Parametrization of Realistic Bethe-Salpeter Amplitude for the Deuteron

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Abstract

The parametrization of the realistic Bethe-Salpeter amplitude for the deuteron is given. Eight components of the amplitude in the Euclidean space are presented as an analytical fit to the numerical solution of the Bethe-Salpeter equation in the ladder approximation. An applicability of the parametrization to the observables of the deuteron is briefly discussed.

1 Motivations

Since the first solution of the realistic Bethe-Salpeter (BS) equation for the deuteron [1], the BS-amplitudes have been applied to describe various processes with the deuterons [1, 2, 3, 4, 5, 6, 7]. The obvious advantages of the approaches based on the BS formalism are the explicit covariance and connection to the covariant dynamical (field) theory. In spite of this, practical use of the BS amplitudes is not as popular as of nonrelativistic wave functions [6, 7]. A more complicated physical interpretation and technical complexity of the approaches based on the BS amplitudes are the main reasons for that.

In a series of recent papers it has been argued that a new intuition can be developed in working with the BS amplitudes [3, 4, 5]. It has been shown that calculations of many observables for the deuteron are reduced to calculations similar to those in field theory. It has also been stressed that the usage of the BS amplitude for the deuteron in the Dirac matrix basis can be more convenient than in the spinor basis. In this case computations are formalized enough to extensively apply analytical computing software, such as the Mathematica [9], to calculate the matrix elements of observables in terms of the components of the BS amplitude. However, the promotion of a new technique should assume that all basic ingredients of the calculation are available to a potential user. The BS formalism still lacks this feature, since there is no simple parametrization available for the realistic deuteron amplitude, such as is available for nonrelativistic wave functions [3, 10] or relativistic wave functions of the spectator equation [11].

This letter presents the analytical parametrization of the Bethe-Salpeter amplitude for the deuteron. The parameters are fixed by fitting to the recent numerical solution of the homogeneous BS equation using the Dirac matrix basis [3, 4]. The one-boson exchange potential from ref. [1, 12] was used with a minor adjustment of its parameters [3], so in this sense the solution does not contain new physics (or different physics) then the pioneer paper.

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2 Definitions and kinematics

The realistic BS amplitude of the deuteron, $\Phi$, can be obtained as a solution to the homogeneous BS equation with the effective one-boson-exchange kernel [1, 3]:

$$\Phi(p, P_D) = iS(p_1, p_2) \sum_B \int \frac{d^4 p'}{(2\pi)^4} \frac{g^2_B \Gamma^{(1)} \otimes \Gamma^{(2)}(p - p')}{(p - p')^2 - \mu^2_B + i\epsilon} \Phi(p', P_D),$$

(1)

where $P_D$ is the deuteron momentum, $\mu_B$ is the mass of the meson $B$, $\Gamma^{(k)}$ is the meson-nucleon vertex, corresponding to the meson $B$ and connected to the $k$-th nucleon. The tensor product in the r.h.s. of eq. (1) is for a possible interconnection of the quantum numbers in two vertices (such as in the case of the vector or isovector mesons). The two-nucleon propagator, $S(p_1, p_2)$, is defined as:

$$S(p_1, p_2) \equiv \hat{p}_1 + m \cdot \hat{p}_2 + m = (\hat{p}_1 + m)(\hat{p}_2 + m)D(p, P_D),$$

(2)

$$p_{1,2} = \frac{P_D}{2} \pm p,$$

(3)

where $m$ is the nucleon mass, $p_{1,2}$ are nucleon momenta, $\hat{p}_k = \gamma_\mu p^\mu_k$ and $D(p, P_D)$ is “scalar two-particle propagator”.

It is convenient to use the amplitude, $\Psi$, conjugated with respect to one of the nucleon lines [3]:

$$\Phi = \Psi \gamma^c \quad \text{or} \quad \Psi = -\Phi \gamma^c,$$

(4)

where $\gamma^c = \gamma_3 \gamma_1$. Then the amplitude $\Psi$ can be decomposed in terms of a complete set of the Dirac matrices, their bilinear combinations and the 4 $\times$ 4-identity matrix, $\mathbf{1}$, with sixteen components being the coefficients of decomposition:

$$\Psi = \mathbf{1}\psi_2 + \gamma_5 \psi_p + \gamma_{\mu} \psi^\mu_v + \gamma_5 \gamma_{\mu} \psi^\mu_a + \sigma_{\mu\nu} \psi^{\mu\nu}_t.$$

(5)

In the deuteron rest frame the notions are used:

$$\psi^{\mu}_v \equiv (\psi^0_v, \psi_\nu^\mu), \quad \psi^{\mu}_a \equiv (\psi^0_a, \psi_\nu^\mu),$$

$$\psi^{ij}_t \equiv \psi^0_t, \quad \psi^{ij}_t \equiv \varepsilon^{ijk} \psi^k_t,$$

(6)

(7)

where $i, j, k = 1, 2, 3$ and other tensor components of $\psi^{\mu\nu}_t$ are equal to zero.

In order to separate the amplitude with the deuteron’s quantum numbers, a partial wave decomposition of the four vector and four scalar functions, (6)-(7), is performed:

$$\psi = \sum_{JM} \psi(p_0, |p|; J) Y_{JM}(\Omega_p)$$

(8)

$$\psi = \sum_{JM} \left\{ \psi(p_0, |p|; J - 1) Y^{J - 1}_{JM}(\Omega_p) + \psi(p_0, |p|; J + 1) Y^{J + 1}_{JM}(\Omega_p) \right\},$$

(9)
where \( Y_{JM} \) and \( Y_{JM}^f \) are the spherical harmonics and vector spherical harmonics respectively.

Fixing the total momentum \( J = 1 \) and separating the components with positive parity, the deuteron’s amplitude components read as:

\[
\psi_p(1), \psi_v(1), \psi_a(1), \psi_a(01), \psi_a(21), \psi_t(01), \psi_t(21).
\] (10)

The components \( \psi_v^0(1) \) and \( \psi_t^0(11) \) are odd functions of \( p_0 \) and all others are even.

The BS equation with the realistic one-boson exchange potential is solved using the Wick rotation, which corresponds to replace \( p_0 \to i p_4 \) and \( \psi^0_a(1) \to i \psi^0_a(1) \). This procedure removes singularities from the exchange meson propagators in eq. (11) and from the scalar propagator, \( D \), which in the deuteron rest frame takes the form:

\[
D(p,P_D)^{-1} = D(p_4,|p|)^{-1} = [m^2 + p^2 + p_4^2 - \frac{1}{4}M_D^2]^2 + p_4^2M_D^2,
\] (11)

where \( M_D = 2m + \epsilon_D \) is the deuteron mass.

After the Wick rotation, the components of the deuteron amplitude are computed along the imaginary axe in the complex \( p_0 \)-plane. Since the inverse Wick rotation of the numerically known amplitude is an ill-defined operation, the parametrization for the components is obtained in the Wick rotated case. The possibility to analytically continue those amplitudes into a physical region is discussed in Section 4.

### 3 The parametrization

The parametrization of all components has the form (index \( J = 1 \) is omitted):

\[
\psi(p_4,|p|;L) = f(p_4,|p|;L)Exp\left\{g(|p|;L)p_4^2\right\}D(p_4,|p|m^4,
\]

where \( L = J, J \pm 1 \), depending on the quantum numbers of the component and functions \( f \) and \( g \) are given by:

\[
f(p_4,|p|;L) = \sum_{i=0}^{N_f} A_i(p_4) \frac{|p|^L}{\alpha_i^2 + p^2}, \quad g(|p|;L) = \sum_{i=1}^{N_g} B_i \frac{|p|^L}{\beta_i^2 + p^2}.
\] (13)

The form of parametrization (13) and the scale of the parameters \( \alpha_i \) are prompted by the previous works with parametrizations of the wave functions [7, 10, 11]:

\[
\alpha_0 = \mu_0/\sqrt{2}, \quad \alpha_i = i\mu_0, \quad i = 1 \ldots N_f, \\
\beta_i = i\mu_1, \quad i = 1 \ldots N_g, \\
\mu_0 = 0.139 \text{ GeV}, \quad \mu_1 = 2\mu_0, \\
m = 0.939 \text{ GeV}, \quad M_D = 2m + \epsilon_D, \quad \epsilon_D = -2.2246 \text{ MeV}.
\] (14)

The number \( N_f \) is equal to 11 for all components, whereas \( N_g \) differs for different components. The \( p_4 \)-dependence of the coefficients \( A_i(p_4) \) is given by:

\[
A_i(p_4) = A_i + p_4^2A_i', \quad \text{for} \quad \psi_p(1), \psi_v(1), \psi_a(0), \psi_a(2), \psi_t(0), \psi_t(2); \\
A_i(p_4) = p_4(A_i + p_4^2A_i'), \quad \text{for} \quad \psi^0_a(1), \psi^0_t(1).
\] (15)
Coefficients $A_i$, $A'_i$ and $B_i$ for all components are given in Appendix A, Tables [1-8]. The presented parametrization contains a seemingly large number of parameters, 27 to 29 per every of eight components plus three parameters common for all of them, including the nucleon mass, $m$, deuteron binding energy, $\epsilon_D$, and an additional mass scale parameter, $\mu_0$. This looks rather unusual for such type of parametrizations. The parametrizations of wave functions [7, 10, 11], for instance, contain only $n \sim 10$ parameters per component. The reason for this difference is that the components of the BS amplitude depend upon two independent variables, the relative momentum, $p$, and “relative energy”, $p_4$. It is clear now, that the presented parametrization contain quite a modest number of parameters; it is not even $n^2$ compared to the one dimensional fit of the wave functions.

4 The applicability of the parametrization

The parametrization (12)-(15) is obtained by fitting the numerical solution to the BS equation, using the least-squares procedure [9]. The domain of validity of the parametrization in relative momentum is $0 < |p| < 3$ GeV, means that the solution of the BS equation was fitted up to this point. The domain of validity in relative energy $p_4$ (which is actually $i p_0$) is defined as follows. First, the singular structure of the BS amplitude in the Minkowski space is governed by the singularities of the propagator $D(P_D, p)$, eqs. (2) and (11), where the closest nucleon pole is most important for the physical applications. Thus, the parametrization is valid at least up to $p_4 \sim M_D^2/2 - \sqrt{m^2 + |p|^2}$, corresponding to the nucleon pole at given $|p|$. Second, the parametrization allows for the integration in the matrix elements over $p_4$ with infinite limits, $(-\infty, +\infty)$, in the Euclidean space.

The starting point for calculating any quantity with the BS amplitude is the relativistic impulse approximation. In many cases the relativistic impulse approximation is presented by the Feynman “triangle diagram” with zero transfer of the momentum [8, 9, 10, 11, 12], $q = 0$ (Fig. 1):

$$\langle \hat{O} \rangle = \int \frac{d^4 p}{(2\pi)^4} Tr \left\{ \bar{\Psi}(p_0, p) \hat{O} \Psi(p_0, p) (\hat{p}_2 - m) \right\},$$

(16)

where $\bar{\Psi} = \gamma_0 \Psi \gamma_0$. Two important examples are the matrix elements of the vector and axial currents, $\hat{O} = \gamma_\mu, \gamma_5 \gamma_\mu$.

The matrix element $\langle \gamma_0 \rangle$, the vector charge, is used to normalize the BS amplitude:

$$1 = \frac{1}{2M_D} \int \frac{d^4 p}{(2\pi)^4} Tr \left\{ \bar{\Psi}(p_0, p) \gamma_0 \Psi(p_0, p) (\hat{p}_2 - m) \right\}$$

(17)

$$= -\frac{1}{M_D} \int \frac{dp_4 dp|p|p^2}{(2\pi)^4} \left\{ -8m (\psi_a(0)\psi_t(0) + \psi_a(2)\psi_t(2)) + \frac{4p}{\sqrt{3}} (-2\psi_p(1)\psi_t(0) + 2\sqrt{2}\psi_p(1)\psi_t(2)$$
$$+\sqrt{2}\psi_{a}(0)\psi_{v}(1) + \psi_{a}(2)\psi_{v}(1) \right)$$

$$+(M_d - 2p_4) \left( \psi_{a}^0(1)^2 + \psi_{a}(0)^2 + \psi_{a}(2)^2 + \psi_{p}(1)^2 \right.$$ 

$$\left. + \psi_{v}(1)^2 + 4\psi_{l}(0)^2 + 4\psi_{l}(2)^2 + 4\psi_{l}^0(1)^2 \right). \quad (18)$$

The components in eq. (18) are parametrized by eqs. (12)-(15). (Note that factor $2\pi$ from integration over angle $\phi$ is absorbed by the parametrization.) Integrating over $p_4$ in eq. (18) but keeping $|p|$-dependence, one gets the charge density in the momentum space, analogous to the square of the deuteron wave function in a nonrelativistic approach. This charge density is shown in Fig. 2 together with the density of the 3-rd component of the axial current (omitting terms, vanishing after integration over $\theta$):

$$\langle \gamma_5 \gamma_3 \rangle = \frac{1}{2M_D} \int \frac{d^4 p}{(2\pi)^4} \text{Tr} \left\{ \Psi(p_0,p)\gamma_5 \gamma_3 \Psi(p_0,p)(\hat{p}_2 - m) \right\} \quad (19)$$

$$= \frac{1}{M_D} \int \frac{dp_4 d|p|p^2}{(2\pi)^4} \left\{ 2m \left( 4\psi_{a}(0)\psi_{l}(0) - 2\psi_{a}(2)\psi_{l}(2) \right. \right.$$ 

$$\left. - 2\sqrt{2}\psi_{a}^0(1)\psi_{l}^0(1) + \sqrt{2}\psi_{p}(1)\psi_{v}(1) \right) \right.$$ 

$$+ \frac{2p}{\sqrt{3}} \left( 4\psi_{p}(1)\psi_{l}(0) + 2\sqrt{2}\psi_{p}(1)\psi_{l}(2) \right.$$ 

$$\left. - 2\sqrt{2}\psi_{a}(0)\psi_{v}(1) + \psi_{a}(2)\psi_{v}(1) \right) \right.$$ 

$$+(M_d - 2p_4) \left( -\psi_{a}(0)^2 + 1/2 \psi_{a}(2)^2 - 1/2 \psi_{v}(1)^2 \right.$$ 

$$-4\psi_{l}(0)^2 + 4\psi_{l}(2)^2 - 2\psi_{l}^0(1)^2 \right\}. \quad (20)$$

The quality of the parametrization has been checked by a comparison of the charge and axial densities, as well as their integrals, computed using the parametrization and original numerical components. The original amplitude is normalized by (17) and is exactly equal to 1.0, whereas the parametrization gives the normalization equal to 0.9997. This is not a trivial result, since all components were fitted independently. One can use this number for the “renormalization” of observables. The original amplitude gives an axial charge value of 0.9215, while the parametrization yields the same. The error of the parametrization describing the densities is $\sim 0.01\%$ at small $|p|$ to $\sim 1-2\%$ at $|p| \sim 1-3$ GeV.

Finally, the issue of an “inverse Wick rotation” should be addressed. The analysis of the singular structure of the “triangle graph” and behavior of the BS amplitude result in the conclusion that, perhaps, the presented parametrization can be used for an analytical continuation, $p_4 \to -ip_0$, of the BS amplitude up to the closest nucleon pole of $p_0 = M_D/2 - \sqrt{m^2 + |p|^2}$. However, such a procedure works well (with accuracy $\sim 10\%$) only up to $|p| \sim m$. The accuracy was estimated by calculating the vector and axial densities for the processes with the second nucleon on mass-shell. If it is used further, the procedure gives an accuracy of $\sim 50\%$ at $|p| = 1.5$ GeV and it should not be used beyond this point.
5 Summary

The parametrization of the realistic Bethe-Salpeter amplitude for the deuteron has been presented. All eight components of the amplitude are given in the Wick rotated case in the form of analytical functions. Simple examples of the use of the parametrization are presented and the applicability domain is discussed.

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Appendix A. Tables of parameters

Table 1: Parameters for the $\psi_p(1)$ component

| $L$ | $i$ | $A_i$ | $A'_i$ | $B_i$ |
|-----|-----|-------|--------|-------|
| 1   | 0   | -0.0108242476 | -34.3742135 | -   |
| 1   | 1   | 0.0576888290   | 119.943051  | 0    |
| 2   | -3.00806368 | -1257.32744  | 0       |       |
| 3   | 52.5918636  | 13865.0551   | -222.089494|       |
| 4   | -549.793133 | -101125.416  | 890.102891 |       |
| 5   | 3325.75711  | 472699.731   | -1210.29749|       |
| 6   | -11944.6774 | -1417223.72  | 548.300818 |       |
| 7   | 26383.0580  | 2743193.30   | -       |       |
| 8   | -34689.7448 | -3406750.03  | -       |       |
| 9   | 24977.5913  | 2621309.83   | -       |       |
| 10  | -8159.59409 | -1137897.83  | -       |       |
| 11  | 607.051002  | 213102.794   | -       |       |

Table 2: Parameters for the $\psi^0_a(1)$ component

| $L$ | $i$ | $A_i$ | $A'_i$ | $B_i$ |
|-----|-----|-------|--------|-------|
| 1   | 0   | 0.113315679 | 15.2791178 | -   |
| 1   | -0.565717405 | -42.6551270 | 0    |       |
| 2   | 12.3795242   | 292.530922  | 0    |       |
| 3   | -211.521767  | -2058.70255 | 0    |       |
| 4   | 2025.71260   | 8992.57139  | -48.3735989|       |
| 5   | -11769.4095  | -20393.3149 | 91.9530671|       |
| 6   | 43037.5609   | 10486.7684  | -44.7438523|       |
| 7   | -101273.551  | 55592.5995  | -       |       |
| 8   | 151268.732   | -141733.721 | -       |       |
| 9   | -36889.618   | 152338.654  | -       |       |
| 10  | 67943.7391   | -80778.8808 | -       |       |
| 11  | -14143.4907  | 17289.2804  | -       |       |
### Table 3: Parameters for the $\psi_v(1)$ component

| $L$ | $i$ | $A_i$       | $A'_i$      | $B_i$    |
|-----|-----|-------------|-------------|---------|
| 1   | 0   | 0.00545480918 | 0.452976149 | -       |
| 1   | -1  | -0.0413469671 | 3.58498830  | 0       |
| 2   | -2  | -0.626170875  | 49.3118036  | 0       |
| 3   | -3  | -12.5904324   | -435.917083 | 0       |
| 4   | -4  | 144.575745    | 3114.24317  | 6.14953994 |
| 5   | -5  | -1128.73423   | -14069.8986 | -25.2161192 |
| 6   | -6  | 4901.27381    | 41906.4275  | 19.9844772 |
| 7   | -7  | -13706.4378   | -85174.0821 | -       |
| 8   | -8  | 24829.8901    | 114516.487  | -       |
| 9   | -9  | -26877.9006   | -95556.5511 | -       |
| 10  | -10 | 15516.3123    | 44352.4015  | -       |
| 11  | -11 | -3665.63223   | -8706.31030 | -       |

### Table 4: Parameters for the $\psi_a(0)$ component

| $L$ | $i$ | $A_i$       | $A'_i$      | $B_i$    |
|-----|-----|-------------|-------------|---------|
| 0   | 0   | -0.00198690442 | -2.91350897 | -       |
| 1   | 1   | 0.01915782253 | 12.2001594  | -0.853805793 |
| 2   | 2   | -0.154455300  | -214.362824 | 17.7585282 |
| 3   | 3   | 25.2282913    | 3289.28876  | -89.3945864 |
| 4   | 4   | -361.376166   | -30582.8134 | 155.578411 |
| 5   | 5   | 2946.98165    | 166962.671  | -92.0411385 |
| 6   | 6   | -13477.6590   | -553839.568 | -       |
| 7   | 7   | 37613.2426    | 1152552.96  | -       |
| 8   | 8   | -63648.9139   | -1515457.41 | -       |
| 9   | 9   | 62158.0044    | 1223772.96  | -       |
| 10  | 10  | -31778.3109   | -554471.928 | -       |
| 11  | 11  | 6523.12231    | 107982.421  | -       |
## Table 5: Parameters for the $\psi_a(2)$ component

| $L$ | $i$ | $A_i$       | $A'_i$     | $B_i$  |
|-----|-----|-------------|------------|-------|
| 2   | 0   | 0.0906145663 | -54.7995054 | -      |
| 1   | -0.712220945 | 256.049408   | -57.8195768 |       |
| 2   | -20.3136219  | 470.222091   | 211.630253  |       |
| 3   | 81.4188182   | -8294.9022   | -385.318964 |       |
| 4   | -544.595070  | 33870.9853   | 367.461861  |       |
| 5   | 2355.01212   | -77139.6959  | -137.187405 |       |
| 6   | -6864.79033  | 118585.336   | -         |       |
| 7   | 13318.8325   | -138016.983  | 1         |       |
| 8   | -16303.3461  | 126552.418   | -         |       |
| 9   | 11929.7419   | -84889.6419  | -         |       |
| 10  | -4708.14062  | 35162.7881   | -         |       |
| 11  | 756.740280   | -6501.81818  | -         |       |

## Table 6: Parameters for the $\psi_0^0(1)$ component

| $L$ | $i$ | $A_i$       | $A'_i$     | $B_i$  |
|-----|-----|-------------|------------|-------|
| 1   | 0   | 0.0126177910 | 0.547674806 | -      |
| 1   | -0.0622969395 | -3.75788455 | 0         |       |
| 2   | 1.64026310   | 30.8407337  | 0         |       |
| 3   | -25.8788379  | -220.882836 | 0         |       |
| 4   | 241.662795   | 1370.42460  | 7.63938144 |       |
| 5   | -1410.95190  | -5648.39611 | -31.1836535 |       |
| 6   | 5126.52517   | 15857.5305  | 24.3738723 |       |
| 7   | -12077.1617  | -30611.8247 | -         |       |
| 8   | 18231.6691   | 39147.3503  | -         |       |
| 9   | -16701.2532  | -31118.3495 | -         |       |
| 10  | 8364.33221   | 13774.6556  | -         |       |
| 11  | -1750.41655  | -2578.09116 | -         |       |
Table 7: Parameters for the $\psi_t(0)$ component

| $L$ | $i$ | $A_i$   | $A'_i$  | $B_i$   |
|-----|-----|---------|---------|---------|
| 0   | 0   | -0.000764090007 | -0.909552636 | -       |
| 1   |     | 0.00774111957  | 3.53114793  | 0.0266757851 |
| 2   |     | 0.081210854    | -79.1547771 | 4.16947945  |
| 3   |     | 8.49620518     | 1058.66511  | -3.26685212 |
| 4   |     | -122.622299    | -8772.66567 | -36.1206906 |
| 5   |     | 1056.75816     | 43565.4328  | 36.1389858  |
| 6   |     | -5058.22423    | -132777.961 | -       |
| 7   |     | 15091.7728     | 258802.623  | -       |
| 8   |     | -28171.6682    | -327964.927 | -       |
| 9   |     | 31347.0373     | 263416.014  | -       |
| 10  |     | -18926.2139    | -122064.787 | -       |
| 11  |     | 4783.25176     | 24814.8930  | -       |

Table 8: Parameters for the $\psi_t(2)$ component

| $L$ | $i$ | $A_i$   | $A'_i$  | $B_i$   |
|-----|-----|---------|---------|---------|
| 2   | 0   | 0.0927963894 | 6.63409360 | -       |
| 1   |     | -0.566806578 | 27.0403716 | -26.4480841 |
| 2   |     | -6.23310249  | 628.891454 | 39.0979395 |
| 3   |     | -22.0317803  | -5172.06340 | -12.4959784 |
| 4   |     | 299.860807   | 22767.0450  | -       |
| 5   |     | -2053.92122  | -74280.5598 | -       |
| 6   |     | 8124.81954   | 177690.047  | -       |
| 7   |     | -20191.0789  | -294391.655 | -       |
| 8   |     | 31928.1425   | 323661.633  | -       |
| 9   |     | -30700.6358  | -224618.740 | -       |
| 10  |     | 16220.4293   | 89089.3349  | -       |
| 11  |     | -3598.88935  | -15407.7777 | -       |
Figure captions

Figure 1: The diagram for the matrix element of operator $\hat{O}$ over the deuteron state in the impulse approximation.

Figure 2: Densities of the vector (solid line) and axial (dashed line) charges calculated with the presented parametrization.
Fig. 1. A. Umnikov...
