Int J Theor Phys (2017) 56:3139–3146
DOI 10.1007/s10773-017-3482-8

$SU(2)$ Non-Abelian Photon

Xiang-Yao Wu[1] · Xiao-Jing Liu[1,2] · Hong Li[1] · Si-Qi Zhang[2] · Ji Ma[1] · Ji-Ping Liu[1] · Yu Liang[1]

Received: 12 March 2017 / Accepted: 17 July 2017 / Published online: 31 July 2017

Abstract In this paper, we have proposed $SU(2)$ non-Abelian electromagnetism gauge theory. In the theory, photon has self-interaction and interaction between them, which can explain photon entanglement phenomenon in quantum information. Otherwise, we find there are three kinds photons γ^+, γ^- and γ^0, they have electric charge $+e_\gamma$, $-e_\gamma$ and 0, respectively, these prediction are accordance with some experiment results.

Keywords QED · SU(2) gauge theory · Photon

1 Introduction

The concept of photon as the quanta of the electromagnetic field dates back to the beginning of this century. In order to explain the spectrum of black-body radiation, Planck postulated the process of emission and absorption of radiation by atoms occurs discontinuously in quanta, i.e., the emission of black-body was energy quantization with value of $\hbar\omega$ [1], In 1905, Einstein had arrived at a more drastic interpretation. From a statistical analysis of the Planck radiation law and from the energetics of the photoelectric effect he concluded that it was not merely the atomic mechanism of emission and absorption of radiation which is quantized, but that electromagnetic radiation itself consists of photons [2]. The Compton effect confirmed this interpretation.

✉ Xiao-Jing Liu
xjliu2006@163.com

Xiang-Yao Wu
wuxy2066@163.com

1 Institute of Physics, Jilin Normal University, Siping 136000, China

2 Institute of Physics, Jilin University, Changchun 130012, China

The foundations of a systematic quantum theory of field were laid by Dirac in 1927. From the quantization of the electromagnetic field one is naturally led to the quantization of any classical field, the quanta of the field being particles with well-defined properties. We have successfully quantized the free Dirac electron, we would like to discuss the question of coupling the Dirac electron to a spin-one Maxwell field. The resulting theory had been called quantum electrodynamics, namely QED. Over the past decades, the quantum electrodynamics (QED) has attracted a considerable scientific attention [3, 4]. As we have already stated, QED is an Abelian gauge theory, which based on a $U(1)$ gauge symmetry. In 1954, Yang and Mills [5] extended the gauge principle to non-Abelian gauge symmetry, which based not on the simple one-dimensional group $U(1)$ of electrodynamics, but on a three-dimensional group, the group $SU(2)$ of isotopic spin conservation, in the hope that this would become a theory of the strong interactions. In particular, because the gauge group was non-Abelian there was a self-interaction of the gauge bosons, and the $U(1)$ Abelian gauge theory there was not a self-interaction.

Entanglement [6] is a unique feature of quantum theory having no analogue in classical physics. Spontaneous parametric down-conversion (SPDC) has been used as a source of entangled photon pairs for more than two decades [7] and provides an efficient way to generate non-classical states of light for fundamental tests of nature [8, 9], for quantum information processing [10–12] or for quantum metrology [13]. Entanglement between two photons emitted by SPDC can occur in one or several possible degrees of freedom of light [14], namely polarization, transverse momentum and energy. At present, the two-photon, three-photon and multi-photon entanglement have been observed in experiment [15, 16]. The photon entanglement is from photon self-interaction and the interaction among photons.

In order to study the photon entanglement, which is from the interaction between photons, we have extended the Abelian QED to the $SU(2)$ non-Abelian QED, they can describe the photon self-interaction and the interaction among photons, the theory can explain photon entanglement phenomenon in quantum information. Otherwise, we find there are three kinds photons γ^+, γ^- and γ^0, they have electric charge $+e_\gamma$, $-e_\gamma$ and 0, respectively, which are accordance with some experiment results.

2 QED with Abelian $U(1)$ Gauge Theory

In quantum theory, QED is an Abelian gauge theory. It is instructive to show that the theory ban be derived by the Dirac free electron theory to be gauge invariant and renormalizable. Consider the Lagrangian for a free electron field $\psi(x)$

$$L_0 = \bar{\psi}(x)(i\gamma^\mu \partial_\mu - m)\psi(x), \tag{1}$$

the Dirac fields $\psi(x)$ and $\bar{\psi}(x)$ under the $U(1)$ local gauge transformations

$$\begin{aligned} \psi(x) \to \psi'(x) &= e^{-i\alpha(x)}\psi(x) \\ \bar{\psi}(x) \to \bar{\psi}'(x) &= e^{i\alpha(x)}\bar{\psi}(x) \end{aligned} \tag{2}$$

where $\alpha(x)$ is a real number. The derivative term will now have a rather complicated transformation

$$\bar{\psi}(x)\partial_\mu\psi(x) \to \bar{\psi}'(x)\partial_\mu\psi'(x) = \bar{\psi}(x)\partial_\mu\psi(x) - i\bar{\psi}(x)\partial_\mu\alpha(x)\psi(x), \tag{3}$$

The second tern spoils the invariance. We need to form a gauge-covariant derivative D_μ, to replace ∂_μ, and $D_\mu \psi(x)$ will have the simple transformation

$$D_\mu \psi(x) \to [D_\mu \psi(x)]' = e^{-i\alpha(x)} D_\mu \psi(x), \tag{4}$$

so that the combination $\bar{\psi}(x) D_\mu \psi(x)$ is gauge invariant. In other words, the action of the covariant derivative on the field will not change the transformation property of the field. This can be realized if we enlarge the theory with a new vector field $A_\mu(x)$, the gauge field, and form the covariant derivative as

$$D_\mu \psi(x) = (\partial_\mu + ieA_\mu)\psi(x), \tag{5}$$

where e is a free parameter which we eventually will identify with electric charge. Then the transformation law for the covariant derivative (4) will be satisfied if the gauge field $A_\mu(x)$ has the transformation

$$A_\mu(x) \to A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu \alpha(x), \tag{6}$$

Form (1) we now have

$$L = \bar{\psi} i\gamma^\mu(\partial_\mu + ieA_\mu) - m\bar{\psi}\psi, \tag{7}$$

defining gauge field tensor $F_{\mu\nu}$ as

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \tag{8}$$

under a transformation (6), the field tensor $F_{\mu\nu}$ is invariant, and we can structure the Lagrangian of $U(1)$ gauge field

$$L_A = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \tag{9}$$

under a transformations (2) and (6), the invariant total Lagrangian of QED is

$$L = \bar{\psi} i\gamma^\mu(\partial_\mu + ieA_\mu)\psi - m\bar{\psi}\psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}. \tag{10}$$

The following features of (10) should be noted

(1) The photon is massless because a $A_\mu A^\mu$ term is not gauge invariant and not included in (10).
(2) The Lagrangian of (10) does not have a gauge field self-interaction.

3 QED with Non-Abelian $SU(2)$ Gauge Theory

In 1954, Yang and Mills extended the gauge principle to non-Abelian symmetry, it is $SU(2)$ transformation group of isotopic spin. In order to study the photon entanglement, we have extended the Abelian QED to the non-Abelian QED. In the following, we shall study electromagnetism interaction with the $SU(2)$ gauge theory. We know the Dirac equation and K-G equation describe the particles of spin $s = \frac{1}{2}$ and $s = 0$, respectively. they are

$$[\gamma^\mu \partial_\mu - m]\psi(x) = 0, \tag{11}$$

and

$$[\partial^\mu \partial_\mu + m]\varphi(x) = 0. \tag{12}$$

In electromagnetism field, their equation are

$$[\gamma^\mu(\partial_\mu - ieA_\mu) - m]\psi(x) = 0, \tag{13}$$

and

$$[(\partial^\mu - ieA^\mu)(\partial_\mu - ieA_\mu) + m]\varphi(x) = 0, \tag{14}$$

the spin $s = \frac{1}{2}$ charged particle, its $SU(2)$ doublet is

$$\psi(x) = \begin{pmatrix} \psi' \\ \psi \end{pmatrix}, \tag{15}$$

the spin $s = 0$ charged particle, its $SU(2)$ doublet is

$$\psi = \begin{pmatrix} \varphi' \\ \varphi \end{pmatrix}. \tag{16}$$

Where ψ' and φ' are particle final states of spin $\frac{1}{2}$ and 0.

For (15), under an SU(2) transformation, we have

$$\psi(x) \to \psi'(x) = e^{-iT^i \cdot \theta^i}\psi(x), \tag{17}$$

where $T^i = \frac{1}{2}\sigma^i$, $\sigma^i (i = 1, 2, 3)$ are the usual Pauli matrices, satisfying

$$\left[\frac{\sigma_i}{2}, \frac{\sigma_j}{2}\right] = i\epsilon_{ijk}\frac{\sigma_k}{2} \qquad i, j, k = 1, 2, 3, \tag{18}$$

and $\theta = (\theta_1, \theta_2, \theta_3)$ are the SU(2) transformation parameters. The free Lagrangian for electrons field $\psi(x)$

$$L_0 = \bar{\psi}(x)(i\gamma^\mu\partial_\mu - m)\psi(x), \tag{19}$$

is invariant under the global SU(2) symmetry with θ_i being space-time independent. However, under the local symmetry transformation

$$\psi(x) \to \psi'(x) = u(\theta)\psi(x), \tag{20}$$

with

$$u(\theta) = e^{-iT^i \cdot \theta^i(x)}, \tag{21}$$

the free Lagrangian L_0 is no longer invariant because the derivative term transforms as

$$\bar{\psi}(x)\partial_\mu\psi(x) \to \bar{\psi}'(x)\partial_\mu\psi'(x) = \bar{\psi}(x)\partial_\mu\psi(x) + \bar{\psi}(x)u^{-1}(\theta)[\partial_\mu u(\theta)]\psi(x), \tag{22}$$

To construct a gauge-invariant Lagrangian we follow a procedure similar to that of the Abelian case. First we introduce the vector gauge fields A^i_μ, $i = 1, 2, 3$ (one for each group generator) to form the gauge-covariant derivative through the minimal coupling

$$D_\mu(x) = \partial_\mu + A_\mu(x), \tag{23}$$

where

$$A_\mu(x) = -igA^i_\mu(x)T^i, \tag{24}$$

where g is the coupling constant in analogy to e in (5). We demand that $D_\mu\psi$ have the same transformation property as ψ itself, i.e.

$$D_\mu\psi \to (D_\mu\psi)' = D'_\mu\psi' = D'_\mu u(x)\psi = u(\theta)D_\mu\psi, \tag{25}$$

This implies that

$$(\partial_\mu - igT^i A'^i_\mu)(u(\theta)\psi) = u(\theta)(\partial_\mu - igT^i A^i_\mu)\psi, \tag{26}$$

or

$$[\partial_\mu u(\theta) - igT^i A'^i_\mu u(\theta)] = -igu(\theta)T^i A^i_\mu, \tag{27}$$

or

$$T^i A'^i_\mu = u(\theta) T^i A^i_\mu u^{-1}(\theta) - \frac{i}{g}[\partial_\mu u(\theta)]u^{-1}(\theta), \tag{28}$$

which defines the transformation law for the gauge field. For an infinitesimal gauge change $\theta(x) \ll 1$,

$$u(\theta) \cong 1 - i\vec{T} \cdot \vec{\theta}(x), \tag{29}$$

ignoring the higher order terms of θ^j, (28) becomes

$$\begin{aligned} T^i A'^i_\mu &= (1 - iT^j\theta^j)T^i A^i_\mu (1 + iT^j\theta^j) - \frac{i}{g}(-i\vec{T} \cdot \partial_\mu \vec{\theta})(1 + i\vec{T} \cdot \vec{\theta}) \\ &= T^i A^i_\mu + iT^i A^i_\mu (T^j\theta^j) - i(T^j\theta^j)T^i A^i_\mu - \frac{1}{g}(\vec{T} \cdot \partial_\mu \vec{\theta}), \\ &= T^i A^i_\mu + iA^k_\mu \theta^j T^k T^j - iA^k_\mu \theta^j T^j T^k - \frac{1}{g}(\vec{T} \cdot \partial_\mu \vec{\theta}) \\ &= T^i A^i_\mu - iA^k_\mu \theta^j [T^j, T^k] - \frac{1}{g}(\vec{T} \cdot \partial_\mu \vec{\theta}) \\ &= T^i A^i_\mu + A^k_\mu \theta^j \epsilon^{ijk} T^i - \frac{1}{g}(\vec{T} \cdot \partial_\mu \vec{\theta}) \end{aligned} \tag{30}$$

or

$$A'^i_\mu = A^i_\mu + \epsilon^{ijk} A^k_\mu \theta^j - \frac{1}{g}\partial_\mu \theta^i, \tag{31}$$

defining gauge field intensity $F^\alpha_{\mu\nu}$, it is

$$F_{\mu\nu} = D_\mu A_\nu - D_\nu A_\mu \tag{32}$$

and

$$F_{\mu\nu} = -igF^\alpha_{\mu\nu} T^\alpha, \tag{33}$$

and

$$\begin{aligned} -igF^\alpha_{\mu\nu} T^\alpha &= (\partial_\mu - igA^\alpha_\mu T^\alpha)(-igA^\beta_\nu T^\beta) - (\partial_\nu - igA^\beta_\nu T^\beta)(-igA^\alpha_\mu T^\alpha) \\ &= -ig\partial_\mu A^\beta_\nu T^\beta + ig\partial_\nu A^\alpha_\mu T^\alpha - g^2 A^\alpha_\mu A^\beta_\nu [T^\alpha, T^\beta] \\ &= -ig(\partial_\mu A^\alpha_\nu - \partial_\nu A^\alpha_\mu)T^\alpha - ig^2 \epsilon^{\alpha\beta\nu} A^\alpha_\mu A^\beta_\nu T^\nu, \end{aligned} \tag{34}$$

or

$$F^\alpha_{\mu\nu} = \partial_\mu A^\alpha_\nu - \partial_\nu A^\alpha_\mu + g\epsilon^{\alpha\beta\nu} A^\beta_\mu A^\alpha_\nu. \tag{35}$$

From (28), we have

$$A'_\mu(x) = u(\theta)A_\mu(x)u^{-1}(\theta) + u(\theta)\partial_\mu u^{-1}(\theta), \tag{36}$$

$F'_{\mu\nu}$ gauge transformation is

$$\begin{aligned} F'_{\mu\nu} &= D'_\mu A'_\nu - D'_\nu A'_\mu \\ &= (\partial_\mu + A'_\mu)A'_\nu - (\partial_\nu + A'_\nu)A'_\mu \\ &= (\partial_\mu + uA_\mu u^{-1} + u\partial_\mu u^{-1})(uA_\nu u^{-1} + u\partial_\nu u^{-1}) \\ &\quad -(\partial_\nu + uA_\nu u^{-1} + u\partial_\nu u^{-1})(uA_\mu u^{-1} + u\partial_\mu u^{-1}), \end{aligned} \tag{37}$$

the first term is

$$
\begin{aligned}
(\partial_\mu + uA_\mu u^{-1} + u\partial_\mu u^{-1})(uA_\nu u^{-1} + u\partial_\nu u^{-1}) &= (\partial_\mu u)A_\nu u^{-1} + u(\partial_\mu A_\nu)u^{-1} \\
&\quad + uA_\nu(\partial_\mu u^{-1}) + (\partial_\mu u)\partial_\nu u^{-1} + u\partial_\mu\partial_\nu u^{-1} \\
&\quad + uA_\mu u^{-1}uA_\nu u^{-1} + uA_\mu u^{-1}u\partial_\nu u^{-1} \\
&\quad + u(\partial_\mu u^{-1})uA_\nu u^{-1} + u(\partial_\mu u^{-1})u\partial_\nu u^{-1} \\
&= u(\partial_\mu A_\nu)u^{-1} + uA_\nu(\partial_\mu u^{-1}) \\
&\quad + u\partial_\mu\partial_\nu u^{-1} + uA_\mu A_\nu u^{-1} + uA_\mu\partial_\nu u^{-1}
\end{aligned} \tag{38}
$$

and the second term is

$$
\begin{aligned}
(\partial_\nu + uA_\nu u^{-1} + u\partial_\nu u^{-1})(uA_\mu u^{-1} + u\partial_\mu u^{-1}) &= u(\partial_\nu A_\mu)u^{-1} + uA_\mu(\partial_\nu u^{-1}) \\
&\quad + u\partial_\nu\partial_\mu u^{-1} + uA_\nu A_\mu u^{-1} + uA_\nu\partial_\mu u^{-1}
\end{aligned} \tag{39}
$$

substituting (38) and (39) into (37), we have

$$
\begin{aligned}
F'_{\mu\nu} &= u[(\partial_\mu + A_\mu)A_\nu - (\partial_\nu + A_\nu)A_\mu]u^{-1} \\
&= u(D_\mu A_\nu - D_\nu A_\mu)u^{-1} \\
&= uF_{\mu\nu}u^{-1},
\end{aligned} \tag{40}
$$

under an infinitesimal gauge change (29), there is

$$F_{\mu\nu} \to F'_{\mu\nu} = (1 - iT^a\theta^a)F_{\mu\nu}(1 + iT^b\theta^b), \tag{41}$$

or

$$
\begin{aligned}
F'^c_{\mu\nu}T^c &= (1 - iT^a\theta^a)F^c_{\mu\nu}T^c(1 + iT^b\theta^b) \\
&= F^c_{\mu\nu}T^c + iF^c_{\mu\nu}T^cT^b\theta^b - iF^c_{\mu\nu}T^aT^c\theta^a + F^c_{\mu\nu}T^aT^c\theta^aT^b\theta^b \\
&= F^c_{\mu\nu}T^c + iF^c_{\mu\nu}[T^c, T^b]\theta^b \\
&= F^c_{\mu\nu}T^c - \epsilon^{abc}F^a_{\mu\nu}T^c\theta^b,
\end{aligned} \tag{42}
$$

or

$$F'^c_{\mu\nu} = F^c_{\mu\nu} - \epsilon^{abc}F^a_{\mu\nu}\theta^b, \tag{43}$$

i.e.,

$$F'^a_{\mu\nu} = F^a_{\mu\nu} - \epsilon^{cba}F^c_{\mu\nu}\theta^b = F^a_{\mu\nu} + \epsilon^{abc}F^c_{\mu\nu}\theta^b. \tag{44}$$

From (40), we have

$$F'_{\mu\nu}F^{\mu\nu'} = uF_{\mu\nu}u^{-1}uF^{\mu\nu}u^{-1} = uF_{\mu\nu}F^{\mu\nu}u^{-1}, \tag{45}$$

and

$$TrF'_{\mu\nu}F^{\mu\nu'} = TruF_{\mu\nu}F^{\mu\nu}u^{-1} = TrF_{\mu\nu}F^{\mu\nu}, \tag{46}$$

or

$$
\begin{aligned}
TrF_{\mu\nu}F^{\mu\nu'} &= Tr[(-igF^{\alpha}_{\mu\nu}T^{\alpha})(-igF^{\mu\nu\beta}T^{\beta})] \\
&= -g^2F^{\alpha}_{\mu\nu}F^{\mu\nu\beta}Tr(T^{\alpha}T^{\beta}) \\
&= -\frac{1}{2}g^2F^{\alpha}_{\mu\nu}F^{\mu\nu\beta}\delta_{\alpha\beta} \\
&= -\frac{1}{2}g^2F^{\alpha}_{\mu\nu}F^{\mu\nu\alpha}, \qquad (47)
\end{aligned}
$$

the Lagrangian of gauge field can be taken as

$$L_F = -\frac{1}{4}F^{\alpha}_{\mu\nu}F^{\mu\nu\alpha}, \qquad (48)$$

and the total Lagrangian is

$$
\begin{aligned}
L &= \bar{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi - \frac{1}{4}F^{\alpha}_{\mu\nu}F^{\mu\nu\alpha} \\
&= \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi - g\bar{\psi}\gamma^{\mu}A^{\alpha}_{\mu}T^{\alpha}\psi - \frac{1}{4}F^{\alpha}_{\mu\nu}F^{\mu\nu\alpha}. \qquad (49)
\end{aligned}
$$

The $U(1)$ and $SU(2)$ gauge theory of Abelian and non-Abelian have been introduced in many quantum field theory books [17–19]. In this paper, we apply the non-Abelian gauge theory to describe the electromagnetic interaction, and obtain some new results:

(1) The photon is massless because a $A_{\mu}A^{\mu}$ term is not gauge invariant and not included in (49).
(2) The Lagrangian of (49) has a photon self-interaction, because of the term $\frac{1}{4}F^{\alpha}_{\mu\nu}F^{\mu\nu\alpha}$ in (49) contains products of three and four factors of A_{μ}, i.e., there are the three-photon and four-photon vertex diagrams.
(3) In $SU(2)$ gauge theory, there are three kinds photons γ^{+}, γ^{-} and γ^{0}, they have three different electric charge $+e_{\gamma}$, $-e_{\gamma}$ and 0. In the electromagnetism interaction, the charge is conservative. The initial state particle charge is e, and the final states particle charge is $e - e'$, where the e' are $+e_{\gamma}$, $-e_{\gamma}$ and 0, respectively. The electric charge quantity of photon is more less than the electric's. i.e., $e_{\gamma}/e \ll 1$. In Refs. [20–22], these experiments have given the ratio of photon electric charge and electron electric charge $e_{\gamma}/e < 3.4 \times 10^{-5}$.

4 Conclusion

In this paper, we have proposed $SU(2)$ non-Abelian electromagnetism gauge theory. In the theory, photon is massless, and it has self-interaction and interaction between them, there are the three-photon and four-photon vertex, which can explain photon entanglement phenomenon in quantum information theory. Otherwise, we find there are three kinds photons γ^{+}, γ^{-} and γ^{0} in the $SU(2)$ gauge theory, and they have electric charge $+e_{\gamma}$, $-e_{\gamma}$ and 0, respectively, which are accordance with some experiment results.

References

1. Planck, M.: The Theory of Heat Radiation. Philadelphia (1914)
2. Einstein, A.: Concerning a heuristic point of view to-ward the emission and transformation of light. Ann. Phys. **17** (1905)

3. Di Piazza, A., Muller, C., Hatsagortsyan, K.Z., Kietel, C.H.: Rev. Mod. Phys. **84**, 1177 (2012)
4. Ritus, V.I.: J. Sov. Laser Res. **6**, 497 (1985)
5. Yang, C.N., Mills, R.L.: Phys. Rev. **96**, 191 (1954)
6. Horodecki, R., Horodecki, P., Horodecki, M., Horodecki, K.: Rev. Mod. Phys. **81**, 865 (2009)
7. Ghosh, R., Mandel, L.: Phys. Rev. Lett. **59**, 1903 (1987)
8. Zeilinger, A.: Rev. Mod. Phys. **71**, 288 (1999)
9. Genovese, M.: Phys. Rep. **413**, 319 (2005)
10. Gisin, N., Ribordy, G., Tittel, W., Zbinden, H.: Rev. Mod. Phys. **74**, 145 (2002)
11. Gisin, N., Thew, R.: Nat. Photonics **1**, 165 (2007)
12. Kok, P., Munro, W.J., Nemoto, K., Ralph, T.C., Dowling, J.P., Milburn, G.J.: Rev. Mod. Phys. **79**, 135 (2007)
13. Giovannetti, V., Lloyd, S., Maccone, L.: Nat. Photonics **5**, 222 (2011)
14. Barreiro, J.T., Langford, N.K., Peters, N.A., Kwiat, P.G.: Rev. Phys. Lett. **95**, 260501 (2005)
15. Bouwmeester, D., Pan, J.-W.: Phys. Rev. Lett. **82**, 1345 (1999)
16. Sackett, C.A.: Nature **404**, 256 (2000)
17. Bjorken, J.B., Drell, S.D.: Relativistic Quantum Fields. Mc-Graw-Hill (1965)
18. Itzykson, C., Zuber, J.B.: Quantum Field Theory. Mc-Graw-Hill (1980)
19. Lichtenberg, D.B. Unitary Symmetry and Elementary Particles, 2nd edn. Academic Press, New York (1978)
20. Dobroliubov, M.I., Ignatiev, A.Y.: Phys. Rev. Lett. **65**, 679 (1990)
21. Mitsui, T., Fujimoto, R., Ishisaki, Y., Ueda, Y., Yamazaki, Y., Asai, S., Orito, S.: Phys. Rev. Lett. **70**, 2265 (1993)
22. Badertscher, A., et al.: Phys. Rev. D **75**, 032004 (2007)