Ministério da Ciência e Tecnologia

CBPF

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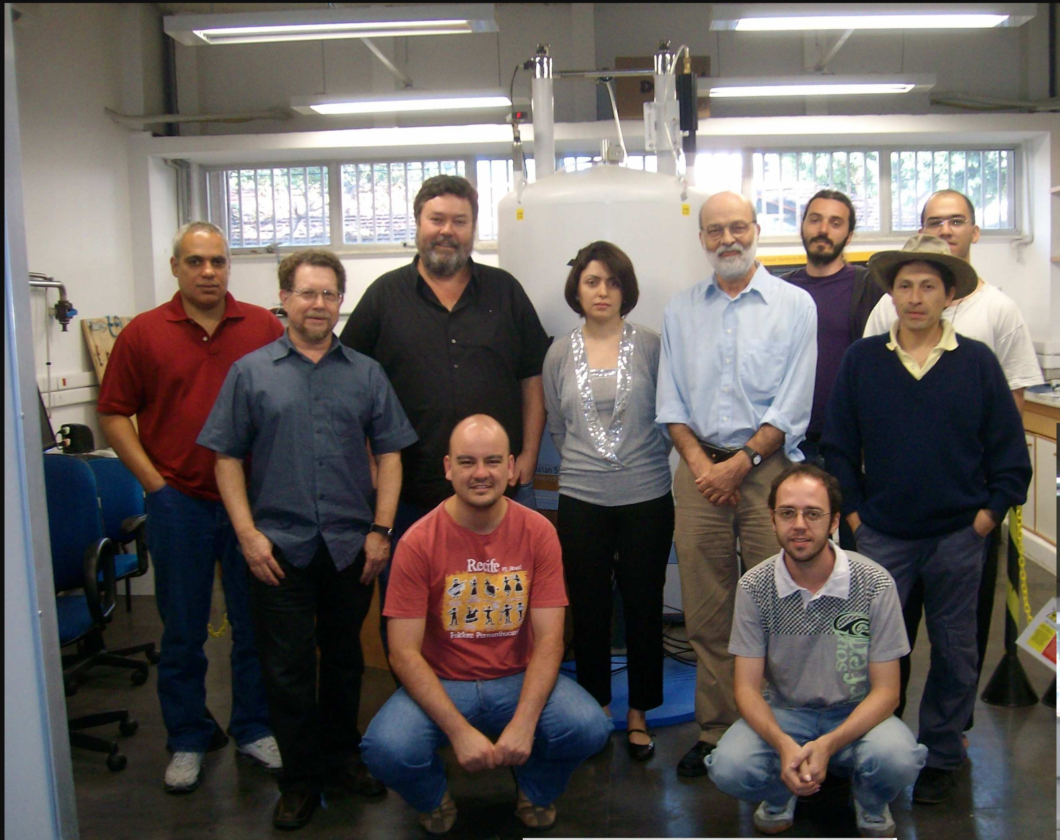
50 anos
PÓS-GRADUAÇÃO CBPF

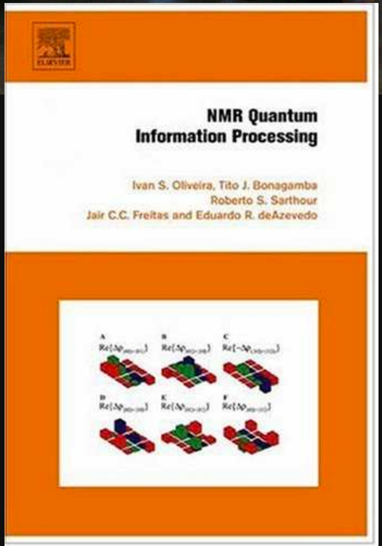
O Fantástico computador quântico de 2 q-bits

Ivan S. Oliveira

Grupo de Processamento da Informação Quântica por RMN



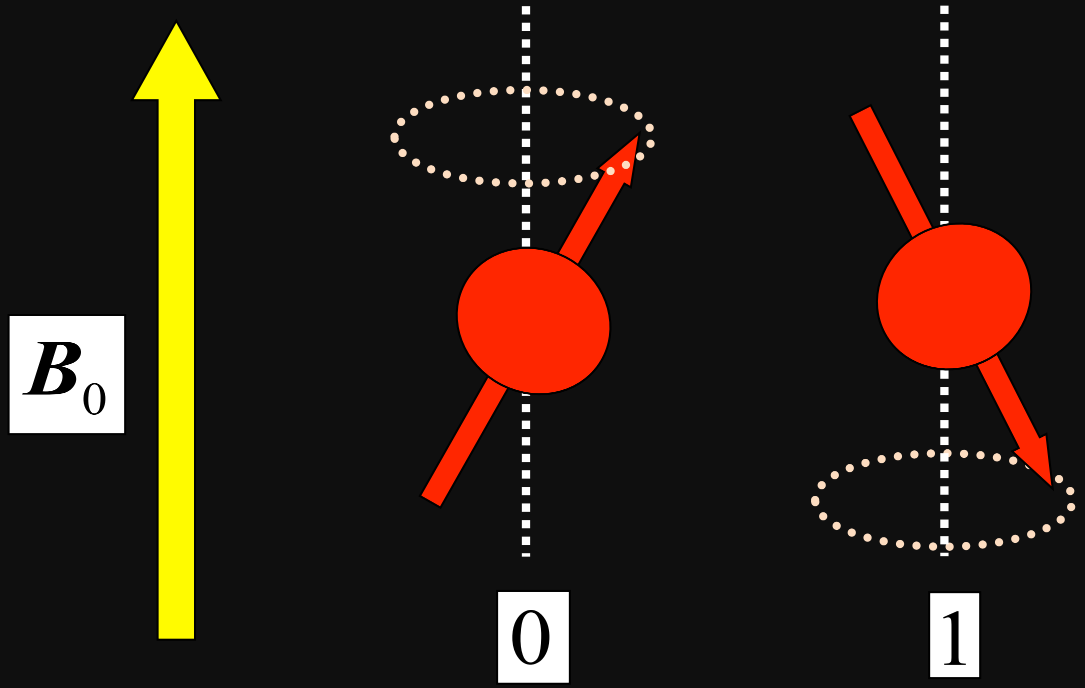
Varian 500 MHz (12 T),
para sólidos e líquidos.
Faperj 2008.

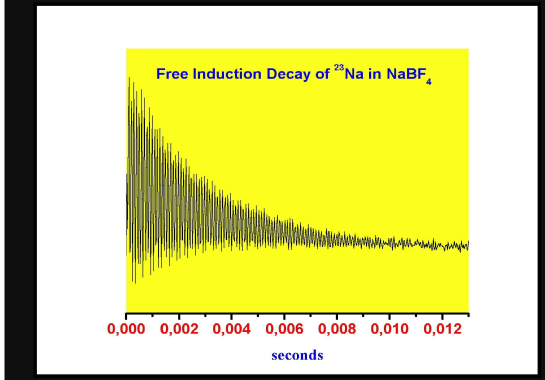


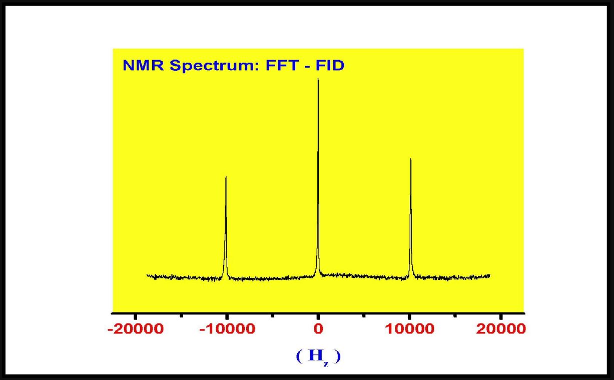
NMR Quantum Information Processing

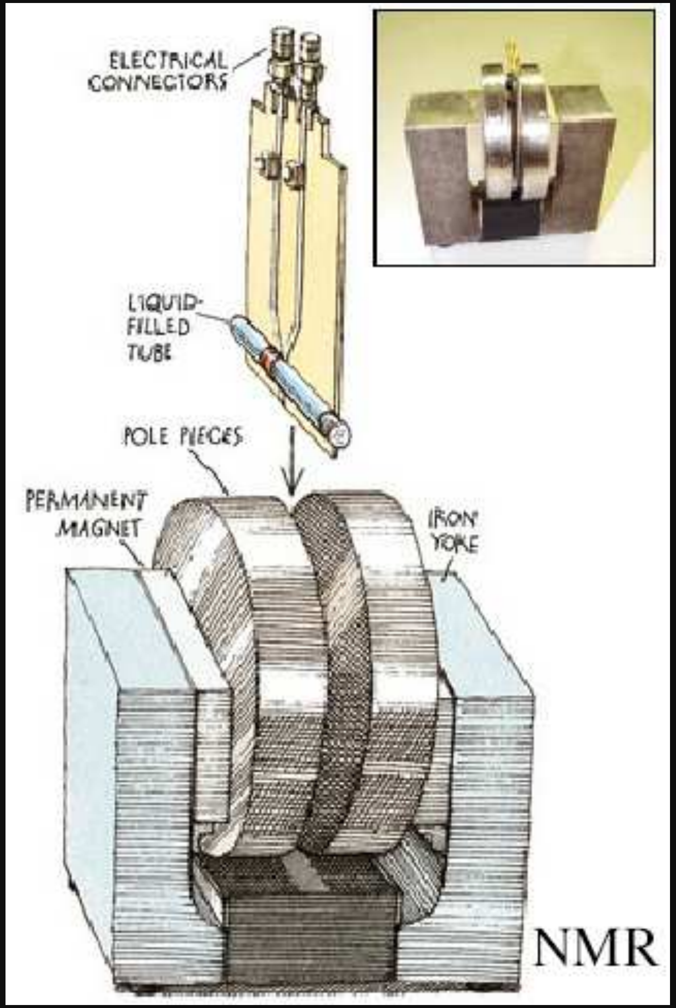
Ivan S. Oliveira, Tito J. Bonagamba
Roberto S. Sarthour
Jair C.C. Freitas and Eduardo R. deAzevedo

RMN


B_0
0
1


Free Induction Decay of ^{23}Na in NaBF$_4$
0,000
0,002
0,004
0,006
0,008
0,010
0,012
seconds

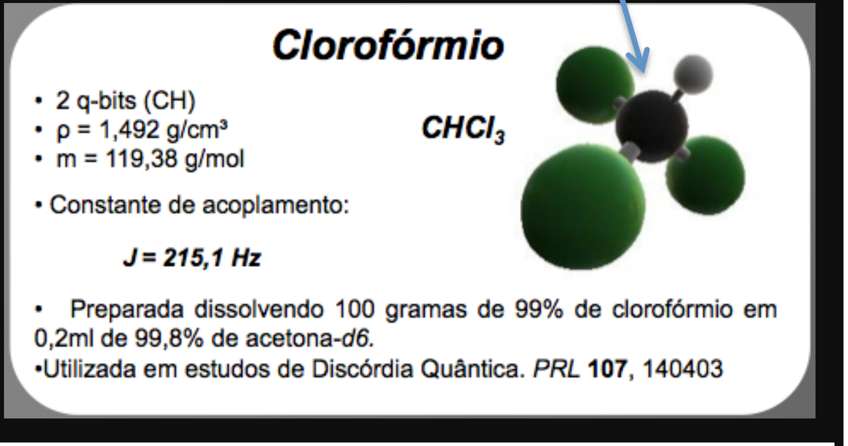

NMR Spectrum: FFT - FID
-20000
-10000
0
10000
20000
(H$_z$)


ELECTRICAL CONNECTORS
LIQUID-FILLED TUBE
POLE PIECES
PERMANENT MAGNET
IRON YOKE
NMR

Protótipo do Computador Quântico

Enriquecer Carbono custa caro!

^{13}C: 99,9%



Cloroformio

- 2 q-bits (CH)
- ρ = 1,492 g/cm³
- m = 119,38 g/mol

CHCl$_3$

- Constante de acoplamento:

J = 215,1 Hz

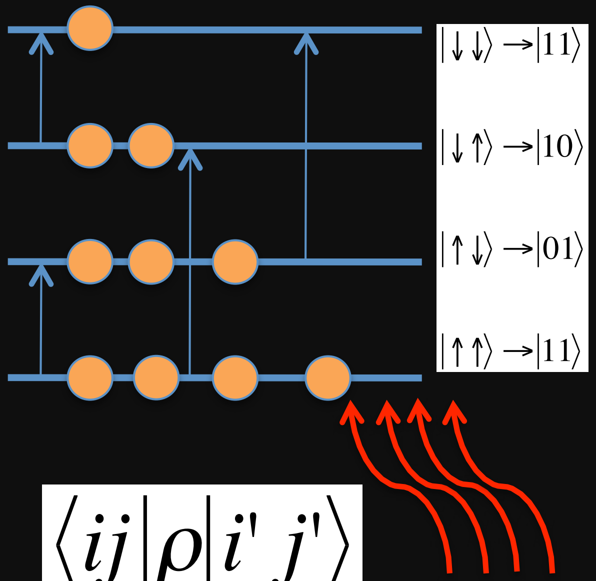
- Preparada dissolvendo 100 gramas de 99% de clorofórmio em 0,2ml de 99,8% de acetona-*d6.*
- Utilizada em estudos de Discórdia Quântica. *PRL* **107**, 140403

Dois spins ½ acoplados

$$\mathcal{H}_{CH} = -\gamma_{nC}\hbar B_0 I_{zC} - \gamma_{nH}\hbar B_0 I_{zH} + 2\pi J I_{zC} I_{zH}$$

Espectro de energias:

$$E_{m,m'} = -\hbar\omega_C m - \hbar\omega_H m' + 2\pi J\, m m'$$

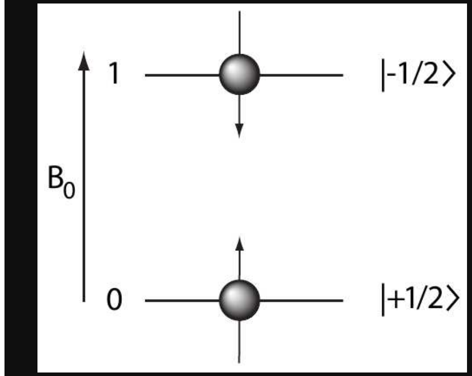


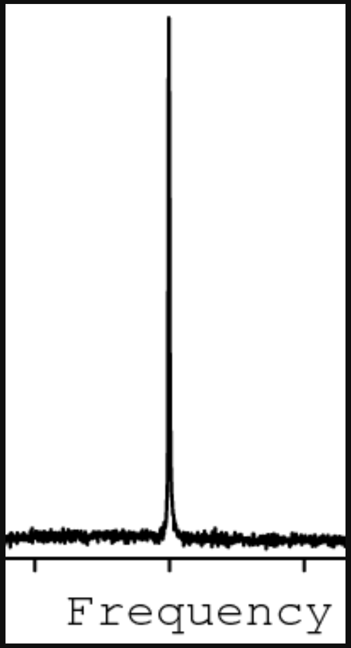
$$\langle ij|\rho|i'\,j'\rangle$$

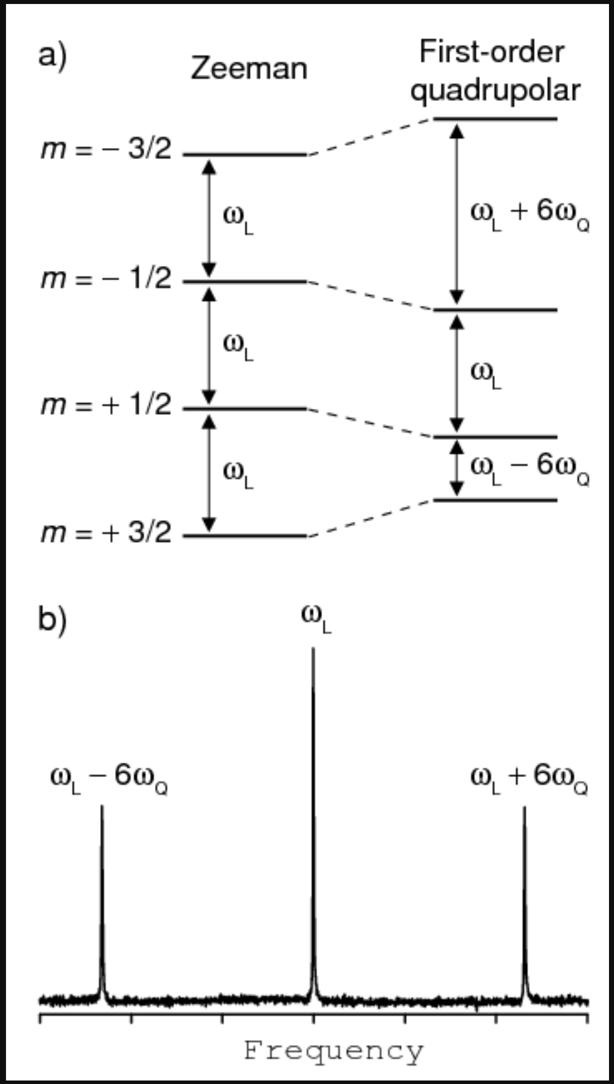
<u>Atenção</u>! Em uma amostra real, não lidamos com 1 molécula, mas com um líquido contendo uma Infinidade de moléculas. Para que o hamiltoniano acima seja válido, é preciso que as moléculas não interajam entre si. Neste caso, o único efeito do número de moléculas é o fato de que os níveis de energia do espectro serem populados estatisticamente. Este problema será visto adiante.

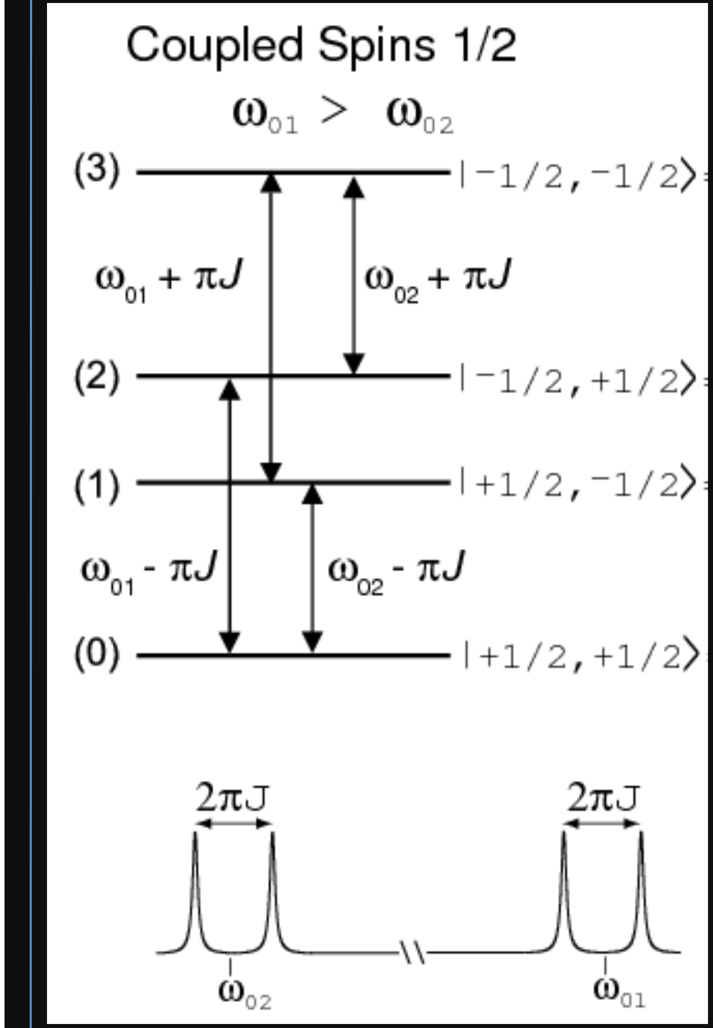
Com radiofrequência é possível manipular todos os elementos de ρ.

Espectro de RMN

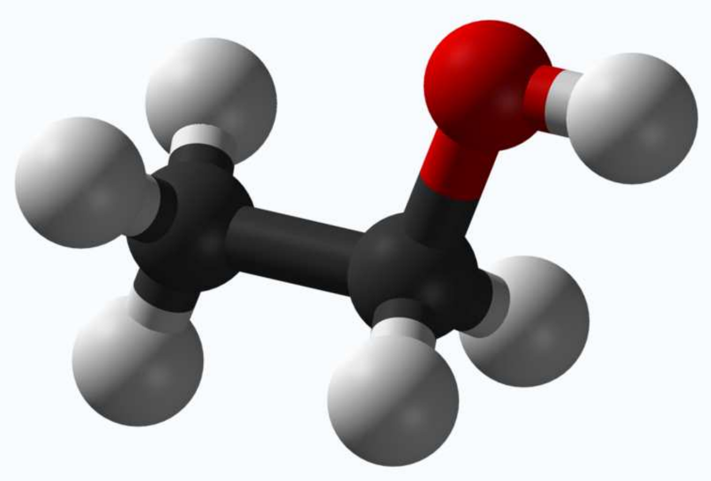


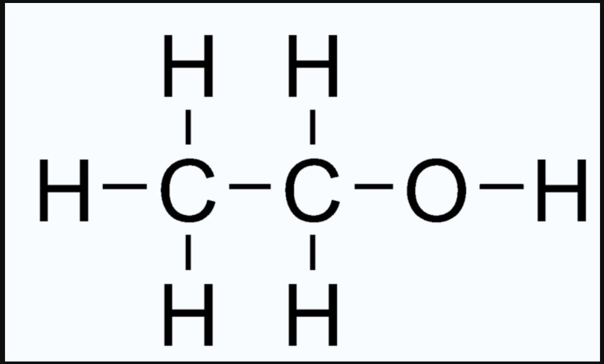




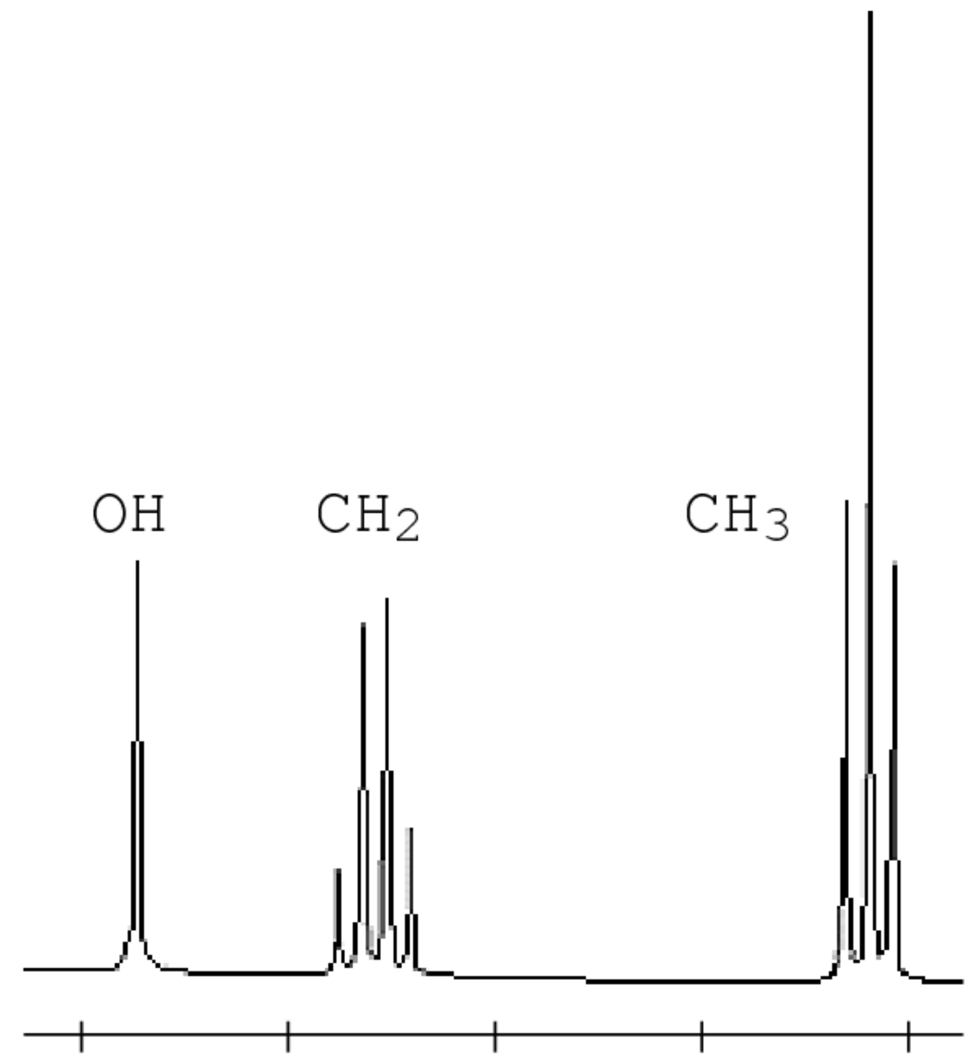


Um exemplo didático: álcool etílico (Cuidado! cachaça é álcool!)





$$\mathrm{H{-}\overset{\displaystyle H}{\underset{\displaystyle H}{C}}{-}\overset{\displaystyle H}{\underset{\displaystyle H}{C}}{-}O{-}H}$$



Formalismo essencial

$$H = -\hbar\omega_{0H} I_{ZH} - \hbar\omega_{0C} I_{ZC} + 2\pi J I_{ZC} I_{ZH}$$

$$\rho_{eq} = \frac{\exp(-H/kT)}{Z} \Rightarrow M_{eq} = n g_n \mu_n Tr\{I^{\pm}\rho_{eq}\}$$

$$U(t) = \exp(-i\omega_1 t I_x)$$

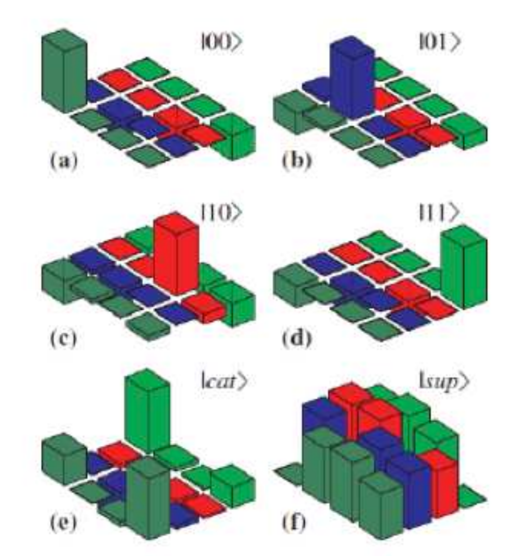
$$\rho(t) = U(t)\rho_{eq}U(t)^{+}$$

$$M^{\pm}(t) = n g_n \mu_n Tr\{I^{\pm}\rho(t)\}$$

Pulsos de RF implementam corretamente transformações unitárias.
Sequências de pulsos, combinadas com médias, permitem:
1. Produção de estados do tipo:

$$\rho_{\varepsilon} = \frac{1-\varepsilon}{4} I + \varepsilon|\psi\rangle\langle\psi| \Rightarrow Tr\{I^{\pm}\rho_{\varepsilon}\} = \varepsilon Tr\{I^{\pm}|\psi\rangle\langle\psi|\}$$

2. A determinação experimental completa
da matriz densidade



O Que se estuda?

- Implementação de protocolos quânticos de computação e comunicação;
- Simulações de sistemas quânticos;
- Descoerência de estados quânticos;
- Desenvolvimento de ferramentas para caracterização do “conteúdo quântico” de estados mistos;
- Técnicas de engenharia de pulsos para estudos em sistemas com muitos q-bits.

Testando a Localidade

New Journal of Physics

The open-access journal for physics

NMR analog of Bell's inequalities violation test

A M Souza[1,3], A Magalhães[2], J Teles[2], E R deAzevedo[2], T J Bonagamba[2], I S Oliveira[1] and R S Sarthour[1]

50 anos
PÓS-GRADUAÇÃO CBPF

Q,S, R and *T* are dichotomic classical variables

Correlation: $(Q+R)S+(R-Q)T$

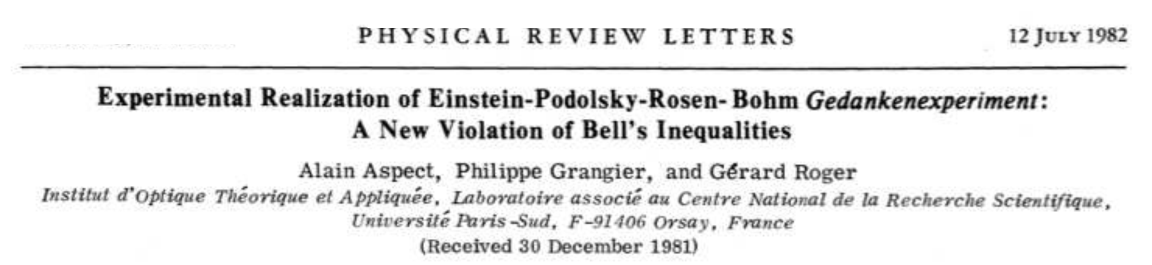
$$Q=R=+1 \Rightarrow Q+R=2, R-Q=0$$
$$Q=+1, R=-1 \Rightarrow Q+R=0, R-Q=-2$$
$$Q=-1, R=+1 \Rightarrow Q+R=0, R-Q=2$$
$$Q=-1, R=-1 \Rightarrow Q+R=-2, R-Q=0$$

$$\Rightarrow (Q+R)S+(R-Q)T=\pm 2$$

Desigualdade de Bell

$$\langle QS\rangle+\langle RS\rangle+\langle RT\rangle-\langle QT\rangle \le 2$$

$$Q,T,R,S=\sigma_k$$
$$|\psi\rangle=\frac{|01\rangle-|10\rangle}{\sqrt{2}} \Rightarrow \sum\langle i\rangle=2\sqrt{2}$$



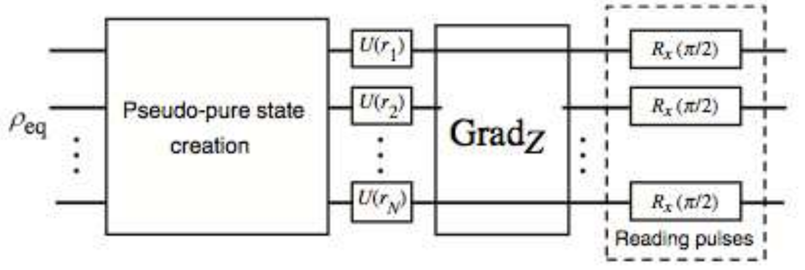
PHYSICAL REVIEW LETTERS — 12 July 1982

Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

Alain Aspect, Philippe Grangier, and Gérard Roger

Institut d'Optique Théorique et Appliquée, Laboratoire associé au Centre National de la Recherche Scientifique, Université Paris-Sud, F-91406 Orsay, France

(Received 30 December 1981)



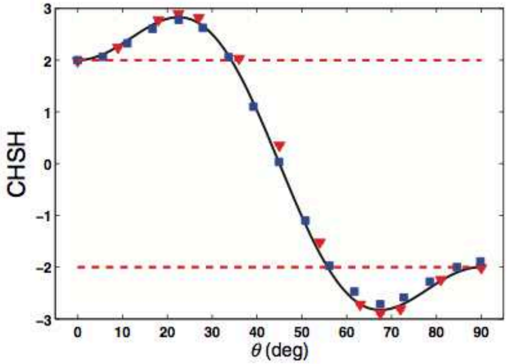


Figure 3. Experimental results for the cat state. ▼, NMR experiment; ■, photon experiment taken from [10]. The solid line is the quantum mechanical prediction.

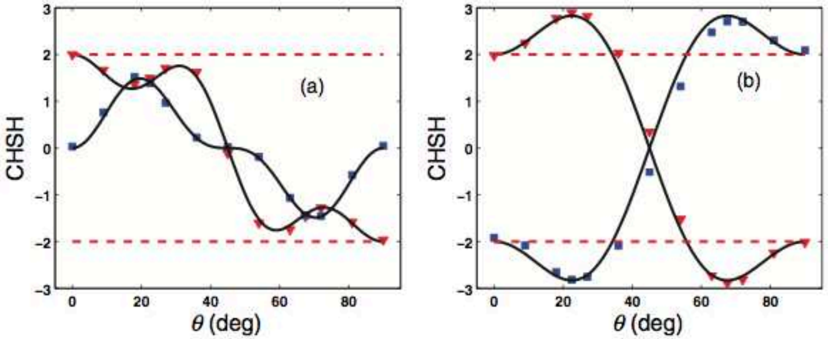
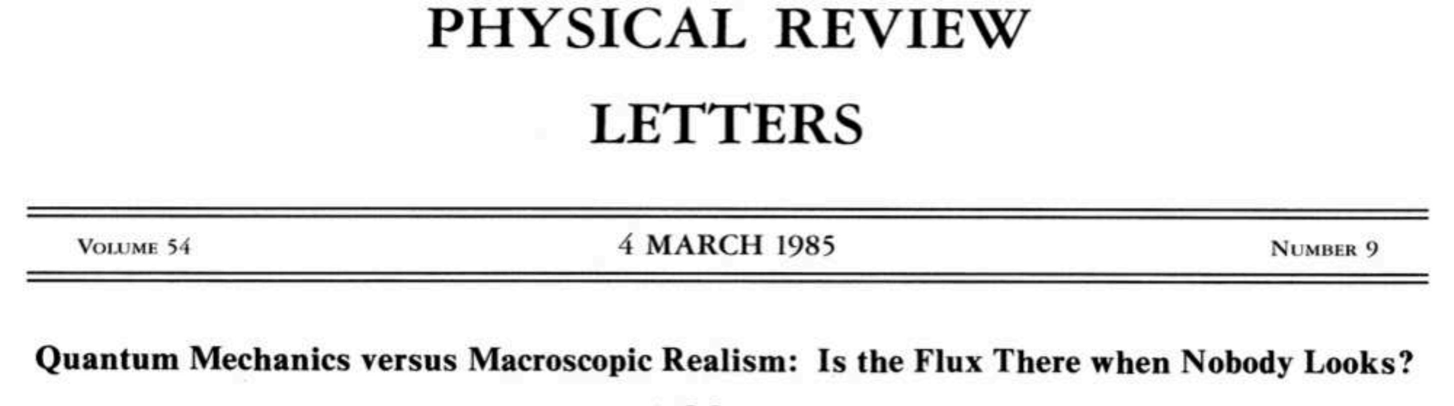


Figure 4. Experimental results of the CHSH quantity as a function of the angle θ. (a) ▼, $|00\rangle$; ■, $(|00\rangle+|01\rangle+|10\rangle+|11\rangle)/2$. (b) ▼, $(|00\rangle+|11\rangle)/\sqrt{2}$; ■, $(|01\rangle-|10\rangle)/\sqrt{2}$. The continuous lines are the predictions of the LRHVM described in [29]. The NMR data shown here are the same as those in figure 3.

Testando o Realismo

50 anos
PÓS-GRADUAÇÃO CBPF

Leggett-Garg inequality with NMR



PHYSICAL REVIEW
LETTERS

VOLUME 54 | 4 MARCH 1985 | NUMBER 9

Quantum Mechanics versus Macroscopic Realism: Is the Flux There when Nobody Looks?

A. J. Leggett

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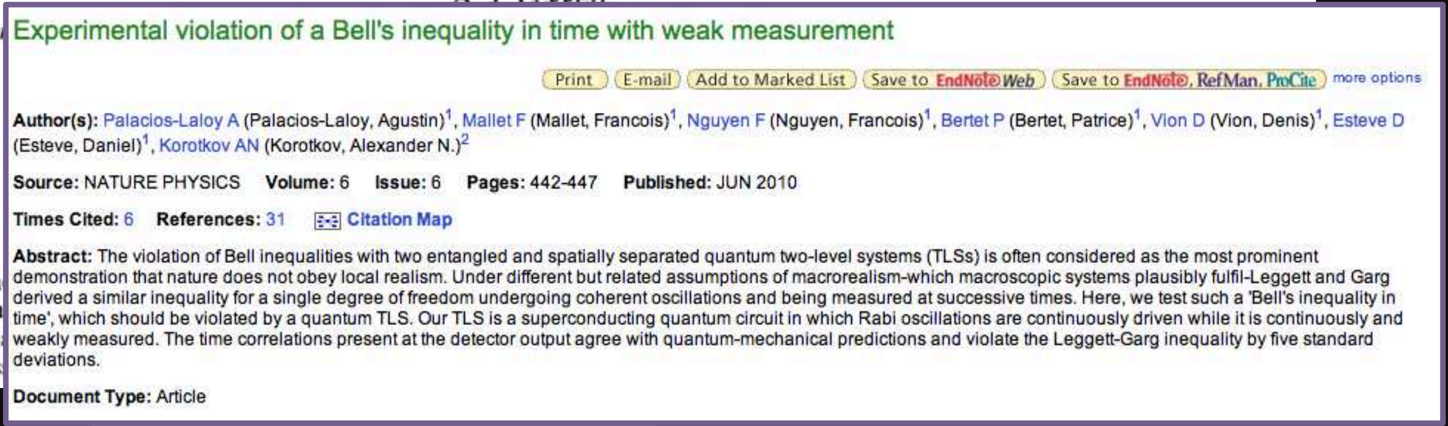


Experimental violation of a Bell's inequality in time with weak measurement

Author(s): Palacios-Laloy A (Palacios-Laloy, Agustin)[1], Mallet F (Mallet, Francois)[1], Nguyen F (Nguyen, Francois)[1], Bertet P (Bertet, Patrice)[1], Vion D (Vion, Denis)[1], Esteve D (Esteve, Daniel)[1], Korotkov AN (Korotkov, Alexander N.)[2]

Source: NATURE PHYSICS **Volume:** 6 **Issue:** 6 **Pages:** 442-447 **Published:** JUN 2010

Times Cited: 6 **References:** 31 Citation Map

Abstract: The violation of Bell inequalities with two entangled and spatially separated quantum two-level systems (TLSs) is often considered as the most prominent demonstration that nature does not obey local realism. Under different but related assumptions of macrorealism-which macroscopic systems plausibly fulfil-Leggett and Garg derived a similar inequality for a single degree of freedom undergoing coherent oscillations and being measured at successive times. Here, we test such a 'Bell's inequality in time', which should be violated by a quantum TLS. Our TLS is a superconducting quantum circuit in which Rabi oscillations are continuously driven while it is continuously and weakly measured. The time correlations present at the detector output agree with quantum-mechanical predictions and violate the Leggett-Garg inequality by five standard deviations.

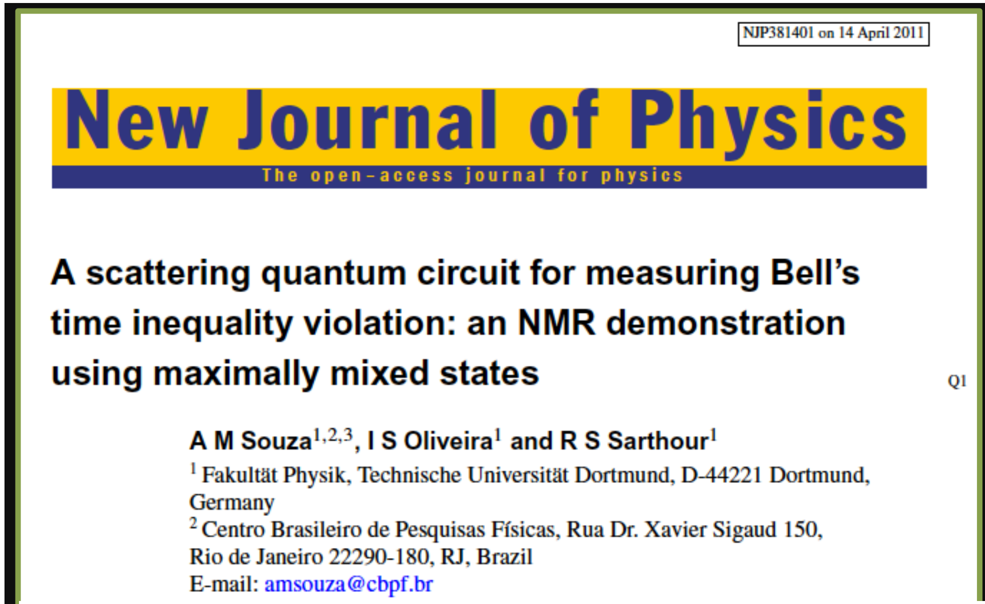
Document Type: Article

$$K \equiv C_{1,2} + C_{2,3} - C_{1,3} \leq 1$$

$$C_{i,j} = \langle O(t_i) O(t_j) \rangle$$

$$K = 2\cos\left(\frac{\Delta E \Delta t}{\hbar}\right) - \cos\left(2\frac{\Delta E \Delta t}{\hbar}\right) \leq 1$$

where ΔE is the energy separation between the qubit eigenlevels. This inequality is clearly violated for $0 < \Delta E \Delta t/\hbar < \pi/2$, and is maximally violated for $\Delta E \Delta t/\hbar = \pi/3$.



NJP381401 on 14 April 2011

New Journal of Physics

The open-access journal for physics

A scattering quantum circuit for measuring Bell's time inequality violation: an NMR demonstration using maximally mixed states

Q1

A M Souza[1,2,3], I S Oliveira[1] and R S Sarthour[1]

[1] Fakultät Physik, Technische Universität Dortmund, D-44221 Dortmund, Germany

[2] Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150, Rio de Janeiro 22290-180, RJ, Brazil

E-mail: amsouza@cbpf.br

50 anos

PÓS·GRADUAÇÃO CBPF

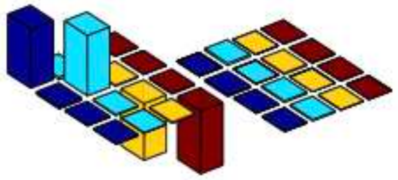


FIG. 2: Tomographed input density matrix of the maximally mixed state. The state is obtained after a $\pi/2$ pulse followed by a z-field gradient. The advantage of using such a state is that it since it does not undergoes unitary transformations, time quantum correlations can be directly tested.

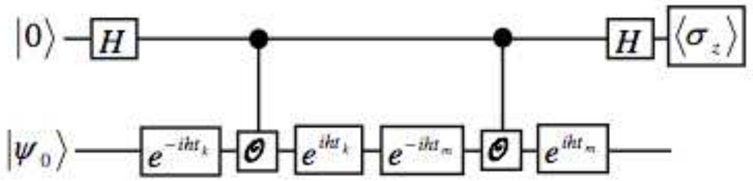
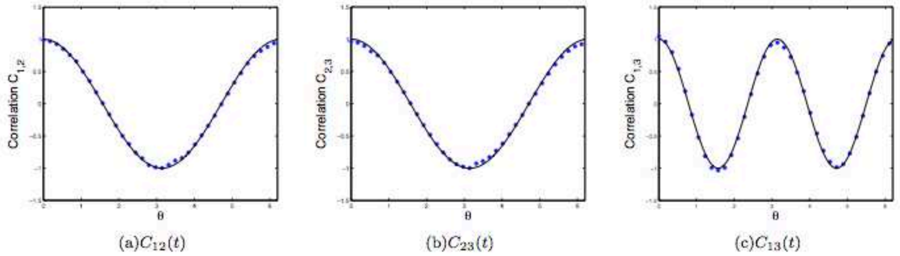


FIG. 1: Quantum scattering circuit to measure time correlation functions. The expected value $\langle\sigma_z\rangle$ of the ancillary qubit is a noninvasive measurement of $\langle\mathcal{O}(t_m)\mathcal{O}(t_k)\rangle$, the correlation function at t_m and t_k. Here h stands for $H/\hbar$.



(a)$C_{12}(t)$ (b)$C_{23}(t)$ (c)$C_{13}(t)$

FIG. 3: Correlation functions obtained in three different experiment run. With extra ancillary qubits it is possible to measure them all in a single run. The x-axis corresponds corresponds to one full 2π cycle and θ stands for $\Delta E\Delta t/\hbar$.

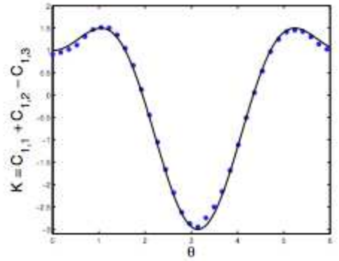
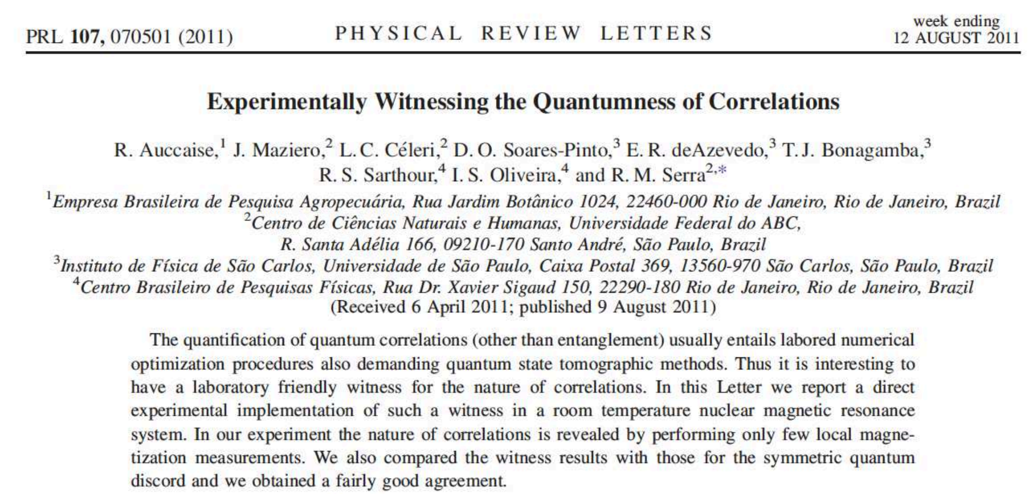


FIG. 4: Total correlation function, showing a clear violation of Leggett-Garg inequality, Eq. (1). The x-axis corresponds corresponds to one full 2π cycle and θ stands for $\Delta E\Delta t/\hbar$. The maximum violation occurs at $\pi/3$ and $5\pi/3$.

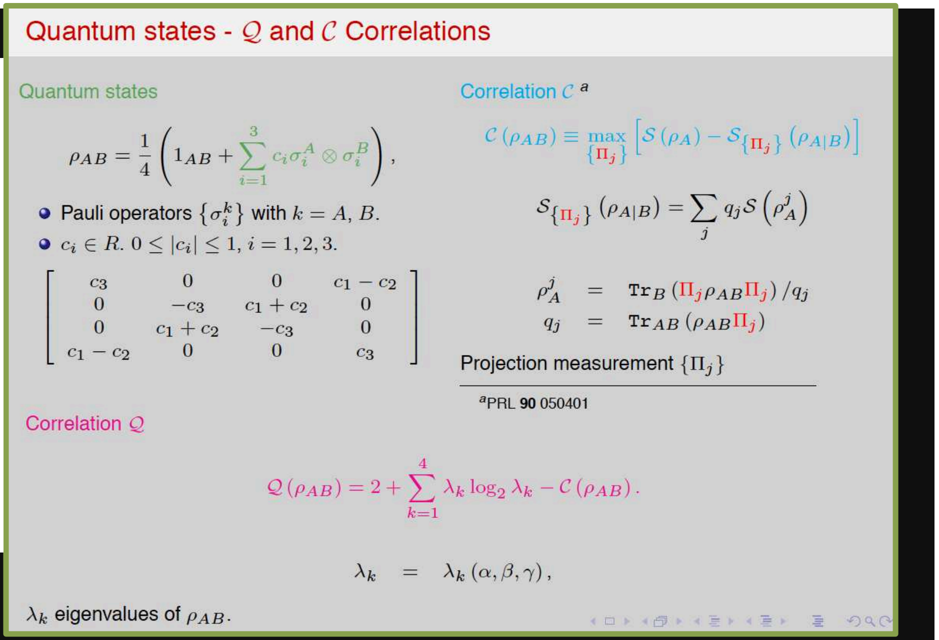


PRL **107,** 070501 (2011) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2011

Experimentally Witnessing the Quantumness of Correlations

R. Auccaise,[1] J. Maziero,[2] L.C. Céleri,[2] D.O. Soares-Pinto,[3] E.R. deAzevedo,[3] T.J. Bonagamba,[3]
R.S. Sarthour,[4] I.S. Oliveira,[4] and R.M. Serra[2,*]
[1]*Empresa Brasileira de Pesquisa Agropecuária, Rua Jardim Botânico 1024, 22460-000 Rio de Janeiro, Rio de Janeiro, Brazil*
[2]*Centro de Ciências Naturais e Humanas, Universidade Federal do ABC,*
R. Santa Adélia 166, 09210-170 Santo André, São Paulo, Brazil
[3]*Instituto de Física de São Carlos, Universidade de São Paulo, Caixa Postal 369, 13560-970 São Carlos, São Paulo, Brazil*
[4]*Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150, 22290-180 Rio de Janeiro, Rio de Janeiro, Brazil*
(Received 6 April 2011; published 9 August 2011)

The quantification of quantum correlations (other than entanglement) usually entails labored numerical optimization procedures also demanding quantum state tomographic methods. Thus it is interesting to have a laboratory friendly witness for the nature of correlations. In this Letter we report a direct experimental implementation of such a witness in a room temperature nuclear magnetic resonance system. In our experiment the nature of correlations is revealed by performing only few local magnetization measurements. We also compared the witness results with those for the symmetric quantum discord and we obtained a fairly good agreement.



Quantum states - $\mathcal{Q}$ and $\mathcal{C}$ Correlations

Quantum states

$$\rho_{AB} = \frac{1}{4}\left(1_{AB} + \sum_{i=1}^{3} c_i \sigma_i^A \otimes \sigma_i^B\right),$$

- Pauli operators $\{\sigma_i^k\}$ with $k = A, B$.
- $c_i \in R.\ 0 \leq |c_i| \leq 1,\ i = 1, 2, 3.$

$$\begin{bmatrix} c_3 & 0 & 0 & c_1 - c_2 \\ 0 & -c_3 & c_1 + c_2 & 0 \\ 0 & c_1 + c_2 & -c_3 & 0 \\ c_1 - c_2 & 0 & 0 & c_3 \end{bmatrix}$$

Correlation $\mathcal{C}$ [a]

$$\mathcal{C}(\rho_{AB}) \equiv \max_{\{\Pi_j\}} \left[\mathcal{S}(\rho_A) - \mathcal{S}_{\{\Pi_j\}}(\rho_{A|B})\right]$$

$$\mathcal{S}_{\{\Pi_j\}}(\rho_{A|B}) = \sum_j q_j \mathcal{S}\left(\rho_A^j\right)$$

$$\begin{aligned} \rho_A^j &= \mathrm{Tr}_B\left(\Pi_j \rho_{AB} \Pi_j\right)/q_j \\ q_j &= \mathrm{Tr}_{AB}\left(\rho_{AB} \Pi_j\right) \end{aligned}$$

Projection measurement $\{\Pi_j\}$

---

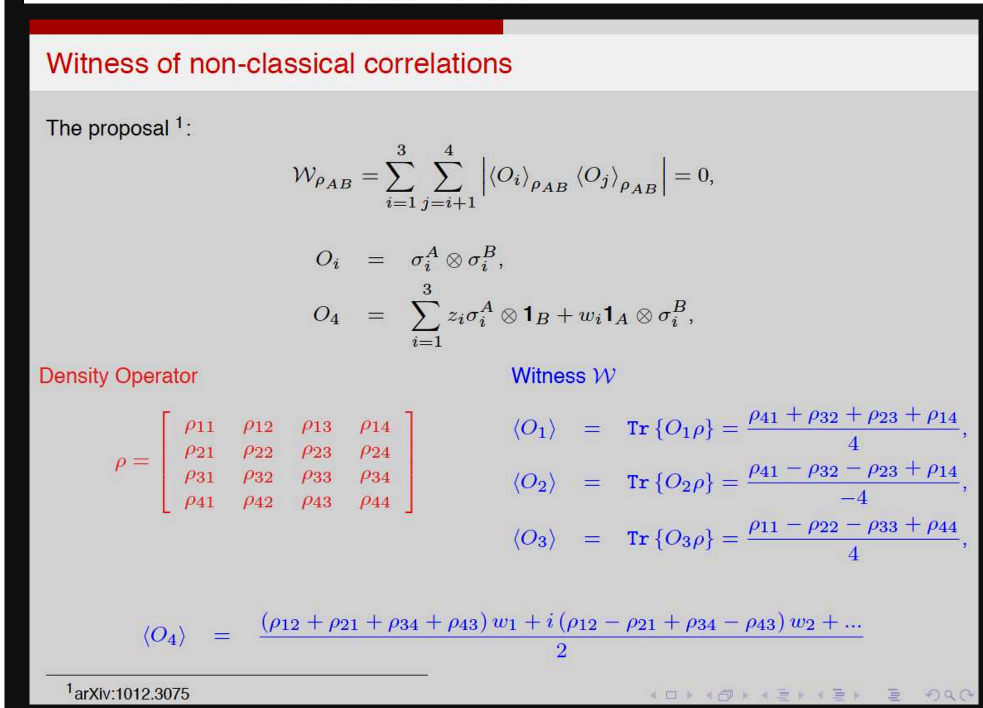
[a] PRL **90** 050401

Correlation $\mathcal{Q}$

$$\mathcal{Q}(\rho_{AB}) = 2 + \sum_{k=1}^{4} \lambda_k \log_2 \lambda_k - \mathcal{C}(\rho_{AB}).$$

$$\lambda_k = \lambda_k(\alpha, \beta, \gamma),$$

λ_k eigenvalues of ρ_{AB}.



Witness of non-classical correlations

The proposal [1]:

$$\mathcal{W}_{\rho_{AB}} = \sum_{i=1}^{3} \sum_{j=i+1}^{4} \left|\langle O_i\rangle_{\rho_{AB}} \langle O_j\rangle_{\rho_{AB}}\right| = 0,$$

$$\begin{aligned} O_i &= \sigma_i^A \otimes \sigma_i^B, \\ O_4 &= \sum_{i=1}^{3} z_i \sigma_i^A \otimes \mathbf{1}_B + w_i \mathbf{1}_A \otimes \sigma_i^B, \end{aligned}$$

Density Operator

$$\rho = \begin{bmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} \end{bmatrix}$$

Witness $\mathcal{W}$

$$\begin{aligned} \langle O_1\rangle &= \mathrm{Tr}\{O_1\rho\} = \frac{\rho_{41} + \rho_{32} + \rho_{23} + \rho_{14}}{4}, \\ \langle O_2\rangle &= \mathrm{Tr}\{O_2\rho\} = \frac{\rho_{41} - \rho_{32} - \rho_{23} + \rho_{14}}{-4}, \\ \langle O_3\rangle &= \mathrm{Tr}\{O_3\rho\} = \frac{\rho_{11} - \rho_{22} - \rho_{33} + \rho_{44}}{4}, \end{aligned}$$

$$\langle O_4\rangle = \frac{(\rho_{12} + \rho_{21} + \rho_{34} + \rho_{43})\,w_1 + i\,(\rho_{12} - \rho_{21} + \rho_{34} - \rho_{43})\,w_2 + \ldots}{2}$$

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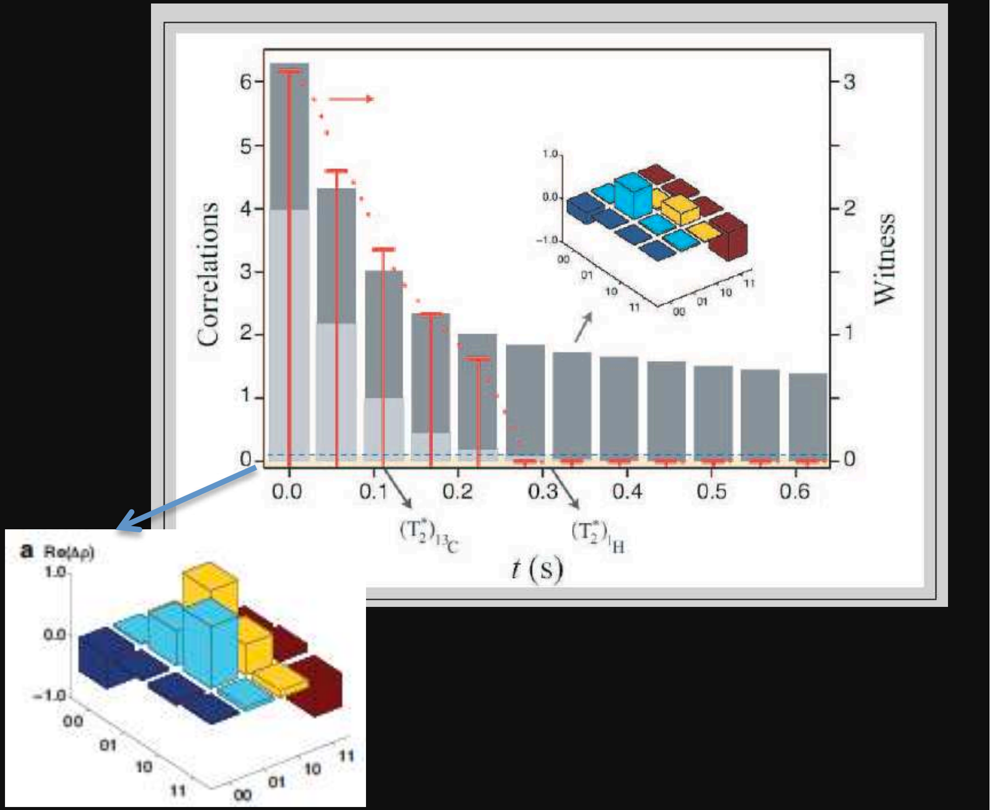
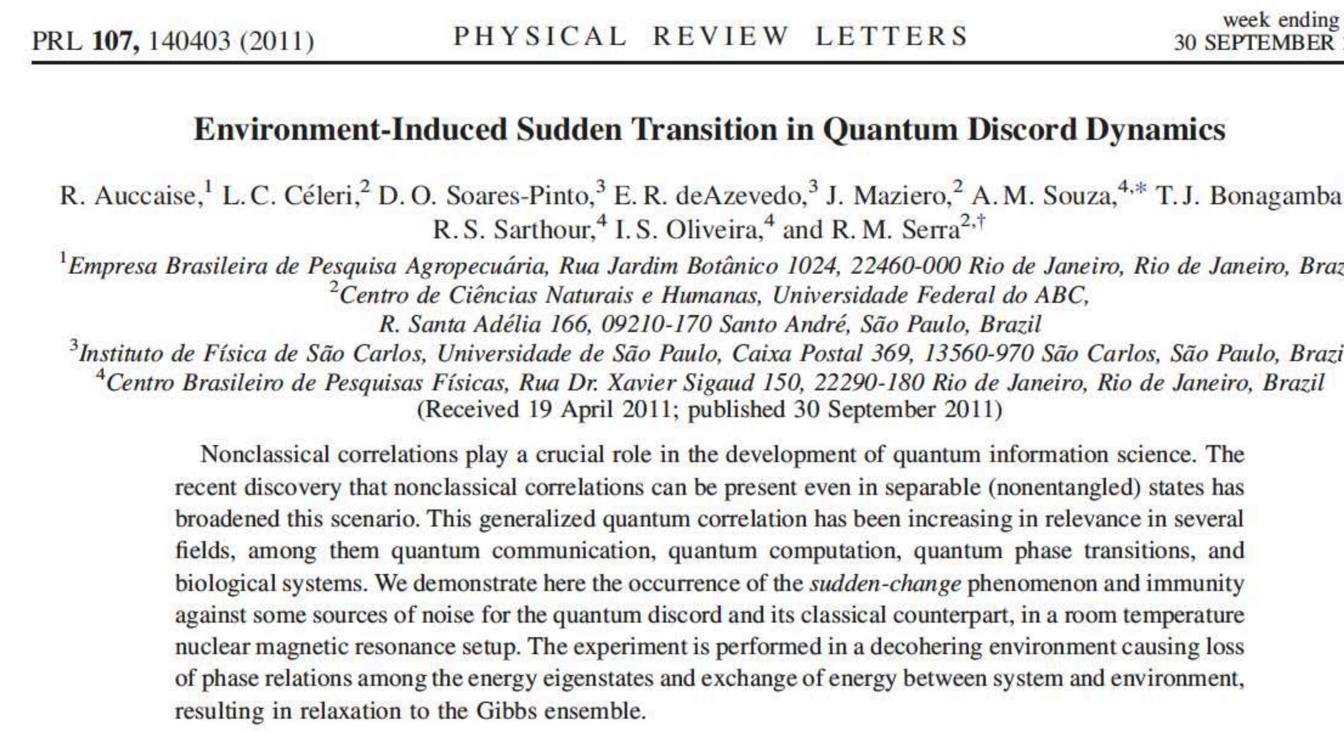
[1] arXiv:1012.3075



50 anos
PÓS·GRADUAÇÃO CBPF



PRL **107,** 140403 (2011) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2011

Environment-Induced Sudden Transition in Quantum Discord Dynamics

R. Auccaise,[1] L. C. Céleri,[2] D. O. Soares-Pinto,[3] E. R. deAzevedo,[3] J. Maziero,[2] A. M. Souza,[4,*] T. J. Bonagamba,[3] R. S. Sarthour,[4] I. S. Oliveira,[4] and R. M. Serra[2,†]

[1]*Empresa Brasileira de Pesquisa Agropecuária, Rua Jardim Botânico 1024, 22460-000 Rio de Janeiro, Rio de Janeiro, Brazil*
[2]*Centro de Ciências Naturais e Humanas, Universidade Federal do ABC,*
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(Received 19 April 2011; published 30 September 2011)

Nonclassical correlations play a crucial role in the development of quantum information science. The recent discovery that nonclassical correlations can be present even in separable (nonentangled) states has broadened this scenario. This generalized quantum correlation has been increasing in relevance in several fields, among them quantum communication, quantum computation, quantum phase transitions, and biological systems. We demonstrate here the occurrence of the *sudden-change* phenomenon and immunity against some sources of noise for the quantum discord and its classical counterpart, in a room temperature nuclear magnetic resonance setup. The experiment is performed in a decohering environment causing loss of phase relations among the energy eigenstates and exchange of energy between system and environment, resulting in relaxation to the Gibbs ensemble.

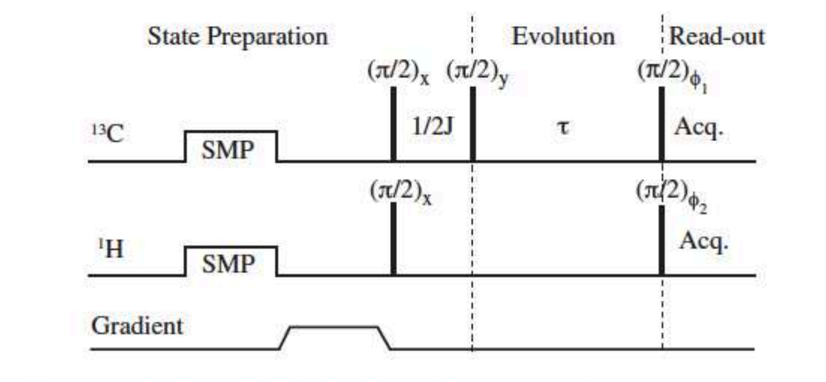

FIG. 1. Sketch of the pulse sequence used experimentally to follow the dynamics of quantum and classical correlations under decoherence. The sequence consists of three blocks: the initial state preparation, relaxation delay, and readout by quantum state tomography.

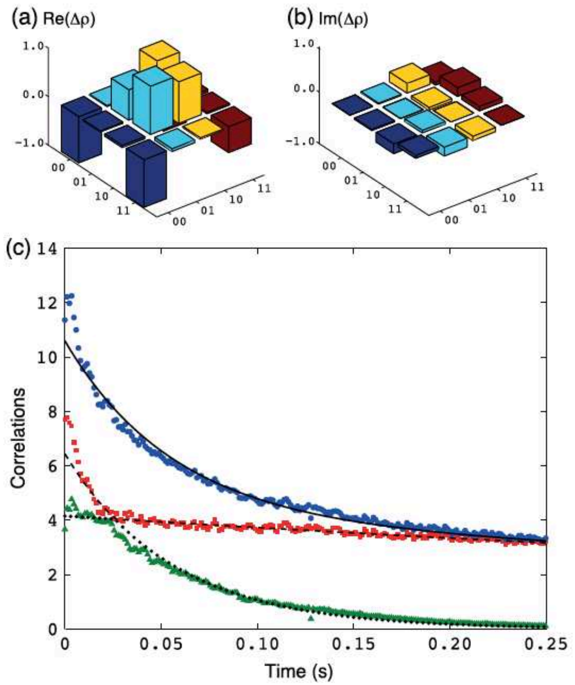

FIG. 2 (color online). Sudden change in behavior of correlations. (a) Bar representation of the real and, (b) imaginary parts of the initial deviation matrix for the sudden-change experiment, reconstructed by quantum state tomography. We adopted the usual computational basis, where $|0\rangle$ and $|1\rangle$ represent the eigenstates of σ_z for each qubit. (c) displays the predicted sudden change in behavior of the correlations during their dynamic evolution to thermal equilibrium. The blue circles are the experimental data for the quantum mutual information, while the red squares and green triangles represent the classical and quantum correlations, respectively. The black lines are the theoretical predictions. The initial state is analogous to the state in Eq. (2) with $|c_x|, |c_y| > |c_z|$. The correlations are displayed in units of $(\varepsilon^2/\ln 2)$bit.

Princípio da Complementaridade com RMN

PHYSICAL REVIEW A **85**, 032121 (2012)

Experimental analysis of the quantum complementarity principle

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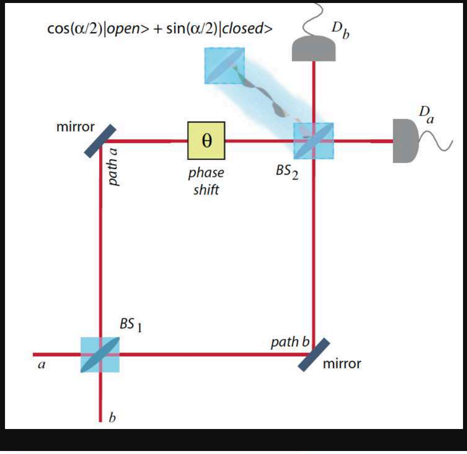
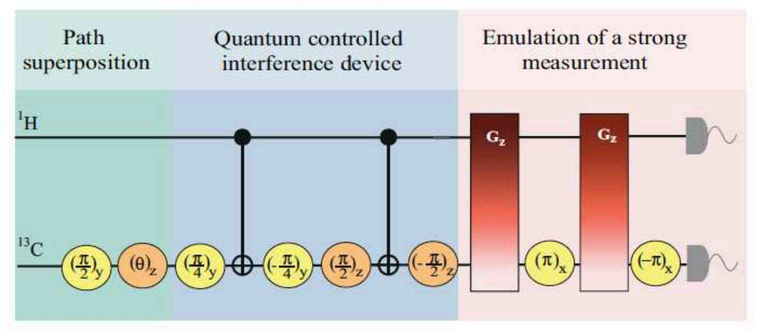
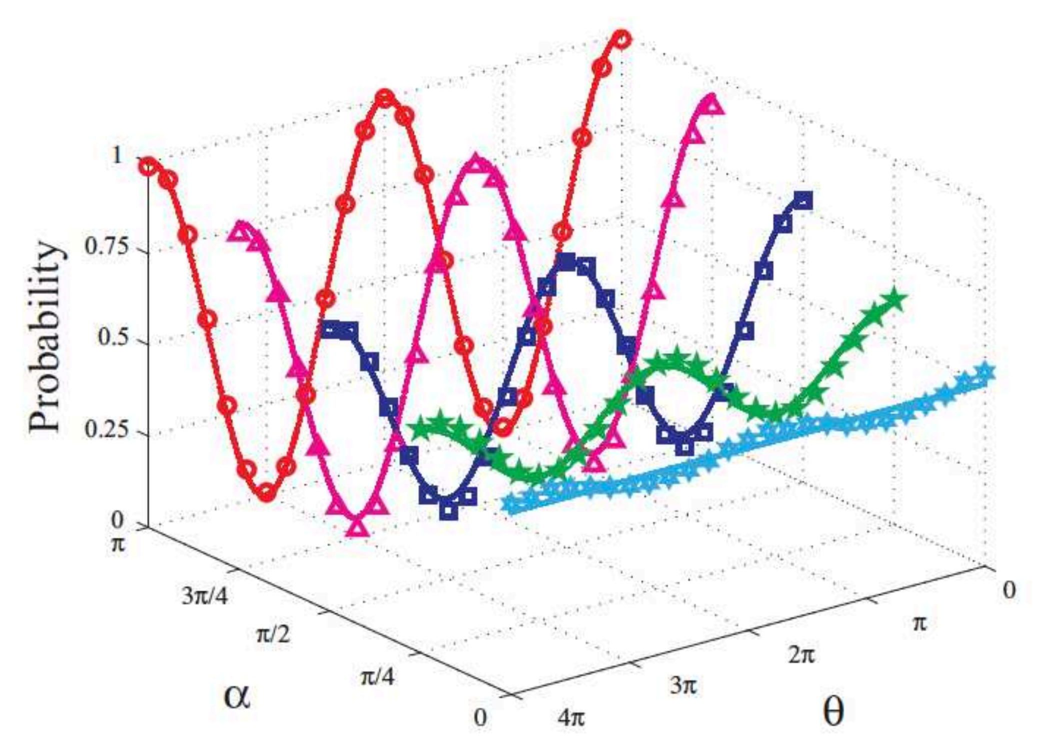
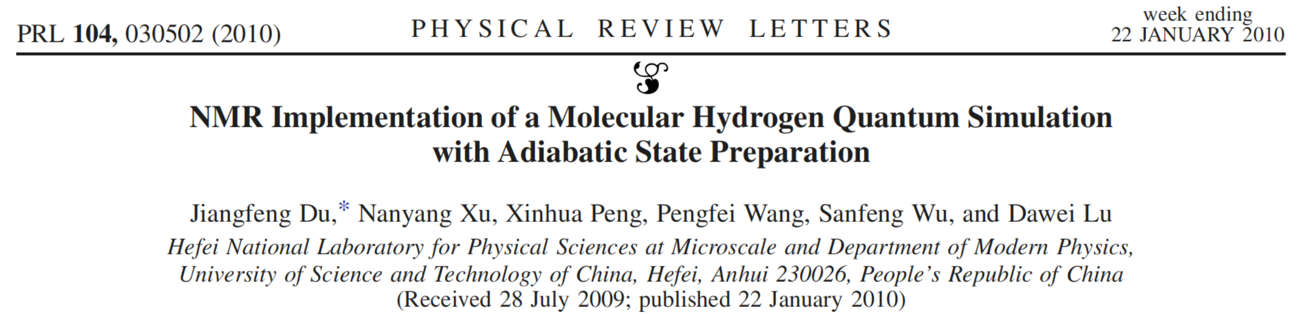
(Received 27 January 2012; published 21 March 2012)







Last, but not least...


PRL **104,** 030502 (2010) PHYSICAL REVIEW LETTERS week ending 22 JANUARY 2010

NMR Implementation of a Molecular Hydrogen Quantum Simulation with Adiabatic State Preparation

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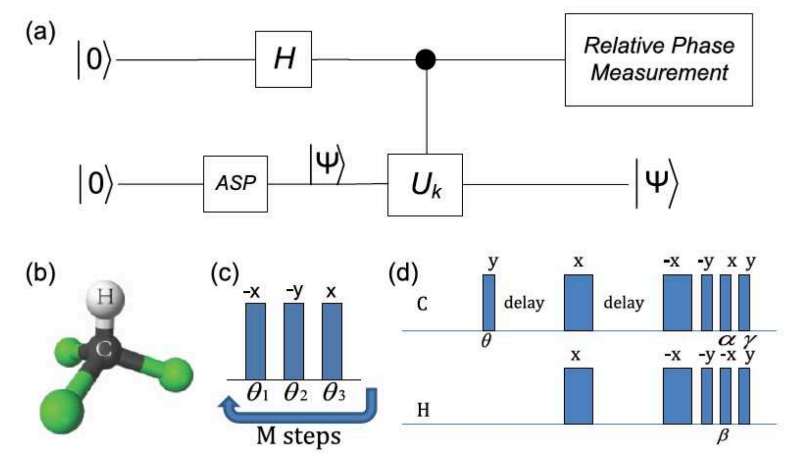
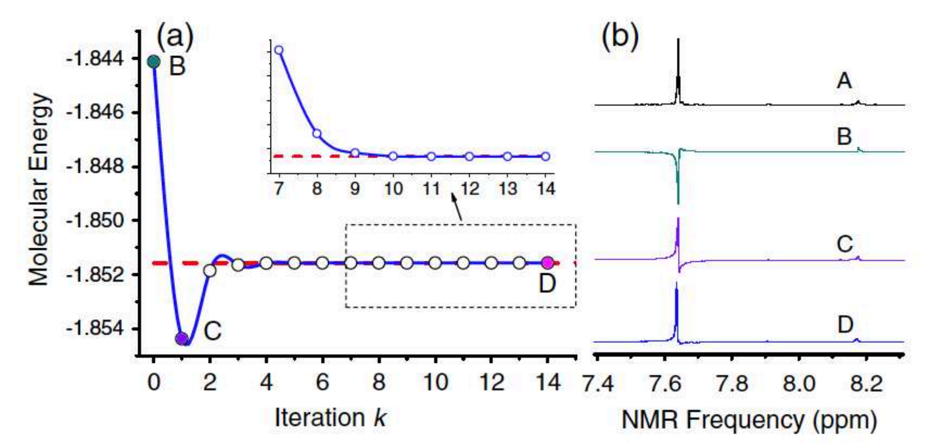
(Received 28 July 2009; published 22 January 2010)





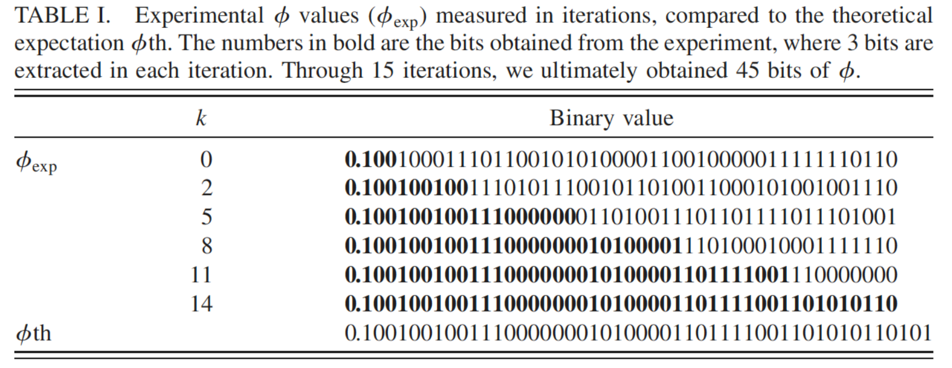


TABLE I. Experimental ϕ values (ϕ_{exp}) measured in iterations, compared to the theoretical expectation ϕth. The numbers in bold are the bits obtained from the experiment, where 3 bits are extracted in each iteration. Through 15 iterations, we ultimately obtained 45 bits of ϕ.

	k	Binary value
ϕ_{exp}	0	**0.100**100011101100101010000110010000011111110110
	2	**0.100100100**111010111001011010011000101001001110
	5	**0.100100100111000000**011010011101101111011101001
	8	**0.100100100111000000010100001**110100010001111110
	11	**0.100100100111000000010100001101111001**110000000
	14	**0.100100100111000000010100001101111001101010110**
ϕth		0.100100100111000000010100001101111001101010110101

Pessoal

OBRIGADO!!

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2. Alfredo Ozorio;
3. Itzhak Roditi;
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2. Eduardo de Azevedo – IFSC;
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Fazemos coisas com solo e petróleo.