# ФІЗІКА

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## *The Non-Relativistic Approximation in the Theory of a Spin ½ Particle with Three Additional Characteristics in Electromagnetic Fields*

*We start with the well-known Dirac-type four-component equation for a spin ½ particle with three additional characteristics, which includes several interaction terms interpreted as related to certain additional electromagnetic characteristics of a spin ½ particle. In this paper, we investigate the nonrelativistic approximation for this theory in the presence of electromagnetic fields. It turns out that in the nonrelativistic approximation, the derived equation takes the form of the standard Pauli-like equation for a spin ½ particle with an anomalous magnetic moment, defined as the sum of three parameters* $(\mu+\sigma+\eta)$ *interpreted differently in the relativistic case.*

***Key words:*** *spin ½ particle, generalized Dirac equation, additional characteristics, external electromagnetic fields, non-relativistic approximation.*

## НЕРЕЛЯТИВИСТСКОЕ ПРИБЛИЖЕНИЕ В ТЕОРИИ ЧАСТИЦЫ СО СПИНОМ ½ И ТРЕМЯ ДОПОЛНИТЕЛЬНЫМИ ХАРАКТЕРИСТИКАМИ В ПРИСУТСТВИИ ЭЛЕКТРОМАГНИТНЫХ ПОЛЕЙ

*Исходим из известного 4-компонентного уравнения дираковского типа для частицы со спином ½ и тремя дополнительными характеристиками, в которое входят несколько членов взаимодействия, интерпретируемых как связанные с некоторыми дополнительными электромагнитными характеристиками частицы со спином ½. В настоящей работе исследован вопрос о нерелятивистском пределе для этой теории в присутствии электромагнитных полей. Оказалось, что в нерелятивистском приближении уравнение принимает вид обычного уравнения Паули для частицы со спином ½ и аномальным магнитным моментом* $(\mu+\sigma+\eta)$*, определяемым как сумма трех параметров, интерпретируемых по-разному в релятивистском случае.*

***Ключевые слова:*** *частица со спином ½, обобщенные уравнения Дирака, дополнительные характеристики, внешние электромагнитные поля, нерелятивистское приближение.*

### Introduction

In [1], within the general method by Gel'fand and Yaglom, starting with the extended 28-component representation of the Lorentz group – it includes four bispiniors and one spinor of the 3rd rank – for a spin ½ particle, it was constructed a relativistic *P*-invariant generalized system of equations for a spin ½ particle with three additional to electric charge characteristics.

First, this model was developed for a free particle, and the system of spinor equations was derived; then it was transformed to spin-tensor form in presence of external electromagnetic fields. After eliminating the accessory variables of the complete wave function, it was derived the minimal 4-component Dirac-like equation, the last includes several new interaction terms which were interpreted as related to some additional electromagnetic characteristics of a spin ½ particle. For more detail see [2–4].

In order to get additional arguments for correct interpreting the physical meaning of additional characteristics, in the present paper we have studied the non-relativistic limit for the theory under consideration. It turns out that in the non-relativistic approximation, the generalized equation takes the form of the ordinary Pauli-like equation for a spin ½ particle with anomalous magnetic moment $(\mu+\sigma+\eta)$; detemined as the sum of three paremeters, which in relativistic case were interpretted as different.

**1. The non-relativistic approximation**

Extended relativistic equation for a spin ½ particle with three additional characteristics $\mu,\sigma,\eta$ has the form [1]

$$\{i\gamma^c D_c - M + \frac{e\mu}{M} F_{kl} j^{kl} + \frac{e\sigma}{M^2}(\gamma^c D_c) F_{kl} j^{kl} +$$

$$+\frac{e\eta}{M^3}(D^2 F_{kl} j^{kl} + F^n_{\ l} F^l_{\ n} + 2F_{kl} F^l_{\ n} j^{kn} + \frac{1}{2} F_{kl} F^{kl} + \frac{1}{4}\gamma_5 \epsilon^{mnkl} F_{mn} F_{kl})\}\Psi = 0, \tag{1}$$

where

$$D_c = \partial_c + ieA_c, \quad D^2 = (\partial_c + ieA_c)(\partial^c + ieA^c), \quad J^{kl} = \frac{1}{4}(\gamma^k\gamma^l - \gamma^l\gamma^k).$$

$F_{kl}$ is a electromagnetic tensor, and $J^{kl}$ are the Lorentzian bispinor generators.

Let us make the $(3+1)$-splitting in eq. (1):

$$\begin{gathered}\{i(\gamma^0 D_0 + \gamma^j D_j) - M + \\ +\frac{2e\mu}{M}(F_{01} j^{01} + F_{02} j^{02} + F_{03} j^{03} + F_{23} j^{23} + F_{31} j^{31} + F_{12} j^{12}) + \\ +\frac{2e\sigma}{M^2}(\gamma^0 D_0 + \gamma^j D_j)(F_{01} j^{01} + F_{02} j^{02} + F_{03} j^{03} + F_{23} j^{23} + F_{31} j^{31} + F_{12} j^{12}) + \\ +\frac{e\eta}{M^3}\{2(D_0^2 - D_j D_j)(F_{01} j^{01} + F_{02} j^{02} + F_{03} j^{03} + F_{23} j^{23} + F_{31} j^{31} + F_{12} j^{12} + \\ +F^n_{\ l} F^l_{\ n} + 2F_{kl} F^l_{\ n} j^{kn} + \frac{1}{2} F_{kl} F^{kl} + \frac{1}{4}\gamma_5 \epsilon^{mnkl} F_{mn} F_{kl})\}\Psi = 0.\end{gathered} \tag{2}$$

Taking in mind the identities (we apply the notations $E_1 = F_{01}, B_1 = F_{23}, \ldots$)

$$\begin{gathered}F^n_{\ l} F^l_{\ n} = 2F_{01}^2 + 2F_{02}^2 + 2F_{03}^2 - 2F_{23}^2 - 2F_{31}^2 - 2F_{12}^2 = 2(\vec{E}^2 - \vec{B}^2), \\ F_{kl} F^l_{\ n} j^{kn} \equiv 0, \quad \frac{1}{2} F_{kl} F^{kl} = \vec{B}^2 - \vec{E}^2, \quad \frac{1}{4}\gamma_5 \epsilon^{mnkl} F_{mn} F_{kl} = \gamma^5 \vec{E}\,\vec{B};\end{gathered} \tag{3}$$

and the notations

$$(K_i) = (j^{01}, j^{02}, j^{03}), (J_i) = (j^{23}, j^{31}, j^{12});$$

we can present eq. (2) differently

$$\{i(\gamma^0 D_0 + \gamma^j D_j) - M +$$
$$+\frac{2e\mu}{M}(\vec{E}\,\vec{K} + \vec{B}\vec{J}) + \frac{2e\sigma}{M^2}(\gamma^0 D_0 + \gamma^j D_j)(\vec{E}\,\vec{K} + \vec{B}\vec{J}) +$$
$$+\frac{e\eta}{M^3}(2(D_0^2 - D_j D_j)(\vec{E}\,\vec{K} + \vec{B}\vec{J}) + (\vec{E}^2 - \vec{B}^2) + \gamma^5 \vec{E}\,\vec{B})\Psi = 0. \tag{4}$$

For the following, it is convenient to use the Pauli basis for the Dirac matrices:

$$\gamma^0 = \begin{vmatrix} I & 0 \\ 0 & -I \end{vmatrix}, \gamma^j = \begin{vmatrix} 0 & \sigma_j \\ -\sigma_j & 0 \end{vmatrix}, \gamma^5 = -i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{vmatrix} 0 & -I \\ -I & 0 \end{vmatrix},$$
$$\sigma_0 = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix}, \quad \sigma_1 = \begin{vmatrix} 0 & 1 \\ 1 & 0 \end{vmatrix}, \quad \sigma_2 = \begin{vmatrix} 0 & -i \\ i & 0 \end{vmatrix}, \quad \sigma_3 = \begin{vmatrix} 1 & 0 \\ 0 & -1 \end{vmatrix}. \tag{5}$$

Also we need expressions for generators $j^{ab} = \frac{1}{4}(\gamma^a\gamma^b - \gamma^b\gamma^a)$ in this basis:

$$K_1 = j^{01} = \frac{1}{2}\begin{vmatrix} \sigma_1 & 0 \\ 0 & -\sigma_1 \end{vmatrix}, \quad K_2 = j^{02} = \frac{1}{2}\begin{vmatrix} \sigma_2 & 0 \\ 0 & -\sigma_2 \end{vmatrix}, \quad K_3 = j^{03} = \frac{1}{2}\begin{vmatrix} \sigma_3 & 0 \\ 0 & -\sigma_3 \end{vmatrix},$$
$$J_1 = j^{23} = -\frac{i}{2}\begin{vmatrix} \sigma_1 & 0 \\ 0 & \sigma_1 \end{vmatrix}, \quad J_2 = j^{31} = -\frac{i}{2}\begin{vmatrix} \sigma_2 & 0 \\ 0 & \sigma_2 \end{vmatrix}, \quad J_3 = j^{12} = -\frac{i}{2}\begin{vmatrix} \sigma_3 & 0 \\ 0 & \sigma_3 \end{vmatrix}. \tag{6}$$

Further, we apply the method of projective operators [3]:

$$P_+ = P_1 = \frac{I + \gamma^0}{2} = \begin{vmatrix} I & 0 \\ 0 & 0 \end{vmatrix}, \quad P_- = P_2 = \frac{I - \gamma^0}{2} = \begin{vmatrix} 0 & 0 \\ 0 & I \end{vmatrix},$$
$$\Psi = \begin{vmatrix} \varphi_+(x) \\ \varphi_-(x) \end{vmatrix}, \quad \Psi_1 = P_1\Psi = \begin{vmatrix} \varphi_+(x) \\ 0 \end{vmatrix}, \quad \Psi_2 = P_2\Psi = \begin{vmatrix} 0 \\ \varphi_-(x) \end{vmatrix}; \tag{7}$$

in the non-relativistic approximation, the component $\varphi_+(x)$ should be considered as large, and $\varphi_-(x)$ as small one.

Taking this in mind, we present the main equation in the block form

$$\begin{vmatrix} (iD_0 - M) & iD_k\sigma_k \\ -iD_k\sigma_k & (-iD_0 - M) \end{vmatrix}\begin{vmatrix} \varphi_+ \\ \varphi_- \end{vmatrix} + \frac{e\mu}{M}\begin{vmatrix} (\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma}) & 0 \\ 0 & (-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma}) \end{vmatrix}\begin{vmatrix} \varphi_+ \\ \varphi_- \end{vmatrix} +$$
$$+\frac{e\sigma}{M^2}\begin{vmatrix} D_0 & D_k\sigma_k \\ -D_k\sigma_k & -D_0 \end{vmatrix}\begin{vmatrix} (\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma}) & 0 \\ 0 & (-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma}) \end{vmatrix}\begin{vmatrix} \varphi_+ \\ \varphi_- \end{vmatrix} +$$
$$+\frac{e\eta}{M^3}[(D_0^2 - D_j D_j)\begin{vmatrix} (\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma}) & 0 \\ 0 & (-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma}) \end{vmatrix}\begin{vmatrix} \varphi_+ \\ \varphi_- \end{vmatrix} +$$
$$+\begin{vmatrix} (\vec{E}^2 - \vec{B}^2) & 0 \\ 0 & (\vec{E}^2 - \vec{B}^2) \end{vmatrix}\begin{vmatrix} \varphi_+ \\ \varphi_- \end{vmatrix} + \begin{vmatrix} 0 & -I \\ -I & 0 \end{vmatrix}\vec{E}\,\vec{B}]\begin{vmatrix} \varphi_+ \\ \varphi_- \end{vmatrix} = 0; \tag{8}$$

whence it follows

$$\begin{vmatrix} (iD_0 - M)\varphi_+ + iD_k\sigma_k\varphi_- \\ -iD_k\sigma_k\varphi_+ + (-iD_0 - M)\varphi_- \end{vmatrix} + \frac{e\mu}{M}\begin{vmatrix} (\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ \\ (-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- \end{vmatrix} +$$

$$+\frac{e\sigma}{M^2}\begin{vmatrix} D_0(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ + D_k\sigma_k(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- \\ -D_k\sigma_k(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ - D_0(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- \end{vmatrix} +$$

$$+\frac{e\eta}{M^3}\begin{vmatrix} (D_0^2 - D_jD_j)(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ + (\vec{E}^2 - \vec{B}^2)\varphi_+ - (\vec{E}\,\vec{B})\varphi_- \\ (D_0^2 - D_jD_j)(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- + (\vec{E}^2 - \vec{B}^2)\varphi_- - (\vec{E}\,\vec{B})\varphi_+ \end{vmatrix} = 0. \qquad (9)$$

Thus, we arrive at the following two equations:

$$(iD_0 - M)\varphi_+ + iD_k\sigma_k\varphi_- + \frac{e\mu}{M}(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ +$$

$$+\frac{e\sigma}{M^2}[D_0(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ + D_k\sigma_k(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_-] +$$

$$+\frac{e\eta}{M^3}[(D_0^2 - D_jD_j)(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ + (\vec{E}^2 - \vec{B}^2)\varphi_+ - (\vec{E}\,\vec{B})\varphi_-] = 0,$$

$$-iD_k\sigma_k\varphi_+ + (-iD_0 - M)\varphi_- + \frac{e\mu}{M}(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- +$$

$$+\frac{e\sigma}{M^2}[-D_k\sigma_k(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ - D_0(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_-] +$$

$$+\frac{e\eta}{M^3}[(D_0^2 - D_jD_j)(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- + (\vec{E}^2 - \vec{B}^2)\varphi_- - (\vec{E}\,\vec{B})\varphi_+] = 0.$$

Now, we should separate the rest energy, by using the formal changes

$$D_0 \;\Rightarrow\; (D_0 - iM), \quad iD_0 \;\Rightarrow\; (iD_0 + M), \quad D_0^2 \;\Rightarrow\; (D_0^2 - 2iMD_0 - M^2);$$

then we obtain

$$(iD_0 + M - M)\varphi_+ + iD_k\sigma_k\varphi_- + \frac{e\mu}{M}(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ +$$

$$+\frac{e\sigma}{M^2}[(D_0 - iM)(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ + D_k\sigma_k(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_-] +$$

$$+\frac{e\eta}{M^3}[(D_0^2 - 2iMD_0 - M^2 - D_jD_j)(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ + (\vec{E}^2 - \vec{B}^2)\varphi_+ - (\vec{E}\,\vec{B})\varphi_-] = 0,$$

$$-iD_k\sigma_k\varphi_+ + (-iD_0 - 2M)\varphi_- + \frac{e\mu}{M}(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- +$$

$$+\frac{e\sigma}{M^2}[-D_k\sigma_k(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ - (D_0 - iM)(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_-] +$$

$$+\frac{e\eta}{M^3}[(D_0^2 - 2iMD_0 - M^2 - D_jD_j)(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- + (\vec{E}^2 - \vec{B}^2)\varphi_- - (\vec{E}\,\vec{B})\varphi_+] = 0.$$

Dividing both equations by $M$, we get

$$i\frac{1}{M}D_0\varphi_+ + i\frac{1}{M}D_k\sigma_k\varphi_- + \frac{e\mu}{M^2}(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ +$$
$$+\frac{e\sigma}{M^2}[(\frac{1}{M}D_0 - i)(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ + \frac{1}{M}D_k\sigma_k(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_-]+$$
$$+\frac{e\eta}{M^2}[(\frac{1}{M^2}D_0^2 - 2i\frac{1}{M}D_0 - 1 - \frac{1}{M^2}D_jD_j)(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ + \frac{1}{M^2}(\vec{E}^2 - \vec{B}^2)\varphi_+ - \frac{1}{M^2}(\vec{E}\,\vec{B})\varphi_-] = 0,$$
$$-i\frac{1}{M}D_k\sigma_k\varphi_+ + (-i\frac{1}{M}D_0 - 2)\varphi_- + \frac{e\mu}{M^2}(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- +$$
$$+\frac{e\sigma}{M^2}[-\frac{1}{M}D_k\sigma_k(\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_+ - (\frac{1}{M}D_0 - i)(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_-]+$$
$$+\frac{e\eta}{M^2}[(\frac{1}{M^2}D_0^2 - 2i\frac{1}{M}D_0 - 1 - \frac{1}{M^2}D_jD_j)(-\vec{E}\vec{\sigma} - i\vec{B}\vec{\sigma})\varphi_- + (\vec{E}^2 - \vec{B}^2)\varphi_- - \frac{1}{M^2}(\vec{E}\,\vec{B})\varphi_+] = 0.$$

It is known (for instance, see in [3]) that we should assume the following orders of smallness for the involved quantities (magnetic components $B_j$ arise from commutators $D_{[kl]}$, electric components $E_k$ arise from commutators $D_{[0k]}$, whence follow their smallness orders shown below):

$$\varphi_+ \sim 1, \quad \varphi_- \sim x, \quad \frac{1}{M}D_j \sim x, \quad \frac{1}{M}D_0 \sim x^2, \quad \frac{B_j}{M^2} \sim x^2, \quad \frac{E_j}{M^2} \sim x^3. \tag{10}$$

In both equations, we will equate to zero only the terms of the primary orders, $x$ and $x^2$; in this way, we obtain two approximate equations:

$$x, \qquad \varphi_- = -i\frac{1}{2M}D_k\sigma_k\varphi_+ = 0;$$
$$x^2, \qquad i\frac{1}{M}D_0\varphi_+ + i\frac{1}{M}D_k\sigma_k\varphi_- - i\frac{e\mu}{M^2}(\vec{B}\vec{\sigma})\varphi_+ - \frac{e\sigma}{M^2}(\vec{B}\vec{\sigma})\varphi_+ + i\frac{e\eta}{M^2}(\vec{B}\vec{\sigma})\varphi_+ = 0.$$

Further, eliminating the small component $\varphi_-$, we derive an equation for the large component

$$i\frac{1}{M}D_0\varphi_+ + i\frac{1}{M}(D_k\sigma_k)(-i\frac{1}{2M}D_n\sigma_n\varphi_+) - i\frac{e\mu}{M^2}(\vec{B}\vec{\sigma})\varphi_+ - \frac{e\sigma}{M^2}(\vec{B}\vec{\sigma})\varphi_+ + i\frac{e\eta}{M^2}(\vec{B}\vec{\sigma})\varphi_+ = 0,$$

or shorter

$$iD_0\varphi_+ + \frac{1}{2M}(D_k\sigma_k)(D_n\sigma_n)\varphi_+ + \frac{e}{M}(-i\mu - \sigma + i\eta)(\vec{B}\vec{\sigma})\varphi_+ = 0;$$

it is convenient to change the notations: $-\mu \Rightarrow \mu, i\sigma \Rightarrow \sigma$. Taking in mind the multiplication rules for the Pauli matrices, we get

$$(D_k\sigma_k)(D_n\sigma_n) = D_kD_n(\delta_{kn} + i\epsilon_{knm}\sigma_m) = D_nD_n + ieB_n\sigma_n = D^2 + ieB_n\sigma_n;$$

so we arrive at the equation (let $\varphi = \Psi$).

$$iD_0\Psi_+ + \frac{1}{2M}D^2\Psi + \frac{ie}{2M}\vec{B}\vec{\sigma}\,\Psi + \frac{ie}{M}(\mu+\sigma+\eta)\,\vec{B}\vec{\sigma}\,\Psi = 0. \tag{11}$$

Thus, in the non-relativistic limit, the generalized equation takes the form of the ordinary Pauli equation for a spin ½ particle with anomalous magnetic moment $(\mu+\sigma+\eta)$.

**Conclusion**

For the theory under consideration, we have studied the non-relativistic approximation in the theory of a particle with 3 additional characteristics. It is shown that in this limit, the generalized equation takes the form of the ordinary Pauli equation for a spin ½ particle with anomalous magnetic moment; detemined as the sum of three paremeters $(\mu+\sigma+\eta)$.

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