Objective 1. Formulation of the general gauge theory with $SU(n)\times SO(p,q)$ as structural group

1.1. Obtaining the structure equations of the gauge group

The SO(p, q) group has the dimension equal to $m(m-1)/2$ where $m = p + q$, and the SU(n) group is non-abelian, having the dimension n^2-1. The infinitesimal generators of the SO(p, q) group are denoted by $M_{ab},\ a,b=1,2,3,\ldots,m$ and those of SU(n) group by $T_\alpha,\ \alpha=1,2,3,\ldots,n^2-1$. Generally, $M_{ab}=L_{ab}+\Sigma_{ab}$, where L_{ab} are the angular momentum operators and Σ_{ab} denotes the spin operators in the considered representation. The equations of structure have the form [2, 7]:

$$[M_{ab},M_{cd}]=\eta_{bc}M_{ad}-\eta_{ac}M_{bd}-\eta_{bd}M_{ac}+\eta_{ad}M_{bc}, \tag{1.1a}$$

$$[T_\alpha,T_\beta]=f^{\gamma}_{\alpha\beta}T_\gamma, \tag{1.1b}$$

$$[M_{ab},T_\alpha]=0, \tag{1.1c}$$

where

$$\eta_{ab}=diag\left(\underbrace{1,1,\ldots,1}_{p},\underbrace{-1,-1,\ldots,-1}_{q}\right)$$

is the m-dimensional Lorentz metric, and $f^{\gamma}_{\alpha\beta}=-f^{\gamma}_{\beta\alpha}$ are the structure constants of the group $SU(n)$. In the particular case of the group $SU(2)$ the structure constants coincides with the total anti-symmetric tensor $\varepsilon_{\alpha\beta\gamma}$ having the property $\varepsilon_{123}=+1$. The equation (1.1c) shows that the group $SU(n)\times SO(p,q)$ has a direct product structure. In order to describe the gravitational field we will choose $SO(1,4)$ as gauge group whose dimension is $m=p+q=5$. Therefore, we have $a=b=0,1,2,3,5$, or denoting $i=j=k=0,1,2,3$ we can write $a=i,5$ etc.

1.2. Definition of the gauge invariant derivative

We define now the gauge covariant derivative, associated to the local group of symmetry $SU(n)\times SO(p,q)$ [2]:

$$\nabla_\mu\Phi(x)=\left(\partial_\mu+\frac{g'}{2}A^{ab}_{\mu}\Sigma_{ab}+g''A^{\alpha}_{\mu}T_\alpha\right)\Phi(x), \tag{1.2}$$

where $A^{ab}_{\mu}(x)=-A^{ba}_{\mu}(x)$ are the $SO(p,q)$ gauge potentials describing the gravitational field, and $A^{\alpha}_{\mu}(x)$ are the internal gauge potentials associated to the group SU(n). The quantities g' and g'' denote the coupling constants of the gravitational and respectively internal SU(n) gauge fields. In the particular case of the group $SU(2)\times SO(1,4)$ the potentials $A^{\alpha}_{\mu}(x)$ correspond to the isospin states and $A^{ab}_{\mu}(x)$ decompose in two parts: the spin connection $\omega^{ij}_{\mu}(x)=A^{ij}_{\mu}(x),\ i,j=0,1,2,3$ and the tetrads $e^{i}_{\mu}(x)=A^{i5}_{\mu}(x)$.

1.3. Obtaining the general expressions of the tensors associated to gauge potentials

In order to determine the tensors associated to gauge potentials $A^{\alpha}_{\mu}(x)$ and $A^{ab}_{\mu}(x)$, we calculate the commutator $[\nabla_{\mu}, \nabla_{\nu}]$. Using the equations of structure (1.1), we obtain [7]:

$$
\begin{aligned}
[\nabla_{\mu},\nabla_{\nu}]\Phi(x) = \Big\{ & \frac{g'}{2}\left[\partial_{\mu}A^{ab}_{\nu} - \partial_{\nu}A^{ab}_{\mu} + g'\left(A^{a}_{c\mu}A^{cb}_{\nu} - A^{a}_{c\nu}A^{cb}_{\mu}\right)\right]\Sigma_{ab} + \\
& + \left(\partial_{\mu}A^{\alpha}_{\nu} - \partial_{\nu}A^{\alpha}_{\mu} + g'' f^{\alpha}_{\beta\gamma}A^{\beta}_{\nu}A^{\gamma}_{\nu}\right)T_{\alpha}\Big\}\Phi(x).
\end{aligned}
\tag{1.3}
$$

If we use the general definition

$$
[\nabla_{\mu},\nabla_{\nu}]\Phi(x) = \left(\frac{g'}{2}F^{ab}_{\mu\nu}\Sigma_{ab} + g''G^{\alpha}_{\mu\nu}T_{\alpha}\right)\Phi(x), \tag{1.4}
$$

and identify the Eqs. (1.3) and (1.4), then we obtain

$$
F^{ab}_{\mu\nu} = \partial_{\mu}A^{ab}_{\nu} - \partial_{\nu}A^{ab}_{\mu} + g'\left(A^{a}_{c\mu}A^{cb}_{\nu} - A^{a}_{c\nu}A^{cb}_{\mu}\right), \tag{1.5}
$$

$$
G^{a}_{\mu\nu} = \partial_{\mu}A^{\alpha}_{\nu} - \partial_{\nu}A^{\alpha}_{\mu} + g'' f^{\alpha}_{\beta\gamma}A^{\beta}_{\nu}A^{\gamma}_{\nu}. \tag{1.6}
$$

In particular, if we consider the case of SU(2) $\times$SO(1, 4), chose $a = i,5; b = j,5; c = k,5$ with $i, j, k = 0,1,2,3$ and denote $A^{i5}_{\mu} = 2\lambda e^{i}_{\mu}$, then the Eq. (1.5) becomes [10]

$$
F^{ij}_{\mu\nu} = \partial_{\mu}A^{ij} - \partial_{\nu}A^{ij}_{\mu} + g'\left(A^{i}_{k\mu}A^{kj}_{\nu} - A^{i}_{k\nu}A^{kj}_{\mu}\right) - 4\lambda^{2}g'\left(e^{i}_{\mu}e^{j}_{\nu} - e^{i}_{\nu}e^{j}_{\mu}\right), \tag{1.7}
$$

$$
F^{i}_{\mu\nu} = \partial_{\mu}e^{i}_{\nu} - \partial_{\nu}e^{i}_{\mu} + g'\left(A^{i}_{k\mu}e^{k}_{\nu} - A^{i}_{k\nu}e^{k}_{\mu}\right). \tag{1.8}
$$

In a Riemann-Cartan model the quantities $F^{i}_{\mu\nu}$ are interpreted as the components of the torsion tensor $T^{i}_{\mu\nu}$, and $F^{ij}_{\mu\nu}$ as the components of the curvature tensor $R^{ij}_{\mu\nu}$ of the space-time.

Objective 2: Obtaining the field equations for the gauge potentials

2.1. Construction of the action integral for the gauge potentials

The potentials $A^{ij}_{\mu}(x), e^{i}_{\mu}(x)$ describe the gravitational field and $A^{\alpha}_{\mu}(x)$ - the internal properties (isospin, hypercharge, etc) of the considered physical system. The tetrads $e^{i}_{\mu}(x)$ can be used to define a metric tensor

$$
g_{\mu\nu} = \eta_{ij}e^{i}_{\mu}e^{j}_{\nu}, \tag{2.1}
$$

where $\eta_{ij} = diag(1,1,1.-1)$ is the Lorentz metric. The gauge potentials allow to define the integral of the action of the considered model. It contains two terms, one corresponding to the sector SO(p, q) and the other to the $SU(n)$ sector:

$$
S_{EYM} = \int d^{4}x\, e\left[-\frac{1}{16\pi G}F - \frac{1}{4Kg'^{2}}Tr\left(T_{\alpha}T_{\beta}\right)G^{\alpha}_{\mu\nu}G^{\beta\mu\nu}\right]. \tag{2.2}
$$

In this expression we used the definitions

$$F = F^{ij}_{\mu\nu}\bar{e}_i^{\mu}\bar{e}_j^{\nu},\; e = \det\left(e^{i}_{\mu}\right), \tag{2.3}$$

where $\bar{e}_i^{\mu}(x)$ denotes the inverse of $e^i_{\mu}(x)$, i.e.

$$e^i_{\mu}\bar{e}^{\nu}_i = \delta^{\nu}_{\mu}, \quad e^i_{\mu}\bar{e}^{\mu}_j = \delta^i_j. \tag{2.4}$$

From now on we choose $Tr(T_\alpha T_\beta) = K\delta_{\alpha\beta}$ and $T_\alpha = \frac{1}{2}\sigma_\alpha$, where σ_α denotes the Pauli matrices. $K = \frac{1}{2}$. The gravitational constant G in (2.2) is the only dimensional quantity in action, because we will use the units $\hbar = c = 1$.

2.2. Obtaining the field equations by the variational method

We impose the condition $\delta S_{EYM} = 0$ (the variational principle) with respect to A^{α}_{μ}, A^i_{μ} and A^{ij}_{μ}. Then we obtain respectively the following field equations:

$$\frac{1}{e}\partial_{\mu}\left(eG^{\alpha\mu\nu}\right) + \varepsilon^{\alpha\beta\gamma}A^{\beta}_{\mu}G^{\gamma\mu\nu} = 0, \tag{2.5}$$

$$F^i_{\mu} - \frac{1}{2}Fe^i_{\mu} = 8\pi G T^i_{\mu}, \tag{2.6}$$

where T^i_{μ} is the energy-momentum tensor [3, 7] of the gauge fields $A^{\alpha}_{\mu}(x)$

$$T^i_{\mu} = \frac{1}{Kg'^2}\left(-G^{\alpha}_{\mu\rho}G^{i\rho}_{\alpha} + \frac{1}{4}e^i_{\mu}G^{\alpha}_{\rho\lambda}G^{\rho\lambda}_{\alpha}\right), \tag{2.7}$$

and respectively

$$F^i_{\mu\nu} = 0. \tag{2.8}$$

In the case of the group $SU(2)\times SO(1,4)$ the equations (2.5) determine the isospin states, those from (2.6) correspond to the Einstein equations, and (2.8) shows that we have a space without torsion. They are known as Einstein-Yang-Mills equations (EYM). By integrating the equations EYM we obtain the gauge potentials as solutions.

2.3 Formulation of the self-duality conditions

We can obtain easier solutions of the field equations if we impose the self-duality condition for the tensor of the gauge fields. To do that we define the dual tensors

$$\tilde{G}^{\alpha}_{\mu\nu} = \frac{1}{2}\sqrt{-g}\,\varepsilon_{\mu o\rho\sigma}G^{\alpha\rho\sigma}, \tag{2.9}$$

$$\tilde{F}^{ab}_{\mu\nu} = \frac{1}{2}\sqrt{-g}\,\varepsilon_{\mu o\rho\sigma}F^{ab\rho\sigma}. \tag{2.10}$$

where $g = \det(g_{\mu\nu})$, $\varepsilon_{\mu\nu\rho\sigma}$ is the total anti-symmetric Levi-Civita tensor ($\varepsilon_{0123} = +1$) and

$$G^{\alpha\rho\sigma} = g^{\rho\tau}g^{\sigma\lambda}G^{\alpha}_{\tau\lambda}, \quad F^{ab\rho\sigma} = g^{\rho\tau}g^{\sigma\lambda}F^{ab}_{\tau\lambda}. \tag{2.11}$$

Then, the self-duality condition is given by the relations

$$\tilde{G}^{\alpha}_{\mu\nu} = i\,G^{i}_{\mu\nu}, \quad \tilde{F}^{ab}_{\mu\nu} = i\,F^{ab}_{\mu\nu}. \tag{2.12}$$

These are equations of the first order in contrast with the equations EYM which are of second order and the obtaining of their solutions is easier. Any solution of the self-duality equations (2.12) is also a solution of the EYM equations but reverse is not true.

Objective 3: Applications to the spherically symmetric case

3.1. Obtaining spherically symmetric solutions

For the spherically symmetric case, the Minkowski space-time is endowed with the metric

$$ds^2 = dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right) - dt^2 . \tag{3.1}$$

We present now three examples of solutions of the previous field equations.

1) Solution with cosmological constant

We consider, as an example, the particular form of spherically gauge fields of the SO(1,4) group given by the following ansatz:

$$e_\mu^0 = (A,0,0,0),\quad e_\mu^1 = (0,B,0,0),\quad e_\mu^2 = (0,0,rC,0),\quad e_\mu^3 = (0,0,0,rC\sin\theta), \tag{3.2}$$

and

$$\begin{aligned} &A_\mu^{01} = (U,0,0,0),\quad A_\mu^{12} = (0,0,W,0),\quad A_\mu^{13} = (0,0,0,Z\sin\theta) \\ &A_\mu^{23} = (0,0,0,V\cos\theta),\quad A_\mu^{02} = A_\mu^{03} = (0,0,0,0) \end{aligned} \tag{3.3}$$

where A, B, C, U, V, Z and W are functions only of the three-dimensional radius r. In addition, the spherically symmetric SU(2) gauge fields will be parametrized as:

$$A = uT_3 dt + \mathrm{w}\left(Td\theta - T_1 \sin\theta d\varphi\right) + T_3\cos\theta d\varphi , \tag{3.4}$$

where u and w are functions also depending only of variable r. Then, imposing the constraints $A = \frac{1}{B} = \sqrt{N}, C = 1$ where $N(r)$ is a new unknown positive defined function, we obtain:

$$\begin{aligned} &(N\mathrm{w}')' = \frac{\mathrm{w}(\mathrm{w}^2-1)}{r^2} - \frac{u^2\mathrm{w}}{N}, \\ &(r^2u')' = \frac{2u\mathrm{w}^2}{\mathrm{N}}, \\ &\frac{\mathrm{w}'^2}{\mathrm{r}} + \frac{u^2\mathrm{w}^2}{rN^2} = 0, \\ &\frac{1}{2}(rN' + N - 1) + \frac{r^2u'^2}{2} + \frac{u^2\mathrm{w}^2}{N} + N\mathrm{w}'^2 + \frac{(\mathrm{w}^2-1)}{2r^2} + \frac{\Lambda r^2}{2} = 0, \end{aligned} \tag{3.5}$$

where we used $K = \frac{1}{2}$ and $\frac{4\pi G}{\mathrm{g}''} = 1$ units. These equations admit the following solution (Schwarzschild-Reissner-Nordstrom-de-Sitter) with a nontrivial gauge field describing colored black holes [4, 5, 6]:

$$u(r)=u_0+\frac{Q}{r},\quad \mathrm{w}(r)=0,\quad N(r)=1-\frac{2m}{r}+\frac{Q^2+1}{r^2}-\frac{\Lambda}{3}r^2, \tag{3.6}$$

where $\Lambda=-12\lambda^2$ is the cosmological constant of the model. The equations (3.5) admit also the self-dual solution (Schwarzschild):

$$u(r)=0,\quad \mathrm{w}(r)=\pm1,\quad N(r)=1-\frac{2m}{r}-\frac{\Lambda}{3}r^2, \tag{3.7}$$

But, the solution (3.6) is not a self-dual one.

Making a contraction $\lambda\to 0$ of the SO(1, 4) group, we obtain the Poincaré gauge theory coupled with the isospin group SU(2). The solutions of the field equations are given by (3.6) and (3.7) where $\Lambda=0$. Therefore, the Poincaré gauge theory do not allows a cosmological constant.

2) Model with the quantum gauge group $G\times SU(2)$

The gauge gravitational group G has the generators $P_\alpha=-i\partial_\alpha$, $\alpha=1,2,3,0$ considered as differential operators which commutes [12]:

$$\lfloor P_\alpha, P_\beta \rfloor=0. \tag{3.8}$$

The generators of $SU(2)$ are denoted by T_a, $a=1,2,3$ and they satisfy of the form given in (1.1b). The internal and gravitational gauge fields with values in the Lie algebra are:

$$A_\mu(x)=A_\mu^a(x)T_a,\quad C_\mu(x)=C_\mu^\alpha(x)P_\alpha. \tag{3.9}$$

We choose the spherically symmetric gauge fields in the form [1]:

$$C_r^r=U(r), C_\theta^\theta=\frac{r-1}{rg}, C_\varphi^\varphi=\frac{r\sin\theta-1}{rg\sin\theta}, C_t^t=\frac{U(r)}{1-gU(r)}, A_r^t=V(r), \tag{3.10}$$

where $U(r), V(r)$ are functions depending only of *r* and *g* is the gravitational coupling constant. Then, the corresponding field equations are [1]

$$(1-gU)(rV''+2V')-grVU''-2gVU'-2grV'U'=0, \tag{3.11}$$

$$2grU'(1-gU)\_2U-gU^2=0. \tag{3.12}$$

The general solution of the equation (3.12) is [1]

$$U(r)=\frac{1\pm\sqrt{1+\frac{a}{r}}}{g}, \tag{3.13}$$

where *a* is an arbitrary constant of integration. Choosing *a* = - 2*Gm*, the solution (3.13)gives the Schwarzschild metric [1]:

$$ds^2=\frac{dr^2}{1-\frac{2Gm}{r}}+r^2\left(d\theta^2+\sin^2\theta d\varphi^2\right)-\left(1-\frac{2Gm}{r}\right)dt^2. \tag{3.14}$$

Then, we obtain from (3.11) two corresponding solutions for $SU(2)$ gauge potentials:

$$V_1(r)=\sqrt{1+\frac{a}{r}},\quad V_2(r)=\sqrt{\frac{r}{r+a}}. \tag{3.15}$$

These results show that there are only gravitational couplings into the considered model but no $SU(2)$ internal couplings because the solution we obtained do not contains the $SU(2)$ coupling constant.

The model presented here allows the quantization of the gravitational field by using path integral method [10] on the same way as for internal gauge theories. Because the gauge group G is considered here as a pure internal symmetry, the property of renormalization is assured for our unified gauge model [1, 10].

3) Solutions for gauge fields on non-commutative space-time

We suppose now that the space-time is non-commutative with the coordinates $x^{\mu} = (r, \theta, \varphi, t)$ satisfying the following commutation relations:

$$\left[x^{\mu}, x^{\nu}\right] = i\Theta^{\mu\nu}, \tag{3.16}$$

where $\Theta^{\mu\nu} = -\Theta^{\nu\mu}$ are constant parameters. We will consider the space-space non-commutativity [2] when the only non-vanishing components are $\Theta^{12} = -\Theta^{21} = \Theta$, where Θ is a constant parameter of deformation. To describe different gauge fields we use the star product "*" defined by relation [2, 3]:

$$(\Phi * \Psi)(x) = \Phi(x) e^{\frac{i}{2}\Theta^{\mu\nu}\overleftarrow{\partial}_{\mu}\otimes\overrightarrow{\partial}_{\nu}}\Psi(x). \tag{3.17}$$

Let us suppose now that the gauge group is $SU(2)\times SO(1,4)$ and denote the gauge fields (potentials) by $\hat{A}^{a}_{\mu}(x), \hat{e}^{i}_{\mu}(x)$. We define the metric of the non-commutative space-time as

$$\hat{g}_{\mu\nu}(x, \Theta) = \frac{1}{2}\eta_{ij}\left(\hat{e}^{j}_{\mu} * \hat{e}^{j+}_{\nu} + \hat{e}^{i}_{\mu} * \hat{e}^{i+}_{\nu}\right), \tag{3.18}$$

Then,using the Witten-Seiberg map [2, 3, 13], we obtain the following corrections [2, 3]:

- for the internal $SU(2)$ gauge fields (with the commutative solution (3.7)):

$$\begin{aligned} &\hat{A}^{3}_{3} + \cos\theta + \frac{1}{2}\sin\theta\ \Theta + O(\Theta^2), \\ &\hat{A}^{r}_{0} = u_0 + \frac{Q}{r} + O(\Theta^2), \end{aligned} \tag{3.19}$$

- for the Schwarzschild metric

$$\begin{aligned} \hat{g}_{11} &= \frac{1}{1-\frac{\alpha}{r}} - \frac{\alpha(4\mathrm{r}-3\alpha)}{16r^2(\mathrm{r}-\alpha)^2}\theta^2 + O(\theta^4), \\ \hat{g}_{22} &= r^2 + \frac{2\mathrm{r}^2 - 17\alpha\mathrm{r} + 17\alpha^2}{32r(\mathrm{r}-\alpha)}\theta^2 + O(\theta^4), \\ \hat{g}_{33} &= r^2\sin^2\theta + \frac{(\mathrm{r}^2 + \alpha\mathrm{r} - \alpha^2)\cos^2\theta - \alpha(2\mathrm{r}-\alpha)}{16r(\mathrm{r}-\alpha)}\theta^2 + O(\theta^4), \\ \hat{g}_{00} &= -\left(1-\frac{\alpha}{r}\right) - \frac{\alpha(8\mathrm{r}-11\alpha)}{16r^4}\theta^2 + O(\theta^4), \end{aligned} \tag{3.20}$$

where $\alpha = 2Gm$. These solutions can be used to the determination of some quantum characteristics of the black holes such as temperature, entropy, etc.

3.2. Establishing conditions non-singular solutions of the field equations

We construct now an integral of the action of the gauge fields $e_{\mu}^{i}(x)$ under the form [2, 14]:

$$S_g = -\frac{1}{16\pi G}\int d^4x\left[F + \varphi_1(t)f_1(I_1) + \varphi_2(t)f_2(I_2) + V(\varphi_1,\varphi_{21})\right], \tag{3.21}$$

where I_1 and I_2 are two invariants of theory, and $\varphi_1(t)$, $\varphi_2(t)$ are Lagrange multipliers introduced in order to assure the existence of nonsingular solutions. The potentials $V(\varphi_1,\varphi_2)$ satisfy the conditions:

$$f_1(I_1) = -\frac{\partial V}{\partial \varphi_1}, \quad f_2(I_2) = -\frac{\partial V}{\partial \varphi_2}. \tag{3.22}$$

A possible form of the functions $f_1(I_1)$ and $f_2(I_2)$ is [14]:

$$f_1(I_1) = I_1, \;\; f_2(I_2) = -\sqrt{I_2}, \;\; I_1 = F - \sqrt{3}\left(4F_{\mu}^{i}F_{i}^{\mu} - F^2\right)^{1/2}, \;\; I_2 = 4F_{\mu}^{i}F_{i}^{\mu} - F^2. \tag{3.23}$$

If we know the metric of the space-time, we can determine then the functions $f_1(I_1), f_2(I_2)$ and the potential $V(\varphi_1,\varphi_2)$.

3.3. Construction of a non-singular solution

We consider the case of the Robertson-Walker metric

$$g_{\mu\nu} = diag\left(a(t)^2, r^2a(t)^2, r^2a(t)^2\sin^2\theta, -1\right)$$

and suppose that $\varphi_1(t) = 0$. We denote $\varphi_2(t) = \varphi(t)$ and respectively $V(0,\varphi_2) = V(\varphi)$. Then, imposing the variational principle $\delta S_g = 0$ with respect to $a(t)$ and $\varphi_2(t) = \varphi(t)$, we obtain the following conditions which assure the existence of non-singular solutions:

$$H' \equiv \left(\frac{a'}{a}\right)' = -2\lambda^2\varphi, \quad \varphi'(t) = \frac{3H^2 - \lambda^2\varphi^2}{H}. \tag{3.24}$$

where λ is the deformation parameter of the Lie algebra [see eq. (1.8)]. These equations admit the periodic solution:

$$\varphi(t) = \varphi_0\sin(\omega t),\; H(t) = \frac{\omega\varphi_0}{2\sqrt{3}}\left[\cos(\omega t) - 1\right], \tag{3.25}$$

where φ_0 is an integration constant and $\omega = 2\times 3^{1/4}\lambda$ is the frequency of the gravitational field described by the gauge fields $e_{\mu}^{i}(x)$ and $A_{\mu\nu}^{ab}(x)$. This solution has no singularities and is associated with a negative cosmological constant $\Lambda = -12\lambda^2 < 0$. The case when this constant is positive can be studied analogous by using the anti-de-Sitter group $SO(2,3)$.

It is possible to obtain and other solutions without singularities supposing that the cosmological "constant" itself has a dependence of time. Using the method described in this section we can obtain non-singular solutions for case of gauge theories with internal groups of symmetry.

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