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[a] Present address: Fermi National Accelerator Laboratory, Batavia, Ill. 60510.

[b] Present address: Bell Laboratories, Murray Hill, N. J. 07974.

[1] P. Estabrooks and A. D. Martin, Nucl. Phys. B95, 322 (1975).

[2] B. Hyams *et al.*, Nucl. Phys. B100, 205 (1975).

[3] W. D. Apel *et al.*, Phys. Lett. 57B, 403 (1975).

[4] A. D. Martin and M. R. Pennington, Ann. Phys. (N.Y.) 114, 1 (1978).

[5] M. J. Corden *et al.*, Nucl. Phys. B157, 250 (1979).

[6] H. Becker *et al.*, Nucl. Phys. B151, 46 (1979).

[7] A. E. Baumbaugh *et al.*, to be published.

[8] P. E. Cannata, Ph.D. thesis, University of Notre Dame, 1980 (unpublished).

[9] N. N. Biswas *et al.*, Phys. Rev. Lett. 47, 1378 (1981); N. M. Cason *et al.*, in *High Energy Physics—1980*, edited by Loyal Durand and Lee G. Pondrom, AIP Conference Proceedings No. 68 (American Institute of Physics, New York, 1981), p. 5.

[10] W. Hoogland *et al.*, Nucl. Phys. B69, 266 (1974).

[11] C. Bricman *et al.* (Particle Data Group), Phys. Lett. 75B, 115 (1978).

[12] Our thanks to R. Longacre, Brookhaven National Laboratory, for supplying the Barrelet zero program.

[13] G. Costa *et al.*, Nucl. Phys. B175, 402 (1980).

[14] This fit has a rather large χ^2 (136 for N.D. = 24) coming mainly from two bins (centered at 1.36 and 1.44 GeV) which alone contribute 65 units of χ^2. A dramatic improvement is produced ($\chi^2 = 36$, N.D. = 20) by introducing a third, rather narrow Breit-Wigner amplitude at 1.4 GeV which is out of phase with the $f^0(1270)$.

[15] R. J. Jaffe, Phys. Rev. D 15, 267, 281 (1977).

[16] S. K. Bose, Nuovo Cimento 46, 419 (1966); S. K. Bose and E. G. Sudarshan, Phys. Rev. 162, 1398 (1967).

[17] J. F. Donoghue, K. Johnson, and B. A. Li, Phys. Lett. 99B, 416 (1981).

[18] I. Cohen, N. Isgur, and H. J. Lipkin, Argonne National Laboratory Report No. ANL-HEP-PR-81-45, 1981 (to be published); N. Isgur, private communication; J. F. Donoghue, private communication.

Nucleon-Antinucleon Optical Potential

J. Côté,[a] M. Lacombe, B. Loiseau, B. Moussallam, and R. Vinh Mau
Division de Physique Théorique, Insitiut de Physique Nucléaire, F-91406 Orsay, France, and
Laboratoire de Physique Théorique et des Particules Elementaires, Université Pierre et
Marie Curie, F-75230 Paris Cédex 05, France

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A model has been constructed for nucleon-antinucleon annihilation which is of short range but is state (energy, spin, isospin, . . .) dependent as dictated by the calculation of annihilation diagrams. This model fulfills general theoretical requirements and, at the same time, provides a good fit of the presently available $p\bar{p}$ experimental data, better than the existing models which are state independent but effectively long ranged. The present results contradict the generally accepted claim that fitting the $p\bar{p}$ data requires an effective long-ranged annihilation potential.

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The low-energy antiproton ring (LEAR) will be in operation at CERN within a short time and several proposals for high-statistics antiproton-nucleon experiments on cross sections as well as on polarization (or analyzing power) have already been scheduled.[1] It is hoped that these new generation experiments will (i) improve the accuracy of the existing experimental data and (ii) provide results on new observables such as spin-correlation parameters, etc. In view of these prospects, a careful study of the $N\bar{N}$ interaction is very desirable.

The interest in the study of the $N\bar{N}$ interaction has also been revived during the last few years by the experimental indication of narrow-width bosons strongly coupled to the $N\bar{N}$ system, the baryonia. Although more recent experiments[2] seem to question the existence of these narrow baryonium states, theoretical interest still remains. On the one hand, a baryonium state can be viewed as a state of two quarks and two antiquarks confined in a color singlet system, and very narrow widths are predicted.[3] On the other hand, a baryonium state can in a more conventional way be viewed as a $N\bar{N}$ bound state or resonance and a serous study of these states requires an accurate knowledge of the $N\bar{N}$ interaction.

As we are concerned here mostly with the low-energy region covered by LEAR, a simple and appropriate approach to the $N\bar{N}$ interaction is that using an optical potential. This has been adopted in the past by many authors.[4] They generally used the G-parity-transformed one-boson-exchange NN potentials for the real part, and for the imaginary part a phenomenological local and state-independent (i.e., central) potential of the Woods-Saxon type. By fitting the experimental data known at that time, or part of them, they found the annihilation potential to be effectively long ranged, i.e., still very strong even at large distances (~150 MeV at $r=1$ fm). As a consequence, the produced bound states and resonances are extremely broad, and it was prematurely concluded that narrow baryonium states cannot be interpreted as $N\bar{N}$ bound states or resonances.

The present note reports on some results of our $N\bar{N}$ study program. These provide the first example of an $N\bar{N}$ annihilation potential which, in contrast with earlier models,[4] is of short range, but state (energy, spin, isospin, angular momentum) dependent as given explicitly by the calculation of annihilation diagrams. More in agreement with general theoretical principles,[5] our model also fits the entire set of existing experimental data very well and can serve as a guide for future experiments at LEAR or at the $\bar{p}$ facilities of Brookhaven National Laboratory and National Laboratory for High Energy Physics (Japan).

Our model for the $N\bar{N}$ optical potential $V_{N\bar{N}} = U_{N\bar{N}} - iW_{N\bar{N}}$ is as follows: (i) $U_{N\bar{N}}$ is the G-parity transform of the (Paris) NN potential of Lacombe *et al.*[6] for the long- and medium-ranged parts ($r \gtrsim 0.9$ fm). The short-ranged part ($r \lesssim 0.9$ fm) is described phenomenologically, and for computational convenience we used a quadratic function constrained to join the medium-ranged part through two points in the neighborhood of $r=1$ fm, the third parameter being adjusted to fit the data. (ii) The absorptive part $W_{N\bar{N}}$ is of short range, and energy and state dependent:

$$W_{N\bar{N}}(\vec{r},T_L)=\left(g_C(1+f_C T_L)+g_{SS}(1+f_{SS}T_L)\vec{\sigma}_1\cdot\vec{\sigma}_2+g_T S_{12}+\frac{g_{LS}}{4m^2}\vec{L}\cdot\vec{S}\frac{1}{r}\frac{d}{dr}\right)\frac{K_0(2mr)}{r}\,. \tag{1}$$

This form is suggested by detailed calculations[7] of annihilation diagrams with two-meson (π,ϵ,ρ,ω) intermediate states which yield in momentum space

$$\tilde{W}_{N\bar{N}}(s,t)=\sum_i\int_{4m^2}^{\infty}dt'\,\frac{\rho_i(s,t')}{t'-t}\tilde{\Omega}_i\,. \tag{2}$$

In the above formulas, m is the nucleon mass, $s=(p_1+n_1)^2=2m(T_L+2m)$, $t=(p_1-p_2)^2$, and $\tilde{\Omega}_i$ are the usual invariants (central, spin-spin, spin-orbit, tensor, and quadratic spin-orbit).

Equation (1) is obtained from Eq. (2) in the following way: As we are concerned with the low-energy region, we made a Taylor expansion of the functions ρ_i near threshold, $s=4m^2$, and retained only the first or the first two terms. The t' dependence of the resulting coefficients is essentially of the form $1/[t'(t'-4m^2)]^{1/2}$ which in turn gives rise to the modified Bessel function

$$K_0(2mr)=\int_{4m^2}^{\infty}dt'\,\frac{\exp[-(t')^{1/2}r]}{[t'(t'-4m)^2]^{1/2}}$$

when translated by a Fourier transformation from momentum to coordinate space. For simplicity, Eqs. (1) and (2) are written for a given isospin state. A complete treatment of $W_{N\bar{N}}$ as given by Eq. (2) is very complicated and the coefficients g_i, f_i are thus for the moment considered as effective parameters.

The parameters are adjusted to fit an up-to-date set of 915 $\bar{p}p$ data points in the energy do-

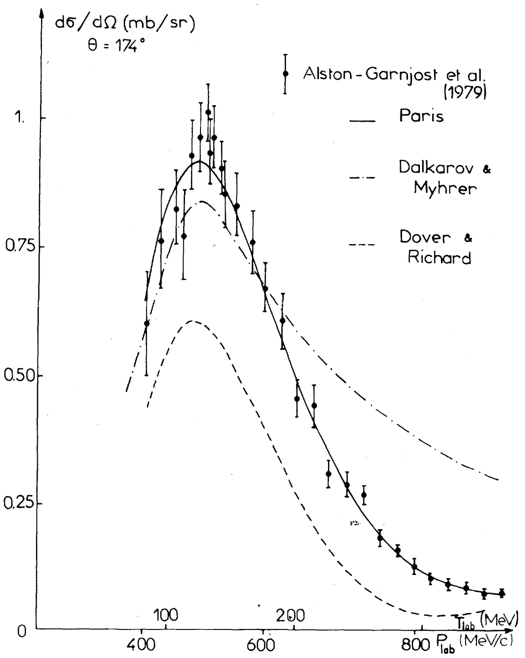

FIG. 1. Backward differential elastic cross section vs T_L.

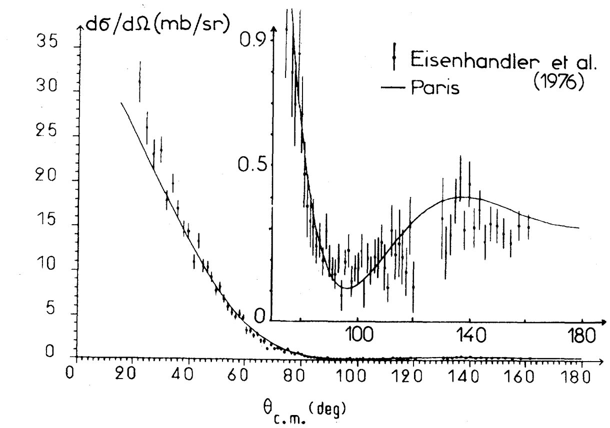

FIG. 2. Differential elastic cross section at $T_L = 226.4$ MeV.

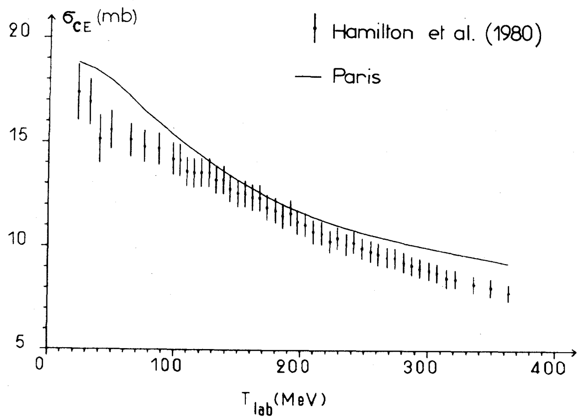

FIG. 4. $\bar{p}p \rightarrow \bar{n}n$ cross section vs T_L.

main 20 MeV $\lesssim T_L \lesssim$ 370 MeV. We did not include in our compilation data on integrated elastic cross sections $\sigma_{el}(T_L)$; these are usually obtained by integrating differential cross sections extrapolated to the very forward angles, with the related ambiguities in the treatment of Coulomb effects. Anyway, $\sigma_{el}(T_L)$ are redundant whenever $d\sigma_{el}/d\Omega$ are given. In this work, elastic cross sections and polarization are calculated including Coulomb effects, while total and charge-exchange cross sections are obtained from pure nuclear amplitudes.

As our compilation covers experiments performed between 1968 and 1981, some of them are more accurate and hence more constraining than others. The most accurate are those on the differential elastic cross section at backward angles ($\theta_{c.m.} \simeq 174°$) measured recently by Alston-Garnjost *et al.*[8] We found these data very constraining in the search for our solution. Our fit, displayed in Fig. 1, shows an excellent agreement between theory and experiment with a χ^2/(number of data) of 0.61. It is worth noting that if the spin-orbit and tensor terms in Eq. (1) are dropped, the χ^2/(number of data) climbs as high as 1.95. For comparison, we also show in Fig. 1 the results by Dover and Richard and by Dalkarov and Myhrer as quoted in Ref. 8. Other measurements[9,10] of the differential elastic cross sections were performed for 20 MeV $\lesssim T_L \lesssim$ 369 MeV. Again the agreement is good, yielding χ^2/(number of data) of 2.87 for the whole set of data. An example of our fit is shown in Fig. 2.

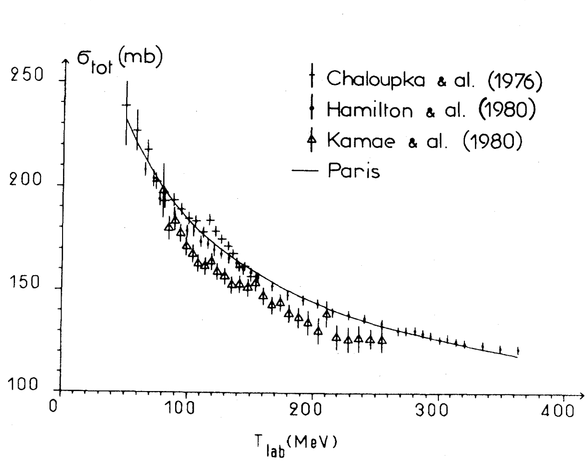

FIG. 3. Total elastic cross section vs T_L.

The total cross section $\sigma_{tot}(T_L)$ was measured by different groups[11,12] and their results are not fully consistent as can be seen in Fig. 3. We chose to fit the data of Ref. 11 since they cover a larger energy range, and we obtained a χ^2/(number of data) of 0.96 for 65 MeV $\lesssim T_L \lesssim$ 370 MeV. Our total cross section was obtained via the optical theorem.

In Fig. 4, our results for the total charge-exchange cross section $\sigma_{CE}(T_L)$ are compared with the data of Hamilton *et al.*[13] The χ^2/(number of data) is 3.25 while it is 2.41 for the few available results[14] on $d\sigma_{CE}/d\Omega$.

Our results (Fig. 5) reproduce the polarization below 370 MeV[10,15] very well [χ^2/(number of data) $\simeq 1$]. The polarization is significant and very sensitive to the values of our parameters, especially for angles above 90°. In view of this, accurate polarization measurements are therefore very desirable.

In summary, we have produced a $N\bar{N}$ interaction whose physical properties differ from those of previous models and which fits the presently

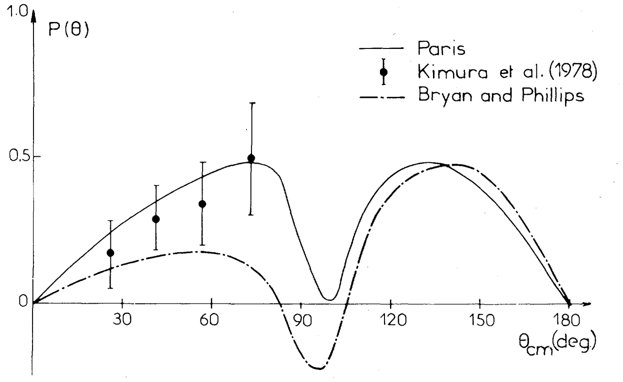

FIG. 5. $\bar{p}p$ polarization at T_L = 232.35 MeV.

TABLE I. The parameters of the absorptive part $W_{N\bar{N}}$.

i	g_i	f_i (MeV^{-1})
$T = 0$:		
C	850.45	0.01874
SS	−569.69	0.01466
LS	74.468	
T	53.191	
$T = 1$:		
C	659.91	0.01893
SS	−473.93	0.02636
LS	74.468	
T	23.404	

available $N\bar{N}$ data very well. The χ^2/(number of data) is 2.80 for our complete set of 915 data. The values for the parameters of the absorptive part $W_{N\bar{N}}$ as defined in Eq. (1) are listed in Table I. It should be noticed that the decrease of $W_{N\bar{N}}$ with r is very rapid. For example, in the singlet-isosinglet state its values are 5 GeV at $r = 0.5$ fm and 9 MeV at $r = 1$ fm for $T_L = 0$. In this note, only some samples of different observables are shown. Values for other observables like depolarization, spin correlation parameters, etc. for various energies can be provided upon request. The masses and widths of the bound states and resonances can be predicted from the present $N\bar{N}$ potential and are currently under investigation. Also, our model can be expected to be highly relevant to antiproton-nucleus reactions which are known to be very sensitive[16] to the range of the $N\bar{N}$ annihilation.

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[a] Now at Centre Météorologique Canadien, Dorval, Quebec, Canada.

[1] See, e.g., K. Kilian, in *Proceedings of the Symposium on High Energy Physics with Polarized Beams and Targets* (Birkhäuser, Basel, 1981), p. 219.

[2] See, e.g., T. Kamae, in Nucl. Phys. A374, 25c (1982), Proceedings of the Ninth International Conference on High Energy Physics and Nuclear Structure, Versailles, France, 1981, edited by P. Catillon, P. Radvanyi, and M. Porneuf.

[3] See, e.g., H. M. Chan, in *High Energy Physics and Nuclear Structure*, edited by D. F. Measday and A. W. Thomas (North-Holland, Amsterdam, 1980), p. 219.

[4] R. A. Bryan and R. J. N. Phillips, Nucl. Phys. B5, 201 (1968); C. B. Dover and J. M. Richard, Phys. Rev. C 21, 1466 (1980).

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

[6] M. Lacombe *et al.*, Phys. Rev. C 21, 861 (1980).

[7] R. Vinh Mau, in *Proceedings of the Fourth European Symposium on $N\bar{N}$ Interactions* (Centre National de la Recherche Scientifique, Paris, 1979), p. 463; B. Moussallam, thesis, Université Paris VI, 1980 (unpublished).

[8] M. Alston-Garnjost *et al.*, Phys. Rev. Lett. 43, 1901 (1979).

[9] B. Conforto *et al.*, Nuovo Cimento A54, 441 (1968); D. Spencer and D. N. Edwards, Nucl. Phys. B19, 501 (1970); E. Eisenhandler *et al.*, Nucl. Phys. B113, 1 (1976).

[10] M. G. Albrow *et al.*, Nucl. Phys. B137, 349 (1972).

[11] R. P. Hamilton *et al.*, Phys. Rev. Lett. 44, 1182 (1980).

[12] V. Chaloupka *et al.*, Phys. Lett. 61B, 487 (1976); T. Kamae *et al.*, Phys. Rev. Lett. 44, 1439 (1980).

[13] R. P. Hamilton *et al.*, Phys. Rev. Lett. 44, 1179 (1980).

[14] R. Bizzarri *et al.*, Nuovo Cimento 54, 456 (1968); H. Khono *et al.*, Nucl. Phys. B41, 485 (1972).

[15] T. Oshugi *et al.*, Nuovo Cimento A17, 456 (1973); M. Kimura *et al.*, in *Proceedings of the Fourth European Symposium on $N\bar{N}$ Interactions* (Centre National de la Recherche Scientifique, Paris, 1979), p. 539.

[16] E. H. Auerbach *et al.*, Phys. Rev. Lett. 46, 702 (1981).