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Gauge symmetry and background independence: Should the proton spin decomposition be path independent?

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Abstract

Exploring the similarities between the Chen et al. approach, where physical and gauge degrees of freedom of the gauge potential are explicitly separated, and the background field method, we provide an alternative point of view to the proton spin decomposition issue. We show in particular that the gauge symmetry can be realized in two different ways, and discuss the relations between the concepts of path dependence, Stueckelberg dependence and background dependence. Finally, we argue that path/Stueckelberg/background-dependent decompositions of the proton spin are in principle measurable and therefore physically meaningful.

Keywords: Proton spin decomposition; Gauge invariance; Background field method

1. Introduction

Until 2008, there were essentially two decompositions of the proton spin into quark/gluon and spin/orbital angular momentum (OAM) contributions. On the one hand, the Ji decomposition [1]

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$$\vec{J} = \underbrace{\int \mathrm{d}^3x\,\psi^\dagger \frac{1}{2}\vec{\Sigma}\psi}_{\vec{S}^q_{\text{Ji}}} + \underbrace{\int \mathrm{d}^3x\,\psi^\dagger(\vec{x}\times i\vec{D})\psi}_{\vec{L}^q_{\text{Ji}}} + \underbrace{\int \mathrm{d}^3x\,\vec{x}\times\left(\vec{E}^a\times\vec{B}^a\right)}_{\vec{J}^g_{\text{Ji}}} \tag{1}$$

with $\vec{D} = -\vec{\nabla} - ig\vec{A}^a t^a$, is gauge invariant but does not provide any split of the gluon angular momentum $\vec{J}^g_{\text{Ji}}$ into spin and OAM contributions. On the other hand, the Jaffe–Manohar decomposition [2]

$$\vec{J} = \underbrace{\int \mathrm{d}^3x\,\psi^\dagger \frac{1}{2}\vec{\Sigma}\psi}_{\vec{S}^q_{\text{JM}}} + \underbrace{\int \mathrm{d}^3x\,\psi^\dagger\left(\vec{x}\times\frac{1}{i}\vec{\nabla}\right)\psi}_{\vec{L}^q_{\text{JM}}} + \underbrace{\int \mathrm{d}^3x\,\vec{E}^a\times\vec{A}^a}_{\vec{S}^g_{\text{JM}}} + \underbrace{\int \mathrm{d}^3x\,E^{ia}(\vec{x}\times\vec{\nabla})A^{ia}}_{\vec{L}^g_{\text{JM}}} \tag{2}$$

provides a complete split into quark/gluon and spin/OAM contributions, but is not gauge invariant. In practice, the Jaffe–Manohar decomposition is then considered in a fixed gauge, casting doubts on its measurability and therefore physical relevance.

In 2008, Chen et al. [3,4] proposed a complete decomposition of the proton spin consistent with gauge symmetry

$$\vec{J} = \underbrace{\int \mathrm{d}^3x\,\psi^\dagger \frac{1}{2}\vec{\Sigma}\psi}_{\vec{S}^q_{\text{Chen}}} + \underbrace{\int \mathrm{d}^3x\,\psi^\dagger(\vec{x}\times i\vec{D}_{\text{pure}})\psi}_{\vec{L}^q_{\text{Chen}}} + \underbrace{\int \mathrm{d}^3x\,\vec{E}^a\times\vec{A}^a_{\text{phys}}}_{\vec{S}^g_{\text{Chen}}} + \underbrace{\int \mathrm{d}^3x\,E^{ia}\left(\vec{x}\times\vec{\mathcal{D}}^{ab}_{\text{pure}}\right)A^{ib}_{\text{phys}}}_{\vec{L}^g_{\text{Chen}}} \tag{3}$$

with $\vec{D}_{\text{pure}} = -\vec{\nabla} - ig\vec{A}^a_{\text{pure}}t^a$ and $\vec{\mathcal{D}}^{ab}_{\text{pure}} = -\delta^{ab}\vec{\nabla} - gf^{abc}\vec{A}^c_{\text{pure}}$. The crucial assumption was the possibility to separate the gauge degrees of freedom from the physical degrees of freedom in the gauge potential $\vec{A}(x) = \vec{A}_{\text{pure}}(x) + \vec{A}_{\text{phys}}(x)$. In particular, they were able to define a gauge-invariant gluon spin contribution $\vec{S}^g_{\text{Chen}}$, in apparent contradiction with textbook claims [5,6]. This approach reopened old controversies, triggered numerous studies and finally led to the conclusion that there exist in principle infinitely many possible decompositions of the proton spin. For a review of the recent developments, see Refs. [7,8].

The Chen et al. decomposition turned out to be a *gauge-invariant extension* (GIE) [9,10] of the Jaffe–Manohar decomposition, in the sense that it is formally gauge invariant but gives the same results as the Jaffe–Manohar decomposition considered in a fixed gauge. Ji criticized the Chen et al. approach, arguing that their notion of gauge invariance does not coincide with the "usual textbook type" [11,12]. Moreover, Ji, Xu and Zhao [10] wrote that "the GIE of an intrinsically gauge-non-invariant quantity is not naturally gauge invariant" and that "GIE operators are in general unmeasurable. So far, the only example is offered in high-energy scattering in which certain partonic GIE operators may be measured". This kind of statement is pretty confusing and seems at first sight self-contradictory. Indeed, how can a measurable quantity be "not naturally gauge invariant" or, using Wakamatsu's words [13], "not a gauge-invariant quantity in a *true* or *traditional* sense"?