ANTIPROTON ANNIHILATION AND QUARK DYNAMIC SELECTION RULES

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ABSTRACT

Two puzzling $\bar{p}p$ experimental results are discussed which might shed some light on the quark dynamics involved in the annihilation process. Both type of reactions needs high intensity antiproton beams at low energy.

DOES QUARK CONFINEMENT OBSCURE THE DYNAMICS AT LOW ENERGY?

For low energy antinucleon-nucleon interactions only a few channels are open

$$N\bar{N} \to N\bar{N} \quad (1a)$$

and

$$N\bar{N} \to \text{mesons} \quad (1b)$$

where both processes above are competing. Low energy $\bar{p}p$ scattering is not like black sphere scattering although the annihilation process (1b) has a large cross section

$$\sigma(\text{annih.}) \cong 2\ \sigma(\text{tot})/3$$

compared to the elastic scattering one (including charge exchange)

$$\sigma(\text{elastic}) \cong \sigma(\text{tot})/3$$

This means even for simple scattering processes ($\bar{p}p \to \bar{p}p$ and $\bar{p}p \to \bar{n}n$) we can test some physics ideas of the nuclear forces (through G-invariance) if we study the peripheral $p\bar{p}$ scattering. Low energy $p\bar{p}$ scattering is very different from high energy scattering where particle production dominates and where, for high momentum transfer processes, one can use perturbative QCD to describe selected reactions. At low energies quark confinement is dominant and its dynamical implications unknown. So far only very simple models have been proposed to account for quark confinement. To discuss dynamical quark processes involved in $p\bar{p}$ annihilation at low energy, we start with these simple quark models. These models should be constrained to describe the static hadronic properties and we can extend these models (or use the basic ideas of these models) to search for definite predictions of specific, "simple" $p\bar{p}$ annihilation channels.

The non-relativistic quark model does describe the static properties of hadrons including form factors and radiative transitions of excited nucleonic states[1]. However, we do not know how the u and d quark effective mass ≅ 300 MeV behaves in dynamical processes. Some specific $p\bar{p}$ annihilation channels may shed light on the question: how to understand the non-relativisitc model; by comparing the prediction for the "simple" process $p\bar{p} \to$ two mesons in the naive quark models versus e.g. the MIT bag model where the u and d quarks have very small masses ∿ 10 MeV. Specifically, with a high intensity low energy $\bar{p}$ beam we can look at branching ratios for $p\bar{p} \to$ two mesons and search for "surprises". The question then is can a quark model explain the observation. Two concrete examples are discussed which will illustrate what is meant by "surprises".

EXAMPLE ONE: "THE $\pi\rho$ PUZZLE"

Here we will discuss stopped antiprotons in a hydrogen target annihilating into two mesons where annihilation takes place form an atomic S- or P-state[2,3]. Experimentally and via theoretical models, we want to look for suppressed annihilation channels which are allowed by symmetry arguments alone. To illustrate this hunt for quark-dynamics we concentrate on the reaction.

$$p\bar{p} \rightarrow \pi\ \rho \tag{2}$$

The ASTERIX collaboration has measured this reaction at LEAR and find[2]:

$$p\bar{p}(^3S_1, {}^1P_1) \rightarrow \pi\rho \quad (I = 0) \tag{3a}$$

$$p\bar{p}(^1S_0, {}^3P_{1,2}) \rightarrow \pi\rho \quad (I = 1) \tag{3b}$$

Here the notation of the $p\bar{p}$ state is $^{2S+1}L_J$ where $\underline{J} = \underline{L} + \underline{S}$ and $\underline{I}$ = isospin. The last reaction (3b) is allowed by strong interaction symmetries, but is suppressed (or not seen) according to the ASTERIX experiment. The question is why is the reaction (3b) suppressed relative (3a). (The π^o ρ^o channel of reaction

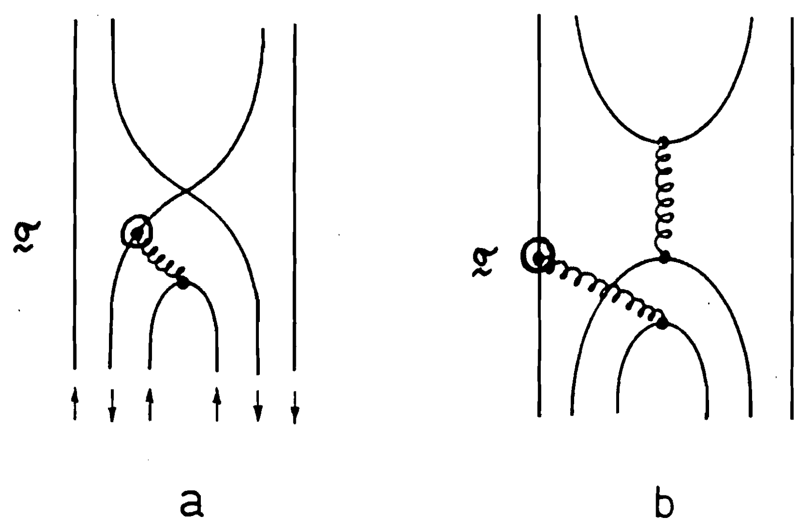

Fig. 1 Two possible ways of coupling timelike gluons to quarks. In diagram b one gluon generate a new $q\bar{q}$ pair the other gluon couple to any quark line.

(3b) is forbidden by C-invariance). To explain the experimental result we need some type of dynamical suppression.

First one word of caution. The $p\bar{p}$ initial states are not pure $p\bar{p}$ (Coulomb) states but are influenced by the strong interaction especially the long range pion interaction. This means the $p\bar{p}$ atomic wave function at shorter distances has the isospin of the most attractive potential at shorter distances (for $^1P_1$ it is I = 0 and for $^3P_1$ it is I = 1 according the Kaufmann and Pilkuhn[4]). For a recent discussion on this point, see ref. 5.

In the following we will used a naive quark picture to illustrate (fig. 1) the reaction $p\bar{p} \rightarrow \pi\rho$. Assume a $q\bar{q}$ pair (or two pairs) annihilate into (timelike) gluons. This vector field has to couple to a quark's spin-operator σ (circled vertex in the diagram). This σ will explore the spin-wave functions in the reactions. The initial N and $\bar{N}$ have total spin ½ and some relative angular momentum L(=0,1). We add all possible diagrams (of the types in fig. 1a or 1b), ignore all soft, confining gluons and we find the observed $p\bar{p} \rightarrow \pi\rho$ selection rule, eq. (3).[6] What this means is not yet clear. We know that perturbation in terms of quark-gluon vertices cannot be used at these low energies since the energy flow through the $q\bar{q} \rightarrow$ gluon vertices are only $\cong 2\, m_q \cong 600$ MeV both in the non-relativistic quark model as well as the MIT model. Also the effective spin-operator σ used is an effective non-relativistic operator and we know the u and d quarks are almost massless. Another question is whether these timelike gluons are "special". If they are, is it meaningful to draw naive diagrams like in fig. 1 ?. We obviously cannot compare the magnitudes of diagrams of type 1a and 1b since we do not know the strengths of the vertices nor do we know precisely how the soft gluons will modify the above results (apart from providing some (initial/final) confined quark wave functions).

However, one conclusion we can draw is that the effective spin operator σ can produce the observed suppression. Do the other two-meson channels have similar suppression and simple explanations? If so we might learn something more about quark dynamics from $p\bar{p}$ annihilation studies.

The proponents of the $^3P_0$ annihilation model now also can explain[5] the ASTERIX data. In this model the $q\bar{q}$ annihilate into vacuum which in this reaction is an energetic "soup of gluons" out of which one can generate new $^3P_0$ $q\bar{q}$ pairs. This model has different predictions from the gluon annihilation model discussed above and future experiments can hopefully settle which model if any of these two does describe other annihilation channels.

EXAMPLE TWO: $p\bar{p} \rightarrow \pi^+\pi^-$ versus K^+K^- scattering.

Here as seen in figure 2 on the next page the recent data from KEK[7] shows that the reaction $p\bar{p} \rightarrow \pi^+\pi^-$ peaks in the forward direction whereas $p\bar{p} \rightarrow K^+K^-$ has a strong backward peak. Data at the higher energies (p(lab) = 780 MeV/c) are consistent with the data of Eisenhandler et al[8]. If we want to explore this with quark models then diagrams of the type 1a and 1b are the natural first ones to be examined. Only the latter (fig. 1b) can contribute to $p\bar{p} \rightarrow K^+K^-$ and, as said, the relative strength between diagrams are unknown (a free parameter) so one should think we can "fit" the data.

To calculate the differential cross sections we need to know the initial $N\bar{N}$ interaction, the reaction mechanism and the final state meson-meson interaction. This is illustrated in fig. 3 below. These processes have been calculated using different models[9,10]. Basically we need at low energy:

a) Knowledge of $\pi\pi$ and $K\bar{K}$ S- and P-wave interactions to generate the outgoing distorted wave
b) Some reaction mechanism like diagrams of the type illustrated in fig. 1 (used by Kohno and Weise[9]) where the strength of the two diagrams are two free parameters. Or a baryon exchange mechanism with knowledge of the timelike $NN\pi$ form factors (Moussallam[10]).

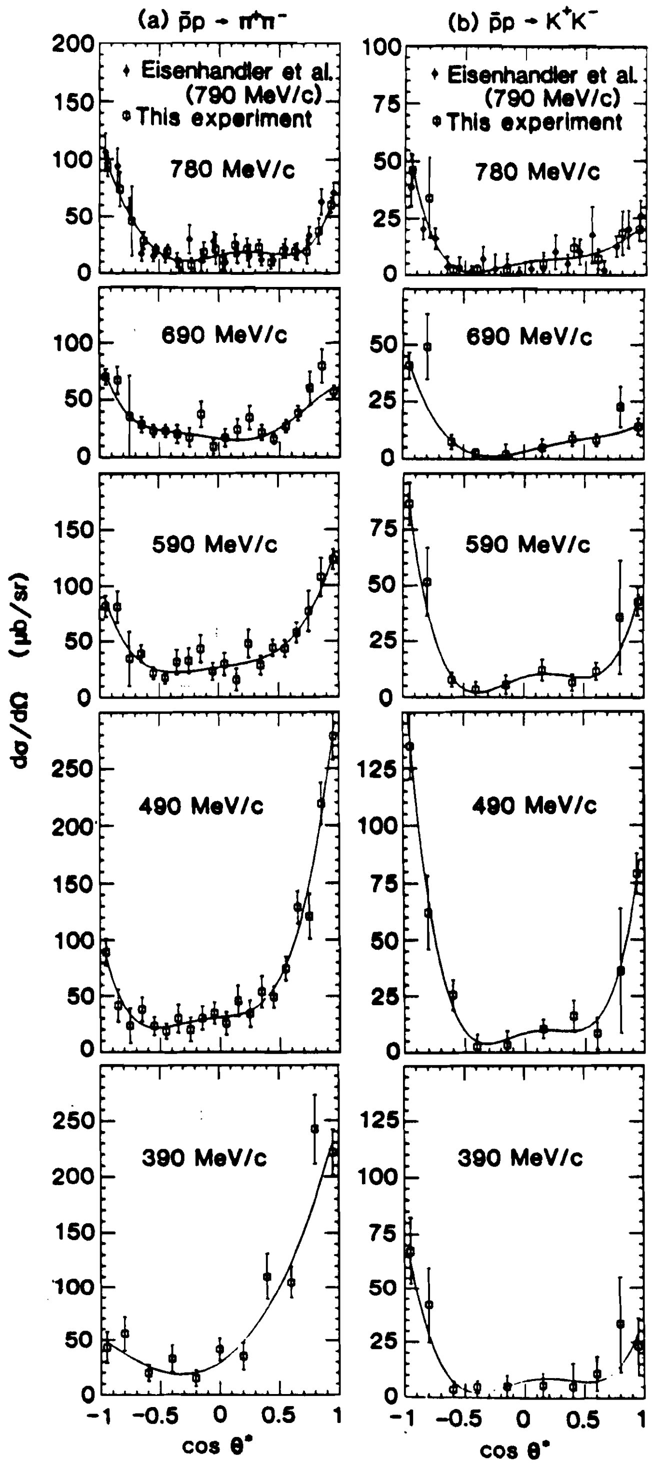

Fig. 2 Experimental results of Tanimori et al.[7] The curves show a Legendre-expansion fit to the data.

c) Initial state $N\bar{N}$ distortion generated by the long-range meson exchanges and some model (or cut-off prescription) for the short-range NN forces. The final cross-sections for $p\bar{p} \to \pi^+\pi^-$ (or K^+K^-) should not depend strongly on the $N\bar{N}$ forces.

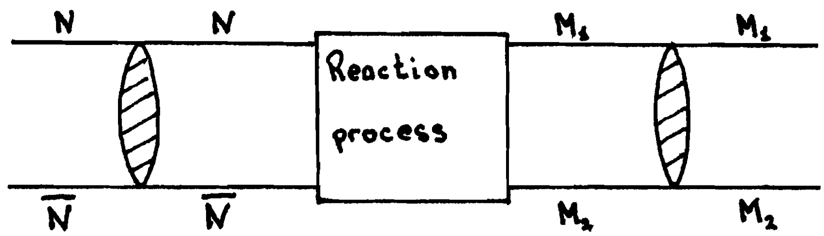

Fig. 3 Illustration of input to a calculations of $p\bar{p} \to M_1M_2$ scattering

The theoretical calculations sketched above are unable to reproduce the $p\bar{p} \to K\bar{K}$ backward peak (the forward $p\bar{p} \to \pi\pi$ peak is relatively easy to generate). Why are $d\sigma/d\Omega$ for $p\bar{p} \to \pi\pi$ and $K\bar{K}$ so different? The two types of quark diagrams (1a and 1b) contribute to $p\bar{p} \to \pi\pi$ whereas only diagram (1b) will contribute to $p\bar{p} \to K\bar{K}$. Also calculations of $p\bar{p} \to K^+K^-$ and $K^o\bar{K}^o$ on the hadronic level (exchange of baryons in t-channel) are unsuccessful[10]. Again the experimental results are puzzling. Can we learn something about the effective quark dynamics (or effective transition operators) from the comparison of these two reactions? Here the calculations are not simple and several sources of uncertainty exists.

A COMMENT ON $N\bar{N}$ SCATTERING

The long range meson exchange forces for NN and $N\bar{N}$ are relatively well known and a modern view of this potential V(r) is based on the chiral quark models[11] where the nucleon consists of a quark core surrounded by a pionic cloud. The pions distribute

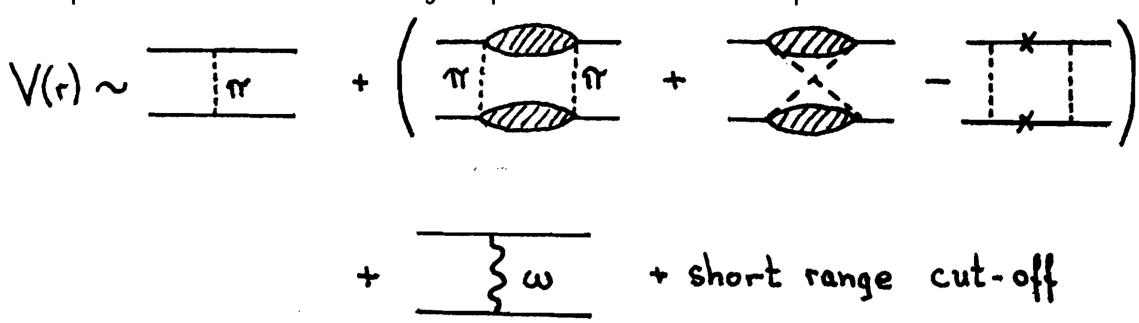

Fig. 4 An illustration of the content of e.g. the Paris[13] NN (and $N\bar{N}$) potential where the cross on the nucleon propagators means this box diagram is the interated pion-exchange one in a particular wave equation.

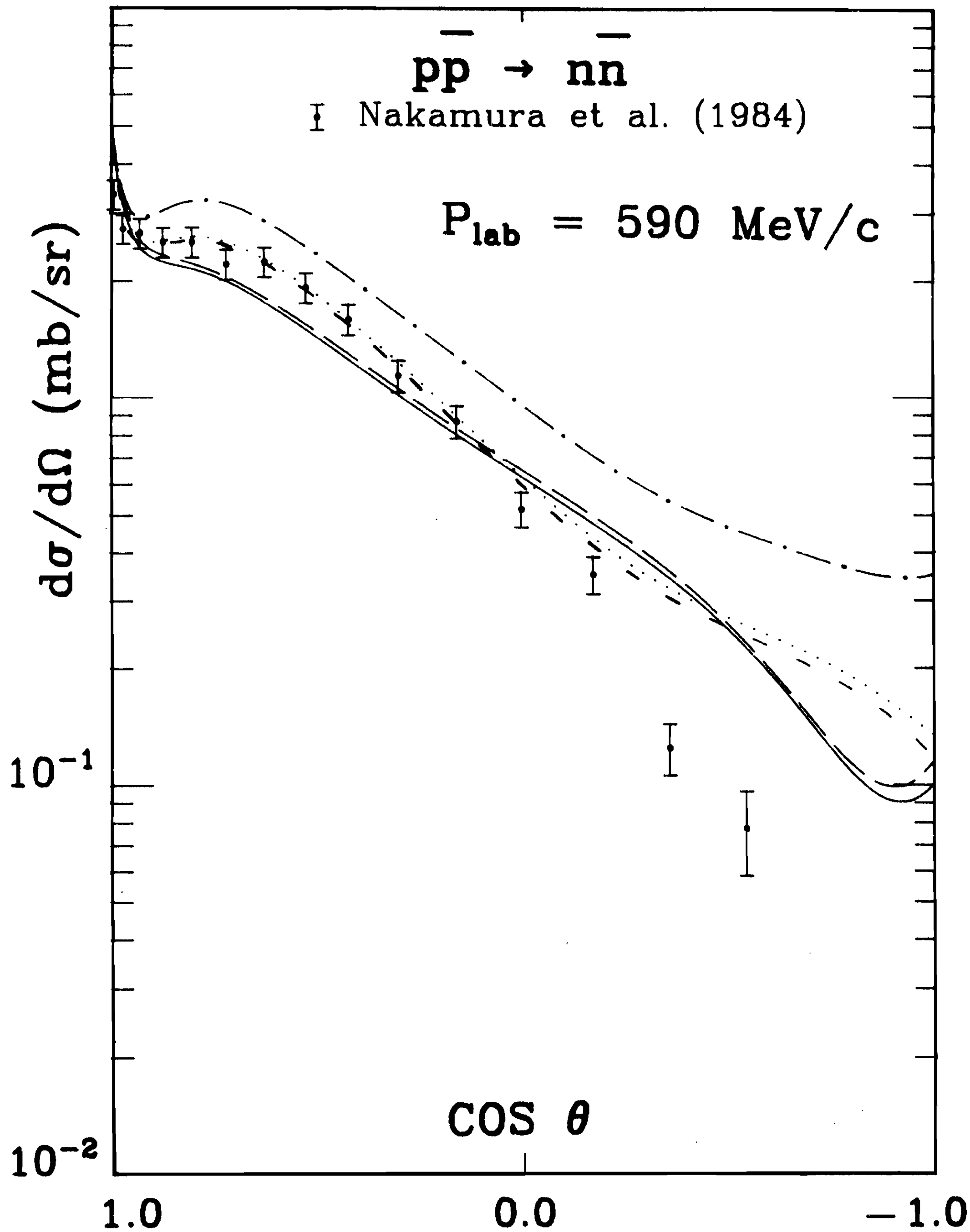

Fig. 5 The charge-exchange data taken from Nakamura et al.[15] The solid and the long dashed curves use the Bryan-Scott OBEP[16] with an annihilation model based on the Regensburg[17] r^3 quark model (of quark core r.m.s. equals 0.60fm) or the MIT bag model (R=0.9fm) respectively. The dotted and short dashed curves use the Nijmegen OBEP[18] with the same two quark models. The dashed-dotted curve use the static Paris potential[19] with the annihilation model based on the MIT bag. As seen the major differences are due to the different NN models used.

around the quark core so as to preserve chiral symmetry, a symmetry which also account for the pion-nucleon coupling strength[11,12]. In these considerations the pion is treated as a field which makes sense only for low momentum transfers. But this should be reasonable for large impact parameter NN and $N\bar{N}$ scattering where only the pionic clouds of N and $\bar{N}$ will overlap and no annihilation takes place. The potential used to generate the initial distortion is illustrated in fig. 4. This potential describes well pp and np scattering, e.g. ref. 13, for which the amplitudes are in the isospin combination $\frac{1}{\sqrt{2}}(|I = 0\rangle + |I = 1\rangle)$ and $|I = 1\rangle$ respectively. This potential gives the $N\bar{N}$ potential through G-invariance arguments. For the charge-exchange scattering, $p\bar{p} \to n\bar{n}$, the difference of two large isospin amplitudes $|I = 0\rangle$ and $|I = 1\rangle$ is probed. Thus in this reaction we can test details of the long range ($r \sim$ 2-4fm) isospin dependence of the $N\bar{N}$ potential (really the two-pion exchange part of this potential which is the same in NN and $N\bar{N}$). In figure 5 we show an example of this were different meson exchange models which fit NN data give different behavior for $p\bar{p} \to n\bar{n}$. The forward shoulder is due mainly to one pion exchange spin-flips[14]. Some differences can be traced to different long distance (2-4 fm) isospin behavior of the NN potential. But large uncertainties are introduced by the arbitrary short-range "cut-off" functions used which for $N\bar{N}$ is coupled to the annihilation process.

CONCLUSIONS

In this presentation two puzzling reactions in low energy antiproton physics have been discussed. To do these experiments one needs intense, good quality antiproton beams.

For stopped antiprotons annihilating into two mesons one wants to prepare the initial $p\bar{p}$ state better through coincidences/anti-coincidences with atomic X-rays. This is feasible with ASTERIX at LEAR and we just want more antiprotons to search for other allowed (by symmetry) but suppressed annihilation channels. We are really looking for a pattern in the suppression. This pattern can then help us to determine the effective operators involved in this annihilation process.

The measured $N\bar{N} \to \pi\pi$ versus $K\bar{K}$ differential cross section is another problem. On the one hand one wants another experiment to confirm the KEK data[7]. On the other our theoretical adoption of the naive annihilation mechanism does not seem to work (confinement is partly built in through, e.g., the quark wave functions). If this is correct it might mean we have to revise our quark picture at low energy such that the quarks really interact with "a soup of gluons". This implies we go back to pre-QCD-days when only quark lines (with no gluon) diagrams were drawn and Zweig rule suppressed some decays channels of mesons. But why? This is precisely what we want to understand and if we can find some pattern in $p\bar{p}$ scattering producing a few mesons with some suppressed decay modes and puzzling scattering data, we can get a better understanding of low energy quark dynamics and what role confinement really plays.

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