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ΛNK and ΣNK Couplings from LEAR PS185 Data*

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I. INTRODUCTION

Experimental information on the low-energy YN (ΛN, ΣN, ΞN) and YY ($\Lambda\Lambda$, $\Lambda\Sigma$, $\Sigma\Sigma$) interactions is scarce. Important for the understanding of the YN interaction are therefore the reactions $\overline{N}N \to \overline{Y}Y$, studied by the PS185 collaboration at the Low-Energy Antiproton Ring (LEAR) at CERN. These reactions provide a window on strangeness. High-quality data for $\overline{p}p \to \overline{\Lambda}\Lambda$ have been obtained [1]. Some data are already available for $\overline{p}p \to \overline{\Lambda}\Sigma, \overline{\Sigma}\Lambda$ [2], and the $\overline{\Sigma}\Sigma$ channels will follow. A particularly nice feature of these reactions is that they are "self-analyzing": due to the (electro)weak decay of the hyperons spin-observables can be measured without the need for secondary scattering [3, 4]. In $\overline{p}p \to \overline{\Lambda}\Lambda$, for example, the decays $\Lambda \to p\pi^-$ and $\overline{\Lambda} \to \overline{p}\pi^+$ allow one to reconstruct the spin properties of the $\overline{\Lambda}\Lambda$ pair if one detects the four charged decay products. Also, the quality of the LEAR antiproton beam is such that its momentum can be tuned very close to the $\overline{Y}Y$ thresholds, where only few partial waves contribute.

The reaction $\overline{p}p \to \overline{\Lambda}\Lambda$ has been studied by many groups, both in a meson-exchange and quark picture. Coupled-channels calculations including all the $\overline{Y}Y$ channels ($\overline{\Lambda}\Lambda$, $\overline{\Lambda}\Sigma$, $\overline{\Sigma}\Lambda$, $\overline{\Sigma}\Sigma$) have been done by the Nijmegen group [5, 6, 7] using the soft-core YN potential [8], and by the Jülich group [9] using its YN potential [10]. DWBA approaches to $\overline{p}p \to \overline{\Lambda}\Lambda$ can be found in Refs. [11, 12, 13], examples of quark models in Refs. [14, 15, 16]. An effective-range study was done by Tabakin, Eisenstein, and Lu [17].

II. HYPERON-NUCLEON POTENTIAL

The Nijmegen group has been constructing meson-exchange models for the YN interaction for many years now. Realistic models for the hyperon-nucleon (YN) and hyperon-hyperon (YY) interaction are relevant to the study of flavor symmetry in strong interactions, the understanding of the properties of hypernuclei, multiquark states, neutron-star matter, and so on. In Ref. [18] a recent review can be found of the different NN models and their YN counterparts: the hard-core models A to F, and the soft-core model [8].

The existing YN data are few and of low quality. In building a YN model, therefore, one can use only a few (about 5) adjustable parameters. Flavor-$SU(3)$ symmetry is a good starting point to reduce the number of parameters. It is clear, however, that $SU(3)$ is not a very good symmetry of the strong interactions (for a review see Ref. [19]). It is e.g. very much broken by the low pion mass. Unbroken $SU(3)$ would predict a $\{10^*\}$ of bound BB states, to which the deuteron belongs, and a $\{27\}$ of virtual bound states [20]. Realistically, one can only expect to see remnants of $SU(3)$. In the Nijmegen models, the kinematic breaking of $SU(3)$ is taken into account by using the correct masses of the mesons and baryons, but it is assumed that $SU(3)$ is still valid dynamically, i.e. $SU(3)$ is assumed for the coupling constants of the exchanged mesons. For consistency therefore, *complete* nonets must be included. Using only a few parameters, these NN models can then be extended to the YN channels. An additional advantage of this strategy is that predictions can be made for the YY and ΞN channels.

$SU(3)$ for the coupling constants is very probably broken, and although there are indications that this breaking is not enormous, it is still too early to make more definite statements about this. From the reactions $\overline{N}N \rightarrow \overline{Y}Y$ we can learn something about the coupling constants of the kaon and about $SU(3)$ for the couplings of the pseudoscalar-meson nonet.

The soft-core YN model [8] is derived from Regge-pole theory. At low energies the exchange of the lowest-lying trajectories in the complex-J plane reduces to the exchange of the conventional pseudoscalar, vector, and scalar mesons. Additional contributions come from the dominant $J = 0$ parts of the pomeron P and tensor-meson trajectories. The following complete nonets are included in the NN–YN model:

$$\begin{aligned} J^{PC} &= 0^{-+} : \ \pi; \eta, \eta'; K, \quad & J^{PC} &= 0^{++} : \ a_0; \varepsilon, f_0; K_0^*, \\ J^{PC} &= 1^{--} : \ \rho; \omega, \phi; K^*, \quad & J^{PC} &= 2^{++} : \ a_2; P \oplus f_2, f_2'; K_2^*. \end{aligned}$$

The soft-core potential contains therefore the conventional one-boson-exchange forces, plus a few exchanges that follow from Regge-pole theory. In particular, the pomeron is a unique feature of the soft-core potential. It is reponsible for a significant part of the repulsion at short distances, in all flavor channels. Pomeron exchange can be understood as a phenomenological manner to take into account color-singlet two- or multigluon exchange [8, 18]

III. PARTIAL-WAVE ANALYSIS

In Ref. [6] a partial-wave analysis (PWA) was performed of the available $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$ data from the $\overline{\Lambda}\Lambda$ threshold at 1435 MeV/c to 1546 MeV/c. The method of analysis is adapted from the Nijmegen PWAs of pp [21, 22], np [23], and $\overline{p}p$ [24, 25] data. The coupled-channels Schrödinger equation is solved on the particle basis with an energy-dependent complex boundary condition at $r = b = 1.2$ fm. In the region $r > b$ the soft-core NN–YN potential is used. Closed channels are treated correctly. The Coulomb interaction and the mass difference between charged and neutral pions and kaons are taken into account. In this PWA the intermediate- and long-range interaction for $r > b$ can be studied without significant model dependence. For a data set of 157 observables, 99 cross sections, 38 polarizations, and 20 spin correlations, $\chi^2_{\rm min}/N_{\rm obs} = 1.15$ was obtained. It was shown that the transitions with $\ell(\overline{\Lambda}\Lambda) = \ell(\overline{p}p) - 2$, in particular ${}^3D_1 \rightarrow {}^3S_1$, ${}^3F_2 \rightarrow {}^3P_2$, and ${}^3G_3 \rightarrow {}^3D_3$, dominate this reaction. Scattering in the singlet states is negligible to an extent that one can speak of a dynamical selection rule. This can be understood as a consequence of the strong coherent tensor force from $K(494)$ and $K^*(892)$ exchange, together with wave-function overlap between initial and final state for these tensor-force transitions.

IV. KAON COUPLING CONSTANTS

In the 1991 PWA [6], the ΛNK coupling constant could be determined at the kaon pole. The result for the pseudovector coupling was

$$f^2_{\Lambda NK}/4\pi = 0.071(7) \ , \tag{1}$$

where the error is statistical only. The corresponding pseudoscalar coupling is

$\overline{p}p \to \overline{\Lambda}\Lambda$		$\overline{p}p \to \overline{\Lambda}\Sigma^0$+cc		$\overline{p}p \to \overline{\Sigma}\Sigma$	
type	# data	type	# data	type	# data
$\sigma_{\overline{\Lambda}\Lambda}$	10	$\sigma_{\overline{\Lambda}\Sigma}$	2	$\sigma_{\overline{\Sigma}\Sigma}$	1
$d\sigma/d\Omega$	270	$d\sigma/d\Omega$	33	$d\sigma/d\Omega$	8
P_y	103	P_y	24	P_y	—
C_{ij}	168	C_{ij}	28	C_{ij}	—
all	551	all	87	all	9

TABLE I. PS185 database on $\overline{p}p \to \overline{Y}Y$ (July 1994).

$$g^2_{\Lambda NK}/4\pi = 15.4(1.5)\ . \tag{2}$$

It was checked that there are no significant systematic errors due to ΛNK form-factor effects or due to $K^*(892)$ exchange. As a systematic check also the kaon mass was determined, which gave 480(60) MeV, indicating that we are indeed looking at a one-kaon-exchange mechanism in this reaction. A strong correlation was seen between the coupling constant and the kaon mass. Since the mass comes out right, this again indicates that the determination of the coupling is essentially unbiased. Using the state-of-the-art pion-nucleon coupling constant $f^2_{NN\pi}/4\pi = 0.0745(6)$ from the Nijmegen pp PWA [26],and assuming flavor-$SU(3)$ for the coupling constants at the pole, one can determine the $\alpha = F/(F+D)$ ratio. We found: $\alpha_{\rm PV} = 0.34(4)$ and $\alpha_{\rm PS} = 0.42(4)$, for pseudovector and pseudoscalar coupling, respectively.

$SU(3)$ symmetry (Cabibbo theory) in neutron and hyperon β-decays gives the value $\alpha_{\rm W} = 0.355(6)$ for the hadronic axial-vector current. The $SU(3) \times SU(3)$ Goldberger-Treiman relations (see below; for an informative recent review, see Ref. [27]) allow one to relate $\alpha_{\rm W}$ and $\alpha_{\rm PV}$. Only in case of pseudovector coupling the agreement between the two methods of extracting α is seen to be good.

Since the PWA of 1991, new PS185 data on $\overline{p}p \to \overline{\Lambda}\Lambda$ up to 1.92 GeV/c as well as more data on $\overline{\Lambda}\Sigma$ and $\overline{\Sigma}\Lambda$ production have become available. An overview of the PS185 database, as it stood in July 1994, can be found in Table 1. It should be mentioned that these data are of high quality and that our PWA finds the whole PS185 database to be consistent. The 1991 PWA of Ref. [6] has been updated to extract an improved ΛNK and the ΣNK coupling constant. The results are the following:

$$f^2_{\Lambda NK}/4\pi = 0.069(4)\ , \quad \text{or} \quad g^2_{\Lambda NK}/4\pi = 14.9(9)\ , \tag{3}$$

and

$$f^2_{\Sigma NK}/4\pi = 0.005(2)\ , \quad \text{or} \quad g^2_{\Sigma NK}/4\pi = 1.2(5)\ . \tag{4}$$

If we now determine the kaon mass, we find $m_K = 475(30)$ MeV. These values should be considered preliminary, because many systematic checks still have to made. Also, the most recent PS185 are still preliminary.

Since the pseudoscalar mesons are the Goldstone bosons of an (approximate) chiral symmetry of the strong interactions, one can write down so-called Goldberger-Treiman relations, which fix the strong couplings of pion, kaon, and eta in terms of their weak-decay couplings. For the pion-nucleon coupling constant one has the usual $SU(2) \times SU(2)$ version:

$$f_{NN\pi}/m_{\pi^\pm} = g_A/2f_\pi \ , \tag{5}$$

where $g_A = -1.2573(28)$ is the Gamow-Teller coupling in neutron β-decay, and $f_\pi = 92.4(2)$ is the pion decay constant. Using again the pion-nucleon coupling constant from Ref. [26], one finds that this relation is satisfied to about 2%. Theory predicts that this violation should be of the order $(m_u + m_d)/2M_\rho$ [27], or indeed about 1 to 2%, if one uses the standard quark masses. For the kaon, one can write down similar relations, generalized to $SU(3) \times SU(3)$, viz.

$$f_{\Lambda NK}/m_{\pi^\pm} = g_A(\Lambda \to p)/2f_\pi \ , \tag{6}$$

and similar for $\Sigma^- \to n$. The Gamow-Teller couplings for the hyperons are accurately known: $g_A(\Lambda \to p) = -0.718(15)$ and $g_A(\Sigma \to n) = 0.340(17)$, whereas the kaon decay constant is $f_K = 1.22(1)f_\pi$. Using the above values for the strong kaon coupling constants, one finds that the corresponding Goldberger-Treiman relations are violated by about 25%, whereas one expects this number to be about m_s/M_ρ, where m_s is the mass of the strange quark [27]. Most of the violation of $SU(3)$ appears to be due to the breaking between f_π and f_K.

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