Relativistic Theory of Few-Body Systems

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Abstract. Very significant advances have been made in the relativistic theory of few body systems since I visited Peter Sauer and his group in Hannover in 1983. This talk provides an opportunity to review the progress in this field since then. Different methods for the relativistic calculation of few nucleon systems are briefly described. As an example, seven relativistic calculations of the deuteron elastic structure functions, A , B , and T_{20} , are compared. The covariant SPECTATOR[®] theory, among the more successful and complete of these methods, is described in more detail.

1 Prologue

In 1983, Peter Sauer invited me to Hannover to lecture to his students on my SPECTATOR[®] approach to the relativistic theory of few body systems.¹ This was an exciting time, and I am very glad to have this opportunity today to thank Peter and his students for their interest, and for the many good questions and interesting discussions we had during and after those lectures. Peter and I never wrote a paper together, but my collaboration with Alfred Stadler and Teresa Peña eventually grew from this beginning. The calculation of the relativistic three nucleon bound state done with Alfred Stadler is based in part on notes I originally prepared for the Hannover lectures.

In preparing this talk I decided to summarize progress made since 1983, as if I were resuming discussion with Peter again on a Monday morning in 1983 (after an unusually long “19 year weekend”). Many of the results discussed here are covered in more detail in the recent review I wrote with Ron Gilman [1].

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¹At this conference some speakers used the term “spectator” to refer to an approximation in point-form quantum mechanics. When I pointed out that this usage would increase the confusion already present in this field, they jokingly suggested that I should copyright the term, and my notation is a response to this suggestion.

Table 1. Relativistic calculations referred to in figures 1 and 2.

Greens function dynamics	
VODG PWD	Manifestly covariant SPECTATOR [®] theory [2] "Equal time" calculation based on the Mandelsweig-Wallace equation [3]
Hamiltonian dynamics	
SPR ARW CK LPS AKP	instant-form; no v/c expansion [4] instant-form; with v/c expansion [5] front-form; dynamical light-front [6] front-form; fixed light-front [7] point-form [8]

2 Relativistic approaches reviewed and compared

Since 1983 several alternative relativistic approaches have been developed. Attempts to classify and compare them is a continuing challenge.

These relativistic approaches fall into two major "schools." Both of these schools, and several alternatives within each, have recently been used to calculate the deuteron structure functions and form factors relativistically. These seven calculations (referred to as the "c7" below) are summarized in Table 1.

2.1 Greens function dynamics

In applications to the deuteron and NN scattering below the pion production threshold, methods based on Greens function dynamics

- start from a covariant effective field theory that takes nucleons and mesons to be the effective degrees of freedom,
- use this effective theory to define the covariant generalized meson-exchange ladder sum (the sum of all ladder and crossed ladder diagrams, either omitting vertex corrections and self energies entirely, or treating them phenomenologically using form factors),
- *define* a free NN propagator, G_x , and use it to reorganize the generalized ladder sum into an infinite series of "irreducible" kernels (potentials) $V^{(i)}$ (involving the exchange of i mesons), and products of these kernels, such as $V^{(i)}G_xV^{(j)}$, $V^{(i)}G_xV^{(j)}G_xV^{(k)}$, etc.,
- evaluate the ladder (ie. one boson exchange) amplitude using the integral equation $M_x^{\text{OBE}} = V^{(1)} + V^{(1)}G_xM_x^{\text{OBE}}$, and
- evaluate the contributions from multi-boson exchange kernels ($V^{(i)}$ with $j \geq 2$), perturbatively.

For $j \geq 2$, it is usually either assumed that $V^{(j)} \ll V^{(1)}$, or that $\sum_j V^{(j)} \simeq V^{(1)}$ so the last step need not be done. There are several different choices for the free Greens function, G_x , and hence my use of the term “Greens function dynamics.”

This approach is manifestly covariant. This means that the action of *all* of the 10 generators of the Poincaré group on matrix elements can be fully specified in terms of the kinematics, so that the action of finite Poincaré transformations can be calculated in simple, closed form. Momentum, energy, and angular momentum are strictly conserved, and finite boosts are given by a simple operation on the matrix elements, with no further calculations needed. [In practice, approximations are sometimes made that spoil this covariance.] A further advantage is that the effective field theory used to construct the generalized ladder sum can also be used to construct consistent, manifestly covariant electromagnetic currents. A very general method of constructing these currents consistently was published in 1987 [9], opening up the application of these methods to electromagnetic interactions. Unfortunately, the construction is not unique, so additional phenomenology is needed to fix the currents.

The disadvantages of the Greens function approach are that

- the Greens function, G_x , will include the propagation of negative energy (or antiparticle) states, requiring that the Hilbert space of quantum mechanical states be expanded, and that we learn to deal with the mathematical and physical interpretation of these states,
- the kernels and the propagator can include unphysical singularities that must be removed or avoided, complicating either the theoretical development or the numerical calculations, and
- the NN scattering amplitudes, which now include contributions from virtual negative energy states, should be fit directly to the NN data, thus increasing the “investment” required to develop and apply these methods.

2.2 Hamiltonian dynamics

In elementary quantum mechanics, states are defined at $t = 0$ and their evolution away from $t = 0$ is given by the Schrödinger equation

$$i \frac{\partial}{\partial t} \Phi(\mathbf{r}, t) \Big|_{t=0} = H \Phi(\mathbf{r}, 0). \quad (1)$$

In 1949, Dirac [10] pointed out that it is possible to generalize the initial hypersurface on which the states are defined, leading also to a generalization of the Hamiltonian. Methods using Hamiltonian dynamics are so named because they use one of the three forms of generalized dynamics identified by Dirac [11]. These are²

²Please beware of some misprints in the discussion of Hamiltonian dynamics in Ref. [1].

- *Instant form*: the states are defined on the $t = 0$ hyperplane, and the Hamiltonian is the usual generator of time translations, H . The generators of space translations (the momentum operators P^i) and rotations (the angular momentum operators J^i) form a subalgebra of the Poincaré group that leaves the $t = 0$ hypersurface invariant, so they may be defined without regard to the interactions living in H . The generators of the boosts, K^i , do not leave the hyperplane invariant, so must also include the interactions, and this is the disadvantage of this method.
- *Front form*: the states are defined initially on the light-front $t_+ \equiv t + z = 0$, and the generalized Hamiltonian is $H_- \equiv H - P^z$. The subgroup leaving this light-front invariant is composed of the *seven* generators H_+ , K^z , J^z , $\mathbf{E}_\perp = \{K^x + J^y, K^y - J^x\}$, and $\mathbf{P}_\perp = \{P^x, P^y\}$. The dynamical interactions are in the three generators H_- , and $\mathbf{J}_\perp \simeq \{J^x, J^y\}$. This method is very popular for high energy interactions where the dynamics evolves along the light cone $t = z$ and it is a great advantage to have the boost K^z among the kinematic generators. Its disadvantage is that the conservation of angular momentum becomes a dynamical issue.
- *Point form*: Here the states are defined on the forward hyperboloid: $t > 0$ and $t^2 - \mathbf{r}^2 = a^2$. The homogeneous Lorentz group, generated by the boost and angular momentum operators, K^i and J^i , leaves this surface invariant, and the dynamics are in H and the momentum operators P^i . This method automatically conserves angular momentum and gives boosts independent of the dynamics, but its disadvantage is that the conservation of momentum becomes a dynamical issue.

All of these methods use quantum mechanical states that span the positive energy spectrum only, leading to the standard interpretation of quantum mechanics. In each case it is possible to transform the generalized Schrödinger equation into an equivalent instant form, and hence use the excellent phenomenological potentials that have recently been fit to low energy NN scattering.

The disadvantages of Hamiltonian dynamics depend in part on the specific form chosen. In the instant form it is difficult to boost the states, and the front and point forms require special care to insure that either angular or linear momentum is conserved. Perhaps the most serious disadvantage of Hamiltonian dynamics is that they provide little or no guidance on how to construct consistent, conserved, covariant electromagnetic currents. The construction of currents is phenomenological and sometimes ad-hoc.

2.3 Predictions for the deuteron form factors

The predictions of the c7 listed in Table 1 are shown in figure 1. I conclude the following:

- Only the VODG and SPR calculations provide a reasonable description of *all three* of these observables. This is probably due to the fact that these

Figure 1. Predictions for the structure functions A , B , and T_{20} . The models, in order of the Q^2 of their minima in B , are: CK (long dot-dashed line), PWD (dashed double-dotted line), AKP (short dot-dashed line), VODG full calculation (solid line), VODG in RIA (long dashed line), LPS (dotted line), a quark model calculation not discussed here (widely spaced dotted line), SPR (medium dashed line), and ARW (short dashed line). None of the curves shown include the $\rho\pi\gamma$ exchange current. (This figure is taken from Ref. [1].)

are the only calculations valid to all orders in $(v/c)^2$ that also include complete currents consistent with the dynamics.

- The magnetic structure function, B , is by far the most sensitive to the calculations, and provides a stringent test of the theory.

To get some insight into the differences between these calculations, it is useful to think of each as built from the same three (roughly defined and over-

lapping) ingredients: (i) the “leading” nonrelativistic S and D -state deuteron wave functions, (ii) the single nucleon electromagnetic current, and (iii) all the rest, including $I = 0$ interaction currents and relativistic modifications (which are model dependent and not small) to both wave functions and currents.

All of the c7 use modern “realistic” deuteron wave functions, so the differences between them is not due to the choice of the leading, nonrelativistic part of the wave function. The large differences arise instead from the treatment of relativistic effects, and the construction of the current.

Some of the c7 include relativistic effects to all orders in $(v/c)^2$, while others only include the lowest order terms. By expanding in powers of $(v/c)^2$ it would be possible to compare the relativistic effects obtained from all of the c7. To a limited extent this has already been done; in the 1970’s and 1980’s Friar and others found that the one pion exchange corrections for the instant-form and SPECTATOR[®] theory agreed to lowest order (for a review see Ref. [12]). The comparison was very informative – it showed that the “pair term” corrections (for example) differed in the two cases, and agreement was only obtained after *all* of the corrections were added together. This leads to the expectation that a similar comparison of the c7 would lead to agreement *only for those calculations that include all possible corrections*. I believe that such a benchmark calculation comparing the different methods could significantly increase our understanding.

Another difference in the c7 is the choice of current. Even the one body current is not the same for all of the c7. For example, in the point-form it turns out [8] that the single nucleon form factors must be evaluated at a momentum transfer Q^2 *larger* than that transmitted to the deuteron as a whole (possible because momentum is not conserved). Because the nucleon form factors decrease rapidly in Q^2 , this leads to a strong suppression of the prediction for A , as shown in figure 1. This could be corrected by adding an interaction current, but the point-form approach itself does not tell us what this should be. In the absence of an underlying field theory to guide the physics, the currents are purely phenomenological.

The currents in the SPECTATOR[®] theory are well constrained, but even here they cannot be uniquely determined. I will conclude this discussion by showing how we can exploit this flexibility, and adjust the single nucleon SPECTATOR[®] current to give an excellent fit to all of the elastic electron-deuteron data.

Following Ref. [9], current conservation requires that the single nucleon current satisfy the Ward-Takashi identity

$$q_\mu j_N^\mu(p', p) = S^{-1}(p) - S^{-1}(p') \quad (2)$$

where $S(p)$ is the propagator of a nucleon with four-momentum p . The NN model used in the VODG calculation [13] uses the dressed nucleon propagator

$$S(p) = \frac{h^2(p)}{m - \not{p}} = \frac{h^2(p)}{\Lambda_-(p)} \quad (3)$$

with $h(p)$ a phenomenological scalar function of p^2 . The *simplest* solution of Eq. (2) gives the following one nucleon current

$$j_N^\mu(p', p) = F_0 \left\{ F_1(Q^2) \gamma^\mu + F_2(Q^2) \frac{i\sigma^{\mu\nu} q_\nu}{2m} \right\} + G_0 F_3(Q^2) \Lambda_-(p') \gamma^\mu \Lambda_-(p) \quad (4)$$

where terms proportional to q^μ have been dropped (they are required by the identity (2) but vanish when contracted into the conserved electron current),

$$\begin{aligned} F_0 &= \frac{h(p)(m^2 - p'^2)}{h(p')(p^2 - p'^2)} - \frac{h(p')(m^2 - p^2)}{h(p)(p^2 - p'^2)} \\ G_0 &= \left[\frac{h(p')}{h(p)} - \frac{h(p)}{h(p')} \right] \frac{4m^2}{p^2 - p'^2}, \end{aligned} \quad (5)$$

and $F_3(Q^2)$ is *completely undetermined* except for the requirement that $F_3(0) = 1$. The VODG calculation shown in figure 1 uses the "standard" dipole form for F_3

$$F_3(Q^2) = \left(\frac{\Lambda^2}{\Lambda^2 - Q^2} \right)^2 \quad (6)$$

with $\Lambda^2 = 0.71 \text{ GeV}^2$. Clearly other choices of F_3 are possible.

Another source of uncertainty is the famous $\rho\pi\gamma$ exchange current. This current is separately gauge invariant and strongly dependent on the $\rho\pi\gamma$ form factor, $f_{\rho\pi\gamma}(Q^2)$ [14]. The value of $f_{\rho\pi\gamma}(0)$ is constrained by meson radiative decays, and its contribution to the deuteron form factors at small Q^2 is negligible. Its importance at high Q^2 depends strongly on the assumed dependence of $f_{\rho\pi\gamma}(Q^2)$, which is unknown but can be estimated from quark models. One of the best calculations of this form factor is that of the Rome group [15]. To clarify the comparison between models, the versions of the c7 shown in figure 1 did not included this current, and it could be added to any of them.

Taking the VODG calculation in RIA approximation (discussed in Ref. [2]) as our "standard," I now consider the effect of (i) altering the Q^2 dependence of F_3 , or (ii) adding the $\rho\pi\gamma$ exchange current. The "standard" calculation is the long dashed lines shown in figure 1 and the dotted lines reproduced in figure 2. The effect of changing F_3 to a tripole form

$$F_3(Q^2) = \left(\frac{\Lambda^2}{\Lambda^2 - Q^2} \right)^3 \quad (7)$$

with $\Lambda^2 = 5 \text{ GeV}^2$ (and continuing to keep $f_{\rho\pi\gamma} = 0$) are shown as solid lines. The effect of adding a $\rho\pi\gamma$ exchange current using a dipole form factor with $\Lambda^2 = 1.5 \text{ GeV}^2$ (and keeping the standard dipole form for F_3) are shown as the dashed curves. [The F_3 and $\rho\pi\gamma$ form factors themselves are compared to the Rome form factor and the standard dipole (6) in the lower left panel.] To see the effects on A and B more clearly, the middle two panels show the ratios of A/A_0 and B/B_0 , where A_0 and B_0 are the standard calculation.

Figure 2. Upper panels (A and B) and lower right panel (T_{20}) compare data to three theoretical models based on VODG: (i) "standard" case referred to in the text (dotted line), (ii) model with the tripole F_3 (solid line), and (iii) model with the dipole $f_{\rho\pi\gamma}$ (dashed line). The center two panels show the data and models (ii) and (iii) divided by model (i). The lower left panel shows form factors: standard dipole with $\Lambda^2 = 0.71$ (solid line), dipole with $\Lambda^2 = 1.5$ (short dashed line), Rome $f_{\rho\pi\gamma}$ (dot-dashed line) [15], and the tripole with $\Lambda^2 = 5$ (long dashed line). (This figure is taken from Ref. [1].)

We see that a reasonable adjustment of F_3 at high Q^2 can give an excellent description of all of the elastic deuteron observables. This is perfectly permissible within the theory, since the form factor F_3 , while it *must* be present, cannot be determined by on-shell data, and must be treated phenomenologically. From this point of view the deuteron data has now determined the unknown form factor F_3 , and the isoscalar single nucleon current is now fixed. It remains to be seen whether the same F_3 will give excellent results for other electron scattering observables.

What are we to say about the $\rho\pi\gamma$ exchange current? My own belief is that this exchange current is being overestimated, even using the Rome form factor. While this current is certainly present, it is probably either negligible, or cancelled by the many other short range currents neglected in these calculations.

3 Progress with the SPECTATOR[©] theory

In the remainder of this talk I return to the SPECTATOR[©] theory and report on developments since 1983, and on my expectations for the future.

3.1 Definition of the theory

The SPECTATOR[©] propagator for two nucleons with four momenta p_1 and p_2 is

$$G_S = 2\pi i \delta_+(m^2 - p_2^2) S(p_1) \sum_{\lambda} u(\mathbf{p}_2, \lambda) \bar{u}(\mathbf{p}_2, \lambda) \quad (8)$$

where the δ_+ function restricts p_2 to its positive energy mass-shell, so that $p_2 = \{E(p_2), \mathbf{p}_2\}$, and $u(\mathbf{p}_2, \lambda)$ is the free Dirac spinor for a nucleon with three-momentum $\mathbf{p}_2$ and helicity λ , normalized to $\bar{u}(\mathbf{p}, \lambda) u(\mathbf{p}, \lambda') = 2m \delta_{\lambda\lambda'}$. This propagator insures that the integration over the internal energy will place particle 2 on its positive energy mass-shell, giving the SPECTATOR[©] equation. It was already known before 1983 that this equation is manifestly covariant, has the right one-body limit, a smooth nonrelativistic limit, satisfies the cluster property, and produces a gauge invariant one-photon-exchange interaction [16]. The manifest covariance means that momentum and angular momentum are trivially conserved, and that the boosts are known exactly, to all orders in $(v/c)^2$.

3.2 Progress since 1983

Progress since 1983 has been substantial. Theoretically, we have seen (i) the development of a general method for constructing consistent, conserved currents [9] (already discussed), and (ii) the recent demonstration that all vertex corrections and momentum dependent self energies *cancel* in massive scalar QED [17]. This last result means that the generalized ladder sum gives the full result for the interaction of scalar bosons with a massive photon. Combining

this with the already known fact that the generalized ladder sum is well approximated by the ladder approximation to the SPECTATOR[®] equation, and we have the first demonstration that solutions of the SPECTATOR[®] equation are a good approximation to the *exact* solutions of massive scalar QED. It is not known if this result also holds for other effective theories.

Many applications have been developed since 1983. These include:

- Mesons as $q\bar{q}$ bound states, including covariant treatment of scalar confinement consistent with chiral symmetry breaking [18, 19].
- Unitary model of $\pi N \rightarrow \pi N$ and $\gamma N \rightarrow \pi N$ processes up to 600 MeV including Δ , Roper, and D_{13} resonances. [20].
- NN scattering and bound state solutions to 350 MeV lab kinetic energy with $\chi^2 \sim 2$ and 13 fitting parameters [13].
- Exact numerical solution of the relativistic three body equations that give a good binding energy for 3H without relativistic three body forces [21].
- Good description of the deuteron form factors [2] reviewed above.
- General classification of inelastic scattering observables [22] and first calculation of inelastic scattering in relativistic impulse approximation [23].
- Derivation of the pA multiple scattering series [24] and applications to proton nucleus scattering [25].

When I visited Peter Sauer in 1983, the goal was to do a relativistic three-body calculation. Peter and I never completed this, but my contacts with Peter lead eventually to my collaboration with Alfred Stadler, and to the desired calculation.

The major result of this relativistic calculation of the three body binding energy [21] is shown in figure 3. We obtain good agreement with the binding energy only after introducing an off-shell scalar meson coupling

$$g_s \Lambda(p', p) = g_s \left\{ 1 - \frac{\nu_s}{2m} [\Lambda_-(p') + \Lambda_-(p)] \right\} \quad (9)$$

with the off-shell coupling parameters ν_σ and ν_δ proportional to the ν shown in figure 3. The exciting conclusion is that the same ν that fits the experimental binding energy also gives the best fit to the two-body data.

3.3 The NEW SPECTATOR[®] theory

The SPECTATOR[®] theory raises a number of questions:

- In the n -body problem, why should $n - 1$ particles be on shell, and which ones should they be?
- Can all spurious singularities be removed from the theory?

Figure 3. Upper panel shows the three body binding energy as a function of the off-shell coupling parameter ν discussed in the text. The lower panel shows the variation in χ^2 of the fit to the two-body data (up to lab energies of 350 MeV).

- What are the Feynman rules for the general case?
- Can the theory be formulated as a quantum mechanics, with a well defined Hilbert space of states?

Many of these questions were raised initially by Peter Sauer and his students during my visit in 1983, and I have answered some of them to my satisfaction. I am currently preparing a new formulation of the SPECTATOR[®] theory that I believe will provide more complete answers. Like a good salesman of computer games, I want to advertize my product in advance of its "public" release.

Figure 4 shows the real part of Bethe-Salpeter propagator, iG_{BS} , as a function of the relative energy $p_0 = \frac{1}{2}(p_{10} - p_{20})$ and the square of the relative three-momentum, p^2 , evaluated in the c.m. system (to aid in seeing the structure the ϵ 's in the $-\epsilon$ prescriptions were given a finite value). This figure shows clearly that the propagator is dominated by the two positive energy mass-shell poles. Using Cauchy's residue theorem to evaluate the integral over p_0 gives the result that the integration is dominated by the on-shell contribution from

Figure 4. Mass-shell peaks in the free propagator for two particles with equal mass m a total rest mass of $M/m = 1.8$. The figures on the right show slices through the surface at various constant values of p^2 . (All quantities are in units of m .)

one particle, but when interpreted as an ordinary integral along the real axis the same result requires the contribution of *both* peaks (each giving one-half of the residue result). Looked at from this point of view, the wave function is the sum of two terms, one with particle 1 on-shell and one with 2 on-shell. These two terms have support in separate regions of phase space, so adding them together leaves some things unchanged, but continuing in this direction leads to a reformulation of the SPECTATOR[©] theory that gives nice answers to the questions above. Watch for the release of this theory in the near future!

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