核磁共振與磁振造影

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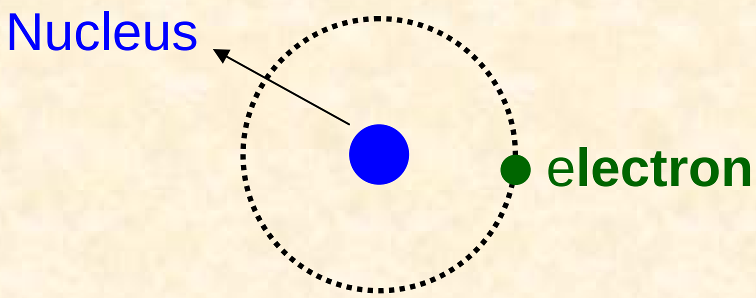
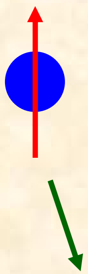
核磁共振 Nuclear Magnetic Resonance (NMR)

This technique observes signals from nuclear spins to obtain the structural & dynamical information of the sample.

Nuclear spin



The Bohr model of H atom



Nuclear spin (自旋) I ⟶ An intrinsic property of the nucleus

Nuclear magnetic moment (磁矩) $\mu_I = \gamma_n \hbar \mathbf{I}$

Can be though of as a strange tiny magnet 小磁矩(鐵)

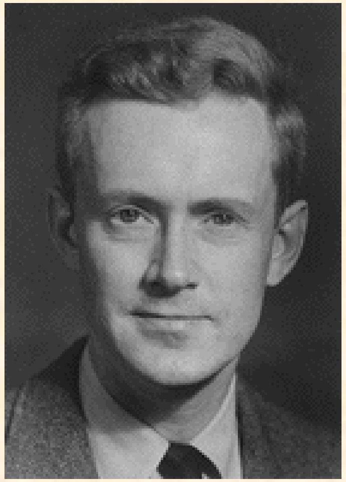
Why & how to observe nuclear spins?

Timeline I

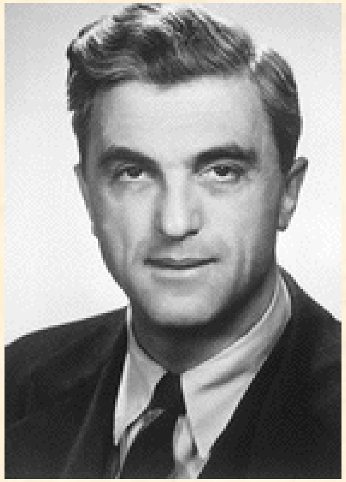
1946: Discovery of nuclear magnetic resonance phenomenon
Purcell et al. (Harvard) & Bloch et al. (Stanford)

1949: Chemical shift

1952: Nobel Prize in physics - Bloch and Purcell
for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith



Edward M. Purcell



Felix Bloch

Timeline II

1960s: Solid state NMR – Waugh
NMR imaging was demonstrated

1966: Ernst and Anderson
Fourier Transform technique for NMR

1970: 2D NMR

1980s: Macromolecular structure determination in solution by NMR.

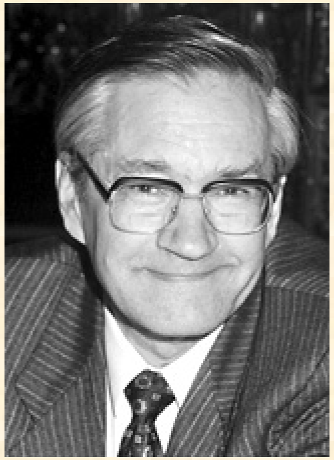
1973: Back projection MRI (P. Lauterbur)

1975: Fourier Imaging – R. Ernst

1977: the first study performed on a human took place

1991: Nobel prize in Chemistry - Ernst

for his contributions to the development of the methodology of high resolution NMR spectroscopy



Richard R. Ernst

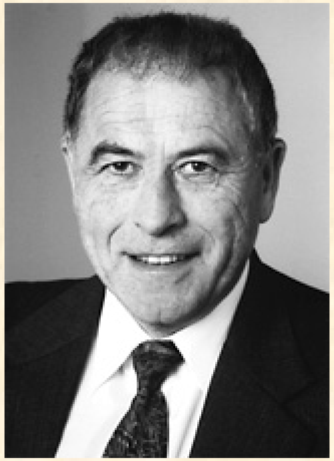
1990s: Heteronuclear multi-dimensional NMR permit the determination of protein structure up to 50 KDA.
MRI become a major radiological tool in medical diagnostic.

2002: Nobel prize in Chemistry - Wüthrich (1/2)

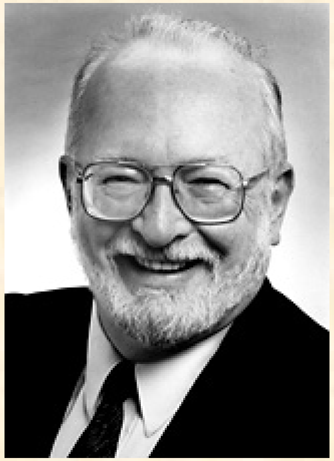
for his development of NMR spectroscopy for determining the 3D structure of biological macromolecules in solution.

2003: Nobel Prize in Physiology or Medicine – Lauterbur and Mansfield

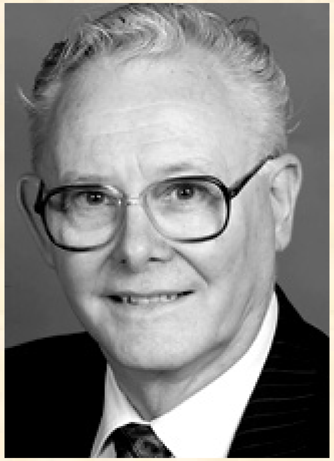
discoveries concerning magnetic resonance imaging



Kurt Wüthrich

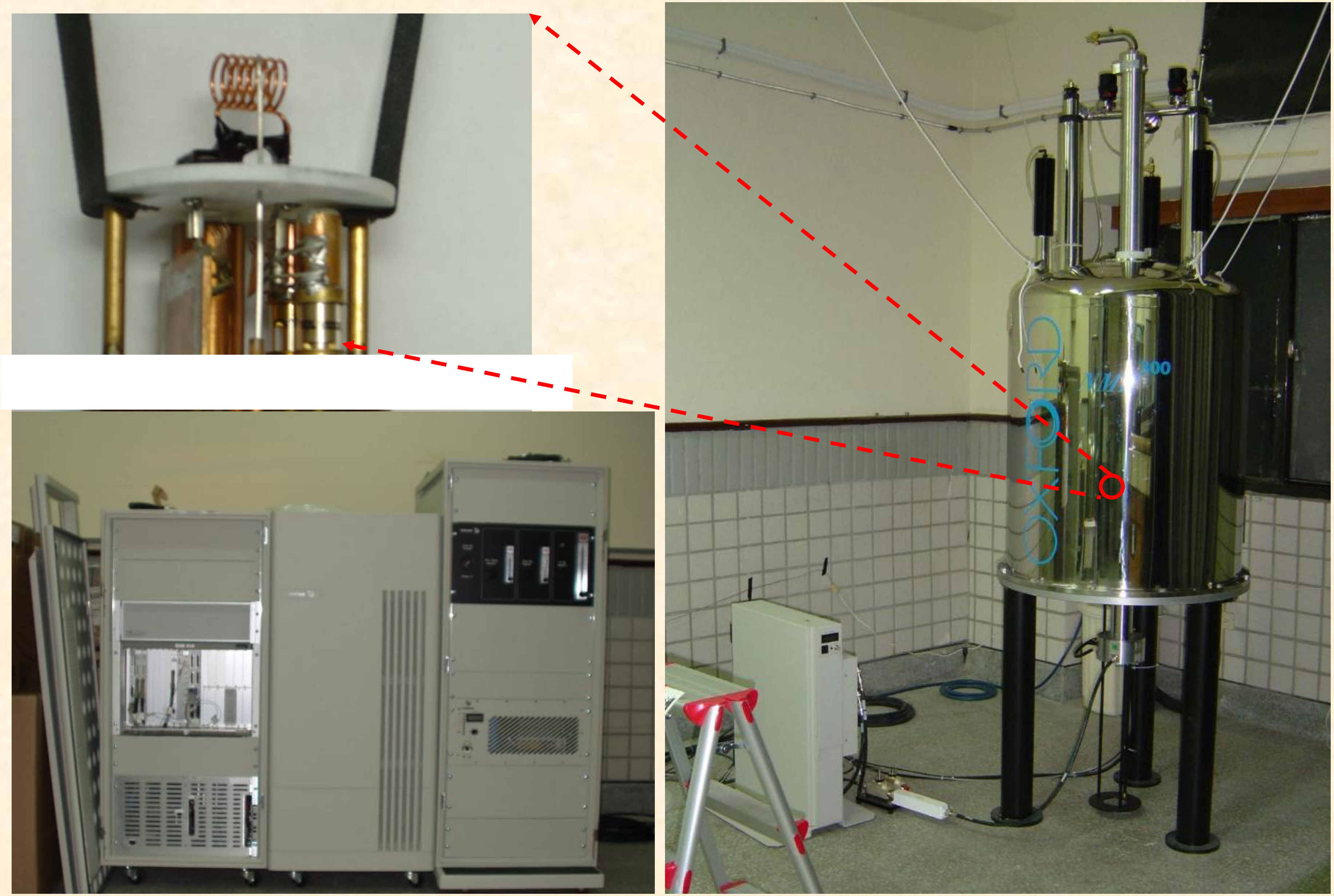


Paul C. Lauterbur

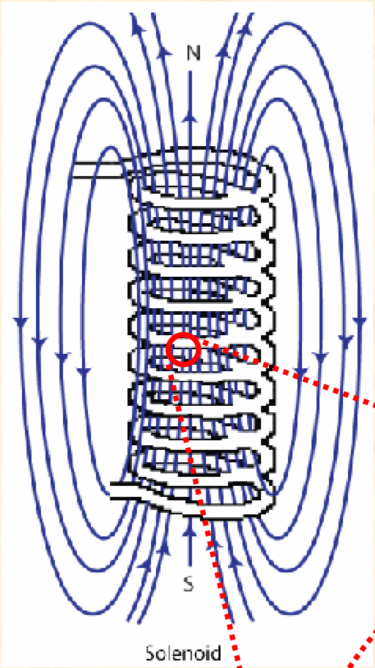


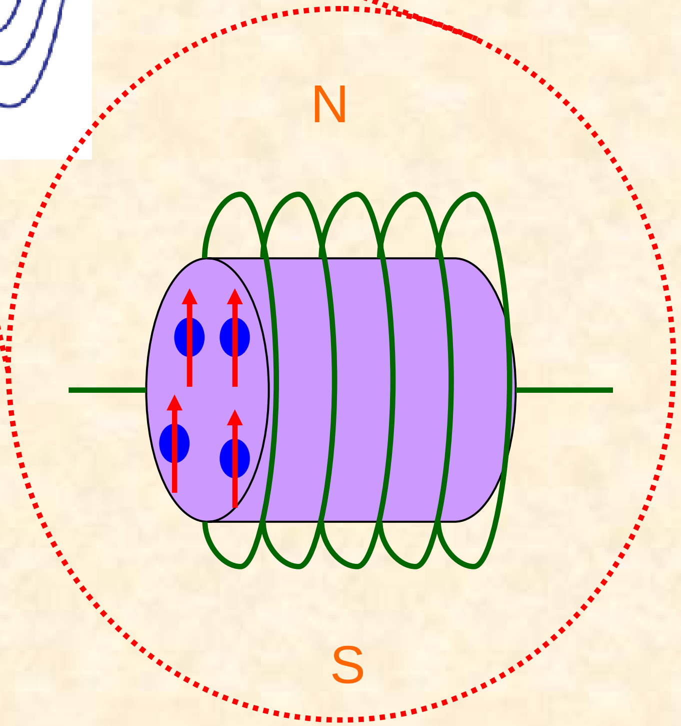
Sir Peter Mansfield

Solid-state NMR spectrometer (固態核磁共振儀)



Set-up

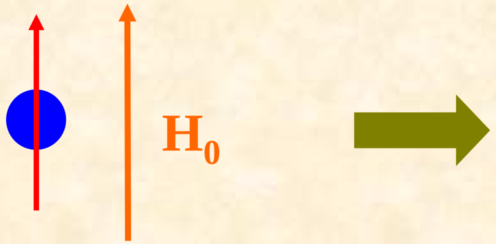




H_1(t): Alternating Field with frequency ω (交流磁場)

H_0 : Static Magnetic Field (靜磁場)

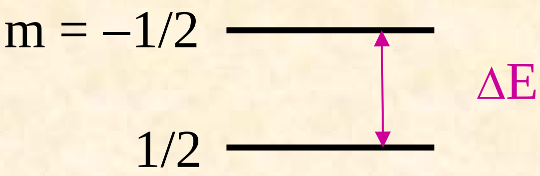
A bare nuclear spin in a magnetic field H_0

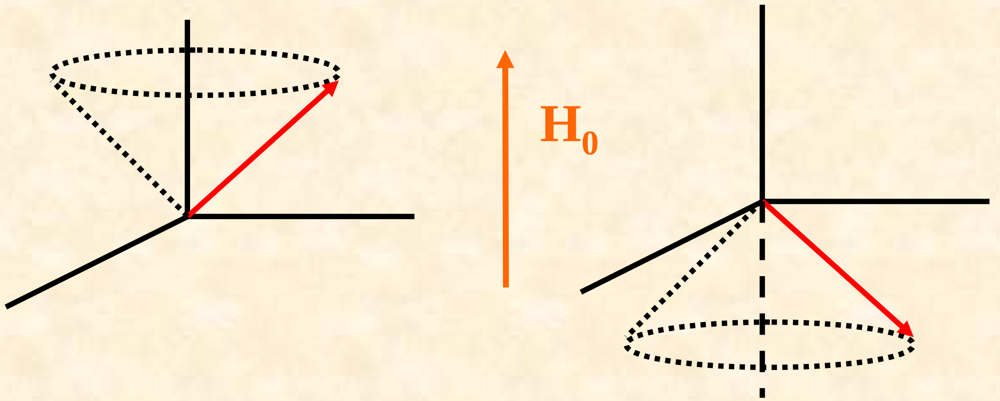


What happened?

Quantum mechanics tells us: μ_I precession with the Larmor frequency ω_L

2 states for ^{1}H nuclear spin (I =1/2)





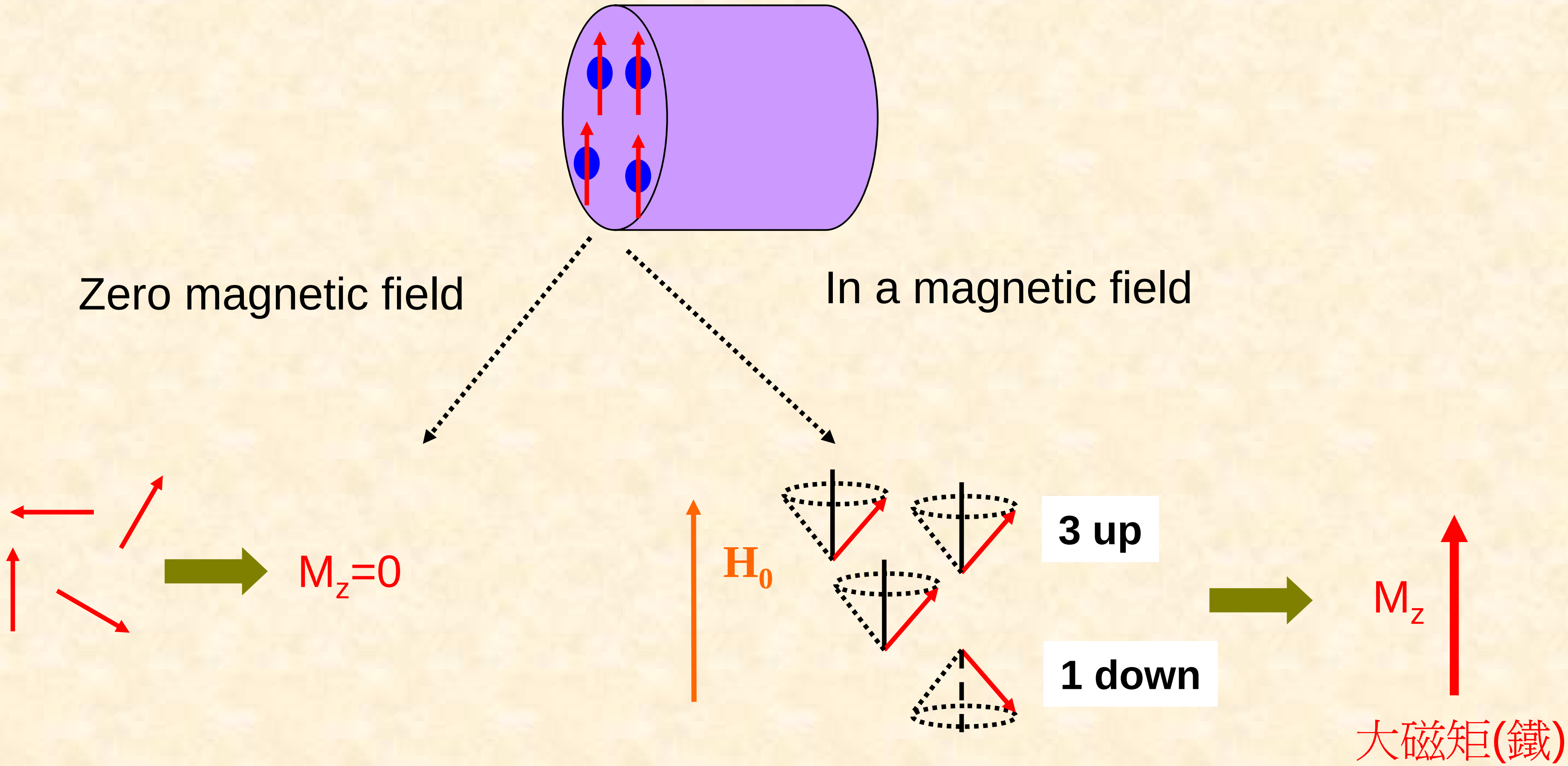
Low-energy state
up

high-energy state
down

Energy difference between the states (levels)

$$\Delta E = \gamma_n \hbar H_0 = \hbar \omega_L$$

The sample in a magnetic field

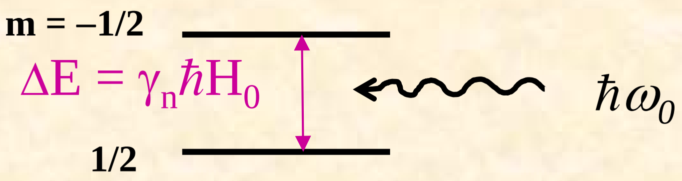


Nuclear magnetization M_z is what we are going to measure.

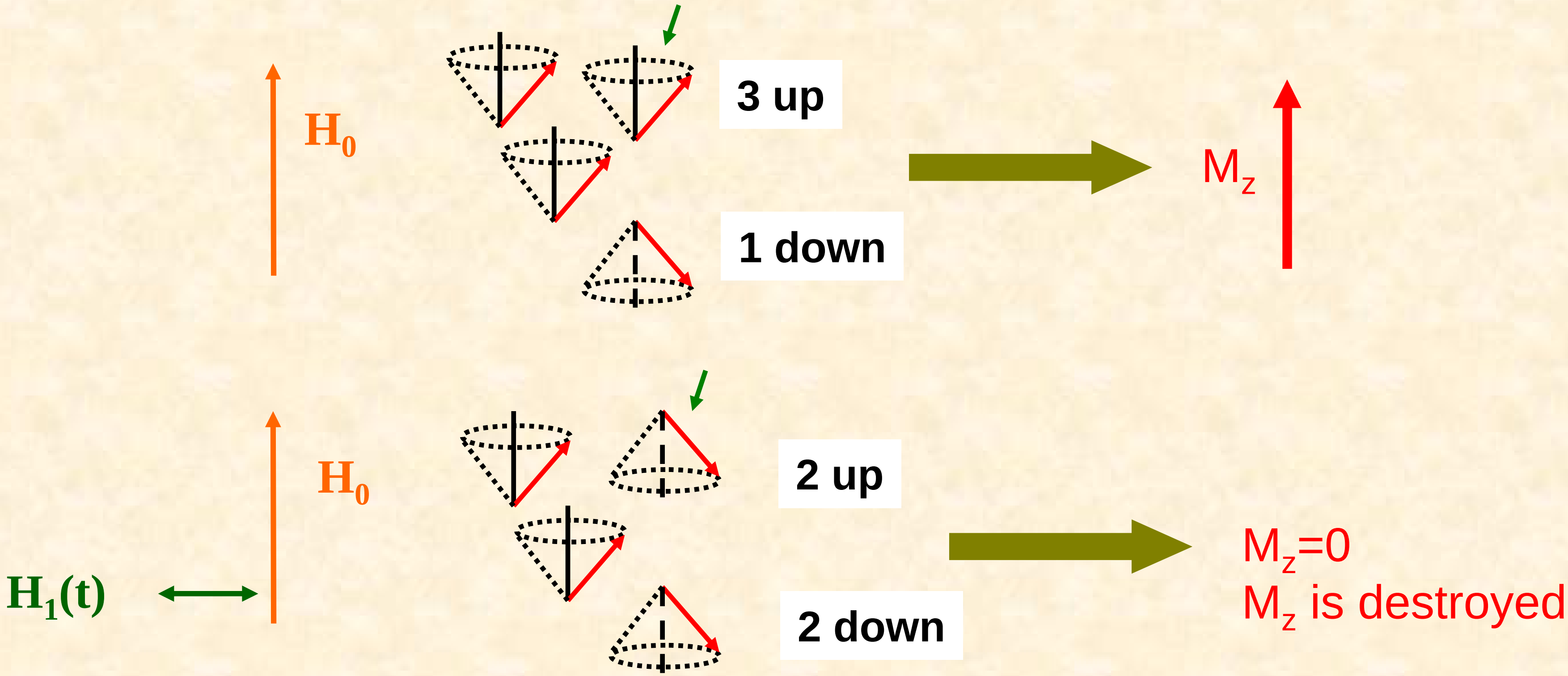
A powerful magnetic field H_0 is used to produce the nuclear magnetization

Principle of magnetic resonance

Apply radio frequency field $H_1(t)$ with frequency ω_0,
when $\hbar\omega_0 = \Delta E \Rightarrow$ resonance occurs



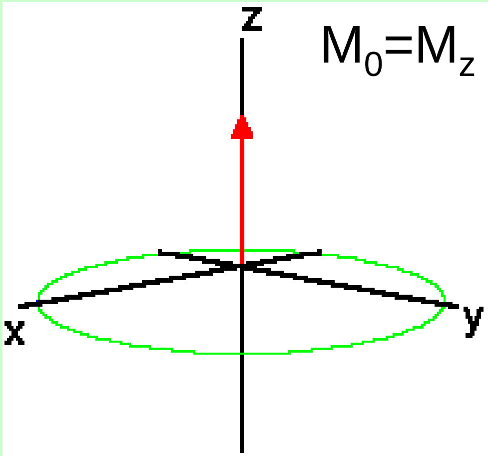
Therefore, $\omega_0 = \gamma_n H_0$



Detect the NMR signal

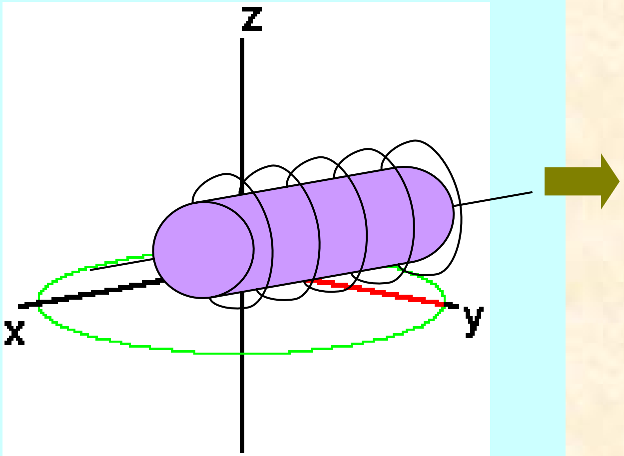
Radio frequency (RF) fields with frequency ω_0 are used to systematically alter the alignment of this magnetization, causing the hydrogen nuclei to produce a rotating magnetic field detectable by the scanner.

$H_1(t)$ on



Knock down M_0

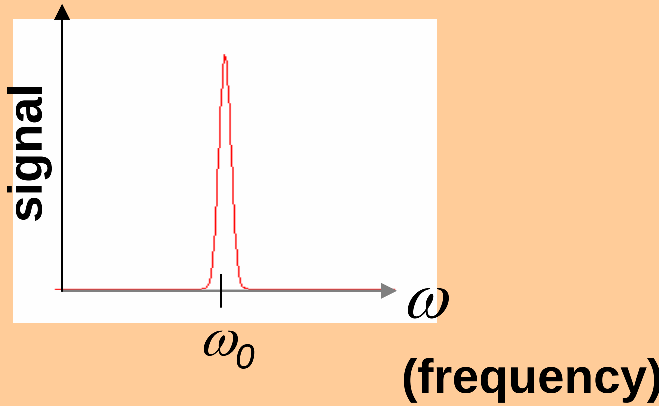
$H_1(t)$ off



M_0 rotates in x-y plane,
the coil pick up the signal.

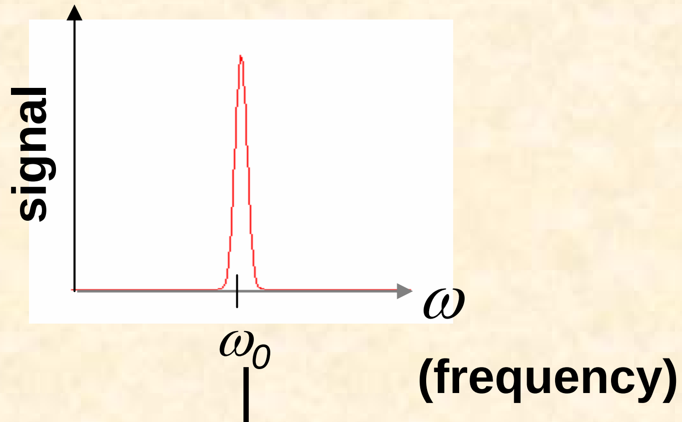
$V \propto dM_0(t)/dt$ 感應電動勢

NMR spectrum

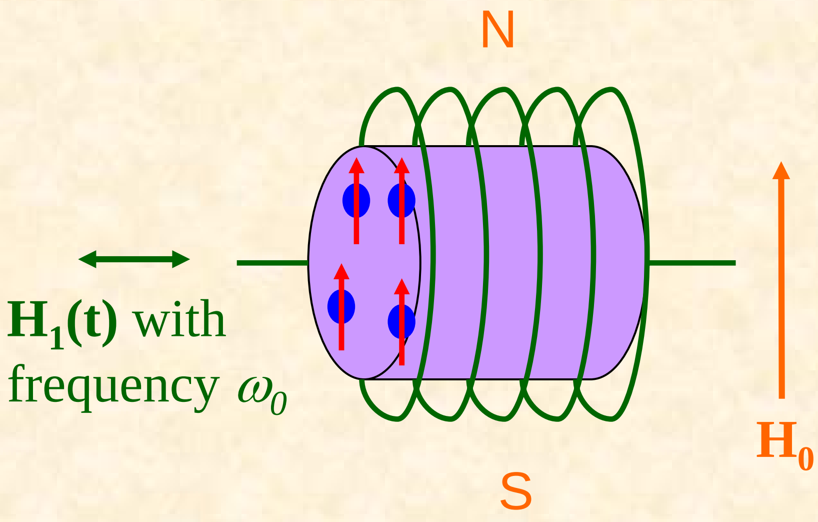


a signal at ω_0

Remarks



$\omega_0 = \gamma_n H_0,$



Each species of atom has its own γ_n value

→ Signal appears at different frequency (position) ➡ Site assignment

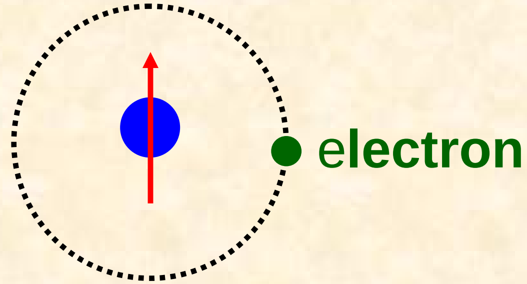
For the same spin:

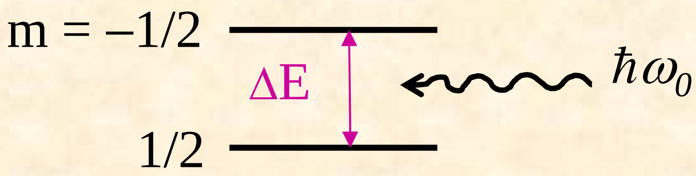
Increase H_0 → ω_0 increases → Signal shifts to higher frequency

➡ Basics of MRI

In addition to H_1 and $H_0(t)$, the nuclear spin in materials also senses the fields produced by:

- Other nuclear spins
- Electron spins (Knight shift)
- Electron orbital motion (chemical shift)
- Electric quadrupole effect
- ……

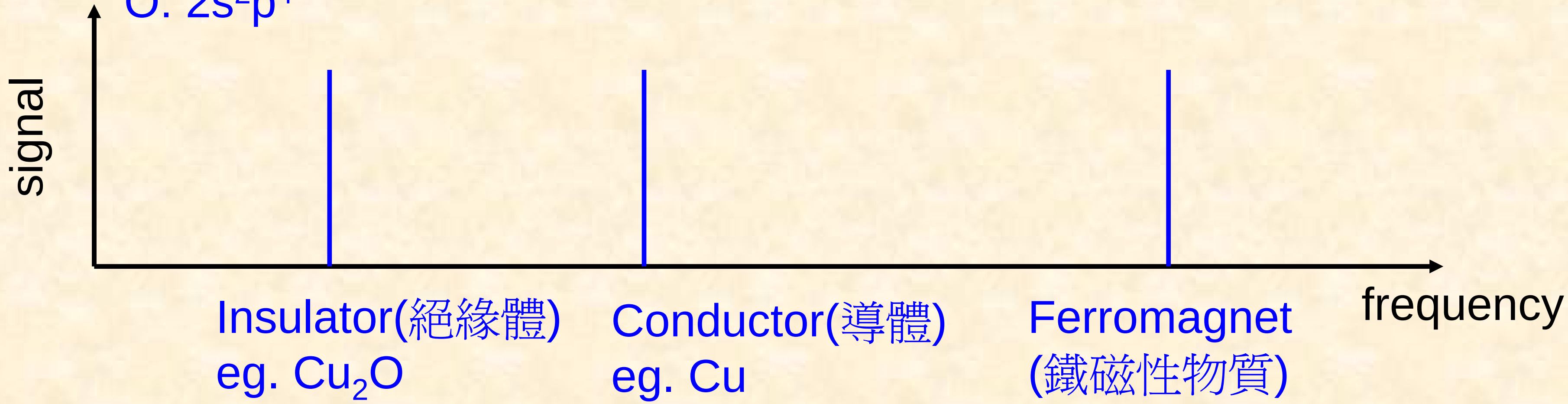




The above fields will affect the energy difference ΔE

affect the position and shape of the signal in frequency

Cu: $3d^{10}4s^1$
O: $2s^2p^4$



The applications of NMR in physics

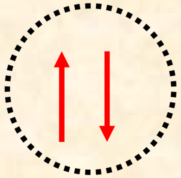
Probing the electronic properties

- Electron spins (Knight shift)
- Electric quadrupole effect

- superconductors:

For a conventional superconductor, electrons form pairs (cooper pairs) in the superconducting state.

spin singlet S=0



First observed by NMR

- the magnetic materials

The applications of NMR in chemistry

NMR is chemists's eyes - a technique of analytical chemistry

- Identify functional group by probing electron orbital motion (chemical shift)

Protons (^1H) spectrum from CH_3CH_2OH

Peak assignments (which peak is what) can be done using NMR Database

Frequency

- determine the structure of many compounds

The applications of NMR in bio- & medical- related fields

- living tissue (chemical shift)
- Biomolecules: Lipids Proteins , nucleic acids, including RNA and DNA

Macromolecules

Sequence → 3D structure

nsp1 protein

MDSNTVSSFQ VDCFLWHVRK
RFADQELGDA PFLDRLRRDQ
KSLRGRGSTL GLDIRTATRE
GKHIVERILE EESDEALKMT
IASVPAPRYL TEMTLEEMSR
DWLMLIPKQK VTGSLCIRMD
QAIMDKDIIL KANFSVIFNR
LEALILLRAF TDEGAIVGEI
SPLPSLPGHT EEDVKNAIGV
LIGGLEWNDN TVRVSETLQR
FTWRSSDENG RSPLPPKQKR
KMERTIEPEV **(230 amino acids)**

→ **1D ^{1}H NMR** → **MultiD, Heteronuclear, …etc**

Each amino acid contains C, N, H, O

Non-destructive technique

Earth Field NMR (EFNMR)

Make use of earth magnetic field (30~60 μT, protons resonate ~ 2kHz)

→ A special case of low field NMR

- investigating the structure of ice crystals in polar ice-fields, to rocks and hydrocarbons in the field.
- Detect ferrous objects (鐵磁性物質) on land and at sea

- Earth's field MRI scanners

Advantage: Portability - to analyze substances on site
lower cost

Antarctic (南極)

Superconducting magnet

An electromagnet that is built using superconducting coils

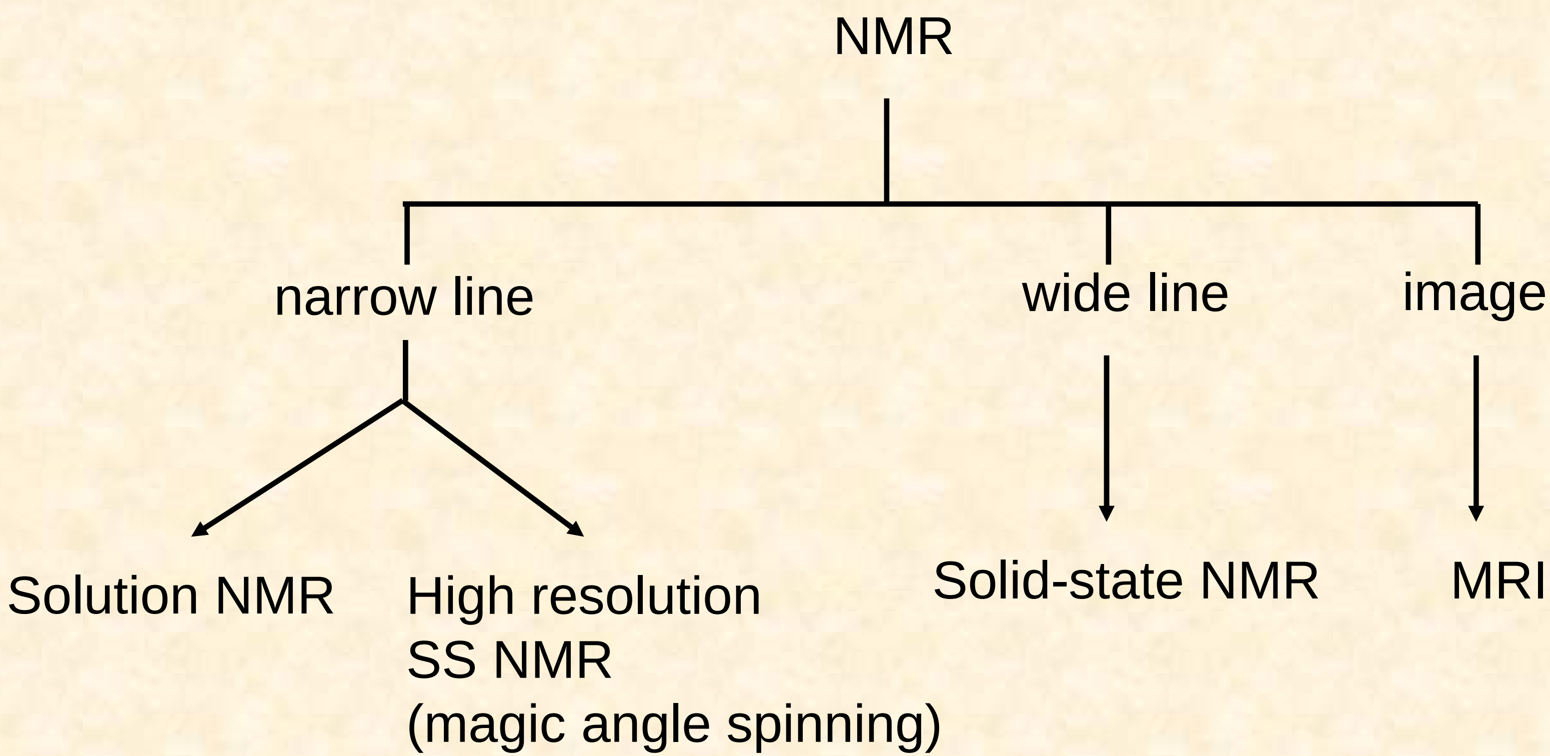
- operate at liquid helium temperature (4K) to achieve SC state
- produce stronger magnetic fields than ordinary iron-core electromagnets
- no power is lost to ohmic resistance in the windings
- cheaper to operate

SC coil: niobium-titanium (NbTi)
or niobium-tin (Nb3Sn)

Higher field ⟶ larger signal (signal/noise)

800 MHz,18.8 T NMR spectrometer

900MHz, 21.2 T NMR Magnet


NMR
narrow line
wide line
image
Solution NMR
High resolution
SS NMR
(magic angle spinning)
Solid-state NMR
MRI

Magnetic resonance imagong (MRI) 磁振造影

Was called Nuclear magnetic resonance imaging (NMRI)

Now called Magnetic resonance imaging (MRI) to avoid using “Nuclear”.

- An imaging technique (used to map the inside of human body)

- Relatively new technique compared with X-ray radiography (over 110 years)

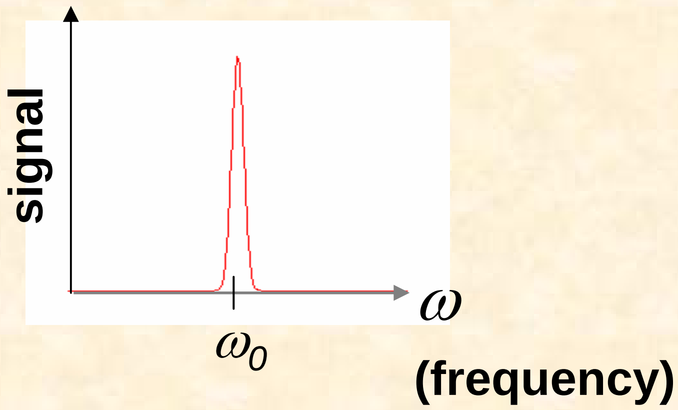
- Based on the principles of nuclear magnetic resonance (NMR)

Basic of MRI

Recall ~~~

Signal appears at

$\omega_0 = \gamma_n H_0$



For the same spin:

Increase H_0 ⟶ ω_0 increases ⟶ Signal shifts to higher frequency

Signal (peak) position is proportional to the field strength

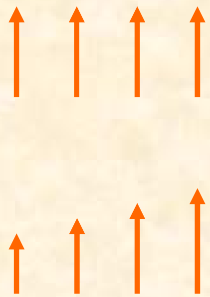
Principle of imaging

Idea - using magnetic field gradients
to introduce spatial localization

A third field $\delta H(x)$ is needed to provide
a gradient field

Signal position

H_o



$\omega_0 = \gamma_n H_0$

$H_o + \delta H(x)$

$\omega_0 = \gamma_n H_0 + \delta H(x)$

➡ Frequency coding

(frequency tells you which
location the signal is from)

Producing image

Data processing

δH(y)

δH(x)

Typical field: 1 ~ 3 T

Typical field gradient:

20 - 100 mT/m

MRI scanner

takes about 45 minutes to complete each body part .

no ionizing radiation

Non-destructive technique

1.5 T scanners: 1 ~1.5 million USD.

3.0T scanners: 2 ~2.3 million USD.

Animal MRI

Cod in MRI swimtunnel
(*In vivo* MR studies)

horses

Field safety

- Earth's magnetic field 30~60 μT (0.03~0.06 mT) depending on location

- Direct current (DC) transmission lines: 0.02 mT

- Small magnets (**audio speakers components, battery-operated motors, microwave ovens, refrigerator magnets**) : 1-10 mT

- MRI: 1~3T

- NMR: up to ~21T (shielding to 0.5mT at 2m from field center)

Exposure limit:

The general public: 40 mT

Occupational whole-body exposure: 2T

The end