Bethe–Salpeter Approach with the Separable Interaction for the Deuteron

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The study of electromagnetic properties of light nuclei, $A \leq 4$, facilitates the construction of the theory of strong interactions and, in particular, the nucleon–nucleon interaction (see [1] and references therein). A large amount of available experimental data stimulate a further development of theoretical methods which are often restricted to qualitative predictions. The forthcoming experiments are expected to provide high precision data which will allow us to explore the region of large momentum transfer in elastic, inelastic and deep inelastic (DIS) electron-nucleus reactions.

These data will be able to furnish qualitatively new information about the fine nuclear structure at small distance. This is the reason why the role of the non-nucleon degrees of freedom as mesons, Δ-isobars, quarks etc. on intermediate and high energy phenomena is widely discussed Clear understanding and consistent interpretation of the experimental information is not possible without the consideration of the relativistic kinematics of reactions and the dynamics of the interaction. For this reason, the construction of a covariant approach and a detailed analysis of relativistic effects in electromagnetic reactions with light nuclei become the tasks of the highest priority.

The fact that nuclei consist of bound nucleons introduces a major problem for theoretical description of relativistic $l-A$ interactions. The deuteron is naturally the first object in the row of many other nuclei, and has received a vast number of treatments within many different approaches. One finds also that non-relativistic schemes of calculations are widely employed in the analysis, which can be justified for a few particular cases. On the other hand, the consistent consideration of the relativistic bound states is offered within the Bethe-Salpeter (BS) formalism [2, 3], which makes it most promising for the class of the tasks considered in the present review. What is even more important is that the BS formalism allows qualitatively a new interpretation of the physics of the relativistic bound state and should not be regarded as an alternative scheme only.

In the present report have considered the formulation of the Bethe-Salpeter equation. It is realized for the two-nucleon system by using the multipole expansion with the spinor structure of the two nucleons. The separable ansatz for the interaction kernel for each partial wave has provided a manageable system of the linear homogeneous equations for the BS amplitude. We have demonstrated then the construction of the separable interaction by taking only one term in the Yamaguchi form. Even with the two parameters for the $^1S_0$ and $^3S_1$ channels, we have found good reproduction of the phase shifts up to about 100 MeV in addition to the deuteron binding energy. This part has demonstrated the details of the formulation of the BS equation with the separable interaction.

We have switched then to the case with the use of the covariant revision of the Graz II separable potential with the summation of several separable functions. The calculated results have been compared, first, to the static deuteron properties. The comparison shows very good agreement. We have applied then the BS amplitude for the calculation of the nucleon form factors that determine eD elastic scattering cross sections. Comparison of the obtained results with the experimental data is good in general. But there exist definitely some defects in the comparison with the data as the charge form factor and the tensor polarizations, which indicate the necessity of improvement.

The comparison with the elastic scattering has brought us to discuss the ingredient of the BS formalism by taking the simple cases as the deuteron magnetic moment, deuteron quadruple moment and further the electro-disintegration of the deuteron. In this discussion, we have taken all the possible channels in the BS amplitude. We have found that the relativistic covariant description automatically include the meson exchange currents, in particular, the pair current through P-wave (negative energy state) component in the BS amplitude. We find it necessary to extend the partial waves to include the P-wave in order to construct the relativistic deuteron state. The P-wave components were not included in considered separable interaction kernels.

Reactions of the elastic lepton scattering off the deuteron and the deuteron electro-disintegration served as a testing ground for the method under investigation and helped to outline both strong and weak points of the approach. The analysis has proved the technique to be very promising, even if we find a few evident discrepancies with data at this stage of development. Several items can be suggested for the program of further theoretical studies. 1) Construction of the separable potential of higher rank in order to reach better understanding of the properties of the deuteron, phases of NN- scattering, and to study hadron-deuteron processes (for example, the reaction $p + D \to p + X$); 2) Research into the relativistic two-body currents; 3) Studies of the off-shell effects in lepton-deuteron scattering.

One specific feature of the BS formalism deserves a special comment. The BS amplitude depends on the zeroth component of the relative coordinate (relative time) of the bound nucleons, which is reflected in the dynamical observables of the n-nucleon bound state. In momentum space, this leads to the dependence on the zeroth component of the nucleon relative momentum (relative energy). The dependence is manifested as observable effects in DIS of leptons off the lightest nuclei.

The extension of the approach to the process of deep inelastic lepton scattering off the deuteron has been realized in a model-independent way. This quality is of particular importance for the consideration of the relatively small effects of the modification of the nucleon structure function $F_2^{\rm N}(x)$ by the NN binding forces. Based on the the model-free technique, the method for calculations of the evolution of the nucleon structure in the lightest nuclei as a function of A has been developed.

We have found that the effects from asynchronous nucleons which naturally follow from the relativistic treatment of the two-nucleon bound state are decisive in obtaining differences between the structure functions of bound and free nucleons. The characteristic modification of the nucleon structure functions found for $A = 2$ serves as a priming for the modifications in the three- and four-nucleon systems and plays, therefore, a fundamental role in the evolution of the bound nucleon structure. The EMC effect, which was essentially the observation that partonic structures of $A = 2$ and $A = 56$ nuclei were different, can be now regarded as a particular case of the whole class of modifications of the free nucleon structure in nuclear environment.

We have reviewed the covariant description of few-nucleon systems in the framework of the Bethe-Salpeter approach. This trial is still at primitive stage as compared to the widely used quasi-potential description of the BS equation. We thought it important though to write up the present status of this new development in the review form. Hence, the purpose of this investigation is not to tell all the consequences of the present approach but to show what is included in the covariant description of the BS approach and what has to be done further in this framework. Even at this simple stage it is clear that covariant four-dimensional approach give qualitatively new point of view on the present problems in the nuclear physics.

References

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