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Non-unitary evolution in high energy physics: a brief overview

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Abstract

Unitarity and locality are fundamental postulates of Quantum Field Theory (QFT). By construction, QFT is a replica of equilibrium thermodynamics, where evolution settles down to a steady state after all transients have vanished. Events unfolding in the TeV sector of particle physics are prone to slide outside equilibrium under the combined action of new fields and un-suppressed quantum corrections. In this region, the likely occurrence of critical behavior and the approach to scale invariance blur the distinction between "locality" and "non-locality". We argue that a correct description of this far-from-equilibrium setting cannot be done outside nonlinear dynamics and complexity theory.

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Non-equilibrium phenomena are abundant in nature and society [1-2]. Examples range from interface fluctuations, dissipation in turbulent flows, reaction-diffusion processes, DNA mutations, dynamics of neuronal connections, fluctuations of the stock market, emergence of unexpected weather patterns, voltage oscillations in arrays of resistors, the propagation of earthquakes and so on. Systems that are *nonlinear* and *open* to internal or external perturbations are prone to display collective behavior that is often *self-organized* and difficult (if not impossible) to predict from the underlying dynamics of individual components.
In recent years the study of non-equilibrium dynamics in QFT has received a lot of attention. Out-of-equilibrium quantum fields are believed to play an essential role in inflationary cosmology, the "would be" composition of dark matter, non-perturbative quantum chromodynamics (relativistic quark-gluon plasma, glueball states, multi-quark states, the mechanisms of confinement and chiral symmetry breaking), strongly coupled field theories and condensed matter physics.

It is known that Renormalization Group (RG) is an important computational tool for both *equilibrium* thermodynamics and QFT. In a nut shell, RG amounts to a two step procedure: coarse-graining short-scale fluctuations followed by a redefinition of observables. Time and again, particle physics has hinted that probing matter at high energy densities or high temperature creates new collective degrees of freedom and a wealth of residual radiative corrections. Irreversible phenomena arising in large scale quantum field systems are well described by *non-equilibrium field theory* (NEFT). In our view, this is the right conceptual framework for dealing with the TeV sector of particle physics, where residual fluctuations can no longer be suppressed and take full control of dynamics. It is for this reason that TeV phenomena are likely to invalidate the coarse-graining procedure and challenge the applicability of S-matrix formalism and Path Integral quantization [3].

A general feature that distinguishes NEFT from equilibrium statistical physics is a *continuous* and *positive* production of entropy. There is an incessant transfer of matter and charges either through the boundary conditions or through the action of bulk driving fields [1-2]. As a result, NEFT has a rich spectrum of attributes that sets it *far apart* from equilibrium dynamics and QFT. Among them we mention:

a) Decoherence and the transition from quantum to classical behavior [3, 12]

b) Breaking of temporal symmetry and the onset of dynamical anisotropy [4-5]

c) Violation of the fluctuation-dissipation theorem [6]

d) Violation of the ergodic hypothesis [7]

e) Pattern formation and phase transitions out of equilibrium [8]
f) Use of fractal operators or non-extensive statistical physics for characterization of dynamics with long-range interactions [9-11]
g) Onset of power-law correlations and self-organized criticality [3, 12]
h) Universal approach to chaos and to fractal topology of underlying space-time and phase space [13-15].
i) Emergence of unstable vacuum states that, in general, do not coincide with the minima of the energy function [16].
j) A dynamics rich in anomalous transport, relaxation and multiple symmetry breaking events [3, 12].
Given the magnitude, depth and subtlety of topics pertaining to NEFT, any exhaustive listing of relevant papers and results is impractical. As of today, NEFT is slowly reaching maturity and its current status is "work in progress". We emphasize here that, regarding b), e), f) and h), a number of introductory contributions have been initiated by the author over the last decade or so. Main highlights are listed below:

1) Hierarchical structure of elementary particle masses and interaction strengths stems from the *universal route to chaos in nonlinear dissipative systems*. Masses and coupling charges are organized in a series that follow the Feigenbaum scenario, irrespective of the Higgs mechanism for electroweak symmetry breaking [15, 17-18].

2) A long-standing puzzle of the current Standard Model for particle physics is that both leptons and quarks arise in replicated patterns. The number of fermion flavors may be derived from the *nonlinear dynamics of RG equations*. Specifically, the number of flavors follows from demanding stability of RG equations about the fixed-point solution [19].

3) The gauge hierarchy problem in particle physics refers to the large numerical disparity between the value of the Planck mass $(M_{Pl} \approx 1.22 \times 10^{19} GeV)$ and the mass scale of the electroweak interaction $(M_{EW} \approx 100 \div 300\ GeV)$. Explaining this paradox has been attempted in super-symmetric field theories (SUSY) and string theories having either a large number of extra dimensions or warped extra dimensions. As of today, neither one of these field models have been backed up by experimental evidence. We have suggested that the gauge hierarchy problem *may be naturally solved in the framework of fractional dynamics and fractal operators*, without having to retort to SUSY or string theories [20].

4) Working in the framework of NEFT, we tentatively reached the following conclusions [21-25]:

(a) Fractional dynamics in Minkowski space–time is equivalent to *field theory in curved space–time*. This finding points out to a rather counterintuitive integration of classical gravity in the TeV regime of field theory.
(b) The three gauge groups of the standard model ($U(1)$, $SU(2)$ and $SU(3)$), as well as the spin observable, are rooted in the topological concept of *fractional dimension*.
(c) Fractional dynamics is the underlying source of *parity non-conservation* in weak interactions and of the *breaking of time-reversal invariance* in weak interaction channels involving neutral kaons and B-mesons.
(d) Fractional dynamics is the underlying source of the *anomalous magnetic moment of leptons.*
(e) Fractional dynamics leads to a *dynamic unification* of gauge boson and fermions as objects with fractional spin. This is in contrast with SUSY where the symmetry between the two is discrete and is not rooted in the non-equilibrium dynamics of these fields.
(f) Recently, the possibility of a scale-invariant hidden sector of particle physics extending beyond SM has attracted a lot of attention. A strange consequence of this hypothesis is the emergence of a continuous spectrum of massless fields having non-integral scaling dimensions called *unparticles*. We have shown that such exotic states, if they exist, emerge as a natural manifestation of NEFT and fractional dynamics.

Although all these findings are preliminary, we believe that they call for a *long overdue paradigm shift*: non-unitary evolution and NEFT need to become an integral part of future developing efforts in theoretical high energy physics. To paraphrase Ilya Prigogine [26]:

"I believe that we are at an important turning point in the history of science. We have come to the end of the road paved by Galileo and Newton, which presented us with an image of a time-reversible, deterministic universe. We now see the erosion of determinism and the emergence of a new formulation of the laws of physics".

References:

1. RACZ Z., "Non-Equilibrium Phase Transitions", Les Houches Summer School, Volume 77, 0924-9099, Springer Berlin/Heidelberg, 2004.

2. HINRICHSEN H.,"Non-Equilibrium Phase Transitions", ISBN 978-1-4020-8764-6, Springer, 2008.
3. See e.g., MANFREDINI E., "Aspects of Non-Equilibrium Dynamics in Quantum Field Theory" at arxiv: hep-ph/101202 and included references.
4. BERTINI L. *et al*, Phys. Rev. Lett. 87, 040601 (2001).
5. BERTINI L. *et al*, J. Stat. Phys. 107, 635 (2002).
6. DROZ M., "Noise and fluctuations in equilibrium and non-equilibrium statistical physics" in "Noise and Fluctuations", Ed. Frontier Group, (2001).
7. HILFER R., "Fractional dynamics, irreversibility and ergodicity breaking", Chaos, Solitons and Fractals, 5 (8), 1475-1484, (1995).
8. CROSS M.C. and HOHENBERG P., "Pattern Formation Out of Equilibrium", Reviews of Modern Physics, 65**,** 851—1112, (1993).
9. ZASLAVSKY G. M., "Hamiltonian Chaos and Fractional Dynamics", Oxford University Press, 2004.
10. WEST B. J. *et al*, "Physics of Fractal Operators", Springer, 2003.
11. TSALLIS C., "Remarks on the Non-Universality of Boltzmann-Gibbs Statistical Mechanics" in "Scaling and Disordered Systems", World Scientific, 2002.
12. FEREYDOON F. *et al* (Editors), "Scaling and Disordered Systems", World Scientific, 2002.
13. EL NASCHIE M. S., "Elementary Prerequisites for E-infinity theory" Chaos, Solitons & Fractals, 20:579-605,(2006).
14. EL NASCHIE M. S. "A review of E-infinity theory and the mass spectrum of high energy particle physics". Chaos, Solitons & Fractals, 19:209–36, (2004).
15. GOLDFAIN E., "Bifurcations and Pattern Formation in Particle Physics: An Introductory Study", Europhysics Letters 82, 11001, (2008).
16. See e.g. MARRO J. *et al*., "Modeling Non-equilibrium Phase Transitions and Critical Behavior in Complex Systems" at cond-mat/0209324.
17. GOLDFAIN E., "Feigenbaum Attractor and the Generation Structure of Particle Physics", Intl. Journal for Bifurcation and Chaos, 18, 3, 891-896, (2008).
18. GOLDFAIN E., "Chaotic Dynamics of the Renormalization Group Flow and Standard Model Parameters", Intl. Journal of Nonlinear Science, 3, 3, 170-180, (2007).
19. GOLDFAIN E., "Stability of Renormalization Group Trajectories and the Fermion Flavor Problem", Comm. Nonlinear Sciences and Num. Simulation, 13, 9, 1845-1850, (2008).
20. GOLDFAIN E., "Fractional Dynamics, Cantorian Space-Time and the Gauge Hierarchy Problem", Chaos, Solitons and Fractals, 22, 3, 513-520, (2004).

21. GOLDFAIN E., “Fractional Dynamics and the Standard Model for Particle Physics”, Comm. in Nonlinear Science and Num. Simulation, 13, 7, 1397-1404, (2008).
22. GOLDFAIN E., “Fractional Dynamics and the TeV Regime of Field Theory”, Comm. in Nonlinear Science and Num. Simulation, 13, 3, 666-676, (2008).
23. GOLDFAIN E., “Complexity in Quantum Field Theory and Physics Beyond the Standard Model”, Chaos, Solitons and Fractals, 28, 4, 913-922, (2006).
24. GOLDFAIN E., “Non-equilibrium dynamics as origin of anomalous behavior in particle physics”, in press, Hadronic Mechanics Journal, (2008).
25. GOLDFAIN E. and SMARANDACHE F. “On Emergent Physics, “Unparticles’ and Exotic ‘Unmatter’ States”, Progress in Physics, 4, 10-15, (2008).
26. PRIGOGINE I., “The End of Certainty”, The Free Press, New York, 1996.