Spontaneous Symmetry Breaking Induced by Quantum Monitoring

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Spontaneous symmetry breaking (SSB) is responsible for structure formation in scenarios ranging from condensed matter to cosmology. SSB is broadly understood in terms of perturbations to the Hamiltonian governing the dynamics or to the state of the system. We study SSB due to quantum monitoring of a system via continuous quantum measurements. The acquisition of information during the measurement process induces a measurement backaction that seeds SSB. In this setting, by monitoring different observables, an observer can tailor the topology of the vacuum manifold, the pattern of symmetry breaking, and the nature of the resulting domains and topological defects.

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Spontaneous symmetry breaking (SSB) occupies a central stage in modern physics [1]. It governs physical mechanisms such as BCS superconductivity, the existence of Nambu-Goldstone bosons [2,3], and the generation of mass via the Higgs mechanism [4–6]. It is also considered to play a key role in the early history of the Universe [7,8], and may have contributed to structure formation in this context [9]. Symmetry breaking arises in nature when observable phenomena lack the symmetry of the underlying physical laws dictating them. A system can thus be found in configurations in conflict with the invariance manifested by its equations of motion.

SSB is characteristic of phase transitions from a high-symmetry phase to a lower symmetry phase in which a new kind of macroscopic order emerges, that can be detected by an order parameter [10]. In a specific system, SSB is analyzed through the symmetries of its free energy landscape or field Eq. [9]. An intuitive understanding of the spontaneous rupture of symmetry is acquired by picturing a spin chain initially prepared in a paramagnetic phase and driven by a Hamiltonian $H \propto -\sum_j \sigma_j^z \sigma_{j+1}^z$, which favors ferromagnetic order. The ensuing dynamics preserves the symmetries of the Hamiltonian, and in the absence of external perturbations nothing in the evolution biases the choice between the degenerate ground states $|\uparrow\uparrow\ldots\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\ldots\downarrow\downarrow\rangle$. However, in the thermodynamic limit any infinitesimal external magnetic field is enough to break the tie, and single out one of these states as the observed ground state. In this case the symmetry is explicitly broken. In physical systems of finite size, the breaking of the symmetry can be generally understood as a consequence of random fluctuations, either in the Hamiltonian governing the evolution, or in the state of the system at a given time. In the example of the spin chain driven from the symmetric paramagnetic phase, a local perturbation of the magnetization is enough to implant a seed that leads to symmetry breaking along the whole system. Whenever present, spatial fluctuations of the magnetization can thus favor the local growth of domains where spins align in a certain direction. This example serves to illustrate the general physical mechanism of domain formation.

A characteristic feature of the canonical description of SSB is its focus on static features: it is understood via the properties of the state of the system in thermal equilibrium. This approach is frequently pursued using elements of homotopy theory to characterize the topology of the vacuum manifold, spanned by the degenerate ground states in the broken-symmetry phase [9,11].

In this Letter, we study an alternative mechanism for symmetry breaking, induced by the continuous monitoring of a quantum system. During the monitoring by continuous quantum measurements, symmetry breaking is induced by the quantum measurement backaction [12] associated with the acquisition of information by the observer. The latter can thus alter the topology of the vacuum manifold and the pattern of symmetry breaking. By selecting different kinds of measurements, an observer can thus control the nature of the resulting domains and topological defects, and even achieve a complete suppression of the later.

Monitoring-induced symmetry breaking.—For the sake of illustration, we consider N $1/2$ spins prepared in the ground state of a paramagnetic Hamiltonian $H_0 = -\Lambda \sum_{j=1}^{N} \sigma_j^x$, where Λ represents a global energy scale. The initial state of the chain is then

$$|\Psi(0)\rangle = \bigotimes_{j=1}^{N} |{\rightarrow}\rangle_j, \tag{1}$$

where $|{\rightarrow}\rangle_j$ denotes the eigenstate of σ_j^x with eigenvalue 1. Following a sudden quench at $t = 0$, the system evolves for $t > 0$ according to the ferromagnetic Hamiltonian

$$H = -\Lambda \sum_{j=1}^{N} \sigma_j^z \sigma_{j+1}^z, \tag{2}$$

taking periodic boundary conditions $\sigma_{N+1}^z \equiv \sigma_1^z$ for concreteness.

The initial state of the chain shares a symmetry of the Hamiltonian, which is preserved in the case of unitary evolution. This can be easily seen, for instance, by noting that the Hamiltonian commutes with the magnetization $M = \sum_j \sigma_j^z$ of the chain. In the adiabatic limit, since the initial state satisfies $\langle\Psi(0)|M|\Psi(0)\rangle = 0$, the subsequent evolved state necessarily has equal weights on the states $|\uparrow\uparrow\ldots\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\ldots\downarrow\downarrow\rangle$, and is therefore incapable of selecting between them. However, experience shows that in practice a particular direction for the chain's magnetization is spontaneously chosen by the system, even if the Hamiltonian and initial state are symmetric with respect to the z direction. In a sudden quench scenario, excitations in the system are constrained by the conservation law $\langle\Psi(t)|M|\Psi(t)\rangle = 0$. The symmetry is broken locally with the formation of domains in which spins are homogeneously polarized along a given direction (up or down) and the formation of topological defects at the interface between adjacent domains. In the example at hand, the latter are the so-called $\mathbb{Z}_2$ kinks, as the broken $\mathbb{Z}_2$ symmetry is restored at their core. In the canonical approach to symmetry breaking, domain formation is explained by assuming a small perturbation to the Hamiltonian or to the state of the system, locally breaking the symmetry "by hand."

We consider an alternative SSB scenario that results from monitoring a quantum system during time evolution. Such quantum monitoring can be modeled by continuous quantum measurements [13–15], which can be thought of as a sequence of infinitesimally weak measurements. More specifically, they arise as the consequence of a weak coupling between the system being measured and an apparatus that gets entangled with the state of the system. Upon observing a particular outcome in the measurement apparatus the joint state is collapsed. In contrast to strong projective measurements, which can drastically perturb the state of the system, a weak measurement provides only partial information of the state. In doing so, this process induces a mild backaction on the state of the system at any given time. The collective information obtained from the continuous measurement record over a period of time can provide full information of the system though [16], and can thus serve as a way to perform full state tomography [17,18], parameter estimation [19,20], quantum error correction [21], and quantum control [22]. Note that the action of the observer is in practice tantamount to the coupling to a monitoring environment, whenever the latter weakly interacts with the system of interest in such a way that information of a physical quantity is probed and registered [23]. The relation between quantum dynamics, decoherence, and SSB have been studied in the past [24,25]. Particular aspects of the connection between quantum measurement and symmetry breaking have been considered, mostly as an effective description to explain the interference fringes in Bose-Einstein condensates and superfluids [26–32]. In what follows we focus on the agency of the observer to control symmetry breaking via the selection of the continuous measurement, i.e., the observable that is monitored. In particular, we shall discuss symmetry breaking induced by the monitoring of local, coarse-grained and global observables.

The dynamics of the system undergoing continuous monitoring of an arbitrary set of observables $\{A_\alpha\}$ is well described by a stochastic master equation dictating the change in the state,

$$d\rho_t = L[\rho_t]dt + \sum_\alpha I_\alpha[\rho_t]dW_t^\alpha, \tag{3}$$

when expressed in Itô form [14,15]. Here, $L[\rho_t]$ takes the standard Lindblad form for the set of measured operators, which includes the evolution due to the Hamiltonian and dephasing due to the monitoring process:

$$L[\rho_t] = -i[H, \rho_t] - \sum_\alpha \frac{1}{8\tau_m^\alpha}[A_\alpha, [A_\alpha, \rho_t]]. \tag{4}$$

In turn, the "innovation terms"

$$I_\alpha[\rho_t] = \sqrt{\frac{1}{4\tau_m^\alpha}}[\{A_\alpha, \rho_t\} - 2\mathrm{Tr}(A_\alpha\rho_t)\rho_t] \tag{5}$$

account for the change in the state of the system due to the acquisition of information during the measurement process. These innovation terms encompass the effect of the backaction on the state of the system due to the quantum measurement. Here, dW_t^α denote independent Gaussian random variables of mean 0 and width dt, while τ_m^α is the "characteristic measurement time" with which observable A_α is monitored; i.e., it provides the timescales over which information of the expectation value of the observable is acquired. The output of such measurements over an interval dt, given by $dr_\alpha(t) = \langle A_\alpha\rangle(t)dt + \sqrt{\tau_m^\alpha}dW_t^\alpha$, provides information of the expectation value of the observables, hidden by additive white noise [13–15]. The time evolution is unraveled by modeling continuous measurements with a sequence of infinitesimally weak measurements, which can

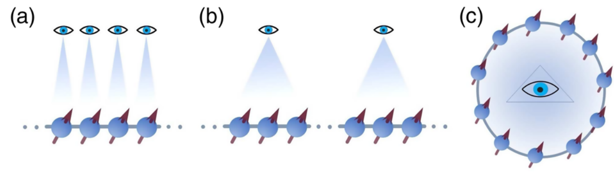

FIG. 1. From single spin to coarse-grained monitoring. The nature of the monitoring process determines the pattern of measurement-induced symmetry breaking, deciding the size of the domains, the distribution of the local magnetization, and the type of topological defects formed in the system. (a) Independent observers measuring each single spin induce random, independent measurement outcomes for each spin, which end up either "up" or "down." (b) Independent observers measuring the magnetization of clusters of spins provoke the formation of local and independent domains, which can take different values of the magnetization. (c) In the limiting case of one single observer measuring the whole spin chain, the induced global magnetization due to quantum monitoring is homogeneous.

be described by Kraus operators acting on the state at every time step dt of the evolution; see, for example, [13]. In the limit of dt smaller than any other relevant timescales, such an approach gives the same dynamics as Eq. (3). All simulations are performed in QuTiP [33,34].

We shall focus on the local, coarse-grained, and global magnetization as the choice of monitored observables. To start with, assume that independent observers continuously monitor the single-spin components $\{\sigma_j^z\}$ of individual spins along the chain, as illustrated in Fig. 1(a). The dynamics is dictated by Eq. (3), with $\{\sigma_j^z\}$ $(j = 1, \ldots, N)$ as the set of measured observables $\{A_\alpha\}$.

This scenario makes apparent the connection between the dynamics under continuous measurements and that of an open system in contact with an environment. Observers without access to the measurement output, who need to average over the unobserved measurement outcomes, obtain an averaged description of the state of the system ρ_t^m. The latter evolves according to $d\rho_t^m = L[\rho_t^m]dt$, and its evolution is thus identical to that of the system coupled to an environment through the spin components $\{\sigma_j^z\}$. Importantly, such density matrix does not show signs of symmetry breaking, given that the evolution commutes with the magnetization. That is, without registering the measurement outcomes and in the absence of any further perturbations to Hamiltonian or state, symmetry is fully preserved. In particular, the spin components $\langle\sigma_j^z\rangle(t) = \mathrm{Tr}(\rho_t^m \sigma_j^z)$ remain constant.

By contrast, the measurement process does break the symmetry, forcing individual spins to collapse to one of the eigenstates of σ_j^z. Indeed, when conditioning the state to the observed outcomes the measurement backaction breaks the symmetry in individual realizations. To prove this, let us focus on the evolution of the component of spin j in the ferromagnetic part of the quench, with $t \geq 0$. The evolution of the expectation value of the spin components is dictated by

$$\begin{aligned} d\langle\sigma_j^z\rangle(t) &= -\mathrm{Tr}(I[\rho_t]\sigma_j^z)dW_t^j \\ &= -\sqrt{\frac{1}{\tau_m}}\Delta^2_{\sigma_j^z}(t)dW_t^j, \end{aligned} \tag{6}$$

where the trace $\langle\cdot\rangle(t) \equiv \mathrm{Tr}(\rho_t \cdot)$ is taken with respect to the state ρ_t, and $\Delta_{\sigma_j^z}(t) = \sqrt{\langle(\sigma_j^z)^2\rangle(t) - \langle\sigma_j^z\rangle^2(t)}$ is the corresponding standard deviation. This means that, due to quantum monitoring, the spin component evolves whenever its quantum uncertainty is nonzero. Such uncertainty is zero if and only if the spin is in one of the eigenstates $|\uparrow\rangle_j$ or $|\downarrow\rangle_j$ of σ_j^z. Therefore, only states with definite values of the spin component are stable under monitoring. SSB is thus a consequence of the measurement backaction encoded in the innovation terms $I_j[\rho_t]$ in Eq. (5).

Effectively, monitoring the spin components breaks the symmetry in the chain, in the basis selected by the measurement process, as illustrated in Fig. 2. The characteristic measurement time τ_m dictates the rate at which symmetry breaking occurs and individual spins collapse up or down. The stochastic dynamics naturally leads to the formation of localized topological defects [11], $\mathbb{Z}_2$ kinks,

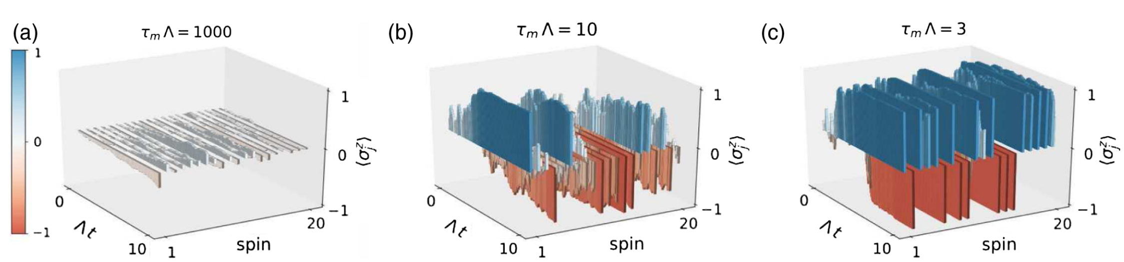

FIG. 2. Dynamics of symmetry breaking induced by monitoring of each spin for different measurement strengths. (a) A weak monitoring of the individual spins slightly affects their spin components, barely perturbing the otherwise symmetric evolution. (b) As the measurement strength is increased symmetry is broken by the measurement process, leading to spins collapsing to the stable up or down configurations. (c) A strong monitoring process rapidly leads to the formation of localized topological defects in individual realizations of the stochastic evolution.

from the sole effect of the quantum measurement backaction due to the monitoring of the spin chain.

The previous analysis applies to a sudden quench in the dynamics. We now consider the scenario of a slow transition from a paramagnetic to a ferromagnetic regime, with a time-dependent Hamiltonian

$$H(t) = -\Lambda\left(1 - \frac{t}{\tau_Q}\right)\sum_{j=1}^{N}\sigma_j^x - \Lambda\frac{t}{\tau_Q}\sum_{j=1}^{N}\sigma_j^z\sigma_{j+1}^z, \quad (7)$$

where τ_Q is a timescale that dictates completion of the quench. For times $t \geq \tau_Q$ we assume $H(t) = H(\tau_Q)$. In contrast to sudden quenches, the finite-time crossing of the critical point reduces excitations, favoring dynamics constrained to the lowest energy subspace [35]. However, without access to measurement outcomes nothing in the dynamics breaks the symmetry between degenerate ground states of the ferromagnetic Hamiltonian. The monitoring of the system feeds in a seed of asymmetry, as Fig. 3 illustrates. In this case there is a competition between monitoring backaction, which singles out individual spins, and the natural tendency of the system to remain excitationless due to adiabatic dynamics. Domains with different definite values of magnetization form, with a size that depends on measurement strength and quench time [36].

The measured observable is also crucial in determining the nature of the symmetry breaking, and in particular, in governing structure formation in the end state. To illustrate this, we analyze the case in which a coarse-grained local magnetization is probed on the chain. Let us then consider that, instead of monitoring each individual spin component as in Fig. 1(a), the local magnetization over clusters of K consecutive spins is continuously measured, as on Fig. 1(b). We denote local magnetization observables by

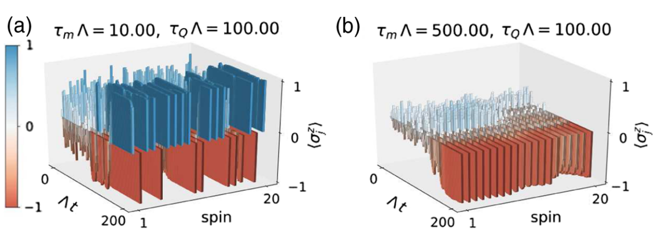

FIG. 3. Monitoring-induced symmetry breaking for a slow quench. A system undergoing a slow quench ($1/\tau_Q \ll \Lambda$) tends to remain close to the ground state, but in the absence of monitoring and other sources of symmetry breaking the system cannot select between degenerate ferromagnetic ground states $|\uparrow\uparrow\ldots\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\ldots\downarrow\downarrow\rangle$. (a) A strong monitoring of the individual spins ($1/\tau_m \sim 1/\tau_Q \ll \Lambda$) generates a symmetry broken state where spins are uncorrelated. (b) A weak monitoring ($1/\tau_m \ll \{\Lambda, 1/\tau_Q\}$) leads to an almost uniform domain, and a final state that is close to one of the possible symmetry-broken ground states of the ferromagnetic Hamiltonian.

$$m_\alpha = \sum_{j\in\mathcal{I}_\alpha}\sigma_j^z, \qquad \alpha = \{1, \ldots, N/K\}, \quad (8)$$

where $\mathcal{I}_\alpha = [K(\alpha - 1) + 1, K\alpha]$.

Once again, symmetry is broken by the monitoring process, given that $d\langle m_\alpha\rangle(t) = -\sqrt{1/\tau_m}\Delta_{m_\alpha}^2(t)dW_t^\alpha$, where $\Delta_{m_\alpha}(t)$ denotes the standard deviation of the monitored coarse-grained magnetization. In this case, the stable states to which the measurement process leads, eigenvectors of the set of measured observables $\{m_\alpha\}$, are starkly different, given that each spin cannot be singled out by the measurement process. Such eigenstates have definite values of the magnetization, $\lambda_m = \{-K, -K + 1, \ldots, K - 1, K\}$, on each of the coarse-grained regions. This causes a symmetry breaking with nonuniform magnetization along the chain, but homogeneous behavior within individual spin clusters, as illustrated in Fig. 4(a). The resulting domains involve coherent quantum superpositions and have no classical counterpart. Further, a topological defect formed at the interface between such quantum domains is no longer restricted to the type of $\mathbb{Z}_2$ kinks, but can result from a discontinuity in the local magnetization between any two of its $(K + 1)$ possible values. Monitoring the coarse-grained magnetization broadens the class of topological defects to $\mathbb{Z}_{K+1}$ kinks, with the value of K being controlled by the observers.

An interesting limiting case concerns the choice $K = N$, that corresponds to the monitoring of a single observable, the global magnetization $M = \sum_j \sigma_j^z$ of the spin chain, illustrated in Fig. 1(c). In this scenario, the final state in the broken phase has very different properties from the case in which spin clusters are monitored. As shown in Fig. 4, it results in a homogeneous magnetization along the chain, facilitating the growth of a single quantum domain,

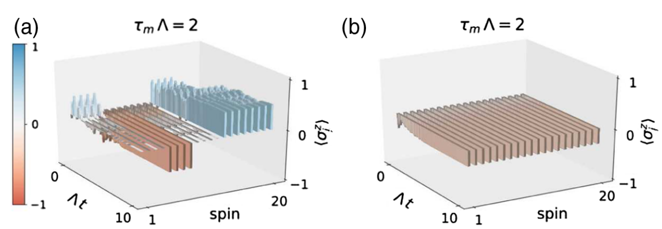

FIG. 4. Evolution of $\langle\sigma_j^z\rangle$ for coarse-grained measurements. (a) The continuous monitoring of the coarse-grained local magnetization breaks the symmetry, resulting in the formation of independent domains. For independent observers monitoring the local magnetization over the spin chain, the typical size of the domains is determined by the number of spins K over which the independent measurement operators m_α act on. Moreover, the stable final states within each domain need not correspond to all spins pointing up or down, as m_α can take $(K + 1)$ different values. (b) In the extremal case of one observer monitoring the global magnetization, a single domain is formed. The nature of the monitoring process thus governs structure formation in the final state.

possibly including coherent quantum superpositions of spins with different components in the z axis. In this case, a complete suppression of topological defects is achieved. By comparing the different choices of $\{A_\alpha\}$, we further conclude that the structure of states in the broken symmetry phase provides information of the nature of the monitoring process.

Discussion.—We have studied the breaking of symmetry induced by the measurement backaction resulting from continuous measurements performed on the system of interest. In this context, we have emphasized the agency of the observer to control symmetry breaking. In particular, we have analyzed the dynamics of a monitored many-body spin chain and identified strikingly different physics depending on the nature of the monitored observables. The individual monitoring of spins is consistent with a classical description and results in spins with definite up or down states, randomly assigned. By contrast, the use of local coarse-grained measurements of the local magnetization of clusters of spins leads to quantum domains characterized by coherent quantum superpositions, broadening the class of topological defects that the system can exhibit. Further, when a global magnetization is monitored, symmetry can be broken while the formation of topological defects is fully suppressed. Thus, an observer can control the patterns of symmetry breaking by a choice of the measurement observables. This choice determines the nature of the final state in the broken symmetry phase, including the size and kind of domains, and the statistics of the magnetization. In such a scenario, the classification of the resulting topological defects is no longer described by the symmetries of the system Hamiltonian, e.g., using homotopy theory [9,11]. The nature of the domains produced in this setting provides information of the monitoring process. In a broader context, the measurement backaction is expected to govern pattern formation. Notably, the engineering of the patterns of symmetry breaking by continuous monitoring is amenable to experimental test in superconducting qubit platforms with current technology [39,40]. It also opens up the possibility of using quantum control methods [41–47] to tailor the end state in the broken-symmetry phase.

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