EMERGENCE IN PARTICLE PHYSICS*

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Hadron properties and interactions are emergent from QCD. Atomic and condensed matter physics are emergent from QED. Could the local gauge symmetries of particle physics also be emergent? We give an introduction to this question and recent ideas connecting it to the stability of the Standard Model Higgs vacuum and the value of the cosmological constant.

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1. Introduction

Hadrons, their properties and interactions are emergent from more fundamental QCD quark and gluon degrees of freedom [1]. The world of everyday experience (atoms, molecules, superconductors ...) is emergent from QED [2]. At a deeper level, could the local gauge symmetries which drive the dynamics of particle physics also be emergent, perhaps connected to new critical phenomena in the ultraviolet? [3–7]. Emergent gauge symmetries would "dissolve" in the ultraviolet, in contrast to unification models which exhibit maximum symmetry at the highest scales. Emergent local gauge symmetries are seen in quantum and condensed matter systems [8–13]; that is, where one makes symmetry as well as breaking it.

We first recall the physics of emergent hadrons from QCD and then discuss the open issue whether the gauge structure of the Standard Model might also be emergent.

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2. Hadrons as emergent bound states

QCD exhibits asymptotic freedom. In high-energy processes, the interaction coupling α_s decreases logarithmically with increasing four-momentum transfer squared. In the infrared, quark–gluon interactions become strong. Low-energy QCD is characterised by confinement and dynamical chiral symmetry breaking. The physical degrees of freedom are emergent hadrons (protons, mesons ...) as bound states of quarks and gluons. Spontaneous chiral symmetry breaking is associated with a non-vanishing chiral quark condensate. The light mass pions (and kaons) are the corresponding would-be Goldstone bosons. Confinement and chiral dynamics generate a rich physics structure which is the focus of a vigorous global programme of theory and experiments.

Emergent properties include the proton's mass and spin. The proton's mass is generated from the confinement potential. The proton has spin $\frac{1}{2}$ and a complex internal spin structure. Polarised deep inelastic scattering experiments have taught us that just about 30% of the proton's spin is carried by its quarks [14]. The rest is carried by gluons and by quark and gluon orbital angular momentum. Scalar confinement generates dynamical chiral symmetry breaking, *e.g.* in the Bag model, the Bag wall connects left- and right-handed quarks leading to quark–pion coupling and the pion cloud of the nucleon [15]. Relativistic quark motion inside the nucleon shifts some of the quark spin into the orbital angular momentum. (The lower component of the quark spinor is in p-wave and confinement generates a finite transverse scale in the proton.) The pion cloud takes further orbital angular momentum through quark–pion coupling in the nucleon [16]. One finds a consistent picture where pion cloud dynamics, modest gluon polarisation (up to about 50% of the proton's spin at the scale of typical deep inelastic experiments) and perhaps non-local gluon topology describe the internal spin structure of the proton [17].

Hadron properties such as the proton and meson masses are modified in nuclear media — for recent reviews, see [18]. The EMC nuclear effect in unpolarised deep inelastic scattering tells us that the quark structure of the proton is modified when the proton is in a nucleus. An open question is what happens to the glue. An interesting recent discovery by the CBELSA/TAPS Collaboration in Bonn is that the effective mass of the η' meson decreases by about 40 MeV in medium at nuclear matter density [19], in a very good agreement with the prediction of the Quark Meson Coupling model [20] and consistent with the COSY-11 measurement of the η'-nucleon scattering length [21]. Without the gluonic contribution to the η' mass, after SU(3) breaking this meson would be a strange-quark pseudoscalar partner of the Goldstone pion without coupling to the σ mean field in the nucleus and with much less interaction with the nuclear medium [20].

3. Emergent gauge symmetries and the Standard Model

One of the big surprises from the LHC is that the Standard Model works so well! With the couplings and particle masses measured at the LHC, the Standard Model works as a consistent theory up to the Planck scale without need for coupling to extra new particles [4, 22–27].

Some extra new physics is still needed, *e.g.* to explain the origin of tiny neutrino masses, the matter–antimatter asymmetry in the Universe, the strong CP puzzle, the origin of dark matter, and the vacuum energies associated with the cosmological constant and initial inflation. The origin of this new physics and how it interacts with the Standard Model is unknown and not yet given by experiments.

In seeking to understand physics behind and beyond the Standard Model, a key open question is whether the local gauge symmetries of particle physics might be emergent.

With the Higgs and top-quark masses measured at the LHC, the Higgs vacuum sits very close to the border of stable and metastable (with half-life much greater than the present age of the Universe) [4, 22–27] if we assume no coupling to undiscovered new particles, suggesting possible new critical phenomena in the ultraviolet [4, 22]. The stability of the Higgs vacuum is very sensitive to the value of the top-quark mass and the technical details of higher-order radiative corrections. Near-criticality here might be interpreted through a statistical system in the ultraviolet where criticality is an attractor point of the dynamical evolution [22].

An emergent Standard Model connected to new critical phenomena in the ultraviolet has been suggested in early papers by Bjorken [5, 6] and Jegerlehner [3, 4]. In this scenario, the Standard Model would be the long-range tail of a critical system which exists close to the Planck scale.

Possible emergent gauge symmetries in particle physics are also discussed in Refs. [9, 10, 28, 29]. Emergent gravity scenarios are explored in Ambjørn *et al.* [30] and Verlinde [31].

For a statistical mechanics system near a critical point, the long-range asymptote is a renormalisable Euclidean quantum field theory with non-trivial interactions for dimensions less than or equal to 4 [4, 32]. If the theory includes vector fields, one then has a gauge theory [33]. With a chiral gauge theory like the Standard Model, anomaly cancellation collects the chiral fermions into families. One finds a plausible scenario where the collective vector modes preferentially arrange themselves into smaller gauge groups such as *e.g.*, U(1), SU(2) and SU(3) [4]. Supposing such a critical system at a scale M close to the Planck scale, non-renormalisable contributions from high dimensional operators and gauge-dependent terms would be proportional to powers of energy divided by M and very much suppressed, much below the Planck scale. An open issue is how a possible emergent Standard Model might constrain extra new physics scenarios, *e.g.* axions, new gauge bosons and dark matter candidates as well as generating the matter–antimatter asymmetry.

Might the massless photons and gluons be emergent? The Weinberg–Witten theorem [34] tells us that if there are massless composite gauge bosons, then Lorentz invariance should also be violated or emergent. Bjorken has argued that any violations of Lorentz and gauge symmetries in the emergence scenario might appear with a coefficient suppressed by powers of the cosmological constant scale divided by the large scale M [6], thus vanishing in the limit of a vanishing cosmological constant and too small to be manifest in present experiments.

If the gauge symmetries of the Standard Model are emergent, this differs from the paradigm of unification with maximum symmetry at the highest possible energies. In unification scenarios, a unification big gauge group is spontaneously broken through various Higgs condensates to the Standard Model with each new condensate introducing an extra large contribution to the vacuum energy and the cosmological constant.

The cosmological constant measured in astrophysics corresponds to a vacuum energy density

$$\rho_{\rm vac} = \mu_{\rm vac}^4 \sim (0.002 \text{ eV})^4 \, . \qquad (1)$$

The scale $\mu_{\rm vac} \sim 0.002$ eV is similar to the value that we expect for the light neutrino mass [35, 36] with the normal hierarchy of neutrino masses [37], and much less than the electroweak and Planck scales. One observes the phenomenological relation

$$\mu_{\rm vac} \sim m_\nu \sim \Lambda_{\rm ew}^2 / M \, , \qquad (2)$$

where $\Lambda_{\rm ew}$ is the electroweak scale ~ 250 GeV and $M \sim 3 \times 10^{16}$ GeV is logarithmically close to the Planck mass $M_{\rm Pl} \sim 10^{19}$ GeV. This formula was also suggested by Bjorken [5, 6] without connection to neutrinos in the "gaugeless limit" of the Standard Model with connection to gravity and with composite or emergent gauge bosons being born at a large mass scale M, and no or only very small coupling to new physics between the electroweak and ultraviolet mass scales. If taken literally, Eq. (2) connects the cosmological constant (dark energy), neutrino physics and electroweak symmetry breaking to a new high-mass scale which needs to be understood [5, 7, 35]. The gauge bosons in the Standard Model which have a mass through the Higgs mechanism are also the gauge bosons which couple to the neutrino. Perhaps the cosmological constant and the electroweak hierarchy problem might be connected and the hierarchy problem resolved at a scale close to the Planck scale rather than at the TeV-scale (?)

Within the framework of perturbative renormalization group calculations, there is an important issue of whether the Higgs mass and vacuum energy counterterms cross zero at some very high scale in the ultraviolet, in which case the Higgs mechanism might be associated with a first order phase transition [4]. This crossing can happen below the Planck scale in calculations with a stable vacuum [4, 38] and above the Planck scale in calculations with a metastable Higgs vacuum [22]. If the vacuum energy counterterm crosses zero, then the size of the physical vacuum energy relevant to the cosmological constant might become a renormalization condition like fixing the value of the fine structure constant, to be determined by experiment [39] and perhaps connected to some new principle which might favour a Universe with large distance flat geometry, see *e.g.* [40].

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REFERENCES

[1] A.W. Thomas, W. Weise, *The Structure of the Nucleon*, Wiley, 2001.

[2] P.W. Anderson, *Science* **177**, 393 (1972).

[3] F. Jegerlehner, `arXiv:hep-th/9803021`; *Helv. Phys. Acta* **51**, 783 (1978).

[4] F. Jegerlehner, *Acta Phys. Pol. B* **45**, 1167 (2014).

[5] J.D. Bjorken, *Phys. Rev. D* **64**, 085008 (2001).

[6] J.D. Bjorken, `arXiv:hep-th/0111196`; `arXiv:1008.0033 [hep-ph]`.

[7] S.D. Bass, *Acta Phys. Pol. B* **47**, 485 (2016).

[8] F. Wilczek, A. Zee, *Phys. Rev. Lett.* **52**, 2111 (1984).

[9] M. Levin, X.-G. Wen, *Rev. Mod. Phys.* **77**, 871 (2005).

[10] G. 't Hooft, *AIP Conf. Proc.* **957**, 154 (2007).

[11] J. Zaanen, A.J. Beekman, *Ann. Phys.* **327**, 1146 (2012).

[12] S. Sachdev, *Philos. Trans. R. Soc. Lond. A* **374**, 20150248 (2016).

[13] G.E. Volovik, *The Universe in a Helium Droplet*, Oxford Univ. Press, 2003.

[14] S.D. Bass, *Rev. Mod. Phys.* **77**, 1257 (2005).

[15] A.W. Thomas, *Adv. Nucl. Phys.* **13**, 1 (1984).

[16] S.D. Bass, A.W. Thomas, *Phys. Lett.* **B684**, 216 (2010).

[17] C.A. Aidala, S.D. Bass, D. Hasch, G.K. Mallot, *Rev. Mod. Phys.* **85**, 655 (2013).

[18] G. Krein, A.W. Thomas, K. Tsushima, `arXiv:1706.02688 [hep-ph]`; V. Metag, M. Nanova, E.Ya. Paryev, `arXiv:1706.09654 [nucl-ex]`; K. Saito, K. Tsushima, A.W. Thomas, *Prog. Part. Nucl. Phys.* **58**, 1 (2007).

[19] M. Nanova *et al.* [CBELSA/TAPS Collaboration], *Phys. Lett. B* **727**, 417 (2013).

[20] S.D. Bass, A.W. Thomas, *Phys. Lett. B* **634**, 368 (2006); *Acta Phys. Pol. B* **45**, 627 (2014).

[21] E. Czerwiński *et al.* [COSY-11 Collaboration], *Phys. Rev. Lett.* **113**, 062004 (2014).

[22] G. Degrassi *et al.*, *J. High Energy Phys.* **1208**, 098 (2012); D. Buttazzo *et al.*, *J. High Energy Phys.* **1312**, 089 (2013).

[23] F. Bezrukov, M.Yu. Kalmykov, B.A. Kniel, M. Shaposhnikov, *J. High Energy Phys.* **1210**, 140 (2012); F. Bezrukov, M. Shaposhnikov, *J. Exp. Theor. Phys.* **120**, 335 (2015).

[24] S. Alekhin, A. Djouadi, S. Moch, *Phys. Lett. B* **716**, 214 (2012).

[25] I. Masina, *Phys. Rev. D* **87**, 053001 (2013).

[26] Y. Hamada, H. Kawai, K-y. Oda, *Phys. Rev. D* **87**, 053009 (2013) [*Erratum ibid.* **89**, 059901 (2014)].

[27] A.V. Bednyakov, B.A. Kniehl, A.F. Pikelner, O.L. Veretin, *Phys. Rev. Lett.* **115**, 201802 (2015).

[28] S. Chadha, H.B. Nielsen, *Nucl. Phys. B* **217**, 125 (1983); J.L. Chkareuli, C.D. Frogatt, H.B. Nielsen, *Phys. Rev. Lett.* **87**, 091601 (2001).

[29] C. Wetterich, *Nucl. Phys. B* **915**, 135 (2017).

[30] J. Ambjørn, J. Jurkiewicz, R. Loll, *Phys. Rev. Lett.* **95**, 171301 (2005).

[31] E.P. Verlinde, *J. High Energy Phys.* **1104**, 029 (2011).

[32] K.G. Wilson, J.B. Kogut, *Phys. Rep.* **12**, 75 (1974); F. Jegerlehner, *Lect. Notes Phys.* **37**, 114 (1975).

[33] G. 't Hooft, Cargese lecture, *NATO Sci. Ber. B* **59**, 101 (1980).

[34] S. Weinberg, E. Witten, *Phys. Lett. B* **96**, 59 (1980).

[35] S.D. Bass, *Mod. Phys. Lett. A* **30**, 1540033 (2015).

[36] G. Altarelli, *Nucl. Phys. B Proc. Suppl.* **143**, 470 (2005).

[37] G. Altarelli, `arXiv:1111.6421 [[hep-ph]]`; H. Fritzsch, S. Zhou, *Phys. Lett. B* **718**, 1457 (2013).

[38] I. Masina, M. Quiros, *Phys. Rev. D* **88**, 093003 (2013).

[39] F. Jegerlehner, *Acta Phys. Pol. B* **45**, 1215 (2014); `arXiv:1503.00809 [hep-ph]`.

[40] G. 't Hooft, *The Cellular Automaton Interpretation of Quantum Mechanics*, Springer, 2016.