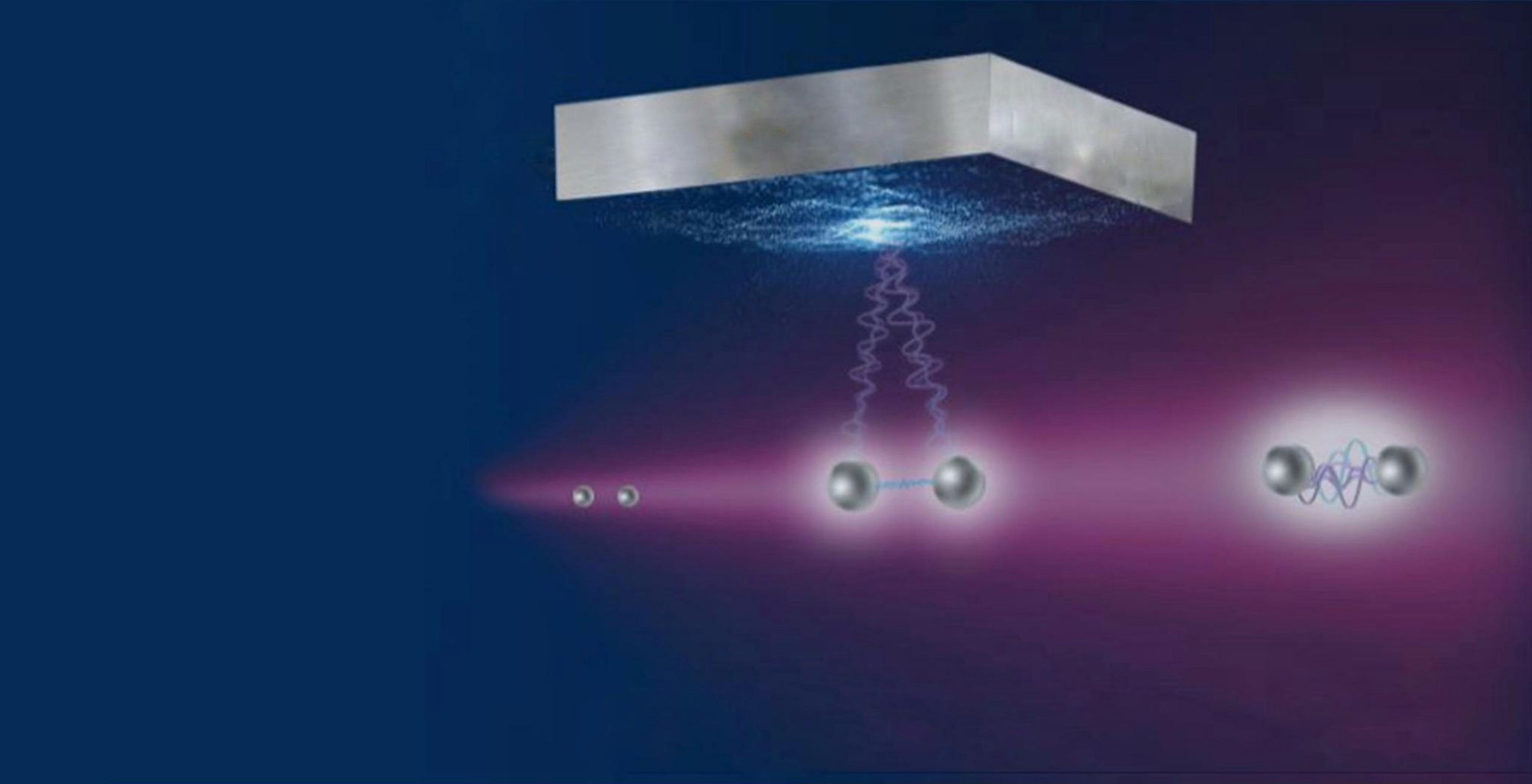


ARTICLE OPEN

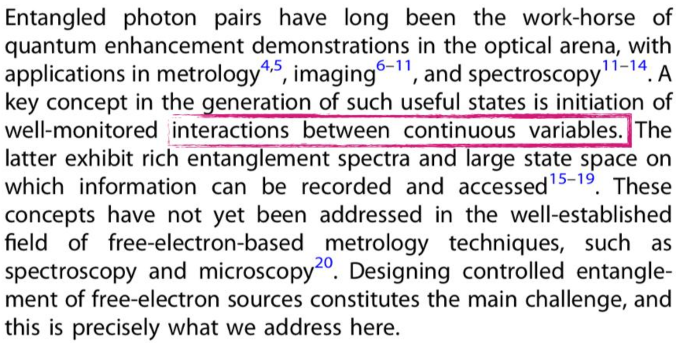
Generation, characterization, and manipulation of quantum correlations in electron beams

Shahaf Asban[1] and F. Javier García de Abajo[1,2]

npj Quantum Information (2021)7:42 ; https://doi.org/10.1038/s41534-021-00376-4

Entangled photon pairs have long been the work-horse of quantum enhancement demonstrations in the optical arena, with applications in metrology[4,5], imaging[6–11], and spectroscopy[11–14]. A key concept in the generation of such useful states is initiation of well-monitored interactions between continuous variables. The latter exhibit rich entanglement spectra and large state space on which information can be recorded and accessed[15–19]. These concepts have not yet been addressed in the well-established field of free-electron-based metrology techniques, such as spectroscopy and microscopy[20]. Designing controlled entanglement of free-electron sources constitutes the main challenge, and this is precisely what we address here.

INTRODUCCION

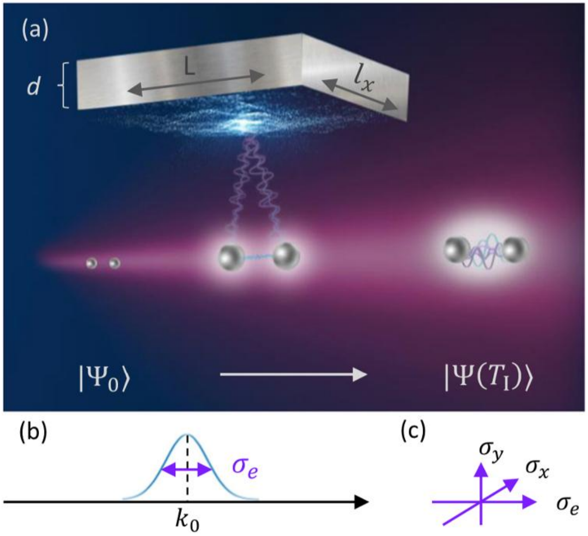


Entangled photon pairs have long been the work-horse of quantum enhancement demonstrations in the optical arena, with applications in metrology[4,5], imaging[6–11], and spectroscopy[11–14]. A key concept in the generation of such useful states is initiation of well-monitored interactions between continuous variables. The latter exhibit rich entanglement spectra and large state space on which information can be recorded and accessed[15–19]. These concepts have not yet been addressed in the well-established field of free-electron-based metrology techniques, such as spectroscopy and microscopy[20]. Designing controlled entanglement of free-electron sources constitutes the main challenge, and this is precisely what we address here.

interactions between continuous variables.

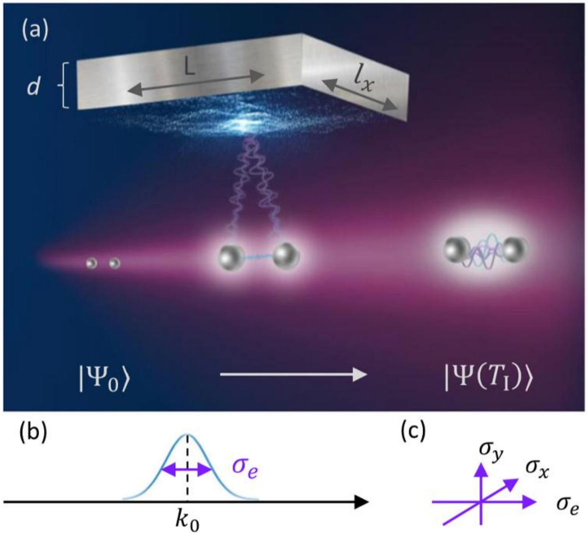
INTRODUCCION

Here, we study the quantum correlations generated by abrupt interactions of electron pairs with a neighboring medium, as depicted in Fig. 1, for a controlled time interval T_I. We explore the transient state generated by abrupt interactions, as well as the steady-state limit in the perturbative regime. By varying two control parameters—interaction time T_I and initial electron bandwidth σ_e—we effectively scan the degree of entanglement. The entanglement in the longitudinal dimension is characterized by the Schmidt decomposition of the wave function. We then calculate the coincidence probability and display it versus the degree of entanglement. We denote the resulting eigenstate electronic temporal modes (ETMs) in analogy to their photonic counterparts[31,32]. Finally, we propose a technique that is useful for real-time discrimination between ETMs, essential for state tomography and related quantum information processing applications.



INTRODUCCION

Here, we study the quantum correlations generated by abrupt interactions of electron pairs with a neighboring medium, as depicted in Fig. 1, for a controlled time interval T_I. We explore the transient state generated by abrupt interactions, as well as the steady-state limit in the perturbative regime. By varying two control parameters—interaction time T_I and initial electron bandwidth σ_e—we effectively scan the degree of entanglement. The entanglement in the longitudinal dimension is characterized by the Schmidt decomposition of the wave function. We then calculate the coincidence probability and display it versus the degree of entanglement. We denote the resulting eigenstate electronic temporal modes (ETMs) in analogy to their photonic counterparts[31,32]. Finally, we propose a technique that is useful for real-time discrimination between ETMs, essential for state tomography and related quantum information processing applications.

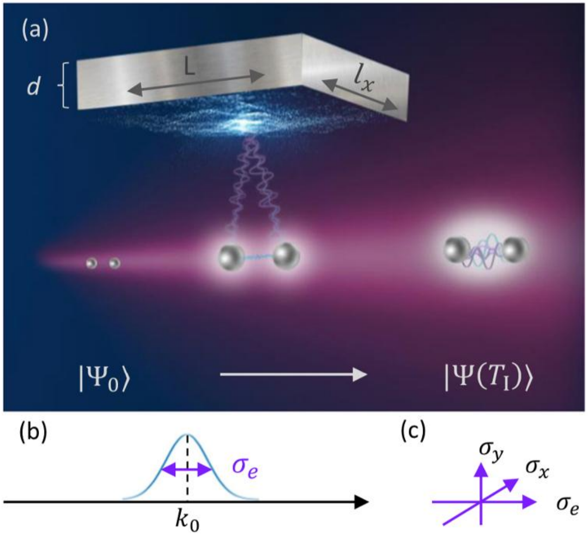


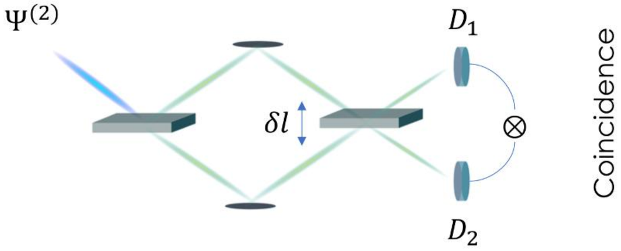
$$\left|\Psi^{(2)}\right\rangle_\lambda = \int_\Omega d\mathbf{k}_1 d\mathbf{k}_2 \Phi^\lambda_{s_1 s_2}(\mathbf{k}_1,\mathbf{k}_2) c^\dagger_{s_1}(\mathbf{k}_1) c^\dagger_{s_2}(\mathbf{k}_2)|\emptyset\rangle,$$

$$\Phi^\lambda_{s_1 s_2}(k_1,k_2) = \sum_n \sqrt{p_n}\,\psi_n(k_1)\phi_n(k_2),$$

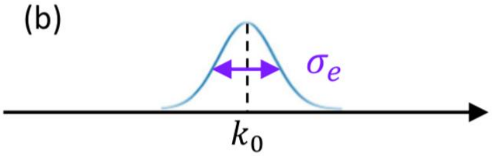
INTRODUCCION

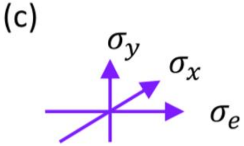
Here, we study the quantum correlations generated by abrupt interactions of electron pairs with a neighboring medium, as depicted in Fig. 1, for a controlled time interval T_I. We explore the transient state generated by abrupt interactions, as well as the steady-state limit in the perturbative regime. By varying two control parameters—interaction time T_I and initial electron bandwidth σ_e—we effectively scan the degree of entanglement. The entanglement in the longitudinal dimension is characterized by the Schmidt decomposition of the wave function. We then calculate the coincidence probability and display it versus the degree of entanglement. We denote the resulting eigenstate electronic temporal modes (ETMs) in analogy to their photonic counterparts[31,32]. Finally, we propose a technique that is useful for real-time discrimination between ETMs, essential for state tomography and related quantum information processing applications.





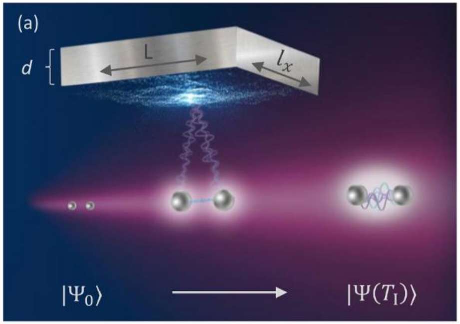
INTRODUCCION



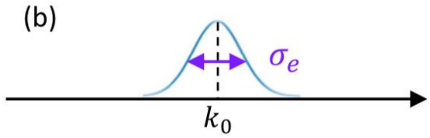


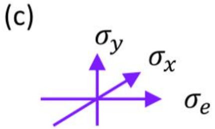
$$|\Psi_0\rangle = \int_\Omega \mathrm{d}\boldsymbol{k}_1 \mathrm{d}\boldsymbol{k}_2 a^{(1)}_{s_1}(\boldsymbol{k}_1) a^{(2)}_{s_2}(\boldsymbol{k}_2) c^\dagger_{s_1}(\boldsymbol{k}_1) c^\dagger_{s_2}(\boldsymbol{k}_2)|\emptyset\rangle$$

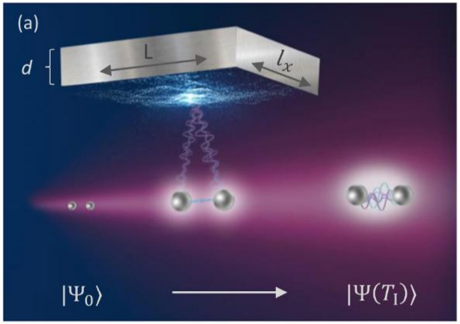
We consider the initial state to be prepared using a spin polarized electron source, allowing separate single-particle manipulation prior to the interaction[51–53]. One way to attempt such state preparation is by energy sorting electrons ionized by a pulse sequence that generates altering spin polarization[54,55].



51. Kohashi, T., Konoto, M. & Koike, K. High-resolution spin-polarized scanning electron microscopy (spin SEM). *J. Electron Microsc.* **59**, 43–52 (2009).
52. Kuwahara, M. et al. Development of spin-polarized transmission electron microscope. *J. Phys. Conf. Ser.* **298**, 012016 (2011).
53. Kohashi, T. Chapter two - spin-polarized scanning electron microscopy. In *Advances in Imaging and Electron Physics* 83–125 (Elsevier, 2015).
54. Barth, I. & Smirnova, O. Spin-polarized electrons produced by strong-field ionization. *Phys. Rev. A* **88**, 013401 (2013).
55. Hartung, A. et al. Electron spin polarization in strong-field ionization of xenon atoms. *Nat. Photonics* **10**, 526–528 (2016).







$$|\Psi_0\rangle = \int_\Omega \mathrm{d}\boldsymbol{k}_1 \mathrm{d}\boldsymbol{k}_2 \alpha^{(1)}_{s_1}(\boldsymbol{k}_1)\alpha^{(2)}_{s_2}(\boldsymbol{k}_2) c^\dagger_{s_1}(\boldsymbol{k}_1) c^\dagger_{s_2}(\boldsymbol{k}_2)|\emptyset\rangle$$

$$\mathcal{H} = \mathcal{H}_\mathrm{e} + \mathcal{H}_\phi + \mathcal{H}_{\mathrm{e}-\phi}$$

$$\mathcal{H}_\mathrm{e} = \sum_{\boldsymbol{k},\boldsymbol{s}} \epsilon_{\boldsymbol{k}} c^\dagger_{\boldsymbol{k},s} c_{\boldsymbol{k},s}$$

$$\mathcal{H}_{\mathrm{e}-\phi} = \frac{e\lambda_C}{2\pi} \sum_{\mathbf{k},\mathbf{q},s} c^\dagger_{\mathbf{k}+\mathbf{q},s} c_{\mathbf{k},s} \mathbf{k} \cdot \mathbf{A}(\mathbf{q})$$

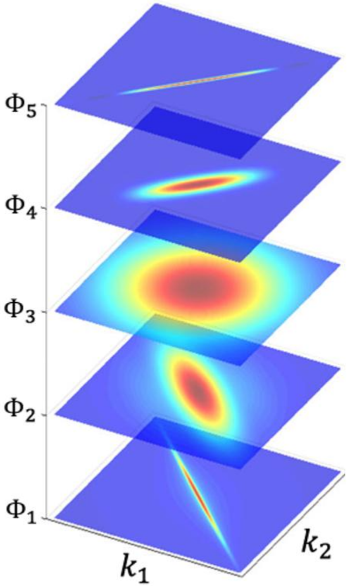
$$\left|\Psi^{(2)}\right\rangle_\lambda = \int_\Omega d\boldsymbol{k}_1 d\boldsymbol{k}_2 \Phi^\lambda_{s_1 s_2}(\boldsymbol{k}_1, \boldsymbol{k}_2) c^\dagger_{s_1}(\boldsymbol{k}_1) c^\dagger_{s_2}(\boldsymbol{k}_2)|\emptyset\rangle,$$

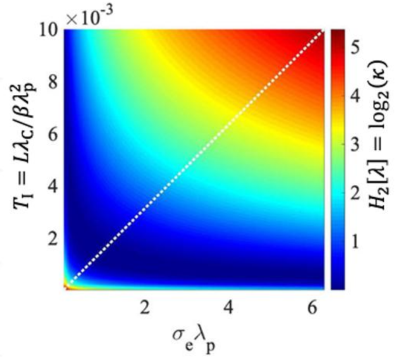
$$\Phi^\lambda_{s_1 s_2}(k_1, k_2) = \sum_n \sqrt{p_n}\psi_n(k_1)\phi_n(k_2),$$

TEORÍA

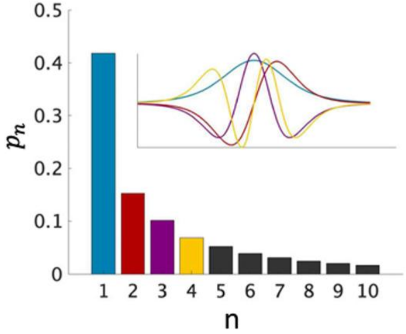
$$\boxed{\Phi^{\lambda}_{s_1 s_2}(k_1,k_2)=\sum_n \sqrt{p_n}\,\psi_n(k_1)\phi_n(k_2),}$$

$$\boxed{H_2[\lambda]=-\log\left(\sum\nolimits_n \mathrm{p}_n^2\right)}$$





$$\boxed{\kappa \equiv 2^{H_2[\lambda]}}$$

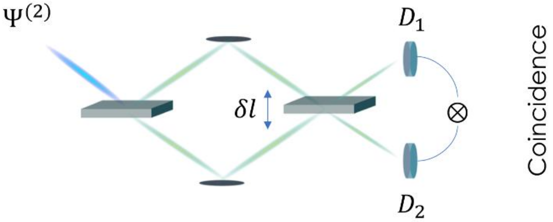


$$T_\mathrm{I} = L\lambda_\mathrm{C}/\beta\lambda_\mathrm{p}^2$$

$$\sigma_\mathrm{e} = \frac{2\pi}{\lambda_\mathrm{p}}$$

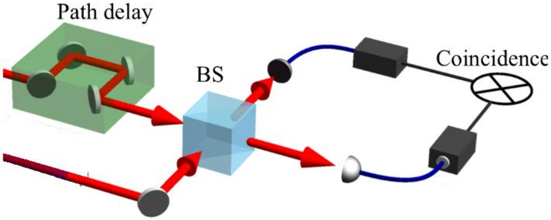
RESULTADOS: ENTRELAZAMIENTO

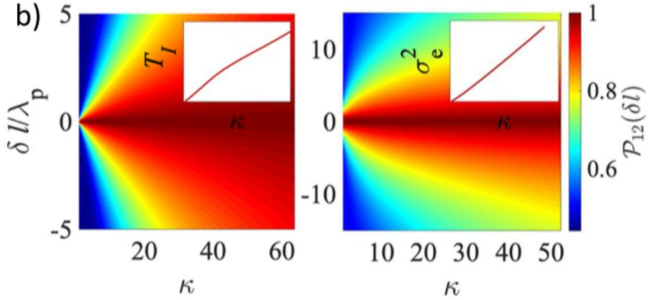
RESULTADOS: COINCIDENCE PROBABILITY

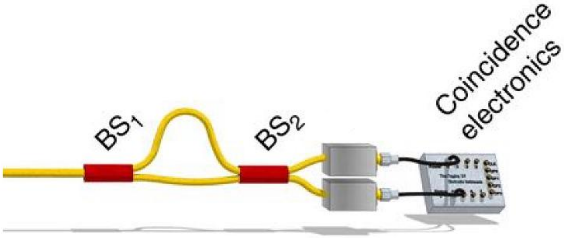


$$\boxed{\mathcal{P}_{12}(\delta l) = \frac{1}{2} + \frac{1}{2}\sum_{nm}\sqrt{p_n p_m}\,|\mathcal{I}_{nm}(\delta l)|^2,}$$

$$\boxed{\mathcal{I}_{nm}(\delta l) = \int \mathrm{d}k\; \phi_n^*(k)\phi_m(k)\mathrm{e}^{-\frac{i}{\hbar}E_k\delta l/\mathbf{v}}}$$







RESULTADOS: COINCIDENCE PROBABILITY

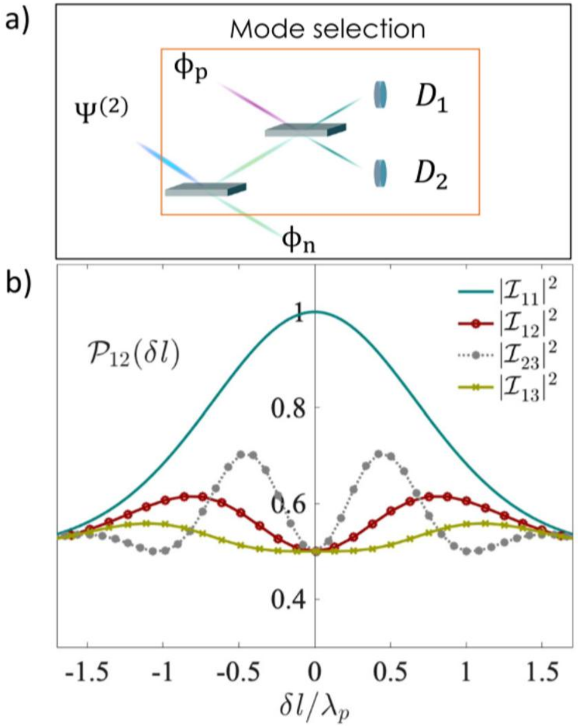
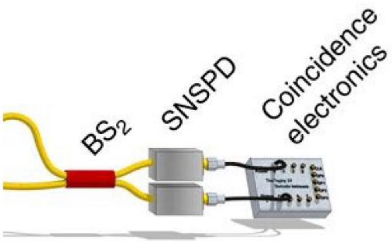
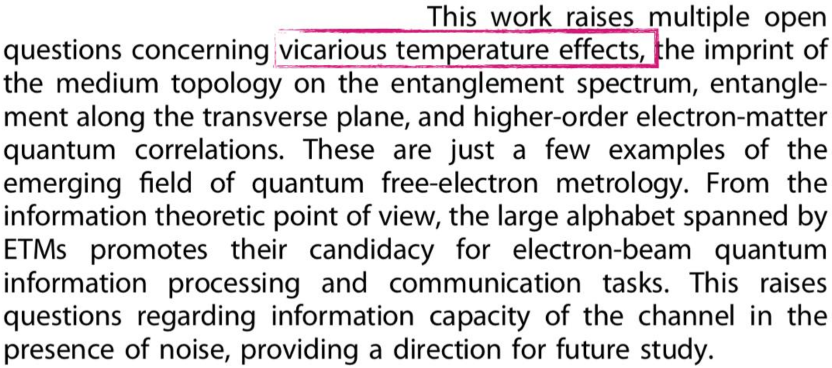


Fig. 4 ETM discrimination. **a** An incoming electron pair prepared in a superposition of ETMs is separated by a first BS, then combined with a (shaped) probe mode ϕ_p and finally measured in coincidence. **b** Coincidence outcomes of the probe with three possible incoming modes $n, p \in \{1, 2, 3\}$, as a function of path difference δl. The interference pattern displays increased response for identical probe and incoming ETM.

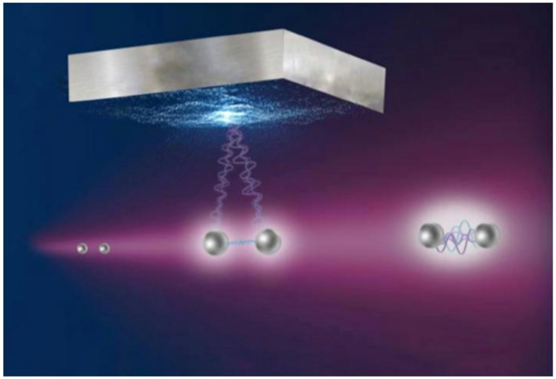


$$\mathcal{P}_{12}\left(\Delta\right) = \frac{1}{2} + \frac{1}{2}\left|\mathcal{I}_{np}\left(\Delta\right)\right|^2 .$$

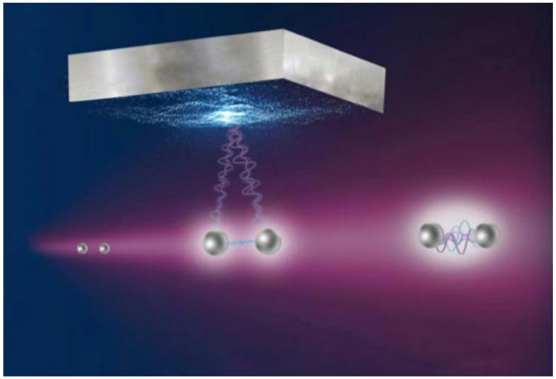
PREGUNTAS ABIERTAS



This work raises multiple open questions concerning vicarious temperature effects, the imprint of the medium topology on the entanglement spectrum, entanglement along the transverse plane, and higher-order electron-matter quantum correlations. These are just a few examples of the emerging field of quantum free-electron metrology. From the information theoretic point of view, the large alphabet spanned by ETMs promotes their candidacy for electron-beam quantum information processing and communication tasks. This raises questions regarding information capacity of the channel in the presence of noise, providing a direction for future study.

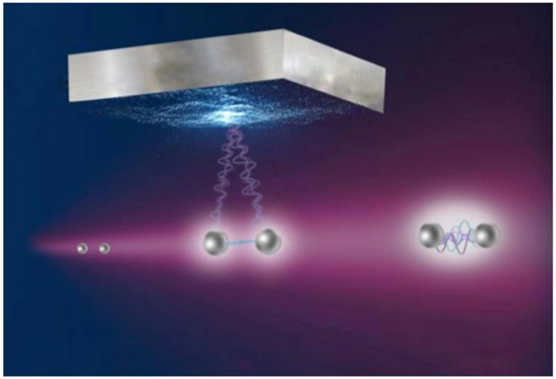


This work raises multiple open questions concerning vicarious temperature effects, the imprint of the medium topology on the entanglement spectrum, entanglement along the transverse plane, and higher-order electron-matter quantum correlations. These are just a few examples of the emerging field of quantum free-electron metrology. From the information theoretic point of view, the large alphabet spanned by ETMs promotes their candidacy for electron-beam quantum information processing and communication tasks. This raises questions regarding information capacity of the channel in the presence of noise, providing a direction for future study.

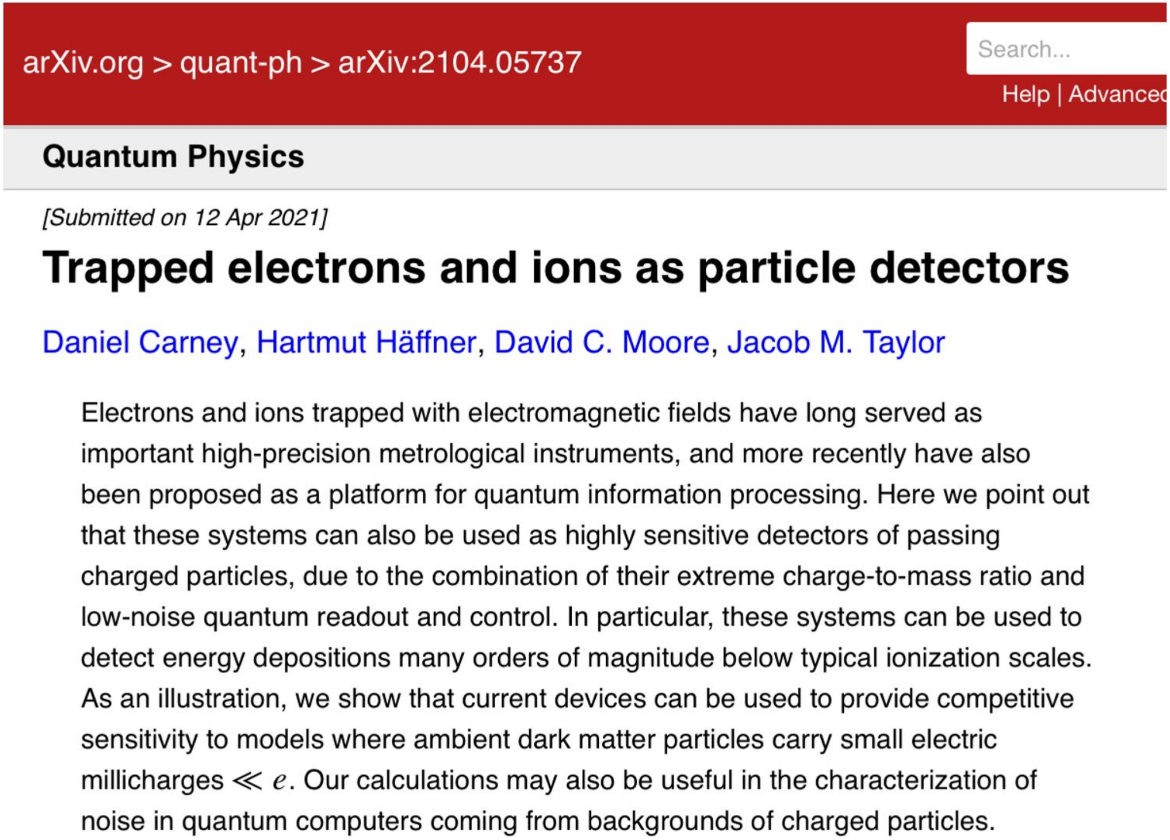


PREGUNTAS ABIERTAS

This work raises multiple open questions concerning vicarious temperature effects, the imprint of the medium topology on the entanglement spectrum, entanglement along the transverse plane, and higher-order electron-matter quantum correlations. These are just a few examples of the emerging field of quantum free-electron metrology. From the information theoretic point of view, the large alphabet spanned by ETMs promotes their candidacy for electron-beam quantum information processing and communication tasks. This raises questions regarding information capacity of the channel in the presence of noise, providing a direction for future study.



PREGUNTAS ABIERTAS



arXiv.org > quant-ph > arXiv:2104.05737

Quantum Physics

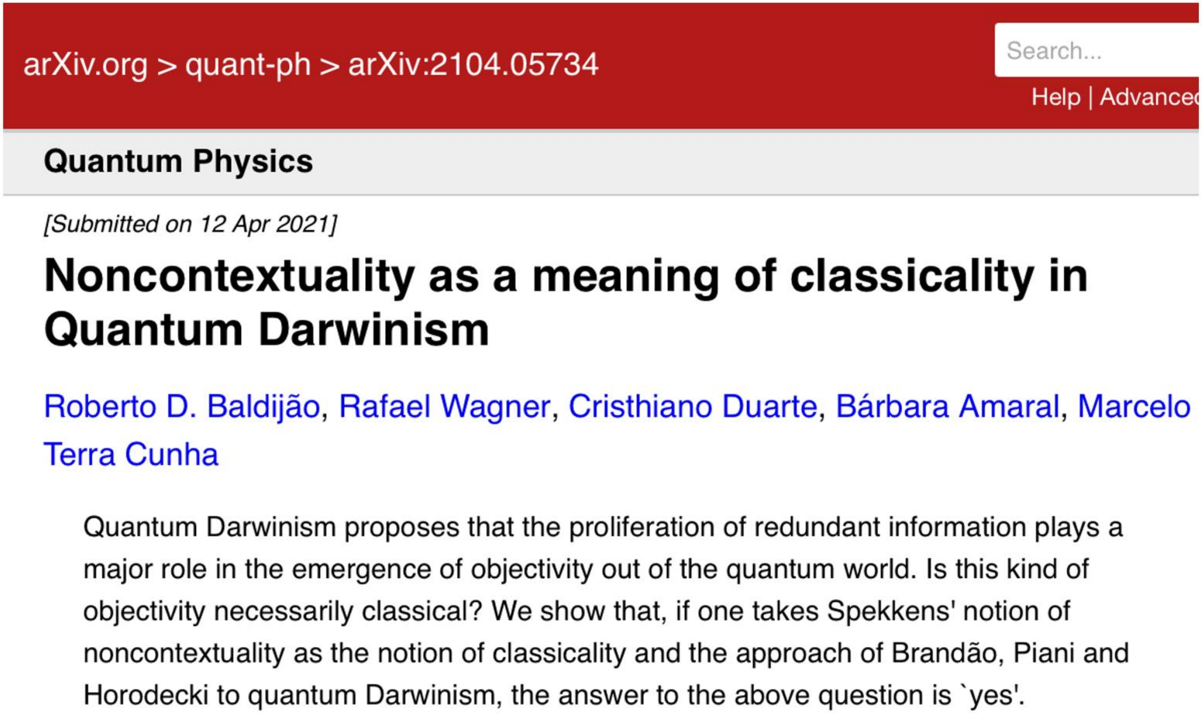
[Submitted on 12 Apr 2021]

Trapped electrons and ions as particle detectors

Daniel Carney, Hartmut Häffner, David C. Moore, Jacob M. Taylor

Electrons and ions trapped with electromagnetic fields have long served as important high-precision metrological instruments, and more recently have also been proposed as a platform for quantum information processing. Here we point out that these systems can also be used as highly sensitive detectors of passing charged particles, due to the combination of their extreme charge-to-mass ratio and low-noise quantum readout and control. In particular, these systems can be used to detect energy depositions many orders of magnitude below typical ionization scales. As an illustration, we show that current devices can be used to provide competitive sensitivity to models where ambient dark matter particles carry small electric millicharges $\ll e$. Our calculations may also be useful in the characterization of noise in quantum computers coming from backgrounds of charged particles.

PREGUNTAS ABIERTAS



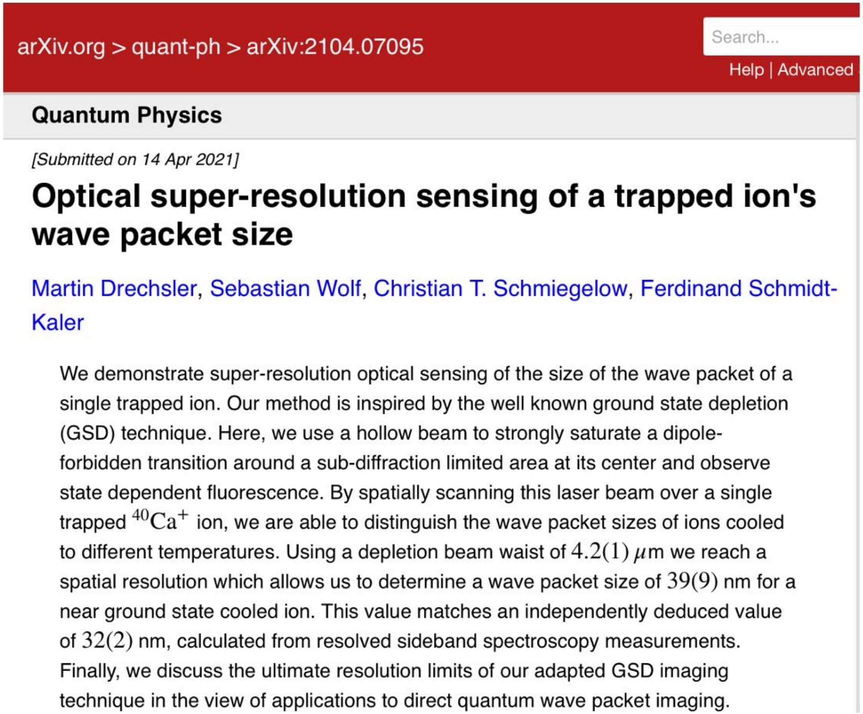
Quantum Physics

[Submitted on 12 Apr 2021]

Noncontextuality as a meaning of classicality in Quantum Darwinism

Roberto D. Baldijão, Rafael Wagner, Cristhiano Duarte, Bárbara Amaral, Marcelo Terra Cunha

Quantum Darwinism proposes that the proliferation of redundant information plays a major role in the emergence of objectivity out of the quantum world. Is this kind of objectivity necessarily classical? We show that, if one takes Spekkens' notion of noncontextuality as the notion of classicality and the approach of Brandão, Piani and Horodecki to quantum Darwinism, the answer to the above question is `yes'.



Quantum Physics

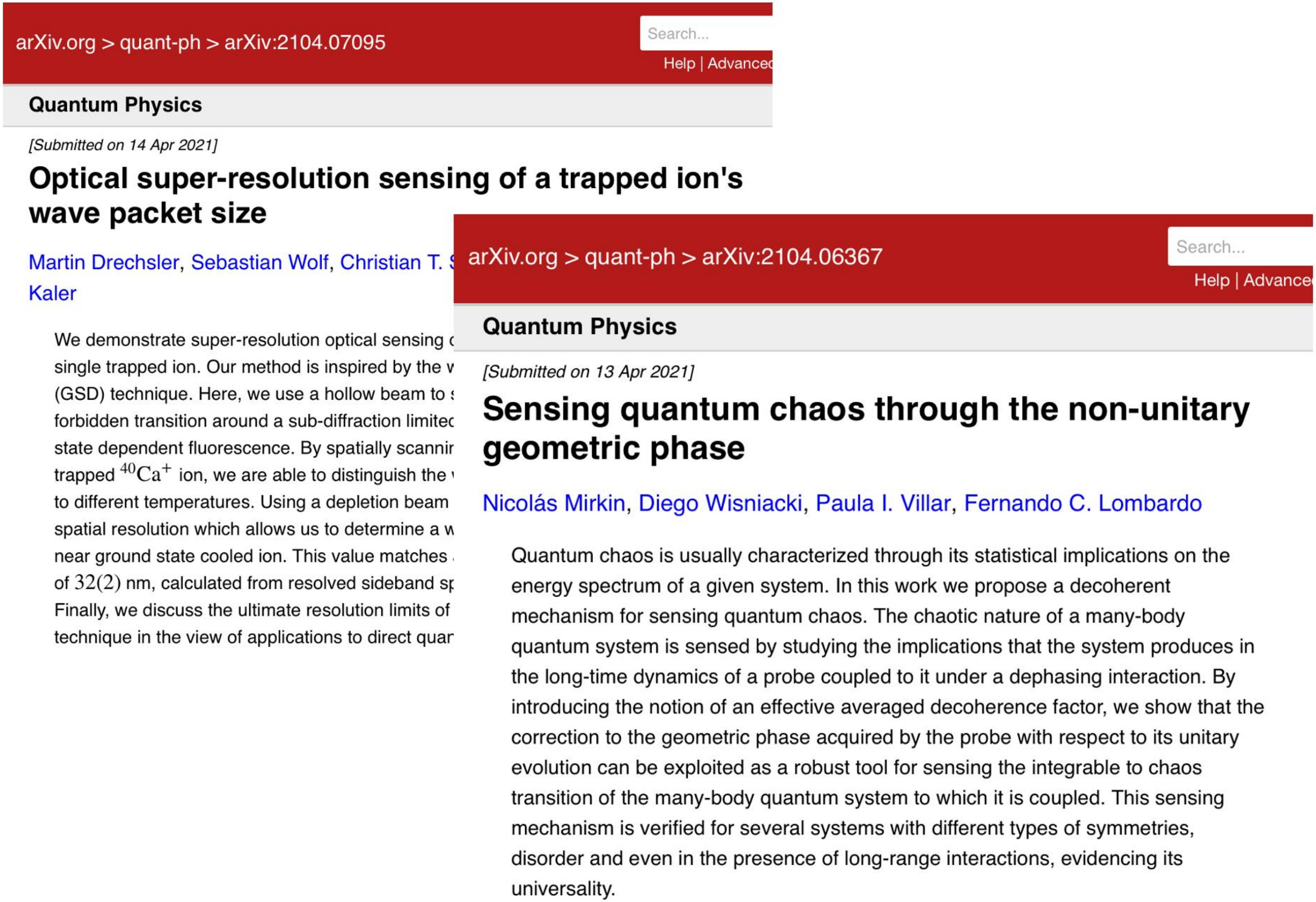
[Submitted on 14 Apr 2021]

Optical super-resolution sensing of a trapped ion's wave packet size

Martin Drechsler, Sebastian Wolf, Christian T. Schmiegelow, Ferdinand Schmidt-Kaler

We demonstrate super-resolution optical sensing of the size of the wave packet of a single trapped ion. Our method is inspired by the well known ground state depletion (GSD) technique. Here, we use a hollow beam to strongly saturate a dipole-forbidden transition around a sub-diffraction limited area at its center and observe state dependent fluorescence. By spatially scanning this laser beam over a single trapped $^{40}\mathrm{Ca}^+$ ion, we are able to distinguish the wave packet sizes of ions cooled to different temperatures. Using a depletion beam waist of $4.2(1)\,\mu$m we reach a spatial resolution which allows us to determine a wave packet size of $39(9)$ nm for a near ground state cooled ion. This value matches an independently deduced value of $32(2)$ nm, calculated from resolved sideband spectroscopy measurements. Finally, we discuss the ultimate resolution limits of our adapted GSD imaging technique in the view of applications to direct quantum wave packet imaging.

PREGUNTAS ABIERTAS



Quantum Physics

[Submitted on 14 Apr 2021]

Optical super-resolution sensing of a trapped ion's wave packet size

Martin Drechsler, Sebastian Wolf, Christian T. S

Kaler

We demonstrate super-resolution optical sensing c
single trapped ion. Our method is inspired by the v
(GSD) technique. Here, we use a hollow beam to s
forbidden transition around a sub-diffraction limitec
state dependent fluorescence. By spatially scannir
trapped $^{40}\mathrm{Ca}^+$ ion, we are able to distinguish the v
to different temperatures. Using a depletion beam
spatial resolution which allows us to determine a w
near ground state cooled ion. This value matches
of $32(2)$ nm, calculated from resolved sideband sp
Finally, we discuss the ultimate resolution limits of
technique in the view of applications to direct quar

Quantum Physics

[Submitted on 13 Apr 2021]

Sensing quantum chaos through the non-unitary geometric phase

Nicolás Mirkin, Diego Wisniacki, Paula I. Villar, Fernando C. Lombardo

Quantum chaos is usually characterized through its statistical implications on the energy spectrum of a given system. In this work we propose a decoherent mechanism for sensing quantum chaos. The chaotic nature of a many-body quantum system is sensed by studying the implications that the system produces in the long-time dynamics of a probe coupled to it under a dephasing interaction. By introducing the notion of an effective averaged decoherence factor, we show that the correction to the geometric phase acquired by the probe with respect to its unitary evolution can be exploited as a robust tool for sensing the integrable to chaos transition of the many-body quantum system to which it is coupled. This sensing mechanism is verified for several systems with different types of symmetries, disorder and even in the presence of long-range interactions, evidencing its universality.

PREGUNTAS ABIERTAS