INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

NUCLEON-NUCLEON SCATTERING AND DIFFERENT MESON EXCHANGES

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ABSTRACT

The iterative and noniterative diagrams with different meson exchange are investigated. The $\pi$, $\eta$, and $\gamma$ meson exchange, (where $\alpha = \pi, \rho, \sigma, \omega, \eta$ and $\beta = \pi, \rho, \sigma$ and $\omega$; $\gamma = \pi$ and $\rho$), are considered. These diagrams are taken to involve the nucleon-nucleon, the nucleon-isobar and the isobar-isobar intermediate states. The diagrams are calculated in momentum space following the noncovariant perturbation theory. The role of each of these diagrams is examined by calculating its contribution to the nucleon-nucleon interaction. The potential model is taken to include one-boson-exchange terms in addition to these diagrams. The nucleon-nucleon scattering phase shifts are described successfully showing the importance of tensor force. The contributions of the different parts are studied in the nucleon-nucleon scattering.

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The nucleon-nucleon interaction is the fundamental input for calculations concerning nuclear structure and nucleon-nucleon scattering. The experimental measurements of the nucleon-nucleon phase shifts predict that the nucleon-nucleon interaction becomes strongly repulsive at short distances. Several attempts have been introduced to explain this phenomena. The most interesting understanding of the nature of these forces is that by the derivation of the nucleon-nucleon interactions from elementary processes as the meson exchanges and quark dynamics. All the results of calculations concerning nuclear reactions, nuclear structure and nuclear matter depend essentially on the realistic two-nucleon potential which is taken to fit the two-nucleon experimental data as the phase shifts of the nucleon-nucleon scattering and the nucleon-nucleon bound-state (the deuteron). Calculations of the empirical nuclear matter properties from the Brueckner-Hethe theory and using the soft core Reid potential show the importance of the tensor force. The Bonn potential which contains a smaller deuteron D-state probability than the Reid potential, yields more binding than the Reid potential for the infinite nuclear matter. The binding energies of light nuclei depend on the value of the deuteron D-state probability assigned by the potential model. The calculated binding energies increase strongly as well by increasing the density of the system. The calculated binding energy increases by decreasing the tensor force, with a very sensitive dependence on the amount of the tensor force contained in the nucleon-nucleon interaction. Thus, the tensor force is very important and is an essential quantity for calculating the binding energies of light nuclei. The amount of tensor force should be small in realistic nucleon-nucleon potentials to be able to describe few-body reactions. The binding energies of light nuclei can also be extracted effectively by using small tensor force. Therefore, the existence and contribution of the tensor force in the nucleon-nucleon interaction should be calculated as accurately as possible.

In the meson exchange theory, the one-pion-exchange gives most of the tensor force, especially the longer-range part. The shorter-range part, \(<2 \text{ fm}\), the tensor force of the one-pion-exchange is cut down because of the mechanism of the \(\rho\) meson exchange. So, additional tensor force contributions of short range are needed in order for nuclear calculations to be consistent for all densities. In the framework of the meson theory, these are obtained from the \(2\pi\) meson exchange which gives the intermediate-range attraction. Then, the effects from \(\sigma\) meson exchange should also be included since the \(\rho\) mass is large and the \(\rho\) interaction is therefore short-ranged. The two contributions of the \(\pi\) meson and \(\rho\) meson exchanges to the potential include vertex corrections and enter with opposite signs. The tensor force from the \(\rho\) meson exchange cuts off that from the \(\pi\) meson exchange at large separations. Then, the strong part of the nucleon-nucleon interaction is given by scalar-isoscalar \(\omega\) meson and \(\sigma\) meson exchange, while the weaker spin-isospin dependent interaction is taken into account in first order. The strong interaction in the scalar-isoscalar channel involves a cancellation between two large contributions, one of them is the repulsive part due to the \(\omega\) meson exchange and the other is the attractive part due to the\(\sigma\) meson exchange.

The nucleon-nucleon interaction has also been represented using one-boson-exchange models. In this representation, the intermediate-range attraction is described by a scalar isoscalar \(\sigma\) meson exchange. This contribution effectively gives the same contribution of the \((\sigma^2 = 0^+, I = 0)\) part of the whole \(2\pi\) meson exchange after subtracting the twice-iterated one-pion-exchange, which is included already in the scattering amplitude by iterating the one-pion-exchange potential. This contribution is obtained also from dispersion-theoretic methods by using empirical \(\pi\) nucleon and \(\pi\pi\) data and performing analytic continuation. The two methods consider this contribution only as a part of the nucleon-nucleon potential and treat it as a lowest-order contribution. Modifications due to Pauli and dispersion effects of the \(2\pi\) exchange in the medium is clear in a many-body theory. These modifications should be taken into account with the nucleon box diagram, treated as the second iteration of one-pion-exchange potential. These effects are very clear in many-body systems and nuclear matter. Therefore, an explicit description of the whole \(2\pi\) meson exchange contribution is required. The iterative isobar box diagram with both nucleon-isobar and isobar-isobar intermediate states, as well as the noniterative diagrams involving nucleon-nucleon, nucleon-isobar and isobar-isobar intermediate states in the \(2\pi\) meson exchange diagrams are evaluated. From these calculations, the noniterative diagrams are found as important as the iterative diagrams and cannot be neglected. In spite of the fact that there is strong cancellation between the single \(\pi\) meson and \(\rho\) meson exchange contributions to the nucleon-nucleon interaction, contributions from both \(\pi\pi\) meson and \(\pi\rho\) meson exchange should be considered. The \(\pi\pi\) meson exchange refers to the \(2\pi\) meson exchange, while the \(\pi\rho\) meson exchange belongs to the \(3\pi\) meson exchange. The iterative and noniterative
• \( \pi \rho \) meson exchange diagrams with nucleon-nucleon, nucleon-isobar and isobar-isobar intermediate states are evaluated \(^{19,20}\). The noniterative \( \pi \rho \) meson exchange with isobar-isobar intermediate states are small, while those with nucleon-isobar intermediate states are sizable and repulsive \(^{20}\) and such contributions replace a part of the contribution of the \( \omega \) meson exchange in the one-boson-exchange potentials. Also, the sum of contributions of \( \pi \pi \) meson and \( \pi \rho \) meson exchange replace \(^{21}\) the contribution of the \( \sigma \) meson exchange in simple one-boson-exchange models.

In the present work, the different meson exchanges in the nucleon-nucleon interaction are considered. Theoretical calculations of the \( \pi \), \( \pi \rho \), \( \rho \), \( \sigma \) and \( \omega \) meson exchanges are given. These different meson exchanges are investigated with iterative and noniterative diagrams. Calculations for these diagrams involving nucleon-nucleon, nucleon-isobar and isobar-isobar intermediate states are carried out. The contribution of each of these diagrams to the nucleon-nucleon interaction is examined.

In Sec. II, the theoretical expressions and equations are introduced. Numerical calculations and results are given in Sec. III. Sec. IV is devoted to discussion and conclusions.

II. THEORETICAL EXPRESSIONS AND EQUATIONS

In the present section, the basic features for evaluating the nucleon-nucleon interaction with different meson exchanges are introduced. For this purpose, different diagrams representing the different exchanges processes are considered. These diagrams are shown in Figs. 1-4. In these figures the solid lines refer to the nucleons, while the dashed lines denote the mesons. Fig. 1 represents the single meson exchange where \( \alpha \) stands for \( \pi \), \( \rho \), \( \sigma \), \( \omega \), \( \pi \), \( \rho \), \( \sigma \), and \( \omega \) mesons. These different meson exchanges are investigated with iterative and noniterative diagrams. The double-solid line in Figs. 3 and 4 denotes an isobar. Therefore, Figs. 3 and 4 represent the different processes of the iterative and noniterative, stretched-box and crossed-box diagrams involving nucleon-isobar and isobar-isobar intermediate states for the \( \gamma \) exchange, where \( \gamma \) stands for the \( \pi \) and \( \rho \) mesons.

In calculating the diagrams shown in Figs. 1-4, a dynamical scheme and formalism have to be introduced. The field-theory Hamiltonian \( H \) is given to contain the interaction part. This interaction part is not the nucleon-nucleon potential, but contains the nucleon-nucleon-meson and nucleon-isobar-meson vertices. The antinucleons are being neglected from the beginning. In the framework of Ref. 6, the Hamiltonian is given as

\[
H = \left( h_0^{\pi} + h_0^{\rho} + c \right) + \left( \sigma^{\pi} + \sigma^{\rho} \right)
\]

where \( H \) refers to an intermediate-nucleon state and \( \Lambda \) represents an intermediate \( \Lambda \) isobar state. Also

\[
\begin{align*}
\left( \mathbf{N} \right) & = \mathbf{N}^+ \mathbf{N}^+ \\
\left( \mathbf{A} \right) & = \mathbf{A}^+ \mathbf{A}^+ \\
\left( \mathbf{B} \right) & = \mathbf{B}^+ \mathbf{B}^+ \\
\left( \mathbf{C} \right) & = \mathbf{C}^+ \mathbf{C}^+ \\
\end{align*}
\]

are the creation operators of the nucleons, isobars and bosons, respectively, while \( \mathbf{N} \), \( \mathbf{A} \), \( \mathbf{B} \), and \( \mathbf{C} \) are the corresponding relativistic kinetic energies.

\( \lambda \), \( \kappa \) and \( \mu \) denote all the quantum numbers specifying the state completely. \( \mathbf{W}_{\lambda \kappa \mu}^{\mathbf{N}} \) describes the nucleon-nucleon-meson vertices, while \( \mathbf{W}_{\lambda \kappa \mu}^{\mathbf{A}} \) and \( \mathbf{W}_{\lambda \kappa \mu}^{\mathbf{B}} \) stand for the nucleon-isobar-meson vertices.

The sum of the nucleon-nucleon-meson and the nucleon-isobar-meson vertices, \( \left( \mathbf{W}_{\lambda \kappa \mu}^{\mathbf{N}} + \mathbf{W}_{\lambda \kappa \mu}^{\mathbf{A}} \right) \), is treated in an old fashioned three-dimensional noncovariant perturbation theory. Then, the nucleon-nucleon scattering amplitude \( T \) is given by series expansion representing all diagrams which contain two ingoing and two outgoing nucleon lines. Thus, \( T \) is partially summed by solving an integral equation of the Lippmann-Schwinger form which contains an energy-dependent quasipotential as a deriving term. This two-body Lippmann-Schwinger equation
is given as

$$T(z) = V_{\text{eff}}(z) + V_{\text{eff}}(z) - \frac{1}{z - h_{N}^{(0)}} T(z) \tag{3}$$

where $z$ is the relativistic starting energy for free two-body scattering. The quasipotential $V_{\text{eff}}(z)$ is the infinite sum of all of the irreducible diagrams which have one or more of meson or isobar in each intermediate state. Then, the quasipotential, $V_{\text{eff}}(z)$ is the sum of all the diagrams shown for the $\pi$, $\sigma$, and $\gamma$ meson exchanges. Also, the diagrams with $\sigma$, $\omega$, and $\omega$ meson exchanges are taken into account, in spite of the fact that they did not appear in the Figs. 2-4. In the process of calculations we take care not to duplicate the calculations (e.g. for the case of $\omega \pi$ and $\omega \pi$ when $\omega$ denotes the $\omega$ meson, and for the case of $\pi \gamma$ and $\pi \gamma$ when $\gamma$ denotes the $\gamma$ meson). In all these $\pi$, $\pi$, $\sigma$, $\omega$, and $\omega$ meson exchanges, all the diagrams involving the nucleon-nucleon, nucleon-isobar and isobar-isobar intermediate states are summed out to refer to the quasipotential $V_{\text{eff}}(z)$.

The interaction Lagrangian for the nucleon-nucleon-meson and nucleon-isobar-meson vertices are written as

$$L_{\text{NNS}} = \sqrt{2\pi} \bar{u}_{\text{N}} \gamma^{\mu} \gamma^{5} \phi_{\mu} + \sqrt{2\pi} \frac{1}{4\pi} \bar{u}_{\text{N}} \gamma^{\mu} \gamma^{5} \phi_{\mu} \psi_{\mu} \gamma^{5} \phi_{\mu} + \text{H.C.} \tag{4}$$

$$L_{\text{NAY}} = \sqrt{2\pi} \frac{g_{\text{NAY}}}{\pi} \bar{u}_{\text{N}} \gamma^{5} \gamma^{\mu} \gamma^{5} \phi_{\mu} + \frac{1}{16\pi} \bar{u}_{\text{N}} \gamma^{\mu} \gamma^{5} \phi_{\mu} \psi_{\mu} \gamma^{5} \phi_{\mu} + \text{H.C.} \tag{5}$$

where $\beta$ and $\gamma$ stand for different mesons as is shown in Figs. 2-4. In the case that $\beta$ represents a $\omega$ meson and in case that $\gamma$ denotes a $\omega$ meson, then the interaction Lagrangians for the case of $\omega$ meson are given as

$$L_{\text{NNS}} = \sqrt{2\pi} \bar{u}_{\text{N}} \gamma^{\mu} \gamma^{5} \phi_{\mu} + \sqrt{2\pi} \frac{1}{4\pi} \bar{u}_{\text{N}} \gamma^{\mu} \gamma^{5} \phi_{\mu} \gamma^{5} \phi_{\mu} + \text{H.C.} \tag{6}$$

$$L_{\text{NAY}} = \sqrt{2\pi} \frac{f_{\text{NAY}}}{\pi} \bar{u}_{\text{N}} \gamma^{5} \gamma^{\mu} \gamma^{5} \phi_{\mu} + \frac{1}{16\pi} \bar{u}_{\text{N}} \gamma^{\mu} \gamma^{5} \phi_{\mu} \gamma^{5} \phi_{\mu} + \text{H.C.} \tag{7}$$

In equations (4)-(7), $\phi_{\mu}$ is the $\omega$ meson-nucleon coupling constant, $g_{\beta}$ is the vector coupling of the $\beta$ meson to the nucleon, $f_{\text{NAY}}$ is the coupling constant at the nucleon-isobar-$\omega$ meson vertex, $f_{\text{NAY}}$ is the $\gamma$-meson coupling constant at the nucleon-isobar-$\tau$ meson vertex, and $f_{\text{NAY}}$ is the tensor coupling of the $\beta$ meson to the nucleon. $\psi$ represents the nucleon field operator, $\gamma$ denotes the $\gamma$ meson field, $\gamma$ is the field operator of the $\gamma$ isobar, and $\gamma$ stands for the field of the $\beta$ or $\gamma$ mesons. $\gamma$ and $\gamma$ are the Dirac matrices. $\gamma$ and $\gamma$ are the isospin matrices. $\gamma$ and $\gamma$ are the Dirac matrices.

All the different meson exchange diagrams with nucleon-nucleon, nucleon-isobar and isobar-isobar intermediate states of stretched-box and crossed-box diagrams have been introduced in Figs. 1-4. To evaluate these diagrams, some samples are introduced in Fig. 5. These samples stand for the stretched-box and crossed-box diagrams with nucleon-nucleon (Figs. 5a, 5b), nucleon-isobar (Figs. 5c, 5d) and isobar-isobar (Figs. 5e, 5f) intermediate states. After complicated mathematical work and lengthy expressions, the evaluations of the different diagrams shown in Figs. 1-4 are, however, straightforward.

Then, the contributions and partial wave amplitudes corresponding to the sum of all of the stretched-box diagrams for the $\pi\pi$ and $\pi\pi$ meson exchange with nucleon-nucleon intermediate states, (given in Fig. 2) with a selected diagram of it shown in Fig. 5a) showing the notations used), are given by

$$\sum_{J}^{\pi\pi} \sum_{i}^{j} | \langle q_{1}, q_{2}, \pi \mid 0 \rangle | A_{i}^{\Lambda_{1}} A_{j}^{\Lambda_{2}} = -2 \pi z \times 2 \pi \delta_{\pi\pi} 2 \pi \delta_{\pi\pi} \sum_{i=1}^{4} \frac{1}{2} \times \delta_{\pi\pi} 1_{i} \times 1_{i} \times 1_{i}$$

The partial wave amplitudes corresponding to the sum of all of the crossed-box diagrams with nucleon-isobar intermediate states, (given in Fig. 2) with a selected one of it shown in Fig. 5b) for the notations used), are given by
\[
\langle \Delta_1^{1/2}\Delta_2^{1/2} | H^{1/2}_{\gamma\gamma}(q',q) | \Delta_1^{1/2}\Delta_2^{1/2} \rangle = -2\pi x^2 \left(\frac{4\pi}{m^2 \tau}\right)^2 \sum_{j=1}^{q-2} \frac{1}{\sin^2 \theta_{H\gamma}^j}(9)
\]

The diagrams introduced in Fig. 4 represent the \( \gamma \gamma \) meson exchange involving isobar-isobar intermediate states. The contributions and partial wave amplitude of the stretched-box diagrams, (given in Fig. 4) with a selected sample given in Fig. 5e , are given as

\[
\langle \Delta_1^{1/2}\Delta_2^{1/2} | H^{1/2}_{\gamma\gamma}(q',q) | \Delta_1^{1/2}\Delta_2^{1/2} \rangle = 2\pi x^2 \left(\frac{4\pi}{m^2 \tau}\right)^2 \sum_{j=1}^{q-2} \frac{1}{\sin^2 \theta_{H\gamma}^j}(10)
\]

In Fig. 3 , the contributions of the crossed-box diagrams for the \( \gamma \gamma \) meson exchange with nucleon-isobar intermediate states shown in Fig. 3 , their evaluation is also straightforward. For the stretched-box diagrams in Fig. 3, with a selected example shown in Fig. 5c , the contribution is given as

\[
\langle \Delta_1^{1/2}\Delta_2^{1/2} | H^{1/2}_{\gamma\gamma}(q',q) | \Delta_1^{1/2}\Delta_2^{1/2} \rangle = 2\pi x^2 \left(\frac{4\pi}{m^2 \tau}\right)^2 \sum_{j=1}^{q-2} \frac{1}{\sin^2 \theta_{H\gamma}^j}(11)
\]

The other part of the crossed-box diagrams on Fig. 3 involving isobar-isobar intermediate states with a selected sample on Fig. 5f , contribute with partial wave amplitudes as

\[
\langle \Delta_1^{1/2}\Delta_2^{1/2} | H^{1/2}_{\gamma\gamma}(q',q) | \Delta_1^{1/2}\Delta_2^{1/2} \rangle = 2\pi x^2 \left(\frac{4\pi}{m^2 \tau}\right)^2 \sum_{j=1}^{q-2} \frac{1}{\sin^2 \theta_{H\gamma}^j}(12)
\]
In equations (6)-(13):

\[ g_\alpha = (g^2 + m^2)^{1/2} \]

(14)

\[ q^2 = (E^2 - m^2)^{1/2} \]

(15)

where \( m \) is the nucleon mass \((m = 938.9 \text{ MeV})\), and \( n_\alpha \) is the mass of the \( \alpha \) meson \((\alpha \) stands for \( \pi, \sigma, \omega, \eta, \) and \( \delta \) mesons). \( \theta \) is the angle between \( q \) and \( q' \). \( q_{\Lambda M}^{\alpha}(\theta) \) are the usual rotation matrices, \( \Lambda = \hat{\Lambda}_1 - \hat{\Lambda}_2, \Lambda' = \hat{\Lambda}_1' - \hat{\Lambda}_2' \).

Also, the form factors \( F_\alpha \) are parametrized as

\[ F_\alpha (q^2) = \left( \frac{1}{\Lambda^2} - \frac{m^2}{\Lambda_0^2} \right) \frac{n_\alpha}{k^2} \]

(16)

where \( n_\alpha = 1 \) for the case of \( \pi \) meson, and in the case of \( \rho \) meson \( n_\rho = 1 \) for \( F_{\rho NN} \) and \( n_\rho = 2 \) for \( F_{\rho N\pi} \). The helicity amplitudes \( \hat{\Lambda}_1, \hat{\Lambda}_1' \) and the denominators \( \Lambda \) are lengthy mathematical expressions. The basis of obtaining these expressions are followed from the formalism introduced in a review article by Ertelenz.

**III. NUMERICAL CALCULATIONS AND RESULTS**

In Sec. II an effective potential is introduced for the nucleon-nucleon interaction. This interaction is represented by different meson exchanges. The iterative and noniterative, stretched-box and crossed-box diagrams involving nucleon-nucleon, nucleon-isobar and isobar-isobar intermediate states which represent the different mesons exchanges are shown in Figs. 1-4. The different contributions and partial wave amplitudes of these diagrams are given by the theoretical mathematical expressions (9)-(13). The integrations presented in these expressions are calculated numerically.

Numerical calculations for the different contributions to the effective nucleon-nucleon interaction with different meson exchanges are carried out. For this purpose, the different meson's different parameters together with the values of the vertex parameters, (coupling constants, meson masses and cutoff parameters), which are used in the present numerical calculations are given in Table I. With these parameters, some phase shifts for some important partial waves have been calculated numerically and presented in Figs. 6-14. In these calculations, one-boson-exchange potential is used. The dashed-dotted curves in Figs. 6-14 stand for the contribution when we use only the one-boson-exchange potential only. The dotted lines denote the calculations taking into account contributions from all diagrams with nucleon-nucleon intermediate states, (Fig. 2), only. The dashed curves describe the case of using the contributions from diagrams with nucleon-nucleon and nucleon-isobar intermediate states, (Fig. 2 + Fig. 3). The solid curves represent the calculations obtained by using the effective nucleon-nucleon interaction with contributions from all diagrams involving nucleon-nucleon, nucleon-isobar and isobar-isobar intermediate states (Fig. 2 + Fig. 3 + Fig. 4). The experimental data for the phase shifts are shown by the black dots from the analysis of Arndt and Verwest, and by circles from the analysis of Dubois et al. From Figs. 6-14, good agreement between the present theoretical calculations and the experimental phase shifts is obtained.

**IV. DISCUSSION AND CONCLUSIONS**

In the present paper we have calculated the different contributions from different mesons exchanges. These contributions are described by the different diagrams shown in Figs. 1-4 for the iterative and noniterative, stretched-box and crossed-box diagrams involving nucleon-nucleon, nucleon-isobar and isobar-isobar intermediate states. From the present calculations, the individual contributions from each exchange process is sizeable, but there are strong cancellations between the different contributions of the different mesons. Although, the net result of taking the contributions of all of the exchanged mesons together is relatively small, however, it is non-negligible and so it is requested to calculate this contribution of all processes together.
From Figs. 6 -14, we can draw some points and conclusions. The contribution of the noniterative diagrams are as important as the iterative diagrams and should always be taken into account. The contributions of the different mesons exchanges diagrams involving nucleon-isobar intermediate states are important and should be included and it is repulsive. Contributions from exchange diagrams involving isobar-isobar intermediate states are smaller but sizeable and should also be included. Therefore, we can conclude that it is very important to group all the contributions from the different mesons exchanges together.

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REFERENCES

The different parameters of the effective nucleon-nucleon interaction $V_{\text{eff}}(r)$. $m_0$ and $A_0$ are given in MeV.

<table>
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<th>$r_0^2_{\text{NNN}}$</th>
<th>$r_0^2_{\text{NNO}}/r_0^2_{\text{NNO}}$</th>
<th>$m_0$</th>
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<td>575</td>
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<tr>
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<td></td>
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**Figure Captions**

- **Fig. 1**: Diagrams of meson exchange and contributing to $V_{\text{eff}}(r)$. $\alpha$ stands for $\pi$, $\rho$, $\sigma$, $\omega$, $\delta$ and $\eta$ mesons.
- **Fig. 2**: Diagrams of $\gamma\delta$ exchange with nucleon-nucleon intermediate states and contributing to $V_{\text{eff}}(r)$. $\alpha$ denotes $\gamma$, $\rho$, $\omega$, $\delta$ and $\eta$ mesons.
- **Fig. 3**: Diagrams of $\gamma\gamma$ exchange with nucleon-nucleon intermediate states and contributing to $V_{\text{eff}}(r)$. $\gamma$ represents $\pi$ and $\rho$ mesons.
- **Fig. 4**: Diagams of $\gamma\gamma$ exchanges with nucleon-nucleon intermediate states and contributing to $V_{\text{eff}}(r)$. $\gamma$ represents $\pi$ and $\rho$ mesons.
- **Fig. 5**: Selected (a), (c), (e) stretched-box diagrams and (b), (d), (f) crossed-box diagrams, involving nucleon-nucleon, nucleon-isobar and isobar-isobar intermediate states.
- **Fig. 6**: Nucleon-nucleon nuclear bar phase shifts (in deg) as a function of the nucleon laboratory energy (in MeV), in the $^3S_1$ partial wave. The curves represent the present theoretical calculations. The solid curve stands for a one-boson-exchange potential with contributions from all diagrams in figures 2, 3 and 4 added to it. The dashed line describes the one-boson-potential together with contributions from diagrams in Figs. 2 and 3. The dotted line denotes the one-boson-exchange potential in addition to contributions from diagrams in Fig. 2. The dashed-dotted curve is the one-boson exchange potential only. The experimental data are taken from reference 22) as the black dots and from reference 23) as the circles.
- **Fig. 7**: The same as in Fig. 6, but for $^3P_0$.
- **Fig. 8**: The same as in Fig. 6, but for $^3P_1$.
- **Fig. 9**: The same as in Fig. 6, but for $^3P_2$.
- **Fig. 10**: The same as in Fig. 6, but for $^1D_2$. 

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Fig. 11  The same as in Fig. 6, but for $^3S_1$.

Fig. 12  The same as in Fig. 6, but for $^3D_1$.

Fig. 13  The same as in Fig. 6, but for $^3P_1$.

Fig. 14  The same as in Fig. 6, but for $^3D_2$.

\[ \mathbf{V}^{(1)}(x) = \begin{array}{c}
\end{array} \]
\[ V(x) = \sum_{\gamma} \frac{\pi}{\gamma} \]
Fig. 6

-21-

Fig. 7

-22-
Fig. 12

Fig. 13
Phase Shift (deg)

Lab Energy (MeV)

$^3D_2$