

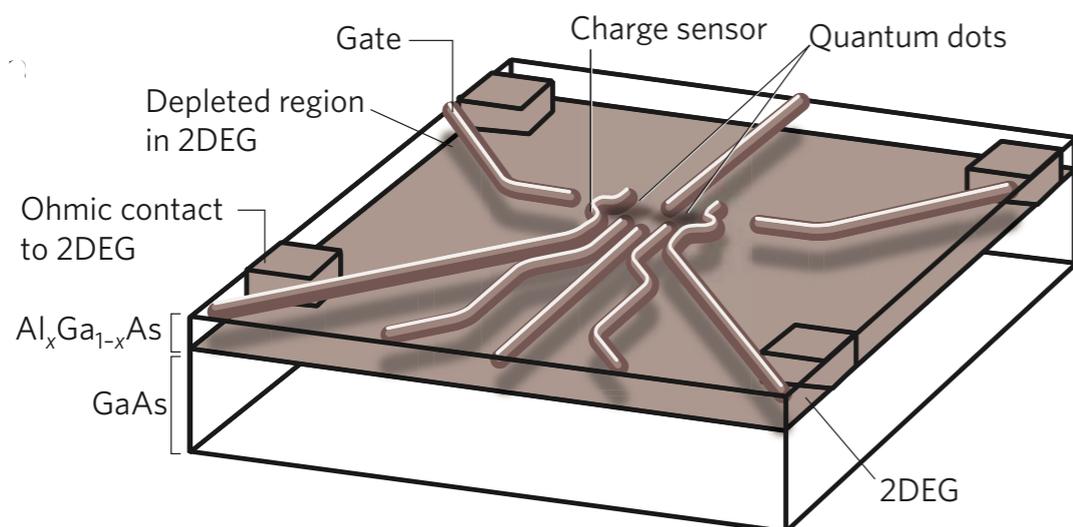
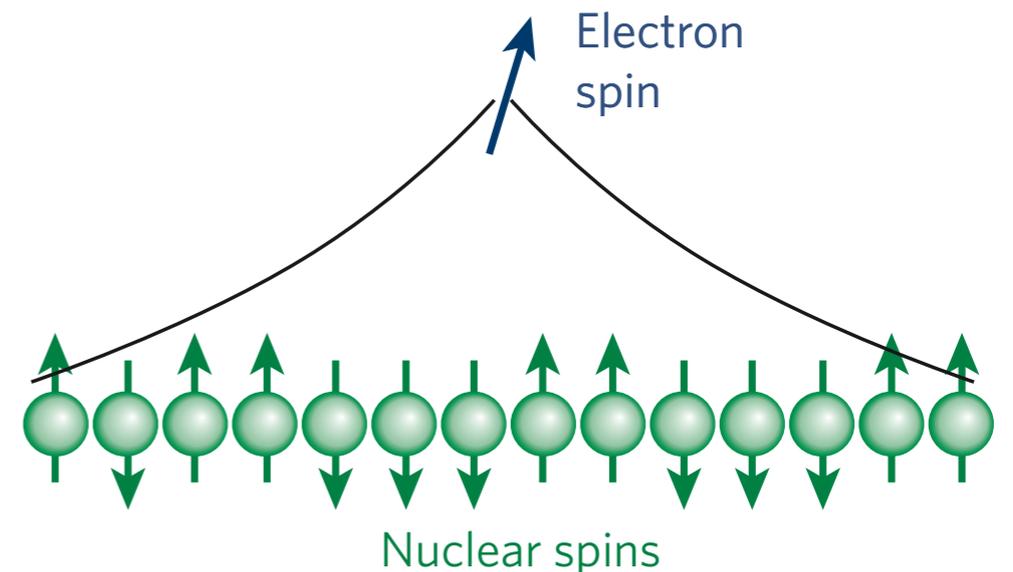
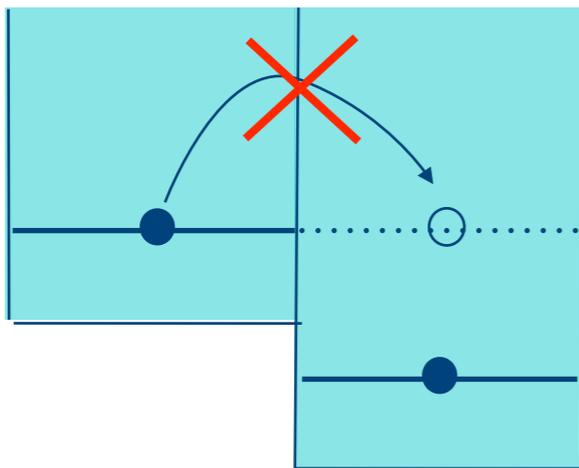
Spin qubits szilárdtestekben

(Spinblokádkettős kvantumdotokban)

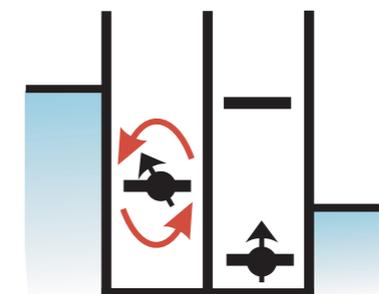
Pályi András

(1) Department of Physics, University of Konstanz, Németország

(2) Anyagfizikai Tanszék, Fizikai Intézet, ELTE



Spin manipulation

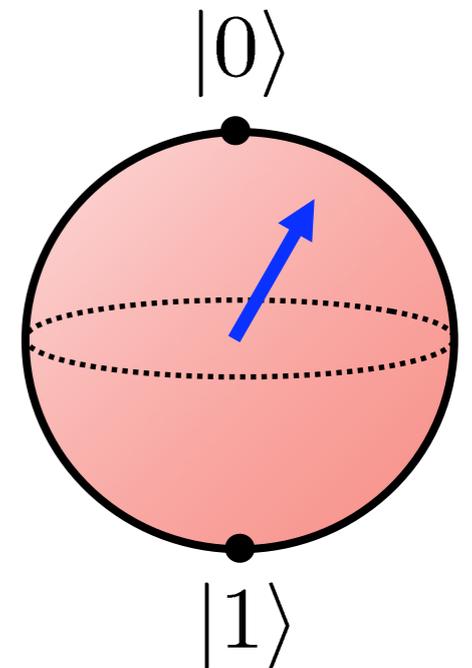


Bevezetés - spin qubitek szilárdtestekben

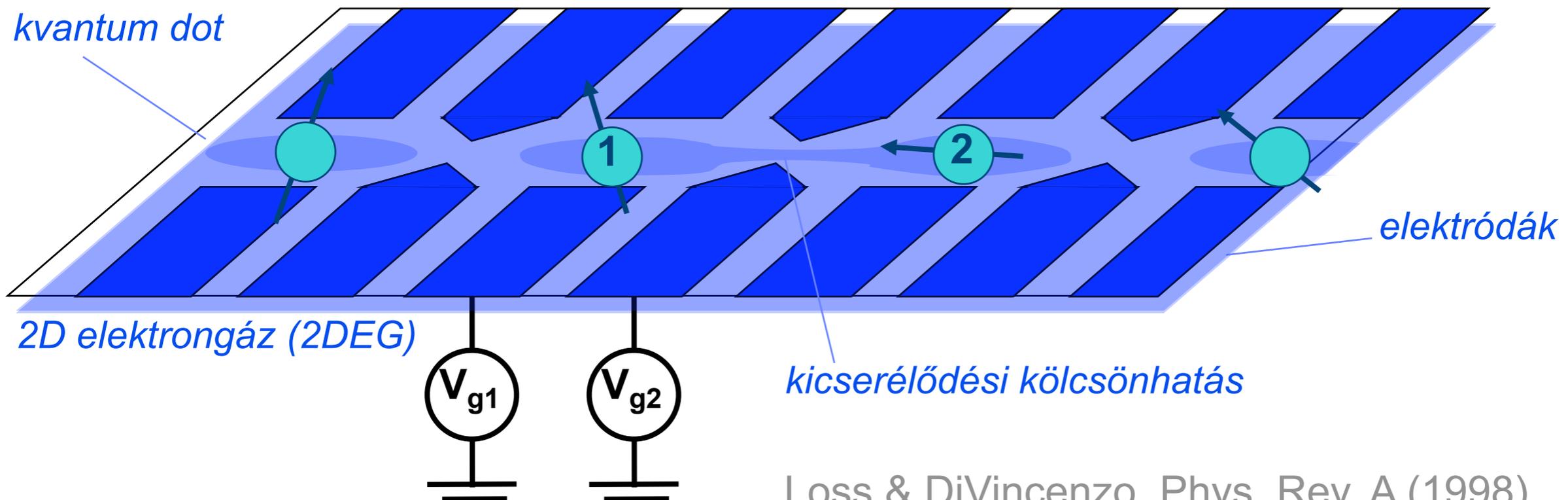
- **qubit** $\Psi = \alpha|0\rangle + \beta|1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$ $|\alpha|^2 + |\beta|^2 = 1$

- elektron: feles spin: **spin qubit**

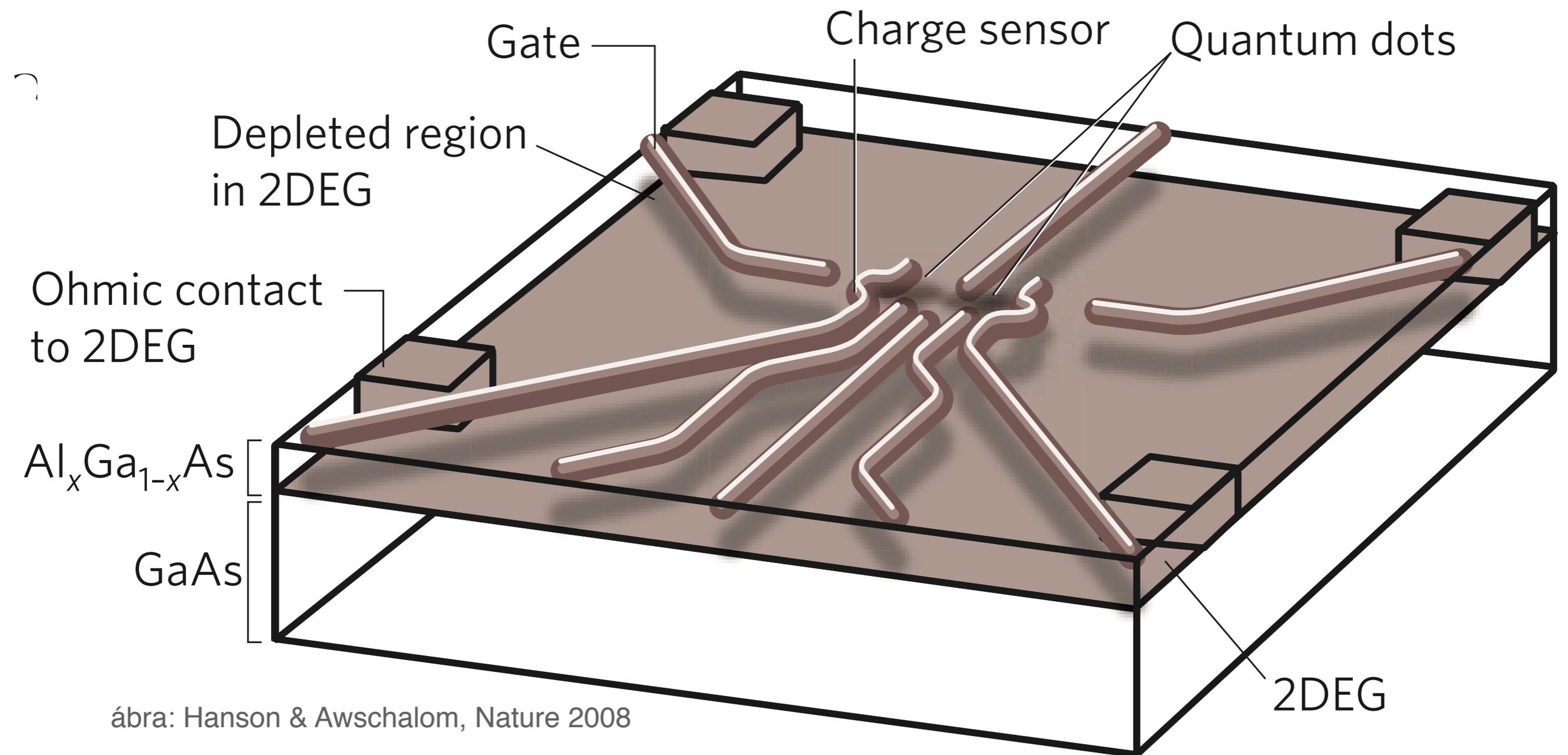
$$|0\rangle = \uparrow \quad |1\rangle = \downarrow$$



- kvantum dot: elektroncsapda, kicserélődési kcsh

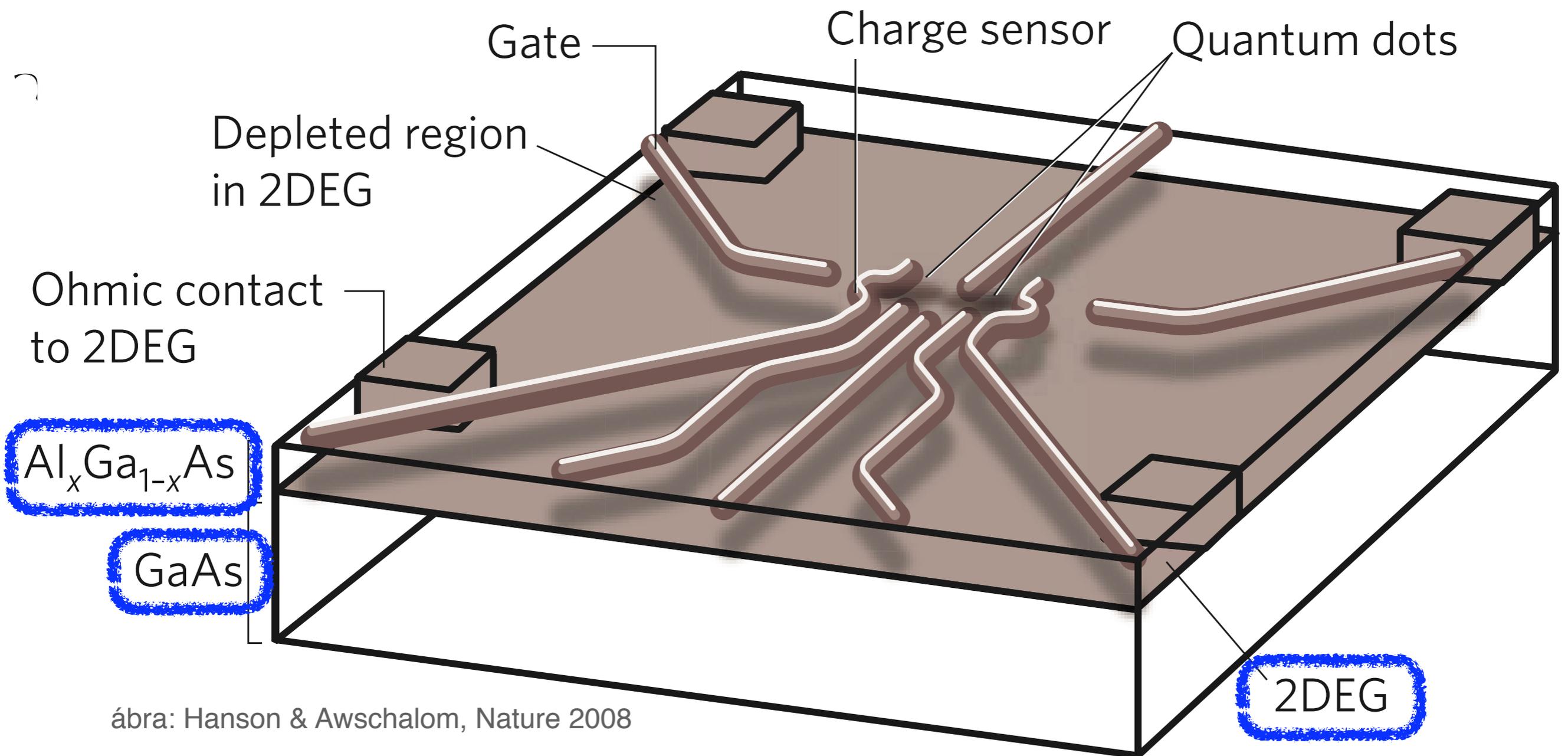


Bevezetés - kettős kvantumdotok



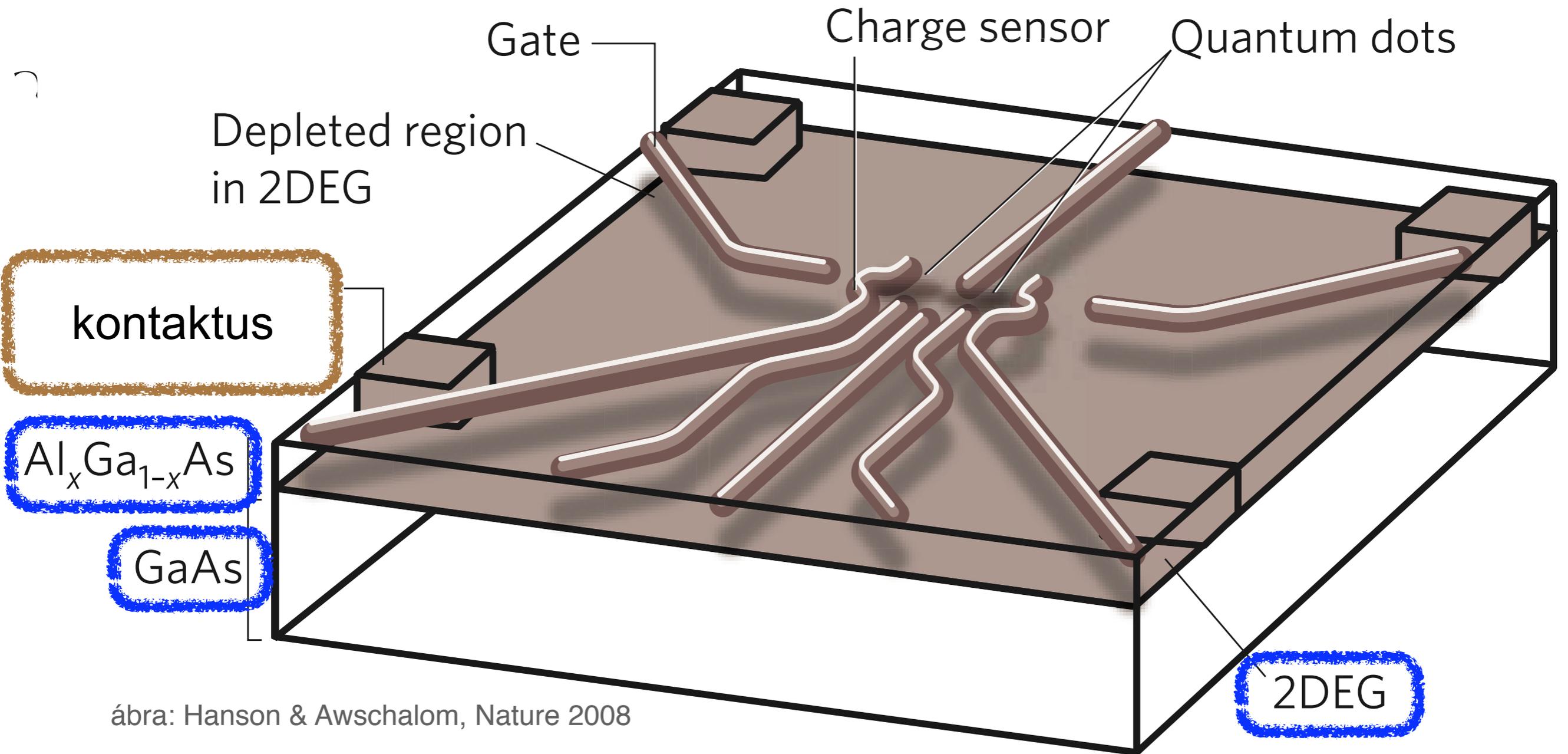
ábra: Hanson & Awschalom, Nature 2008

Bevezetés - kettős kvantumdotok

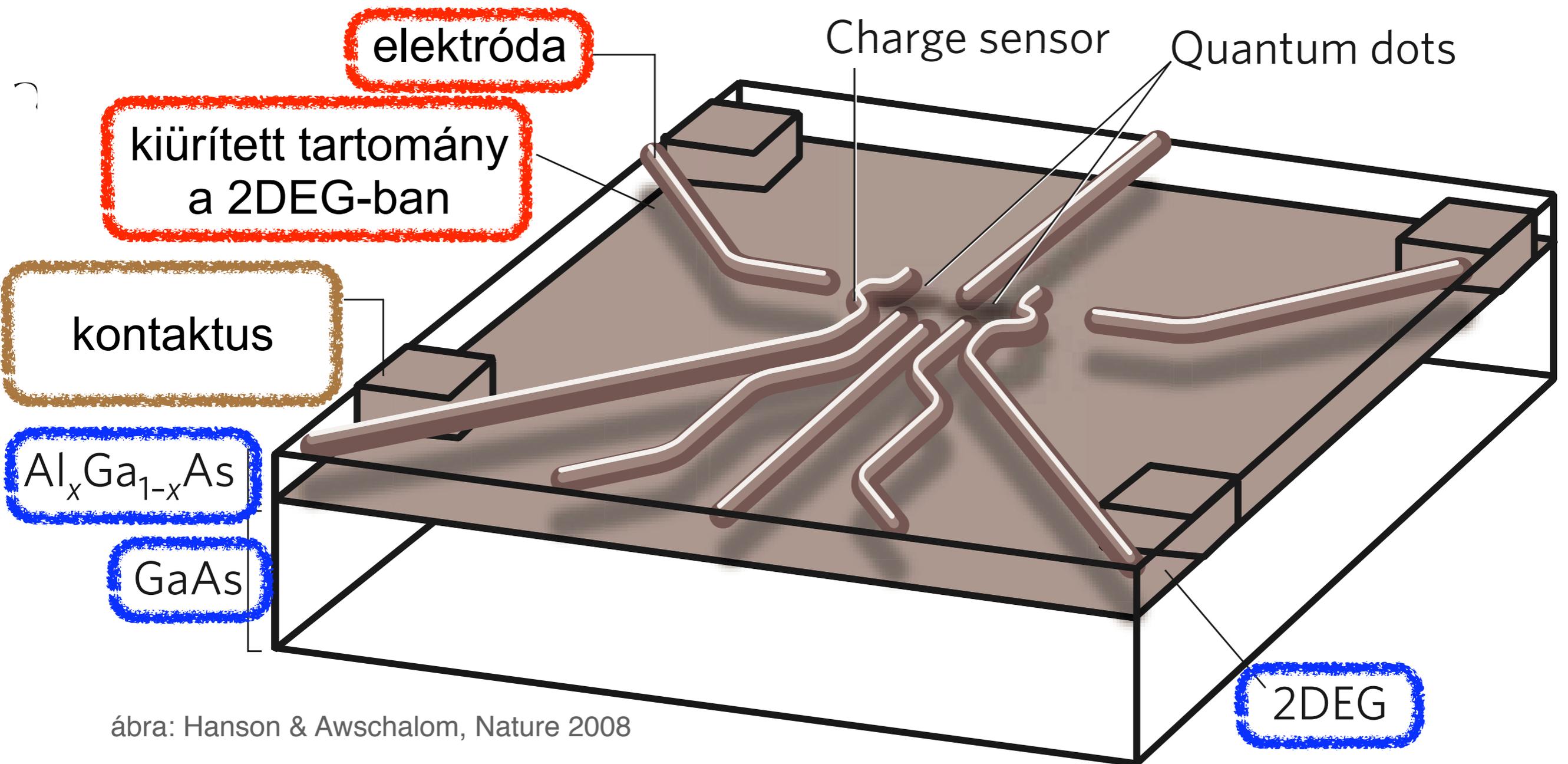


ábra: Hanson & Awschalom, Nature 2008

Bevezetés - kettős kvantumdotok

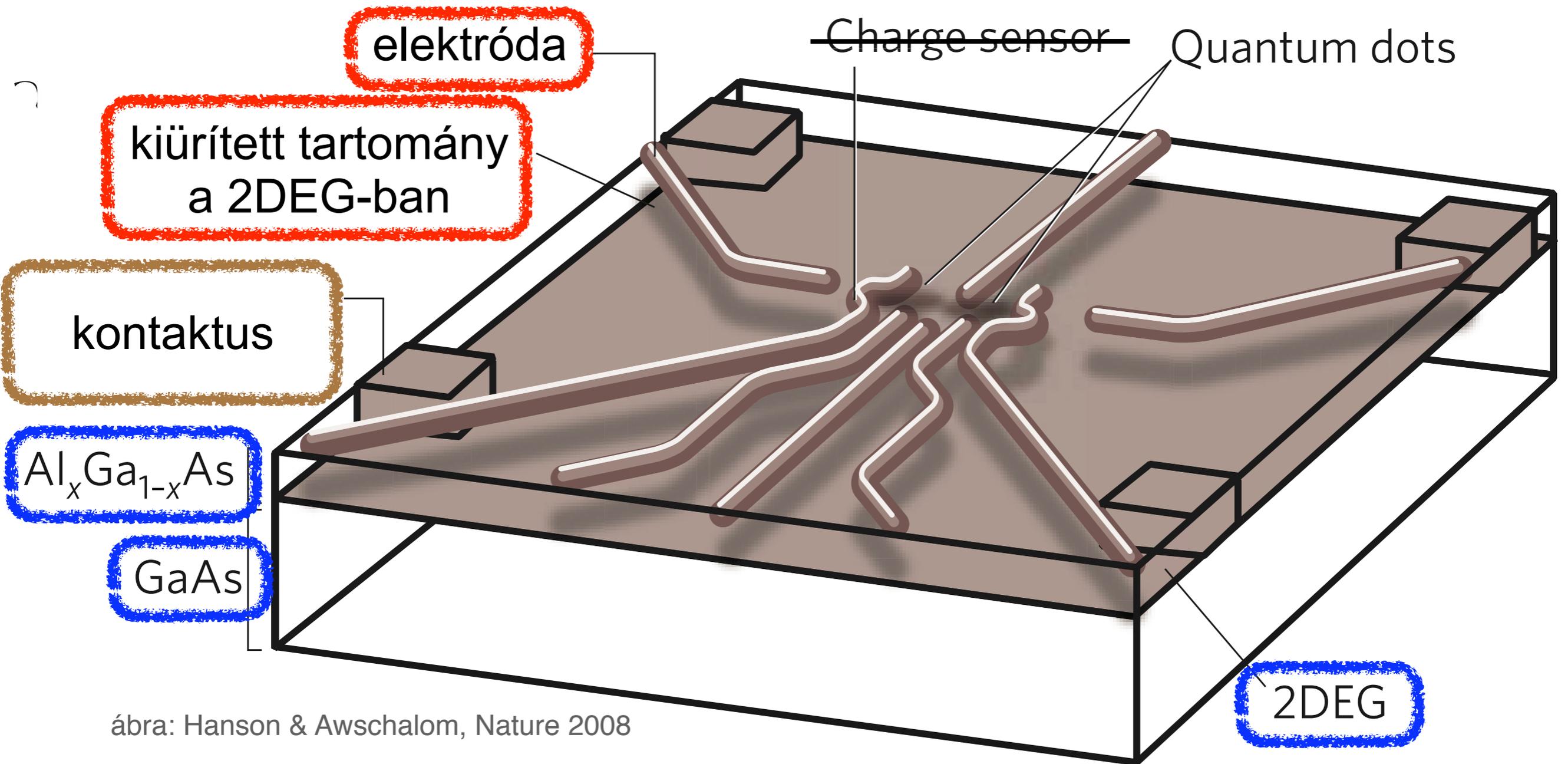


Bevezetés - kettős kvantumdotok



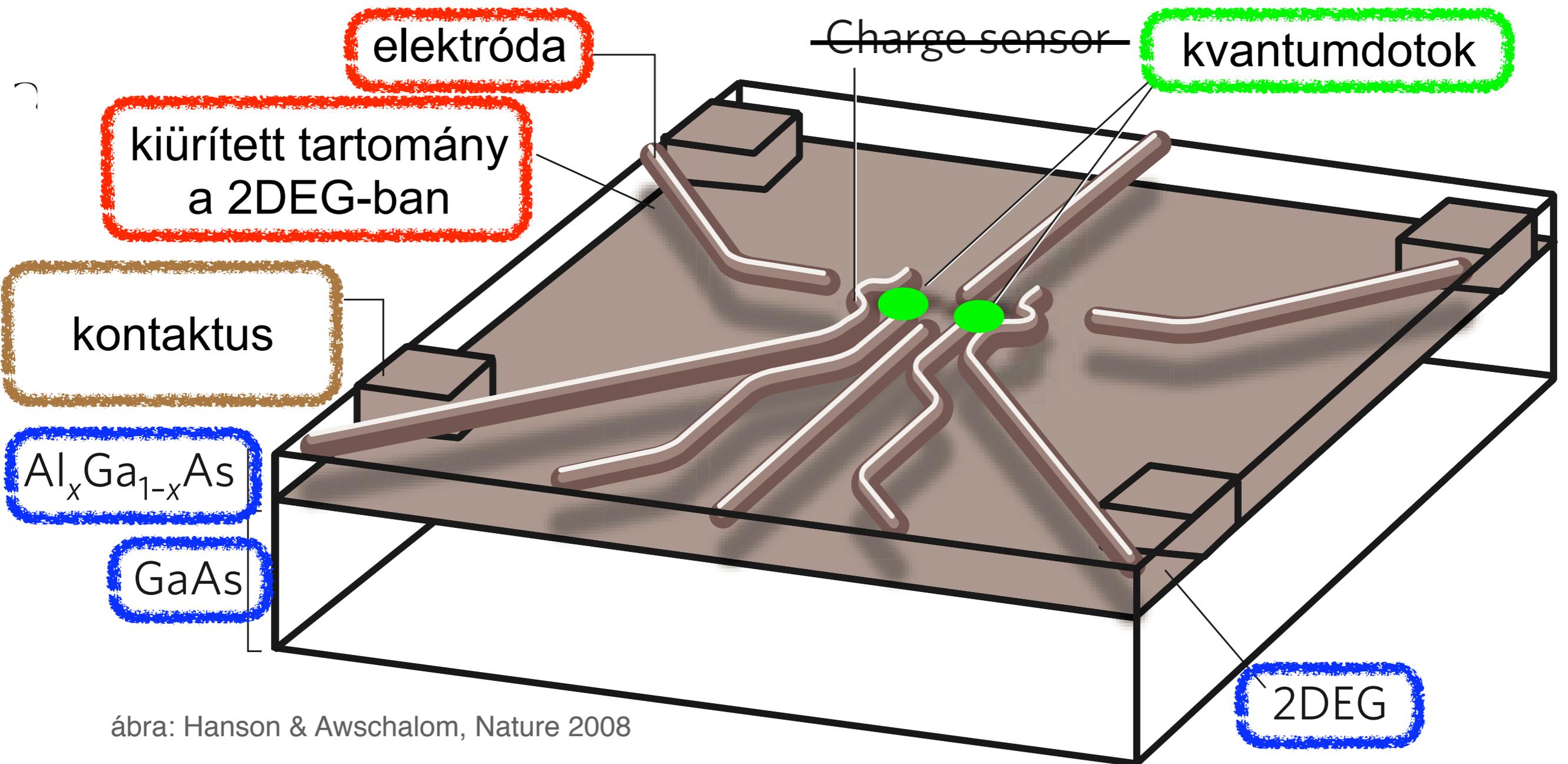
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Bevezetés - kettős kvantumdotok



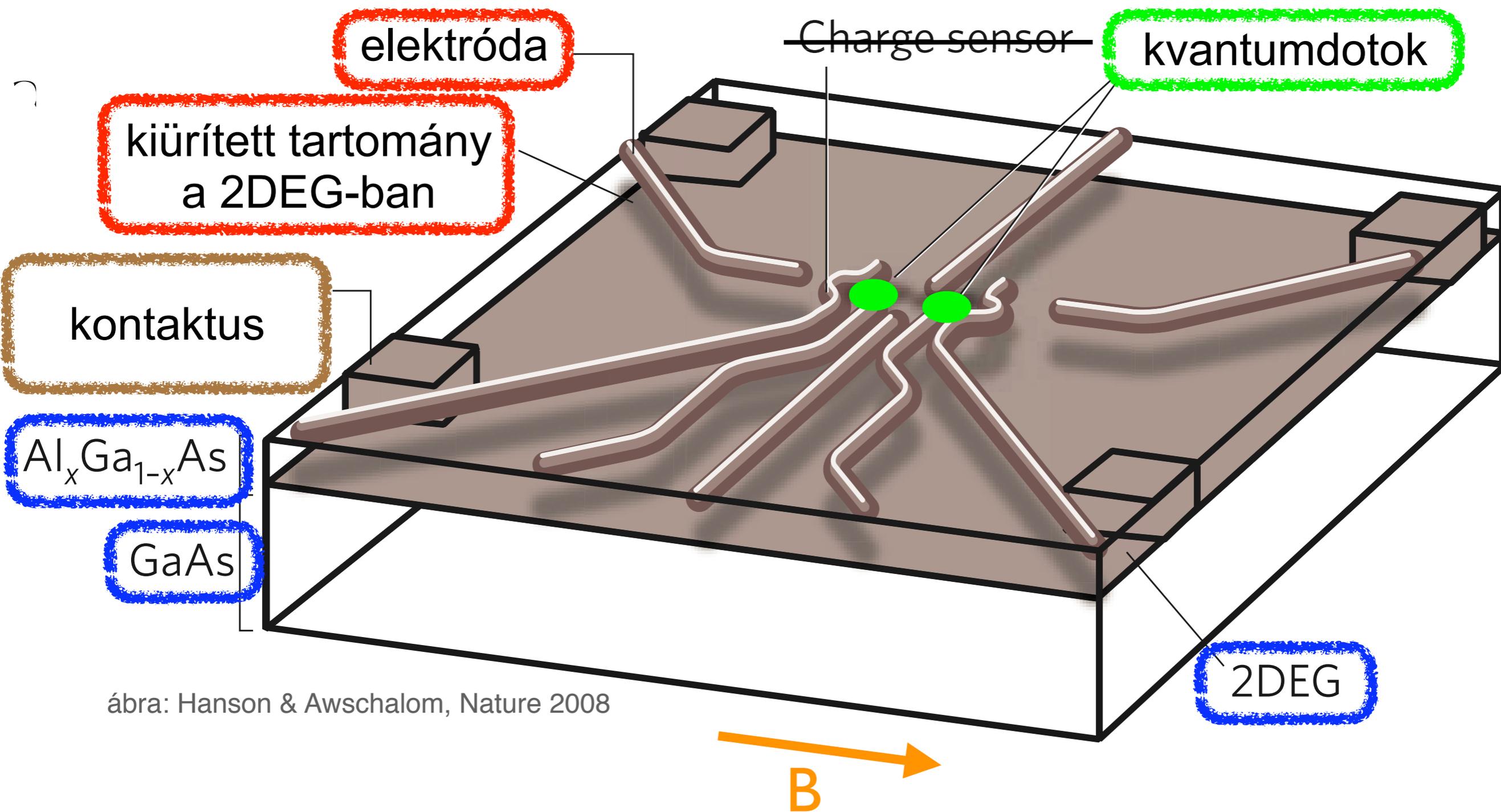
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Bevezetés - kettős kvantumdotok



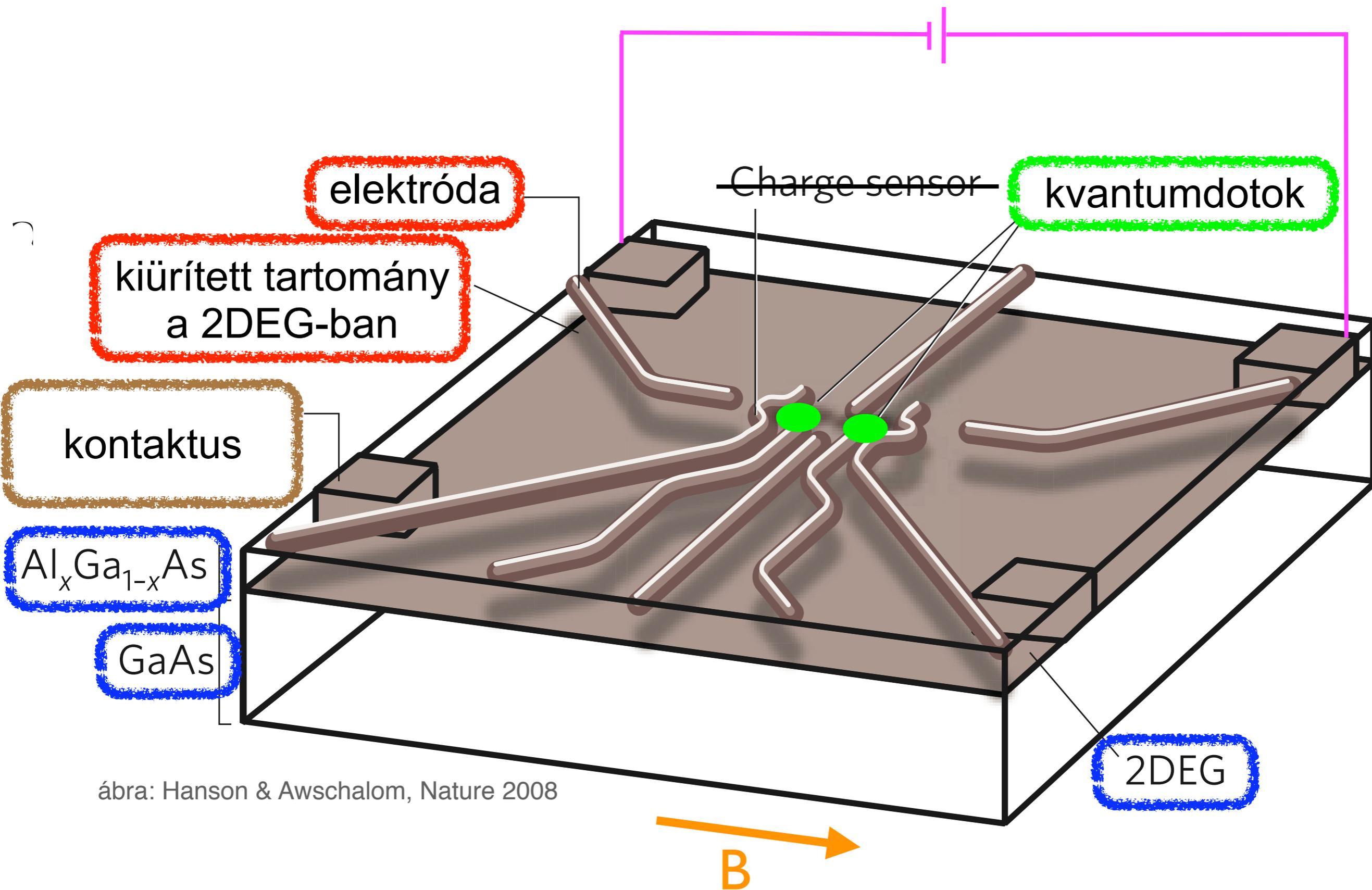
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Bevezetés - kettős kvantumdotok



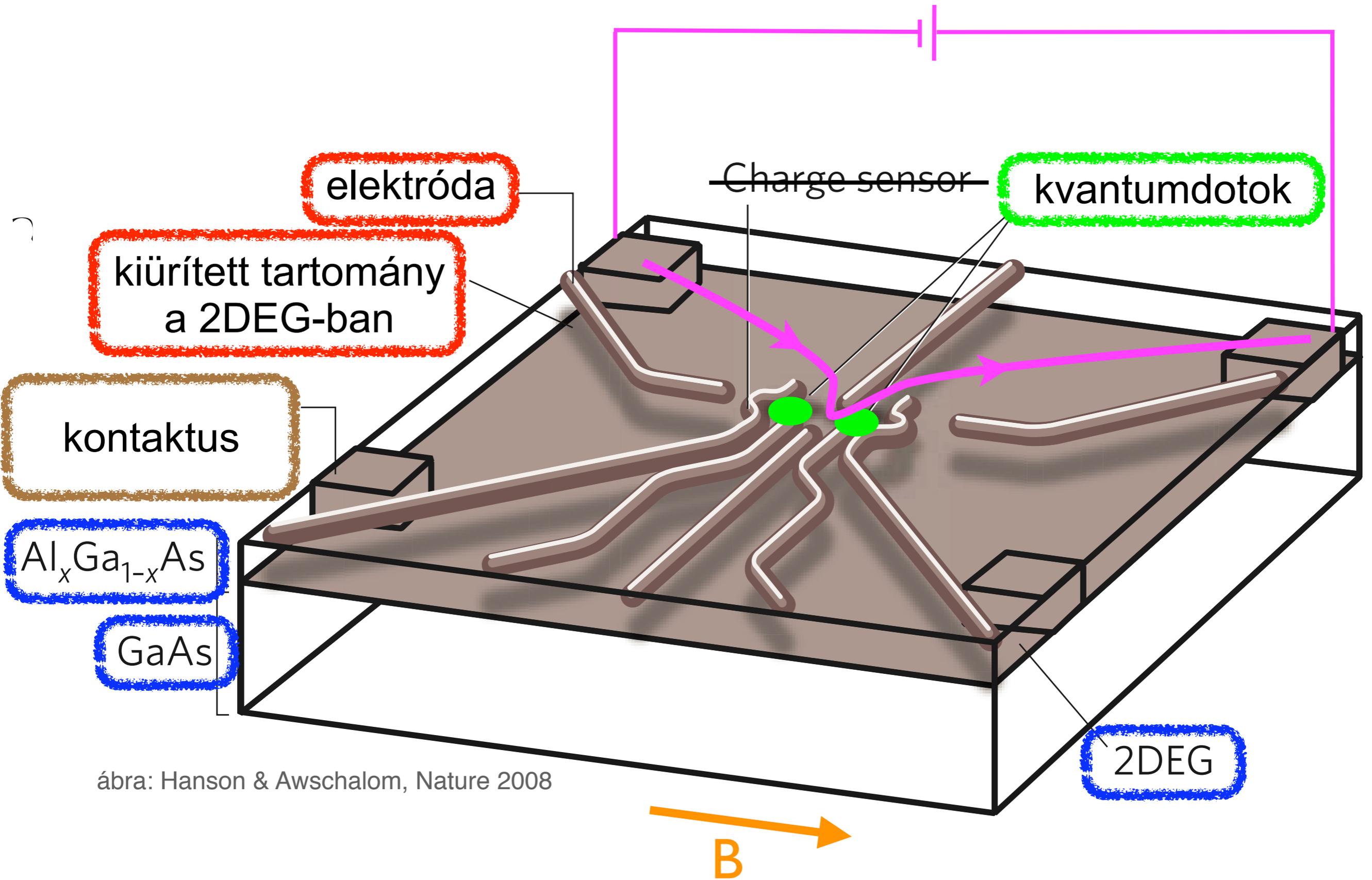
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Bevezetés - kettős kvantumdotok



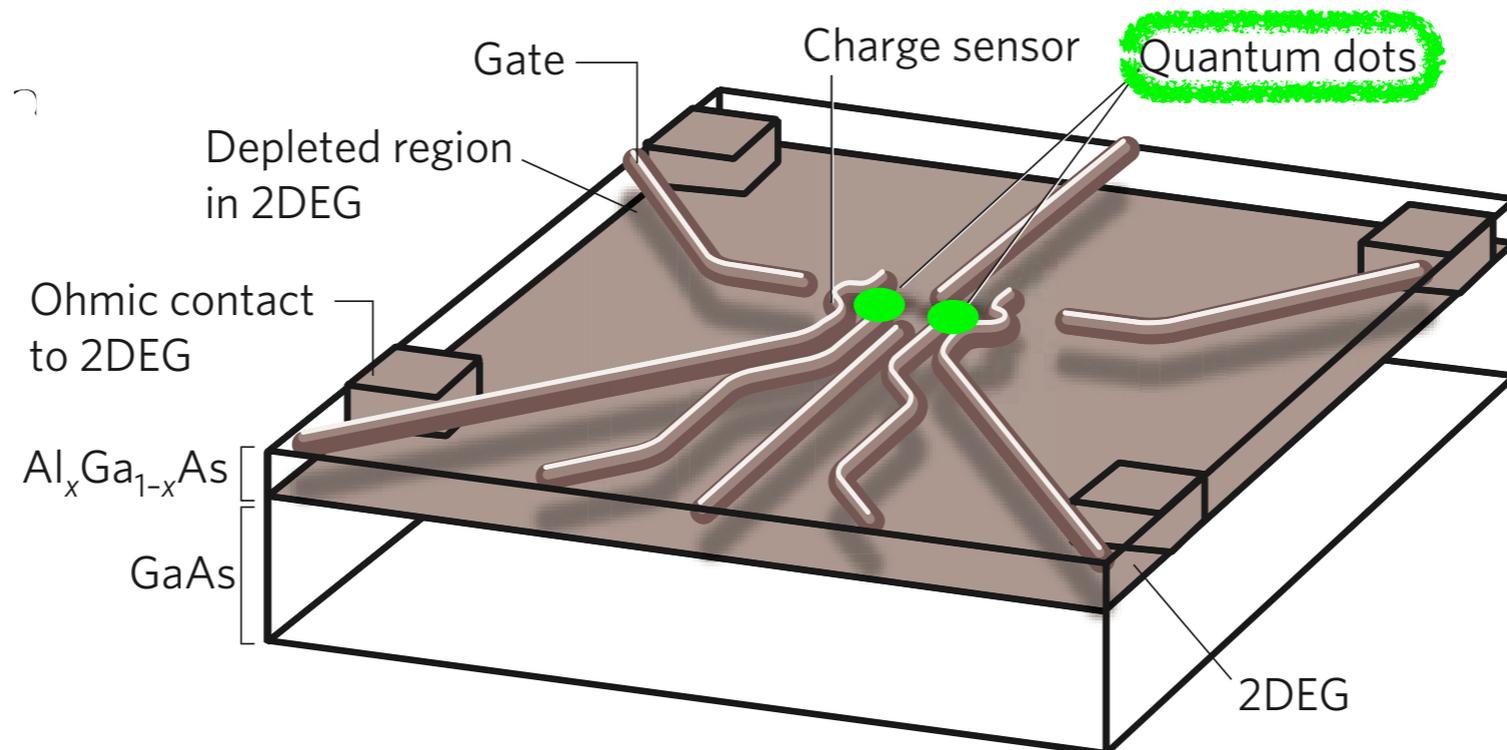
ábra: Hanson & Awschalom, Nature 2008

Bevezetés - kettős kvantumdotok



ábra: Hanson & Awschalom, Nature 2008

Bevezetés - spinblokáád

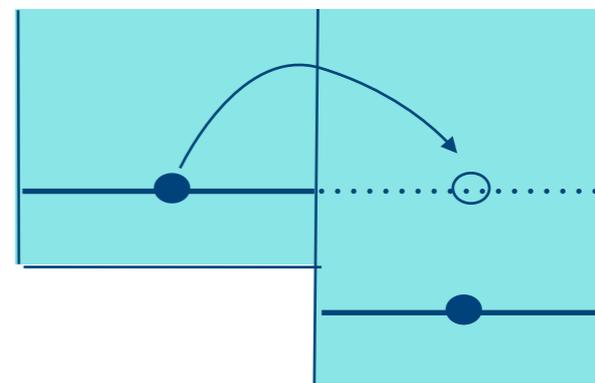


$$|s, m_s\rangle$$

1 szinglet

$$|0, 0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

S



3 triplet

$$|1, 1\rangle = |\uparrow\uparrow\rangle$$

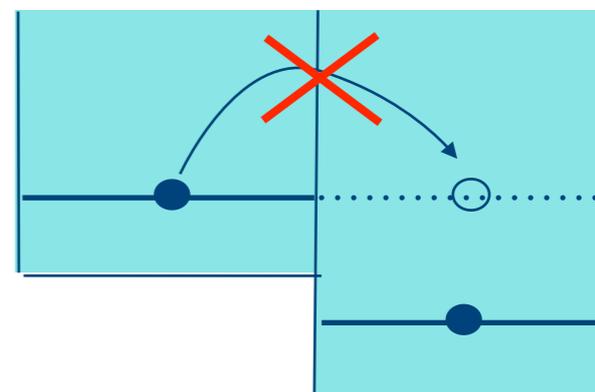
$$|1, 0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

$$|1, -1\rangle = |\downarrow\downarrow\rangle$$

T_+

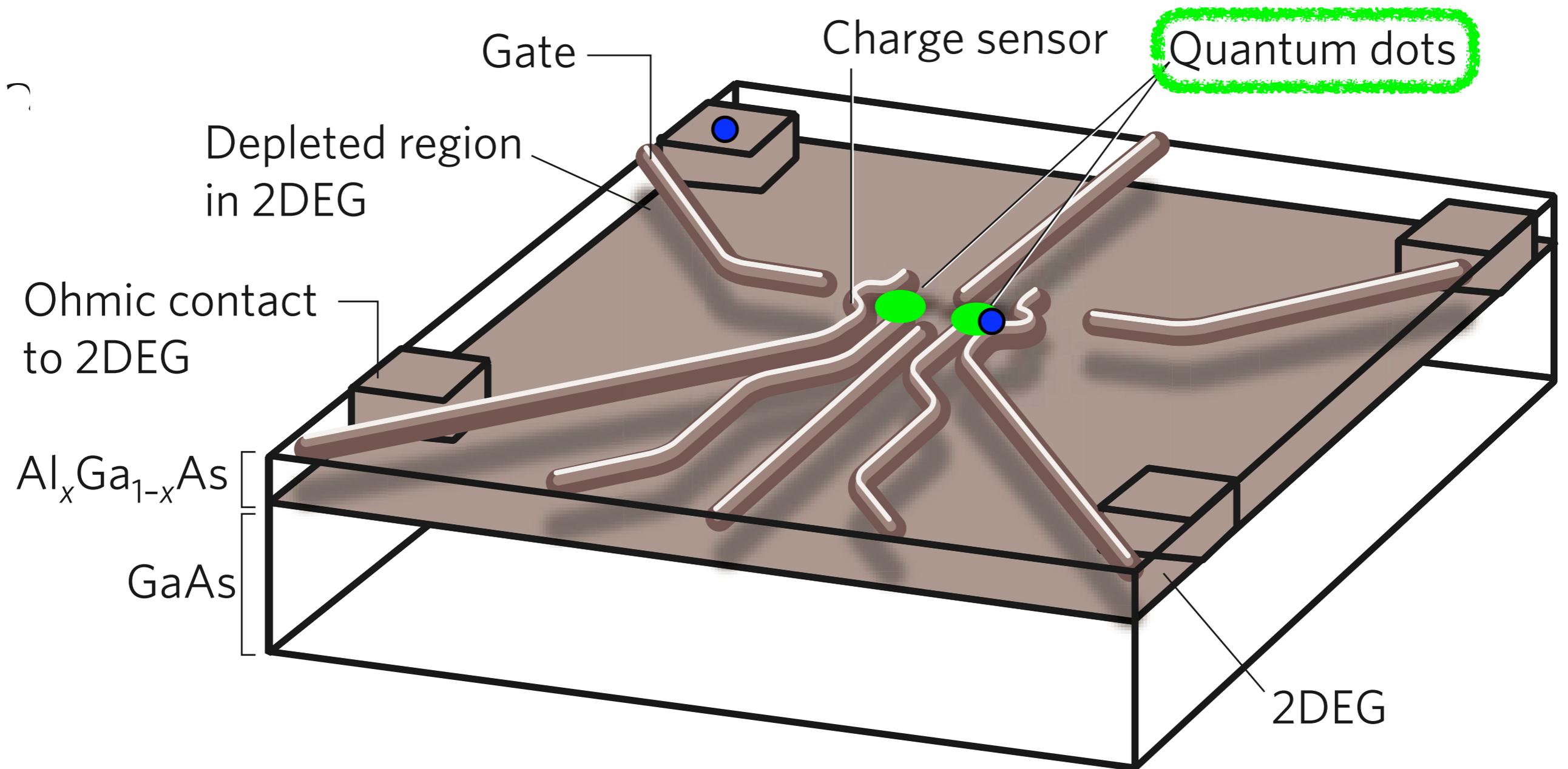
T_0

T_-



Bevezetés - spinblokád

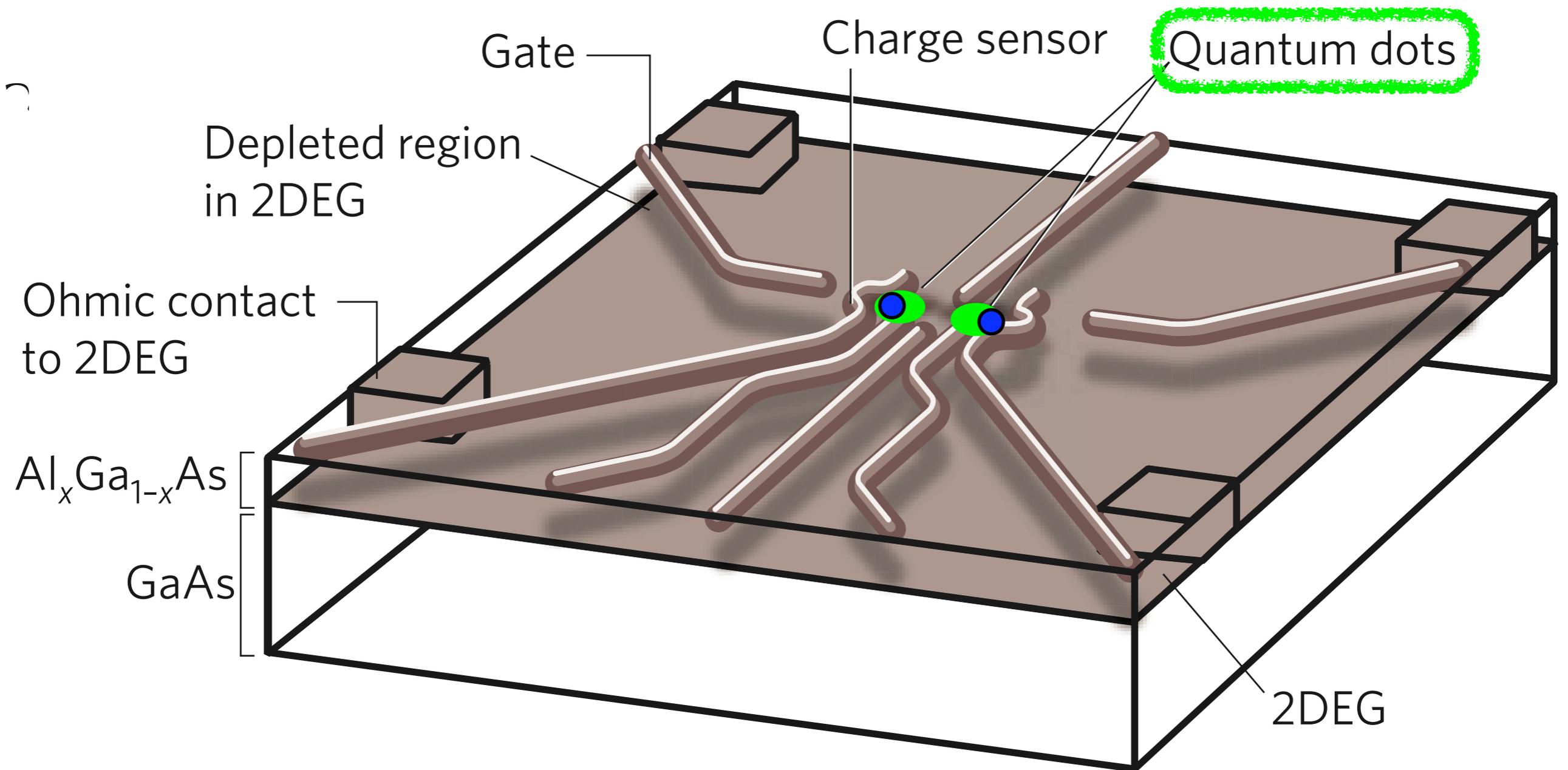
Ono et al., Science 2002, Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



(0,1)

Bevezetés - spinblokád

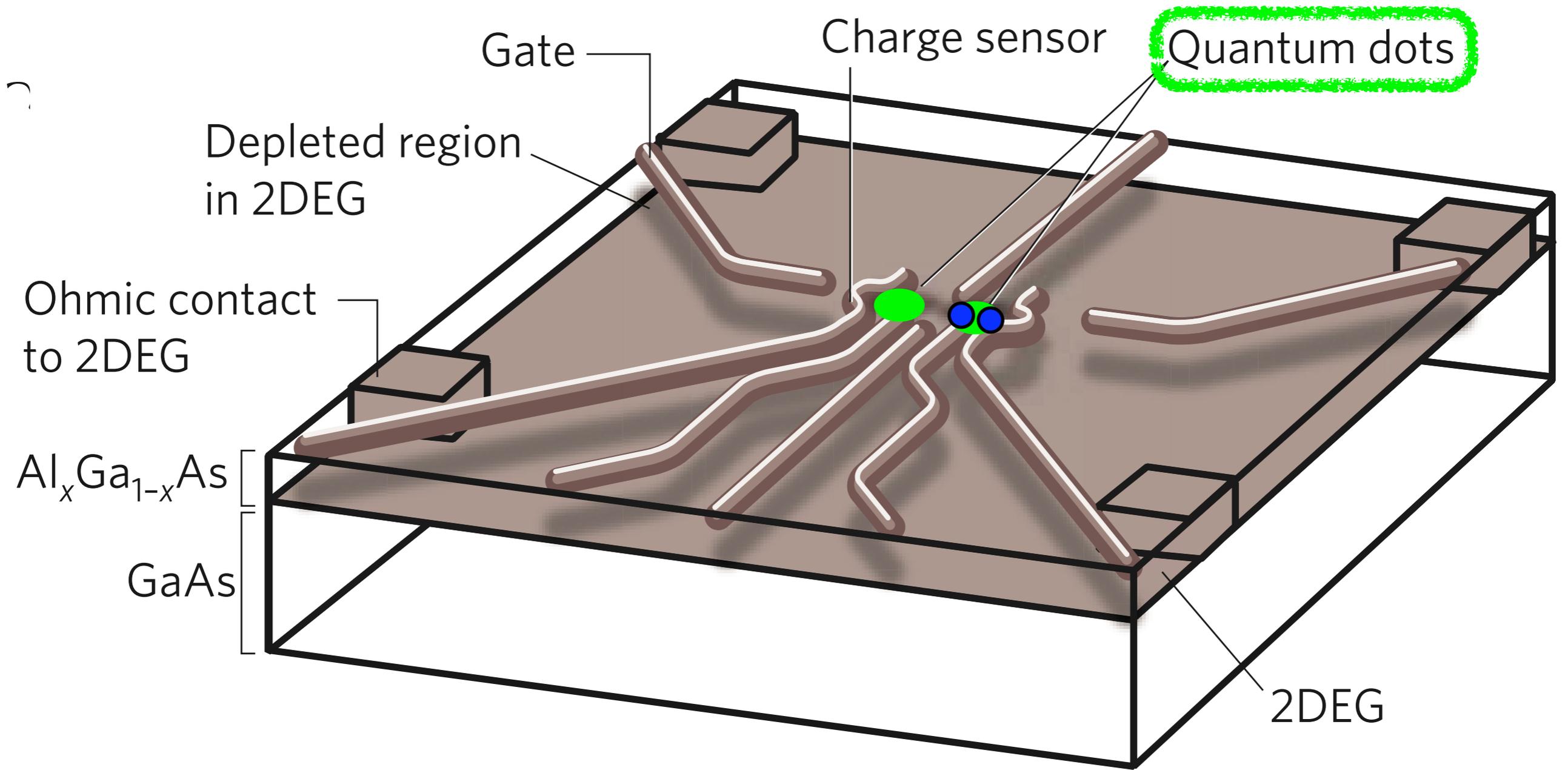
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(1,1)

Bevezetés - spinblokád

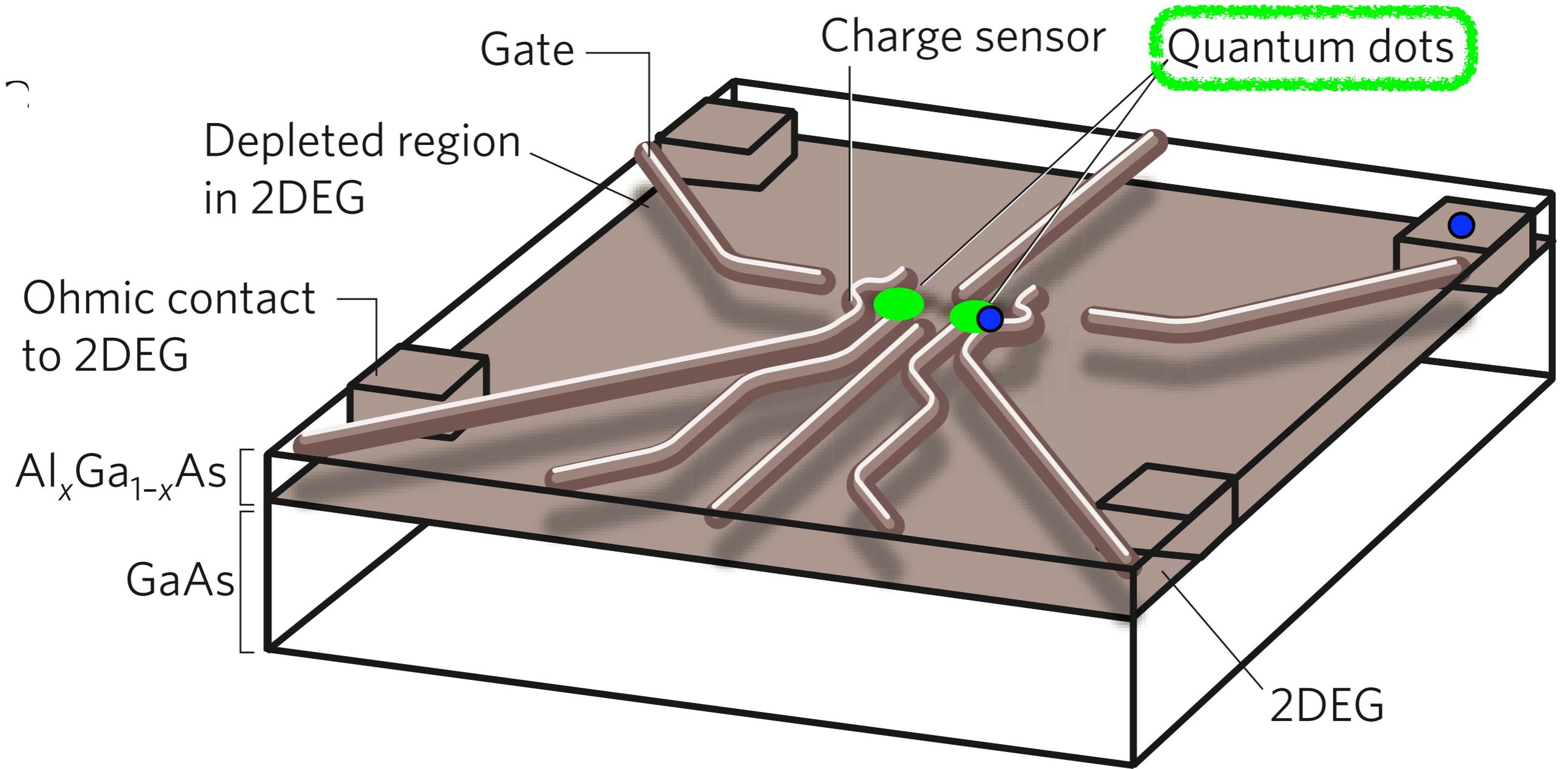
Ono et al., Science 2002, Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



(0,2)

Bevezetés - spinbloká

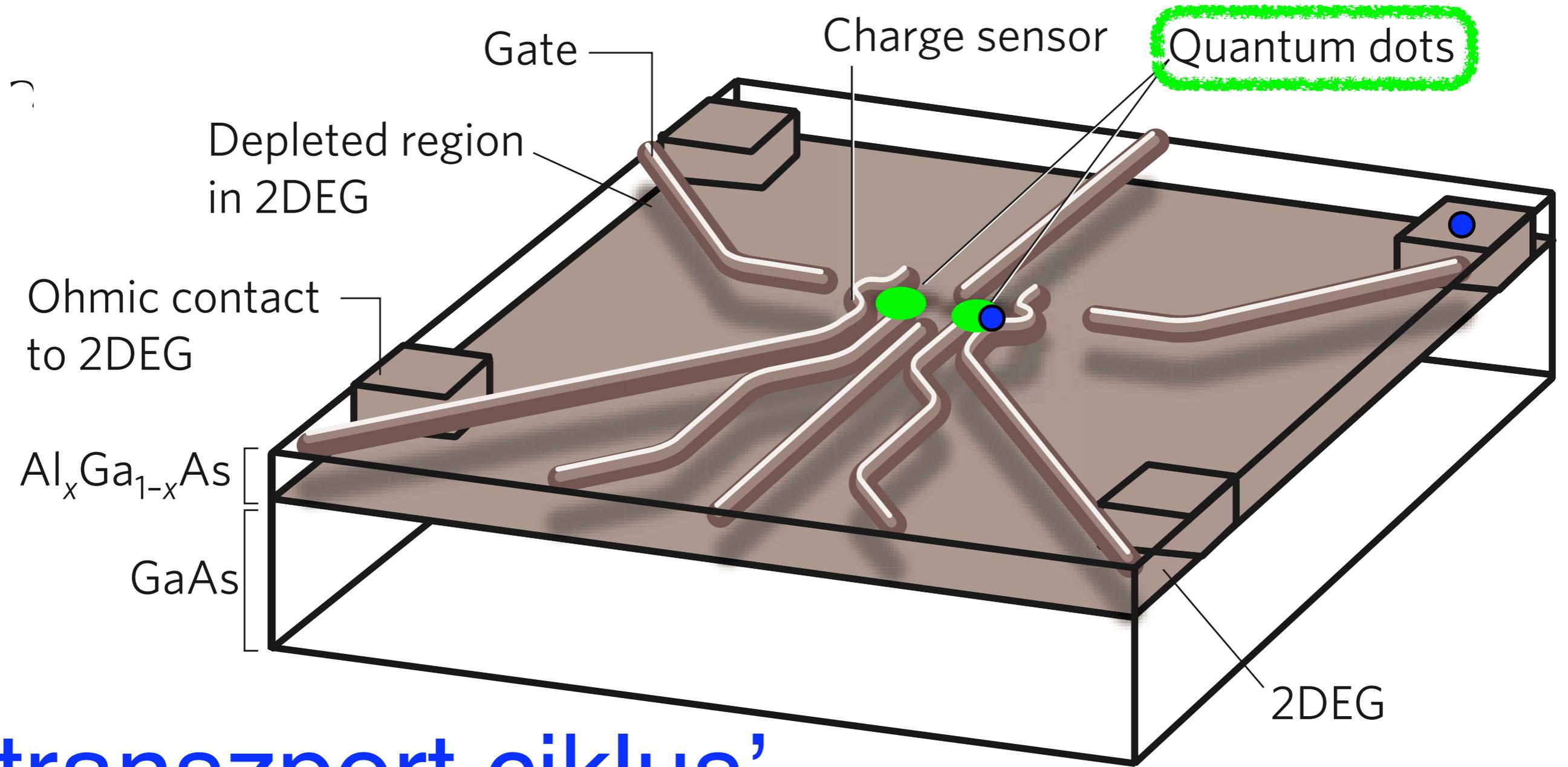
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(0,1)

Bevezetés - spinblokád

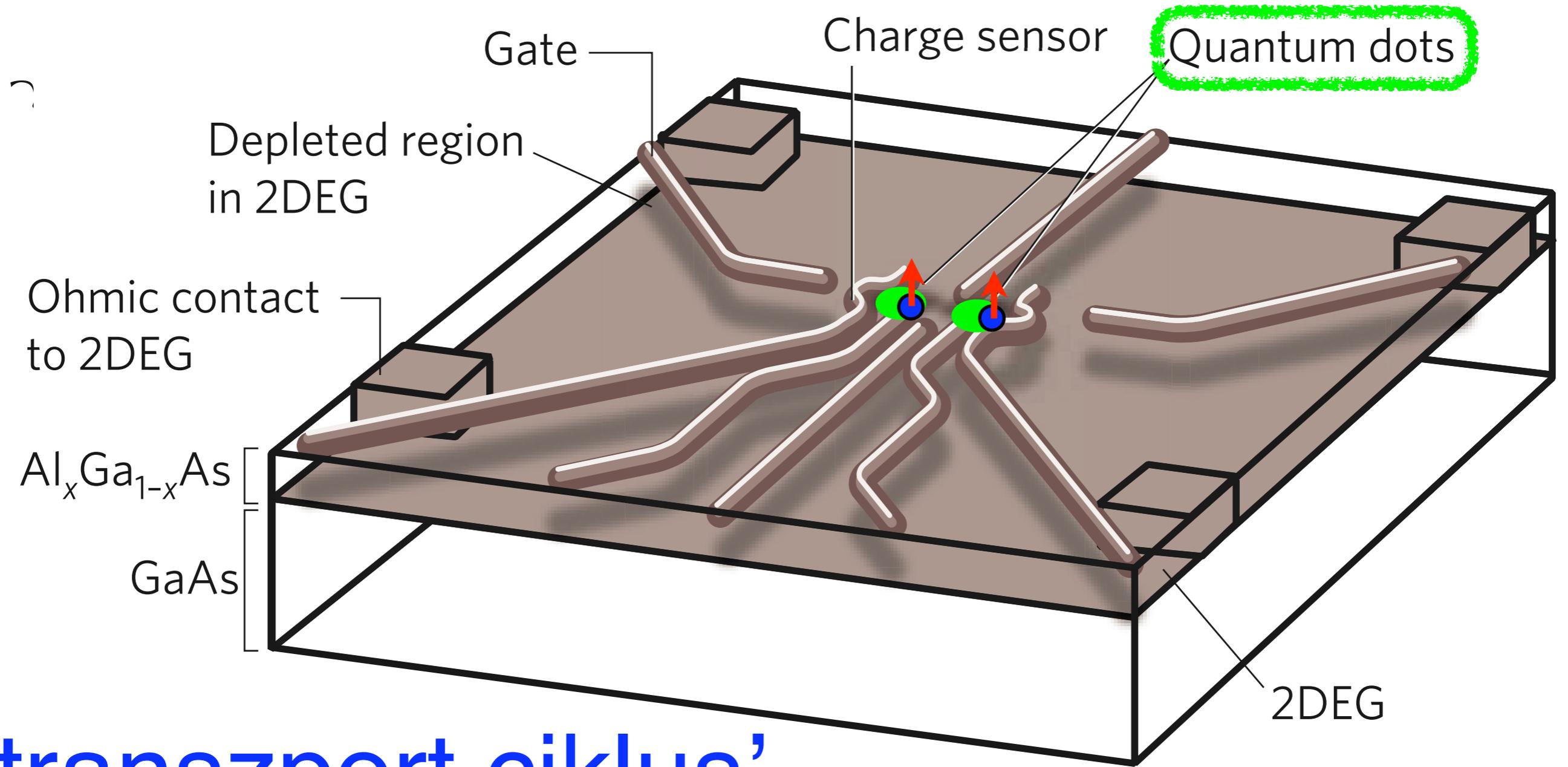
Ono et al., Science 2002, Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



‘transzport ciklus’
(0, 1) -- (1, 1) -- (0, 2) -- (0, 1)

Bevezetés - spinblokád

Ono et al., Science 2002, Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



‘transzport ciklus’

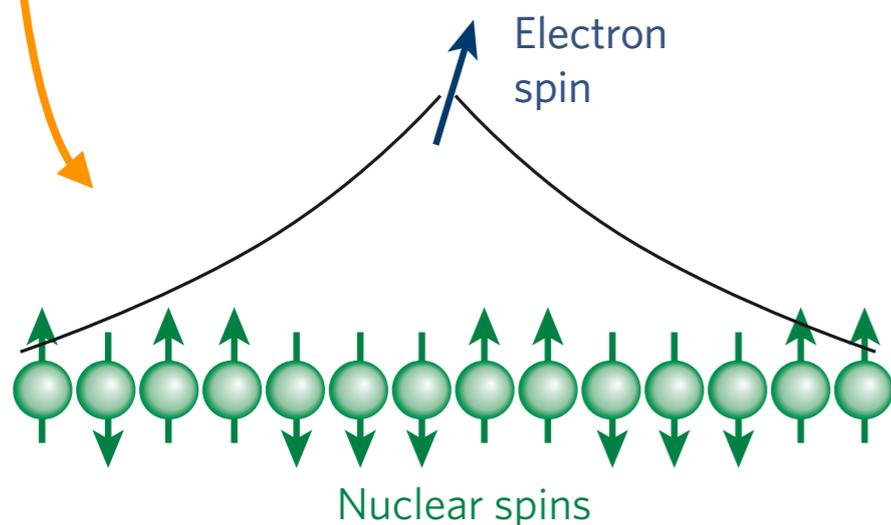
$$(0, 1) \text{ -- } (1, 1) \times (0, 2) \text{ -- } (0, 1)$$

stacionárius állapot:
áram = 0

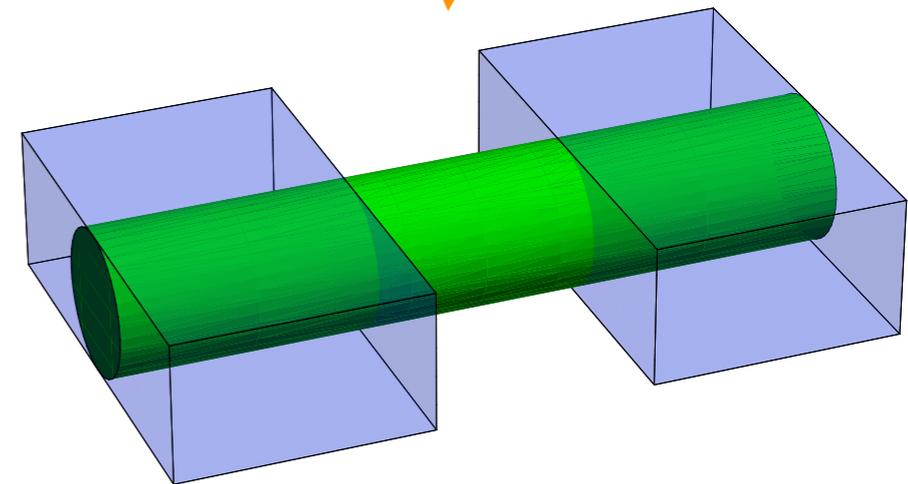
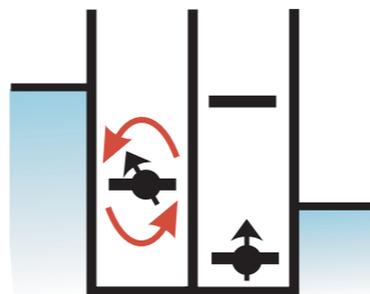
Tartalom

(Spinblokádkettős kvantumdotokban)

- “szonda”: hiperfinom kölcsönhatás
- spin qubit inicializálás és kiolvasás
- kitekintés: szén-alapú kvantumdotok



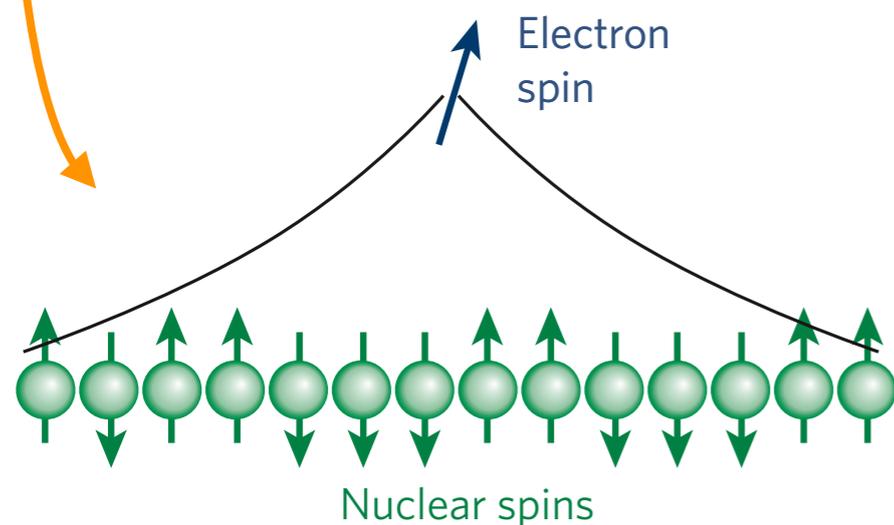
Spin
manipulation



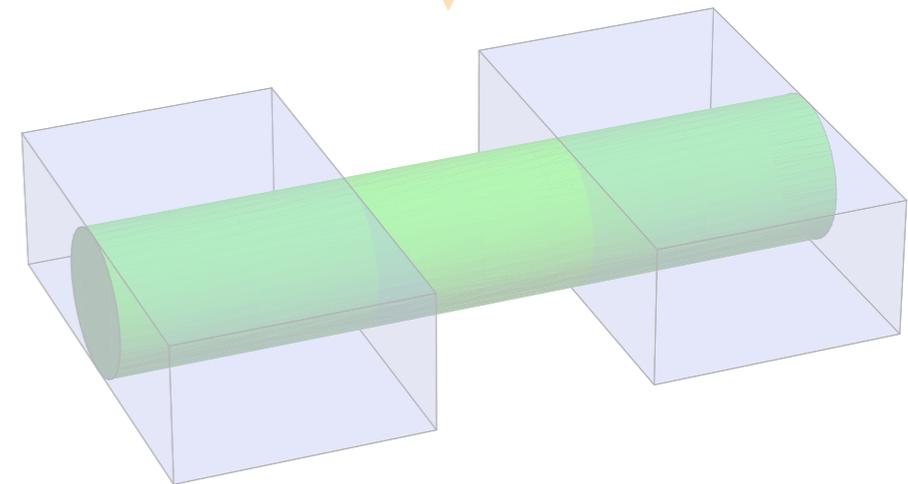
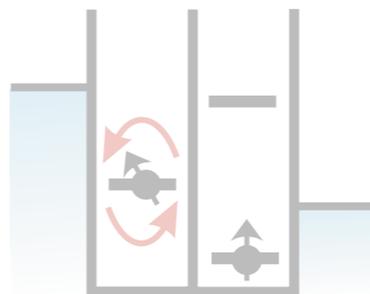
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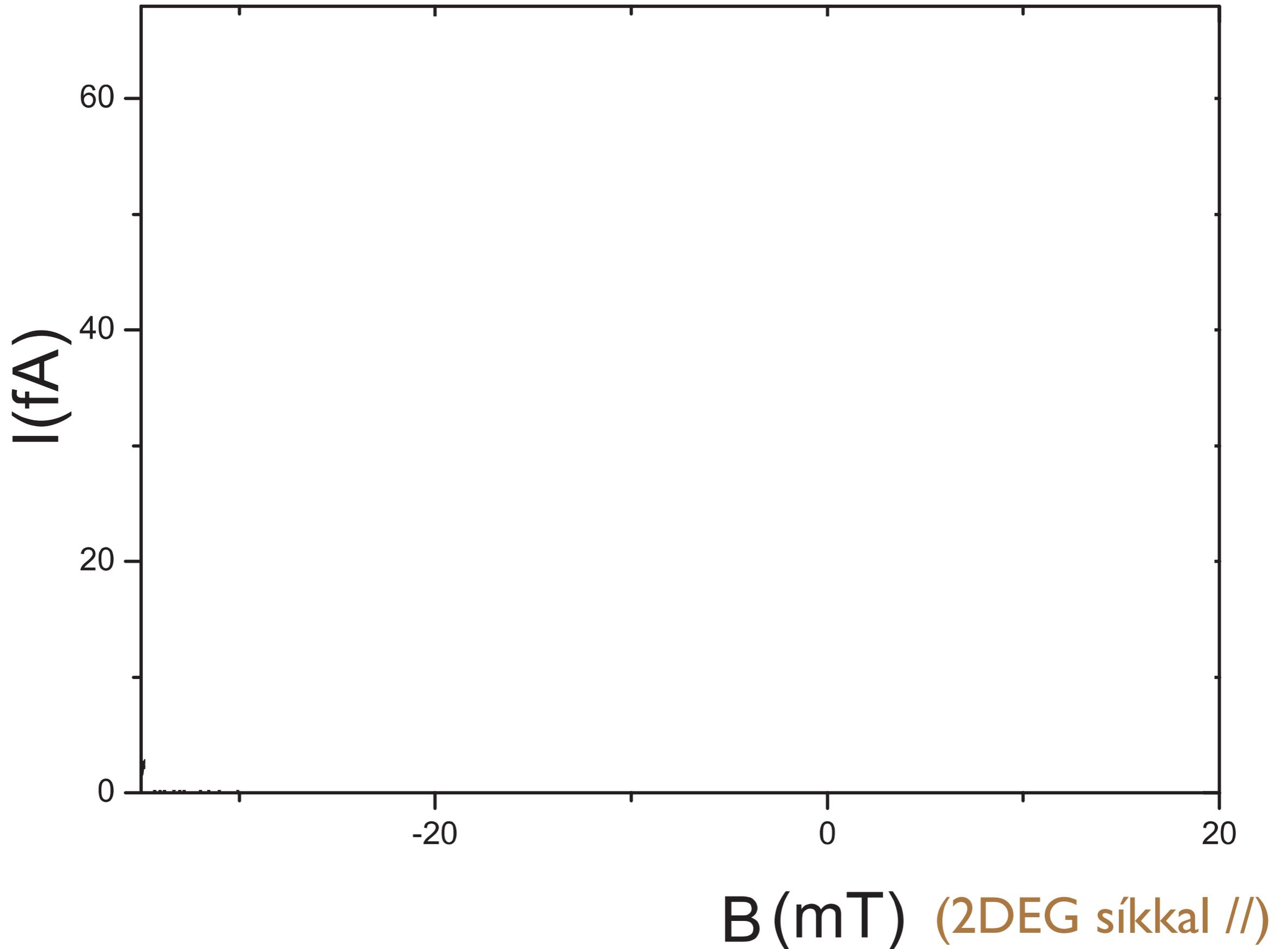


Spin
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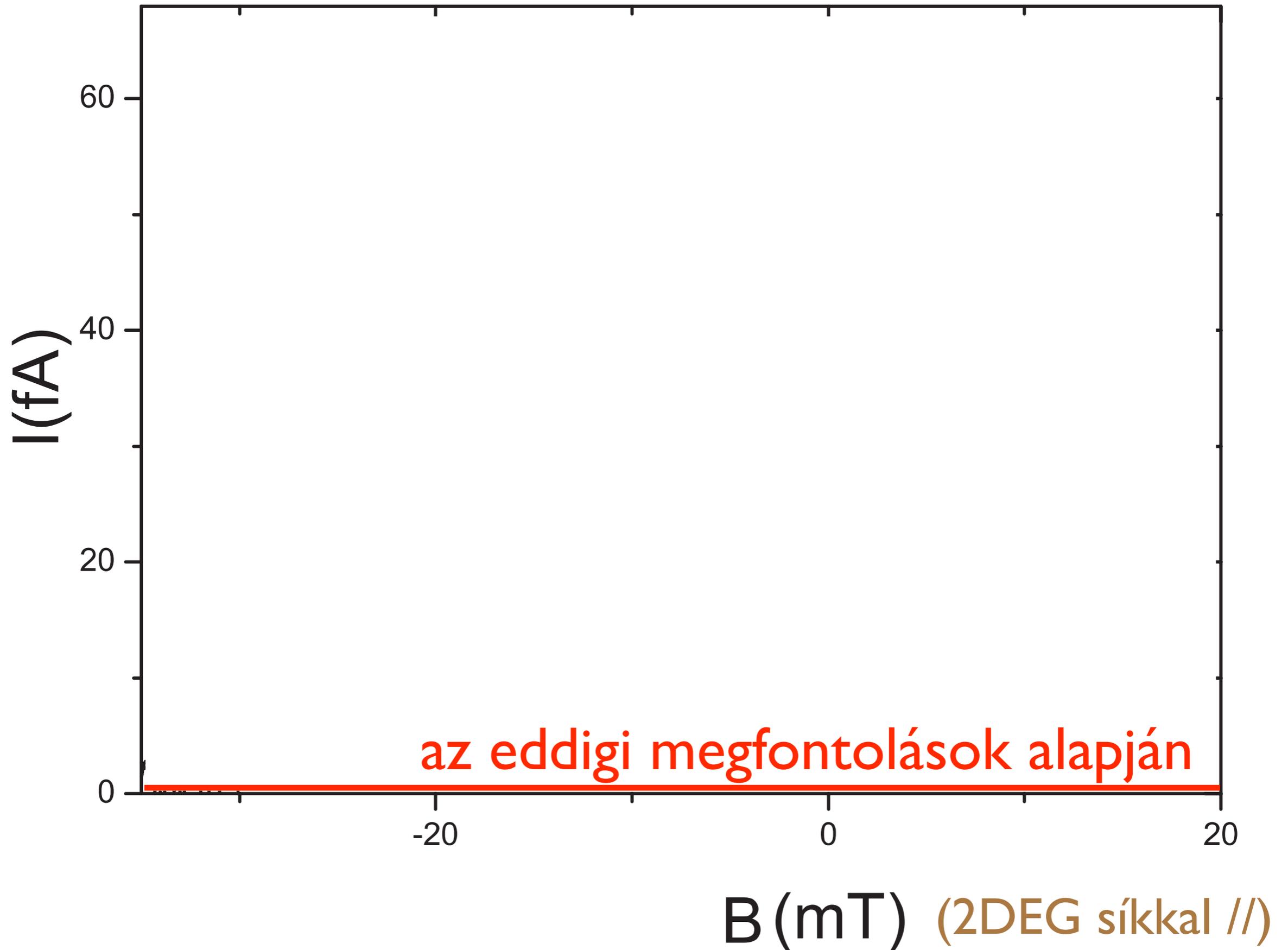
Spinblokáád - mérés

Koppens et al., Science 2005, Jouravlev & Nazarov, PRL 2006



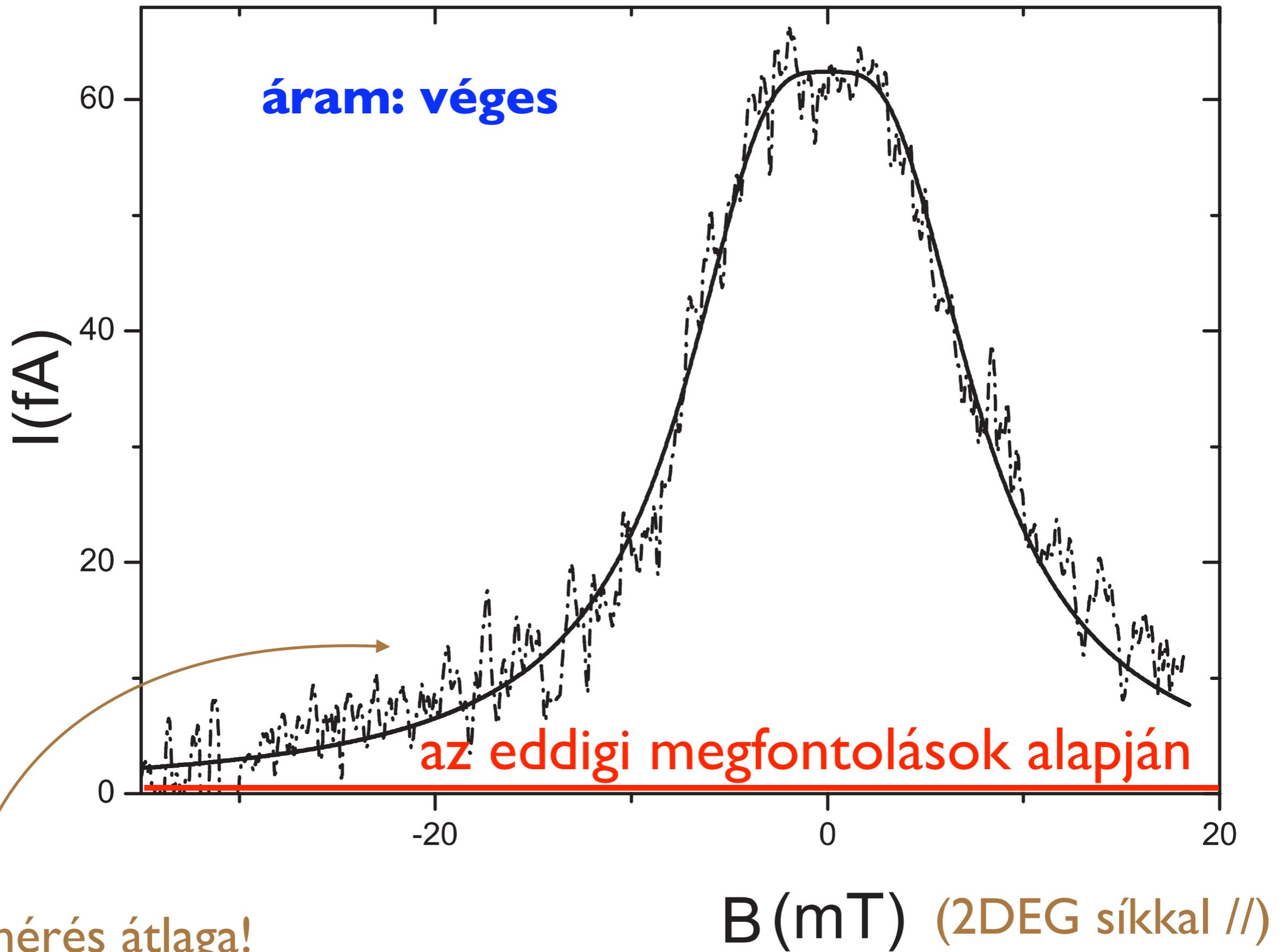
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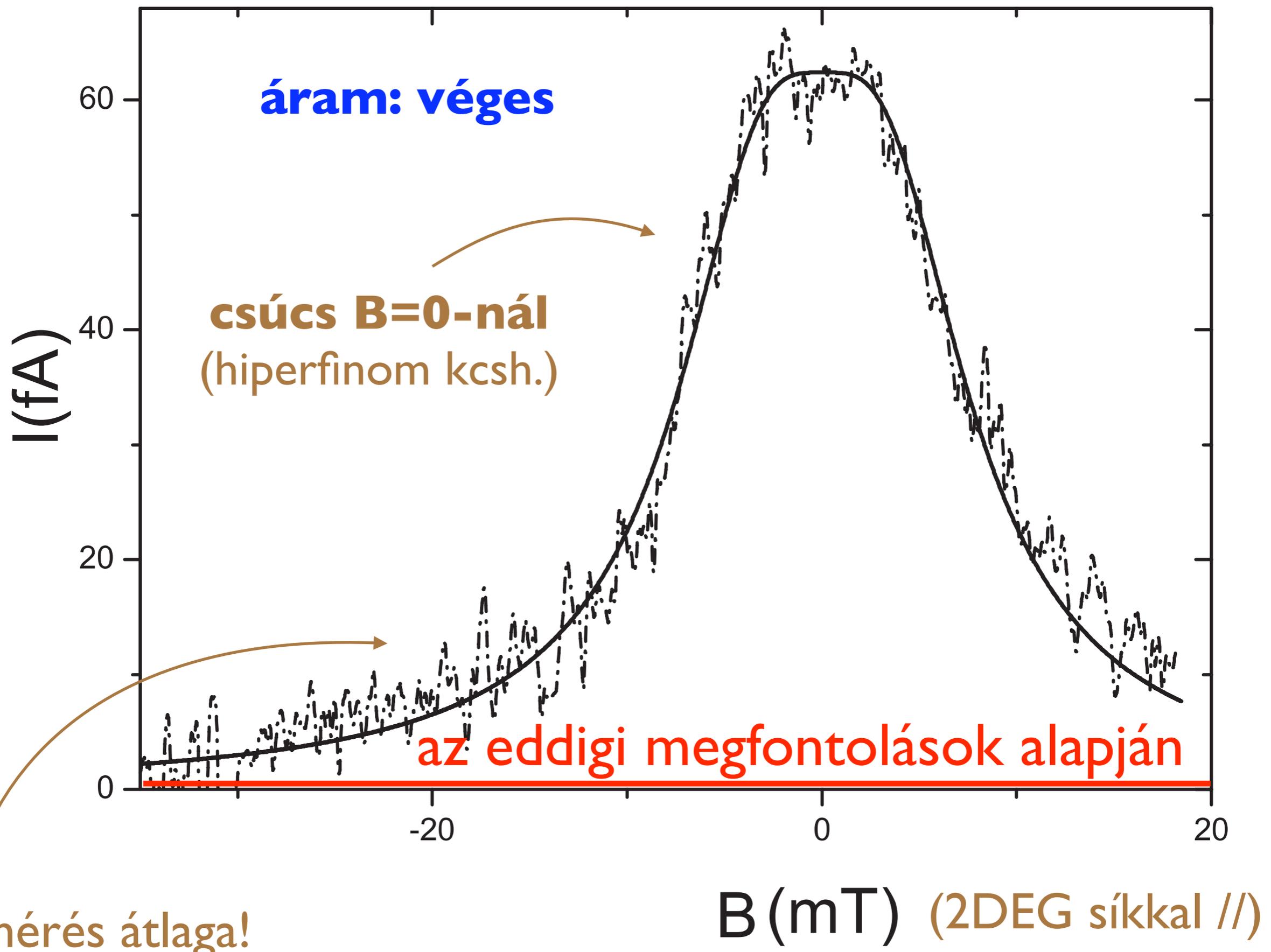
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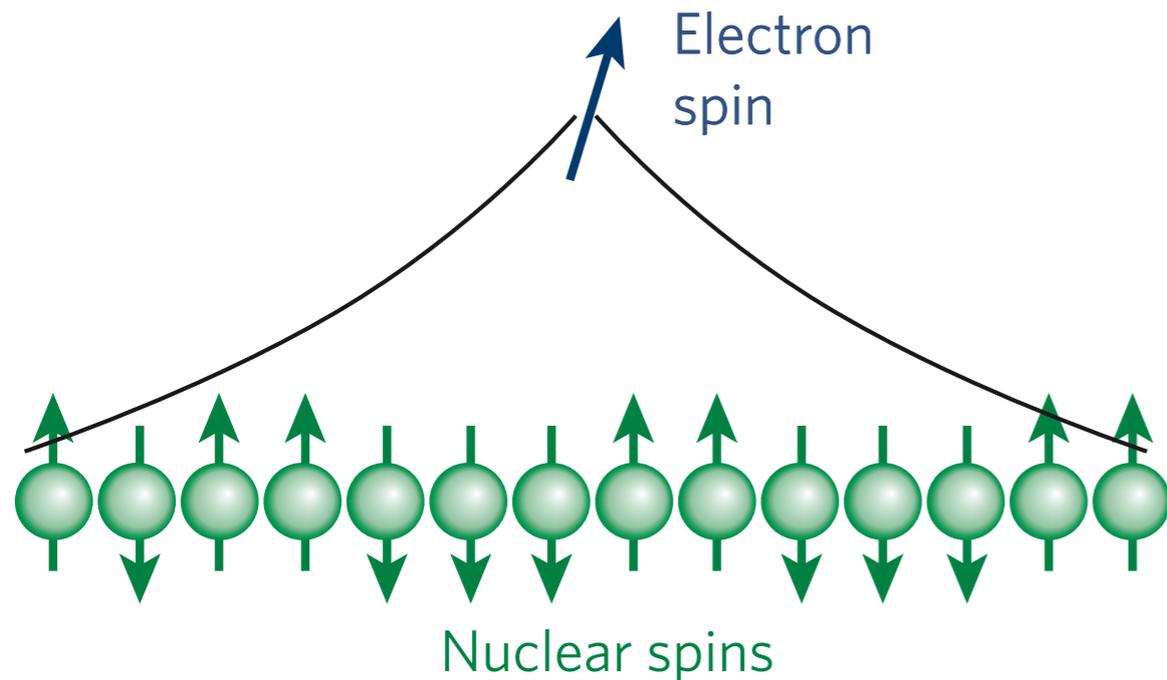


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Hiperfinom kölcsönhatás kvantumdotokban



ábra: Hanson & Awschalom, Nature 2008

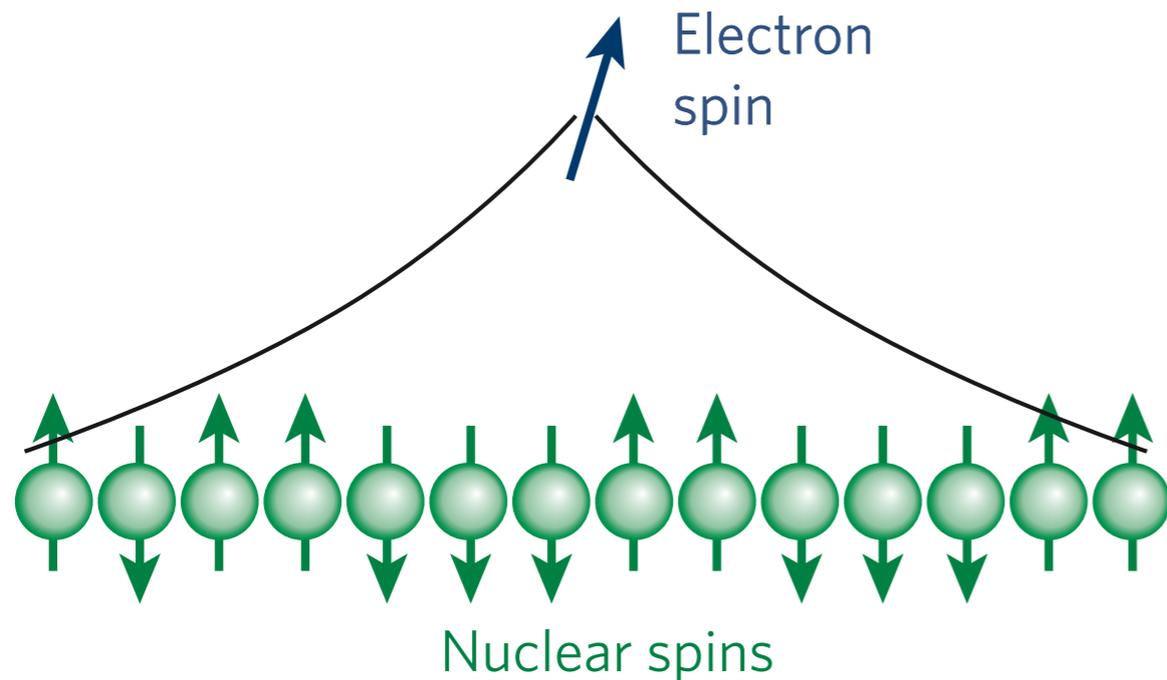
$$h_1^k = \frac{\mu_0}{4\pi} \frac{8\pi}{3} \gamma_S \gamma_{j_k} \delta(\mathbf{r}_k) \mathbf{S} \cdot \mathbf{I}_k, \quad (\text{pl. GaAs, vezetési sáv: s-pályák})$$

izotrop hf-kcsh

$$h_2^k = \frac{\mu_0}{4\pi} \gamma_S \gamma_{j_k} \frac{3(\mathbf{n}_k \cdot \mathbf{S})(\mathbf{n}_k \cdot \mathbf{I}_k) - \mathbf{S} \cdot \mathbf{I}_k}{r_k^3 (1 + d/r_k)},$$

dipólus hf-kcsh
(pl. szén, p-pályák)

Hiperfinom kölcsönhatás kvantumdotokban



ábra: Hanson & Awschalom, Nature 2008

GaAs kvantumdot:

$$H_{\text{hf,GaAs}} = \mathbf{S} \cdot \mathbf{h}$$

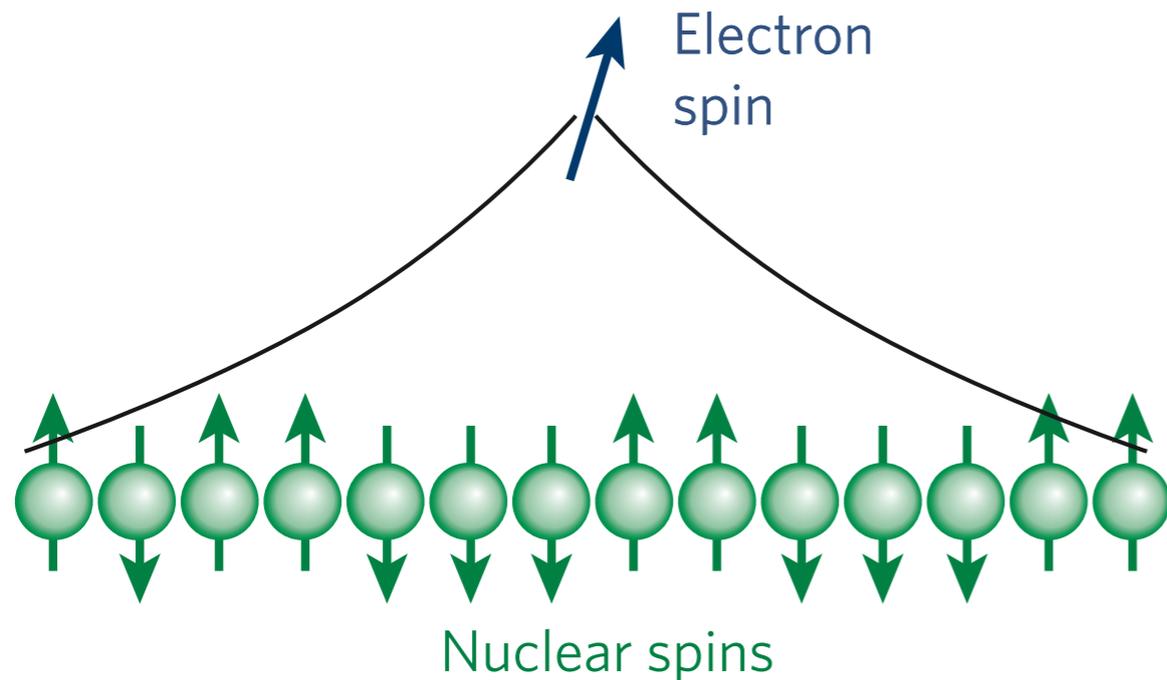
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effektív mágneses tér

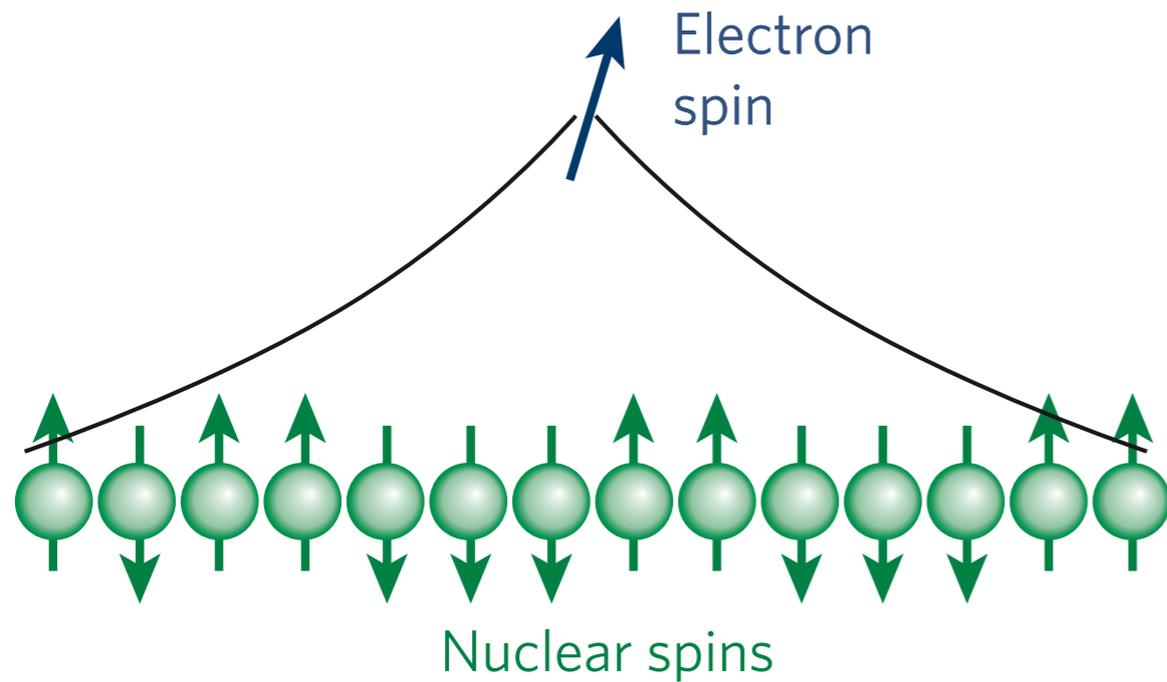
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ábra: Hanson & Awschalom, Nature 2008

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$$H_{\text{hf,GaAs}} = \mathbf{S} \cdot \mathbf{h}$$

effektív mágneses tér
véletlen irány és nagyság
 $\text{StdDev}(h_{x,y,z}) \propto A/\sqrt{N}$

$$h_1^k = \frac{\mu_0}{4\pi} \frac{8\pi}{3} \gamma_S \gamma_{j_k} \delta(\mathbf{r}_k) \mathbf{S} \cdot \mathbf{I}_k, \text{ (pl. GaAs, vezetési sáv: s-pályák)}$$

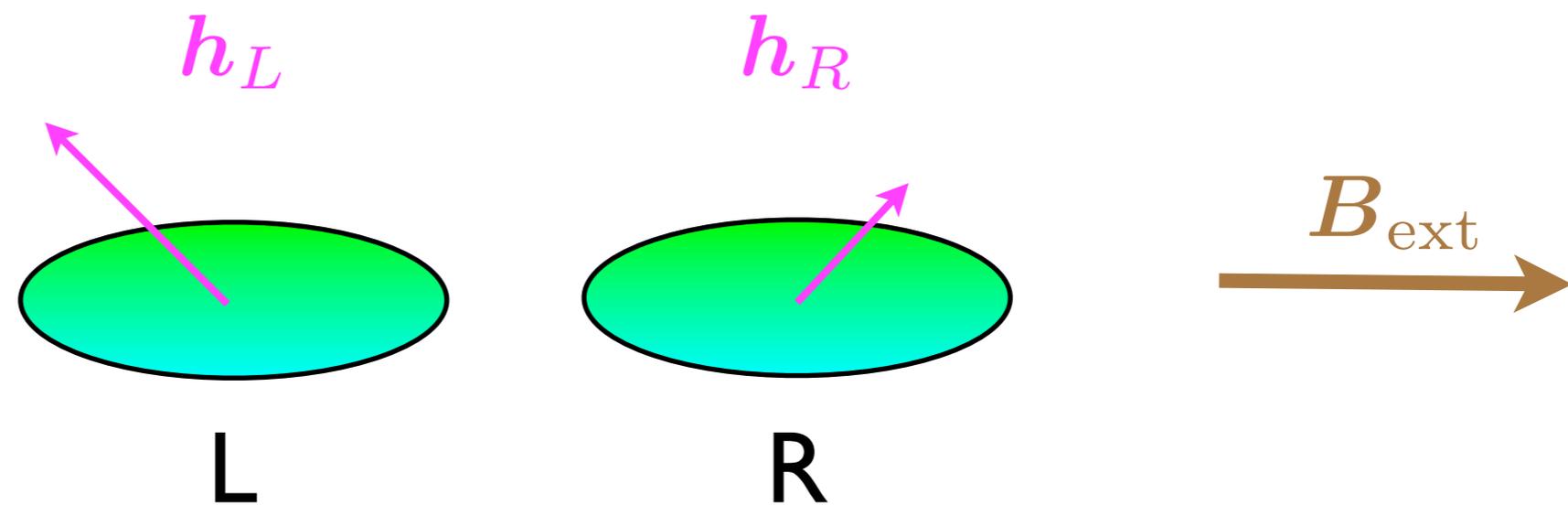
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dipólus hf-kcsh
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Hiperfinom kölcsönhatás a szinglet-triplet bázisban

$$H_{\text{spin}} = \underbrace{\mathbf{S}_L \cdot \mathbf{h}_L + \mathbf{S}_R \cdot \mathbf{h}_R}_{\text{hiperfinom kölcsönhatás}} + \underbrace{(\mathbf{S}_L + \mathbf{S}_R) \cdot \mathbf{B}_{\text{ext}}}_{\text{Zeeman-effektus}}$$

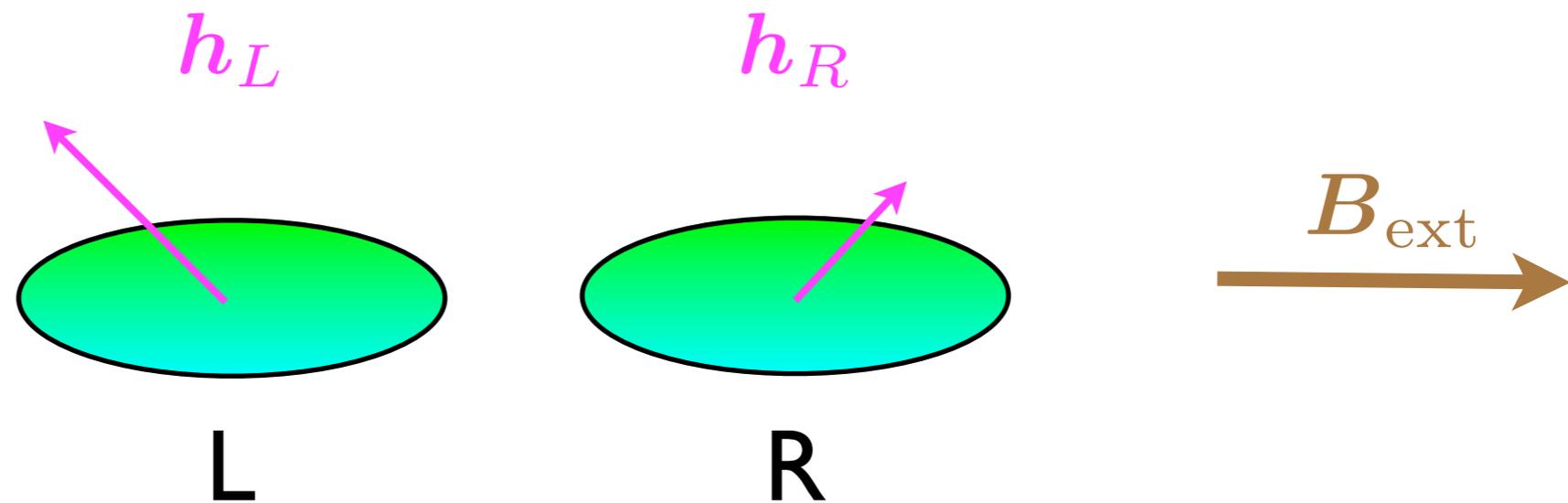


Hiperfinom kölcsönhatás a szinglet-triplet bázisban

véletlen effektív mágneses terek

$$H_{\text{spin}} = \mathbf{S}_L \cdot \mathbf{h}_L + \mathbf{S}_R \cdot \mathbf{h}_R + (\mathbf{S}_L + \mathbf{S}_R) \cdot \mathbf{B}_{\text{ext}}$$

hiperfinom kölcsönhatás Zeeman-effektus

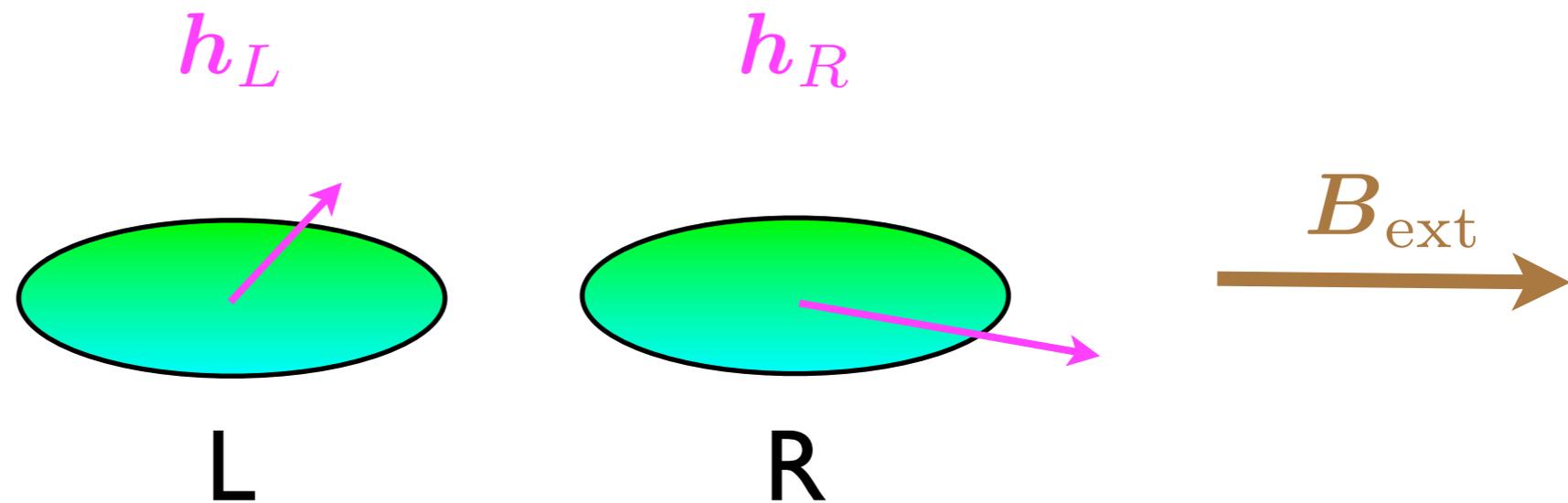


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hiperfinom kölcsönhatás Zeeman-effektus

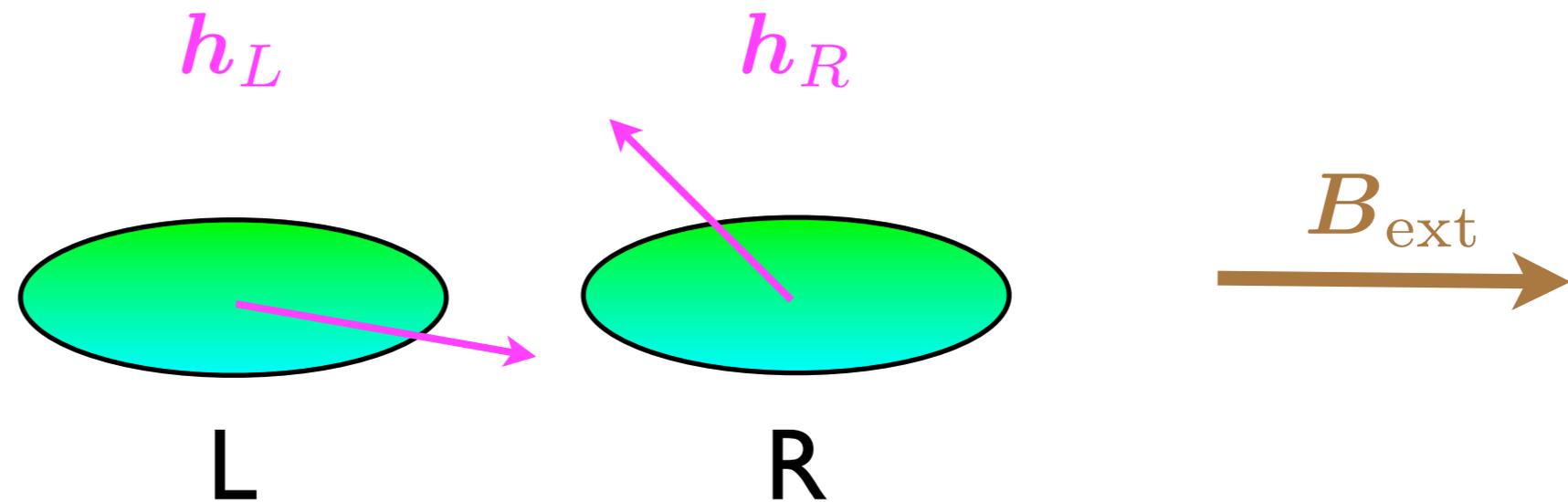


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hiperfinom kölcsönhatás Zeeman-effektus

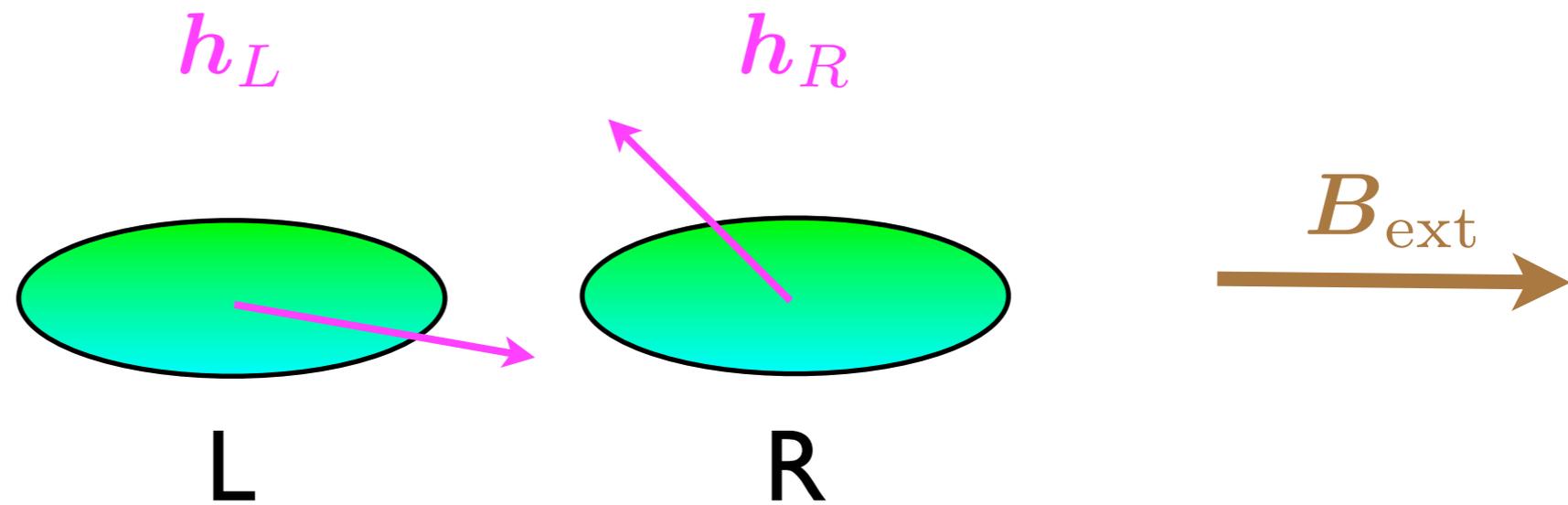


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hiperfinom kölcsönhatás Zeeman-effektus



„szimmetrikus
komponens”

$$\mathbf{B}_s \equiv \frac{\mathbf{h}_L + \mathbf{h}_R}{2} + \mathbf{B}_{\text{ext}}$$

„antiszimmetrikus
komponens”

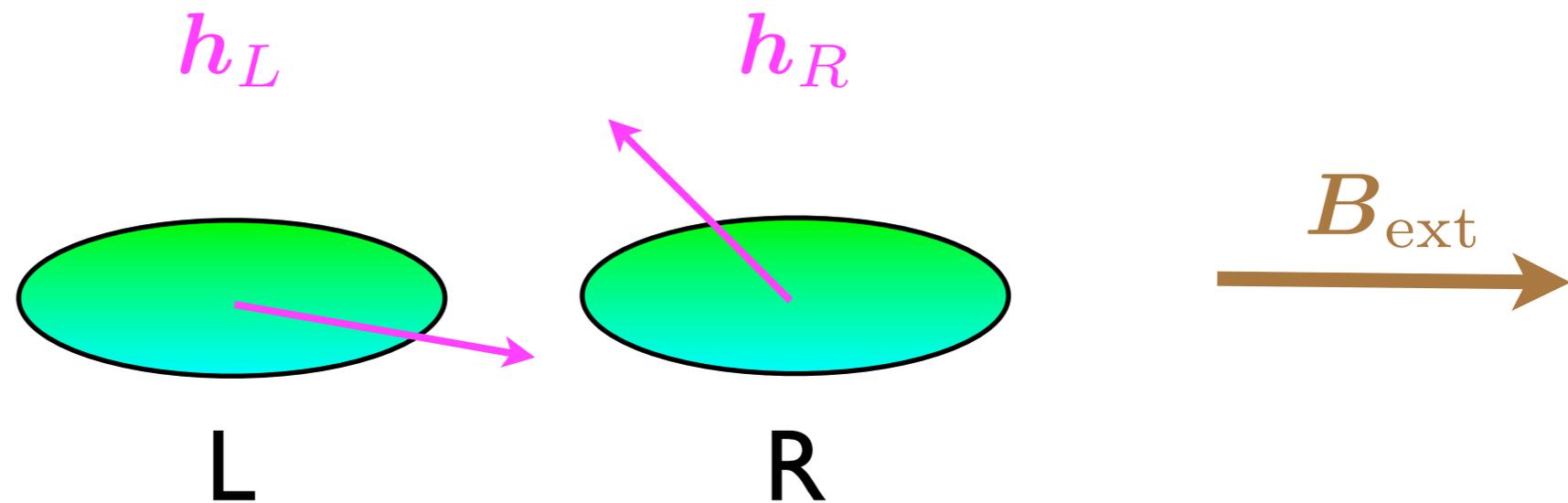
$$\mathbf{B}_a \equiv \frac{\mathbf{h}_L - \mathbf{h}_R}{2}$$

Hiperfinom kölcsönhatás a szinglet-triplet bázisban

véletlen effektív mágneses terek

$$H_{\text{spin}} = \mathbf{S}_L \cdot \mathbf{h}_L + \mathbf{S}_R \cdot \mathbf{h}_R + (\mathbf{S}_L + \mathbf{S}_R) \cdot \mathbf{B}_{\text{ext}}$$

hiperfinom kölcsönhatás Zeeman-effektus



„szimmetrikus
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$$\mathbf{B}_s \equiv \frac{\mathbf{h}_L + \mathbf{h}_R}{2} + \mathbf{B}_{\text{ext}}$$

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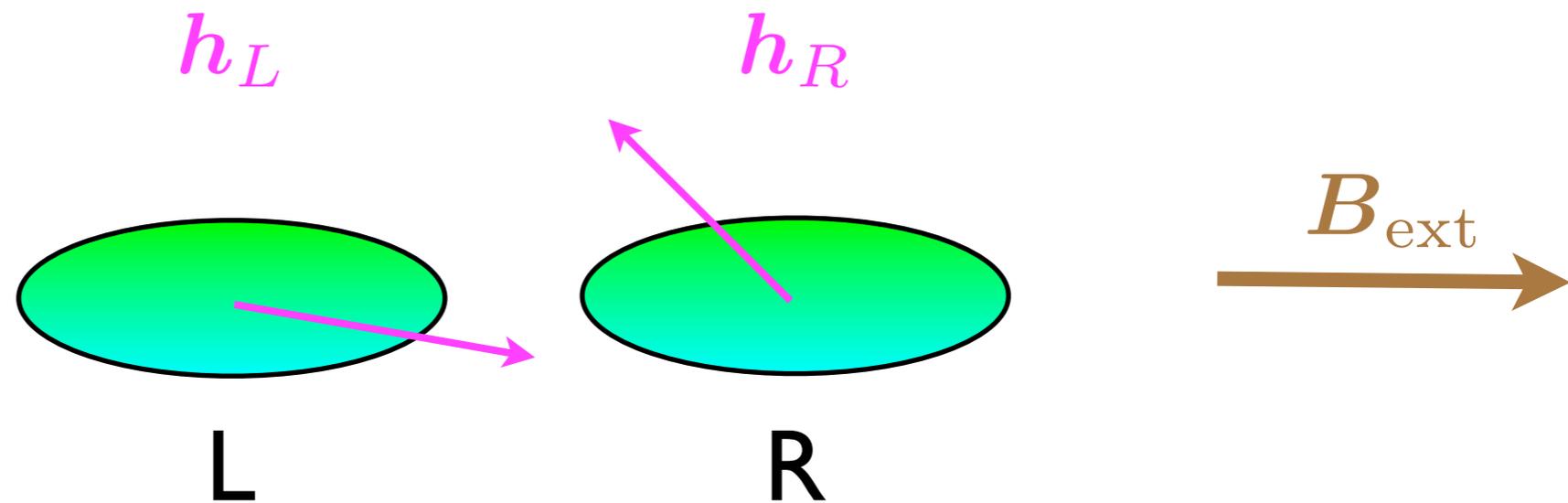
$$\hat{H}_{\text{spin}} = B_s^z \sum_i s_z^i |T_i\rangle\langle T_i| + B_a^z |S\rangle\langle T_0| + \sum_{\pm} \left(\frac{B_s^x \pm iB_s^y}{\sqrt{2}} |T_0\rangle\langle T_{\pm 1}| + \frac{\mp B_a^x - iB_a^y}{\sqrt{2}} |S\rangle\langle T_{\pm 1}| + \text{H.c.} \right),$$

Hiperfinom kölcsönhatás a szinglet-triplet bázisban

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hiperfinom kölcsönhatás Zeeman-effektus



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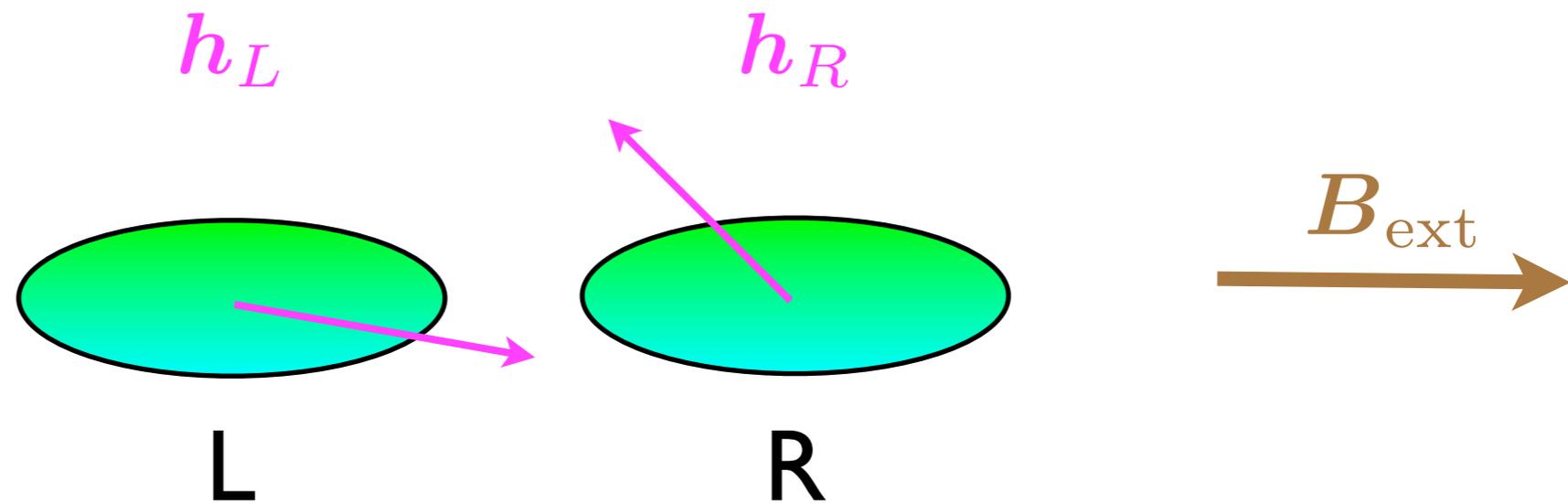
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hiperfinom kölcsönhatás Zeeman-effektus



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$$\mathbf{B}_a \equiv \frac{\mathbf{h}_L - \mathbf{h}_R}{2}$$

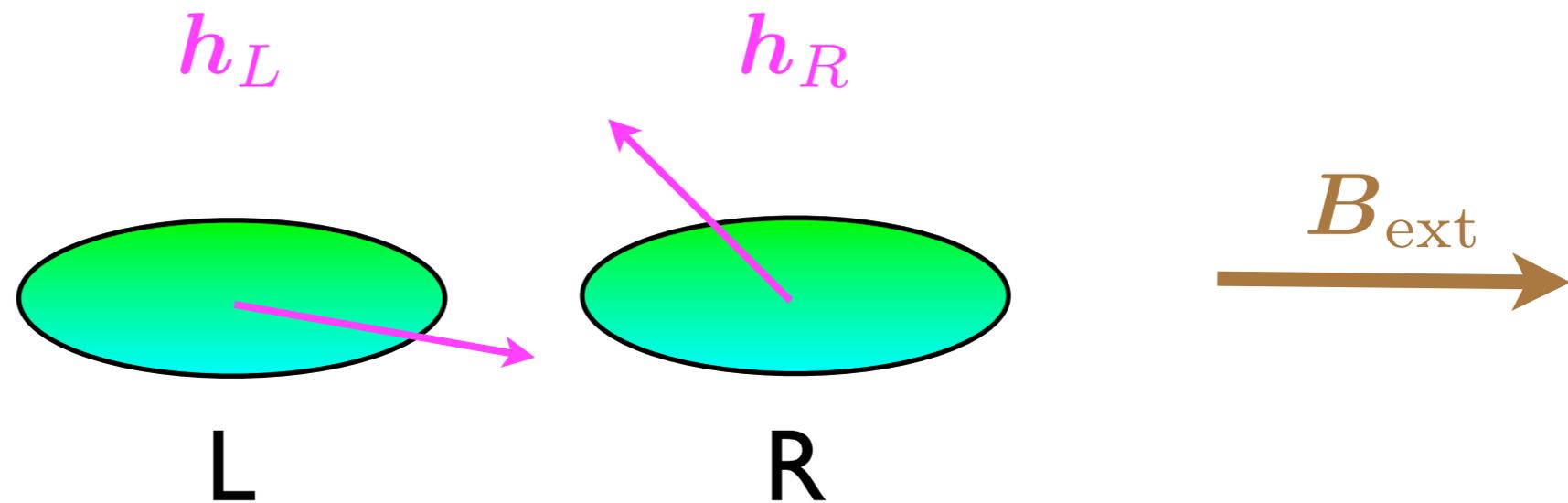
$$\hat{H}_{\text{spin}} = \left(B_s^z \sum_i s_z^i |T_i\rangle\langle T_i| \right) + \left(B_a^z |S\rangle\langle T_0| \right) + \sum_{\pm} \left(\frac{B_s^x \pm iB_s^y}{\sqrt{2}} |T_0\rangle\langle T_{\pm 1}| + \frac{\mp B_a^x - iB_a^y}{\sqrt{2}} |S\rangle\langle T_{\pm 1}| + \text{H.c.} \right),$$

Hiperfinom kölcsönhatás a szinglet-triplet bázisban

véletlen effektív mágneses terek

$$H_{\text{spin}} = \mathbf{S}_L \cdot \mathbf{h}_L + \mathbf{S}_R \cdot \mathbf{h}_R + (\mathbf{S}_L + \mathbf{S}_R) \cdot \mathbf{B}_{\text{ext}}$$

hiperfinom kölcsönhatás Zeeman-effektus



„szimmetrikus komponens”

$$\mathbf{B}_s \equiv \frac{\mathbf{h}_L + \mathbf{h}_R}{2} + \mathbf{B}_{\text{ext}}$$

„antiszimmetrikus komponens”

$$\mathbf{B}_a \equiv \frac{\mathbf{h}_L - \mathbf{h}_R}{2}$$

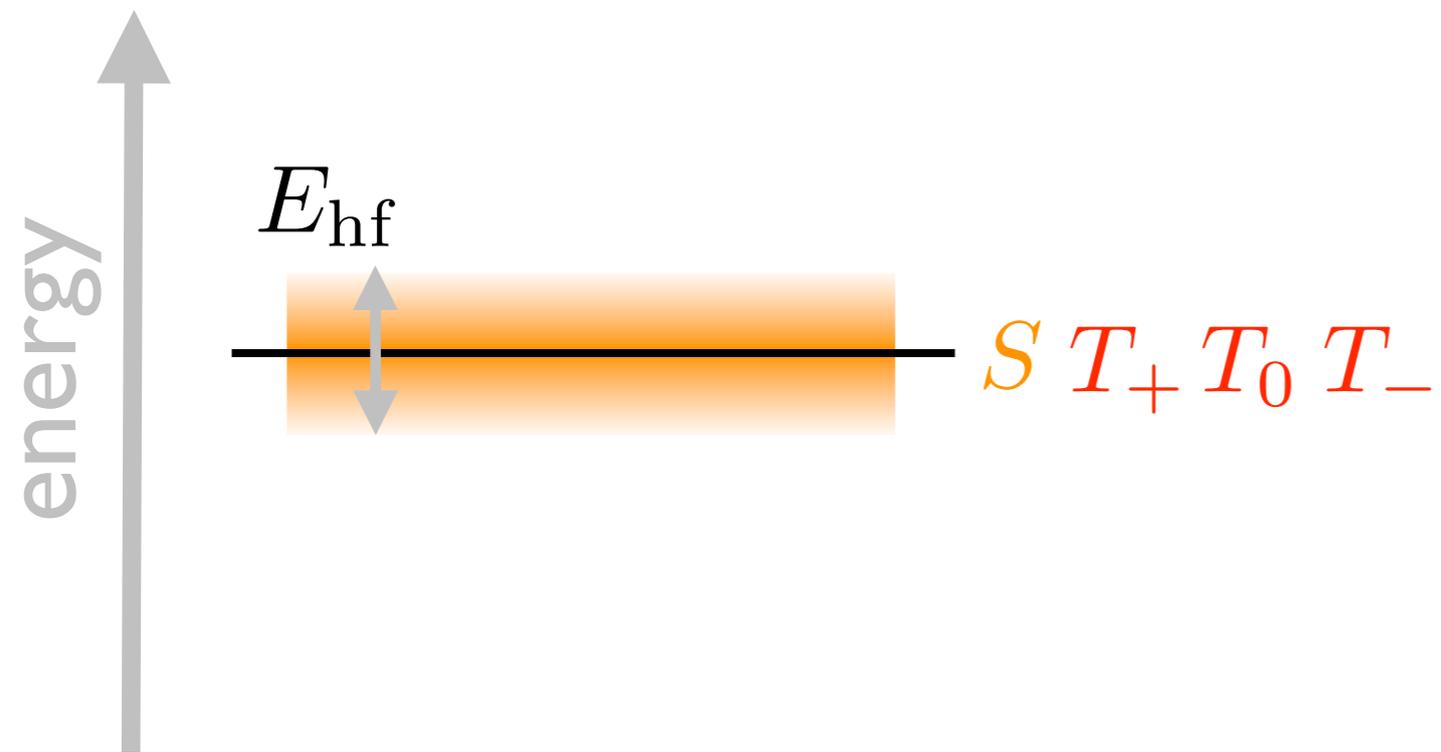
$$\hat{H}_{\text{spin}} = \left(B_s^z \sum_i s_z^i |T_i\rangle\langle T_i| \right) + \left(B_a^z |S\rangle\langle T_0| \right) + \sum_{\pm} \left(\frac{B_s^x \pm iB_s^y}{\sqrt{2}} |T_0\rangle\langle T_{\pm 1}| + \frac{\mp B_a^x - iB_a^y}{\sqrt{2}} |S\rangle\langle T_{\pm 1}| + \text{H.c.} \right),$$

B_a - szinglet-triplet csatolás

Áram mágneses térben

(1,1) energiaszintek

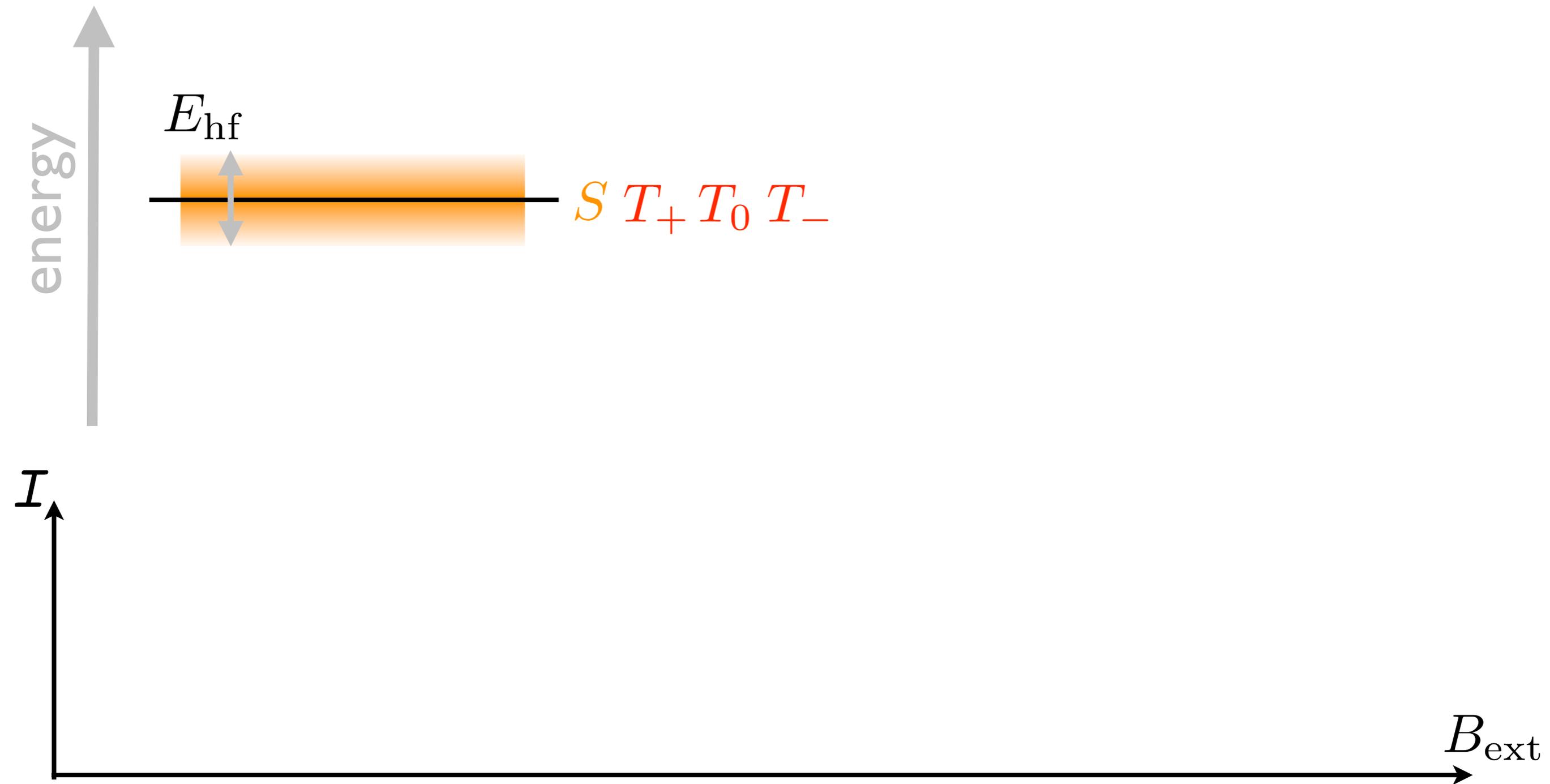
$$B_{\text{ext}} = 0$$



Áram mágneses térben

(1,1) energiaszintek

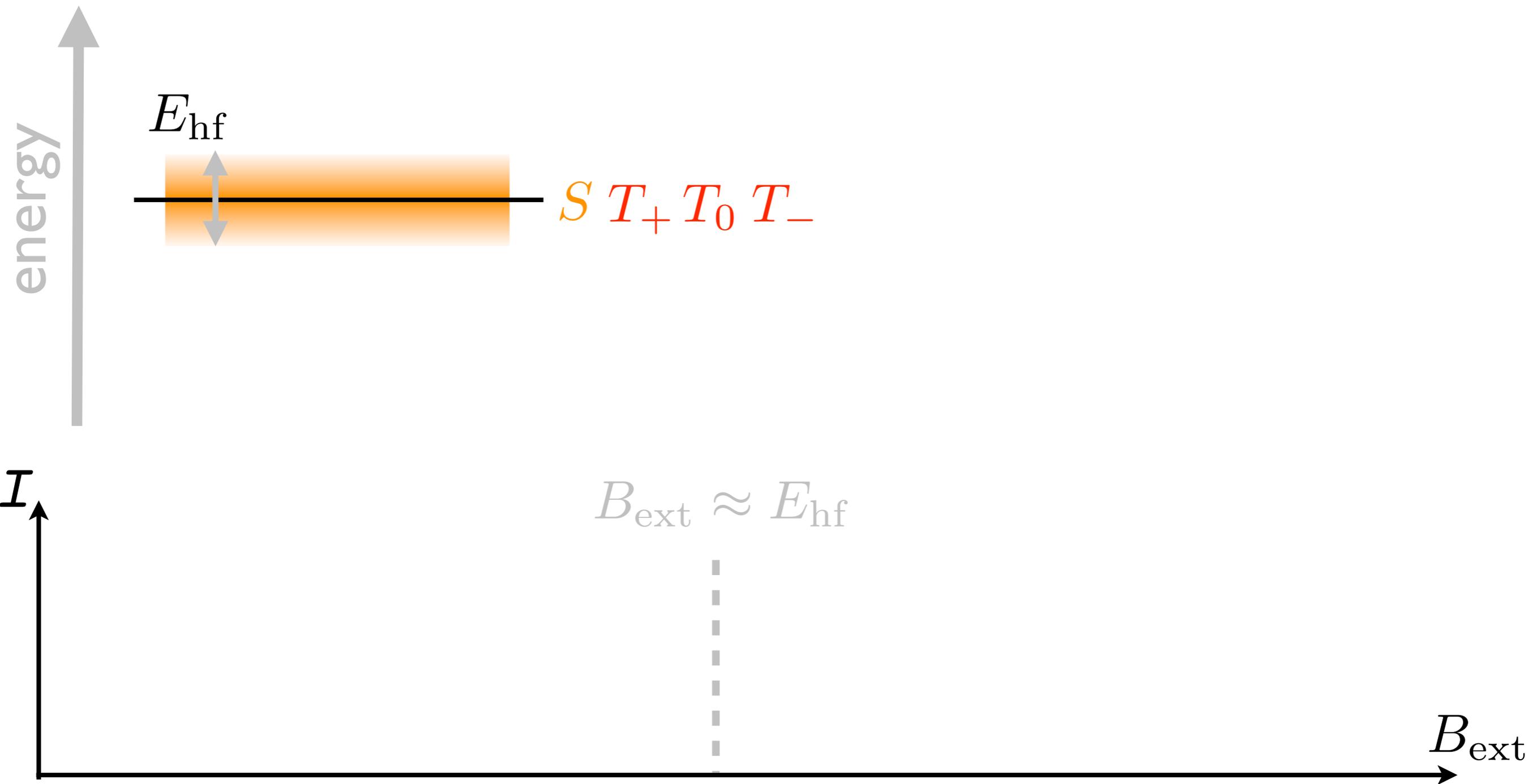
$$B_{\text{ext}} = 0$$



Áram mágneses térben

(1,1) energiaszintek

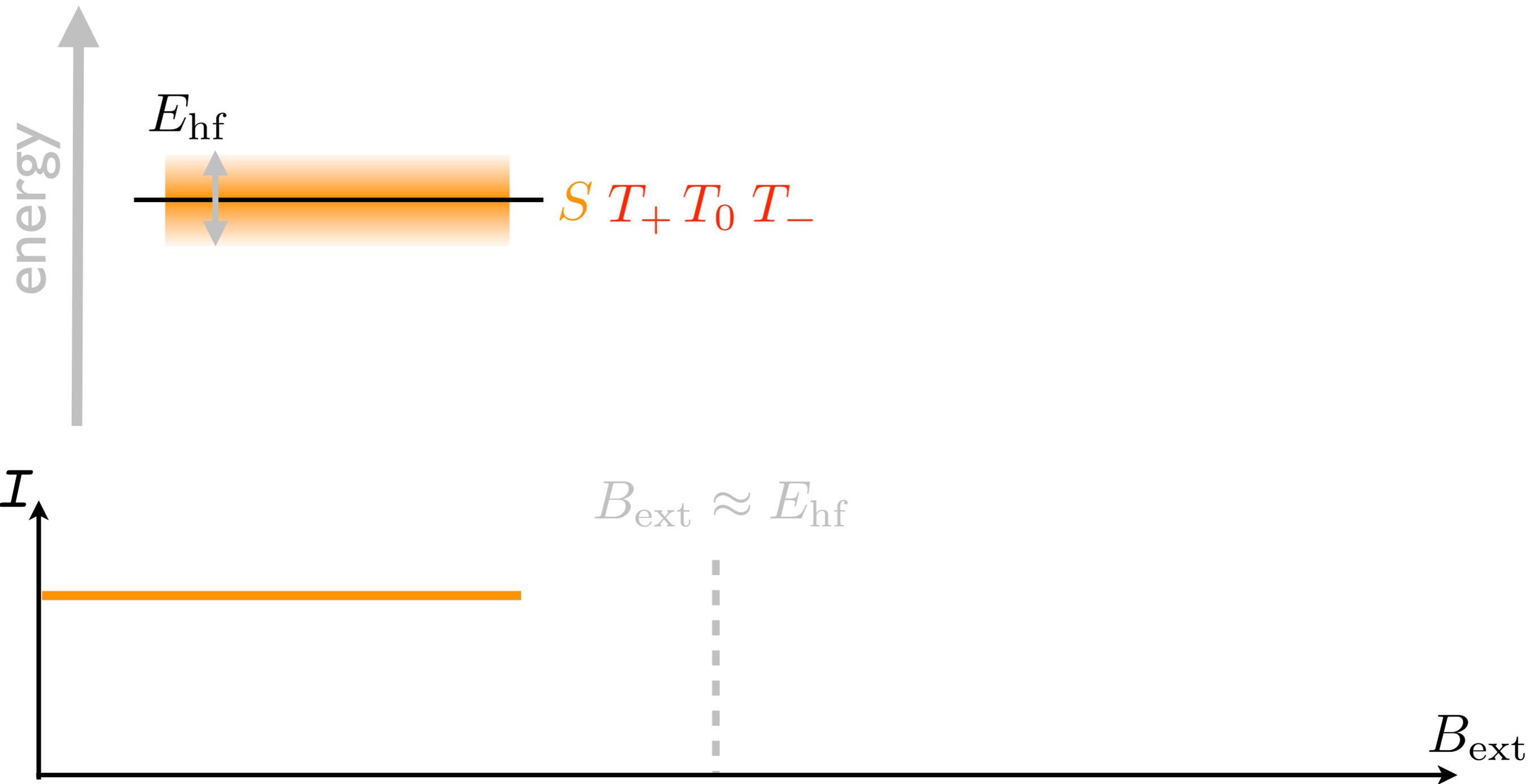
$$B_{\text{ext}} = 0$$



Áram mágneses térben

(1,1) energiaszintek

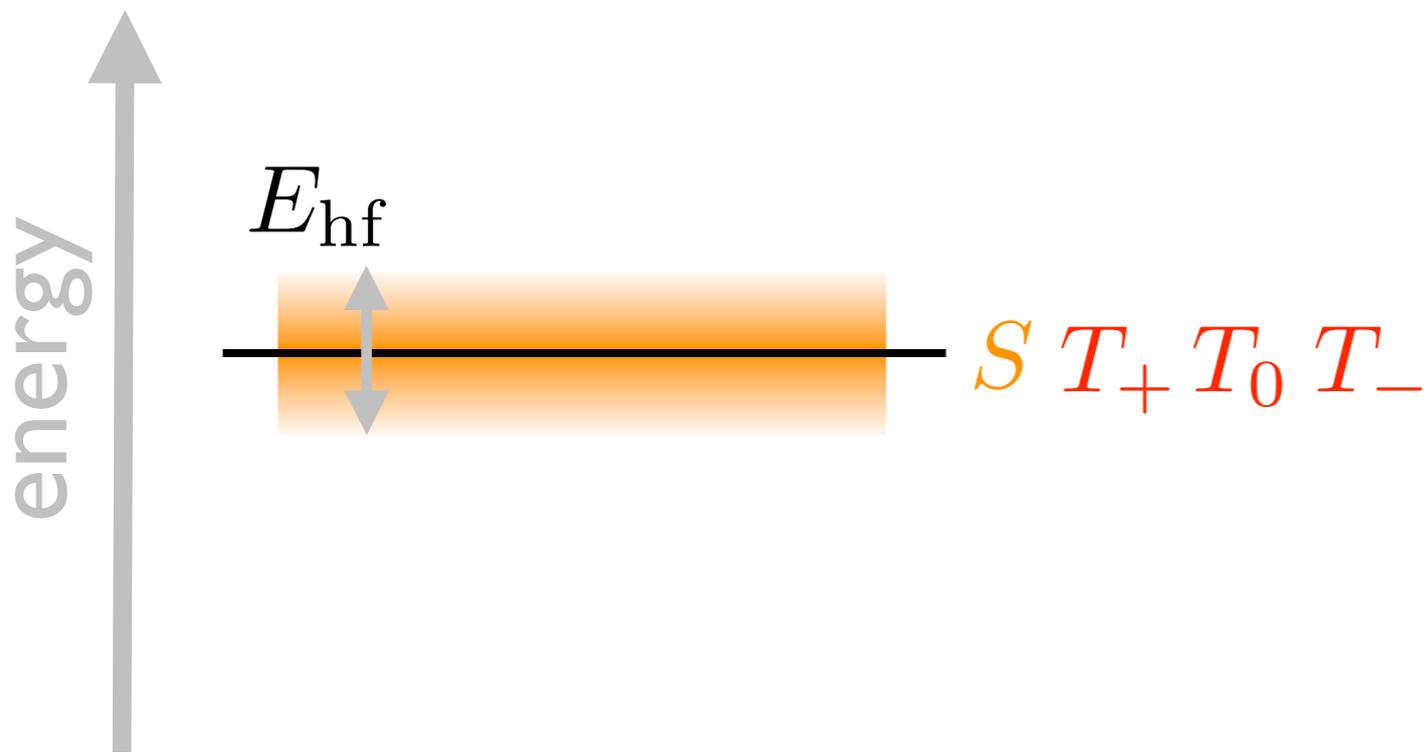
$$B_{\text{ext}} = 0$$



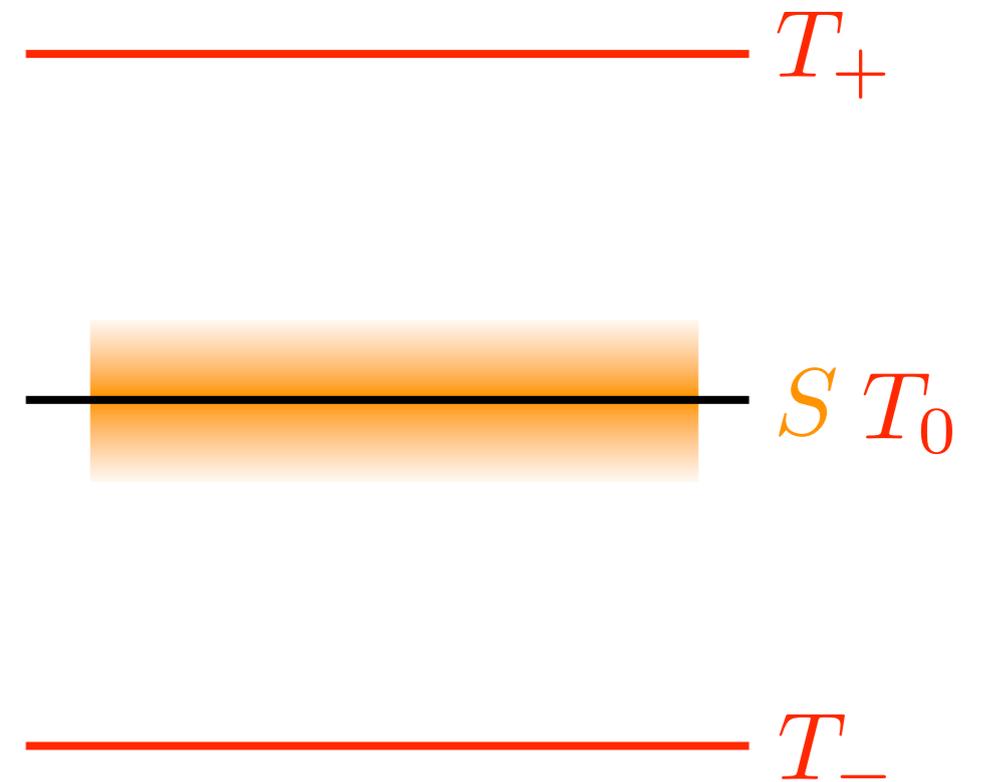
Áram mágneses térben

(1,1) energiaszintek

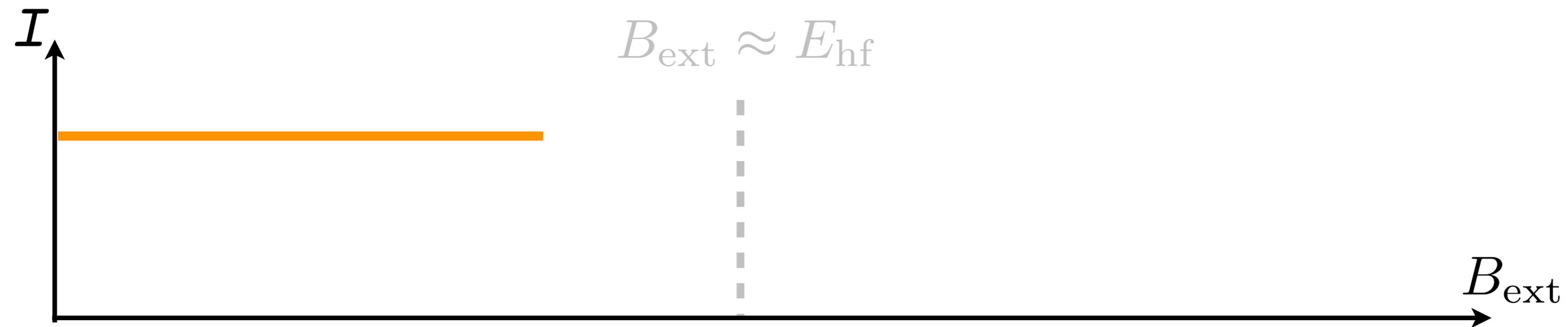
$$B_{\text{ext}} = 0$$



$$B_{\text{ext}} \gg E_{\text{hf}}$$



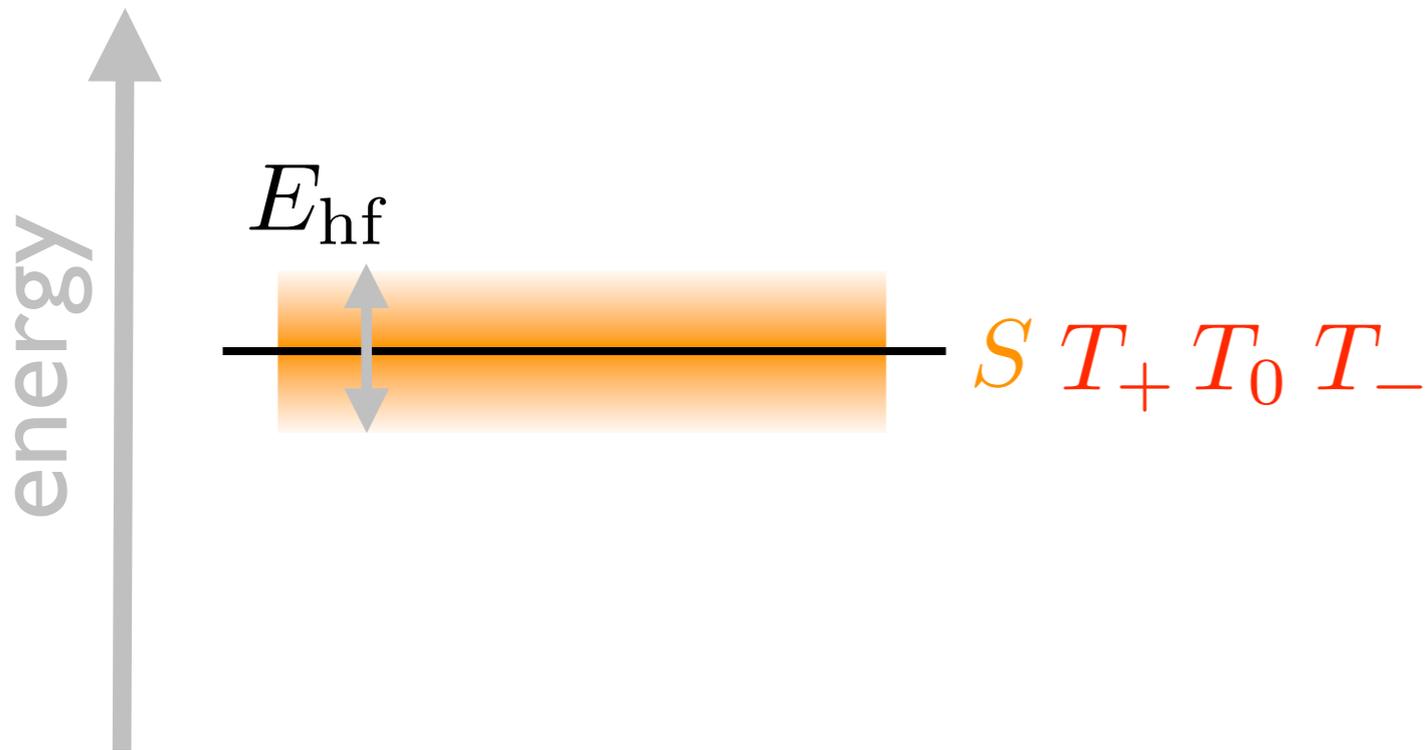
$$B_{\text{ext}} \approx E_{\text{hf}}$$



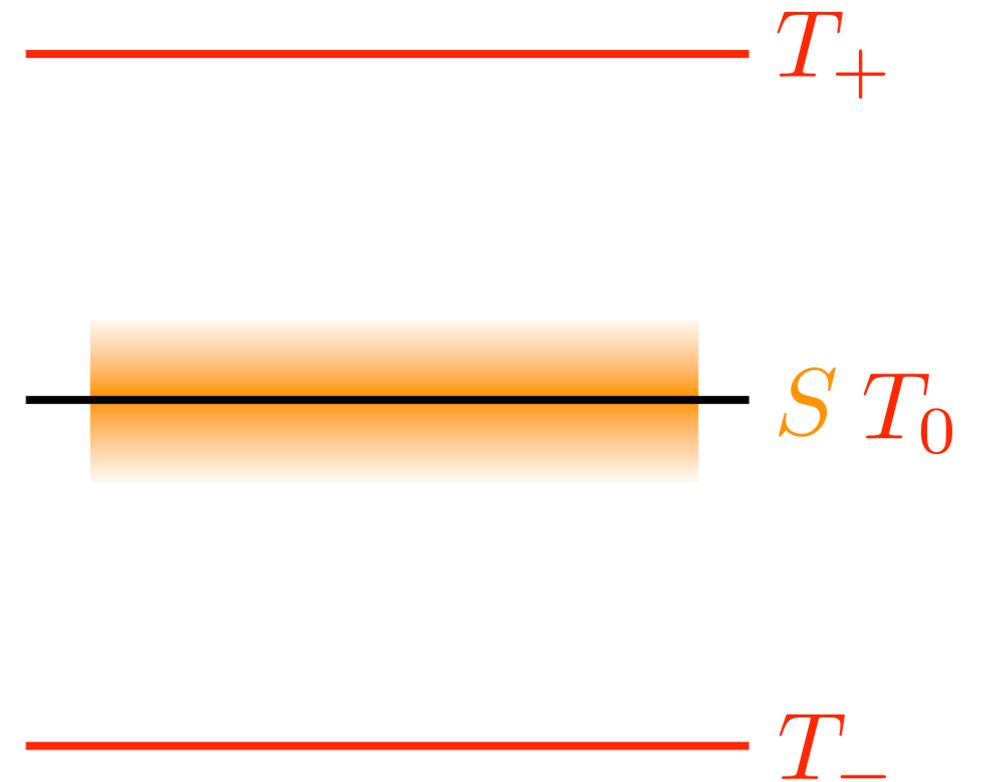
Áram mágneses térben

(1,1) energiaszintek

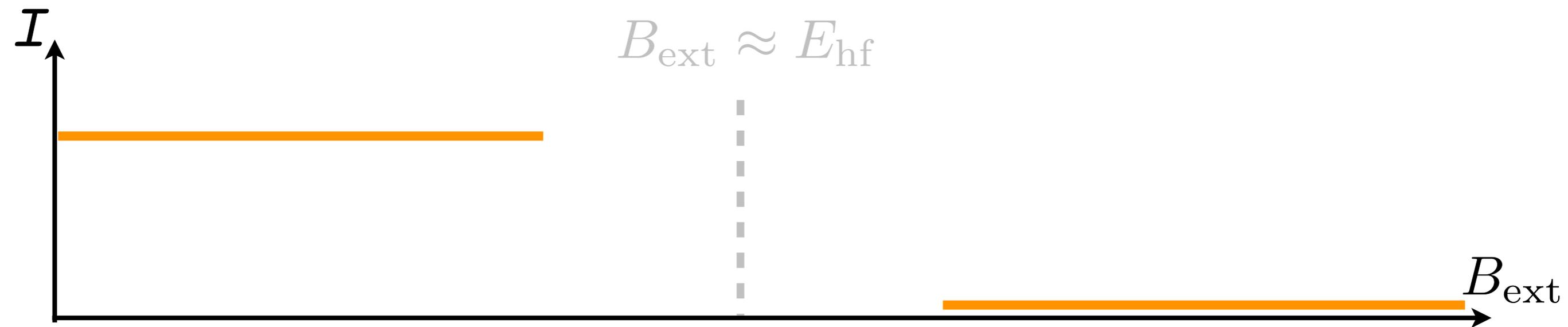
$$B_{\text{ext}} = 0$$



$$B_{\text{ext}} \gg E_{\text{hf}}$$



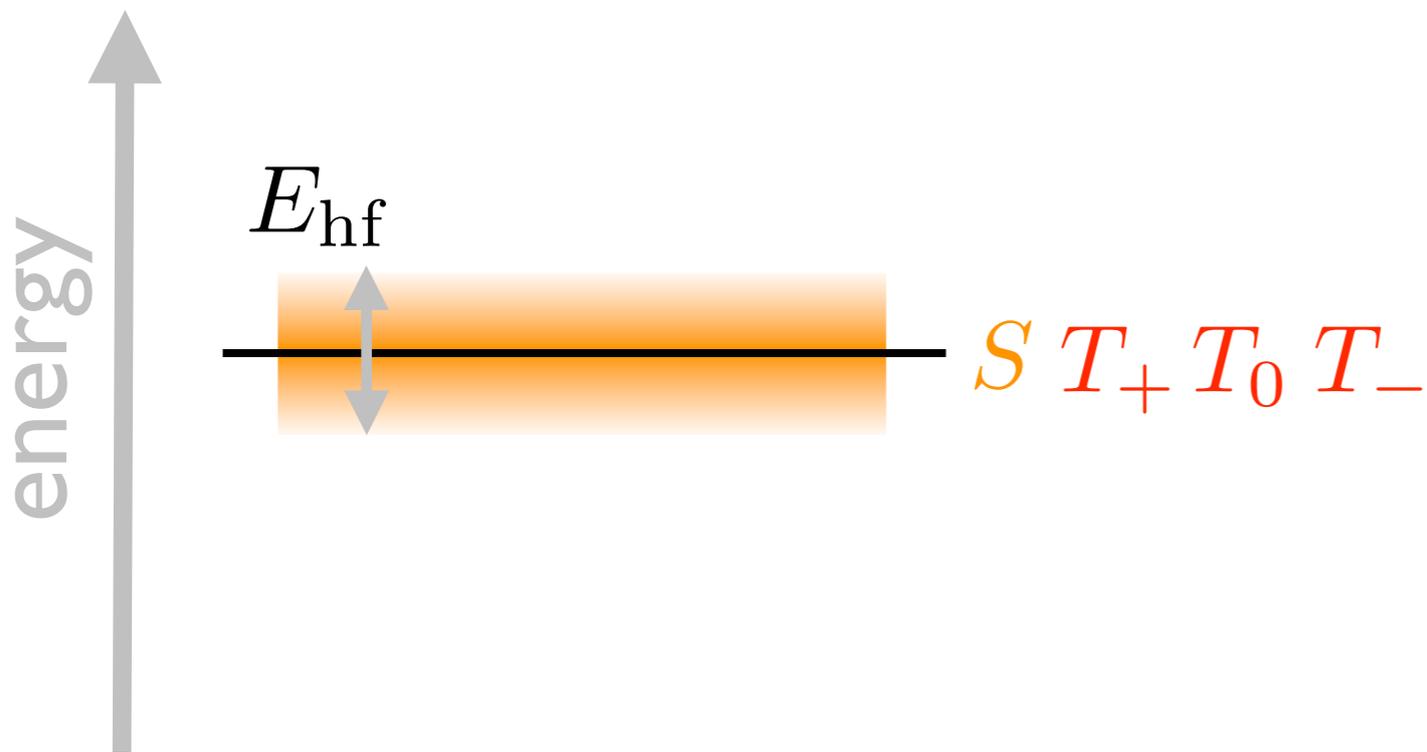
$$B_{\text{ext}} \approx E_{\text{hf}}$$



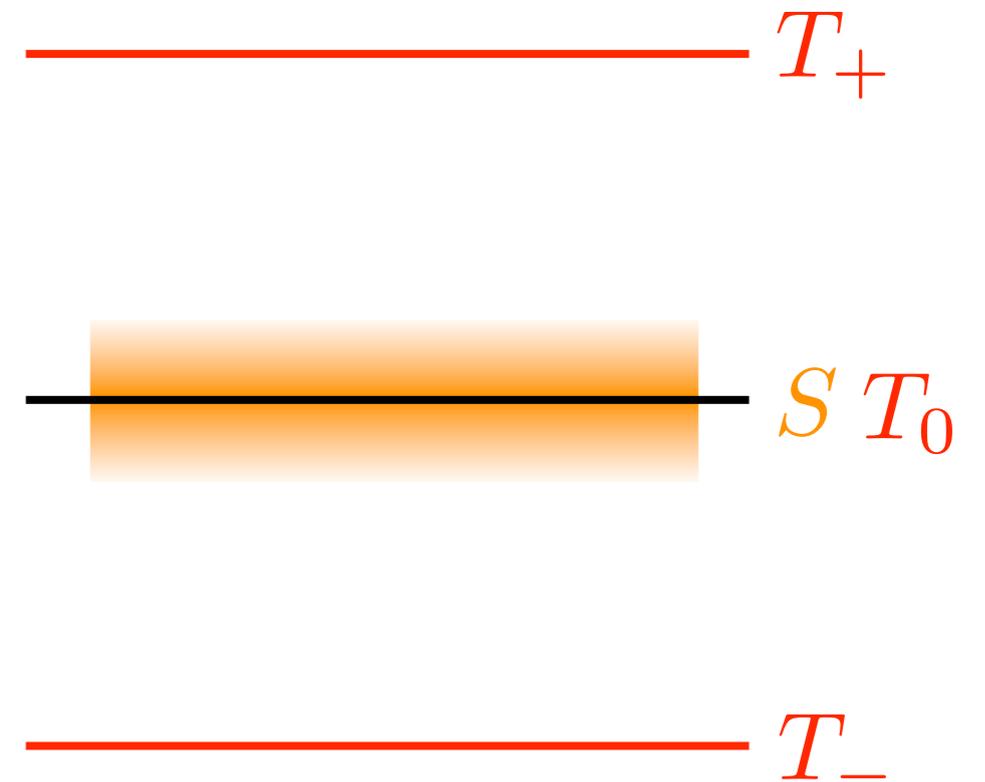
Áram mágneses térben

(1,1) energiaszintek

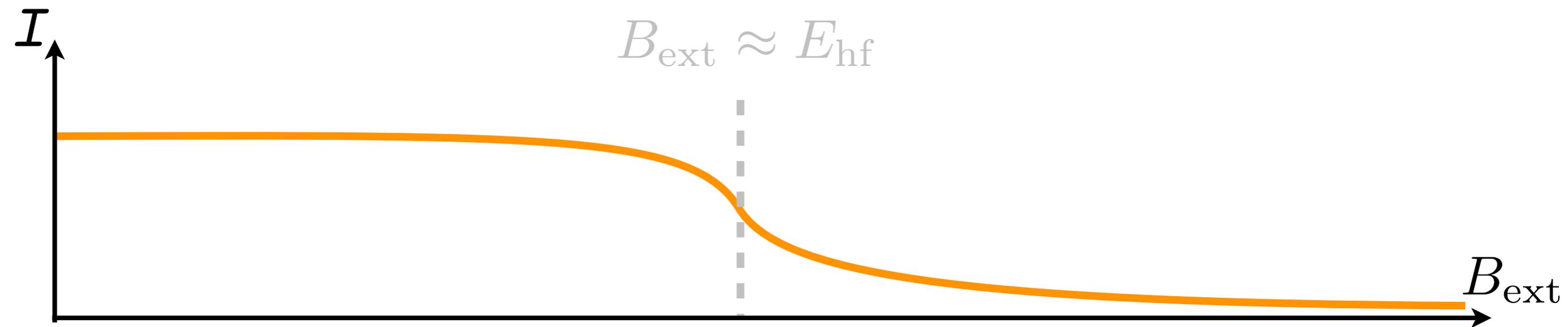
$$B_{\text{ext}} = 0$$

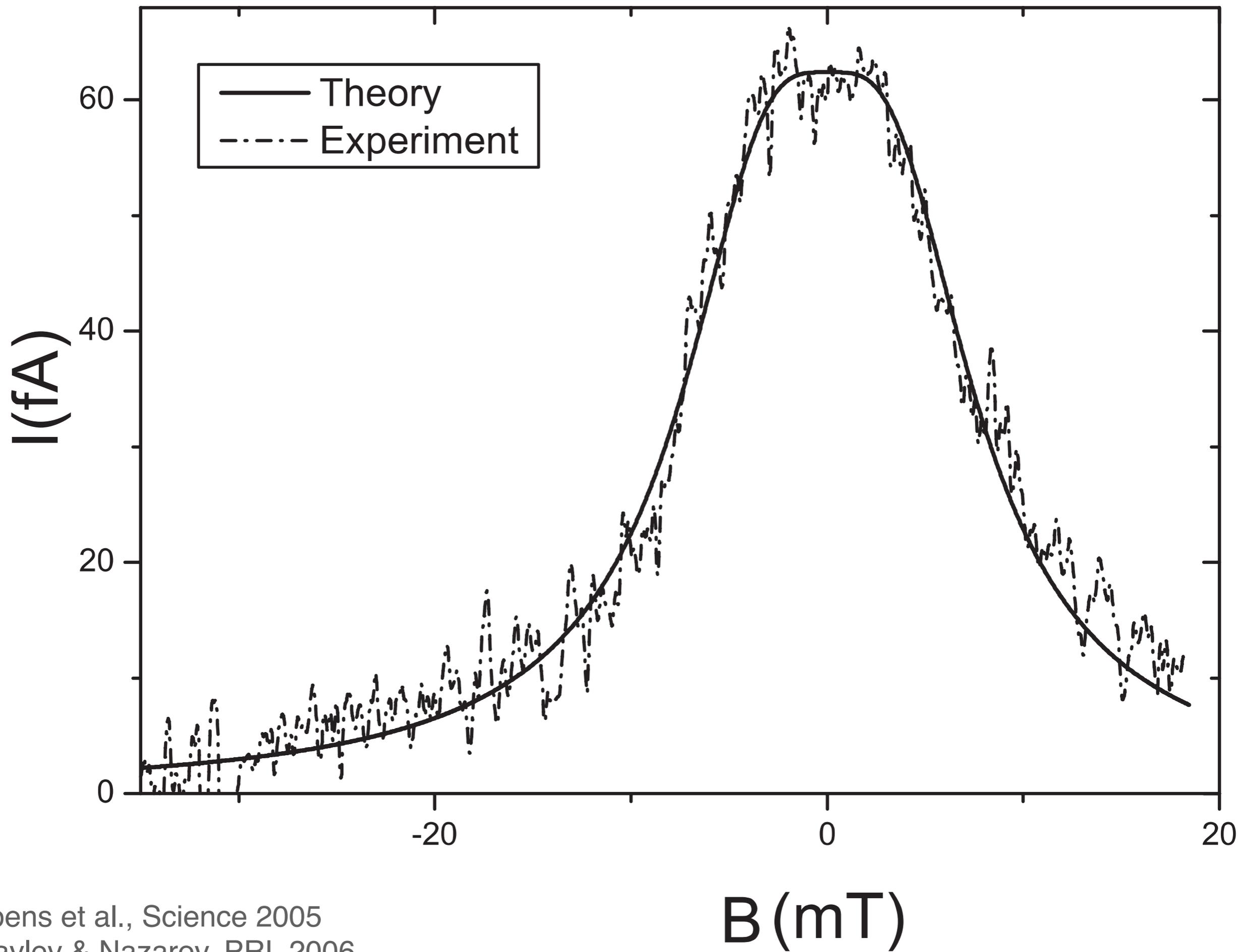


$$B_{\text{ext}} \gg E_{\text{hf}}$$



$$B_{\text{ext}} \approx E_{\text{hf}}$$

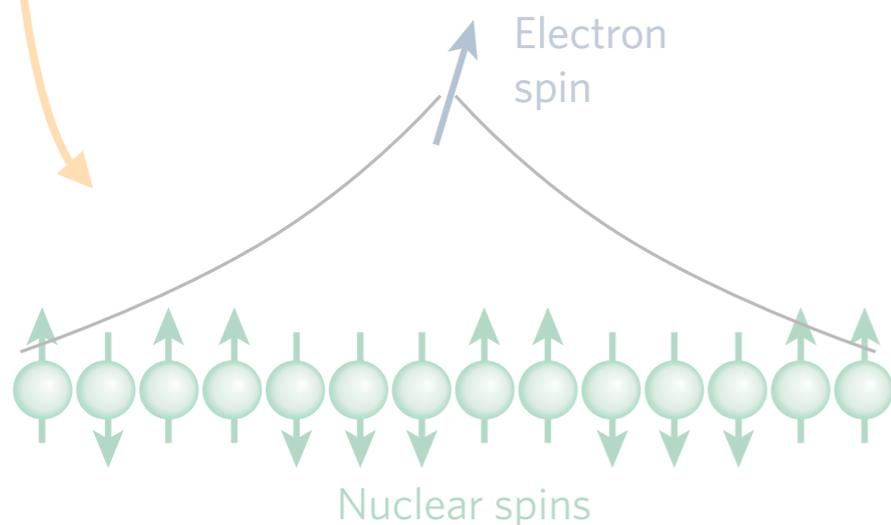




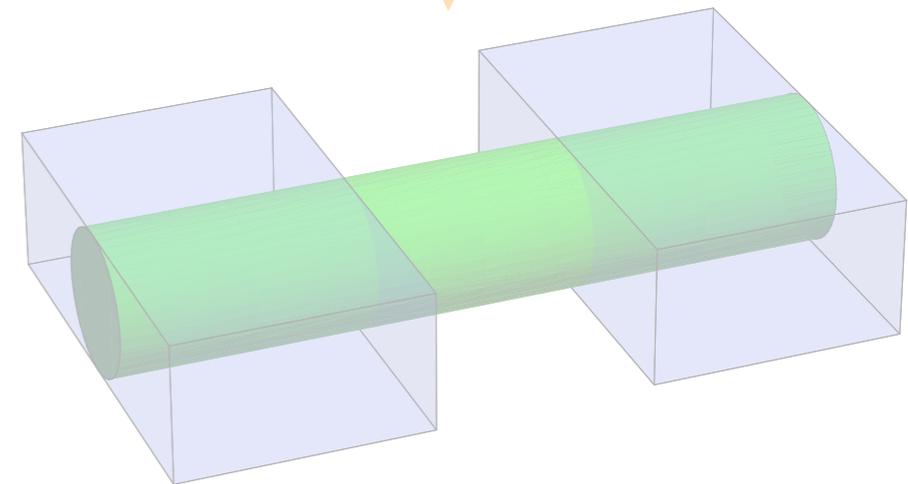
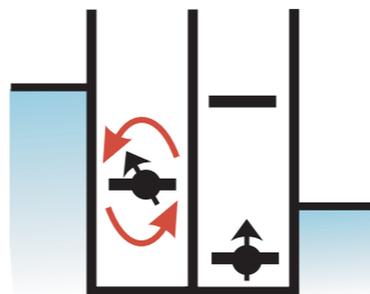
Tartalom

(Spinblokádkettős kvantumdotokban)

- “szonda”: hiperfinom kölcsönhatás
- spin qubit inicializálás és kiolvasás
- kitekintés: szén-alapú kvantumdotok



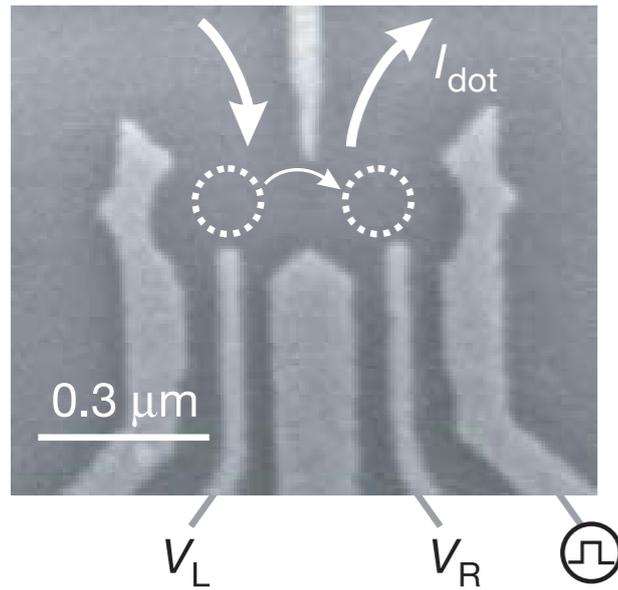
Spin
manipulation



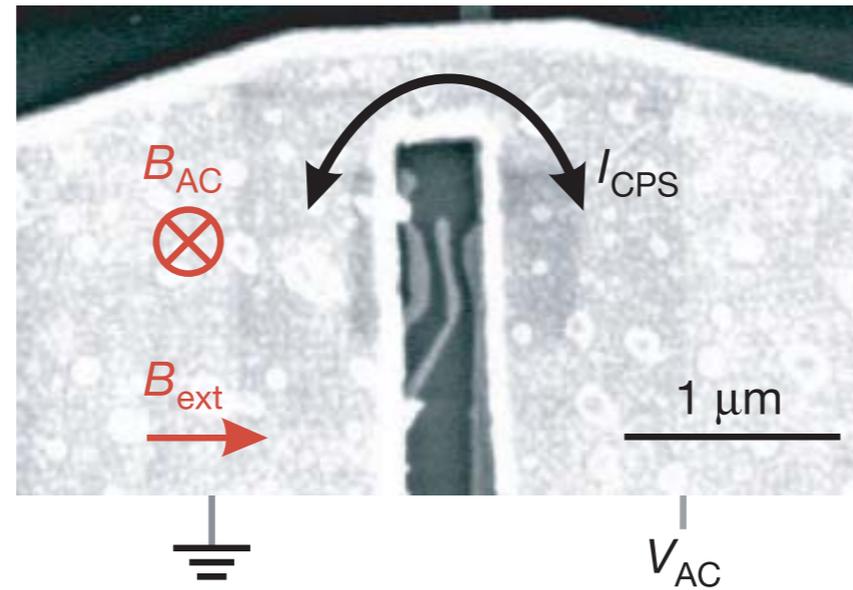
Spin qubit „inicializálás és kiolvasás”

Koppens et al., Nature 2006

a

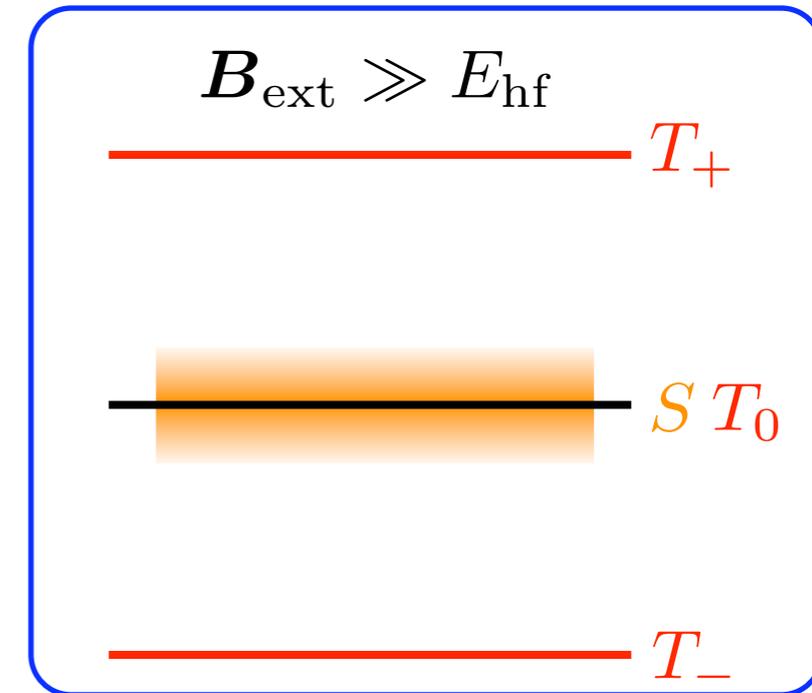
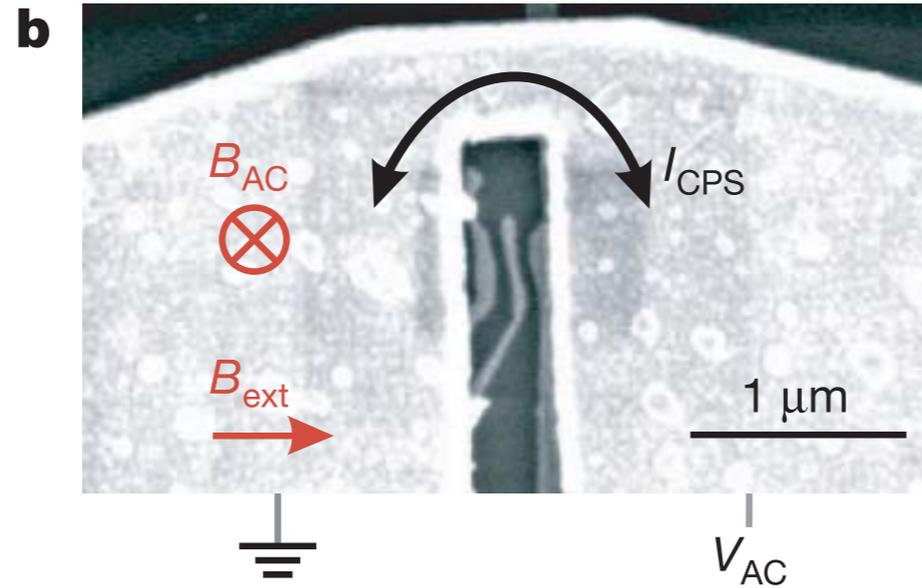
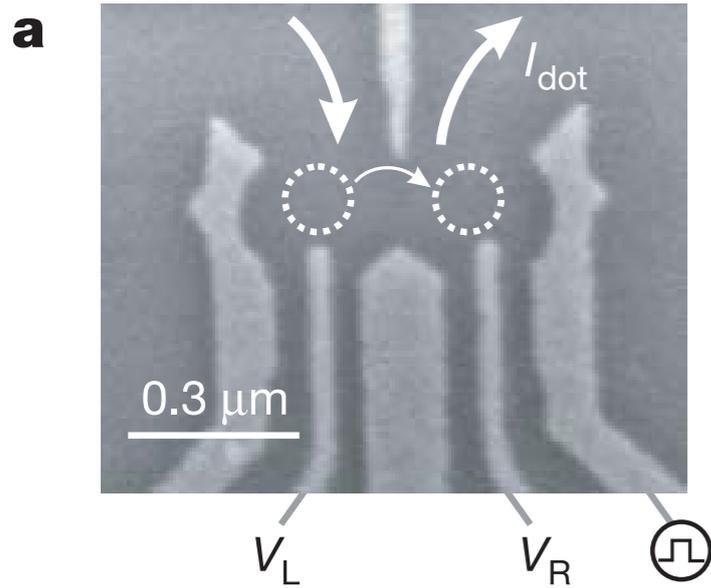


b



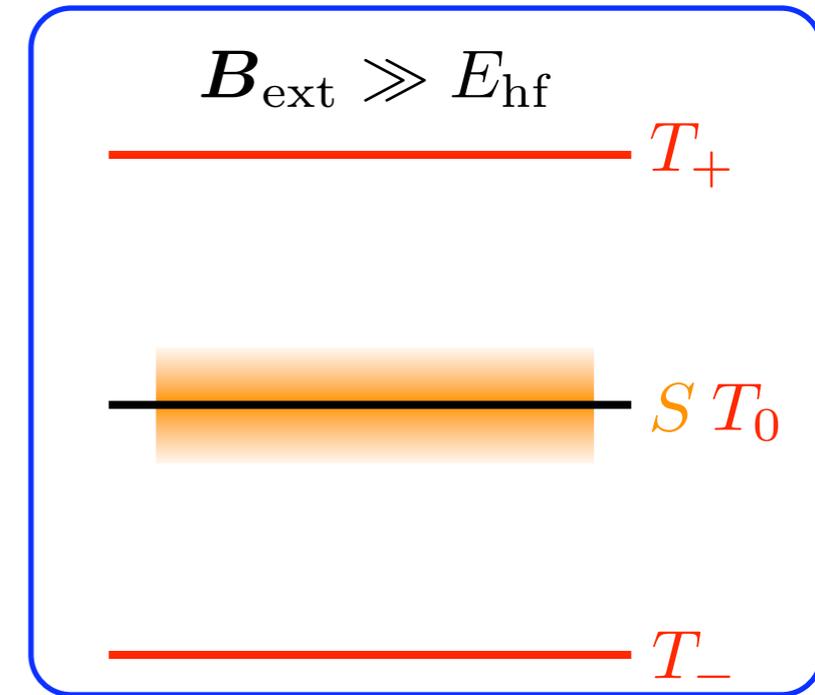
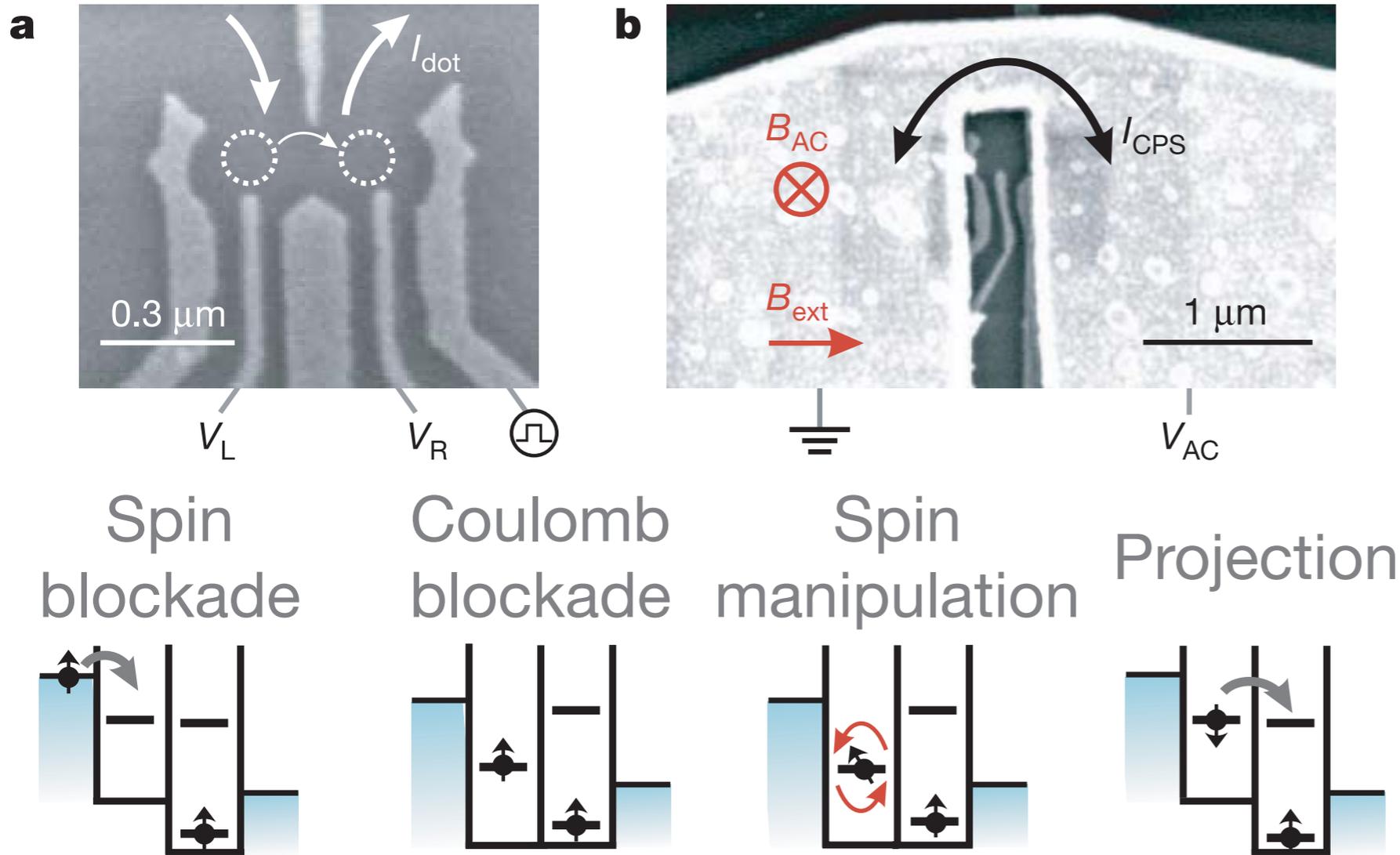
Spin qubit „inicializálás és kiolvasás”

Koppens et al., Nature 2006



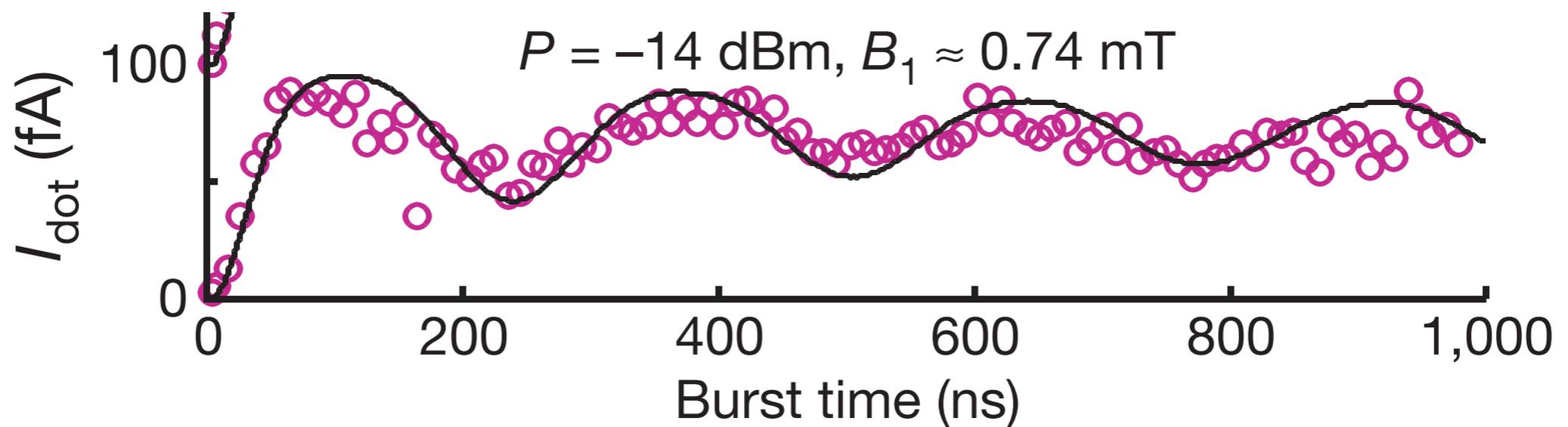
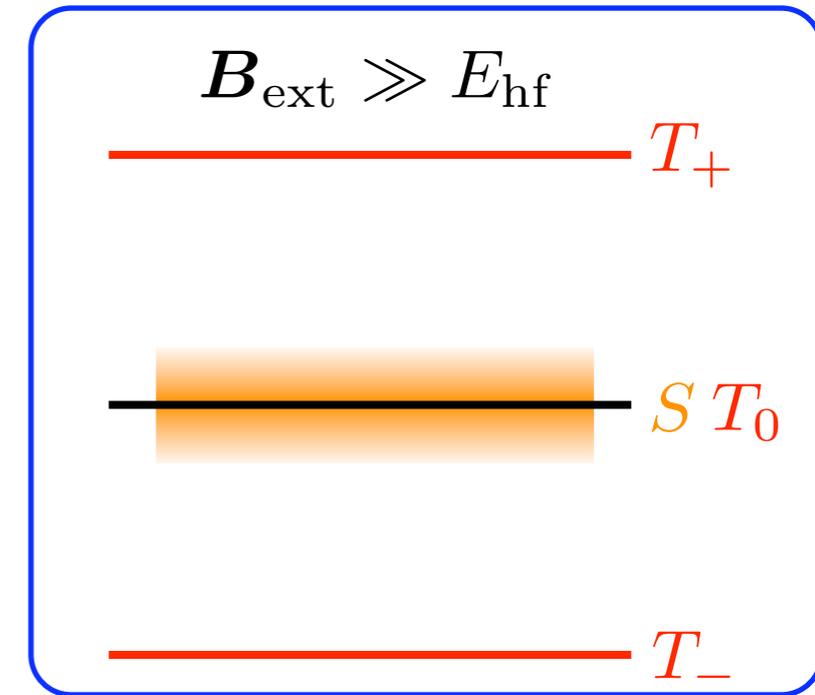
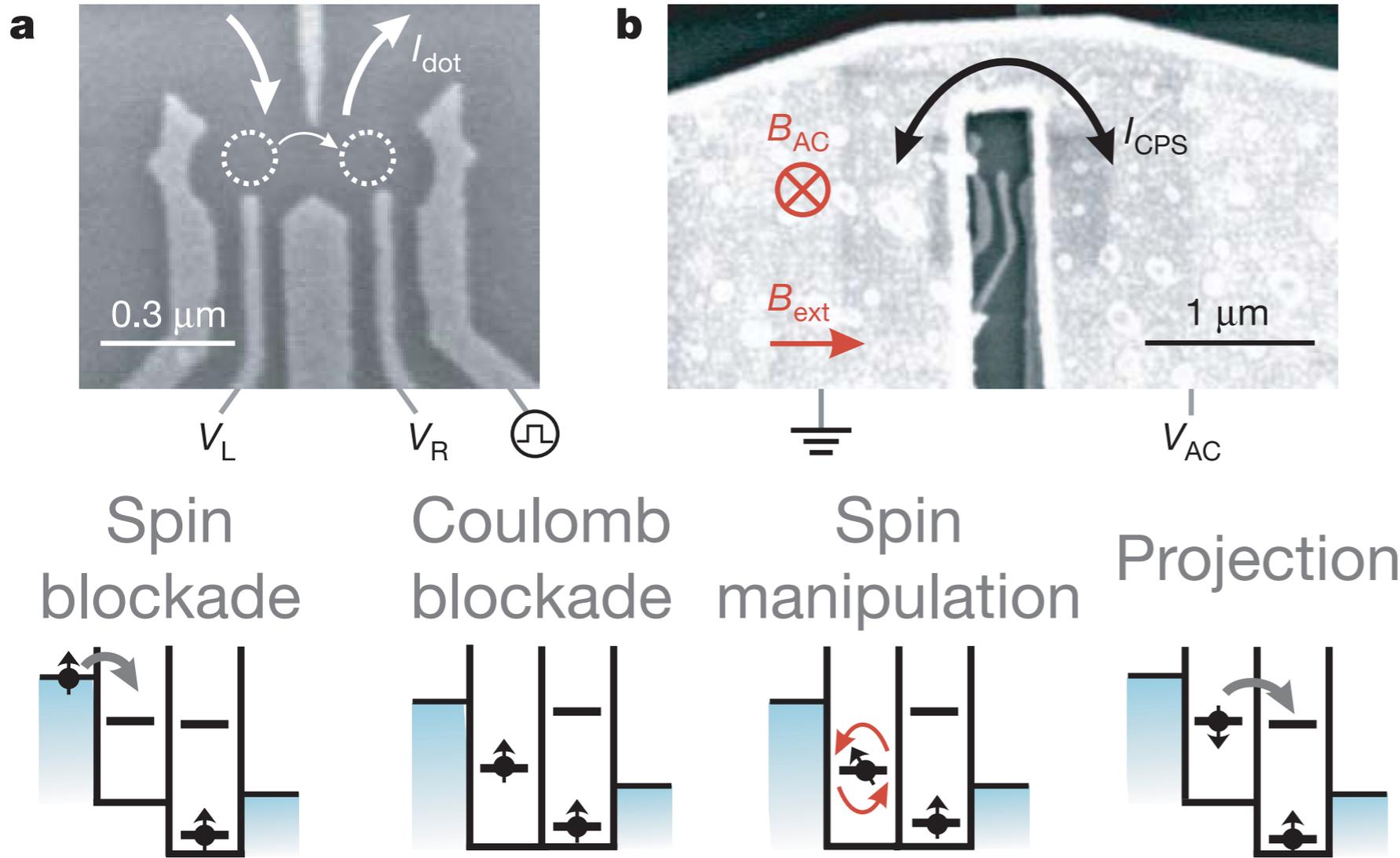
Spin qubit „inicializálás és kiolvasás”

Koppens et al., Nature 2006



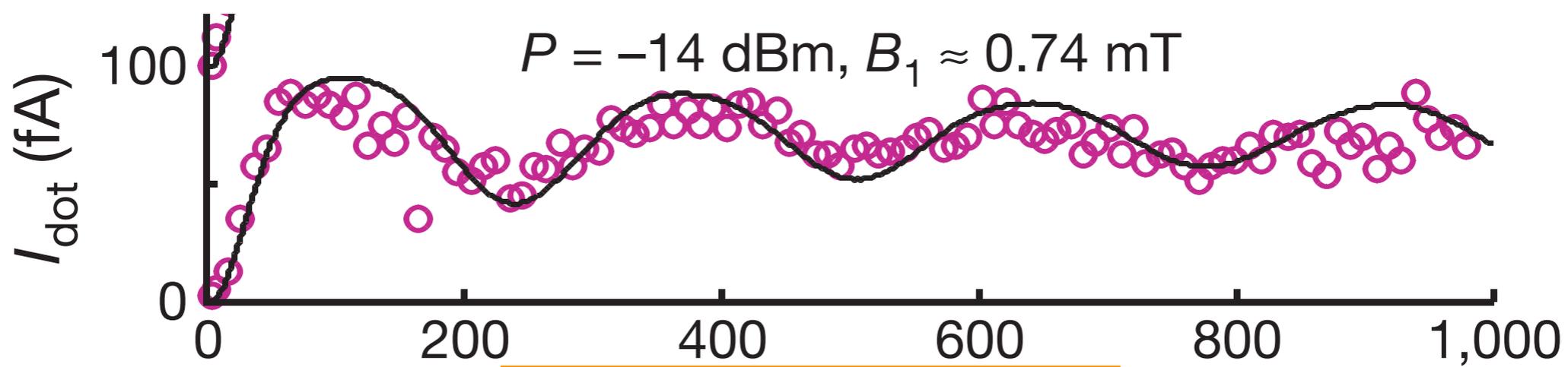
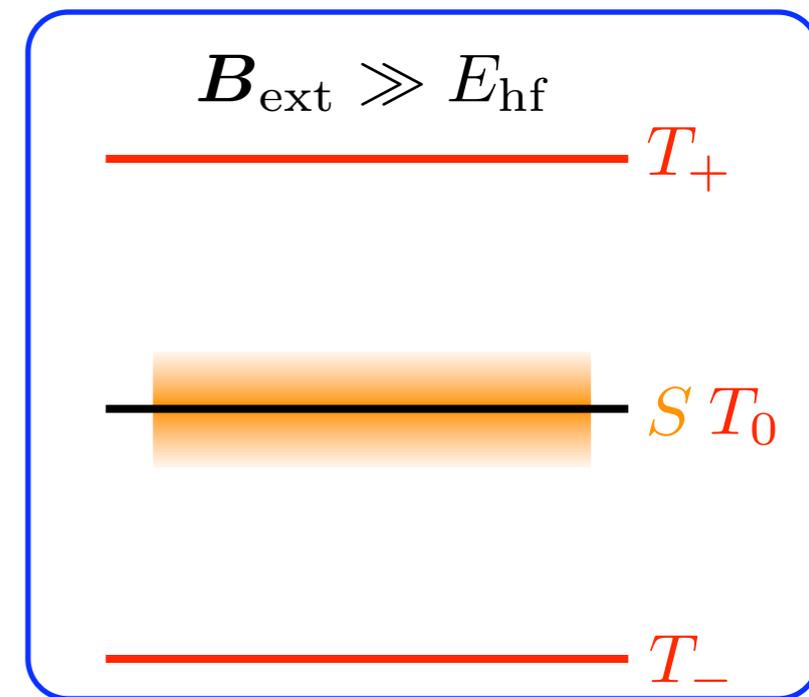
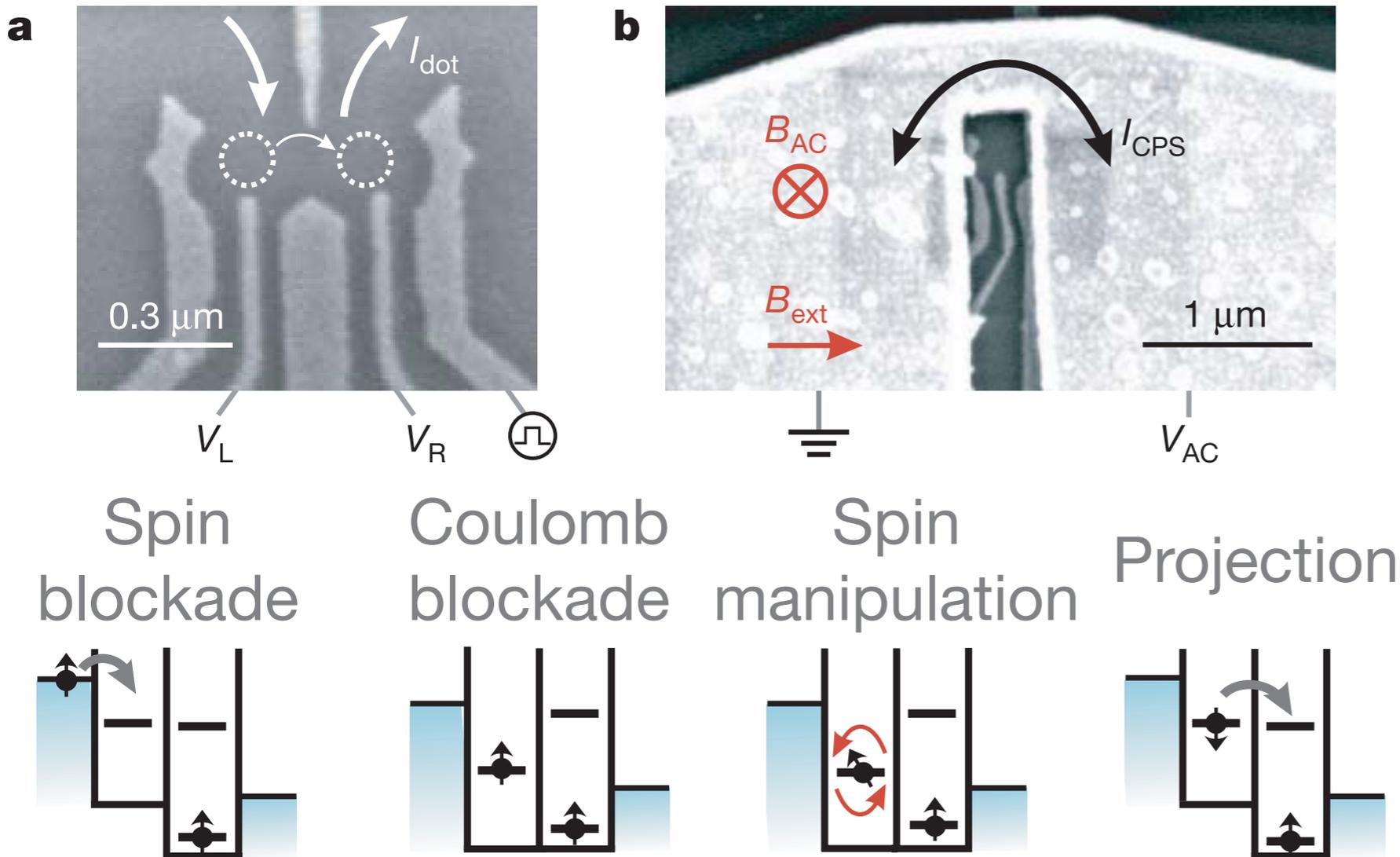
Spin qubit „inicializálás és kiolvasás”

Koppens et al., Nature 2006



Spin qubit „inicializálás és kiolvasás”

Koppens et al., Nature 2006

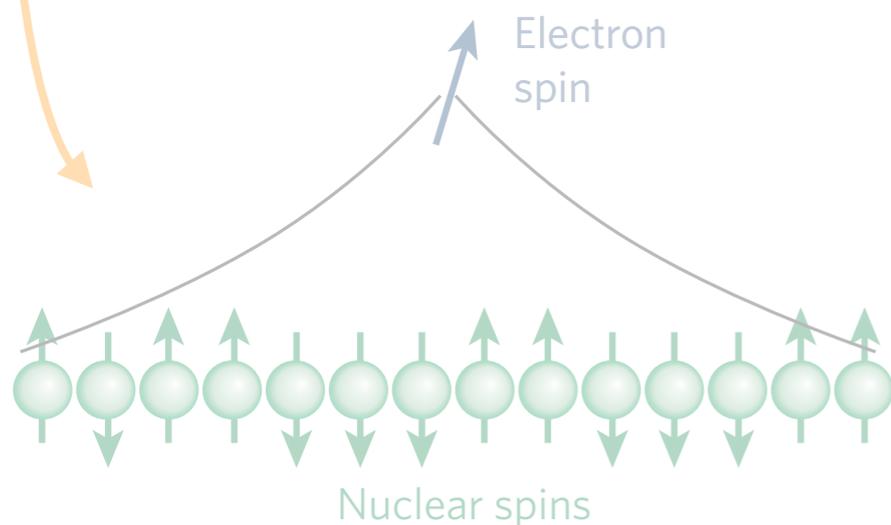


~ spinforgatás szöge

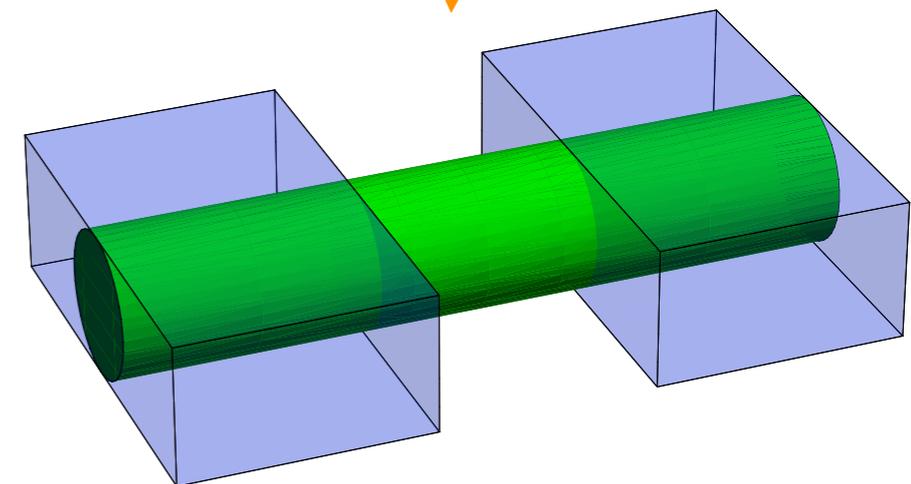
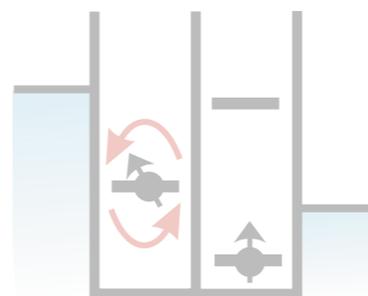
Tartalom

(Spinblokádkettős kvantumdotokban)

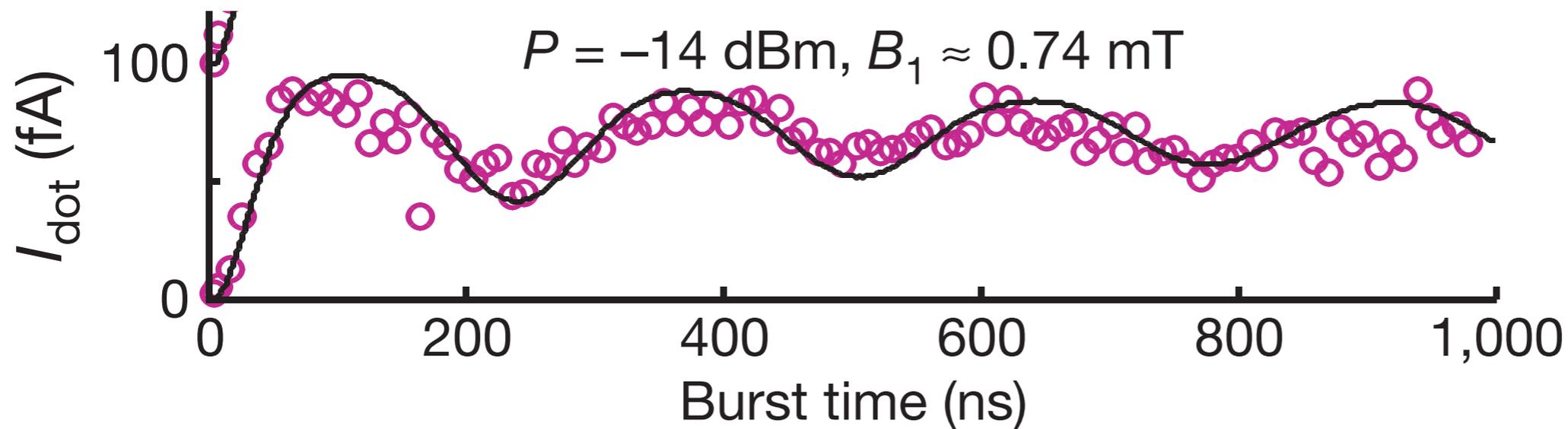
- “szonda”: hiperfinom kölcsönhatás
- spin qubit inicializálás és kiolvasás
- kitekintés: szén-alapú kvantumdotok



Spin manipulation



Szén-alapú kvantumdotok - Motiváció



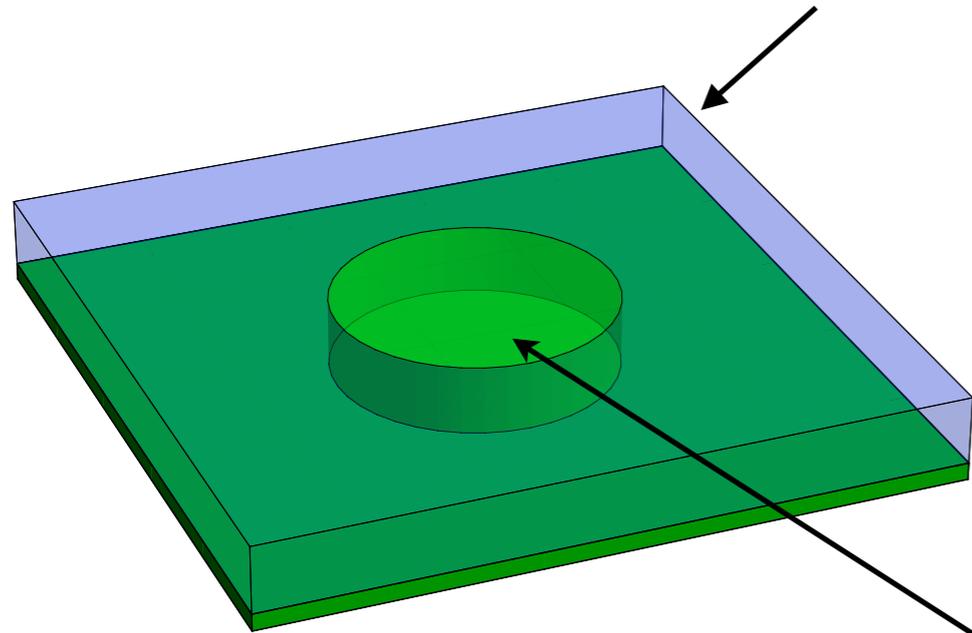
dekoherencia:
véletlen magspin-konfigurációk

Stratégiák a dekoherenciával szemben

- 1) magspinek kontrollja
- 2) zérus magspinű anyagok (C, Si, Ge)

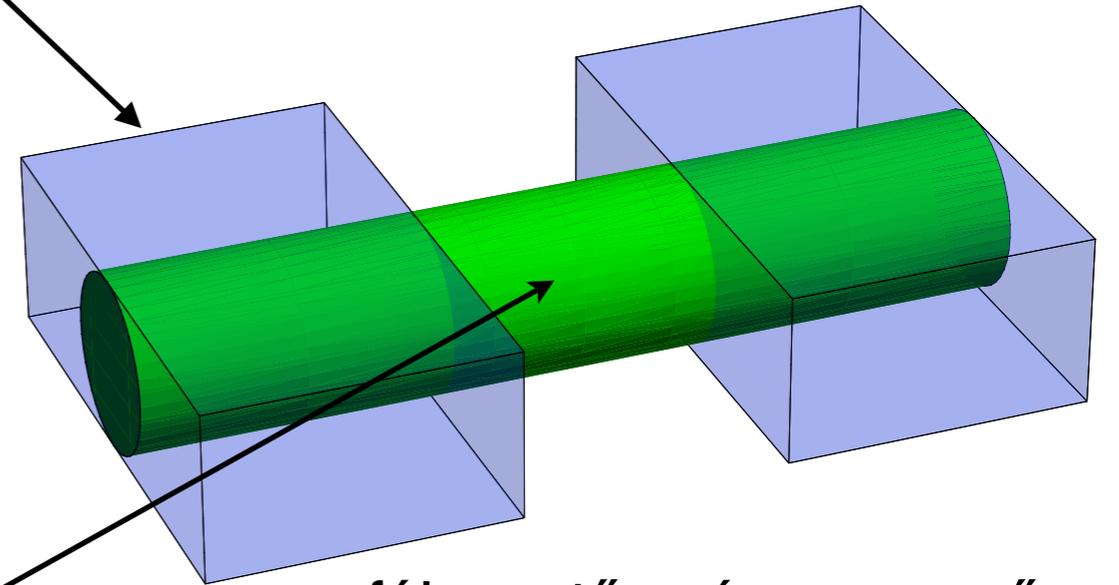
Szén-alapú kvantumdotok

elektrosztatikus potenciálgát



grafén (tiltott sávval)

elmélet: Recher et al. PRB 2009

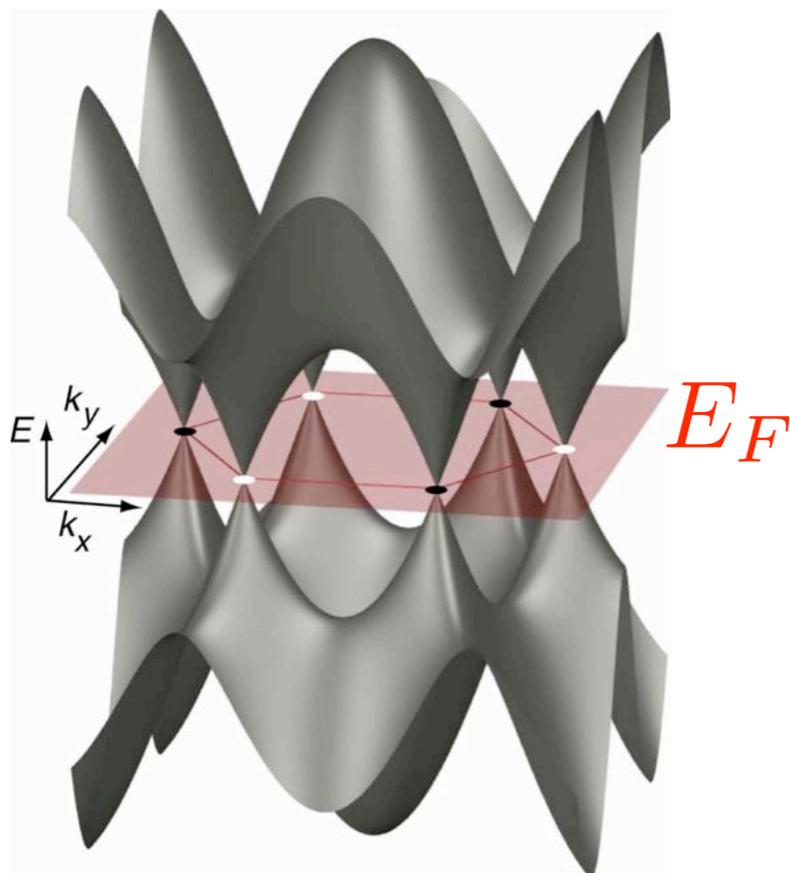


félvezető szén-nanocső

kísérlet: Cornell, Delft, Harvard, Basel,...

energiaszintek:

spin és „völgy” (valley) degeneráció



Melyik az optimális qubit?

- 1) spin?
- 2) valley?
- 3) a kettő kombinációja?