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Meson-exchange models for low-energy nucleon-antinucleon scattering

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We investigate several meson-exchange potentials the parameters of which are fixed to describe nucleon-nucleon phase shifts, and we find some variations in their predictions of $N\bar{N}$ observables which should not be present, as we discuss. We find that most data can be roughly reproduced with only one or two free parameters in very simple annihilation models.

I. INTRODUCTION

The major obstacle to our understanding of the low-energy nucleon-antinucleon ($N\bar{N}$) interaction is our lack of a reasonable model describing the annihilation process. So far each theoretical calculation of the $N\bar{N}$ scattering has used a particular meson-exchange potential [one-boson-exchange potential (OBEP)] model with a specific short-range cutoff supplemented either by a short-range annihilation potential or a small-radius black sphere to describe the annihilation. In order to study the mechanism and effect of the $N\bar{N}$ annihilation it is necessary first to understand the meson-exchange part of the $N\bar{N}$ interaction. The OBEP part of the $N\bar{N}$ interaction is predicted by the G-parity invariance from NN interactions but since the usual one-boson-exchange (OBE) potentials are only effective descriptions of the NN interaction, this G-parity argument must be used with caution. There has not been a systematic study to compare the different $N\bar{N}$ meson-exchange models and/or the effect of their short-range modification in combination with a simple phenomenological annihilation model. Such a systematic study is desirable and can tell which $N\bar{N}$ processes are sensitive to differences in the meson-exchange potentials which all fit NN data. This work is an attempt in that direction and we examine critically various OBEP models. We make the usual G-parity transformation to obtain the $N\bar{N}$ OBE potential while keeping the meson masses and coupling constants fixed as given in the NN interaction, but we vary the *ad hoc* short-range OBEP parametrizations in order to see how $N\bar{N}$ observables will be affected. We use here the real part of the Bryan-Phillips potential[1] which was taken from the NN OBE potential of Bryan and Scott. Another OBE potential used here is the Nijmegen model-D OBEP (Ref. 2). In this model the two-pion-exchange part is approximated by a sum of two Yukawa forces to describe the broad scalar-isoscalar meson as well as the broad ρ-meson exchange. In this respect it is a better description than the Bryan-Phillips model. We will also examine the nucleon-antinucleon potential of Richard, Lacombe, and Vinh Mau.[3] This is derived from the static version of the Paris NN potential,[4] which has one-pion and two-pion exchanges as well as the strongly repulsive ω exchange. The two-pion-exchange potential is calculated via dispersion theory from pion-nucleon and pion-pion phase shifts and contains *in principle* no free parameters. However, they do add an arbitrary short-range cutoff potential. The static $N\bar{N}$ OBEP of Richard *et al.*[3] has been used by Dover and Richard[5] to describe $N\bar{N}$ observables.

These three OBEP models should give the same long-distance $r>1$ fm behavior. However, because the scalar-isoscalar-meson mass in the Bryan-Phillips and Nijmegen potentials is at least 500 MeV, whereas the Paris 2π exchange can have as long a range as $(2\mu\cong 280\text{ MeV})^{-1}$, the central part of these potentials will differ significantly in magnitude at a $N\bar{N}$ distance of 3 fm. We do believe that for the nucleon-nucleon potential this very-long-range behavior is best described in the Paris potential. But, as will be discussed in the Conclusions, we have some reservations about the isospin dependence of the Paris $N\bar{N}$ central potential. However, all three models use different, arbitrary cutoff procedures at short distances ($r<1$ fm) and this is expected to give different predictions for $N\bar{N}$ observables. In a following work[6] we will argue that the long range ($r>1$ fm) should be described by OBEP models, whereas the short-range $N\bar{N}$ forces ($r\ll 1$ fm) as well as $N\bar{N}$ annihilation, when the two baryons will overlap considerably, should be given via explicit quark-gluon degrees of freedom. This is in the spirit of the chiral quark models as reviewed by Myhrer,[7] Thomas,[8] Miller,[8] and Weise.[9]

In this work we will use a state- and energy-independent local $N\bar{N}$ absorptive potential of short range to describe annihilation. In addition, we will also examine another model, a black sphere surrounded by a meson cloud, used by Dalkarov and Myhrer.[10] For earlier works using an absorptive boundary condition model, see, e.g., the review of Phillips.[1] This latter simple one-parameter model does surprisingly well when compared with the new precise differential-cross-section measurements of the charge-exchange reaction $p\bar{p}\to n\bar{n}$ from the National Laboratory for High Energy Physics (KEK).[11] Also, available low-energy elastic-scattering data[12] are used to see where the models investigated here deviate from experimental data. This deviation indicates the need for more refined annihilation models and an attempt to formulate a better, dynamic annihilation model will be presented in a following paper.[6] As we also show, the elastic and charge-exchange reactions are apart from orthogonal isospin dominated by different helicity amplitudes. In order to gain more information about the long-range spin structure of the $N\bar{N}$ interaction we have to study both reactions at the same time; see also here the work of Dover and Richard[5] (1982).

II. THE $N\bar{N}$ INTERACTION

We know that the nucleon and antinucleon at large impact parameters interact via meson exchanges. However, from the nucleon form-factor models we also know that the high-momentum components are dominated by quark and gluon degrees of freedom. The chiral quark models using a bag[7,8,13–16] or quark potentials[9,17] to describe the color confinement have been successful in giving the nucleon charge radii and charge and axial-vector form factors. The picture is that the nucleon has a quark-gluon core surrounded by a meson cloud which couples to the quark core in such a way as to ensure chiral symmetry. Therefore one may divide the nucleon-antinucleon interaction into two parts, the long-range one where mesonic degrees of freedom dominate and a short-range one (with small-$N\bar{N}$ impact parameters) where the two quark cores overlap significantly. Then it is natural to ascribe the $N\bar{N}$ annihilation to the latter short-range part. In the following we discuss first the OBE potentials with their *ad hoc* short-range cutoffs and then the different simple annihilation models adopted here.

A. The OBE $N\bar{N}$ interaction

For large-$N\bar{N}$ separation ($r>1$ fm) we assume here that the $N\bar{N}$ interaction is dominated by low-mass meson exchanges (OBEP) between pointlike nucleons and antinucleons with a possible form-factor correction at the meson-nucleon vertices. We further assume that this $N\bar{N}$ OBE potential is given via a G-parity transformation from the nucleon-nucleon OBE potential. There exist several OBE models in the literature and we use three of these models to investigate how they predict $N\bar{N}$ observables.

The simplest NN OBEP we adopt here is the Bryan-Scott model which includes π, η, ρ, ω, σ_0 (a scalar-isoscalar two-pion exchange), and σ_1 (a scalar-isovector exchange). It also incorporates a cutoff procedure of subtracting from each of the meson exchanges an exchange of mass $\Lambda \cong 1000$ MeV to make the OBEP well behaved at the origin. The main weakness of this model apart from the cutoff is that the ρ, σ_0, and σ_1 are treated as stable particles.

The Nijmegen model-D OBE potential[2] includes several heavy mesons but excludes the σ_1 exchange above. This OBEP has the advantage that it treats the ρ and σ_0 (or ϵ) mesons more realistically as broad resonances. The Nijmegen group approximates the distributed masses of the ρ and the ϵ exchanges in their OBEP by a sum of two Yukawa potentials. Their short-range OBEP is arbitrarily cut off by a linear extrapolation to zero for $r \leq r_c = 0.63$ fm. (In addition to this the Nijmegen group[18] added a purely phenomenological short-distance $N\bar{N}$ potential with many parameters.) We also use here a "flat" cutoff, i.e., $V(r)=V(r_c)$ for $r \leq r_c = 0.63$ fm.

The last meson-exchange potential we use here is the static $N\bar{N}$ version[3,5] of the Paris NN potential.[4] This potential includes only one- and two-pion exchanges (both box and crossed box diagrams are included) in addition to ω exchange. Since both the pion-nucleon coupling constant as well as the ω mass are given in addition to their, *in principle*, parameter-free two-pion-exchange potential, the only parameter they have is the ω coupling constant, *except that* its arbitrary OBEP cutoff procedure for $r \leq 0.8$ fm includes many parameters. The Paris NN potential itself is velocity dependent (to order p^2/M^2) like the Bryan-Scott OBEP. We have here adopted the static $N\bar{N}$ version of Richard *et al.*[3] where the two-pion potential of the Paris group is parametrized as a sum of Yukawa's for easy use by other groups. It should be remarked that the Bonn group[19] has tried to calculate from an underlying model using N and Δ intermediate states the two-pion exchange which the Paris group has generated from dispersion relations.

B. The short-range $N\bar{N}$ annihilation

The short-range interaction which presumably dominates for small impact parameters (e.g., $l=0$ and 1 $N\bar{N}$ partial waves) is, as discussed earlier, given by the quark-gluon interactions, an assumption we will explore in a subsequent paper.[6] In this work, where our task is to examine the different long-range OBE potentials with their short-range cutoff procedure and their different $N\bar{N}$ predictions, we will adopt the simplest approach to the short-range $N\bar{N}$ forces. We will assume that they are dominated by annihilation of short range as argued by Martin.[20] Either we will adopt an absorption potential of Woods-Saxon form, purely imaginary ($V_{N\bar{N}}=0$) or complex, as used by Bryan-Phillips[1] or Dover-Richard,[5] respectively,

$$U_{N\bar{N}}(r)=V_{N\bar{N}}(r)-iW_{N\bar{N}}(r) , \tag{1}$$

where the total $N\bar{N}$ potential is the sum of the long-range OBEP described earlier and $U_{N\bar{N}}(r)$, or we adopt a black-sphere annihilation model at a small radius $r_a \cong 0.5$ fm as done by Dalkarov and Myhrer.[10] We will not use the much more complicated many-parameter annihilation prescriptions of the Paris[21] or the Nijmegen[18] groups which fit data. (In these two models it is not clear how to make the connection between the free parameters of the models, for example, the meson-baryon vertex functions and the finite width of the participating meson and baryon resonances.)

In general the optical potential $U_{N\bar{N}}$ should be energy dependent, nonlocal, and probably dependent on the $N\bar{N}$ scattering state as well. We argue here, for the sake of simplicity, that $U_{N\bar{N}}$ comes from a hot annihilation "fireball" where all spin, isospin dependences are averaged out. Also we neglect energy dependence and nonlocalities as a first approximation. In other words the $U_{N\bar{N}}$ only depends on the relative $N\bar{N}$ distance r.

The Bryan-Phillips[1] annihilation potential has the form

$$U_{N\bar{N}}(r) = -iW_{N\bar{N}}(r) ,$$

where

$$W_{N\bar{N}}(r) = W_0/(1+e^{br}) \tag{2}$$

with $b = 5$ fm^{-1} and $W_0 = 8.3$ GeV. We also use this imaginary potential together with the Nijmegen OBEP discussed earlier.

The Dover-Richard[5] annihilation potential has the form

$$U_{N\bar{N}}(r) = -(V_0+iW_0)/(1+e^{br}) \tag{3}$$

with $b = 5$ fm^{-1} and $V_0 = 21$ GeV and $W_0 = 20$ GeV.

The simple black-sphere (BS) annihilation model[10] avoids the drawbacks of an optical potential and its strength lies in having only one free parameter, the black-sphere radius r_a. In this model the $r > r_a$ are described by the OBE potential and if $\psi_{N\bar{N}}$ reaches the small distance $r = r_a$, we require only incoming waves (no reflection). This means that if the annihilation sphere is shielded by a repulsive potential or by the centrifugal barrier in a given partial wave we will have no (very little) absorption in this partial wave. The underlying picture here is that if the two quark cores of the nucleon (antinucleon) have a significant overlap the quark and antiquark will immediately annihilate into gluons and this intermediate state of quarks, antiquarks, and gluons mainly couples to mesonic channels. Since the energy dependence of this model is indirect it is useful to study where this simple model cannot describe experimental data. This will give a hint as to where to search experimentally for short-distance $N\bar{N}$ dynamics.

III. DISCUSSION OF RESULTS

In our calculation with the above models and combinations thereof, we found an interesting result which gives us a clue as to what experiments to perform later. It turns out that the elastic $p\bar{p}$ and $p\bar{p}$ charge-exchange (CEX) are not only orthogonal $N\bar{N}$ isospin combinations. We find that the two reactions also are given by two almost complementary combinations of the helicity amplitudes. As seen in Fig. 1 the forward elastic $p\bar{p}$ scattering is dominated by the ϕ_1 and ϕ_3 helicity amplitudes ($\phi_1 = \langle ++|M|++\rangle$ and $\phi_3 = \langle +-|M|+-\rangle$ following Yokosawa's notation[22]) whereas the CEX is dominated by ϕ_2 $(=\langle ++|M|--\rangle)$, ϕ_4 $(=\langle +-|M|-+\rangle)$, and partially ϕ_5 $(=\langle ++|M|+-\rangle)$. (We have renormalized the CEX data of Nakamura *et al.*[11] at each energy to reproduce the energy dependence of the directly measured CEX total cross section of Hamilton *et al.*[23] Both sets of data are consistent with each other, but the measurements of Hamilton *et al.* have smaller systematic uncertainties.) To what extent different helicity amplitudes dominate $d\sigma/d\Omega$ for the different reactions does depend on the OBEP version used and we show two extremes in Fig. 1. The Nijmegen potential gives results in between the two extremes in Fig. 1. Figure 1 gives us valuable clues, for example, the shoulder (dip bump) in the forward CEX is an interference between the rapidly decreasing $|\phi_2|^2$ and increasing $|\phi_4|^2$ and $4|\phi_5|^2$. If ϕ_1 and ϕ_3 are too small in the forward direction one has a too pronounced dip-bump structure, which is the case for the static Paris meson-exchange potential. According to the new KEK data,[11] one has a broad shoulder which says the decreasing $|\phi_1|$ and $|\phi_3|$ amplitudes cannot be negligible in this angular range. In the (lowest-order) one-boson-exchange Born contribution what enters ϕ_i $(i=1,\dots,5)$ is schematically

$$\phi_1^{\rm el} \sim \sigma+\rho+\omega, \quad \phi_1^{\rm CEX} \sim 2\rho \text{ (isovector } 2\pi \text{ exchange)} ,$$

$$\phi_2^{\rm el} \sim \sigma+\rho+\omega+\pi, \quad \phi_2^{\rm CEX} \sim 2(\pi+\rho) ,$$

$$\phi_3^{\rm el} \sim \sigma+\rho+\omega, \quad \phi_3^{\rm CEX} \sim 2\rho \text{ (isovector } 2\pi \text{ exchange)} ,$$

$$\phi_4^{\rm el} \sim \sigma+\rho+\omega+\pi, \quad \phi_4^{\rm CEX} \sim 2(\pi+\rho) ,$$

$$\phi_5^{\rm el} \sim \sigma+\rho+\omega, \quad \phi_5^{\rm CEX} \sim 2\rho \text{ (isovector } 2\pi \text{ exchange)} ,$$

where σ means the scalar-isoscalar-meson exchange (like two-pion) and the factor 2 in the charge-exchange amplitudes signifies that the contribution is twice the corresponding one in the elastic helicity amplitude. Judging from the above expressions we can understand why $\phi_2^{\rm CEX}$ and $\phi_4^{\rm CEX}$ are larger than the others since the annihilation tends to suppress the shorter-range exchanges like, e.g., the ω- and ρ-meson exchange. But the non-negligibility of $\phi_1^{\rm CEX}$ and $\phi_3^{\rm CEX}$ to partially fill in the dip-bump structure warns that we should not take the above relations too literally.

When we compared the data with the Bryan-Phillips model we found a large sensitivity to the cutoff parameter Λ (a cutoff used to take care of the r^{-3} behavior of the $\mathbf{L}\cdot\mathbf{S}$ and tensor forces at shorter distances). This shows up most dramatically in the polarization $P(\theta)$ of $p\bar{p} \to p\bar{p}$ for $p_{\rm lab} = 700$ MeV/c (Fig. 2). In the literature this much publicized[21,24,25] polarization curve for $\Lambda = 1$ GeV changes dramatically if Λ is changed by as little as 2% ($\pm$ 20 MeV) (see Fig. 2). The origin of this pathological behavior was noted long ago in a slightly different context (pion-nuclear interactions) by Bethe:[26] The structure of a wave equation with a strong velocity-dependent potential is such that there might exist a singular point at $r = r_\infty > 0$ where the "effective" kinetic term changes from repulsion to attraction. This pathological behavior in the $N\bar{N}$ scattering was noted by Myhrer and Gersten[27] [stated briefly this is due to the strong ω attraction which for the NN interaction is well known to be very repulsive (thus no singularity for the NN case), see the erratum[1] of Bryan and Phillips] and the physical consequences in pion-nuclear physics were discussed in detail by Ericson and Myhrer.[28] This singularity occurs at $r = r_\infty$. If $r_\infty < 0$ we do not have any wave-function singularity, but the velocity-dependent part

$$(1/2m_N)(\nabla^2\phi + \phi\nabla^2) \tag{4}$$

can still result in an abnormally large factor $[1+2\phi(r)]^{-1}$ which renormalizes the static Bryan-Scott potential $V_{N\bar{N}}(r)$ [the velocity part Eq. (4) originates from an ex-

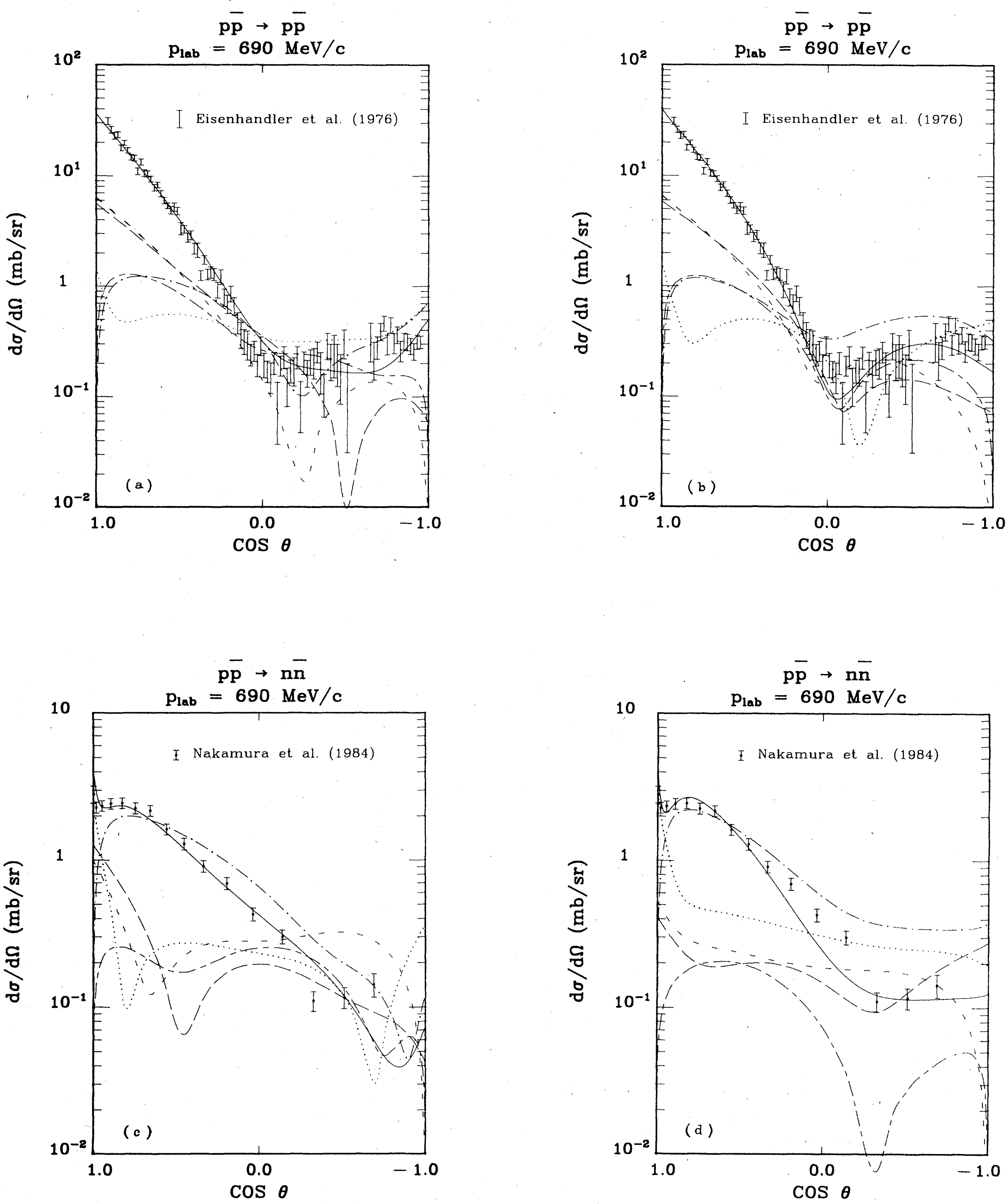

FIG. 1. The absolute value of the five helicity amplitudes in $\mathrm{mb}^{1/2}$ which contribute to the elastic and charge-exchange differential cross sections are shown for two different $N\bar{N}$ models: $|\phi_1|$ (long-dashed curve), $|\phi_2|$ (dotted curve), $|\phi_3|$ (short-dashed curve), $|\phi_4|$ (dashed-dotted curve), and $|\phi_5|$ (short-dashed—long-dashed curve). The solid curve is the total differential cross section. Data are taken from Eisenhandler *et al.* (Ref. 12) and Nakamura *et al.* (Ref. 11) as indicated. We have renormalized the Nakamura *et al.* data to give the total CEX cross section of Hamilton *et al.* (Ref. 23) as explained in the text. (a) Elastic scattering with the black-sphere annihilation model and the Bryan-Scott OBEP (Ref. 1). (b) Elastic scattering with the Dover-Richard model (Ref. 5). (c) Charge exchange with the black-sphere annihilation model and the Bryan-Scott OBEP (Ref. 1). (d) Charge exchange with the Dover-Richard model (Ref. 5).

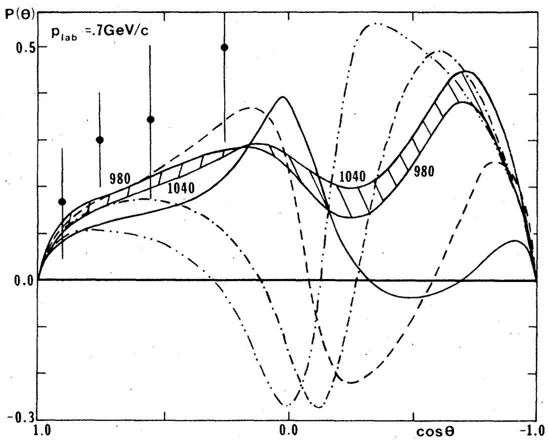

FIG. 2. Polarization at $p_{\rm lab}=0.7$ GeV/c. Data are from Kimura *et al.* (Ref. 24). Predictions of the Bryan-Phillips model for different cutoff Λ (solid curve, 980 MeV; dashed, 970 MeV; dashed-dotted, 1000 MeV; dashed—double-dotted, 1020 MeV). The shaded area is the result of the black-sphere annihilation model with the Bryan-Scott OBEP when Λ varies between 980 and 1040 MeV.

pansion of OBE in p^2/m_N^2 to order p^4/m_N^4 and should not be dominant for this expansion to be valid]. Unfortunately r_∞ is strongly Λ dependent and positive for $\Lambda\sim 1$ GeV. We have plotted in Fig. 3 $r_\infty(\Lambda)$ for the $N\overline{N}$ isospin channels $I=0$ and $I=1$. Clearly for $\Lambda=1$ GeV (the value used by Bryan and Phillips) the singularity occurs at $r_\infty\sim 0.02$ fm. In fact, the Bryan-Phillips model runs into this singularity problem for any choice of $\Lambda\geq 985$ MeV. For $\Lambda>1000$ MeV there are strong effects

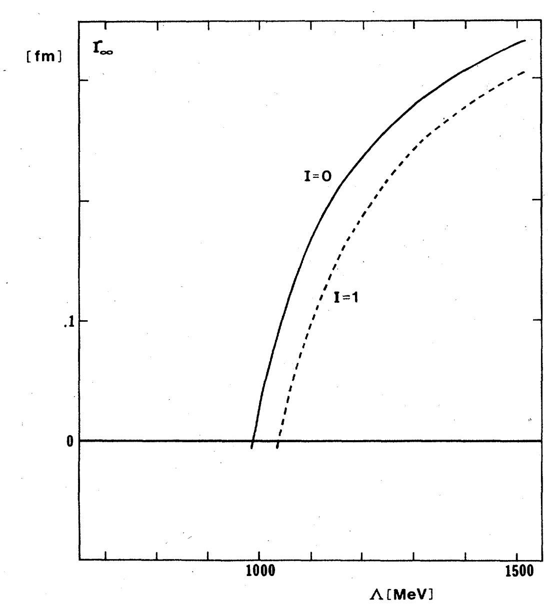

FIG. 3. r_∞ as a function of Λ for the $N\overline{N}$ isospin channels $I=0,1$; see the text.

of this singularity in $d\sigma/d\Omega$ also. In Fig. 2 we also show the uncertainty in the polarization when we use the black-sphere annihilation model with the Bryan-Scott OBEP. The black sphere effectively hides the singularity and the effect is only through the $(1+2\Phi)^{-1}$ enhancement. In the following we use $\Lambda=980$ MeV.

So far we have only analyzed carefully the Bryan-Phillips OBE potential, and it gives us a warning that we should not uncritically G transform a given nucleon-nucleon OBE potential. In the following we will discuss the static Paris meson-exchange potential as well as the Nijmegen OBEP and the uncertainties in their short-distance cutoffs.

The total-elastic-$p\overline{p}$-scattering data (see Fig. 4) are reproduced only for $p_{\rm lab}\geq 0.5$ GeV/c and are, except for the Nijmegen OBEP with a flat cutoff, systematically *larger* than the experiments, whereas the charge-exchange results for the Bryan-Phillips[1] and the black-sphere (BS) model[10] are systematically *below* the data between 0.3 and 0.6 GeV/c. The Dover-Richard model reproduces $\sigma_{\rm CEX}$ well for $p_{\rm lab}>400$ MeV/c. (Any potential model beyond $p_{\rm lab}\sim 1$ GeV/c becomes increasingly unreliable due to relativistic effects.) In Fig. 4 we also compare with the total $p\overline{p}$ cross section. The Bryan-Phillips model prediction is systematically above the data and the Nijmegen model with a flat cutoff is below the data, both the old 1976 data of Chaloupka *et al.*[29] and the more recent data.[30] If we increase the cutoff radius r_c to 0.66 fm for the Nijmegen flat cutoff we obtain almost the same results as with the linear cutoff with $r_c=0.63$ fm. However the energy dependence is different. The Bryan-Phillips model works very well for $p\overline{p}$ backward scattering, Fig. 5, if $p_{\rm lab}\lesssim 650$ MeV/c, whereas the other models do not.

In Fig. 6 the backward structure of $d\sigma/d\Omega$ ($p\overline{p}\to p\overline{p}$) at $p_{\rm lab}=690$, 860 MeV/c (Ref. 12) is reproduced by the Dover-Richard model, but the Bryan-Phillips, the Nijmegen model with a linear cutoff, and the black-sphere annihilation model have a strong backward (180°) peak at these energies which explains why they overshoot the measured backward (174°) elastic cross section for $p_{\rm lab}>650$ MeV/c in Fig. 5. The Dover-Richard optical-potential model[5] gives a $d\sigma/d\Omega$ (174°) ($p\overline{p}\to p\overline{p}$) as a function of $p_{\rm lab}$ much smaller than the experiment,[31(a)] whereas the backward structure in $d\sigma/d\Omega$ at $p_{\rm lab}=690$, 860 MeV/c (see Fig. 6) is nicely reproduced. We would like to stress here that the experimentally observed large-angle dip-bump structure in the elastic $p\overline{p}$ scattering at $T_{\rm lab}\geq 220$ MeV is mainly due to the annihilation potential since without the annihilation potential the differential cross section increases toward the backward angle. This is a common feature of all investigated meson-exchange models, which makes backward $p\overline{p}$ scattering especially suitable for constraining the $N\overline{N}$ annihilation potential.

The two different cutoff procedures for the Nijmegen OBEP give marked differences. However, if we increase r_c to 0.66 fm ($\sim 5\%$) the results for the flat cutoff are not too different from those results with a linear cutoff at $r_c=0.63$ fm at lower energies. The Dover-Richard model is less sensitive to variations of the cutoff.

The very recent charge-exchange data from KEK (Fig. 7) at $p_{\rm lab}=390$, 490, 590, 690, 780 MeV/c show a forward

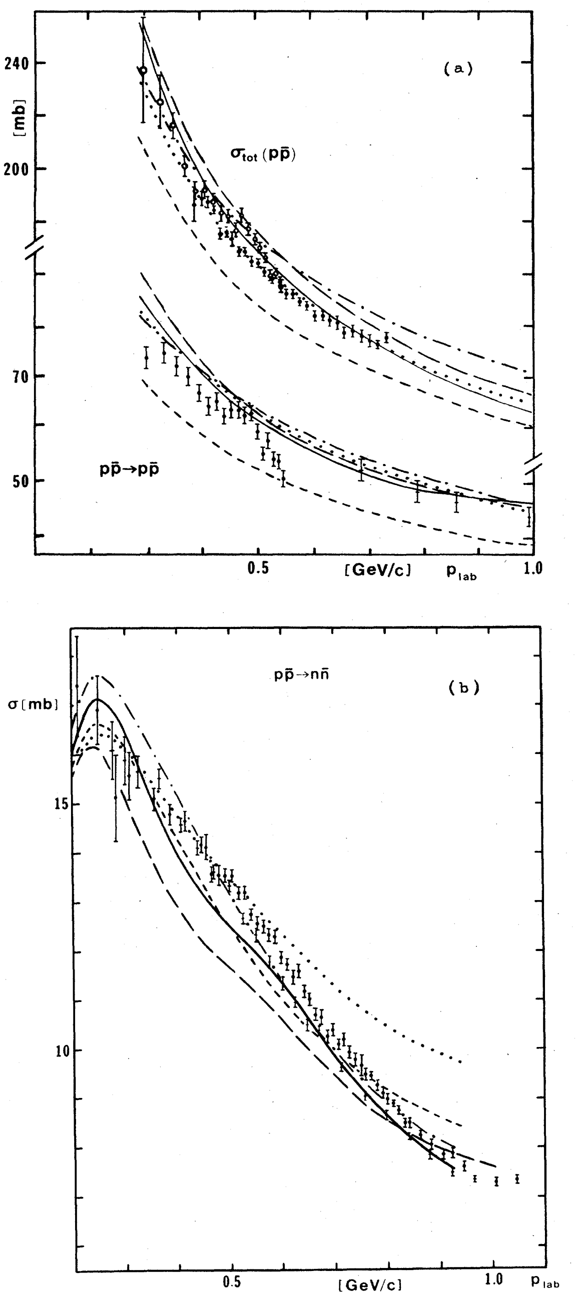

FIG. 4. (a) Total $p\bar{p}$ cross section as a function of p_{lab}. Data: open dots with error bars, Chaloupka *et al.* (Ref. 29); solid dots with error bars, Nakamura *et al.* (Ref. 30). Elastic $p\bar{p}$ cross section as a function of laboratory momentum p_{lab}. Data: solid dots with error bars, Chaloupka *et al.* (Ref. 29); short dashes with error bars, Coupland *et al.* (Ref. 32). Solid curve, black-sphere annihilation model with Bryan-Scott OBEP; long-dashed curve, Bryan-Phillips model; dashed-dotted curve, Dover-Richard model; short-dashed curve, Nijmegen with $V(r)=V(r_c)$ for $r \le r_c = 0.63$ fm; dotted curve, Nijmegen with linear cutoff; see the text. With both Nijmegen OBEP we use the absorption potential of Eq. (2). (b) Charge-exchange $p\bar{p} \to n\bar{n}$ cross section as a function of p_{lab}. Data: Solid dots with error bars, Hamilton *et al* (Ref. 23), short dashes with error bars, Alston-Garnjost *et al.* [Ref. 31(b)].

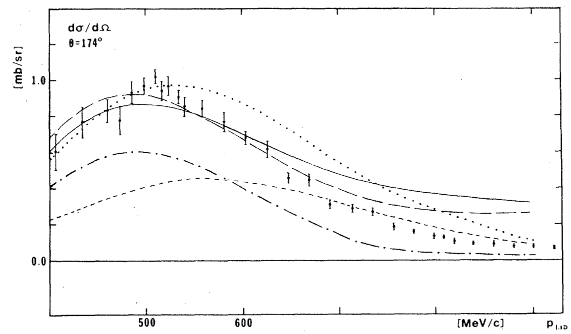

FIG. 5. Differential elastic cross section at backward angles ($\theta_{c.m.}=174°$) measured by Alston-Garnjost *et al.* [Ref. 31(a)]. Curves as in Fig. 4.

structure which is present as a shoulder in the Bryan-Phillips model although the "shoulder" is somewhat too low and the dependence on $\cos\theta$ is weaker in forward directions than observed. However, these data from KEK (Ref. 11) show much less θ dependence than given in the Dover-Richard model (see Fig. 7) which has a very pronounced dip-bump structure in the forward $d\sigma/d\Omega$ and we note that the Paris group[21] finds an even more pronounced forward dip-bump structure, as published in Ref. 11 (remember here our earlier discussion of the helicity amplitudes). The two Nijmegen model calculations as well as the black-sphere model with the Bryan-Scott OBEP show better agreement with the new data. There is a feature of the CEX data which is interesting when we

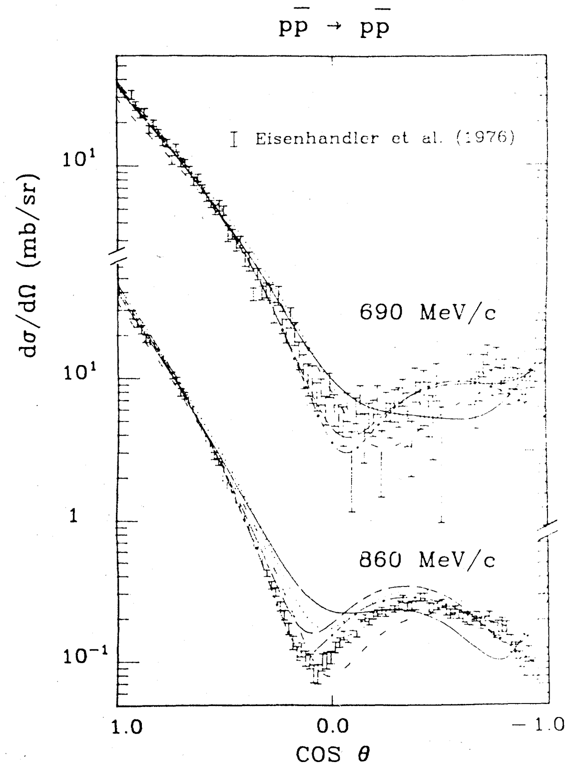

FIG. 6. $d\sigma_{el}/d\Omega$ at $p_{lab}=690$, 860 MeV/c as measured by Eisenhandler *et al.* (Ref. 12). Curves as in Fig. 4.

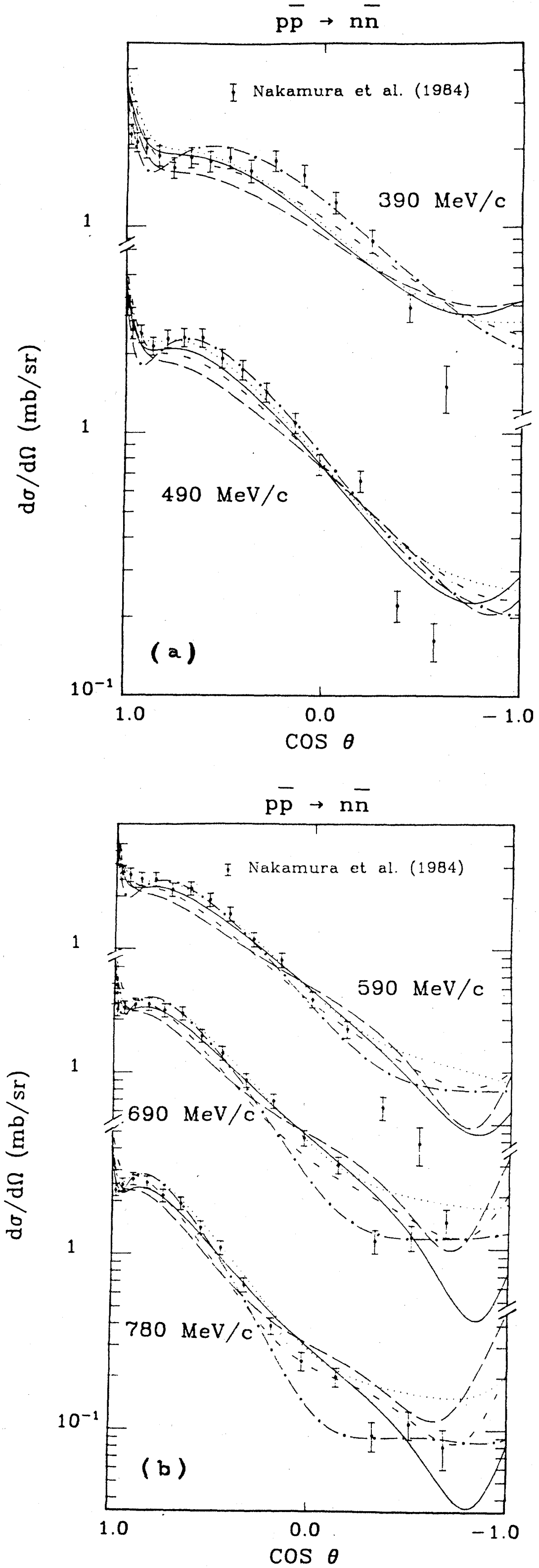

FIG. 7. $d\sigma_{\mathrm{CEX}}/d\Omega$ at $p_{\mathrm{lab}}=390$, 490, 590, 690, 780 MeV/c. Data from Nakamura *et al.* (Ref. 11). We have renormalized these data to the total CEX cross section of Hamilton *et al.* (Ref. 23) as explained in the text. Curves as in Fig. 4.

compare the two cutoff procedures used with the Nijmegen OBEP. With the linear extrapolation version of the OBEP we find a dip-bump structure in the small angle CEX, while only a shoulder is produced by the flat cutoff version, although the larger-angle CEX behavior is similar, see Fig. 7. This says that the small-angle CEX process is sensitive to the intermediate to short-range OBEP of Nijmegen. And again if we increase r_c to 0.66 fm for the flat Nijmegen cutoff we get results very close to the linear Nijmegen cutoff with $r_c=0.63$ fm at the lowest energy. The Bryan-Phillips model peaks towards backward angles (we note that if the annihilation is switched off completely all three OBEP models show a characteristic peaking towards backward scattering angles both for the $p\bar{p}$ elastic and the charge-exchange processes).

The "black-sphere" annihilation is found to work best with the annihilation radius of $r_a=0.5$ fm when the OBEP of Bryan and Phillips is kept for $r>r_a$. A "black-sphere" annihilation model with the Nijmegen OBEP (Ref. 33) for $r>r_a$ gives a CEX cross section larger than the data, and with the static Paris potential for $r>r_a$ σ_{CEX} is more than a factor of 2 too large. This latter is probably due to the different $N\bar{N}$ isospin central attractions in the Paris meson-exchange potential as compared to the two other OBEP's, as we will discuss in the conclusions. The differential cross sections with the black-sphere annihilation peak at backward angles for all OBEP's used, as does the Bryan-Phillips model. This indicates that the "black-sphere" as well as the Bryan-Phillips model do not have sufficient effective annihilation strength for higher-momentum transfers. In the black-sphere annihilation model this means that the OBEP's used are not attractive enough at these energies and momentum transfers. The Dover-Richard model, which has a much larger annihilation strength (21 GeV as compared to 8.3 GeV) but which also adds a strong attractive potential, works better at backward angles.

Finally, we have also calculated the ratio ρ of the real to imaginary forward-elastic-$p\bar{p}$-scattering amplitude and the results are tabulated in Table I. We find that all versions of OBEP give too negative ratios ρ compared to old data.[34] (As pointed out by Vinh Mau and co-workers[35] one has to be careful with extracting ρ from the experimental data, since spin effects cannot be neglected in the determination of ρ. This has the tendency of shifting the values for ρ downwards, as also verified with the new experimental data of Cresti *et al.*[36] All models investigated here seem to favor a negative ρ for $p_{\mathrm{lab}} \leq 300$ MeV/c; how negative depends on the model.

IV. CONCLUSIONS

The available data can, apart from details, be described by the models investigated here but there are unwanted differences among the meson-exchange models used. The one-parameter black-sphere model with the Bryan-Phillips OBEP as well as the Nijmegen OBEP with a Woods-Saxon absorption, Eq. (2), do surprisingly well in describing the new precise CEX data from KEK. The new CEX data[11] show that both the Dover-Richard and the Paris group itself (the latter using 15 or more free parameters[21]

TABLE I. The ratio of the real to imaginary forward amplitude $\rho = \mathrm{Re}f(0°)/\mathrm{Im}f(0°)$ as a function of the antiproton laboratory momentum and different OBEP models. The top two lines are consistent with the data of Cresti *et al.* (Ref. 36), but none can reproduce the new data of Ransome *et al.* (Ref. 34).

p_{lab} (MeV/c)	310	490	690	860
Bryan and Phillips	−0.17	−0.04	0.05	0.13
Black sphere	−0.14	0.03	0.13	0.19
Dover and Richard	−0.34	−0.24	−0.16	−0.11
Nijmegen (linear cutoff)	−0.29	−0.14	−0.03	0.04
Nijmegen (flat cutoff)	−0.32	−0.23	−0.15	−0.10

must modify their potentials since both models have a pronounced CEX dip-bump structure not seen in the data. In principle, the very-long-range part of the Paris NN potential is supposedly parameter free. However, the central part of the $N\bar{N}$ Paris meson-exchange potential, which originates from the two-pion exchange, has the isospin one ($I=1$) more attractive for all distances than the isospin zero ($I=0$) part, whereas both the Nijmegen OBEP as well as the Bryan-Scott OBEP have the central ($I=0$) $N\bar{N}$ potential more attractive than the $I=1$. In order to understand this a careful analysis of the parameter-free Paris two-pion-exchange potential is necessary. We have included both η exchange and a scalar-isovector σ_1 exchange (sum of Yukawa's) missing in the Paris, the latter also in the Nijmegen potential. We find that these exchanges do not change the results very much.

It is clear that the simple black-sphere annihilation model (with an annihilation radius $r_a \cong 0.5$ fm) which implicitly does have some energy dependence, does not describe well the backward $p\bar{p}$ elastic scattering for increasing energy due basically to the peaking of $d\sigma/d\Omega$ in the backward direction, see Fig. 6. In a forthcoming publication[6] we will construct a quark-gluon annihilation model which should describe the physics at shorter distances better and hopefully improve this feature.

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