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Isospin Flip as a Relativistic Effect: $\bar{N}N$ Interactions

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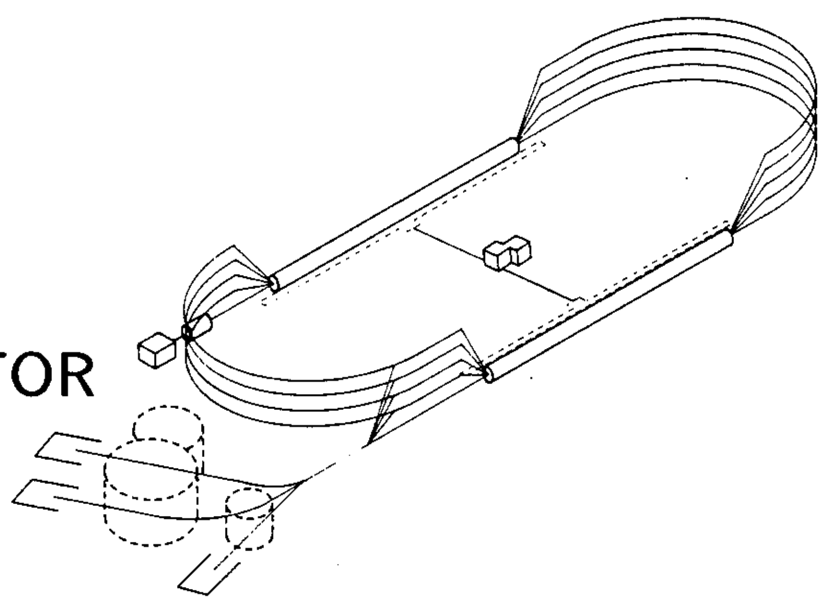

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Abstract

Results are presented of an analytic relativistic calculation of a OBE nucleon-nucleon (NN) interaction employing the Gross equation. The calculation consists of a non-relativistic reduction that keeps the negative energy states. The result is compared to purely non-relativistic OBEP results and the relativistic effects are separated out. One finds that the resulting relativistic effects are expressable as a power series in $\tau_1 \cdot \tau_2$ that agrees, qualitatively, with NN scattering. Upon G-parity transforming this NN potential, one obtains, qualitatively, a short range $\bar{N}N$ spectroscopy in which the S-states are the lowest states.

In the quest to understand short range nuclear forces, many nuclear theorists have embraced QCD and have made progress toward extracting the roles that quarks play. This approach is further fed by the observation that traditional non-relativistic meson exchange models have difficulty providing any new information on these short range forces. In this paper, new results for the short range interactions are presented that arise from a relativistic view of the N-N interaction that contains negative energy states. Preliminary and partial results were presented earlier.[1] This relativistic approach is not new; it was introduced by Gross in 1974.[2] In this present work, that pioneering work is revisited and expanded upon in such a way as to provide further insight into the nature of the short range forces harboured in the relativistic wave equation. It will be shown that, for the One Boson Exchange Potential considered, the short range contribution can be expressed as a power series in $\tau_1 \cdot \tau_2$, the Nucleon-Nucleon isospin operator. This short range contribution is interpreted as a relativistic effect and is a direct result of coupling to negative energy states. It will further be shown that, as a consequence of this relativistic effect, the G-parity transformation of the elastic NN potential[3] gives rise to a new level ordering prediction, at short ranges, for the Antinucleon-Nucleon ($\bar{N}N$) interaction. The final result of the analytic work presented below is a qualitative description of the (NN and $\bar{N}N$) interactions, as no numerical values for the exchanged mesons' masses or coupling constants are employed. A word of caution is needed, however; the NN interaction as presented in this paper is not antisymmetrized. The impact that this may have on the short range NN contributions presented here is uncertain; however, it is assumed that antisymmetrization does not apply to $\bar{N}N$.

The starting point is the Gross equation[2] for the NN system written as:

$$(\tilde{\Gamma}C)_{\mu\nu}(\hat{p}) = -\int \frac{d^3k}{(2\pi)^3} V_{\mu\mu',\nu\nu'}(\hat{p},\hat{k},W) G_{\mu'\mu'',\nu'\nu''}(\hat{k},W)(\tilde{\Gamma}C)_{\mu''\nu''}(\vec{k}) \tag{1}$$

where

$$\begin{aligned}
\text{total 4} - \text{momentum} = P = (W,\vec{0}); \qquad W &= \text{total rest mass} \\
G_{\mu'\mu'',\nu'\nu''}(\vec{k},W) &= \frac{[M + \frac{\not{P}}{2} + \not{k}]_{\mu'\mu''}[M + \frac{\not{P}}{2} - \not{k}]_{\nu'\nu''}}{2E_k W(2E_k - W)} \\
\hat{k} &= (\hat{k}_o,\vec{k}); \hat{p} = (\hat{p}_o,\vec{p}\,) \\
\hat{k}_o &= E_k - \frac{W}{2}; \hat{p}_o = E_p - \frac{W}{2} \\
E_k^2 &= M^2 + \vec{k}^{\,2}, M = \text{nucleon mass}
\end{aligned} \tag{2}$$

$\tilde{\Gamma}$ is the covariant two body vertex function that is state dependent, and C is the charge conjugation matrix. To facilitate making a non-relativistic reduction in order to expose the analytic structure of the interaction, it is useful to write

$$\left[m + \frac{\not P}{2} + \not k\right]_{\mu'\mu''} = 2M\left(\frac{W}{2E_k}\right) u_{\mu'}^{(s)}(\vec{k}\,)\bar{u}_{\mu''}^{(s)}(\vec{k}\,) - 2M\left(\frac{2E_k - W}{2E_k}\right)$$
$$\times\, v_{\mu'}^{(s)}(-\vec{k}\,)\bar{v}_{\mu''}^{(s)}(-\vec{k}\,) \tag{3}$$

By introducing

$$\psi_{rs}^{+}(\vec{p}) = \frac{M}{[2W(2\pi)^3]^{\frac{1}{2}}} \quad \frac{\bar{u}_{\mu}^{(r)}(\vec{p})\bar{u}_{\nu}^{(-s)}(-\vec{p})\tilde{\Gamma}C)_{\mu\nu}(\hat{p})}{E_p(2E_p - W)} \tag{4a}$$

$$\psi_{rs}^{-}(\vec{p}) = \frac{-M}{[2W(2\pi)^3]^{\frac{1}{2}}} \quad \frac{\bar{u}_{\mu}^{(r)}(\vec{p})\bar{v}_{\nu}^{(-s)}(\vec{p})(\tilde{\Gamma}C)_{\mu\nu}(\hat{p})}{E_p W} \tag{4b}$$

where ψ^+ and ψ^- are the positive and negative energy momentum space wave functions respectively, the following set of coupled equations can be extracted:

$$(2E_p - W)\psi_{rs}^{+}(\vec{p}) = -\int \frac{d^3k}{(2\pi)^3}\left\{V^{++}\psi_{r's'}^{+}(\vec{k}\,) + V^{+-}\psi_{r's'}^{-}(\vec{k})\right\} \tag{5}$$

$$-W\psi_{rs}^{-}(\vec{p}) = -\int \frac{d^3k}{(2\pi)^3}\left\{V^{-+}\psi_{r's'}^{+}(\vec{k}) + V_{r's'}^{--}\psi_{r's'}^{-}(\vec{k}\,)\right\} \tag{6}$$

The V^{++},V^{+-},V^{-+}, and V^{--} are related to the one particle on the mass shell interaction kernels $V_{\mu\mu'\nu\nu'}$ by:

$$V^{++} = \frac{M^2}{E_k E_p}\bar{u}_{\mu}^{(r)}(\vec{p}\,)\bar{u}_{\nu}^{(s)}(-\vec{p}\,)V_{\mu\mu',\nu\nu'}u_{\mu'}^{(r')}(\vec{k}\,)u_{\nu'}^{(s')}(-\vec{k}\,) \tag{7}$$

$$V^{+-} = \frac{M^2}{E_k E_p}\bar{u}_{\mu}^{(r)}(\vec{p}\,)\bar{u}_{\nu}^{(s)}(-\vec{p}\,)V_{\mu\mu',\nu\nu'}u^{(r)'}(\vec{k}\,)v_{\nu'}^{(s')}(\vec{k}\,) \tag{8}$$

$$V^{-+} = \frac{M^2}{E_k E_p}\bar{u}_{\mu}^{(r)}(\vec{p}\,)\bar{v}_{\nu}^{(-s)}(\vec{p}\,)V_{\mu\mu',\nu\nu'}u_{\mu'}^{(r')}(\vec{k}\,)u_{\nu'}^{(s')}(-\vec{k}) \tag{9}$$

$$V^{--} = \frac{M^2}{E_k E_p}\bar{u}_{\mu}^{(r)}(\vec{p}\,)\bar{v}_{\nu}^{(-s)}(\vec{p}\,)V_{\mu\mu',\nu\nu'}u_{\mu'}^{(r'}(\vec{k}\,)v_{\nu'}^{(-s')}(\vec{k}\,) \tag{10}$$

Of course, the non-antisymmetrized $V_{\mu\mu',\nu\nu'}$ represent meson exchanges and, as is customary, these interactions will be approximated by single boson exchanges; namely, π, σ, ρ, and ω. One notes that there is no concern at present for the numerical values of the masses and coupling constants of these bosons. Thus there is no concern that the interaction not reproduce the NN phases, effective ranges, etc. One quite simply wants to compare qualitative features of the relativistic interaction to that of the non-relativistic interaction. This is performed by, essentially, subtracting the non-relativistic interaction from the relativistic interaction presented here. That is, the limit as $r \rightarrow 0$ is taken. What remains from this procedure is what one considers the relativistic effect or simply, the interaction difference. To arrive at results that can be treated analytically, a non-relativistic reduction is performed that keeps the negative energy states. Having stated this, one continues with the calculation.

Employing expansion approximations such as $\frac{(E_p+M)(E_k+M)}{E_k E_p} \approx 4$ and $\frac{(E_p+M)(E_k+M)}{M^2} \approx 4$ with $(E_p+M)^{-1}(E_k+M)^{-1} = \frac{1}{4M^2}(1-\frac{p^2}{4M^2}-\frac{k^2}{4M^2}+-\cdots)$. After quite a bit of algebra, equation 5 is reduced to

$$\left[\frac{p^2}{M}-\frac{p^4}{4M^3}-\varepsilon\right]\psi^+_{rs}(\vec{p}\,) \approx g_\sigma^2 \int \frac{d^3}{(2\pi)^3}\frac{1}{(m_\sigma^2+q^2)}$$
$$\times\left\{1-\frac{1}{4M^2}\left[2i\vec{s}\bullet(2\vec{q}x\vec{k}\,)+2\vec{k}^{\,2}\right]\psi^+_{r's'}(\vec{k}\,)+\frac{\vec{\sigma}_2}{2M}\bullet(2\vec{k}-\vec{q}\,)\psi^-_{r's'}(\vec{k}\,)\right\} \quad (11)$$

for the sigma exchange only. Equation 11 is the result of keeping the lowest order of $\frac{v}{c}$ or $\frac{p}{M}$ compared to the leading term. Equation 11 as well as the other boson exchange contributions can now be Fourier Transformed to configuration space. (Similarly treated is equation 6.) The motivation for going to configuration space is the ease in which non-relativistic and relativistic contributions can be compared. Traditionally, non-relativistic potentials are always presented in position space. Keeping in mind that we seek only qualitative comparisons, we then transform our momentum space reduction into position space.

The resulting configuration space coupled equations are written:

$$-\left(\frac{\nabla^2}{M}+\frac{\nabla^4}{4M^3}+\varepsilon\right)\psi^+(\vec{r}\,) = -V^{++}(\vec{r}\,)\psi^+(\vec{r}\,)-V^{+-}(\vec{r}\,)\psi^-(\vec{r}\,) \quad (12)$$

$$-2M\psi^-(\vec{r}\,) = -V^{-+}(\vec{r}\,)\psi^+(\vec{r}\,)-V^{--}(\vec{r}\,)\psi^-(\vec{r}\,) \quad (13)$$

The results of Equation 12 and 13 are not new. Gross presented these equations[2] without the quartic derivative operator.

The potentials V^{++}, V^{+-}, V^{-+}, and V^{--} are:

$$V^{++} = u_c+\sigma_1\bullet\sigma_2 u_{ss}+\widehat{S}_{12}u_T+\vec{L}\bullet\vec{S}i_{LS} \quad (14)$$

$$V^{+-} = \frac{i\vec{\sigma}_1\bullet\vec{r}}{r}\quad V_1^- + \frac{i\vec{\sigma}_2\bullet\vec{r}}{r}\quad V_2^- + \frac{\vec{r}\bullet\vec{\sigma}_1 X\vec{\sigma}_2}{2r}\quad V_3^- + i\vec{\sigma}_2\bullet\vec{\nabla}v_\ell \quad (15)$$

$$V^{-+} = \left(V^{+-}\right)^\dagger \quad (16)$$

$$V^{--} = V_o^\sigma\frac{\vec{L}\bullet\vec{S}}{Mr}\quad V_1^\sigma + V_o^\omega - \frac{\left(\frac{3}{2}+2k_\omega\right)}{Mr}\quad \vec{L}\bullet\vec{S}V_1^\omega$$
$$+\quad \tau_1\tau_2\left[\sigma_1\bullet\sigma_2 V_o^\pi+\widehat{S}_{12}V_2^\pi+V_o^\rho-\frac{\left(\frac{3}{2}+2k_\rho\right)}{Mr}\quad\vec{L}\bullet\vec{S}\quad V_1^\rho\right]$$
$$+\quad \textit{higher order terms} \quad (17)$$

where

$$
\begin{aligned}
u_c &= V_o^\sigma + V_o^\omega + \vec{\tau} \bullet \vec{\tau}_2 V_o^\rho \\
u_{ss} &= \tau_1 \bullet \tau_2 \left[V_o^\pi \frac{m_\rho^2}{6M^2} (1+k_\rho)^2 V_o^\rho \right] + \frac{m_\omega^2}{6M^2} (1+k_\omega)^2 V_o^\omega \\
u_T &= \tau_1 \bullet \tau_2 \left[V_2^\pi - \left(1+R_p\right)^2 \right] - (1+k_\omega)^2 V_2^\omega \\
u_{LS} &= -\frac{m_\pi}{Mx} \left[V_1^\sigma + (1.5+2k_\omega)\, V_1^\omega + \tau_1 \bullet \tau_2 (\left(1.5+2k_\rho\right) V_1^\rho \right]
\end{aligned}
\tag{18}
$$

and

$$
\begin{aligned}
x &= r m_\pi \\
V_1^- &= -\tau_1 \bullet \tau_2 V_1^\pi \\
V_2^- &= V_1^\sigma - \frac{1}{2} k_\omega V_1^\omega - \tau_1 \bullet \tau_2 \frac{k_\rho}{2} \quad V_1^\rho \\
V_3^- &= -\left(1+k_\omega\right) V_1^\omega - \tau_1 \bullet \tau_2 \left(1+k_\rho\right) V_1^\rho \\
v_\ell &= \frac{1}{M} \left[V_o^\sigma + V_o^\omega + \tau_1 \bullet \tau_2 V_o^\rho \right] \\
V_o^\sigma(r) &= \frac{-g_\sigma^2}{4\pi} \quad m_\pi \quad \frac{e^{-\alpha x}}{x} \quad ; \quad \text{where } \alpha = \frac{m_\sigma}{m_\pi} \\
V_1^\sigma(r) &= \frac{g_\sigma^2}{4\pi} \quad \frac{m_\pi^2}{2M} \quad \frac{e^{-\alpha x}}{x} \quad \left(\alpha + \frac{1}{x} \right) \\
V_o^\pi(r) &= \frac{g_\pi^2}{4\pi} \quad \frac{m_\pi^3}{12M^2} \quad \frac{e^{-x}}{x} \\
V_1^\pi(r) &= \frac{\lambda g_\pi^2}{4\pi} \quad \frac{m_\pi^2}{2M} \left(1 + \frac{1}{x} \right) \frac{e^{-x}}{x} \\
V_2^\pi(r) &= \frac{g_\pi^2}{4\pi} \quad \frac{m_\pi^3}{12M^2} \left(1 + \frac{3}{x} + \frac{3}{x^2} \right) \frac{e^{-x}}{x} \\
V_o^{\rho,\omega}(r) &= \frac{g_{\rho,\omega}^2}{4\pi} \quad m_\pi \quad \frac{e^{-\rho x, \omega x}}{x} \quad ; \quad \rho = \frac{m_\rho}{m_\pi}; \quad \omega = \frac{m_\omega}{m_\pi} \\
V_1^{\rho,\omega}(r) &= \frac{g_{\rho,\omega}^2}{4\pi} \quad \frac{m_\pi^2}{M} \quad \frac{e^{-\rho' x}}{x} \left(\rho' + \frac{1}{x} \right); \quad \rho' = \rho \text{ or } \omega \\
V_2^{\rho,\omega}(r) &= \frac{g_\rho^2}{4\pi} \quad \frac{m_\pi^3}{12M^2} \quad \frac{e^{-\rho' x}}{x} \left(\rho^2 + \frac{3\rho' x}{x} + \frac{3}{x^2} \right)
\end{aligned}
\tag{19}
$$

These relations are well known[2] and one can verify them. The next step is to uncouple Equations 12 and 13 to obtain a single Schroedinger like equation. One finds that

$$
-\left(\frac{\nabla^2}{M} + \varepsilon \right) \psi^+(r) = -\left(V^{++} - V_R \right) \psi^+(r) \tag{20}
$$

where

$$V_R = \frac{\nabla^4}{4M^3} + V^{+-} \quad \frac{1}{2M\left(1 - \frac{V^{--}}{2M}\right)} \quad V^{-+} \tag{21}$$

This is the non-relativistic reduction to be examined. In all of the work that follows, V^{--} has been neglected. Thus

$$V_R = \frac{\nabla^4}{4M^3} \quad + \frac{|V^{+-}|^2}{2M} \tag{22}$$

One can show, through the employment of spin and angular momentum "aerobics" that equation 20 is equivalent to

$$-\left(\frac{\nabla^2}{M} + \varepsilon\right)\Phi = -\left(V_T - \frac{\nabla^4}{4M^3}\right)\Phi \tag{23}$$

where

$$\Phi = \left(1 + \frac{v_\ell^2}{2}\right) \tag{24}$$

and

$$V_T = V_c + \vec{\sigma}_1 \bullet \vec{\sigma}_2 V_{ss} + \widehat{S}_{12} V_{S12} + \vec{L} \bullet \vec{S} V_{LS} + \vec{L} \bullet \vec{D} V_{LD} \tag{25}$$

The V's are the same as those described in reference 2 and are a convoluted arrangement of π, ρ, σ, and ω potentials.

For the next phase of the calculation, one can proceed either from Equation 25 or from the potential found in Equation 21. Proceeding from the former choice, one finds after performing some algebra and keeping only the largest contributions as $r \to 0$:

$$\begin{aligned}
V_C &= a_c + b_c \tau_1 \bullet \tau_2 + c_c(\tau_1 \bullet \tau_2)^2 - a_c' - b_c' \tau_1 \bullet \tau_2 - c_c'(\tau_1 \bullet \tau_2)^2 \\
V_{LS} &= -a_{LS} - b_{LS}\tau_1 \bullet \tau_2 - c_{LS}(\tau_1 \bullet \tau_2)^2 \\
V_{S12} &= -a_{S12} - b_{S12}\tau_1 \bullet \tau_2 + c_{S12}(\tau_1 \bullet \tau_2)^2 \\
V_{ss} &= a_{ss} + b_{ss}\tau_1 \bullet \tau_2 + c_{ss}\tau_1 \bullet \tau_2)^2 \\
V_{LD} &= a_{LD} + b_{LD}\tau_1 \bullet \tau_2 + c_{LD}(\tau_1 \bullet \tau_2)^2
\end{aligned} \tag{26}$$

where the a's, b's and c's are positive definite and, to the leading term, are given by

$$\begin{array}{lll}
a_c = \frac{7}{8} F V_o^{\omega^2} & ; \; b_c = \frac{(12+3k_\rho)}{8F} V_o^\rho V_o^\omega & ; \; c_c = (4 + 3k_\rho + 3k_\rho^2)\frac{F}{8} V_o^{\rho^2} \\
a_c' = G V_o^{\omega^3} & ; \; b_c' = 3G V_o^\rho V_o^{\omega^2} & ; \; c_o' = 3G V_o^{\rho^2} V_o^\omega \\
a_{ss} = \frac{F}{3} V_o^{\omega^2} & ; \; b_{ss} = \frac{F}{6}(1 + 3k_\rho) V_o^\rho V_o^\omega & ; \; c_{ss} = \frac{F}{3} V_o^{\rho^2} \\
a_{LD} = 2F V_o^\sigma V_o^\omega & ; \; b_{LD} = F V_o^\omega V_o^\rho & ; \; c_{LD} = \frac{F}{2} V_o^{\rho^2} \\
a_{S12} = \frac{F}{3} V_o^{\omega^2} & ; \; b_{S12} = \frac{F}{6}(1 + 3k_\rho) V_o^\rho V_o^\omega & ; \; c_{S12} = \frac{F}{12}(3 + 2k_\rho) V_o^{\rho^2} \\
a_{LS} = F V_o^{\omega^2} & ; \; b_{LS} = 3F V_o^\omega V_o^\rho & ; \; c_{LS} = \frac{F}{2} V_o^{\rho^2}
\end{array} \tag{27}$$

and

$$F \equiv \frac{m_\pi^2}{M^3 x^2 \left(1+\frac{v_\ell^2}{2}\right)} \quad ; \quad G = \frac{m^2 x^2 F^2}{4 m_\pi^2} \quad ; \quad D_T = 1 + \frac{v_\ell^2}{2}$$

$$\begin{aligned} V_o^B &= \frac{g_B^2}{4\pi}\; m_\pi \;\frac{e^{-Bx}}{x} \quad ; \quad B = \sigma, \rho, \omega \\ \sigma &= \frac{m_\sigma}{m_\pi} \; ; \; \rho = \frac{m_\rho}{m_\pi} \quad ; \quad \omega = \frac{m_\omega}{m_\pi} \end{aligned} \tag{28}$$

One notes that in this limit the pion contributions can be neglected compared to the other terms. To obtain the $\overline{N}N$ potentials for small distances, one G-parity transforms the NN potentials of Equation 26. This effectively changes the sign of the omega coupling constant and, thus, changes the sign of the corresponding coefficients.

The final ingredients that we need before making concluding remarks are the spin matrix elements; all but $\vec{L} \bullet \vec{D}$ can be found elsewhere[3] and the $\vec{L} \bullet \vec{D}$ matrix elements are found in reference 2. For ${}^{33}P_o$ $\overline{N}N$, one finds $L = -2$, $\widehat{S}_{12} = -4$, $\sigma_1 \bullet \sigma_2 = 1$, and $\tau_1 \bullet \tau_2 = 1$. For ${}^{13}P_o$ $\overline{N}N$, one finds that only $\tau_1 \bullet \tau_2$ changes; $\tau_1 \bullet \tau_2 = -3$. Both of these $\overline{N}N\,{}^3P_o$ states have the same $\vec{L} \bullet \vec{D}$. Making the substitutions into Equation 25 gives the qualitative results that the ${}^{13}P_o$ potential lies higher than the ${}^{33}P_o$; a result in agreement with the numerical work of other researchers.[4]. Furthermore, through similar arguments, one finds that the ${}^{11}S_o$ $\overline{N}N$ lies lower than the ${}^{13}P_o$ $\overline{N}N$; an unexpected result. Finally, it is clear that all isoscalar $\overline{N}N$ potentials are more repulsive than their isovector counterparts. Hence, ${}^{11}S_o >{}^{31} S_o, {}^{11}P_1 >{}^{31} P_1, {}^{11}D_2 >{}^{31} D_2$, etc.

These qualitative results should be unaffected by a more complete interaction since it is well known that the omega meson exchange dominates the short range interaction. The omega meson exchange is included explicitly here. More complete interaction models should vary only in their quantitative results such as the amount of energy level shift. It is not clear if the results presented here will affect the $\overline{p}p$ Coulombic states widths. Although, theoretical approaches generally "cut-off" the $\overline{p}p$ interaction inside 1 fm, investigating how the relativistic effects affect Coulombic state widths is worth pursuing.

In conclusion, to obtain analytic results, the Gross equation was examined in a non-relativistic reduction of the NN interaction that keeps the negative energy states. The NN interaction was chosen to be a one boson exchange consisting of π, σ, ρ, and ω. The reduction was then applied to the real part of the $\overline{N}N$ interaction via G-parity. To get a qualitative feeling for what coupling to the negative energy states provides, a short distance limit was taken. One might expect that the difference between relativistic and non-relativistic theoretical descriptions would show up at short distance. This work finds that indeed that is the case; for the ${}^{11}S_o$ has a real $\overline{N}N$ potential that is more attractive than that of the ${}^{13}P_o$; a result rather different from reference 3. The fact that this is the case at very short distance for this work or any other work may be worrysome since annihilation was not taken into account. On the other hand, there is no conclusive evidence that annihilation contributes any more than giving the states widths. Furthermore, this "relativistic effect" may start to be evident at ranges as long as 0.4 fm in some channels. An effort is already underway to include annihilation in order to calculate cross sections and other effects. One final note is that the level orderings are directly related to the isospin coherences of Equations 26 and from a purely non-relativistic viewpoint this can be thought of as a result, in part, of adding the contribution of a Z graph.[5]

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