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Meson-exchange and nonlocality effects in proton-antiproton annihilation into two pseudoscalar mesons

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The large polarization recently measured in the annihilation reactions $p\bar{p} \to \pi^+\pi^-$ and $p\bar{p} \to K^+K^-$ seems to be due to the strong spin dependence of the initial state interaction. The nonlocality of the annihilation operator might also play an important role.

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The annihilation reactions $p\bar{p} \to \pi^+\pi^-$ and $p\bar{p} \to K^+K^-$, hereafter refered to as I and II, respectively, have been studied at various energies [1]. The mass range $2 \leq \sqrt{s} \leq 3\,\mathrm{GeV}$ has been analyzed with special attention, in order to search for s-channel resonances to be interpreted as broad baryonia. A summary can be found in Ref. [1].

A new measurement of the differential cross section $d\sigma/d\Omega$ and analyzing power A has been performed at CERN by the PS172 Collaboration [2]. The spin parameter A is astonishingly large, nearly equal to ∓ 1 in a wide angular range. This immediately implies an intriguing relation $F_{++} = \pm iF_{+-}$ between the two helicity amplitudes, to be defined more explicitly below. Myhrer *et al.* [3], for instance, have tentatively explained this relation by arguing that the helicity flip amplitude is generated mostly at the interaction surface. A more quantitative analysis remains in our opinion necessary.

There are two main physics concerns associated with reactions I and II. Firstly, it was often stressed that the long-range $N\bar{N}$ forces might well be strongly spin dependent [4, 5], and in particular contain a very large tensor component, due to the coherent contributions of pseudoscalar and vector-meson exchanges. This tensor force has not yet been tested in elastic and charge-exchange scattering experiments, restricted so far to angular distributions and polarizations. We note that reactions I and II filter the natural-parity partial waves, where tensor forces are particularly important.

Secondly, annihilation itself is far from being well understood. Several models have been proposed, based on unitary symmetries or on the topological properties of the quark diagrams, but so far none can be considered as fully successful [6–8]. The recent experimental progress and thus the phenomenological analysis were concentrated on the branching ratios for the various channels accessible in annihilation at rest. The results of the PS172 experiment [2] offer an alternative point of view, where one can study a specific channel in flight with a complete set of observables.

The amplitude for I or II can be written as [9]

$$F = \chi_N^\dagger \left[h_1 \boldsymbol{\sigma}\cdot\mathbf{p}_1 + h_2 \boldsymbol{\sigma}\cdot\mathbf{p}_2\right]\chi_{\bar{N}}, \tag{1}$$

where χ_N is the spinor of the nucleon, $\chi_{\bar{N}}$ the spinor of the antinucleon, with the usual convention for antiparticles, $\mathbf{p}_1$ and $\mathbf{p}_2$ the c.m. momenta of the initial and final states, respectively, so that energy conservation reads $s = 4E^2 = 4(\mathbf{p}_1^2 + m^2) = 4(\mathbf{p}_2^2 + \mu^2)$. When spinors correspond to definite helicities, one gets the helicity amplitudes F_{++} and F_{+-} [9] in terms of which the observables $d\sigma/d\Omega$ and A are easily computed [1].

The transition potential has the same structure as the amplitude (1), since they coincide in the weak coupling limit. The Fourier transform of the potential can be written as

$$V(\mathbf{r},\mathbf{r}') = v_1 \boldsymbol{\sigma}\cdot\hat{\mathbf{r}} + v_2 \boldsymbol{\sigma}\cdot\hat{\mathbf{r}}'. \tag{2}$$

This leads to the amplitude

$$F = \int d^3\mathbf{r}\, d^3\mathbf{r}'\, \exp(-i\mathbf{p}_2\cdot\mathbf{r}')V(\mathbf{r},\mathbf{r}')\Psi_{N\bar{N}}(\mathbf{r}). \tag{3}$$

A detailed description of the validity of Eq. (3) will be given in Ref. [10]. If the optical potential accounts for the effect on the initial state of all annihilation channels, including I and II, then Eq. (3) is exact [11], provided there is no direct $\pi\pi$ or $K\bar{K}$ interaction. If the optical potential does not include the feedback of I and II, then Eq. (3) is a distorted wave Born approximation (DWBA). The difference is rather academic, since I and II represent only a small fraction of annihilation. Including a final-state interaction would result in replacing the plane wave $\exp(i\mathbf{p}_2\cdot\mathbf{r}')$ by a more realistic wave function.

To generate the initial state $\Psi_{N\bar{N}}$ we use the optical potential models of Dover-Richard (DR1 [12] and DR2 [13]) and Kohno-Weise (KW [14]). They contain meson exchange, and a complex Wood-Saxon core $W(r)$ to simulate annihilation. The parameters are adjusted to reproduce the elastic and annihilation $N\bar{N}$ cross sections.

For the transition potential, we first use a local model

$$V(\mathbf{r},\mathbf{r}') = \delta^{(3)}(\mathbf{r}-\mathbf{r}')\frac{f_0}{1+\exp\left[(r-R)/a\right]}\,\boldsymbol{\sigma}\cdot\hat{\mathbf{r}}. \tag{4}$$

The corresponding DWBA amplitude can be calculated by partial-wave expansion. There are delicate complications, due to tensor forces which mix the $L = J - 1$ and $L = J + 1$ components. Each helicity amplitude involves a specific solution of the coupled radial equations. Details will be given elsewhere [10]. The Wood-Saxon shape (4) was already suggested in Ref. [15]. It is the same form as for the annihilation component $W(r)$ of the $N\overline{N}$ optical potentials. A typical choice of parameters for $W(r)$ is $a = 0.2$ fm and R=0.55–0.8 fm [12–14]. However, W is in principle obtained from the sum of iterations of the many $V(\mathbf{r}, \mathbf{r}')$'s and it was stressed that the resulting W(or its equivalent local form) is of larger range than $V(\mathbf{r}, \mathbf{r}')$ itself [17]. So, when adopting $a = 0.2$ fm and $R = 0.55$ fm for the numerical illustration, we consider this range as an upper limit.

The results corresponding to the local potential (4) are shown in Fig. 1. For each model of the initial state, the strength f_0 of the transition potential can be adjusted to reproduce the integrated cross sections. In case I, the results are $f_0 = 1200$ MeV for DR1 and 710 MeV for KW, while in case II, $f_0 = 105$ MeV for DR2 and 172 MeV for KW. Once f_0 is fixed, one can focus on the shape of the angular distribution and on the analyzing power. These values result from a crude compromise, since we cannot reproduce the energy dependence of the integrated cross sections, especially for reaction II: the local model gives a too rapid decrease [10].

The differential cross section for I is rather well reproduced, as seen in Fig. 1. We also obtain a good agreement for the analyzing power of both reactions I and II. This is a rather pleasant surprise, given the crudeness of our simple model. As seen in Fig. 1 we cannot reproduce the backward peak of II. This peak has been explained by the coupling to hyperon-antihyperon channels [14], a mechanism which is not contained in our wave function and in our transition operator. The good agreement for the analyzing power is essentially due to the strong tensor forces in the initial state, particularly in the isospin $I = 0$ channel [4]. We have checked that without this tensor force, the analyzing power drops dramatically toward very small values. This will be investigated in more detail in Ref. [10].

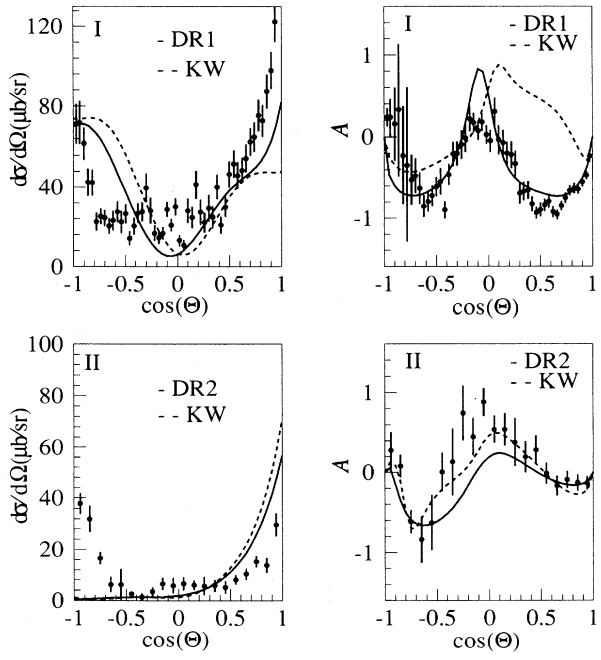

FIG. 1. Differential cross section and analyzing power of reactions I and II at $P_{\rm lab} = 585$ MeV/c. The initial state is generated by the optical models DR1, DR2, or KW.

The results obtained from various optical potentials are generally in good agreement. This is not too surprising, since these potentials are built out of similar ingredients. However processes I and II involve some short-range components of the initial-state wave function, which are not tested in elastic or charge-exchange scattering. This is why potentials which reproduce equally well the $N\overline{N} \to N\overline{N}$ data might sometimes differ in their predictions for annihilation into light mesons.

Anyhow, more realistic $N\overline{N}$ potentials are presently elaborated [16], based on the most recent spin measurements in elastic or charge-exchange scattering at the CERN Low Energy Antiproton Ring (LEAR). It would be useful to repeat the present calculation using improved $N\overline{N}$ potentials.

A more accurate description should of course include the effect of final-state interaction. Its effect is however less dramatically important for the spin parameter than for the angular distribution. Final-state interaction is essentially the same for both helicity amplitudes F_{++} and F_{+-} and does not much change their interference pattern. In practice, the weight of the various partial waves is not exactly the same for F_{++} and F_{+-} and one can observe a small effect [10].

We have also looked at the influence of the parameters of the transition potential given by Eq. (4). Data are not too sensitive to the choice of a and R, once one renormalizes the strength f_0 to guarantee that the integrated cross section is always reproduced.

As an alternative to the local model (4) we use the separable potential

$$V(\mathbf{r}, \mathbf{r}') = b_1(r) b_2(r') \boldsymbol{\sigma} \cdot (\hat{\mathbf{r}} + \lambda \hat{\mathbf{r}}'). \tag{5}$$

In naive microscopic derivations of the annihilation potential in terms of constituent quarks with Gaussian distributions inside hadrons [18], one gets such separable interactions, with form factors

$$b_i(r) = b_0 \exp(-\alpha r^2/2). \tag{6}$$

The hadron size is typically $\alpha^{-1/2} \simeq 0.6$ fm. In principle, the parameter λ is related to the relative weight of annihilation versus rearrangement diagrams, a long-standing controversy [6]. In practice, we have treated λ as a free parameter which governs the ratio of S to P wave transitions.

More dramatic are the changes we register when replacing the local potential by the separable model of Eqs. (5) and (6). Whatever value of the parameter λ we adopt, we cannot reproduce simultaneously the spin parameter

A and the shape of the differential cross section. As noticed by the experimentalists of PS172 [2], the data show partial waves higher than $l = 0$ and 1, which are absent in the simple separable model of Eqs. (5) and (6).

The influence of λ is better seen in the differential cross section. Using the KW model for the initial state we obtain a rough description of $d\sigma/d\Omega$ with $\lambda \approx -1$ and $b_0^{-1} = 0.37$ fm^2 for I, and $\lambda \approx 2.5$ and $b_0^{-1} = 0.63$ fm^2 for II, but a closer look at Fig. 2 confirms the need for higher partial waves. Our values for the strength b_0 are comparable to those used by Kohno and Weise [14]. The larger value of $|\lambda|$ for K^+K^- as compared to $\pi^+\pi^-$ indicates that annihilation into K^+K^- often occurs from initial S state. This is corroborated by the well-known observation that for annihilation at rest, i.e., from atomic orbits, the ratio $R = (p\bar{p} \to K^+K^-/p\bar{p} \to \pi^+\pi^-)$ is larger for S waves than for P waves [19].

A tentative explanation is that the various annihilation processes do not have the same range [20]. Annihilation into $K\overline{K}$ involves several internal annihilations of quark pairs, requiring a good overlap of the incoming N and $\overline{N}$. On the other hand, annihilation into $\pi\pi$ might take more benefit from the rearrangement of the existing constituents, and thus is more peripheral.

Let us summarize. Our study shows the need for the spin dependence of the initial-state interaction, and suggests a plausible scenario for the transition mechanism. Some baryon exchange [21], and maybe some quark rearrangement [18] for the $\pi^+\pi^-$ case, take care of the high partial waves. The corresponding radial wave functions are well localized, and make use only of the local component of the transition operator to ensure a good matching between initial and final states. This explains why our simple local potential gives a reasonable description.

The low partial waves are presumably dominated by direct quark annihilation. This corresponds to highly nonlocal operators, which are separable in explicit constituent-quark calculations with Gaussian wave functions.

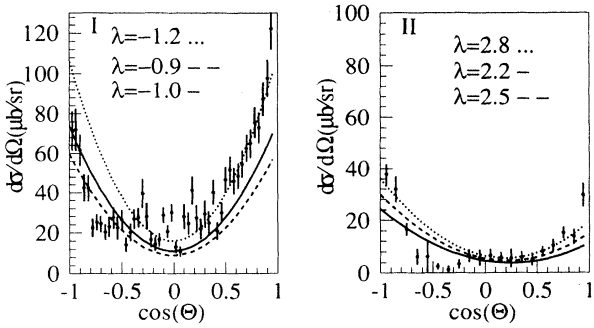

FIG. 2. Differential cross sections of reactions I and II, in the separable transition-potential model. The different curves refer to several values of λ in Eq. (5). The initial state is generated by KW at $P_{\rm lab} = 585$ MeV/c.

We remark upon a different behavior for K^+K^- as compared to $\pi^+\pi^-$. This suggests that a nonplanar diagram with quark rearrangement is not completely negligible.

Our local model predicts large spin effects for $p\bar{p} \to \pi^0\pi^0$, with some dependence upon the choice of the initial-state interaction [10]. Accurate measurements of this reaction could be performed, with the crystal barrel [16] associated with a polarized target.

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