Appendix: A wonderful set of animation of ESR and SDR by Dr. Cochrane, Penn State

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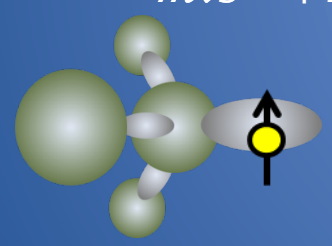
Resonance of Electrons

- Electrons have intrinsic discretized angular moment called spin.
- They are Fermions so they are $s=1/2$ and $m_s=\pm 1/2$.
- In an applied magnetic field, an electron spin will occupy one of these two states.
- With application of EM radiation, one enables electron energy state transitions.

Only unpaired electrons are EPR active!

$$E=-\boldsymbol{\mu}\cdot\boldsymbol{B}=m_s\, g\mu_\beta\, B_0$$

$m_s=+1/2$



$B_0=h\nu/g_e\,\mu_\beta$

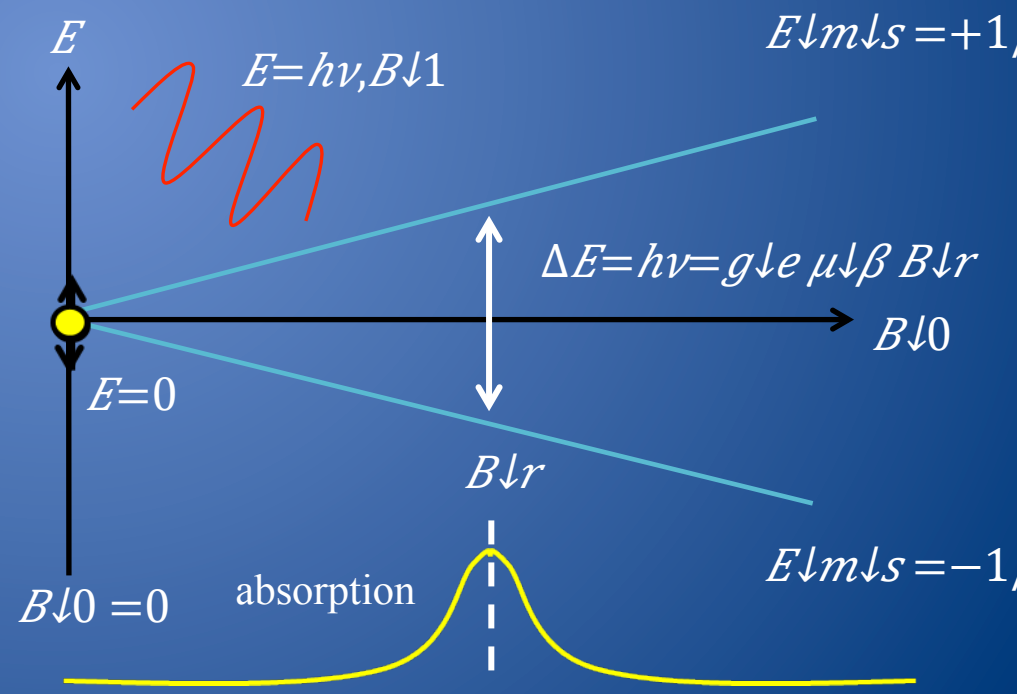
$\boldsymbol{B}=B_0\,k$

μ_β

= Planck's constant, υ = microwave frequency

g = orientation dependent parameter

Bohr magneton, B_r = magnetic field at resonance



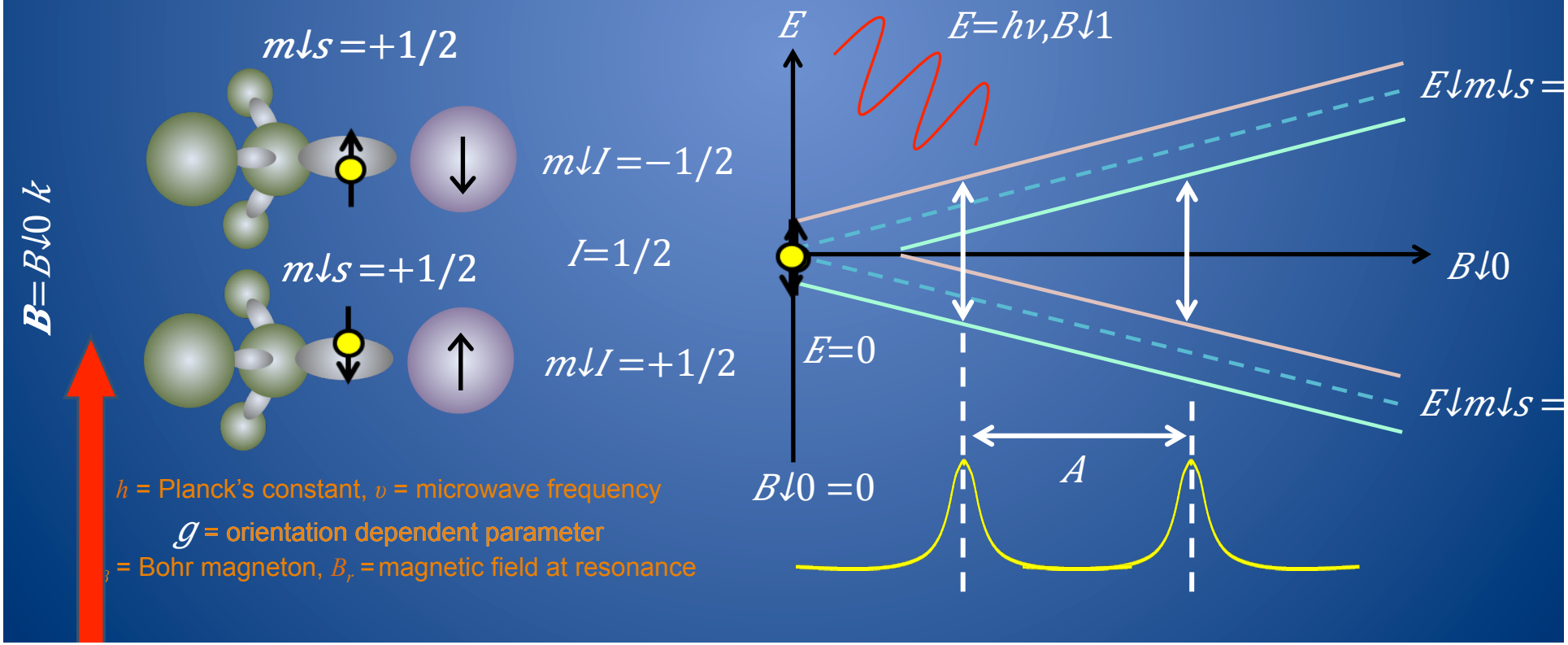
Hyperfine Interactions

- Some nuclei also have intrinsic discretized angular moment called nuclear spin.
- The quantum numbers describing these states are I and m_I, where $-I \leq m_I \leq +I$
- EPR will occur for every discretized nuclear state

Presence of magnetic nuclei will offset the resonant field of the unpaired electron

$$E = -\boldsymbol{\mu}\cdot\boldsymbol{B} = \boldsymbol{\mu}\cdot(\boldsymbol{B}+\boldsymbol{B}_N) = g_e \mu_\beta \boldsymbol{S}\cdot\boldsymbol{B} + A\boldsymbol{S}\cdot\boldsymbol{I}$$

$$\Delta E = h\nu = m_s g_e \mu_\beta (B_0 + A m_I)$$



h = Planck's constant, υ = microwave frequency

g = orientation dependent parameter

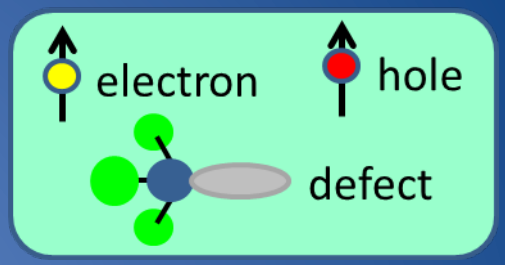
β = Bohr magneton, B_r = magnetic field at resonance

Spin Dependent Recombination

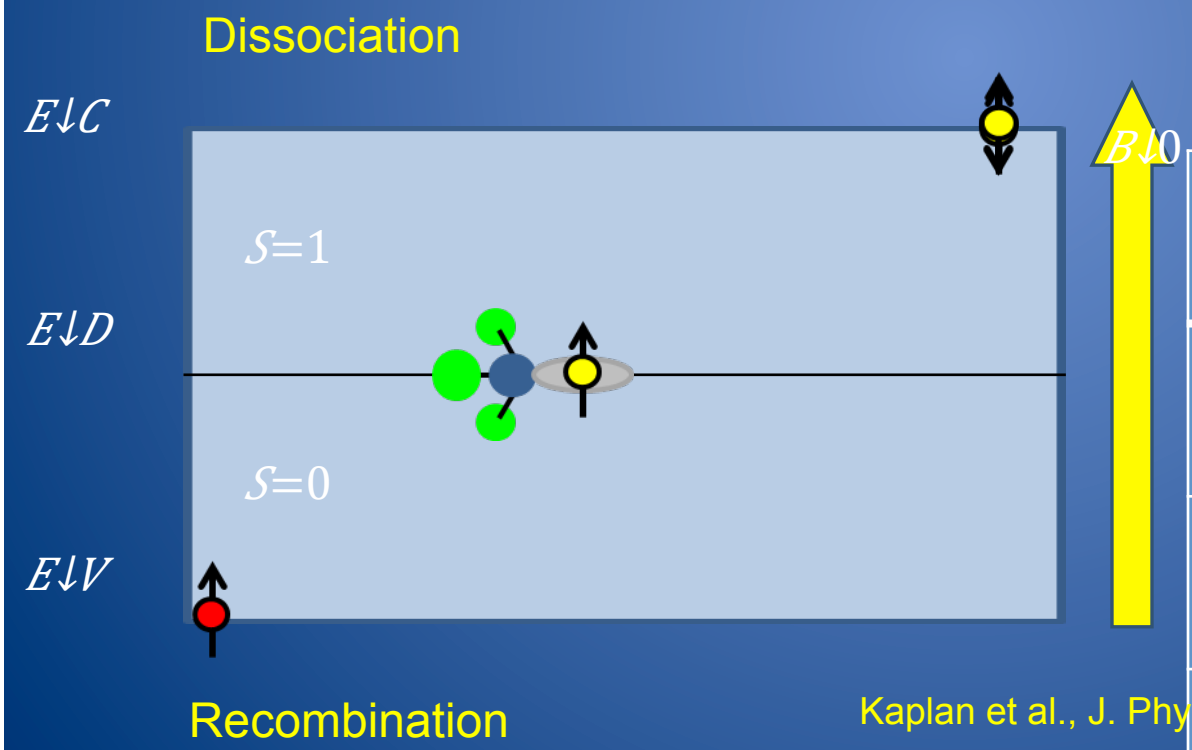
- Spin Dependent Recombination
- Resonant Spin Dependent Recombination

Spin Dependent Recombination (SDR)

SDR fits a model similar to the one Kaplan, Solomon, and Mott (KSM) proposed back in 1978. In this model, electrons pairs are able to couple prior to a recombination event. Because after a recombination event, a system is without spin, only spin pairs with zero angular momentum are able to recombine. This process conserves angular momentum. But why does SDR change in a resonant field?



If spin orbit coupling is negligible, the spin angular momentum of the pair will define the total angular momentum.



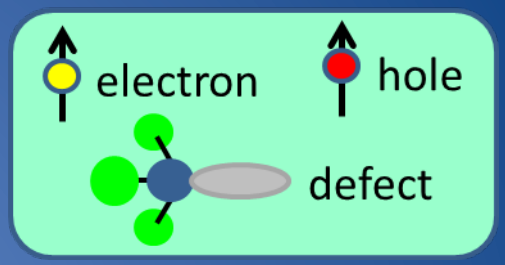
$spin: -s, .., m_s, ..., s, \; 2s+1 \; states$

State	Quantum State	$\lvert s, m_s \rangle$
Triplet (T_{+1})	$\lvert\uparrow\uparrow\rangle$	$\lvert 1,+1 \rangle$
Triplet (T_{-1})	$\lvert\downarrow\downarrow\rangle$	$\lvert 1,-1 \rangle$
Triplet (T_0)	$(\lvert\uparrow\downarrow\rangle + \lvert\downarrow\uparrow\rangle)/\sqrt{2}$	$\lvert 1,0 \rangle$

Kaplan et al., J. Phys. Paris, Lett. 39, L67, 1978.

Resonant Spin Dependent Recombination

The reason SDR increases in a resonant field is because either of the electrons in the precursor pair are able to "flip" when the resonance condition is satisfied. Therefore, triplet states are able to transition into singlet states which enhances recombination.



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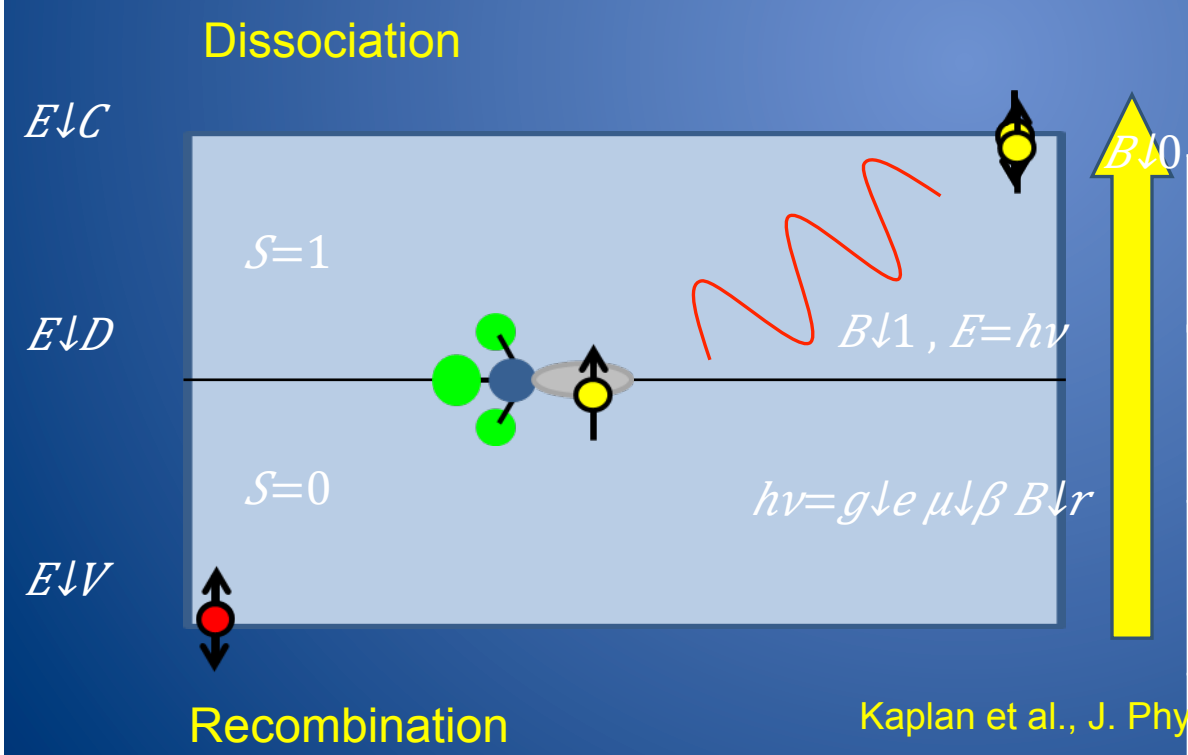

$$spin: -s,..,m_s,...,s,\ 2s+1\ states$$

State	Quantum State	$\lvert s, m_s \rangle$
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Triplet (T_0)	$\frac{(\lvert\uparrow\downarrow\rangle + \lvert\downarrow\uparrow\rangle)}{\sqrt{2}}$	$\lvert 1,0 \rangle$

Kaplan et al., J. Phys. Paris, Lett. 39, L54, 1978.