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The Fundamental Nuclear Interaction

Important developments of the past decade on mesons and the theory of nuclear forces are described.

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The decade which just closed brought forth important advances in our understanding of the fundamental nuclear interaction. In 1960 the state of knowledge might succinctly be summarized by the statement of M. L. Goldberger (*1*).

> There are few problems in modern theoretical physics which have attracted more attention than that of trying to determine the fundamental interaction between two nucleons. It is also true that scarcely ever has the world of physics owed so little to so many. In general, in surveying the field, one is oppressed by the unbelievable confusion and conflict that exists. It is hard to believe that many of the authors are talking about the same problem or, in fact, that they know what the problem is.

However, by 1969, physicists had developed theoretical models which explain all the major features of the interaction between nucleons (N), that is, neutrons (n) and protons (p), established by experiments in the energy range from 0 to 400 million electron volts (Mev). These so-called one-boson exchange models (OBEM) are based essentially upon meson field theory (mesons are bosons), but they involve some adaptations and adjustment of theory to a large body of experimental data.

Meson field theory represents an extension of electromagnetic field theory in which mesons, particles with mass, replace massless photons as the particles which propagate an interaction. Einstein's Special Theory of Relativity allows for the existence of scalar (S), vector (V), tensor (T), axial vector (A), and pseudoscalar (P) fields. Such fields are four-dimensional counterparts of three-dimensional concepts with the same labels. Meson theory was first put forth in scalar form by Yukawa (*2*) in 1935, in vector form by Proca (*3*) in 1936, and in axial vector and pseudoscalar forms by Kemmer (*4*) in 1938. In an attempt to overcome certain singularity problems, Moller and Rosenfeld (*5*) in 1940 proposed the mixing of pseudoscalar and vector fields.

Meson field theory was confused in the 1940's by the erroneous identification of the μ meson as Yukawa's meson. Experimentally it was found that the μ meson interacts much too weakly with nucleons. However, the discovery by Powell and his co-workers (*6*) of the π meson in 1947 and its classification as a pseudoscalar charge triplet by Moyer and and his colleagues (*7*) and Panofsky and his colleagues (*8*) in 1950 revitalized the subject.

The π meson interacts strongly with nucleons and was at first thought to be the nuclear "glue" (*9*). However, π meson theory could not explain the N-N interaction at the close distances of importance in nuclear physics. Thus, in the late 1950's meson theory gave way to alternative efforts to interpret the rapidly unfolding experimental data in terms of phenomenological potentials (*10*).

The potentials proposed during this period indicated that the N-N interaction is just about as complicated as it could possibly be. In addition to central components, the N-N interaction displayed spin-spin, tensor, spin-orbit, and velocity-dependent interactions, each with its own complex dependence upon radial separation. Furthermore, there appeared a complex dependence upon the charge states of the N-N system.

Renewed impetus to pursue meson field theory came in connection with the events surrounding the discovery of the ω meson or resonance, the neutral vector particle with a mass of 782 Mev.

Robert Hofstadter's (*11*) classic experiment in 1956 on the scattering of high energy electrons by protons and neutrons initiated most of these events. This experiment suggested that the electric charge within the proton and neutron is distributed like a cloud throughout the nucleon. A number of theoretical attempts (*12*) to interpret this result invoked the existence of a neutral vector meson ω and a charged triplet (+1, 0, and −1) vector meson ρ. About the same time, Breit (*13*) restated the essential elements of his classic 1937 paper (*14*) on vector fields and gave very convincing phenomenological evidence and theoretical considerations in support of the existence of vector mesons.

These theoretical studies stimulated the search by experimentalists for vector mesons and, in 1961, groups at Berkeley, Wisconsin, and Johns Hopkins found the ω and ρ mesons along with the η, a neutral pseudoscalar meson. These experimental discoveries were described recently by L. Alvarez (*15*).

While the masses of these mesons did

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not conform with predictions, the essential features of the earlier speculations on the existence of vector mesons are now established. In addition to providing a qualitative explanation for Hofstadter's data, heavy vector mesons—as pointed out by Breit (*13*)—could account directly for the short range spin-orbit component in the N-N interaction inferred in phenomenological potential studies and for the short range repulsion evidenced by the saturation of energies and densities of complex nuclei. Furthermore, evidence for an attractive region of the proton-antiproton interaction (to be discussed later) could also be explained with a neutral vector meson.

The discovery of heavy mesons or resonances stimulated a number of theoretical groups to try again to build a meson theory of nuclear forces out of the known pseudoscalar (π and η) and vector (ω and ρ) mesons. These efforts, however, were unsuccessful until hypothetical scalar mesons were also included (*16*). Then the pieces of the intricate jigsaw began to fit together in a rather natural way. Thus, the question, "What holds the nucleus together?" which has been described by Bethe (*17*) as having consumed more man-hours than has been given to any scientific question in the history of mankind, appeared to be nearing an answer. My article is devoted to description of realistic one-boson exchange models of the N-N interaction and a discussion of their successes and current limitations.

Parallel Features of Electromagnetic Interactions

It is helpful to illustrate the component nuclear interaction in terms of corresponding electromagnetic interactions which may be familiar to the reader. For example, the repulsive electrostatic potential energy between two protons is $V_C = e^2/r$ where e is the charge of each proton and r is the radial distance separating them. This potential energy corresponds to the force $f = e^2/r^2$ (Coulomb's law, 1785).

The coulomb potential energy is an example of a "central interaction" in that it depends only on the radial separation. When the interacting objects are dipole-like—for example, two opposite charges separated by a distance—the interaction is more complex. It not only depends upon the radial separation (as r^{-3}) but also on the orientations of the two dipoles relative to the line joining the two. Such a dipole-dipole type interaction also describes the interaction of two magnets (Gilbert, 1595) and the interaction between two small current loops which behave like magnets.

The spin-orbit interaction occurs between a spinning charge, which acts as a little magnet or current loop, and a moving charge which acts as a current element. This corresponds to the well-known interaction of a compass needle or a magnetic dipole and a current (Oersted, 1820). Velocity-dependent interactions between two moving charges correspond to the interaction between two current elements (Ampere, 1821).

Figure 1a illustrates the electromagnetic spin-orbit effect (Oersted) between two protons which are bound together by some nonelectrostatic force (let's say a rod with bearings at both ends). Figure 1b illustrates the "tensor" interaction between two parallel spinning protons (Gilbert). Borrowing upon the reader's experience with magnets, one can see that the system would seek to orient itself as shown at right. In other words, there will be a noncentral component of the force which would act to push the system into alignment. Figure 1c illustrates the velocity-dependent interaction between two protons by virtue of their motion around each other.

These three magnetic interactions are dynamic or relativistic interactions arising from the motion or spin of charged particles. According to modern quantum field theory, these interactions arise because protons exchange "photons" which are the particles of the electromagnetic field. Photons are massless particles, but they convey energy and momentum. They have one unit of angular momentum.

Nuclear Interactions and Phase Shifts

About a century after the discovery of the laws of electromagnetic interactions, nuclear experimentalists began one of the most extensive series of measurements. The objective was now

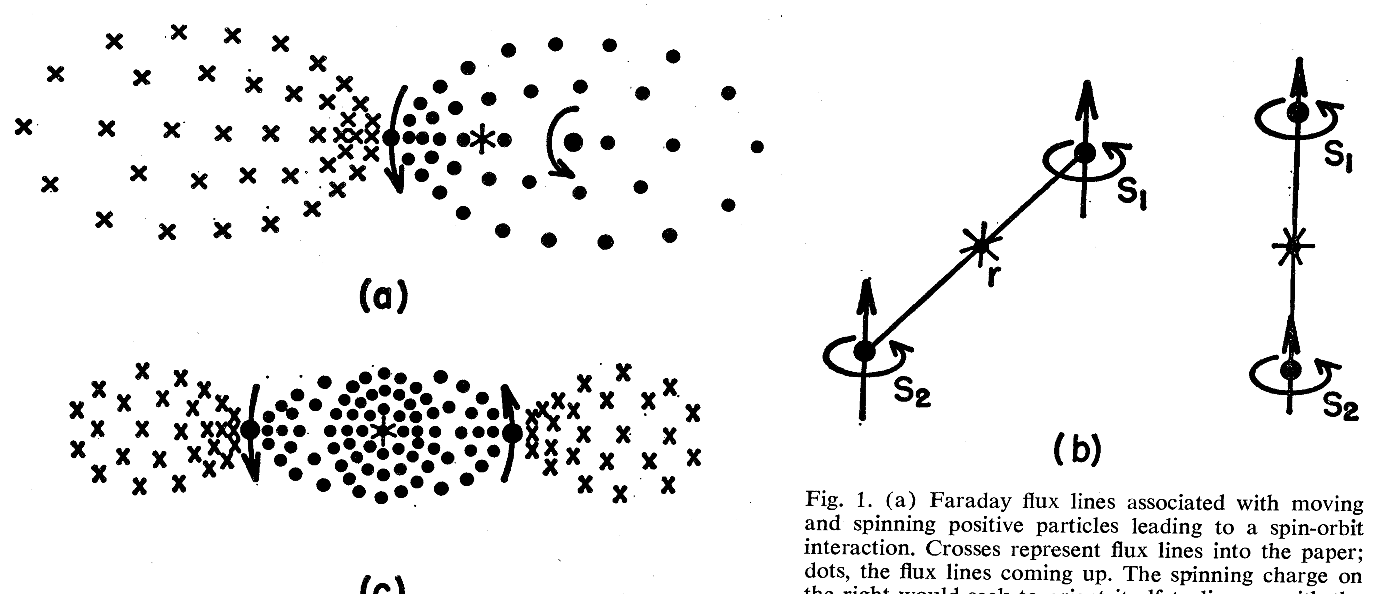

Fig. 1. (a) Faraday flux lines associated with moving and spinning positive particles leading to a spin-orbit interaction. Crosses represent flux lines into the paper; dots, the flux lines coming up. The spinning charge on the right would seek to orient itself to line up with the flux lines set up by the moving particle to the left, for example, the spin and orbital motions of like charges would tend to align in parallel (*44*). (b) Tensor force, a noncentral dipole-dipole type interaction between two spinning positive charges constrained to be parallel. The preferred orientation is to the right. (c) Velocity-dependent forces, or p^2 forces (Ampere). The compression of flux lines between the two particles would tend to push the two protons apart.

to understand the fundamental force which holds the nucleus together. By 1932 it was already clear that nuclear forces only act over very short ranges, ~ 2 fermis (1 fermi is 10^{-13} centimeter). This short radius of action was explained by Yukawa in 1935 (*2*) by assuming that the quanta which convey the nuclear force have a finite mass in contrast to the massless quanta (photons) of the electromagnetic field. The consequence of this feature is that the e^2/r potential of electromagnetic theory is replaced in the corresponding vector form of meson theory by a potential energy $V = \pm g^2 Y(r)$ where $Y(r) = (\exp -\mu r)/r$ and $\mu = mc/\hbar$. Here m is the mass of meson field, and g is a coupling constant analogous to electric charge e. Note that when $m \rightarrow 0$, $\mu \rightarrow 0$; and since $\exp 0 = 1$, $Y(r) \rightarrow C(r) = 1/r$ (C is the Coulomb function). Thus, the Yukawa function contains the Coulomb function of the electrostatic potential as a special case when the mass of the field quanta vanishes.

The function $Y(r)$ is not new in science since it is identical in mathematical form to the Debye potential used in studies of electrolytes and plasmas. The rapid decrease of Yukawa function $Y(r)$ from the $1/r$ term is due to the factor $\exp -\mu r$, which suggests that nuclear forces are only effective at ranges (a) such that $a = \mu^{-1} = \hbar/mc = 1.4$ fermis for π mesons ($\hbar$ is Planck's constant h divided by 2π).

The curve marked $Y\omega(r)$ in Fig. 2 corresponds to the ω meson mass which has the radius of action $a = 0.25$ fermi. The curve C represents the Coulomb function which may be viewed to have an infinite radius of action. The curve GY (for generalized Yukawa) will be discussed later (see Mesons and the N-N Interaction, below).

Yukawa's scalar form of meson field theory leads to a dominating attractive potential $V_s = -g^2 Y(r)$. The vector form of Proca gives rise to a dominating repulsive interaction $V_v = g^2 Y(r)$. These dominating terms in scalar and vector forms of meson theory are much to simple to account for experimental observations.

If the N-N interaction were simply dependent upon radial separation, then the experimental effort to establish this radial dependence would involve firing neutrons or protons at various energies against a hydrogen target and observing the angular distribution of the scattered particles. Figure 3 shows some representative nuclear data of this type.

The theoretical attempt to explain

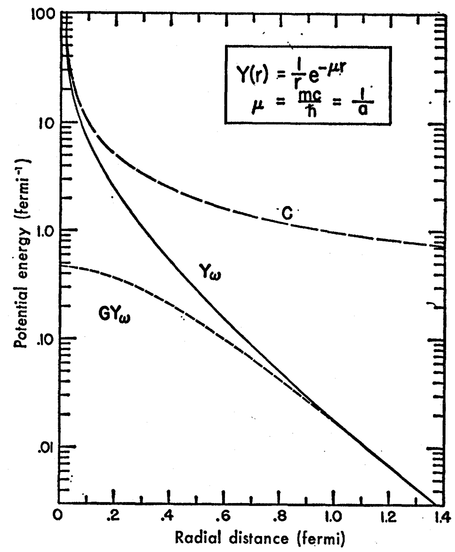

Fig. 2. Static potentials. The equation for the Yukawa function, the decay constant μ, and the range a are given in the box. C denotes the Coulomb function; $Y\omega$, the Yukawa function for the ω meson mass. $GY\omega$ is a generalized Yukawa function associated with the ω meson. A logarithmic vertical scale is used to encompass the large range of values. Note that $Y \rightarrow C$ as $r \rightarrow 0$ and also that $GY\omega \rightarrow Y\omega$ as $r \rightarrow \infty$.

such angular distributions requires the assumption of various N-N potentials for use in conjunction with Schrödinger's wave equation (*18*). For short range potentials such as the Yukawa potential, it is most convenient to solve the wave equation by first decomposing the wave function into partial waves. Just as in atomic physics, these partial waves may be denoted by S, P, D, F, G, H . . . for the corresponding values of the orbital angular momenta $L = 0$, 1, 2, 3, 4, 5 . . . associated with these waves. The mathematical problem is to solve Schrödinger's wave equation for each partial wave and, by examining the solution outside the interaction region, to extract the extent to which it is shifted in its phase angle as a result of the N-N potential. A negative potential region shortens the wavelength in the region of the potential, and hence the accumulated phase angle in proceeding to the outer regions is greater than for a wave in the absence of an interaction. Hence, the phase shift occasioned by a negative or attractive potential is positive. On the other hand, a repulsive potential gives a negative phase shift. The detailed correspondence, however, depends upon the extension, depth, and shape of the interaction potential. The development of electronic computers was necessary to make calculations of phase shifts for arbitrary potential shapes practical.

Figure 4 illustrates the phase shifts obtained from scalar interaction of the type $V_s = -g^2 Y(r)$. Here m is taken at 140 Mev, the π meson mass, and g^2 has been set at 79 Mev · fermi which is sufficient to produce a bound S state. In these units e^2 corresponds to 1.44 Mev · fermi so that $g^2 = 55\ e^2$. There is simple and regular variation of the phase shifts with energy and with L, which results from a simple attractive scalar Yukawa interaction.

The phase shifts obtained from a theoretical potential may be used to generate an angular distribution for the scattered particles (*18*), which can be compared directly with experimental data such as is given in Fig. 3. Alternatively, one may extract experimental phase shifts from the data by resolving angular distribution patterns into Legendre polynomials, a process similar to Fourier analysis. Then we can use such experimental phase shifts to test phase shifts calculated from a theoretical model. Most progress in studies of the N-N interaction has been made via this latter route (*10, 18*).

Figure 5 gives the S, P, and D phase shifts extracted from experimental data by Breit and his collaborators (*19*) (open circles) and MacGregor *et al.* (*20*) (closed circles). One sees immediately that we have a much more complicated interaction than that whose phase shifts are shown in Fig. 4.

Since nucleons are particles with one-half spin, the labels for states in Fig. 5 are same as those used in describing couplings between two electrons. The left superscript on each of the curves denotes the net spin $\mathbf{S} = \mathbf{s}_1 + \mathbf{s}_2$ of the N-N system, the superscript 3 (for triplet), denotes $S = 1$, and the superscript 1 (for singlet), denotes $S = 0$. The right subscript denotes the quantum number J, which characterizes the total angular momentum $\mathbf{J} = \mathbf{L} + \mathbf{S}$.

In Fig. 5 the ${}^3S_1$ phase shift starts at 180°, like the S wave of Fig. 4, but falls off more rapidly at high energies.

The ${}^1S_0$ phase shifts rise to positive values at low energies, but decreases rapidly after 100 Mev and actually goes negative at higher energies. This feature of S waves led to the early suggestion by Jastrow (*21*) that a hard core is present in the N-N interaction. However, we can account for this type of behavior using p^2-type, or velocity-dependent forces, such as illustrated in Fig. 1 (*22*).

The P and D wave phase shifts are shown in relation to the right scales.

Below 100 Mev these are much smaller than the S wave phase shifts. Thus, low energy nuclear interactions are dominated by attractive S wave interactions.

The fact that the $^1P_1$ phase shift goes directly negative signifies that the interaction in this state is repulsive. On the other hand the $^1D_2$ phase shifts climb toward positive values, indicating an attractive interaction in this state.

The ^3P and the ^3D phase shifts depend significantly upon the J value, that is, upon total orbital angular momentum in a complicated way. These are due to the complex competition between spin-orbit and tensor forces of the nature of those illustrated in Fig. 1, a and b.

There are greater discrepancies between the two sets of phenomenological phase shifts for the ^3S, ^1P, and ^3D states as contrasted with the ^1S, ^3P, and ^1D phase shifts. Because of a generalized exclusion principle (*18*) the former nucleon states correspond to isotopic spin zero ($T = 0$). Such states can only be investigated in neutron-proton (n-p) scattering experiments. The latter states correspond to nucleon isotopic spin one ($T = 1$) and can be studied in p-p experiments, which are usually very precise. The $T = 1$ states can also be studied in n-p experiments, but these are experimentally much more difficult to perform.

For the sake of brevity, we will not discuss higher phase shifts or the mixing parameters which measure the couplings between triplet states (*10, 18*).

In addition to the data on phase shifts, we also have the properties of the deuteron, the only bound state of the N-N system. Table 1 presents the deuteron data and certain low energy scattering properties of the N-N system. Also shown are the results of two theoretical models which will be described later. The precision and complexity of these deuteron data along with the phenomenological phase shifts serves now as exceedingly sharp criteria to judge proposed theoretical models of the N-N interaction.

The first quantitatively successful theoretical models of the N-N interaction were phenomenological potential models which were inductively determined from phase shifts and other N-N data. These efforts contributed greatly to the development of computational techniques and to our understanding of the ingredients of the N-N interaction. However, quantitative models became increasingly complex through the years. Recent models require as many as 30 to 50 adjustable constants (*10*), which is almost as many adjustable constants as are needed simply to fit the experimental phase shifts with empirical curves. Let us now consider the approach based upon meson theory.

Mesons and the N-N Interaction

Table 2 lists the properties (*23*) of the lightest mesons now known, the ones that are being used in realistic versions of OBEM. The first two columns give the designation and mass in million electron volts.

Column 3 gives the isotopic spin (designated in the convention of particle physicists as I) and G parity of each meson. Here a neutral ($I = 0$) meson is viewed as a scalar in "isospin space." A trio of positive, neutral, and negative mesons ($I = 1$) is viewed as a vector in isospin space, an "isovector." The G parity relates the meson-nucleon coupling to meson-antinucleon coupling.

Column 4 specifies the net angular momentum (J) of the meson in the fundamental unit $\hbar$. The superscript over the J values specifies the parity of mesons, an intrinsic internal symmetry property. Column 5 specifies the type of meson field associated with such mesons according to the notations S, scalar, V, vector, and P, pseudoscalar.

Column 6 gives the range of these mesons based upon Yukawa's relationship $a = \hbar/mc$. Column 7 gives a recent spectroscopic classification of these mesons afforded by the quark model (see Scalar Mesons and Quarks, below).

The π meson discovered in 1947 has received the greatest attention as the nuclear "glue." It is pseudoscalar having zero spin and negative parity (0−) which means, its own internal field changes sign if $\mathbf{r} \rightarrow -\mathbf{r}$. This contrasts with the scalar particle (0+) in Yukawa's original theory, which does not change sign. The exchange of single pions leads to the one-pion exchange

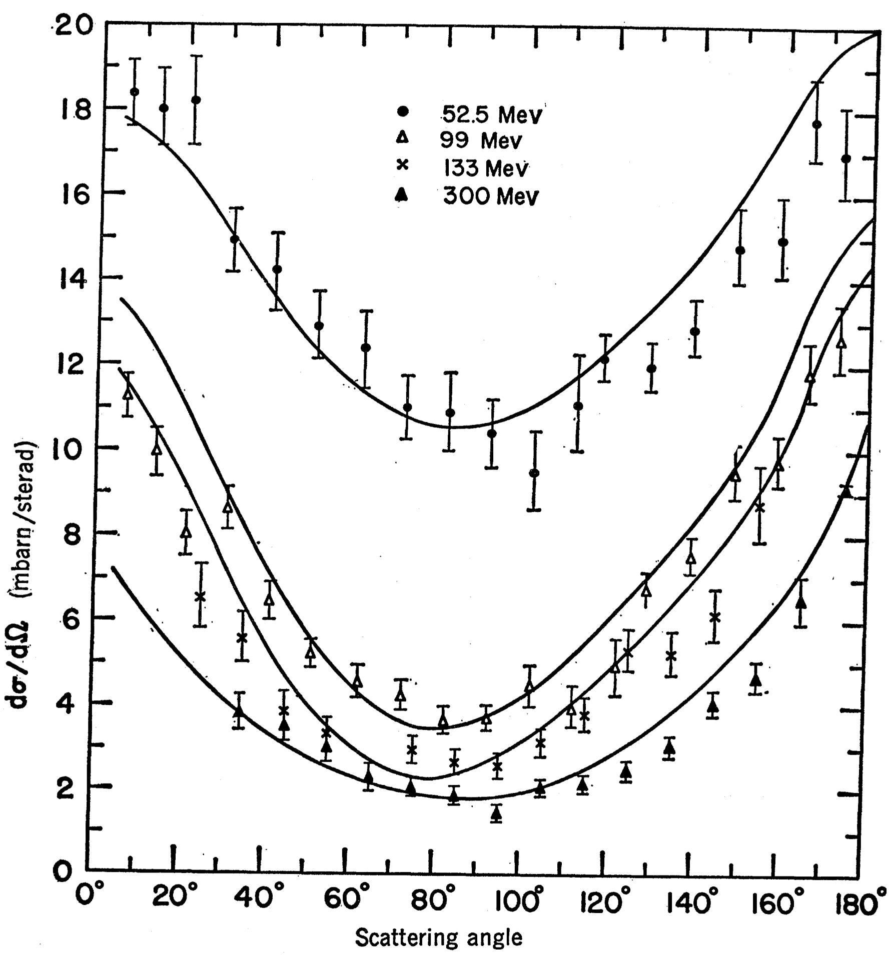

Fig. 3. Angular distributions of neutrons scattered by protons as represented by differential cross sections. The experimental data are shown by points along with error limits. The curves are for the Ueda-Green model III which is illustrative of fits with generalized one-boson exchange potentials.

potential (OPEP) consisting of purely relativistic spin-spin and tensor force terms. Because of its light mass and consequent long range, the π meson should dominate the outer region of the N-N interaction particularly for separations greater than 2 fermis.

The change in sign between ^1P and ^1D phase shifts in Fig. 5 is largely explained in terms of the spin and isotopic spin dependence of the interaction contributed by the π meson. A factor associated with spin and isotopic spin alternates between $-(3/16)$ and $(9/16)$ in singlet spin states. These numbers multiply $(4m\pi^2/3M^2)g\pi^2Y\pi(r)$ where M is the nucleon mass (939 Mev). If $g\pi^2 = 3000$ Mev · fermi almost all of the higher phase shifts and mixing parameters are fitted quite well by OPEP (*24*). However, the inner phase shifts and mixing parameters depart greatly from OPEP.

The difficulty of pseudoscalar theory, as well as other forms of meson theory, with inner phases in part arises because the Yukawa potential is singular near the origin, that is, it goes to infinity as r^{-1} as $r \rightarrow 0$ (see Fig. 2). Such a singularity arises if nucleons are assumed to be point sources. While an r^{-1} singularity can be coped with mathematically, the r^{-3} singularities associated with certain derivatives of Y connected with the tensor and spin-orbit forces present serious mathematical and physical difficulties. Moller and Rosenfeld (*5*) proposed the mixing of pseudoscalar and vector meson fields in an effort to overcome these singularity difficulties.

Another way was found by Green (*25*) by use of a generalized meson field theory. This theory was related to a generalized electrodynamics proposed by Podolsky (*26*) in which the usual $C = r^{-1}$ is replaced by $C - Y(r)$, a nonsingular function. In the generalized meson theory, $Y(r)$ is replaced by a generalized Yukawa function $GY = Y_1 + w_2Y_2 \; . \; . \; . + w_NY_N$, where the weights $w_1, w_2 \ldots$, are given by specified algebraic combinations of the meson masses. The curve labeled GY in Fig. 2 is an example of such a generalized Yukawa function. This function is much weaker than Y at close distances and is so smooth that the significant derivatives are regular at the origin.

The combining of vector with scalar fields was also proposed by Green (*27*) about this time. While the original bases for using a vector-scalar combination are still somewhat speculative, certain qualitative results of these early proposals are of interest. Thus in an interaction mediated by scalar plus vector fields one has a cancellation or approximate cancellation of the nonrelativistic static terms ($-g^2Y$ and g^2Y). With such a cancellation, the surviving spin and velocity-dependent terms, of the nature of those illustrated in Fig. 1, play a dominant role. The pseudoscalar field was also considered since it gives rise only to relativistic interactions. Generalized meson fields were used to avoid singularity difficulties. Unfortunately, computational techniques and experimental data were not sufficiently advanced in 1949 to validate a theory based primarily upon relativistic interactions.

The events described earlier related to the discovery of the ω, ρ, and η mesons in 1961 stimulated attempts to build up an N-N interaction out of a mixture of vector and pseudoscalar mesons. However, in such mixtures the large repulsive static term of the ω meson so dominates the interaction that little sense could be made until a neutral scalar meson was included. Its ad hoc purpose was to cancel or approximately cancel the repulsion of the ω yet preserved the spin orbit term. This approach was adopted almost simultaneously by several groups (*16*) in Japan and America, with several different mathematical formalisms. In applying the model, only exchanges of single mesons (which are bosons) rather than multiple meson exchanges (such as two pions, three pions, and so on) were considered, hence the name one-boson exchange models (OBEM). In effect, the heavier mesons or resonances are viewed to replace the multiple pion exchanges. The fact that these heavy mesons decay into multiple pions makes this view physically plausible.

By 1964 good fits to higher partial waves phase shifts had been obtained by three groups with only ten or so adjustable parameters in contrast to the 30 to 50 used in phenomenological studies. The most systematic studies were by the Japanese group of S. Sawada, S. Otsuki, T. Ueda, W. Watari, N. Hoshizaki, and M. Yonezawa using the so-called unitarized Born approximation, the California group of J. Ball, A. Scotti, and D. Y. Wong using the method of dispersion relations, and the California group of R. L. Bryan and B. L. Scott using the meson potential–Schrödinger equation approach. The close similarity of the potentials in the last study with those obtained in my work between 1947 and 1949, led me to resume my studies of relativistic models with generalized Yukawa functions. Then in a series of studies (*28*) in collaboration with T. Sawada, R. D. Sharma, and G. Darewych (*22*) and others, a number of models involving from one to eight adjustable parameters were found which fit the higher partial waves quite well but, in addition, gave excellent fits to S waves. Because of their close penetration, the S waves are the most important waves from the standpoint of nuclear physics, and particularly for studying the question "What holds the nucleus

Table 1. Properties of the N–N system; NM, nuclear magneton; F, fermi.

Property	Experiment	Model I	Model III
*Deuteron properties**			
Binding energy (Mev)	2.2245	−2.1	−2.6
Quadrupole moment (F^2)	0.282	0.28	0.27
Magnetic moment (NM)	0.857	0.856	0.855
Low energy scattering properties			
$^3S_1$ Scattering length (F)	5.399	5.6	5.2
$^3S_1$ Effective range (F)	1.82	1.8	1.8
$^1S_0$ Scattering length (F)	−23.6	−24	−23
$^1S_0$ Effective range (F)	2.69	2.7	2.7

* See Ueda and Green (*30*) and Gersten and Green (*31*).

Table 2. Strongly interacting mesons (*23*).

1	2	3	4	5	6	7
	Mass (Mev)	I^G	J^P	Field	Range (F)	Quark class
π	140	1^-	0^-	P	1.41	$^1S_0$
η	549	0^+	0^-	P	0.36	$^1S_0$
ρ	765	1^+	1^-	V	0.26	$^3S_1$
ω	783	0^-	1^-	V	0.25	$^3S_1$
δ	960	1^-	0^+	S	0.21	$^3P_0$
ϵ	740	0^+	0^+	S	0.27	$^3P_0$

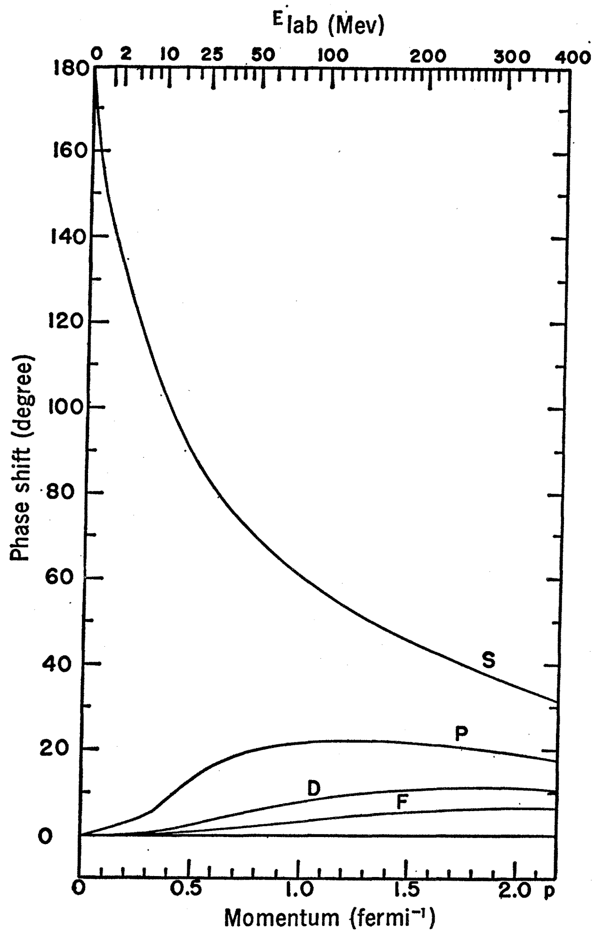

Fig. 4. Phase shifts of S, P, D, and F waves for a Yukawa potential with $g^2 = 79$ Mev · fermi and $m =$ 140 Mev. The vertical scale is in degrees. The lower horizontal scale gives the relative momentum in reciprocal fermis (F^{-1}), and the upper horizontal scale gives the corresponding laboratory energy.

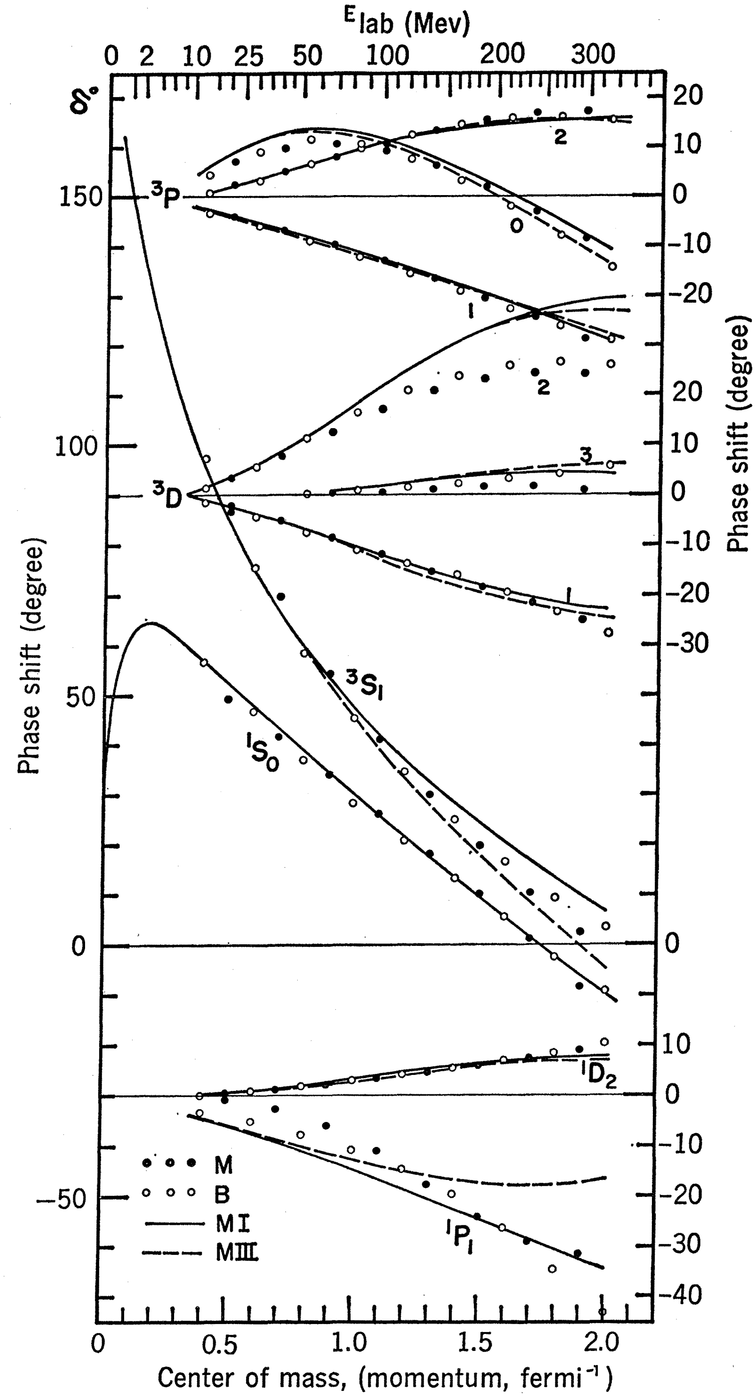

Fig. 5 (above). Phase shifts of S, P, and D waves. Phenomenological phase shifts of Breit *et al.* (*19*) are denoted by open circles and those of MacGregor *et al.* (*20*) by closed circles. Ueda-Green (UG) models MI and MIII are denoted by solid lines and dashed lines, respectively. Use left scale for $^3S_1$ and $^1S_0$ waves and right scales for P and D waves. [From Ueda and Green (*30*)]

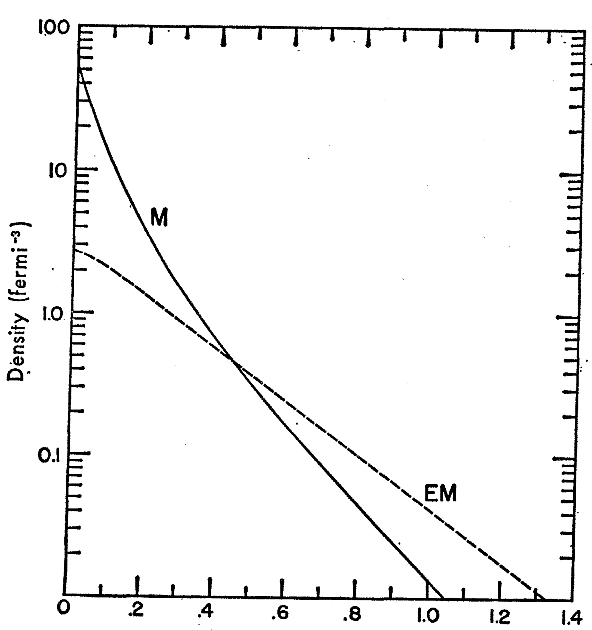

Fig. 6 (left). The curve EM represents a static charge density which can be associated with recent measurements at Stanford Linear Accelerator Center. The M gives the mesonic density on the Green-Ueda peel-off model.

together?" The key elements in the work of my group which accounted for our success with S waves was the inclusion of the p^2 (Ampere) term in the N-N interaction and the use of generalized superpositions of meson fields.

An opportunity for almost all the active experimental, phenomenological, and theoretical groups to get together to compare notes was afforded by the International Conference of the N-N Interaction held at the University of Florida early in 1967 (*29*). It became clear after 3 days of intensive discussion that, despite the great diversity of mathematical formalisms, practically all current theoretical approaches were converging toward similar physical models. The papers at the conference established a thread linking the most recent experimental measurements, their phenomenological interpretations, and the various recent forms of elementary particle theory to the earliest forms of meson field theory.

The two sets of theoretical curves in Fig. 5 are the results of my collaboration with T. Ueda, a member of the original Japanese OBEP group (one-boson exchange potential) (*30*), a collaboration which grew out of this N-N conference. The solid curves represent an eight-parameter model (UG-I) in which we used the π, η, ω, and ρ mesons along with two very heavy scalar mesons, the π_N and η_N, reported in recent meson tables. The dashed curves represent a six-parameter model (UG-III) using π, ω, and ρ mesons along with $I = 0$ and $I = 1$ scalar mesons at 782 Mev, the mass of the ω vector meson. These models contain one hypothetical component, a weakly coupled scalar particle with $m_\sigma = 3m_\pi$ which was in troduced phenomenologically to represent residual effects associated with 2π exchange, and other miscellaneous components. Both models provide good accounts of the deuteron properties, for example, binding energy, magnetic moment, and quadrupole moment (*31*). The theoretical phase shifts have been used to calculate the experimental observables themselves and yield good fits to experimental data (Fig. 3).

The success of both models, particularly for S waves depends critically on the use of generalized Yukawa functions of the type illustrated by GY in Fig. 2. Now there has been a long-standing interpretive difficulty associated with the use of linear superpositions of Yukawa fields. If the associated mesons are unconnected, then, according to certain interpretations, every other meson in a mass sequence would have been viewed to be objectionable—for example, move faster than light, require negative probabilities, or correspond to bosons with negative energy. However, it had been suspected for some time that the use of superpositions of meson fields may be related to the fact that nucleons are extended particles, as observed by Hofstader (*12*), rather than points.

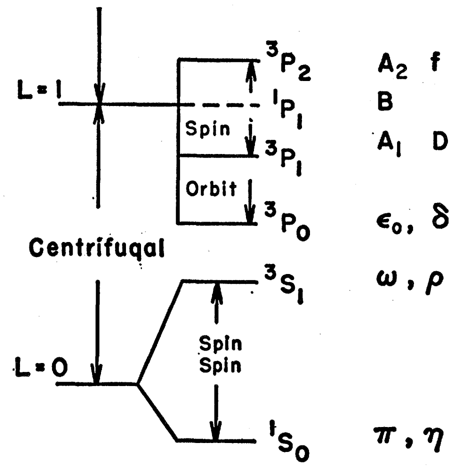

Fig. 7. Schematic diagram illustrating meson states according to $Q\bar{Q}$ or $N\bar{N}$ model. The splittings due to centrifugal, spin-spin, and spin-orbit effects are shown. Isotopic spin splitting and higher L states are not shown.

Recently, Ueda and Green (*32*) have given a detailed reinterpretation of a generalized Yukawa potential in a context of nucleons surrounded by their meson clouds. Indeed, using equations arising out of generalized meson theory they have obtained a very precise fit to the measurements made at the Stanford Linear Accelerator Center with 20-Gev electrons. Figure 6 illustrates a radial charge density (EM) which may be assigned from their final expression. Also shown (M) is the nature of the "nuclear meson charge" which may be assigned by taking a "peel-off" or shell model view of the nucleon source. Such a view seems natural to work with generalized one-boson exchange potentials (GOBEP).

Scalar Mesons and Quarks

One of the mysteries of this past decade has related to the reality or unreality of the scalar mesons that are needed in OBEP models, particularly the $I = 0$, or neutral scalar meson. Such a meson not only provides the primary attractive nuclear interaction in OBEP, but, in addition, it must compensate for the large repulsive interaction due to the $I = 0$ vector meson ω. The absence of a firmly established scalar meson has been viewed as a major weakness in the OBEP picture. Reports of scalar mesons with the necessary properties have appeared over the past 5 years but objections have been raised to interpretation of the data. However, at a conference (*33*) devoted largely to the data related to this resonance or meson, it was the consensus of all the major experimental groups that an S wave resonance or enhancement or a scalar meson ε exists somewhere in the mass neighborhood of the ω and ρ mesons. The resonance has a broad width, but whether this width is 150 or 400 Mev is still a matter of controversy.

Theoretical developments are now favorable to the existence of ε, in contrast to earlier unfavorable trends. For example, Lovelace (*34*) predicts an ε at 698 Mev with a width of 407 Mev using a unitarized Veneziano model, one of the latest developments in elementary particle theory. Speculations by Barger and Kline (*35*), extending the ideas of Regge trajectories, also lead to scalar mesons at the masses of vector mesons. An $I = 1$ scalar meson has gained firm acceptance among particle physicists, although there is still some confusion whether it is the δ at 962 Mev or the π_N at 1016 Mev. Schwinger (*36*) has also recently proposed a mass formula which gives identical masses to 0^+ and 1^- mesons.

The most easily described theoretical consideration favorable to the existence of the ε is the model of mesons as bound states of quark (Q) and antiquark ($\bar{Q}$) (*37*). While it is still uncertain as to whether quarks really exist, their usefullness as a guide to the classification of states of elementary particles has been firmly established (*23*).

According to this model, mesons are viewed to be tightly bound states of quarks and antiquarks. The composition of states follows all of the rules used in the couplings of two electrons in an atom such as the helium atom. Suppose quark and antiquark exist, each having a mass of 10 Gev for a total of 20 billion electron volts. If they are bound so tightly that it requires, say, 19.86 Gev to separate them then their composite mass would be 140 Mev. Such a state of a $Q\bar{Q}$ system would act in most respects like an elementary particle—in particular a pseudoscalar meson. Heavier mesons would be represented by excited states of the $Q\bar{Q}$ system just as the excited states of the helium atom (Fig. 7). These mesons could serve as the glue which is used in the N-N interaction. The recent $Q\bar{Q}$ picture for mesons is very similar to the old $N\bar{N}$ model of mesons put forth by Fermi and Yang in 1949 (*38*) and the Sakata model put forth in 1956 (*39*).

It might be noted that the $Q\bar{Q}$ or $N\bar{N}$ picture of mesons goes together very well with the vector-scalar theory of the nucleon-nucleon interaction. The fact that vector mesons have negative *G* parity (*13*) implies that a repulsive NN force goes over to an attractive $N\bar{N}$ force. On the other hand, the scalar meson having positive *G* parity maintains its attractive nature as one goes from NN to $N\bar{N}$. Thus, whereas a major cancellation of the large static interactions due to vector and scalar mesons occurs in the NN system, a major addition occurs in the $N\bar{N}$ system. If the vector-scalar coupling $g^2 \approx 2000$ Mev · fermi (as in realistic GOBEP) it acts in NN like the scalar coupling constant $(m^2/4M^2)g^2$ or 250 Mev · fermi. On the other hand in $N\bar{N}$ it is effectively like a scalar coupling constant of 4000 Mev · fermi. Since $e^2 = 1.44$ Mev · fermi, it is appropriate to call the NN interaction strong and the $N\bar{N}$ interaction very strong.

Conclusions and Summary

GOPEB based upon known mesons have been found which realistically describe a massive accumulation of the experimental nuclear data up to 400 Mev. The N-N potential according to these models consists primarily of weak residual central terms surviving the cancellation of large repulsive and attractive vector and scalar static components; relativistic interactions arising from the exchange of pseudoscalar, vector, and scalar mesons and dipole type terms arising from the ρ meson. The major dynamic terms are direct analogs of magnetic interactions illustrated in Fig. 1. Allowance must be made for the effective dependence of the coupling constants upon spin and isospin states. The nucleons are distributed sources which give rise to nonsingular generalized Yukawa functions in N-N potentials.

Although we have come a long way during this past decade, much remains to be done. Neutron experiments generally have low accuracy, so that it is difficult to apply statistical criteria in the testing of GOBEP models. The inconsistencies at higher energies between the two sets of phenomenological phase shifts are a reflection of this need for more accurate experimental data. The problem becomes particularly acute in what might be viewed as the intermediate energy region (between 200 Mev and 1 Gev).

As one goes to higher energies not only are π mesons produced but also nucleons are excited into various higher mass states. Such inelastic processes have yet to be incorporated in a realistic way in studies of GOBEP. In view of the relativistic nature of the nucleon-nucleon interaction it is necessary to develop relativistic wave equations particular for higher energy studies; such attempts are already under way (*40*).

In addition, as one goes to higher energy it will probably be necessary to embody the heavier mesons illustrated in Fig. 7, since their effects would be felt. Extensions of GOBEP, which include the totality of meson resonances and possibly the uncorrelated multiple meson exchanges, remain to be achieved.

There is also a great necessity for clarifying further the nature of the neutral scalar meson which cancels the repulsion of the ω and provides an attractive nuclear force in all states. Here it might be noted that, with the broad mass distribution of the scalar meson indicated by current particle physics data, it appears unnecessary to invoke any hypothetical mesons (such as a weakly coupled 416-Mev meson used in UG-1 and UG-III (*41*).

A more comprehensive discussion of the limitations of existing OBEP models has been given recently by Breit (*42*).

It should be noted that, for reasons of familiarity and convenient access, our detailed accounts have dealt largely with my efforts and those of my collaborators. However, other groups have also converged to models whose important ingredients are very similar. In particular, the most recent model of Bryan and Scott (*43*) has almost the same basic features as the GOBEP of Green and Sawada (*29*) and Ueda and Green (*30*).

In final conclusion, much remains to be done in improving theory, in improving experiment, in the matching of theory to experiment, and in relating GOBEP to the main streams of nuclear and particle physics. Nevertheless, it is gratifying that a reasonably simple quantitative description and an appealing physical picture of the major features of the N-N interaction finally appears to be emerging.

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44. I thank Professor Gregory Breit for suggestions and F. Riewe and L. D. Miller for assistance. Figure 1 is adapted from reference (*28*) and Fig. 5 from reference (*30*) with kind permission of the *Reviews of Modern Physics* and *The Physical Review*. Figures 2, 3, and 6 and portions of this work are taken from an article by the author in *OAR Res. Rev.* **8**, No. 4 (1969) with the kind permission of the Office of Aerospace Research Review. Supported by the United States Air Force Office of Scientific Research grant AF-AFOSR-68-1397.

Birth Control after 1984

Carl Djerassi

"It is unmistakingly clear that unless something is done about the population explosion, we will be faced with an unprecedented catastrophe of overcrowding, famines, pestilence and war. . . . If we are to significantly help in the worldwide fight to curb the population explosion, there must be developed a simple and safe method that can be made available to populations on a massive scale."

These are the words of the U.S. Senate's most vocal critic (*1*) of oral contraceptives, and it behooves us to consider what some of the future contraceptive methods might be and especially what it might take, in terms of time and money, to convert them into reality. There are many publications on this subject, but none seems to have concerned itself with the logistic problems associated with the development of a new contraceptive agent. In that connection, it is instructive to note that, in Platt's list (*2*) of world crisis problems, only total nuclear or chemical-biological warfare receives higher ratings than the problems arising from the world's burgeoning population, and that, of the four top priority problems, only fertility control requires experimentation in humans for its ultimate solution.

The surprisingly rapid acceptance during the last decade of intrauterine devices (IUD's) and of steroid oral contraceptives in many developing and developed countries is principally due to the fact that their use separates, for the first time, contraception from copulation, and it is clear that effective birth control methods of the future must exhibit this same property. A long list of new approaches to contraception could be developed from a recent World Health Organization report (*3*), but for the purposes of this article—the outlining of logistic problems, the determination of time and cost figures, and, finally, recommendations for implementation—I have selected only three topics.

1) A new female contraceptive (*4*), consisting of a "once-a-month" pill with abortifacient or luteolytic (menses-inducing) properties. I have selected such a method because it is scientifically feasible, it should lend itself to use in both developed and developing countries, and it addresses itself to the critically important subject of abortion. I also make some mention of prostaglandins in that connection.

2) A male contraceptive pill.

3) A draconian agent, such as an additive to drinking water. I included this approach, not to justify the Orwellian overtones of this article's title, but rather to place into realistic perspective the problems of developing such an agent, which is mentioned with increasing frequency as the final solution if voluntary methods should fail.

Specifically excluded from my list are sterilization, for discussion of which I lack the needed technical familiarity, and mechanical devices. My reason for excluding mechanical devices, such as IUD's, which, unlike condoms or diaphragms, fall within the definition of "contraception divorced from coitus" is as follows: their rapid introduction into public use during the 1960's is due largely to the fact that, until now, clinical research with IUD's has fallen outside the scope of government regulatory agencies such as the Food and Drug Administration (FDA). However, it is highly likely that public (*5*) as well as scientific (*6*) pressure on government regulatory bodies will require that such devices also be brought within the scope of their control and that clinical use of these devices be preceded by the same type of stringent testing that is demanded for contraceptive drugs. I emphasize these arguments only to point out that the cost and time estimates made by me later in this article in connection with new chemical contraceptive agents probably will also apply to new devices of the IUD type.

All the advances in fertility control considered by the World Health Organization group (*3*) are based in one way or another on chemical approaches. As I have pointed out elsewhere (*7*), this type of research on fertility control is exceedingly complicated, in both its preclinical and clinical phases; the required manpower and financial resources are available only in the technologically most advanced countries. I emphasized (*7*) the fact that the new birth control agents of the future, even though they may be used predominantly in the developing countries, will almost certainly be generated only in countries of North America or Europe. They will, therefore, be subject to the government regulatory bodies of those countries, and,

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