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LOW ENERGY NUCLEON-ANTINUCLEON INTERACTION

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1. INTRODUCTION

At this conference the nucleon-nucleon (NN) forces mediated by mesons are particularly under discussion. Here I will discuss a more exotic but closely related subject, nucleon-antinucleon ($N\bar{N}$) meson exchange forces. The NN pion exchange diagrams in Fig. 1 are connected to the $N\bar{N}$ ones by

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

Fig. 1 One-, two-, and three-pion exchange diagrams

More generally NN and $N\bar{N}$ meson exchange diagrams are connected by G conjugation, for example, a meson of odd G-parity changes the sign of the diagram when going from NN to $N\bar{N}$. Since π and ω have odd G-parity, for example, the strong ω -repulsion in NN will lead to a strong ω -attraction in $N\bar{N}$. On the other hand, the $\pi\pi$ ($J = 0$) exchange (the scalar meson exchange, ϵ or σ_0) which has even G-parity, will remain attractive in the $N\bar{N}$ case.

Generally speaking the present NN meson exchange potential predicts a strongly attractive $N\bar{N}$ potential. This attractive $N\bar{N}$ potential will (because of the strong $\underline{L} \cdot \underline{S}$ forces involved) give many $N\bar{N}$ bound states and low-energy resonances, as was recognized early on by Shapiro et al.¹⁾. However, in addition, the $N\bar{N}$ can annihilate. This has no counterpart for NN scattering and a major part of this talk will be focused on the problem of annihilation.

Because of the short time available, I will concentrate on the most recent $N\bar{N}$ theoretical work. But at the same time, I shall try to present some general experimental information. All potential descriptions of low-energy NN scattering are in the spirit of the Ball-Chew model²⁾. For a review of early works see Phillips³⁾. Here a summary of the "predicted" potential resonances will be given. We fit existing $\bar{p}p$ data very well, but there are some open questions that I shall discuss. In the last section I will give a short presentation of the dual quark model approach for $B\bar{B}$ scattering. $B\bar{B}$ resonances are also predicted in this model as discussed recently by Chew⁴⁾, and Rossi and Veneziano⁵⁾.

2. THE POTENTIAL MODEL

Following the arguments presented in the Introduction I should like to use information from NN scattering to predict what will happen for $N\bar{N}$. For a summary of the boson exchange forces see Brown and Jackson, and Vinh-Mau⁶⁾. In this talk I will use the one-boson-exchange potential (OBEP) of Bryan and Scott⁷⁾, and introducing a simple model for annihilation I will show the fit the potential model gives to $\bar{p}p$ data.

Bryan and Phillips⁸⁾ used the OBEP of Ref. 7 (all parameters fixed by fitting NN data), and added an absorptive potential of Wood-Saxon form,

$$W(r) = -i W_0 / (1 + \exp(b r)) \quad (2)$$

The range of the annihilation forces should be short, following arguments by Martin⁹⁾. In Fig. 2 at least two nucleons must be exchanged in the t-channel. Therefore, the inverse range of this graph is at least two nucleon masses (2M). Bryan and Phillips chose $b = 0.2 \text{ fm}^{-1}$ in Eq.(2), and needed $W_0 \approx 8 \text{ GeV}$ in order to fit $\bar{p}p$ data. With a different value for b they had to change W_0 a great deal in order to get a fit^{3,8)}.

Fig. 2 Annihilation graph contributing to $N\bar{N}$ elastic scattering

Not long after the Bryan and Phillips work, Shapiro et al. (see, for example, Ref. 1) pointed out that OBEP will give rise to many $N\bar{N}$ bound states and resonances around $N\bar{N}$ threshold, because (as stated in the Intro-

duction) the $N\bar{N}$ potential is very attractive. The $N\bar{N}$ bound states are deuteron-like objects, consisting of a nucleon and an antinucleon loosely bound together (a few MeV). The radii of these $N\bar{N}$ bound states are roughly 1 fm ¹⁾. Because they can be understood in a Schrödinger picture (like the nucleus, which is also weakly bound, consisting mainly of protons and neutrons), Shapiro calls these $N\bar{N}$ states "quasinuclear" states. However, if the $N\bar{N}$ binding is much stronger than, say, 100 MeV relativistic aspects will be important, if not dominant, and it will no longer be meaningful to think of such an $N\bar{N}$ state as consisting of a nucleon and an antinucleon. One of the major experimental features of these predicted $N\bar{N}$ potential resonances should be that they couple mainly to the $N\bar{N}$ elastic channel.

Later Dover¹⁰⁾ redid the calculations of Shapiro et al.¹⁾ using the same OBEP. He did make some comments concerning Shapiro et al.'s work, but generally speaking confirmed their results. Also Vinh Mau and co-workers¹¹⁾, with their much better NN potential (built from

$\pi + 2\pi + \omega$ exchange plus a core parametrization), support the results of Shapiro et al.¹⁾. The results of Shapiro et al. are summarized in Figs. 3 and 4.

Before I go on to discuss annihilation, a few comments should be made regarding the accuracy of the positions predicted for the above NN resonances. Common for all OBEP (including the Paris potential) is that they need a cut-off to take care of the r^{-3} behaviour of the $L \cdot S$ and tensor forces at shorter distances. One way of introducing this cut-off is the following [for example, Bryan and Scott⁷⁾]. The one-pion exchange (OPE) diagram gives a potential

$$V_{OPE}(r) = g_{\pi}^2 f(\mu r) \frac{e^{-\mu r}}{r} \quad (3)$$

where g_{π}^2 is the coupling constant, μ is the pion mass and $f(\mu r)$ is an analytic expression in μ and r containing the tensor force with the r^{-3} singularity. Instead of using this potential, Eq. (3), in the Schrödinger equation, the following cut-off potential is used

$$V(r) = \left[V_{OPE}(r) - g_{\pi}^2 f(\Lambda r) \frac{e^{-\Lambda r}}{r} \right] \frac{\Lambda^2}{\Lambda^2 - \mu^2} \quad (4)$$

where Λ is the cut-off parameter. This $V(r)$ is free from the r^{-3} behaviour as $r \rightarrow 0$. When this potential is applied to NN this cut-off at short distances ($\Lambda \sim 1-2$ GeV) does not affect the NN phase shifts (apart from the S-waves) very much, because of the strong ω repulsion. But, since in NN we do not have a strong boson-exchange repulsion at shorter distances, a small variation in the value of this cut-off affects the NN phase shifts very much [see Richard et al.¹¹⁾ or Myhrer and Gersten¹²⁾]. A 2% variation of Λ in the Bryan-Phillips OBEP can change the position of the NN resonances by 50-100 MeV¹²⁾.

Another comment concerns how far down (towards shorter distances) one can extrapolate the NN OBEP. From NN data the OBEP is not known beyond roughly 0.8 fm. We should also keep in mind that nucleons and mesons are not point particles but we have a radius of ~ 0.8 fm. So the present OBEP with only $\pi + 2\pi + \omega$ exchange, and constant coupling constant, cannot be expected to reproduce the actual NN and NN forces at shorter distances. A hint that all is not rosy was given by Dalkarov and myself¹³⁾. If we take the Bryan-Phillips OBEP with their cut-off, we find that the NN potential is 1 GeV or deeper at $r \approx 0.5$ fm in all S-, P- and D-waves. With such a deep potential what about relativity? Buck and Gross¹⁴⁾ claim that relativity (v^2/c^2 terms from the negative energy components) will introduce strong repulsion in NN . But this is a controversial subject on which there is still some work to be done.

Fig. 3 $N\bar{N}$ ($I = 0$) states from Ref. 1 and the leading trajectory in Ref. 4. The triangles are from my own recalculation of Ref. 1.

Fig. 4 Same as Fig. 3, $N\bar{N}$ ($I = 1$) states

Despite these critical comments which have to be examined, it is evident that the NN OBE forces predict many weakly bound states and resonances (quasinuclear states). However, in the $N\bar{N}$ system their exact positions are not very well predicted.

We now turn to the annihilation part of the $N\bar{N}$ system. Here only very crude models exist. First I will briefly discuss the arguments of Shapiro et al.¹⁾ They suggest that because the annihilation is of short range ($\sim 2M$), see Fig. 2, they can estimate the influence annihilation has on the bound states and resonances. In particular, since the $N\bar{N}$ bound state has a radius $R \approx 1$ fm, whereas the annihilation amplitude f_a , varies rapidly only over a range $\sim (2M)^{-2}$ ($= 0.1$ fm), the annihilation width of the $N\bar{N}$ states can be estimated by

$$\Gamma \approx f_a \cdot |\Psi(0)|^2 \quad (5)$$

where $\Psi(r)$ is the $N\bar{N}$ wave function from the OBEP.

Here one must face the basic argument of whether or not these states exist! The point is that the bound-state wave function $\Psi(r)$, and its radius R , are given by the strength and the range of OBEP (R is generally smaller than m_π^{-1} because the attraction is mainly given by σ_0 and ω exchange). To find the annihilation widths of these states one must not only know the range of the annihilation forces, but also their strengths as compared to the OBEP strength. It is a mixture of these parameters that will determine if a $N\bar{N}$ bound state or resonance will be wide (washed out), or not, in a particular $N\bar{N}$ partial wave.

To find out at what distances the annihilation is effective Gersten and myself¹²⁾ examined the optical potential model of Bryan and Phillips more closely. If we used their OBEP we found many $N\bar{N}$ resonances [$W_0 = 0$ GeV in Eq. (2)]. Then we slowly turned on the strength of absorption ($W_0 \neq 0$). Figure 5 illustrates what happened when the absorptive strength was increased. At full strength ($W_0 = 8.3$ GeV) we can no longer define a resonance from this Argand diagram. The reason for this is that the Bryan and Phillips imaginary potential is so strong that it is felt in all $N\bar{N}$ channels, even at large distances (~ 1 fm). In a paper with Thomas¹⁴⁾, it was demonstrated that the resonance pole moves away from the physical region very quickly as the absorptive strength is increased. It just becomes a pole in the scattering amplitude, with no observable consequences.

To avoid the long tail of the absorptive potential in Eq. (2), Dalkarov and the author introduced absorption through a boundary condition à la Feshbach and Weisskopf¹⁵⁾ but kept the OBEP of Bryan and Phillips. Here the absorption takes place by demanding only incoming waves at the boundary. Again the same question can be asked. At what distance is the annihilation boundary effective? For small values of ℓ (≤ 4) we force the logarithmic derivative of the radial wave function u_ℓ to satisfy

$$u'_\ell / u_\ell \Big|_{r=r_c} \approx -iK \quad (6)$$

Fig. 6 Cross-section for $\bar{p}p \rightarrow \bar{n}n$ versus plab. The dashed line corresponds to a 10% increase in OBEP cut-off Λ . The other three lines have $\Lambda = 980$ MeV. Data from Ref. 16.

Fig. 5 Argand plot of ${}^{33}\text{P}_1$ $\bar{\text{N}}\bar{\text{N}}$ amplitude for different strengths, W_0 , of the absorptive potential (Ref. 8). Full line: $W_0 = 0.0$ GeV; dashed line: $W_0 = 0.3$ GeV; line with open circles: $W_0 = 2.0$ GeV; and line with black circles: $W_0 = 8.3$ GeV. Numbers on the lines are values of T_{lab} in MeV.

where $\kappa = \sqrt{M[E - V(r_c)]}$ is the effective wave number at radius r_c where $V(r) = \text{OBEP}$, see Ref. 13. Equation (6) is like a WKB approximation, which is valid if κ does not vary too strongly with r . This is alright for $r_c \approx 0.5$ fm. With r_c our only free parameter we reproduce $\bar{p}p$ scattering data rather well (cf. Figs. 6-11).

In Fig. 6 we plot the total σ for $\bar{p}p \rightarrow \bar{n}n$. It is a smooth function of energy as also shown by the data¹⁶⁾. (The fits to data at the lowest momenta in Fig. 6 are not very good, because we have neglected the $\bar{p}-n$ mass difference, which at $p_{\text{lab}} \approx 300$ MeV/c is 10-15% of available $\bar{p}p$ phase space). However, experimentally one finds an $\bar{N}\bar{N}$ resonance in this energy region which is seen in σ_{el} and σ_{tot} ¹⁷⁾. In Fig. 7 we show the results from the experiment of Brückner et al.¹⁷⁾ ($\bar{p}p \rightarrow$ charged mesons) where S(1936) is seen. Clearly, it is a small bump on top of a large background, which will be explained when I discuss Figs. 10 and 11.

Figures 8 and 9 show the $d\sigma/d\Omega$ for $\bar{p}p \rightarrow \bar{n}n$ at two energies. The forward dip-bump is seen experimentally³⁾ and is explained as being due to double spin flip in the one-pion exchange according to Phillips³⁾. Obviously one needs to partly shelter the other boson exchanges by a boundary at $r \geq 0.5$ fm in order to get this dip-bump with the present OBEP. Compare also Figs. 8 and 9 to see the very rapid change in $d\sigma/d\Omega$ at backward angles for increasing energy. Finally in Figs. 10 and 11 we show $(d\sigma/d\Omega)_{\text{el}}$ for different energies (for $r_c = 0.5$ fm). The data in Fig. 10 are from Eisenhandler et al.¹⁸⁾. The curves in Fig. 11 also reproduce the data. In Figs. 8, 9 and 10 one can see the strong dependence of $d\sigma/d\Omega$ (backward) on the boundary radius r_c . Notice also that the forward slope of $d\sigma/d\Omega$ in Fig. 10 does not depend strongly on the annihilation radius r_c . It is evident from Fig. 11 that even at small energies, $T_{\text{lab}} = 50$ MeV, many partial waves contribute to $d\sigma/d\Omega$. Therefore, if one has a resonance in one partial wave this will only have a minor effect on the total elastic cross-section. (The other partial waves will give most of σ_{el} .)

What happens to the OBEP resonances in this model? The annihilation boundary is at a large radius ($r_c \approx 0.5$ fm) compared to the nucleon Compton wavelength, and since the annihilation acts at $r_c = 0.5$ fm in all $\bar{N}\bar{N}$ partial waves, no resonance survives. However, we¹³⁾ know that, for example, for D-waves the OBEP plus the centrifugal barrier becomes repulsive for $r \approx 0.4$ fm. Thus, if in a more realistic model $\text{OBEP} + \ell(\ell + 1)/r^2$ can become repulsive in certain $\bar{N}\bar{N}$ partial waves for $r > r_c$ (the annihilation boundary), then the annihilation region will be sheltered by a repulsive potential and the corresponding resonance (with given LSJT) will survive. Since very little is understood about annihilation I will cut short any speculations, but say that a few OBEP resonances might have a chance of surviving the annihilation. It should be noted that this last statement is not accepted by Shapiro et al. who, as mentioned earlier, think that they can treat annihilation in a perturbative sense.

Fig. 7 Data from Ref. 17 (Brückner et al.)

Fig. 8 Differential cross-section for $\bar{p}p \rightarrow \bar{n}n$ in c.m. versus $\cos \theta$ for $p_{lab} = 0.536$ GeV/c for different annihilation boundaries r_c .

Fig. 9 Same as Fig. 8, but for $p_{lab} = 0.662$ GeV/c.

Fig. 10 The elastic differential cross-section $d\sigma/d\Omega$ for $\Lambda = 980$ MeV and different r_c . The fully drawn line is for $P_{lab} = 0.73$ GeV/c and $r_c = 0.5$ fm. The other lines are for $P_{lab} = 0.66$ GeV/c and different r_c . The experimental data are from Ref. 18 and their $P_{lab} = 0.69$ GeV/c.

Fig. 11 The elastic differential cross-section $d\sigma/d\Omega$ for $\Lambda = 980$ MeV and $r_c = 0.5$ fm for different values of P_{lab}

Before I conclude, let me sketch the arguments of the dual-quark model leading to predictions of low-energy $\bar{p}p$ resonances.

3. THE DUAL-QUARK MODEL AND BARYONIUM

The dual-quark model has had some successes with the mesons ($q\bar{q}$), but as soon as baryons (qqq) were introduced there were problems¹⁹⁾ to face. Before I present the argument concerning baryonium, I shall briefly illustrate the dual-quark model (DQM) arguments as applied to mesons.

Usually one assumes that, for example, $\Phi(1040)$ consists mainly of strange-antistrange ($s\bar{s}$) quarks and π and ρ consist mainly of up and down quarks. In addition one has the Zweig rule which says that, for example, Φ does not like to decay into $\rho\pi$. These rules can be understood with the assumption of the dominance of dual, planar diagrams. In Fig. 12a is shown the allowed Φ decay into $K\bar{K}$ and in Fig. 12b the forbidden decay of Φ into $\rho\pi$ in terms of quark lines.

Fig. 12a Planar diagram for Φ decay

Fig. 12b Illustration of a non-planar diagram for forbidden Φ decay

The diagram in Fig. 12b is disconnected and therefore not allowed according to the Zweig rule. Further we describe $\pi\pi$ scattering by Fig. 13a which can be looked at either in the s-channel, Fig. 13b, producing a $\pi\pi$ resonance, for example ρ , or in the t-channel, Fig. 13c, giving, for example, a ρ exchange. This is in the dual-quark language the same diagram looked at in two different projections.

Fig. 13 Dual-quark diagram for $\pi\pi$ scattering

Fig. 14 Examples of mesons and baryons from quarks as discussed in the text

The mesons themselves can be thought of as a quark and an anti-quark held together by all possible gluon exchanges, which in Fig. 14a is represented by a string between q and $\bar{q}$. A baryon has three quarks and, according to gauge-invariance arguments by Rossi and Veneziano⁵⁾, the strings representing gluon exchanges between the quarks must be connected in a junction, Fig. 14b. If one freezes one degree of freedom in the baryon, Fig. 14b, one arrives at the quark-antiquark picture of baryons, Fig. 14c, suggested by Lichtenberg²⁰⁾. The justification is that only the $SU(6)$ 56-plet (with even L) and 70-plet (with odd L) are seen.

This quark-antiquark system was recently applied to $B\bar{B}$ scattering by Rosenzweig²¹⁾ and Chew⁴⁾. In analogy to Fig. 13b for $\pi\pi$ scattering, we can draw planar, dual diagrams for $B\bar{B}$ scattering -- see Fig. 15a. We find in the s -channel $Q\bar{Q}$ states, called baryonium by Chew⁴⁾. Using the fact that Q can have spin 1 and isospin 1 and that they have relative angular momentum ℓ , Chew finds the possible quantum numbers for the $Q\bar{Q}$ states as in $q\bar{q}$. He then draws Regge trajectories and the leading one is the dashed-dotted line in Figs. 3 and 4 with intercept $-1/2$. The $Q\bar{Q}$ states do not like to decay into mesons, since one will then have a disconnected diagram, Fig. 15c, analogous to Fig. 12b. Therefore baryonium should be narrow. Unfortunately, this is not a dynamical theory, and nothing is known about $Q\bar{Q}$ coupling to mesons other than the rule of the dominance of planar diagrams taken over from mesons.

Fig. 15 Dual diagrams of $B\bar{B}$ scattering. In (c) is shown the coupling of $Q\bar{Q}$ to ordinary mesons via a non-planar diagram.

To go one step further, I will discuss the Rossi and Veneziano approach to baryonium. In Fig. 14b one sees that the baryon is a planar object. To describe $B\bar{B}$ scattering I will draw the quark diagrams in three dimensions. There are three diagrams plus three more because of $B\bar{B}$ crossing. In Figs. 16a, b and c three s-channel $B\bar{B}$ scattering diagrams are shown in two projections, where on the r.h.s. are shown the projections along the cuts A, B and C of the l.h.s. diagram. The diagram in Fig. 16a gives the s-channel resonance M_4^J ($J = \text{junction}$)⁵⁾, which corresponds roughly to the $Q\bar{Q}$ states of Chew⁴⁾. The s-channel resonance M_2^J in Fig. 16b contains $q\bar{q}$ with two junctions and M_0^J in Fig. 16c is just a gluon ball.

To find the Regge trajectories for these three objects one can look at the diagram of Fig. 16a in the t-channel projection, Fig. 16d. In Fig. 16d the s-channel intermediate state represents $B\bar{B}$ annihilation into a single $q\bar{q}$ meson plane. At high energies this ladder graph is controlled by Regge exchange of M_4^J . Using arguments from a simple multiperipheral-like model on Fig. 16d, Rossi and Veneziano find the intercept of M_4^J to be

$$\alpha_4^J(0) = 2\alpha_B(0) - 1 + (1 - \alpha_R) = -1/2 \quad (7a)$$

since $\alpha_R = 1/2$ and $\alpha_B = 0$. They⁵⁾ find for M_2^J and M_0^J

$$\alpha_2^J(0) = 2\alpha_B(0) - 1 + 2(1 - \alpha_R) = 0 \quad (7b)$$

$$\alpha_0^J(0) = 2\alpha_B(0) - 1 + 3(1 - \alpha_R) = 1/2 \quad (7c)$$

To get the slopes Rossi and Veneziano use arguments from a multiperipheral chain model. Since (for example) Fig. 16d has $q\bar{q}$ as an intermediate state (as does Fig. 13), they find that M_4^J has the same slope as the normal meson (ρ , A_2 , ...) trajectory. Their results are shown in Fig. 17, where I have placed S(1936) in a possible position as a star.

Why are these resonances narrow? This is because their junction has to be conserved, for example, M_4^J will not decay easily into mesons, because they do not contain the junction. This means that they⁵⁾ propose a new Zweig rule, illustrated in Fig. 16e, where the r.h.s. does not contain a junction, and therefore is "disconnected" like Fig. 12b or Fig. 15c. Not very much is understood about Zweig rule breaking, and the new Zweig rule for baryonium is only a proposal. The dual models for baryons are based on very rough arguments, which do nevertheless result in Regge trajectories. As yet, no explicit calculation has been made to substantiate these arguments.

Fig. 16 Dual quark diagrams for $B\bar{B}$ scattering. The dashed line in the l.h.s. diagrams is the junction which in the r.h.s. diagrams is denoted by a dashed circle.