

Noninvasive Quantum Measurement of Arbitrary Operator Order by Engineered Non-Markovian Detectors

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The development of solid-state quantum technologies requires the understanding of quantum measurements in interacting, non-isolated quantum systems. In general, a permanent coupling of detectors to a quantum system leads to memory effects that have to be taken into account in interpreting the measurement results. We analyze a generic setup of two detectors coupled to a quantum system and derive a compact formula in the weak-measurement limit that interpolates between an instantaneous (text-book type) and almost continuous - detector dynamics-dependent - measurement. A quantum memory effect that we term *system-mediated detector-detector interaction* is crucial to observe non-commuting observables simultaneously. Finally, we propose a mesoscopic double-dot detector setup in which the memory effect is tunable and that can be used to explore the transition to non-Markovian quantum measurements experimentally.

Historically the interpretation of quantum measurement uses the projection postulate implying an instantaneous collapse of the wave function in the measurement process [1]. Whereas this scheme fits e.g. ideal photo-detection very well, it is unsuitable in most other measurement procedures. For instance, in a measurement of a current in a solid-state environment, the system-detector interaction is much weaker and a collapse is avoided. A great deal of theoretical and experimental investigations have been carried out since von Neumann's work [1–3]. In particular, the limit of noninvasive measurement processes has been studied theoretically [4] as well as experimentally [5, 6]

In mesoscopic physics, the question of current noise in the quantum regime has attracted a lot of interest over the years [7]. In particular, the question of measuring the current correlator was addressed early on [8–12]. While most experiments address high-frequency correlations in agreement with the symmetrized correlator [13–15], with on-chip detectors the quantum non-symmetrized noise can be extracted [16–18]. First theoretical strides towards the measurement and interpretation of general unsymmetrized operator orders have been reported [19–24].

The goal of this Letter is to understand which system correlations are obtained in a generalized quantum measurement if two detectors coupled weakly and continuously to a system are read out independently. We find that the measurement outcomes can be expressed by noise and response functions of the system and the detectors. Hence, these outcomes depend crucially on the internal dynamics of the detectors and, therefore, by suitably engineered detectors the measurement can be tuned such that a specific operator order is measured. We propose a mesoscopic double-dot detector setup to explore the transition to non-Markovian quantum measurements experimentally. Going beyond the usually discussed bath-induced non-Markovian self-interaction [25],

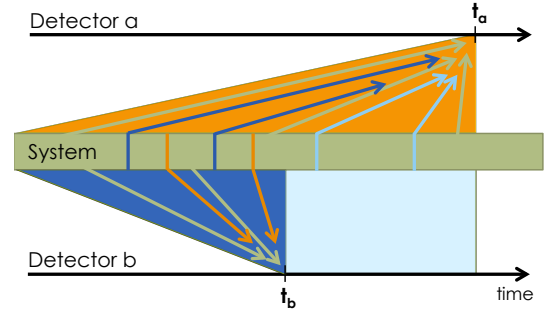


FIG. 1: Non-Markovian cross-correlation measurement: Two detectors a and b are coupled to a system for a finite time and read out at times $t_a > t_b$. Detector b collects information directly on the system and on detector a (which are transmitted through the system). The presence of detector b after its readout (light blue) also contributes to the information which detector a collects on detector b at a later time t_a .

we identify the *system-mediated detector-detector interaction* as crucial ingredient to observe non-commuting observables simultaneously.

In the following, we will assume that two detectors are coupled to a common system by small interaction Hamiltonians, which allows us to linearize the time-evolution and obtain a microscopic expression for the observed quantum correlation. The measurement procedure is illustrated in Fig. 1: Besides the direct influence of the system onto the detector observables (green arrows), the detectors influence *each other* mediated by the system (blue and orange arrows). This influence depends on the time-dependent response of the system and will lead to interesting consequences. We start by deriving the second-order cross correlation for a non-Markovian weak quantum measurement from a microscopic model. We will show that the different contributions can be understood in terms of a linear-response interaction of the sub-

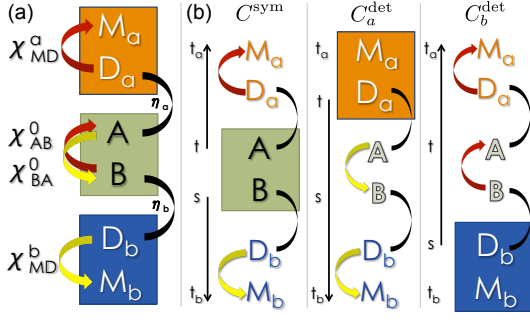


FIG. 2: (a) Couplings and correlations between the different variables. The inter-system couplings η_α connect the detector variables \hat{D}_α to the system variables \hat{A} and \hat{B} at equal times. Within the system and the detectors information is transmitted non-locally in time via the response functions χ . (b) Schematic representation of the second-order processes which contribute to the cross-correlation measurement. The straight arrows indicate the direction and causality of the time flow.

systems involved. After making some general statements on the properties and relevance of terms beyond the textbook approach of symmetric operator order, we will illustrate our findings in several examples.

Microscopic model. — The Hamiltonian of the system to be measured is denoted as \hat{H}_0 , and we will consider two independent detectors described by \hat{H}_a and \hat{H}_b that are coupled to the system by \hat{H}_{int} . The total Hamiltonian is given by

$$\hat{H} = \sum_{\alpha=0,a,b} \hat{H}_\alpha + \hat{H}_{\text{int}}. \quad (1)$$

The two detectors with detector variables \hat{D}_a and \hat{D}_b are weakly and linearly coupled to the system observables \hat{A} and \hat{B} ,

$$\hat{H}_{\text{int}} = \eta_a \hat{D}_a \hat{A} + \eta_b \hat{D}_b \hat{B}, \quad (2)$$

where η_a and η_b denote small coupling parameters which in general can be modulated in time. There are no restrictions on the detector Hamiltonians \hat{H}_α .

In the following we will study the correlation measurement scheme shown in Fig. 1. The density matrix of the total system is assumed to be in a product state $\hat{\rho} = \hat{\rho}_0 \hat{\rho}_a \hat{\rho}_b$ at the initial time t_0 (not shown). The measurement/readout procedure of the detectors is described by Kraus operators \hat{K}_{m_i} [3]. The first measurement ends with the readout of detector b at time t_b with result m_b and the density matrix $\hat{\rho}' = \frac{\hat{K}_{m_b} \hat{U}(t_b) \hat{\rho}_0 \hat{\rho}_a \hat{\rho}_b \hat{U}^\dagger(t_b) \hat{K}_{m_b}^\dagger}{\text{Tr}\{\hat{K}_{m_b} \hat{U}(t_b) \hat{\rho}_0 \hat{\rho}_a \hat{\rho}_b \hat{U}^\dagger(t_b) \hat{K}_{m_b}^\dagger\}}$. The unitary time evolution operator can be separated as $\hat{U}(t) = \hat{U}_0(t) \hat{U}_I(t)$. Here, $\hat{U}_0(t) = e^{-\frac{i}{\hbar}(\hat{H}_0 + \hat{H}_a + \hat{H}_b)(t-t_0)}$ generates the time evolution in the uncoupled subsystems and $\hat{U}_I(t) = \mathcal{T} e^{-\frac{i}{\hbar} \int_{t_0}^t \hat{H}_{\text{int}}(t') dt'}$ describes the time evolution in the interaction picture induced by \hat{H}_{int} . Here, \mathcal{T} denotes the time-ordering operator. The second measurement ends with the readout of detector a at

time $t_a \geq t_b$ with result m_a . The (unnormalized) total state after this procedure is given by $\hat{\rho}'' = \hat{K}_{m_a} \hat{U}(t_a - t_b) \hat{\rho}' \hat{U}^\dagger(t_a - t_b) \hat{K}_{m_a}^\dagger$. Its trace $\text{Tr}\{\hat{\rho}''\} = p(m_a, t_a | m_b, t_b)$ gives the conditional probability of finding m_a if m_b has been measured before; the unconditional probability is obtained by applying Bayes' theorem $p(m_a, t_a; m_b, t_b) = p(m_a, t_a | m_b, t_b) p(m_b, t_b)$. To establish the relation between measurement results of the two detectors and operator order of the corresponding observables we consider

$$C(t_a, t_b) = \int dm_a \int dm_b m_a m_b p(m_a, t_a; m_b, t_b) - \int dm_a m_a p(m_a, t_a) \int dm_b m_b p(m_b, t_b). \quad (3)$$

Using the weak-coupling assumption, expanding \hat{U}_I to second order in η and rescaling $C \rightarrow C/\eta_a \eta_b$, we find that the correlation function can be written as the sum of three contributions

$$C(t_a, t_b) = C^{\text{sym}}(t_a, t_b) + C_a^{\text{det}}(t_a, t_b) + C_b^{\text{det}}(t_a, t_b), \quad (4)$$

with

$$\begin{aligned} C^{\text{sym}}(t_a, t_b) &= \int dt ds \chi_{MD}^a(t_a, t) \chi_{MD}^b(t_b, s) S_{AB}^0(t, s), \\ C_a^{\text{det}}(t_a, t_b) &= \int dt ds \chi_{MD}^b(t_b, s) \chi_{BA}^0(s, t) S_{MD}^a(t_a, t), \\ C_b^{\text{det}}(t_a, t_b) &= \int dt ds \chi_{MD}^a(t_a, t) \chi_{AB}^0(t, s) S_{MD}^b(t_b, s). \end{aligned} \quad (5)$$

Here we introduced the response functions

$$\chi_{XY}^\alpha(t, t') = -\frac{i}{\hbar} \theta(t - t') \langle [\hat{X}_\alpha(t), \hat{Y}_\alpha(t')] \rangle_\alpha, \quad (6)$$

and the symmetrized noise functions

$$S_{XY}^\alpha(t, t') = \frac{1}{2} \langle \{\delta \hat{X}_\alpha(t), \delta \hat{Y}_\alpha(t')\} \rangle_\alpha. \quad (7)$$

The expectation values in Eqs. (6) and (7) are calculated with the initial system density matrix $\hat{\rho}_0$ respectively the density matrices $\hat{\rho}_\alpha(t) = \theta(t_\alpha - t) \hat{\rho}_\alpha + \theta(t - t_\alpha) \hat{\rho}'_\alpha$ of the detectors ($\alpha = a, b$), which can incorporate a change of the detector state from $\hat{\rho}_\alpha$ to $\hat{\rho}'_\alpha$ due to its readout at time t_α . The detector observable is given by $\hat{M}_\alpha = \int dm_\alpha m_\alpha \hat{K}_{m_\alpha}^\dagger \hat{K}_{m_\alpha}$.

Equations (4) and (5) are the main result of our Letter. The origin of the various terms is illustrated in Fig. 2. C^{sym} describes the symmetrized correlation of the system observables \hat{A} and \hat{B} which is transmitted to both detectors via χ^a and χ^b . C_a^{det} corresponds to the internal correlation of \hat{M}_a and \hat{D}_a in detector a where \hat{D}_a is measured by detector b via χ^0 and χ^b (and similarly for C_b^{det}). The system takes a new role as a linear-response mediator here, since the commutators in the response

function Eq. (6) make information accessible that is not contained in the symmetrized noise, Eq. (7).

If system and detectors are initialized in stationary states, Eqs. (6) and (7) depend only on the time differences and Eq. (4) can be expressed in Fourier space as $C(\omega) = \int d(t_a - t_b) e^{i\omega(t_a - t_b)} C(t_a, t_b)$ with the result

$$\begin{aligned} C^{\text{sym}}(\omega) &= \chi_{MD}^a(\omega) \chi_{MD}^b(-\omega) S_{AB}^0(\omega), \\ C_a^{\text{det}}(\omega) &= \chi_{MD}^b(-\omega) \chi_{BA}^0(-\omega) S_{MD}^a(\omega), \\ C_b^{\text{det}}(\omega) &= \chi_{MD}^a(\omega) \chi_{AB}^0(\omega) S_{MD}^b(-\omega). \end{aligned} \quad (8)$$

For simplicity we concentrate on the second-order cross-correlation here, the generalization is discussed in [26]. Hence, in the frequency domain and for equal detectors we have $C^{\text{sym}}(\omega) = |\chi_{MD}(\omega)|^2 S_{AB}^0(\omega)$. Thus, the non-Markovian nature of our setup results in a simple frequency filter effect for the symmetric part of the measurement.

We will now focus on the system-mediated detector-detector interactions C_a^{det} and discuss their relevance and properties, especially their effect on the finally measured operator order. Since the detectors measure each other's noise in linear response through the system, the presence of the commutator in the response functions leads to the appearance of antisymmetrically ordered system terms in addition to the symmetrized expressions which can combine in various ways. We find that (i) C^{det} is a non-Markovian quantity as it depends on the memory of the detector and the time history of the measurement process. (ii) the response-to-noise ratio χ/S of a detector is an indicator of the relevance of C^{det} and therefore the measured operator order. (iii) C_a^{det} and C_b^{det} can cancel with clever detector engineering. (iv) For certain systems, C^{det} leads to observable effects even in the Markovian coupling limit, i.e. for instantaneous interaction of system and detectors. The observations (i)-(iv) are illustrated in the corresponding examples in the following.

(i) *Ladder-operator measurement:* We study a system that is assumed to be a harmonic oscillator with frequency Ω . The detectors are assumed to be identical harmonic oscillators with frequency Ω' , and their memory is controlled by the damping parameter λ . This damping results from the dissipation to a bath, see [26]. The measurement is taken at coinciding times $t_a = t_b = 0$. We are interested in the correlation of the ladder operators \hat{a} and \hat{a}^\dagger of the system. Since they are not hermitian, we have to perform two measurements in which the detectors are coupled to the position in one measurement with the resulting correlation function C_{xx} and to the momentum in the other measurement resulting in C_{pp} . The sum of these correlators $C = (C_{xx} + C_{pp})/2$ corresponds to the scalar relation $\alpha\alpha^* = (x^2 + p^2)/2$ with $\alpha = (x + ip)/\sqrt{2}$ and is given by

$$C = \xi_s \langle \{\hat{a}, \hat{a}^\dagger\} \rangle - \xi_a \langle [\hat{a}, \hat{a}^\dagger] \rangle, \quad (9)$$

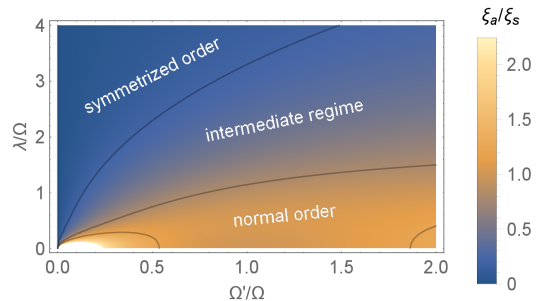


FIG. 3: Ratio of the weights ξ_a and ξ_s of the antisymmetric and symmetric contributions to Eq. (9) as a function of the detectors frequency Ω' and damping λ in units of the system frequency Ω at zero detector temperature.

where $\xi_s = \frac{1}{2} \int dt ds \chi_{MD}^a(t) \chi_{MD}^b(s) \cos(\Omega(t-s))$ and $\xi_a = \int dt ds \theta(s-t) [\chi_{MD}^b(t) S_{MD}^a(s) + \chi_{MD}^a(t) S_{MD}^b(s)] \times \sin(\Omega(s-t))$ are the weights of the symmetric and antisymmetric contributions. The antisymmetric contribution is essentially determined by the system-mediated detector-detector interaction C_{det} . Choosing the detector variable $\hat{D} = \hat{p}$ and the detector observable $\hat{M} = \hat{x}$ yields $\chi_{MD}(t) = \theta(t) e^{-\lambda t} \cos(\Omega' t)$ and $S_{MD}(t) = e^{-\lambda t} \sin(\Omega' t) \coth(\beta\Omega'/2)/2$ with the detectors inverse thermal energy β . Figure 3 shows the ratio of the weights ξ_a and ξ_s as a function of Ω' and λ . If the detector oscillators are only slightly damped ($\lambda \ll \Omega'$), i.e. have a long memory, the symmetric and antisymmetric contributions are of the same size and lead to normal order of the operators in the expression for $C \propto \langle \hat{a}^\dagger \hat{a} \rangle$. If the detector oscillators are overdamped ($\lambda \gg \Omega'$), i.e. approach the Markovian limit, the antisymmetric contribution vanishes and the correlation function corresponds to symmetrized operator order $C \propto \langle \{\hat{a}^\dagger, \hat{a}\} \rangle$.

(ii) *Relevance of the system-mediated contributions:* The response to noise ratio χ/S of the detector characterizes the strength of the asymmetric system operator order, which can be illustrated e.g. with a monochromatic laser beam. S and χ resemble a harmonic oscillator in many respects, with the difference that the noise is proportional to the photon number N whereas the response is unaffected by it. Thus we have $\chi/S \approx 1/N$. A single photon behaves very much like a harmonic oscillator and C^{sym} and the C_a^{det} contribute in the same order with a fine tuning possible by damping and resonance effects as shown in Fig. 3. Multiple photons will almost exclusively measure the system's response function, i.e. neither symmetric nor normal ordering but the antisymmetric operator order, $C_a^{\text{det}} \gg C^{\text{sym}}$ and the direct symmetric system measurement is negligible.

(iii) *Detector engineering:* We now use the possibility to prepare the two detectors in different states. We consider a mesoscopic electronic realization with two ($\alpha = a, b$) double quantum-dot detectors capacitively coupled to the system as depicted in Fig. 4(a). The two dots in each detector are connected via a tunnel cou-

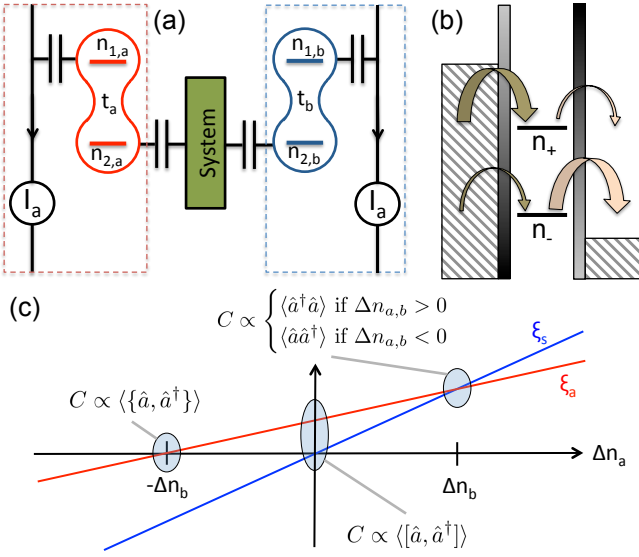


FIG. 4: Sketch of the setup. (a) Two double-dot detectors are capacitively coupled to a system and the occupation of one of the dots is recorded via a bypassing current. (b) The state of each detector can be set by additional contacts (not shown in (a)) which are biased to adjust the occupation difference of the high and low energy eigenstate n^+ and n^- . (c) Weights ξ_s and ξ_a as a function of the occupation difference of the energy eigenstates $\Delta n_\alpha = n_\alpha^- - n_\alpha^+$, $\epsilon_\alpha = 0$, no damping.

pling t_α and the energy difference of the left and right level ϵ_α can be tuned via a gate voltage. Both double dots are capacitively connected to a quantum point contact in which the current I_α is measured. We assume the current correlation function $\langle I_a(t)I_b(t') \rangle$ to be proportional to the occupation number correlation function $\langle \sigma_z^a(t)\sigma_z^b(t') \rangle$ with $\sigma_z^\alpha = n_{1,\alpha} - n_{2,\alpha}$.

The state of the double dots is controlled via a bias voltage, see Fig. 4(b). It can be characterized by the occupation difference of the energy eigenlevels $\Delta n_\alpha = n_\alpha^- - n_\alpha^+$. By tuning Δn_α from positive to negative values, i.e. setting a level inversion, the detector can be switched from absorption to emission mode. By using the cross-correlation of two detectors one can combine these modes to obtain the symmetrized noise not accessible to a single detector in either mode. The rates in and out of the dot are assumed to be low enough to allow the detector to evolve undisturbed during the measurement, i.e. we assume the tunneling rates to determine the initial state and the measurement taking place between two successive tunneling events. The detector Hamiltonian is given by $\hat{H}_\alpha = \epsilon_\alpha \hat{\sigma}_z^\alpha + t_\alpha \hat{\sigma}_x^\alpha$, and the interaction Hamiltonian reads $\hat{H}_{\text{int}} = \sum_\alpha \eta_\alpha \hat{\sigma}_z^\alpha \hat{A}$, where both detectors measure the same system variable \hat{A} . This leads to the response function

$$\chi_{\sigma_z \sigma_z}^\alpha(t, t') = -\theta(t - t') \frac{8t_\alpha^2}{\omega_\alpha^2} \sin(\omega_\alpha(t - t')) \Delta n_\alpha$$

and the noise

$$S_{\sigma_z \sigma_z}^\alpha(t, t') = \frac{8t_\alpha^2}{\omega_\alpha^2} \cos(\omega_\alpha(t - t')) + \frac{8\epsilon_\alpha^2}{\omega_\alpha^2} (1 - (\Delta n_\alpha)^2),$$

with $\omega_\alpha = 2\sqrt{t_\alpha^2 + \epsilon_\alpha^2}$. For measuring the ladder operators of a harmonic oscillator we can again write the correlator in the form of Eq. (9). The results for ξ_s and ξ_a are shown in Fig. 4(c). When both detectors are set to the same occupation difference $\Delta n_\alpha = n_\alpha^- - n_\alpha^+$ the noise contributions of both detectors sum up and we obtain normal order (anti-normal if both detectors are switched to emission mode) near resonance and for sufficient low damping. This regime was already explored in Fig. 3. Since $C_\alpha^{\text{det}} \propto \Delta n_\alpha$, tuning one of the detectors to level inversion of the other $\Delta n_a = -\Delta n_b$ results in a cancellation of the terms C_α^{det} and we are able to measure the pure symmetrized noise/correlation of the system. If one of the Δn_α equals zero, not only the corresponding C_α^{det} but also S^{sym} vanishes. In this case the only remaining contribution to C is the linear-response measurement of this detector's noise by the other detector via the system, i.e., C only contains information about the antisymmetric operator order. Tuning the voltage that controls Δn_α any of these regimes can be selected.

A regime to measure the antisymmetric system contribution completely independent of the system state can be explored by utilizing the constant term in the noise. In the frequency domain $C_\alpha^{\text{det}}(\omega = 0)$ will be directly proportional to the zero-frequency detector noise $S_{MD}^\alpha(\omega = 0) = 8(\epsilon_\alpha/\omega_\alpha)^2(1 - (\Delta n_\alpha)^2)$ which is tunable over a wide range by the gate voltage that controls ϵ_α . If we set a sufficiently large level difference ϵ the measurement outcome will be dominated by the detectors measuring each other's noise through the system. In this way we obtain the pure antisymmetric system operator order incorporated in $\chi_{A,B}^0(\omega)$.

(iv) *Markovian limit:* We now consider the correlation in the limit of short coupling times, $\eta_\alpha \rightarrow \delta(t - t_\alpha)$ in Eq. (2), in a stationary setup

$$\begin{aligned} C^{\text{sym}}(t_a, t_b) &= \chi_{MD}^a(0) \chi_{MD}^b(0) S_{AB}^0(t_a - t_b) \\ C_a^{\text{det}}(t_a, t_b) &= \chi_{MD}^b(0) S_{MD}^a(0) \chi_{BA}^0(t_b - t_a) \\ C_b^{\text{det}}(t_a, t_b) &= \chi_{MD}^a(0) S_{MD}^b(0) \chi_{AB}^0(t_a - t_b). \end{aligned} \quad (10)$$

Note that only one of the terms C_α^{det} will contribute depending on whether $t_a > t_b$ or $t_b > t_a$. For thermal detectors $\chi_{M,D}^\alpha(0)$ and $S_{MD}^\alpha(0)$ are related via the fluctuation-dissipation theorem and one finds a general requirement on the detectors for measuring the symmetrized correlation. If χ_{MD}^α (without the Heaviside function) is symmetric in t , e.g. in example (i), S_{MD}^α is antisymmetric in t and therefore $C_\alpha^{\text{det}} = 0$ and C reduce to the symmetrized expression. This is independent of the frequency filter effect of the detector or any system properties. However, any antisymmetric contribution in χ_{MD}^α will cause

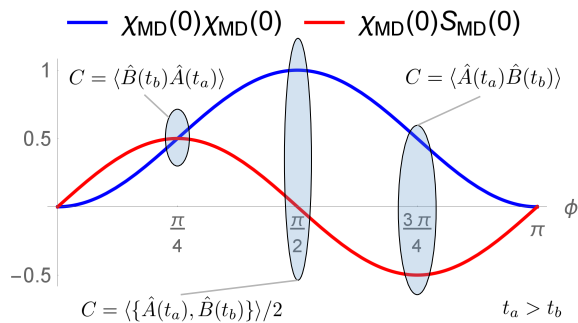


FIG. 5: Markovian coupling: The prefactors of S_{AB}^0 and $\chi_{A,B}^0$ as a function of the angle ϕ for $\langle \hat{\sigma}_z \rangle = 1$ and $\langle \hat{\sigma}_x \rangle = \langle \hat{\sigma}_y \rangle = 0$.

a finite value of C_α^{det} . For non-thermal detector states there are even less restrictions for C_α^{det} to remain in the Markovian limit.

To be concrete, we consider two identical ($a = b$) two-level detectors. The detector variable is set to $\hat{D} = \hat{\sigma}_x$ and the detector observable points in direction $\hat{M} = \vec{r}\vec{\sigma}$ with $\vec{r} = (\cos(\phi), \sin(\phi), 0)^T$. We obtain $\chi_{MD}(0) = -\sin(\phi)\langle \hat{\sigma}_z \rangle$ and $S_{MD}(0) = \cos(\phi) - \langle \vec{r}\vec{\sigma} \rangle \langle \hat{\sigma}_x \rangle$. Figure 5 shows that by tuning the angle ϕ we can realize the full range of operator orders from normal over symmetric to antisymmetric order with continuous transitions.

Conclusion and Outlook. — In contrast to theoretical models which assume instantaneous measurements, constantly coupled detectors appear naturally in many experiments. In our work we include the non-Markovian effects in such a setup and explore a variety of possible outcomes corresponding to non-symmetrized operator orders. Our results open the avenue to design tunable quantum detection systems which can observe tailored correlation functions.

We have proposed a quantum detector consisting of a pair of double quantum dots which realizes such a tunable scheme in a mesoscopic nanostructured circuit. Applying our analysis to develop quantum detector setups in the ultrafast optical domain [27–29] or in the optical detection of coherence [30] appears to be a promising research direction. Furthermore, a weak detection scheme is potentially useful to perform a weak quantum process tomography, which might present an alternative to the standard route to test quantum algorithms [31]. Another interesting future challenge will be to explore the full statistics of quantum systems in a non-Markovian detection scheme, eventually even going beyond the weak-measurement limit.

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