REVIEWS OF MODERN PHYSICS VOLUME 39, NUMBER 3 JULY 1967

Antinuclear Forces

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Theoretical models of the nucleon–antinucleon interaction are surveyed in the few-hundred MeV region. Their relation to the nucleon–nucleon interaction, and any light they may shed on it, are discussed.

1. INTRODUCTION

Antinuclear forces are not an isolated problem. Meson theory relates them to ordinary nuclear forces, and this is why they come up at the present conference. We can learn from them—in principle, anyway—more about the meson couplings and about the validity of various ideas and approximations.[1–4]

Fundamentally, $\bar{N}N$ and NN interactions have the same Feynman diagrams. You can read Fig. 1 either as $N_1+N_2\rightarrow N_3+N_4$ or as $\bar{N}_3+N_2\rightarrow\bar{N}_1+N_4$. Both scattering amplitudes are given by a single operator, but it is a function of the external momenta p_i $(i=1, \cdots, 4)$. The physical regions for NN and $\bar{N}N$ scattering are separated; for the former $(p_1+p_2)^2\geq 4m_N^2$; for the latter $(p_1+p_2)^2\leq 0$. These regions are too far apart to extrapolate information readily from one to the other.

If we consider only pion-exchange diagrams (Fig. 2), however, the physical NN and $\bar{N}N$ terms are related by a simple symmetry and no extrapolation is needed. Charge conjugation shows the $\bar{N}\pi$ coupling constant is just -1 times the $N\pi$ coupling.[5] Hence if we replace one nucleon by an antinucleon, keeping momenta, spins, and i spins fixed, the amplitude for any n-pion exchange process changes by $(-1)^n$:

$$T_{NN}(n\pi \text{ exchange})=(-)^n T_{\bar{N}N}(n\pi \text{ exchange}). \quad (1)$$

This symmetry generalizes to exchanging other mesons or complex systems with well-defined G parity[6]; the proportionality factor is $(-)^G$.

In the meson theory of nuclear forces,[2,4] these exchanges generate a real NN potential V_{NN}. Given any prescription for V_{NN}, there is a corresponding $\bar{N}N$ potential:

$$V_{\bar{N}N}=V_{NN}(\text{even } G \text{ exchange})-V_{NN}(\text{odd } G \text{ exchange}). \quad (2)$$

It would help to have experimental information about $V_{\bar{N}N}$ as well as V_{NN}, so that even and odd G exchanges could be separated. In V_{NN} the even and odd parts tend to cancel. For example, scalar and vector meson exchanges contribute with opposite signs in V_{NN} but with the same sign in $V_{\bar{N}N}$.

What about other diagrams, without this special symmetry? There are two kinds.

(*a*) *Intermediate annihilation diagrams* (Fig. 3). $\bar{N}+N\rightarrow$mesons$\rightarrow\bar{N}+N$. These are like the effects of an absorptive $\bar{N}N$ potential, representing the coupling to annihilation channels. But they also contribute a real part to the potential; for example, diagrams with 20 intermediate pions are not related to absorption, at least below the 20-pion threshold energy. Since there are many annihilation channels, we expect little net spin or i-spin dependence from these processes. There are no direct NN counterparts.

(*b*) *Intermediate deuteron diagram* (Fig. 4). For NN this represents the deuteron bound state and generates no potential. For $\bar{N}N$ it gives a short-range exchange potential.

Most models of the $\bar{N}N$ interaction have the following basis. Meson exhanges are taken from an NN model, with suitable sign changes; this part has no free parameters. Annihilation is represented by a phenomenological absorption—a potential or a boundary condition—with some free parameters but no spin or i-spin dependence. The absorption suppresses short-range effects achieving a result like a repulsive core. Deuteron exchange and nonabsorptive effects of annihilation diagrams are ignored. This semifundamental approach with few free parameters is the most promising way, since the data are far from complete and will long remain so.

2. SCATTERING AMPLITUDES

Let M be the $\bar{N}N$ c.m. scattering amplitude. Its general properties are like the NN case,[3,4] but without antisymmetry. Assuming charge independence,

$$M(\bar{p}n\rightarrow\bar{p}n)=M_1, \quad (3)$$

$$M(\bar{p}p\rightarrow\bar{p}p)=\tfrac{1}{2}M_0+\tfrac{1}{2}M_1, \quad (4)$$

$$M(\bar{p}p\rightarrow\bar{n}n)=\tfrac{1}{2}M_0-\tfrac{1}{2}M_1, \quad (5)$$

where M_0 and M_1 are the amplitudes for i spin $I=0$ and 1. Each M_i is an operator in spin space, of the general form

$$M=\lambda_1+i\lambda_2(\boldsymbol{\sigma}^{(1)}+\boldsymbol{\sigma}^{(2)})\cdot\mathbf{N}+\lambda_3\boldsymbol{\sigma}^{(1)}\cdot\mathbf{N}\boldsymbol{\sigma}^{(2)}\cdot\mathbf{N}+\lambda_4\boldsymbol{\sigma}^{(1)}\cdot\mathbf{P}\boldsymbol{\sigma}^{(2)}\cdot\mathbf{P}+\lambda_5\boldsymbol{\sigma}^{(1)}\cdot\mathbf{K}\boldsymbol{\sigma}^{(2)}\cdot\mathbf{K} \quad (6)$$

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[1] For previous surveys of the $\bar{N}N$ interaction, see E. Segrè, Ann. Rev. Nucl. Sci. **8**, 127 (1958); G. F. Chew, Proc. Natl. Acad. Sci. **45**, 456 (1959); J. McConnell, Progr. Elem. Particle Cosmic Ray Phys. **5**, 205 (1960).

[2] For surveys of the meson theory of nuclear forces, see Ref. 4 and R. J. N. Phillips, Rept. Progr. Phys. **22**, 562 (1959); M. J. Moravcsik and H. P. Noyes, Ann. Rev. Nucl. Sci. **11**, 95 (1961).

[3] For surveys of NN phenomenology, see Ref. 4 and J. L. Gammell and R. M. Thaler, Progr. Elem. Particle Cosmic Ray Phys. **5**, 99 (1960); H. P. Stapp, M. H. MacGregor, and M. J. Moravcsik, Ann. Rev. Nucl. Sci. **10**, 291 (1960).

[4] M. J. Moravcsik *The Two-Nucleon Interaction* (Clarendon Press, Oxford, England, 1963).

[5] The i-spin doublets are defined $N=(p, n)$, $\bar{N}=(\bar{n}, -\bar{p})$.

[6] T. D. Lee and C. N. Yang, Nuovo Cimento **3**, 749 (1956).

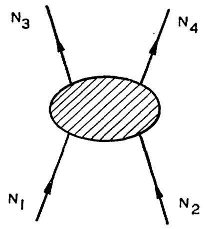

Fig. 1. A general scattering diagram.

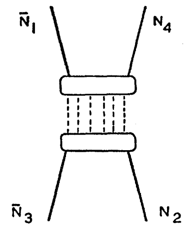

Fig. 3. Intermediate annihilation.

just as for NN.[7] Here $\boldsymbol{\sigma}^{(1)}$ and $\boldsymbol{\sigma}^{(2)}$ are the Pauli spin operators for the two particles; **N**, **P**, and **K** are unit vectors in the directions $\mathbf{k}\times\mathbf{k}'$, $\mathbf{k}'+\mathbf{k}$, and $\mathbf{k}'-\mathbf{k}$; $\mathbf{k}$ and $\mathbf{k}'$ are initial and final relative momenta; $\lambda_1\cdots\lambda_5$ are complex coefficients, functions of energy and angle (but not of azimuth).

Hence at a given energy and angle there are ten complex coefficients (five for each i spin), needing in general at least nineteen independent experiments to determine them all, within an over-all phase. The same can be said of NN, but the $\bar{N}N$ case is more difficult for the following reasons.

(i) For NN scattering below meson production threshold, unitarity adds powerful constraints, and only half as many experiments are needed.[8] In partial wave analysis, all phase shifts are real. But for $\bar{N}N$, annihilation can always happen and all phase shifts are potentially complex.

(ii) For NN scattering, antisymmetry eliminates half the partial waves. In a given range of angular momenta, there are twice as many $\bar{N}N$ phase shifts (which means four times as many real parameters).

(iii) The easiest NN system to study experimentally, namely pp, has pure $I=1$ and involves only half the parameters. It offers a chance to solve half the problem cleanly. The easiest $\bar{N}N$ system is $\bar{p}p$, with mixed i spin; the full quota of unknown parameters come in from the start.

There are also many practical difficulties with antinucleon experiments, which it ill befits a theorist to discuss.

The ratio of elastic scattering to absorption is important. Consider a partial wave with S-matrix element $\eta\exp(2i\delta)$, δ being the real phase shift and η representing the degree of absorption ($\eta\leq 1$). Then total, elastic, and absorption cross sections are proportional to $(2-2\eta\cos 2\delta)$, $(1+\eta^2-2\eta\cos 2\delta)$, and $(1-\eta^2)$, respectively. For complete absorption, $\eta=0$ and $\sigma_{\mathrm{el}}/\sigma_{\mathrm{abs}}=1$. For partial absorption, this ratio can be made as small as we please, by taking η and $\cos 2\delta$ both close to 1—but the net cross section is then also small. To get a big cross section with a small proportion of elastic scattering we need many partial waves: in fact, there is a minimum theorem[9]

$$(\sigma_{\mathrm{tot}})^2/\sigma_{\mathrm{el}}\leq 4\pi(L+1)^2/k^2. \tag{7}$$

Here L is the highest orbital angular momentum taking part, k is the relative momentum and units $\hbar=c=1$ are used. Early results suggested relatively little elastic scattering, and hence a very-long-range weak absorption,[10] but present data are consistent with quite short-range absorption.

Martin[11] has shown that the absorptive potential has range less than $\frac{1}{2}M_N^{-1}$, assuming the Mandelstam representation. Few empirical potentials have such a short range, however.

3. EXPERIMENTAL DATA

The $\bar{p}p$ data below 300 MeV include total cross sections, elastic cross sections, and inelastic cross sections (subdivided into 0-, 2-, 4-, and 6-prong events) (see Refs. 12–17 and other work cited there). The ratio $\sigma_{\mathrm{el}}/\sigma_{\mathrm{tot}}\approx 0.37$ from 50 to 200 MeV: the minimum

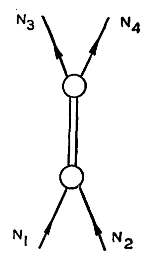

Fig. 4. Intermediate deuteron.

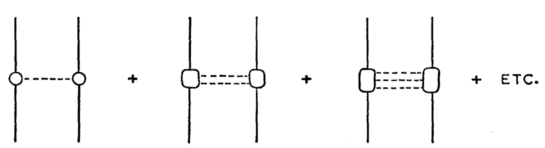

Fig. 2. Meson exchanges.

[7] There is no $(\boldsymbol{\sigma}^{(1)}-\boldsymbol{\sigma}^{(2)})\cdot\mathbf{N}$ term here because of charge-conjugation invariance; for NN, the reason is particle identity.

[8] L. Puzikov, R. Ryndin, and J. Smorodinsky, Nucl. Phys. **3**, 436 (1957).

[9] W. Rarita and P. Schwed, Phys. Rev. **112**, 271 (1958).

[10] M. Lévy, Nuovo Cimento **8**, 92 (1958); Phys. Rev. Letters **5**, 380 (1960).

[11] A. Martin, Phys. Rev. **124**, 614 (1961).

[12] C. A. Coombes, B. Cork, W. Galbraith, G. R. Lambertson, and W. A. Wenzel, Phys. Rev. **112**, 1303 (1958).

[13] B. Cork, O. I. Dahl, D. H. Miller, A. G. Tenner, and C. L. Wang, Nuovo Cimento **25**, 497 (1962).

[14] J. Loken and M. Derrick, Phys. Letters **3**, 334 (1963).

[15] U. Amaldi, T. Fazzini, G. Fidecaro, C. Ghesquière, M. Legros, and H. Steiner, Nuovo Cimento **34**, 825 (1964).

[16] A. Hossain and M. Shaukat, Nuovo Cimento **38**, 737 (1965).

[17] U. Amaldi, B. Conforto, G. Fidecaro, H. Steiner, G. Baroni, R. Bizzarri, P. Guidoni, V. Rossi, G. Brautti, E. Castelli, M. Ceschia, L. Chersovani, and M. Sessa, Nuovo Cimento **46**, 171 (1966).

theorem shows that some D waves take part in absorption here. There are some angular distributions for $\bar{p}p$ elastic scattering[12,16,18] and charge exchange.[19] Polarization results exist at higher energies, with very poor statistics.[20,21]

The data are very sparse below 50 MeV, because of practical difficulties.

Zero-prong inelastic events are made up from charge exchange and annihilation to neutral mesons, and most experiments do not distinguish between the two.[22] We must allow for this when comparing theory with experiment. The proportion of all-neutral annihilations is known to be 3.5% at rest (S-wave capture)[14]; but these modes are unfavored in S states, being even under charge conjugation and therefore confined to singlet spin states. All-neutral annihilations in flight are plausibly 7% or even more.[23]

No $\bar{p}n$ in-flight data are published yet. Preliminary uncorrected results[24] suggest the ratio of $\bar{p}p$ and $\bar{p}n$ visible annihilations (no zero prongs) is about 1.2 at 95 and 170 MeV. There is a similar trend at zero energy: annihilation at rest in deuterium suggests a ratio 1.33 ± 0.07 (including zero prongs).[25,26]

4. THEORETICAL MODELS

Various $\bar{N}N$ models will now be described, treating earlier work rather briefly and putting most emphasis on recent results with one-boson-exchange potentials.

(a) *Koba and Takeda*[27] suggest a mesonic outer potential with an absorptive core. They only make preliminary calculations, first taking the core alone with an ingoing-wave boundary condition, then adding an outer square well to illustrate possible effects.

(b) *The Ball–Chew model*[28] is the first realistic attempt to confront experiment. At the time, Signell and Marshak[29] had the most successful NN meson potential. It consisted of one- and two-pion exchanges, calculated to lowest order in perturbation theory with the Brueckner–Watson prescription and a cutoff,[30] plus and empirical spin–orbit potential.

Ball and Chew reverse the sign of the one-pion potential and keep the rest unchanged—assuming in effect that the spin–orbit term comes from even-pion exchanges. Annihilation is represented by an absorptive boundary condition at a core radius near 0.4 F. Calculations use the WKB approximation; any partial wave that can reach the core classically is assumed completely absorbed, otherwise absorption is zero.

This boundary assumption has two important effects. First, since there is no partial absorption, the model gives more scattering than annihilation, contrary to experiment. Gourdin *et al.*[31] tried to put this right by adding an imaginary outer potential and using other prescriptions for the core, but with limited success. Second, since the onset of absorption in any partial wave is sudden, the predicted cross sections have a saw-toothed look as functions of energy. This effect has not been seen.

Some other treatment of absorption is therefore needed. Also, on the meson-theory side, there are objections to treating two-pion exchange by perturbation theory, and the Signell–Marshak potential is now superseded. But the Ball–Chew model is pioneer work and later models are all based on it in spirit.

Subsequent work all avoids the WKB approximation and uses numerical integration of the Schrödinger equation.

(c) *Elagin and co-workers* first make a purely empirical complex potential, without any spin or i-spin dependence.[32]

Later they introduce spin and i-spin dependence through the one-pion potential, with a cutoff tensor term.[33] To this they add an empirical potential $V+iW$,

$$V = -V_0 \exp(-2\mu r)/(\mu r) \cdot \{1 - \exp[-(2\mu r)^4]\},$$

$$W = -W_0 \exp[-(5\mu r)^4], \tag{8}$$

where $\mu = m_\pi$, $U_0 = 65$ MeV and $W_0 = 4$ GeV. A spin–orbit term was also tried, but does not appear in the best fit.

Elagin *et al.* get reasonable agreement with the data of the time, but later results show that $\sigma_{el}(\bar{p}p)$ is underestimated by 20%.[17] They also predict a charge-exchange angular distribution with strong forward and backward peaks; the former is expected from one-pion exchange, but a big backward peak is surprising.

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[18] Differential cross sections at nine energies from 63 to 175 MeV have been obtained by the authors of Ref. 17; R. Bizzarri (private communication).

[19] U. Amaldi, B. Conforto, G. Fidecaro, H. Steiner, R. Bizzarri, U. Dore, G. C. Gialanella, P. Guidoni, F. Marcejia, G. Brautti, E. Castelli, M. Ceschia, L. Chercovani, and M. Sessa, report submitted to the High Energy Physics Conference at Dubna (1964); and R. Bizzarri (private communication).

[20] J. Button and B. Maglic, Phys. Rev. **127**, 1297 (1962).

[21] L. Dobrzynski, C. Ghesquière, N. H. Xuong, and H. Tofte, Phys. Letters **23**, 614 (1966).

[22] Neutral pion modes are largely rejected in Ref. 11. Their "zero-prong" points at 133, 197, 265, and 333 MeV are systematically lower than other data, presumably for this reason.

[23] B. R. Desai, Phys. Rev. **119**, 1390 (1960).

[24] R. Bizzarri (private communication).

[25] W. Chinowsky and G. Kojoian, Nuovo Cimento **43A**, 685 (1966).

[26] Annihilation in emulsion nuclei gives the ratio 0.97 ± 0.05 instead, but there may be nuclear structure effects. A. J. Apostolakis, G. A. Briggs, N. A. Khan, and J. V. Major, Nuovo Cimento **37**, 1364 (1965).

[27] Z. Koba and G. Takeda, Progr. Theoret. Phys. (Kyoto) **19**, 269 (1958).

[28] J. S. Ball and G. F. Chew, Phys. Rev. **109**, 1385 (1958); J. R. Fulco, Phys. Rev. **110**, 784 (1958); J. S. Ball and J. R. Fulco, Phys. Rev. **113**, 647 (1959).

[29] P. S. Signell and R. E. Marshak, Phys. Rev. **106**, 832 (1957).

[30] This part is the Gartenhaus potential; S. Gartenhaus, Phys. Rev. **100**, 900 (1955).

[31] M. Gourdin, B. Jancovici, and L. Verlet, Nuovo Cimento **8**, 485 (1958).

[32] P. E. Nemirovskii and Yu. P. Elagin, Zh. Eksperim. i Teor. Fiz. **44**, 1099 (1963) [English transl.: Soviet Phys.—JETP **17**, 740 (1963)].

[33] Yu. P. Elagin, P. E. Nemirovskii, and Yu. F. Strokov, Phys. Letters **7**, 352 (1963).

This model takes the minimum from meson theory—only the noncontroversial one-pion term. This is reasonable enough for a phenomenological study, but it does not bring the nuclear and antinuclear force problems any closer together.

(d) *Ceschia and Perlmutter*[34] start from two alternative NN potentials. One is the Yale potential,[35] consisting of the one-pion term plus phenomenological terms; they assume the latter represent even-pion exchanges only. The other potential contains one- and two-pion exchanges in fourth-order perturbation theory, with Gupta's prescription that includes a small spin-orbit term.[36] They add a large semitheoretical spin-orbit term, of a form derived from direct $\pi\pi$ coupling effects in lowest order, with coupling constant adjusted for NN scattering.[37]

To these outer potentials, suitably modified for $\bar{N}N$, Ceschia and Permutter add an ingoing-wave boundary condition. At radius $r=r_c$ the radial wave function is matched to an interior wave function.

$$u(r)=u_0 \exp(-iKr). \tag{9}$$

The radius r_c and internal wave number K are assumed the same for all angular momenta, and are adjustable. There is moderate agreement with experiment, for both potentials, choosing $r_c \approx \frac{2}{3} m_\pi^{-1}$ (independent of energy) and $K=\frac{1}{2}k$. However, the predicted elastic scattering below 100 MeV is rather too high.[17]

The core radius is twice the Ball–Chew value; this is apparently needed to get enough absorption. It is perhaps unsatisfactory that K should be so energy-dependent.

(e) *Spergel*[38] also uses an ingoing wave boundary condition [see Eq. (9)], but determines K for each energy and partial wave by maximizing absorption. Thus r_c is the only free parameter, assumed to be the same in all states.

For the outer potential, Spergel tries two fourth-order meson potentials, the so-called BW and TMO forms,[39,40] with appropriate sign changes. He tabulates results for a range of r_c values. There are passable fits to the data of that time with $r_c=0.55m_\pi^{-1}$ and $0.50m_\pi^{-1}$ for modified TMO and BW forms, respectively. The fit is better if r_c varies with energy. However, later and more accurate data are not fitted well anywhere in the tabulated range.

This model predicts systematically bigger total and absorption cross sections for $\bar{p}n$ than for $\bar{p}p$, unlike any other model and contrary to experiment.

(f) *One-boson exchange: dispersion relations.* Single-meson exchanges are both easy to calculate and noncontroversial, unlike all multimeson exchanges.[2,4] The discovery that multimeson systems have resonances suggests that multimeson exchanges may be approximated by the exchange of single resonances—treated as single bosons. This approach is very successful in the NN problem.

One way to use the one-boson-exchange (OBE) idea is through dispersion relations, solving by the N/D method, first exploited for the NN system by Scotti and Wong.[41]

Ball, Scotti, and Wong[42] apply this method to the $\bar{N}N$ system. They consider the exchange of π, η, ρ, ω, ϕ and an effective $I=0$ scalar meson σ; σ may perhaps be regarded as parameterizing non-resonant exchanges with the same quantum numbers. The σ mass, a cutoff energy and various coupling constant are adjusted first to fit NN data (slightly altering the Scotti–Wong fit) and the $\bar{N}N$ interaction is then inferred by reversing terms with odd G.

Ball *et al.* do not add absorption. They just want to see how well OBE forces can account for the existence of mesons as bound $\bar{N}N$ states—part of a bootstrap problem. So they solve for bound states without absorption. They find five and only five bound states, with the quantum numbers of π, η, ω (or ϕ), ρ, and σ, though not with the right masses.

Their results support the idea that all mesons are composite particles, and the hope that much of the antinuclear force can be ascribed to OBE.

However, this is not yet a realistic model of the $\bar{N}N$ interaction. It would be interesting to add absorption, somehow, into the N/D calculations and then to compare with scattering data.

TABLE I. OBE parameters for the Bryan–Scott NN models: BS1, BS2, and BS3 denote the static model and the two velocity-dependent cases. g^2 is the rationalized, renormalized (pseudoscalar, vector, scalar) coupling constant. f/g is the ratio of tensor to vector coupling, assumed zero for ω; the BS1 value of $f/g(\rho)$ has been multiplied by 2 m_N/m_ρ, to bring the definition of Ref. 43 in line with Ref. 45. m denotes mass in MeV.

Parameter	BS1	BS2	BS3
$g^2(\pi)$	11.7	12.66	12.5
$g^2(\eta)$	7.0	3.0	10.6
$g^2(\rho)$	0.68	2.44	1.36
$f/g(\rho)$	4.4	1.13	3.82
$g^2(\omega)$	21.5	23.7	19.1
$g^2(\sigma_0)$	9.4	9.46	9.9
$m(\sigma_0)$	560	550	590
$g^2(\sigma_1)$	6.1	1.97	5.8
$m(\sigma_1)$	770	600	770

[34] M. Ceschia and A. Perlmutter, Nuovo Cimento **33**, 578 (1964).
[35] K. E. Lassila, M. H. Hull, H. M. Ruppel, F. A. MacDonald, and G. Breit, Phys. Rev. **126**, 881 (1962).
[36] S. N. Gupta, Phys. Rev. **117**, 1146 (1960); **122**, 1923 (1961).
[37] R. L. Anderson, S. N. Gupta, and J. Huschilt, Phys. Rev. **127**, 1377 (1962).
[38] M. S. Spergel, University of Rochester report UR-875-24 (March 1964).
[39] K. A. Brueckner and K. M. Watson, Phys. Rev. **92**, 1023 (1953).
[40] M. Taketani, S. Machida, and S. Ohnuma, Progr. Theoret. Phys. (Kyoto) **7**, 45 (1952).
[41] A. Scotti and D. Y. Wong, Phys. Rev. **138**, B145 (1965).
[42] J. S. Ball, A. Scotti, and D. Y. Wong, Phys. Rev. **142**, 100 (1966).

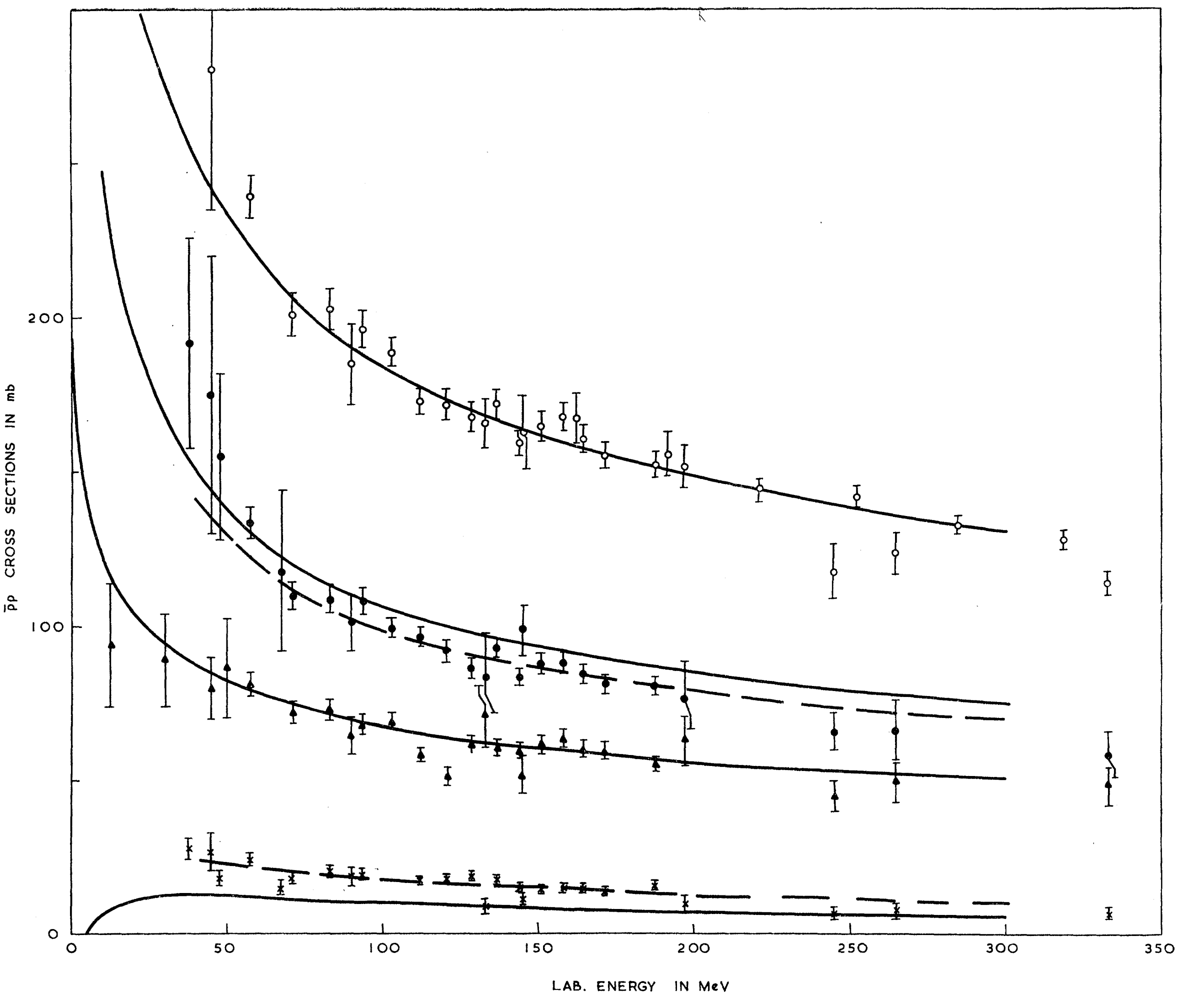

FIG. 5. $\bar{p}p$ cross sections from the static OBE potential. Solid lines, reading from the top, are total, annihilation, elastic, and charge-exchange cross section. Dashed lines are estimates of visible annihilations and zero-prong events. Open circles, black circles, triangles, and crosses represent total, visible annihilation, elastic, and zero-prong cross-section data: see Refs. 12–17 and 22.

(g) *One-boson exchange: static potential.* OBE potentials for the NN case are considered by Bryan and Scott.[43] They make some simplifications, omitting velocity-dependent terms of order k^2/m_N^2 and corrections of order $(\mu/m_N)^4$, μ being the boson mass. They then take the π, η, ρ and ω mesons, plus two effective scalar mesons σ_0 and σ_1 (with $I=0$ and 1), and adjust the coupling constants and scalar meson masses to fit NN phase shifts. The couplings and masses are listed in Table I, in the column labeled BS1. These are to be understood as parameterizing, not only true OBE processes, but also nonresonant exchanges with the same quantum numbers

The resulting potential is close to the Yale[35] and other phenomenological NN potentials, but has the advantage that the exchange G parity of each component is known. Because the OBE potentials have r^{-3} singularities, some cutoff is needed; all potentials are set equal to zero for $r<0.6$ F. S phase shifts are not well reproduced.

Bryan and Phillips[44] investigate the $\bar{N}N$ counterpart, by changing the signs of the π, ω, and σ_1 terms and adding an imaginary Woods–Saxon potential iW,

$$W(r) = -W_0/[1+a \exp(br)]. \qquad (10)$$

$W(r)$ is not truncated. The fact that S waves are given poorly for NN is immaterial, since for $\bar{N}N$ they are almost completely absorbed anyway. A good fit to data is found with $a=1$, $b=6$ F^{-1} and $W_0=62$ GeV.

The predicted $\bar{p}p$ cross sections are shown in Fig. 5: total, annihilation, elastic, and charge exchange. For comparison with the data, dotted lines show estimated "visible annihilation" and "zero-prong" events, found by taking 7% of the annihilation and adding it to charge exchange. The ratio σ_{el}/σ_{tot} is 0.35 at 50 MeV,

[43] R. A. Bryan and B. L. Scott, Phys. Rev. **135**, B434 (1964).

[44] R. A. Bryan and R. J. N. Phillips, Bull. Am. Phys. Soc. **10**, 737 (1965). It is intended to publish a full account soon.

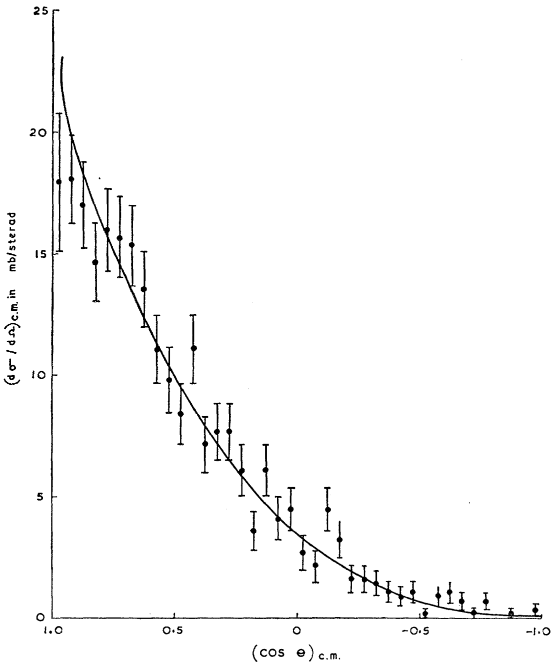

FIG. 6. $\bar{p}p$ differential cross section at 62.7 MeV from the static OBE potential, compared with data from Ref. 18.

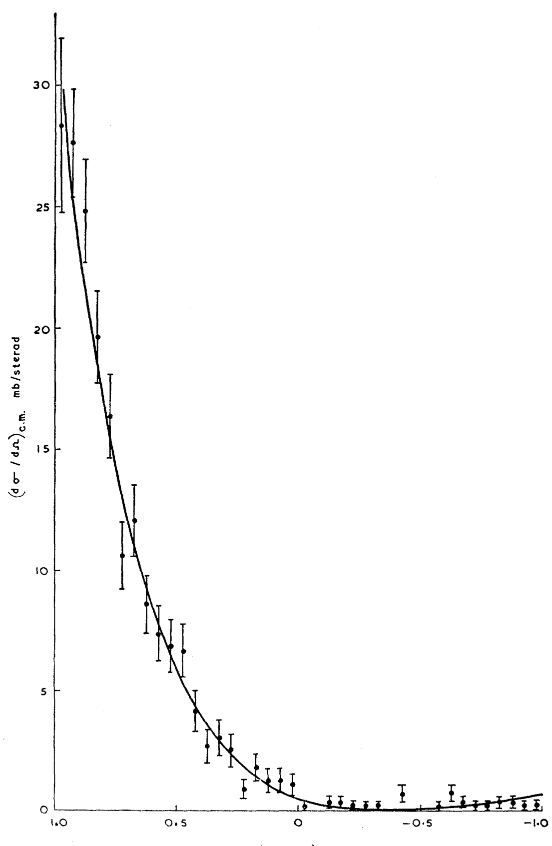

FIG. 7. $\bar{p}p$ differential cross section at 163.3 MeV from the static OBE potential, compared with data from Ref. 18.

rising to 0.38 at 250 MeV. Figures 6–9 illustrate angular distributions for $\bar{p}p$ elastic scattering and charge exchange. Figure 10 compares $\bar{p}p$ and $\bar{p}n$ cross sections: $\sigma_{abs}(\bar{p}n)$ is somewhat higher than preliminary data.[24] The zero-energy ratio of $\bar{p}p$ to $\bar{p}n$ absorption is 1.17. Figure 11 shows polarization predictions at 140 MeV.

The real potential is strongly attractive on average, and enhances the absorption by pulling the wave function inward. If we take the absorptive potential alone, at 100 MeV, $\sigma_{tot}(\bar{p}p)$ drops from 184 to 105 mb, and $\sigma_{abs}(\bar{p}p)$ drops from 106 to 57 mb.

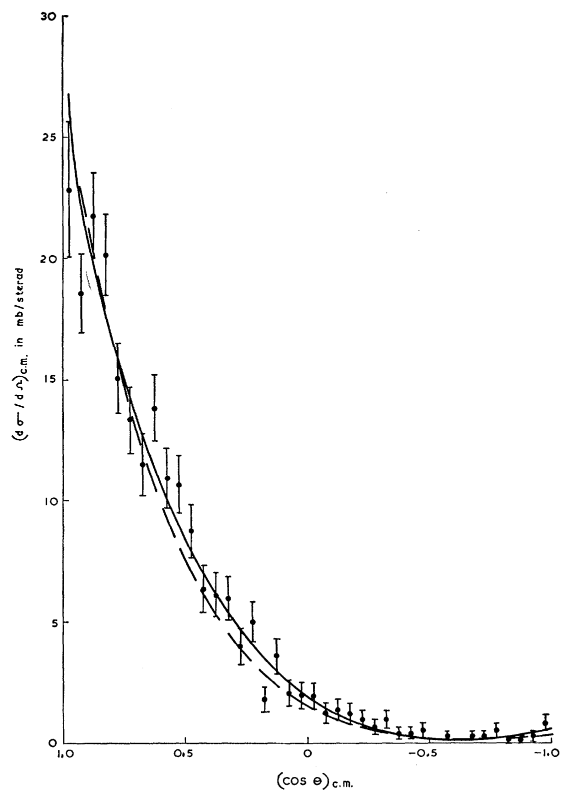

FIG. 8. $\bar{p}p$ differential cross sections at 99.8 MeV from the static OBE potential (solid line) and the OPE comparison potential (dashed line). The pure-absorption comparison potential predicts a curve very close to the OPE case. Data points are from Ref. 18.

(h) *One-boson exchange: velocity-dependent potential.* As a further step in the NN problem, Bryan and Scott[45] include central velocity-dependent terms of the form $\mathbf{p}^2U(r)+U(r)\mathbf{p}^2$, where $\mathbf{p}$ is the momentum operator. Such terms can be integrated by adapting standard methods; in effect, they renormalize the static potentials.[46] Furthermore, they reduce the r^{-3} singularity of the OBE potentials to an effective r^{-2} at the origin.

To remove the remaining singularity, a short-range subtraction is made. From each meson potential is subtracted the corresponding potential for a heavy

[45] R. A. Bryan and B. L. Scott (to be published)
[46] A. M. Green, Nucl. Phys. **33**, 218 (1962).

meson of mass Λ with the same coupling constant. This cancels the leading singularity at the origin.

A preliminary fit[47] to *NN* phase shifts was found with parameters listed in Table I, in the column labeled BS2, with $\Lambda = 1$ GeV.

Later it was found[45] that *NN* phase shifts for $L \geq 1$ can be fitted without any Λ-subtraction, because with the chosen couplings the r^{-2} singularity was either repulsive or overcome by the centrifugal term. This potential will not do for *S* waves. The parameters are listed in Table I in the column labeled BS3.

Bryan and Phillips[44] have adapted these velocity-dependent potentials to the $\bar{N}N$ case. For the preliminary version, changing suitable signs and adding a Woods–Saxon absorption with $a = 1$, $b = 5$ F^{-1} and $W_0 =$

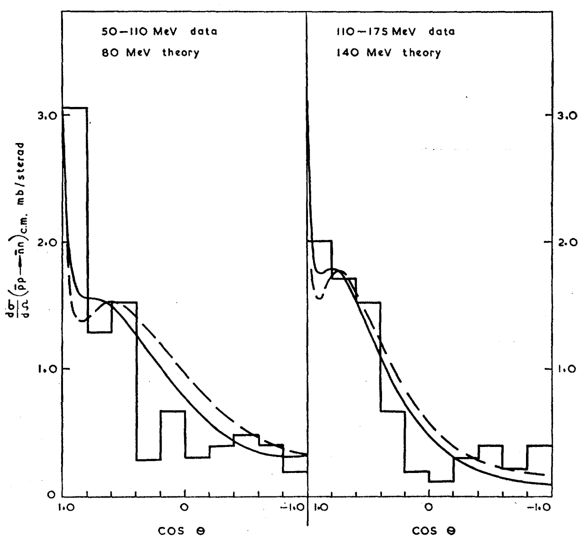

FIG. 9. $\bar{p}+p \to \bar{n}+n$ angular distributions at 80 and 140 MeV, from the static OBE potential (solid lines) and the OPE comparison potential (dashed lines). Experimental data,[19] averaged over the ranges 50–110 MeV and 110–175 MeV, have no absolute scale and are normalized to agree with theory.

8.3 GeV gives a good fit to data, comparable to the static case described above.

For the later version there are difficulties. First, the r^{-2} singularity must be removed: this is done with a Λ-subtraction, with $\Lambda = 1$ GeV. Then it is found that the real potential has less net attraction than before, and this affects the energy dependence of cross sections. When $W(r)$ has been readjusted, $\sigma_{\text{tot}}(\bar{p}p)$ and $\sigma_{\text{abs}}(\bar{p}p)$ both fall off too slowly as energy increases. A compromise solution, looking best near 100 MeV, is achieved with $a = 1$, $b = 4$ F^{-1} and $W_0 = 6.0$ GeV, but the fit to data is less good than before. This trouble can probably be righted by making the absorptive potential $W(r)$ energy-dependent, or by altering its shape.

(i) *Comparison potential: one-pion exchange.* For

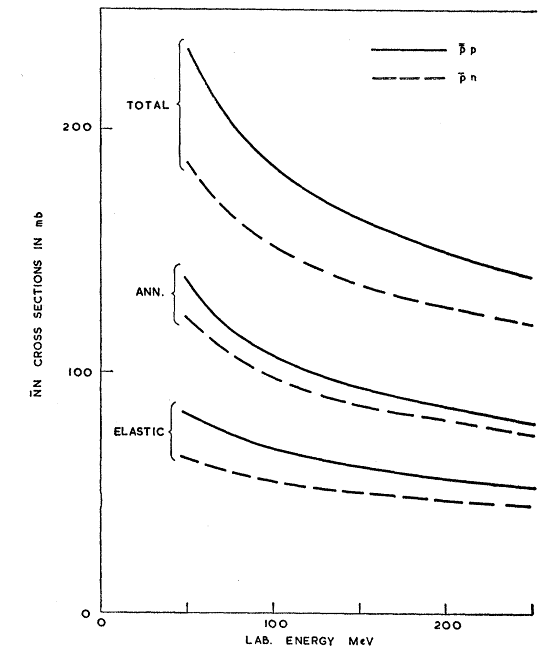

FIG. 10. $\bar{p}p$ and $\bar{p}n$ cross section comparison, for the static OBE potential.

comparison, let us make a model using the one-pion-exchange (OPE) potential alone, with the same coupling $g^2 = 12.5$ and subtraction mass $\Lambda = 1$ GeV as in case BS3, plus a Woods–Saxon absorption like Eq. (10). OPE has no velocity dependence, so an r^{-2} singularity remains: this is cut off by a small hard core.

This potential has the same trouble as the second velocity-dependent case: the outer attraction is weaker,

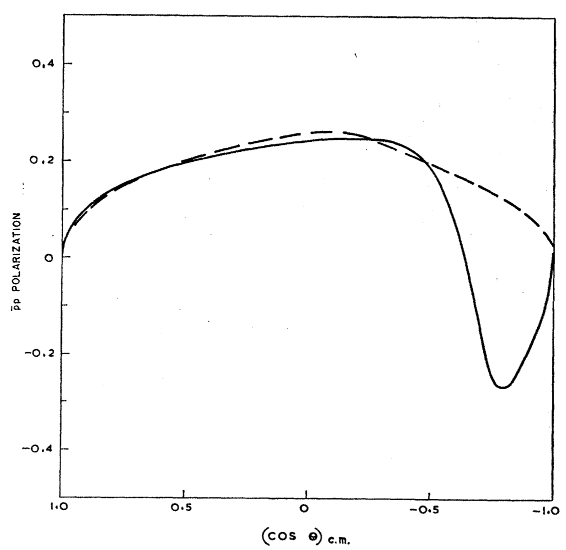

FIG. 11. $\bar{p}p$ polarization at 140 MeV, from the static OBE potential (solid line) and the OPE comparison potential (dashed line).

[47] We denote $\sigma(\bar{p}p) - \sigma(\bar{p}n) = \Delta\sigma$.

making the energy dependence of cross sections not quite right. Choosing $a=1$, $b=3$ F^{-1}, and $W_0=2.4$ GeV gives a compromise solution, fitting best near 100 MeV.

Predicted $\bar{p}p$ elastic and charge-exchange angular distributions are shown in Figs. 8 and 9. The elastic peak is steeper than in the static OBE model, presumably because $W(r)$ has a longer range; charge exchange is very similar to static OBE.

Integrated $\bar{p}p$ cross sections are fairly close to the static OBE curves, but the $\bar{p}p-\bar{p}n$ differences are much less: $\Delta\sigma_{\text{tot}}$ is halved and $\Delta\sigma_{\text{abs}}$ is very small.[47]

(j) *Comparison potential: absorption only.* As an extreme example, let us make a model for $\bar{p}p$ scattering from a pure imaginary Woods–Saxon potential (counting charge-exchange as an absorption here). Choosing $a=1$, $b=3$ F^{-1} and $W_0=3.3$ GeV gives a reasonable compromise solution, fitting best near 100 MeV. The energy dependence is not quite right, as in the OPE case: again, a different shape might correct this.

The $\bar{p}p$ differential cross section is very close to the OPE case, illustrated in Fig. 8.

The range of $W(r)$ is the same as for OPE but the depth is 37% more, to make up for the missing real potential.

5. DISCUSSION

The static OBE potential, and the first velocity-dependent version, both fit existing data well. The only doubt is whether the $\bar{p}p-\bar{p}n$ cross section differences are big enough, but the data here are still preliminary. The prospects for explaining experiment with this kind of theory seem good.

This approach depends on investing information from the NN system. Will there be any return? Can we learn anything new about meson exchanges from the highly incomplete $\bar{N}N$ data available now, or soon?

In the models considered, meson exchanges contribute (i) a long-range potential that is real, (ii) spin dependence, (iii) i-spin dependence, and (iv) an attraction that contributes to scattering and enhances absorption.

The first point clearly refers to pion exchange alone. Other exchanges, with masses ≥ 550 MeV, have ranges comparable to that of the absorption. Any information we can extract, by exploiting the long range plus reality, will only be about OPE—which is pretty well known already.

Point (ii) should be probed by polarization measurements. However, the two curves in Fig. 11 show that OPE apparently dominates, at least with the couplings used here. Perhaps OPE does not dominate all the higher-rank polarization tensors, but these would be excessively hard to measure.

We test point (iii) by charge exchange and by $\bar{p}p-\bar{p}n$ cross-section differences. Figure 9 shows that OPE dominates charge-exchange, but shorter-range terms modify the curve a little and might be detectable this way. The second maximum is a typical OPE effect, coming from a double-spin-flip amplitude; the absorption model predicts a similar effect at high energy.[48] Shorter-range OBE play a bigger role in $\bar{p}p-\bar{p}n$ cross-section differences. The OPE comparison case gives only half the full OBE value for $\Delta\sigma_{\text{tot}}$, and very little for $\Delta\sigma_{\text{abs}}$. If these differences are actually bigger than the static OBE model predicts, we shall have to look to the short-range terms.

Point (iv) is important but hard to separate cleanly. A change in the real meson potential can be compensated, approximately, by changing the absorption. A strong attraction allows the absorption to have shorter range. At present we know little about the latter, but more accurate data should limit this uncertainty. For example, the longer range of absorption in comparison potentials (i) and (j) gives a steeper elastic peak in Fig. 8, which should be distinguishable some day.

Most of what we learn will therefore be about OPE, especially from charge exchange and polarization. Hopefully, these measurements will just confirm what we already believe, but they are not uninteresting: they will test the common predictions of a whole class of models. Present charge-exchange data already give some confirmation.

It is not surprising that shorter-range meson forces are less prominent. We expect their effects to be damped, compared to the NN case, because absorption attenuates the wave function at small distances. Nevertheless we shall learn something about these forces too; first, through the cross section differences, where there are some data already; later, through a more accurate knowledge of details, in angular distributions and energy dependences. We can expect to learn enough to distinguish gross differences, and perhaps enough to fix a free parameter or two.

Finally, we must recall that all these models and all our conclusions are founded on three assumptions: that the potential concept is good, that meson exchanges dominate the real potential and that the absorption is independent of spin and i-spin.

ACKNOWLEDGMENTS

I am very grateful to Dr. R. Bizzarri, Dr. R. A. Bryan, and Dr. B. L. Scott for advance information about experimental and theoretical results.

[48] R. J. N. Phillips and G. A. Ringland, Phys. Letters **20**, 205 (1966).