Quantum Information Processing IRC

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Kyriakos Porfyrakis
David Pettifor
Alexei Tyryshkin
Andrew Watt

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www.qipirc.org

QIPRC

QIP IRC postdoctoral opportunities

Postdoctoral Research Assistant in the Theory of Quantum Information Processing

- Postdoctoral Research Assistant in the Theory of Quantum Information Processing Grade 7 / Salary in the range £25,889 to £27,465 pa / Job Ref: DJ07/021. The closing date for applications is 31 August 2007.

Theoretical studies of electrically detected magnetic resonance in carbon nanostructures

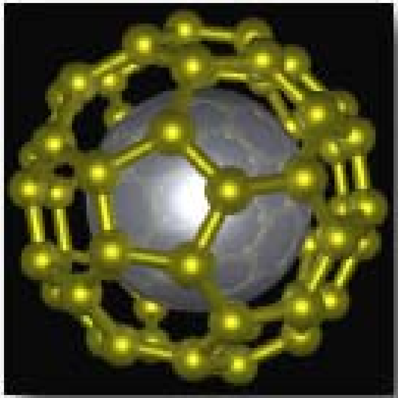
- Theoretical studies of electrically detected magnetic resonance in carbon nanostructures. Grade 7 / Salary in the range £25,889 to £29,138 pa / Job Ref: DJ07/020. The closing date for applications is 31 August 2007.

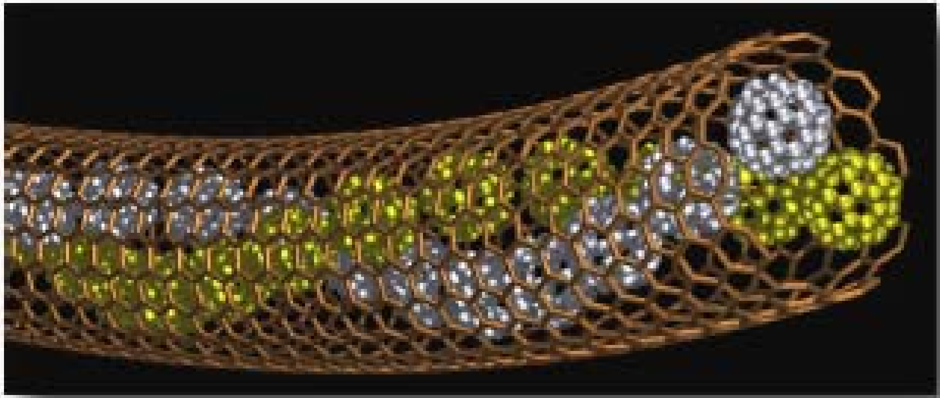
Carbon Nanomaterials for Quantum Information Processing

- Carbon Nanomaterials for Quantum Information Processing Grade 7 / Salary in the range £26,666 to £29,139 pa / Job Ref: DJ07/022. The closing date for applications is 28 September 2007.

www.materials.ox.ac.uk/vacancies/index.htm

Spins in carbon nanomaterials for qubits





Quantum transport and dynamics in nanostructures

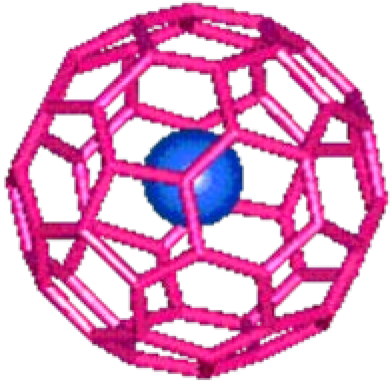
Windsor

11th August 2007

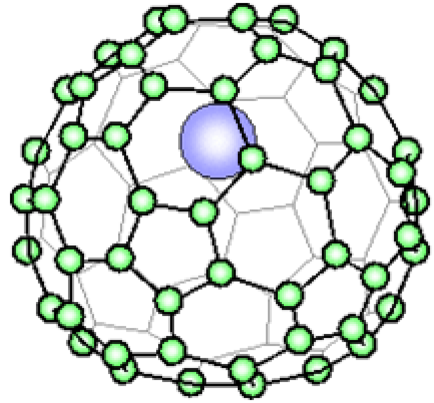
www.qipirc.org

Atoms in fullerenes

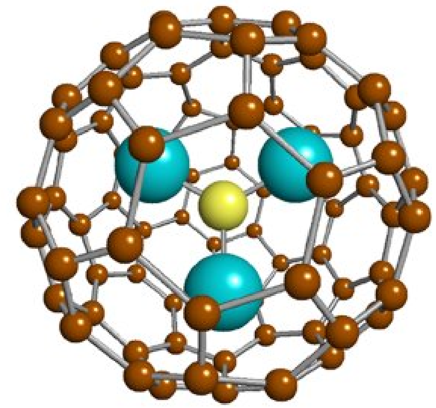
The fullerene cage can encapsulate other species:



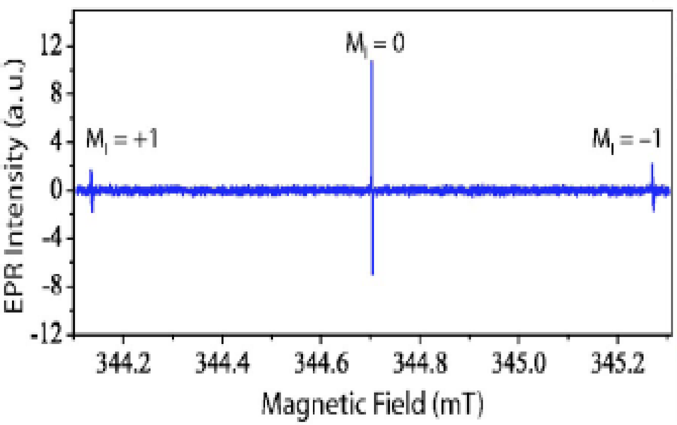
$N@C_{60}$

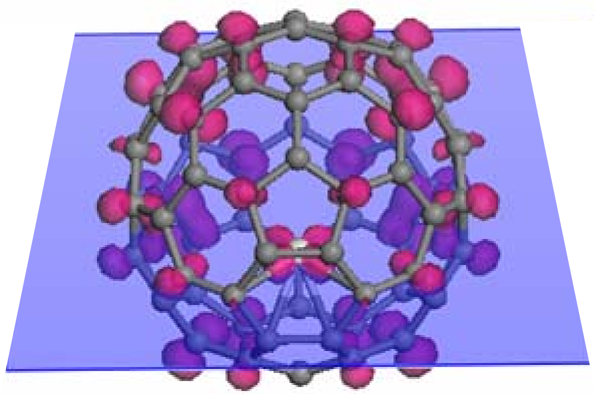


Sc, La, Ce, ... $@C_{82}$

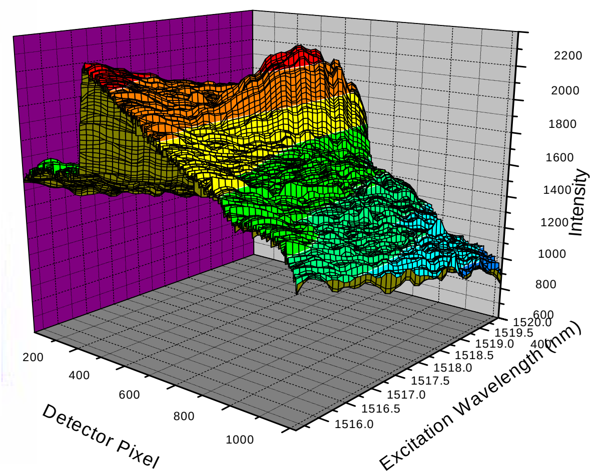


$Er_3N@C_{80}$





Spin density: > 0.01 μ_B



1-D spin arrays

Gas-Phase Nanotube Filling (300-500^{o}C):

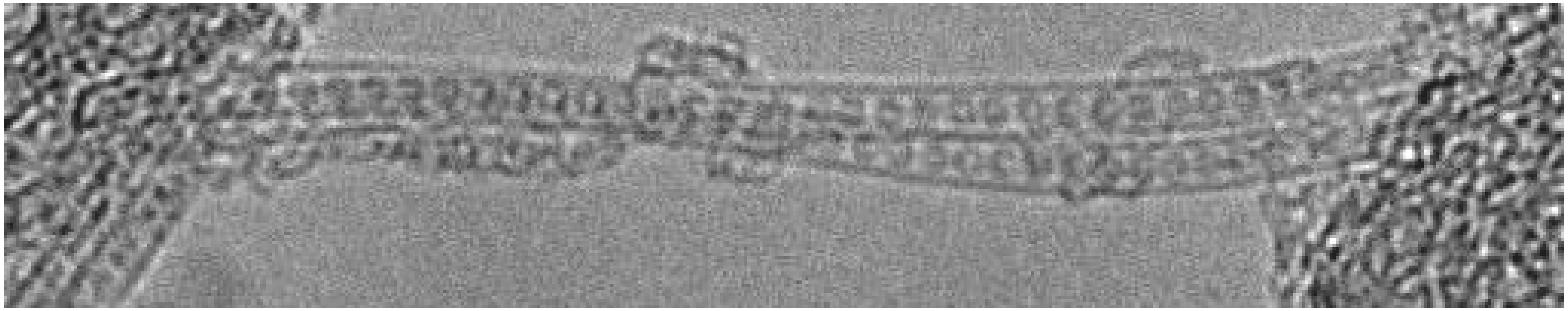
Fullerene

C_{60}, C_{70}, C_{82}, $Sc@C_{82}$, $Ce@C_{82}$, $Nd@C_{82}$
$Sc_2@C_{80}$, $Ce_2@C_{80}$, $Er_3N@C_{80}$, $Sc_3N@C_{80}$

+

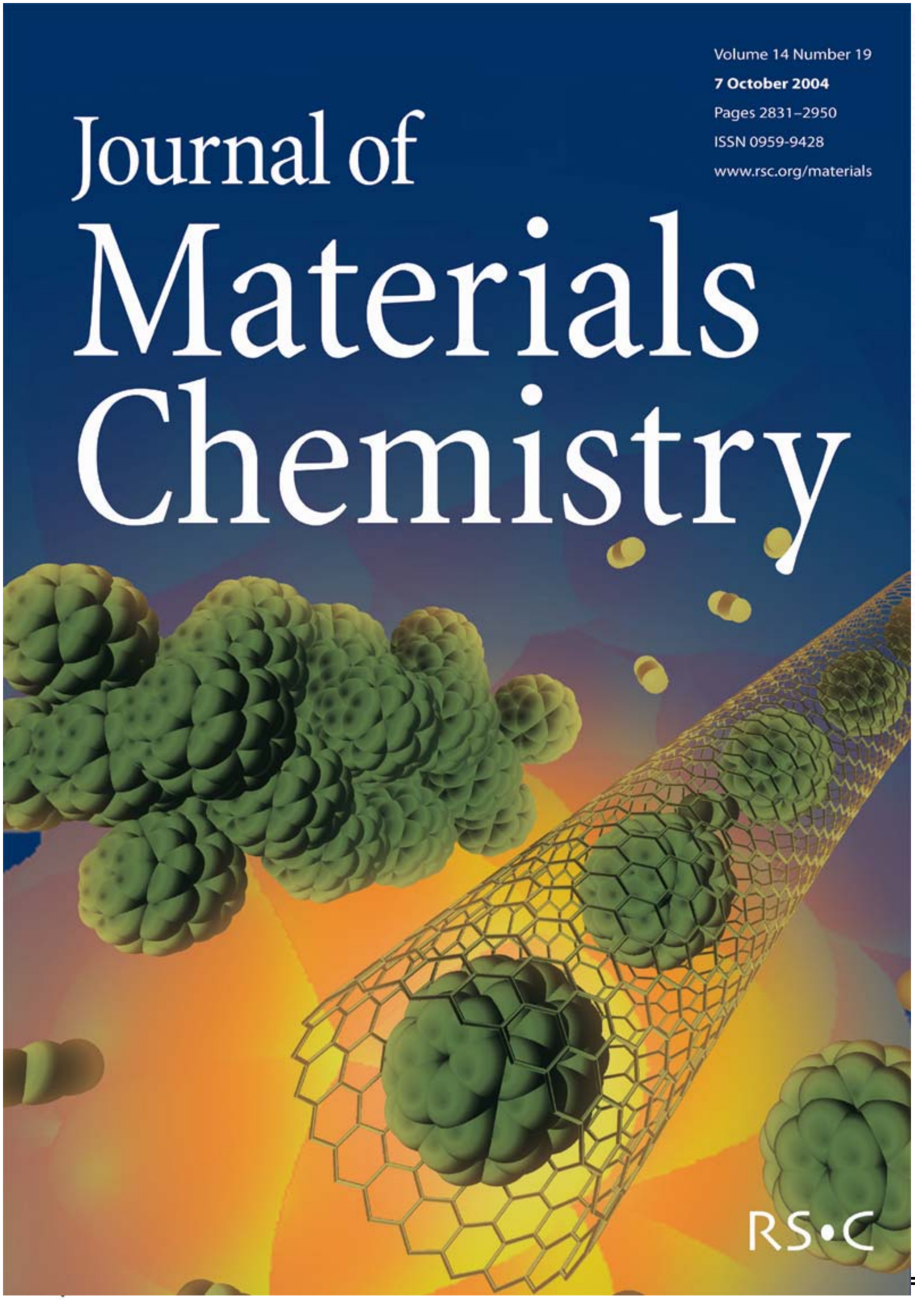
Nanotubes

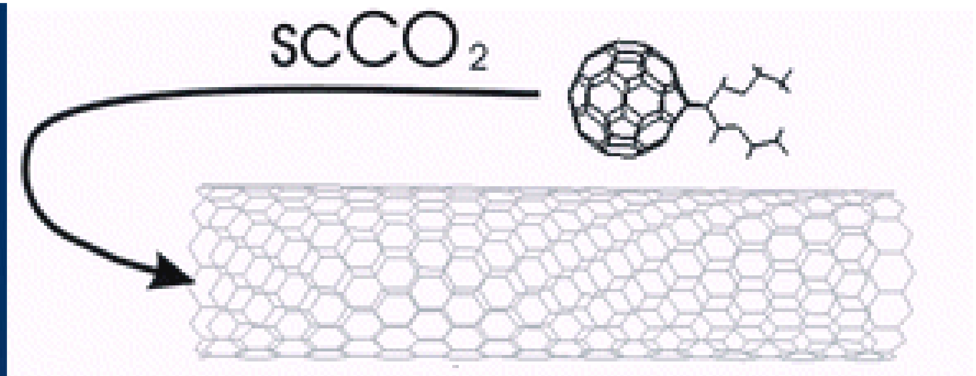
(diameters 1.36nm and 1.49nm)

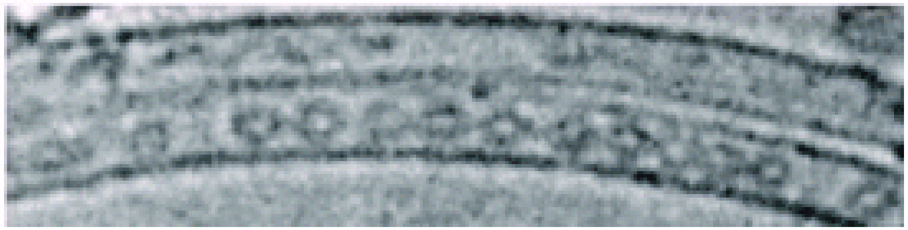


www.nanotech.org

Filling nanotubes using supercritical CO_2



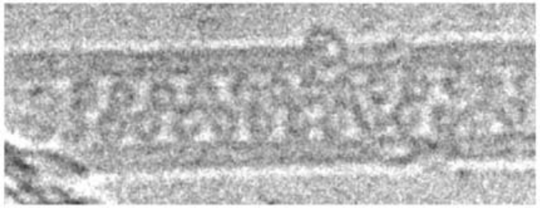


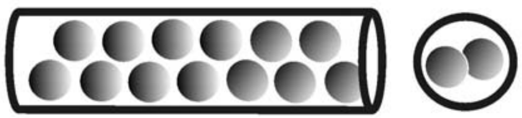


A.N. Khlobystov *et al.*,
J. Mater. Chem. **14**,
2852-2857 (2004)

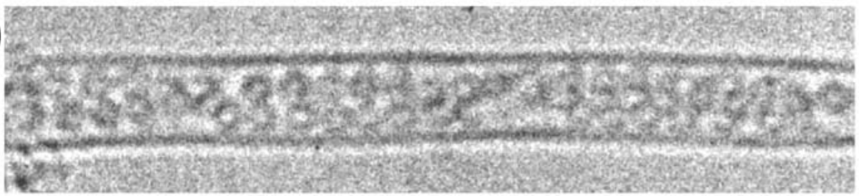
Fullerene molecules in carbon nanotubes

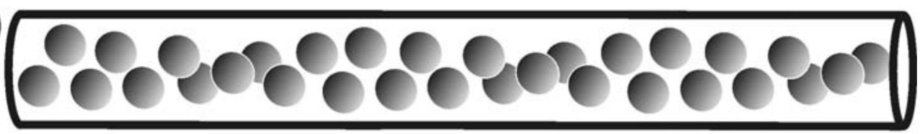
(a, b) C_{60}@DWNTs zigzag

a)


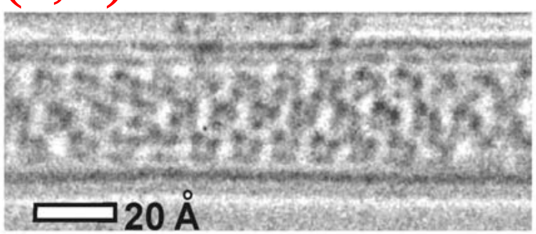
b)


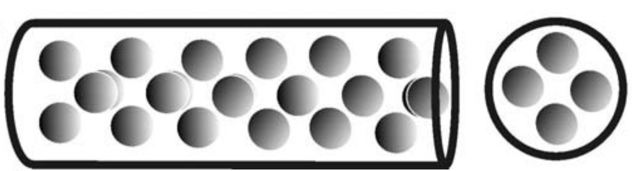
(c, d) C_{60}@SWNT chiral

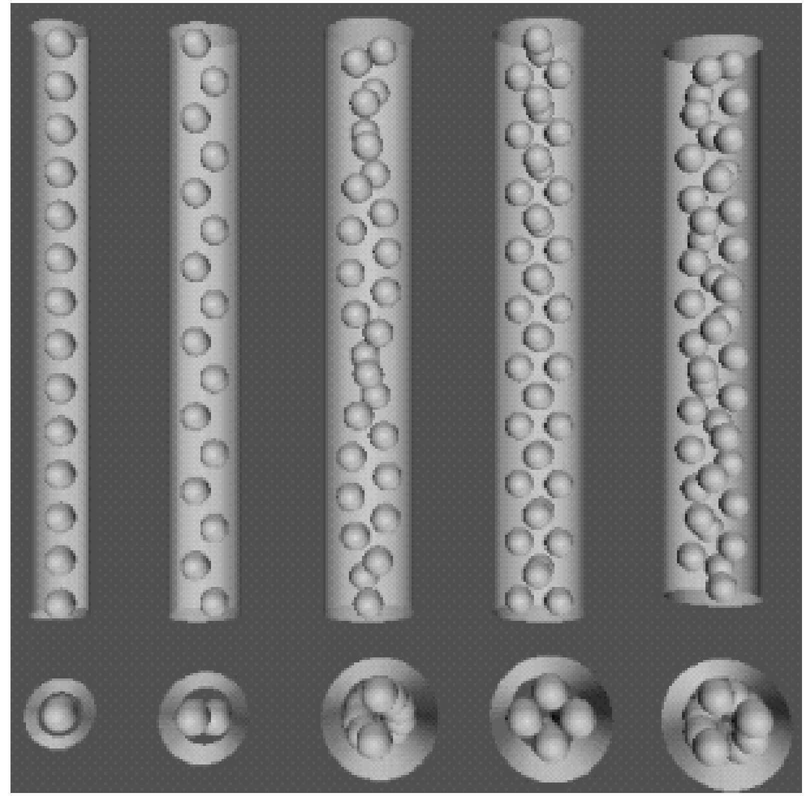
c)


d)


(e, f) two-molecule layer

e)


f)




Simulated annealing

Hodak and Girifalco

Phys Rev B **67**, 075419 (2003)

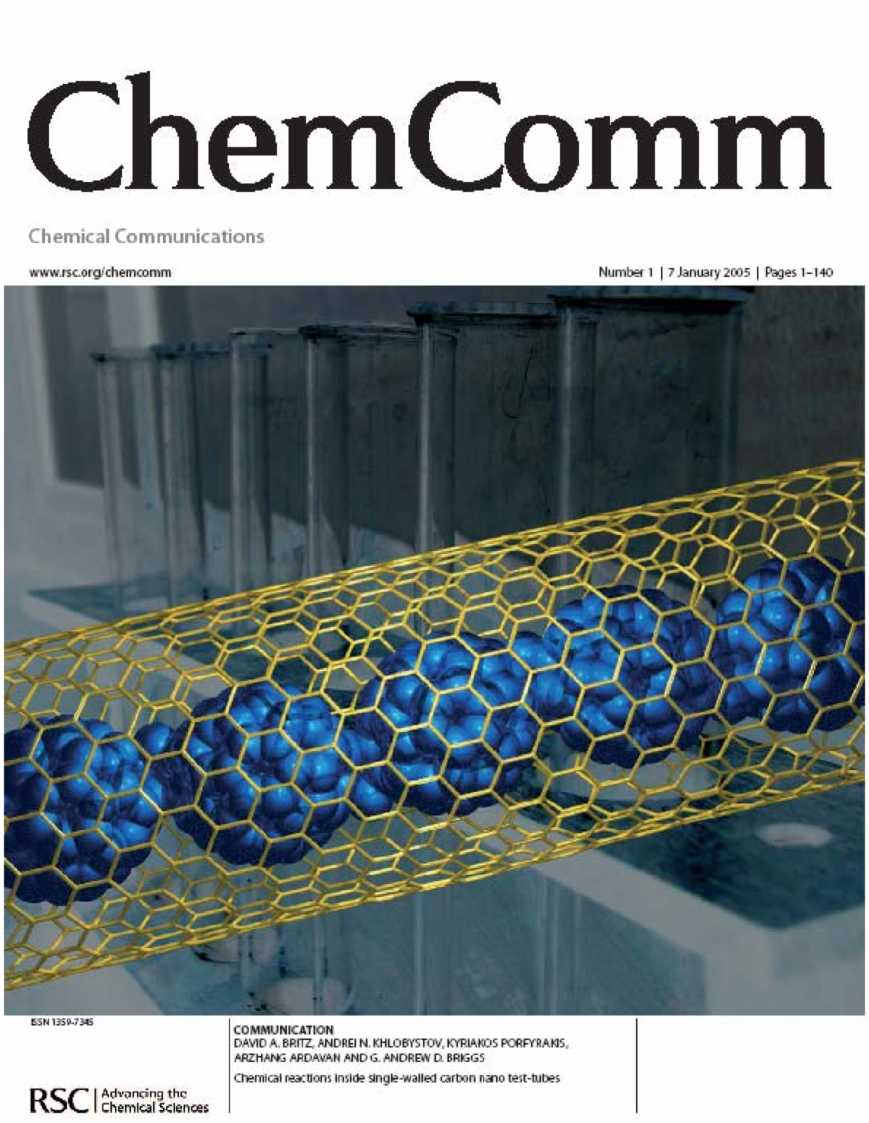
A.N. Khlobystov *et al.*

Phys. Rev. Lett. **92**, 245507 (2004)

QIRC

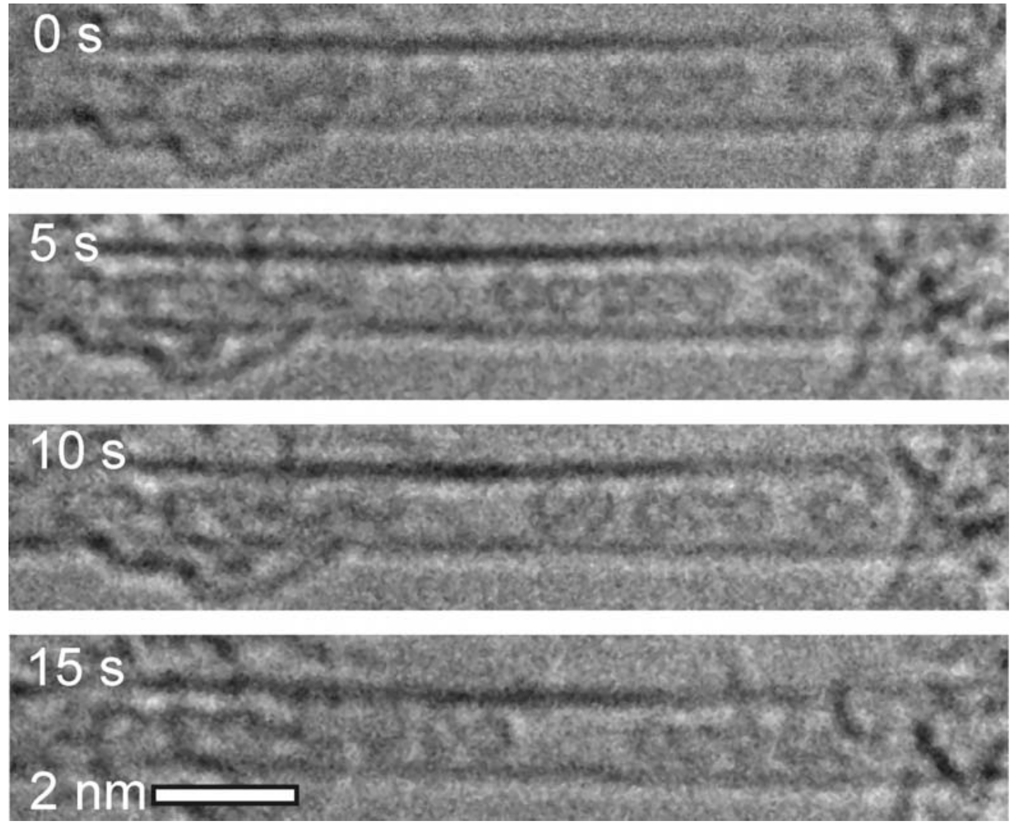
10 yoctolitre test tubes

Chemical reactions inside single-walled carbon nano test-tubes. *Chem. Commun.* **2005**, 37-39 (2005)
Hot Paper (19 November 2004)
cover story of Issue 1 of 40th Anniversary Year
Blueprint **5**, 3 (18 November 2004)
New Scientist (23 November 2004)
BBC News
Iran Daily Newspaper (25 November 2004) p. 4
Financial Times 35621, 13 (26 November 2004)
Chemical & Engineering News **82** (48) 7 (29 November 2004)
Chemistry World **12** (December 2004)
Editor's Choice, *Science* **306**, 1863 (10 December 2004)
Smallest reactor ever, *Materials Today* **8** (1) 9 (January 2005)
"The smallest test tube" in *The Guinness Book of World Records* (2006)



D.A. Britz *et al.*, *Chem. Commun.* **2005**, 37-39.

10 yoctolitre test tubes

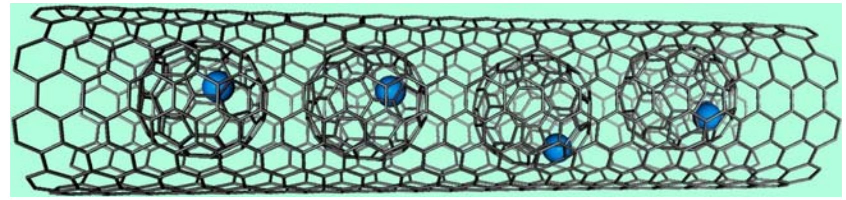


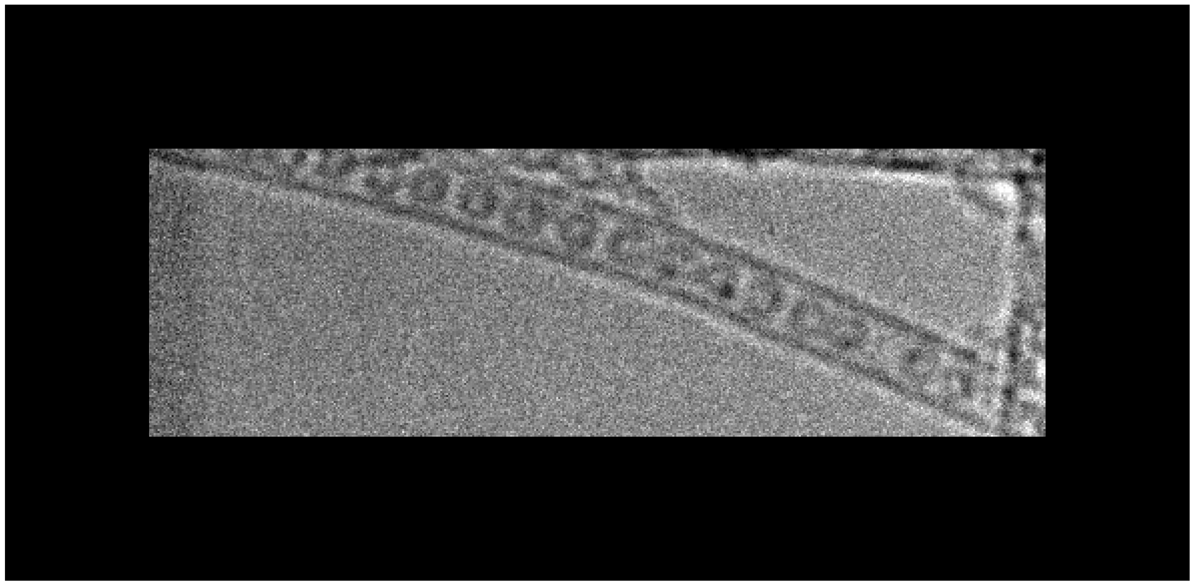
Chemical reactions inside single-walled carbon nano test-tubes.

D.A. Britz *et al.*, *Chem. Commun.* **2005**, 37-39.

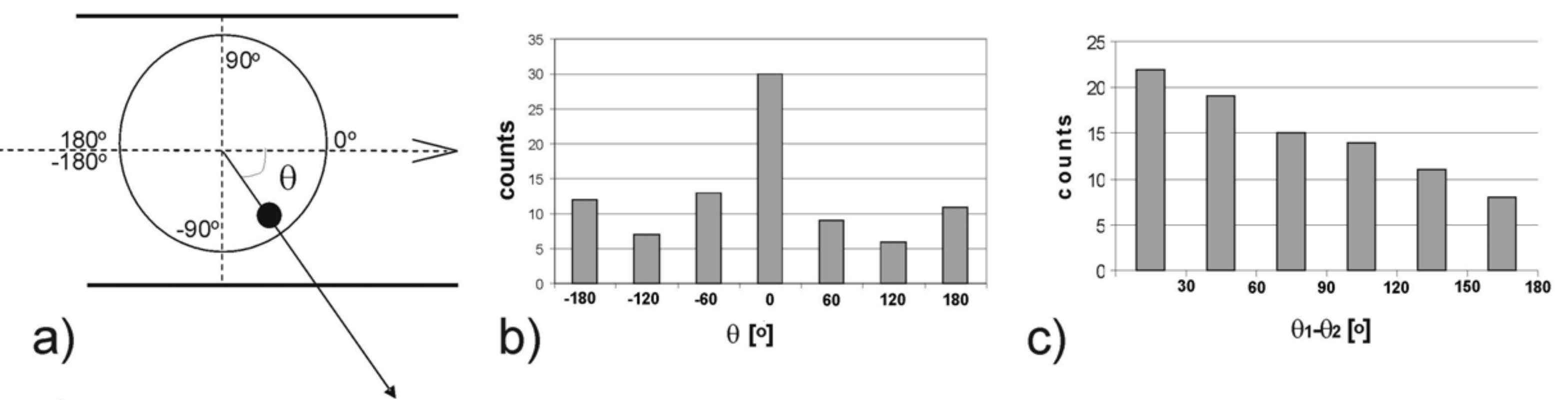
$Ce@C_{82}$ in SWCNT

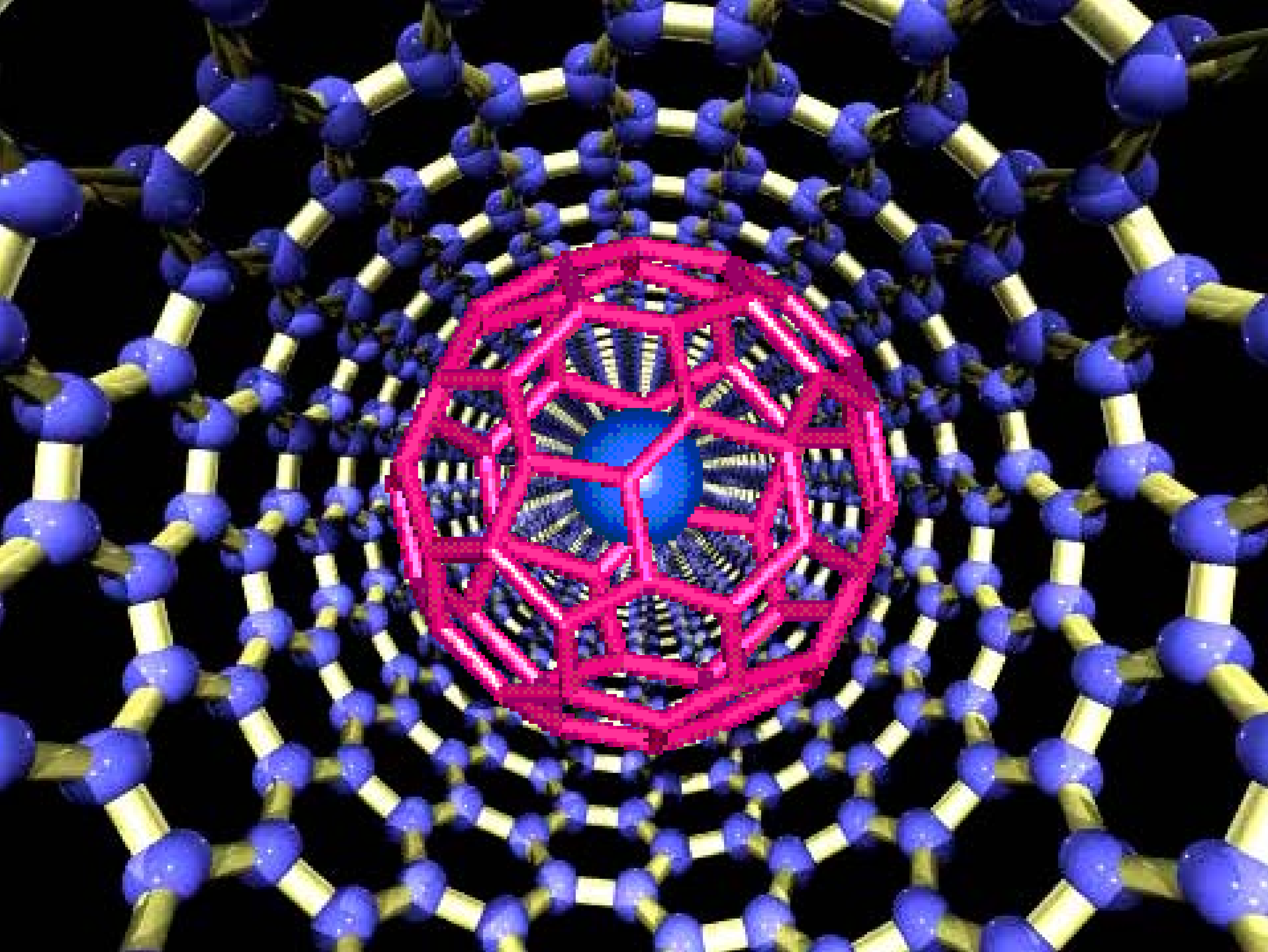
A. Khlobystov *et al. Angewandte Chemie International Edition* **43**, 1386-1389 (2004, "hot paper")



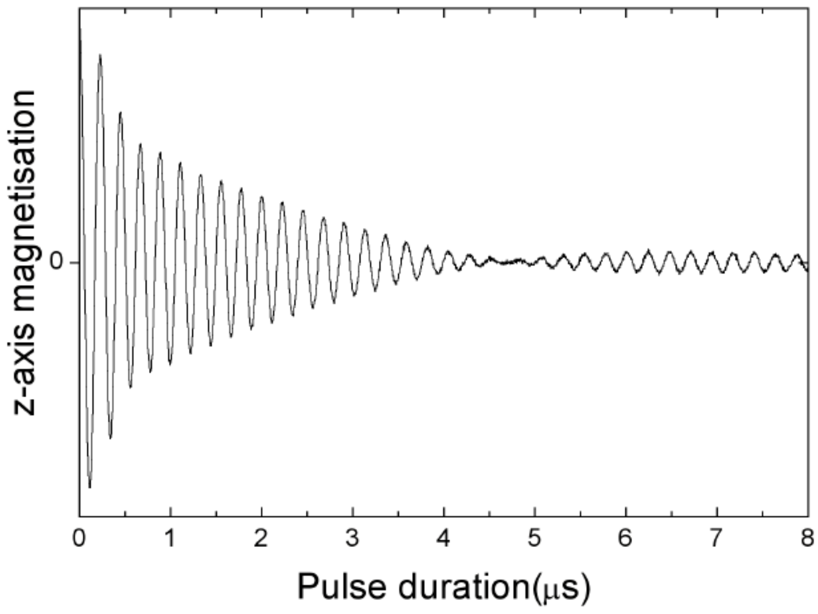


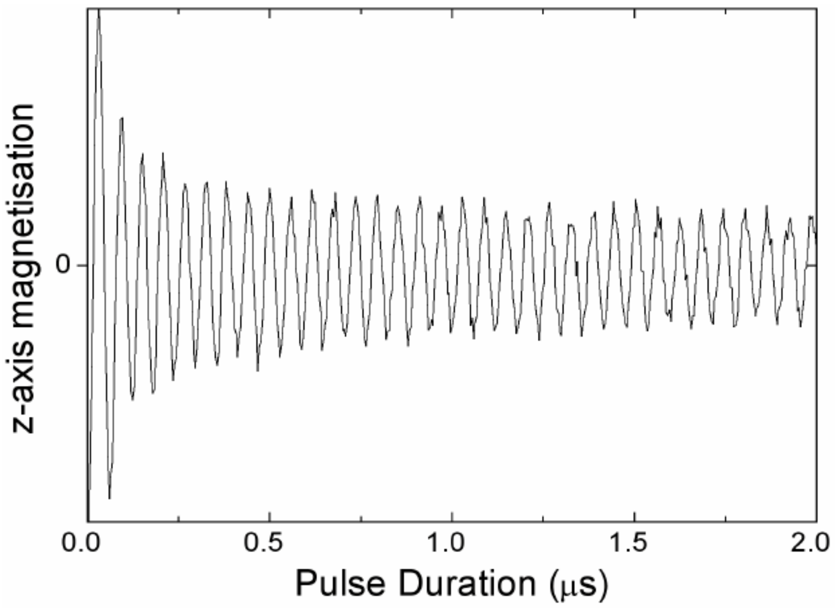
5 nm





Imperfect pulses





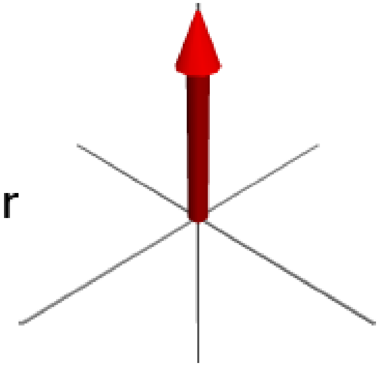
The Rabi oscillation envelope is determined by inhomogeneities in the microwave field, not by spin coherence time.

A smaller sample fares better (note different time scale), but does not eliminate the problem.

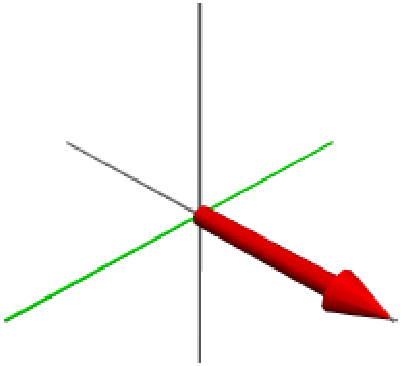
Imperfect pulses

How well can we perform unitary transformations in an ESR spectrometer?

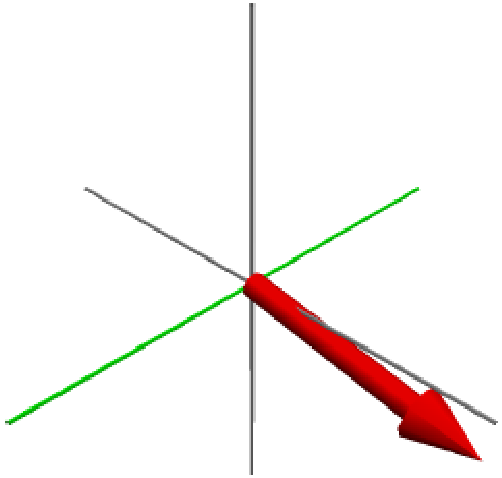
Doing a $\pi/2$-pulse or give



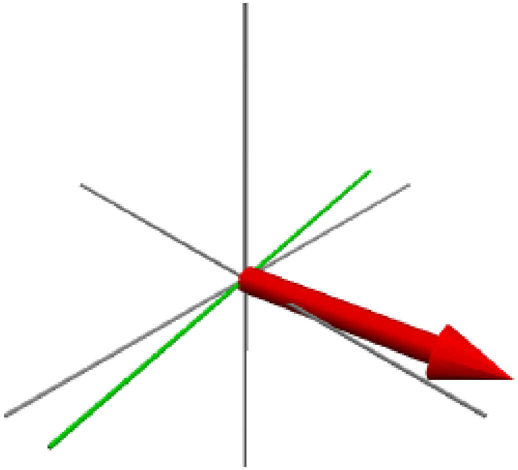
should



But we might get rotation angle errors



or rotation axis errors:



And can we perform complicated pulse sequences?

BB1 sequence for spin manipulation

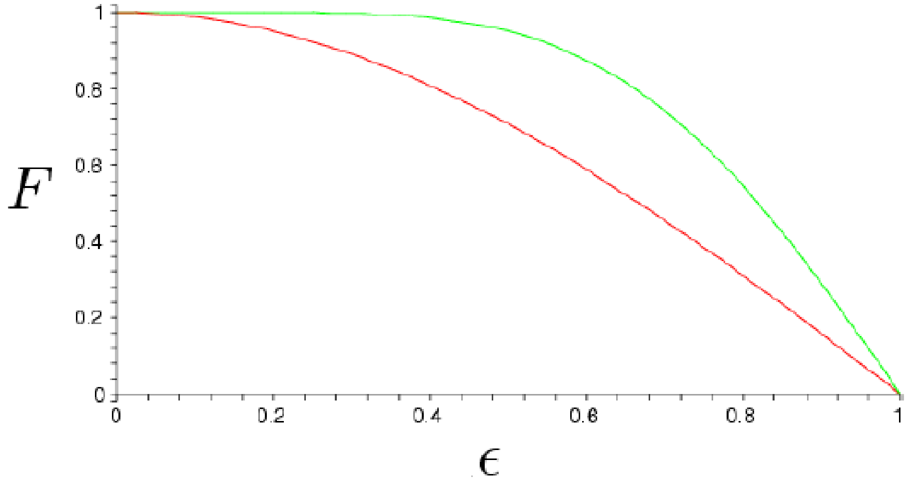
Defining the fidelity of two unitary operators *A*, *B*, as

$$F(A,B) = \frac{1}{2}\mathrm{Tr}(A.B^{-1})$$

expand fidelity of composite operator in powers of the error,

$$F(\mathcal{R}_{\mathrm{composite}}, \mathcal{R}_\theta^0) = 1 + F_2\epsilon^2 + F_4\epsilon^4 + \ldots$$

where $F_i = F_i(\theta, \alpha, \beta)$

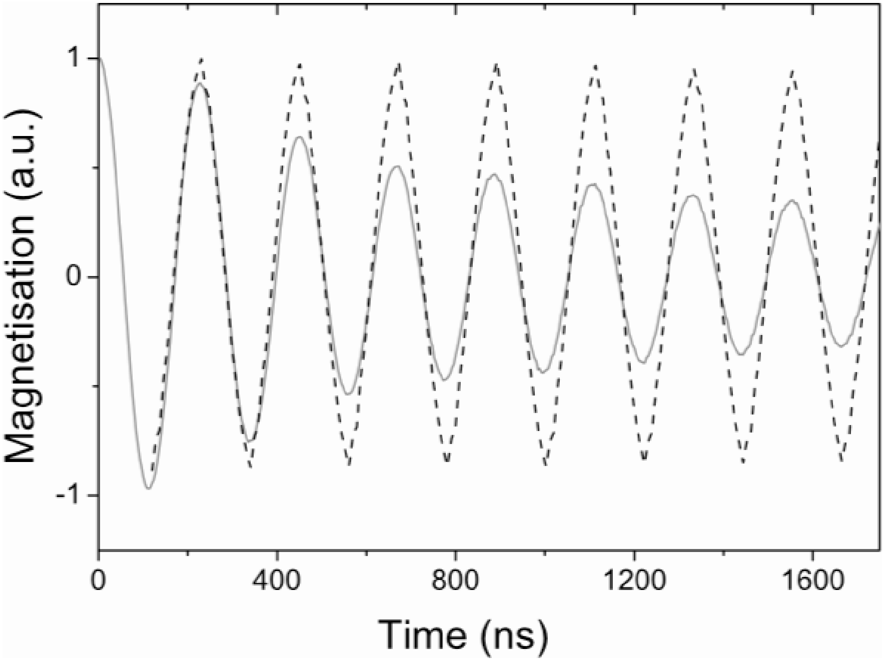


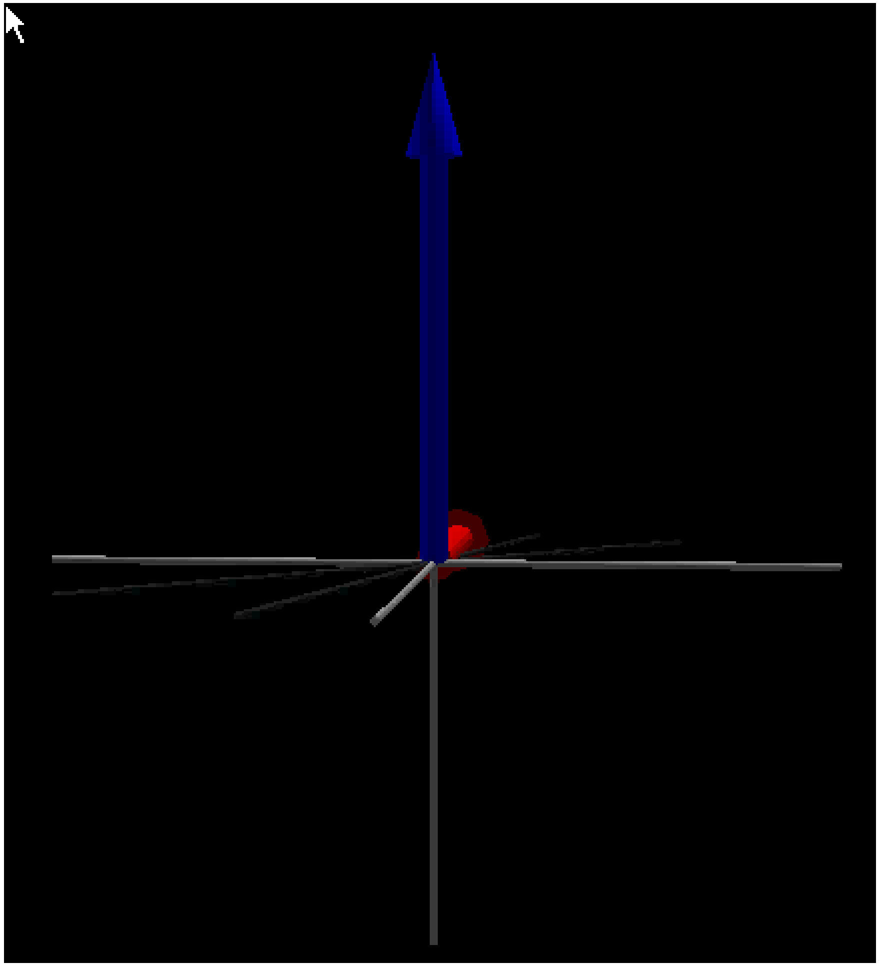
The BB1 composite sequence:

$(1+\epsilon)\pi_x$ – $(1+\epsilon)\pi_{104.5°}$ – $(1+\epsilon)2\pi_{313.4°}$ – $(1+\epsilon)\pi_{104.5°}$

is a better π_x rotation.

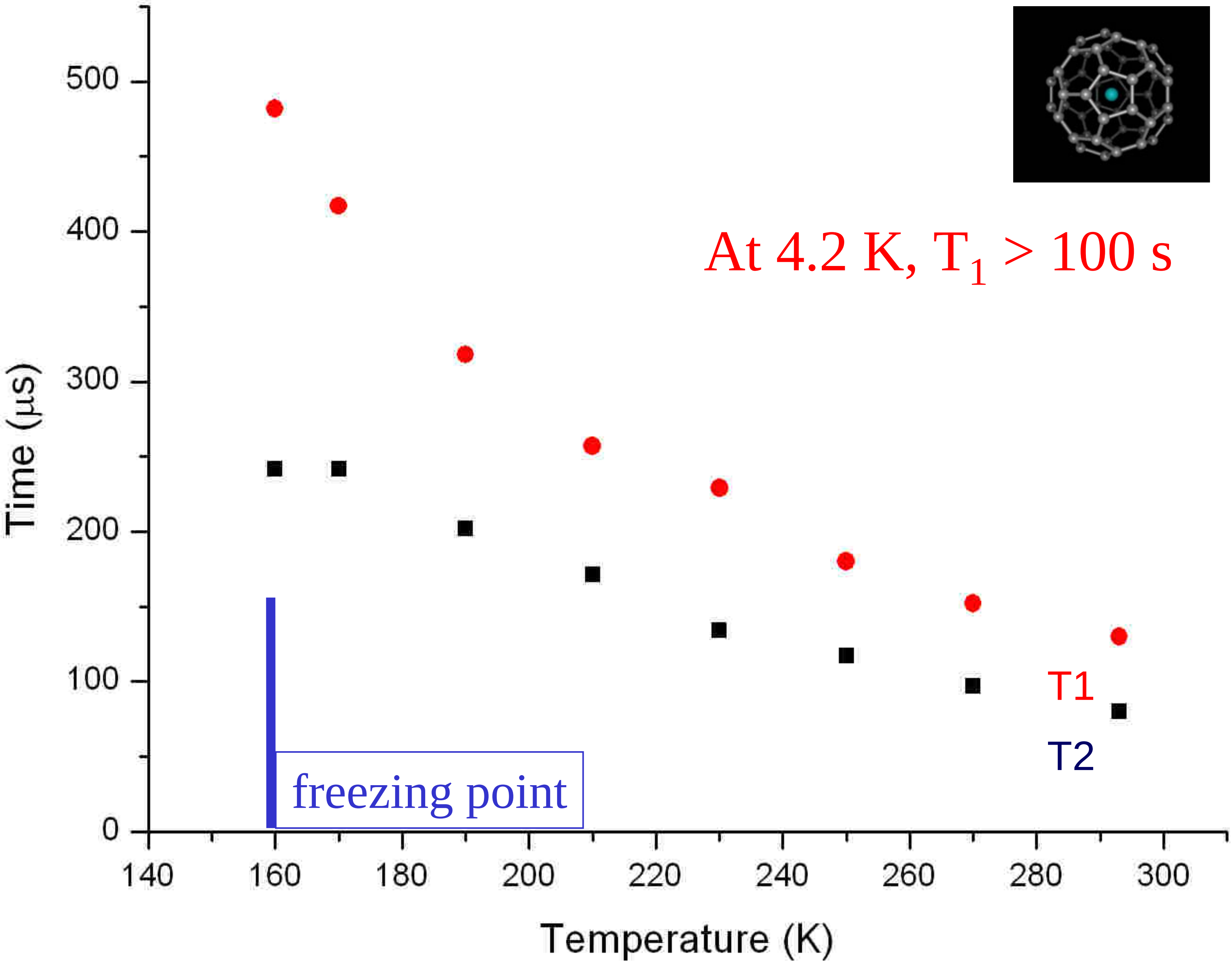
BB1 sequence for spin manipulation



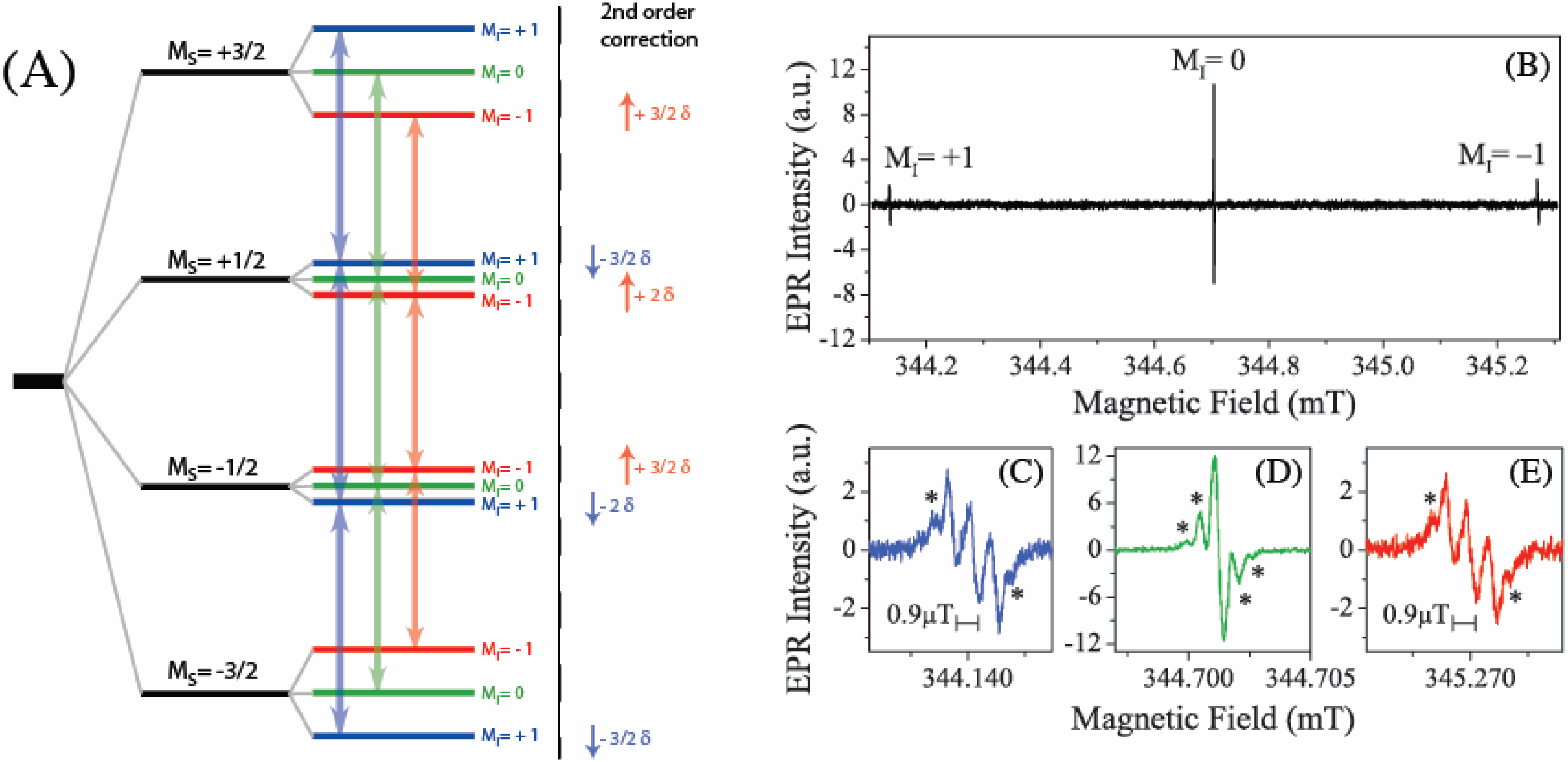


J.J.L. Morton *et al.*, *Phys. Rev. Lett.* **95**, 200501 (2005)

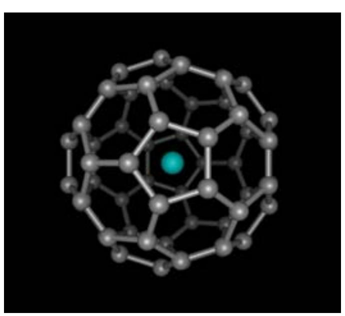
Electron spin resonance of $^{14}N@C_{60}$

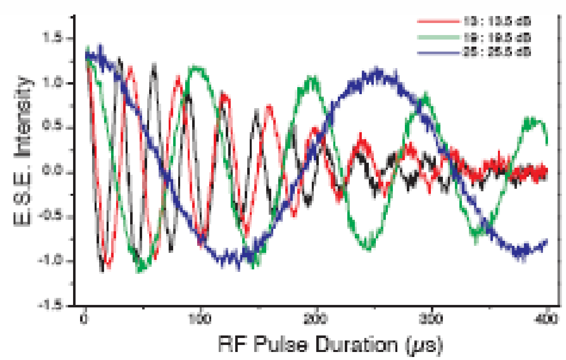


$^{14}N@C_{60}$

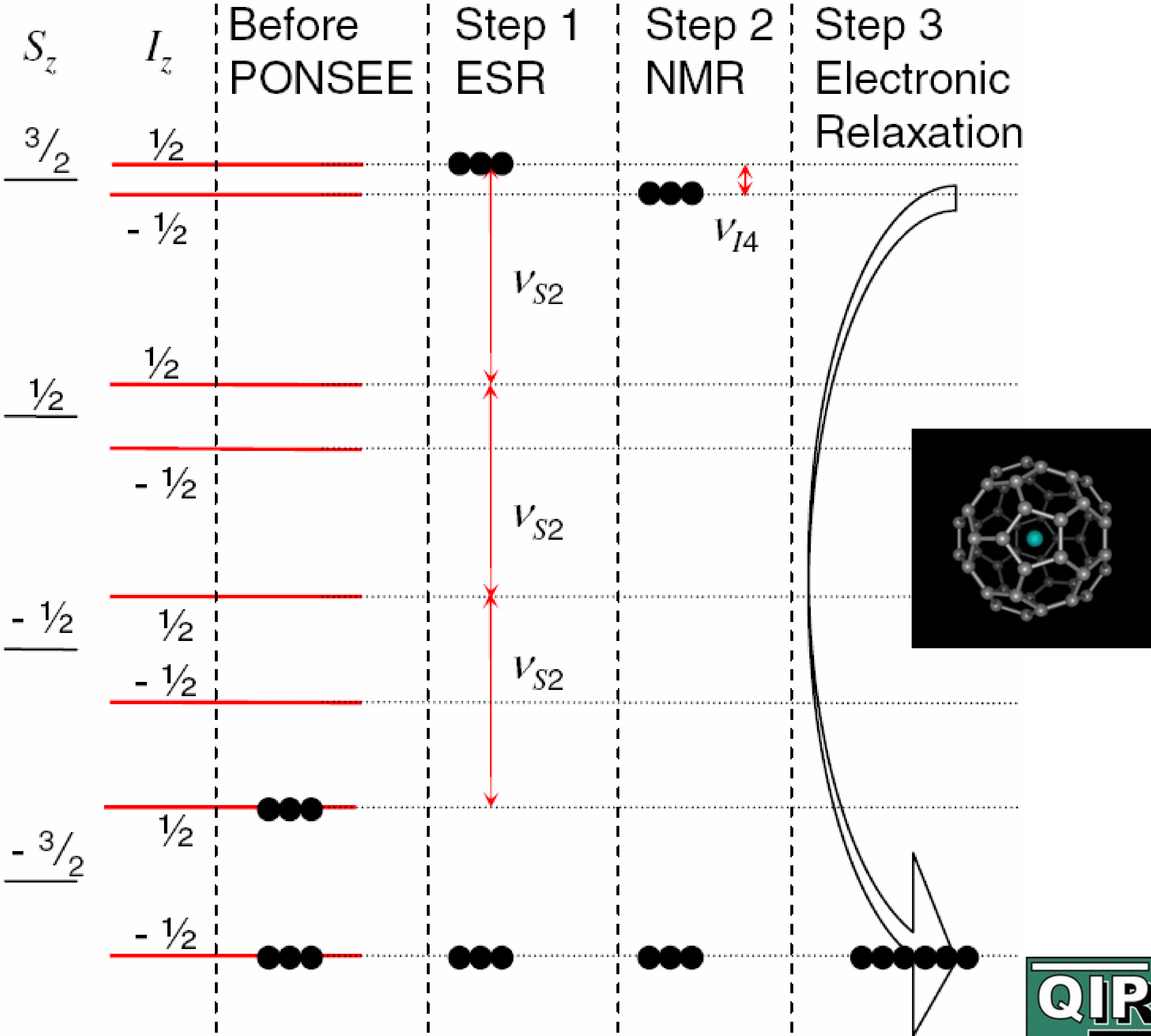


(A)
M_S= +3/2
M_S= +1/2
M_S= -1/2
M_S= -3/2
M_I= + 1
M_I= 0
M_I= - 1
2nd order correction
+ 3/2 δ
- 3/2 δ
+ 2 δ
- 2 δ
(B)
M_I= 0
M_I= +1
M_I= –1
EPR Intensity (a.u.)
Magnetic Field (mT)
344.2
344.4
344.6
344.8
345.0
345.2
(C)
(D)
(E)
0.9μT
344.140
344.700
344.705
345.270



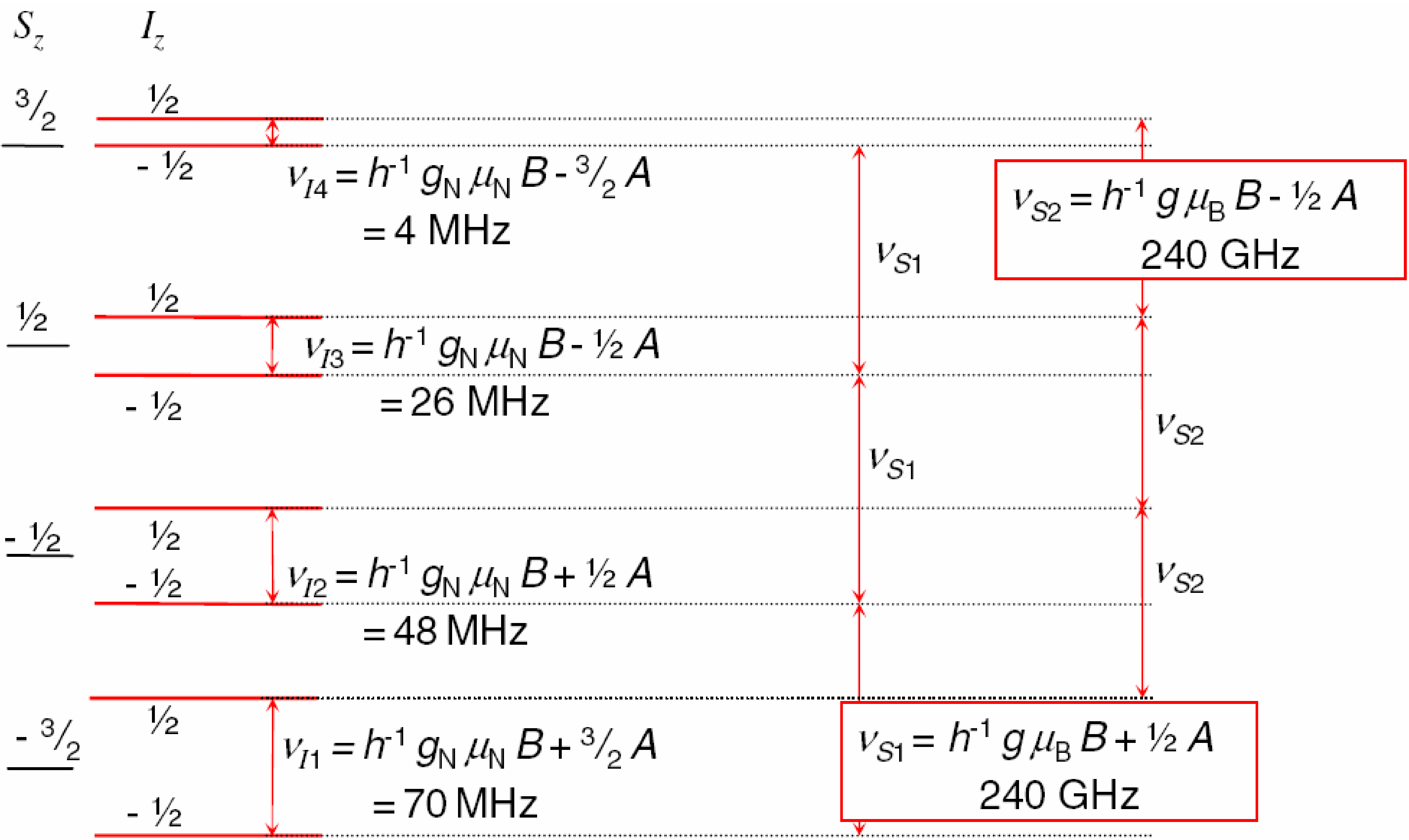


E.S.E. Intensity
RF Pulse Duration (μs)



S_z
I_z
Before PONSEE
Step 1 ESR
Step 2 NMR
Step 3 Electronic Relaxation
3/2
½
- ½
½
½
- ½
- ½
½
- ½
- 3/2
½
- ½
ν_{S2}
ν_{S2}
ν_{S2}
ν_{I4}

Dynamic nuclear polarisation of $^{15}N@C_{60}$



G. Morley *et al.*, *Phys. Rev. Lett.* **98**, 220501 (2007)

Dynamic nuclear polarisation of $^{15}N@C_{60}$

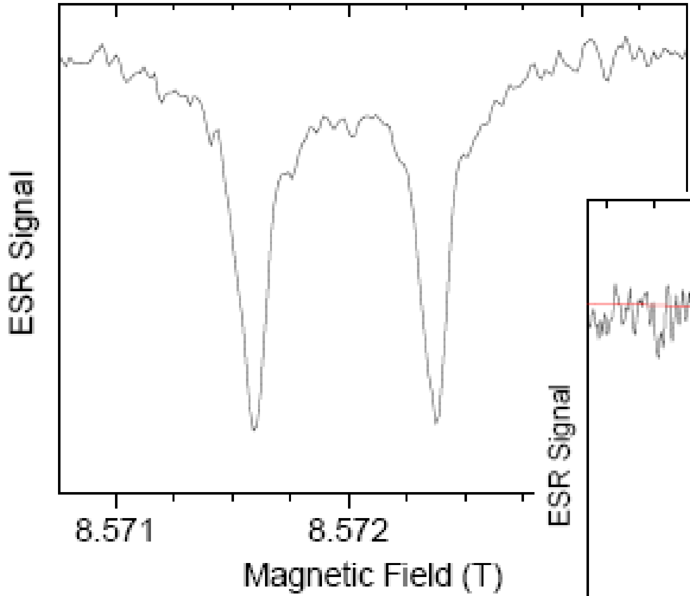


Figure 6.3: CW ESR scan of $^{15}N@C_{60}$ in deuterated deoxyg
unusual lineshape is due to saturation.

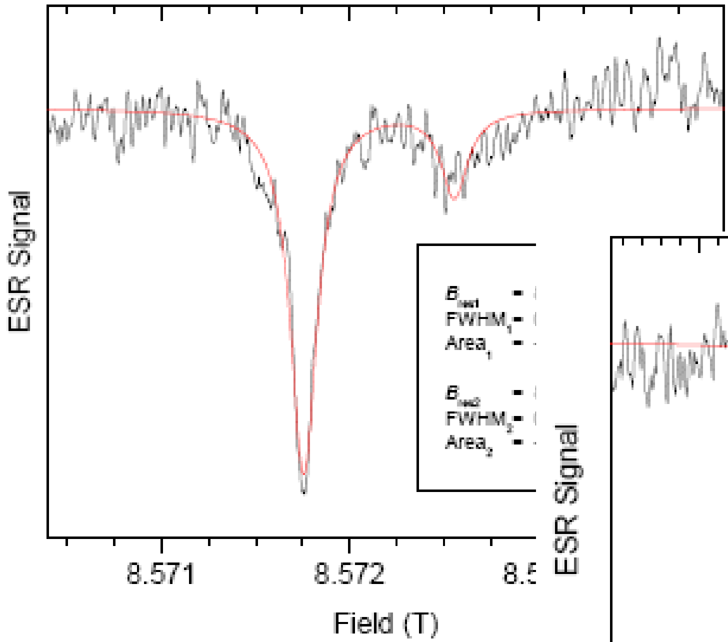


Figure 6.6: Averaged CW ESR scan of $^{15}N@C_{60}$ at 3 K
red line is the bi-Lorentzian best fit with the parameters gi
peaks was set to be the same.

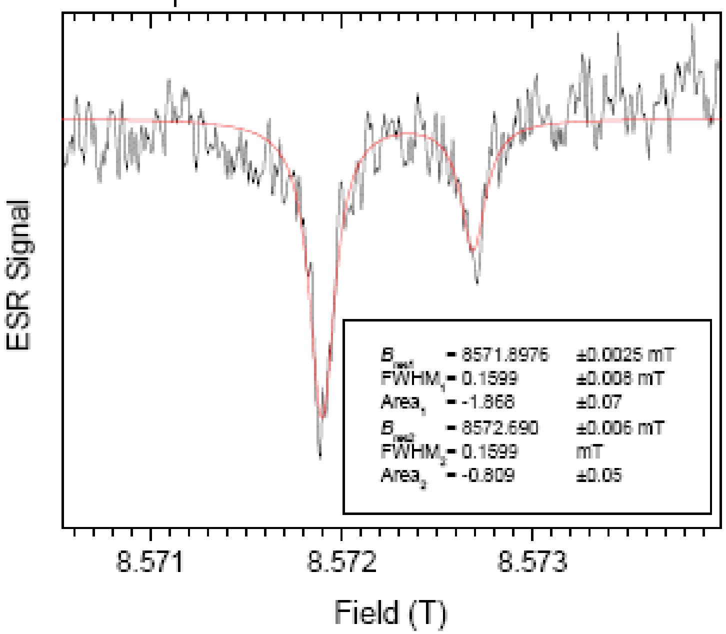
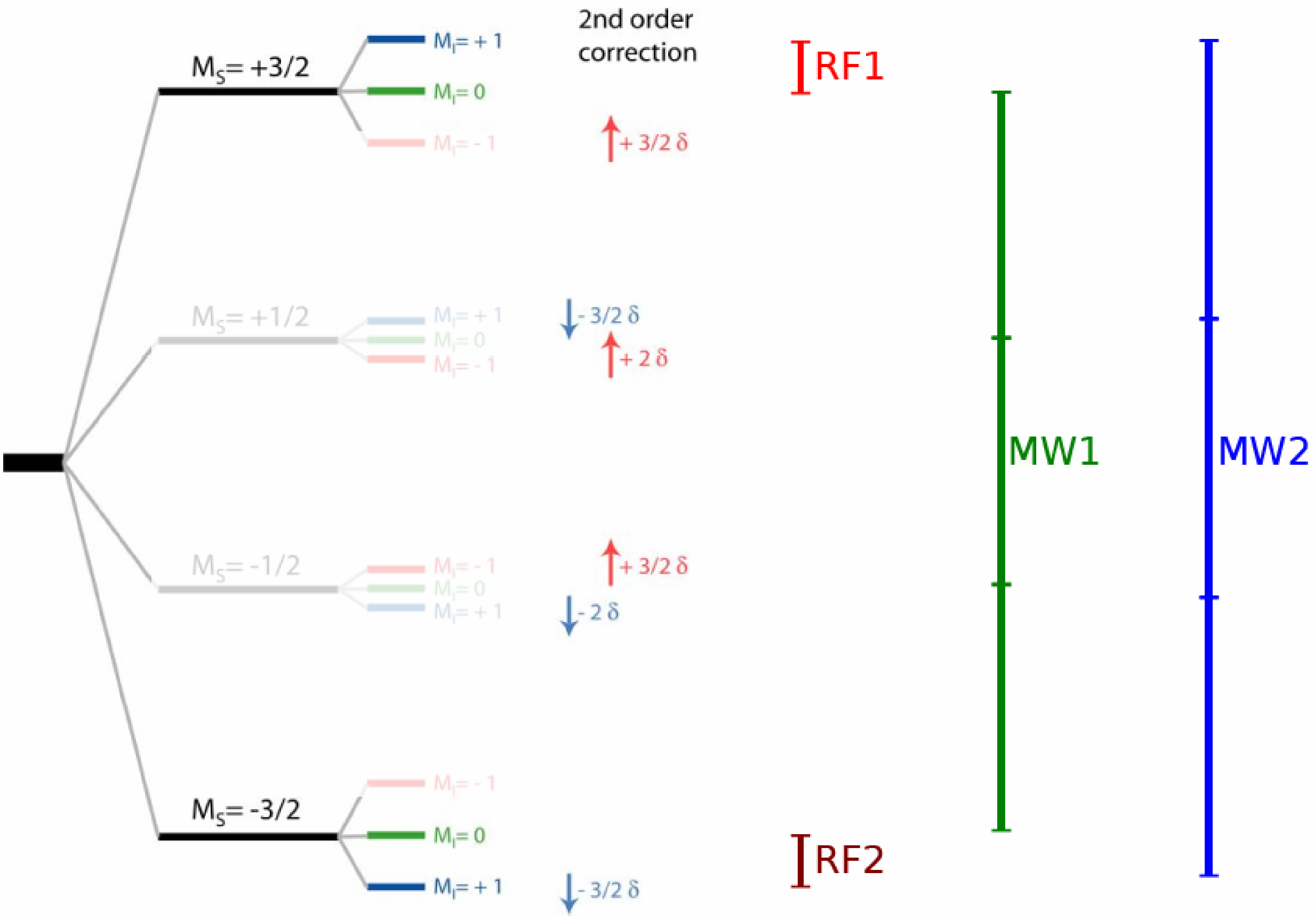


Figure 6.9: CW ESR scan of $^{15}N@C_{60}$ at 4.2 K 11.5 hours after DNP polarization. In this time, the polarization has fallen from 4.3 (see Figure 6.6) to 2.3. The red line is the bi-Lorentzian best fit with equal line-widths.

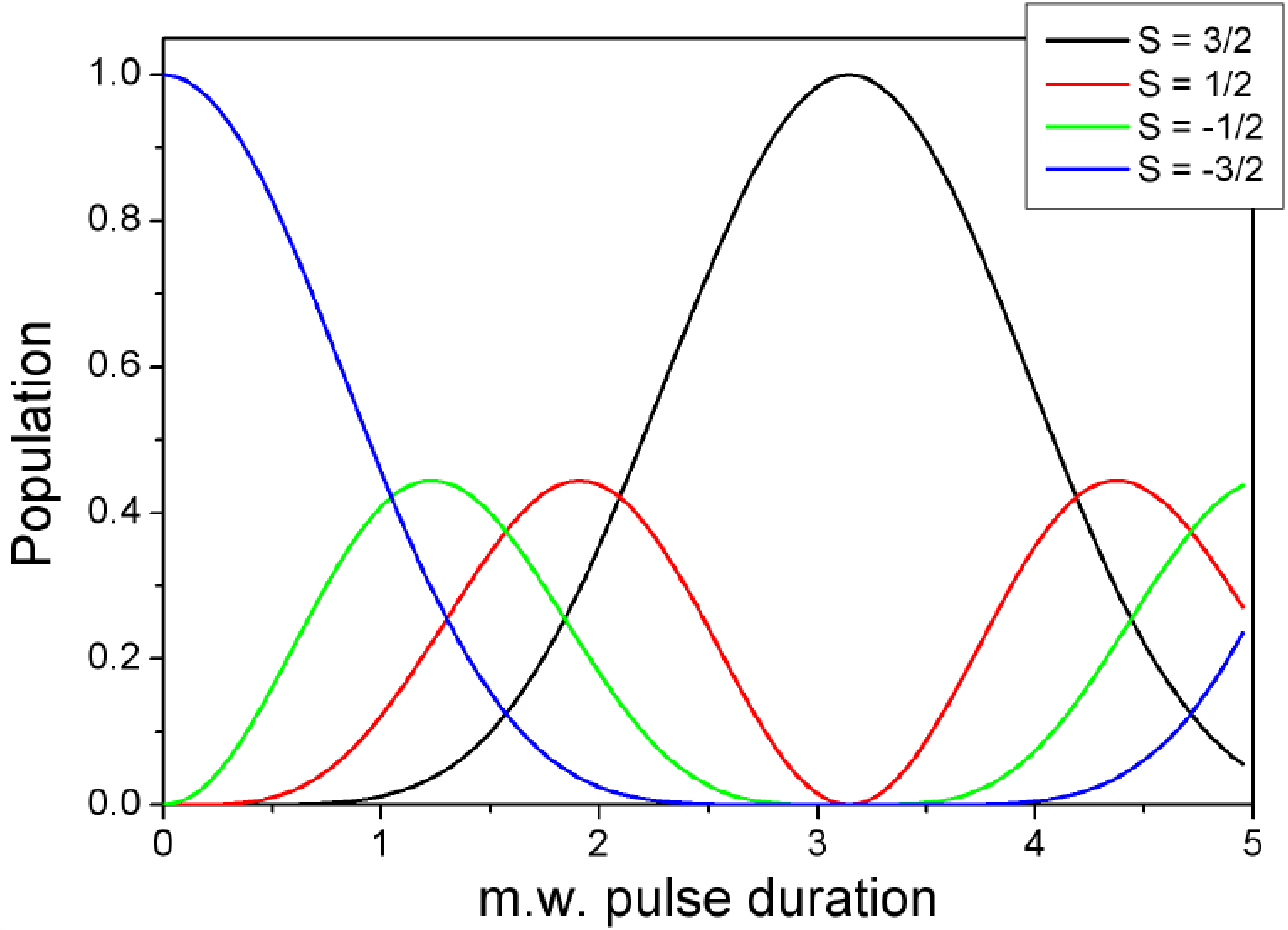
G. Morley *et al.*, *Phys. Rev. Lett.* **98**, 220501 (2007)

$^{14}N@C_{60}$



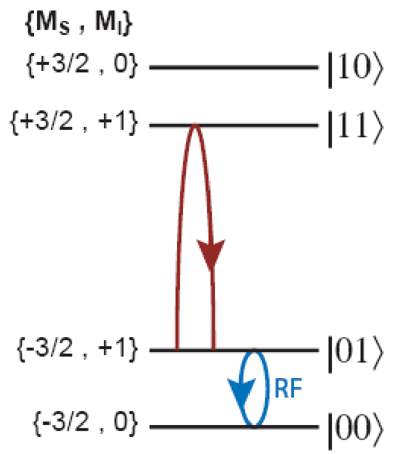
S.C. Benjamin *et al.*, *J. Phys.: Condens. Matter* **18**, S867-883 (2006)

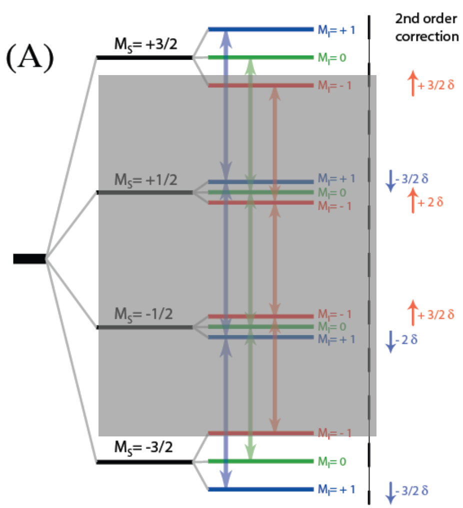
N@C_{60}

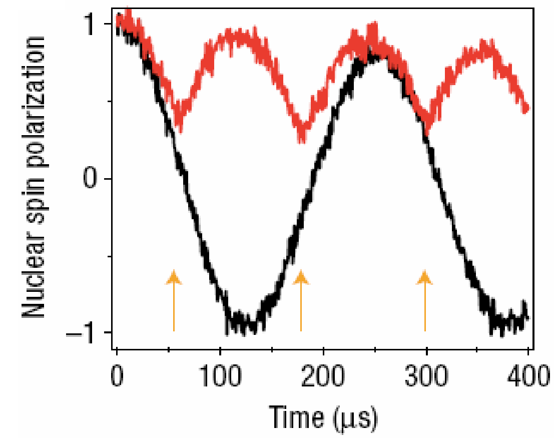


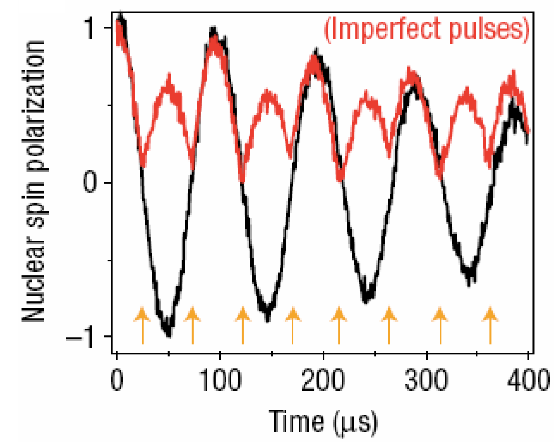
S = 3/2
S = 1/2
S = -1/2
S = -3/2
1.0
0.8
0.6
0.4
0.2
0.0
Population
0
1
2
3
4
5
m.w. pulse duration

Bang-bang control



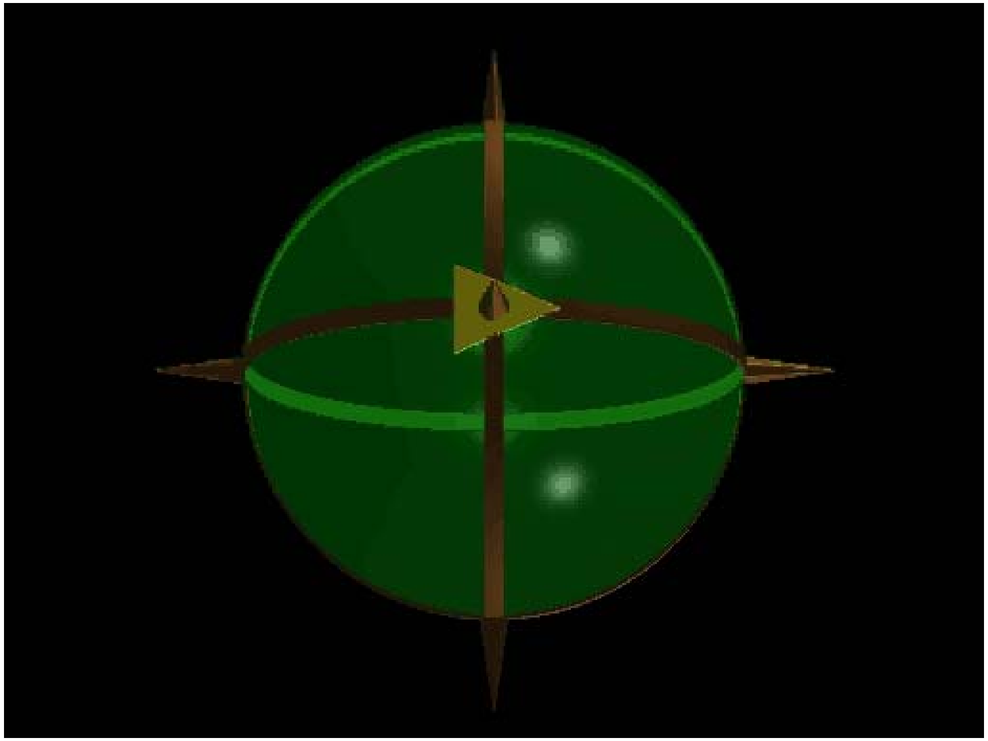






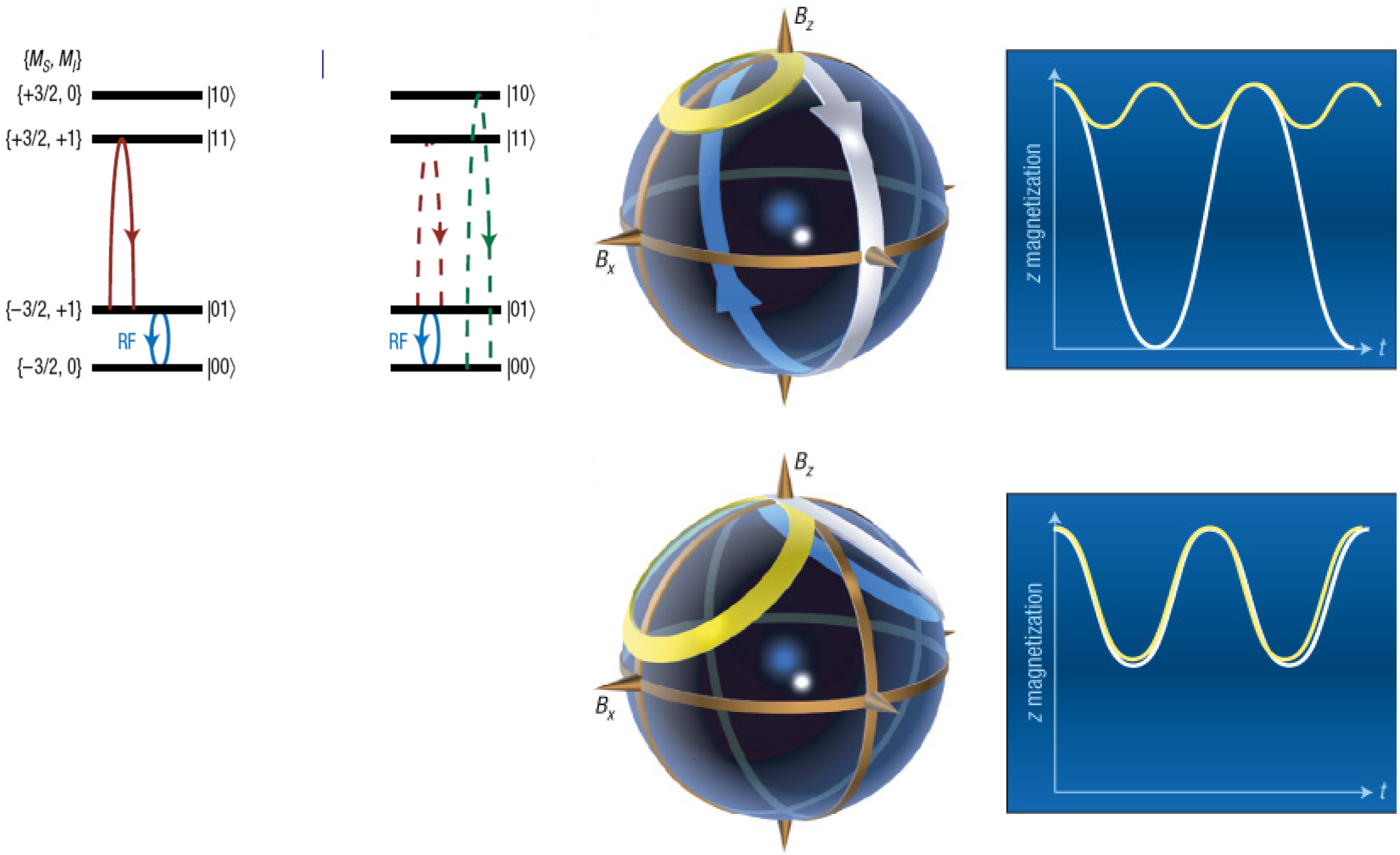
J.J.L. Morton *et al.*, *Nature Physics* **2**, 40-43 (2006)

Bang-bang control



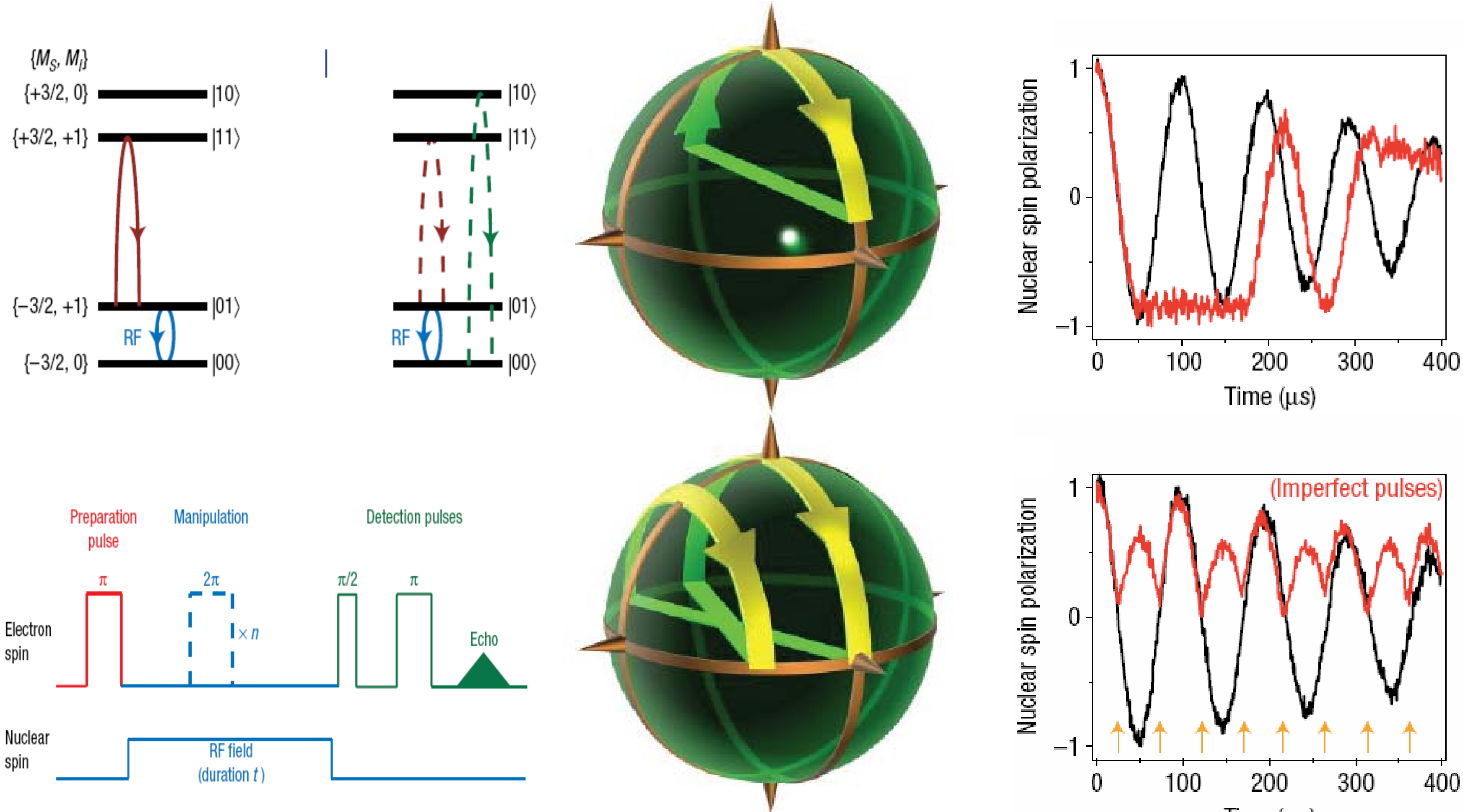
J.J.L. Morton *et al.*, *Nature Physics* **2**, 40-43 (2006)

Bang-bang control



J.J.L. Morton *et al.*, *Nature Physics* **2**, 40-43 (2006)

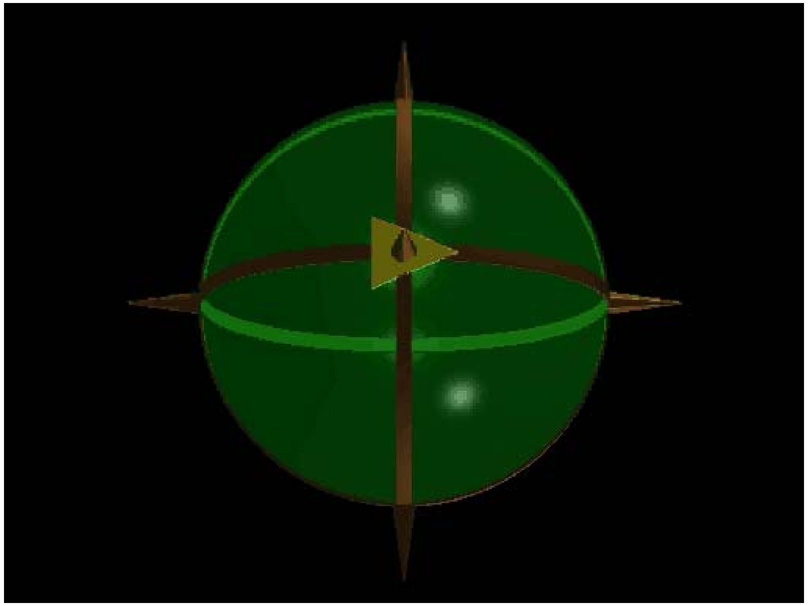
Bang-bang control



J.J.L. Morton *et al.*, *Nature Physics* **2**, 40-43 (2006)

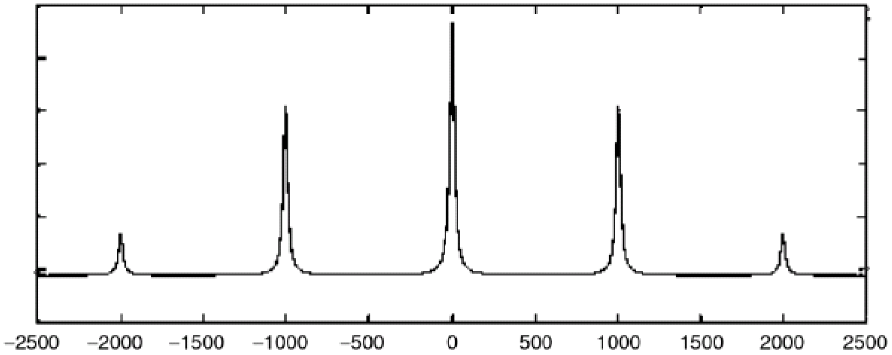
Bang-bang control

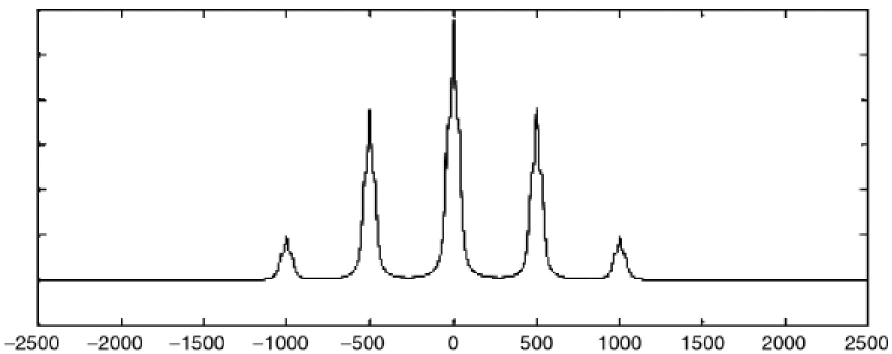
- Unlike quantum Zeno, *bang-bang* control is fully deterministic.
- *Bang-bang* control can be used for control of the nuclear spin qubit with speed determined by the electron spin manipulation.
- The principle of *bang-bang* control can be applied to other systems with three or more levels.

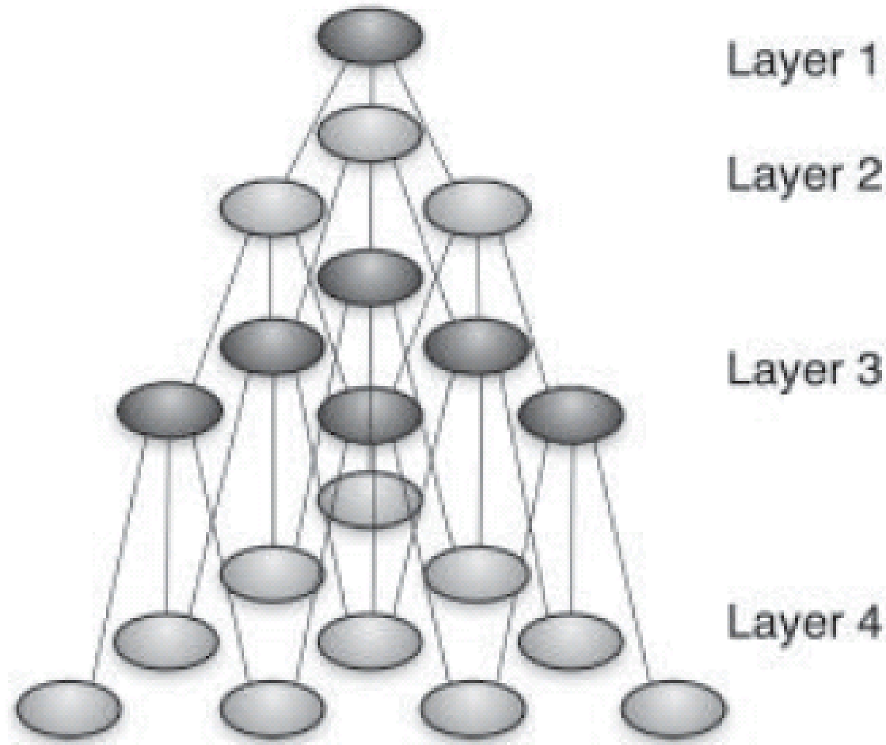


J.J.L. Morton *et al.*, *Nature Physics* **2**, 40-43 (2006)

Spin amplification for measurement



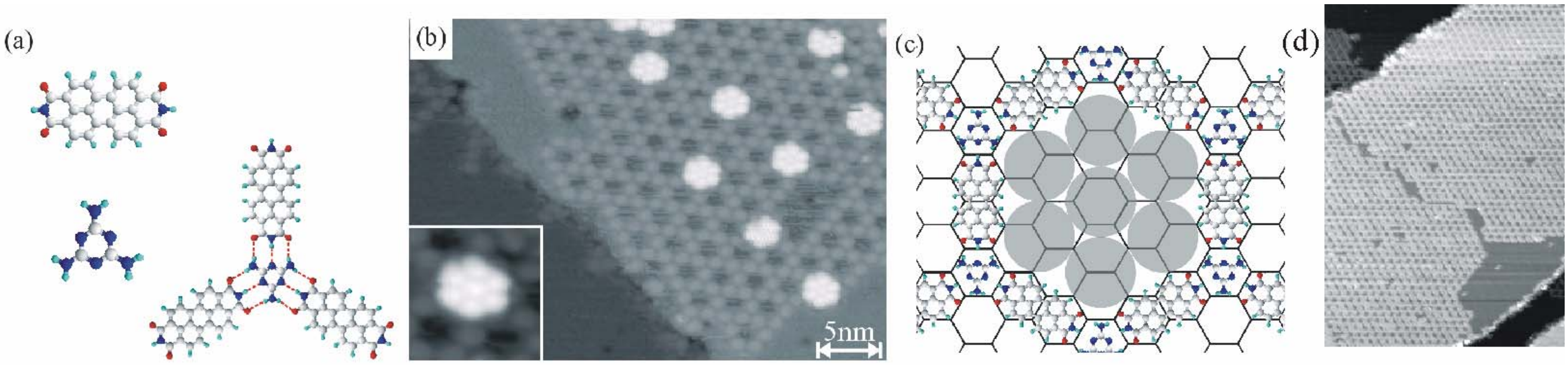




$O(\sqrt[3]{N})$ steps $\rightarrow$ N correlated spins

Perez-Delgado *et al.*, *Phys. Rev. Lett.* **97**, 100501 (2006)

2-D spin arrays



(a) Component molecules melamine and perylene tetra-carboxylic di-imide (PTCDI) can be connected by three hydrogen bonds per molecular junction.

(b) The molecules are sublimed onto a silicon surface. Melamine forms the vertices and PTCDI forms the edges of a network that assembles spontaneously. The open network provides a template for adsorption of fullerenes.

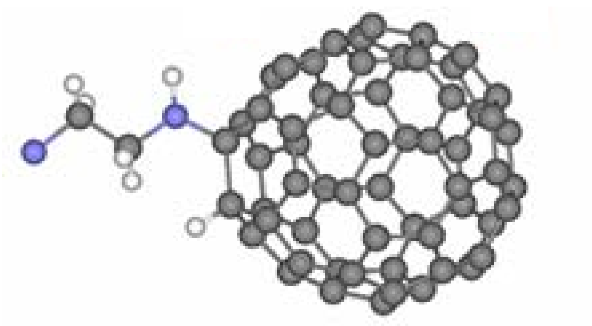
(c) The pores in the network form nanoscale traps which capture fullerene molecules and stabilise heptameric C_{60} clusters.

(d) Networks can extend over several hundreds of nanometres.

Theobald *et al.*, *Nature* **424**, 1029 (2003)

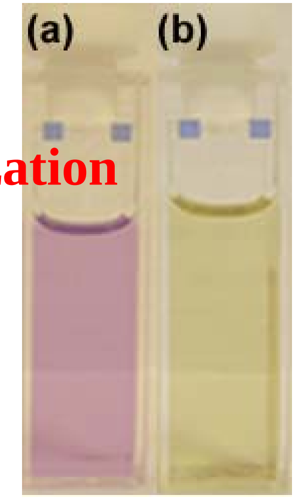
3-D spin arrays

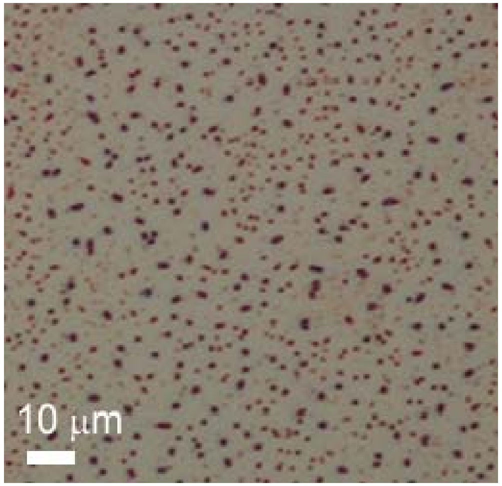
Functionalized fullerenes

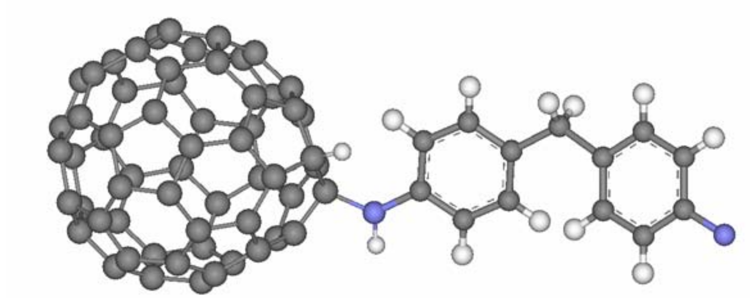


C_{60}-ethylenediamine

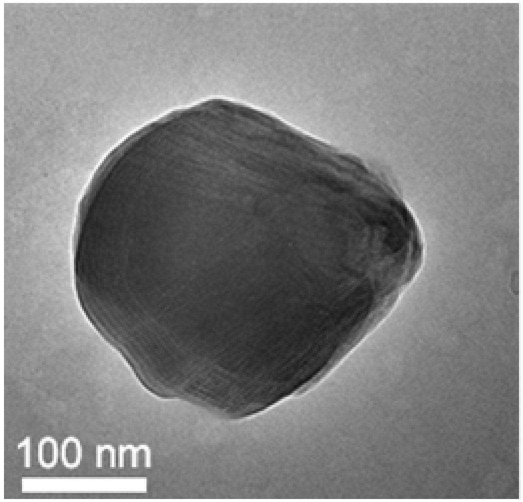
(a) before
(b) after
functionalization

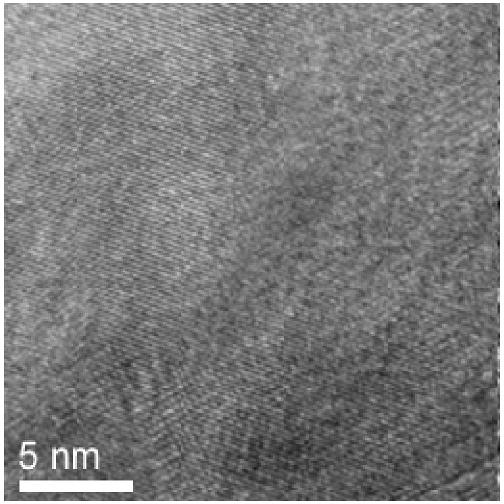






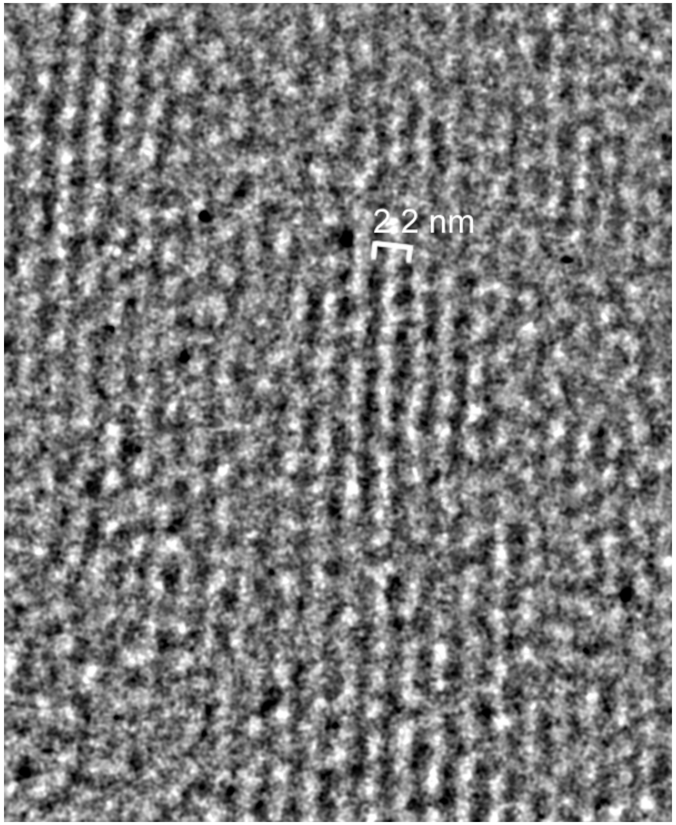
C_{60}-4,4'-methylenedianiline

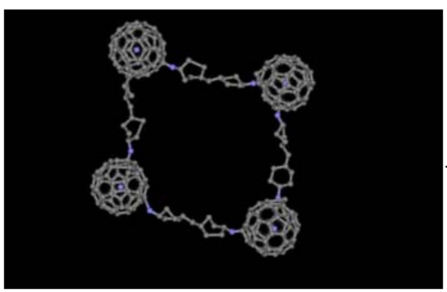




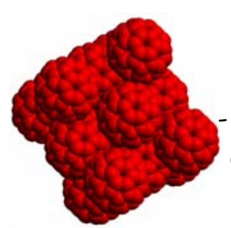
Watt *et al.*, *Chem. Commun.*, **2006**, 1944-1946

3-D spin arrays

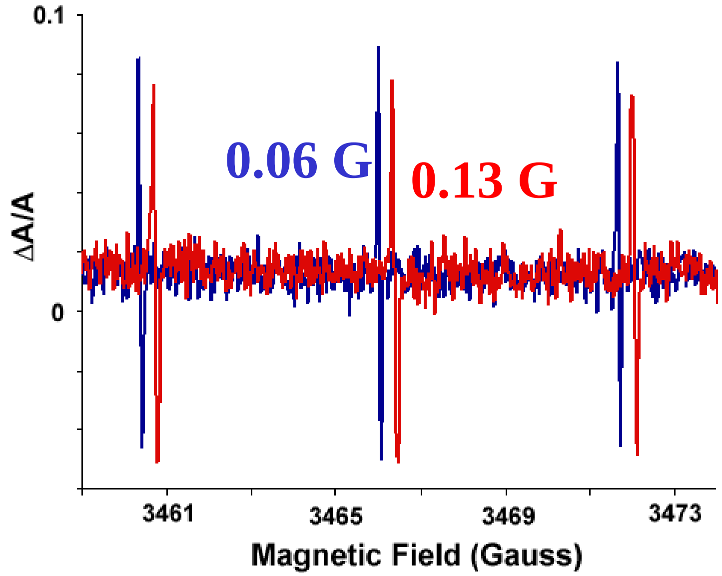


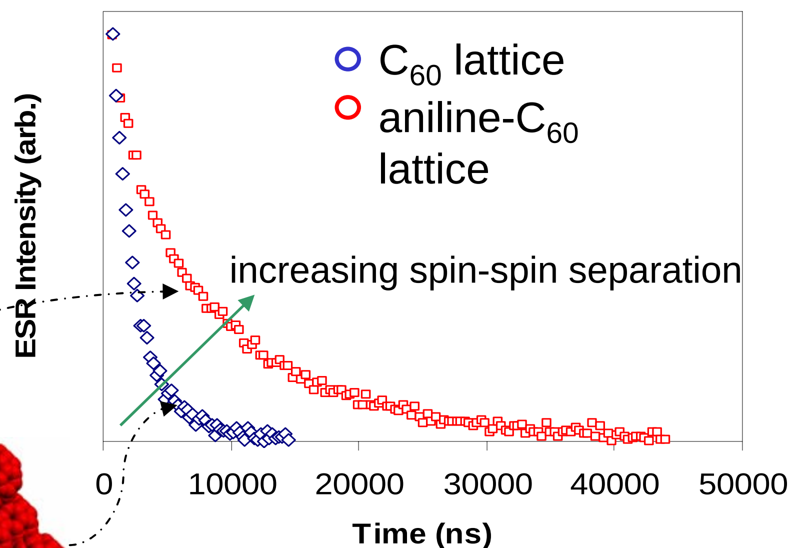


C_{60}-4,4'-methylenedianiline

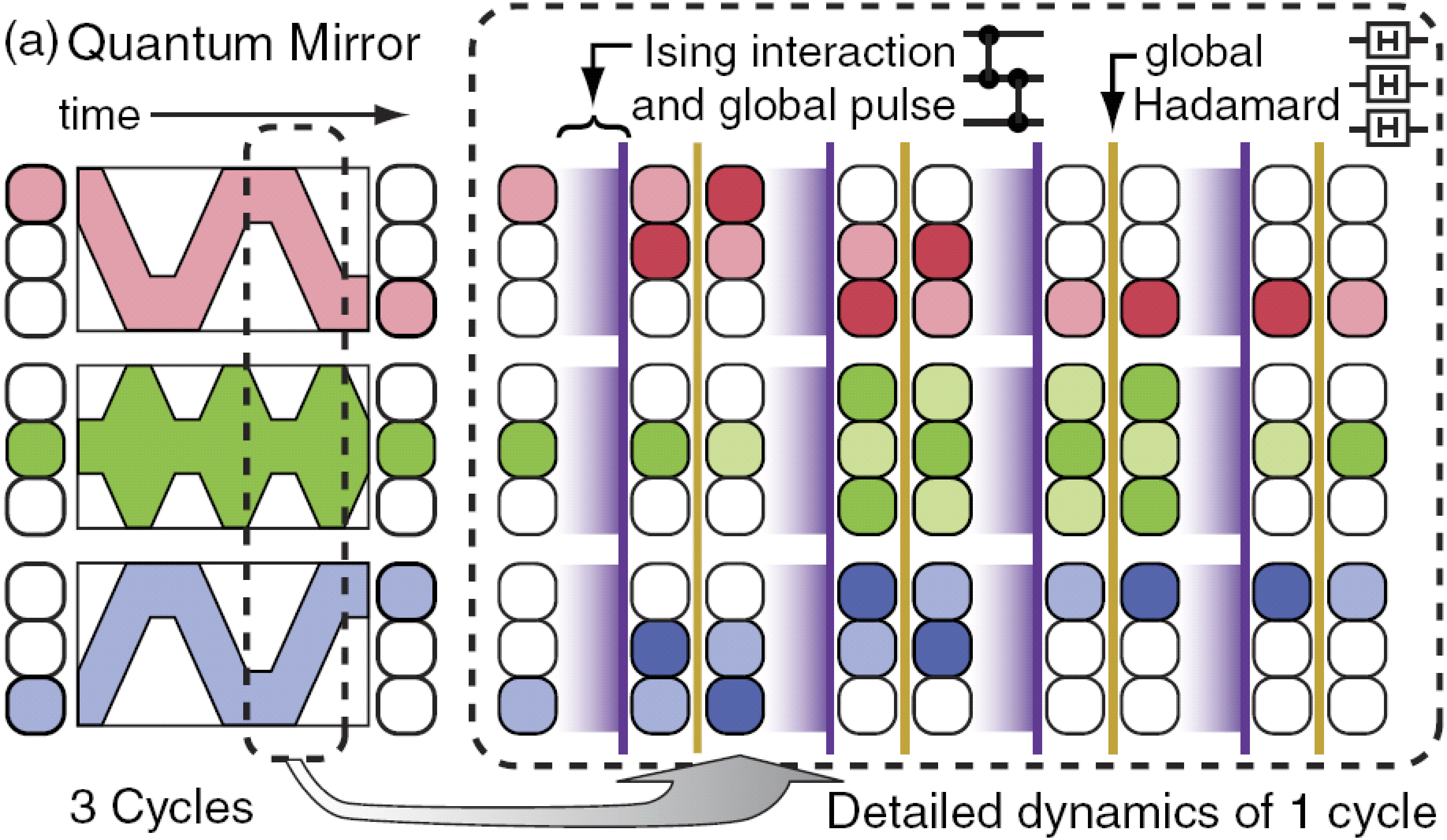


C_{60}

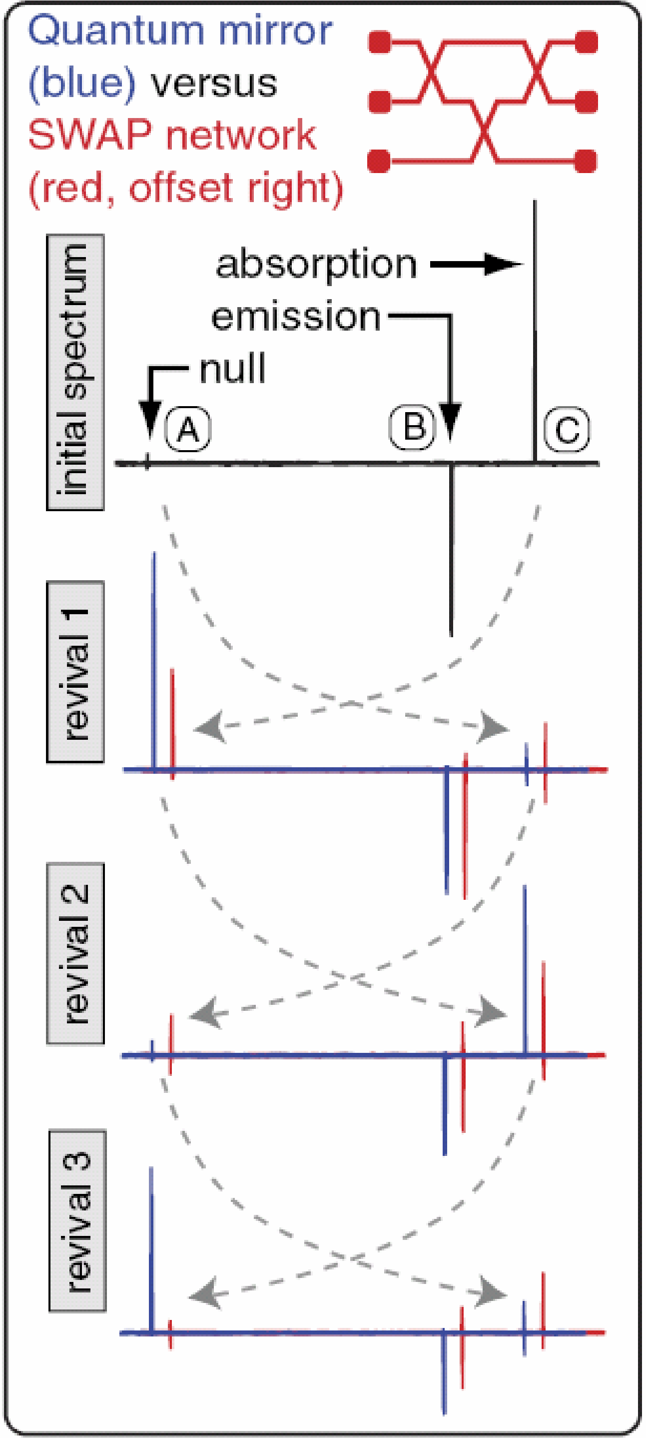


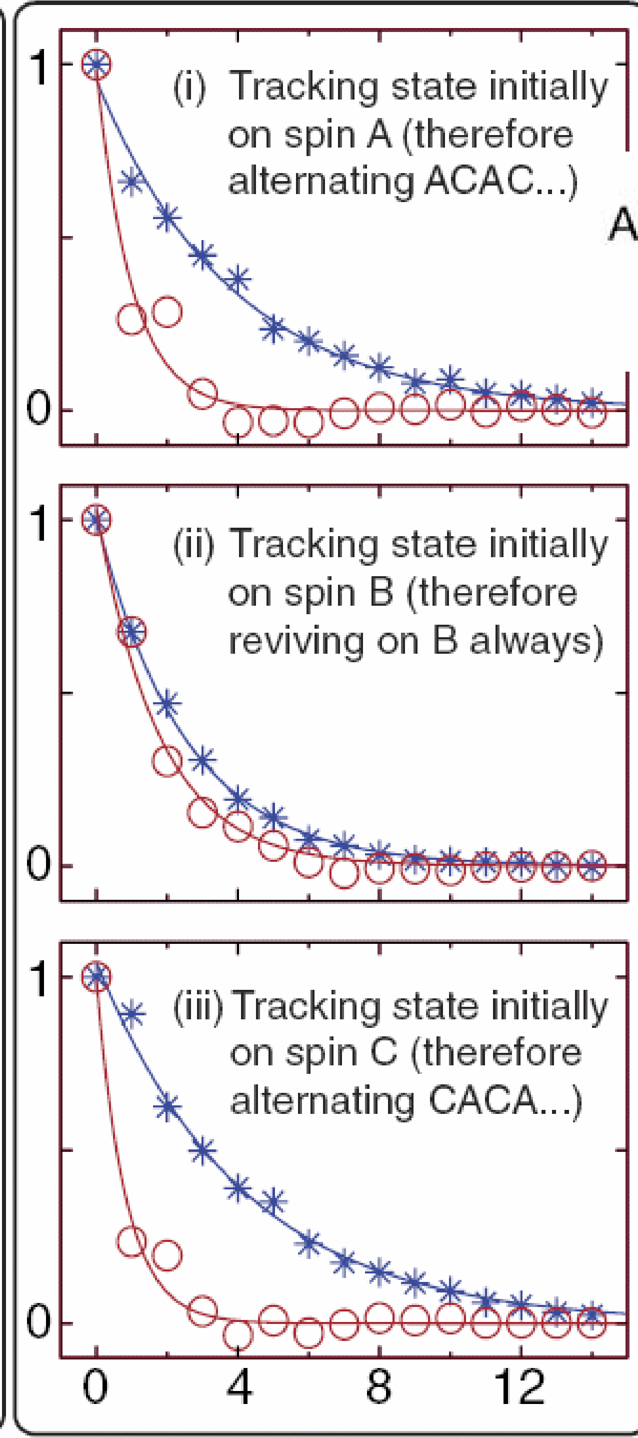


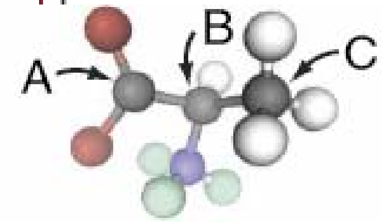
Decolalize-and-revive



J. Fitzsimons *et al.*, *Phys. Rev. Lett.* **99**, 030501 (2007)

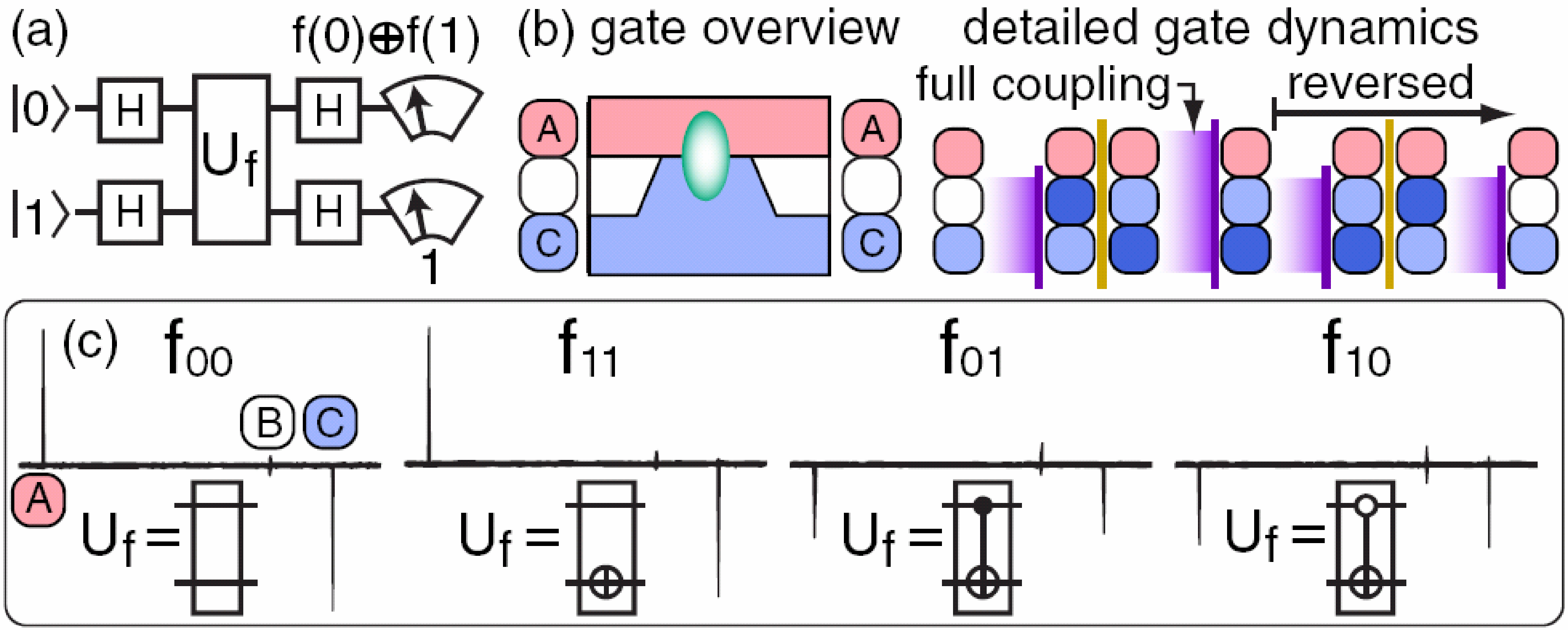






^{13}C-labeled analine in D_2O

Deutsch's algorith



J. Fitzsimons *et al*., *Phys. Rev. Lett.* **99**, 030501 (2007)

Can you build a quantum computer with carbon?