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The emergence of gauge invariance: The stay-at-home gauge versus local–global duality

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ABSTRACT

In condensed matter physics, gauge symmetries other than the $U(1)$ of electromagnetism are of an emergent nature. Two emergence mechanisms for gauge symmetry are well established: the way in which it arises in Kramers–Wannier type local–global dualities, and the way in which local constraints encountered in (doped) Mott insulators are encoded. We demonstrate that these gauge structures are closely related, and appear as counterparts in the canonical and field-theoretical languages. The restoration of symmetry in a disorder phase transition is due to having the original local variables subjected to a coherent superposition of all possible topological defect configurations, with the effect that correlation functions are no longer well-defined. This is completely equivalent to assigning gauge freedom to those variables. Two cases are considered explicitly: the well-known vortex duality in bosonic Mott insulators serves to illustrate the principle; and the acquired wisdom is then applied to the less familiar context of dualities in quantum elasticity, where we elucidate the relation between the quantum nematic and linearized gravity. We reflect on some deeper implications for the emergence of gauge symmetry in general.

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1. Introduction

Breaking symmetry is easy but making symmetry is hard: this wisdom applies to global symmetry but not to local symmetry. The study of systems controlled by emergent gauge symmetry has become mainstream in modern condensed matter physics. Although one discerns only the gauge invariance of electromagnetism in the ultraviolet for condensed matter physics, it is now very well understood

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that in a variety of circumstances gauge symmetries that do not exist on the microscopic scale control the highly collective physics on the macroscopic scale. An intriguing but unresolved issue is whether the gauge structures involved in the Standard Model of high energy physics and perhaps even general relativity could be of such an emergent kind.

The mechanisms for gauge symmetry emergence fall into two broad categories: (1) the “stay-at-home” gauge invariance associated with (doped) Mott insulators and the gauge fields associated with the slave-particle theories encountered in this context, describing the fractionalization of the quantum numbers of the microscopic degrees of freedom, and (2) the global-to-local symmetry correspondence encountered in the strong–weak (Kramers–Wannier, S -) dualities of relevance to the quantum field theories describing the collective quantum physics of condensed matter systems. In the common perception these appear as quite different. The purpose of this note is to clarify that at least in the context of bosonic physics, they are actually closely related. In fact, this highlights complementary aspects of the vacuum structure, and it is just a matter of convenience whether one views the vacuum using the canonical/Hamiltonian language (stay-at-home) or field-theoretical/Lagrangian (local–global duality) language. The case is very simple and we will illustrate it in Section 2 with the most primitive of all many-particle systems governed by continuous symmetry: the Bose–Hubbard model at zero chemical potential, or alternatively the Abelian–Higgs duality associated with complex-scalar field theory. Although we do not claim any new result in this particular context, the freedom to switch back and forth between the Lagrangian and Hamiltonian viewpoints yields some entertaining vistas for this well-understood theory. To make the case that it can yield new insight, we apply it in Section 3 to the less familiar context of dualities in quantum elasticity. This deals with the description of quantum liquid crystals in terms of dual condensates formed from the translational topological defects (dislocations) associated with the fully ordered crystal. Using the Lagrangian language it was argued that such quantum nematics have equivalence to (linearized) Einstein gravity [1]. Here we will demonstrate that this is indeed controlled by the local symmetry associated with linearized gravity: translations are gauged, turning into infinitesimal Einstein transformations.

This could have been a very short communication, but we wish to address a readership with diverse backgrounds. We therefore first review at length the basics of Mottness (Section 2.1) and vortex duality (Section 2.2) which should be quite familiar to the condensed matter physicists, presenting in Section 2.3 our argument revealing how the stay-at-home gauge is encoded in the vortex duality. Section 3 is devoted to duality in quantum elasticity and the relation to gravity. We again take the time to review the basics since this subject is unfamiliar even in mainstream condensed matter physics. In Section 2.3 we review the basics of these duality structures while in Section 3.2 we turn to the way in which this is related to gravitational physics, employing the insights derived from vortex duality to show why the effective space realized in the quantum nematics behaves like the spacetime of general relativity when it is nearly flat.

2. Vortex duality versus Bose–Mott insulators

In this section we will first review two standard views of the physics of the Bose–Hubbard model [2], with the intention of confusing the reader. We first highlight the emergence of the compact $U(1)$ stay-at-home gauge which emerges in the Bose–Mott insulator in a trivial way when one sticks to the canonical, second-quantized language focusing on the large- U limit. In the second subsection we turn to the field-theoretical Abelian–Higgs duality, reviewing the standard argument that in $2 + 1$ D the quantum disordered partner of the superfluid is actually dual to a superconducting condensate formed from the vortices of the superfluid, which interact via effective $U(1)$ gauge fields [3–8]. These should be equivalent descriptions of the Bose–Mott insulator, but at face value this is far from obvious. In the last subsection we present a very simple resolution of this conundrum, having some interesting ramifications for the way that one should think in general about “Mott insulators” in field theory.

2.1. The stay-at-home gauge of the Bose–Mott insulator

The mainstream gauge theories in condensed matter physics date back to the late 1980s when the community was struggling with the fundamentals of the problem of high- T_c superconductivity. It was

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