpha}^*_{\pi 0}(s = 4m_\pi^2) = \bar{\alpha}_{\pi 0}[9(1 - \frac{\pi^2}{4}) - \frac{m_\pi^2}{m_K^2} + O(\frac{m_\pi^4}{m_K^4})], \tag{20}$$

and is determined primarily by $\bar{\alpha}_{\pi 0}$. If the O(p^6) contributions are negligible near threshold, the π^0-polarizability as defined in Compton scattering at t=0 can therefore be equivalently determined from $\gamma\gamma \to \pi^0\pi^0$ at threshold. We return to this point later.

Let us examine the experimental situation. Total cross section data for $\gamma\gamma \to \pi^+\pi^-$ were obtained by the PLUTO, DM1, DM2 and MARK-II collaborations. From the review of the data presented in Ref. [23], it is quite evident that a feature common to all these experiments is a cross section in excess of the Born contribution in the low energy region ($M_{\pi\pi} \leq 0.5$ GeV). This could either be interpreted as evidence for some unpredicted dynamical effect in this energy region, or as simply reflecting some systematical error [23].

A large enhancement effect at low energy would yield a pion polarizability larger than expected. To determine $\bar{\alpha}_\pi$ we used Eq. 7 to fit the data for a given experiment in the restricted energy region $M_{\pi\pi} \leq 0.45$ GeV. For the DM1 and DM2 experiments, we use the inferred differential cross sections at 90°, which do not include systematic errors, from the data analysis of Ref. [23]. For PLUTO [24], we consider only the two points at $\sqrt{s}$ = 0.38 GeV and 0.42 GeV. The higher energy points lie consistently below the Born cross-section up to $\sqrt{s} = 0.7$ GeV and therefore suggest alterations in the Born amplitude that we do not consider in this analysis. The PLUTO estimated systematic uncertainty below 0.5 GeV is ± 20% . The resulting $\bar{\alpha}_\pi$ and uncertainties are given in Table I together with Compton scattering values. The prediction from χPT and other theoretical results are also shown. The DM1, DM2, PLUTO, and Lebedev results suggest large values for $\bar{\alpha}_\pi$ not remotely consistent with the chiral prediction $\bar{\alpha}_\pi$ = 2.7 ± 0.1. The high quality data (with uncertainties dominated by systematic errors) from the MARK-II experiment at SLAC [25] seem to exclude a large enhancement at low energy. The MARK-II polarizability value is in striking contrast to the above four results. Considering its uncertainties, it is consistent with the chiral prediction. The Serpukov value, considering its uncertainties, differs by roughly two standard deviations from the chiral prediction.

Table I.- Values for $\bar{\alpha}_\pi$ from data and theory.

PLUTO	19.1	$\pm 4.8_{stat} \pm 5.7_{syst}$
DM1	17.2	$\pm 4.6_{stat}$
DM2	26.3	$\pm 7.4_{stat}$
LEBEDEV	20.	$\pm 12._{stat}$
MARK II	2.2	$\pm 1.6_{(stat+syst)}$
SERPUKOV	6.8	$\pm 1.4_{stat} \pm 1.2_{syst}$
Dispersion Sum Rule	5.6	
Chiral	2.7	$\pm$ 0.1
Bernard et al.	7-14	

We now consider the $\gamma\gamma \to \pi^0\pi^0$ process. Total cross section data in the threshold region for the reaction $\gamma\gamma \to \pi^0\pi^0$ were obtained by the Crystal Ball [26] collaboration. In Fig.(1) we compare the values of $\bar{\alpha}^*_{\pi 0}$(x) extracted from this data set with the χPT prediction of Eq. (17). The trend of the data points is consistently higher than the χPT-prediction up to $\sqrt{s} = 0.45$ GeV. Neglecting the first data point, which appears to be affected by some systematic threshold effect, and assuming that the 1-loop expression is fully justified in this energy region, these data yield the π^0-polarizability value $\mid \bar{\alpha}^{EXP}_{\pi 0} \mid \approx 1.4 \mid \bar{\alpha}_{\pi 0} \mid$. At O($p^4$)-level in χPT, there is no way to make any adjustment. At O(p^6), the vector meson resonance contributions (corresponding to tree diagrams with one vertex from $L^{(6)}$), were found to be negligible for $\sqrt{s} \leq 0.4$ GeV [27]. Although a complete 2-loop calculation is not yet available, preliminary results indicate that this contribution can be sizeable in the threshold region [28]. This may improve the agreement, but this still needs to be confirmed. The Crystal Ball data therefore determine an experimental π^0-polarizability 40% larger than the chiral prediction, and significantly smaller than the dispersion sum rule result $\bar{\alpha}_{\pi 0} =$ - 4.5. The only previous experimental determination [29] was $\mid \bar{\alpha}^{EXP}_{\pi 0} \mid \leq 35$, a limit that is too large to be useful.

In summary, charged pion polarizabilities were deduced from $\gamma\gamma \to \pi^+\pi^-$ data. These polarizabilities including values deduced from dispersion sum rules and Compton scattering are compared to chiral symmetry predictions. The experimental values for $\bar{\alpha}_\pi$ range from 2.2 to 26.3, and the spread in values do not allow precision tests of any theory. We fitted $\gamma\gamma \to \pi^0\pi^0$ data to deduce for the first time an experimental π^0 polarizability value of $\mid \bar{\alpha}^{EXP}_{\pi 0} \mid = 0.69 \pm 0.07_{(stat)} \pm 0.04_{(syst)}$. This value is more than two standard deviations higher than the chiral prediction. The experimental situation points to the need for much higher quality data and more attention to the systematic uncertainties arising from different measurement techniques. A concerted experimental attack on these questions is planned at the LEGS [30], DAΦNE [31], and FNAL [4] facilities.

ACKNOWLEDGEMENTS

We thank L. Maiani and G.Pancheri for valuable suggestions and helpful discussions, S. Dawson for a useful discussion, and R. Baldini-Ferroli for a critical analysis of the experimental data. This work was supported by the Istituto Nazionale di Fisica Nucleare (Italy), by US Department of Energy under contract No. DE-AC02-76CH00016, and by the U.S.-Israel Binational Science Foundation (BSF), Jerusalem, Israel.

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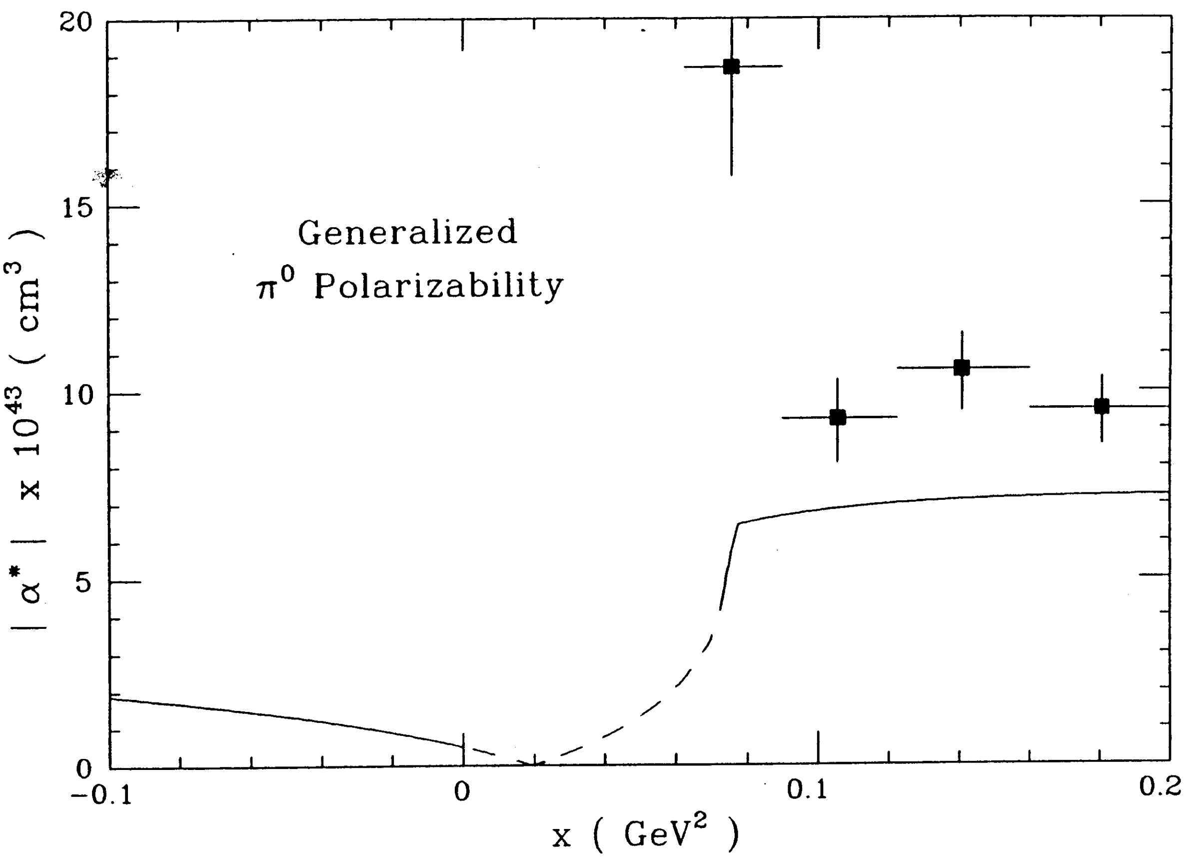

FIG. 1: Absolute value of the χPT effective pion polarizability for the neutral pion. Experimental points are based on the Crystal Ball data of Ref. [26]. The errors shown are only statistical, and do not include the $\pm$ 11% estimated [26] systematic errors. A dashed line is drawn in the unphysical region.