# MESON AND ISOBAR DEGREES OF FREEDOM IN NUCLEAR FORCES*

R. Vinh Mau
Physics Department
State University of New York at Stony Brook
Stony Brook, N.Y. 11794

and

Division de Physique Theorique**
Institut de Physique Nucleaire
91406 Orsay

## Abstract

The current status of the low energy theory of the NN and $N\bar{N}$ interactions is reviewed, with special attention given to the role of the meson and isobar degrees of freedom. Phenomenology and fits to recent data are also described.

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## ABSTRACT

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## 1. INTRODUCTION

I think that it is appropriate, at a workshop devoted to the manifestations of subhadronic structure in nuclear physics, to recapitulate the successes and/or the deficiencies of the approach to nuclear physics in terms of hadronic degrees of freedom. Such an analysis if conducted closely could help in turn to uncover situations exhibiting clear manifestations of subhadronic structure. For this purpose, I choose the particular field of nuclear forces since there the account of those degrees of freedom is the most complete and the most reliable. It is also there that one finds the most numerous and the most accurate experimental results so that theoretical predictions can be stringently tested.

As the nucleon-nucleon and nucleon-antinucleon interactions are closely related, I shall discuss both of them in the following.

## 2. THE NN INTERACTION

For this part, the material presented in my oral report at this workshop is extracted from my talk[1] at the International Conference on Nuclear Physics held in Florence in September 1983. To avoid duplication, I shall here summarize only briefly the salient features, referring the reader to that talk for a more detailed account and further references.

Nowadays, there is little doubt that nucleons and, more generally hadrons, are made up of subhadronic constituents (quarks, gluons, etc. ). One is therefore entitled to demand that the whole theory of nuclear forces should be derived from those fundamental constituent degrees of freedom. The program in its full generality is however very difficult to carry out with accuracy. As a matter of fact, simple arguments based on the confinement of quarks and gluons lead us to expect the following situation in a nucleus:

i) for large separation distances, only colorless objects, namely mesons can be exchanged between the nucleons since quarks and gluons must be confined. In the process of these exchanges, the nucleons can also find themselves, during part of the time, in excited states, namely isobars.

ii) for small separation distances where the overlap of the nucleons is significant, the various subhadronic constituents can interact with each other and contribute to the nuclear interaction energy.

In view of these simple considerations, I believe that a reasonable and realistic approach to the problem of nuclear forces is to proceed from the outer fringe towards the inner core in breaking the interaction into two parts:

i) the long range and medium range (LR+MR) part where the meson and isobar degrees of freedom are expected to provide a good approximation. In this part, taking into account explicitly the quark and gluon degrees of freedom is probably unnecessary and uneconomical.

ii) the short range (SR) part where the quark and gluon degrees of freedom can play a significant role. Present attempts to calculate the quark contribution to the NN interaction do not yield quantitative results yet. Moreover these calculations are based on the perturbative quark-gluon exchange. It is argued[3] recently that these effects are not the dominant ones, they are two orders in $1/N_c$ ($N_c$ = number of colors) smaller than those obtained[4] in the chiral soliton model considered as an approximation to QCD at low energies and for $N_c \to \infty$. In any event, a careful theoretical derivation of the subhadronic contribution to the NN interaction in this region is very desirable.

Meanwhile, as the amount of available NN data is very large, one can, at least provisionally, adopt a phenomenological viewpoint and try to determine the SR part from this wealth of data. Moreover many of these data are of very high precision.

## 2.1. THE PARIS NN POTENTIAL[5]

This potential is representative of the philosophy described above:

i) The LR+MR part is assumed to be given by the one-pion, two-pion and $\omega$ meson (as part of the three-pion) exchange contributions. The two-pion exchange contribution was derived via unitarity and dispersion relations from pion-nucleon phase shifts and pion-pion S and P-wave amplitudes. In this way, the properties of pions and their interactions both amongst themselves and with nucleons - i.e. the degrees of freedom of mesons and of isobars - are taken into account automatically and completely.

The question of whether this calculation provides a realistic description of the actual (LR+MR) NN forces has been checked by comparing the calculated peripheral ($J>2$) phase shifts with the experimental ones. An even better way to check the validity of these (LR+MR) parts is to compare directly the predictions with data for observables sensitive to these parts. This is the case for very low energy polarizations or analyzing powers, since at very low energies the S wave is accurately known from the effective range formula, and the P and higher waves are only sensitive to the LR+MR forces. The agreement between theory and experiment is, in both cases, very satisfactory.

This success in providing a good understanding of the (LR+MR) NN interaction, and at the same time, a good quantitative fit to the data is very encouraging since the whole scheme is based on properties as fundamental as unitarity, analyticity and crossing.

ii) the SR part - i.e. that for internucleon distances smaller than 0.8 fm - is described by a phenomenological parameterization, the parameters of which are adjusted to fit ≳ 3000 pp and np data in the energy region $3 < E_{lab} < 350$ MeV.

The quality of the fit is assessed by the very satisfactory values of the $\chi^2$/degrees of freedom: 1.99 for pp scattering and 2.17 for np scattering, to be compared, for reference, with 1.33 and 1.80 for the most recent phase-shift-analysis[6]. These values are also to be compared with 4.76 and 9.99 obtained with the Reid potential[7]. It should be noted that the fit was performed to the data themselves; the results obtained clearly show that two different potentials can yield fits of different quality to the data even though their fits to the phase shifts are equally good.

Finally, an important and meaningful feature of the results should be emphasized: in the full potential as obtained by the fit, the theoretical LR+MR parts are preserved for internucleon distances beyond 0.8 fm. This fact in conjunction with the ability of the Paris potential to provide a very good fit to the present world set of NN data up to 350 MeV suggests that we have gained during the last few years a theoretical understanding of the NN interaction for distances larger than 0.8 - 1 fm. This also suggests that any ultimate theory of strong interaction should recover somehow the same results in that region.

## 3. THE N$\bar{N}$ INTERACTION

The N$\bar{N}$ interaction differs from the NN interaction by the presence of annihilation processes. As we are concerned mostly with the low energy region, a simple and appropriate approach to the N$\bar{N}$ interaction is that using an optical potential.

$$V_{N\bar{N}} = U_{N\bar{N}} - i\, W_{N\bar{N}} \qquad (1)$$

### 3.1. GENERAL PROPERTIES OF THE N$\bar{N}$ OPTICAL POTENTIAL

Before discussing specific models, let me recall a few general and model independent properties of the N$\bar{N}$ optical potential that we should keep in mind:

i) the real part $U_{N\bar{N}}$ can be derived, via the G parity rule, from the NN potential if the latter is due to particle exchanges in the t channel. From the previous discussion it follows that the LR+MR part of $U_{N\bar{N}}$ is known from theory whereas the SR part is still phenomenological.

ii) below the production threshold ($E_{lab}$ < 300 MeV), the imaginary part $W_{N\bar{N}}$ describes annihilation processes. It is given, just from unitarity, by diagrams of the type shown in Fig. 1, where the intermediate states are physical states observed in these annihilation processes. Experimentally, these states consist of pions, mostly four or five pions. Of course, inelastic processes other than annihilation into pions can also develop an imaginary part for the optical potential. One should however be careful not to include these spurious states in the calculation of $W_{N\bar{N}}$ at low energies since they do not correspond to the observed states.

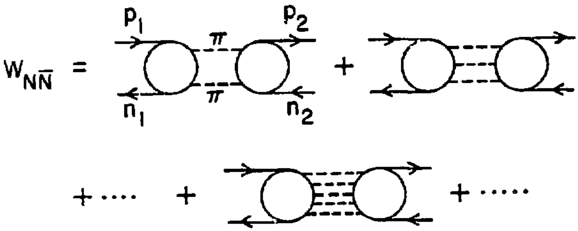


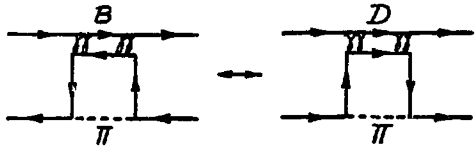

Fig. 1

A dispersion relation can be written for $W_{N\bar{N}}$:

$$W_{N\bar{N}}(s,t) = \sum_i \Omega_i \int_{4m^2}^{\infty} \frac{\rho_i(s,t')}{t'-t}\, dt' \qquad (2)$$

where $s = (p_1+n_1)^2$, $t = (p_1-p_2)^2$, m = nucleon mass and the $\Omega_i$'s are the usual spin and isospin invariants. Since the intermediate states are meson states with different masses, the spectral functions $\rho_i$'s are expected to be strongly dependent on s, and the resulting potential $W_{N\bar{N}}$ to be non local. In equation (2), the integration starts from $4m^2$. This is simply due to the conservation of baryon number: each blob of the diagrams shown in Fig. 1 contains at least one baryon (or antibaryon); therefore, the lowest mass which can be exchanged in the t channel is 2m, independently of the nature of the intermediate states in the s channel. This implies that, for fixed energy (fixed s), $W_{N\bar{N}}$ is of short range. This general property of $W_{N\bar{N}}$ being non local or, in a local approximation, short ranged but state (energy, angular momentum, spin, isospin) dependent, should be taken into consideration by any realistic model[8].

A.M. Green and collaborators[9] considered other possible contributions to $W_{N\bar{N}}$ from inelastic processes involving a baryonium B (regarded as a $N\bar{N}$ bound state) and a pion as represented in Fig. 2a. Although presence of bound states could induce anomalous thresholds the previous reasoning still applies in this case.




(a) (b)

Fig. 2

It is however stated, in reference 9 that such contributions are of the following form:

$$\psi_B(r)\ \psi_B(r')[(E + B)^2 - m_\pi^2]^{3/2} \qquad (3)$$

where $\psi_B$ is the wave function of the bound state, B its binding energy and E the antiproton CMS energy. From this expression, it was concluded that this absorptive part is of long range since the bound state (assumed to be produced by the real part $U_{N\bar{N}}$ only) has a wave function $\psi_B$ with a maximum at $r \cong 1$ fm. To my mind, this result is unexpected from a theoretical point of view since it does not depend on the nature of the exchanged system in the t channel, as it should. Moreover, if one transposes this result to the NN case where the equivalent diagram is shown also in Fig. 2b, with a deuteron and a pion in the intermediate state, one would get a very long ranged contribution to the NN forces since the deuteron wave function is peaked at $r \cong 1.5 - 2$ fm. This contribution would modify strongly the well known OPEP. To my knowledge, there is no evidence for such an effect in the well established long range part of the NN potential at low energies. Of course, the mechanism $NN \to d\pi \to NN$ as shown in Fig. 2b can contribute to the NN inelasticities, that is only above the π production threshold, as part of the inelastic processes. Likewise, the corresponding mechanism $N\bar{N} \to B\pi \to N\bar{N}$ can contribute to the $N\bar{N}$ amplitude as part of the π production processes but not as an annihilation process (see the discussion above). Moreover if this baryonium B is to be identified with the narrow states observed by the B. K. S. S. T. Collaboration[10], the diagram shown in Fig. 2a will contribute very little to the $N\bar{N}$ annihilation since the B state is very weakly coupled to pions.

iii) Another general property of the $N\bar{N}$ optical potential deserves being mentioned. The LR+MR parts of $U_{N\bar{N}}$ as derived from realistic particle exchange NN potentials are strongly attractive. This is because of the sign reverse of the ω-exchange under the G parity transformation whereas the two-pion exchange remains attractive. Therefore, in the absence of $W_{N\bar{N}}$, one expects $U_{N\bar{N}}$ to produce a rich spectrum of $N\bar{N}$ bound states or resonances. Of course, the widths of these bound and resonant states are given by $W_{N\bar{N}}$. This has some relevance with the so called baryonium states which were discussed very much some years ago[11].

### 3.2 REVIEW OF SOME OPTICAL MODELS

i) The first optical model for the $N\bar{N}$ interaction was proposed by Bryan and Phillips[12] where $U_{N\bar{N}}$ is the G parity transform of the Bryan-Scott OBE potential and where $W_{N\bar{N}}$ is assumed to be local, state independent (i.e. central) and of the Saxon-Wood form:

$$W_{N\bar{N}} = \frac{W_0}{1 + e^{r/r_0}} \qquad (3)$$

$r_0$ is taken to be 0.17 fm, compatible with the short range property as it should be. Fitting the data known at that time, $W_0$ is found to be 62 GeV. With these values for $W_0$ and $r_0$, $W_{N\bar{N}}$ = 150 MeV at 1 fm, which is effectively a long ranged potential. The results of this particular model have led some people to consider this characteristic as a quite general property.

ii) More recently, Dover and Richard[13] use for $V_{N\bar{N}}$ the following form:

$$V_{N\bar{N}} = V_t + V_{ann} \qquad (4)$$

$$\text{where } V_t(r) = \begin{cases} V_{N\bar{N}}^{Paris}(r_1), & r < r_1 \\ V_{N\bar{N}}^{Paris}(r), & r > r_1 \end{cases} \quad \text{with } r_1 = 0.8 \text{ fm}$$

$$\text{and } V_{ann}(r) = -(V_0 + iW_0)/(1 + e^{r/r_0}) \text{ with } r_0 = 0.2 \text{ fm}$$

By fitting the shapes of the integrated elastic, total and charge exchange cross sections ($\sigma_{el}$, $\sigma_{tot} = \sigma_{el} + \sigma_{ann}$, $\sigma_{C.E.}$) they found $V_0 = 18 - 21$ GeV and $W_0 = 20$ GeV. This still gives a long ranged effective annihilation potential. Also with such values of $V_0$, their phenomenological real "short range" part modifies significantly the LR+MR part of $V_t$ even at distances as large as 1 fm. On the other hand, "experimental" elastic cross sections $\sigma_{el}$ are obtained by integrating the data on $d\sigma_{el}/d\Omega$ extrapolated to the very forward angles where the Coulomb effects must be substracted out. In most of the experimental papers, this substraction is performed in a rather ambiguous way, leading to inconsistent $\sigma_{el}$. Because of this, it is preferable to use the data $d\sigma_{el}/d\Omega$ themselves rather than the integrated $\sigma_{el}$.

With effective long ranged annihilation as those of references[12,13], the bound and resonant states produced are very broad as shown by Dalkharov, Gerstein, Myhrer and Thomas[14].

iii) Attempt to calculate the contribution of annihilation diagrams was made by the Paris group. As a large fraction (80-90%) of the $N\bar{N}$ annihilation goes mostly to 4 or 5 pions, it is expected that the dominant annihilation potential arises from diagrams with multipion (4 or 5) intermediate states. The calculation of such diagrams is, prohibitively complicated, and I suggested some time ago[6] that a reasonable approximation would consist in grouping these pions in clusters (the $\epsilon, \rho, \omega$ mesons) as presented in Fig. 3.

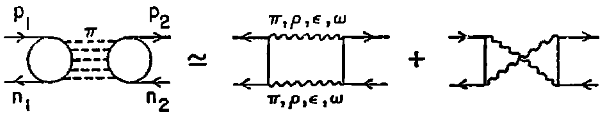



Fig. 3

Since the $\rho$ meson and especially the $\epsilon$ meson are rather broad resonances, it is hoped that effects of uncorrelated multipion states are partially contained in these clusters. This approximation is supported by the fact that multiparticle decays of unstable mesons are dominated by resonant two-body final states when these are available. It is, however, criticized recently by A.M. Green[15]. The objections concern the neglect of $\Delta(1236)$ exchange, the possible effects of form factor, and the "lack of natural cut-off in the meson masses". As for the first point, his argument rests on the relative values of the $\pi NN$ and $\pi N\Delta$ coupling constants ($f^2_{\pi NN}/4\pi = 0.08$ versus $f^2_{\pi N\Delta}/4\pi = 0.35$). This argument, however, can be applied only to diagrams with two pions in the intermediate states, and the contribution of this channel is any way very weak since $N\bar{N}$ annihilation into two pions represents only few per cent. The effects of form factor can be seen by replacing in the spectral functions $\rho_i(s,t')$ the direct coupling of the $\varepsilon$ and $\rho$ mesons to the nucleons by the partial wave helicity amplitudes $f_0^{N\bar{N}\to 2\pi}$ and $f_1^{N\bar{N}\to 2\pi}$. Here, contrary to the NN case, these amplitudes depend on the $\pi\pi$ subenergy $s_1$ in the direct channel but not on $t'$, and consequently cannot affect much the range of $W_{N\bar{N}}$. Finally, our "natural cut-off of the meson masses" or our way of picking out the dominant diagrams among all the annihilation diagrams is simply dictated by the experimental facts that $N\bar{N}$ annihilation into four or five pions is largely dominant and that the $\varepsilon,\rho,\omega$ mesons exist, due to the strong $\pi\pi$ interactions.

Within this approximation, the spectral functions $\rho_i$'s and therefore $W_{N\bar{N}}$ can be calculated explicitly[16]. However, their actual expressions are still quite complicated, and before treating the complete problem with this non local potential it is preferable to study a phenomenological but simpler model possessing however all the same physical properties. As a first step, the Paris group considers the following model[17]:

1) $U_{N\bar{N}}$ is the G parity transform of the Paris NN potential for the long and medium range parts ($r > 0.9$ fm). The short range part ($r < 0.9$ fm) is described phenomenologically, and for computational convenience, one uses a quadratic function constrained to join the medium range part through two points in the neighborhood of $r = 1$ fm, the third parameter being adjusted to fit the data.

2) The absorptive part $W_{N\bar{N}}$ is of short range, energy and state dependent:

$$W_{N\bar{N}}(\vec{r},T_L) = [g_C(1+f_C T_L) + g_{SS}(1+f_{SS}T_L)\vec{\sigma}_1\cdot\vec{\sigma}_2 + g_T S_{12} + \frac{g_{LS}}{4m^2}\vec{L}\cdot\vec{S}\,\frac{1}{r}\frac{d}{dr}]\;\frac{K_0(2mr)}{r} \qquad (5)$$

This representation is obtained from eq. 2 in the following way: as one is concerned with the low energy region, one can make a Taylor expansion of the functions $\rho_i$'s near threshold $s = 4m^2$ and retain only the first or the first two terms. The $t'$ dependence of the resulting coefficients is essentially of the form $1/\sqrt{t'(t'-4m^2)}$ which in turn gives rise to the modified Bessel function

$$K_0(2mr) = \int_{4m^2}^{\infty} dt'\;\frac{e^{-\sqrt{t'}r}}{\sqrt{t'(t'-4m^2)}}$$

when translated by a Fourier transform from momentum to coordinate space. For simplicity, eqs. 2 and 5 are written for a given isospin state. The coefficients $g_i$, $f_i$ are for the moment considered as effective parameters.

It is worth noting that the number of these parameters (6 for each isospin state) is a minimum required by the energy and spin dependence of $W_{N\bar{N}}$.

### 3.3 FIT OF THE EXISTING DATA

The parameters are adjusted to fit a set of 915 $p\bar{p}$ data points in the energy domain 20 MeV < $T_L$ < 370 MeV. This up to date compilation consists of available results on $\bar{p}p$ total cross sections $\sigma_{tot}(T_L)$, differential elastic cross sections $d\sigma_{el}/d\Omega$, differential and total charge exchange cross sections $d\sigma_{CE}/d\Omega$ and $\sigma_{CE}(T_L)$, and a few measurements on polarization in elastic scattering. Data on integrated elastic cross sections $\sigma_{el}(T_L)$ are not included in this compilation because of the ambiguities mentioned earlier in the treatment of Coulomb effects. Anyway, $\sigma_{el}(T_L)$ are redundant whenever $d\sigma_{el}/d\Omega$ are given. Elastic cross sections and polarization are calculated including Coulomb effects while total and charge exchange cross sections are obtained from pure nuclear amplitudes.

As this 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 ($\theta_{cm} \approx 174^o$) measured recently by Alston-Garnjost et al.[18]. These data were found to be very constraining in the search for the solution. The fit, displayed in Fig. 4, shows an excellent agreement between theory and experiment

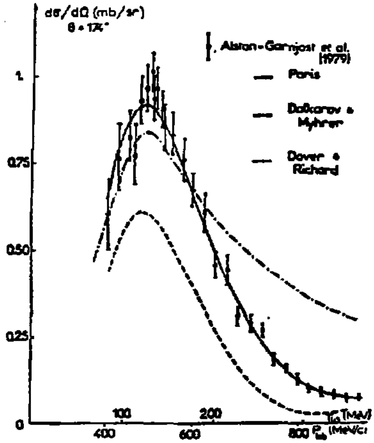



Fig. 4

with a $\chi^2$/data of 0.61. For comparison, are also shown in Fig. 4 the results by Dover and and Richard and by Dalkharov and Myhrer as quoted in reference 18. Other measurements[19,20] of the differential elastic cross sections were performed for 20 MeV < $T_L$ < 369 MeV. Again the agreement is good yielding $\chi^2$/data of 2.87 for the whole set of data. An example of the fit is shown in Fig. 5.

The total cross section $\sigma_{tot}(T_L)$ was measured by different groups and their results are not fully consistent. As can be seen in Fig. 6, the values of Chaloupka et al.[21] are higher than those

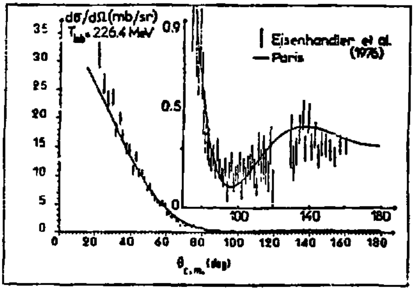



Fig. 5

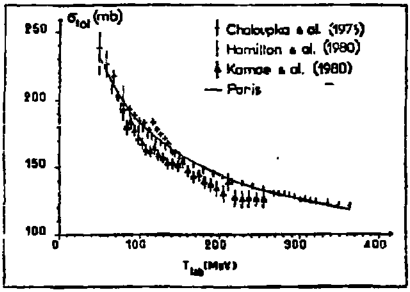



Fig. 6

of Hamilton et al.[22] which in turn are larger than those of Kamae et al.[23] For the data of reference 22 which cover a larger energy range, a $\chi^2$/data of 0.96 for 65 MeV < $T_L$ < 370 was obtained. This solution yields then a $\chi^2$/data of 2.16 for the results of reference 21 (49 MeV < $T_L$ < 150 MeV) and of 5.69 for those of reference 23 (80 MeV < $T_L$ < 255 MeV). We have been informed recently[24] that the results of reference 23 have been remeasured and they are now even higher than those of reference 22.

In Fig. 7, the results for the total charge exchange cross section $\sigma_{CE}(T_L)$ are compared with the data of Hamilton et al.[25]. The $\chi^2$/data is 3.25. The fit of the few available results[26] on $d\sigma_{CE}/d\Omega$ gives a $\chi^2$/data of 2.41.

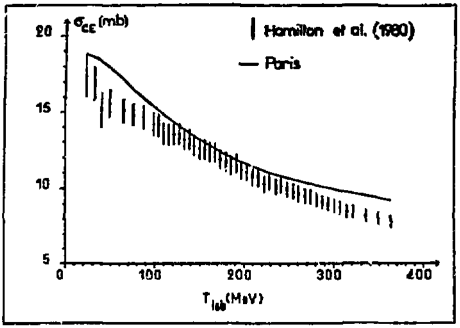



Fig. 7

The only measurements on polarization below 370 MeV were performed at 220 MeV[27] and 232 MeV[28] for angles below 80° and at 368 MeV[29] but with larger uncertainties. The theoretical results reproduce the data very well ($\chi^2$/data ≅ 1). Apart from a dip near 90° close to that of the differential cross section (see Fig.5 ), the polarization is significant. As can be seen in Fig. 8, the model of Bryan and Phillips gives a different behavior than the present model for angles below 90°. It is also found the polarization is very sensitive to the values of the parameters especially for angles above 90°. In view of this, accurate polarization measurements are therefore very desirable.

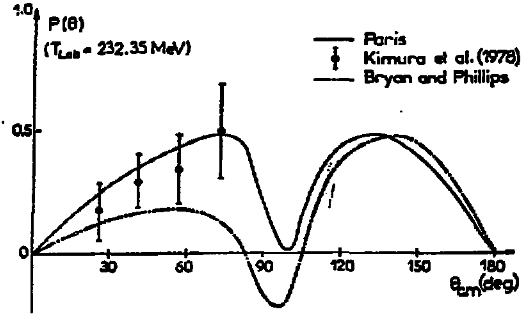



*Fig. 8*

For the complete set of 915 data, the $\chi^2$/data is 2.80. This value does not reflect the actual quality of the fit since some data, especially for $\frac{d\sigma_{el}}{d\Omega}$ and $\sigma_{tot}$ as seen above, are inconsistent. We made our own choice for the determination of the parameters but all data are taken into account for the calculation of the $\chi^2$. The values for the parameters $g_i$ and $f_i$ that appear in eq. 5 are listed in Table I.

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 | |

It is noticeable 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 14 MeV at r = 1 fm for $T_L = 0$. In this talk, 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 present model is expected to be relevant in antiproton-nucleus reactions since these reactions are known to be very sensitive to the range of the $N\bar{N}$ annihilation potential. Actually, it has been used very recently[29] for the interpretation of the first data obtained with the LEAR in the elastic scattering of the antiprotons on $^{12}C$. Also, the characteristics (masses and widths) of the bound states and resonances can be predicted[30] from the present $N\bar{N}$ optical potential.

In short, the Paris group has constructed a model for nucleon-antinucleon annihilation which is of short range but is state (energy, spin, isospin,...) dependent. This model fulfills general theoretical requirements and is based on the calculation of annihilation diagrams in terms of hadronic degrees of freedom. At the same time, it provides a good fit of the presently available $\bar{p}p$ experimental data, better than the existing models which are state independent but effectively long ranged. These results contradict the generally accepted claim that fitting $\bar{p}p$ data requires an effective long ranged annihilation potential.

## 3.4 MODELS INVOLVING QUARK DEGREES OF FREEDOM

During the last two years, several authors have attempted to derive a $N\bar{N}$ annihilation potential $W_{N\bar{N}}$ from quark degrees of freedom[31-33]. In references 31 and 32, it is assumed that the $N\bar{N}$ annihilation is due to the annihilation of a quark of the nucleon with an antiquark of the antinucleon into a gluon (Fig. 9). It is, however, not clear that one can build up from this mechanism the $N\bar{N}$ annihilation into pions. By contrast, this mechanism clearly contributes to the $N\bar{N}$ scattering. In reference 33, it is assumed that the $N\bar{N}$ annihilation is due to a particular rearrangement of the quarks of the nucleon with the antiquarks of the antinucleon into three mesons. A detailed discussion supporting this model can be found in reference 15. Actually, in the derivation of $W_{N\bar{N}}$ there is no compelling reasons to favor this particular process against those represented in Fig. 11, for example. One important point, which was

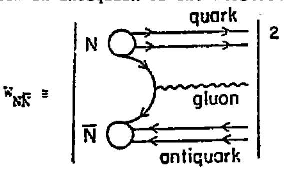


Fig. 9

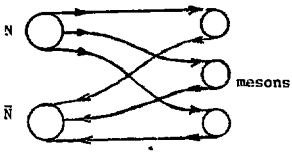


Fig. 10

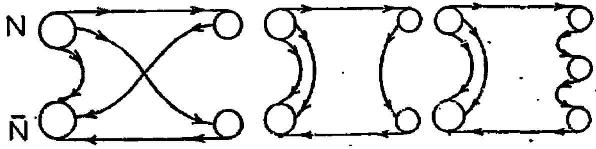



Fig. 11

disregarded in reference 15, concerns the topology the different diagrams yielding $W_{N\bar{N}}$. These diagrams result from the iteration of the various processes shown in Figs. 10 and 11, with integration over the intermediate quark lines. One can easily see that, among the different mechanisms considered here, the rearrangement process of Fig. 10 gives rise to the most non-planar diagram. This is because of the crossing quark lines. From a theoretical point of view, either in the topological expansion[34] or in the 1/N expansion[35], non-planar diagrams are higher order corrections to planar diagrams. Moreover, from a phenomenological point of view, a recent analysis[36] of some $p\bar{p}$ annihilation data seems to indicate also that processes with crossing quark lines are weaker than those with no crossing quark lines.

### 3.5 A GEOMETRICAL MODEL

In the calculations of $W_{N\bar{N}}$ dealing with quark degrees of freedom, one ends up with expressions containing essentially two factors. The first one is associated with the elementary process responsible for the annihilation, the other is just the overlap of the nucleon and antinucleon wave functions (the overlap of two bags if one uses, as in reference 31, the bag model to describe the hadrons). As the elementary subhadronic mechanism responsible for the $N\bar{N}$ annihilation is still unknown, one can try to make a provisionally phenomenological description of it. In so doing, one is led to the following geometrical model:

$$W_{N\bar{N}} \simeq W_0(E,S,T\ldots)\ [(1-\frac{r}{2R})^2(1+\frac{r}{4R})]^2 \quad \text{for } r \lesssim 2R$$

$$= 0 \quad \text{for } r > 2R \qquad (6)$$

In this expression, the dynamical factor $W_0$ depends on energy, spin, isospin, etc..., the geometrical factor is simply given by the bag model, namely, the overlap of two bags of radius R. The annihilation takes place when the N and $\bar{N}$ bags overlap so that quarks and antiquarks can annihilate or rearrange into mesons. This geometrical model can give some idea about the radius R, i.e. the size of the confinement region. It has been used in reference 31 as an alternative to the one gluon annihilation model in a fit of $p\bar{p}$ data. However, $W_o$ was chosen to be constant. This means that $W_{N\bar{N}}$ is again local and state independent (i.e. central and energy independent). The best fit, although not very good ($\chi^2$/data = 10), is obtained with $W_o$ = (8.3 ± 0.7) GeV and R = (1.01 ± .01) fm.

This model was recently reconsidered[35] in the light of the points discussed in Section 3-1. Accordingly, $W_o$ is chosen to be energy, spin and isospin dependent, i.e.

$$W_{N\bar{N}}(r,T_L)=[\lambda_c(1+\alpha_c T_L)+\lambda_{ss}(1+\alpha_{SS}T_L)\vec{\sigma}_1\cdot\vec{\sigma}_2](1-\frac{r}{2R})^4(1+\frac{r}{4R})^2 \text{ for } r\leq 2R$$

$$= 0 \text{ for } r > 2R \qquad (7)$$

Again, for simplicity, Eq. (7) is written for a given isospin state.

Using the same real part $U_{N\bar{N}}$ as in Section 3-2-iii, the parameters $\lambda_i$, $\alpha_i$, as well as the radius R are adjusted to fit the same set of data as that of Section 3-3. The results for total cross section $\sigma_{tot}(T_L)$, differential elastic cross section $d\sigma_{el}/d\Omega$, and charge exchange cross section $\sigma_{CE}(T_L)$ are shown in Figs. (12-15) for

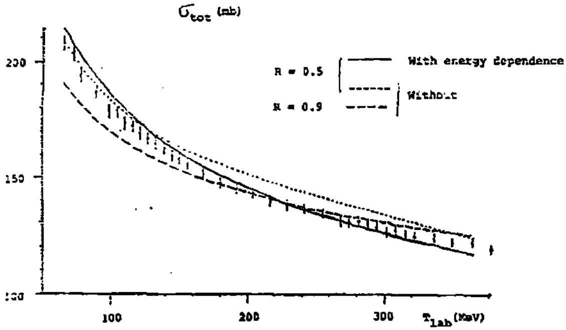



Fig. 12. Total cross section vs. $T_L$. The experimental points are from ref. 22. The solid line refers to results obtained with values of $g_i$ and $\alpha_i$ given in Table II and with R=0.5 fm. The dotted (...) and dashed (---) lines refer to results obtained without energy dependence and R=0.5 and 0.8 fm respectively.

different assumptions on the dynamical factor $W_o(E,S,T,....)$.

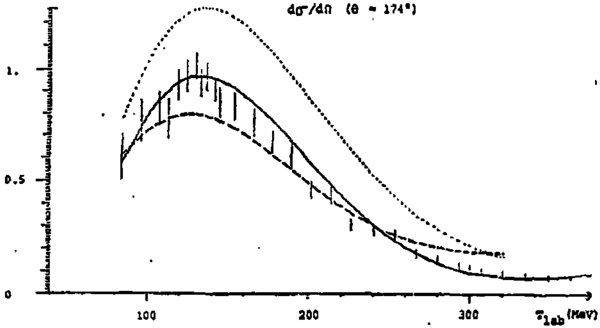



Fig. 13. Backward differential elastic cross section vs $T_L$. The experimental points are from ref. 18. The curve captions are the same as in Fig. 12.

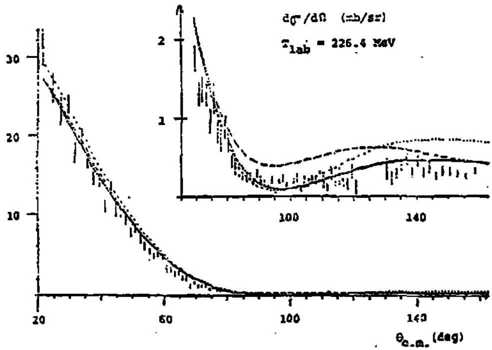



Fig. 14. Differential elastic cross section at $T_L$ = 226.4 MeV. The experimental points are from ref. 19 (Eisenhandler et al.). The curve captions are the same as in Fig. 12.

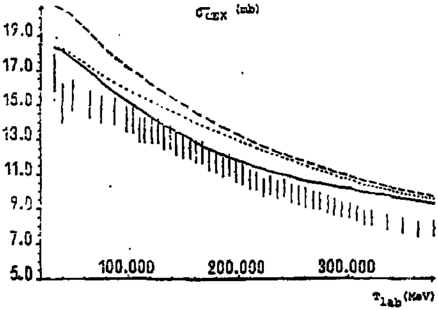



Fig. 15. $\bar{p}p \to \bar{n}n$ cross section vs $T_L$. The experimental points are from ref. 26. The curve captions are the same as in Fig. 12.

These results clearly show that the energy, spin, isospin dependence is definitely needed to get a good fit, the best fit ($\chi^2$/data = 3 ) being obtained with a rather small value of the bag radius, R = 0.5 fm. When one neglects the energy dependence ($\alpha_c = \alpha_{ss} = 0$), one fails to fit, with this value of R, the data in the energy region $T_L \geq 100$ MeV. With a larger value R = 0.9 fm, one can get a better fit in the energy domain $150 \leq T_L \leq 250$ MeV but not for $T_L \leq 150$ MeV nor for $T_L \geq 250$ MeV.

The values for the parameters of the absorptive part $W_{N\bar{N}}$ as defined in Eq. (7) are listed in Table II.

| i | $\lambda_i$ (MeV) | $\alpha_i$ (MeV$^{-1}$) |
|---|---|---|
| T = 0 | | |
| C | 8688 | 0.0131 |
| SS | − 4705 | 0.009 |
| T = 1 | | |
| C | 7312 | 0.0243 |
| SS | − 5740 | 0.0303 |

Table II

The study of this very simple model shows that

i) the description of the $N\bar{N}$ annihilation in terms of the static bag model is not accurate enough. This is to be expected since the energy release here is significant. Static bag models can only account for averaged features of the mechanism leading to rather large "average" value of R.

ii) if some simple dynamical dependence is allowed, the description in terms of the bag model is satisfactory with a rather small radius for the bag (R = 0.5 fm).

## 4. CONCLUDING REMARKS

For the NN interaction, experimentalists have provided us, during the last few years, a very large number of data on various observables. Also, it should be emphasized that most of these data are of very high level of accuracy. Of course, the real task for theorists is to cope with the stringent constraints originating from these data. So far, in this challenge, the hadronic (meson and isobar) degrees of freedom, when they are treated carefully, have proved their ability to provide a theoretical and quantitative understanding of the (LR+MR) parts of nuclear forces. There. in my opinion, their contribution can be considered as an accurate approximation to any ultimate theory of strong interactions involving more fundamental constituents. As for the SR part, the subhadronic (quark and gluon) degrees of freedom can play, in principle, a significant role. However, their contribution can be made meaningful only through a proper account of the quark and gluon dynamics. On the other hand, it is also possible that in the low energy regime like in nuclear physics, an approximate but nevertheless correct description of the hadronic substructure is provided by effective models where the quark and gluon degrees of freedom are averaged out[38].

The data for the $N\bar{N}$ interaction are, at present, less numerous and less accurate than in the NN case. Here also, the description of the $N\bar{N}$ interaction, both for scattering and annihilation, in terms of hadronic degrees of freedom gives a good fit to the existing data. However, to attain the same situation as in the NN case, much hope is placed in the LEAR facility at CERN.

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