REPORT OF THE WORKING GROUP ON GOLDSTONE BOSONS

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An overview is presented of the talks in the working group on Goldstone Bosons. Topics touched on are CP-violation in the Kaon system, rare Kaon decays, $\pi\pi$-scattering, ϕ-meson decays, scalar mesons, form-factors and polarizabilities, η-decays, chiral symmetry breaking, connections with QCD at short-distances and effective theories for electroweak physics.

1 Introduction

In this talk we report on the working group on Goldstone Bosons of the Chiral Dynamics 2000, theory and Experiment, meeting at Jefferson Laboratory, Newport News, Virginia, USA, July 17-22, 2000. We had 28 presentations during four afternoon sessions divided into 7 main areas. There was of course the unavoidable overlap between the different main areas and with the plenary talks. In this report we summarize the main issues discussed in our working group. More details for each of the presentations and further references can be found in the individual contributions which follow this overview. The discussion below and the order of the contributions is organized by the chronological order of the presentations at the meeting.

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2 Kaons

Kaon-physics covered a little more than one of the afternoons in our working group. In addition there were four plenary talks that can be classified as belonging to this part.

The discussions were divided in three areas: $K \to \pi\pi$-decays and CP-violation, rare Kaon decays and the third topic was specifically related more to $\pi\pi$-scattering, i.e. the calculations and measurements of $K_{\ell 4}$-decays.

2.1 Rare Kaon Decays

The subject of rare Kaon decays was covered in talks by Nakano[1], Schmidt[2] and Arenton. In addition Isidori gave an overview in his plenary talk[4].

The first set of rare decays discussed fall under the category tests of chiral dynamics. Here we have the new BNL result on $K^+ \to \pi^+\pi^0\gamma$ on the direct photon emission contribution[1]. This decay is interesting since its magnetic amplitude tests the interplay of the anomaly and the weak interaction. The result is somewhat surprising in that it indicates no contribution from the direct weak-anomaly term[5]. The second set of weak CHPT-testing decays on which new data were presented was $K_L \to \pi^0\gamma\gamma$ and $K_S \to \gamma\gamma$. The new NA48 data on the latter decay[2,6] are in perfect agreement with the older data and with the parameter-free CHPT prediction[7]. In $K_L \to \pi^0\gamma\gamma$ a similar parameter-free predictions at order p^4 exists[8] but while it predicts the shape of the di-photon mass spectrum well, it does underestimate the rate. The new data presented here show now clear evidence for the vector-meson-exchange contribution at low values of $m_{\gamma\gamma}$. This will hopefully allow for a clean determination of both the p^4 CHPT effects and the additional p^6 contributions.

The question of Vector-Meson-Exchange contributions is also important in the rare decays presented by Arenton[3] as discussed in e.g. Ref.[9]. The knowledge of all the decay modes of this type allows to disentangle the various models. The decay $K_L \to \pi^+\pi^-e^+e^-$ has a T-violating asymmetry in the final state that is observed in agreement with predictions[10]. Further refinement of the latter mode might allow a test of the chiral prediction for the neutral Kaon charge radius.

2.2 CP-violation and $K \to \pi\pi$-decays

This area was covered experimentally and theoretically. The experimental results of KTeV and NA48 were treated by Arenton[3,11] and Cenci[12,13] respectively. The NA48 results are combined from the 97 and 98 data. The KTeV results are from 20% of the 96/97 data. Both experiments are in the process of analyzing substantially larger data sets. So we hope that the difference

$$\begin{aligned}\mathrm{Re}(\varepsilon'/\varepsilon)(\mathrm{NA48}) &= (14.0 \pm 4.3) \times 10^{-4} \\ \mathrm{Re}(\varepsilon'/\varepsilon)(\mathrm{KTeV}) &= (28.0 \pm 4.1) \times 10^{-4}\end{aligned} \quad (1)$$

will soon be resolved[a]. These results still present a clear indication that the source of CP-violation is at the weak scale and not at some very much higher scale. In that sense the qualitative prediction of Gilman and Wise[14] has been confirmed.

The measurement at DAΦNE should provide an independent confirmation of this result using an entirely different approach. This was discussed in the plenary talk by P. Franzini[15].

On the theory side, things have progressed but are still rather uncertain. The problems facing lattice gauge theory calculations but also the way to solutions, which involves a lot of chiral dynamics, were discussed in some detail by M. Golterman[16]. A short overview of the theoretical problems facing analytical approaches was presented by Isidori in his plenary talk. An optimistic view of the results of analytical calculations was presented by Bijnens[17], where it was concluded that both the $\Delta I = 1/2$ rule and the above given values of ε'/ε can be understood in the framework of the $1/N_c$-expansion enhanced with modeling the intermediate energy regime. References to other approaches can be found in Ref.[4] or in the lectures Ref.[18].

That ε'/ε is a quantity beset by small effects was exemplified by Cirigliano[19] who showed that electromagnetic effects beyond the electromagnetic Penguin[20] can play a rather important role. In particular the discrepancy between the phase deduced from $\pi\pi$-scattering and the phase in $K \to \pi\pi$ could come from this source. A similar analysis can be found in Ref.[21].

2.3 $K_{\ell 4}$

This decay was discussed in two contributions at this meeting. There are the new data from BNL[22] on $K^+ \to \pi^+\pi^-e^+\nu$. These show the future precision to be expected in fixed target measurements of $\pi\pi$-scattering and on the three-form-factors and their dependence on the kinematical variables. In anticipation of these new measurements the old Pais-Treiman method has been reanalyzed[23] and the alternative method of using form-factor parametrizations was updated to reflect the expected precision in Ref.[24].

The other talk concerned the theoretical progress on this decay[25]. Since the absolute values of the form-factors in $K_{\ell 4}$ are the major input for L_1,

[a] Systematic and statistical errors were combined quadratically.

L_2 and L_3 an analysis beyond the existing one-loop and dispersive ones in CHPT[26] became necessary. The calculation does now exist to two-loops[27] and was fitted to the existing data[28]. The new data from BNL and Frascati will improve the precision rather much. The predictions for $\pi\pi$-scattering using these parameters also agree well with the data and the Roy analysis[25,29]

3 $\pi\pi$-Scattering

The subject of $\pi\pi$-scattering was discussed rather extensively at this meeting. A first introduction to the CHPT calculation was given by Leutwyler[30] and more details as well as the results of the new Roy equation analysis[31] by Colangelo[29], see also Ref. [32]. The theoretical issues involved were also discussed by Gasser in his talk about sigma terms[33].

As discussed above the calculation of $K_{\ell 4}$ was used to predict the $\pi\pi$-scattering lengths and it fitted well. The other to be expected precise measurement comes from pionium decays. The theory behind these decays including isospin breaking and especially photonic corrections was discussed by A. Rusetsky[34]. The experimental side, with the DIRAC proposal, was presented in our working group by Schacher[35]. The highlight here was the preliminary evidence for atomic pairs showing that the prospects for an accurate measurement of $a_0^0 - a_0^2$ via the pionium lifetime are very good.

That measurements very near threshold are important to determine the threshold parameters was also stressed by J. Sá Borges in his talk[36]. Using a simple unitarization procedure they showed that the present $\pi\pi$-data set is not sufficient to discriminate between the small and large condensate scenario. The latter is one of the main reasons for the theoretical and experimental effort regarding $\pi\pi$-scattering. We will discuss this aspect below in Sect. 7.1.

4 ϕ

ϕ decays are a very useful ground for different aspects of chiral dynamics and their importance has been underlined in many talks of this working group.
J.R. Pelaez [37], in his talk on $\phi \to \pi\pi$, has drawn our attention on this decay which is interesting since it violates isospin, it is OZI suppressed and has an interplay with the $\phi - \omega$ mixing. Moreover, the most recent measurements at the VEPP-2M collider are in conflict: CMD-2 measures $BR = (2.20 \pm 0.25 \pm 0.20) \times 10^{-4}$ while the SND result is $BR = (0.71 \pm 0.11 \pm 0.09) \times 10^{-4}$. The main contributions to this process come from $\phi - \rho$ mixing and from $\phi - \omega - \rho$ mixing. In the first case we can distinguish the electromagnetic contribution $\phi - \gamma - \rho - \pi\pi$ and the strong contribution due to Kaon loops. In this latter

case Pelaez and collaborators[38] have used the unitarized chiral amplitude with strong isospin breaking to calculate $g^{K\bar{K}}_{\phi\pi\pi}$. For the $\phi-\omega-\rho$ mixing the three different scenarios present in the literature have been taken into account: the "Strong $\phi-\omega$ mixing", the "Weak $\phi-\omega$ mixing" and the "Hidden Local Symmetry (HLS)" scenario. The final results depend on the $\phi-\omega-\rho$ mixing: the Strong scenario gives a result compatible with the CMD-2 measurement while the Weak and HLS give results comparable with SND. New and more precise experimental results will play a crucial role in solving the question.

In the work presented by E. Oset [39] on ϕ radiative decays again a chiral unitary approach is used to describe the decays $\phi \to \pi^0\pi^0\gamma$ and $\phi \to \eta\pi^0\gamma$. These decays are forbidden at tree level but can proceed via Kaonic loops, which involve K^+K^- transition to $\pi^0\pi^0$ and $\pi^0\eta$ where the $f_0(980)$ and $a_0(980)$ resonances appear. The definition of the nature of these two scalar mesons is a longstanding problem in light meson spectroscopy and many hypothesis, like $qq\bar{q}\bar{q}$ or $K\bar{K}$ molecules, apart from the standard $q\bar{q}$, have been made in the last decades. In the framework developed by Oset and collaborators[40,41,42] these resonances would be ordinary meson-meson scattering resonances coming from multiple scattering of the mesons. The diagrams of these decays involve charged Kaon loops with the photon coupled in all possible ways to the loops and to the final state particles. The $\pi^0\pi^0$ and $\pi^0\eta$ mass spectrum have been evaluated and both the f_0 and the a_0 are well visible in such distributions and in good agreement with the experimental spectra from VEPP-2M experiments, CMD-2 and SND. In the case $\phi \to \eta\pi^0\gamma$ there is also a good agreement with the branching ratio calculated in the framework of chiral unitary approach (0.87×10^{-4}) and the results of SND $(0.83 \pm 0.23) \times 10^{-4}$ and CMD-2 $(0.90 \pm 0.24 \pm 0.10) \times 10^{-4}$, thus representing a successful application of such approach.

ϕ radiative decays are being studied experimentally at CEBAF as reported by P. Rubin [43] in his talk on the RadPhi experiment (TJNAF E94-016) approved in 1995 and which has started taking data in summer 2000. It is a neutral apparatus suited for photo-production of the ϕ meson and for the detection of $\phi \to$all-photon final state decay modes such as $\phi \to f_0(980)\gamma$, $\phi \to a_0(980)\gamma$, $\phi \to \rho\gamma$, $\phi \to \eta'\gamma$, $\phi \to \omega\pi^0$. The physics motivations of RadPhi are: the nature of $f_0(980)$ and $a_0(980)$, the radiative width of the ϕ, the gluonic and strangeness content of η', searches for C- and I-violating decays, the radiative decays of the ρ and ω.
Similar studies have been done in the last years at the VEPP-2M collider, by the SND [44] and CMD-2 [45] experiment, and are being done presently at the DAΦNE collider by the KLOE experiment [15,46,47]. The RadPhi apparatus

is capable of photo-producing ∼2.5 million ϕ mesons per day with a photon beam of 5.65 GeV and all-photon final states are detected with efficiency ranging from 3% to 35%. In a 30-day run during summer 2000, corresponding to a total statistics of $\sim$ 10 millions ϕ decays, they expect to reach a sensitivity $\mathcal{O} \sim 10^{-5}$ on the rare ϕ decays.

5 Scalar Mesons

A. Fariborz [48], in his talk on "A Chiral Lagrangian Framework for Scalar Mesons", has drawn our attention on the important roles played by light scalar mesons in low-energy QCD. Scalars are probes of the QCD vacuum and are important from a phenomenological point of view, as they are intermediate states in Goldstone boson interactions away from threshold, where chiral perturbation theory is not applicable. Among the lowest-lying scalar mesons ($m < 1$ GeV) the $f_0(980)$ and $a_0(980)$ are rather well established experimentally, the $\sigma(560)$ or $f_0(400-1200)$ has still uncertain mass and decay width and the $\kappa(900)$ is not listed but mentioned in the PDG 2000. It is known that a simple $q\bar{q}$ picture does not explain the properties of these mesons, as already underlined by E. Oset in his talk.
The next-to-lowest scalars (1 GeV $< m <$ 2 GeV) are: $K_0^*(1430)$, $a_0(1450)$, $f_0(1370)$, $f_0(1500)$, $f_J(1710)$, and are all listed in the PDG 2000. These states are generally believed to be closer to $q\bar{q}$ objects, except for the $f_0(1500)$ which is a good candidate for the lowest scalar glueball state.
Within a non-linear chiral Lagrangian framework, developed by Fariborz and collaborators [49,50,51,52] different Goldstone boson interactions $(\pi\pi, \pi\eta, \pi k)$ away from threshold can be studied. In this approach, a description of scattering amplitudes which are, to a good approximation, both crossing symmetric and unitary, is possible. This leads to probing light scalar mesons and extracting their unknown physical properties by fitting the scattering amplitudes to experimental data.

A big effort in studying the properties of the scalar mesons $f_0(980)$, $a_0(980)$ in ϕ radiative decays is presently being done by the KLOE experiment [53] as reported by A. Farilla [46] in her talk on "First KLOE results on scalar mesons". Since the branching ratios of $\phi \to f_0\gamma$,$\phi \to a_0\gamma$ can range from 10^{-4} to 10^{-6}, depending on the nature of these particles, their accurate measurement at a ϕ factory, together with a precise determination of the shape of the $\pi\pi$ mass spectrum and of the $\eta\pi$ mass spectrum can help in establishing a realistic model for these particles. The KLOE detector is suited for the detection of all-photon final states and final states with photons and charged particles. During its first year of data taking in 1999 the KLOE experiment, which is presently running at the DAΦNE collider in Frascati, has collected 2.4 pb^{-1} of integrated luminosity corresponding to ~8 millions ϕ decays. This data sample has been used to study the radiative decays $\phi \to f_0\gamma$,$\phi \to a_0\gamma$ [54]. The decay $\phi \to f_0\gamma \to \pi^0\pi^0\gamma$ has relevant background from $e^+e^- \to \omega\pi^0$. Other background processes are $\phi \to \rho\pi^0$, $\phi \to a_0\gamma$, $\phi \to \eta\gamma$ with only photons in the final state. A constrained kinematic fit and suitable topological cuts are applied to reduce the background, with a final detection efficiency of $\sim$ 40%. A preliminary measurement gives Br($\phi \to f_0\gamma \to \pi^0\pi^0\gamma$)= $(0.81 \pm 0.09_{stat} \pm 0.06_{syst}) \cdot 10^{-4}$. The decay $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$ has high background both from Initial State Radiation and from Final State Radiation and interference with the latter is expected. $\pi^+\pi^-\gamma$ events have been selected with an overall efficiency of $\sim$ 50%. They obtain the upper limit: Br($\phi \to f_0\gamma \to \pi^+\pi^-\gamma$)$<1.6 \cdot 10^{-4}$ at 90% C.L. The decay $\phi \to a_0\gamma \to \eta\pi^0\gamma$ has similar background as the $\phi \to f_0\gamma \to \pi^0\pi^0\gamma$ and again a constrained kinematic fit and suitable topological cuts are applied to reduce the background, with a final detection efficiency of $\sim$ 23%. Their preliminary measurement gives Br($\phi \to \eta\pi^0\gamma$)= $(0.77 \pm 0.15_{stat} \pm 0.10_{syst}) \cdot 10^{-4}$.

6 Form-factors and Polarizabilities

There were four experimental and three theoretical presentations in this section. These fell into the general areas of pion form-factors and polarizabilities, measurements of anomalous amplitudes $\pi \to \gamma\gamma$ and $\gamma \to 3\pi$, and J/ψ decays to $\phi(\omega)\pi^+\pi^-$, K^+K^-.

6.1 Pion form-factors and polarizabilities

T. Walcher[55] presented plans at Mainz for a new measurement of the π^+ electromagnetic polarizability. They plan to make a completely exclusive measurement of the $\gamma p \to \pi^+\gamma n$ reaction, where all particles in the final state are detected. Preliminary results from a test run at $E_\gamma = 700$ MeV show that the measured $\gamma p \to \pi^+\gamma n$ cross sections are close to theoretical estimates, providing confidence in the experimental apparatus and the theoretical calculations that will be used to extract the polarizabilities. D. Mack[56] presented results from Jefferson Lab on the π^+ form factor, and plans for new measurements at higher Q^2. Data were taken at W=1.95 GeV and a Rosenbluth separation was made of the longitudinal and transverse response functions. A Regge analysis (VGL) of the longitudinal response was used to extract the pion form factor. The new data that go up to $Q^2 \approx 2$ GeV^2 do not show evidence for the Q^2

scaling that is expected in the PQCD regime. Higher Q^2 data are needed.

In theory J. Palomar [57] presented calculations of the pion and Kaon vector form factors using a unitarization method to take into account final state interaction corrections to the tree level amplitude from lowest order CHPT. This calculation describes very precisely the pion and Kaon vector form factors and the p-wave $\pi\pi$ phase shifts up to about s=1.44 GeV^2. Agreement is much better with the two loop CHPT pion vector form factor than with the one loop calculation. A. Radyushkin[58] presented PQCD calculations of the π^+ and π^0 form factors, where it was shown how to combine the exclusive QCD reaction mechanism with the others. This work shows that there is some hope to reach perturbative QCD down to an energy level where resummation methods as presented by Palomar and others are valid, thus holding out hope for an eventual practically usable connection between chiral dynamics and QCD.

6.2 The anomalous reactions $\pi \to \gamma\gamma$ and $\gamma \to 3\pi$

There were two presentations that described measurements of amplitudes dominated by the Chiral anomaly. A. Gasparian[59] presented plans for a future high precision measurement of the π^0 lifetime at JLab, the PRIMEX experiment. This experiment will measure the Primakoff production cross section for π^0 on nuclear targets using 6 GeV incident tagged photons. A 1000+ element hybrid calorimeter that consists of lead glass with a high resolution lead tungstate insert is under construction for this experiment. The uncertainly in measuring the π^0 lifetime is estimated to be less than 1.5%. There are also plans for measuring the π^0 form factor at low Q^q, and when higher energies are available, the radiative widths and low Q^q form factors of the η and η'. R. Miskimen [60] presented preliminary results on $\gamma \to 3\pi$ from an analysis of $\gamma p \to \pi^+\pi^0 n$ data taken on the CLAS detector at JLab. The photon energy was approximately 2 GeV. A Chew-Low analysis was used to extract $F^{3\pi}$ from the cross sections over a range in s from 18 to 38 m_π^2. The results are in good agreement with a calculation by Holstein that includes the effects of $\pi\pi$ FSI and, at low s, with several other calculations[61]. Analysis of the data at $s < 18m_\pi^2$ are continuing.

J. Oller [62] presented calculations of $J/\Psi \to \phi(\omega)\pi^+\pi^-$, K^+K^- where the ϕ is treated as a spectator. They obtained good agreement with data up to $\sqrt{s} < 1.2$ GeV. These decays are very sensitive to OZI violating physics, supporting the statement that the OZI rule is subjected to large corrections in the 0^{++} sector.

7 Other

7.1 Chiral symmetry breaking and generalized CHPT

One of the main underlying assumptions in the way we normally perform CHPT is that the quark-anti-quark vacuum-expectation-value is of natural size, or equivalently, that the Gell-Mann-Oakes-Renner (GOR) formula for the pion mass has only small corrections. This assumption does not need to be made[63] and it is in fact surprisingly difficult to experimentally prove this assumption even though a lot of qualitative evidence has been accumulated. The measurement of the $\pi\pi$-threshold parameters has been promoted as one of the places where there is a significant difference. An introduction with lots of references can be found in the plenary talk by Jan Stern in the previous Chiral Dynamics meeting[64]. In this meeting there were references to this in the plenary talks by Leutwyler[30] and Gasser[33]. In this working group two new related developments in this area were discussed.

One of the questions in CHPT has always been how to determine the large N_c suppressed couplings and in particular L_4^r and L_6^r. In most fits to the L_i^r these two are taken as input using large N_c argument and at best a check on the dependence is done[27]. Moussallam[65] presented how the scalar charge radius of the pion and especially its strange scalar charge radius of the ion can be used to determine these constants. In addition, sum rules involving the scalar correlator

$$\Pi_S \sim \langle 0|T\left(\bar{s}s(x)(\bar{u}u+\bar{d}d)(0)\right)|0\rangle \tag{2}$$

can be used to put strong constraints on L_6^r. He obtained positive values somewhat outside the large N_c-error bars usually assumed. One consequence of these substantial violations of large N_c or the OZI-rule is that the critical number of flavours above which there is no spontaneous chiral symmetry breaking is expected to be much less than $N_f = 16.5$ where asymptotic freedom is no longer valid.

The same question was taken up by Stern[66]. Defining condensates by the number of massless quark flavours, we look for deviations from the GOR relation via the difference of $X(N_{\text{massless}}) = -2\hat{m}\langle\bar{u}u\rangle(N_{\text{massless}})/(F_\pi^2 M_\pi^2)$ from 1. The conclusion is that $X(3)$ is rather suppressed unless $L_6^r(M_\rho) \approx -0.00026$. The quantity $X(2)$ which is measured in $\pi\pi$-scattering threshold parameters is not suppressed unless $r = m_s/\hat{m} < 20$. In fact, $X(2) - X(3)$ can be related to $\Pi_S(0)$ and must be positive. This means that $\bar{l}_3$ can be quite different from the usual estimates since these involve $X(3)$. It is therefore quite possible that standard CHPT is valid for two-flavours but not for three. Notice however that Ref.[27] find order 10% corrections to F_π and order 25 to 30% to M_π^2

already accounting for a 50% correction in the denominator of $X(3)$.

7.2 Large N_c QCD and understanding hadronic parameters

One of the subjects that was somewhat underrepresented at this meeting but looming as a large background problem in many of the talks was the connection between QCD and chiral dynamics at a higher than symmetry considerations level. One of the more recent approaches here is to combine large N_c-methods with meson dominance assumptions. This approach was discussed shortly by Golterman[67] where a curious relation between F_π and M_ρ was derived from global duality in the large N_c limit. This approach has grown out of attempts at understanding the successes of chiral models like the chiral quark model or the ENJL model. More references are in Ref.[67].

7.3 CHPT methods at other energy scales

The Higgs sector of the standard model is really just the linear sigma model with some parts of the chiral symmetry group gauged. It is therefore very tempting to simply replace it with a nonlinear sigma model. This is basically the technicolor scenario. In its simplest version it assumes a scale up of the QCD dynamics to the weak scale. This simplest version is ruled out by the precision LEP experiments. However, simply replacing the Higgs sector by the equivalent of the CHPT Lagrangian is not quite correct as described by Nyffeler[68] in his contribution. There are subtleties involved with gauge invariance and due to the presence of fermions more terms are in principle possible. In the light of this more general approach, LEP has not ruled out a strongly interacting Higgs sector à la technicolor, but only its scaled version from QCD. It is thus possible that future colliders will serve us with a next level of Chiral Dynamics.

8 η

The large N_c limit of QCD [69] is the background of the work presented by R. Kaiser [70] in his talk on "Chiral perturbation theory and $1/N_c$-expansion", an argument already discussed by H. Leutwyler in his plenary talk[30]. Kaiser briefly reviews the effective theory that describes the low energy properties of QCD with three light quarks and a large number of colours, N_c, and then discusses the mechanisms that forbid the Kaplan-Manohar transformation in this framework. At large N_c the occurrence of a new energy scale ($M_{\eta'}$) leads to a more complicated structure of QCD. In the limit $N_c \to \infty$, the $\mathrm{U}(1)_A$-anomaly is suppressed and this symmetry breaks down: $\mathrm{U}(3)_R \times \mathrm{U}(3)_L \to U(3)_V$. The formulation of the effective theory at large N_c involves a simultaneous expansion in powers of momenta, quark masses and $1/N_c$: δ-expansion [71]. The symmetry of Kaplan and Manohar is not realized at large N_c. Within this framework quark mass ratios may be determined unambiguously also at next-to-next-to leading order.

F. Ambrosino [47] in his talk on "KLOE first results on η, η'", reported about the preliminary measurement of $\phi \to \eta\gamma$, $\phi \to \eta'\gamma$ [54] with the $\sim$8 millions ϕ decays detected by the KLOE experiment in the 1999 data taking with $2.4 pb^{-1}$. The value of BR($\phi \to \eta'\gamma$) is a probe of the gluonium content of the η' [72] while the ratio $R = \frac{\Gamma(\phi\to\eta'\gamma)}{\Gamma(\phi\to\eta\gamma)}$ is strictly related to the pseudoscalar mixing angle [73,74]. The decays $\phi \to \eta\gamma$, $\phi \to \eta'\gamma$ have both been studied in the final states $\pi^+\pi^-\gamma\gamma\gamma$ and 7γ. $\phi \to \eta\gamma$ decays are the main background for the rare $\phi \to \eta'\gamma$ channel and at the same time they constitute a high statistics control sample in the selection of $\phi \to \eta'\gamma$ events. Preliminary results show a perfect agreement between data and Monte Carlo. A constrained kinematic fit, together with topological cuts, is used to improve the S/B ratio. After the selection 21 ± 4.6 η' events survive in the $\pi^+\pi^-\gamma\gamma\gamma$ final state and $6^{+3.3}_{-2.2}$ in the 7γ final state with less than one expected background event at 90% CL. This is the first observation of the $\phi \to \eta'\gamma \to 7\gamma$ decay chain. For the $\pi^+\pi^-\gamma\gamma\gamma$ final state they obtain $R = (7.1 \pm 1.6(\mathrm{stat.}) \pm 0.3(\mathrm{syst.})) \cdot 10^{-3}$ or $\mathrm{BR}(\phi \to \eta'\gamma) = (8.9 \pm 2 \pm 0.6) \cdot 10^{-5}$. This result has the same level of accuracy of the current world average.The high value of $\mathrm{BR}(\phi \to \eta'\gamma)$ disfavours models with large gluonium admixtures of the η'. Using formulas given in [74], the value of R is used to extract a mixing angle $\vartheta_P \simeq -19°$.

η decays are a powerful test of CHPT as underlined by B. Nefkens [75] in his talk on "New Tests of Chiral Perturbation Theory in η Decays using the Crystal Ball". The G-parity violating $\eta \to 3\pi^0$ decay occurs primarily as a consequence of the up-down quark mass difference, $m_u - m_d$. Thus far CHPT has not succeeded in accounting fully for the experimental $\eta \to 3\pi$ decay rate. The role played by dynamical effects with terms $\mathcal{O}(p^6)$ may be explored by a precise measurement of the quadratic slope parameter α in $\eta \to 3\pi^0$ decay which, according to present theory [76], is expected to be $\alpha = -(14 \text{ to } 7) \times 10^{-3}$. The existing experimental data from GAMS-2000 [77] and Crystal Barrel [78] have rather low accuracy. The Crystal Ball [79] apparatus at the AGS has produced a sample of 6×10^6 $\eta \to 3\pi^0$ in $\pi^- p \to \eta n$ near threshold and a very pure subsample of 1×10^6 $\eta \to 3\pi^0$ decays, with a background $< 1\%$, has been selected using a kinematic fit to the process $\pi^- p \to \eta n \to 3\pi^0 n \to 6\gamma n$. With this data the value $\alpha = -(33 \pm 3_{\rm stat} \pm 6_{\rm syst}) \times 10^{-3}$ which is in agreement with theory in the sign but not in the value of α. Analogous measurement in $\eta \to \pi^+\pi^-\pi^0$ decays is planned by the WASA[80] and KLOE collaborations: a comparison of α^{000} and α^{+-0} in an important test of isospin invariance. The Crystal Ball collaboration has also performed preliminary measurements of η rare decays such as $\eta \to \pi^0\gamma\gamma$, $\eta \to 3\gamma$ and $\eta \to \pi^0\pi^0\gamma\gamma$.

9 Conclusions

From the breadth of topics covered in this working group it is obvious that chiral dynamics in the Goldstone sector is a very active field with progress both on the experimental and theoretical front. As is also obvious, enough puzzles and challenges remain to keep all of us busy till the next Chiral Dynamics meeting.

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