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Editorial

Editorial for Special Issue "Quantum Field Theory, 2nd Edition"

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This second Special Issue on Quantum Field Theory is a continuation of the first Special Issue on quantum field theory [1], where the motivation of many of my colleagues and my own for our continued activity in this fascinating research field is explained.

The present edition contains insightful contributions on approaching the strong coupling limit in pure 4D Yang–Mills theory within the framework of the effective locality concerning gauge-field propagation in covariant gauges [2]. The conclusion is that, for resolutions smaller than an effective mass scale Δ, gauge fields do not propagate over finite Minkowskian separations. This work rests on a series of predecessor contributions, starting with a consideration of quark/antiquark scattering in a quenched, eikonal model at high energy and large coupling, whose amplitude is shown to be decomposable into a set of finite, local integrals [3,4]. In this limit, a Fradkin representation of Green's functional can be derived that accommodates the transverse imprecision of quark or antiquark coordinates in elastically scattered bound states (preudoscalar mesons or nucleons/antinucleons) [4,5]. Effective renormalisation was analysed [6], showing that, due to the ensuing locality low-energy, transverse-momentum quark–quark or quark–antiquark interactions, color-charge renormalisation is finite. In [7], it is shown that in fermionic QCD amplitudes, apart from a dependence on the quadratic Casimir operator in the fundamental presentation of $SU(3)_c$ encountered in perturbation theory, there is also dependence on the cubic Casimir operator.

The stability properties of coherent states of gravitons in closed type-II string theory, argued in [8] as representing de Sitter spacetime within definite temporal bounds (quantum break-time), was investigated in [9]. In contrast to [8] and [10,11], the de Sitter state of coherent gravitons de-coheres by steepest entropy ascent quantum thermodynamics, where the quantum evolution is driven by a maximal increase in entropy triggered by the presence of other states in the string spectrum.

In [12], the Weyl–Wigner representation of quantum electromagnetism, where the classical field strength is promoted to a random field including Gaussian zero-point fluctuations, is analysed. This contribution represents a line of research on stochastic electrodynamics where electric point charges (see below for two proposals for resolving them classically or in terms of an emergent, explicit quantum theory) interact in terms of random classical radiation with a Lorentz-invariant spectrum whose scale is set by Planck's quantum of action [13]. An important question asked in [12] is the following: "Why does the Wigner representation of Quantum Mechanics (for systems of particles) not admit a realistic interpretation?" This is answered by the author as follows: "I believe that the reason is that quantum particles are dramatically different from classical particles." I agree with this conclusion [14]. However, unlike the approach voiced in [15], I am convinced that it takes more than the action of a random radiation field to promote a classical, charged point particle to a quantum particle.

A computation of the average topological susceptibility χ of thermal SU(3) Yang–Mills theory in 4D within the model of the stochastic vacuum [16,17] is performed in [18], in agreement with general reflection positivity. For high temperatures, χ is positive and

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$\chi \propto T^4$, which, even qualitatively, contradicts lattice results [19,20]. The latter seem to support dilute-instanton gas or instanton liquid models of the deconfining ground state [21–23]. In [24], we observed, however, that with the typical spatial sizes employed in simulations lattices "fall" through the centers of the (anti)calorons comprising the thermal grounds state such that important quantum correlations, which determine χ, are not captured by these simulations; see the discussion in [25]. Close to the critical temperature, the string tension, dominated by the quadratic cumulant, receives a negative correction from the quartic cumulant [18], which puts it to values that are in much better agreement with phenomenological extractions. When the methods used in [18] are adapted to the case of effective thermal SU(2) Yang–Mills theory in the free quasiparticle limit (which is a very good approximation in computing thermal quantities [26]), they are a useful framework for estimating the associated small correction w.r.t. the caloron/anticaloron contribution to χ [24].

In [27], spin-orientation-dependent (cosmic) neutrino oscillations and CP violation are related to constant and linearly time-dependent torsion backgrounds perturbing flat spacetime by quantising the neutrino spinor. Note that torsion is introduced in the Einstein–Cartan theory framework or modifications thereof (non-symmetric connection, see, e.g [28–31]). New oscillation formulae are derived in [27], where the energy splitting induced by the torsion term affects the oscillation frequencies and the Bogoliubov coefficients. As a result, the spin dependence of the oscillation is maximal for values of torsion comparable to the neutrino momentum and masses. Increasing torsion away from this regime leads to flavour oscillations, which become independent of spin. The authors point out that experiments studying neutrinos with very low momenta, such as PTOLEMY, could differentiate between quantum mechanical flavour oscillations [32] and the here-proposed scenario of torsion-driven oscillations of quantised spinors.

All of these contributions are original, highly interesting, and potentially useful. In this editorial I will, however, discuss in more detail the contributions [33,34], which are continuations of work presented in the first edition [35] and are based on the first publication of [36]. This work on the electron being a classical, field-theoretic soliton represents an alternative to our own proposal of a model of the electron as a thermal quantum object [14]. Therefore, to discuss [33,34] and its predecessors touches my immediate, personal research interests.

In [36], the electron is associated with a unimodular quaternion, that is, a topologically nontrivial SU(2)-group element Q covering the group manifold S_3), which links to an SU(2)–Lie algebra valued field strength R_{st} and a connection Γ_s (living in the tangent space to Q) by differentiation with respect to t and s, each parameterising curves on S_3, e.g., $\Gamma_s = iQ(s)\partial_s Q(s)^\dagger$. In a particular static and radially symmetric Ansatz for Q, introducing a profile function $\alpha(r)$ s.t. certain boundary conditions, a Skyrme term is employed in defining the energy functional for the electric field strength $\vec{E}$ obtained from R_{st}. Such a soliton's far field resembles that of a monopole (similar to what happens for the 't Hooft–Polyakov or BPS monopole in an SU(2)-adjoint Higgs model [37–39]). The field energy $\propto \int d^3x \vec{E}^2$ is finite. However, a stabilising term needs to be added to such an energy density (scaling argument, Derrick's theorem), which is introduced in [36] as a monomial in the field Q. Subsequently, the function $\alpha(r)$ is determined by minimising the total energy (equivalent to solving a certain second-order equation for $\cos\alpha$ s.t. spatial boundary conditions). Setting this energy equal to the rest mass of the electron yields a radial extent r_0, which is comparable to the classical electron radius $r_0 = 2.2 \times 10^{-15}$ m. The particle properties of this model have been investigated for a long time. Namely, in [35], a correspondence of the above-described solitons with the Dirac equation is argued to take place in the limit of zero extent with and without coupling them to external electromagnetic fields. This would suggest that certain quantum effects inherent to solutions of the Dirac

equation (wave-like propagation of the amplitude, magnetic moment, charge distribution) are contained in the classical soliton solution already. Along this vein, ref. [33] numerically computes the static energy $E(d)$ of an electron–positron dipole state (d is the distance between the centres-of-mass of these particles) with total zero spin in the soliton model and compares it to the static energy of the same dipole system but now subject to point charges (the asymptotic dependencies of $E(d)$ must match for $d \to \infty$ in both cases). The differences at finite d can be interpreted as a running of the fine-structure constant α. Even though, qualitatively, there is an interesting rise in the thus extracted $\alpha(d)$, which resembles that of long-distance perturbative QED; there are difficulties in controlling the computation quantitatively due to the implementation of infinite-distance boundary conditions on finite-size lattices. In [34], the 4/3 problem, which states that the boosted classical Coulomb field energy for an ad hoc stabilised radius r_0 is 4/3 larger than the boosted rest energy of a classical particle solely characterised by its mass m, is solved by introducing a potential for the scalar field Q , out of which the electric field of a particle at rest is derived (as it is in the soliton model).

However, a static classical soliton, whose charge distribution is fixed, must reveal its structure in scattering experiments with deviations from QED predictions (e.g. Bhabha scattering of e^+ and e^-) as the centre-of-mass energy of two head-on colliding solitons starts exceeding the rest mass of the electron (there are mild indications in [40,41] that deviations may take place for momentum transfers in a small vicinity of the electron mass m_0, but there should be large deviations for *all* momentum transfers larger than m_0 for scattering between classical solitons). Also, de Broglie's basic idea was to view the electron as a vibrating system of frequency ω_0 in its rest frame, with its mass m_0 given by $m_0 = \hbar\omega$. Only under this assumption could de Broglie derive his relation $p = \hbar k$ between wave number $k = 2\pi/\lambda$, ensuing from such a standing oscillation under a Lorentz boost, and the particle's momentum p. Where is this vibration in a static soliton (which does not require it to explain its mass classically)? Moreover, a model that addresses the properties of the electron beyond classical pointlikeness should also address dimensionless parameters characterising its (electroweak) interactions such as the fine-structure constant α and the electroweak mixing angle θ_W. Finally, the stabilisation of a finite radius r_0 has to be considered in the soliton model by adding a potential for Q to the Skyrme term, which is not fixed from basic principles. In [14], a proposal for modelling the electron as a finite-extent quantum soliton was provided that invokes the thermal phase structure of two mixing, effectively quantum SU(2) Yang–Mills theories, which tries to address these points. Note that it is notoriously difficult (if not impossible) to compute scattering cross-sections for such quantum solitons directly—a theoretically and experimentally well-established procedure in the Standard Model of Particles.

Having said this, I maintain that the classical soliton model of the electron [36] is inspiring, beautiful, and technically sound. It is also useful since it helps to ask relevant questions concerning the resolution of long-standing conceptual problems with the quantisation of classical point particles, see, e.g. [42].

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