HADRONIC PHYSICS

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ABSTRACT

I review the novel results and developments presented at the Third Workshop on Physics and Detectors for DAΦNE that deal with hadronic physics. Topics discussed include: the scalar quark condensate, kaon decays, the sector of scalar and vector mesons, kaon-nucleon scattering, pion- and kaon-nucleon sigma terms, and strange nuclear physics.

1 Hadronic physics at DAΦNE energies: Why bother?

Hadronic physics at DAΦNE covers energies of about 1 GeV and below. This is a particularly challenging regime since standard perturbation theory in the strong coupling constant $\alpha_s(Q^2)$ is not applicable. In fact, we do not even know from basic principles whether $\alpha_s(Q^2)$ increases monotonically with decreasing $Q^2$, as suggested by the $\beta$–function calculated in the perturbative regime, or flattens out. Therefore, nonperturbative methods need to be developed and employed. This is in stark contrast to say e.g. the precise physics of the Standard Model tested at LEP and

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elsewhere. As I will discuss in section 2, chiral perturbation theory, eventually combined with other methods like e.g. dispersion relations, allows one to pin down some very fundamental parameters of QCD. These are the ratios of the light quark masses as well as the size of the scalar quark–antiquark condensate, which is linked to the spontaneous symmetry violation in QCD. One can also extend these methods to include baryons, some pertinent remarks are made in section 3. In particular, the so–called pion and kaon nucleon sigma terms have attracted a lot of attention over a long time, simply because they are the proton matrix elements of the explicit chiral symmetry breaking part of the QCD Hamiltonian. In addition, this energy regime offers a rich phenomenology. For example, it now appears that in the sector of scalar resonances, excitations have been observed which are not simple $\bar{q}q$ quark model states, but have some gluon components - either as hybrids or glueball–meson mixtures. Many models of QCD as well as its lattice formulation (with all its intrinsic problems) call for the existence of such states. Other interesting aspects of the properties of mesons in the energy range of relevance here are also touched upon in section 3. Last but not least, the nucleus can act as a filter and lets us study some processes that are forbidden in free space, one particularly interesting example being the $\Lambda\Lambda \rightarrow \Lambda N$ transition which leads to the so–called non–mesonic decays of hypernuclei. This and other recent developments are briefly surveyed in section 4. All the interesting new results related to CP violation and rare kaon decays, which might hint at physics beyond the Standard Model, are reviewed by Chris Quigg 1). To summarize this brief motivation, despite many decades of studying phenomena in the energy range accessible to DAΦNE, there are many open questions and only recently precise theoretical tools have been developed to answer some of these questions in a truly quantitative manner. In addition, there is a host of new precise data mostly related to kaon decays. Hopefully, DAΦNE will further increase this data base soon. For other motivations and a different point of view, I refer to Pennington’s talk 2).

2 The baryon number zero sector

In this section, I will first make some comments on novel developments concerning the chiral structure of QCD and then move to higher mass states, such as the $\phi(1020)$ and the scalar sector.
2.1 Chiral QCD

It is well known that the QCD Lagrangian for the three light quark flavors can be written as

\[ \mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{QCD}}^0 - \bar{q} M q , \]

where \( q^T = (u, d, s) \) collects the light quark fields, \( M = \text{diag}(m_u, m_d, m_s) \) is the current quark mass matrix and the term \( \mathcal{L}_{\text{QCD}}^0 \) exhibits a chiral \( SU(3)_L \times SU(3)_R \) symmetry. This symmetry is spontaneously broken down to its vectorial subgroup \( SU(3)_V \) with the appearance of eight Goldstone bosons, collectively denoted as “pions”. The pions interact weakly at low energies. They can couple directly to the vacuum via the axial current. The corresponding matrix element \( \langle 0 | A_\mu | \pi \rangle \) is characterized by the typical scale of strong interactions, the pion decay constant \( F_\pi \simeq 100 \text{ MeV} \). These pions are not exactly massless but acquire a small mass due to the explicit symmetry violation, such as \( M_{\pi}^2 = (m_u + m_d)B + \ldots \), where \( B \) parametrizes the strength of the scalar–isoscalar quark condensate, \( B = |\langle 0 | \bar{q} q | 0 \rangle|/F_\pi^2 \). Based on these facts, one can formulate an effective field theory (EFT) which allows one to exactly explore the consequences of the chiral QCD dynamics. This EFT is chiral perturbation theory. Its present status has been reviewed by Gasser recently.

2.1.1 News on the quark condensate

Over the last few years, the question about the size of \( B \) has received a lot of attention. In the standard scenario, \( \langle 0 | \bar{q} q | 0 \rangle \simeq (-230 \text{ MeV})^3 \), so that \( B \simeq 1.4 \text{ GeV} \) and one can make very precise predictions, as reviewed here by Colangelo. In particular, the isospin zero S–wave \( \pi \pi \) scattering length \( a_0^0 \) can be predicted to better than 5% accuracy. However, the value of \( B \) might be smaller. In fact, one can reorder the chiral expansion allowing to float \( B \) from values as small as \( F_\pi \simeq 100 \text{ MeV} \) to the standard case. For a small value of \( B \), the quark mass term has to be counted differently and to a given order in the chiral expansion, one has more parameters to pin down. For \( B \) on the small side, \( a_0^0 \) could be as much as 30% larger than in the standard case. These two scenarios lead also to a significant difference in the quark mass expansion of the Goldstone bosons. Consider e.g. the charged pions,

\[ M_{\pi^\pm}^2 = (m_u + m_d)B + (m_u + m_d)^2A + \mathcal{O}(m_{u,d}^3) . \]

In the standard scenario the linear term is much bigger than the quadratic one, in the large \( B \) case they are of comparable size. An immediate consequence is that while in the first case the Gell-Mann–Okubo relation \( 4M_K^2 = 3M_\eta^2 + M_\phi^2 \) comes out naturally, in the other scenario parameter tuning is necessary. For a discussion of what can be
learned from lattice gauge theory in this context, see e.g. the lectures by Ecker 8). Ultimately, this question has to be decided experimentally. So far, the best “direct” information on the S-wave $\pi\pi$ scattering phase close to threshold comes from $K_{\ell 4}$ decays, since due to the final–state theorem of Fermi and Watson, the phase of the produced pion pair is nothing but $\delta_0(s) - \delta_1(s)$ with $\sqrt{s} \in [280, 380]$ MeV and $\delta_1(s) < 1^\circ$ in this energy range. All data from the seventies seem to indicate a large scattering length with a sizeable error. This unsatisfactory situation will be improved very soon. The preliminary data from the BNL E865 collaboration were shown by J. Lowe 9) (for a glimpse on these data, see the contribution of S. Pislak to HadAtom 99 10)). They are not yet final, in particular radiative corrections have not yet been accounted for, but taken face value, they are clearly supporting the standard scenario.

2.1.2 Pionic atoms

Another method to measure the elusive S-wave scattering length comes from the lifetime of $\pi^+\pi^-$ atoms. This electromagnetic bound state with a size of approximately 400 fm can interact strongly and decay into a pair of neutral pions. The lifetime of this atom is directly proportional to the S-wave scattering length difference $|a_0^0 - a_2^0|^2$. Therefore, a determination of this lifetime to 10% gives the scattering length difference to 5%. The DIRAC experiment at the CERN SPS is well underway as reported by Adeva 11). Also, the theory is well under control. Recent work by the Bern group 12) has lead to a very precise formula relating the lifetime to $\pi\pi$ scattering including isospin breaking in the light quark mass difference and the electric charge (the formalism is developed in refs. 13, 14)). It is mandatory that the experimenters use this improved Deser–type formula in their analysis! It would also be interesting to calculate the properties of $\pi K$ atoms and measure their lifetime. For a much more detailed discussion I refer to the proceedings of HadAtom 99 10).

2.1.3 Kaon decays

As stressed in the talks by D’Ambrosio 15) and Colangelo 13), there are many chiral perturbation theory predictions for all possible kaon decay modes. It was therefore very interesting to see that a huge amount of new data is available and still to come, as detailed in the talks of Lowe 11), Kettell 16) and Flyagin 17). For the sake of brevity, I will only discuss three topics here.

- $K_0^0 \rightarrow \pi^0\gamma\gamma$: This is a particularly interesting decay with a long history. It vanishes at leading order $O(p^2)$ in the chiral expansion and is given by a
finite loop effect at next-to-leading order, $O(p^4)$. While the predicted two-photon spectrum \cite{18} agreed well with the data \cite{19}, the branching ratio was underestimated by about a factor of three. To cure that, unitarity corrections and higher order contact terms have been considered. In particular, at order $p^6$ there is an important vector–meson–dominance contribution, parametrized in terms of the coupling $a_V$. The $O(p^6)$ calculation with $a_V = -0.7$ not only improves the two-photon spectrum but also the branching ratio agrees with experiment. More important, as stressed by D’Ambrosio, this value for $a_V$ is consistent with a VMD model and analysis of the process $K_L \to \gamma\gamma^*$.  

- $K \to \pi\gamma^*$: This decay mode was discussed by d’Ambrosio and Lowe. The matrix element for this process is given in terms of one invariant function, $A(K \to \pi l^+l^-) \sim W(z)$, with $z = (M_{ll}/M_K)^2$ and $M_{ll}$ the mass of the lepton pair. The invariant function $W(z)$ has the generic form

$$W(z) = \alpha + \beta z + W_{\pi\pi}(z),$$

where $\alpha$ and $\beta$ are related to some low–energy constants, but the momentum dependence of the pion loop contribution $W_{\pi\pi}(z)$ is unique and leads to unambiguous prediction. The data shown by Lowe can indeed be described significantly better with the form given in eq.(3) than with a linear polynomial with also two free parameters. Thus, we have another clear indication of chiral pion loops.

- $K \to 3\pi$: The non-leptonic weak chiral Lagrangian has a host of undetermined parameters at next-to-leading order. For specific reactions, like e.g. $K \to 2\pi$ or $K \to 3\pi$, only a few of these enter. It is thus important to have some data to pin down these constants and based on that, make further predictions. Flyagin showed some results from SERPUKHOV on the mode $K^+ \to \pi^+\pi^0\pi^0$. In terms of slope and quadratic slope parameters, the invariant matrix element squared can be written as $|M|^2 \sim 1 + gX + hX^2 + kY^2$, with $X, Y$ properly scaled relative pion momenta. The three slopes $g, h$ and $k$ could be determined and thus further tests of the weak non-leptonic chiral Lagrangian are possible.

2.2 Higher masses

In the region between 1 and 2 GeV, the spectrum of states is particularly rich and interesting. As explained in detail by Barnes \cite{20} and Donnachie \cite{21}, we now have some first solid evidence for glueballs and hybrids. Glueballs are states made of glue
with no quark content. In an ideal world of very many colors, \( N_C \to \infty \), the glueball sector decouples from the sector made of mesons and baryons, i.e. the states made of quarks and anti–quarks, see refs.\(^2\)\(^2\)\(^3\). In the real world with \( N_C = 3 \), matters are more complicated. The decay pattern of the glueball candidate as mapped out in big detail by the Crystal Barrel collaboration\(^2\)\(^4\) is most simply interpreted in terms of mixing, most probably of two genuine meson and one glueball state. Similarly, there are evidences for hybrids, i.e. states made of quarks and “constituent” gluons, a particularly solid candidate being the \( 1^{-+}(\rho\pi)(1600) \). Clearly, if one such state exists, there is no reason to believe that there are not many more (Pandora’s box?). In particular, DAΦNE could contribute significantly to the search for vector hybrids like the \( \phi' \sim |s\bar{s}g⟩ \) or the \( \omega' \) – if these are not too heavy. After these more general remarks, let me turn to two special topics.

2.3 Remarks on the scalar sector

The scalar meson sector is still most controversial. It consists of the elusive “sigma”, the \( a_0 \), the \( f_0 \) and so on. Much debate is focusing about the nature of these states, which of them belong to the quark model octet/nonet (assignment problem), which of these are \( K\bar{K} \) molecules (structure problem) and so on. Certainly, these scalars can be produced in photon–photon fusion at DAΦNE. I will not dwell on these issues here but rather add some opinion about the the “sigma”, which is labeled \( f_0(400 – 1200) \) by PDG. First, a “charming” new result was reported by Appel\(^2\)\(^7\) in one parallel session. The invariant mass distribution of the final state of the decay \( D^+ \to \pi^+\pi^0\pi^0 \) measured at FNAL was analyzed in terms of conventional resonances and could not be explained. If one adds, however, a \( \pi\sigma \) contribution, this turns out to be a strong channel and the \( \sigma \) parameters from a best fit are \( M_\sigma = 486 \text{ MeV} \) and \( \Gamma_\sigma = 351 \text{ MeV} \), in agreement with other interpretations of \( \pi\pi \) scattering data, for a recent review see e.g.\(^2\)\(^8\). The role of such a state in the \( \phi \to \pi^+\pi^-\gamma \) decay was discussed here by Lucio\(^2\)\(^9\). I would like to take the opportunity to add my opinion about this state:

- It is not a “pre–existing” resonance, but rather a dynamic effect due to the strong pion–pion interaction in the isospin zero, S–wave. Specific examples how to generate such a light and broad sigma are the modified Omnès resummation in chiral perturbation theory\(^3\)\(^0\),\(^3\)\(^1\) or the chiral unitary approach.\(^1\)

\(^1\)Notice that it is important that such states have “exotic” quantum numbers. If not, one can always cook up some minor modifications of the quark model to explain states with constituent gluons by some other mechanism. One quite old example is debated in refs.\(^2\)\(^5\),\(^2\)\(^6\).
of Oller and Oset \cite{32,33}, or others.

- It is certainly not the chiral partner of the pion, as suggested by models based on a linear representation of chiral symmetry. For a critical analysis of the renormalizable $\sigma$-model in the context of QCD, I refer to ref. \cite{4}.

- It is long known in nuclear physics that the intermediate range attraction between two nucleons can be explained by the exchange of a light sigma. It is also known since long how to generate such a state in terms of pion rescattering and box graphs including intermediate delta isobars, for a nice exposition see e.g. ref. \cite{34}.

I was particularly amazed to see the many new and interesting data from $e^+e^-$ annihilation at VEPP–2M (Novosibirsk), which were presented by Sainkiv \cite{35} and Milstein \cite{36}. I will only pick out three aspects of these results, which I found most interesting:

- The three pion final state $\pi^+\pi^-\pi^0$ indicates the existence of a low–lying $\omega'$ mesons at $M_{\omega'} = (1170 \pm 10)$ MeV with a width of $\Gamma_{\omega'} = (197 \pm 15)$ MeV. Also confirmed is the $\omega'(1600)$, whereas the $\omega'(1420)$ was not seen. The role of low–lying (effective) excited omegas in the analysis of the strange vector currents and the violation of the OZI rule is discussed e.g. in ref. \cite{37}.

- The analysis of the decays $\phi \to f_0\gamma, a_0\gamma, \eta\pi\gamma$ lends credit to the hypothesis that the $a_0$ and $f_0$ are $qq\bar{q}\bar{q}$ and not simple $q\bar{q}$ states.

- The channel $e^+e^- \to 4\pi$ is dominated by the $a_1(1260)\pi$ intermediate state. The $a_1\pi$ amplitude extracted by the Novosibirsk group from electron–positron annihilation \cite{38} is completely consistent with the one obtained from analyzing the high precision data on $\tau \to 3\pi\nu_\tau$ from CLEO and ALEPH \cite{39}.

3 The baryon number one sector

I now turn to processes involving exactly one baryon in the initial and the final state. Of most relevance for DAΦNE is, of course, the kaon–nucleon system. However, before one can hope to tackle this problem in a truly quantitative manner, it is mandatory of having obtained a deep understanding of the somewhat “cleaner” pion–nucleon system. This refers to a) the smallness of the up and down quark masses compared to the strange quark mass, which makes explicit symmetry breaking easier to handle (i.e. a faster convergence of the chiral expansion) and b) to
the appearance of very close to or even subthreshold resonances in the KN sys-
tem, like e.g. the famous Λ(1405) – such interesting complications do not arise in
pion–nucleon scattering. Before considering explicit examples, we should address
the following question:

3.1 What can we learn?

Clearly, the chiral structure of QCD in the sector with baryon number one is inter-
esting per se. Some prominent examples which have attracted lots of attention are
neutral pion photoproduction, real and virtual Compton scattering off the proton
or hyperon radii and polarizabilities, to name a few. In all these cases, the relevance
of chiral pion loops is by now firmly established and underlines the importance
of the pion cloud for the structure of the ground state baryons in the non–perturbative
regime. The analysis of the baryon mass spectrum allows to give further constraints
on the ratios of the light quark masses, see e.g. ref. [10], [11]. Furthermore, in the
pion–nucleon system, isospin breaking \( \sim (m_u - m_d) \) and explicit chiral symmetry
\( \sim (m_u + m_d) \) start at the same order, quite in contrast to the pion case. In addition,
much interest has been focused on the question of “strangeness in the nucleon”, more
precisely the expectation values of operators containing strange quarks in nucleon
states. The sigma terms discussed below are sensitive to the scalar operator \( \bar{s}s \).
Complementary information can be obtained from parity–violating electron scatter-
ing (\( \sim \bar{s}\gamma_\mu s \)) or polarized deep inelastic lepton scattering (\( \sim \bar{s}\gamma_\mu \gamma_5 s \)).

3.2 Lessons from πN

It is important to recall some lessons learned from pion–nucleon scattering (in some
cases the hard way). As emphasized in the clear talks by Gasser [12] and Rusetsky
[13], not only is the scalar sector of chiral QCD intrinsically difficult but also
for making precise predictions at low energies, one has to consider strong and elec-
tromagnetic isospin violation besides the hadronic isospin–conserving chiral correc-
tions. Often, it is mandatory to combine chiral perturbation theory with dispersion
relations to achieve the required accuracy. As a shining example, I recall the pion–
nucleon sigma term story (a very basic and clear introduction using the pion sigma
term as a guideline is given in Gasser’s talk [13]). The quantity that one wants to
determine is

\[
\sigma(t = 0) = \langle p|\hat{m}((\bar{u}u + \bar{d}d)|p\rangle ,
\]

with \( |p\rangle \) a proton state of momentum \( p \), \( \hat{m} \) is the average light quark mass and
\( t \) the invariant momentum transfer squared. Clearly, momentum transfer zero is
not accessible in the physical region of $\pi N$ scattering. So how can one get to this quantity? The starting point is the venerable low–energy theorem of Brown, Pardee and Peccei \cite{14}

$$\Sigma = \sigma(0) + \Delta \sigma + \Delta R .$$

(5)

Here, $\Sigma = F_\pi^2 \bar{D}^+(\nu = 0, t = 2M_\pi^2)$ is the isoscalar $\pi N$ scattering amplitude with the pseudovector Born term subtracted at the Cheng–Dashen point\cite{32}, and $M_\pi$ and $F_\pi$ are the charged pion mass and the weak pion decay constant, respectively. The numerical value of $\Sigma$ can be obtained by using hyperbolic dispersion relations and the existing pion–nucleon scattering data base. The most recent determination of $\Sigma$ based on this method is due to Stahov \cite{45}, $\Sigma = 65 \ldots 75$ MeV, not very different from the much older Karlsruhe analysis. The scalar form factor, $\Delta \sigma = \sigma(2M_\pi^2) - \sigma(0)$ has been most systematically analyzed in ref. \cite{46}. The resulting value of $\Delta \sigma \simeq 15$ MeV translates into a huge scalar nucleon radius of $r_S^2 \simeq 1.6$ fm$^2$ (note that the typical electromagnetic nucleon radii are of the order of 0.7 fm$^2$). A similar enhancement of the scalar radius also appears for the pion, see e.g. refs. \cite{4,30}. Finally, $\Delta R$ is a remainder not fixed by chiral symmetry. The most systematic evaluation of this quantity has lead to an upper bound, $\Delta R \simeq 2$ MeV \cite{47}. Putting all these small pieces together, one arrives at $\sigma(0) \simeq (45 \pm 10)$ MeV which translates into $y = 2 \langle p|\bar{s}s|p\rangle / \langle p|\bar{u}u + \bar{d}d|p\rangle \simeq 0.2 \pm 0.1$. These results have been confirmed recently using a quite different approach \cite{18} (using also the Karlsruhe–Helsinki phase shift analysis as input). This determination of $\Sigma$ has been challenged over the years by the VPI/GW group (and others). Their most recent number is sizeably larger, $\Sigma \simeq 90 \pm 8$ MeV \cite{49}. However, if one employs the method of ref. \cite{18} to the $\bar{A}^+$ amplitude of the latest two VPI/GW partial analyses (SP99 and SM99), one gets a much larger sigma term, $\sigma(0) \simeq 200$ MeV. This casts some doubts on the internal consistency of the VPI/GW analysis. Personally, I do not understand how such a large value for the sigma term could be made consistent with other implications of chiral dynamics in the meson–baryon sector. In this context, I also wish to point out that so far, we have considered an isospin symmetric world. In ref. \cite{50} it was shown that isospin violation can amount to a 8% reduction of $\sigma(0)$ and Rusetsky \cite{43} demonstrated that the electromagnetic corrections used so far in the analysis of pionic hydrogen to determine the S–wave scattering length \cite{9} have presumably been underestimated substantially. The moral is that to make a precise statement in this context, many small pieces have to be calculated precisely. Committing a

\footnote{This point in the Mandelstam plane is special because chiral (pion mass) corrections are minimal.}
sin at any place leads to a result which should not be trusted. Finally, I mention
that astrophysical consequences of the strange scalar nucleon matrix element are
discussed in ref. 52).

3.3 Status and perspectives for KN

After this detour, I come back to kaons, i.e. the kaon–nucleon system as discussed by
Olin 53), touched upon by Gasser 42) and for a recent review, see ref. 54). Because
of the strange quark, one can form two new sigma terms, which are labelled $\sigma_{K_N}^{(1,2)}$ in the isospin basis or $\sigma_{K_N}^{(u,d)}$ in the quark basis,

$$\sigma_{K_N}^{(1)} = \frac{1}{2} \langle \hat{m} + m_s | \bar{u}u + \bar{s}s | p \rangle ,$$

$$\sigma_{K_N}^{(2)} = \frac{1}{2} \langle \hat{m} + m_s | -\bar{u}u + 2\bar{d}d + \bar{s}s | p \rangle ,$$

(6)

with $t = (p' - p)^2$. These novel sigma terms in principle encode the same information
about $y$ as does the pion–nucleon sigma term. This is one reason for attempting
to determine them. One also needs to know the kaon–nucleon scattering amplitude as input for strangeness nuclear physics, as discussed in the next section. So
there is ample need to improve the data basis and obtain a better theoretical understand-
ing. I briefly review where we stand with respect to low–energy kaon–nucleon interactions.

3.3.1 Status report

I begin with a summary of the data, as reviewed by Olin 53). Consider first $K^+N$. For total isospin $I = 1$ (obtained from elastic $K^+p$ scattering), the S–waves are fairly well known and the P–waves are small. The situation for the $I = 0$ data based on $K^+d$ scattering and $K^0\bar{p} \rightarrow K^+n$ is very unsatisfactory - the S–waves are very uncertain and the P–waves are very large already at small momentum. This is the equivalent channel to the isoscalar S–wave $\pi N$ amplitude, i.e. to leading chiral order (current algebra) the pertinent scattering length vanishes. $K^-N$ is, of course, resonance dominated due to the presence of the strange quark. The most famous state here is the $\Lambda(1405)$, which has been interpreted by some as a KN subtreshold (virtual) bound state whereas others consider it a “normal” three quark state. Clearly, such very different pictures should lead to very pronounced differences in the electromagnetic radii or other observables. These two pictures can eventually be disentangled by electroproduction experiments. How that can work has been shown for the $S_{11}(1535)$ in ref. 55), where it was demonstrated that
electroproduction off deuterium, \(e+d \rightarrow e'+N+N^*\), can be sensitive to the structure of the resonance \(N^*\) under consideration. Data on \(K^0N\) are not very precise. There is also information on the \(K^-p\) bound state. The long standing discrepancy between the data from kaonic hydrogen and extrapolation of \(KN\) scattering data to zero energy was resolved by the fine experiment at KEK \(^{56}\). The strong interaction shift turned out to be negative and also the width could be determined, but not very precisely.

3.3.2 Prospects for DAΦNE

The DEAR experiment, which was discussed by Guaraldo \(^{57}\), attempts to determine the strong interaction shift and width of kaonic hydrogen to an accuracy of 1% and 3%, respectively. If that will be achieved, it would essentially pin down zero energy S-wave scattering and become a benchmark point. Beware, however, that to determine the \(KN\) sigma terms much more precise information (coming from scattering) will be needed. Also, the theoretical analysis needs to be sharpened since the \(KN\) Cheng–Dashen point at \(t = 4M_K^2 \simeq 1\) GeV\(^2\) is very far away from the zero energy point. As stressed by Olin \(^{53}\), FINUDA will attempt to measure \(K_L^0p\) scattering reactions to 5% accuracy, however, in a fairly small momentum interval. The good news is that the theoretical machinery has considerably improved over the last years. First, the rigorous work by the Bern group on \(\pi^+\pi^-\) and \(\pi^-p\) bound states \(^4\) \(^{12}\), \(^43\) can certainly be extended to the \(K^-p\) case (for that, a detailed investigation of electromagnetic corrections for \(K\pi\) scattering has to be done – and is underway \(^{58}\)). Second, \(KN\) scattering has been considered based on SU(3) chiral Lagrangian using coupled channel techniques \(^59\), \(^60\). In these approaches, one uses chiral symmetry to constrain the potentials between the various channels and with a few parameters (some from the chiral Lagrangian and other from the regularization), one can describe a wealth of data related to scattering, decays and also electromagnetic reactions. It would still be interesting to implement even stronger constraints on the \(KN\) system, such as the leading Goldstone boson loop effects. One particularly interesting outcome of these studies is that not only the \(\Lambda(1405)\) but also the \(S_{11}(1535)\) are quasi–bound \(\bar{K}N\) and \(K^+Y\) states, respectively (as mentioned above). So it appears that more precise data as expected from DAΦNE are timely and will contribute significantly to our understanding of three flavor meson–baryon dynamics.
4 The baryon number greater than one sector

I now turn to the nucleus, more precisely, to systems with more than one nucleon. The objects to be studied are hypernuclei, i.e. nuclei with one (or more) bound hyperon(s) (or even cascades) and also atomic and nuclear kaonic bound states. This is the realm of what is often called strangeness nuclear physics\(^3\). Before discussing some specific examples, we have to address the following question:

4.1 Why “strange” nuclear physics?

The properties of hypernuclei are of course sensitive to the fundamental \(YN\) and \(YY\) (for strangeness \(S = -2\)) interactions. A solid determination of interactions in such systems allows one e.g. to address the question of flavor SU(3) symmetry in hadronic interactions. Furthermore, one can study the weak interactions of baryons in the nuclear medium. Of special interest are novel mechanisms like \(\Lambda N \rightarrow NN\), which have \(\Delta S = 1\) and have parity conserving as well as parity violating components. This might eventually give some novel insight into the \(\Delta I = 1/2\) rule. Electromagnetic production of hypernuclei is complementary to the usual hadronic mechanisms like e.g. stopping of kaons and thus one can access different levels and get a more complete picture of hypernuclear properties. One can also study the \(\bar{K}N\) effective interaction or the kaon–nucleus interaction at rest in deeply bound kaonic states. Mesons and baryons with strangeness can also affect the nuclear equation of state significantly and thus might lead to interesting phenomena in astrophysics and relativistic heavy ion collisions. For these reasons (and others), an intense experimental program is underway or upcoming at KEK, BNL, Dubna, TJNAF and DAΦNE, COSY and other labs.

4.2 Example 1: Non-mesonic decays of hypernuclei

Spectroscopy of \(\Lambda\)–hypernuclei allows one to study the fundamental \(\Lambda N\) interaction. The weak decays of such nuclei give additional tests of elementary particle physics theories, as discussed in the talk by Ramos. In free space, the \(\Lambda\) decays into \(p\pi^-\) and \(n\pi^0\), with a relative branching fraction of about 2. This is another manifestation of the \(\Delta I = 1/2\) rule. In typical nuclei, the Fermi momentum is about 300 MeV, i.e. larger than nucleon momentum in the free \(\Lambda\) decay, \(p_N \simeq 100\) MeV. Thus, the mesonic decay is Pauli blocked and new decay channels open, like the one–nucleon induced decay, \(\Lambda n \rightarrow nn\) and \(\Lambda p \rightarrow p\) with the corresponding partial width

\(^3\)I prefer to call it \textit{strange nuclear physics} because of the many “strange”, that is: interesting, phenomena happening in such systems.
\( \Gamma_n \) and \( \Gamma_p \), respectively. Another non-mesonic channel is the 2N–induced decay, \( \Lambda np \to nnp \). In the one–pion-exchange (OPE) model, one can describe roughly the total non–mesonic decay rate, but for that one has to include form factors at the vertices as well as to account for the strong \( \Lambda N \) and \( NN \) interactions in the final and initial state, respectively. The form factor dependence is particularly troublesome, since in a truly field theoretic description of one–boson–exchange, such a concept makes no sense. Also, in OPE tensor transitions are enhanced, which lets one expect that \( \Gamma_n/\Gamma_p \) is small, quite in contrast to the experimental finding \( \Gamma_n/\Gamma_p \simeq 1 \). As shown by Ramos, the inclusion of other mechanisms like exchanges of heavier mesons, correlated two–pion exchange or the two-nucleon induced decay do not resolve this problem. Even worse, calculations within seemingly equivalent models lead to very different results for the partial rates. So it seems mandatory to develop better models, based e.g. on the latest Nijmegen \( YN \) potential or the upcoming improved Jülich model \(^{67}\)). I would like to issue two warnings here: First, as already remarked, the area of meson–exchange models supplemented by form factors is certainly at its end, more systematic effective field theory approaches will eventually take over. Such a change of dogma is presently happening on the level of the \( NN \) force. Second, it should also be stressed that very few is known about the underlying \( YNM \) couplings - this has been stressed in another context in ref. \(^{68}\).

4.3 Example 2: \( \Lambda \Sigma^0 \) mixing effects

An important effect in \( \Lambda \)–hypernuclei is the mixing of the \( \Lambda \) with the \( \Sigma^0 \). Consequences of this mixing were discussed by Akaishi \(^{69}\) and Motoba \(^{70}\). It solves e.g. the overbinding problem in \( ^5\Lambda\text{He} \), which was pointed out by Dalitz and others \(^{71}\) long time ago. The \( 0^+ \) level in \( ^3\Lambda\text{He} \) moves to the correct binding energy due to the transition potential \( V_{\Lambda N,\Sigma N}(Q/e)V_{\Sigma N,\Lambda N} \) taken e.g. from the Nijmegen potential (version D). Here, the operator \( Q \) assures the Pauli principle and the energy denominator \( e \) deviates from its free space version \( e_0 \) due to energy dissipation. It was also pointed out by Motoba that the \( \Lambda \Sigma^0 \) coupling in the \( 0^+ \) states of \( ^4\Lambda\text{H} \) and \( ^4\Lambda\text{He} \) is significantly enhanced due to coherent addition of various components, which leads to a very strong and attractive \( NNN \to NNA \) three–body force. Of course, all these findings are very sensitive to the underlying \( YN \) interaction, which can not yet be pinned down very reliably due to the lack of sufficiently many precise data.
4.4 Other interesting results

There were many other interesting developments, I just mention three examples:

- Friedman \(^7\) described work on deeply bound kaonic atomic states, which can be calculated by use of an optical potential, \(V_{\text{opt}}\). It was demonstrated that if this optical potential is obtained from a fit to the existing kaonic atom data, the predictions for the deeply bound states are independent of the precise form of \(V_{\text{opt}}\). These states can best be produced by the \((\phi, K^+)\) reaction for \(p_\phi \simeq 170\) MeV (which can e.g. be achieved in an asymmetric \(e^+e^-\) collider).

- Motoba \(^{70}\) and Imai \(^{62}\) discussed the possible role of the \(\Lambda\) as “glue” in the nucleus, leading to a shrinkage of nuclear radii. A particular example is \(^7\Lambda\text{Li}\), which in a cluster model can be described by an alpha–particle plus \(\Lambda\)–“core” surrounded by a neutron–proton pair. From the measurement of E2 and M1 transitions, one can deduce the radius, which indeed turns out smaller than the one of the equivalent system composed of nucleons only.

- As discussed by Imai \(^{62}\), the H–dibaryon simply does not want to show up. Even after a long term dedicated effort to find this six quark state, no signal has been found. Despite its uniqueness, it seems to have the same fate as all predicted dibaryon – nonexistence.

5 Expectations for the next DAΦNE workshop

With KLOE, FINUDA and DEAR hopefully soon producing data with the expected precision and experiments at other laboratories also supplying precision data, we can expect to discuss significant progress in our understanding of hadronic physics in the GeV region. On the theoretical side, apart from all the surprises to come, I mention a few topics which need to and will be addressed (this list is meant in no way to be exhaustive but rather reflects some of my personal preferences):

- In two as well as three flavor meson chiral perturbation theory, hadronic two loop calculations have been performed for a variety of processes. It has, however, become clear that at that accuracy one also needs to consider electromagnetic corrections. For the kaon decays to be measured at DAΦNE and elsewhere, such calculation must also include the leptons. The corresponding machinery to perform such investigations is found in ref. \(^{73}\).
• The calculation of the properties of hadronic atoms has received considerable attention over the last years, triggered mostly by the precise data from PSI for pionic hydrogen and deuterium and the DIRAC experiment ("pionium"). The effective field theory methods, which have proven so valuable for these systems, should be extended to the cases of $\pi^- K^+$ and $\pi^- d$ bound states to learn more about SU(3) chiral symmetry and the isoscalar S–wave pion–nucleon scattering length, respectively.

• Better models, eventually guided by lattice gauge theory, are needed to understand the structure of the observed exotic states and scalar mesons. It would be valuable to combine the quark model with constraints from chiral symmetry and also channel couplings. Only then a unique interpretation of these states can be achieved. Needless to say that besides the spectrum one also has to calculate decay widths and so on.

• A new dispersion–theoretical analysis of the pion–nucleon scattering data, including also isospin breaking effects (beyond the pion, nucleon and delta mass splittings) is called for to get better constraints on the pion–nucleon scattering amplitude in the unphysical region and thus pin down the sigma term more reliably. Presently available partial wave analyses are not including sufficiently many theoretical constraints (or are based on an outdated data set).

• Chiral Lagrangian approaches to low energy kaon–nucleon interactions should be refined. So far, the necessary resummation methods start from the leading or next–to–leading order effective Lagrangian. Thus, only certain classes of loop graphs are included. I consider it mandatory to also include the leading effects of the meson cloud consistently. How this can be done in the (much simpler) pion–nucleon system is demonstrated in ref. [74].

• The fundamental hyperon–nucleon interaction, which is not only interesting per se but also a necessary ingredient for the calculation of hypernuclei, has to be studied in more detail. As already mentioned, the Jülich group is presently working on a refined meson–exchange model [67]. I also expect studies based on effective field theory to give deeper insight, for a first step see ref. [75].

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