Introduction to Solid Polarized Targets

for Nuclear and Particle Physics

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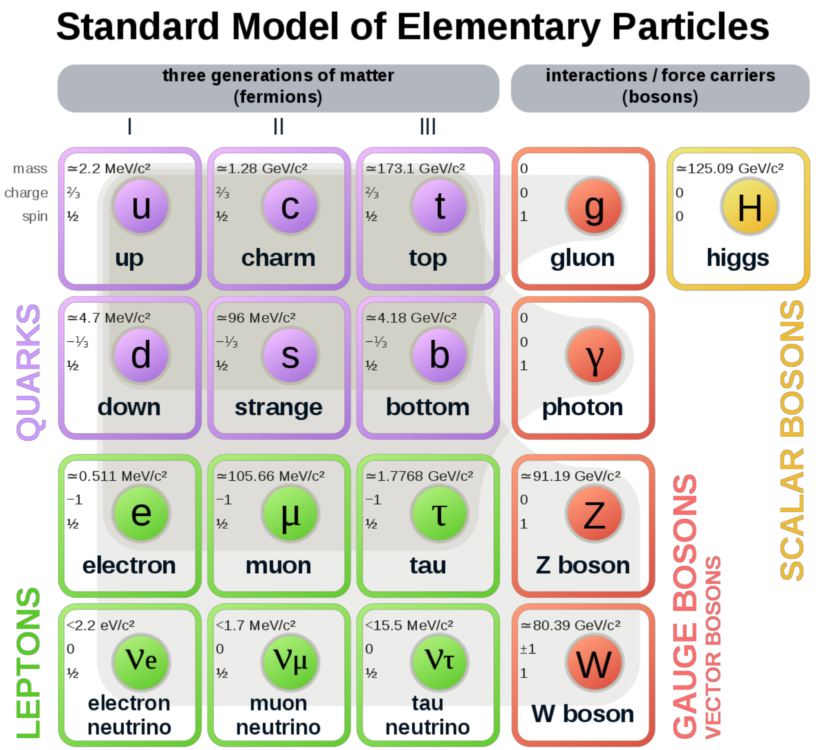
JLab Target Group

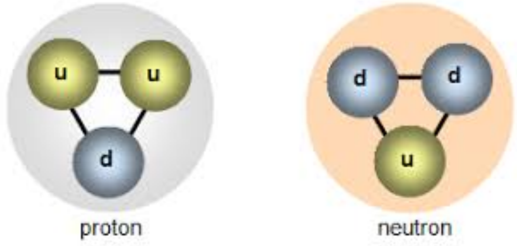
Jefferson Lab
Target Group

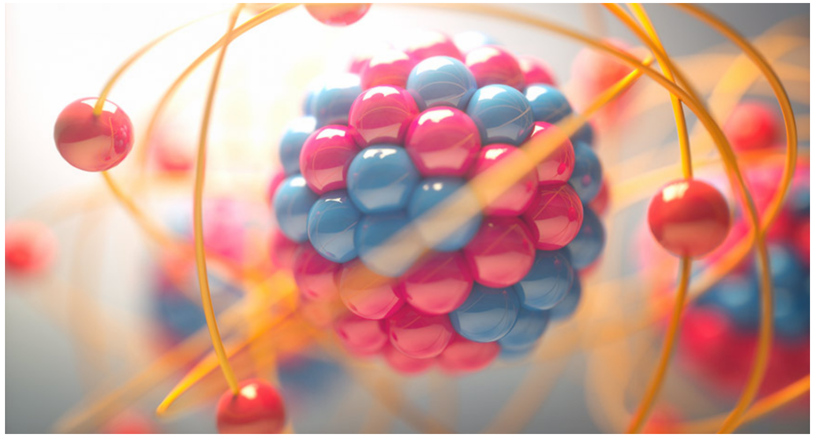
The basics

Spin is an intrinsic property of all elementary particles
(pay no attention to the higgs)



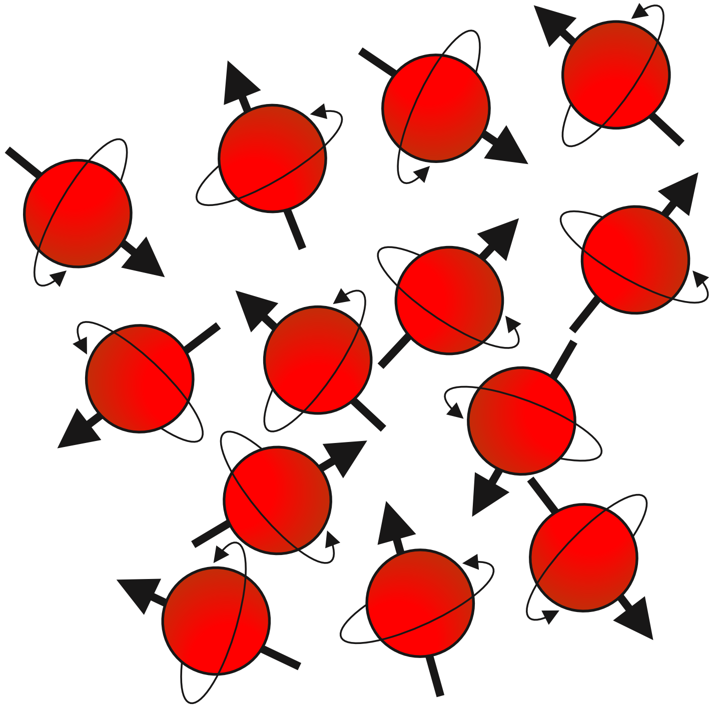
As well as many composite particles (baryons, mesons, nuclei, atoms…)

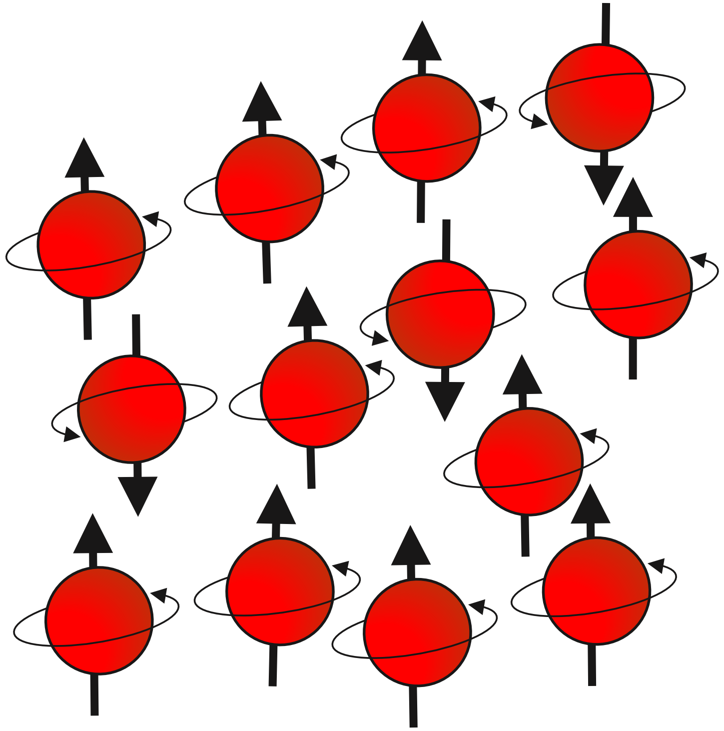




The basics

A polarized target is a collection of nuclei (solid or gas) used for a scattering experiment in which *most the nuclear spins point in the same direction*





Uses for polarized targets

- Spin structure of hadrons
- Sum rules
- Form Factors
- Baryon spectroscopy
- Transverse momentum distributions
- Generalized parton distributions
- Polarized PDFs

HALL A

(E12-11-108) *SIDIS with a transversely polarized proton target*
(E12-11-108A) *Target single spin asymmetries using SoLID spectrometer*

HALL B

(E12-06-109) *Longitudinal spin structure of the nucleon*
(E12-06-119) *DVCS with CLAS at 12 GeV*
(E12-07-107) *Spin-orbit correlations with a longitudinally polarized target*
(E12-09-009) *Spin-orbit correlations in kaon electroproduction in DIS*
(E12-14-001) *EMC effect in spin structure functions (^{6}LiH & ^{7}LiD)*
(E12-15-004) *DVCS on the neutron with a longitudinally polarized target*
(C12-11-111) *SIDIS on a transversely polarized target*
(C12-12-009) *Dihadron production in SIDIS on a transversely pol. target*
(C12-12-010) *DVCS on a transversely polarized target in CLAS12*

HALL C

(E12-14-006) *Helicity correlations in wide-angle Compton scattering*
(C12-13-011) *The deuteron tensor structure function b1*
(C12-15-005) *Meas. of quasi-elastic and elastic deuteron tensor asymm.*
(LOI-12-14-001) *Search for exotic gluonic states in the nucleus*

HALL D

(LOI-12-15-001) *Physics opportunities with a secondary K^o_L beam*

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Polarization

The terms *polarization* and *orientation* are used to describe the distribution of a system of spins amongst their *(2I+1)* magnetic substates.

Orientation parameters P_{ij} are defined in terms of expectation values of irreducible spin tensors I_{ij} which act as the basis set for the ensemble's density matrix. The magnitude of the spin determines how many P_{ij} are required to describe the ensemble.

Vector polarization
$$P_z \equiv \frac{\langle I_z \rangle}{I}$$

Tensor polarization or *alignment*
$$P_{zz} \equiv \frac{\langle 3I_{zz}^2 - I(I+1) \rangle}{I^2}$$

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Polarization

Spin-½

$$P_z = \frac{N_+ - N_-}{N_+ + N_-}$$

$$P_{zz} = 0$$

Spin-1

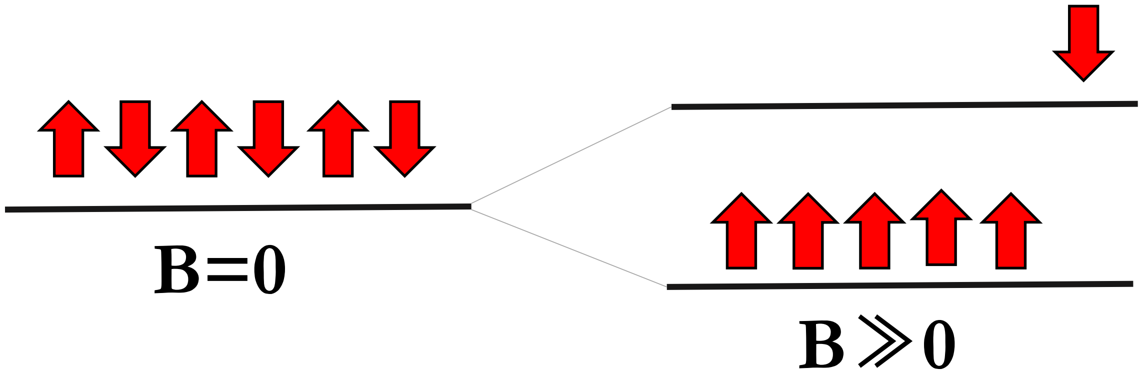
$$P_z = \frac{N_+ - N_-}{N_+ + N_0 + N_-}$$

$$P_{zz} = 1 - \frac{3N_0}{N_+ + N_0 + N_-}$$

Today we're only going to talk about spin-1/2 systems...

Brute force polarization

The simplest method to polarize the spins is to use the Zeeman Effect and leverage the interaction between the magnetic field and the nuclei's magnetic moment, $\vec{\mu} \cdot \vec{B}$



The Zeeman interaction tends to orient (polarize) the magnet moments.

Oscillating EM fields produced by atomic vibrations (phonons) tends to randomize (de-polarize) the magnetic moments. Characterized by lattice thermal energy *kT.*

Eventually an equilibrium state is reached – *thermal equilibrium (TE) polarization*.

Brute force polarization

At equilibrium the populations of the Zeeman levels will obey a Boltzmann distribution.

$$N(\uparrow)/N(\downarrow) = \exp\left[\frac{(-2\mu B)}{kT}\right]$$

T = temperature

$$P_{te} = \frac{[N(\uparrow) - N(\downarrow)]}{[N(\uparrow) + N(\downarrow)]} = \tanh\left(\frac{\mu B}{kT}\right)$$

Thermal equilibrium polarization, spin ½

The polarization will approach thermal equilibrium with a *1/e* time constant called t_1, *the spin-lattice relaxation time.*

$$P(t) = P_{te}\left[1 - e^{-t/t_1}\right]$$

t_1 depends on the temperature and the magnetic field. Nuclear t1 can be VERY LONG. It's usually determined by paramagnetic impurities.

Brute force polarization

$$P = \tanh\left(\frac{\vec{\mu}\cdot\vec{B}}{kT}\right) \longrightarrow \begin{array}{l}\text{maximize } B \\ \text{minimize } T\end{array}$$

Advantages:

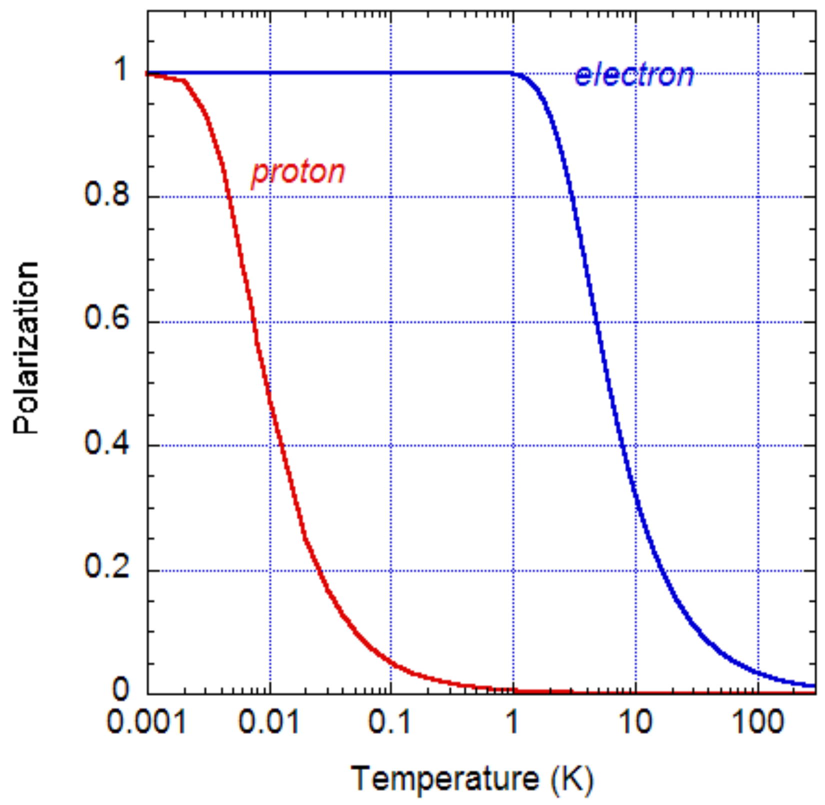
- Works for almost any material
- Easy to explain

Disadvantages:

- Requires very large magnet
- Low temperatures mean low luminosity
- Polarization can take a very long time

Notice that it's much easier to polarize electrons!! $\mu_e \sim 1000\ \mu_p$

Polarization in a 5 Tesla field



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Dynamic nuclear polarization

For best results, DNP is performed at *B/T* conditions where the electron t_1 is short (ms) and the nuclear t_1 is long (minutes or hours)

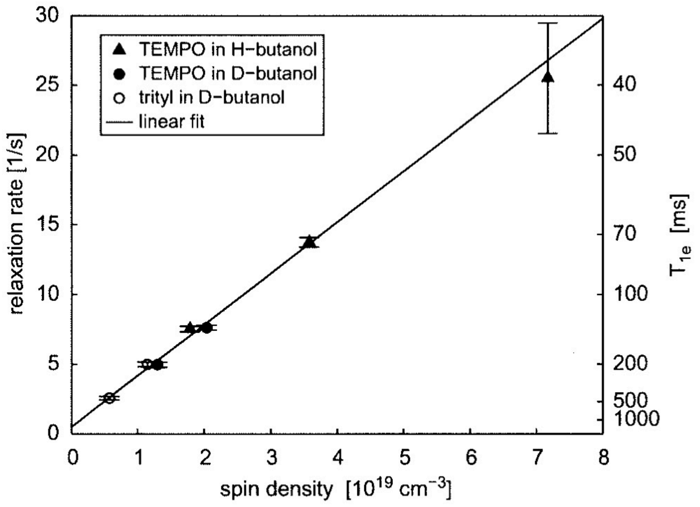
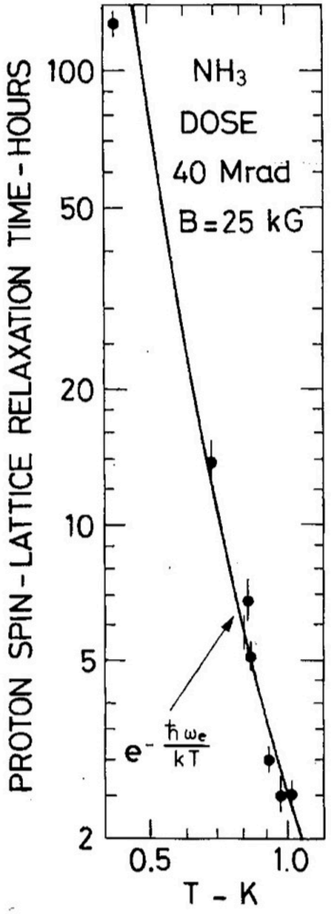


Fig. 3. Paramagnetic relaxation rate versus electron spin density for samples 1–7, with a linear fit. The right ordinate shows the corresponding relaxation time T_{1e}.

C. Hess et al., NIM A694 (2012) 69.

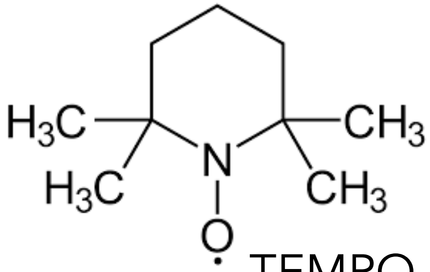
T.O. Niinikoski and J.-M. Rieubland, Phys. Lett. 72A (1979) 142.



At 2.5 tesla and 1 kelvin, t_{1p} is almost 10^5 times longer than t_{1e} !!

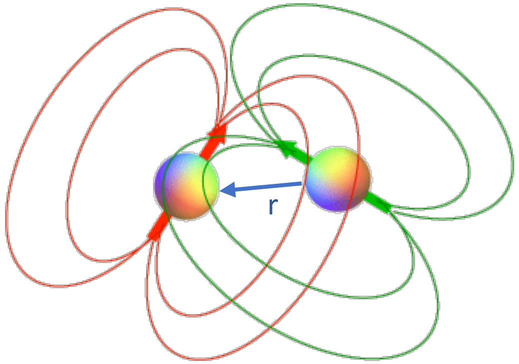
Dynamic nuclear polarization

- Implant target material with paramagnetic impurities ~ 10^{19} e^- spins/cc
- Polarize the electrons in the radicals via brute force
- Use microwaves to "transfer" this polarization to nuclei



TEMPO

The dipole-dipole interaction between the electrons and nearby nuclear spins permits transitions in which both spins flip.



$$\mathcal{H}_{SI} = \hbar^2 \left(\frac{\mu_0}{4\pi}\right)\gamma_S\gamma_I \left[\frac{\vec{S}\cdot\vec{I}}{r^3} - \frac{3(\vec{S}\cdot\vec{r})(\vec{I}\cdot\vec{r})}{r^5}\right]$$

$$= \hbar^2 \left(\frac{\mu_0}{4\pi}\right)\gamma_S\gamma_I \frac{1}{r^3}(A + B + C + D + E + F)$$

$$A = (1 - 3\cos^2\theta)S_z I_z$$

$$B = -\frac{1}{4}(1 - 3\cos^2\theta)(S_+I_- + S_-I_+)$$

$$C = -\frac{3}{2}\sin\theta\cos\theta\, e^{-i\phi}(S_+I_z + S_zI_+)$$

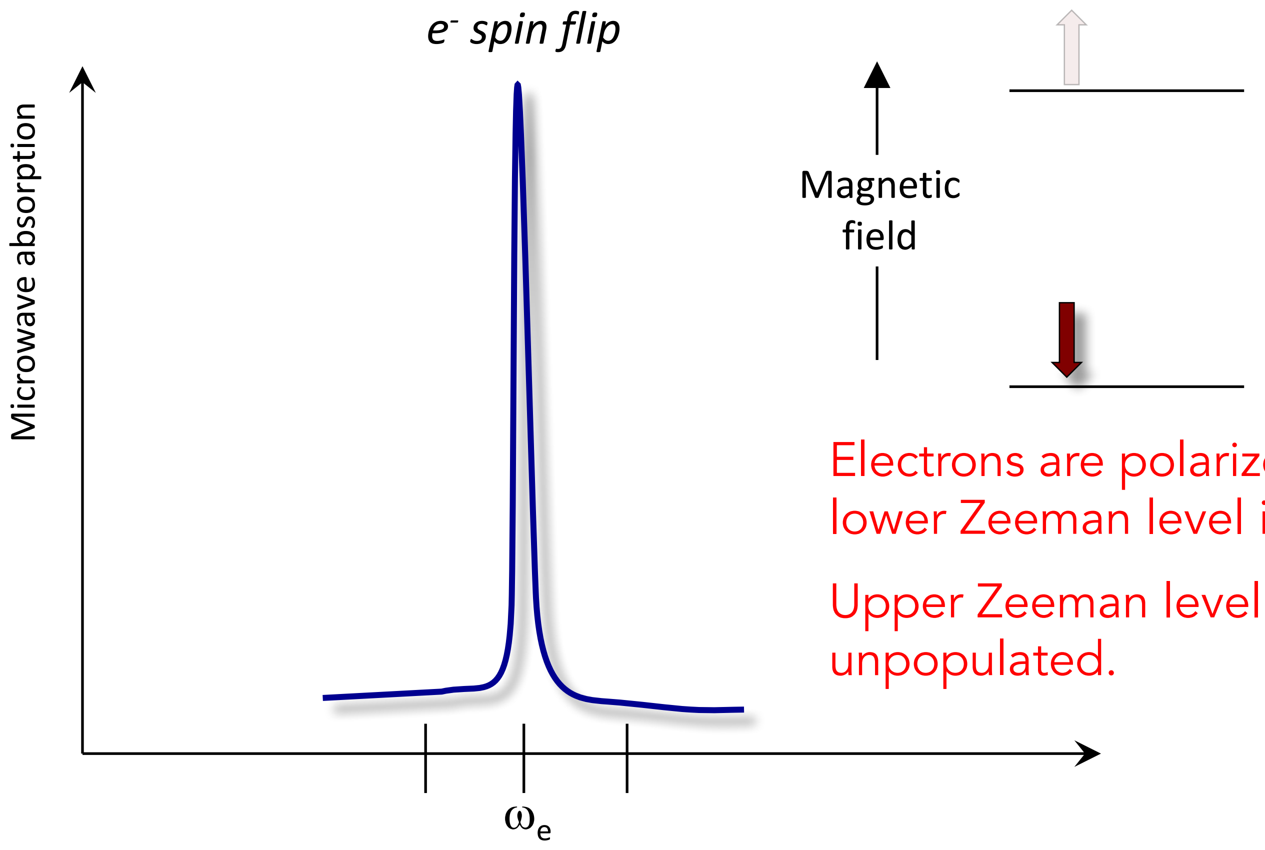
$$D = -\frac{3}{2}\sin\theta\cos\theta\, e^{i\phi}(S_-I_z + S_zI_-)$$

$$E = -\frac{3}{4}\sin^2\theta\, e^{-2i\phi}S_+I_+$$

$$F = -\frac{3}{4}\sin^2\theta\, e^{2i\phi}S_-I_-$$

Electron Spin Resonance of a polarized solid target

- a solid dielectric with ~10^{19} cm^{-3} unpaired electrons
- low temperature
- high field



Electrons are polarized, so lower Zeeman level is filled.

Upper Zeeman level is unpopulated.

DNP: the solid effect

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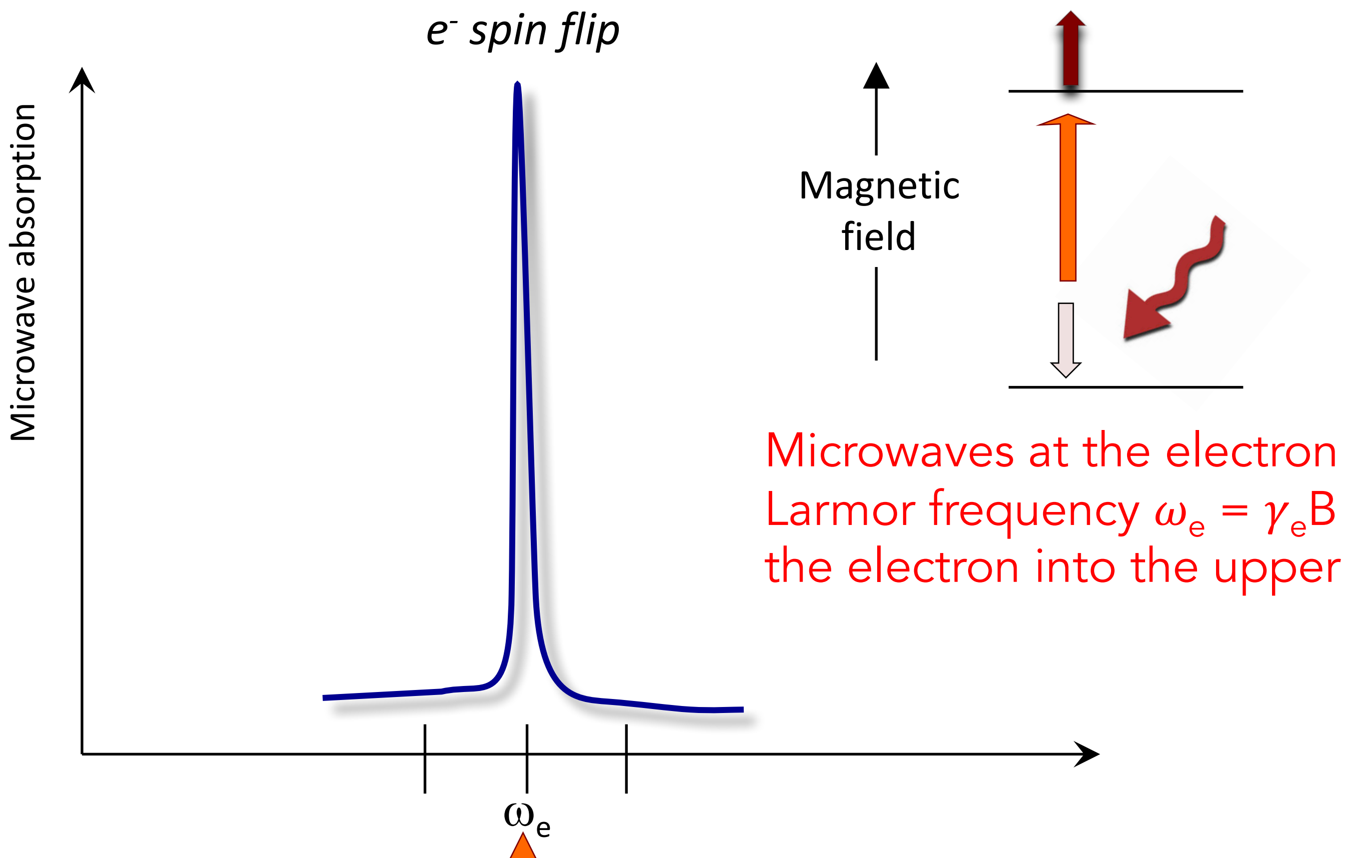

Microwaves at the electron Larmor frequency $\omega_e = \gamma_e B$ flip the electron into the upper level.

140 GHz at 5 tesla

DNP: the solid effect

Electron Spin Resonance of a polarized solid target

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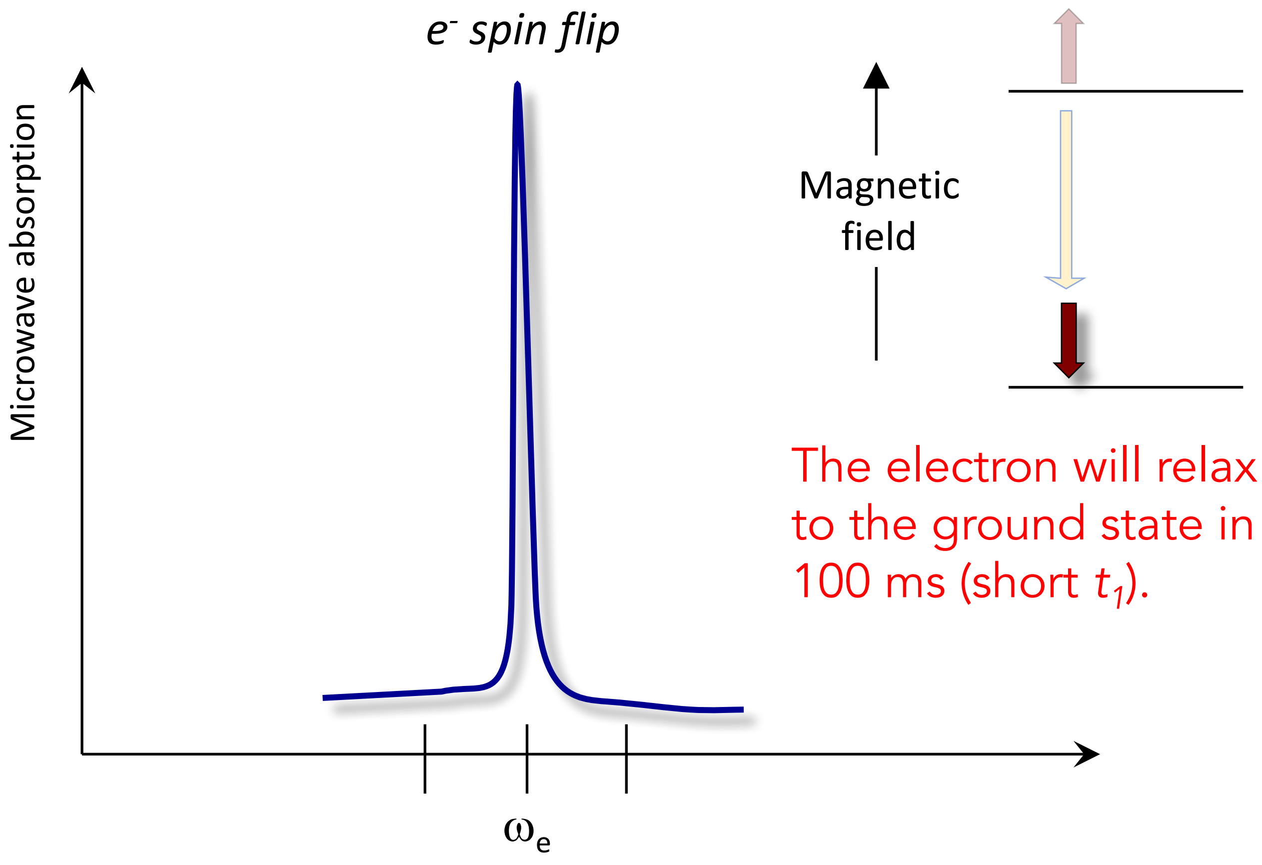

The electron will relax back to the ground state in about 100 ms (short t_1).

DNP: the solid effect

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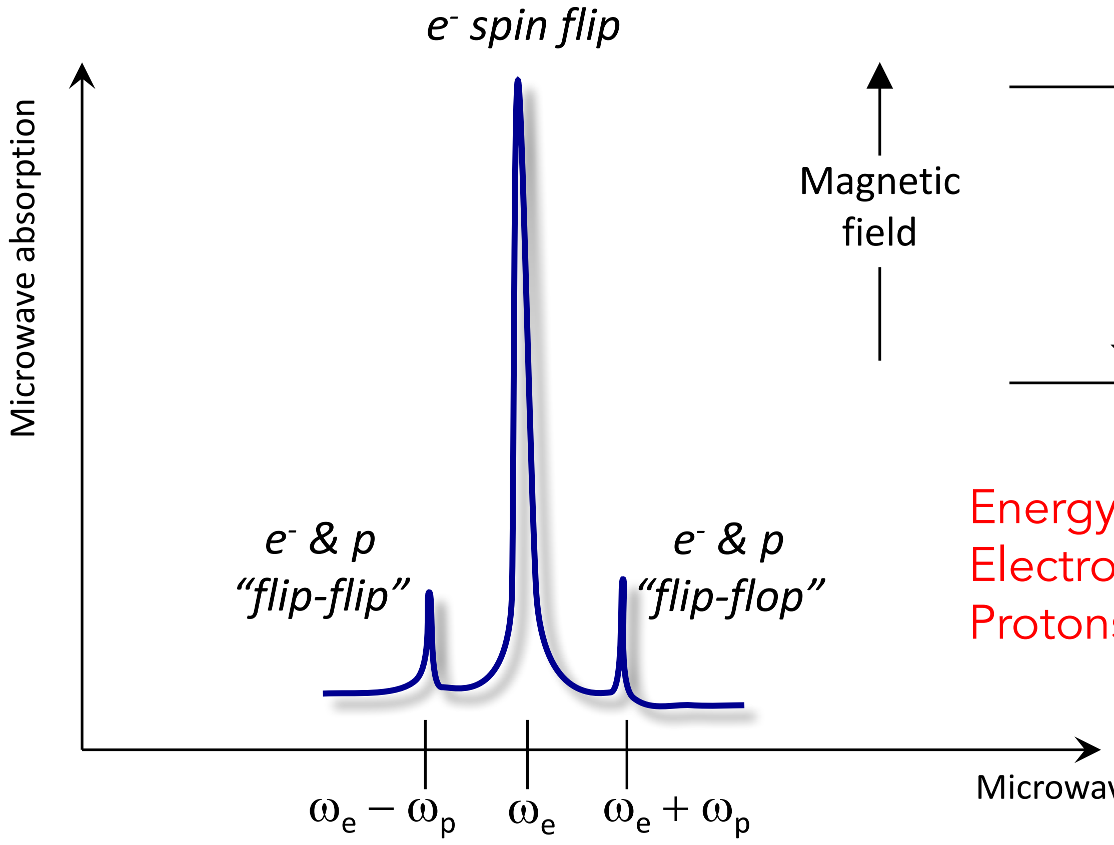

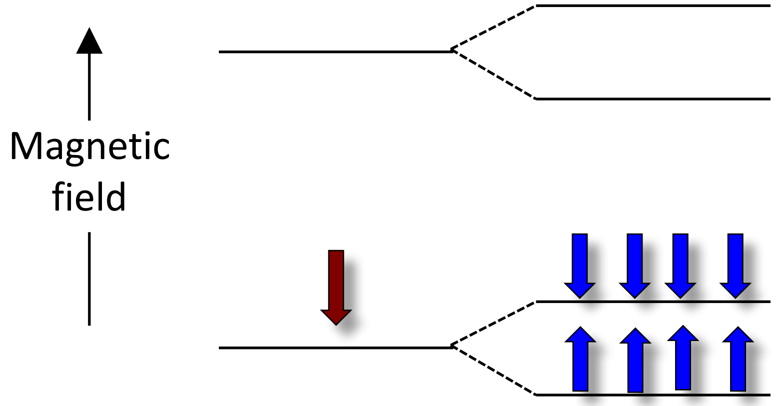

Energy levels of a electron+ protons.
Electron is polarized.
Protons are not.

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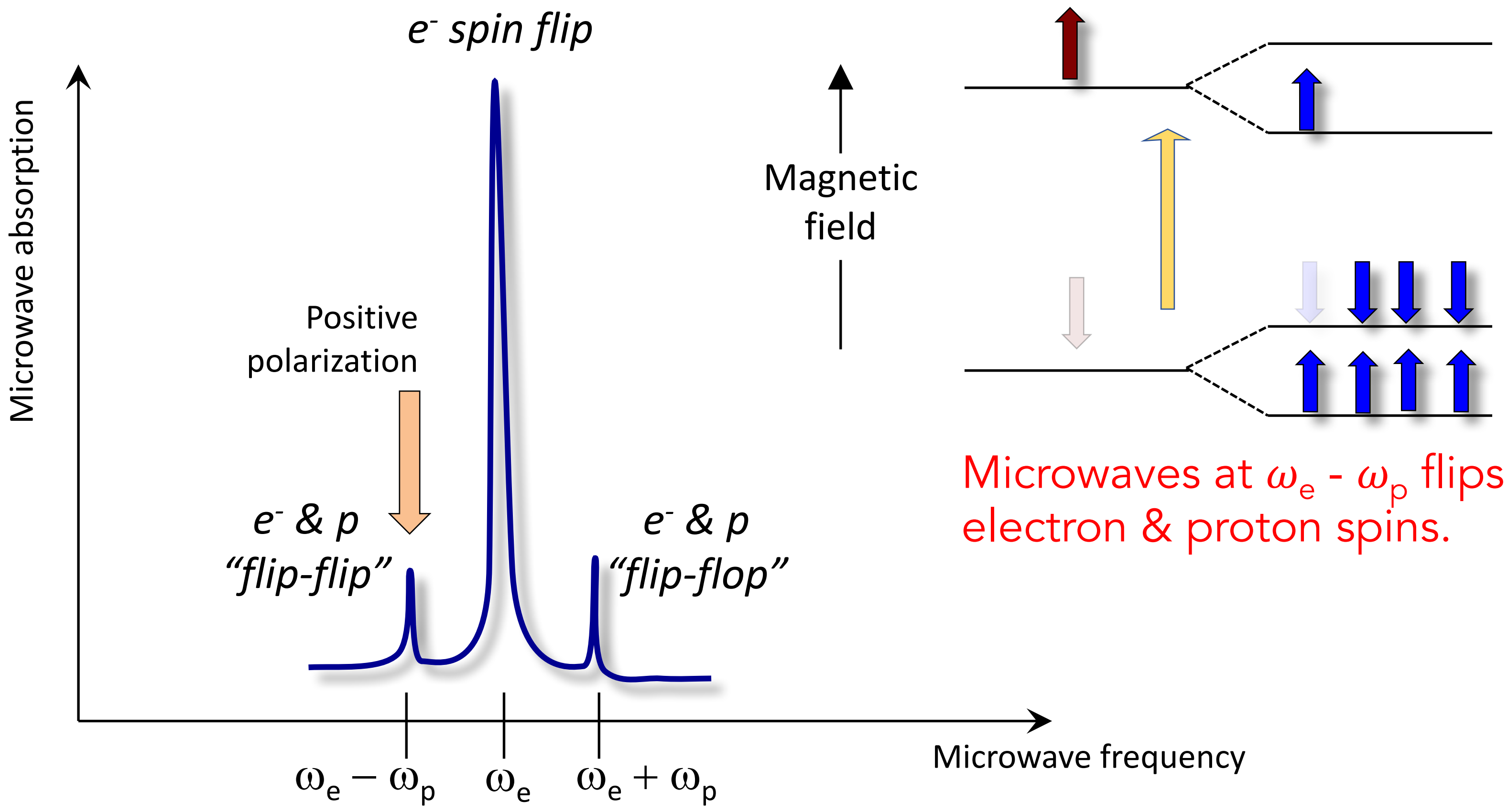

Microwaves at ω_e - ω_p flips both electron & proton spins.

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DNP: the solid effect

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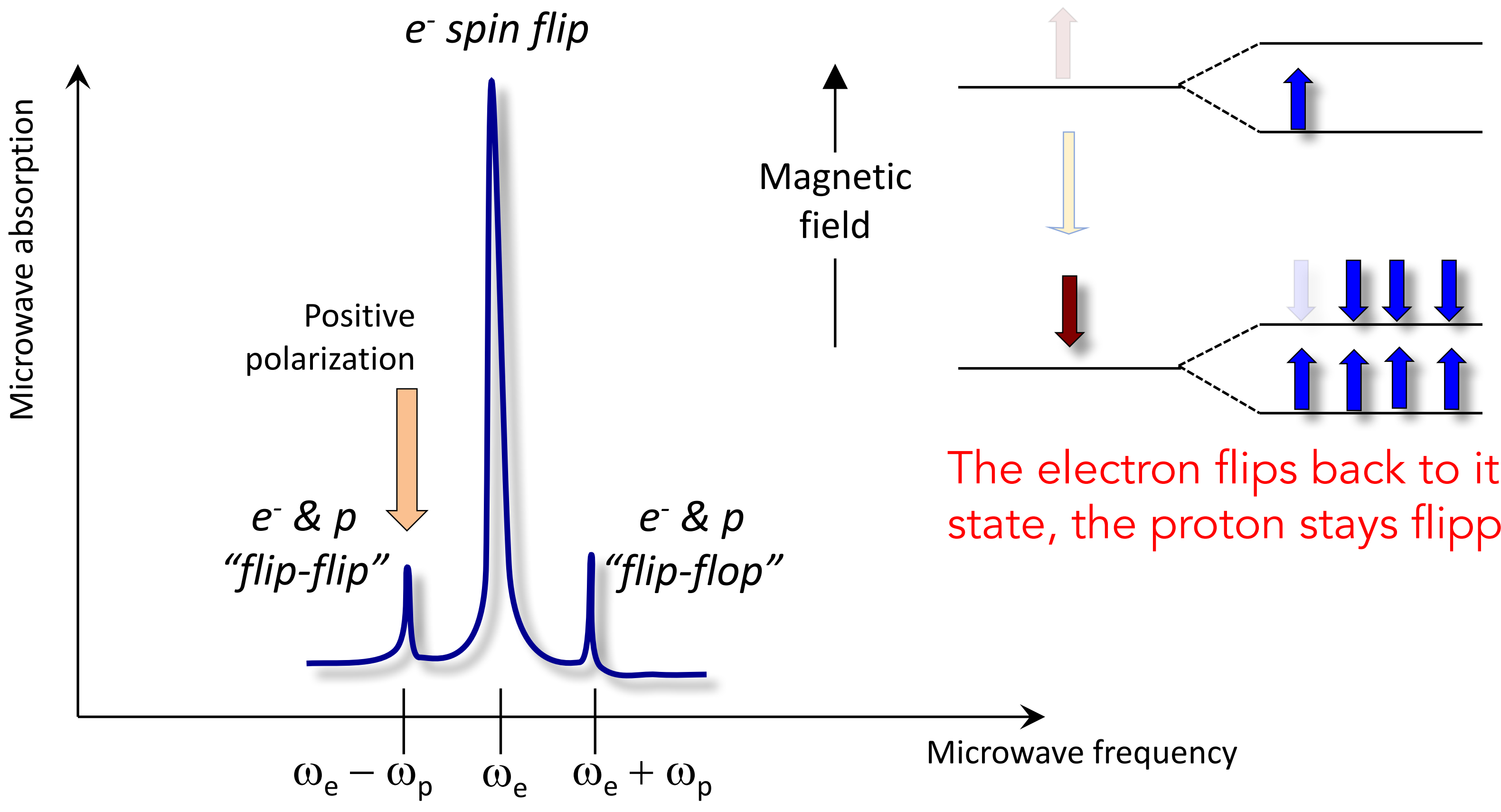

The electron flips back to its ground state, the proton stays flipped (long t_1).

DNP: the solid effect

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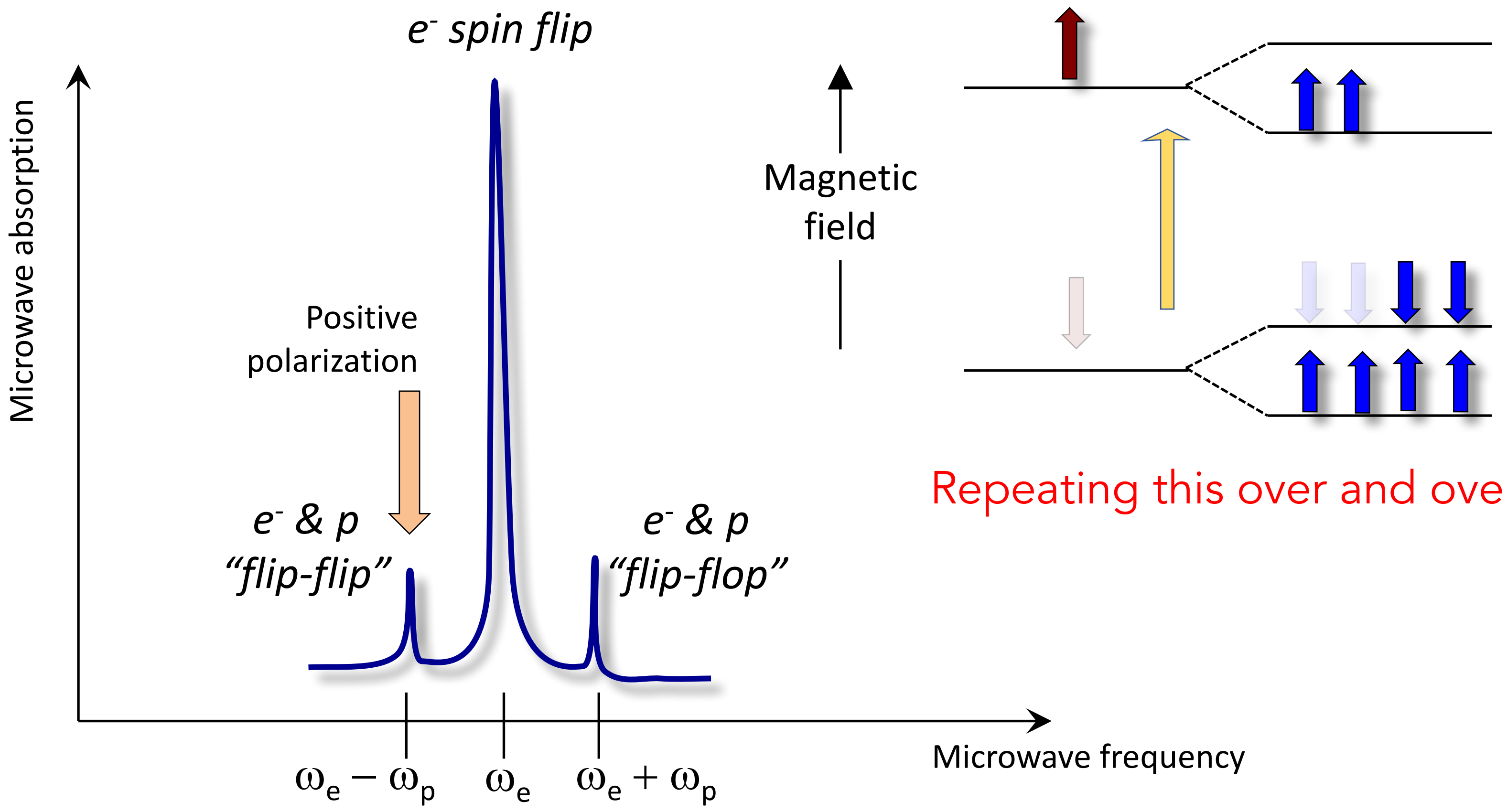

Repeating this over and over…

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DNP: the solid effect

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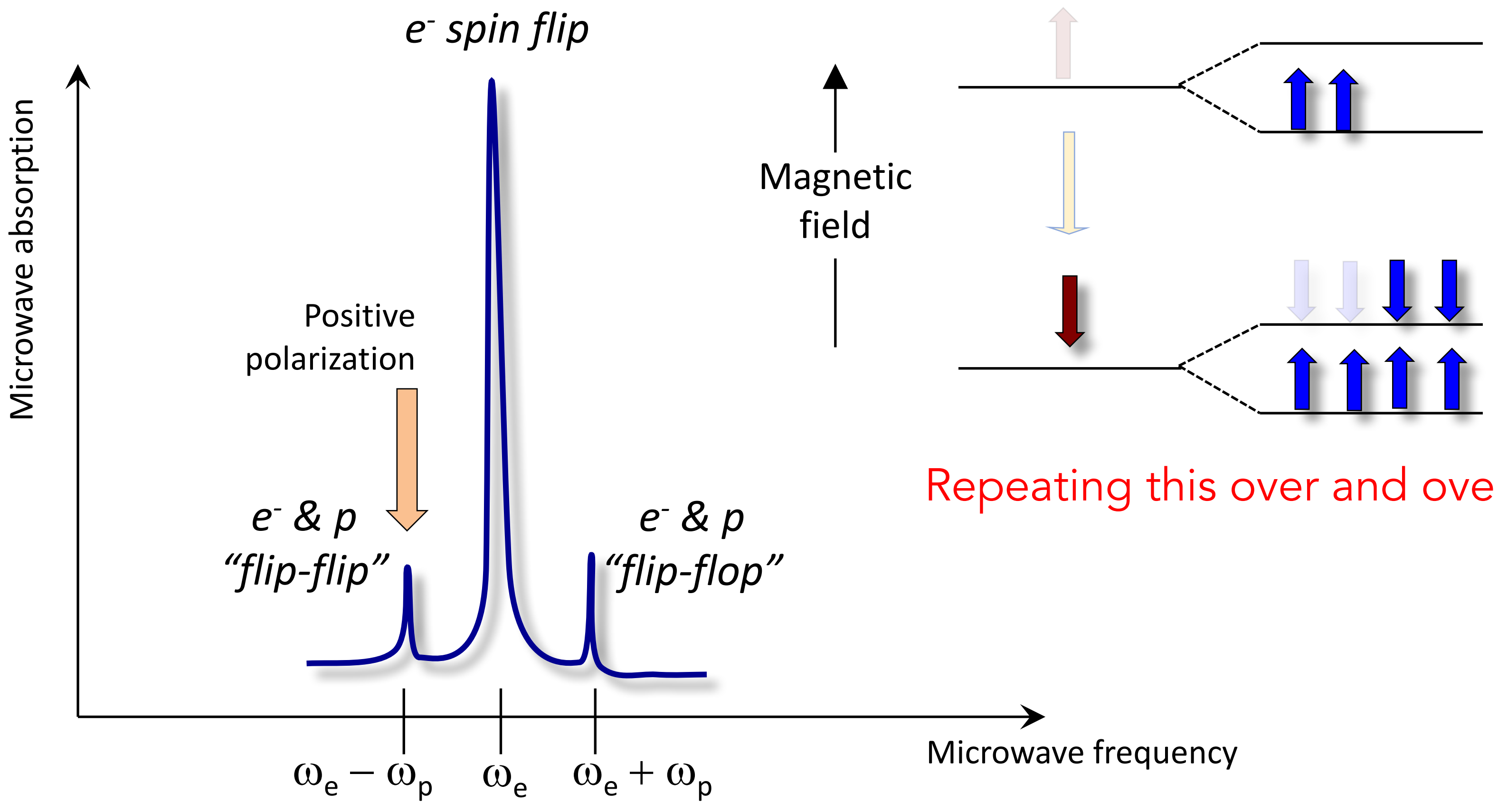

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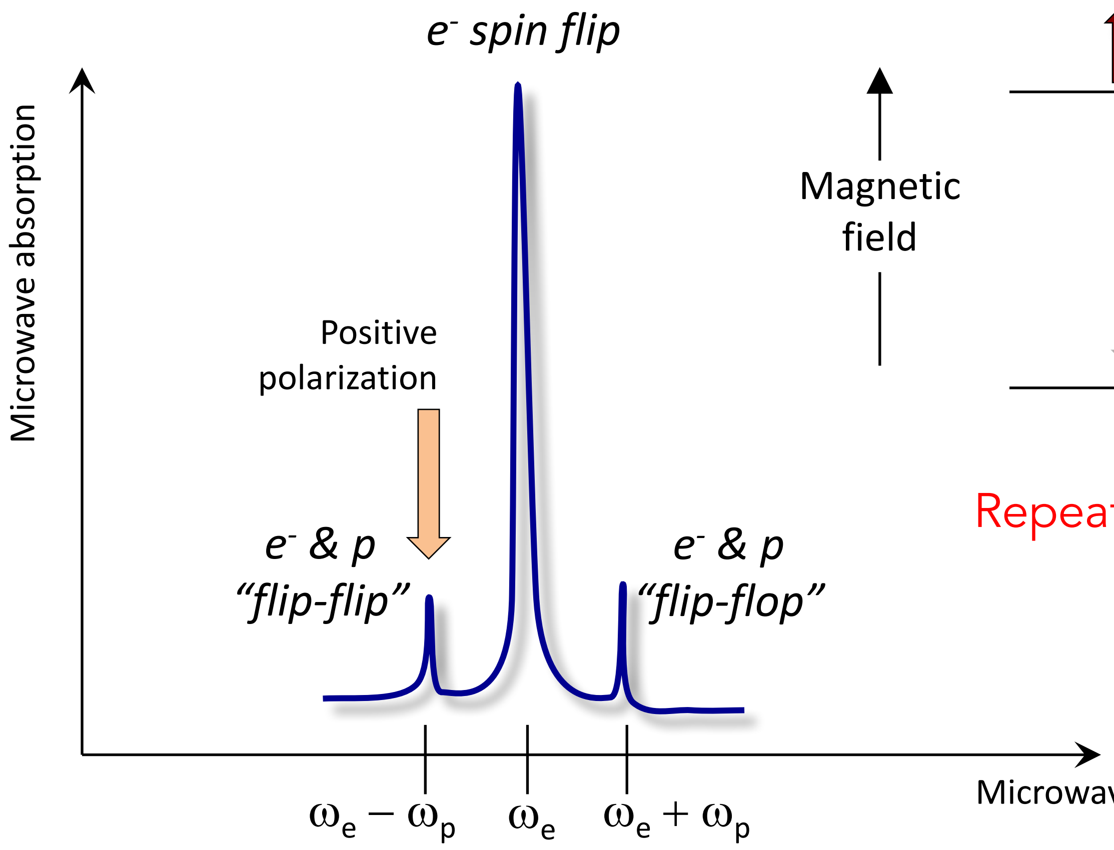

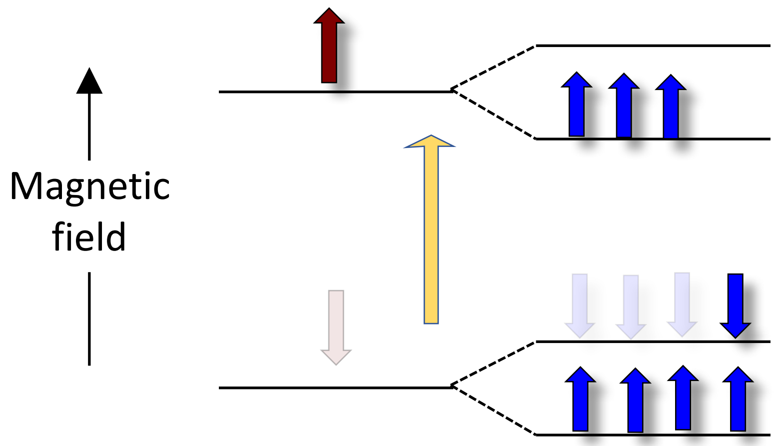

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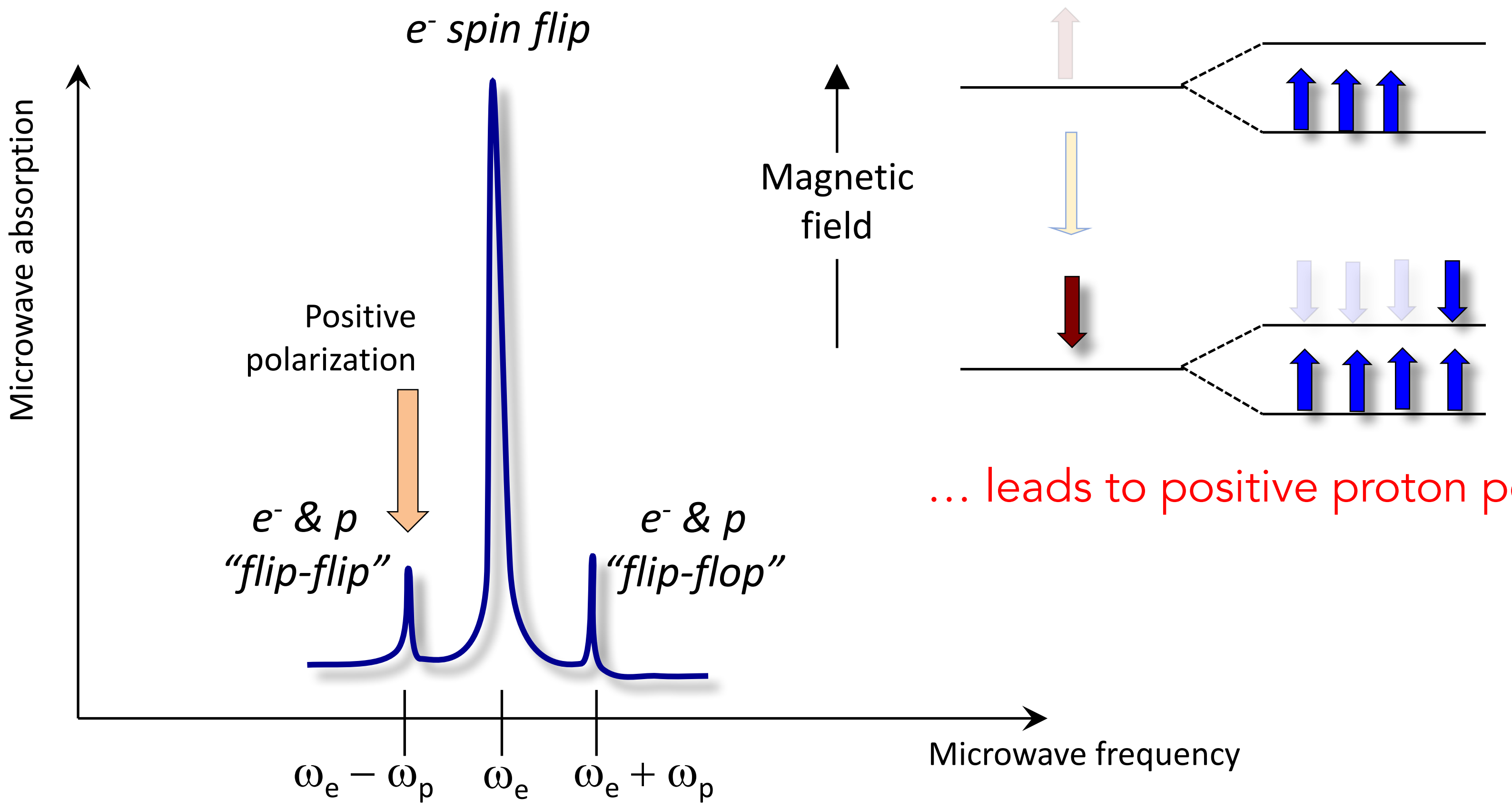

… leads to positive proton polarization.

DNP: the solid effect

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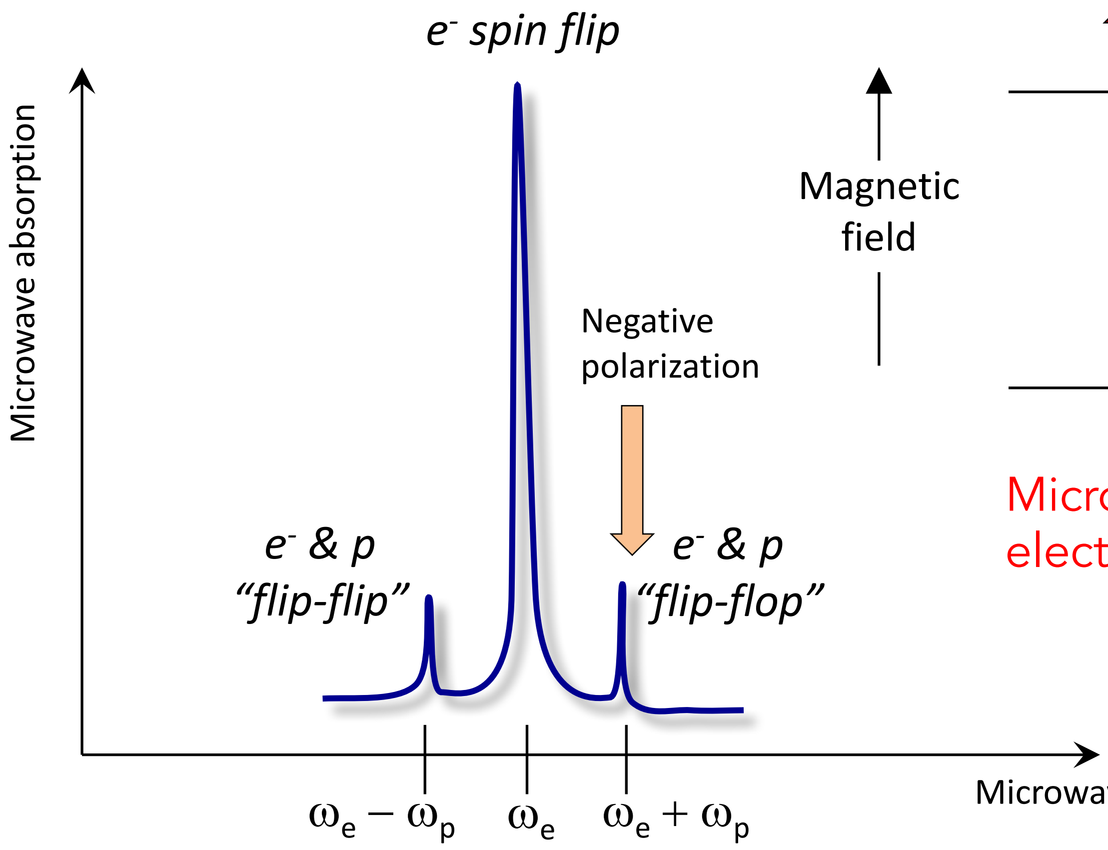

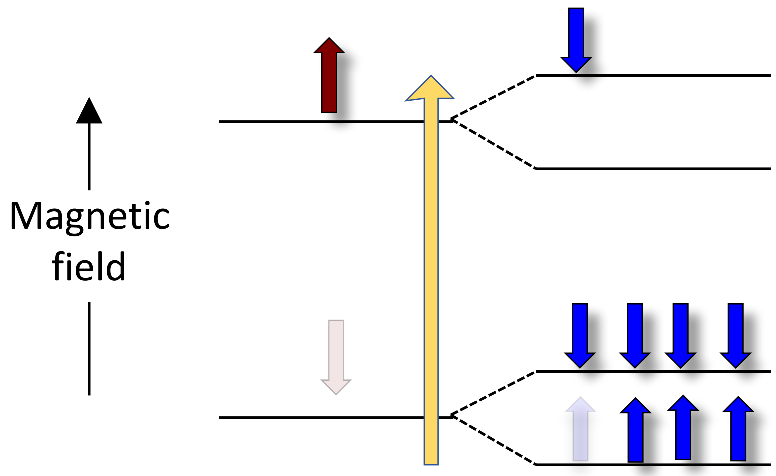

Microwaves at $\omega_e + \omega_p$ produces an electron-proton "flip-flop"…

Electron Spin Resonance of a polarized solid target

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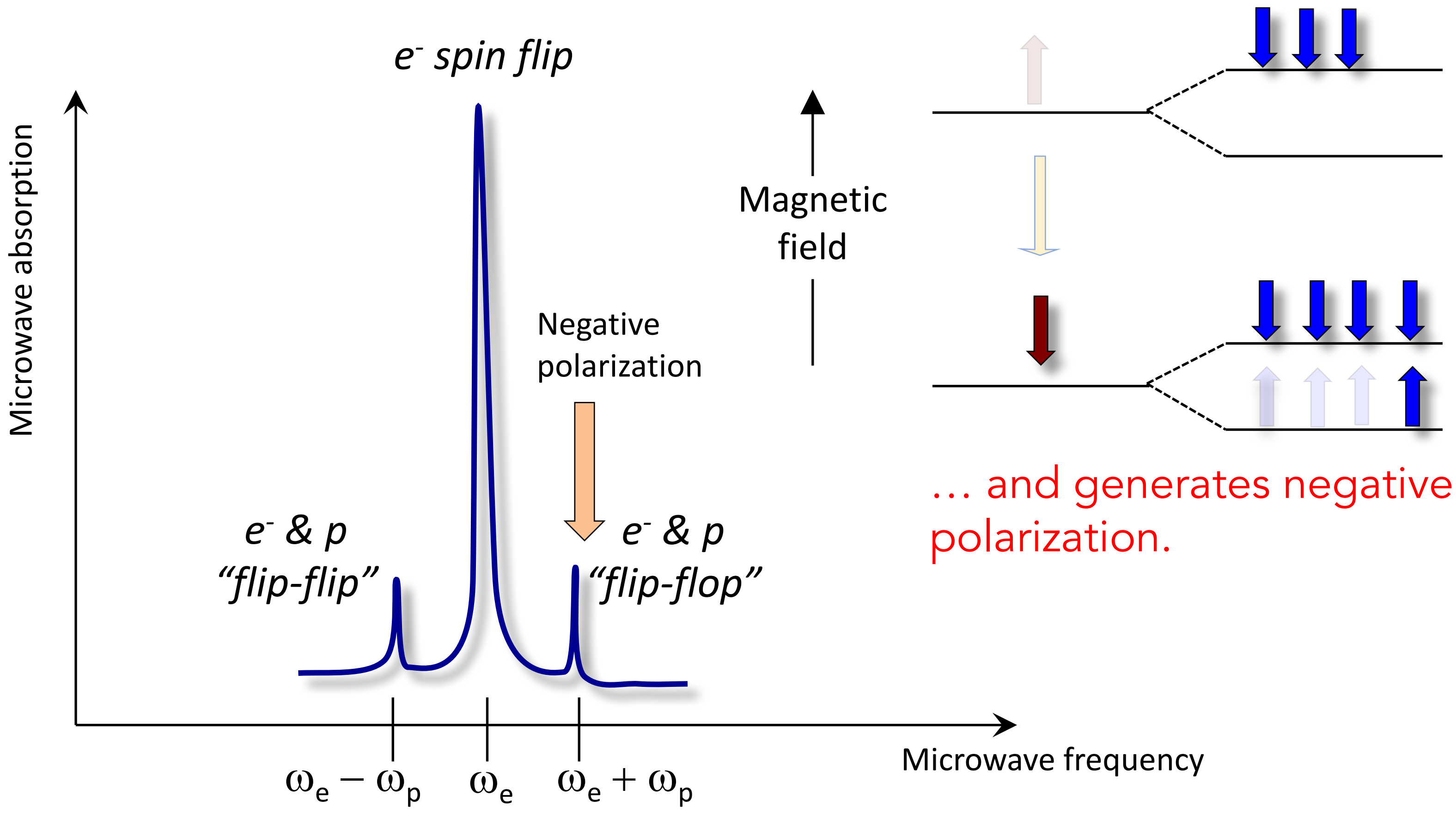
- high field



… and generates negative proton polarization.

DNP: the solid effect

Electron Spin Resonance of a polarized solid target

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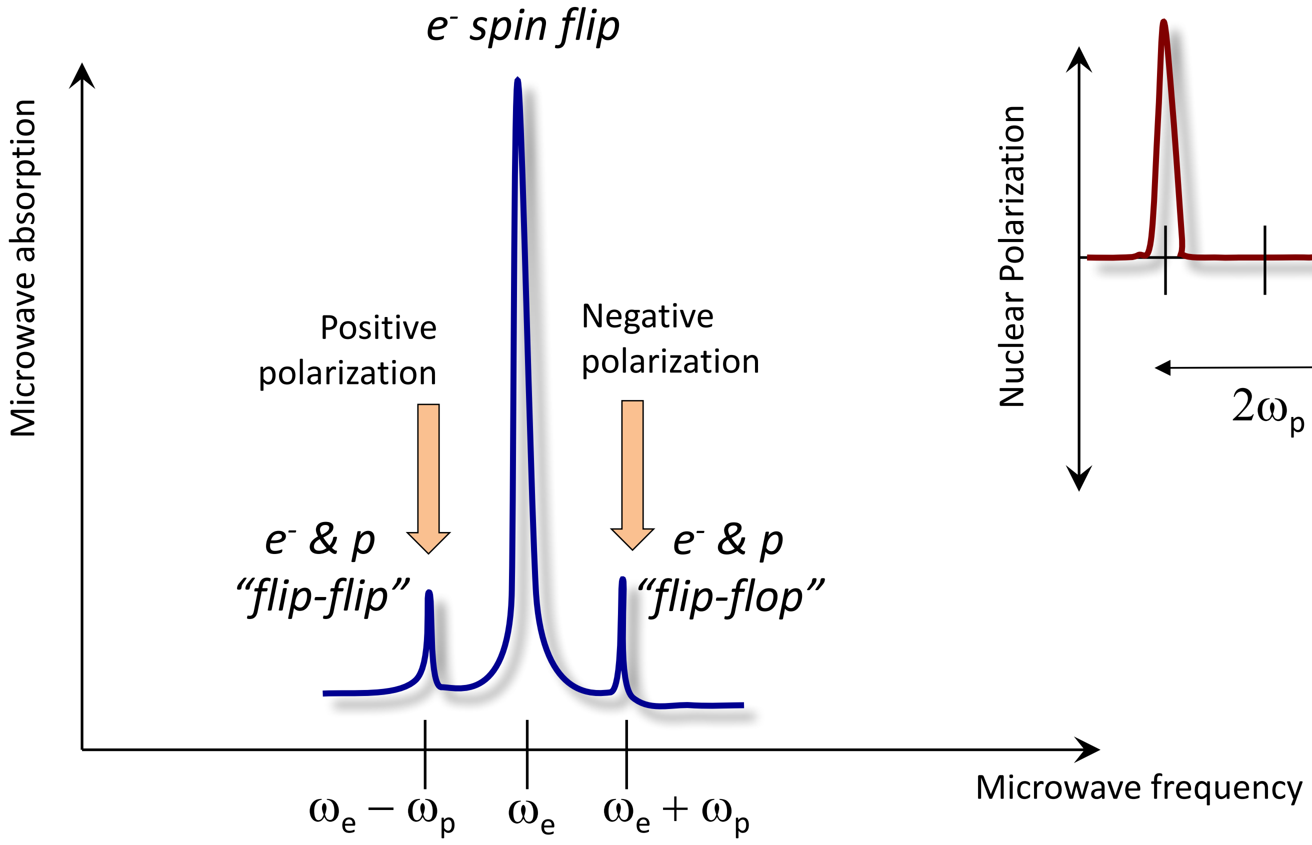
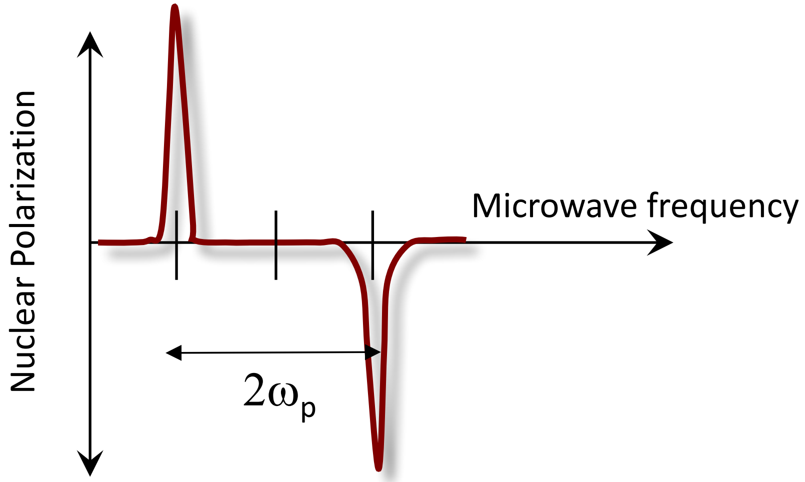
- high field



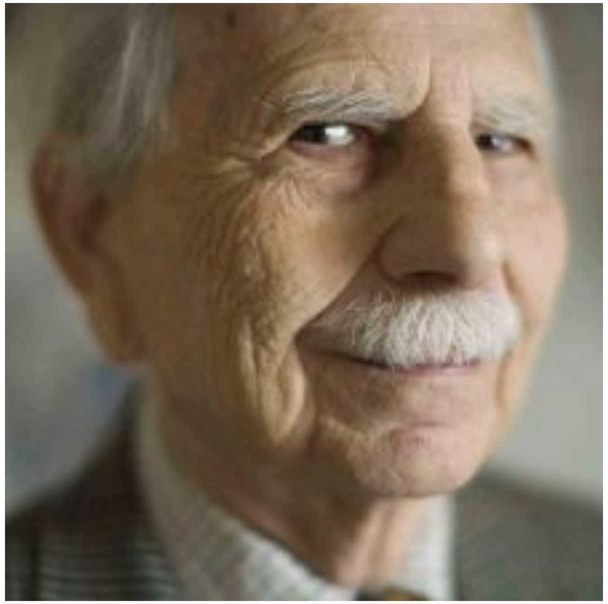


DNP: the solid effect

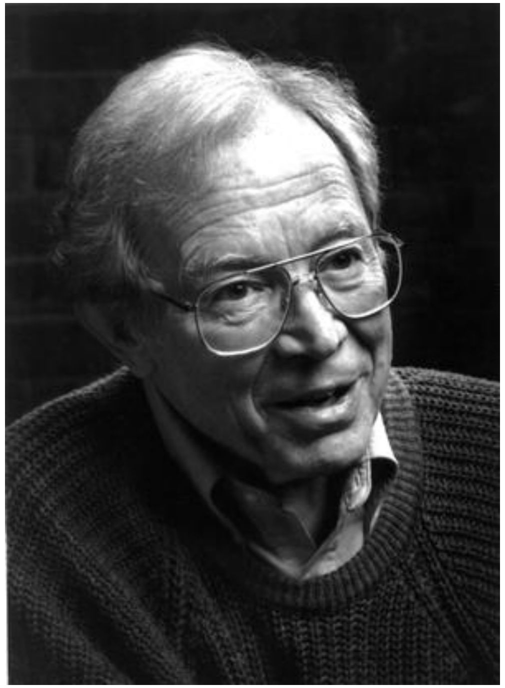
In 1957 Anatole Abragam (Saclay) and Carson Jefferies (Berkeley) independently demonstrate the transfer of electron polarization to nuclei by driving *forbidden* transitions directly in dielectric solids containing paramagnetic impurities.

Abragam called this “l'effet solide”, The Solid Effect.

Within 5 years, both were enlisted to build polarized targets for scattering experiments!



Anatole Abragam, 1914-2011

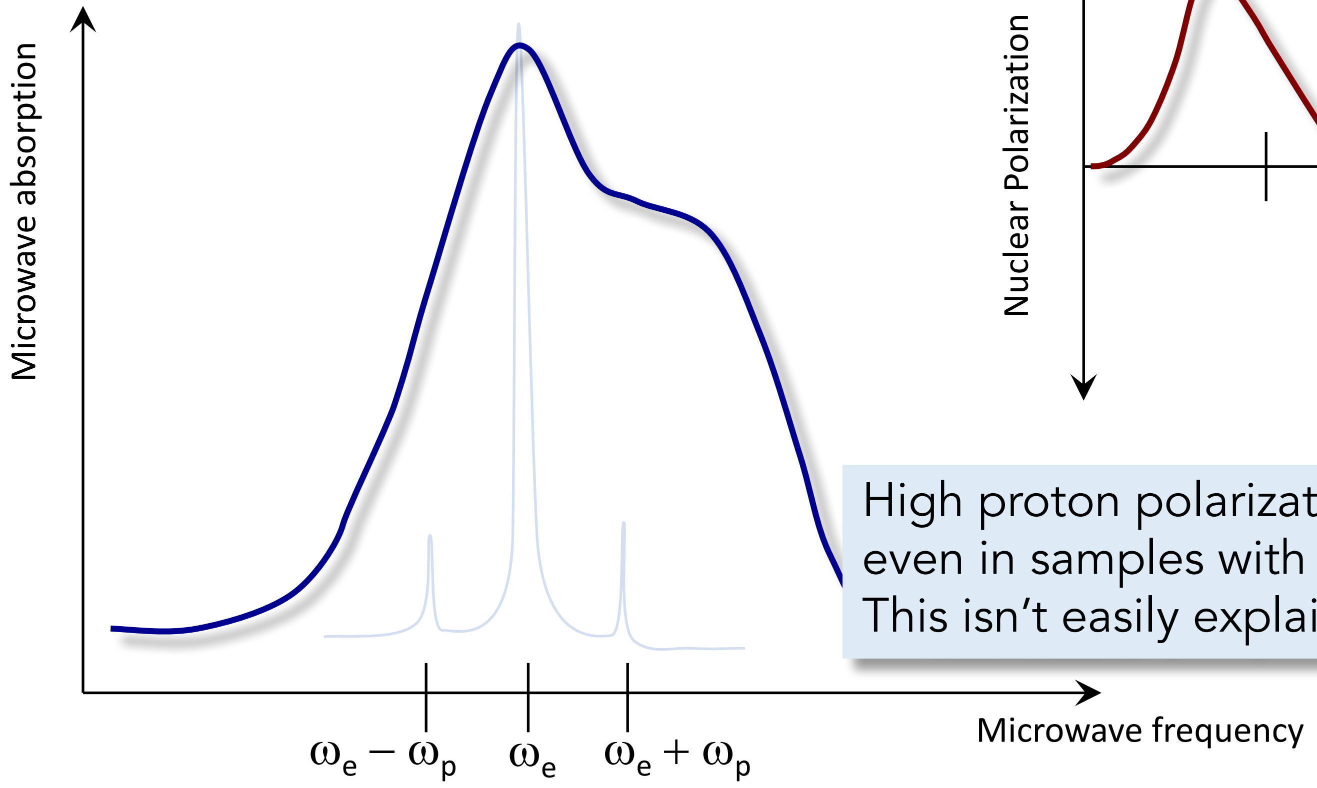


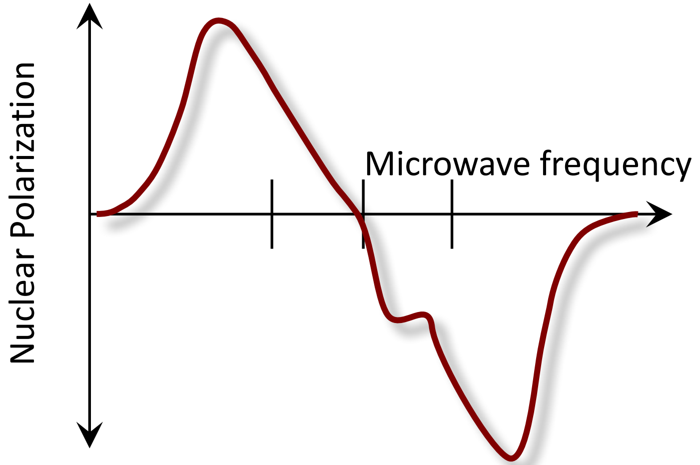
Carson Jeffries, 1922-1995

DNP: beyond the solid effect

Electron Spin Resonance of a polarized solid target Irradiated Ammonia (NH_3)

- a solid dielectric with ~10^{19} cm^{-3} unpaired electrons
- low temperature
- high field





High proton polarizations have been observed even in samples with broad ESR line.
This isn't easily explained by the Solid Effect.

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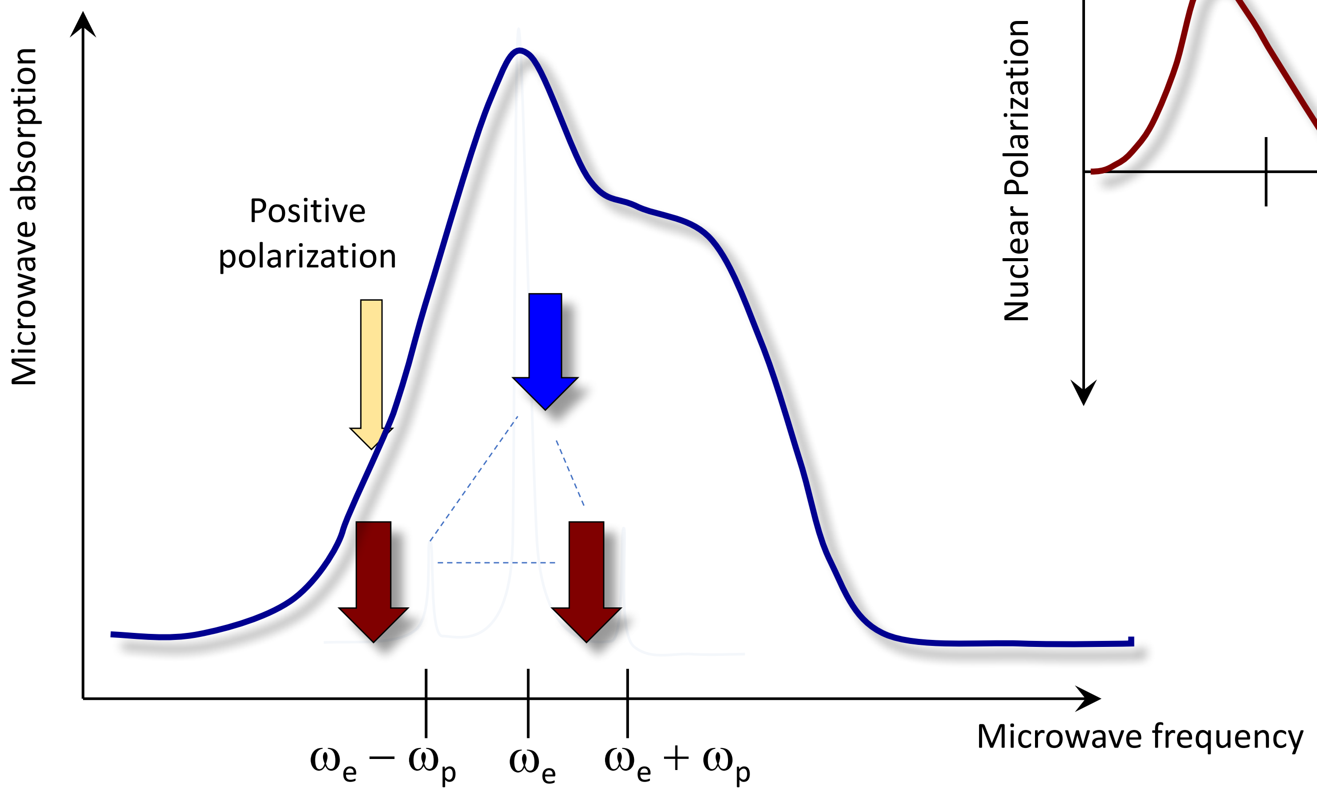
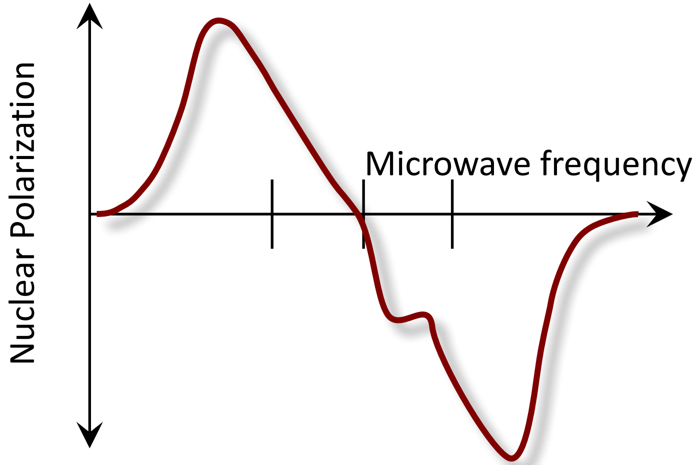
DNP: beyond the solid effect

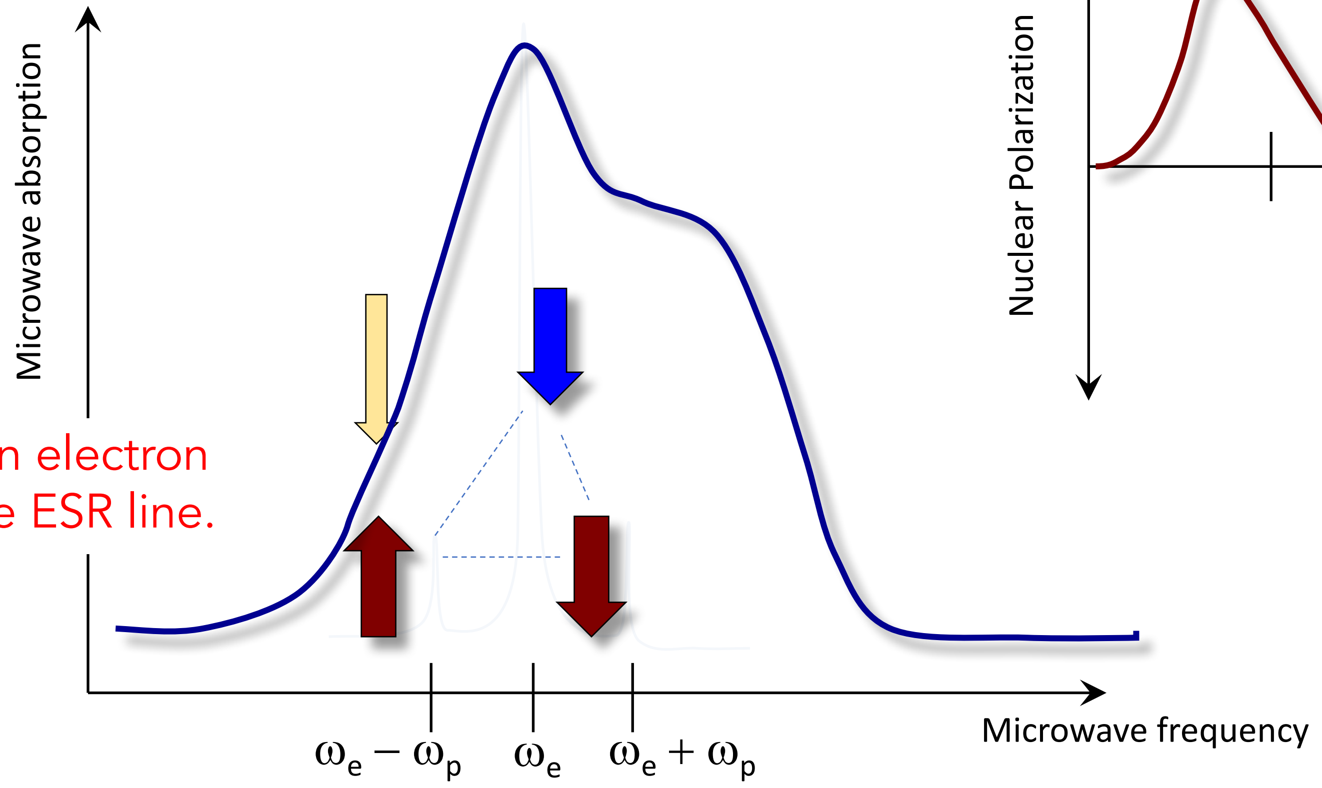
Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.



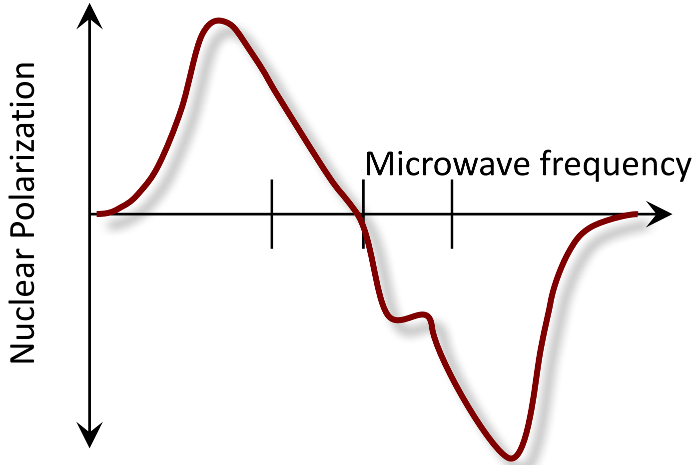


DNP: beyond the solid effect

Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one proton.



Microwaves flip an electron on one side of the ESR line.



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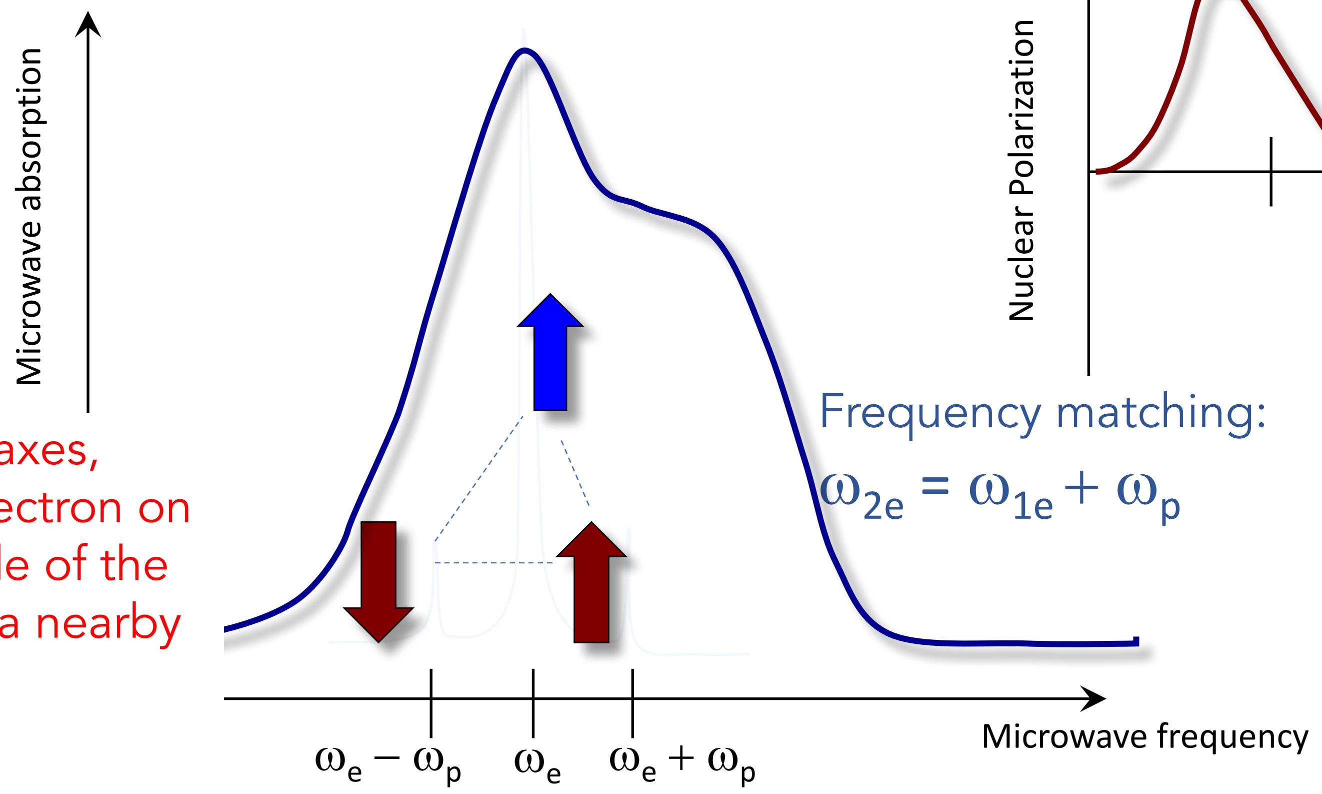
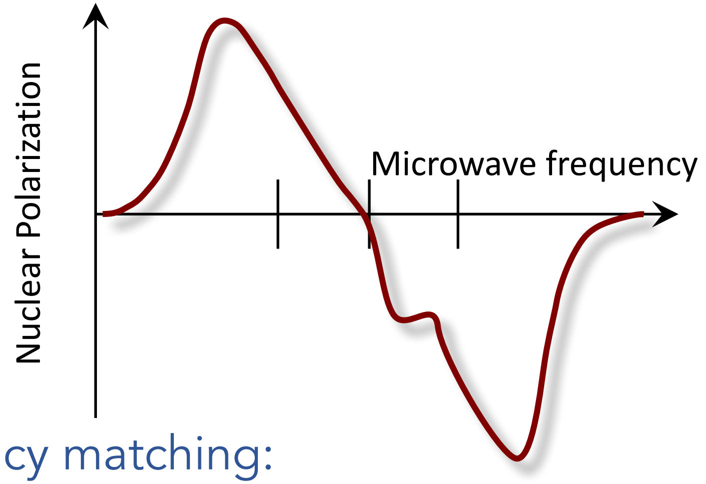




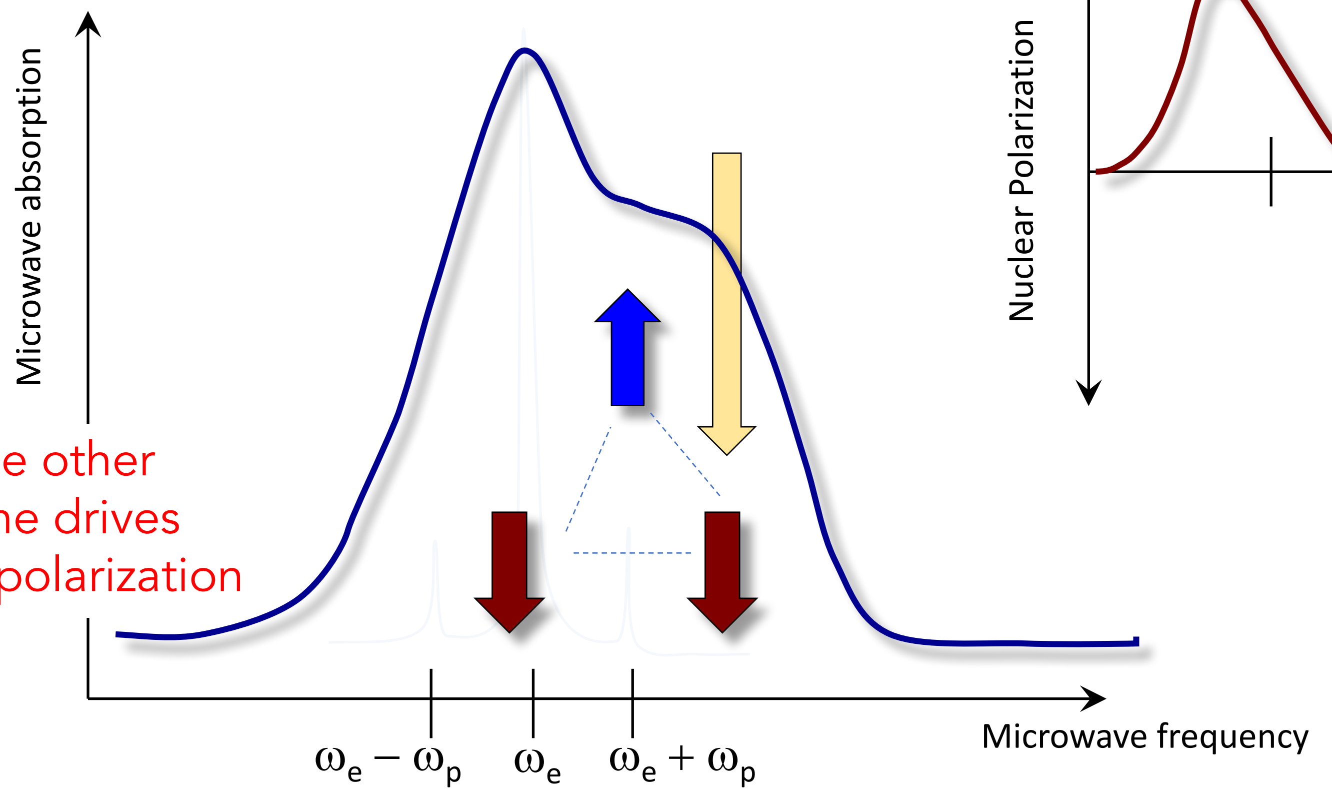
The electron relaxes, flipping a 2nd electron on the opposite side of the line, along with a nearby nuclear spin.

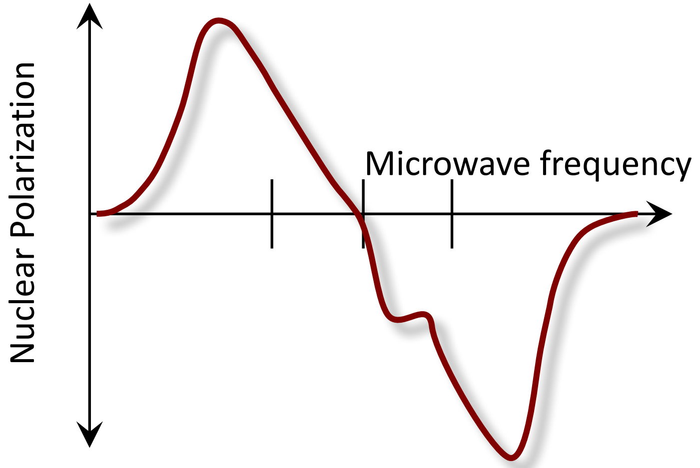
Frequency matching:

$\omega_{2e} = \omega_{1e} + \omega_p$

DNP: beyond the solid effect

Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.

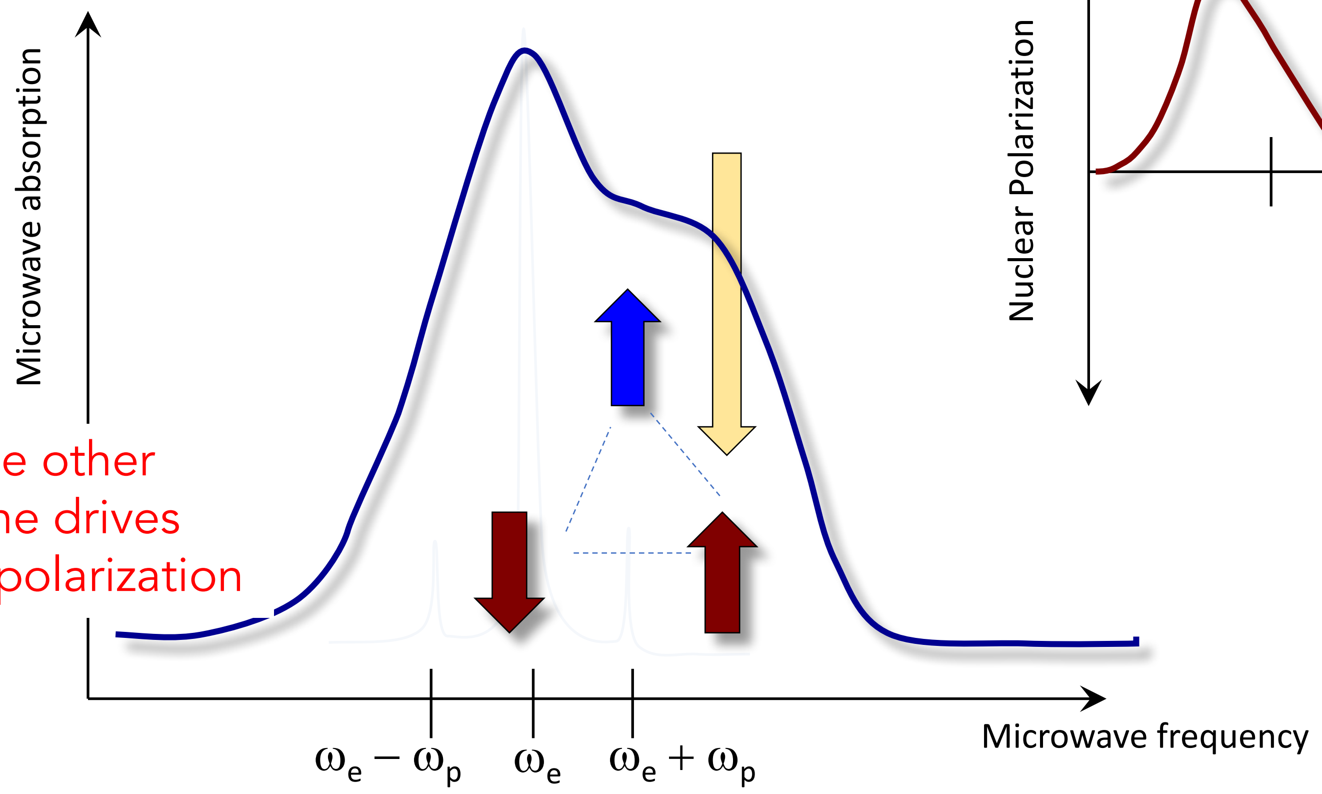


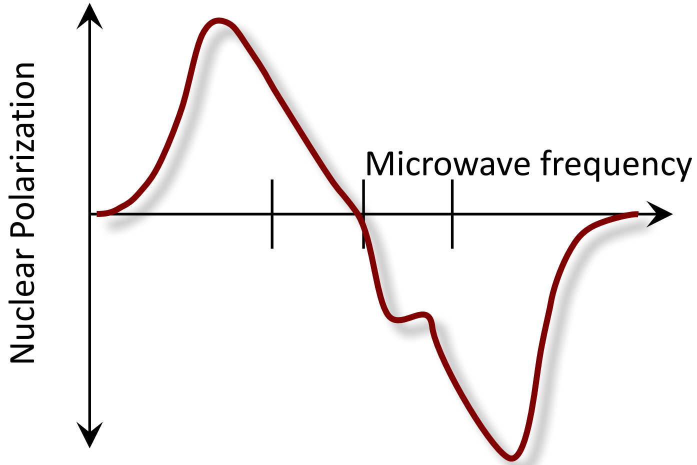


Microwaves on the other side of the ESR line drives negative nuclear polarization

DNP: beyond the solid effect

Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.





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DNP: beyond the solid effect

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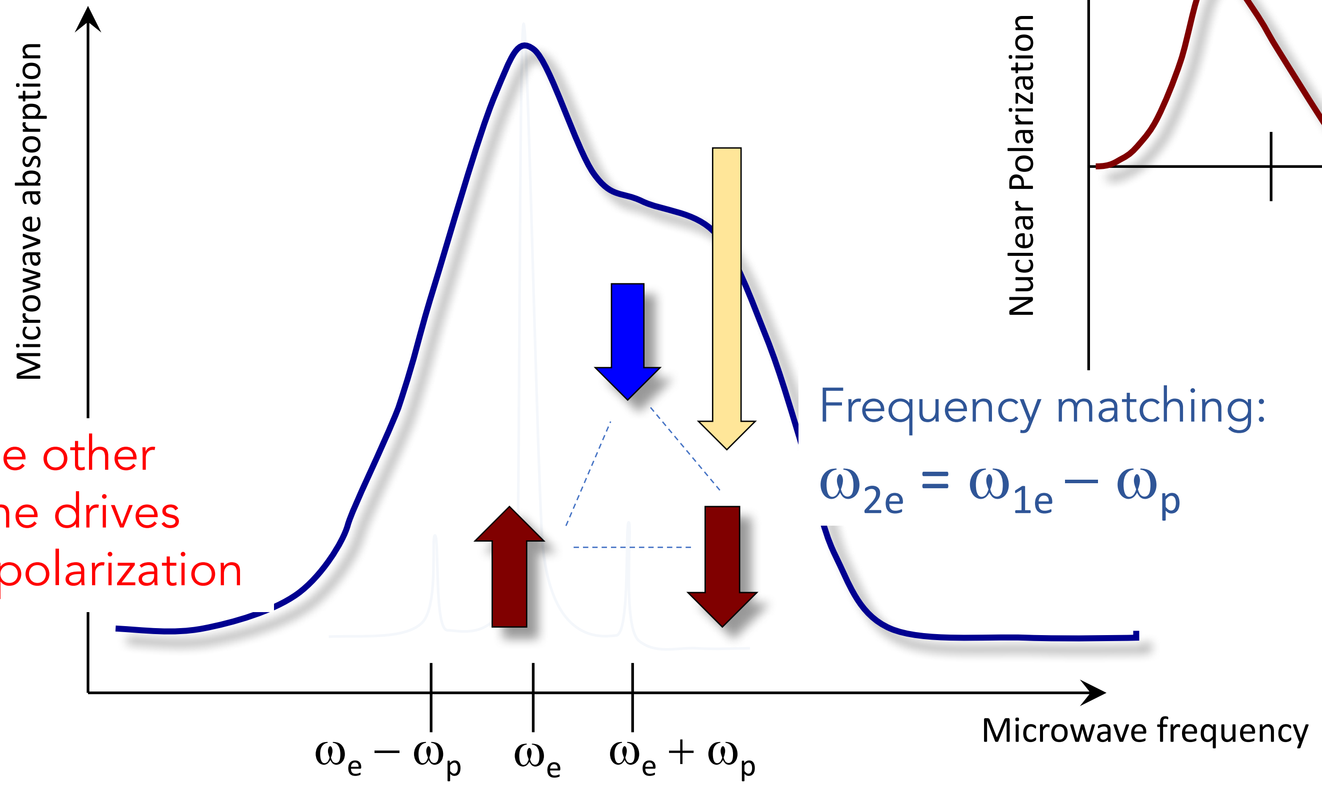
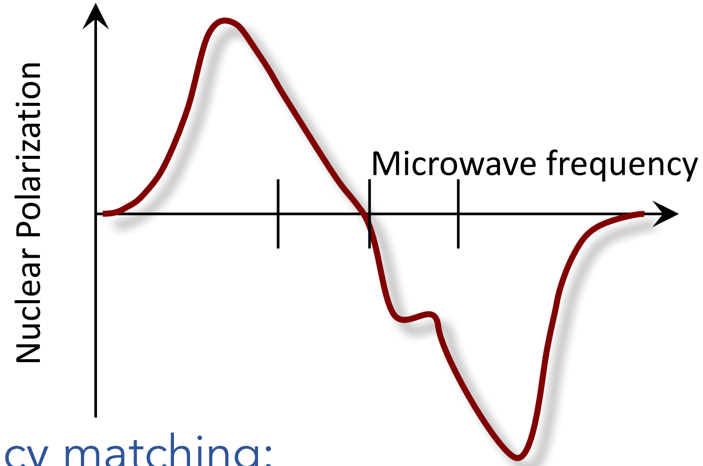


Microwaves on the other side of the ESR line drives negative nuclear polarization

Frequency matching:

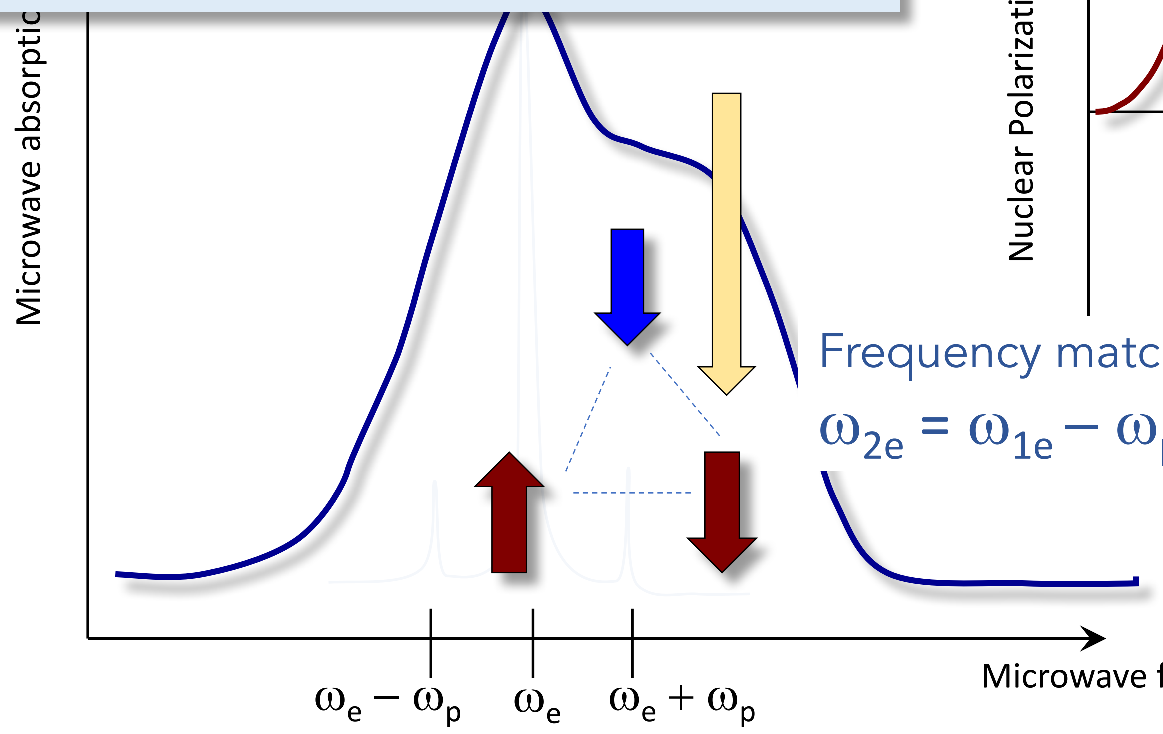
$\omega_{2e} = \omega_{1e} - \omega_p$



DNP: beyond the solid effect

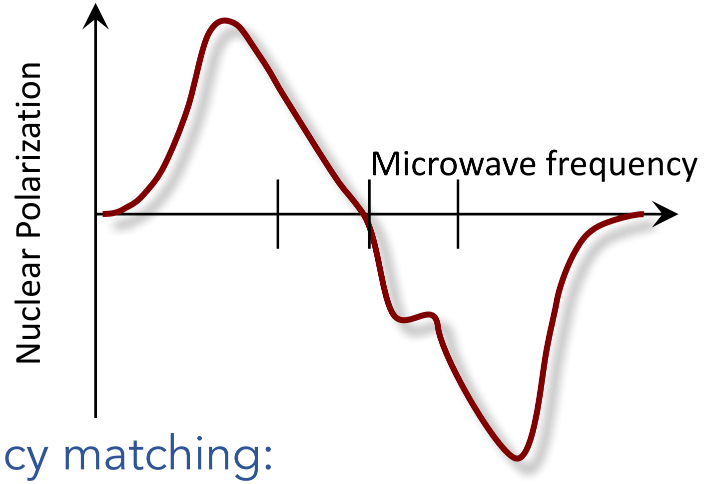
Polarization transfer occurs through a cross-relaxation process involving three spins: two electrons and one nucleus.

The *Cross Effect* and/or *Thermal Mixing*

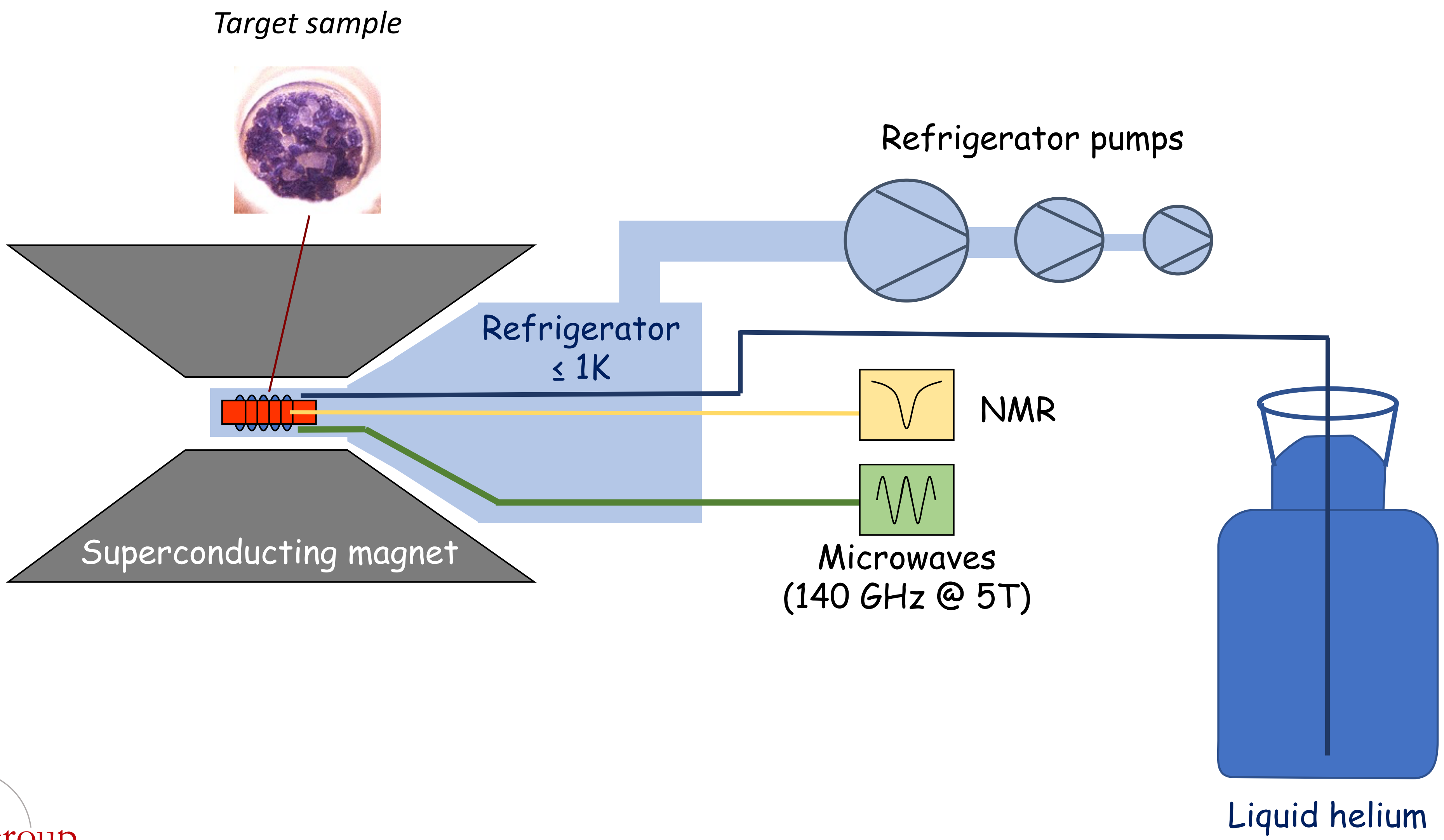


Frequency matching:

$\omega_{2e} = \omega_{1e} - \omega_p$



Instrumentation



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Target Group

Target samples

Polarized target material can be characterized by four quantities

Maximum polarization

"Can you make it higher?"

Speed of polarization

"How much longer?"

Polarization resistance to ionizing radiation

"Why is the polarization going down!?"

Ratio of polarized-to-total number of nuclei

"What's all this other junk?"

dilution factor, f

$$\boxed{\text{Figure-of-Merit} = t \cdot f^2 \cdot P^2}$$

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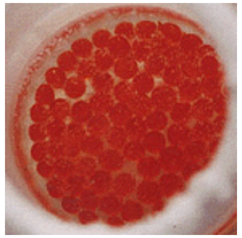
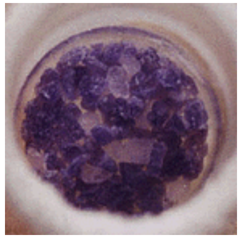
Target samples


Material	Butanol, C_4H_9OH	Ammonia, NH_3	Lithium hydride, ^7LiH
Dil. Factor (%)	13.5	17.7	25.0
Polarization (%)	> 90%	> 90%	90%
Material	D-Butanol, C_4D_9OD	D-Ammonia, ND_3	Lithium deuteride, ^6LiD
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	> 80%	50%	55%
Doping method	Chemical	Radiation	Radiation
Rad. resistance	moderate	high	extremely high
Comments	*Easy to produce and handle*	*Works well at 5T and 1K*	*Slow polarization, long relaxation*

Refrigerator

courtesy of James Brock, Jefferson Lab

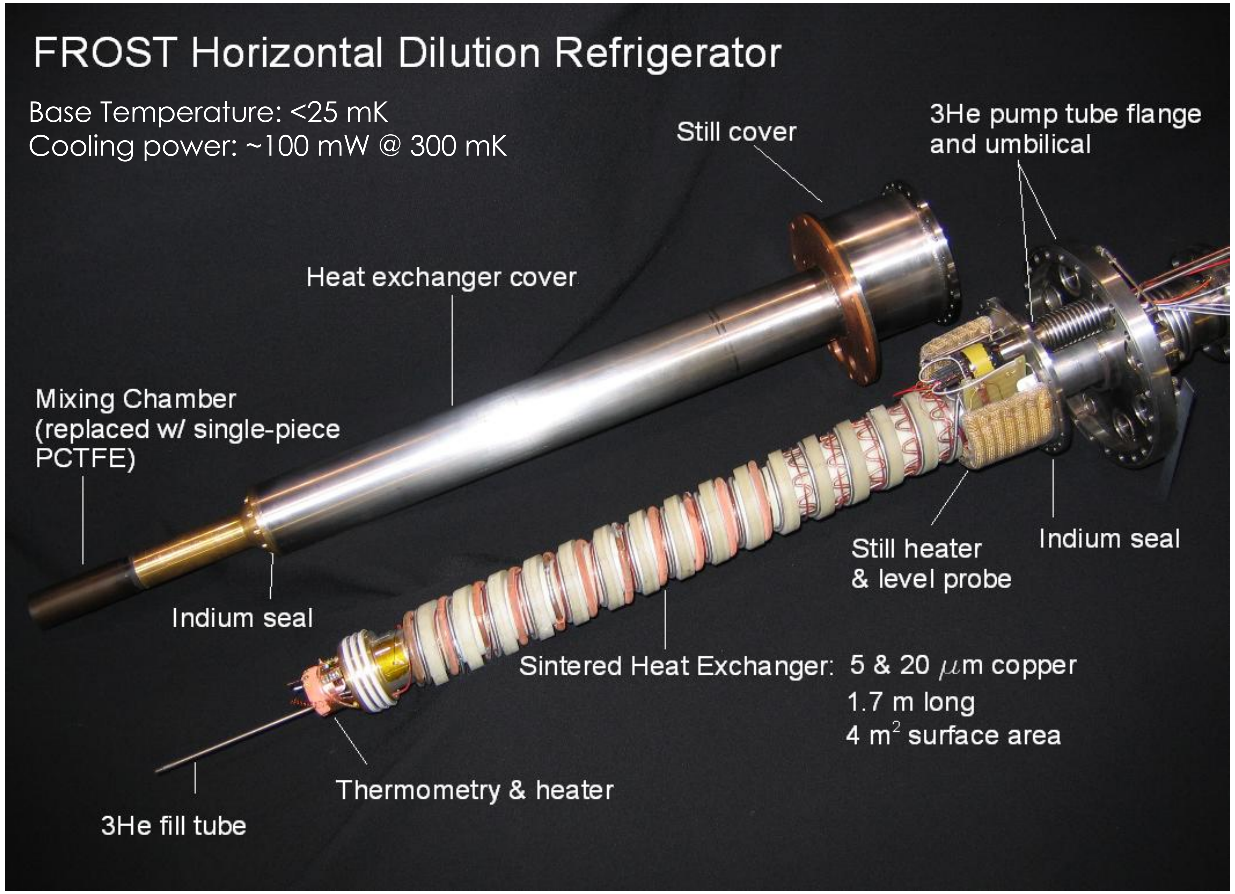
<u>1 K ^{4}He evaporation refrigerator</u>

base temperature: ≤1.0 K

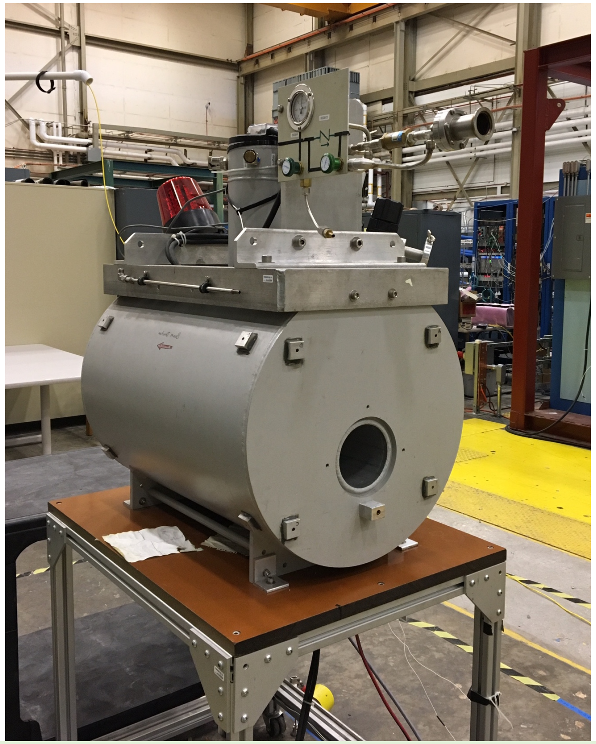
Cooling power: 0.8 W @ 1.0 K

Refrigerator

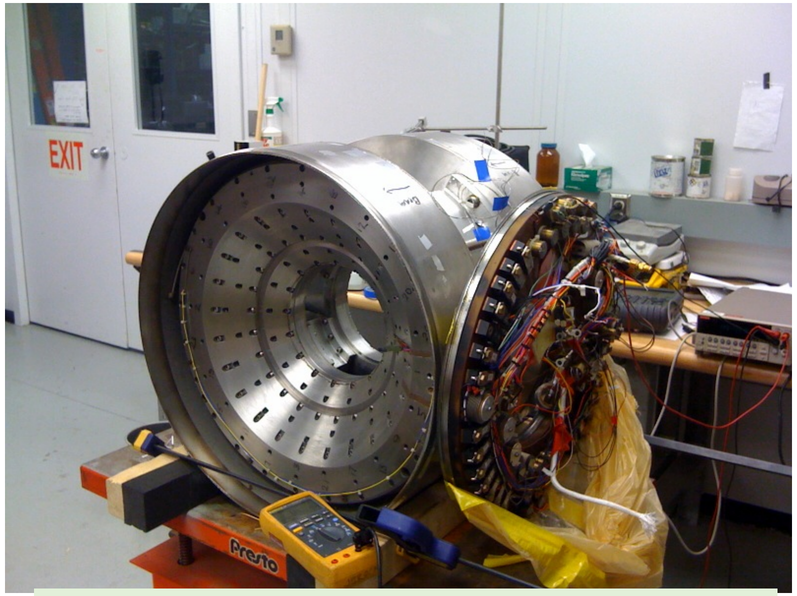
^{3}He-^{4}He dilution refrigerator
base temperature: < 25mK
cooling power: 0.1 W @ 0.3 K



Superconducting magnets



5.0 T solenoid for Hall B Frozen Spin Target
(Cryomagnetics, Inc.)



5.0 T Split pair for Hall C Polarized Target
(Oxford Instrments, Inc.)

5.0 T Solenoid for CLAS12
(Everson Tesla, Inc.)

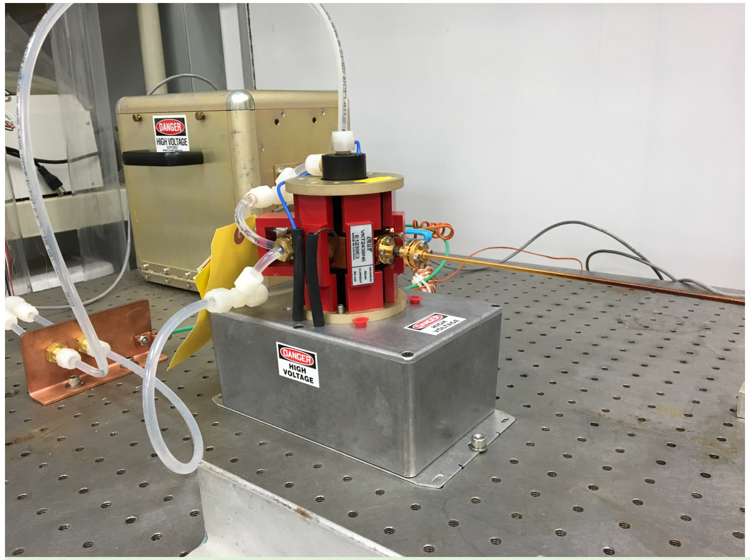
For optimum DNP, the field should be uniform over the volume of the target sample at a level of about 100 ppm

Microwave sources

Microwave frequency: 28 GHz/Tesla

Power requirements: ~4 mW/g @ 2.5 T (70 GHz)
~20 mW/g @ 5.0 T (140 GHz)

IMPATT Diode, 0.3 W @ 70 GHz
VA Diode, Inc



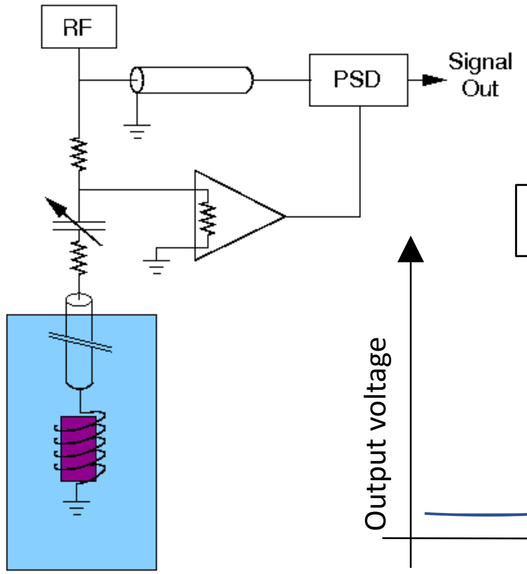
Extended Interaction Oscillator, 20 W @ 140 GHz
CPI Canada

Polarization measurement

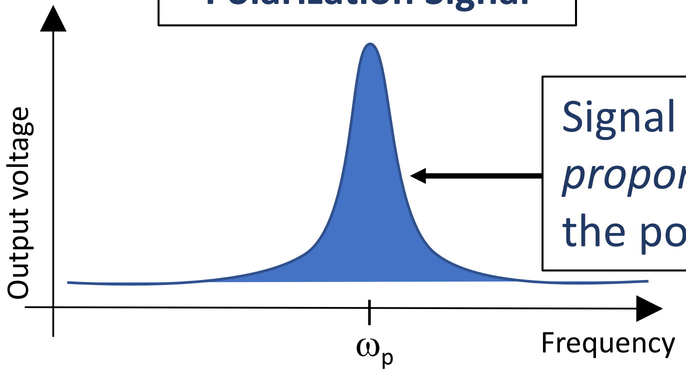
NMR frequencies(MHz):	Proton	Deuteron
5 tesla	212.9	32.7
2.5 tesla	106.4	16.3

CW-NMR using Q-meter is the standard detection scheme.
G. Court *et al*, NIM A324 (1993) 433

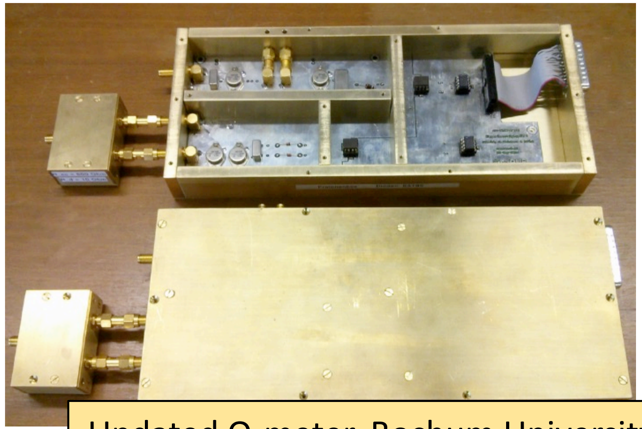
Typical polarization accuracy is $\Delta P/P \approx 3 - 4$ %



Polarization Signal



Signal Area is *proportional* to the polarization



Updated Q-meter, Bochum University
Improved S/N and stability
G. Reichertz, SPIN2016

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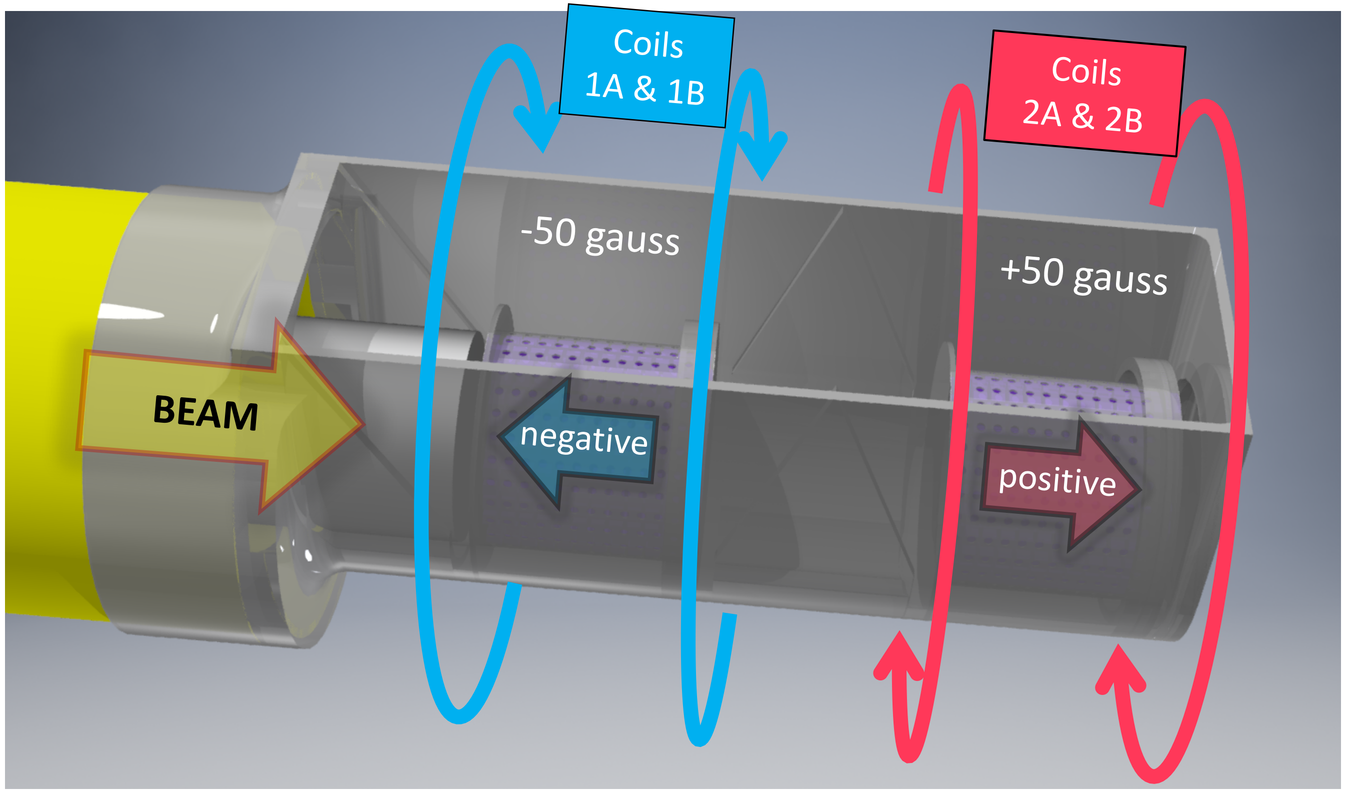
Polarization measurement

A new project at Jlab: Can we polarize two samples at once, in opposite directions?

Microwaves are tuned halfway between the normal (+) and (-) polarization frequencies:

- high field sample will polarize (+)
- low field sample will polarize (-)



Jefferson Lab
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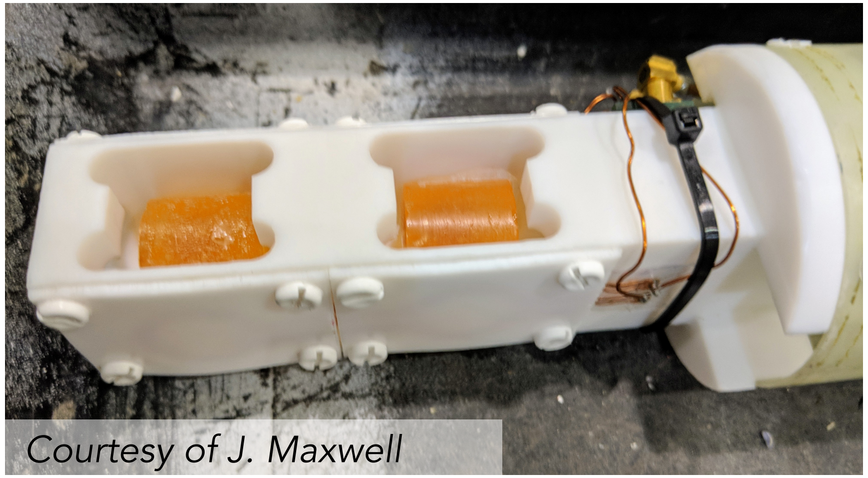
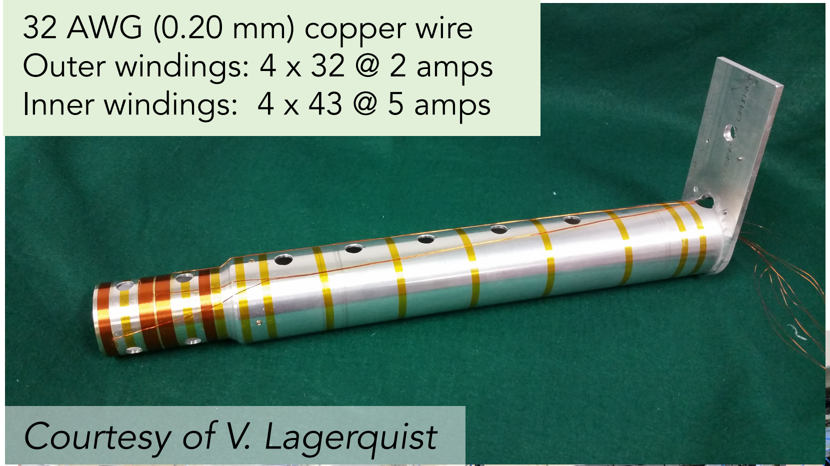
Polarization measurement

A new project at Jlab: Can we polarize two samples at once, in opposite directions?

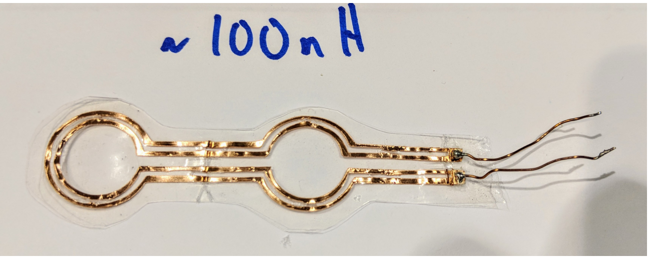


Courtesy of J. Maxwell

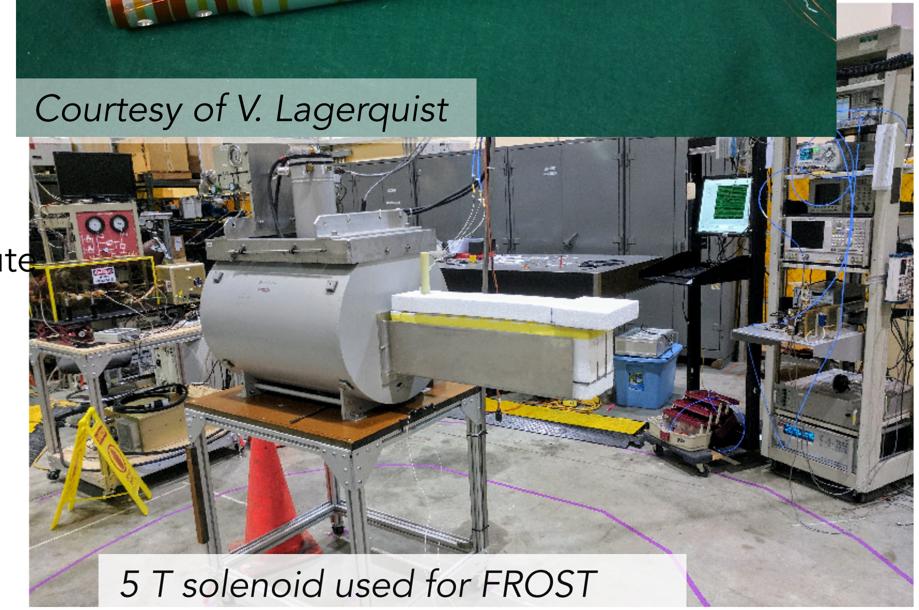


32 AWG (0.20 mm) copper wire
Outer windings: 4 x 32 @ 2 amps
Inner windings: 4 x 43 @ 5 amps

Courtesy of V. Lagerquist



- Samples are 5-minute epoxy doped with TEMPO radical
- Two samples
- One NMR coil



5 T solenoid used for FROST

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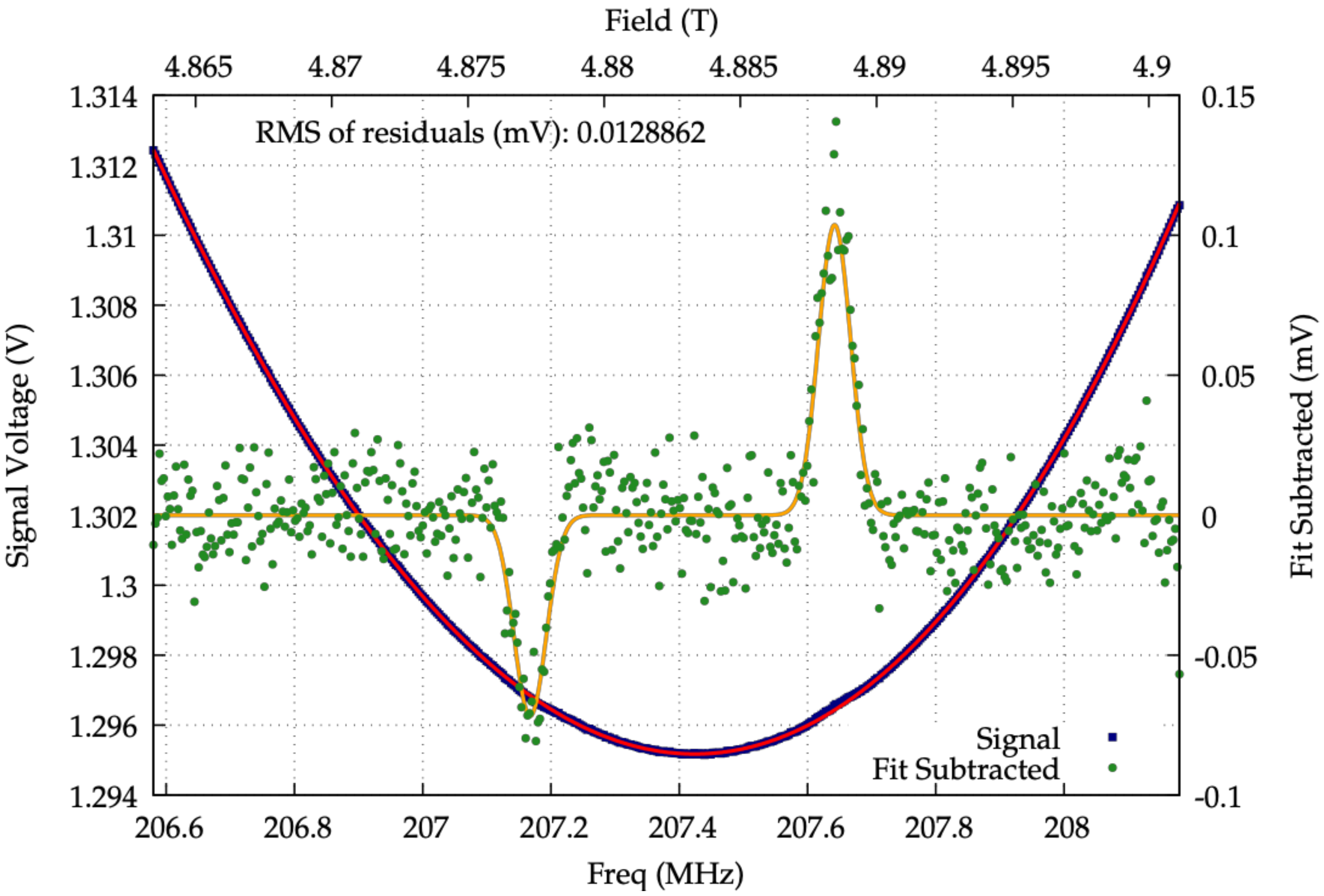
Polarization measurement

A new project at Jlab: Can we polarize two samples at once, in opposite directions?

Answer: YES!



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Further reading

Books

A. Abragam, “Principles of Nuclear Magnetism”, Oxford University Press, 1982

C. Jeffries, "Dynamic Nuclear Orientation", New York, Interscience Publishers, 1963

T. Wenckebach, “Essentials of Dynamic Nuclear Polarization”, Spindrift Publications, 2016

Review Articles

St. Goertz, W. Meyer, and G. Reicherz, “Polarized H, D, and 3He Targets for Particle Physics Experiments”, Prog. in Part. and Nucl. Phys., 49 (2002) 403.

D.G. Crabb and W.. Meyer, “Solid Polarized Targets for Nuclear and Particle Physics Experiments”, Annu. Rev. Nucl. Part. Sci. 47 (1997) 67.

A. Abragam and M. Goldman, “Dynamic Nuclear Polarization“, Rep. Prog. Phys. 41 (1978) 396.

T. Maly, et al, “Dynamic Nuclear Polarization at High Magnetic Fields”, J. Chem. Phys. 128 (2008) 052211.

Biannual Workshops & Symposia

Workshop on Polarized Sources, Targets, and Polarimetry (PSTP): (Knoxville, 2019)

International Spin Physics Symposium: (Japan, 2020)

Summary

Polarized targets are fun instruments to build & work with (usually)

- condensed matter physics
- low temperature physics
- cryogenics
- magnet technology
- vacuum technology

They're useful for nuclear and particle physics too

- Structure functions
- Sum rule rules
- Baryon spectroscopy

Technology developed for Polarized Targets is expanding into other areas of research

- Chemistry
- Biology
- Neutron crystallography

DNP is a mature technology, but a lot of advances in recent decades, and plenty of room for more!