

Harvesting magic from the vacuum

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(Received 31 October 2024; accepted 23 June 2025; published 23 July 2025)

Magic is the quantum resource allowing a quantum computer to perform operations that cannot be simulated efficiently by classical computation. As such, generating magic in a quantum system is crucial for achieving quantum advantage. This article shows that magic can be harvested by a three-level Unruh-DeWitt detector (a qutrit) interacting with a quantum field in an initial vacuum state. While the idea of extracting resources from Quantum Field Theories (QFT) was born from the harvesting of entanglement, our result extends the protocol to evolve a qutrit from a nonmagical state to a magical one, making it possible to generate magic from QFT.

DOI: [10.1103/9ph7-cyzh](https://doi.org/10.1103/9ph7-cyzh)

I. INTRODUCTION

Magic is the quantum resource quantifying the ability of a quantum state to perform computational tasks that exceed the capabilities of classical systems [1,2]. Therefore, this resource is indispensable for achieving quantum advantage and is even more relevant than entanglement in quantum computing and the design of efficient quantum algorithms [3,4]. Indeed, while entanglement describes nonclassical correlations, i.e., quantifies the extent to which a state can be used for quantum information processing and communication protocols such as quantum teleportation, superdense coding, and quantum cryptography [5,6], this resource alone does not quantify quantum advantage, since merely creating entanglement can be efficiently simulated classically [1].

In Relativistic Quantum Information (RQI), entanglement harvesting [7] is the protocol that exploits a quantum field's vacuum state to generate entanglement between two causally disconnected nonrelativistic quantum mechanical systems [8–13]. Despite being a relatively new concept, entanglement harvesting has already led to advancements in our understanding of the entanglement properties of Quantum Field Theory (QFT) [14–17]. It is natural to ask if one can generate other qualitatively different quantum resources by interacting with a quantum field. This article takes a step forward by introducing a protocol for “harvesting” magic from the vacuum state of a QFT. Specifically, we investigate how coupling a nonrelativistic three-level system, called a *detector*, to a generic quantum

field can make the detector's state magical, demonstrating that the interaction with a field's vacuum can enhance the computational resources of a quantum system. As a proof of concept, we apply the framework to the case of a three-level system (in quantum computation, a qutrit) coupled to a massless scalar field in flat spacetime, a paradigmatic example of what is known as an Unruh-DeWitt detector. By this setting, we find that the amount of harvested magic depends on the detector's internal structure, the details of the detector–field coupling, and the specific properties of the field's vacuum state, i.e. the values taken by one- and two-point functions.

In short, this article introduces magic harvesting as a possible concept and outlines potential practical implementations and theoretical extensions.

II. UNRUH-DEWITT DETECTORS

In RQI, an important model involves a nonrelativistic quantum system - typically a two-level system (i.e., a qubit) - coupled to a quantum field, to explore the nontrivial notion of a vacuum state in noninertial frames; in this context the system is called an Unruh-DeWitt detector after its pioneers [18,19]. For this article, it is more useful to consider a three-level system $\mathcal{D}$ with a free Hamiltonian

$$\hat{H}_{\mathcal{D}} = \text{diag}(0, \Omega_1, \Omega_1 + \Omega_2), \quad (1)$$

and energy levels $\{|0\rangle, |1\rangle, |2\rangle\}$ where Ω_1, Ω_2 are the first and second energy gap, respectively. This system moves in a D -dimensional spacetime along a trajectory parameterized via its proper time τ as $x(\tau)$ and interacts with a quantum field Φ ; following the standard convention, we call it an Unruh-DeWitt detector. Specifically, the detector-field coupling is given by the interaction picture Hamiltonian

$$\hat{H}_{\text{int}}(\tau) = \lambda \chi(\tau) \hat{\mu}(\tau) \otimes \hat{\mathcal{O}}_{\Phi}(x(\tau)), \quad (2)$$

where λ is an interaction-strength parameter, $\chi(\tau)$ is a switching function describing the range of times for which the

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detector and the field are allowed to interact, $\hat{\mu}$ is the (interaction picture) monopole moment operator

$$\hat{\mu}(\tau) = \frac{1}{\sqrt{2}}(|1\rangle\langle 0|e^{i\Omega_1\tau} + |2\rangle\langle 1|e^{i\Omega_2\tau}) + \text{H.c.} \quad (3)$$

describing level transitions in the detector [20], and $\hat{O}_\Phi$ is some Hermitian field operator evaluated along the trajectory of the detector. For the sake of simplicity, we require $\langle \Phi_0 | \hat{O}_\Phi | \Phi_0 \rangle = 0$, where $|\Phi_0\rangle$ is the vacuum state of the field. The above choice of Hamiltonian makes the interaction localized along the trajectory of the detector and provides the interaction picture joint time evolution operator

$$\hat{U}_{\tau_i, \tau_f} = \mathcal{T} \left[\exp \left(-i \int_{\tau_i}^{\tau_f} d\tau \hat{H}_{\text{int}}(\tau) \right) \right], \quad (4)$$

where $\mathcal{T}$ denotes the time-ordered product. Starting from the global state

$$|\Psi\rangle = |0\rangle \otimes |\Phi_0\rangle, \quad (5)$$

the state of the detector after the interaction, as shown in Sec. S1 of the Supplemental Material [21], is represented by the density operator

$$\hat{\rho}_D = \begin{bmatrix} p & 0 & \beta^* \\ 0 & q & 0 \\ \beta & 0 & 1 - p - q \end{bmatrix}, \quad (6)$$

where the probability of finding one when measuring the system on the energy eigenbasis is

$$q = \langle 1 | \hat{\rho}_D | 1 \rangle = \langle \Phi_0 | \hat{U}^\dagger \hat{U} | \Phi_0 \rangle, \quad (7)$$

where $\hat{U} = \langle 1 | \hat{U}_{\tau_i, \tau_f} | 0 \rangle$ is some (possibly smeared) field operator completely determined by the interaction and trajectory above. In what follows, we will occasionally use quantum computation terminology, referring to the vectors $\{|0\rangle, |1\rangle, |2\rangle\}$ as the (qutrit's) computational basis.

Assuming λ to be small enough to allow the use of perturbation theory, we can find q as

$$q = \lambda^2 \mathcal{F}_q + \mathcal{O}(\lambda^4), \quad (8)$$

where

$$\mathcal{F}_q = \int_{\tau_i}^{\tau_f} d\tau \int_{\tau_i}^{\tau_f} d\tau' \chi(\tau) \chi(\tau') e^{-i\Omega_1(\tau - \tau')} \mathcal{O}(\tau, \tau') \quad (9)$$

with

$$\mathcal{O}(\tau, \tau') = \langle \Phi_0 | \hat{O}_\Phi(x(\tau)) \hat{O}_\Phi(x(\tau')) | \Phi_0 \rangle; \quad (10)$$

as we will see later, it is common to take $\hat{O}_\Phi$ as the field operator evaluated along the trajectory or some smeared version of it [22]. Likewise, we obtain the off-diagonal element

$$\beta = \langle 2 | \hat{\rho}_D | 0 \rangle =: \lambda^2 \mathcal{F}_\beta + \mathcal{O}(\lambda^4) \quad (11)$$

with

$$\begin{aligned} \mathcal{F}_\beta = & -\frac{1}{2} \int_{\tau_i}^{\tau_f} d\tau \int_{\tau_i}^{\tau_f} d\tau' \chi(\tau) \chi(\tau') \\ & \times [\Theta(\tau - \tau') e^{i(\Omega_1\tau' + \Omega_2\tau)} \mathcal{O}(\tau, \tau') \\ & + \Theta(\tau' - \tau) e^{i(\Omega_1\tau + \Omega_2\tau')} \mathcal{O}(\tau', \tau)], \end{aligned} \quad (12)$$

where the Heaviside step functions Θ appear by virtue of the time-ordering.

We stress that, while necessary to obtain analytical and numerical results, the analysis in the next section does not rely on the use of perturbation theory: all our results can be obtained entirely in terms of q and β , which is expressed exactly through Eq. (6).

III. MAGIC HARVESTING

By Gottesman-Knill theorem, if a quantum algorithm does not contain non-Clifford operations, it can be simulated on a classical computer in polynomial time [1]. Moreover, a universal set of gates must include a non-Clifford gate such as the T gate ($\pi/8$ gate) or the Toffoli gate [23]. Hence, non-Clifford gates are imperative for attaining quantum advantage in computation. Formally, the necessary non-Clifford gates belong to the set $\mathcal{C}_3 := \{\hat{U} \mid \hat{U}\mathcal{C}_1\hat{U}^\dagger \subseteq \mathcal{C}_2\}$, where $\mathcal{C}_2$ denotes the Clifford group, which is the normalizer of the Pauli group $\mathcal{C}_1$. Indeed, the set $\mathcal{C}_3$ includes both the Toffoli and T gates [24]. Alternatively, $\mathcal{C}_3$ gates can be replaced by Clifford gates and a supply of ancillary qubits in states containing a resource called non-Cliffordness or nonstabilizerness, which is often referred to as *magic* [2,3]. Therefore, magic is the resource that describes the ability of a quantum system to perform tasks that cannot be efficiently simulated classically. Importantly, magic quantifies the advantage of quantum computation more fundamentally than entanglement, since highly entangled states may be classically simulable. For instance, the maximally entangled Bell states are contained in the stabilizer set, i.e., the orbit of $\mathcal{C}_2$, and thus contain zero magic [1]. More generally, in quantum computing with qudits instead of qubits, the counterpart of requiring magic is asking for Wigner negativity, i.e., for states whose Wigner function in the discrete quantum phase-space takes negative values. Any computation involving only Wigner non-negative states can be efficiently simulated classically, while Wigner negativity enables quantum advantage in universal computation [25–27].

In this section, we propose a novel protocol to harvest magic from the vacuum state of a quantum field. More specifically, we show that the interaction Hamiltonian (2) can drive the state of the three-level system, a qutrit, to a state that cannot be efficiently simulated classically, i.e., has magic (i.e., Wigner negativity) [28,29]. While magic is a basis-dependent concept, here there is a natural preferred basis: the energy eigenstates of the detector. Note that magic is not directly extracted from the field [30]; instead, the interaction with the field generates magic in the qutrit. To this end, we quantify magic by *mana*, a quantity introduced in Ref. [3]. By this measure, the magic of a mixed state $\hat{\rho}$ in some basis $\mathcal{B}$ is obtained as

$$M(\hat{\rho}) := \ln \left[\sum_{a,a'=0}^{n-1} |W_{(a,a')}(\hat{\rho})| \right], \quad (13)$$

where

$$W_{\mathbf{a}}(\hat{\rho}) := n^{-1} \text{Tr}(\hat{A}_{\mathbf{a}} \hat{\rho}) \quad (14)$$

is the discrete Wigner function [28,31], with n denoting the dimensionality of the detector's Hilbert space and $\mathbf{a} := (a, a') \in$

$\mathbb{Z}_n \times \mathbb{Z}_n$ labeling the points of a discrete phase space. Note that the discrete Wigner function is defined only for odd n [32], which is why we focus our attention on qutrits rather than on the two-level systems naturally arising in RQI. As it is clear, computation of mana requires knowing the phase-space-dependent operators

$$\hat{A}_0 := n^{-1} \sum_{\mathbf{a}} \hat{T}_{\mathbf{a}}, \quad \hat{A}_{\mathbf{a}} := \hat{T}_{\mathbf{a}} \hat{A}_0 \hat{T}_{\mathbf{a}}^\dagger \quad (15)$$

given by the generalized Pauli matrices $T_{\mathbf{a}}$, also known as the Weyl-Heisenberg matrices. These are generated by the shift and clock operators

$$\hat{X} := \sum_{k=0}^{n-1} |k+1 \bmod n\rangle \langle k|, \quad \hat{Z} := \sum_{k=0}^{n-1} \omega^k |k\rangle \langle k|, \quad (16)$$

as

$$\hat{T}_{aa'} = \omega^{-\frac{(n+1)}{2}aa'} \hat{Z}^a \hat{X}^{a'}, \quad (17)$$

where we employed a common shorthand notation for the phase $\omega := e^{2\pi i/n}$. Note that, as magic is basis dependent, in this article we calculate mana in the interaction picture of the energy eigenbasis.

Using the density operator (6), and thus setting $n = 3$, we obtain the magic for the detector as

$$M(\hat{\rho}) = \ln \left\{ 1 - q + \frac{1}{3} [|q + 2 \operatorname{Re}(\beta)| + |q - \operatorname{Re}(\beta)| - \sqrt{3} \operatorname{Im}(\beta)| + |q - \operatorname{Re}(\beta) + \sqrt{3} \operatorname{Im}(\beta)|] \right\}. \quad (18)$$

As it is clear, the state of the detector is mixed at the end of the protocol. While using mixed states to realize non-Clifford operations is possible, one often needs purer magical states for practical implementations. Magic state distillation was invented for this purpose. This method converts several copies of a mixed magical density operator into one magical state with higher purity [2,33]. A possible topic for further investigation is to apply magic distillation to multiple copies of Unruh-DeWitt detectors prepared by the above protocol, to harvest a more practical resource for quantum applications.

IV. HARVESTING MAGIC BY AN INERTIAL POINTLIKE DETECTOR

As an example, in this section we compute the magic harvested by a pointlike detector from the vacuum of a massless scalar quantum field. As proven above, we only need to compute q , i.e., the probability of finding the detector in $|1\rangle$, and β , i.e., the only off-diagonal element, after some interaction with the field takes place. To proceed further, we need to specify more details about the field state and the interaction. Specifically, we take the detector to move along an inertial trajectory $x(\tau) = (\tau, \mathbf{x}_0)$, for which the massless scalar field operator reads

$$\hat{\phi}(x) = \int \frac{d^D k}{(2\pi)^{D/2}} (\hat{a}_{\mathbf{k}}^\dagger e^{ik \cdot x} + \hat{a}_{\mathbf{k}} e^{-ik \cdot x}), \quad (19)$$

with roman letters x, k denoting D -dimensional vectors in spacetime and $\hat{a}_{\mathbf{k}}^{(\dagger)}$ being the annihilation (creation) operators in momentum space. For the sake of simplicity, we also take $D = 4$, the detector to be pointlike, the field to initially be

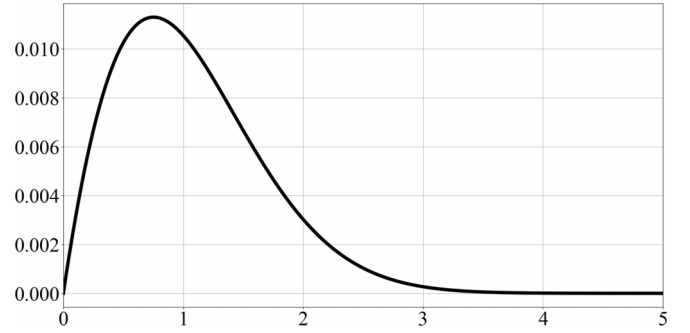


FIG. 1. Mana M/λ^2 as function of the product of the energy gap and interaction length $\Omega\sigma_t$.

in the Minkowski vacuum state $|\phi_0\rangle$, and the interaction to be described by a direct coupling between the monopole moment and the field operator. We also set the energy gaps to equal $\Omega := \Omega_1 = \Omega_2$ to avoid divergences. Thanks to these choices, Eq. (2) becomes

$$H_{\text{int}}(\tau) = \lambda \chi(\tau) \hat{\mu}(\tau) \otimes \hat{\phi}(x(\tau)), \quad (20)$$

and the expectation value (10) becomes the Wightman two-point function

$$\mathcal{W}(\tau, \tau') = \langle \phi_0 | \hat{\phi}(x(\tau)) \hat{\phi}(x(\tau')) | \phi_0 \rangle. \quad (21)$$

Finally, we must fix some switching function and the range of times for which the interaction is on. For the sake of simplicity, we pick $\chi(\tau)$ to be the unnormalised Gaussian

$$\chi(\tau) = e^{-\tau^2/\sigma_t^2} \quad (22)$$

with variance $\sigma_t^2/2$. Considering contributions up to λ^2 , we obtain the mana

$$M(\hat{\rho}) = \frac{\lambda^2}{12\sqrt{2\pi}} \Omega \sigma_t \left[1 - \operatorname{erf}\left(\frac{\Omega \sigma_t}{\sqrt{2}}\right) \right] + \mathcal{O}(\lambda^4), \quad (23)$$

which we plot for different values of σ_t and Ω in Fig. 1 (see Secs. S2 and S3 of the Supplemental Material for details [21]). First, the magic harvested can be optimized by choice of energy gap Ω multiplied by the interaction length modulated by σ_t . Second, fixing the energy gap, the amount of magic harvested increases with σ_t only up to a certain point. After this point, increasing the interaction time will decrease the magic. We interpret this as the fact that the full system approaches a regime where its state is time-translation invariant, for which no excitation can occur: an inertial detector that is uniformly switched on for an infinite time gives a zero response regardless of the specific details of the interaction employed [22]. Yet, the amount of harvested magic at finite times depends on the specific switching utilized. While using Gaussian smearing is customary in RQI, other functions may also be considered, and a bestiary of finite-time switchings has been presented in Ref. [34], where their extensions to infinite-time switching are also discussed. Hence, a more detailed analysis of the harvested magic vs shape and time of detector-field interaction is easily accessible; yet, we here only consider the Gaussian switching since the purpose of this example is only that of presenting a proof-of-concept for our magic harvesting protocol.

V. CONCLUSIONS

We presented a protocol harvesting magic from QFT states. Our findings build on the principles of entanglement harvesting, showing these can be extended to magic and, therefore, used to extract computationally valuable resources from QFTs. Our results have several potential future applications and extensions, with possible impact on both foundational and experimental relativistic quantum information theory.

On the one hand, recent studies on magic are showing its relevance not only as a computational-related quantity but also as an additional way to characterize the natural world. For example, magic has been used to characterize the quantum complexity of nuclear systems [35], exotic matter [36], and neutrino physics [37], and has been employed as a witness for quantum phase transitions in many-body systems [38], and related to gravitational back-reaction via the holographic principle [39]. In a similar vein, we conjecture harvesting could serve as a novel tool for revealing previously unexplored properties of quantum field theoretic states, much like entanglement harvesting is illuminating the entanglement structure of field theories [8,9]. Specifically, understanding the relevance of magic in describing fundamental properties of QFT will likely require studying several extensions of our protocol, which are easily achieved from the present discussion by exploring generic probes, diverse interactions, and other field theories. A first nontrivial extension mimicking entanglement harvesting would be to consider two spacelike separated detectors interacting with a field, and investigate whether non-local magic [39] could be generated into the joint state of the detectors. Another question is whether one could construct a measure to directly quantify the magic in the time-evolution operator (4), in analogy of the Pauli instability developed to quantify magic in unitary circuits [40]. More straightforward extensions could consider different switching functions such as those mentioned in Ref. [34], focusing on the finite time interactions. This study would enable a selection of those switchings allowing a more efficient magic harvesting. Furthermore, the interaction Hamiltonian can be further generalized by considering different detector-field couplings or adding a finite extension of the detector in space; the latter can be achieved by using a standard procedure based on Fermi normal coordinates [22,41]. Considering different kinds of fields is also possible. This is in line with the fact that, as mentioned above, we expect magic generation to be

feasible in various settings involving a qudit interacting with an environment.

More speculatively, one could envision implementing our protocol to provide costly quantum resources (i.e., non-Clifford operations) relatively inexpensively; based on this, RQI may provide novel tools for performing nonclassically simulable tasks. Specifically, one can ask the question of implementing the harvesting protocol with real-life devices in the laboratory, thus enabling speculations on alternative methods providing magical resources to a quantum computer without requiring the design of non-Clifford gates. Indeed, our proof-of-concept lets one imagine a quantum computer that exclusively performs Clifford operations but is supplemented with a collection of ancillary qubits or qudits coupled to a quantum field as proposed herein, thus performing Clifford operations freely and requesting magical ancillas only when needed. These are coupled with the field to extract magic and then included as a resource in the quantum registers used for the computation. Another scenario could be to use the quantum field as a channel to transmit magic between detectors [42,43], e.g., through quantum dots coupled with a Luttinger liquid [44].

It is important to emphasize that, like any novel exploratory approach in its infancy, this article serves only as a proof-of-concept for the magic harvesting protocol: any potential experimental or technological applications remain in the realm of future possibilities rather than that of assured outcomes.

ACKNOWLEDGMENTS

The authors thank O. Veltheim for valuable comments and discussions, and A. Robertson for a helpful lunch conversation. N.P. acknowledges financial support from the Magnus Ehrnrooth Foundation and the Academy of Finland via the Centre of Excellence program (Projects No. 336810 and No. 336814). N.P. and E.K.-V. acknowledge the financial support of the Research Council of Finland through the Finnish Quantum Flagship project (358878, UH). Open access funded by Helsinki University Library.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

- [1] D. Gottesman, The Heisenberg Representation of quantum computers, in *22nd International Colloquium on Group Theoretical Methods in Physics* (International Press, Cambridge, MA, 1999), pp. 32–43.
- [2] S. Bravyi and A. Kitaev, Universal quantum computation with ideal Clifford gates and noisy ancillas, *Phys. Rev. A* **71**, 022316 (2005).
- [3] V. Veitch, S. A. H. Mousavian, D. Gottesman, and J. Emerson, The resource theory of stabilizer quantum computation, *New J. Phys.* **16**, 013009 (2014).
- [4] S. F. E. Oliviero, L. Leone, A. Hamma, and S. Lloyd, Measuring magic on a quantum processor, *npj Quantum Inf.* **8**, 148 (2022).
- [5] C. H. Bennett, Quantum information, *Phys. Scr.* **1998**, 210 (1998).
- [6] R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, Quantum entanglement, *Rev. Mod. Phys.* **81**, 865 (2009).
- [7] “Harvesting” is a standard name for the protocol, but note a difference in terminology: Entanglement is not necessarily removed from the vacuum, whereas, e.g., harvesting corn from a field leaves few cobs left.
- [8] A. Valentini, Nonlocal correlations in quantum electrodynamics, *Phys. Lett. A* **153**, 321 (1991).
- [9] B. Reznik, Entanglement from the vacuum, *Found. Phys.* **33**, 167 (2003).

- [10] E. Martín-Martínez and N. C. Menicucci, Entanglement in curved spacetimes and cosmology, *Class. Quantum Grav.* **31**, 214001 (2014).
- [11] A. Pozas-Kerstjens and E. Martín-Martínez, Harvesting correlations from the quantum vacuum, *Phys. Rev. D* **92**, 064042 (2015).
- [12] G. Salton, R. B. Mann, and N. C. Menicucci, Acceleration-assisted entanglement harvesting and ranging, *New J. Phys.* **17**, 035001 (2015).
- [13] C. Suryaatmadja, R. B. Mann, and W. Cong, Entanglement harvesting of inertially moving Unruh-DeWitt detectors in Minkowski spacetime, *Phys. Rev. D* **106**, 076002 (2022).
- [14] B. de S. L. Torres, K. Wurtz, J. Polo-Gómez, and E. Martín-Martínez, Entanglement structure of quantum fields through local probes, *J. High Energy Phys.* **05** (2023) 058.
- [15] T. R. Perche, J. Polo-Gómez, B. de S. L. Torres, and E. Martín-Martínez, Fully relativistic entanglement harvesting, *Phys. Rev. D* **109**, 045018 (2024).
- [16] I. Agullo, B. Bonga, P. Ribes-Metidieri, D. Kranas, and S. Nadal-Gisbert, How ubiquitous is entanglement in quantum field theory? *Phys. Rev. D* **108**, 085005 (2023).
- [17] I. Agullo, B. Bonga, E. Martín-Martínez, S. Nadal-Gisbert, T. R. Perche, J. Polo-Gómez, P. Ribes-Metidieri, and B. de S. L. Torres, Multimode nature of spacetime entanglement in QFT, *Phys. Rev. D* **111**, 085013 (2025).
- [18] W. G. Unruh, Notes on black-hole evaporation, *Phys. Rev. D* **14**, 870 (1976).
- [19] B. S. DeWitt, Quantum Gravity: The new synthesis, in *General Relativity: An Einstein Centenary Survey*, edited by S. W. Hawking and W. Israel (Cambridge University Press, Cambridge, 1980), pp. 680–745.
- [20] C. Lima, E. Patterson, E. Tjoa, and R. B. Mann, Unruh phenomena and thermalization for qudit detectors, *Phys. Rev. D* **108**, 105020 (2023).
- [21] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/9ph7-cyzh> for a brief introduction to resource theories in general and magic in particular, and additional calculations essential for deriving the analytical results in the manuscript.
- [22] S. Schlicht, Considerations on the Unruh effect: Causality and regularization, *Class. Quantum Grav.* **21**, 4647 (2004).
- [23] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information: 10th Anniversary Edition* (Cambridge University Press, Cambridge, 2010).
- [24] D. Gottesman and I. L. Chuang, Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations, *Nature (London)* **402**, 390 (1999).
- [25] V. Veitch, C. Ferrie, D. Gross, and J. Emerson, Negative quasiprobability as a resource for quantum computation, *New J. Phys.* **14**, 113011 (2012).
- [26] A. Mari and J. Eisert, Positive Wigner functions render classical simulation of quantum computation efficient, *Phys. Rev. Lett.* **109**, 230503 (2012).
- [27] V. Veitch, N. Wiebe, C. Ferrie, and J. Emerson, Efficient simulation scheme for a class of quantum optics experiments with non-negative Wigner representation, *New J. Phys.* **15**, 013037 (2013).
- [28] D. Gross, Hudson's theorem for finite-dimensional quantum systems, *J. Math. Phys.* **47**, 122107 (2006).
- [29] D. Gross, Non-negative Wigner functions in prime dimensions, *Appl. Phys. B* **86**, 367 (2007).
- [30] For a discussion of whether the ground state of a field could have magic, see Ref. [45].
- [31] W. K. Wootters, A Wigner-function formulation of finite-state quantum mechanics, *Ann. Phys. (NY)* **176**, 1 (1987).
- [32] C. Ferrie and J. Emerson, Framed Hilbert space: Hanging the quasi-probability pictures of quantum theory, *New J. Phys.* **11**, 063040 (2009).
- [33] H. Anwar, E. T. Campbell, and D. E. Browne, Qutrit magic state distillation, *New J. Phys.* **14**, 063006 (2012).
- [34] L. Sriramkumar and T. Padmanabhan, Finite-time response of inertial and uniformly accelerated Unruh - DeWitt detectors, *CQG* **13**, 2061 (1996).
- [35] F. Brökemeier, S. M. Hengstenberg, J. W. T. Keeble, C. E. P. Robin, F. Rocco, and M. J. Savage, Quantum magic and multipartite entanglement in the structure of nuclei, *Phys. Rev. C* **111**, 034317 (2025).
- [36] C. E. P. Robin and M. J. Savage, The magic in nuclear and hypernuclear forces, [arXiv:2405.10268](https://arxiv.org/abs/2405.10268).
- [37] I. Chernyshev, C. E. P. Robin, and M. J. Savage, Quantum magic and computational complexity in the neutrino sector, *Phys. Rev. Res.* **7**, 023228 (2025).
- [38] A. G. Catalano, J. Odavić, G. Torre, A. Hama, F. Franchini, and S. M. Giampaolo, Magic phase transition and nonlocal complexity in generalized W state, [arXiv:2406.19457](https://arxiv.org/abs/2406.19457).
- [39] C. Cao, G. Cheng, A. Hama, L. Leone, W. Munizzi, and S. F. E. Oliviero, Gravitational back-reaction is magical, [arXiv:2403.07056](https://arxiv.org/abs/2403.07056).
- [40] R. J. Garcia, G. Bhole, K. Bu, L. Chen, H. Arthanari, and A. Jaffe, On the hardness of measuring magic, [arXiv:2408.01663](https://arxiv.org/abs/2408.01663).
- [41] J. Louko and A. Satz, How often does the Unruh-DeWitt detector click? Regularization by a spatial profile, *Class. Quantum Grav.* **23**, 6321 (2006).
- [42] P. Simidzija, A. Ahmadzadegan, A. Kempf, and E. Martín-Martínez, Transmission of quantum information through quantum fields, *Phys. Rev. D* **101**, 036014 (2020).
- [43] M. Kasprzak and E. Tjoa, Transmission of quantum information through quantum fields in curved spacetimes, *J. Phys. A: Math. Theor.* **58**, 095301 (2025).
- [44] E. W. Aspling, J. A. Marohn, and M. J. Lawler, Design constraints for Unruh-DeWitt quantum computers, *SciPost Phys. Core* **7**, 019 (2024).
- [45] C. D. White, C. Cao, and B. Swingle, Conformal field theories are magical, *Phys. Rev. B* **103**, 075145 (2021).