Explicitly Covariant Light-Front Dynamics and Deuteron

V.A.Karmanov
Lebedev Physical Institute
Leninsky Prospekt, 53, 117924, Moscow, Russia

Abstract

A brief review of the explicitly covariant light-front dynamics is given. The approach is applied to the relativistic deuteron and continuous spectrum wave functions, to the deuteron electromagnetic form factors and electrodisintegration.

1. Introduction

The present talk is devoted to brief description of a version of the light-front dynamics which I call "explicitly covariant light-front dynamics" (see for review ref.[1]). This approach turns out to be very useful in applications to relativistic nuclear physics, in particular, to the relativistic deuteron wave functions, its electromagnetic form factors at high momentum transfer and electrodisintegration. The explicit covariance can give also advantages in solving the field-theoretical problems, in particular, in QCD.

The main difference of the explicitly covariant light-front dynamics from the ordinary one is the definition of the light-front surface. The lack of covariance of the ordinary light-front dynamics results from noncovariant definition of the light front $t+z=0$, where the state vector is defined. The state vector depends dynamically on the position of the light-front surface. The latter is changed under some transformations of the reference system. This dynamical dependence on the system of reference manifests itself as a lack of covariance. The crucial point to restore the covariance consists in the following generalization of ordinary approach: the light-front surface is defined by the invariant equation[1,2]: $\omega x = 0$, where $\omega = (\omega_0, \vec{\omega})$, $\omega^2 = 0$. As a result, the kinematical transformations of the reference system are separated from dynamical transformations of the light-front surface. Namely this fact ensures the covariance relative to transformations of the reference system. Like in any version of the light-front dynamics our wave functions depend dynamically on position of the light-front surface, however in our case this dependence is parametrized explicitly in terms of the four-vector ω without loss of the relativistic covariance. In particular case, when $\omega = (1,0,0,-1)$, we return to usual light-front dynamics.

2. Light Front Graph Technique

The calculating machinary is based on the special graph technique developed by Kadyshevsky[3] and adjusted later[2] to the case of the light-front dynamics. Kadyshevsky defined the state vector on the surface $\lambda x = \sigma$ with $\lambda^2 = 1$ and considered evolution of the state vector along the "time" σ from one to other surface within this family. The covariant light-front graph technique is obtained then by the replacement $\lambda \to \omega/\delta$ and taking the limit $\delta \to 0$. The rules of the graph technique are given in refs.[1,2] for the spinless case and in ref.[4] for the case with spin 1/2. This graph technique is three-dimensional one: the four-momenta of all the particles are on the corresponding mass shells. For example, the fermion propagator has the form $\theta(\omega p)(\hat{p} + m)\delta(p^2 - m^2)$. However, the intermediate vertices and amplitudes are generally off-energy shell. This means that the difference of initial and final four-momenta of particles is not equal to zero, but is directed along the light-front four-vector ω, i.e., equals to $\omega\tau$, where τ is a scalar parameter. There is integration over the internal four-momenta of particles (constrained by the mass shells) and over all the internal parameters τ_i.

Before integration over τ_i the amplitudes are finite. This is due to the fact that in any vertex we have conservations of the on-mass shell four-momenta (including $\omega\tau_i$). Since the initial energies are finite, all the intermediate energies are finite too. Divergences appear after integration over τ_i in infinite limits[3]. This gives a covariant way to introduce a cutoff in the light-front dynamics, in terms of the cutoff of the scalar parameters τ_i. This fact can be usuful in applications to QCD.

On the energy shell the amplitudes calculated by this graph technique in any given order of perturbation theory coincide with the corresponding Feynman amplitudes on mass shell. Off energy shell they differ from the Feynman ones. For the spinless particles the amplitudes after replacement of variables coincide with ones obtained by the Weinberg rules.

For the spin 1/2 particles the graph technique contains so called contact terms which are a track of disappeared vacuum fluctuations. They can be introduced in Lagrangian from the very beginning[4,5]. For example, for the Lagrangian with initial $NN\pi$ interaction the light-front graph technique contains a contact interaction corresponding to the irreducible $NN\pi\pi$ vertex with four legs.

The graph technique is applied in ref.[6] to derivation of the relativistic NN kernel on the light front. Practicaly we restrict ourselves by the one boson exchange kernel, however don't make in this framework any nonrelativistic approximations. We use this kernel for calculation of the relativistic NN wave functions (both for deuteron and for continuous spectrum).

3. Light Front Wave Functions

The covariant light-front wave function, due to its dependence on the position of the light front, depends (in addition to the relative momentum $\vec{q}$) on extra variable[1,2], an unit vector $\vec{n} = \vec{\omega}/\omega_0$. The analogous approach was later developed and extended by Fuda, who obtained, in particular, similar results for the parametrization of the covariant light-front wave function (see ref.[7] and references therein).

The structure of the relativistic light-front wave function of deuteron has been given in ref.[8]. It turns out that, due to its $\vec{n}$-dependence, the light-front deuteron wave function is determined by six components instead of two ones (S- and D-waves) in nonrelativistic limit. Similary, the relativistic counterpart of the continuous spectrum np wave function in $^1S_0$ state is determined on the light front by two components instead one component at small q. In nonrelativistic limit the $\vec{n}$-dependence of the wave functions and the extra components disappear and we return to well known nonrelativistic description. The equation for the wave function after replacement of variables coincides for the spinless particles with the Weinberg equation and turns into the Schödinger equation in nonrelativistic limit. Some peculiarities of relativistic wave functions are explained[1] by examples in the explicitly solvable Wick-Cutkosky model. The explicitly covariant representation of the light-front state vector in terms of the Fock states can be usuful in the Hamiltonian approach to QCD.

All the components both for the deuteron and for the scattering state wave functions versus two scalar variables (q and $z = \cos\widehat{\vec{n}\vec{q}}$) are calculated numerically. It was found[6] that one of the components of the deuteron wave function (so called f_5) dominates rather early, at $q > 500$ MeV/c, over other components, including S- and D-waves. The same was found[9] for the extra conponent g_2 of the scattering state wave function. These important properties of the wave functions (extra components and their dependence on extra variable) should be observed experimentally. We discuss this problem below.

4. Electromagnetic Form Factors

The spin structure of the deuteron electromagnetic vertex in the covariant light-front dynamics is investigated in refs.[10]. The decomposition of the light-front deuteron electromagnetic vertex in independent spin structures contains 11 form factors instead of three physical ones. Eight of these form factors are unphysical, they are coefficient at the ω-dependent spin structures.

We emphasize that any off-energy shell object, like the off-energy shell amplitude and the wave function, may depend on ω and indeed depend on it. At the same time, any correct on-energy shell amplitude should not depend on the light-front. However, a residual ω-dependence can survive due to an inaccuracy of approximation. This point was investigated in ref.[11]. The deuteron electromagnetic vertex is exhaustively described by three ω-independent form factors. The explicit formulas which allow to extract three physical form factors from the ω-dependent electromagnetic vertex containing 11 form factors are given in refs.[10]. It is shown that most of previous papers calculated not the physical deuteron form factors but their superposition with unphysical contributions. Analogous formulas are obtained also for spin 1/2 system (e.g., nucleon) and for the deuteron electrodisintegration amplitude. This problem is explained in the talk[12] given by A.V. Smirnov at the present conference.

5. Link with the Meson Exchange Currents

Using these formulas in leading $1/m$ order we find[13] the deuteron electrodisintegration amplitude incorporating extra components f_5 and g_2. Substituting for f_5 and g_2 their analytical expressions also calculated in leading $1/m$ order we discover that their contribution reproduces exactly the contribution of the meson exchange current (MEC) for the pion pair term of usual approach, except for the coefficient which is by the factor two smaller. In addition, having taken into account the contact interaction mentioned above we found that it gives exactly the same contribution as the extra components. Sum of them coincides with the pair term with the correct coefficient. To avoid misunderstanding, we emphasize that there is no any pair term in the light-front dynamics. However, the result is the same as in usual approach incorporating this pair term, though it is reproduced by other contributions (extra components and the contact term). This point was discussed in detail in the talk by J.-F. Mathiot.

This fact explains, why the extra components of relativistic NN wave function dominate: they reproduce half of the dominating contribution of the MEC. Since this contribution is firmly established in the deuteron electrodisintegration, one can say that the indications on the extra components of relativistic deuteron wave function have been already found in experiment. The leading $1/m$ order analysis is done to simplify the analytical formulas. However, the approach contains all the orders from the very beginning. There is no any need to develop approximatons in this point.

The approach is applied to calculations of the deuteron electrodisintegration cross section[14] and to the deuteron electromagnetic form factors[10,15]. Calculations incorporate all the orders of relativistic effects. It was shown that extra components of the wave function and the contact terms influence considerably the results and, hence, have to be taken into account. Calculations contain also current uncertainties in the nucleon electromagnetic form factors, NN interaction kernel, etc. So, our results are not final. More sophisticated analysis can be done on the ground of experiments to be carried out at CEBAF.

6. Conclusion

Our conclusion is the following: the covariant light-front dynamics provides a completely coherent framework in which the forthcoming data at high momentum transfer can be safely analysed. Its applications to QCD could be useful.

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