Calculation of Nucleon-Nucleon Scattering from the Gartenhaus Potentials*

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Nucleon-nucleon scattering and polarization are computed by using potentials calculated by Gartenhaus from the cutoff pseudoscalar symmetric meson theory proposed by Chew. The results are compared with experiment.

GARTENHAUS[1] has calculated the nucleon-nucleon potentials from the cut-off pseudoscalar symmetric meson theory in the form proposed by Chew.[2] The even-parity potentials are shown in Figs. 1 and 2 of reference 1. The potentials adjusted to fit the binding energy of the deuteron and the *n-p* singlet scattering length are used in the present calculations. The odd-parity potentials are shown in Figs. 1 to 3. The authors are indebted to Dr. Gartenhaus for sending them the odd-parity potentials.

As mentioned by Gartenhaus in the final paragraph of his paper, these potentials have not been tested for higher energies. It is the purpose of this note to compare the angular distributions and polarizations calculated from the Gartenhaus potentials with experimental data.

The phase shifts which result from these potentials are shown in Figs. 4 to 6 for the energy range 0–340 Mev. These may be compared with the results of the phase-shift analyses of Feshbach and Lomon,[3] Hull *et al.*,[4] and Stapp.[5] (Hull *et al.* and Stapp have analyzed only the 310-Mev *p-p* data).

Neutron-proton and proton-proton angular distributions and polarizations calculated from the phase shifts shown in Figs. 4 to 6 are presented in Figs. 7 to 10 and compared with experiment.

There is no evidence in these results that Gartenhaus' even-parity potentials are far from correct. However, Gartenhaus' $^1S_0$ phase shift is not negative at 310 Mev. For all of Stapp's solutions to the phase shift analysis problem for 310-Mev *p-p* scattering, the $^1S_0$ phase shift is negative by at least 10°. Perhaps Gartenhaus' singlet even-parity repulsive core is not deep enough or of sufficiently long range. All of Stapp's $^1D_2$ phase shifts are positive and in good agreement with Gartenhaus' $^1D_2$ phase shift for the two of Stapp's four solutions which have the largest $^1D_2$ shifts. The $^1D_2$ phase shifts of Hull *et al.* are negative or zero, a result which is hard to reconcile with any potential model, and which is more evidence against the solutions of Hull *et al.* than against the potentials of Gartenhaus.

Gartenhaus' singlet odd-parity attractive core is too deep; the $^1P_1$ state is bound. However, it may be as-

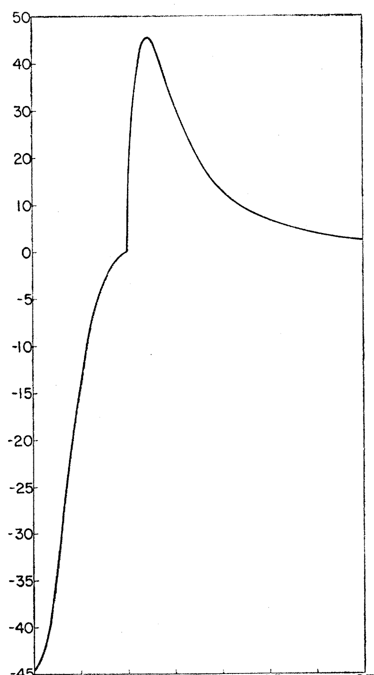

FIG. 1. The singlet odd-parity potential as calculated by Gartenhaus from the cut-off pseudoscalar symmetric meson theory of Chew. The radial distance r is given in units of 4.315×10^{-13} cm. The ordinate for positive energy is given in Mev. The ordinate for negative energy is given in units of 100 Mev.

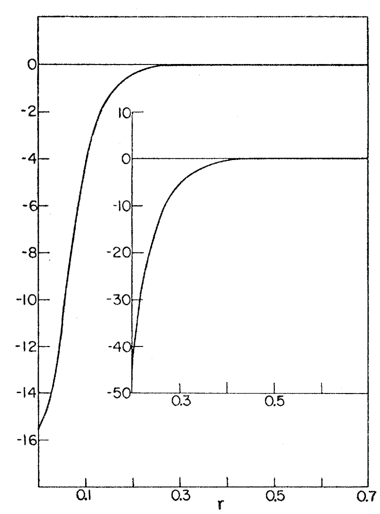

FIG. 2. The triplet central odd-parity potential as calculated by Gartenhaus from the cut-off pseudoscalar symmetric meson theory of Chew. The radial distance r is given in units of 4.315×10^{-13} cm. The ordinate is given in units of 100 Mev. The inset represents part of the potential on an expanded scale, with ordinate in Mev.

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[1] S. Gartenhaus, Phys. Rev. 100, 900 (1955).
[2] G. Chew, Phys. Rev. 95, 285 (1954); 95, 1669 (1954).
[3] H. Feshbach and E. Lomon, Phys. Rev. 102, 891 (1956).
[4] Hull, Ehrman, Hatcher, and Durand, Phys. Rev. 103, 1047 (1956).
[5] H. Stapp, University of California Radiation Laboratory Report UCRL 3098 (unpublished). For a preliminary account of this work see Phys. Rev. 98, 267(A) (1955).

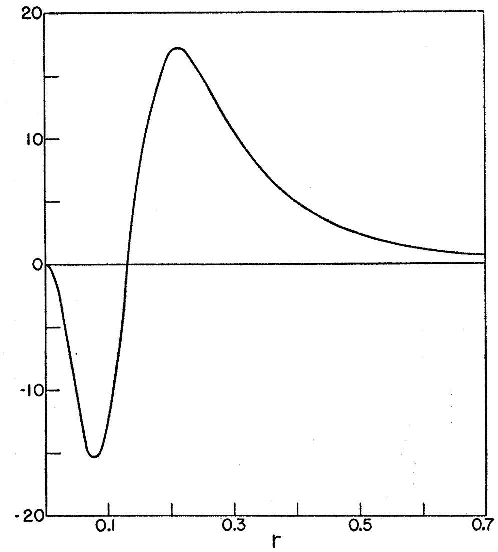

FIG. 3. The triplet tensor odd-parity potential as calculated by Gartenhaus from the cut-off pseudoscalar symmetric meson theory of Chew. The radial distance r is given in units of 4.315×10^{-13} cm. The ordinate is given in Mev.

sumed that Gartenhaus' calculations have no validity for distances less than (say) 0.5×10^{-13} cm, and the core region may be treated phenomenologically. In this way it might be possible that Gartenhaus' potentials are valid for distances greater than 0.5×10^{-13} cm.

For all of the solutions of Stapp and most of the solutions of Hull *et al.*, the $^3P_0$ phase shift is negative at 310 Mev. Feshbach and Lomon's $^3P_0$ phase shift is negative at all energies. Gartenhaus' triplet odd-parity

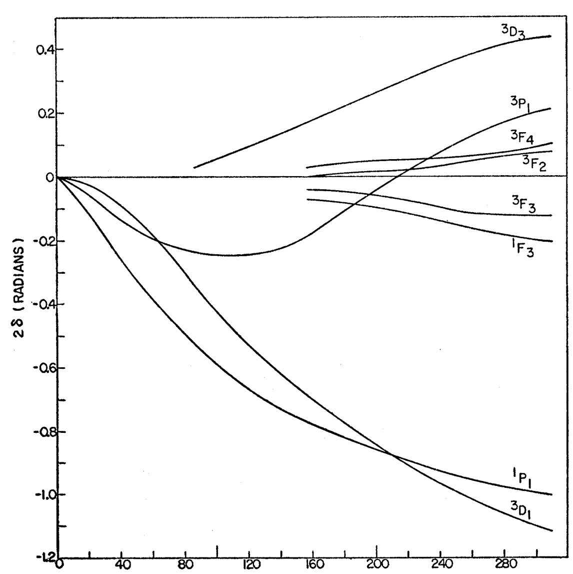

FIG. 4. Phase shifts computed from the Gartenhaus potentials *versus* energy. The ordinate represents twice the phase shift calculated according to the formalism of J. M. Blatt and L. C. Biedenharn [Revs. Modern Phys. 24, 258 (1952)].

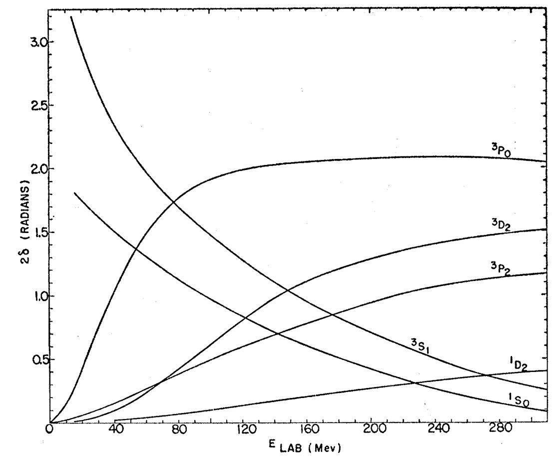

FIG. 5. Phase shifts computed from the Gartenhaus potentials *versus* energy. The ordinate represents twice the phase shift calculated according to the formalism of Blatt and Biedenharn.

potentials are attractive in the $^3P_0$ state, and the $^3P_0$ phase shift is positive. Only a repulsive core could make the $^3P_0$ phase shift negative at 310 Mev if it is assumed that Gartenhaus' potentials are valid for distances greater than 0.5×10^{-13} cm, that the $^3P_0$ state is not bound, and that the $^3P_0$ phase shift does not pass through 90° in the energy range 0–310 Mev.

It seems probable that the $^3P_0$ phase shift does not pass through 90° in the energy range 0–310 Mev. A $^3P_0$ phase shift which passes through 90° at an energy E_{lab} contributes $2600/E_{\text{lab}}$(Mev) millibarns to the n-p total cross section. This contribution seems too large.

With regard to the possibility that the $^3P_0$ state is bound (say with zero binding energy), it is very interesting that the order of three out of four of Stapp's solutions cannot be achieved with any combination of central and tensor potentials unless the $^3P_0$ state is bound or the $^3P_0$ phase shift passes through 90° in the energy range 0–310 Mev. This agrees with a remark of

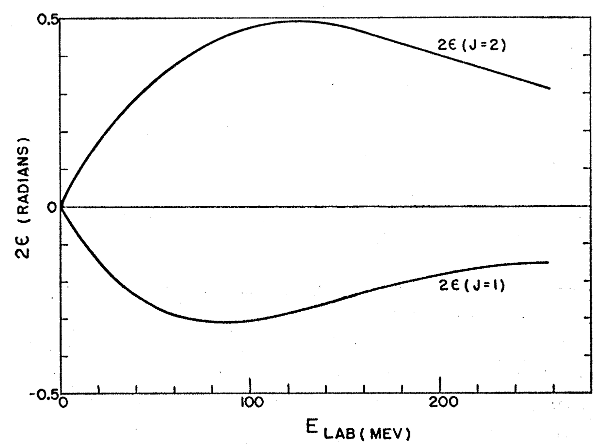

FIG. 6. The coupling constants for $^3S_1-{}^3D_1$ and $^3P_2-{}^3F_2$ states computed from the Gartenhaus potentials *versus* energy. The ordinate represents twice the coupling constant calculated according to the formalism of Blatt and Biedenharn.

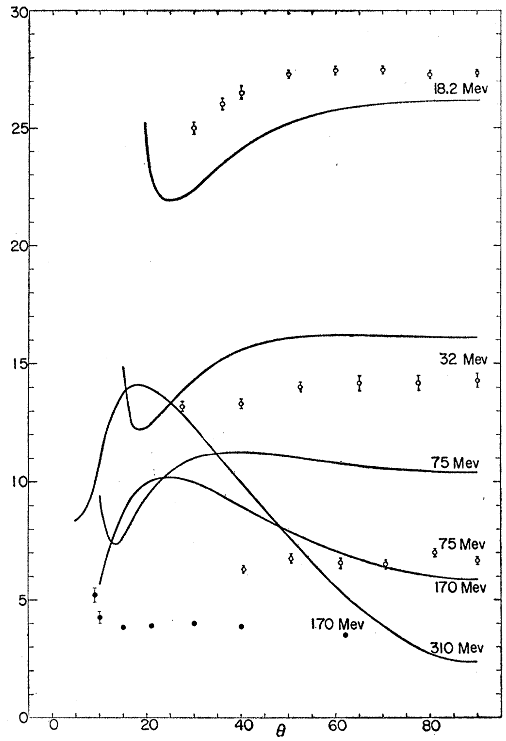

FIG. 7. Proton-proton angular distributions for various experimental energies as calculated from the Gartenhaus potentials. The abscissas represent center-of-mass angles in degrees. The ordinates are differential cross sections in millibarns.

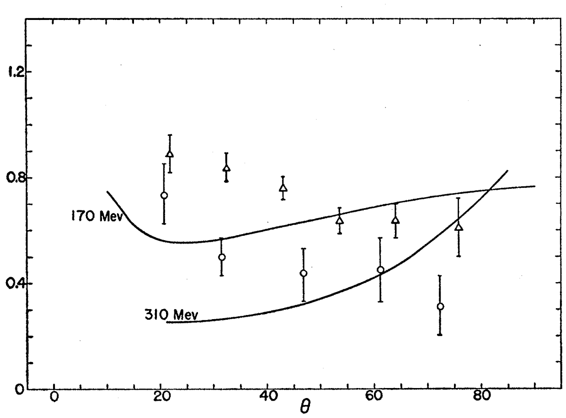

FIG. 8. Proton-proton polarization at 170 and 310 Mev as calculated from the Gartenhaus potentials. The ordinate represents the polarization divided by $\sin\theta \cos\theta$. The abscissas represent center-of-mass angles in degrees. The circles give the 170-Mev data, the triangles the 310-Mev data.

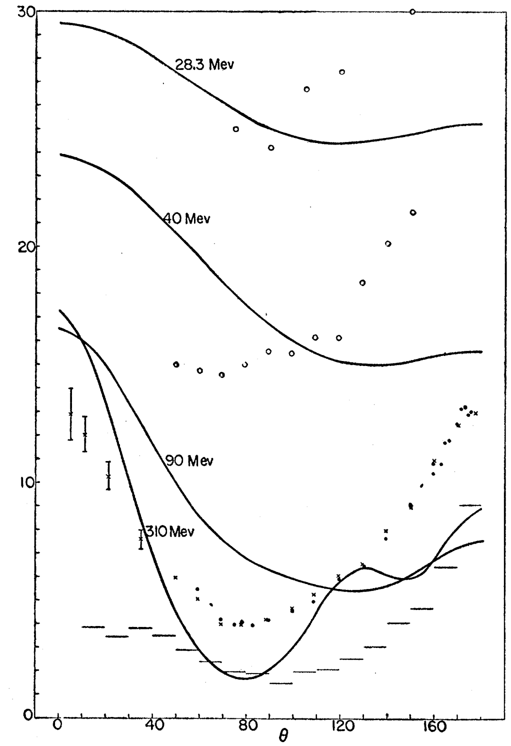

FIG. 9. Neutron-proton angular distributions for various experimental energies as calculated from the Gartenhaus potentials. The abscissas represent center-of-mass angles in degrees. The ordinates are differential cross sections in millibarns. The dots and the crosses give the 90-Mev data; the horizontal lines give the 310-Mev data.

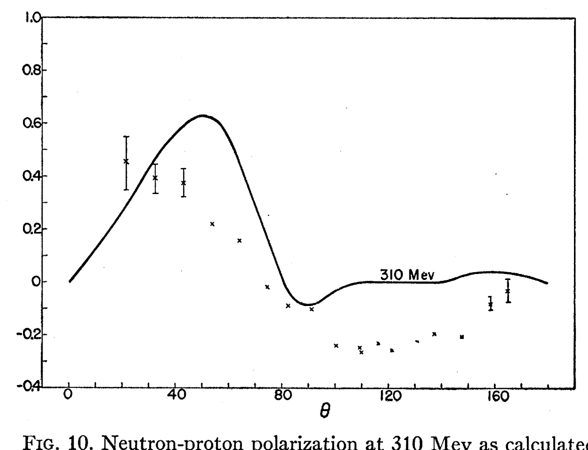

FIG. 10. Neutron-proton polarization at 310 Mev as calculated from the Gartenhaus potentials. The abscissas represent center-of-mass angles in degrees.

Wolfenstein[6] that if Born's approximation is valid, a large spin-orbit term is present in the interaction.

One of Stapp's solutions can be fit with triplet odd potentials very similar to those of Gartenhaus. The depth of the attractive core is adjusted to bind the $^3P_0$ state with zero binding energy. One gets into trouble with charge independence; it is necessary to bind the n-p and n-n systems with a finite binding energy in order to bind the p-p system with zero binding energy. We do not wish to elaborate on these points here.

We do not regard these calculations as proving anything except that the Gartenhaus potentials are not correct in detail in the core region, especially in the odd-parity states. The qualitative picture of attractive odd-parity cores cannot be ruled out unless one is unwilling to assume that the $^3P_0$ state is bound.

[6] L. Wolfenstein, Bull. Am. Phys. Soc. Ser. II, 1, 36 (1956).