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The One-Boson-Exchange Potential Model Approach*

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Abstract

A review is given of the present situation in YN scattering. Special attention is given to the handling of SU(3) in the various meson exchanges. The importance of the almost always ignored contribution of the Pomeron is reiterated.

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I. INTRODUCTION

The experimental data on the hyperon-nucleon (ΛN, ΣN, and ΞN) and the hyperon-hyperon ($\Lambda\Lambda$, $\Lambda\Sigma$, $\Sigma\Sigma$) interactions are very scarce and have moreover large errors. To give a satisfactory description [1–3] of these data one needs a **large** theoretical input. This input is then not allowed to have too many free parameters, because the scarce data do not allow us to determine reliably too many parameters. The strategy is therefore to start with a known description of the NN-data [4–6], then apply SU(3) flavor symmetry to this NN-model in order to obtain this way an YN-model [7,8,6]. Such an approach can only be successful, when the relevant NN-model is already consistent with SU(3). Many models of the NN-interaction are not suitable for such an SU(3) generalization. An example of this is the Paris model [9]. To calculate the two-pion-exchange potential for NN in this model one needs phenomenological input from πN-scattering. For the YN-interactions one needs the analogous results from $\pi\Lambda$ and $\pi\Sigma$ scattering. Such results are not available.

The possibility of SU(3) generalization has in NN-models implications for the exchanged mesons. In NN-potentials one needs not only the pion-exchange potential, but one needs also the potentials due to the exchange of the other non-strange members η and η' of the same pseudoscalar octet. Next to the ρ and ω exchange potentials, one also needs to include the ϕ exchange potential. An NN-potential model is not suitable for SU(3) generalization, when it contains only 2π-exchange, because it should also contain from the outset $\pi\eta$, $\pi\eta'$, $\eta\eta$, etc. exchange potentials. It is clear that not every NN-model is suitable for generalization to YN and YY. The Nijmegen potential models [4–6,10] have always been constructed with this generalization to YN and YY in mind.

II. THE EXPERIMENTAL DATA

It is interesting to compare the description of the YN-interaction directly with our description of the NN-interaction. In the Nijmegen partial wave analyses [11] Nijm PWA93 of the NN-scattering data with $T_{\rm lab} < 350$ MeV we have in pp-scattering 1787 datapoints and we use 21 model parameters.

In np-scattering we have 2514 datapoints and for a good description of these data in our PWA we use 19 **extra** model parameters. In the model we have roughly speaking about 100 datapoints per parameter. This allows for a good determination of these parameters in NN.

In Figure 1 we show pp and np differential cross sections. Shown are the datapoints with their error bars and the fit of the Nijm PWA93. We show this to indicate the quality difference between these data sets and the YN-data sets.

For the YN-channels it has been customary to use a set of 35 selected datapoints [14]. This is essentially the only scattering information available about the low energy YN-interaction. The data were obtained from an experiment of slopping K^--mesons in the 81 cm Saclay hydrogen bubble chanber at CERN. There are a few extra scattering data available, but these extra data do not really carry extra information. Important to note is, that these data stem from prior to 1971. Finally one has the hyperfragment data [15], which supply some insight in the YN-interactions.

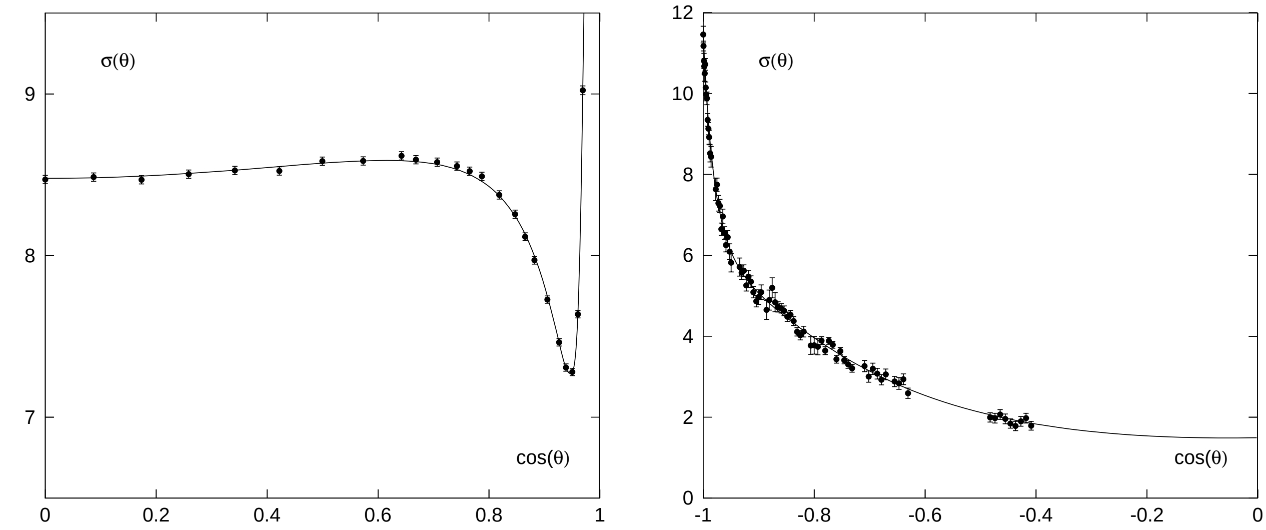

FIG. 1. (a) pp differential cross section at 50.06 MeV [12]. The 24 datapoints contribute $\chi^2 = 12.8$ in the Nijm PWA93.
(b) np backwards differential cross section at 344.3 MeV [13]. The 80 datapoints contribute $\chi^2 = 74.53$ to the Nijm PWA93 and have the normalization 1.035 ± .005.

This selected data set of YN-scattering data is described below. The predictions in the figures correspond to the unpublished Nijmegen SCW-model [16], which fits these 35 data with the $\chi^2 = 16.9$.

For elastic Λp scattering (see Figure 2) there exist 12 datapoints in the momentum range 120 MeV/c $< p_{\rm lab} <$ 330 MeV/c, which corresponds to the kinetic energy in the laboratory system 6.5 MeV $< T_{\rm L} <$ 50 MeV. From these data 6 come from the Rehovoth-Heidelberg group [17] and 6 come from the Maryland group [18].

For elastic $\Sigma^+ p$-scattering (see Figure 3) there exist 4 datapoints [21] in the momentum range 145 MeV/c $< p_{\rm L} <$ 175 MeV/c which corresponds to
9 MeV $< T_{\rm lab} <$ 13 MeV.

For elastic $\Sigma^- p$-scattering, and the charge exchange reactions $\Sigma^- p \rightarrow \Sigma^0 n$ and $\Sigma^- p \rightarrow \Lambda n$ one has for each reaction 6 datapoints [21,22] in the momentum interval 142 MeV/c $< p_{\rm L} <$ 168 MeV/c or 9 MeV $< T_{\rm L} <$ 12 MeV (see Figure 4).

The restricted dataset contains finally also the ratio at rest r_R from the production of Σ^0 and Σ^0 and Λ^0 hyperons, when stopped Σ^- hyperons are captured by protons [23]. This ratio $r_R = \Sigma^0/(\Sigma^0 + \Lambda) = 0.468(10)$ is one of the few numbers in these reactions with a rather good accuracy.

It is clear from this dataset, that the data are really scarce and that they have large errors. Because of the low energies these data contain mainly s-wave information. The allowable number of parameters is of the order of 6, one for each of the 5 reactions and one for the ratio at rest.

More recently there have come available beautiful data [24] for the strangeness exchange reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$. These data are taken at the laboratory momenta $p_L <$ 1.55 GeV/c, which corresponds to the energy E in the center of mass,

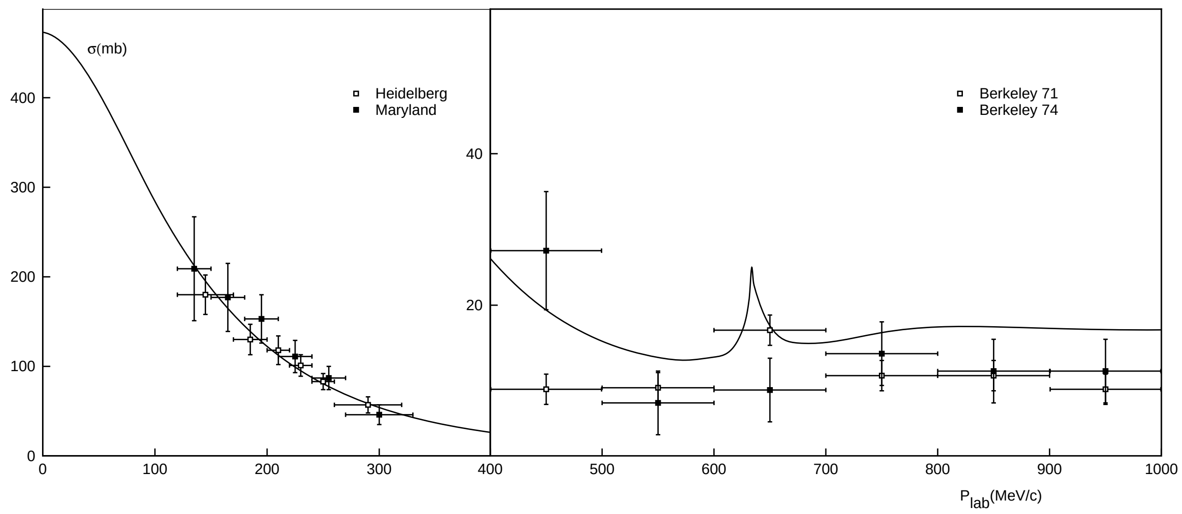

FIG. 2. Cross sections for elastic Λp scattering. The data are taken from [17–20].

$$E = \sqrt{s} - 2m_\Lambda \leq 39.1 \text{ MeV} .$$

Available at present are $N_d = 157$ datapoints corresponding to 99 differential cross sections, 38 polarizations, 20 spin-correlations. This part of the database is rapidly growing. There are also already some measurements available [25] of the reactions

$$\bar{p}p \to \Lambda\bar{\Sigma},\ \Sigma\bar{\Lambda},\ \Sigma\bar{\Sigma},\ \text{etc.}$$

III. FLAVOR SU(2): ISOSPIN

Isopin symmetry is a good symmetry in the YN-interactions, when the Coulomb interactions can be neglected and when there are no important mass differences between particles of the same isomultiplet. So when no $(n,\ p)$, and $(\Sigma^+,\ \Sigma^0,\ \Sigma^-)$ mass differences are taken into account. The most important manifestation of this approximation is the coincidence of the various ΣN-thresholds. Also the Coulomb interaction in the $\Sigma^+ p$ and $\Sigma^- p$ channels should be neglected.

However, it is important to take the breaking of the isospin symmetry of SU(2) flavor into account. The Coulomb interaction in the $\Sigma^- p$-channel is very important for the ratio r_R at rest, because the attractive Coulomb interaction enhances the strong reaction rates. The Coulomb interaction manifests itself also in the differential cross sections $d\sigma/d\Omega$ for the elastic scatterings $\Sigma^- p$ and $\Sigma^+ p$.

The mass differences between members of the same isomultiplet are another source of breaking of the isospin symmetry. A first manifestation of this is the presence of the different ΣN thresholds

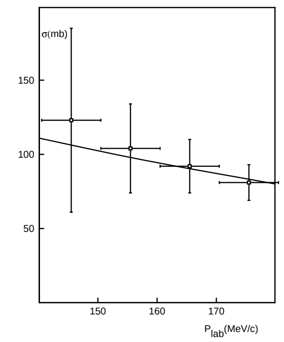

FIG. 3. The $\Sigma^+ p$ elastic total cross section [21].

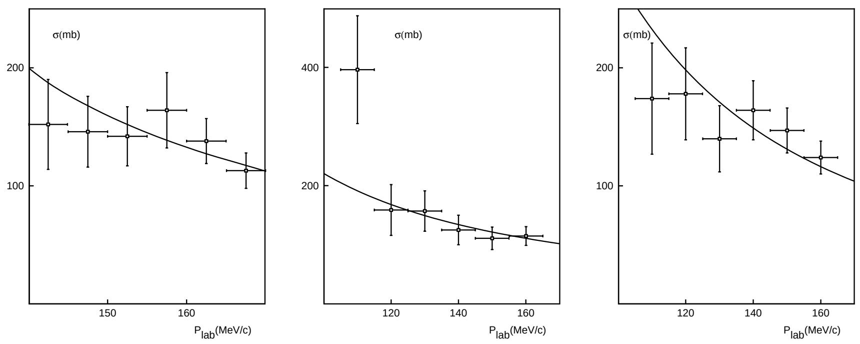

FIG. 4. The total elastic cross sections $\Sigma^- p \to \Sigma^- p$ and the charge exchange reactions $\Sigma^- p \to \Sigma^0 n$ and $\Sigma^- p \to \Lambda^0 n$ [21,22].

$$E_{\mathrm{th}}(\Sigma^0 p) - E_{\mathrm{th}}(\Sigma^+ n) = 1.8 \text{ MeV} \quad \text{and} \quad E_{\mathrm{th}}(\Sigma^- p) - E_{\mathrm{th}}(\Sigma^0 n) = 3.6 \text{ MeV}$$

The mass difference between the pions $(\pi^0, \pi^\pm)$ gives rise to different interaction strength and different ranges.

In the ΛN interaction there is a very interesting kind of isospin-breaking [26,1]. The isospin of the Λ hyperon is $I = 0$ and this forbids one-pion-exchange in the elastic ΛN-scattering. OPE gives rise to the reaction $\Lambda N \to \Sigma N$. However, the physical Λ is **not** a pure $I = 0$ state. Due to the electromagnetic interaction the Λ has a small Σ^0 component mixed in, such that

$$\Lambda_{\mathrm{phys}} = \cos\theta\ \Lambda + \sin\theta\ \Sigma^0 \quad \text{and} \quad \Sigma^0_{\mathrm{phys}} = -\sin\theta\ \Lambda + \cos\theta\ \Sigma^0$$

The pion π^0, which does not couple to the bare Λ, couples to the physical Λ_{phys}, because it couples to Σ^0. Because the coupling constants of the π^0 to the proton and to the neutron have opposite sign, there is an isospin symmetry breaking due to this one-pion-exchange.

The result is a rather weak, but noticeable, isospin breaking, OPE-potential in the ΛN channel.

IV. FLAVOR SU(3)

An important manifestation of SU(3) flavor symmetry [27] and the quark model [28] is the appearance of mesons in **nonets**. Important nonets are the $J^{PC} = 0^{-+}$ pseudoscalar meson nonet, the $J^{PC} = 1^{--}$ vector meson nonet, and the $J^{PC} = 0^{++}$ scalar meson nonet. The non-strange members of these nonets are (π, η, η'), (ρ, ω, ϕ), and $(a_0(980),\ f_0(975),\ f_0(760))$. The strange members in each nonet appear in two isodoublets with $Y = \pm 1$, (K^+, K^0) and $(\overline{K^0}, K^-)$. They are the pseudoscalar $K(495)$, the vector $K^*(892)$, and the scalar $\kappa(880)$.

The baryons appear mainly in octets $\{\underline{8}\}$, decuplets $\{\underline{10}\}$ and singlets $\{\underline{1}\}$. The most important example being the $J^P = \frac{1}{2}^+$-baryon octet.

When one wants to place the deuteron in an SU(3) multiplet, then this [29] must be an anti-decuplet $\{\underline{10}^*\}$. This multiplet contains presumably also the state with $Y = 1$, $I = \frac{1}{2}$ and mass $M = 2129$ MeV near the ΣN-threshold. The equal spacing rule predicts then a ΞN, $\Lambda\Sigma$ and $\Sigma\Sigma$ resonance with $Y = 0$, $I = 1$ and mass $M = 2382$ MeV near the $\Sigma\Sigma$ threshold and a state with $Y = -1$, $I = \frac{3}{2}$ around $M = 2635$ MeV.

The breaking of the SU(3) symmetry in the baryon masses has a noticeable effect.

For the description of the BB-interaction in general the SU(3) flavor symmetry is useful as a limiting case [1,30–32]. The $J^P = \frac{1}{2}^+$ baryons $(N, \Sigma, \Lambda, \Xi)$ all belong to the $\frac{1}{2}^+$-baryon octet. The flavor wave function of the two-baryon states must belong to one of the SU(3) irreps contained in the right-hand-side of the SU(3) Clebsch-Gordan series:

$$\{8\} \times \{8\} = \underbrace{\{27\} + \{8\}_S + \{1\}}_{\text{symmetric}} + \underbrace{\{10\} + \{10^*\} + \{8\}_A}_{\text{anti-symmetric}} \ .$$

The symmetry of the flavor wave function under interchange of the two baryons is indicated. The total wave function ψ can be written as the product of a space-, a spin-, and a flavor-wave-function:

$$\psi = (\text{space})(\text{spin})(\text{flavor}) \ .$$

The generalized Pauli principle requires that the total wave function ψ is antisymmetric under interchange of the two baryons. This implies for the flavor symmetric states $\{27\}$, $\{8\}_S$ and $\{\underline{1}\}$ the antisymmetric space-spin combinations ${}^1S_0$, ${}^3P_1$, ${}^1D_2$, ${}^3F$, etc, and for the flavor anti-symmetric states $\{\underline{10}\}$, $\{\underline{10}^*\}$ and $\{8\}_A$ the symmetric space-spin combinations ${}^3S_1$, ${}^1P_1$, ${}^3D$, ${}^1F_3$, ${}^3G$, etc.

The NN-states have $Y = 2$ and $I = 0$ and 1:
the $I = 1$ states ${}^1S_0$, ${}^3P$, ${}^1D_2$, ${}^3F$, etc. belong to $F = \{27\}$,
the $I = 0$ states ${}^3S_1$, ${}^1P_1$, ${}^3D$, ${}^1F_3$, etc. belong to $F = \{\underline{10}^*\}$.

The YN-states have $Y = 1$ and $I = \frac{1}{2}$ and $\frac{3}{2}$:
the $I = \frac{3}{2}$ states ${}^1S_0$, ${}^3P$, ${}^1D_2$, ${}^3F$, etc. belong to $F = \{27\}$,
the $I = \frac{3}{2}$ states ${}^3S_1$, ${}^1P_1$, ${}^3D$, ${}^1F_3$, etc. belong to $F = \{\underline{10}\}$.

The situation for the $I = \frac{1}{2}$ states is more complicated:
the $I = \frac{1}{2}$ states ${}^1S_0$, ${}^3P$, etc. belong to a mixture of $F = \{8\}$ and $\{27\}$,
the $I = \frac{1}{2}$ states ${}^3S_1$, ${}^1P_1$, etc. belong to a mixture of $F = \{8\}$ and $\{10^*\}$.

V. *NN*-MODELS

Let us give a quick review of some of the NN-models that appear in the literature. In Nijmegen we have constructed various NN-potential models. They are

- **hard core** models A to F. The models A and B stem [14,33] from 1973, the model D [4,7] from 1975–1977, and the model F [6] from 1979.
- **soft core** models. The Nijmegen soft-core model (Nijm78) based on Regge-trajectory exchange [5] stems from 1978. The corresponding YN-model [8] was constructed in 1989. Recently the NN-model [5] has been updated [34]. This updated version Nijm93 has χ^2/datapoint = 1.87 with respect to all the available NN-scattering data below $T_L = 350$ MeV.
- **extended soft core** (ESC) model. This 1993 soft core model [10], inspired by chiral-symmetry, gives a fit to the available NN-data with χ^2/datapoint = 1.16 (17 MeV $\leq T_{\rm lab} \leq 350$ MeV). The corresponding YN-potentials have not been constructed yet.
- **Reidlike** models. In 1993 several Reidlike models, NijmI and NijmII, based on the Nijm78 potential, have been constructed [34]. Also an update Reid93 of the old Reid soft-core potential (RSC) was constructed [34]. These potentials have all excellent fits with respect to the NN-data; they all have χ^2/datapoint = 1.03.

The Paris NN-potential [9] Paris80 has a fit with the NN-data that is comparable with the old Nijm78 potential.

Also in Bonn one has constructed various NN-potentials. This started with potentials like HM1976 [35]. In 1987 various Bonn NN-potentials were published [36] with various names. In 1989 the Bonn group constructed a special pp-potential [37] and again several NN-potentials, like BonnA, B, C [38], and from each one several versions.

VI. MODELS FOR THE *YN*- AND *YY*-INTERACTION

Of the various models that exist for describing the YN- and the YY-interaction, there are first of all the hard core models Nijmegen D and F. The main difference between these two models is the treatment of the scalar mesons. In D an SU(3) singlet is assumed and in F an SU(3) nonet. This model F was extended [39] to the $Y=0$ channels $\Lambda\Lambda$, ΞN, etc.

The Nijmegen soft-core model Nijm78 for the NN-interaction was extended [8] to the YN-interaction in Nijm89.

Another generalization exists, called the SCW-model [16]. In this model, to the meson theoretical interaction is added in every SU(3) channel either a repulsive soft-core or an attractive soft well. The resulting potential has been generalized to the $Y=0$ channels by P. Maessen et al. With this model an excellent fit to the YN-data has been obtained with only a few parameters (see figures 2 to 4).

Also a boundary condition model was constructed [16]. Here the meson-theoretic potential was used to describe the interaction for values of $r > 1.4$ fm. At the radius $r = 1.4$ fm was specified the boundary condition

$$P = b(d\psi/dx)/\psi \ .$$

VII. OBE-PART OF THE MESON-THEORETICAL POTENTIALS

It has already been stated that the mesons come in **nonets** [9], where $[9] = \{\underline{8}\} \oplus \{\underline{1}\}$ and $\{\underline{8}\}$ and $\{\underline{1}\}$ are an SU(3) octet and singlet. In the NN-channels are exchanged from each nonet:
(i) one meson with $Y=0$, $I=1$ like π, ρ, a_0, and
(ii) two mesons with $Y=0$, $I=0$ like $\eta, \eta', \omega, \phi$, and $f_0(760)$, $f_0(975)$.
When one wants to describe also the YN-channels, then one needs to consider also the exchange of the $Y=\pm 1$ $I=\frac{1}{2}$ strange mesons like $(K^+ K^0), (\overline{K^0}, K^-)$.

The $I=0$ mesons are mixed due to for example the SU(3) breaking of the quark masses. The mixing angle θ is introduced to describe this mixing. For the pseudoscalar mesons one writes

$$\begin{aligned} \eta &= \eta_8 \cos\theta_{ps} - \eta_1 \sin\theta_{ps} \\ \eta' &= \eta_8 \sin\theta_{ps} + \eta_1 \cos\theta_{ps} \end{aligned}$$

From the linear Gell-Mann-Okubo mass formula one predicts $\theta_{ps} = -23$ degrees. Using the quadratic mass formula one gets $\theta_{ps} = -10.1$. Experimentally is seems to be that $\theta_{ps} \sim -20$ degrees. This does not imply that the linear GMO mass formula is better, because the mixing angle is very sensitive to small corrections.

VIII. PSEUDOSCALAR MESONS

The coupling of the pseudoscalar mesons $J^{PC} = 0^{-+}$ with the $J^P = \frac{1}{2}^+$ baryons can be described by
either PS-coupling: $\mathcal{L}_{PS} = g(\overline{\psi}\gamma_5\psi)\phi$
or PV-coupling: $\mathcal{L}_{PV} = \frac{f}{m_s}(\overline{\psi}\gamma_\mu\gamma_5\psi)\partial^\mu\phi$.

In the PV-lagrangian a scaling mass m_s is introduced in order to make the coupling constant f dimensionless. We feel that one must always choose the same mass e.g. $m_s = m(\pi^+) = m_+$ for this scaling mass. The coupling constants we will denote by f in that case.

Some people prefer to take the scaling mass equal to the mass of the exchanged meson $m_s = m_\phi$. The coupling constants we will denote in that case by f'.

For the pseudo-scalar-meson-baryon-baryon vertex there exist an equivalence between PS- and PV-coupling constants:

$$f^2 = \left(\frac{m_s}{M_1 + M_2}\right)^2 g^2 \ .$$

The coupling constant f_p of the π^0 with the proton [40] is $f_p^2 = 0.075$. This corresponds to $g^2 = 13.56$. This same $g^2 = 13.56$ corresponds for this $\pi^0 pp$ vertex to $f'^2 = 0.070$. The question arises now: "Which of these coupling constants f, f', or g is approximately SU(3) symmetric?" It is clear that when the PV-coupling constants f are approximately SU(3) symmetric, that then the PS-coupling constants g and the PV-coupling constants f' have a sizeable SU(3) breaking.

When one assumes SU(3) for the PV-coupling constants f then the Cabibbo theory of the weak interactions and the Goldberger-Treiman relation predict the value [41] $\alpha_{PV} = (F/(F+D))_{PV} = 0.355(6)$. This value was also found in [8] while fitting the YN-data. In a study [42] of the reaction $\bar{p}p \to \bar{\Lambda}\Lambda$ Timmermans et al. found either $\alpha_{PV} = 0.34(4)$ or $\alpha_{PS} = 0.42(4)$. The agreement between the two values of α_{PV} indicates a preference for PV-coupling.

For a complete description of the coupling of the PS-mesons to the baryons we need to know the mixing angle θ, the singlet coupling constant f_1, the octet coupling constant f_8 and the ratio $\alpha_{PS} = F/(F+D)$. However, this is not all. There is still the question: What is better, SU(3) symmetry for the PS or for the PV coupling constants?

These coupling constants are just phenomenological parameters. The spatial extension of the baryons and the mesons introduces a form factor [43]. In first approximation it is assumed that the coupling constants become dependent on the momentum transfer. Then the question arises, where do we assume SU(3) for the coupling constants? At the pole or at $t = 0$? When the values at the meson pole are assumed to be SU(3) symmetric, then the values of the coupling constants at $t = 0$ will in general **not** be SU(3) symmetric anymore and vice versa.

As far as the specific value of the coupling constant is concerned it is interesting to note in 1993 that the value of the πNN coupling constant deduced for the model D in 1975 was $g^2 = 13.4$ or $f^2 = 0.074$ [4].

IX. THE VECTOR MESONS

The $J^{PC} = 1^{--}$ vector meson nonet contains the non-strange mesons ρ, ω, and ϕ. The $Q\overline{Q}$-quark model SU(3) eigenstates are

$$\omega_8 = [u\bar{u} + d\bar{d} - 2s\bar{s}]/\sqrt{6}$$
$$\omega_1 = [u\bar{u} + d\bar{d} + s\bar{s}]/\sqrt{3}$$

When these states are ideally mixed, then

$$\begin{aligned}\omega &= \quad \cos\theta_v\ \omega_1\ +\ \sin\theta_v\ \omega_8\ =\ [u\bar{u}+d\bar{d}]/\sqrt{2}\\ \phi &= -\sin\theta_v\ \omega_1\ +\ \cos\theta_v\ \omega_8\ =\ -s\bar{s}\end{aligned}$$

This ideal mixing angle has then

$$\sin\theta_v = 1/\sqrt{3}\ ,\quad \tan\theta_v = 1/\sqrt{2}\ ,\quad \text{and}\quad \theta_v = 35.26\ .$$

The physical coupling constants are related to the coupling constants g_{ω_8} and g_1 of the unmixed states. Then

$$\begin{aligned}g_\phi &= -\sin\theta_v\ g_1\ +\ \cos\theta_v\ g_{\omega_8}\\ g_\omega &= \quad \cos\theta_v\ g_1\ +\ \sin\theta_v\ g_{\omega_8}\end{aligned}$$

The OZI-rule [44] states that the ϕ-meson is in first approximation not coupled to the nucleons. Thus $g_\phi = 0$. This implies then that

$$g_1 = \sqrt{2} g_{\omega_8}\quad \text{and}\quad g_\omega = \sqrt{3} g_{\omega_8}\ .$$

The coupling constants g_{ω_8} is related to the ρ-coupling constant g_ρ by

$$g_{\omega_8} = [(4\alpha_v - 1)/\sqrt{3}] g_\rho = \sqrt{3} g_\rho\ .$$

In the last step above we used Sakurai's idea that the vector mesons are universally coupled [45]. This requires $\alpha_v = 1$. The coupling constant g_ω is therefore related to the ρ-coupling constant g_ρ by $g_\omega^2 = 9 g_\rho^2$.

In treating the vector mesons there are still many uncertainties. The couplings to the $J^P = \frac{1}{2}^+$ baryons are described either by the Dirac and the Pauli coupling constants or by the electric and the magnetic coupling constants. For which of these holds SU(3)? Again one comes up with the question whether one needs the coupling constants at the particle poles or at $t = 0$.

The ratio $(f/g)_\rho$ is rather controversial. Vector meson dominance (VMD) predicts [46] $(f/g)_\rho = 3.7$. From analyses of the πN data the Karlsruhe people [47] determined long ago that $(f/g)_\rho = 6.1$, but also that $g^2 = 14.28$ for the πNN-coupling constant. It appears that the πN data available at the time of the Karlsruhe analyses were not so great. In Nijmegen we made a fit to the NN-scattering data to determine $(f/g)_\rho$. In Nijm78 we found $(f/g)_\rho = 4.3$. Recently this potential was refitted and now we find that $(f/g)_\rho = 4.1$. We see that the Nijmegen determination is close to the VMD value.

Popular values for the $F/(F+D)$-ratio's α_E and α_M are

$\alpha_E = 1$ from universal coupling à la Sakurai [45], and

$\alpha_M = 0.275$ using relativistic SU(6) (Sakita and Wali [48]).

X. THE SCALAR MESONS

The scalar meson σ, the fictitious σ, with a mass of about $M \sim 550$ MeV was introduced in 1960–1962 by N. Hoshizaki et al. [49] and used in 1964 by Bryan and Scott [50]. This scalar meson was required in OBE-models for NN in order to get

(i) intermediate range attraction, and
(ii) sufficiently strong $\mathbf{L}\cdot\mathbf{S}$-forces.

In $\pi\pi$ production experiments there often appeared a broad structure $\varepsilon(760)$ under the ρ^0. Because the signal of the ρ^0 is so strong, the existence of the broad structure was always unsure.

The $\pi\pi$ interaction is traditionally studied in the reaction $\pi N \rightarrow \pi\pi N$. When the production of the pion goes via pion exchange, we have a $\pi\pi \rightarrow \pi\pi$ vertex and here $\pi\pi$ scattering has been studied. In this scattering sometimes $\varepsilon(760)$ appeared as an established particle, sometimes its existence was denied. In a recent analysis [51] of this production reaction also the exchange of other mesons, besides the pion, was assumed. In this recent analysis the ε-meson has mass $M = 750$ MeV and width $\Gamma \sim 100 - 150$ MeV.

An important development in the treatment of the scalar mesons was the realization [52] in 1971 that the exchange of a wide $\varepsilon(760)$ simulates the exchange [43] of the fictitious, low mass σ. The potential due to the exchange of a wide ε can be calculated [53], where the 2π threshold is taken properly into account. For easy handling, necessary in the older computers, the potential $V(\varepsilon)$ of the wide epsilon was approximated as the sum of two Yukawa's. One of these Yukawa's has a low mass and the other one a high mass. In the Nijm93 potential these masses are $m_{\rm low} = 488$ MeV and $m_{\rm high} = 1021$ MeV.

The $Q\overline{Q}$-mesons with $J^{PC} = 0^{++}$ must belong to the $^3P_0$-states. The assignments of the 2^{++} and the 1^{++} mesons are generally accepted. The assignments of the scalar mesons are more controversial. However, let us start with the masses 2^{++} and 1^{++} mesons.

$$\begin{array}{l} {}^3P_2,\ J^{PC} = 2^{++};\ a_2(1320),\ f_2(1270),\ f_2'(1525) \\ {}^3P_1,\ J^{PC} = 1^{++};\ a_1(1260),\ f_1(1285),\ f_1'(1510)\ , \end{array}$$

and predict the masses of the 0^{++}-mesons

$${}^3P_0,\ J^{PC} = 0^{++};\ a_0(1300),\ f_0(1300),\ f_0'(1500)\ .$$

The Particle Data Group [54] lists an $a_0(1320)$, which needs confirmation and various f_0's. The predicted masses look reasonable. What about the scalar-mesons

$$\delta(980),\ S(975),\quad \text{and}\quad \varepsilon(760)\ ?$$

One notices first of all the non-familiar mass relation

$$m(a_0) \approx m(f_0) \gg m(f_0')\ .$$

This mass relation is just contrary to the mass relation of the $^3P_J - Q\overline{Q}$-mesons, where

$$m(a_J) \simeq m(f_J) \ll m(f_J')\ .$$

The latter mass relation (high f' mass) is easily understood from the quark content. The $Q\overline{Q}$-mesons a_J and f_J contain only non-strange quarks and the heavier $Q\overline{Q}$-meson f_J' contains the strange quarks ($s\bar{s}$).

In a $Q\overline{Q}$-model in 1980 Aerts et al. [55] predicted for the mesons with the non-strange quark content $n\bar{n}$ a mass around 1285 MeV. The $I = 0$ and $I = 1$ mesons being almost degenerate. The $I = 0$ meson with $s\bar{s}$ content was predicted around $M = 1475$ MeV.

A solution for this non-familiar problem in the quark model was given in 1977 by R.L. Jaffe [56]. He calculated in the MIT-bagmodel the $q^2\bar{q}^2$ states. The lowest states were a **nonet of scalar mesons**. A heuristic treatment runs as follows. The lowest q^2 states is a diquark with $F = 3^*$, $C = 3^*$, and $S = 0$, where F is flavor, C is color and S is spin. Because of the $F = 3^*$ assignment we will denote these states by $\overline{Q}$. Thus

$$\overline{Q} = \begin{array}{ccc} & \overline{S} & \\ \overline{U} & & \overline{D} \end{array} = \begin{array}{ccc} & [ud] & \\ [sd] & & [su] \end{array}$$

With $[ud]$ we mean the antisymmetric flavor wave function $ud - du$. The lowest $q^2\bar{q}^2$ states are formed from $\overline{Q}$, an antitriplet, and the antiparticles Q, a flavor triplet. The $\overline{Q}Q$ combination is a flavor nonet. The lowest mass state

$$\overline{S}S = [ud][\bar{u}\bar{d}]$$

is an $I = 0$ scalar meson containing only non-strange quarks with predicted [56] mass $M = 690$ MeV. This is the f_0' meson of this nonet.

There exist in this nonet also a degenerate pair of $I = 0$ and $I = 1$ mesons. The neutral mesons (think of the ρ^0 and ω^0) are

$$(U\overline{U} \pm D\overline{D})/\sqrt{2} = \{[\bar{s}\bar{d}][sd] \pm [\bar{s}\bar{u}][su]\}/\sqrt{2}\ .$$

The predicted mass was $M = 1150$ MeV. It is obvious that these mesons are the $f_0(975)$ and $a_0(980)$ at the $K\overline{K}$-threshold. From the wave function we see that these mesons contain an $\bar{s}s$-pair. This explains for example why the $f_0(975)$ meson with a mass **below** the $K\overline{K}$-threshold can decay for about 22% into a $K\overline{K}$-pair.

The strange partner, called κ, must have flavor wave functions like

$$[ud][\bar{s}\bar{d}] \quad \text{and} \quad [ud][\bar{s}\bar{u}]\ , \quad \text{etc}$$

These mesons contain only one s or one $\bar{s}$. The expected mass is around 880 MeV, just under the strong signal of the $K^*(892)$. This explains why the scalar meson κ is so hard to detect. This meson has been seen by Svec [57] in 1992 with mass $M = 887$ MeV.

How to describe the mixing of these scalar mesons? We write

$$\begin{aligned} f_0' &= \cos\theta_s\ \varepsilon_1 + \sin\theta_s\ \varepsilon_8 \\ f_0 &= -\sin\theta_s\ \varepsilon_1 + \cos\theta_s\ \varepsilon_8 \end{aligned}$$

When we assume ideal mixing, then

$$f_0' = \varepsilon = S\overline{S} \quad \text{and} \quad f_0 = S = (U\overline{U} + D\overline{D})/\sqrt{2}\ ,$$

which means $\tan\theta_s = -\sqrt{2}$ and $\theta_s = \theta_v - 90 = -54.75$. However, this is not the only mixing present. One expects also mixing with the $q\bar{q}$ ($^3P_0$) states, with glueballs, etc.

XI. THE POMERON

In the region above $p_{\rm lab} = 2$ GeV/c boson exchange has to be replaced by Reggeon exchange, because the total cross section becomes there approximately constant, see e.g. [2]. This feature of the total cross section can only be explained in the Regge pole model. It was pointed out in [2] that in Regge pole models, see for example [58], the pomeron gives a very significant contribution already at $p_{\rm lab} = 2$ GeV/c. At this momentum $\sigma_T \approx 45$ mb and $\sigma_{\rm el} \approx 20$ mb. When the pomeron is omitted, the model of [58] would predict $\sigma_{\rm el} \approx 2.3$ mb.

In low energy pion-nucleon and kaon-nucleon scattering the presence of the pomeron has been demonstrated using finite-energy sum rules [59]. There it appeared that, after the subtraction of the baryon resonances, the remaining background amplitude is directly related to pomeron-exchange. This background amplitude is important for the scattering lengths.

Since the Regge-region, $p_{\rm lab} > 2$ GeV/c, is not that remote from the $N\Delta$-region, $p_{\rm lab} \approx 1.32$ GeV/c, or even the low-energy region, $p_{\rm lab} < 0.9$ GeV/c, it is essentially the same physics that governs the low-energy and the Regge-regions. A unified description of these regions is therefore desirable.

A unification for the baryon-baryon channels, using the Khuri-Jones representation [60] of the Regge poles, has been worked out [61] and applied by the Nijmegen group to baryon-baryon scattering [5,61]. Phenomenologically, the inclusion of the pomeron-exchange potential in these models serves to give reasonable values for the ω-coupling. More fundamentally, in these OBE-models, where there are, of course, no $N\overline{N}$-pair contributions to the potentials, the strong εNN-coupling would be at variance with the small s-wave pion-nucleon scattering lengths. The pomeron contribution helps out here by cancelling largely this ε-contribution.

The physical picture of the pomeron has changed over the years in accordance with the progress of our understanding of the hadrons. In the sixties and early seventies, the pomeron was associated with multiperipheral chains. This is natural in chiral theories, where one envisions a cloud of soft pions around constituent quarks. With the advent of QCD, ons tries to explain most of the pomeron features by considering it as a two-gluon (or multigluon) system [62].

The repulsive character of the pomeron-potential appears often a little puzzling, because at low energy it is very similar to scalar-exchange and one would therefore expect an attractive potential. The repulsiveness comes from the Regge phenomenology. The pomeron residue is positive, because pomeron-exchange is directly related to σ_T at high-energy. In the Khuri-Jones procedure this then leads directly to a repulsive potential. To look for a more detailed explanation we examine the two-gluon picture. First of all, we assume that the pomeron couples primarily to the quarks, as indicated by high-energy experiments [63]. This has been related to the QCD-vacuum properties [64]. The pomeron quark-coupling picture restores the "additive quark rules" for the pomeron [28]. This in contrast to the so-called "subtracted" quark-picture, where in the two-gluon coupling to a hadron one sums independently over the quark couplings of the individual gluons [65]. In this latter picture the pomeron-exchange potential would be due to the effects of induced color-electric dipoles, like van der Waals forces. These would then most likely be attractive.

Assuming that the Coulomb part of the two gluons in pomeron-exchange dominates the interaction, it is not unrealistic to consider for the pomeron quark-quark potential a two-scalar exchange model. It is well-known [66] that then in the adiabatic approximation all contributions cancel. The first non-vanishing contribution to the potential comes from non-adiabatic corrections. This gives rise to a repulsive potential between the quarks of the form

$$V_{P_{qq}}(r) \sim g^2_{P_{qq}}(\Lambda r)^2 \exp\left[-\frac{1}{2}(\Lambda r)^2\right] .$$

The same $V_{P_{qq}}(r)$ can be derived in the context of QCD, relating the strength of the potential to the vacuum expectation $\langle 0|G_{\mu\nu a}(x)G^{\mu\nu a}(y)|0\rangle$ [67]. Folding the $V_{P_{qq}}$ potential with the baryon quark-model wave functions, one arrives at a repulsive pomeron-exchange BB-potential. Using gaussian quark wave-functions gives a gaussian pomeron-exchange potential as used in the Nijmegen models.

XII. THE INNER REGION

The treatment of the short range part of the interaction is very phenomenological. In the older models, like NijmD or NijmF we used hard cores. In the NN-model Nijm78 and the corresponding YN-model Nijm89 we used soft cores.

Soft cores are generally introduced in the meson theoretic potentials, when one uses form factors $F(k^2)$, which cut down the high momentum components sufficiently, such that the singularities at $r = 0$ are removed. In the Nijmegen soft core model we use exponential form factors

$$F(k^2) = e^{-(k^2+m^2)/\Lambda_0^2} .$$

In the literature one uses mostly multipole form factors

$$F(k^2) = \{(\Lambda_n^2 - m^2)/(\Lambda_n^2 + k^2)\}^n \qquad \text{with } n = 1, 2, 3, \ldots$$

The advantage of the exponential form factor is that the coordinate space potentials, obtained when using this form factor, are much softer than when using the multipole form factors.

Short-ranged are also the velocity dependent potentials of the form

$$-\frac{\hbar^2}{2m}\{\nabla^2\phi(r) + \phi(r)\nabla^2\} .$$

Such potentials can be viewed as having introduced an r-dependent effective mass

$$m_{\text{eff}} = \frac{m}{1 + 2\phi(r)} .$$

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REFERENCES

[1] J.J. de Swart, M.M. Nagels, Th.A. Rijken, and P.A. Verhoeven, *Springer Tracts Modern Physics* **60**, 138 (1971)

[2] J.J. de Swart, Th.A. Rijken, P.M. Maessen, and R.G. Timmermans, *Nuovo Cimento* **102 A**, 203 (1988)

[3] J.J. de Swart, *Nukleonika* **25**, 397 (1980)
J.J. de Swart and Th.A. Rijken, *Proceedings of the International Conference on Hypernuclear and Kaon Physics*, Heidelberg, Germany (B. Povh, ed, 1982), pp. 271
J.J. de Swart and Th.A. Rijken, *Proceedings of the 1986 INS International Symposium on Hypernuclear Physics*, Tokyo, Japan (H. Bandō, et al., eds, 1986), pp. 303
Th.A. Rijken, P.M.M. Maessen, and J.J. de Swart, *Nucl. Phys.* **A 547**, 245c (1992)

[4] M.M. Nagels, Th.A. Rijken, and J.J. de Swart, *Phys. Rev.* **D 12**, 744 (1975)

[5] M.M. Nagels, Th.A. Rijken, and J.J. de Swart, *Phys. Rev.* **D 17**, 768 (1978)

[6] M.M. Nagels, Th.A. Rijken, and J.J. de Swart, *Phys. Rev.* **D 20**, 1633 (1979)

[7] M.M. Nagels, Th.A. Rijken, and J.J. de Swart, *Phys. Rev.* **D 15**, 2547 (1977)

[8] P.M.M. Maessen, Th.A. Rijken, and J.J. de Swart, *Phys. Rev.* **C 40**, 2226 (1989)

[9] M. Lacombe, B. Loiseau, J.-M. Richard, R. Vinh Mau, J. Côté, P. Pirès, and R. de Tourreil, *Phys. Rev.* **C 21**, 861 (1980)

[10] Th.A. Rijken, *Baryon-Baryon Interactions*, *Proceedings of the XIVth European Conference on Few-Body Problems in Physics*, Amsterdam, The Netherlands (B.L.G. Bakker, R. van Dantzig, eds, 1993)

[11] V.G.J. Stoks, R.A.M. Klomp, M.C.M. Rentmeester, and J.J. de Swart, *Phys. Rev.* **C 48**, 792 (1993)

[12] A. Berdoz, F. Foroughi, and C. Nussbaum, *J. Phys. G* **12**, L133 (1986)

[13] B.E. Bonner et al., *Phys. Rev. Lett.* **41**, 1200 (1978)

[14] M.M. Nagels, Th.A. Rijken, and J.J. de Swart, *Ann. Phys.* (NY) **79**, 338 (1973)

[15] B.F. Gibson, *Nuclear Aspects of Few-Baryon Systems*, *Proceedings of the XIVth European Conference on Few-Body Problems in Physics*, Amsterdam, The Netherlands (B.L.G. Bakker, R. van Dantzig, eds, 1993), see also these proceedings.

[16] P.M.M. Maessen, private communication

[17] G. Alexander, U. Karshon, A. Shapira, G. Yekutieli, R. Engelmann, H. Filthuth, and W. Lughofer, *Phys. Rev.* **173**, 1452 (1968)

[18] B. Sechi-Zorn, B. Kehoe, J. Twitty, and R.A. Burnstein, *Phys. Rev.* **175**, 1735 (1968)

[19] J.A. Kadijk, G. Alexander, J.H. Chan, P. Gaposchkin, and G. Trilling, *Nucl. Phys.* **B27**, 13 (1971)

[20] J.M. Hauptman, J.A. Kadijk, and G.H. Trilling, *Nucl. Phys.* **B125**, 29 (1977)

[21] F. Eisele, H. Filthuth, W. Fölisch, V. Hepp, E. Leitner, and G. Zech, *Nucl. Phys.* **B37**, 204 (1971)

[22] R. Engelmann, H. Filthuth, V. Hepp, and E. Kluge, *Phys. Lett.* **21**, 587 (1966)

[23] V. Hepp, and H. Schleich, *Z. Phys.* **21**, 587 (1968)

[24] P.D. Barnes et al., *Phys. Lett.* **B 189**, 249 (1987); **B 199**, 147 (1987); **B 229**, 432 (1989); *Nucl. Phys.* **A 526**, 575 (1991)

[25] P.D. Barnes et al., *Phys. Lett.* **B 246**, 273 (1990)

[26] R.H. Dalitz, and F. Von Hippel, *Phys. Lett.* **10**, 153 (1964)

[27] J.J. de Swart, *Rev. Mod. Phys.* **35**, 916 (1963)
[28] J.J.J. Kokkedee, *The Quark Model*, Frontiers in Physics, (W.A. Benjamin Inc., 1969)
[29] R.J. Oakes, *Phys. Rev.* **131**, 2239 (1963)
[30] S. Iwao, *Nuovo Cimento* **34**, 1167 (1964)
[31] P.O. deSouza, and G.A. Snow, *Phys. Rev.* **135 B**, 565 (1964)
[32] C.B. Dover and H. Feshbach, *Ann. Phys.* (NY) **198**, 321 (1990)
[33] M.M. Nagels, Th.A. Rijken, and J.J. de Swart, *Phys. Rev. Lett.* **31**, 569 (1973)
[34] V.G.J. Stoks, R.A.M. Klomp, C.P.F. Terheggen, and J.J. de Swart, *Construction of high-quality NN-potential models*, Nijmegen-report THEF-NIJM 93.05, submitted for publication
[35] K. Holinde and R. Machleidt, *Nucl. Phys.* **A 280**, 429 (1977)
[36] R. Machleidt, K. Holinde, and Ch. Elster, *Phys. Rep.* **149**, 1 (1987)
[37] J. Haidenbauer and K. Holinde, *Phys. Rev.* **C 40**, 2465 (1989)
[38] R. Machleidt, *Adv. Nucl. Phys.* **19**, 189 (1989)
[39] W. Maĉek, M.M. Nagels, Th.A. Rijken, and J.J. de Swart (unpublished, 1978)
[40] V. Stoks, R. Timmermans, and J.J. de Swart, *Phys. Rev.* **C 47**, 512 (1993)
[41] O. Dumbrajs, et al., *Nucl. Phys.* **B 216**, 277 (1983)
[42] R.G.E. Timmermans, Th.A. Rijken, and J.J. de Swart, *Phys. Lett.* **B 257**, 227 (1991)
[43] J.J. de Swart, and M.M. Nagels, *Fortschr. Phys.* **28**, 215 (1977)
[44] S. Okubo, *Phys. Lett.* **5**, 165 (1963)
G. Zweig, CERN Report No. 8419/TH142 (1964, unpublished)
J. Iizuka, K. Okada, and O. Shito, *Prog. Theor. Phys.* **35**, 1061 (1966)
[45] J.J. Sakurai, *Ann. Phys.* (NY) **11**, 1 (1960)
[46] J.J. Sakurai, *Currents and Mesons* (University of Chicago Press, Chicago, 1969)
[47] G. Höhler and E. Pietarinen, *Nucl. Phys.* **B 95**, 210 (1975); R. Koch and E. Pietarinen, *Nucl. Phys.* **A 336**, 331 (1980)
[48] B. Sakita and K.C. Wali, *Phys. Rev.* **139**, B1355 (1965)
[49] N. Hoshizaki, I. Lin, and S. Machida, *Prog. Theor. Phys.* (Kyoto) **24**, 480 (1960); N. Hoshizaki, S. Otsuki, W. Watari, and M. Yonezawa, *Prog. Theor. Phys.* (Kyoto) **27**, 1199 (1962)
[50] R.A. Bryan, and B.L. Scott, *Phys. Rev.* **135**, B 434 (1964); *Phys. Rev.* **177**, 1435 (1969)
[51] M. Svec, A. de Lesquen, and L. van Rossum, *Phys. Rev.* **D 45**, 1518 (1992)
[52] J. Binstock and R.A. Bryan, *Phys. Rev.* **D 4**, 1341 (1971); R.A. Bryan and A. Gersten, *Phys. Rev.* **D 6**, 341 (1972)
[53] J. Schwinger, *Phys. Rev.* **D 3**, 1967 (1971)
[54] Particle Data Group, *Phys. Rev.* **D 45**, S1 (1992)
[55] A.T. Aerts, P.J. Mulders, and J.J. de Swart, *Phys. Rev.* **D 21**, 1370 (1980)
[56] R.L. Jaffe, *Phys. Rev.* **D 15**, 267 (1977); *Phys. Rev.* **D 15**, 281 (1977)
[57] M. Svec, A. de Lesquen, and L. van Rossum, *Phys. Rev.* **D 46**, 949 (1992)
[58] V. Barger and M. Olsson, *Phys. Rev.* **148**, 1428 (1966)
[59] R. Dolen, D. Horn, and C. Scjhmid, *Phys. Rev.* **166**, 1768 (1968); H. Harari, *Phys. Rev. Lett.* **20**, 1395 (1968)
[60] C.E. Jones, Lawrence Radiation Laboratory Report UCRL-10700 (unpublished, 1962); N.N. Khuri, *Phys. Rev.* **130**, 429 (1963)
[61] Th.A. Rijken, thesis University of Nijmegen (1975); Th.A. Rijken, *Ann. Phys.* (NY)

164, 1 and 23 (1985)
[62] F.E. Low, *Phys. Rev.* **D 12**, 163 (1975); S. Nussinov, *Phys. Rev. Lett.* **34**, 1286 (1975)
[63] T. Henkes, et al., *Phys. Lett.* **B283**, 155 (1992); A.M. Smith, et al., *Phys. Lett.* **B163**, 267 (1985)
[64] P.V. Landshoff and O. Nachtmann, *Z. Phys. C* **35**, 405 (1987)
[65] J. Pumplin and E. Lehman, *Z. Phys. C* **9**, 25 (1981); J.F. Gunion and D.E. Soper, *Phys. Rev.* **D 9**, 2617 (1977)
[66] E.E. Salpeter and H.A. Bethe, *Phys. Rev.* **84**, 1232 (1951); J.M. Charap and S.P. Fubini, *Nuovo Cimento* **14**, 540 (1959); F. Gross, *Phys. Rev.* **186**, 1448 (1969)
[67] Th.A. Rijken, in preparation (1994).