CONF-790610--3

LA-UR-79-1510

MASTER

TITLE: MESONIC AND RELATIVISTIC EFFECTS IN THE NUCLEAR ELECTROMAGNETIC INTERACTION

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Invited talk given at

International Conference

on

Nuclear Physics with Electromagnetic Interactions

June 5-9, 1979 Mainz, Germany

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CONTRACT W-7405-ENG. 36

MESONIC AND RELATIVISTIC EFFECTS IN THE NUCLEAR ELECTROMAGNETIC INTERACTION*

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It is very convenient to divide the subject of mesonic effects in nuclei into two separate categories: effects which are basically nonrelativistic and those which are of relativistic order.[1] This only makes sense if a nucleus is a weakly bound system of nucleons, with characteristic velocities that are slow compared to the speed of light. Fortunately this is true, since v/c is p/M, where p is a typical momentum (100-200 MeV/c) and M is the nucleon mass. Thus $(v/c)^2$, which characterizes relativistic corrections, is typically 1-few percent and dimensionally will be reckoned as $1/M^2$. Because a nucleus is weakly bound, the potential V and kinetic energy $T(\sim 1/M)$ are roughly equal and opposite, so we count V as order (1/M). Similarly, the charge $(\rho(\vec{x}))$ and current $(\vec{J}(\vec{x}))$ operators can be expanded in powers of 1/M, as shown in Fig. 1.

$\left(\frac{1}{M}\right)^3$ $\Delta\vec{J}_0$, $\Delta\vec{J}_{ex}$ (nonstatic)

$\Delta\rho_0$, $\Delta\rho_{ex}$ $\left(\frac{1}{M}\right)^2$

$\left(\frac{1}{M}\right)$ $\vec{J}_0$ (nonrel), $\vec{J}_{ex}$ (isovector, static)

ρ_0 (nonrel) $\left(\frac{1}{M}\right)^0$

FIG. 1. Relativistic classification of charge and current operators.

The nonrelativistic charge operator ρ_0 is of order $(1/M)^0$, while the relativistic corrections are order $(1/M^2)$ and are of two types: kinetic $(\Delta\rho_0)$, and potential-dependent $(\Delta\rho_{ex})$ of the two-body (or n-body) meson exchange type. The electromagnetic spin-orbit interaction, which generates the fine structure splitting in the hydrogen atom, is an example of one contribution[2,3] to $\Delta\rho_0$. The nonrelativistic current is of order (1/M), while the first correction is of order $(1/M)^3$. The nonrelativistic current itself has two components: the ordinary convection and spin magnetization currents, denoted $\vec{J}_0$, and the static meson exchange currents of order $V(\sim 1/M)$, denoted $\vec{J}_{ex}$. The latter are absolutely necessary if charged mesons participate in the genesis of the nuclear force. This follows from the current continuity equation

$$\vec{\nabla}\cdot\vec{J}(\vec{x}) = -i[H,\rho(\vec{x})] \quad , \tag{1}$$

where H(= T + V) is the nuclear Hamiltonian. Static (local) potentials depend only on coordinates, spins and isospins. Furthermore, the nonrelativistic charge operator ρ_0 has the form of a sum over the nuclear protons

$$\rho_0(\vec{x}) = \sum_i \left(\frac{1+\tau_3(i)}{2}\right) \delta^3(\vec{x}-\vec{x}_i) \quad , \tag{2}$$

assuming point nucleons. Any isospin dependence in V^0_{ij}, the two-body, static potential between nucleons i and j, must have the form $\vec{\tau}_i \cdot \vec{\tau}_j$ and this fails to commute with τ_3, generating isospin factors of the form $(\vec{\tau}(i) \times \vec{\tau}(j))_3$. The latter form is the classical isospin dependence of meson exchange currents. Since the current $\vec{J}_0$ and the usual kinetic energy term in H satisfy Eq. (1) by themselves, we are forced to introduce a two-body current, $\vec{J}_{ex}$, which we call the exchange or interaction current, and which satisfies

$$\vec{\nabla}\cdot\vec{J}_{ex}(\vec{x}) = -\, i[V^0, \rho_0(\vec{x})] \tag{3}$$

Thus, current continuity and the isospin dependence of the nuclear force guarantee the existence of exchange currents.

It is an intractable problem to deduce the form of two-body currents using any kind of phenomenological approach. For this reason exchange current calculations have tended to follow the approach used in ab initio calculations of the nuclear force: concentrate on single and multiple meson exchanges of the lightest mass, which generate the long-range parts of the potential. Short-range parts of the potential are not understood and are generally approached phenomenologically. Most exchange current calculations have concentrated on one-pion-exchange, although single ρ- and ω-meson exchanges are common. Some work has also been performed on the two-pion-exchange currents.[4] Some of the physical processes which contribute to the current in a two-body system are shown in Fig. 2: The impulse approximation is illustrated in (a), with the blobs depicting initial and final wave functions; the "pair" contribution is shown in (b), while the gauge term needed for current conservation in some fundamental (γ,π) theories is depicted in (c); the true exchange graph is shown in (d), while the recoil graph and disconnected graph are shown in (e) and (f); three contributions involving isobars and meson decay vertices are illustrated in (g), (h), and (i).

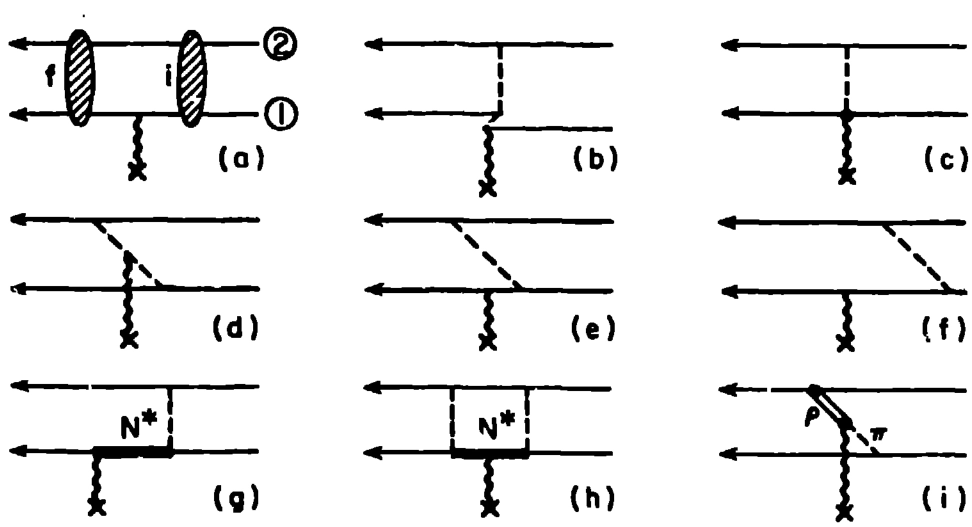

FIG. 2. Time-ordered Feynman diagrams which contribute to exchange currents.

The recoil and disconnected graphs have been the subject of much controversy and will be discussed later. In these figures the cross represents the electromagnetic interaction and the dashed line depicts any meson exchange.

The impulse graph is the usual amplitude of the form $\langle f|\hat{O}|i\rangle$, where $\hat{O}$ is a sum of one-body operators, and is generally the most important contribution to any process. The pair process is usually the second most important process. For the γ_5-model of coupling pions to nucleons it generates large isovector, static currents; in the $\gamma^\mu\gamma_5$-model of π-nucleon coupling, the pair term is small, but the gauge term of Fig. 2c is identical to it. The identity is the result of a powerful (although approximate) theorem known as the equivalence (of the two couplings) theorem.[5] Both diagrams will be referred to as "seagull" diagrams. The true exchange graph also produces a substantial static isovector contribution. Somewhat less important are the isobar diagrams; they will be discussed by Professor Weber and I will have little to say about them or the $(\rho\pi\gamma)$- and $(\omega\pi\gamma)$-contributions illustrated in Fig. (2i).

What is the evidence for meson exchange currents in the nuclear electromagnetic interaction? The classical test for exchange currents is provided by comparing experimental magnetic moments with impulse approximation calculations. Because structure effects are difficult to calculate in many-body systems, the two- and three-body systems provide the best tests. The simplest system is the deuteron; its magnetic moment, expressed in nuclear magnetons, is given by the expression[1]

$$\mu_D = \mu_s^0 - \frac{3}{2} P_D \left(\mu_s^0 - 1/2\right) + \Delta\mu_D = 0.8574 \tag{4}$$

where $\mu_s^0 = \mu_p + \mu_n = 0.8796$ is the isoscalar nucleon magnetic moment, P_D is the percentage D-state of the deuteron and $\Delta\mu_D$ is the contribution of all the meson exchange and relativistic corrections. The first observation is that even if P_D and $\Delta\mu_D$ were zero, the discrepancy would be small, approximately 2 1/2 percent. Assuming $\Delta\mu_D = 0$ yields $P_D = 3.9$ percent; this would be a (doubly) dangerous assumption, however, since $\Delta\mu_D$ is not zero and P_D is inextricably linked to $\Delta\mu_D$ in a way that we will discuss later. Both P_D and $\Delta\mu_D$ are uncertain. Nevertheless, the size of the discrepancy is typical of both isoscalar mesonic and relativistic corrections.

A better example of the kind we are looking for is provided by the ^{3}He-^{3}H system.[6,7] Its magnetic moments may be decomposed into isoscalar and isovector components:

$$\mu_s = \mu_{He} + \mu_H = \mu_s^0 - 2P(D)(\mu_s^0 - 1/2) + \Delta\mu_s = \begin{cases} 0.852 \text{ (exp.)} \\ 0.812 \pm .015 \text{ (theory)} \end{cases} \tag{5}$$

$$\mu_v = \mu_{He} - \mu_H = \begin{cases} -5.106 \text{ (exp.)} \\ -4.280 \pm .070 \text{ (theory)} \end{cases} \tag{6}$$

The theoretical numbers were calculated using impulse approximation and assuming reasonable numbers for the amounts of the small components of the three-body wave function.[8] Errors were generated assuming a ±2% uncertainty in P(D), the total amount of D-state in the trinucleon. The isoscalar magnetic moment formula is nearly the same as the corresponding deuteron equation. A 5% discrepancy exists in μ_s, but this is considerably smaller than the 16% discrepancy in the isovector moment. Calculations[7] estimate the contributions of the pion seagull and exchange graphs and the isobar graphs to be -(0.8-1.0), which are sufficient to bring the isovector calculations close to experiment. The isobars are quite important.

Alternatively, we can look at the magnetic moment distributions[7] in ^{3}He and ^{3}H. Fig. 3 shows the magnetic form factors of ^{3}He and ^{3}H. The difference between the dashed and solid curves shows the importance of the trinucleon D-state to the impulse approximation, while the dashed-dot curve includes exchange currents. The latter effect is rather dramatic, although the sensitivity of the impulse approximation to the details of the wave function makes this process less than perfect evidence for mesonic currents.

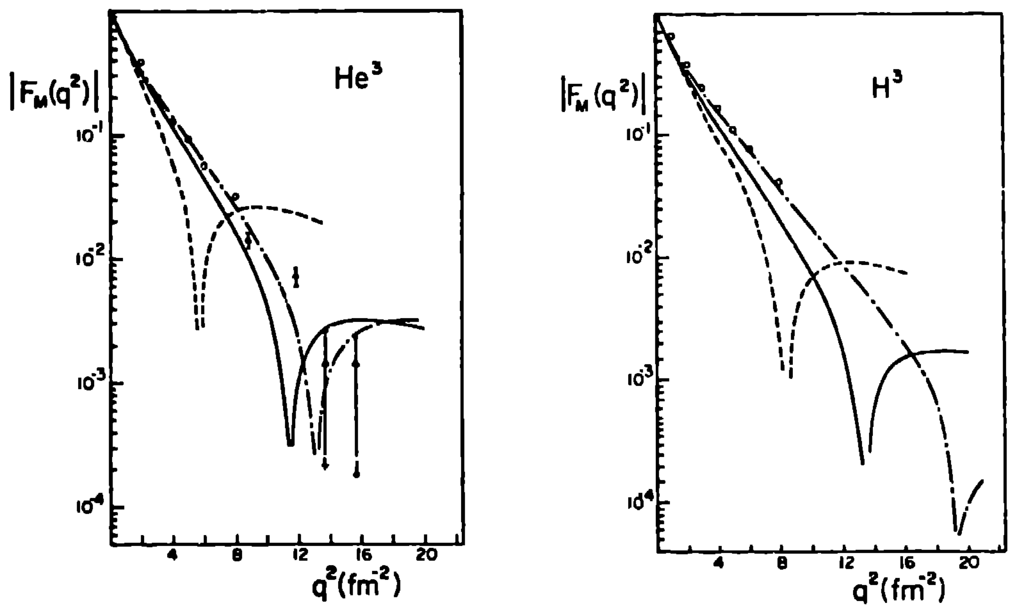

FIG. 3. ^{3}He and ^{3}H magnetic form factors vs. momentum transfer.

The best evidence for exchange currents is not static magnetic moments, but rather transition magnetic moments. Radiative capture of thermal neutrons on protons proceeds from the $^1S_0$ two-nucleon state (d*) to the deuteron ground state via an M1, isovector photon. The experimental cross section is 334.2 ± 0.5 mb, while impulse approximation calculations estimate 302.5 ± 4 mb. This 10% discrepancy had existed for many years, until Riska and Brown[9] calculated the seagull, exchange, and isobar contributions and found that the first two accounted for 6 1/2% and the latter for 2-3% of the missing cross section. Although exchange currents had long been thought to be the culprit, the dominant seagull contribution, astonishingly, had been overlooked.

Even more convincing evidence of exchange currents is provided by the inverse reaction,[10] $\gamma^* + d \rightarrow d^*$, with the virtual photon (γ^*) provided by an electron scattered through 180° in order to isolate the transverse (M1) components of the interaction. The photon has low energy, typically a few MeV, in order to suppress the large p-wave electrodisintegration process, but it may have arbitrary momentum. The experimental cross sections are shown in Fig. 4, compared to an impulse approximation calculation and separate calculations[11] based on pion-exchange currents only (π) and on all contributions including isobars (N*). There is little reason to choose between the latter two calculations in comparison with the data. This reaction, with its factor of 10 between impulse approximation and exchange current contributions, is the most graphic evidence for the latter phenomena. It offers only limited evidence for isobar contributions, however.

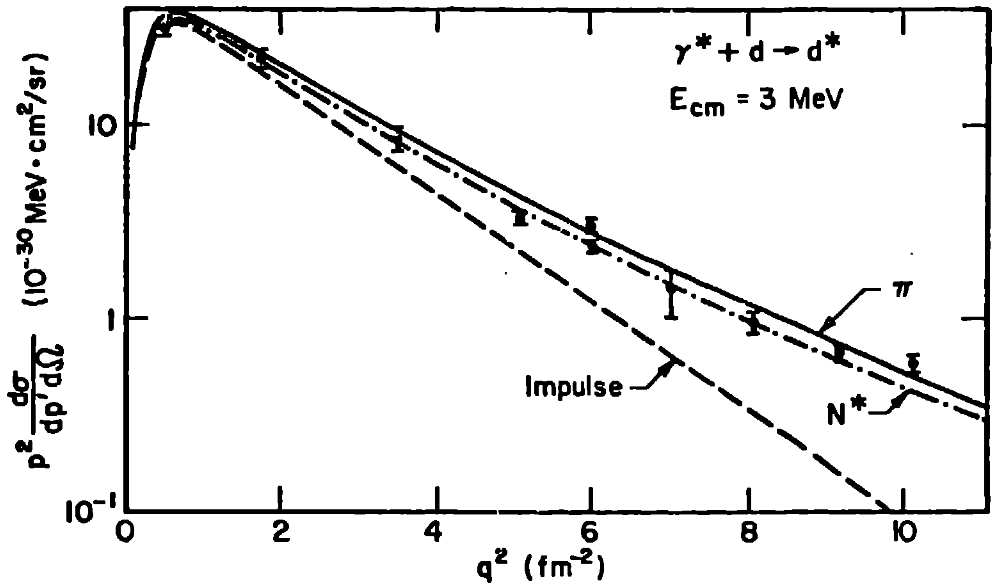

FIG. 4. Electro-excitation cross section for $d \rightarrow d^*(^1S_0)$ vs. momentum transfer.

The remaining physical process we will mention is the three-body analogue of thermal n-p capture, namely, thermal n-d capture to ^{3}H. This is also an M1 process, but is greatly suppressed compared to n-p capture, as shown by Schiff[12] many years ago. A selection rule eliminates the dominant s-wave component of the ^{3}H wave function and the impulse approximation proceeds through small components of the wave function generated by the difference of the n-n and n-p forces. The experimental cross section is 0.65 ± .05 mb, while impulse approximation[13] is estimated to be 0.30 mb; a complete calculation including exchange currents yields 0.52 mb. In view of the uncertainty that surrounds small components of wave functions, this is satisfactory agreement. Hopefully, more work on this interesting and difficult process will be forthcoming, including low energy M1 electro-excitation of the tri-nucleon system.

Although the (roughly) 10% isovector corrections we have examined appear small, they are suppressed because the impulse approximation results are unnaturally large. The isovector magnetic moment of the nucleon, μ_V^0, is 4.7, an enormous enhancement relative to 1 being produced by large isovector "currents" inside the nucleon. Since the isovector spin magnetization operator in a nucleus is proportional to μ_V^0, a 10% exchange current correction in a magnetic process is actually a 50% effect relative to "bare" nucleon currents. The nonrelativistic impulse and exchange current contributions are roughly comparable if we neglect the nucleons' anomalous magnetic moments.

The credible evidence for exchange currents presented above has been largely confined to isovector, static currents corresponding to one-pion-exchange. What about heavier meson exchanges? They obviously contribute; unfortunately there are more uncertainties about calculational details than for pions. In addition, even in the pion case, there are unknown form factors which can substantially affect the short-range part of the exchange operators.[11] Almost every calculation, either implicitly or explicitly, makes use of the fact that short-range operators are suppressed by the strong repulsion built into the nucleon-nucleon potential for small separation. A typical schematic potential is illustrated below with the corresponding deuteron wave function, clearly depicting the "hole" caused by the repulsion. The hole is one reason that contributions from ρ, ω, and other mesons to exchange currents are suppressed. It is fair to state that the interior region of the potential is not understood at all, and that the use of local potentials with soft or hard cores is phenomenology based on expediency. Consequently, there is a fair amount of uncertainty even in the static calculations.

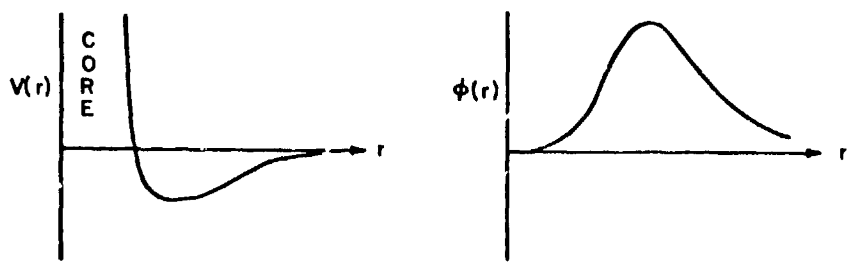

FIG. 5. Schematic depiction of two-nucleon potential, V, and deuteron wave function, φ.

We summarize this section by making the following observations: (1) The static, nonrelativistic isovector exchange currents are needed to explain discrepancies of the order of 10% in various magnetic processes. (2) The corresponding exchange current operators are fairly well-defined and unambiguous, except for unmeasured strong interaction form factors. (3) Wave function and nucleon-nucleon potential uncertainties still plague us, but calculations are reasonably reliable.

Recommendations: (1) Not too much attention should be paid to the last few % of the 10% isovector discrepancies. In addition to the wave function and form factor uncertainties, relativistic effects can also contribute at the level of a few percent of the impulse approximation.

Although the agreement of experiment and theory for the nonrelativistic, isovector processes is impressive, no such agreement exists for relativistic corrections. Indeed, there is little agreement between theorists and, as we will see, no comparison between theory and experiment is possible in many instances. Nevertheless, very substantial theoretical progress has been made in the past half dozen years. We will describe briefly the most important features of relativistic calculations, or more precisely, calculations that include $(v/c)^2$ corrections, which we will denote "relativistic".

An impressive series of papers by Foldy[14] and his collaborator Krajcik[15] has detailed many of the dynamical constraints that a many-body system must satisfy in order that the constraints of relativity be satisfied. One obvious constraint is that if the energy of a system is $\hat{M}$ in its center-of-mass frame, it must be $(\vec{P}^2 + \hat{M}^2)^{1/2}$ in a general frame, when the system has momentum $\vec{P}$. Foldy showed that, to order $(v/c)^2$, this condition implied that the wave function in the general frame must have the form

$$\psi_{\vec{P}} = (1 - i\chi(\vec{P}))\psi_0 e^{i\vec{P}\cdot\vec{R}} \quad (7)$$

expressed in terms of the usual coordinate and momentum variables and the rest frame wave function ψ_0. The function χ can be further split into a kinetic part, χ_0, and a potential-dependent part, χ_v. The former function is completely specified, while the latter is not unique, depending explicitly on the particular dynamics of the system. The function χ_0 is the primary mechanism by which the various phenomena of special relativity such as Lorentz contraction and the Thomas precession[3] enter into calculations of matrix elements. The Lorentz contraction term in χ_0, and the fact that the contraction is different in the initial and final states of a system struck by an electron, are sufficient to show[5] that the usual nonrelativistic charge form factor of the system, $F(\vec{q}^2)$, should be replaced approximately by $F(q^2)$, where $\vec{q}$ and q are the three- and four-momentum transfer. This is illustrated below. Although replacing $\vec{q}^2$ by q^2 is usually done in an ad hoc manner, it is immensely satisfying that the mechanism for this is now understood. An obvious corollary of this argument is that every relativistic formalism contains χ_0, either implicitly or explicitly. A complication is that χ_v can be different for every formalism.

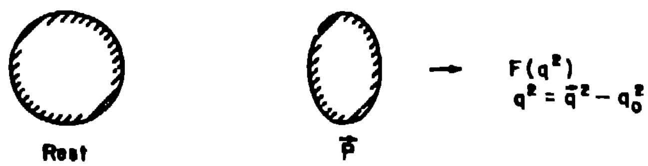

FIG. 6. Schematic Lorentz contraction effect on a nucleus.

Although Foldy's work centered on relativistic constraints, a large body of work has adopted the Bethe-Salpeter equation as its starting point and has "mapped" this four-dimensional equation into a three-dimensional equation, called a quasipotential equation or a Blankenbecler-Sugar reduction.[17] Unfortunately, an infinite number of ways of accomplishing this mapping are possible. The basic problem is easily stated by examining the propagator for exchanging a single meson of mass m and four-momentum $q = (q^0, \vec{q})$ in any Feynman diagram: $V/(\vec{q}^2 - q_0^2 + m^2)$. Ignoring the unimportant vertex factor V, we see that the $\vec{q}^2 + m^2$ term, which has the familiar Yukawa form in coordinate space, is modified by a relative energy variable, which has no nonrelativistic analogue. This variable cannot simply be thrown away. A variety of prescriptions exist for eliminating q_0 in favor of other quantities. The best known of the quasipotential methods is that of Franz Gross.[18]

Another problem is that many of these formalisms generate an effective two-nucleon potential V(E) which depends on the total energy E, as well as the momentum. Momentum-dependent potentials are messy but present no conceptual problems. In fact, relativity demands a momentum-dependent potential. Energy-dependence, on the other hand, requires a serious reexamination of the common theorems of quantum mechanics. In particular, if we posit a Hamiltonian $H_0 + EV'$, where V' is the (Hermitian) energy-dependent potential component and H_0 (also Hermitian) contains the energy-independent component, the usual derivation of wave function orthogonality produces

$$(E_f - E_i)\int \psi_f^+ (1+V')\psi_i = 0 \qquad (8)$$

using

$$(H_0 + E_{f,i}V')\psi_{f,i} = E_{f,i}\psi_{f,i} \quad . \qquad (9)$$

Although there are (justifiable) reasons of expediency for introducing energy-dependence in V, the price we pay is a redefinition of the wave function orthogonality condition. Another problem is that ψ^2 no longer has a clear interpretation as the probability density. One easy way to eliminate the problem[16] is to define $\sqrt{1+V'}\,\psi$ as the "proper" wave function. Nevertheless, every internally consistent formalism "knows" if the effective potential is energy-dependent and will generate transition operators (e.g. the charge operator) containing V' in order to preserve orthogonality.[1] This is the origin of the recoil graph which has been controversial for a number of years. The static limit of this contribution is the V'-term we introduced above; it is present in most perturbation theory expansions because these expansions generate an energy-dependent potential. It is therefore not possible to say that a recoil contribution is correct or incorrect. If the formalism generates such a contribution because the corresponding potential is energy-dependent, it is incorrect to substitute an energy-independent potential and keep the recoil graph. Unfortunately this has been done in the past. It would be just as incorrect to drop the static recoil graph, when using an energy-dependent potential, however.

In our opinion, an energy-dependent potential is a serious technical defect.

Others agree with this assessment, and a variety of formalisms have been developed to eliminate such a dependence; all have a vanishing recoil graph in the static limit. Several of these methods are: (1) the renormalization method that I use,[19] which is analogous to the renormalization technique of field theory; (2) the FST method[20] used by Gari and Hyuga;[21] (3) the folded diagram method of Mikkel Johnson;[22] (4) the quasi-potential method of Franz Gross[18] for one-boson-exchange potentials. The resolution of the recoil graph problem, as it existed for the nuclear charge operator, was originally demonstrated[19] using technique 1. Woloshyn[24] then showed that Gross's formalism does not need a (static) recoil graph. Later Gari and Hyuga repeated our calculation using the FST method. The static recoil graph cancels automatically using the folding method.

Another problem also affects the construction of three-dimensional equations; this is potentially more serious, and certainly more confusing, than any of the problems listed above. In the first complete treatment of the $(v/c)^2$ one-pion-exchange contributions to the isoscalar charge operator, it was pointed out[19] that different methods of calculating the non-static parts of the various graphs gave different results. In addition, the corresponding potentials were calculated from the disconnected graphs and were found to be slightly different in <u>non-static</u> terms. It was demonstrated that the set of different Hamiltonians and corresponding charge operators were <u>unitarily equivalent</u>. This guarantees that matrix elements calculated using the various sets of operators were identical. The values of the quadrupole or magnetic moments must be the same, for example. The unitary transformation which connected the different representations is the mechanism by which the equivalence theorem in a nucleus is proven.[5] This transformation has one remarkable property:[24] it can change the percentage D-state of the deuteron, P_D. This is not particularly difficult to visualize, since the transformation contains a tensor operator which can change S-state wave function components into D-state components. At the same time it changes the amount of exchange currents. For isoscalar systems it is even possible to <u>choose</u> the exchange parts of the charge operator to be <u>zero</u>. Since there is no physics in a unitary transformation (it is a mathematical tool), it follows that it is impossible to measure P_D or the amount of exchange currents. These quantities are of interest only to the theoretician.

Somewhat later another unitary equivalence was discovered[5] which is related to the way retardation of the meson-exchange potential is handled (i.e. the q_0^2-term in the meson propagator we examined earlier). This equivalence was discovered independently by M. Johnson[22] using his folded diagram method. We wish to state categorically that it is not possible to reliably calculate $(v/c)^2$-corrections to matrix elements unless both operators <u>and</u> wave functions are calculated to this order. This point has been stressed by Woloshyn[23] and the author. Unfortunately none of the calculations which have been performed on <u>exchange</u> contributions to charge and isoscalar current operators have calculated the wave function effect; the wave functions they used corresponded to none of the representations which are correct. At the level of reliability of these calculations, they could have chosen to make the answer zero.

Recently, a substantial advance[25] was made when it was shown that the FST, folded diagram, Gross quasipotential, and the author's renormalization methods gave identical one-boson-exchange results for the deuteron charge form factor. These methods generate results in a wide variety of different representations. It was only when the results were converted to a common representation that the equivalence could be proven. We emphasize that matrix elements, not operators, are physical quantities.

After this litany of problems associated with calculations of relativistic exchange phenomena, is it reasonable to assume that there exists definitive evidence of relativistic exchange contributions to charge or current operators? Certainly not in nuclear physics! The best evidence for such relativistic phenomena comes from atomic physics, where the ambiguities we discussed have been known for a long time and a consensus has been reached on how to handle them. There are interaction currents in atomic physics (exchange currents caused by photon exchange) that are identical in origin to certain of the isoscalar meson-exchange currents which contribute to the deuteron. In Helium-like atoms, which have two electrons and a nucleus with arbitrary charge Z, there are several transitions which are forbidden to occur in the unretarded, nonrelativistic limit. The low-lying states of such an atom are shown schematically below.

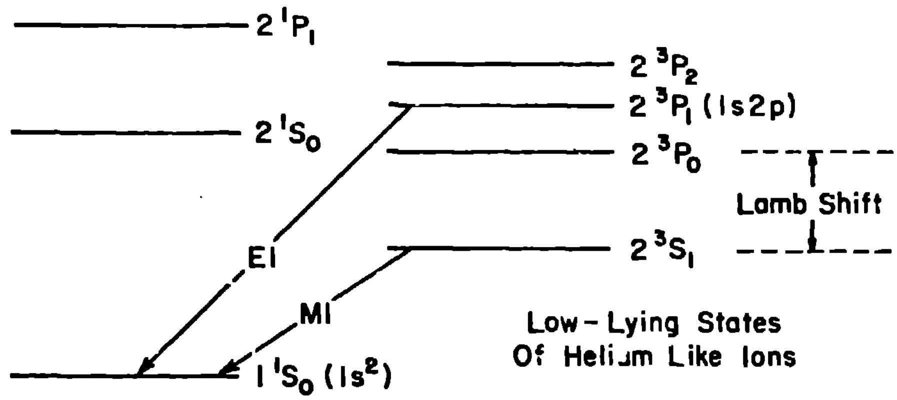

FIG. 7. Low-lying states of Helium-like ions.

One of these special transitions occurs from the $^3S_1$ state to the $^1S_0$ ground state. Relativistic corrections dominate the transition rate. Roughly half of the total rate is due to an interaction current which has been calculated by a method almost identical to the author's method of calculating exchange currents.[26] The figure below illustrates how well experiment and theory agree. Another example is the spin-flip $^3P_1$–$^1S_0$ E1-process, which proceeds through relativistic corrections to the usual nonrelativistic operators and through relativistic components of the wave function.[27,28] As we stated earlier, both operators and wave functions must be calculated to the same accuracy in order to obtain a reliable result.

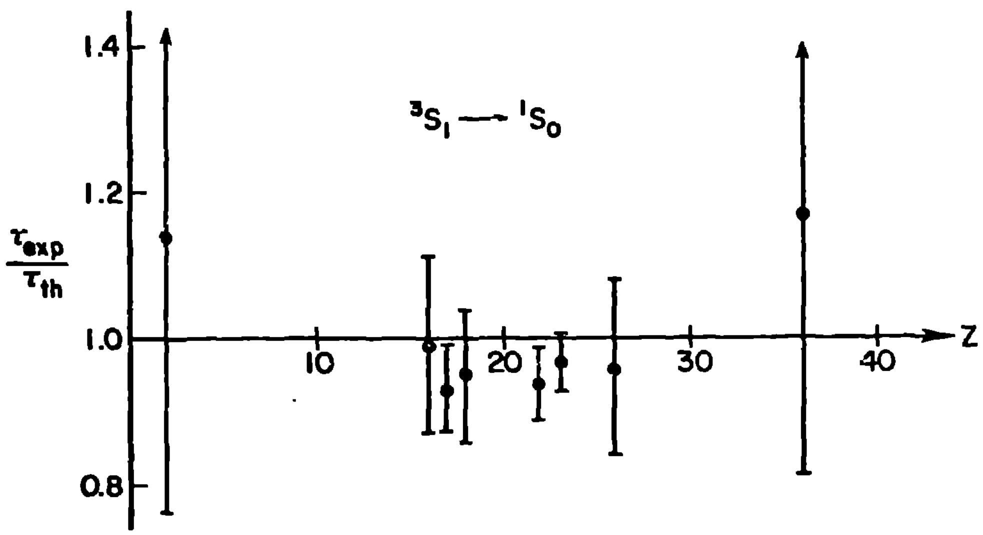

FIG. 8. Experimental to theoretical lifetime ratio appropriate to the $^3S_1$ to $^1S_0$ transition in Helium-like ions.

Conclusions: (1) Many "ambiguities" exist which are a feature of relativistic theories. These ambiguities complicate calculations, but are tractable. (2) No evidence of relativistic exchange currents exists in nuclear physics, although good evidence exists in atomic physics.

Recommendations: (1) It serves no useful purpose to calculate relativistic effects without a corresponding treatment of wave functions. (2) More effort should be spent investigating the properties of quasipotential equations and other methods for performing relativistic calculations. (3) Semiphenomenological nucleon-nucleon forces that include all non-static relativistic effects of order $(v/c)^2$ should be developed and used to investigate isoscalar exchange effects.

*This work was performed under the auspices of the U. S. Department of Energy.

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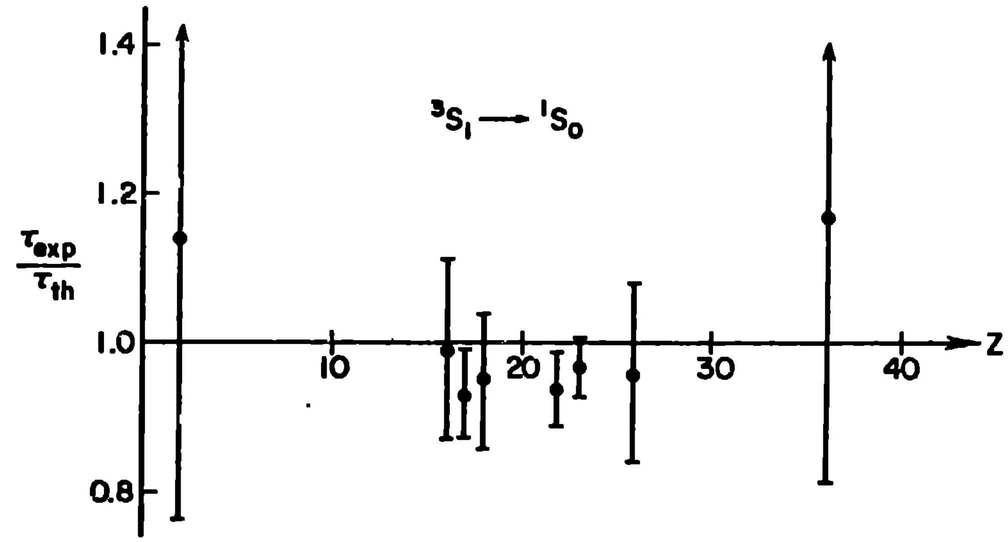

FIG. 8. Experimental to theoretical lifetime ratio appropriate to the $^3S_1$ to $^1S_0$ transition in Helium-like ions.

Conclusions: (1) Many "ambiguities" exist which are a feature of relativistic theories. These ambiguities complicate calculations, but are tractable. (2) No evidence of relativistic exchange currents exists in nuclear physics, although good evidence exists in atomic physics.

Recommendations: (1) It serves no useful purpose to calculate relativistic effects without a corresponding treatment of wave functions. (2) More effort should be spent investigating the properties of quasipotential equations and other methods for performing relativistic calculations. (3) Semiphenomenological nucleon-nucleon forces that include all non-static relativistic effects of order $(v/c)^2$ should be developed and used to investigate isoscalar exchange effects.

*This work was performed under the auspices of the U. S. Department of Energy.

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