variation of the rate of production of mesons with altitude and on the energy spectrum of the produced mesons. To determine how sensitive this method is as a test for the energy spectrum, we have calculated the ratio between the numbers of vertical mesons at the end of their range at the atmospheric depths of 300 g/cm$^2$ and 1000 g/cm$^2$ respectively, under the following assumptions: (a) The meson producing radiation undergoes exponential absorption in the atmosphere with a mean free path $L$. (b) Mesons are produced with a differential energy spectrum which obeys a power law $dE/E^3$ down to an energy $E_0$, and is constant from $E_0$ to zero. (c) Mesons have a mass of $10^8$ ev/c$^2$ and a lifetime of 2.15 microseconds. The calculation was carried out for $L=100$ g/cm$^2$ and for different values of $E_0$. The results were as given in Table III.

The only conclusion one can draw from a comparison between the results listed in Table III and our experimental data is that the comparatively slow increase with height of the slow meson intensity found experimentally indicates that the production spectrum of mesons is not very rich in low energy mesons.

TABLE III. Computed variation of slow meson intensity.

| $E_0$ (ev) | $2.1\times10^8$ | $3.9\times10^8$ | $7.7\times10^8$ |
|---|---|---|---|
| Meson range corresponding to $E_0$ (g/cm$^2$) | 100 | 200 | 400 |
| Increase of slow meson intensity from 1000 to 300 g/cm$^2$ | 137 | 34 | 5.5 |

ACKNOWLEDGMENTS

The research described in this paper was supported in part by contract N5 ORI-78, U. S. Navy Department, Office of Naval Research. The B-29 used for the measurements at high altitudes was provided by the U. S. Army Air Force. The authors wish to express their gratitude to the pilot, Lt. C. C. Davis, and the crew of the aircraft for their cooperation.

PHYSICAL REVIEW VOLUME 72, NUMBER 2 JULY 15, 1947

# On the Meson Theory of Nuclear Forces

LESLIE L. FOLDY*
*Department of Physics and Radiation Laboratory, University of California, Berkeley, California*
(Received April 7, 1947)

The failure of the Møller-Rosenfeld-Schwinger mixture to yield quantitative agreement with the observed properties of the proton-neutron system suggests the possibility that this agreement might be obtained with other such mixtures in which tensor force singularities are cancelled. Several such possibilities exist involving vector, pseudovector, and pseudoscalar mesons, certain of which possess the characteristic that they yield a finite tensor and central interaction in the limit where the meson masses approach equality and the square of the coupling constant increases indefinitely inversely as the difference in masses. The resultant interaction is of an especially simple form so that it was felt warranted to carry out calculations on the proton-neutron and proton-proton systems in spite of admitted conceptual difficulties concerning the result. These calculations indicated that satisfactory agreement with experimental results cannot be obtained with these limiting forms of the interaction, if one employs in the theory the mass of observed cosmic ray mesons. Substantially better agreement can be obtained with a meson mass of the order of 300 electron masses.

## 1. INTRODUCTION

IN spite of the qualitative correctness of the range and spin dependence of internucleonic forces derived from current weak coupling meson theories, it is well known that serious difficulties are encountered when one attempts to obtain quantitative agreement with the available experimental data. A part of these difficulties is connected with the overly singular radial dependence of the non-central or tensor part of the interaction, which, if accepted literally, precludes the existence of a complete set of eigenfunctions for the Schrödinger equation. One solution of this

* National Research Fellow (Predoctoral).

difficulty proposed by Møller and Rosenfeld[1] and improved by Schwinger[2] consists of employing a mixture of pseudoscalar and (heavier) vector mesons with equal coupling to the sources, such that the objectionable singularities are cancelled, at least in the first order non-relativistic approximation. This leaves, in the symmetrical form of the theory, an interaction qualitatively correct in the signs and spin dependence of the various terms. Calculations of Jauch and Hu,[3] however, indicate that quantitative agreement cannot be obtained with this theory in that, if the coupling constant and vector meson mass are adjusted to give the correct thermal neutron-proton scattering cross section and deuteron binding energy, then the predicted quadrupole moment of the deuteron is only 20 percent of the observed value.[4]

The purpose of this paper is to point out the existence of several other possible meson mixtures of the Møller-Rosenfeld-Schwinger type in that the objectionable singularities in the tensor interaction are eliminated by cancellation. Two of these other possible mixtures possess the additional feature that on passing to the limit in which the masses of the various mesons involved approach equality with a simultaneous increase of the square of the coupling constants inversely as the difference in the masses of the mesons, one obtains a limiting form of the interaction of very simple radial dependence.

This interaction is derived in Section 2 by combining linearly the weak coupling interactions obtained from the vector, pseudovector, and pseudoscalar meson theories and then applying the limiting process described above. It may be noted that the result is just the interaction one would obtain by differentiating the interaction obtained in one of the simple theories with respect to the meson mass. The validity and physical interpretation of the method of derivation, in view of the infinite limit of the coupling constants, is admittedly obscure and sufficiently lacking in physical motivation as to make questionable the attachment of any field-theoretic significance to the result. We do not wish to underemphasize these conceptual difficulties and therefore submit these results for their possible interest rather than with any expectation that they represent a key to the solution of the difficulties of meson theories of nuclear forces. Attempts to derive the same result in a more natural way, such as from a single meson field whose solutions reduce into solutions representing mesons of different spin and parity (the "tensor" meson theory, for example), were unsuccessful.[5]

One feature of this interaction is worthy of some mention. One finds that the radial dependence of the central part of the interaction corresponds, in the symmetrical form of the theory, to a strong attraction at small separations, changing to a weak repulsion at large separations in states of even parity. This would presumably lead to a preferential forward scattering of high energy neutrons scattered by protons in view of the exchange character of the interaction.[6] This would be in agreement with the published observations of Amaldi, Bocciarelli, Ferretti, and Trabacchi[7] and of Champion and Powell.[8] However, there now appears some doubt concerning the correctness of these experimental results.[9]

[1] C. Møller and L. Rosenfeld, Kgl. Danske Vid. Sels. Math.-Fys. Medd. **17**, 8 (1940); C. Møller, *ibid.* **18**, 6 (1941).

[2] J. Schwinger, Phys. Rev. **61**, 387(A) (1942).

[3] J. M. Jauch and N. Hu, Phys. Rev. **65**, 289(L) (1944).

[4] Since the quadrupole moment of the deuteron is sensitive to distant parts of the wave functions, it would appear that the method of calculation employed by Jauch and Hu could not yield a very good result for this quantity. However, according to information received through Professor J. R. Oppenheimer, Schwinger, in some unpublished calculations, found that the discrepancy remains when better methods of calculation are employed.

[5] K. C. Wang and K. C. Cheng in a recent paper (Phys. Rev. **70**, 516 (1946)) propose a five-dimensional meson field theory which in ordinary space-time represents several types of mesons with equal coupling to the sources. However, the resultant theory is only invariant with respect to proper Lorentz transformations, with the result that the interaction between two nucleons is not invariant with respect to mirroring transformations in ordinary space. As a consequence, parity would not be conserved in nuclear interactions.

[6] This observation was pointed out to the author by Professor J. R. Oppenheimer. It follows from a calculation by the Born approximation employing only the central part of the force. The effect of the tensor force may lead to a reduction of this effect or a reversion to back scattering.

[7] E. Amaldi, D. Bocciarelli, B. Ferretti, and G. C. Trabacchi, Naturwiss. **30**, 582 (1942); Ricerca Scient. **13**, 502 (1942).

[8] F. C. Champion and C. F. Powell, Proc. Roy. Soc. **A183**, 64 (1944).

[9] According to G. Wentzel, Rev. Mod. Phys. **19**, 1 (1947), footnote 38, C. F. Powell has reported, at the International Physics Conference at Cambridge, July 1946, that the scattering of 14-Mev neutrons by protons is practically isotropic in the center of gravity system. F. Oppenheimer and B. Moyer have also recently found at the Radiation Laboratory, University of California, Berkeley, that the bombardment of hydrogenous materials by high energy

In other respects the interaction appeared to form a satisfactory basis for quantitative calculations on the binding energy and quadrupole moment of the deuteron, as well as proton-proton and neutron-proton scattering, since it is very similar to the empirical interaction employed by Rarita and Schwinger[10] in their calculations on the neutron-proton system. The results of these calculations are presented in Section 3 of this paper and further discussed in Section 4. The general conclusion following from these calculations is that quantitative agreement cannot be obtained with the known properties of the interaction of two nucleons on the basis of the limiting form of the interaction, if one employs for the meson mass the observed mass of cosmic-ray mesons. Substantially better agreement would be obtained with a meson mass of about 300 electron masses.

## 2. THEORY

The first order quasi-static interactions between two nucleons in the various meson theories have been calculated by Kemmer.[11] With a restriction to the symmetrical form of these theories, the interactions in the vector, pseudovector, and pseudoscalar meson theories are respectively:

$$V_{12}=(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\left\{g^2\kappa^2\frac{e^{-\kappa r}}{r}-\tfrac{1}{3}f^2S_{12}\left(\frac{3}{r^3}+\frac{3\kappa}{r^2}+\frac{\kappa}{r}\right)e^{-\kappa r}+\tfrac{2}{3}f^2\kappa^2(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\frac{e^{-\kappa r}}{r}\right\},\quad(1)$$

$$V_{12}=(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\left\{\tfrac{1}{3}(f'^2-g'^2)S_{12}\left(\frac{3}{r^3}+\frac{3\kappa'}{r^2}+\frac{\kappa'^2}{r}\right)e^{-\kappa' r}-(\tfrac{2}{3}f'^2+\tfrac{1}{3}g'^2)\kappa'^2(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\frac{e^{-\kappa' r}}{r}\right\},\quad(2)$$

$$V_{12}=(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\left\{\tfrac{1}{3}g''^2S_{12}\left(\frac{3}{r^3}+\frac{3\kappa''}{r^2}+\frac{\kappa''^2}{r}\right)e^{-\kappa'' r}+\tfrac{1}{3}g''^2\kappa''^2(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\frac{e^{-\kappa'' r}}{r}\right\},\quad(3)$$

(~100-Mev) neutrons, results in a strong forward projection of protons, which appears to indicate that at these energies, the neutrons are preferentially back-scattered in the center of gravity system.

[10] W. Rarita and J. Schwinger, Phys. Rev. **59**, 436 (1941).

[11] N. Kemmer, Proc. Roy. Soc. **A166**, 127 (1938).

with $\boldsymbol{\tau}_1$, $\boldsymbol{\tau}_2$ the isotopic spin operators and $\boldsymbol{\sigma}_1$, $\boldsymbol{\sigma}_2$ the ordinary spin operators for the two nucleons, $r$ their separation, $\kappa$, $\kappa'$, $\kappa''$, the reciprocal Compton wave-lengths of the various mesons, $f, g, f', g', f'', g''$, coupling constants, and

$$S_{12}=\frac{3(\boldsymbol{\sigma}_1\cdot\mathbf{r})(\boldsymbol{\sigma}_2\cdot\mathbf{r})}{r^2}-\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2,\quad(4)$$

the tensor force operator. The delta-function interactions have been omitted since they depend partly on the way in which the theories are formulated.

The possibility of eliminating the $r^{-3}$ and $r^{-2}$ singularities stems from the different signs of these terms in the different theories. In order to obtain the empirically known attraction between nucleons in states of even parity and the proper sign for the quadrupole moment of the deuteron it is necessary that the coefficients of the operators $S_{12}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$ and $(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$ be positive at small separations. Furthermore, the calculations of Rarita and Schwinger[10] strongly suggest that non-spin dependent terms in the braces are unnecessary so that one may choose $g=0$. This choice then automatically guarantees the observed equality of the $^1S$ proton-proton and proton-neutron interactions.[12]

The Møller-Rosenfeld-Schwinger mixture is obtained by linearly combining (1) and (3) with $f=g''$ and $\kappa>\kappa''$. This then yields a non-singular tensor force of the correct sign. If one searches for other possibilities of combining these interactions so as to eliminate the singular parts of the tensor force, one finds:

(A) A combination of (2) and (3) with $g'^2-f'^2=g''^2$. The proper sign for the tensor interaction is then obtained if $\kappa'>\kappa''$; however, the sign of the central interaction is then incorrect.

(B) A combination of (1) and (2) with $f'^2-g'^2=f^2$. The proper signs for both the central and tensor interaction is then obtained if $\kappa>\kappa'$.

(C) The more general combination of (1), (2), and (3) with $f^2-g''^2=f'^2-g'^2$. The proper signs for the terms are then obtained if $f^2(\kappa^2-\kappa'^2)+g''^2(\kappa'^2-\kappa''^2)>0$ and $\tfrac{2}{3}f^2\kappa^2-\tfrac{1}{3}(2f^2-2g''^2+g'^2)\kappa'^2+\tfrac{1}{3}g''^2\kappa''^2>0$.

[12] G. Breit, Article on Proton-Proton Scattering in *Nuclear Physics*, University of Pennsylvania Bicentennial Conference (University of Pennsylvania Press, Philadelphia, 1941).

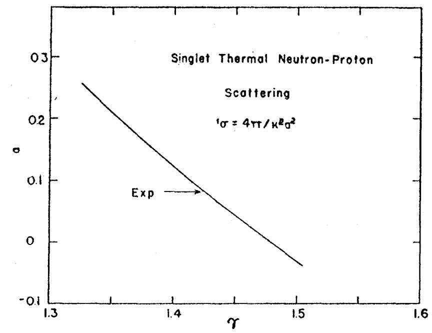


FIG. 1. Variation of parameter $a$ determining singlet thermal neutron-proton scattering cross section with the parameter $\gamma$.

We now note that in (C) if we take $f=g'$ and $f'=g''$, the interaction approaches a finite limit as we let $\kappa''\rightarrow\kappa\rightarrow\kappa'$, provided that simultaneously $f^2$ and $f'^2$ grow indefinitely large as $1/(\kappa-\kappa')$ and $1/(\kappa'-\kappa'')$, respectively. The result may be written as

$$V_{12}=\tfrac{1}{3}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\left\{G^2S_{12}\left(\frac{1}{\kappa r}+1\right)e^{-\kappa r}+2F^2(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\left(\frac{2}{\kappa r}-1\right)e^{-\kappa r}\right\}, \quad (5)$$

with

$$G^2=\lim\{f^2\kappa^2(\kappa-\kappa')+f'^2\kappa^2(\kappa'-\kappa'')\}$$
$$F^2=\lim\{f^2\kappa^2(\kappa-\kappa')-\tfrac{1}{2}f'^2\kappa^2(\kappa'-\kappa'')\} \quad (6)$$

and with the condition

$$0\leq F^2/G^2\leq 1. \quad (7)$$

The corresponding limiting case of (B) can be obtained from this result by setting $F^2=G^2$.

The limiting forms of cases (B) and (C) correspond physically to the existence of charged and neutral mesons, all of the same mass and all of spin unity in case (B) and of spin zero as well in case (C). Cosmic-ray evidence lends some support to the existence of spin zero mesons[13] but does not definitely preclude the existence of shorter-lived mesons of spin unity, at least at higher altitudes.[14] Of course, the validity of combining the weak coupling interactions given by (1), (2), and (3) especially in the limit where the coupling constants become infinite in order to obtain the interaction due to the composite fields is certainly open to question. Justification of this procedure would require a far more incisive investigation of the higher order terms in the interaction than is at present feasible.

### 3. CALCULATIONS

Numerical calculations for the two nucleon system have been carried out with the interaction (5) in the special case $G^2=F^2$ corresponding to case (B) above. If $\kappa=\mu c/\hbar$, where $\mu$ is the meson mass, is selected to correspond to the observed meson mass, $\mu$ equal to 200 electron masses,[15] then the only adjustable parameter in the theory is the quantity $G^2$. The most convenient and accurate means of evaluating this constant is from the singlet thermal neutron-proton scattering cross section. While the observed thermal cross section is a weighted average of singlet and triplet contributions, the triplet cross section is predominantly determined[10] by the binding energy of the deuteron to be approximately $4.3\times10^{-24}$ cm$^2$, which, combined with the experimental total cross section[16] of $21\times10^{-24}$ cm$^2$, gives for the singlet cross section a value of $71\times10^{-24}$ cm$^2$.

The calculation of the singlet thermal neutron-proton scattering cross section was carried out by numerical integration of the differential equation

$$d^2u/dx^2+\gamma(2/x-1)e^{-x}u=0 \quad (x=\kappa r) \quad (8)$$

where $\gamma=MG^2/\hbar^2\kappa^2$, $M$ being the mass of the proton. Properly normalized, the asymptotic form of the solution of this equation which vanishes at the origin is

$$u\sim x+a \quad (9)$$

and the singlet scattering cross section is then given by

$$^1\sigma=4\pi/\kappa^2a^2. \quad (10)$$

The quantity $a$ was calculated as a function of $\gamma$ with the result shown in Fig. 1. The experimental value of $71\times10^{-24}$ cm$^2$ for the cross section then determines $\gamma$ as 1.422. It will be noted that because of the proximity of the virtual singlet state of the deuteron to zero energy the value of $\gamma$ thus determined is quite insensitive to either the exact value of the experimental cross section

[13] R. F. Christy and S. Kusaka, Phys. Rev. **59**, 405, 414 (1941); J. R. Oppenheimer, Phys. Rev. **59**, 462(L) (1941).
[14] R. E. Lapp, Phys. Rev. **69**, 321 (1946).
[15] W. B. Fretter, Phys. Rev. **70**, 625 (1946).
[16] H. B. Hanstein, Phys. Rev. **59**, 489 (1941).

or to the exact assignment of a value to the triplet contribution to the cross section. A ten percent change in the experimental value of the singlet cross section changes the resulting value of $\gamma$ by only 0.3 percent.

With the value of $\gamma$ determined, calculations of the $S$-wave phase shift for proton-proton scattering at 0.670 and 2.392 Mev were carried out by numerical integration of the appropriate equations for values of $\gamma$ in the neighborhood of 1.422. The values of these phase shifts are known quite accurately from the analysis of experiments on proton-proton scattering.[17] The results of these calculations together with the experimental values are given in Fig. 2.[18] It will be noted that while the agreement is satisfactory at 0.670 Mev, the theory yields too rapid an increase of the phase shift with energy so that the theoretical value is definitely too high at 2.392 Mev. The discrepancy is outside the limits of error of the experimental values and is too large to be corrected by taking advantage of the 10 percent uncertainty in the experimental value of the mass of the meson. Calculations of the phase shift $K_0$ at 2.392 Mev for meson masses of 180 and 220 times the electron mass for $\gamma = 1.422$ yielded the following results:

| $\mu$ | $K_0$ (Theor.) | $K_0$ (Exp.) |
|---|---|---|
| $180m$ | 58.5° | 48.1° |
| $200m$ | 56.2° | 48.1° |
| $220m$ | 53.8° | 48.1° |

More serious discrepancies occur when one investigates the properties of the deuteron. The

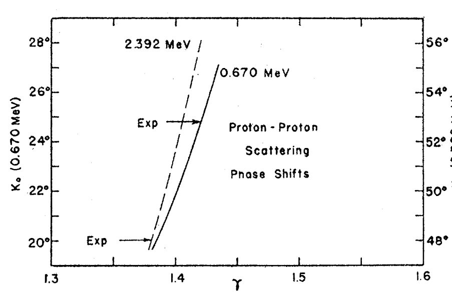


FIG. 2. Proton-proton scattering $S$-wave phase shifts at 0.670 and 2.392 Mev as a function of $\gamma$.

[17] G. Breit, H. M. Thaxton, and L. Eisenbud, Phys. Rev. **55**, 1018 (1939).

[18] The numerical integrations were carried to $r = 3e^2/mc^2$. The small remaining repulsive potential will tend to reduce the calculated phase shifts slightly.

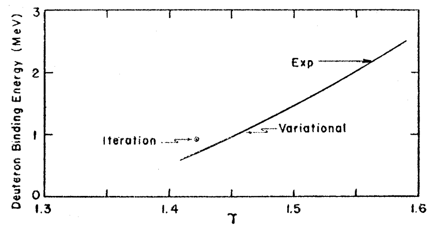


FIG. 3. Deuteron binding energy as a function of $\gamma$ as obtained by the iteration method for $\gamma = 1.422$ and by the variational method.

deuteron equations were solved for $\gamma = 1.422$ by replacing each differential equation by a set of twenty difference equations, and the latter were then solved by an iteration method. The resultant value for the binding energy of 0.85 Mev is less than one-half the experimental value of 2.185 Mev.[19] Because of the great labor involved in the iteration method, the approximate variation of the binding energy with $\gamma$ was obtained by a simple variational calculation with the result shown in Fig. 3. From this it may be seen that a value of $\gamma$ greater than 1.5 would be required to give the observed deuteron binding energy. A value as large as this would mean the existence of a stable singlet state of the deuteron.

While the iteration method employed to solve the deuteron equations gives accurate values for the binding energy, the poor approximation to the wave function at large distances limits the accuracy of the computed quadrupole moment to less than 10 or 20 percent. The computed value of the quadrupole moment was $5.0 \times 10^{-27}$ cm$^2$ which is considerably larger than the experimental value of $2.73 \times 10^{-27}$ cm$^2$ obtained by Rabi and his co-workers.[20] On the other hand, the $D$-state probability was computed to be 3 percent which is considerably lower than the value of 4 percent obtained from the magnetic moments of the proton, neutron, and deuteron.[21]

## 4. DISCUSSION

The scope of the calculations presented in the previous section can be considerably extended by some elementary considerations. Thus we

[19] M. L. Wiedenbeck and C. J. Marhoefer, Phys. Rev. **67**, 54(L) (1945).

[20] J. M. B. Kellogg, I. I. Rabi, N. F. Ramsey, and J. R. Zacharias, Phys. Rev. **57**, 677 (1940); A. Nordsieck, Phys. Rev. **58**, 310 (1940).

[21] W. R. Arnold and A. Roberts, Phys. Rev. **70**, 766(L) (1946).

may investigate the consequences of dropping the restriction $F^2=G^2$ and consider the more general case (C). If we retain the value of 200 electron masses for the meson mass, then, since the tensor force is inoperative in singlet states, the singlet thermal neutron-proton scattering cross section will demand again the value of 1.422 for $\gamma_F=MF^2/\hbar^2\kappa^2$. The $S$-wave phase shifts for proton-proton scattering will again be determined by $\gamma_F$ alone so that we obtain the same values as for the case (B). Thus we cannot eliminate the discrepancy in the proton-proton scattering phase shifts by passing to the more general theory. Insofar as the deuteron is concerned, we may now increase the relative amount of tensor force acting by the fact that we are at liberty to choose $G^2$ subject only to the condition $G^2 \geq F^2$. But increasing the relative amount of tensor force, while allowing us to obtain agreement with the binding energy of the deuteron, will also increase the computed value of the quadrupole moment of the deuteron, thus furthering the discrepancy with the observed value for this quantity. Hence we may conclude that no substantial improvement can be obtained by going to the case (C) than was previously obtained with case (B).

However, substantially better agreement can be obtained even in case (B) if we lift the restriction on the meson mass to agreement with the observed mass. This may be seen by the following arguments: From the formula for the singlet thermal neutron-proton scattering cross section, it will be noted that a change in $\kappa$ would require a corresponding inverse change in $a$ in order to keep the cross section in agreement with the observed value. But because of the relative insensitivity of $\gamma$ to the cross section, the new value of $\gamma$ required for agreement would differ only by a very small amount from the old value even for a change in $\kappa$ of the order of 50 percent. In fact a 50 percent increase in $\kappa$ would require a new value of $\gamma$ of 1.395. Now since the low energy proton-proton scattering is closely related to the singlet thermal neutron-proton scattering through the charge independence of the forces, a change in $\gamma$ and $\kappa$ which held the neutron-proton scattering cross section fixed would be expected to have little effect on the proton-proton scattering phase shift at 0.670 Mev and thus should leave the satisfactory agreement previously obtained unaltered. On the other hand, the calculations of the phase shift at 2.392 Mev for fixed $\gamma$ and varying $\kappa$ indicate that by increasing $\kappa$ we can probably obtain agreement at this energy with an increase in $\kappa$ of the order of 50 percent since the value of this phase shift is considerably more sensitive to $\kappa$ than it is to $\gamma$.

Turning now to the deuteron calculation, if we hold $\gamma$ fixed, then the computed binding energy of the deuteron varies as $\kappa^2$, while for fixed $\kappa$, the computed binding energy is not very sensitive to small changes in $\gamma$. Thus we may expect to improve considerably the agreement with the binding energy of the deuteron by an increase in $\kappa$ again of the order of 50 percent. At the same time the computed quadrupole moment of the deuteron for fixed $\gamma$ varies as $1/\kappa^2$. Thus an increase in $\kappa$ would result in better agreement for the quadrupole moment as well. However, since the $D$-state probability is independent of $\kappa$ for fixed $\gamma$, no substantial improvement would be obtained for this quantity.

We may summarize our results as follows: On the basis of the interaction obtained from mixed meson theories with the restriction that the masses of all the mesons are equal, satisfactory quantitative agreement cannot be obtained with the known characteristics of two body forces if one takes for the meson mass the value observed for cosmic-ray mesons of 200 electron masses. The agreement can be improved considerably if the meson mass is taken to be of the order of 300 electron masses. In general, one may conclude that the outlook for a satisfactory theory of nuclear forces based on the circumvention of singularity difficulties through cancellation of singular terms in mixed theories does not appear promising in view of the past and present calculations.

It is a pleasure to thank Dr. R. Serber, Dr. J. Weinberg, and Dr. D. Bohm, and in particular, Professor J. R. Oppenheimer for many illuminating discussions of the contents of this paper. The generous aid of Mr. V. Frederick with the numerical work is gratefully acknowledged.