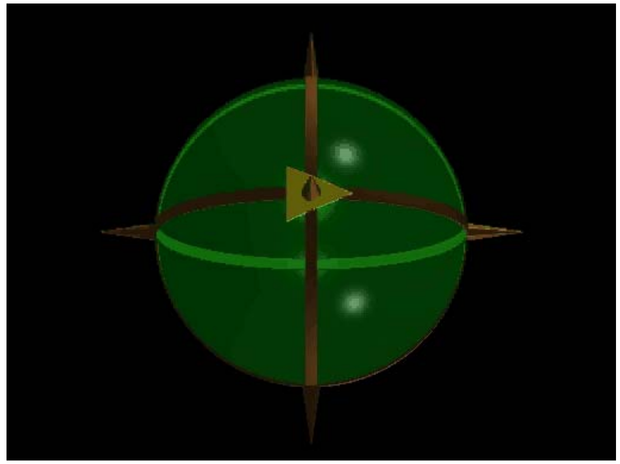
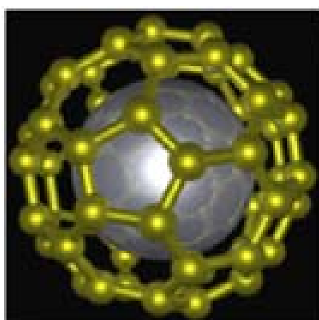
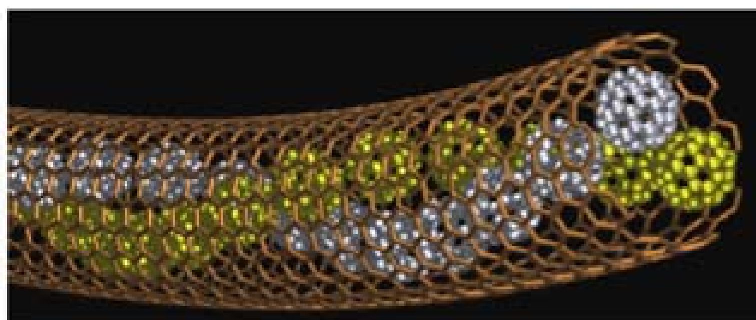


Outstanding problems in using spin states for practical quantum information science





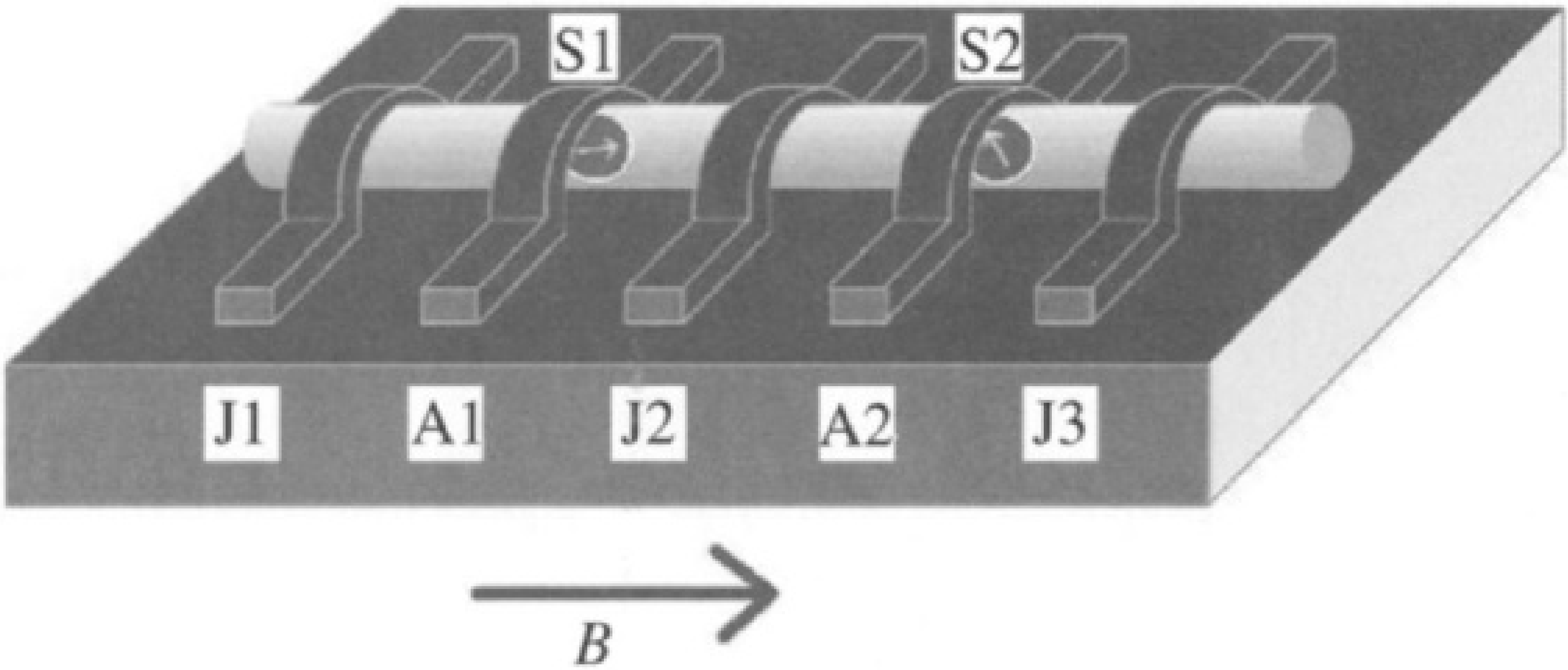
KITP QIS

www.qipirc.org

- “This program will bring together researchers in computer science, mathematics, information theory, and theoretical and experimental physics to tackle outstanding questions in quantum information science.”
- “The program will provide many opportunities to become familiar with these results and to foster collaboration to resolve some of the outstanding problems.”

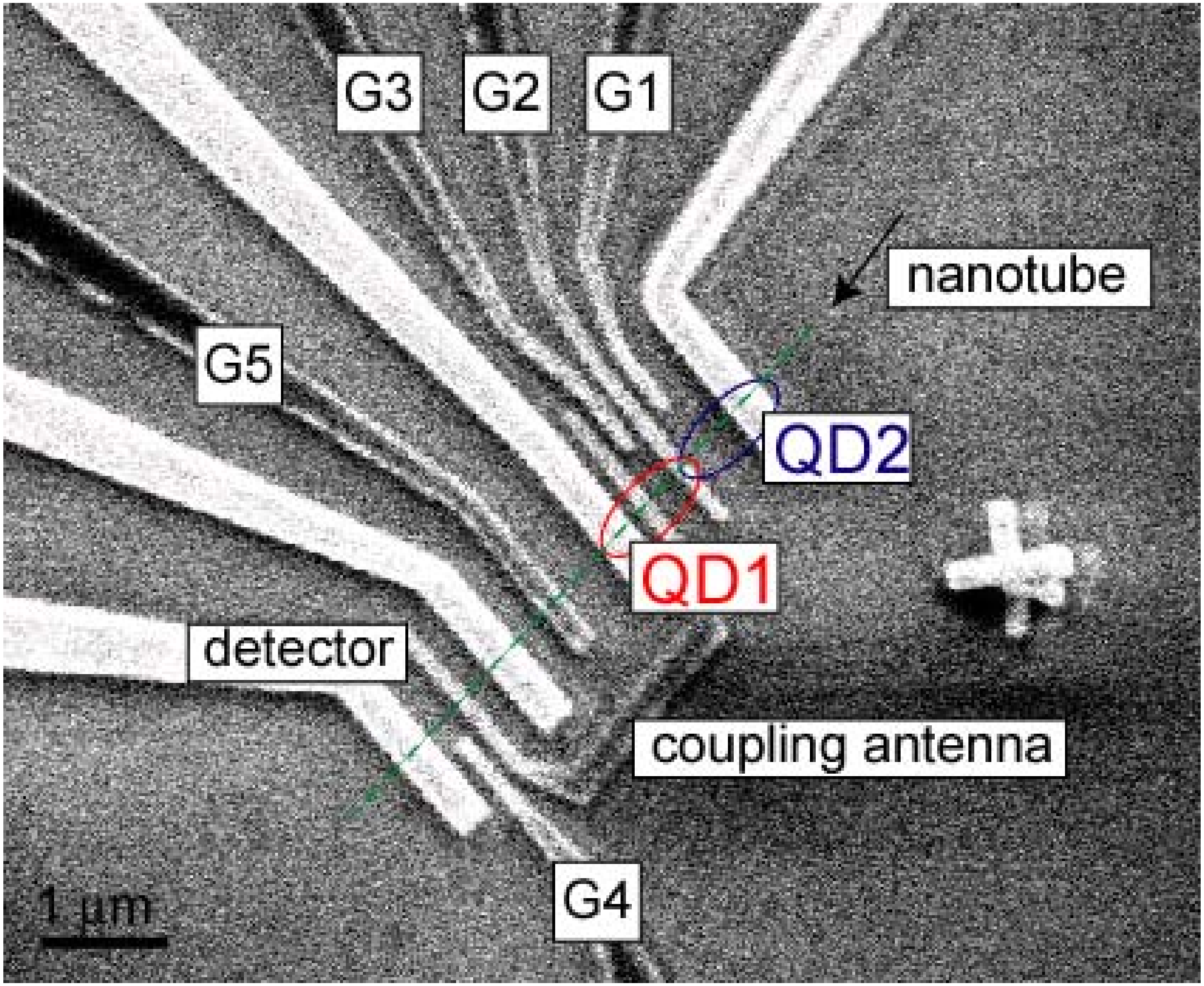
- For acknowledgements of collaborators, see authorship of papers referenced on individual slides.

Nanoscale solid-state quantum computing



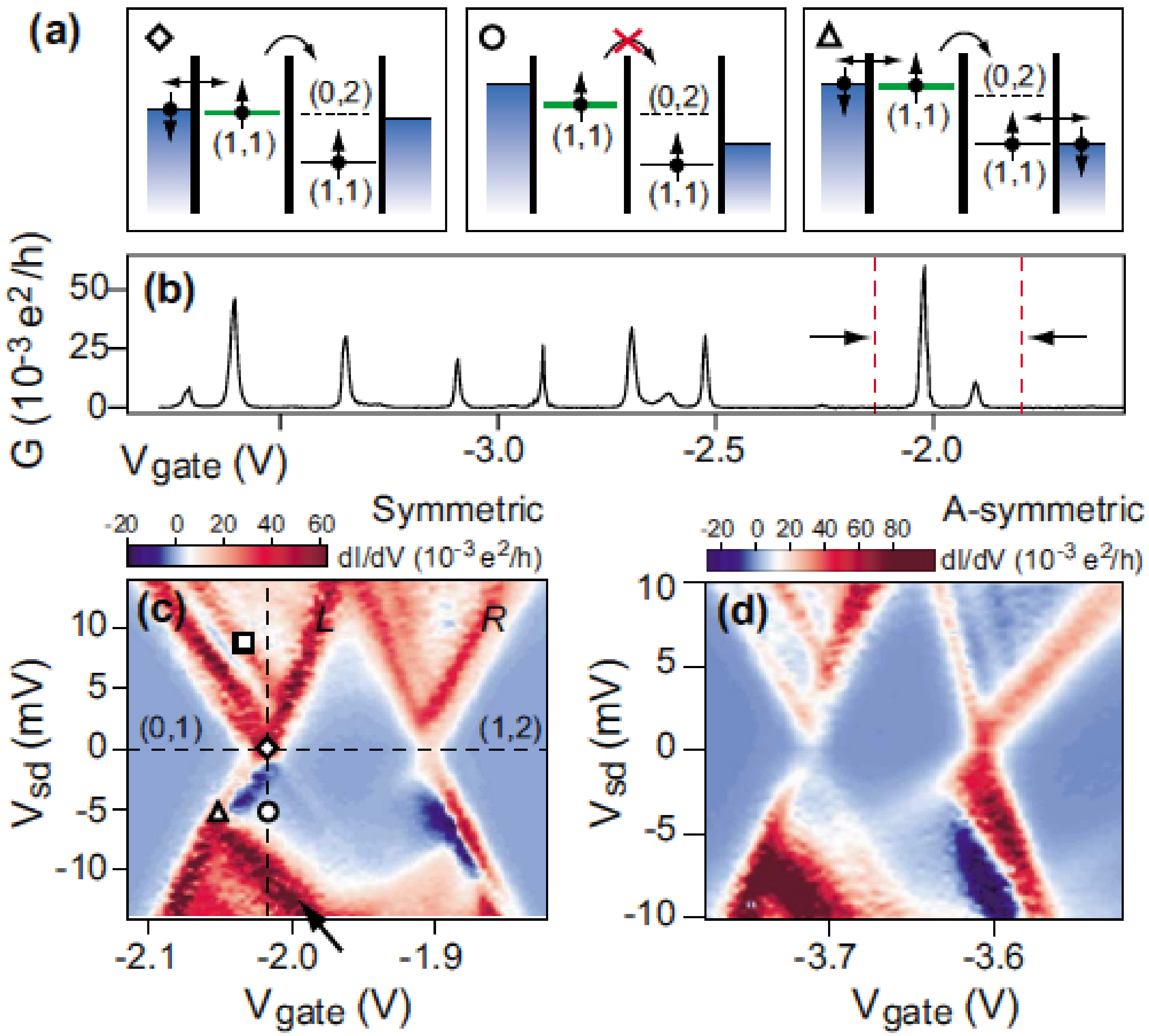
A. Ardavan *et al.*, *Phil. Trans. R. Soc. Lond.* A **361**, 1473-1485 (2003)

Spin blockade in peapod devices



M.R. Buitelaar *et al.*, *Phys. Rev. B* **77**, 245439 (2008)

Spin blockade in peapod devices

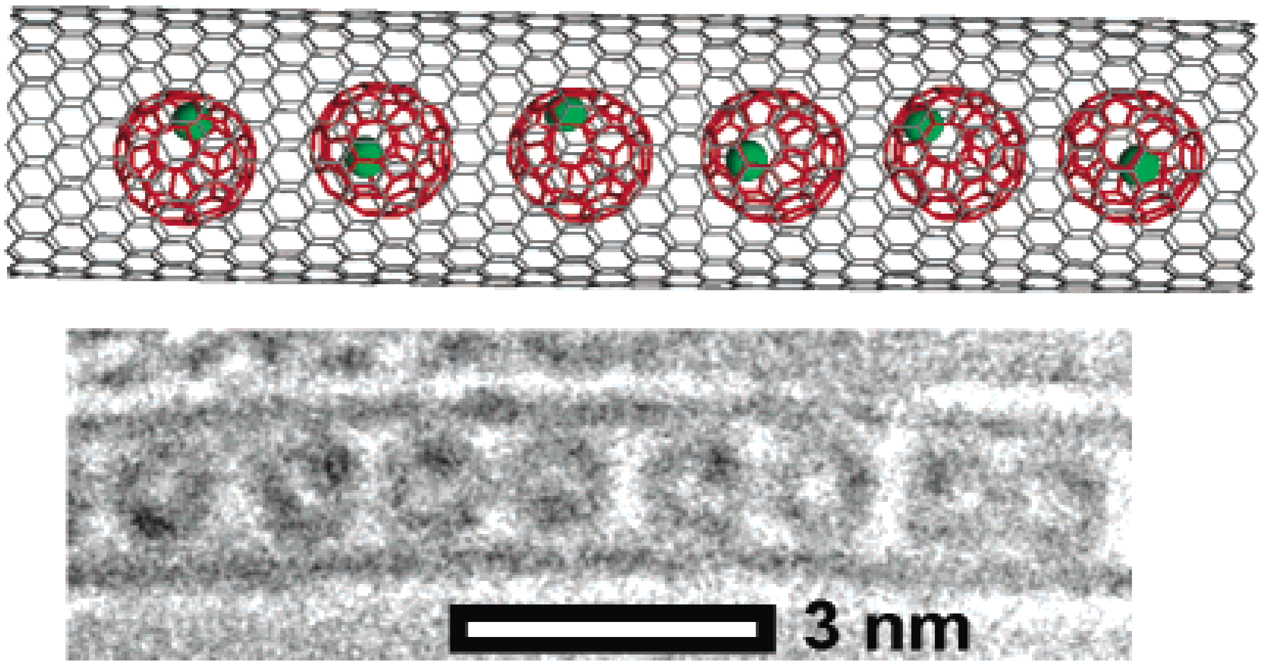


M.R. Buitelaar *et al.*, *Phys. Rev. B* **77**, 245439 (2008)

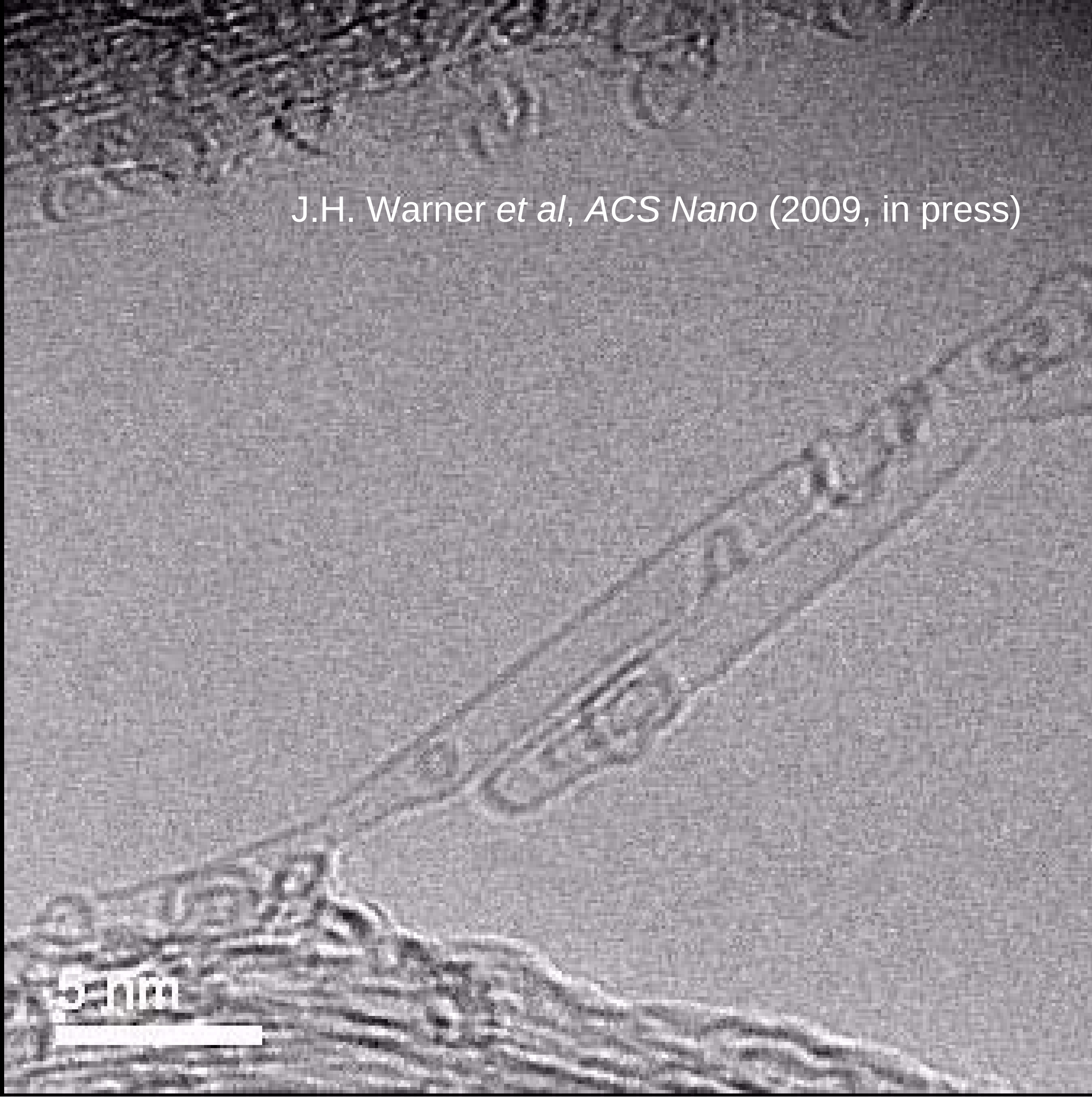
Outstanding problems in using spin states

- In peapods:
  - how can you measure single spins?

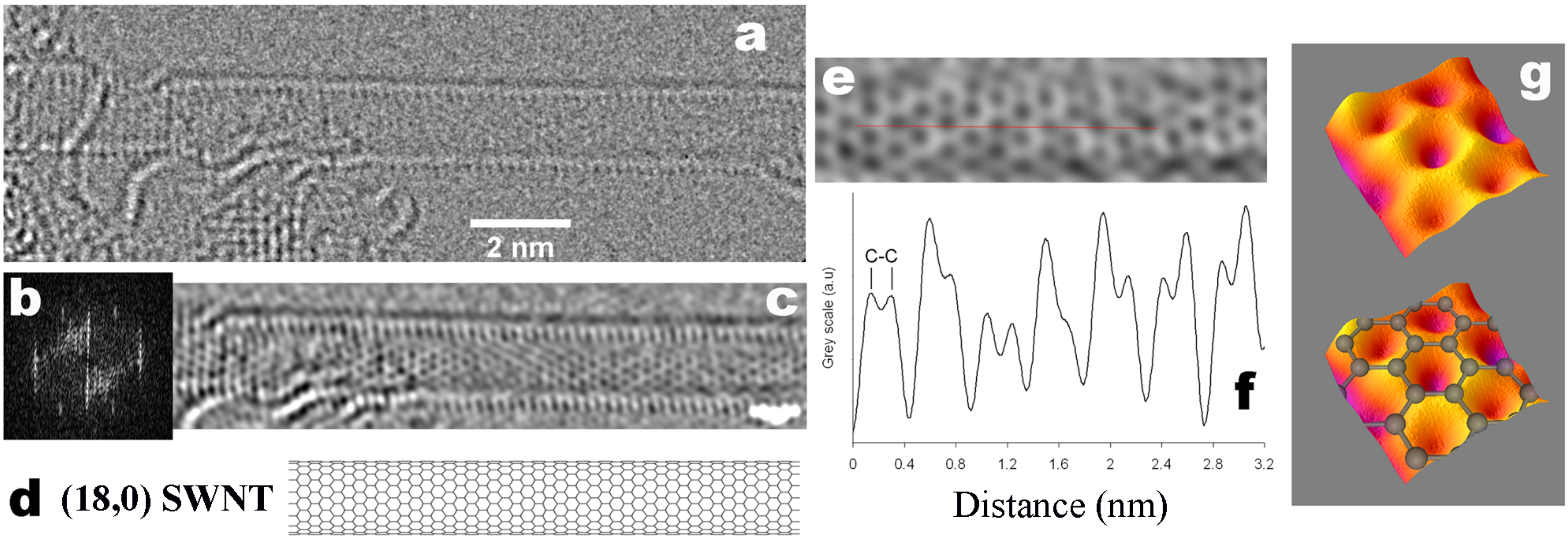
$Ce@C_{82}$ endohedral fullerenes in nanotubes



A.N. Khlobystov *et al.*, *Accounts of Chemical Research* **38**, 901-909 (2005)

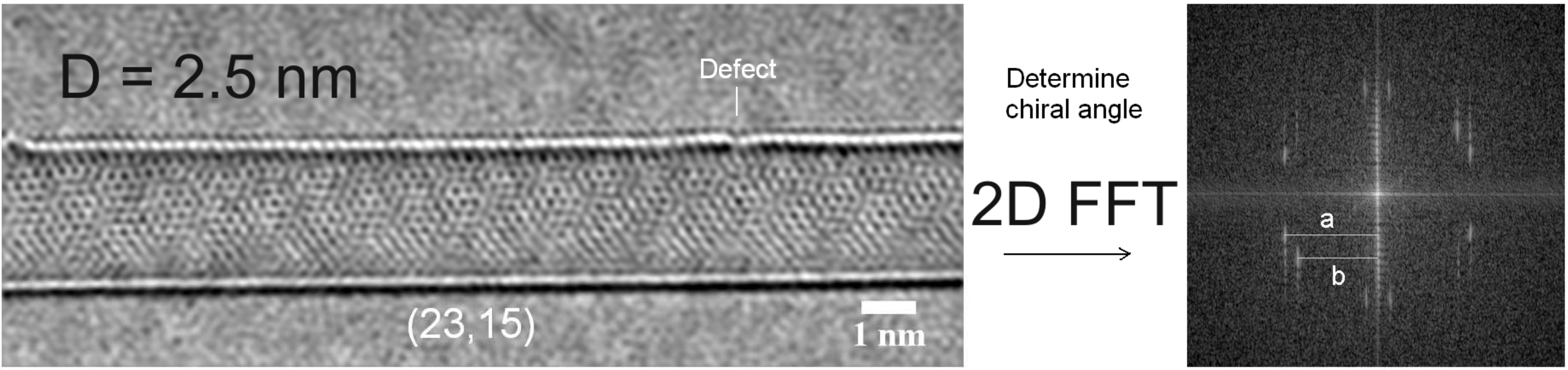

J.H. Warner *et al*, *ACS Nano* (2009, in press)
5 nm

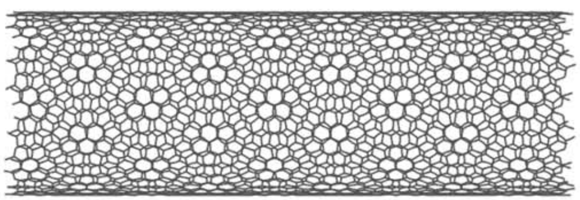
Aberration corrected HRTEM of SWNT



J.H. Warner *et al*, *ACS Nano* **3**, 1557-1563 (2009)

Aberration corrected HRTEM of SWNT





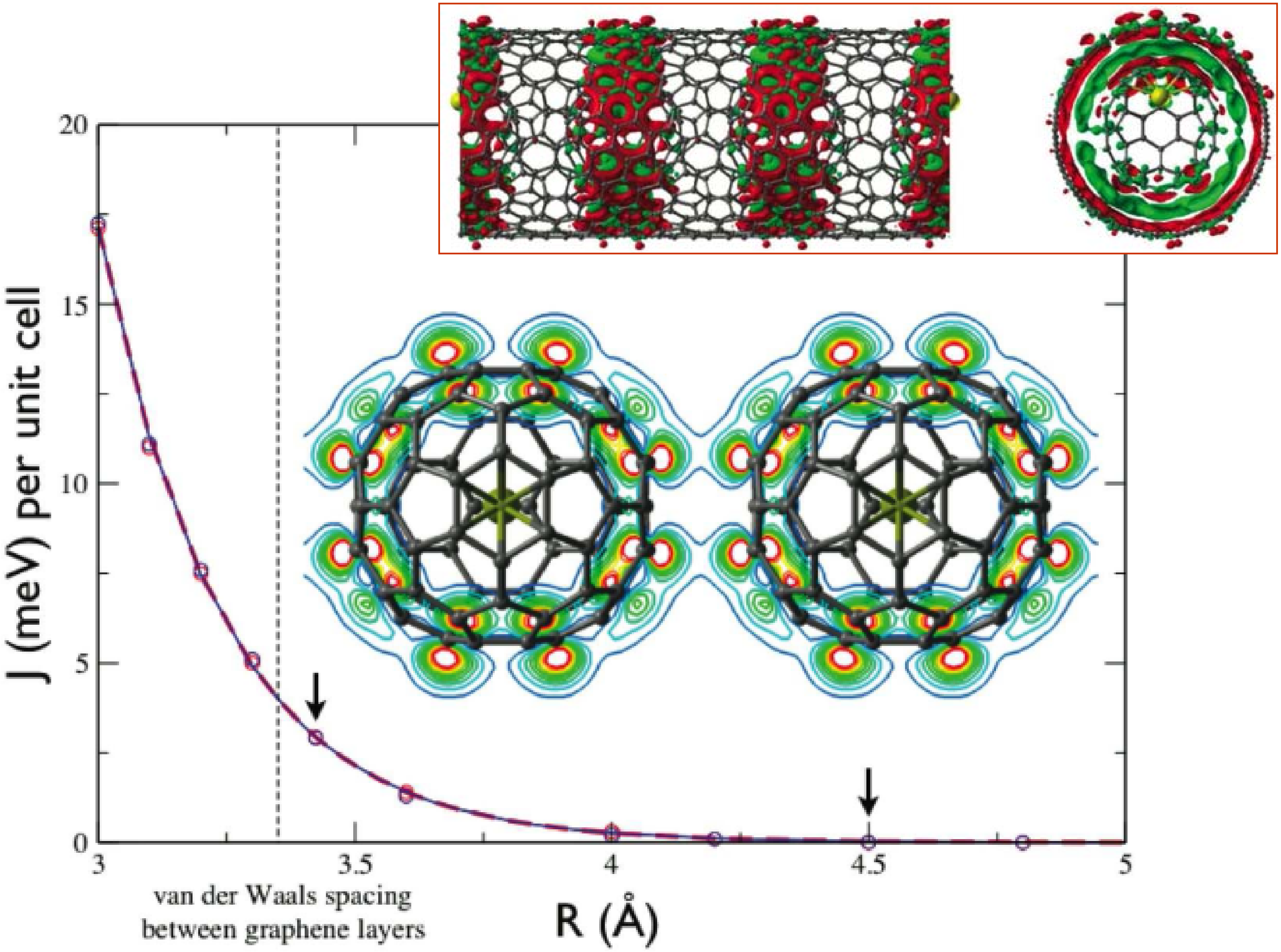
Atomic structural model (23, 15)

J.H. Warner *et al*, *ACS Nano* **3**, 1557-1563 (2009)

Outstanding problems in using spin states

- In peapods:
  - how can you measure single spins?
  - what will be the EDMR mechanisms?

Modelling charge transfer in $Sc@C_{82}@SWNT$

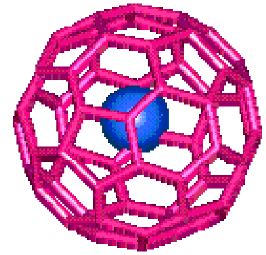


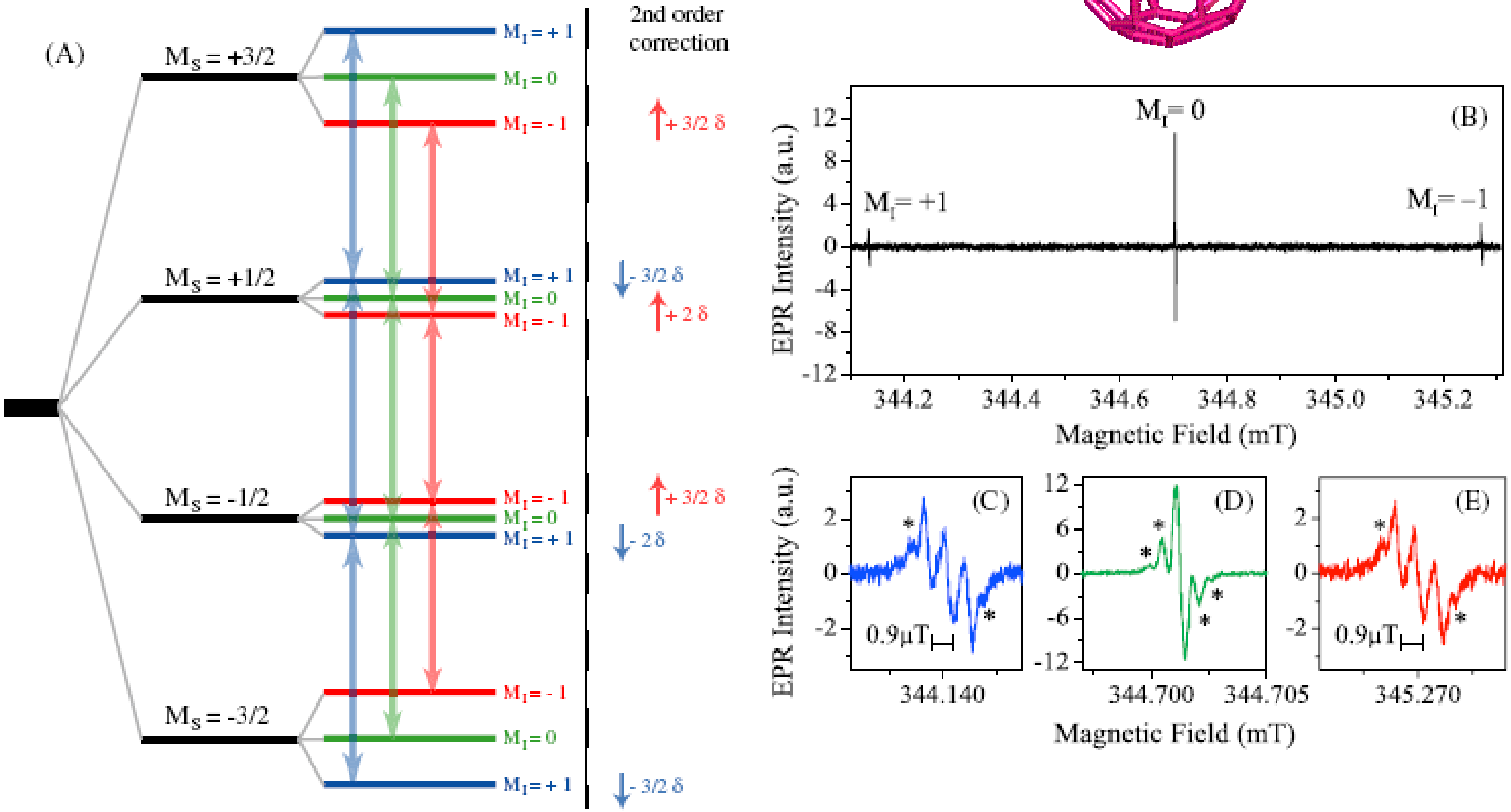
L. Ge *et al*., *Phys. Rev. B* **77**, 235416 (2008)

Outstanding problems in using spin states

- In peapods:
  - how can you measure single spins?
  - what will be the EDMR mechanisms?
  - can you use RKKY for controlled coupling?

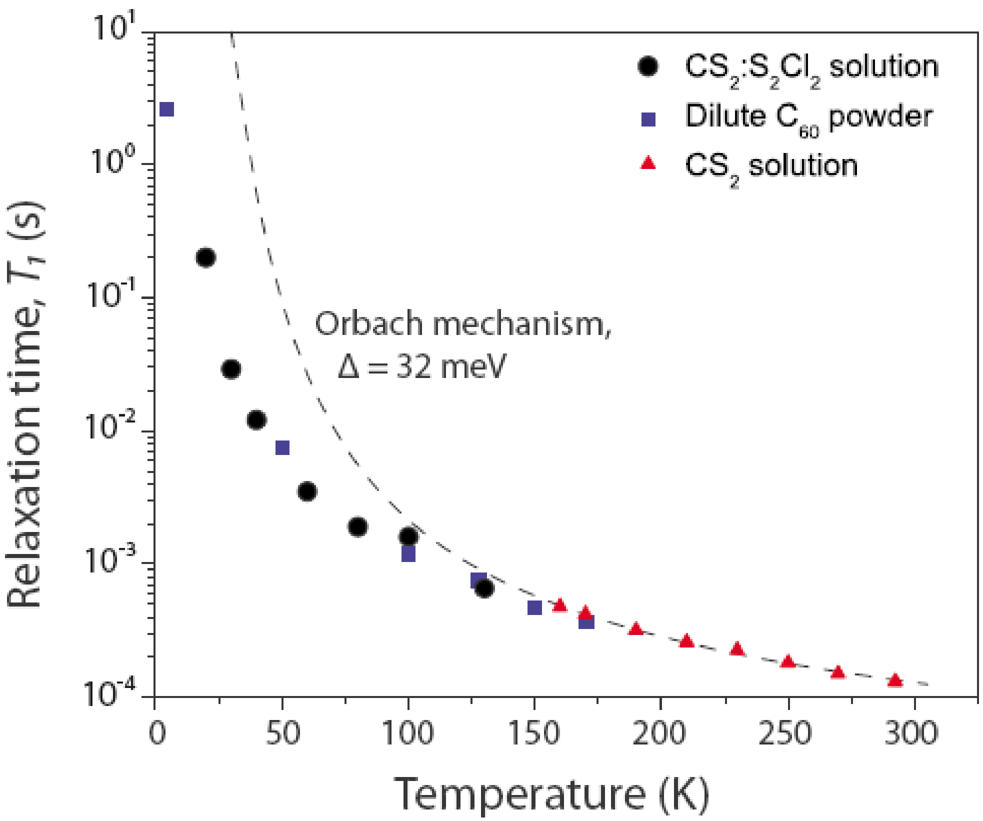
$^{14}N@C_{60}$

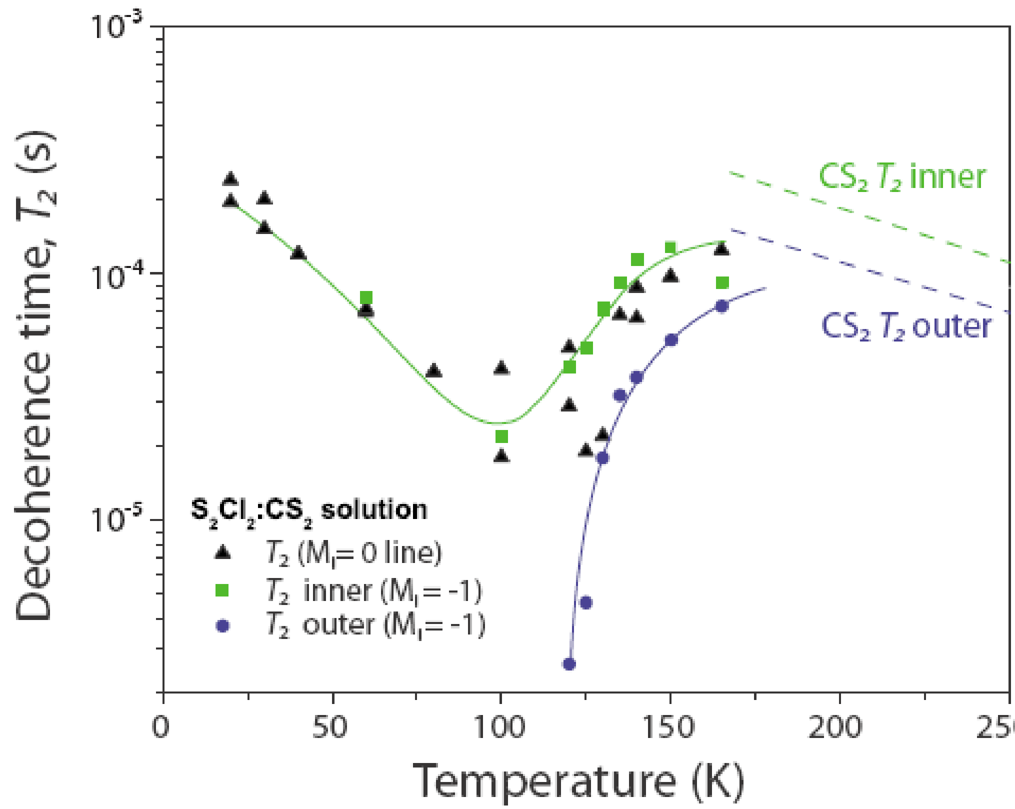




S.C. Benjamin *et al.*, *J. Phys.: Condens. Matter* **18,** S867–S883 (2006)

Spin relaxation and decoherence times of $^{14}N@C_{60}$

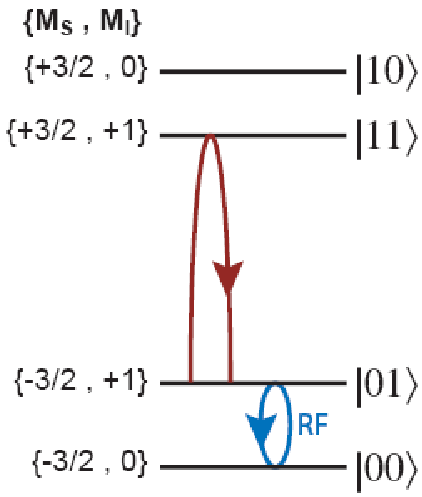


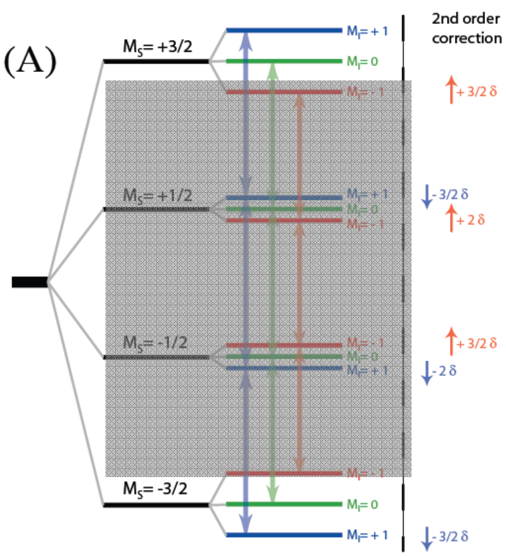


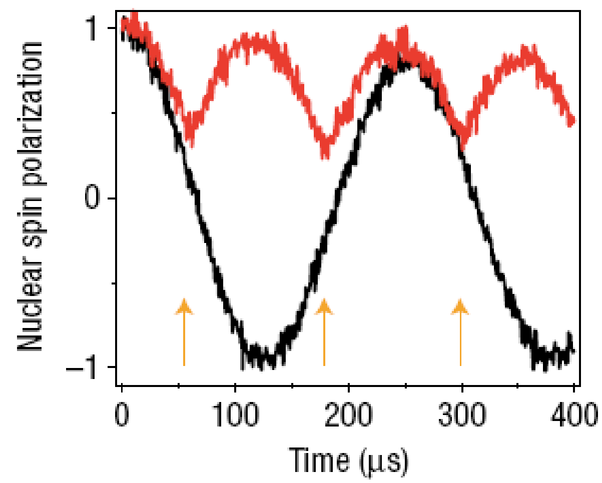
- T_1, above 150 K, follows Orbach mechanism
  - Additional relaxation mechanisms at lower temperature
- T_{2inner} increases below 100 K, and is unaffected by the ^{14}N spin
  - Fall in T_{2outer} is due to dephasing as a result of zero field splitting

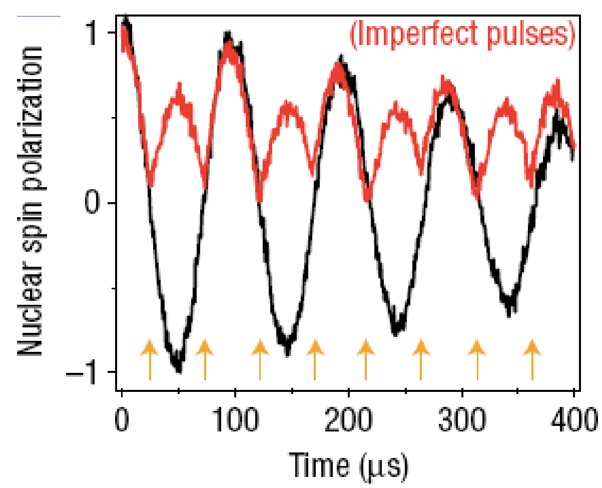
J.J.L. Morton *et al.*, *Phys. Rev. B* **76**, 085418 (2007)

Bang-bang control





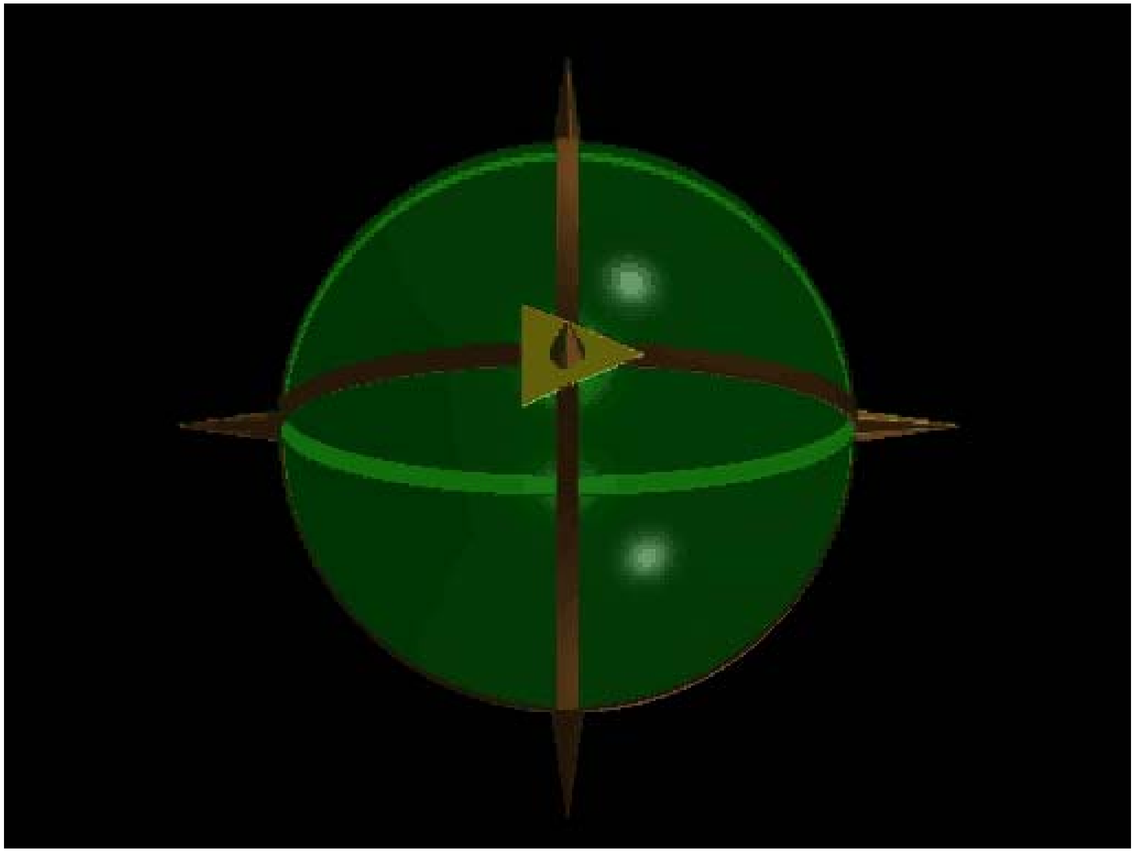




J.J.L. Morton *et al.*, *Nature Physics* **2**, 40-43 (2006)

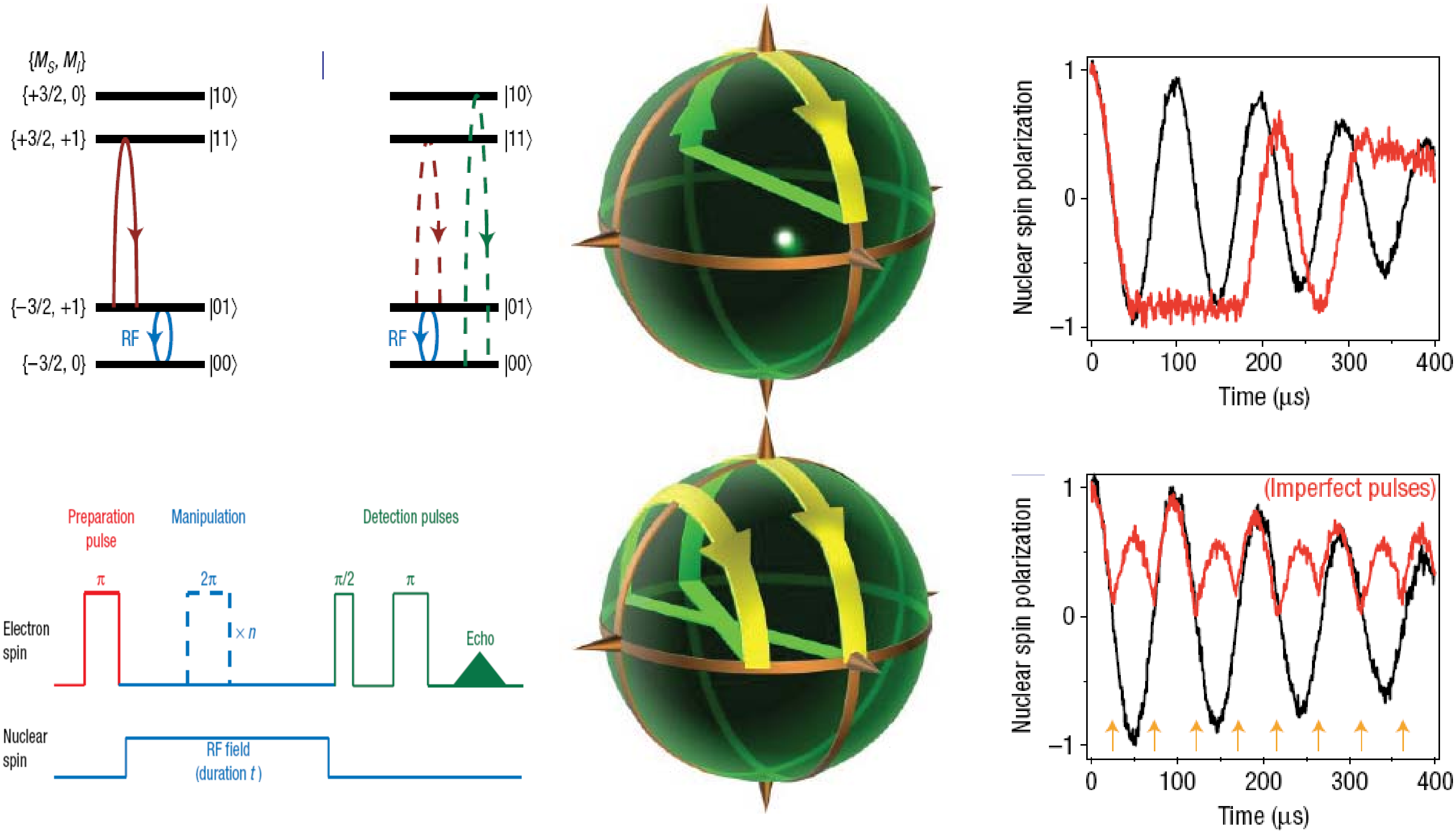
QIRC

Bang-bang control



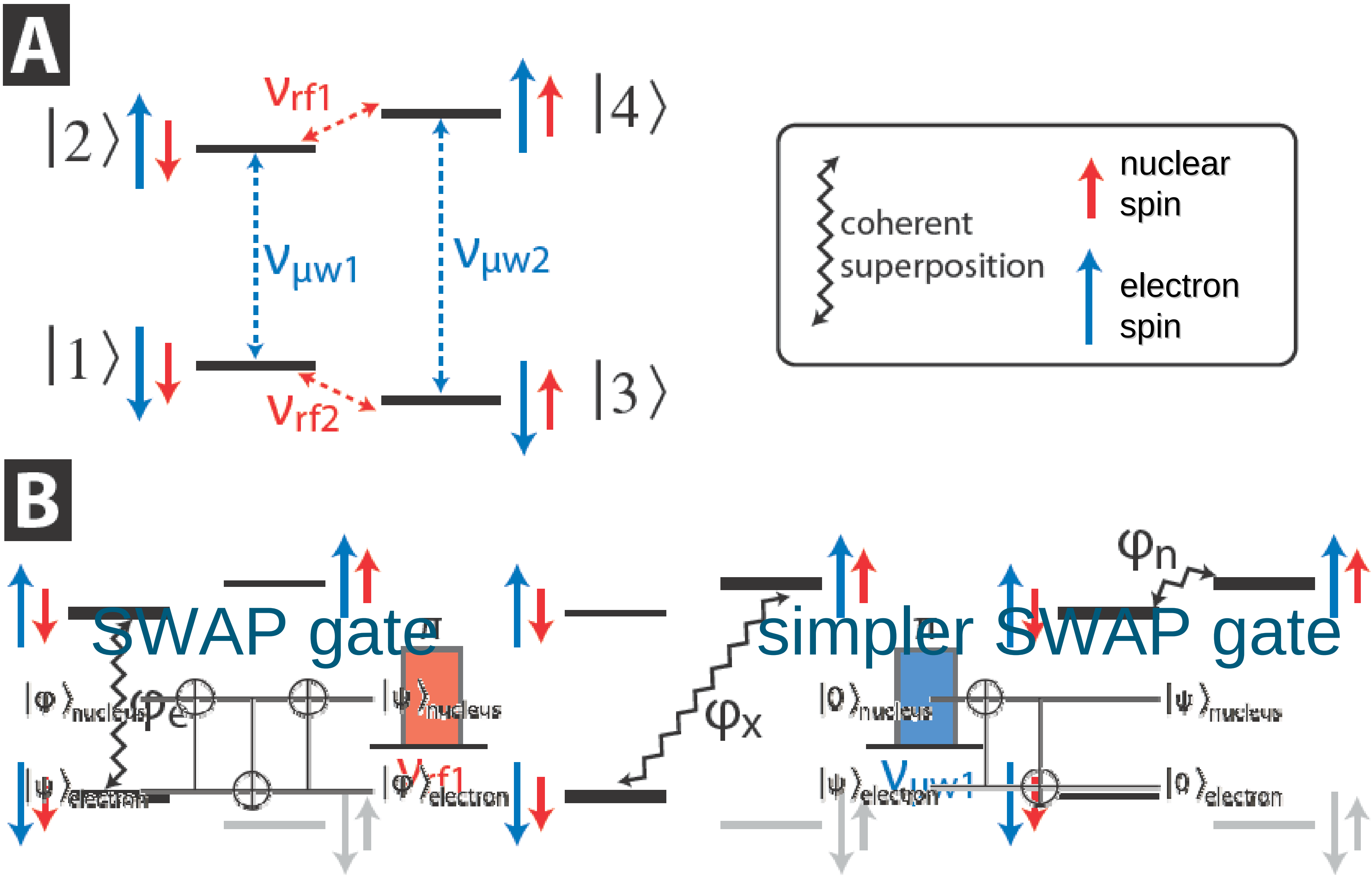
J.J.L. Morton *et al.*, *Nature Physics* **2**, 40-43 (2006)

Bang-bang control



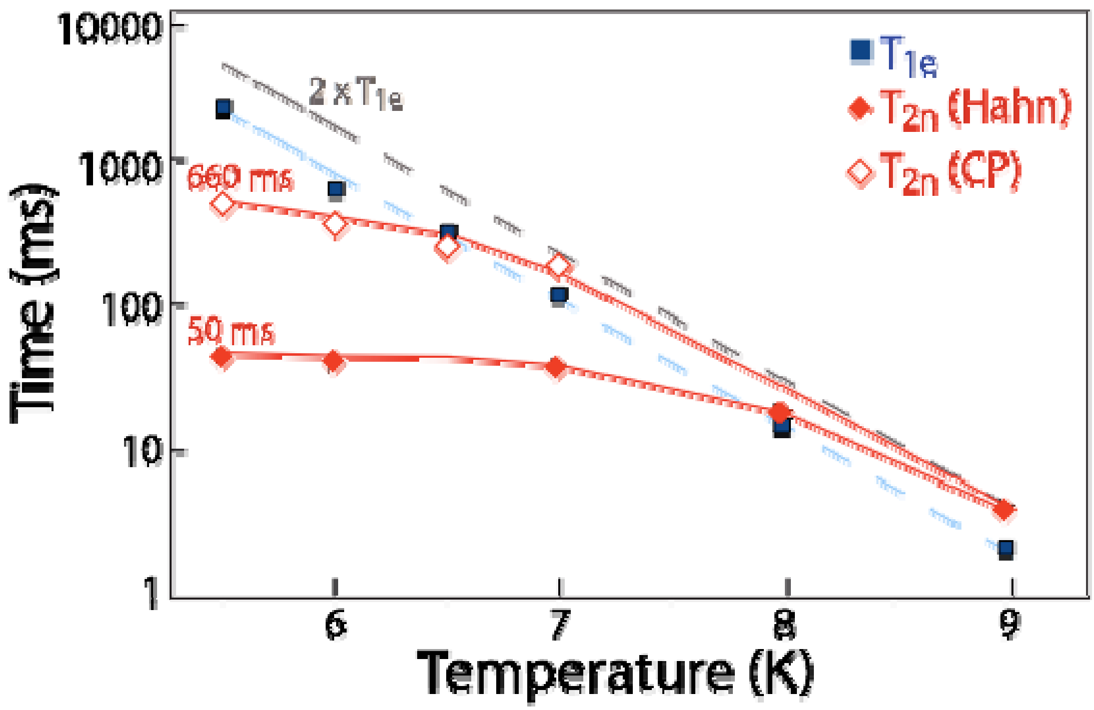
J.J.L. Morton *et al.*, *Nature Physics* **2**, 40-43 (2006)

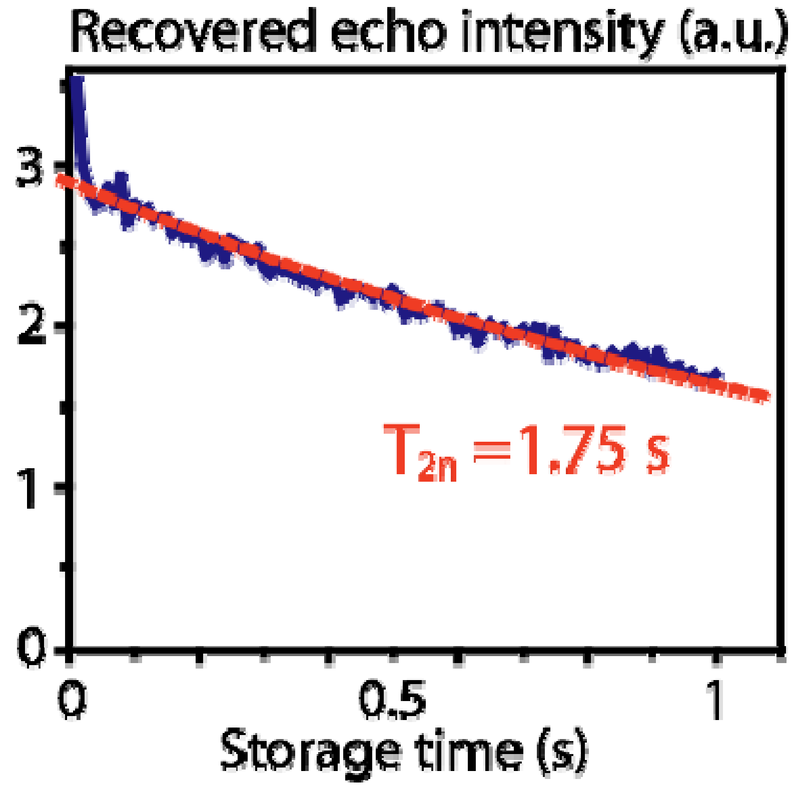
Spin memory



J.J.L. Morton *et al.*, *Nature* **455**, 1085-1088 (2008)

^{31}P in ^{28}Si





J.J.L. Morton *et al.*, *Nature* **455**, 1085-1088 (2008)

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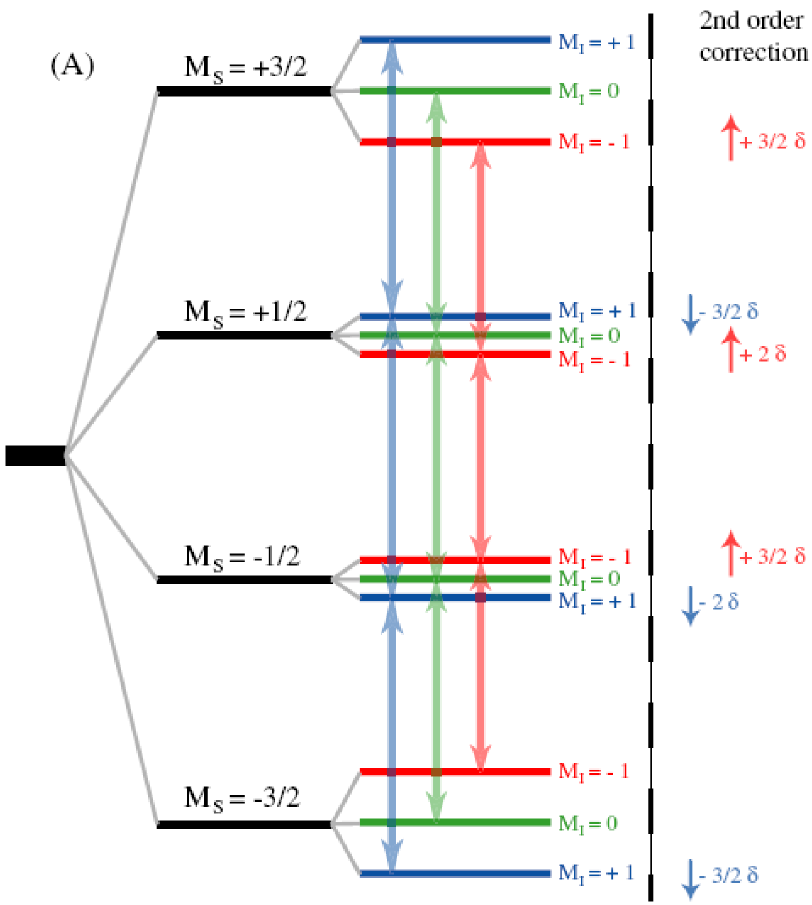
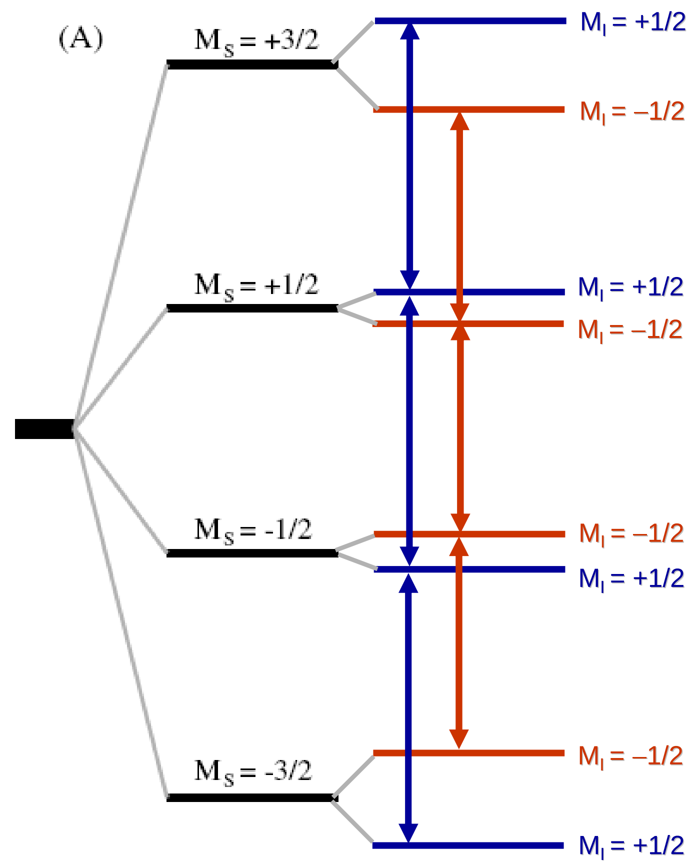
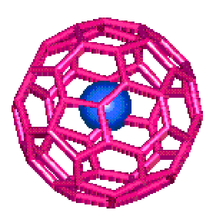
$^{15}N@C_{60}$ / $^{14}N@C_{60}$

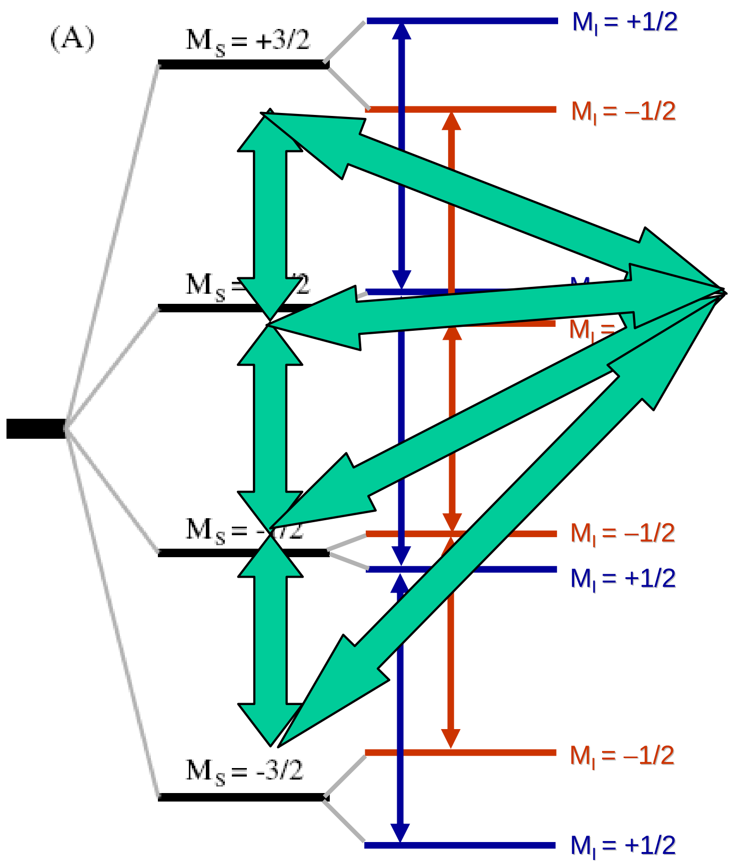


$^{15}N@C_{60}$

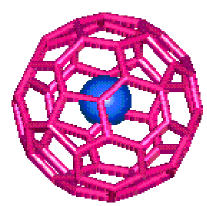




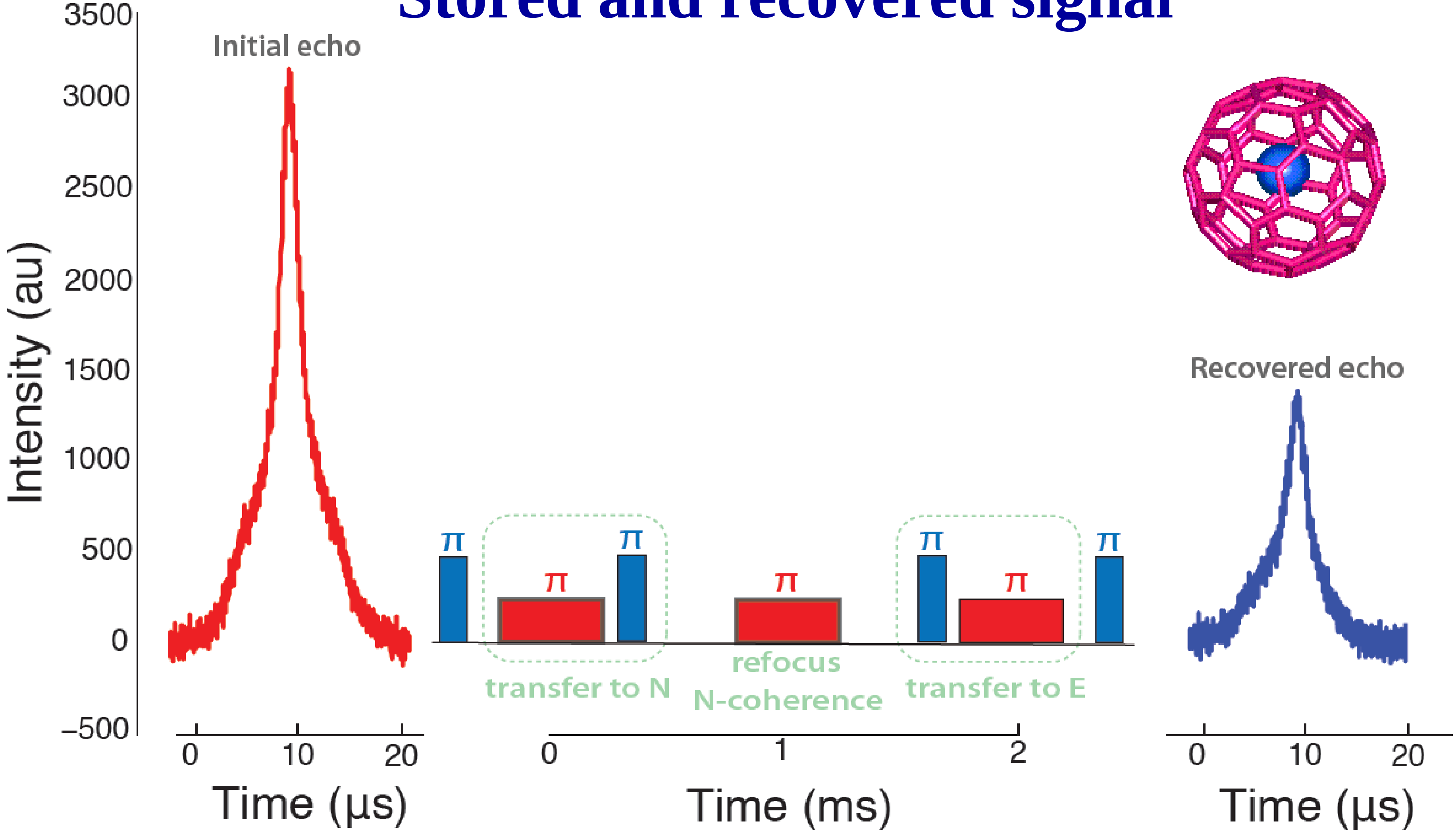
$^{15}N@C_{60}$



1. $\pi/2_{MW}$ to create coherence
2. π_{RF} to flip nuclear spin
3. π_{MW} to flip electron spin
4. Outer coherences rapidly decay
5. Wait several T_{2e}
6. π_{MW} to flip electron spin
7. π_{RF} to flip nuclear spin
8. Original inner coherence of electron spin is now restored



Stored and recovered signal



- Phase cycled m.w. +/– x and r.f. 0/90
  - Evidence that information is stored and retrieved from nuclear spin
- Two-way transfer fidelity $f^2 = 0.44$
  - Known limitations to fidelity are entirely instrumental

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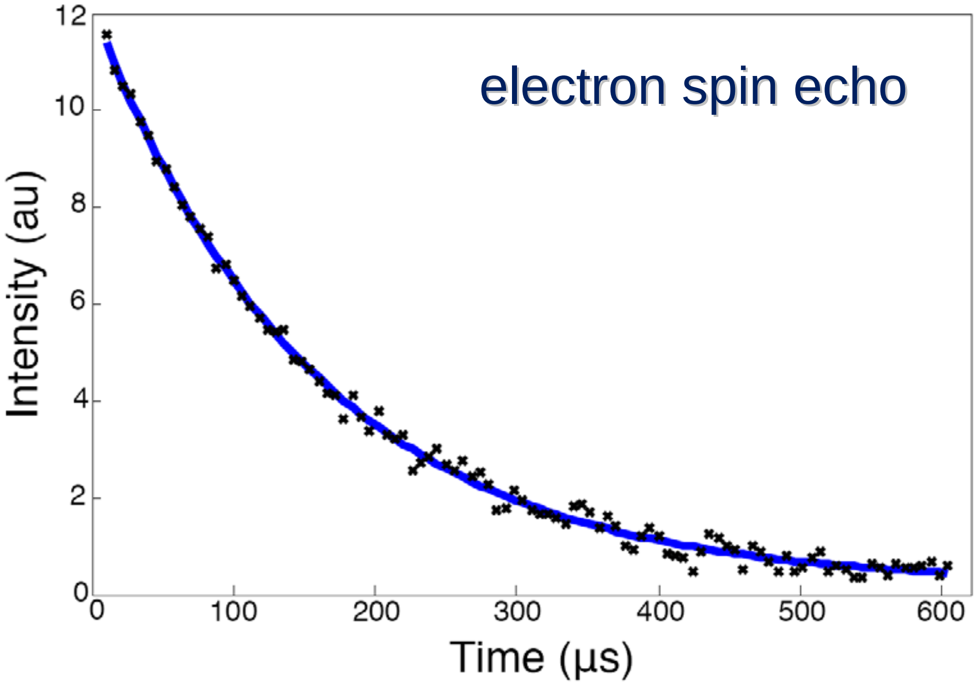
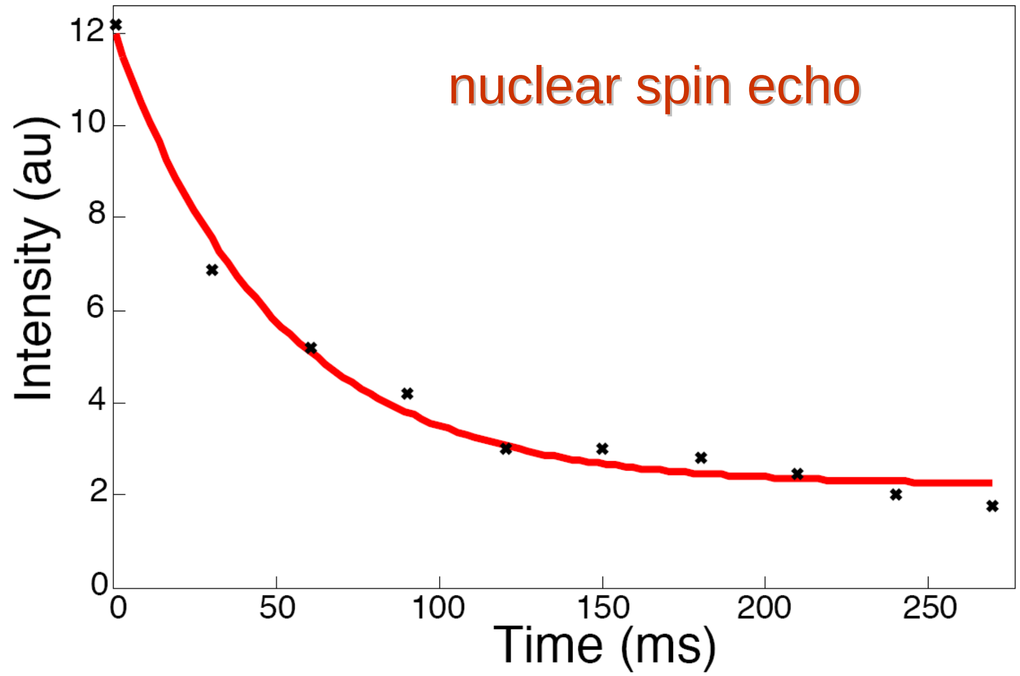
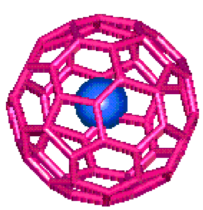
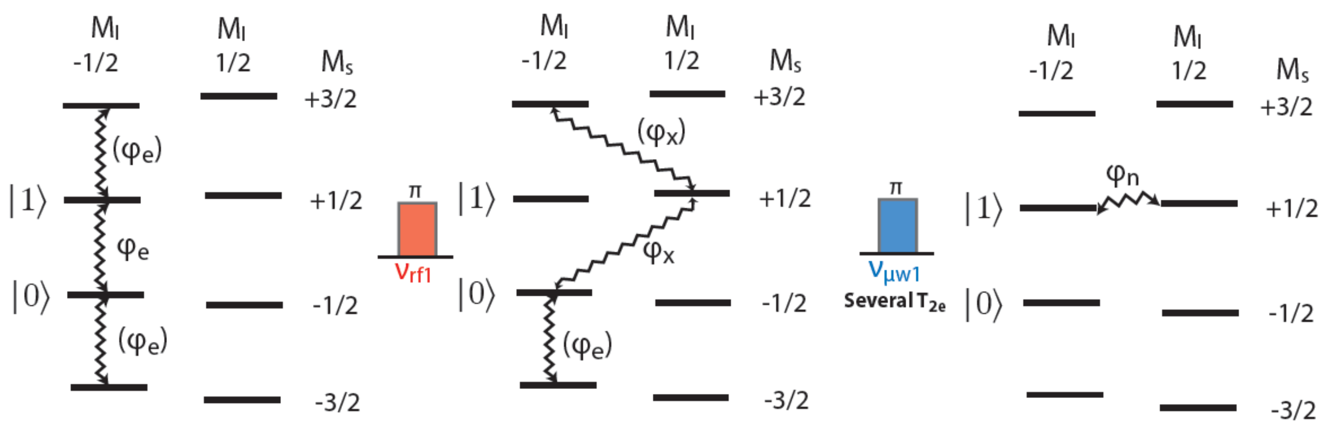
Storage time @ 10 K





- $T_{2e} = 155\ \mu s$
- $T_{2n} = 54$ ms





Richard Brown

Quantum sensing

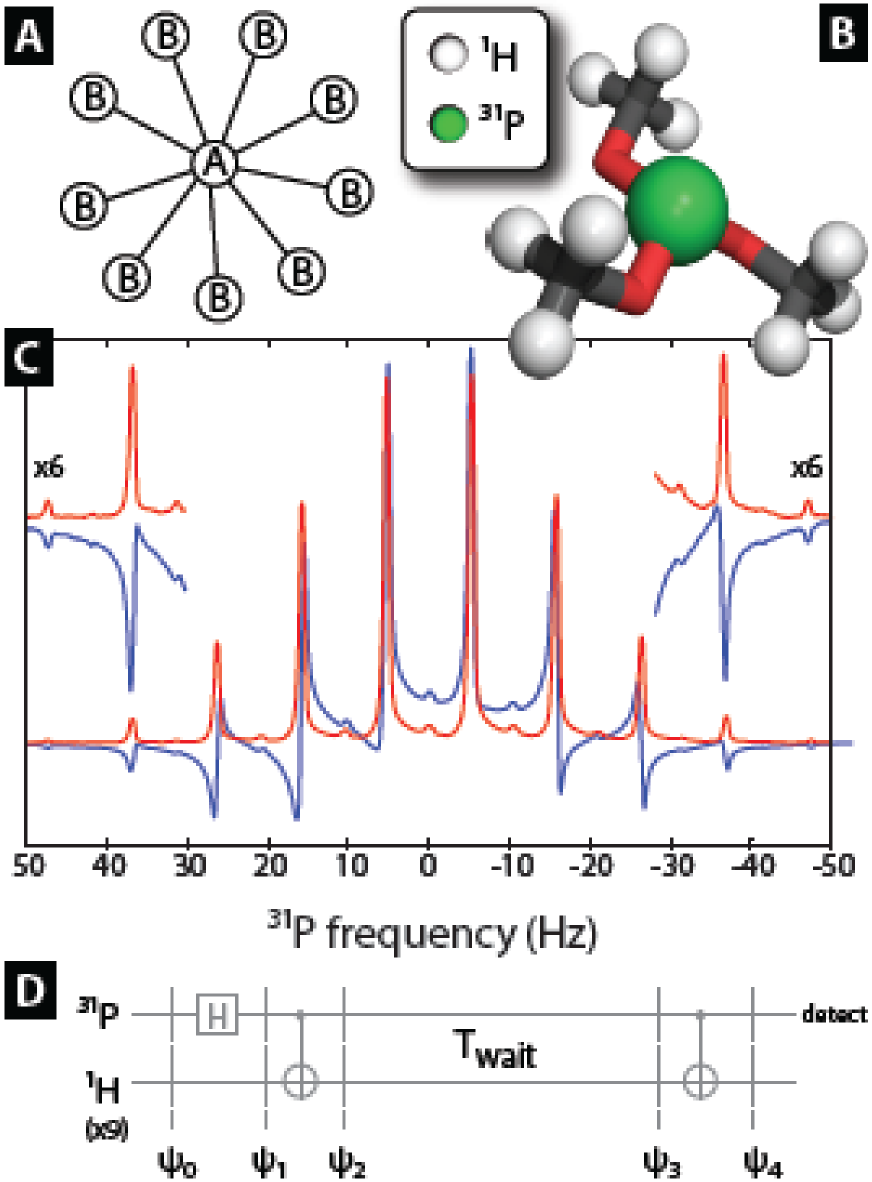
$$|\Psi\rangle = \tfrac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right) \qquad |\Psi\rangle = \tfrac{1}{\sqrt{2}}\left(|0000\rangle + |1111\rangle\right)$$

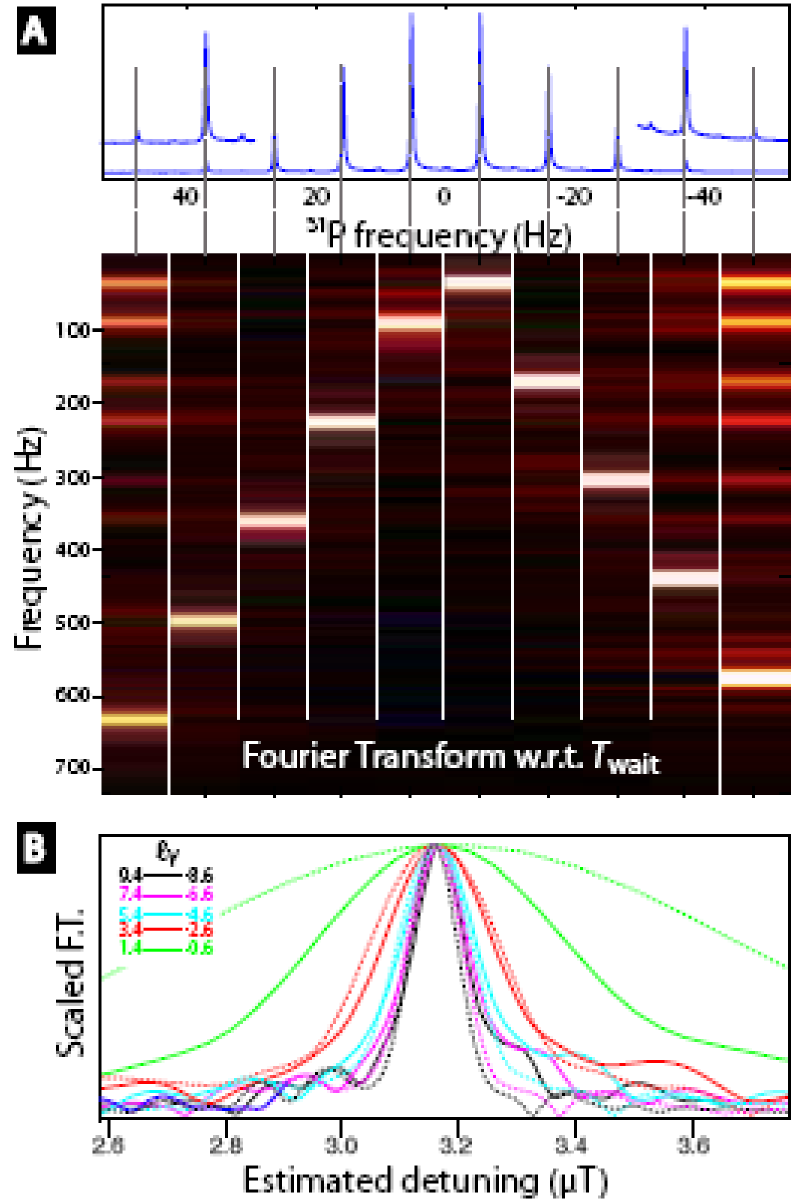
$$|\Psi\rangle = \tfrac{1}{\sqrt{2}}\left(|0\rangle + e^{i\phi}|1\rangle\right) \qquad |\Psi\rangle = \tfrac{1}{\sqrt{2}}\left(|0000\rangle + e^{iN\phi}|1111\rangle\right)$$

- Already demonstrated in optics
- Spin entanglement fully deterministic
- Enhancement by $\sqrt{N}$ in sensitivity to field
- New generation of sensors

QIRC

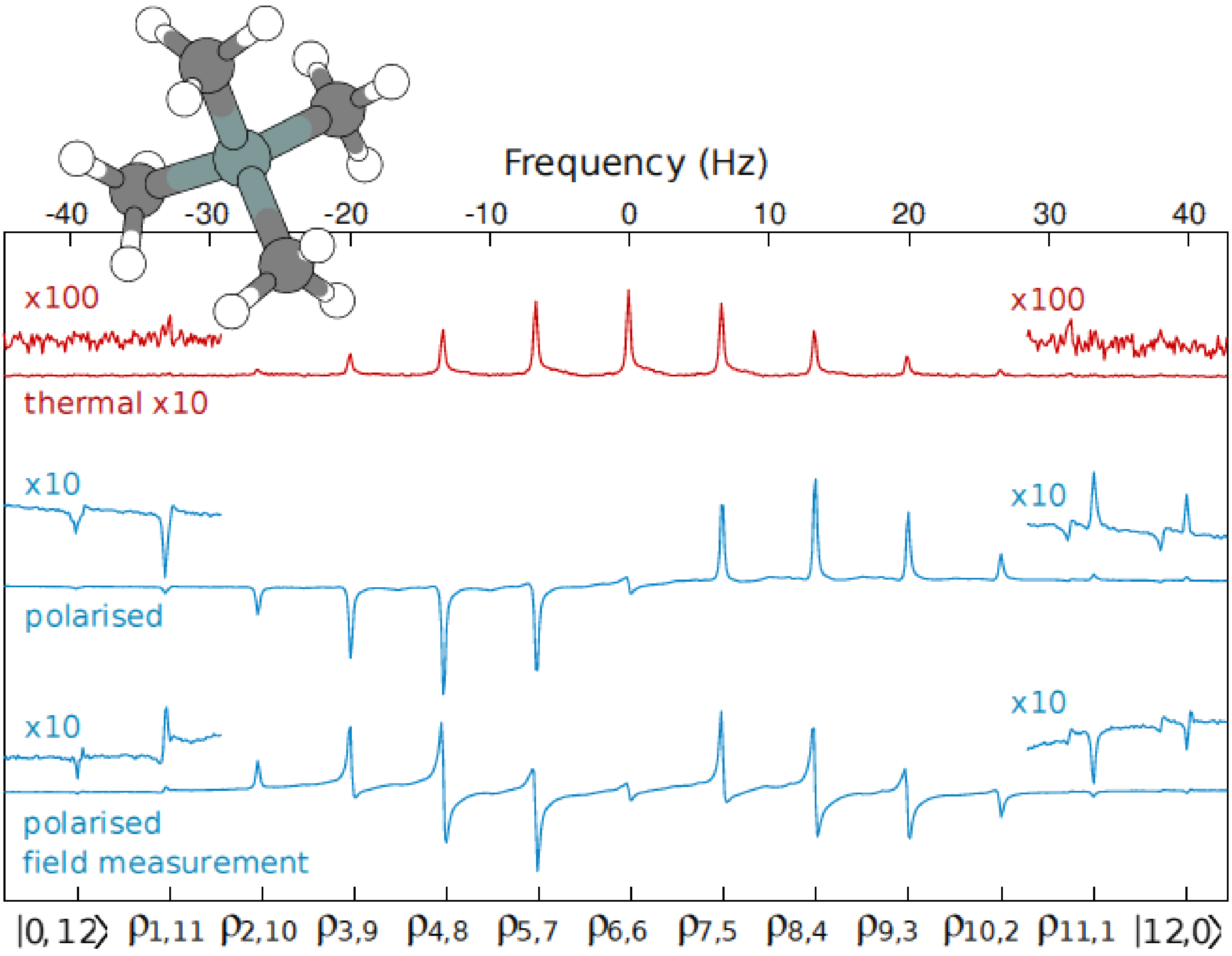
Entanglement enhanced field sensing





J.A. Jones *et al*., *Science* **324**, 1166-1168 (2009)

Entanglement enhanced field sensing



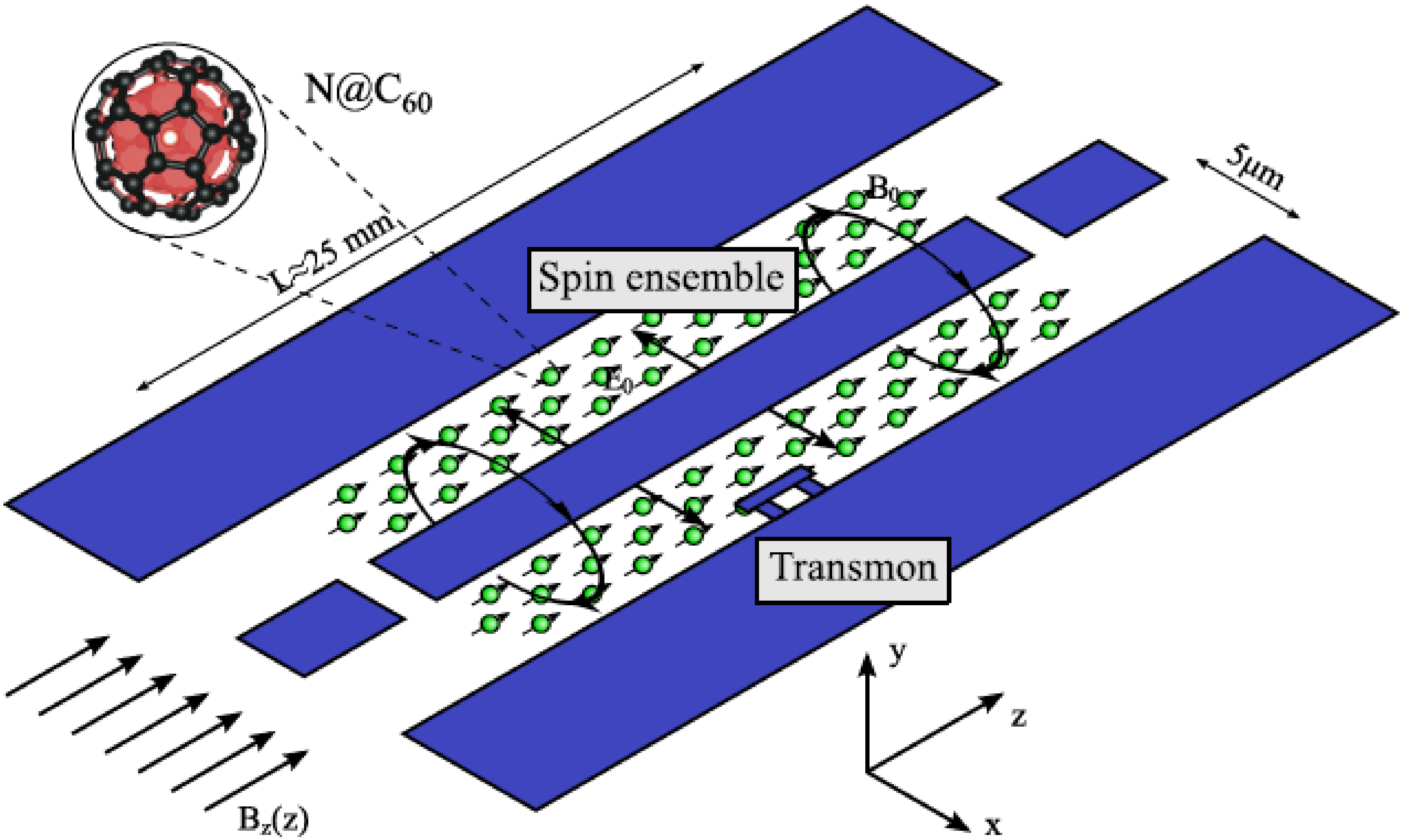
$$\rho_{M,S} = \sum_i |M,S\rangle_i \langle M,S|_i$$

S. Simmons *et al.*, arXiv:0907.1372v1

Outstanding problems in using spin states

- In peapods:
  - how can you measure single spins?
  - what will be the EDMR mechanisms?
  - can you use RKKY for controlled coupling?
- In entanglement enhanced sensing:
  - can you achieve a pure state?

Storage in collective spin states



J.H. Wesenberg *et al.*, *Phys. Rev. Lett.* **103**, 070502 (2009)

Storage in collective spin states

JOURNAL OF APPLIED PHYSICS VOLUME 26, NUMBER 11 NOVEMBER, 1955

Spin Echo Serial Storage Memory

A. G. Anderson, R. L. Garwin, E. L. Hahn,* J. W. Horton, G. L. Tucker,† and R. M. Walker
Watson Scientific Computing Laboratory, Columbia University, New York, New York

(Received July 26, 1955)

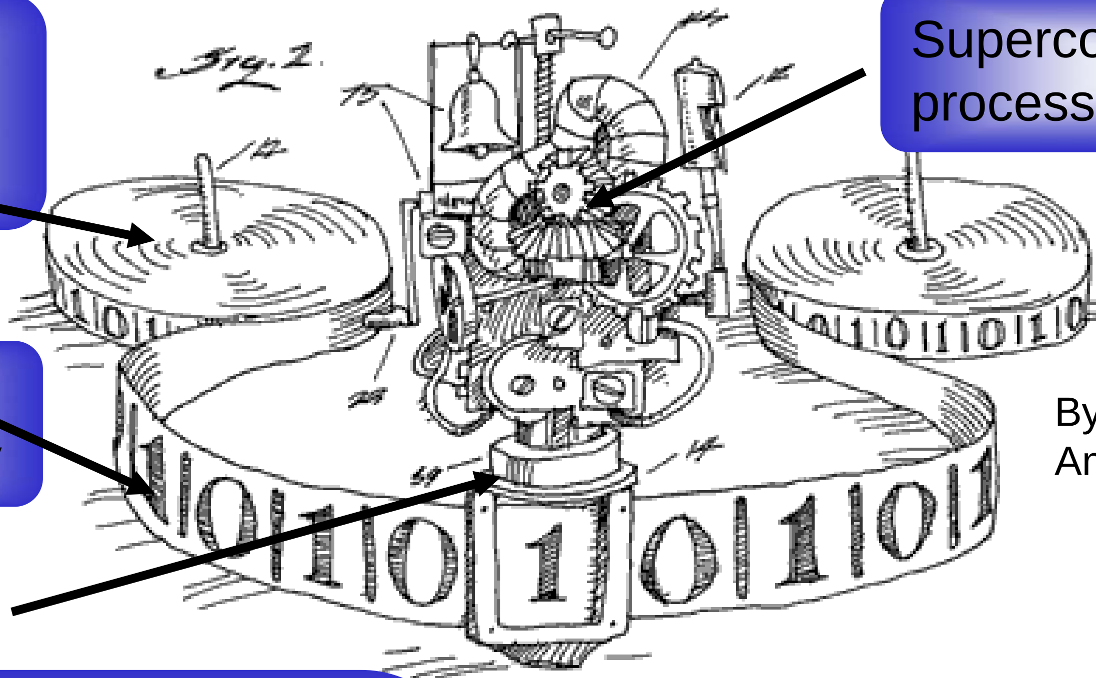
By utilizing the method of pulsed nuclear magnetic resonance, radio-frequency energy in the form of pulses can be stored serially in a sample of nuclear spins and recalled at an arbitrary later time within the memory or relaxation time of the spin sample. Weak pulses of radio-frequency energy condition the nuclear spins to start precessing in phase. After they become completely out of phase, a strong recollection pulse brings about a phase reversal of precession and produces a series of spin echoes in a sequence corresponding to direct or reverse order of input pulses. The echo amplitudes in such a series are given as a function of the number and strength of the input pulses and the conditions for maximum storage capacity in a spin ensemble are determined. The maximum specific storage capacity in liquids is expressed in terms of the thermal noise of the detecting apparatus, the effect of self-diffusion of the molecules, and the relaxation times. The origin of undesired spin echoes arising from the interaction of input pulses is discussed, and means for eliminating these echoes by frequency and magnetic field modulation are discussed and applied. Extensive use is made of a magnetic field modulation technique to destroy undesired echoes, and to permit novel types of recall of serially stored groups of pulses. Whereas Fernbach and Proctor [J. Appl. Phys. 26, 170 (1955)] have demonstrated multiple pulse storage under conditions which reproduce the input pulse shape, the present investigation is concerned with the storage of a maximum number of pulses whose shape is ideally determined by the nuclear spin band width. In practice, the order of 1000 rf pulses can be stored and recalled by this method in a proton sample several cc in volume within a memory time of 10 to 50 milliseconds. Large specific storage capacities expected for existing long relaxation time liquids are not realized because of excessive self-diffusion.

Storage in collective spin states

Magnetic field gradients to shift memory

Electron spin ensemble memory

Cavity interface



Superconducting qubit processor head

By Tom Dunne
American Scientist 2002

Key properties

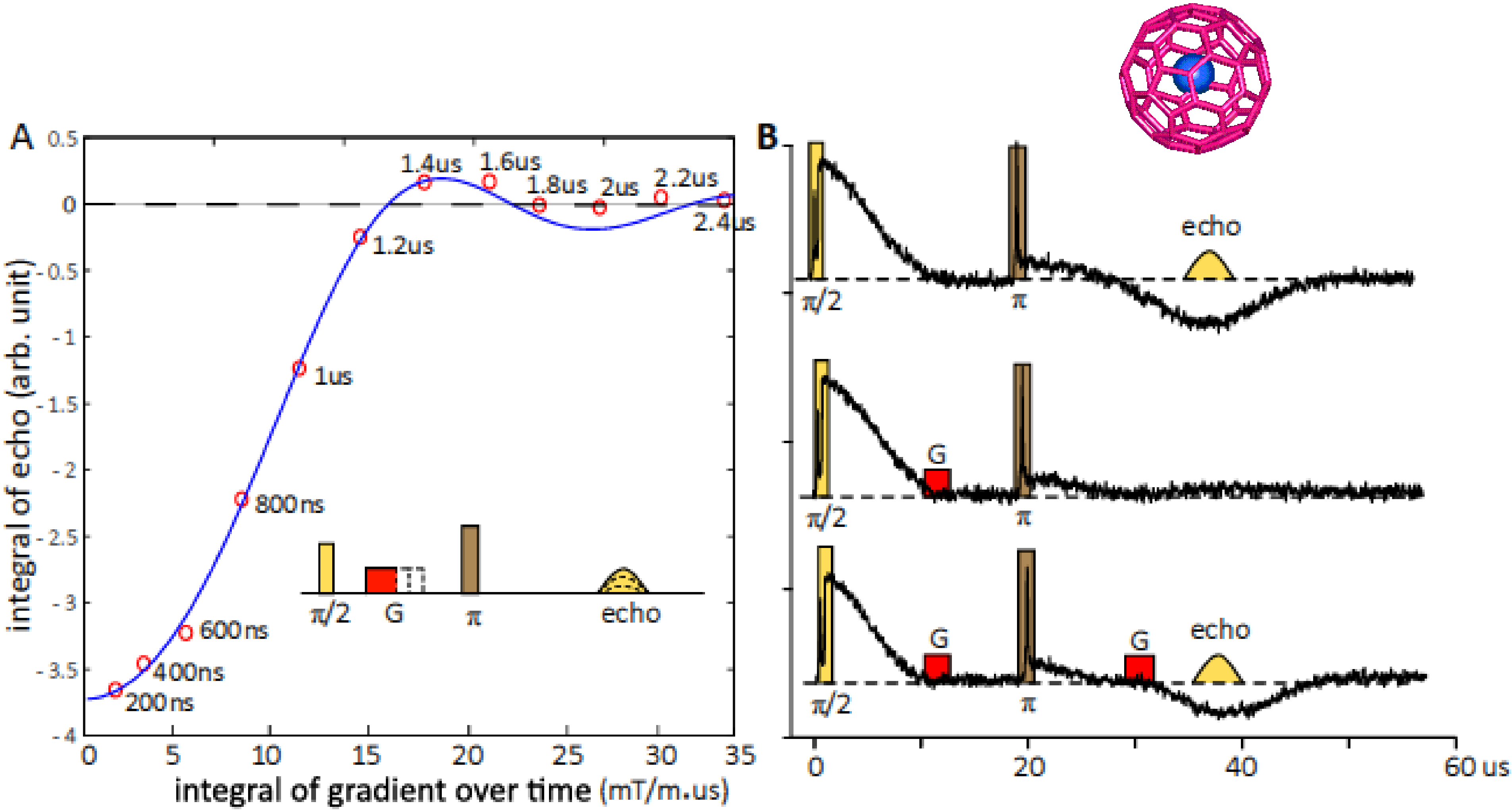
- ✧ A processor head
- ✧ Processor/Memory interface
- ✧ A homogenous storage medium
- ✧ Means of winding the tape

Optimize 4 elements using best suited quantum systems and immediately get many qubits!

Dave Schuster

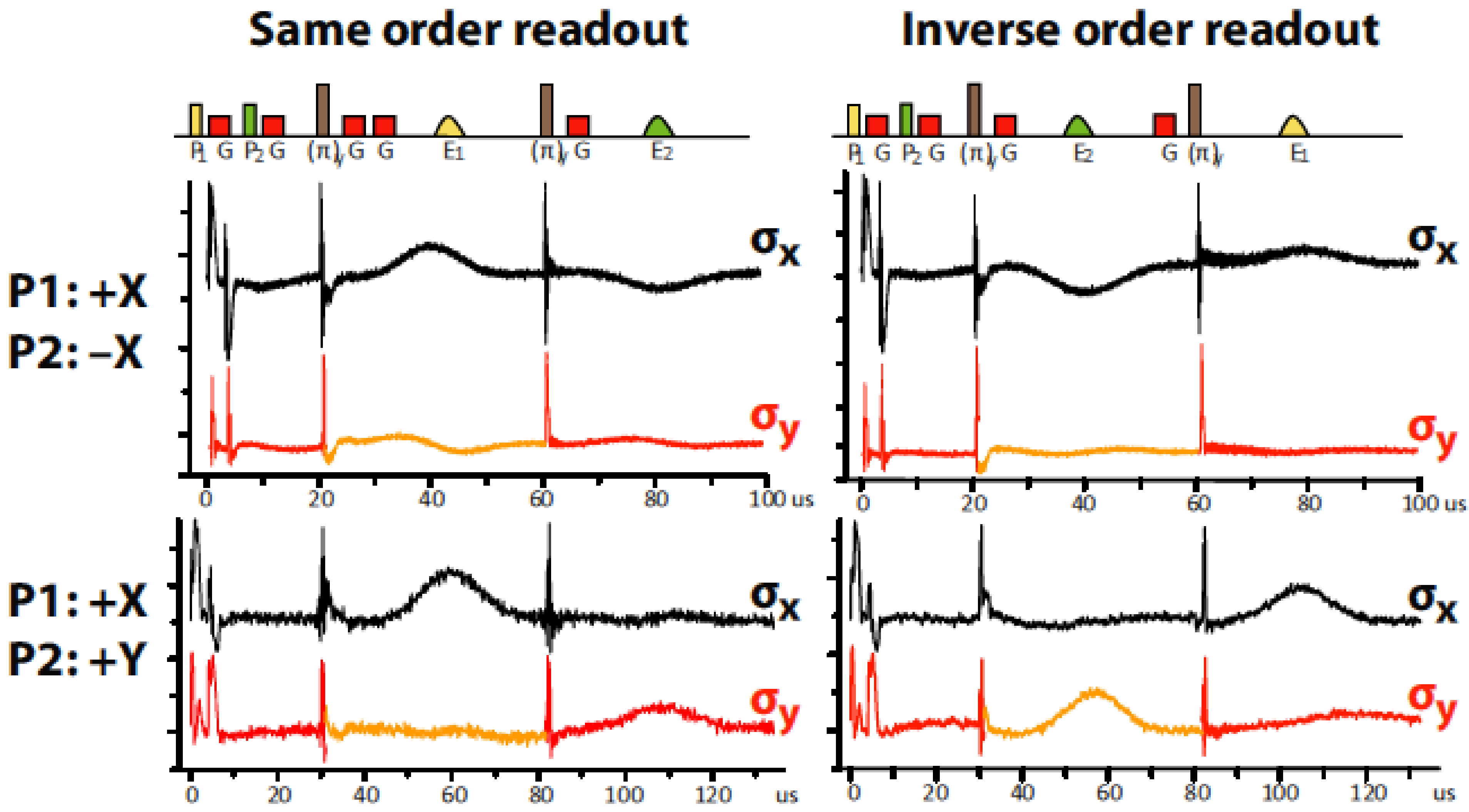
QIRC

Storage in collective spin states



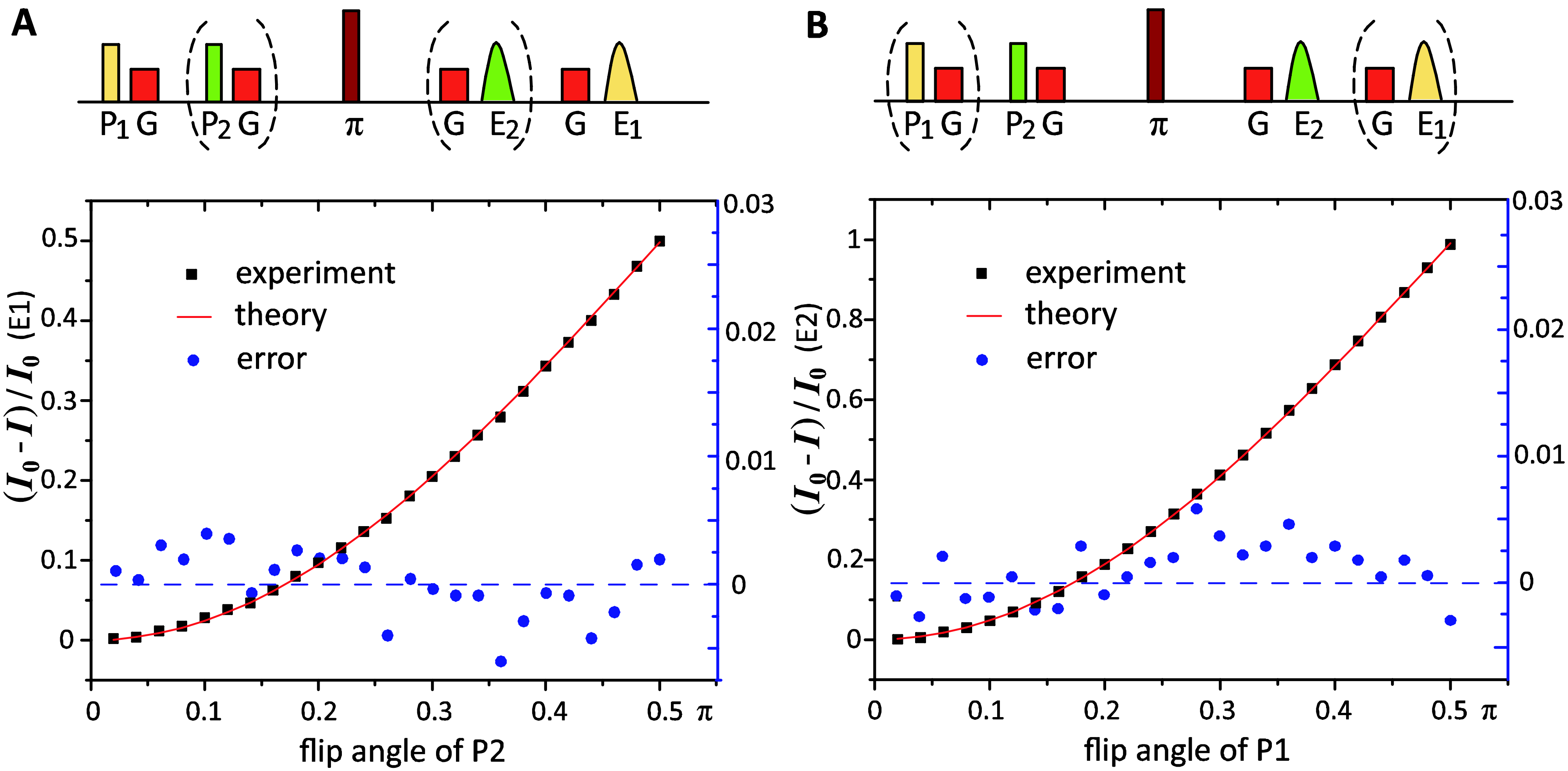
H. Wu *et al.*, arXiv:0908.0101

Storage in collective spin states



H. Wu *et al.*, arXiv:0908.0101

Crosstalk between nominally orthogonal modes



H. Wu *et al.*, arXiv:0908.0101

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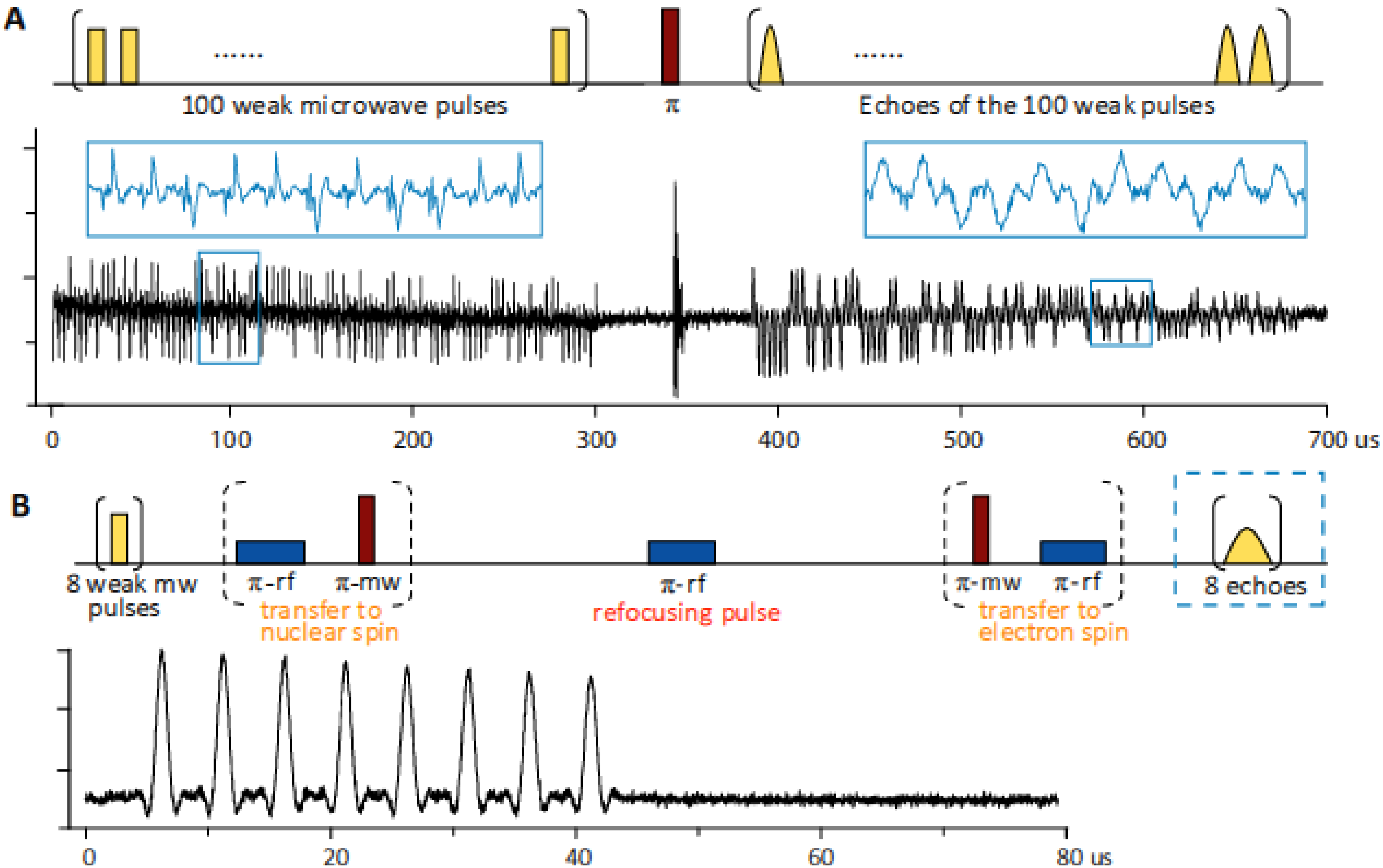
Storage in collective spin states



H. Wu *et al.*, arXiv:0908.0101

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  - how could you avoid using refocusing pulses?
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QIRC