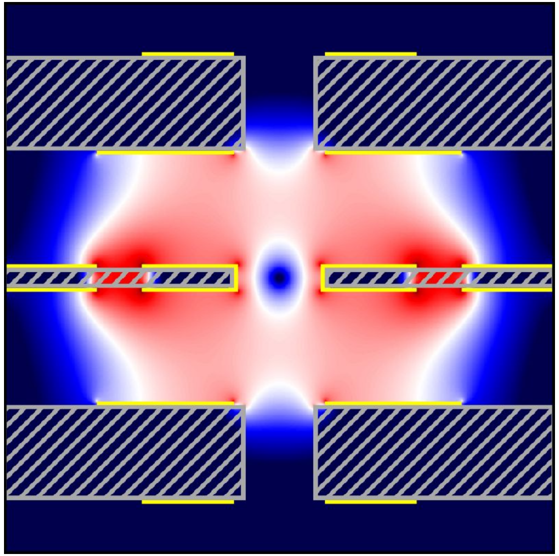
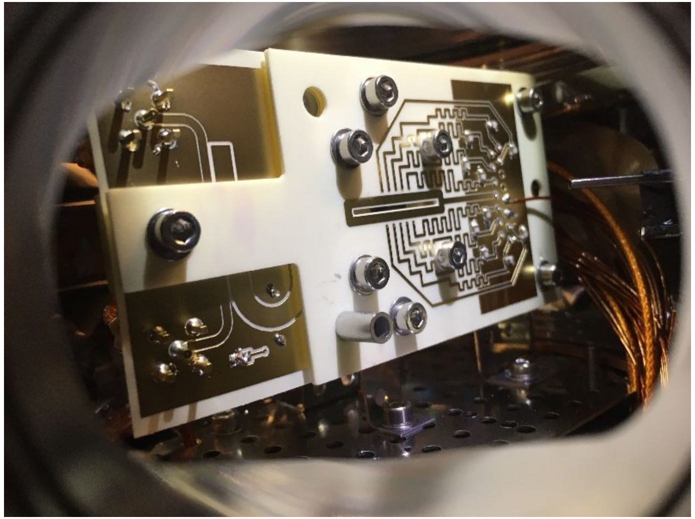
Trapping Electrons in a Room-Temperature Microwave Paul Trap

Clemens Matthiesen, Qian Yu, Jinen Guo, Alberto M. Alonso, and Hartmut Häffner
Phys. Rev. X **11**, 011019 – Published 29 January 2021

Physics See Focus story: New Electron Trap Might Help Quantum Computers https://physics.aps.org/articles/v14/16





Confinando partículas cargadas

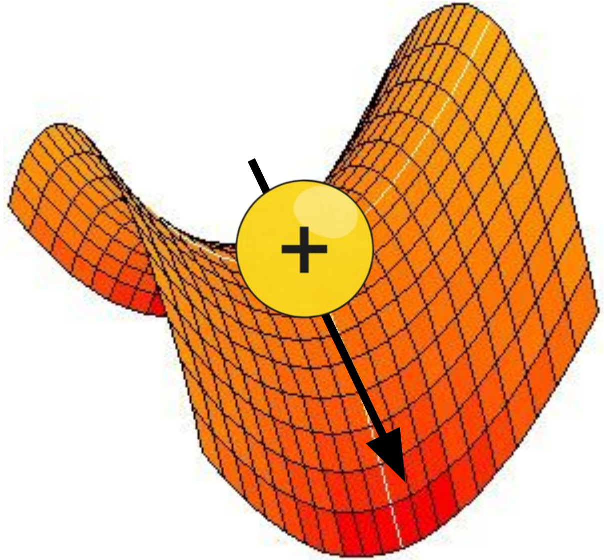
Earnshaw (1842): No es posible confinar **electrostáticamente** una partícula cargada

$$\Phi = \frac{\Phi_0}{2r_0^2}(\alpha x^2 + \beta y^2 + \gamma z^2)$$

+

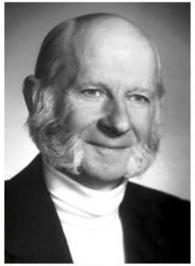
Laplace: $\Delta\Phi = 0$

$$\alpha = \beta = 1, \gamma = -2$$

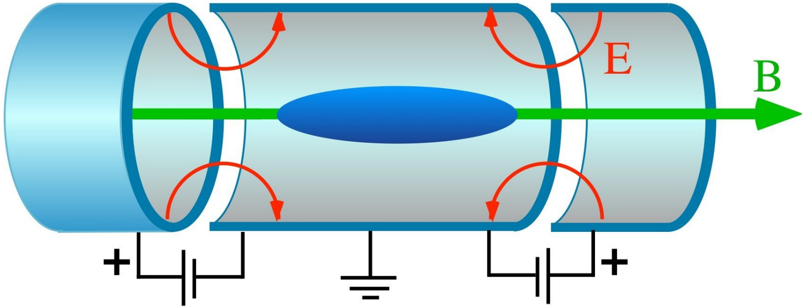


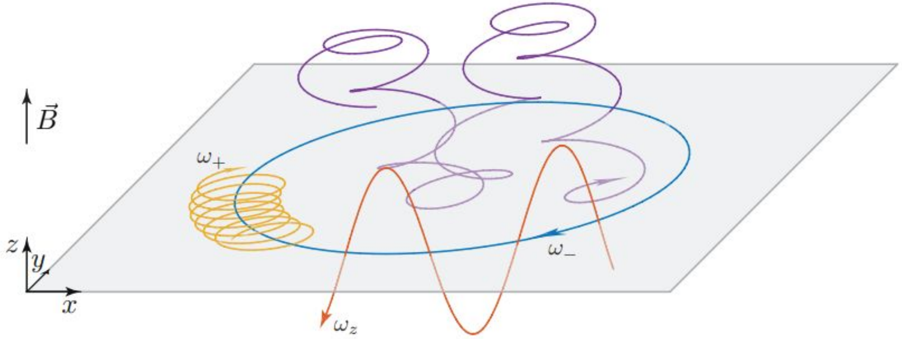
Siempre hay una dirección de confinamiento inestable

Solución 1: Trampas de Penning (1961)



H. Dehmelt





Confinamiento axial (z)
electrostático
+
Confinamiento radial por **B** intenso

Experimentos en trampas de Penning

VOLUME 31 | 19 NOVEMBER 1973 | NUMBER 21

Monoelectron Oscillator

D. Wineland, P. Ekstrom, and H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 13 August 1973)

A single electron has been isolated in a ~6-V-deep Penning trap. Using synchronous detection its forced axial oscillation at 55.7 MHz has been observed continuously. Excitation was either sideband at 54.7 MHz or parametric at 111.4 MHz, the latter making collision-induced 180° phase jumps visible. The monoelectron oscillator is profitably looked upon as a fixed-in-space pseudoatom, free of first- and second-order Doppler shifts.

Atrapado de electrones individuales

VOLUME 47 | 14 DECEMBER 1981 | NUMBER 24

New Comparison of the Positron and Electron *g* Factors

P. B. Schwinberg, R. S. Van Dyck, Jr., and H. G. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 14 September 1981)

A new double Penning trap structure has been built which permits one to trap a positron in a well-compensated experiment trap where measurements have yielded the geonium positron g-factor anomaly, $g(e^+)/2-1 \equiv a(e^+) = (1\,159\,652\,222 \pm 50) \times 10^{-12}$. The uncertainty is based on the resonance linewidths and an estimate of the remaining systematic error associated with extrapolating to zero spin-flip power. By comparison to the electron-spin anomaly, a positron/electron g-factor ratio of $1 + (22 \pm 64) \times 10^{-12}$ is obtained.

PACS numbers: 06.20.Jr, 07.58.+g, 14.60.Cd

Medición de g-factor en positrones y electrones

Experimentos en trampas de Penning: iones

Measurements of the g_J factors of the $6s\,^2S_{1/2}$ and $6p\,^2P_{1/2}$ states in $^{198}Hg^+$

Wayne M. Itano, J. C. Bergquist, and D. J. Wineland

Journal of the Optical Society of America B Vol. 2, Issue 9, pp. 1392-1394 (1985) • https://doi.org/10.1364/JOSAB.2.001392

Journal of Physics B: Atomic, Molecular and Optical Physics

Laser-cooled ion plasmas in Penning traps[1]

J J Bollinger[1,4], J M Kriesel[1,5], T B Mitchell[2], L B King[1,6], M J Jensen[1], W M Itano[1] and D H E Dubin[3]

Published 23 January 2003 • Journal of Physics B: Atomic, Molecular and Optical Physics, Volume 36, Number 3

Citation J J Bollinger *et al* 2003 *J. Phys. B: At. Mol. Opt. Phys.* **36** 499

Experimentos en trampas de Penning: antimateria

ALPHA

A Magnetic Trap for Antihydrogen Confinement

Refereed Publication

The goal of the ALPHA collaboration at CERN is to test CPT conservation by comparing the 1S–2S transitions of hydrogen and antihydrogen. To reach the ultimate accuracy of 1 part in 1018 , the (anti)atoms must be trapped. Using current technology, only magnetic minimum traps can confine (anti)hydrogen. In this paper, the design of the ALPHA antihydrogen trap and the results of measurements on a prototype system will be presented. The trap depth of the final system will be 1.16 T, corresponding to a temperature of 0.78 K for ground state antihydrogen.

W. Bertsche, A. Boston, P.D. Bowe, C.L. Cesar, S. Chapman, M. Charlton, M. Chartier, A. Deutsch, J. Fajans, M.C. Fujiwara, R. Funakoshi, K.Gomberoff, J.S. Hangst, R.S. Hayano, M. J. Jenkins, L. V. Jørgensen, P. Ko, N. Madsen, P. Nolan, R.D. Page, L.G.C. Posada, A. Povilus, E. Sarid, D. M. Silveira, D.P. van der Werf, Y. Yamazaki, B. Parker, J. Escallier, and A. Ghosh

Letter | Open Access | Published: 04 April 2018

Characterization of the 1S–2S transition in antihydrogen

M. Ahmadi, B. X. R. Alves, [...] J. S. Wurtele

Nature **557**, 71–75(2018) | Cite this article

7150 Accesses | **50** Citations | **437** Altmetric | Metrics

Article | Open Access | Published: 31 March 2021

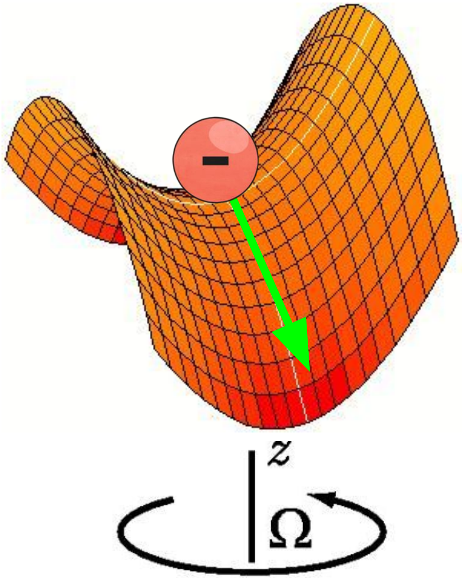
Laser cooling of antihydrogen atoms

C. J. Baker, W. Bertsche, [...] J. S. Wurtele

Nature **592**, 35–42(2021) | Cite this article

23k Accesses | **1** Citations | **639** Altmetric | Metrics

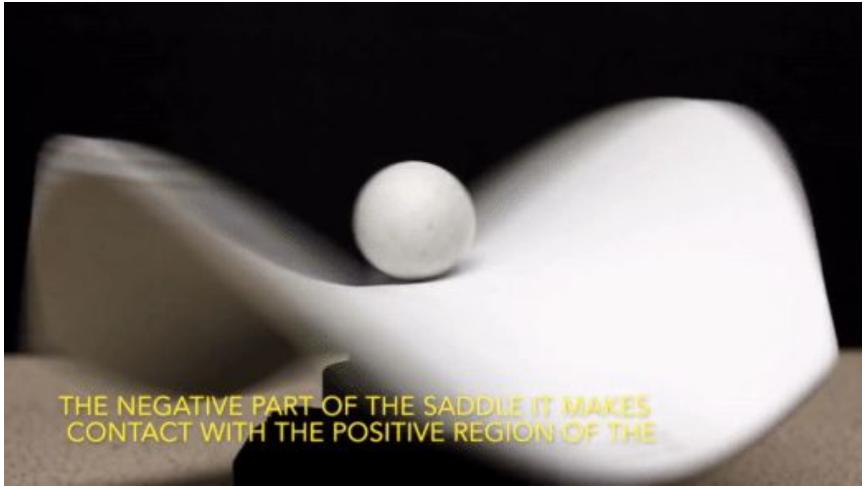
Solución 2: Trampas de Paul



W. Paul

Rotando el potencial a frecuencia Ω se consigue una estabilidad dinámica

$$\varphi(x,y,z,t) = (V_{DC} + V_{AC}\cos\Omega t)\frac{x^2 + y^2 + 2z^2}{2r_0^2}$$



Estabilidad en trampas de Paul

$$a_x = -\frac{a_z}{2} = \frac{8eU_{DC}}{2r_0^2 m\Omega^2}$$

$$q_x = -\frac{q_z}{2} = \frac{4eV_{AC}}{2r_0^2 m\Omega^2}$$

Dependen de:

- Relación **carga/masa**
- Frecuencia de atrapado **Ω**
- Voltaje AC, $\mathbf{V_{AC}}$
- Voltaje DC, $\mathbf{U_{DC}}$
- Parámetro geométrico $\mathbf{r_0}$

Experimentos en trampas de Paul

PHYSICAL REVIEW A VOLUME 22, NUMBER 3 SEPTEMBER 1980

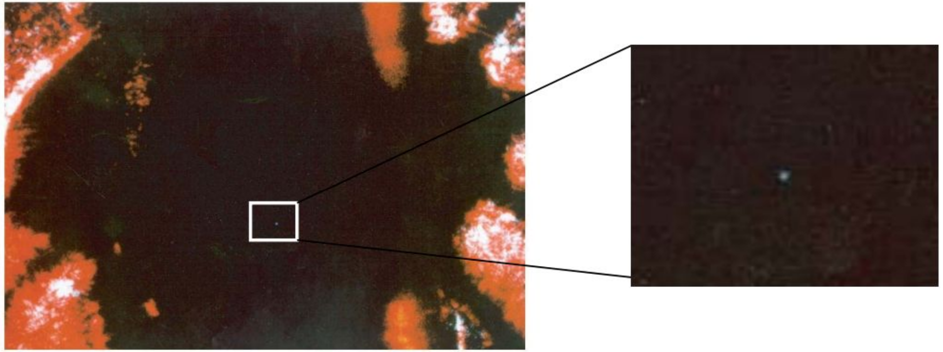
Localized visible Ba^+ mono-ion oscillator

W. Neuhauser, M. Hohenstatt, and P. E. Toschek
Institut für Angewandte Physik I der Universität Heidelberg, D-69 Heidelberg, Federal Republic of Germany

H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195

(Received 11 September 1979)

An individual barium ion, continuously observed by laser fluorescence, has been isolated in a Paul rf quadrupole trap at room temperature. By optical sideband cooling its microscopically measured image has been reduced in thickness to $\sim 2\ \mu m$ in the object plane, the diffraction limit. Estimated ion temperatures reached are $T_i \simeq 10$ to <36 mK. With cooling, the ion could be held indefinitely, without cooling ~ 30 s. In the future the technique seems capable of attaining kinetic temperatures $\sim 10^{-8}$ K, much lower than realized so far by other means, with corresponding far-reaching implications.

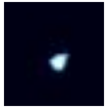


Desafíos para atrapar electrones

$$a_x = -\frac{a_z}{2} = \frac{8eU_{DC}}{2\,r_0^2 m\Omega^2}$$

$$q_x = -\frac{q_z}{2} = \frac{4eV_{AC}}{2\,r_0^2 m\Omega^2}$$

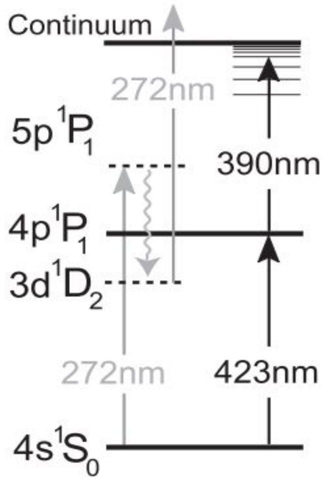
- Frecuencia de atrapado Ω

Partícula	e/m (C/kg)	Frecuencia de atrapado
Ion de calcio 	2.2×10^{6}	10 MHz
Electrón	**1.6×10^{11}**	**1.6 GHz**

Desafíos para atrapar electrones

- No hay mecanismo eficiente para enfriar los electrones: Inyectarlos con baja energía a la trampa ionizando átomos de calcio

Ionización por campos eléctricos de la trampa



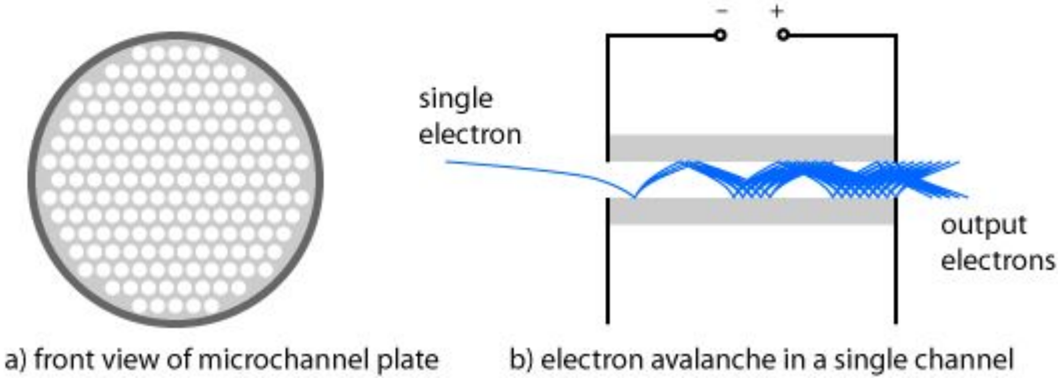
40Ca

Estado de Rydberg, n≅30

S Gulde et al, “Simple and efficient photo-ionization loading of ions for precision ion-trapping experiments”, *Appl. Phys. B* 73, 861-863 (2001)

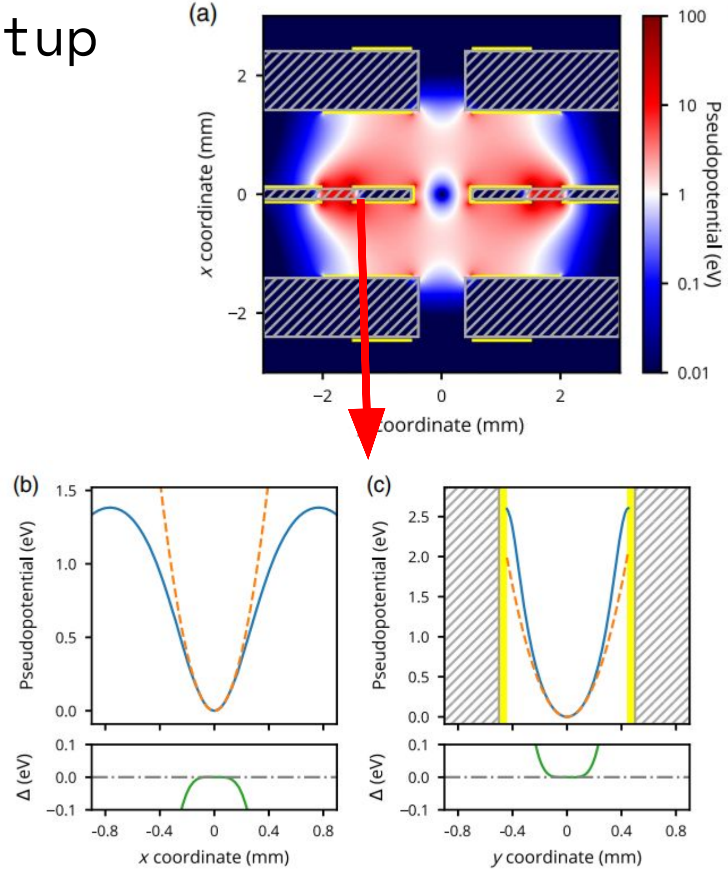
Desafíos para atrapar electrones

- Encontrar un mecanismo de detección (no fluorescencia)

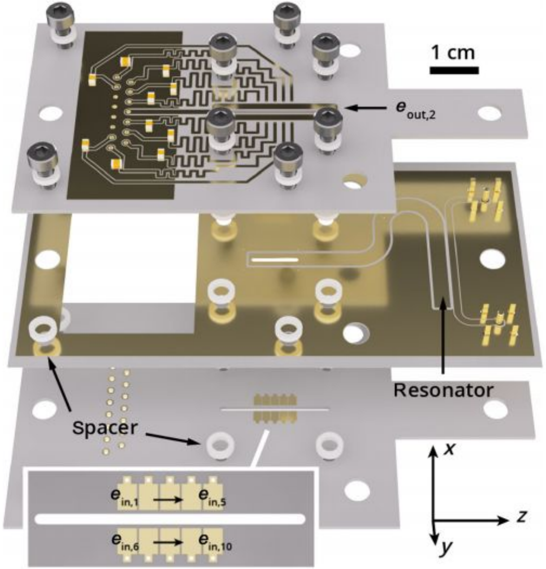


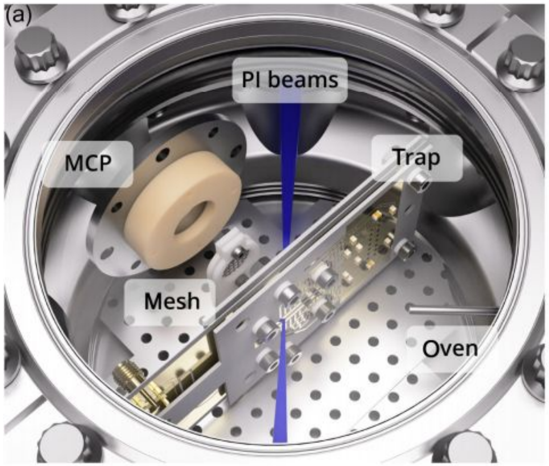
Se aceleran los electrones con voltajes de extracción a un MCP (microchannel plate)

Setup

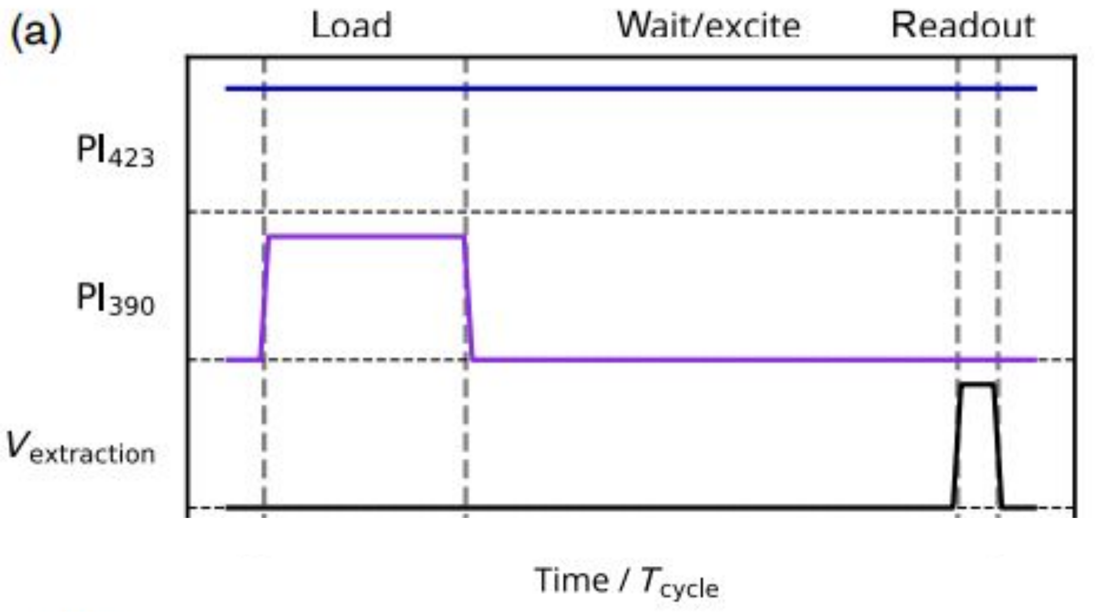


Región armónica: 400 um

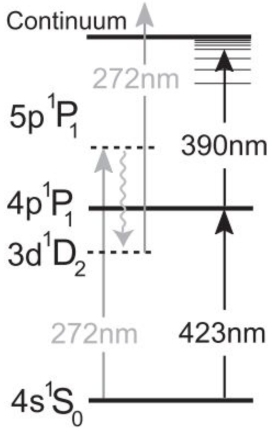




Carga y detección

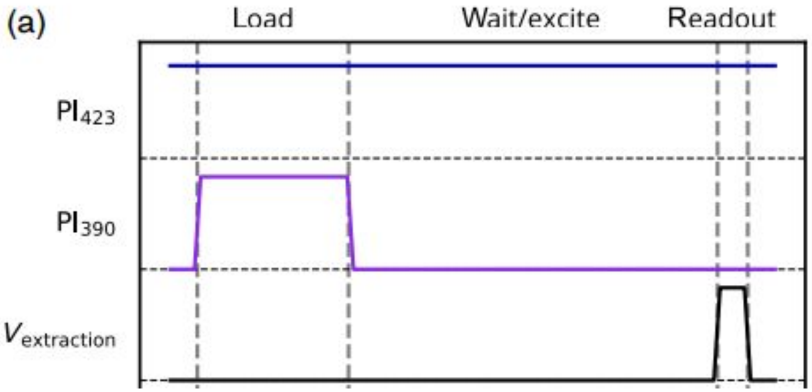


Expulsión del e- hacia el detector

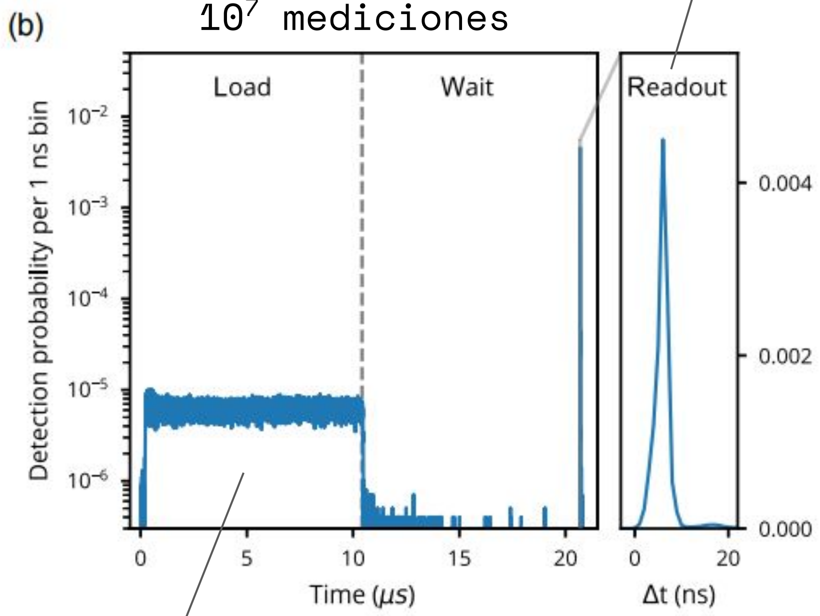


Carga y detección

Hay e- atrapados!

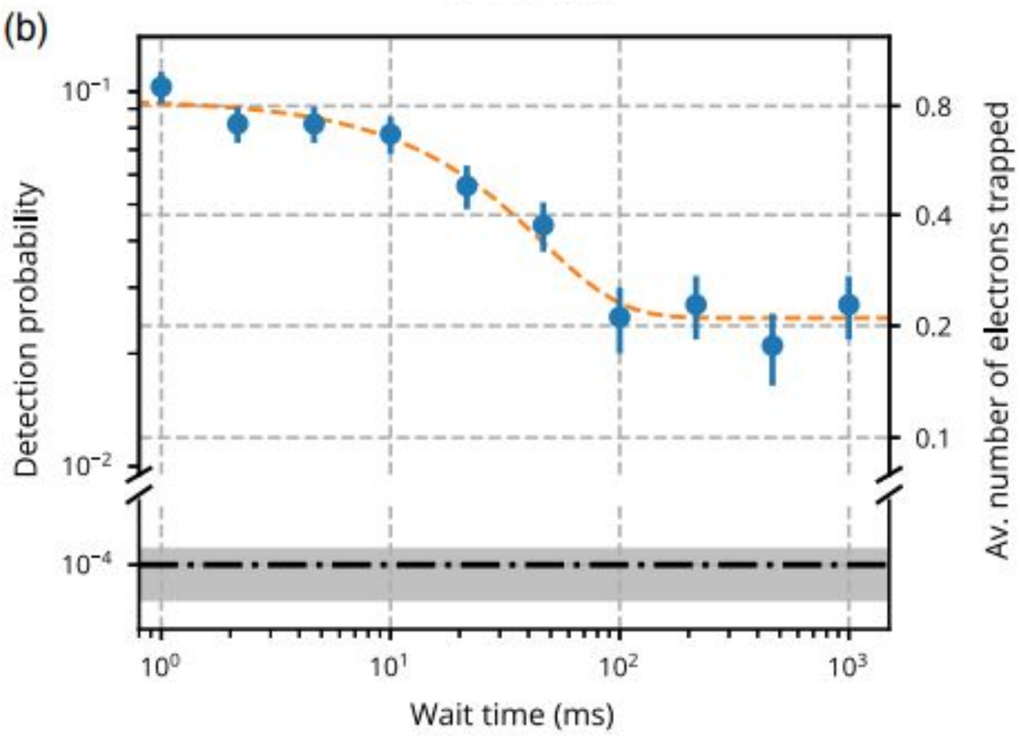


10^7 mediciones



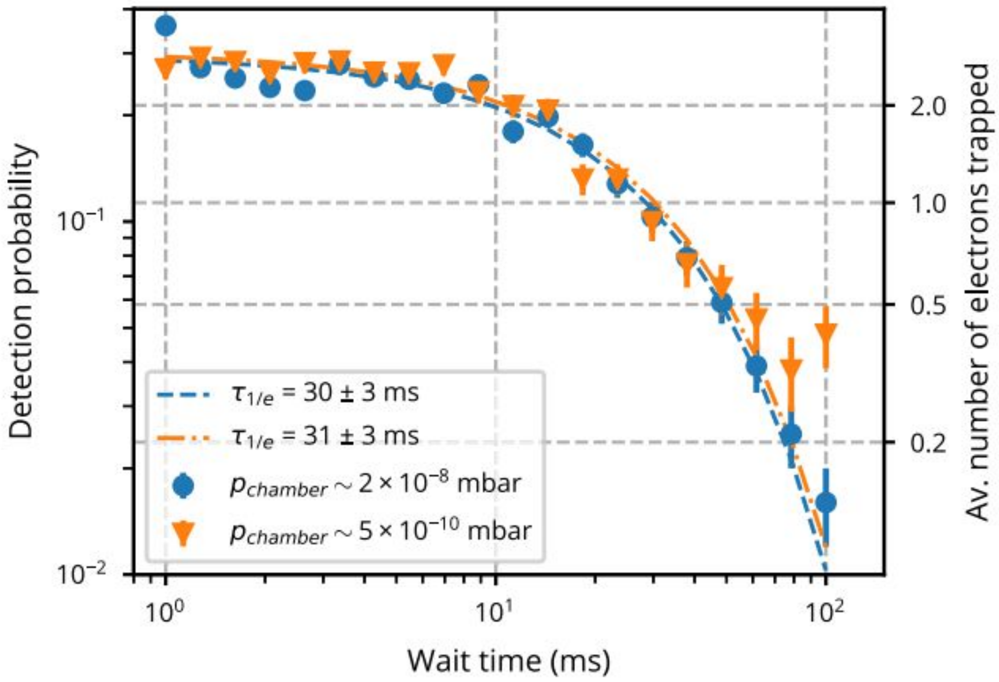
Background de e- no atrapados

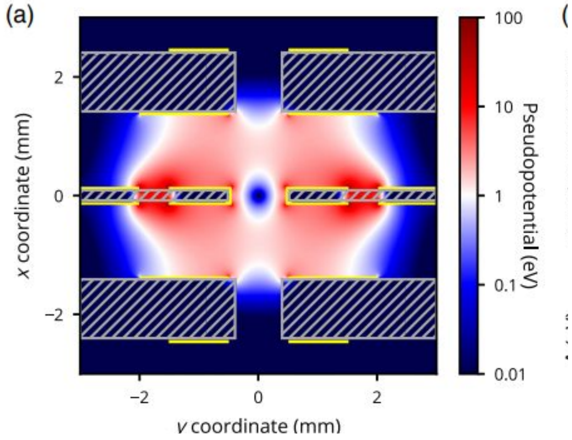
Caracterización del atrapado



El 20% sobrevive atrapado más de 1 segundo

Mecanismos de pérdidas de e-





Principales pérdidas:
atrapado anharmónico

3 **breves** conclusiones

- Primer experimento de atrapado de e- en trampas de Paul, i.e., sin **B** intensos
- Tiempos de vida largos (1 s y más)
- Experimentos a temperatura ambiente

} Candidatos para experimentos de información cuántica

Desafíos posteriores

New Journal of Physics
The open access journal for physics

Quantum information processing with trapped electrons and superconducting electronics

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[2] School of Natural Sciences, University of California Merced, Merced, CA 95343, USA
[3] Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
E-mail: nikos.daniilidis@gmail.com

New Journal of Physics **15** (2013) 073017 (19pp)
Received 17 April 2013
Published 5 July 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/7/073017

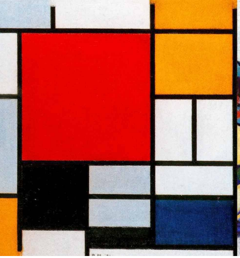
PHYSICAL REVIEW A **95**, 012312 (2017)

Spin readout of trapped electron qubits

Pai Peng (彭湃),[1,2] Clemens Matthiesen,[1] and Hartmut Häffner[1,*]
[1] *Department of Physics, University of California, Berkeley, California 94720, USA*
[2] *School of Physics, Peking University, Beijing 100871, People's Republic of China*
(Received 31 October 2016; published 12 January 2017)

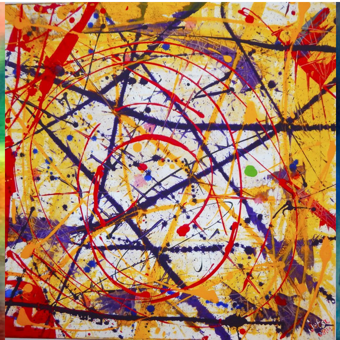
We propose a scheme to read out the spin of a single electron quantum bit in a surface Paul trap using oscillating magnetic-field gradients. The readout sequence is composed of cooling, driving, amplification, and detection of the electron's motion. We study the scheme in the presence of noise and trap anharmonicities at liquid-helium temperatures. An analysis of the four procedures shows short measurement times (25 μs) and high fidelities (99.7%) are achievable with realistic experimental parameters. Our scheme performs the function of fluorescence detection in ion trapping schemes, highlighting the potential to build all-electric quantum computers based on trapped electron-spin qubits.

DOI: 10.1103/PhysRevA.95.012312






Resúmenes de la quincena

Quantum Teleportation between Remote Qubit Memories with Only a Single Photon as a Resource

Stefan Langenfeld,[*] Stephan Welte,[*,†] Lukas Hartung, Severin Daiss, Philip Thomas, Olivier Morin, Emanuele Distante, and Gerhard Rempe
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

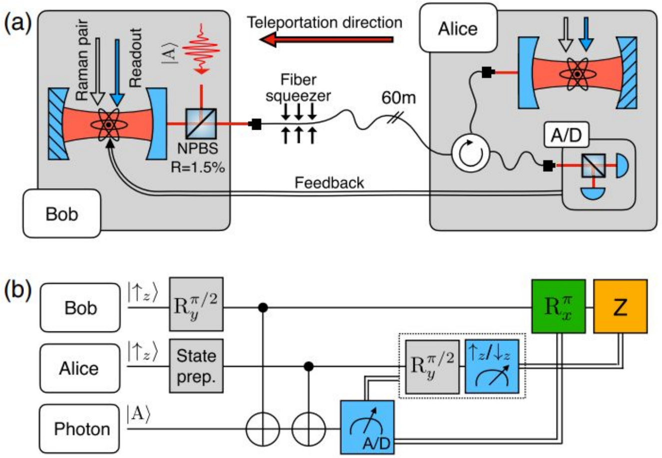
(Received 22 December 2020; accepted 4 March 2021; published 30 March 2021)

Quantum teleportation enables the deterministic exchange of qubits via lossy channels. While it is commonly believed that unconditional teleportation requires a preshared entangled qubit pair, here we demonstrate a protocol that is in principle unconditional and requires only a single photon as an ex-ante prepared resource. The photon successively interacts, first, with the receiver and then with the sender qubit memory. Its detection, followed by classical communication, heralds a successful teleportation. We teleport six mutually unbiased qubit states with average fidelity $\bar{F} = (88.3 \pm 1.3)\%$ at a rate of 6 Hz over 60 m.

DOI: 10.1103/PhysRevLett.126.130502

To conclude, we have devised and implemented a novel and, in principle, unconditional scheme to perform quantum teleportation in a network. An advantage of our

therefore damage it. Lastly, our protocol is platform independent and could be implemented with different carriers of quantum information coupled to resonators such as vacancy centers in diamond [28], rare-earth ions [29], superconducting qubits [30,31], or quantum dots [32–34].



Effect of source statistics on utilizing photon entanglement in quantum key distribution

Radim Hošák,[1,*] Ivo Straka,[1] Ana Predojević,[2] Radim Filip,[1] and Miroslav Ježek[1]
[1]*Department of Optics, Palacký University, 17. listopadu 12, 77146 Olomouc, Czech Republic*
[2]*Department of Physics, Stockholm University, 10691 Stockholm, Sweden*

(Received 17 December 2020; accepted 23 March 2021; published 13 April 2021)

A workflow for evaluation of entanglement source quality is proposed. Based on quantum state density matrices obtained from theoretical models and experimental data, we make an estimate of a potential performance of a quantum entanglement source in quantum key distribution protocols. This workflow is showcased for continuously pumped spontaneous parametric down-conversion (SPDC) source, where it highlights the trade-off between entangled pair generation rate and entanglement quality caused by multiphoton nature of the generated quantum states. We employ this characterization technique to show that secure key rate of down-converted photon pairs is limited to 0.029 bits per detection window due to intrinsic multiphoton contributions. We also report that there exists one optimum gain for continuous-wave down-conversion sources. We find a bound for secure key rate extracted from SPDC sources and make a comparison with perfectly single-pair quantum states, such as those produced by quantum dots.

DOI: 10.1103/PhysRevA.103.042411

VI. CONCLUSION

We predicted the dependence of key rate in entanglement-based QKD on the generation rate of photon-pair sources based on continuous-wave SPDC and enabled their comparison with quantum dot sources of entanglement. The SPDC

PHYSICAL REVIEW E **103**, 042209 (2021)

Quantum chaos and physical distance between quantum states

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[1]*International Center for Quantum Materials, School of Physics, Peking University, 100871 Beijing, China*
[2]*Wilczek Quantum Center, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[3]*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*

(Received 20 July 2020; accepted 15 March 2021; published 13 April 2021)

We show that there is genuine chaos in quantum dynamics by introducing a physical distance between two quantum states. Qualitatively different from existing distances for quantum states, for example, the Fubini-Study distance, the physical distance between two mutually orthogonal quantum states, can be very small. As a result, two quantum states, which are initially very close by physical distance, can diverge from each other during the ensuing quantum dynamical evolution. We are able to use physical distance to define the quantum Lyapunov exponent and the quantum chaos measure. The latter leads to a quantum analog of the classical Poincaré section, which maps out the regions where quantum dynamics is regular and the regions where it is chaotic. Three different systems—a kicked rotor, the three-site Bose-Hubbard model, and the spin-1/2 XXZ model—are used to illustrate our results.

DOI: 10.1103/PhysRevE.103.042209

VI. DISCUSSION AND CONCLUSION

In conclusion, we have shown that there is genuine quantum chaos with the physical distance proposed for two quantum states. This quantum distance is based on the Wasserstein distance between two probability distributions. We call

Featured in Physics   Editors' Suggestion   Open Access

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

B. Abi *et al.* (Muon $g-2$ Collaboration)

Phys. Rev. Lett. **126**, 141801 – Published 7 April 2021

Physics See Viewpoint: Muon's Escalating Challenge to the Standard Model

Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

We present the first results of the Fermilab National Accelerator Laboratory (FNAL) Muon $g-2$ Experiment for the positive muon magnetic anomaly $a_\mu \equiv (g_\mu - 2)/2$. The anomaly is determined from the precision measurements of two angular frequencies. Intensity variation of high-energy positrons from muon decays directly encodes the difference frequency ω_a between the spin-precession and cyclotron frequencies for polarized muons in a magnetic storage ring. The storage ring magnetic field is measured using nuclear magnetic resonance probes calibrated in terms of the equivalent proton spin precession frequency $\tilde{\omega}'_p$ in a spherical water sample at $34.7\,^\circ\mathrm{C}$. The ratio $\omega_a/\tilde{\omega}'_p$, together with known fundamental constants, determines $a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11}$ (0.46 ppm). The result is 3.3 standard deviations greater than the standard model prediction and is in excellent agreement with the previous Brookhaven National Laboratory (BNL) E821 measurement. After combination with previous measurements of both μ^+ and μ^-, the new experimental average of $a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11}$ (0.35 ppm) increases the tension between experiment and theory to 4.2 standard deviations.

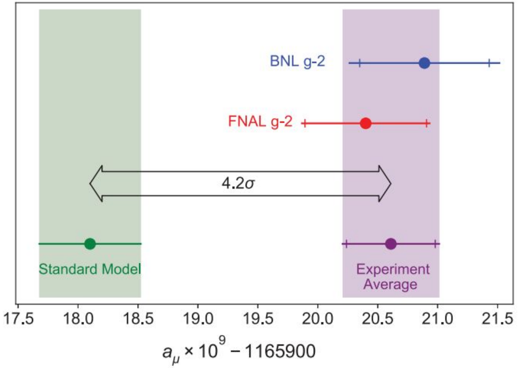

FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

https://physics.aps.org/articles/v14/54