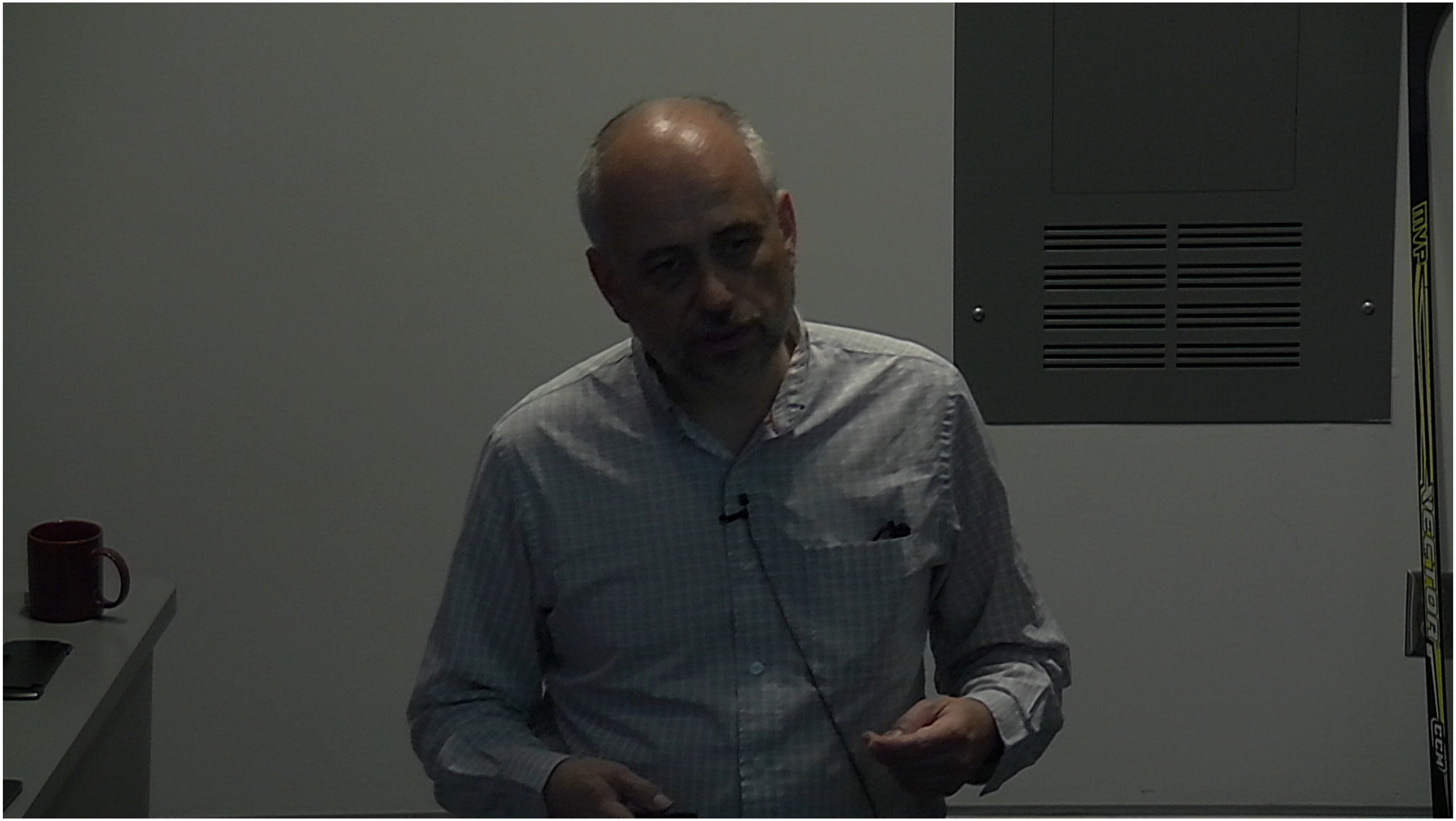
Title: Fundamental Physics with (Weird) Magnetic Resonance

Date: Aug 23, 2017 11:00 AM

URL: http://pirsa.org/17080029

Abstract:


MVP
VECTOR
CCM

Fundamental Physics with (Weird) Magnetic Resonance

Dmitry Budker

Helmholtz-Institute Mainz **UC Berkeley Physics**

Johannes Gutenberg U. **NSD LBNL**

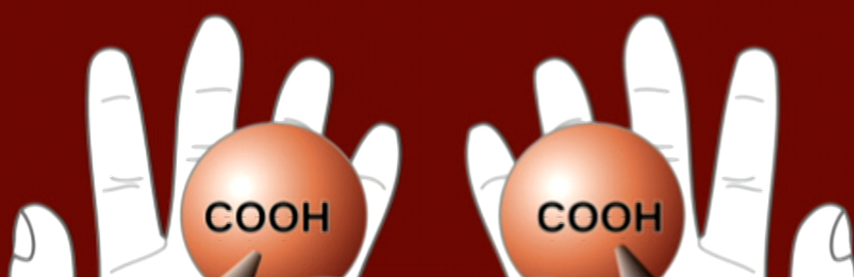
Perimeter Institute, August 23, 2017

1

Measuring molecular parity non-conservation using NMR Spectroscopy

J. Eills,[1,2] J. W. Blanchard,[3,4,5] L. Bougas,[2,6] M. G. Kozlov,[7] A. Pines,[5,4] and D.Budker[2,3,6,8]

arXiv:1707.01759

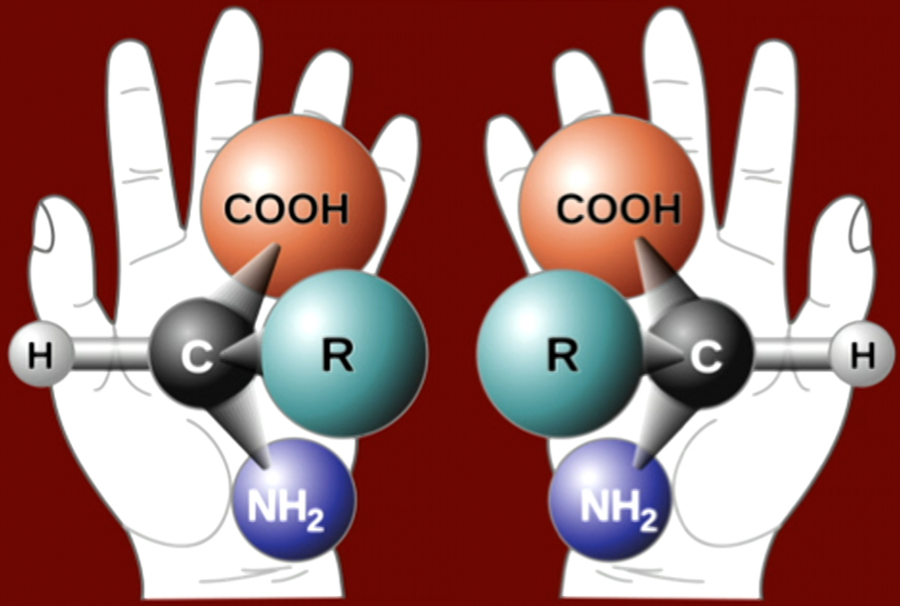


2

Measuring molecular parity non-conservation using NMR Spectroscopy

J. Eills,[1,2] J. W. Blanchard,[3,4,5] L. Bougas,[2,6] M. G. Kozlov,[7] A. Pines,[5,4] and D.Budker[2,3,6,8]

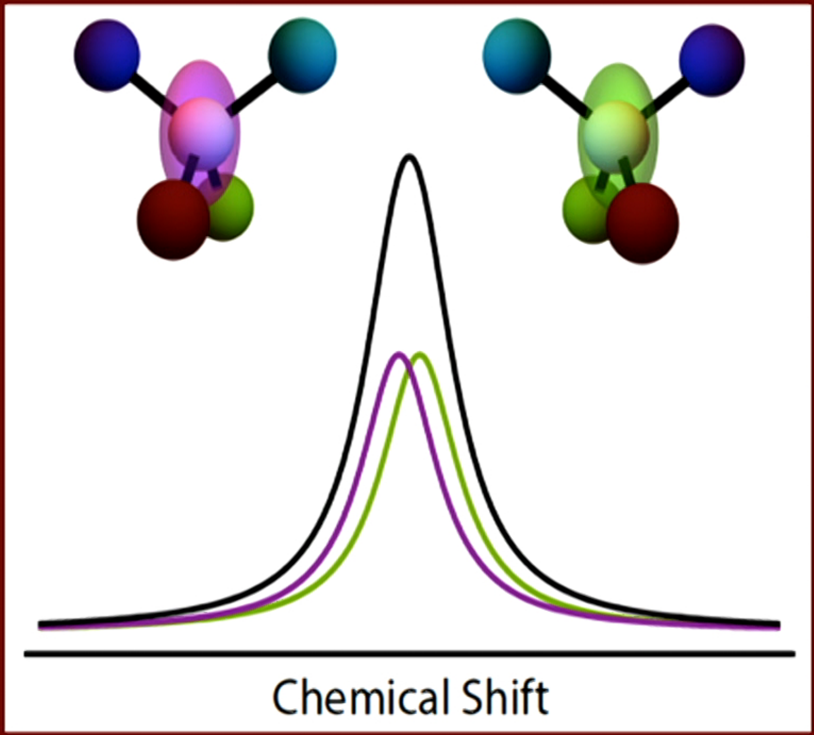
arXiv:1707.01759



A PROVOCATIVE QUESTION:

Why do chiral chiral molecules have
first-order PNC energy shifts ?
(While this is normally forbidden)

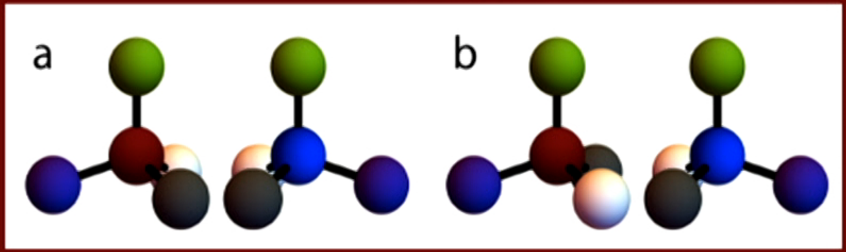
PNC in racemic mixtures: impossible?



- PNC in chiral mol.➜ energy shift
- PNC in NMR ➜ Nucl.Spin.Dep PNC
- B=20 T ➜ ~ 1 mHz line shifts
- No way in a mixture…

4

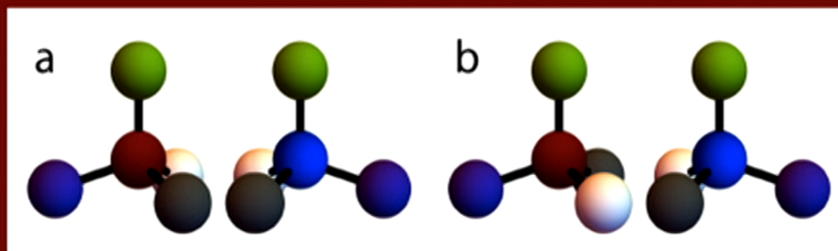
Diastereomeric NMR shift



James Eills (SOTON)
John Blanchard
Lykourgos Bougas
Mikhail Kozlov
Alexander Pines
D.B.

5

Diastereomeric NMR shift



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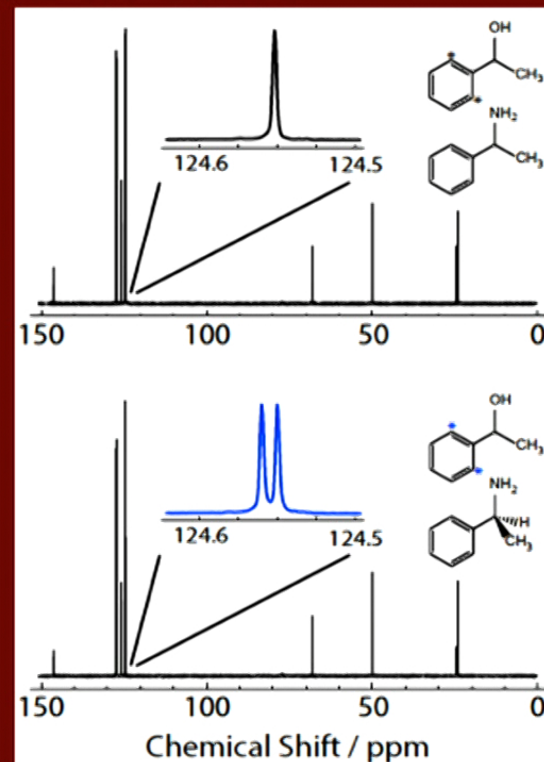

5

Diastereomeric NMR shift

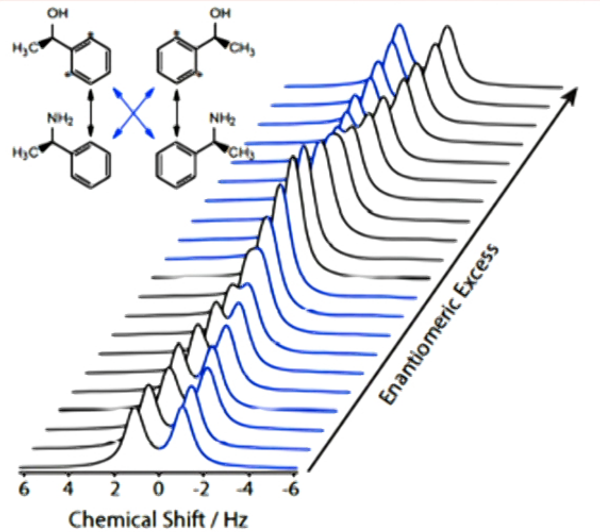

FIG. 4. Stacked [13]C spectra showing diastereomeric splitting of 1-phenylethanol as the enantiomeric excess of the 1-phenylethylamine environment is varied. The scale is in hertz, and centered on the peak of interest. All spectra were acquired at 298 K by averaging 32 transients, with proton decoupling, and have line broadening [35] of 0.5 Hz applied. The inset shows the four possible diastereomeric interactions between the sensor (1-phenylethanol) and chiral solvating reagent (1-phenylethylamine).

6

Diastereomeric NMR shift

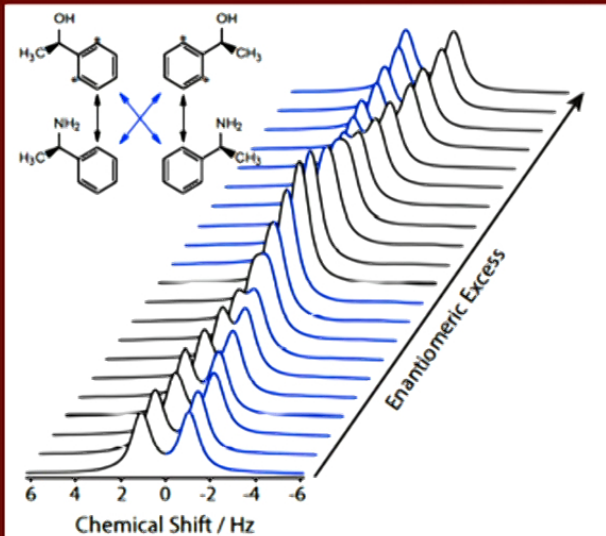

FIG. 4. Stacked ^{13}C spectra showing diastereomeric splitting of 1-phenylethanol as the enantiomeric excess of the 1-phenylethylamine environment is varied. The scale is in hertz, and centered on the peak of interest. All spectra were acquired at 298 K by averaging 32 transients, with proton decoupling, and have line broadening [35] of 0.5 Hz applied. The inset shows the four possible diastereomeric interactions between the sensor (1-phenylethanol) and chiral solvating reagent (1-phenylethylamine).

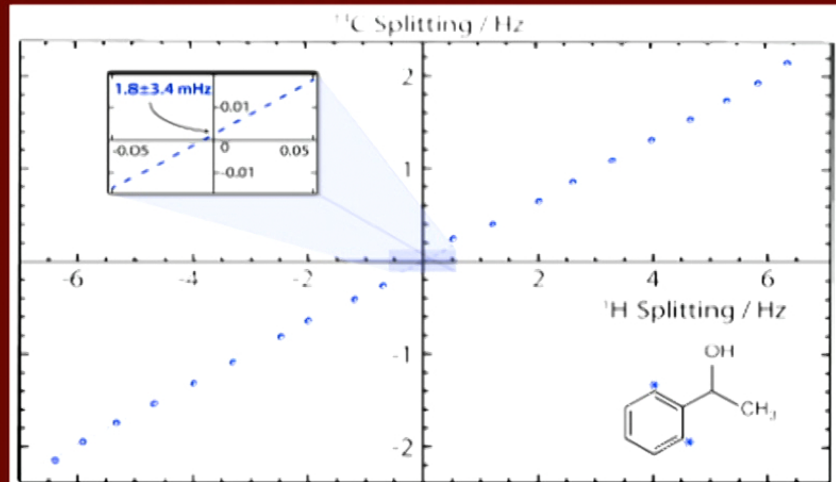

FIG. 5. Experimental data showing the diastereomeric splitting of the ^{13}C peaks as a function of the 1-phenylethylamine enantiomeric excess. Data points were acquired at 20 T and 298 K, by averaging 32 transients. The enantiomeric excess of each solution was determined by measuring the ^1H splitting, as discussed in more detail in the text.

Bottom line(s):

- Measure chiral PNC w/ racemic mixtures

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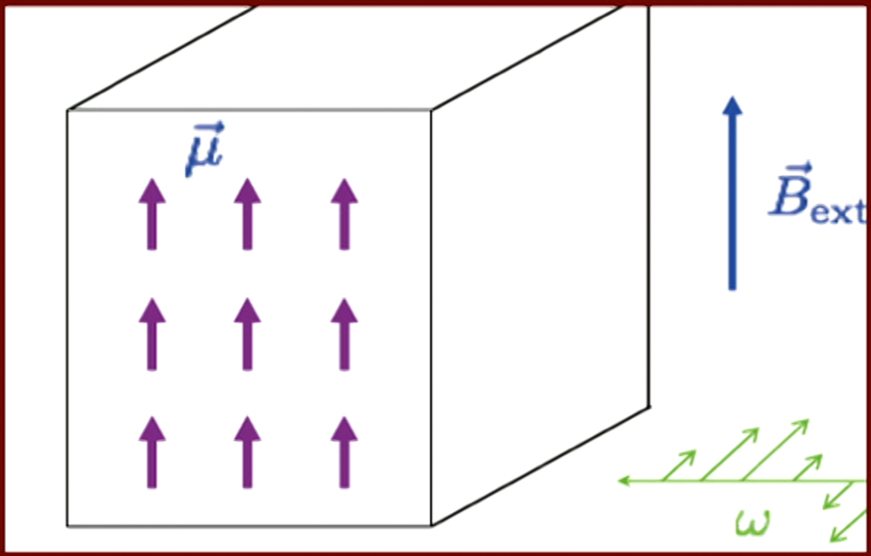
SEARCHING FOR ULTRALIGHT DARK MATTER WITH

nuclear magnetic resonance



8

So what is DM or what mimics it ?

- A gross misunderstanding of gravity (MOND, …) ☹?
- Proca MHD (finite photon mass) ?
- Black holes, dark planets, interstellar gas, … ☹
- WIMPS ☺
- Ultralight bosonic particles
  - Axions (pseudoscalar) ☺
  - ALPs (pseudoscalar) ☺
  - Dilatons (scalar) ☺
  - Vector particles ☺
  - Tensor particles ???

9

So what is DM or what mimics it ?

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  - Dilatons (scalar) ☺
  - Vector particles ☺
  - Tensor particles ???

9

"Most Wanted" file on DM
What do we know?

- Galactic DM density: ~0.4 GeV/cm^3 (10 GeV/cm^3 d.g.)
- Has to be nonrelativistic: $v/c \sim 10^{-3}$ (cold DM)
- Has to be bosonic if $m <\sim 20$ eV (1 keV dwarf galaxies)
- "Bosonic Oscillator" with Q ~ $(v/c)^{-2} \sim 10^6$
- Cannot be lighter than ~ 10^{-22} eV
- … (e.g., BEC ?)

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Why Axions (ALPs) ?

- Big clean-up ?

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How to search for Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

P. Graham
S. Rajendran

+

How to search for Axions (ALPs) ?

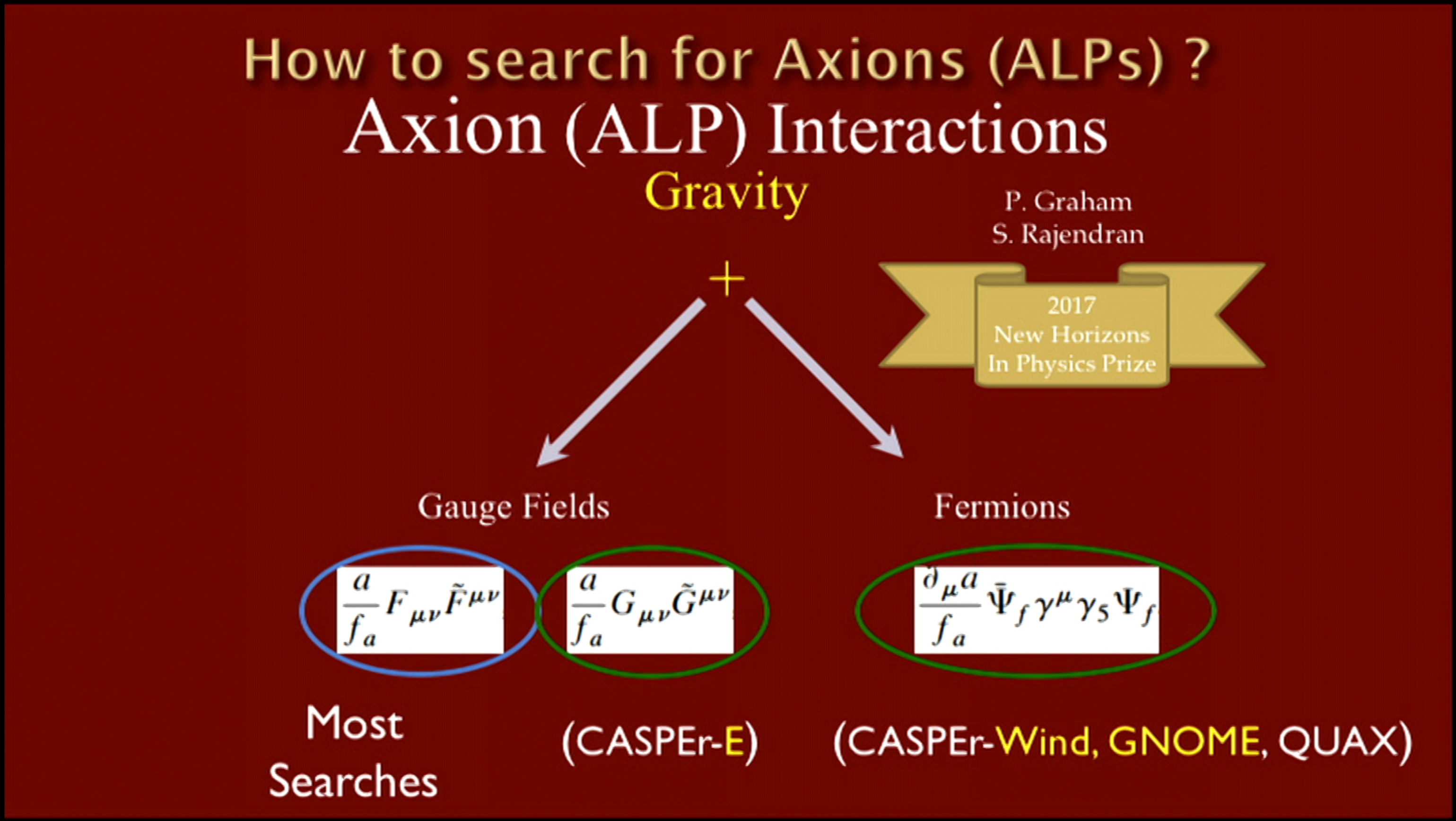
Axion (ALP) Interactions

Gravity

P. Graham
S. Rajendran

+

Gauge Fields		Fermions
$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$	$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\frac{\partial_\mu a}{f_a}\bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$
Most Searches	(CASPEr-E)	(CASPEr-Wind, GNOME, QUAX)



How to search for Axions (ALPs) ?
Axion (ALP) Interactions
Gravity
P. Graham
S. Rajendran
2017
New Horizons
In Physics Prize
+
Gauge Fields
Fermions
$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$
$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$
$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$
Most Searches
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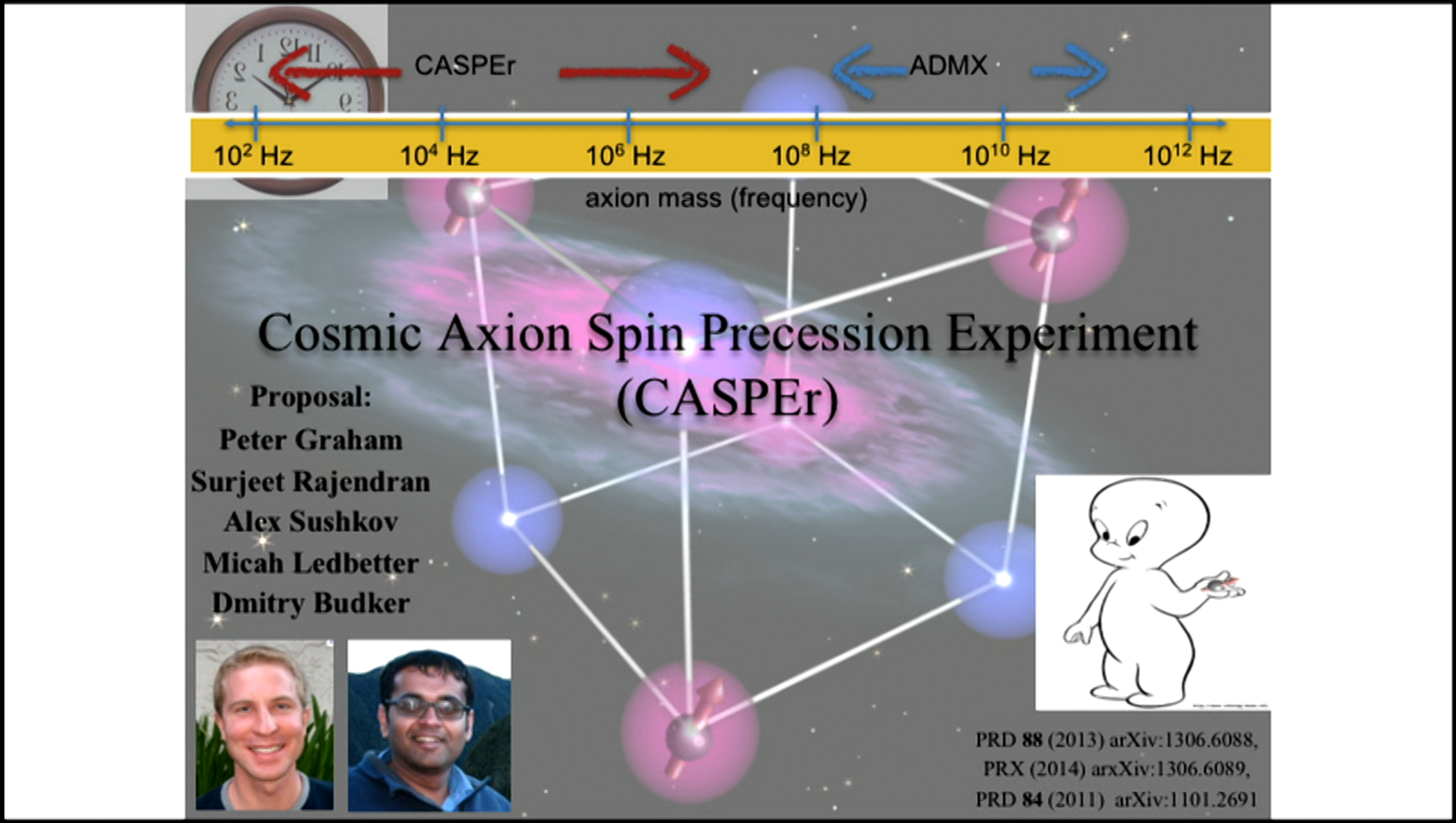
Cosmic Axion Spin Precession Experiment
(CASPEr)
Proposal:
Peter Graham
Surjeet Rajendran
Alex Sushkov
Micah Ledbetter
Dmitry Budker
PRD 88 (2013) arXiv:1306.6088,
PRX (2014) arxXiv:1306.6089,
PRD 84 (2011) arXiv:1101.2691


CASPEr
ADMX
10^2 Hz
10^4 Hz
10^6 Hz
10^8 Hz
10^{10} Hz
10^{12} Hz
axion mass (frequency)
Cosmic Axion Spin Precession Experiment
(CASPEr)
Proposal:
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CASPEr Overview

Key ideas:

- Axion (ALP) field oscillates
- at a frequency equal to its mass (Hz to GHz)
- ➔ time varying CP-odd nuclear moments:
- nEDM, Schiff, … **CASPEr-Electric**
- Also: axion wind (like a magnetic field)

CASPEr-Wind

14

CASPEr Overview

Key ideas:

- Axion (ALP) field oscillates
- at a frequency equal to its mass (Hz to GHz)
- → time varying CP-odd nuclear moments:
- nEDM, Schiff, …

CASPEr-Electric

- Also: axion wind (like a magnetic field)
- $v \sim 10^{-3}\, c$ (virial velocity)

CASPEr-Wind

- Coherence time: $[m_a(v/c)^2]^{-1}$ → $Q{\sim}10^6$

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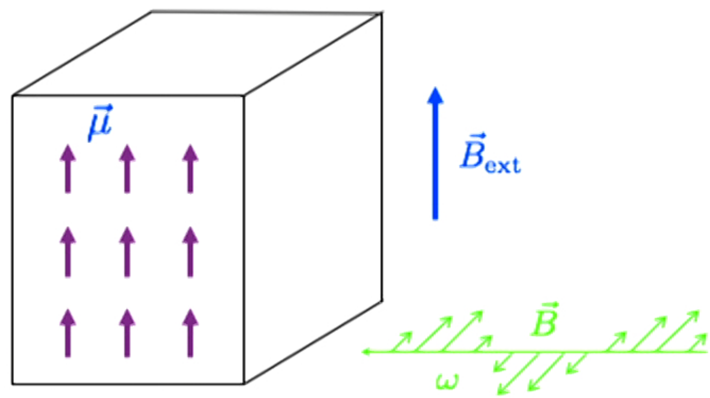
Nuclear Magnetic Resonance (NMR)



Resonance: $2\mu B_{\mathrm{ext}} = \omega$

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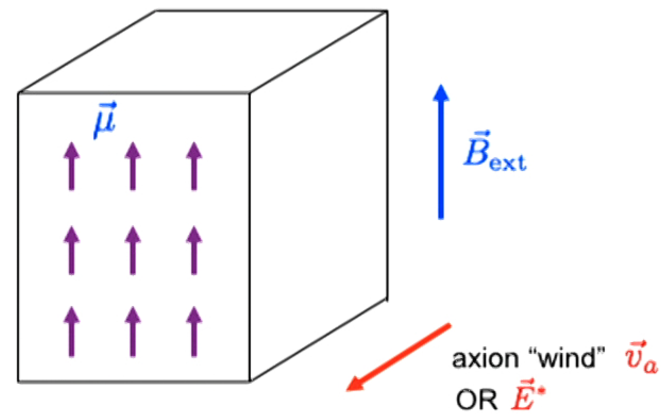
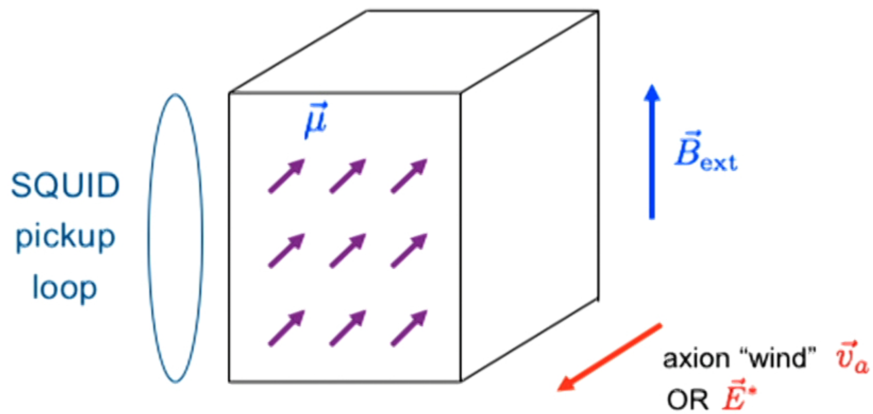
CASPEr



Larmor frequency = axion mass ➔ resonant enhancement

16

CASPEr



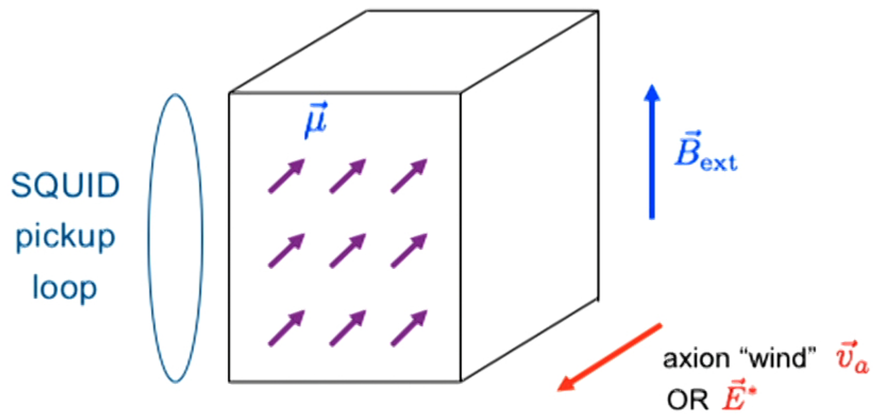
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

Example materials: liquid ^{129}Xe, ferroelectric $PbTiO_3$

16

CASPEr



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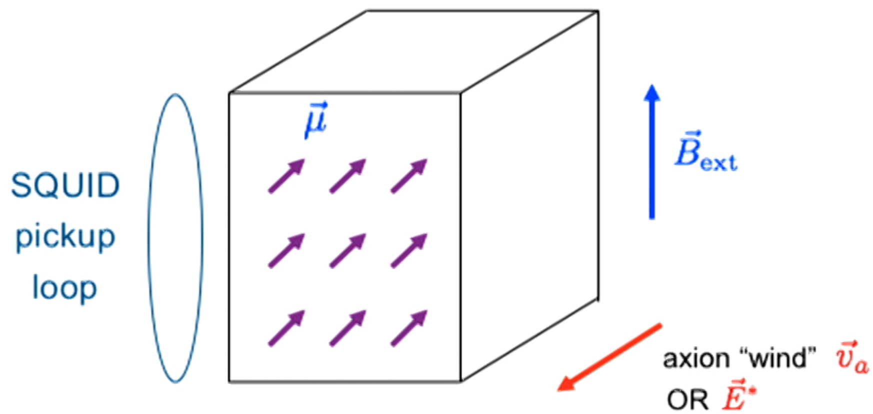
CASPEr



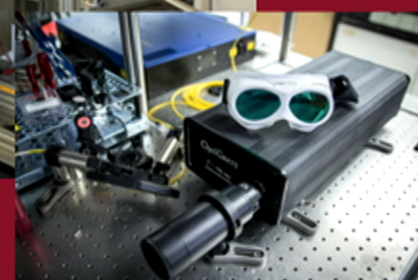
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

Example materials: liquid ^{129}Xe, ferroelectric $PbTiO_3$

16

Xe hyperpolarizer @ Mainz



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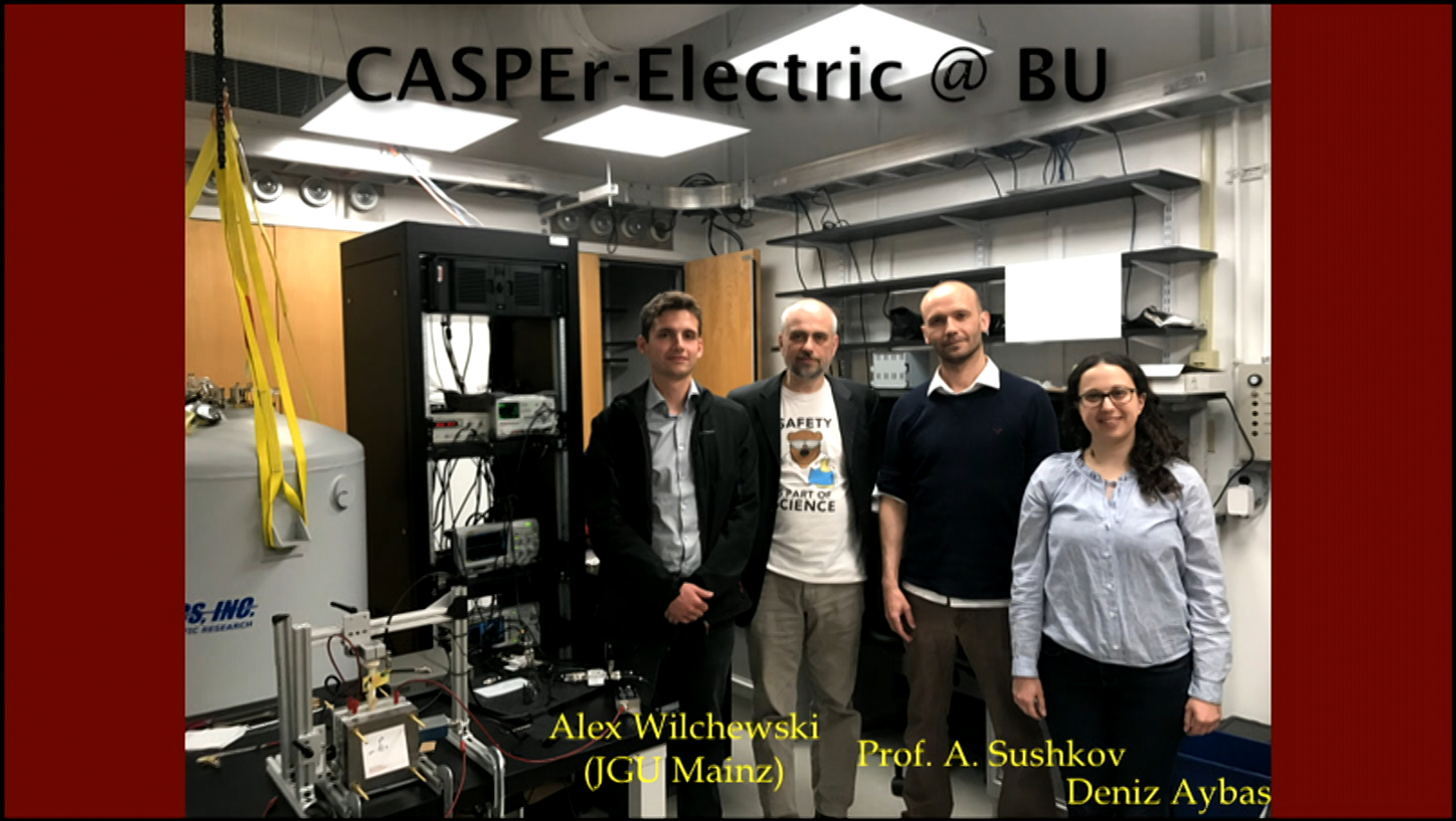
CASPEr-Electric @ BU
Alex Wilchewski
(JGU Mainz)
Prof. A. Sushkov
Deniz Aybas

ZERO-FIELD nuclear magnetic resonance

Micah P. Ledbetter and Dmitry Budker

Counter to intuition, one doesn't necessarily need a strong magnet—or any magnet, for that matter—to extract richly informative spectra from nuclear spins.

April 2013 Physics Today www.physicstoday.org

Micah Ledbetter

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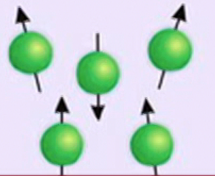
Three Stages of NMR

Polarization
- Thermal equilibration
- Dynamic nuclear polarization
- Parahydrogen-induced polarization
- Spin-exchange optical pumping



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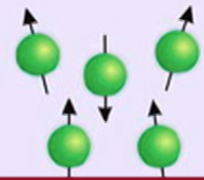
April 2013 Physics Today www.physicstoday.org

Three Stages of NMR

Polarization
- ▶ Thermal equilibration
- ▶ Dynamic nuclear polarization
- ▶ Parahydrogen-induced polarization
- ▶ Spin-exchange optical pumping



No need to polarize in <u>spin-noise spectroscopy</u>
➔ small N

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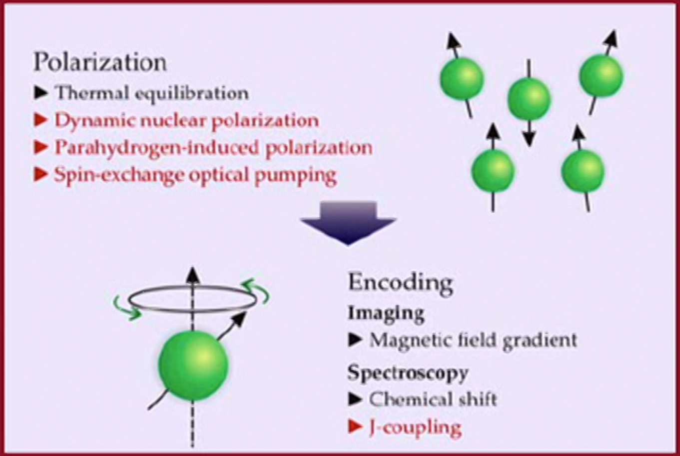
Three Stages of NMR



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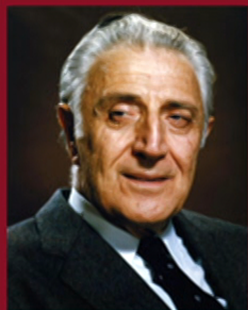
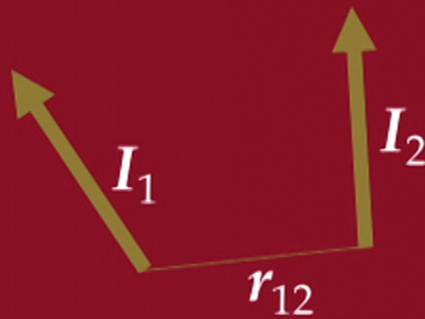
J-coupling



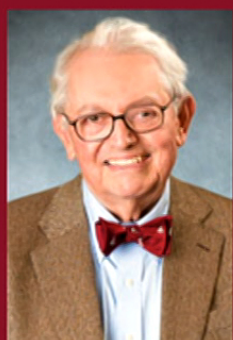
Erwin L. Hahn



<u>Dipole-dipole interaction</u>

$$H \propto \frac{\boldsymbol{I}_1 \cdot \boldsymbol{I}_2}{r_{12}^3}(1 - 3\cos^2\theta)$$

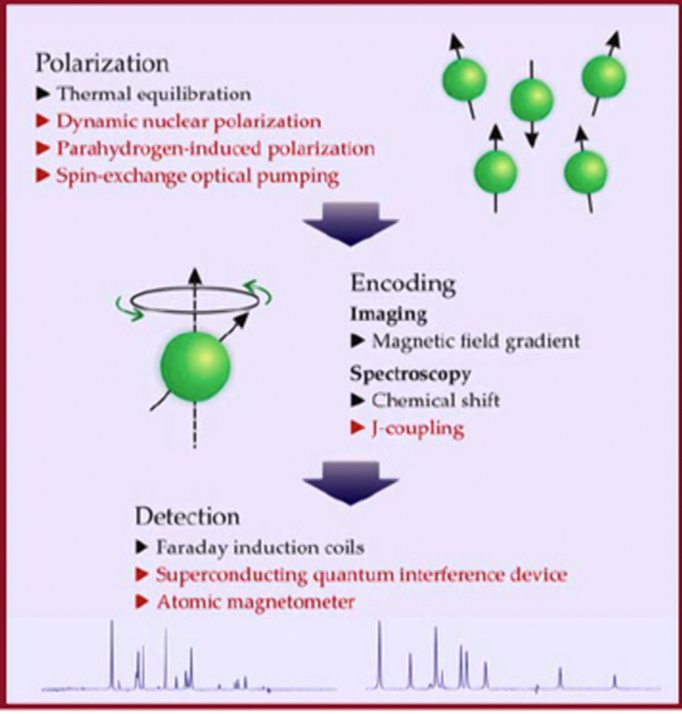
averages by tumbling



C. P. Slichter

Hahn, E.L. & Maxwell, D.E. *Phys. Rev.* **84** 1246-1247 (1952)
Gutowsky, H.S., McCall, D.W., & **Slichter, C.P. J.** *Chem. Phys.* **21**, 279-292 (1953)

Three Stages of NMR



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April 2013 Physics Today www.physicstoday.org

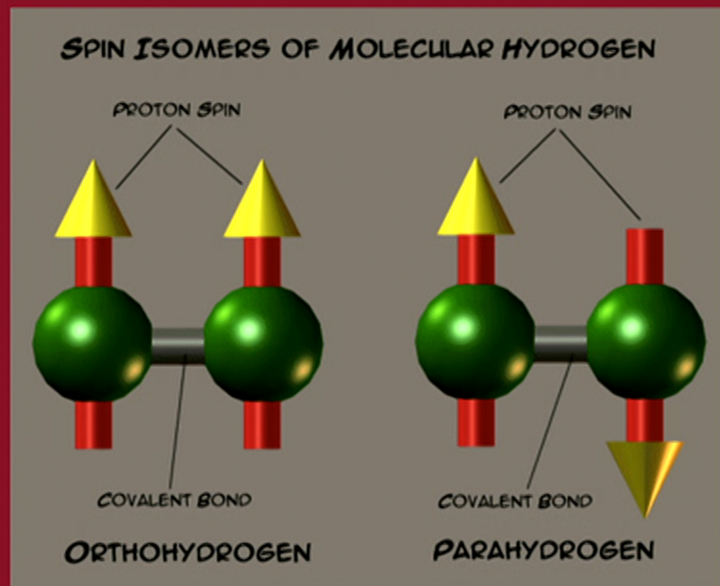
Parahydrogen induced polarization (PHIP)

C. R. Bowers

Daniel P. Weitekamp

Transformation of symmetrization order to nuclear-spin magnetization by chemical reaction and nuclear magnetic resonance
PRL **57** (21): 2645–2648 (1986)

Parahydrogen 101



http://en.wikipedia.org

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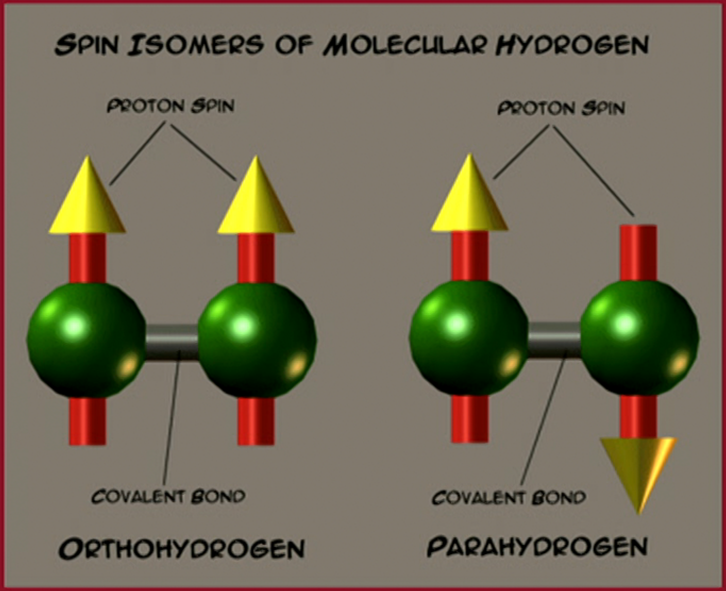
Parahydrogen 101

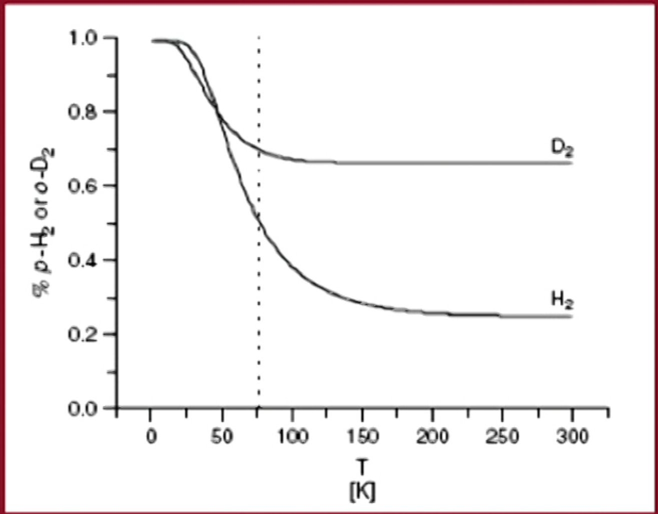


Odd J   Even J

http://en.wikipedia.org

Parahydrogen 102

$$\frac{E_{J=1} - E_{J=0}}{k_B} = 2\theta_{rot} = \frac{\hbar^2}{k_B I} = 174.98\ \mathrm{K}$$



51% para @ 77K

99.9% para @ 4K

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Parahydrogen Induced Polarization

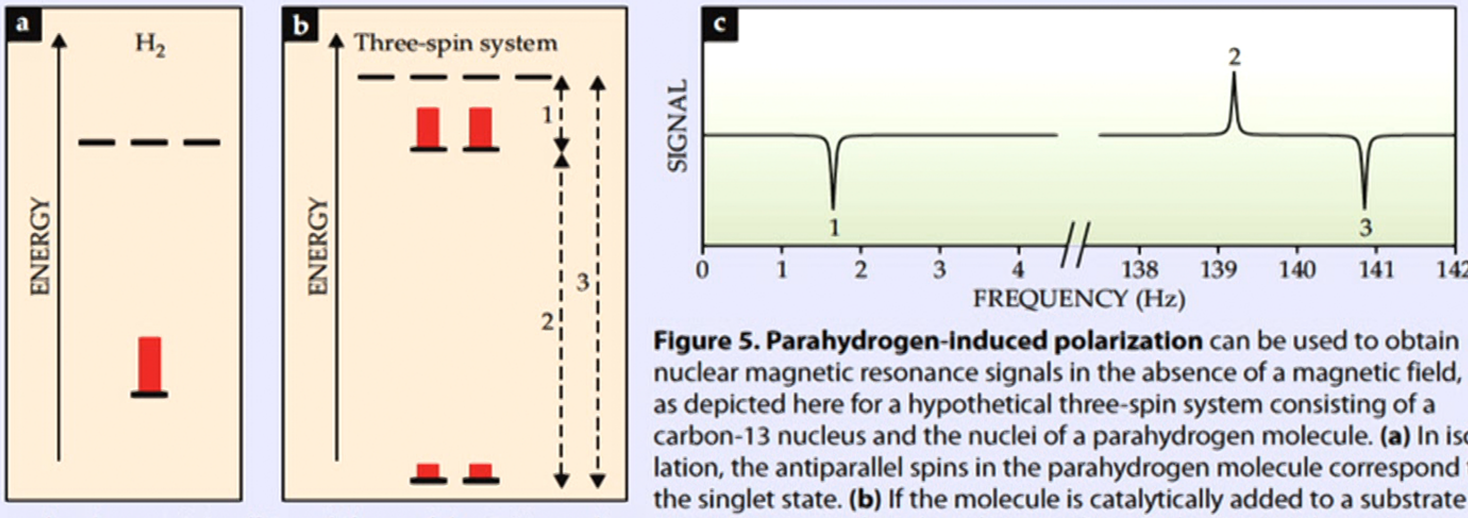
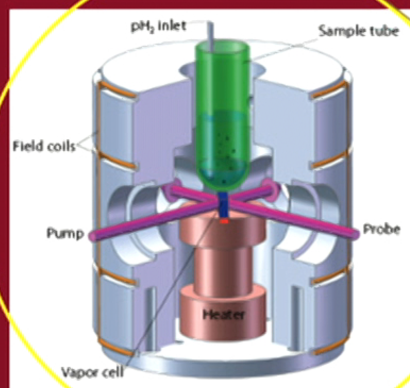
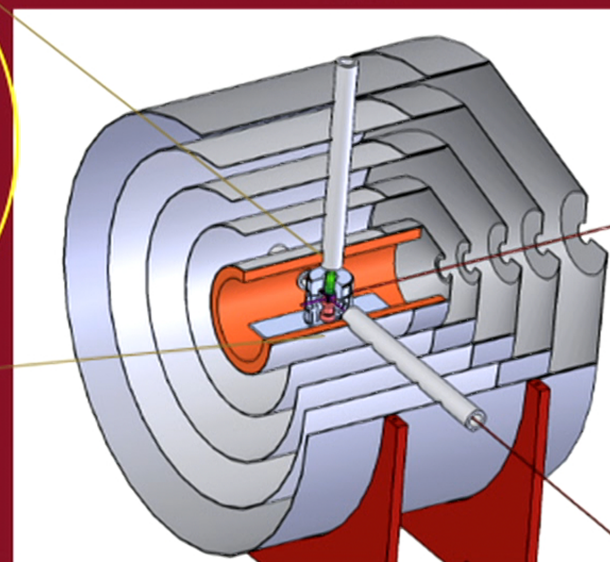


Figure 5. Parahydrogen-induced polarization can be used to obtain nuclear magnetic resonance signals in the absence of a magnetic field, as depicted here for a hypothetical three-spin system consisting of a carbon-13 nucleus and the nuclei of a parahydrogen molecule. **(a)** In isolation, the antiparallel spins in the parahydrogen molecule correspond to the singlet state. **(b)** If the molecule is catalytically added to a substrate molecule containing ^{13}C, and if one of the C–H couplings is much stronger than the other couplings in the system, the symmetry of the parahydrogen spins is broken and in the newly formed three-spin system, the population of the upper doublet is about three times that of the lower one. (Here, we ignore the rotational energies that may be correlated with the nuclear state.) The horizontal lines represent magnetic sublevels and the red rectangles represent the expected populations in each sublevel. **(c)** The simulated spectrum of a system with strong C–H coupling $J_{CH} = 140$ Hz, weak C–H coupling $J_{CH} = -5.2$ Hz, and H–H coupling $J_{HH} = 7.7$ Hz yields the three peaks shown here, which correspond to the three allowed transitions indicated by the dashed arrows in panel b.

NMR inside-out:
pH_2 polarization; laser-mag detection



Magnetic shields



T. Theis
P. Ganssle
G. Kervern
M. P. Ledbetter
D. B.
A. Pines

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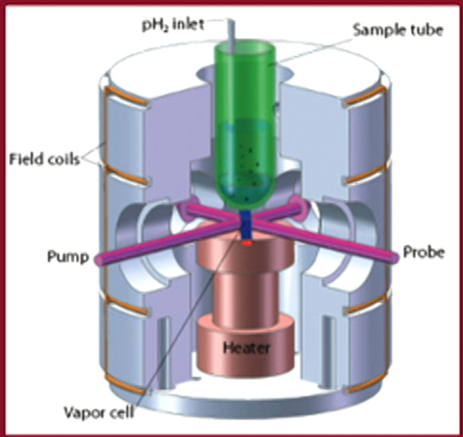
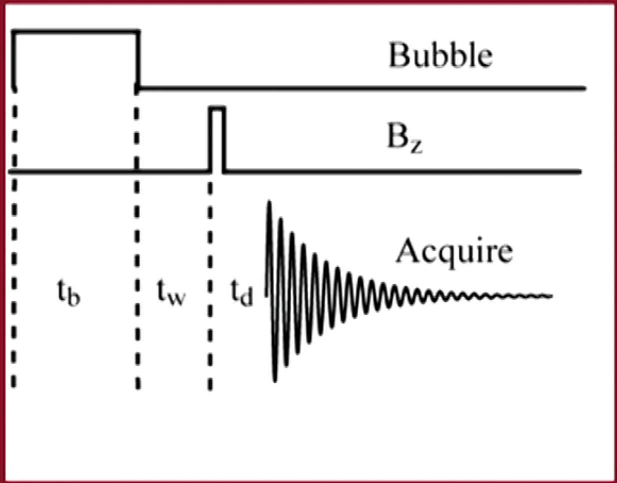
NMR inside-out:
pH_2 polarization; laser-mag detection





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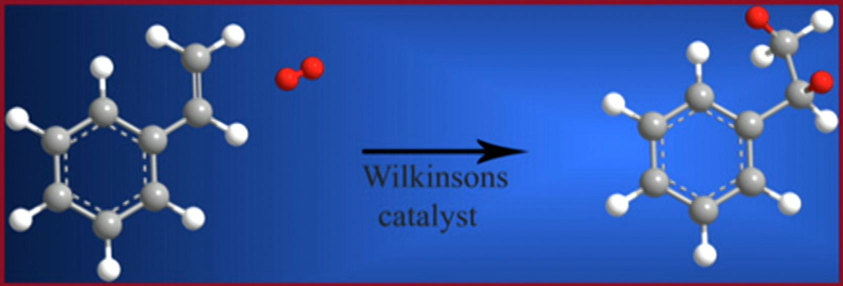
Hydrogenation with pH_2

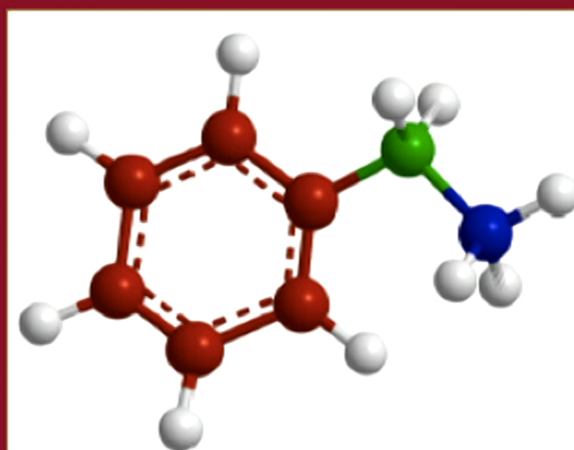


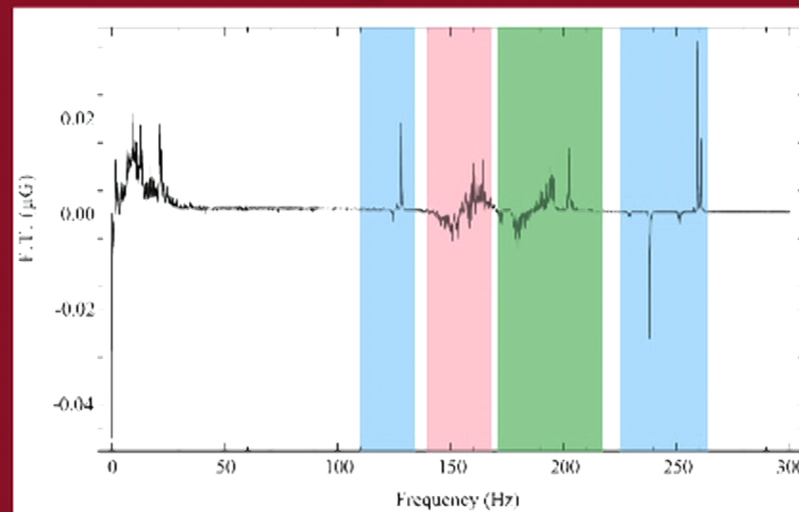
Styrene

Ethylbenzene

Hydrogenation with pH_2

Natural Abundance





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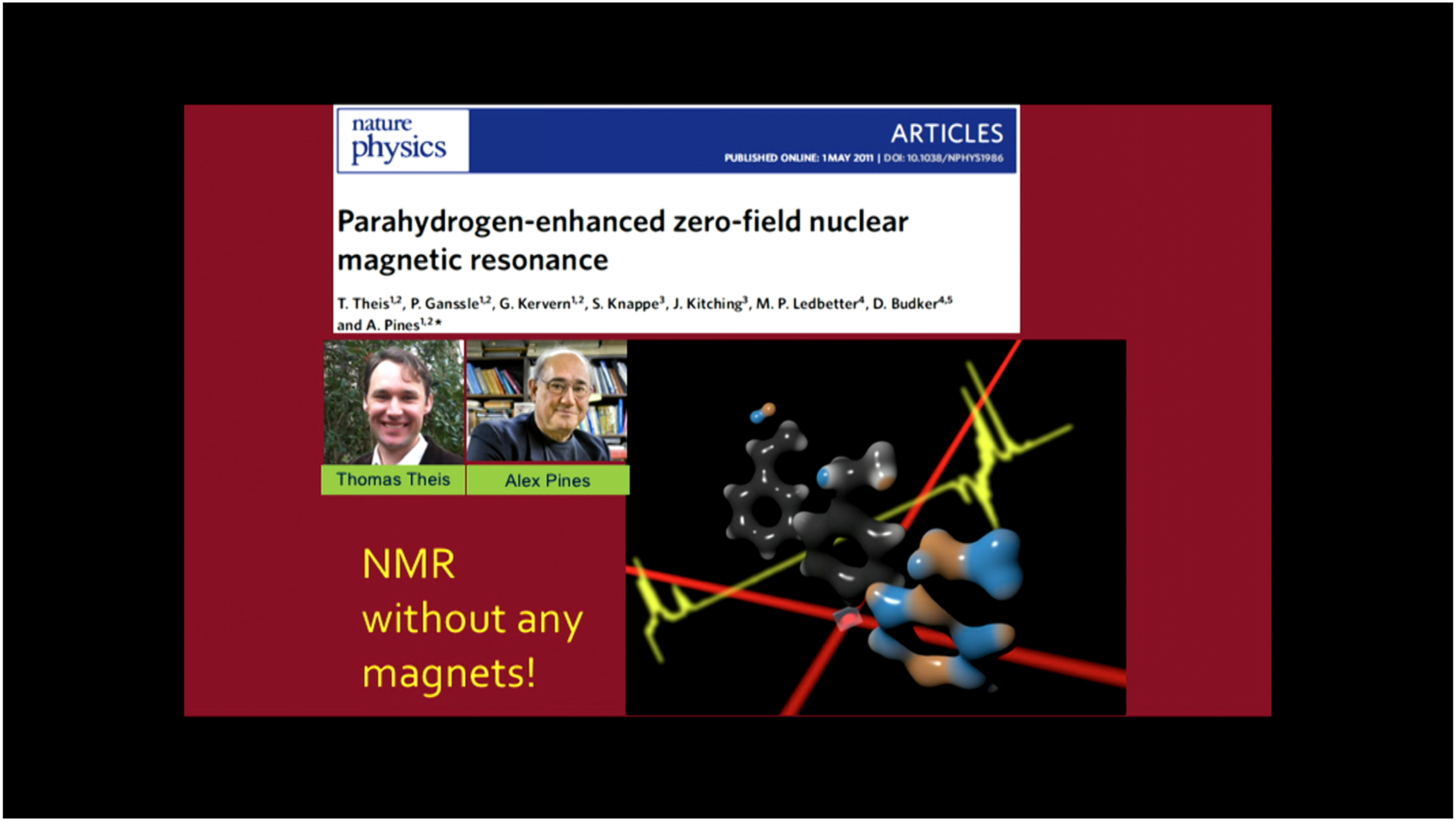
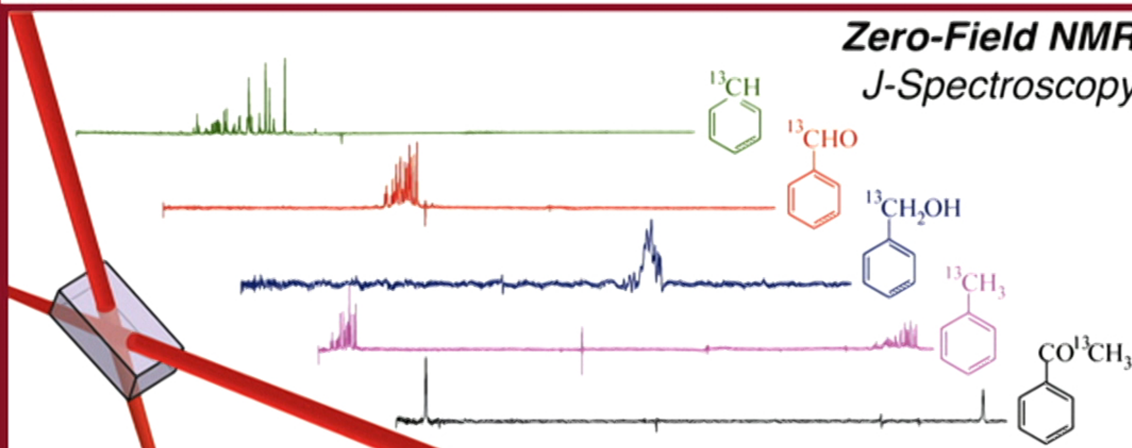
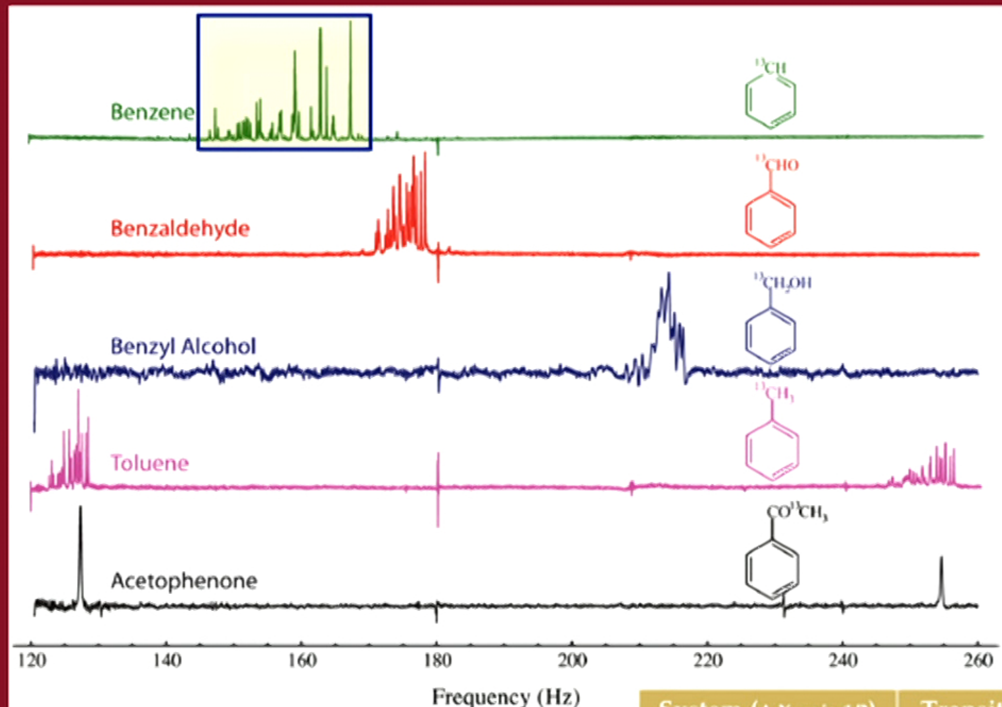

nature physics
ARTICLES
PUBLISHED ONLINE: 1 MAY 2011 | DOI: 10.1038/NPHYS1986
Parahydrogen-enhanced zero-field nuclear magnetic resonance
T. Theis[1,2], P. Ganssle[1,2], G. Kervern[1,2], S. Knappe[3], J. Kitching[3], M. P. Ledbetter[4], D. Budker[4,5] and A. Pines[1,2*]
Thomas Theis
Alex Pines
NMR without any magnets!

JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
135 (9) (2013) Article
pubs.acs.org/JACS

High-Resolution Zero-Field NMR *J*-Spectroscopy of Aromatic Compounds

John W. Blanchard,[*,†,‡] Micah P. Ledbetter,[∥] Thomas Theis,[†,‡,⊥] Mark C. Butler,[†,‡,#] Dmitry Budker,[§,∥] and Alexander Pines[*,†,‡]





- ~ 100 µl samples
- First-order line positions are well resolved
- Line structure reports higher-order couplings
- 11 mHz linewidth (HWHM): high resolution

System (A,X: spin 1/2)	Transitions @
AX	J
AX_2	3J/2

JACS JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
135 (9) (2013)
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High-Resolution Zero-Field NMR *J*-Spectroscopy of Aromatic Compounds

John W. Blanchard,*,†,‡ Micah P. Ledbetter,‖ Thomas Theis,†,‡,⊥ Mark C. Butler,†,‡,# Dmitry Budker,§,‖ and Alexander Pines*,†,‡

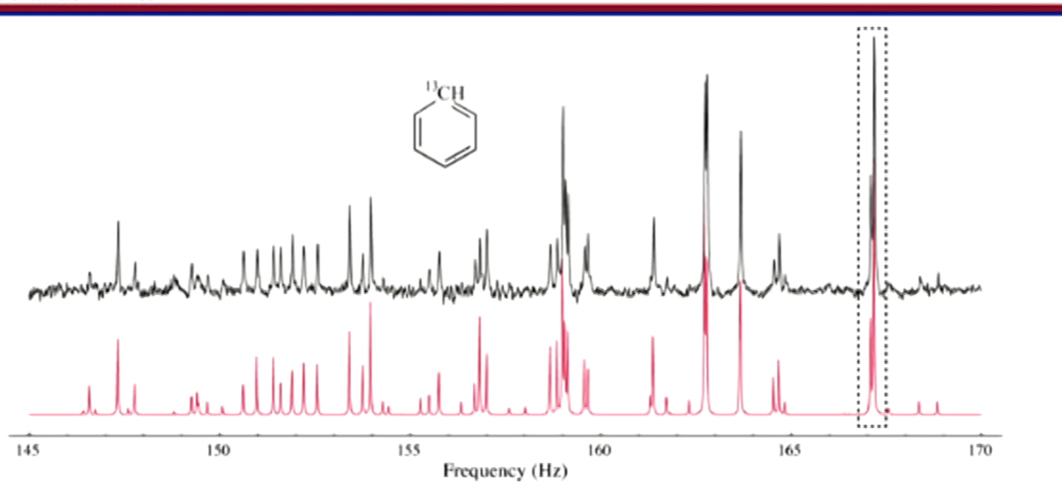

Figure 2. Experimental (upper trace) and simulated (lower trace) spectrum of benzene-$^{13}C_1$ in the neighborhood of $^1J_{CH}$. Inset shows fitting of two high-frequency peaks with 11 mHz half-width at half-maximum, consistent with Fourier resolution limited by 80s acquisition time.

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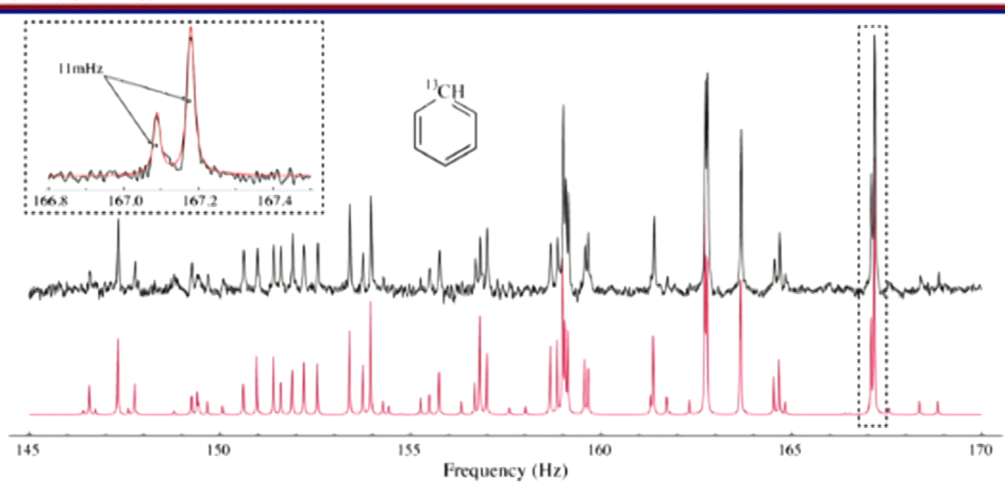

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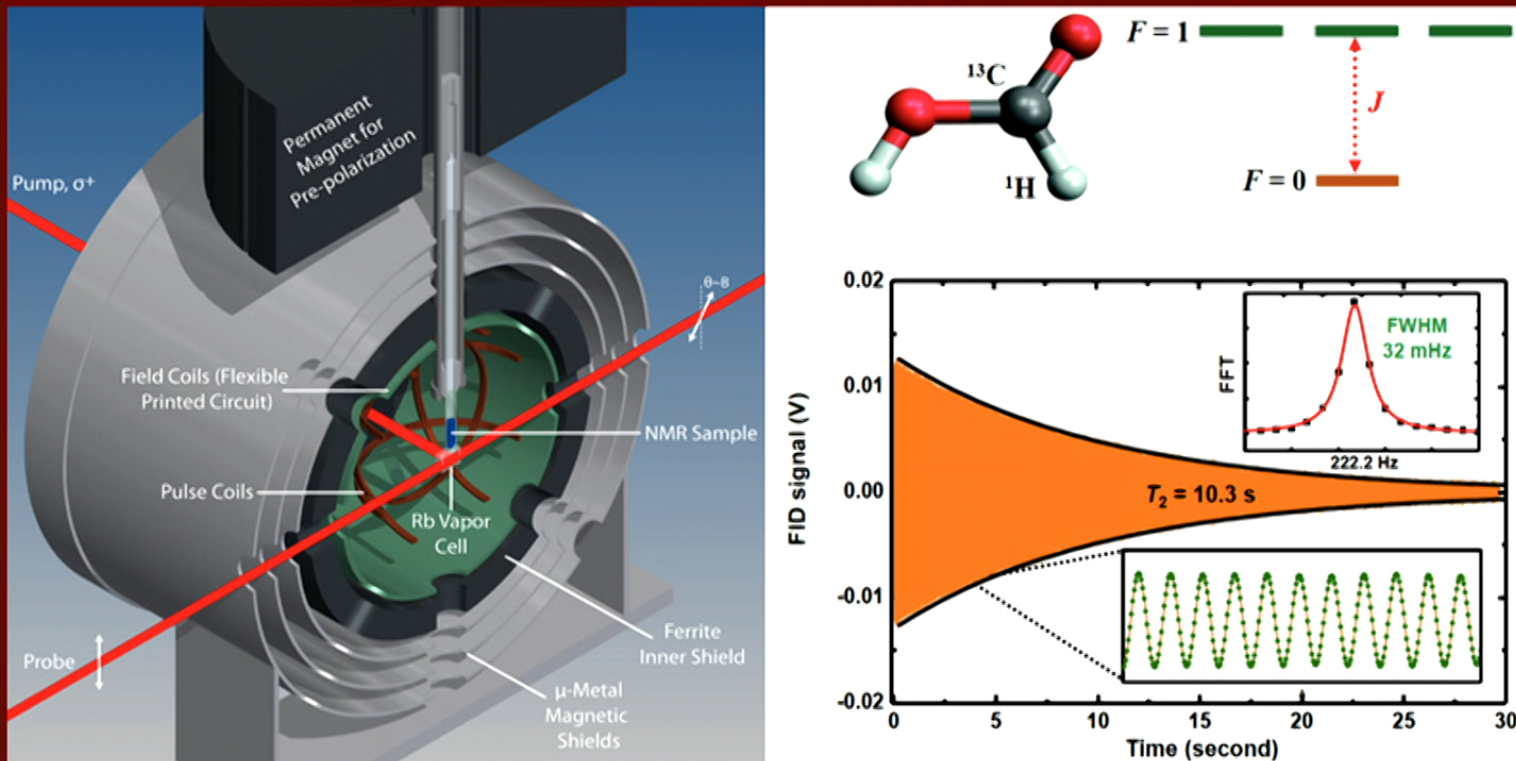
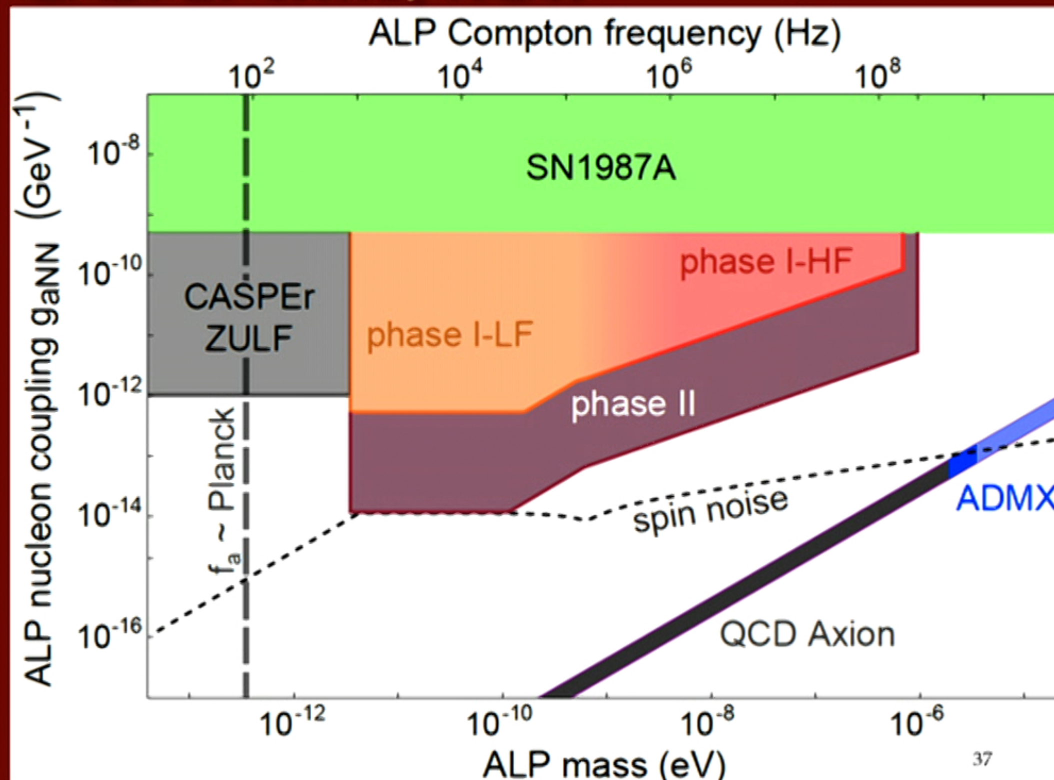
CASPEr-NOW with ZULF NMR

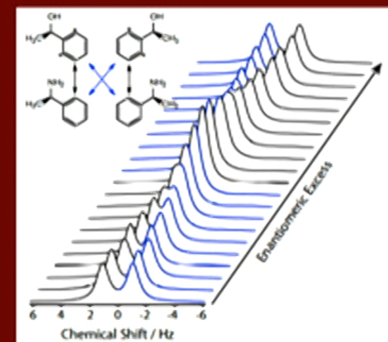


CASPEr-Wind/NOW



Summary: fundamental physics with weird NMR

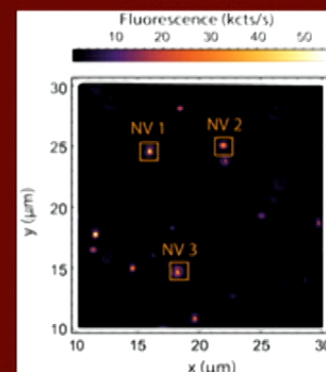
- Chiral parity violation in NMR — New



- Cosmic Axion Spin Precession Experiment
  - CASPEr-E

  - CASPEr-Wind/ZULF/Now — New

- Zero- and Ultralow-Field NMR
  - ParaHydrogen Induced Polarization
  - J-coupling spectroscopy @ ZULF
  - NV-ZULF NMR — New



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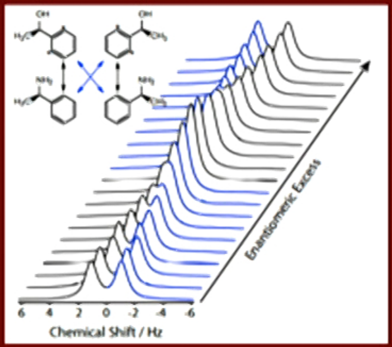

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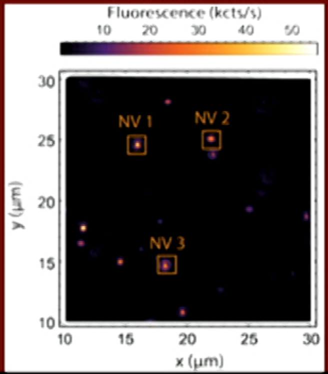

There is more to do with ZULF NMR!

Experimental Benchmarking of Quantum Control in Zero-Field Nuclear Magnetic Resonance

Min Jiang, Teng Wu, John W. Blanchard, Guanru Feng, Xinhua Peng, Dmitry Budker

(Submitted on 21 Aug 2017)

Zero-field nuclear magnetic resonance (NMR) provides complementary analysis modalities to those of high-field NMR and allows for ultra-high-resolution spectroscopy and measurement of untruncated spin-spin interactions. Unlike for the high-field case, however, universal quantum control -- the ability to perform arbitrary unitary operations -- has not been experimentally demonstrated in zero-field NMR. This is because the Larmor frequency for all spins is identically zero at zero field, making it challenging to individually address different spin species. We realize a composite-pulse technique for arbitrary independent rotations of ^{1}H and ^{13}C spins in a two-spin system. Quantum-information-inspired randomized benchmarking and state tomography are used to evaluate the quality of the control. We experimentally demonstrate single-spin control for ^{13}C with an average gate fidelity of $0.9960(2)$ and two-spin control via a controlled-not (CNOT) gate with an estimated fidelity of 0.99. The combination of arbitrary single-spin gates and a CNOT gate is sufficient for universal quantum control of the nuclear spin system. The realization of complete spin control in zero-field NMR is an essential step towards applications to quantum simulation, entangled-state-assisted quantum metrology, and zero-field NMR spectroscopy.

Comments: 19 pages, 3 figures
Subjects: **Quantum Physics (quant-ph)**; Atomic Physics (physics.atom-ph); Chemical Physics (physics.chem-ph)
Cite as: arXiv:1708.06324 **[quant-ph]**


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A hypothetical effect of Maxwell-Proca electromagnetic stresses on galaxy rotation curves

D.D. Ryutov, Dmitry Budker, and V.V. Flambaum

Dmitry Budker

Helmholtz-Institute Mainz — UC Berkeley Physics

Johannes Gutenberg U. — NSD LBNL

GNOME meeting @ Fribourg, 20 August 2017

2

Finite Photon Mass?

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

γ (photon)

$I(J^{PC}) = 0,1(1^{--})$

γ MASS

Results prior to 2008 are critiqued in GOLDHABER 10. All experimental results published prior to 2005 are summarized in detail by TU 05.

The following conversions are useful: $1\text{ eV} = 1.783 \times 10^{-33}\text{ g} = 1.957 \times 10^{-6}\ m_e$; $\lambda\!\!\!^{-}_C = (1.973 \times 10^{-7}\text{ m}) \times (1\text{ eV}/m_\gamma)$.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1 \times 10^{-18}$		[1] RYUTOV	07		MHD of solar wind
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.8 \times 10^{-14}$		[2] BONETTI	16		Fast Radio Bursts, FRB 150418
$<1.9 \times 10^{-15}$		[3] RETINO	16		Ampere's Law in solar wind
$<2.3 \times 10^{-9}$	95	[4] EGOROV	14	COSM	Lensed quasar position
		[5] ACCIOLY	10		Anomalous magn. mom.
$<1 \times 10^{-26}$		[6] ADELBERGER	07A		Proca galactic field
no limit feasible		[6] ADELBERGER	07A		γ as Higgs particle