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THE NUCLEON-ANTINUCLEON INTERACTION

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I. Introduction

The main experimental features of the nucleon-antinucleon interaction are as yet not completely clear but enough is known to have stimulated already a good deal of theoretical speculation and some calculation. I want today to review this rather new subject and to report in particular on some calculations recently carried out at Berkeley.

To begin the review, the fact that total cross sections of complex nuclei for antinucleons are substantially larger than those for nucleons has by now been quantitatively understood in terms of the elementary $\Lambda\Lambda$ cross sections, which are several times larger than the $NN$. Glassgold, for example, has used the observed $pp$ total cross sections to calculate, from the optical model, the total cross sections for complex nuclei ranging from Be to Pb. Using the nuclear density distribution that emerges from optical model analyses of proton scattering he successfully reproduces the observed antiproton cross sections. The increase in effective nuclear size is of course due to the outer fringe, which is transparent for nucleons but opaque for antinucleons. Calculations essentially equivalent to those of Glassgold have been carried out in several laboratories, all with the same result.

We may concentrate our attention, then, on the elementary $\Lambda\Lambda$ interaction. I should say at once that in addition to the rather large total cross sections there is some evidence, at 450 MeV due to
Chamberlain, Segre, Ypsilantis, et al., that as much as 80% of this cross section may be annihilation, with only a small fraction elastic scattering. The evidence here is weak, however, being based on subtraction arguments, and at lower energies photographic emulsion observations suggest a "normal" amount of elastic scattering, i.e. about half of the total. (Seven scatterings in the energy range between 40 and 200 Mev, observed by Goldhaber, Kalogeropoulos and Silberberg, correspond to an average elastic cross section of 75 mb.)

Nothing is known yet about what happens at very low (less than 10 Mev) or very high (greater than 1 Bev) energies. Evidence on slow antiprotons is just now being accumulated in a bubble chamber experiment at Berkeley.

II. Survey of Nucleon Structure

It has been possible to understand many properties of the nucleon in terms of the Yukawa hypothesis that the nucleon is a source of the $\pi$-meson field in the same sense that a charged particle is a source of electromagnetic field. The Yukawa picture of the physical nucleon divides itself roughly into three regions:

1. An outer "fringe" at distances $\gg \frac{h}{m_{\pi}c}$ where virtual $P$-wave pions occur in a well defined distribution, with a strength characterized entirely by the pion-nucleon coupling constant, $f^2 = 0.08 \pm 0.01$. General considerations—such as conservation laws and the uncertainty principle—give us confidence that we understand this region. If the pion is indeed the lightest particle which interacts strongly with the nucleon then it must dominate the outer parts of the nucleon structure; and if we believe that strong interactions conserve parity and isotopic spin and are essentially local in nature, then the distribution of virtual pions at large distances is determined entirely by symmetry considerations. Experiments on the long
range parts of the nucleon-nucleon force and on the zero energy limits of pion-nucleon scattering and photo-pion production give quantitative confirmation of these conclusions. By any ordinary standards, then, we can claim to have a rather complete understanding of the "fringe" of the nucleon.

(2) The intermediate structure of the nucleon, at distances \( \frac{h}{m_{\pi}c} \) but greater than \( \frac{h}{2mc} \), is by no means completely understood but it seems still to be dominated by P-wave virtual pions. The cut-off version of the Yukawa theory, which includes only P-wave pions, has had semi-quantitative success in describing this intermediate region. That is to say, it gives a rough understanding of the well-known \((\frac{3}{2}, \frac{3}{2})\) resonance in the pion-nucleon system, which occurs at a pion wavelength \( \sim \frac{1}{2} \frac{h}{m_{\pi}c} \), and the theory also seems to give a nucleon-nucleon force at intermediate distances which is remarkably close to that required by experiment. When you add the fact that the anomalous nucleon magnetic moments are rather well understood in terms of this purely P-wave pion cloud, one concludes that a good deal is known, at least empirically, about the intermediate structure of the nucleon.

(3) Finally there is the "core" of the nucleon, the structure at distances smaller than the nucleon Compton wavelength \( 2.1 \times 10^{-14} \) cm. Almost nothing is understood about this region theoretically although we expect it to contain virtual strange particles and antinucleons. Empirically it gives rise to a strong repulsive force between two nucleons, the famous "hard core" of the potential.

An admittedly loose screw in this model is the very small neutron-electron interaction. The intermediate range P-wave pion cloud gives an
interaction many times larger than that observed, so some unknown component in the nucleon structure must be cancelling it. I do not think, however, that this difficulty, standing alone, is sufficient cause to abandon the Yukawa approach.

III. Application to Antinucleons. General Considerations

What relevance do these considerations have to antinucleons? Well, if the principle of charge conjugation means what we think it does, the above picture of the nucleon leads us to just as complete a picture of the antinucleon. Every virtual pion in the fringe and intermediate region is simply to be replaced by the corresponding antipion. The point I am trying to make is that if we claim to understand the nucleon-nucleon interaction at large and intermediate distances in terms of the corresponding portions of the pion cloud, then we understand exactly as much about the nucleon-antinucleon interaction. We are not in the position of being able to plead ignorance about the "mysterious" antinucleon. We cannot make ad-hoc assumptions about the $\overline{NN}$ interaction at large and intermediate distances without the danger of doing violence to well established principles.

In particular, the 450 Mev experimental indication of a very large ratio of annihilation to scattering has led to models for the interaction in which some "influence," capable of annihilation, extends to distances even greater than a pion Compton wavelength. It may be that such an influence exists, but we should realize that it does not follow from the field theory which has been successfully used to describe other properties of nucleons.
The magnitude of the $N\bar{N}$ total cross section in itself does not imply that anything beyond the conventional Yukawa interaction mechanism is involved. A classical impact parameter equal to the pion Compton wavelength corresponds to a total cross section of 130 mb. Thus the astonishing fact, if there is one, is that $nn$ and $pp$ cross sections are so small, not that $\bar{p}p$ cross sections are so large.

The usual theoretical description of the $NN$ interaction differs according to the region of structure involved. At large separations, where singly occurring fringe pions are dominant, the potential energy is exactly given by

$$V_{1N} = r^2 \tilde{r}_1 \cdot \tilde{r}_2 \hat{e}_1 \cdot \hat{e}_2 \frac{e^2}{r}$$

where $r^2 = 0.08$ and the length unit is the pion Compton wavelength $(\frac{\hbar}{m_p c} = 1.4 \times 10^{-13}$ cm$)$). Since the pionic charge of the antinucleon is the opposite of that for the nucleon, this part of the interaction simply reverses sign in the $N\bar{N}$ system.

At intermediate distances double pion exchange becomes important, and these contributions have the same magnitude and sign in both $NN$ and $N\bar{N}$ systems. (As a general rule, terms due to exchange of an odd number of pions reverse sign while those due to an even number do not.) Unfortunately no reliable expression exists for the interaction due to multiple pion exchange, and at intermediate distances there also are corrections to the single pion formula due to nucleon recoil. However if one tends to be optimistic there is reason to believe that the most important parts of the interaction at intermediate distances can be and have been calculated in terms of one and two-pion exchange. Thus we are in a position to construct, at least roughly, the $N\bar{N}$ interaction potential, except in the region of the core.
It is for the core that we must make an assumption. We can be guided by two facts, one theoretical and one experimental. (1) In terms of Feynman diagrams there are two distinct contributors to the $\bar{N}N$ interaction. First there are the diagrams in which pions are exchanged:

These are in one-to-one correspondence with diagrams for the $NN$ interaction and are represented by the long and intermediate range potential discussed previously. Second there are the virtual annihilation diagrams:

These diagrams correspond to an interaction whose range is the nucleon Compton wavelength and they reflect the possibility of true annihilation with the production of real pions. (2) The second fact of significance is the large average number of pions experimentally observed in $\bar{N}N$ annihilation. This number is about equal to 5.

Putting these two facts together suggests that the very short range part of the $\bar{N}N$ interaction should be represented not by a hard core but by a black hole. That is to say, once the cores of $N$ and $\bar{N}$ touch, annihilation
is inevitable. If virtual pions are formed, there are so many that the chance of all being reabsorbed to lead back to the NN system is negligible.

Before describing the detailed quantum treatment of this model let me emphasize its classical significance. We have a small black hole, surrounded sometimes by a repulsive "wall" and sometimes by an attractive "wall".

Both situations occur because the nuclear force has a strong spin dependence and may be either attractive or repulsive depending on how the spins are oriented.

The cross section is clearly determined by the outer potential. With a repulsion one usually gets elastic scattering, unless the kinetic energy overcomes the barrier. With an attraction one sometimes gets scattering, but the lower angular momentum collisions may lead to a spiraling in, followed by absorption, that is to say, annihilation. The exact size of the black hole is clearly not important.

IV. The Quantum Mechanical Calculation. WKB Approximation.

James Ball and I undertook to make a calculation of the nucleon-antinucleon scattering and absorption cross sections on the basis of these ideas. We have used the WKB approximation, having verified that the errors thereby introduced are not serious at energies of the order of 100 MeV or greater. Mr. Ball is at present engaged in a study of the low energy
problem, where the WKB approximation cannot be used. I shall however not discuss here this very recent work.

The WKB approximation maintains the attractive feature of the classical limit that the exact position of the annihilation boundary does not matter. Characteristically the sum of the outer NN potential and the centrifugal barrier for a particular eigenstate has one or the other of the shapes shown here. In the first case the potential is repulsive, or if attractive, is too weak to overcome the centrifugal term. Except at high energies the penetration through such a barrier is so small that the annihilation region might as well not be there. At most one gets a negative real phase shift that is determined by the outer part of the potential.

In the second case, where the potential is strongly attractive, the problem from the WKB point of view is that of penetrating or going over the top of a barrier with some reflection from the outside surface. Once part of the wave is over or through one doesn't care how far in it travels before being absorbed. A more precise and complete statement of this principle is that the form of the interaction inside the turning point closest to the origin is unimportant. The WKB approach thus shows that rather little understanding of what happens at small distances is required to perform a plausible calculation of the NN interaction at intermediate energies. Ironically one is better off than with the NN system where the radius of the repulsive core is extremely important, as is the behavior of the potential immediately outside the core.

The maximum orbital angular momentum, for which the centrifugal barrier can be overcome at intermediate distances \((r \sim 1)\) by the Yukawa interaction, seems to be \(l = 2\). A criterion for the validity of the theory presented here, therefore, is that the important annihilations shall
occur in S, P, or D waves but not for higher $\ell$ values. If one is at such energy that absorption occurs through high angular-momentum barriers which continue to rise right to the annihilation boundary, it is clear that the nature of this boundary and the details of the Yukawa interaction in its neighborhood are important. In practice the restriction to $\ell \leq 2$ limits our discussion to laboratory energies less than about 200 Mev. The second slide shows a typical potential for $\ell = 3$. Clearly, in the neighborhood of 400-500 Mev, the detailed nature of the annihilation boundary will be important.

Another great advantage of the WKB approximation is its simplification of the very complicated tensor force problem. As pointed out originally by Christian and Hart, one is led naturally to "effective central potentials" which act in each eigenstate separately.

Our program, then, was to calculate for each of the 20 eigenstates with $\ell \leq 2$ an effective central potential, and then we computed for each state the probability of the wave penetrating to the annihilation boundary and the real phase shift. The penetration coefficients lead immediately to annihilation cross sections, and the scattering cross sections are obtained from a combination of penetration coefficients and phase shifts.

V. The GSM and KMO Potentials

The first potential to be considered was that of Gartenhaus, with the spin orbit term added by Signell and Marshak. The reasons for this choice are: (1) The GSM potential has the correct asymptotic form; (2) At intermediate distances it is not in conflict with meson theoretical ideas, although it cannot really be said to be "derived" therefrom; and
(3) It gives quantitative agreement with NN experiments up to 150-Mev lab energy.

We simply reversed the sign of the single-pion exchange part of the GSM potential and left the remainder untouched. To the extent that the remainder is due to two-pion exchange, this recipe is theoretically sound. Of course the spin-orbit term is phenomenological and of unknown origin, so our handling of this particular part is open to question. The results are as follows for a lab energy of 140 Mev:

| System | $\sigma_{abs}$ | $\sigma_{sc}$ | $\sigma_{total}$ |
|--------|----------------|---------------|-----------------|
| $\bar{p}p$ | 69             | 63 + 22       | 154             |
| $\bar{n}p$ | 69             | 79            | 148             |

These may be compared to the results given by Signell and Marshak for the NN system:

$\bar{p}p$  
$\bar{n}p$

29

60

These results, by the way, are in agreement with experiment.

What is the underlying reason for the small NN cross sections? First of all the S phase shifts of the NN system are anomalously small because of a kind of "Ramsauer effect," a cancellation of the effect of the repulsive core against an attractive outside region. The $\bar{NN}$ system, with the repulsive core replaced by a black hole makes full use of the outside potential. A somewhat similar phenomenon occurs in the $P$ states where the NN system a repulsive long range one-pion potential tends to counteract a short range attractive two-pion potential. The reversal of
sign of the one-pion part in the $NN$ system removes this cancellation, giving a strong overall attraction that accounts for a large part of the total plane-wave cross section.

We have also made calculations with a purely meson-theoretical potential due to Komma, Miyazawa and Otsuki. The results are very similar to those obtained from GSM.

VI. Comparison with Experiment. Conclusion.

This leads me to the comparison with experiment. In the limited range where the present theory makes contact with experiment the agreement is satisfactory. At 190 Mev, Lambertson, Cork, Piccioni and Wenzel have found a total $pp$ cross section of $136 \pm 16$ mb, whereas theory predicts for this energy an absorption cross section of $\sim 55$ mb and a slightly larger scattering cross section. As mentioned earlier, in the energy range between 40 and 200 Mev, emulsion experiments give an average elastic $pp$ scattering cross section of $75^{+50}_{-32}$ mb. Unfortunately at the only energy (450 Mev) where both scattering and absorption measurements are currently available, partial waves higher than $l = 2$ play a large role, and the approach described here is not valid.

Since the theory of the short range parts of the Yukawa interaction promises to be extremely difficult, whereas that for intermediate distances may be under control in the foreseeable future, experimental emphasis on energies below 150 Mev seems desirable. It will be particularly interesting to see if "bumps" that can be identified with individual partial waves are observed in the cross section vs. energy curve. As our understanding of the Yukawa interaction in the intermediate region becomes more refined, it might be possible to use the position and magnitude of such peculiarities to check the details of the theory.
A final word about what to expect at very high energies, i.e., in the multi-Bev range. It is very hard to see how the concepts I have discussed today can lead to large annihilation cross sections in this region of energy. We have been depending on the pion cloud to deflect the antimucleons inward so that they bang into the nucleon core and are annihilated. But for antiprotons in the Bev range the pion cloud cannot do much deflecting. Fringe collisions will lead only to multiple meson production and the annihilation cross section should shrink to the size of the black hole that we have been talking about. Exactly what this size is we do not know but it must be closer to 10 than to 60 mb.

Models of the NN interaction with an extended region of annihilation should of course continue to yield large annihilation cross sections even at high energies. Also at low and intermediate energies they should not lead to irregularities in the cross section vs. energy such as I have described here. There should be no difficulty, therefore, in deciding between these two theoretical approaches once sufficient data is accumulated.
