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Multi-electron Double Quantum Dot Spin Qubits

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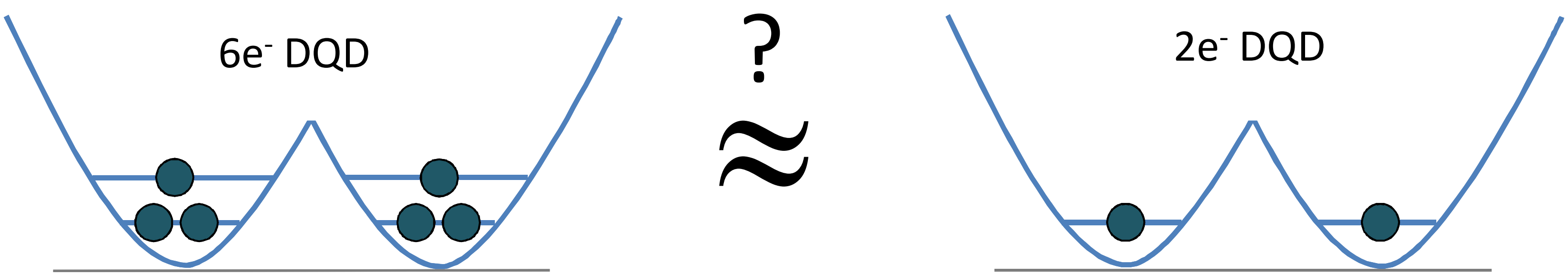
Background

- Double quantum dots (DQDs) as qubits
  - **Charge qubit:** **1** electron, $|L\rangle$ and $|R\rangle$
  - **Spin qubit:** **2** electrons, $|S\rangle$ and $|T\rangle$
  - **? Spin qubit:** **N** electrons, N even, $|S\rangle$ and $|T\rangle$ **?** (E.g. N=6)
- **Central Question of this talk:**



* 2 e- fill lowest "shell" of dot (single valley assumption)

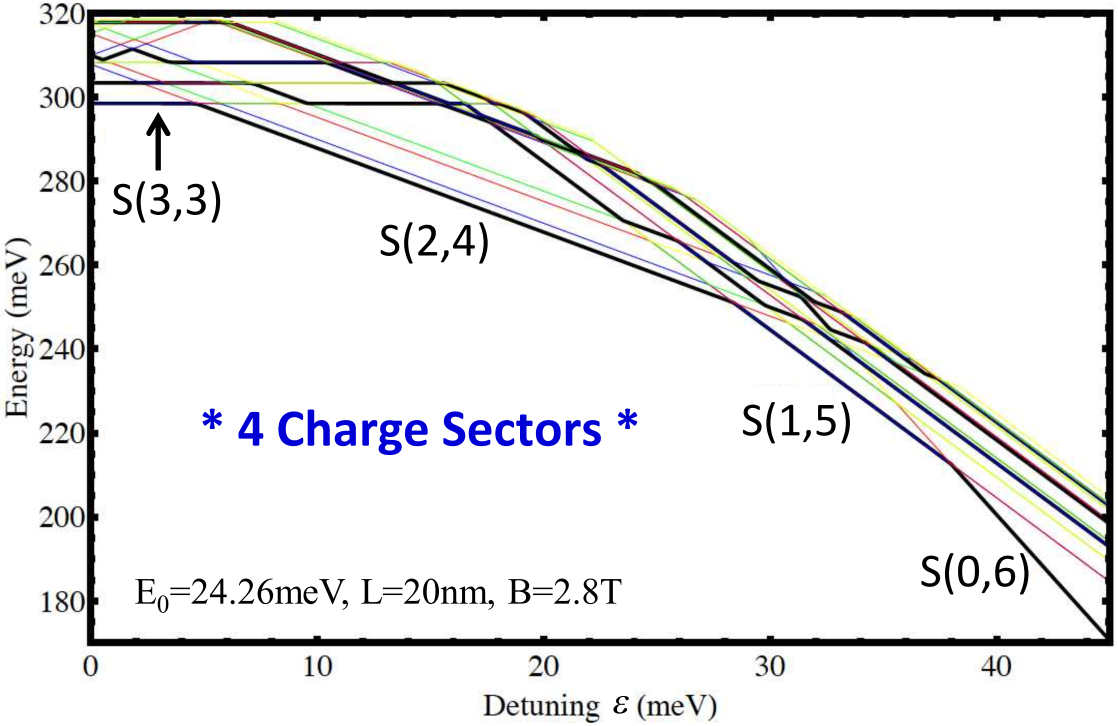
Motivation

Why many-electron DQD qubits?

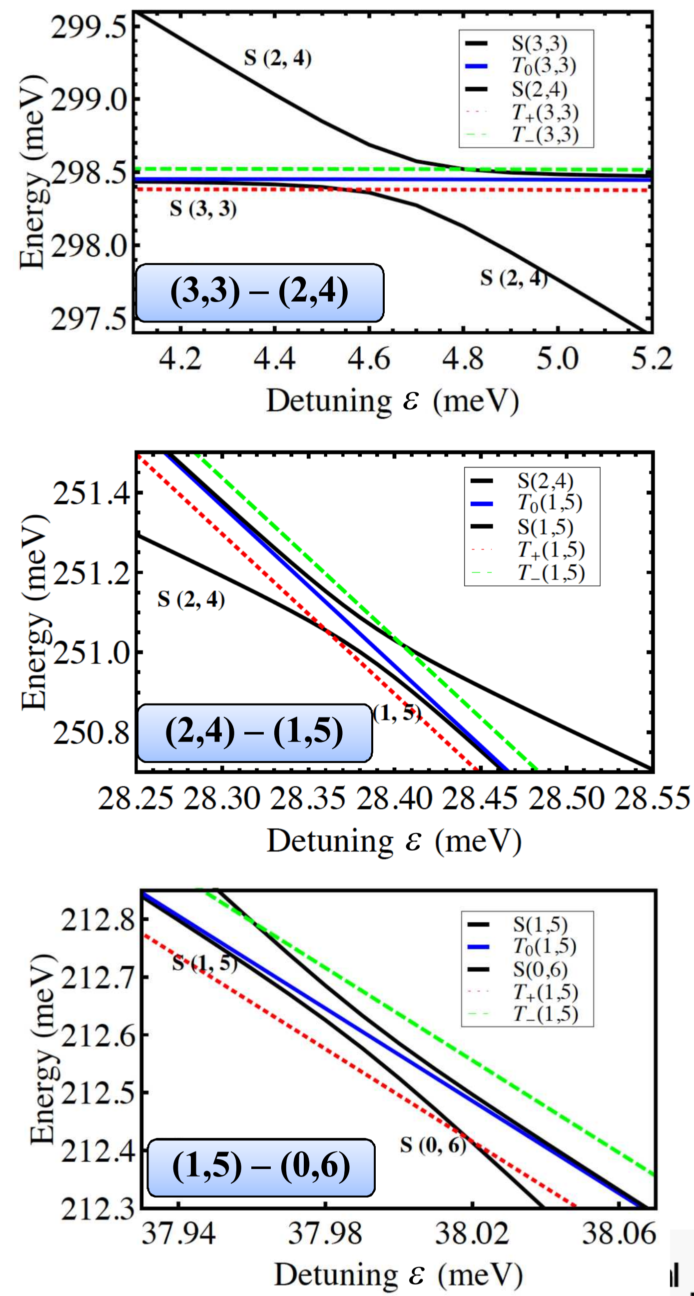
- **Charge Impurities & Noise** [Barnes et al., PRB **84,** 235309 (2011)]
- **Easier** to realize
- Richer **Manipulation**?
- More **robust** to control noise / systematic error?

$6e^-$ small-dot DQD

(representative system)



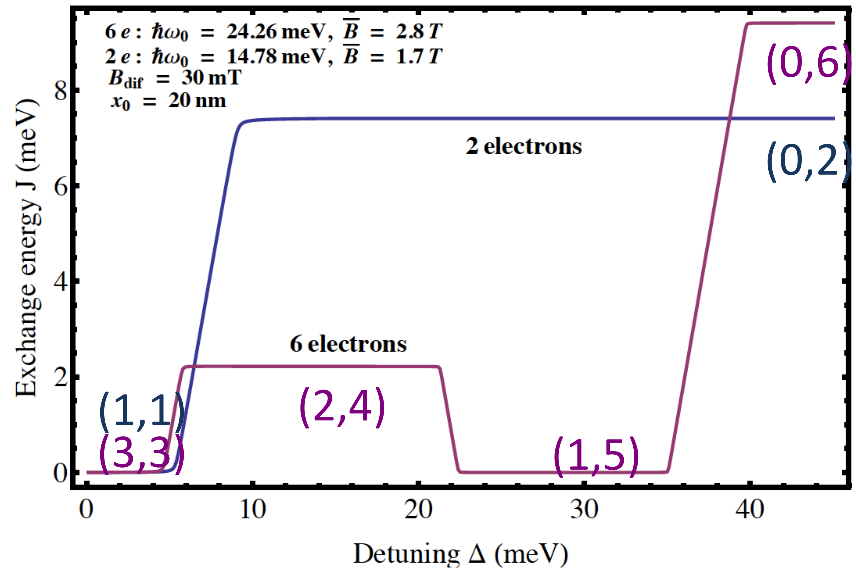
Zoom to avoided crossings



- Singlet and unpolarized triplet **isolated ground space**
- **Init & read-out**: Regions with order **meV splitting**
- **Manipulation**: **smooth** avoided crossings

Comparison: 6e⁻ vs. 2e⁻

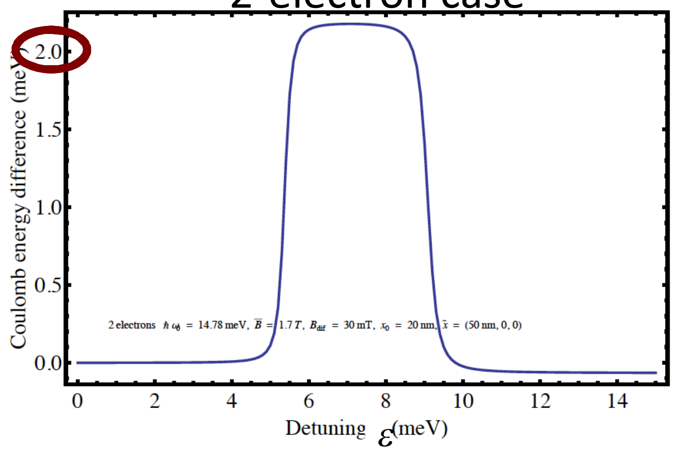
- **Exchange energy (qubit z-rotation)**



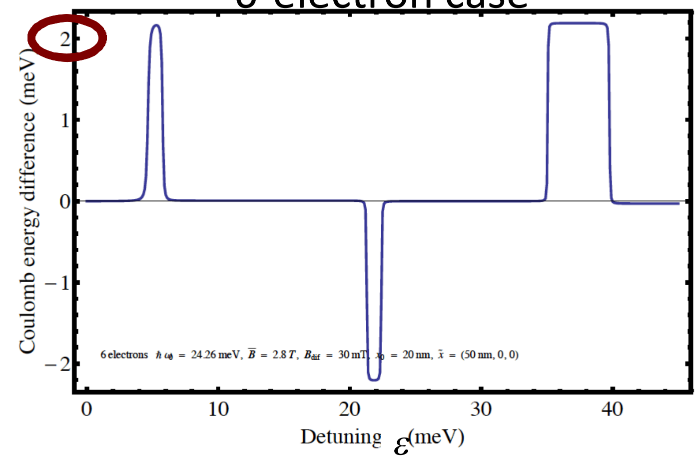
6e has **two** plateaus

- **Charge sensor sensitivity to the dot state**

2-electron case



6-electron case

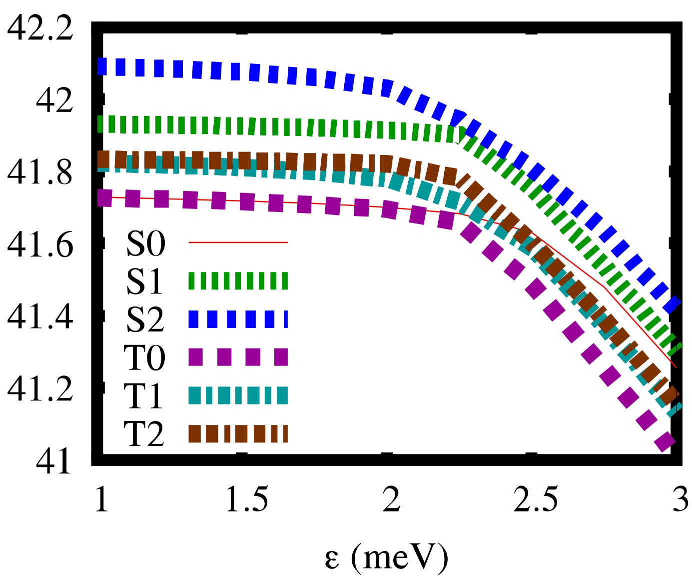


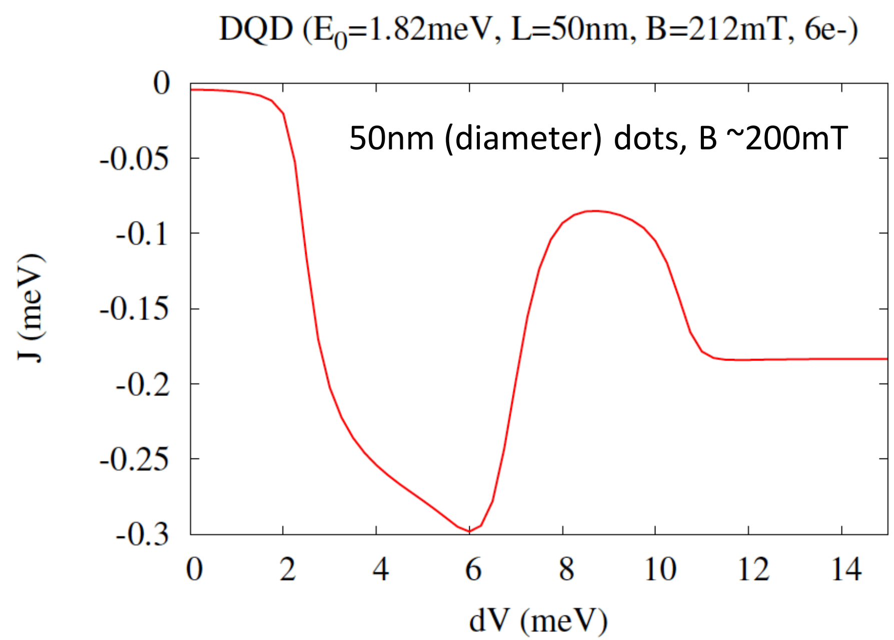
Same order of magnitudes – as nice as a 2e qubit

What about **larger dots**
(what can go wrong?)

When dot size is larger:

- Dots could merge together (but easy to keep **dots separated**)
- Smaller optimal magnetic fields for tuning J may conflict with B needed to split triplets
- **Orbitals gaps are smaller:**
  - **Shell-filling picture breaks down; becomes a strongly correlated double-dot system**
  - **Intervening levels (e.g. multiple triplets below a singlet) / loss of isolated qubit space**
  - **Non singlet (or triplet) ground states?**





Conclusion

6e DQDs are theoretically viable as qubits:

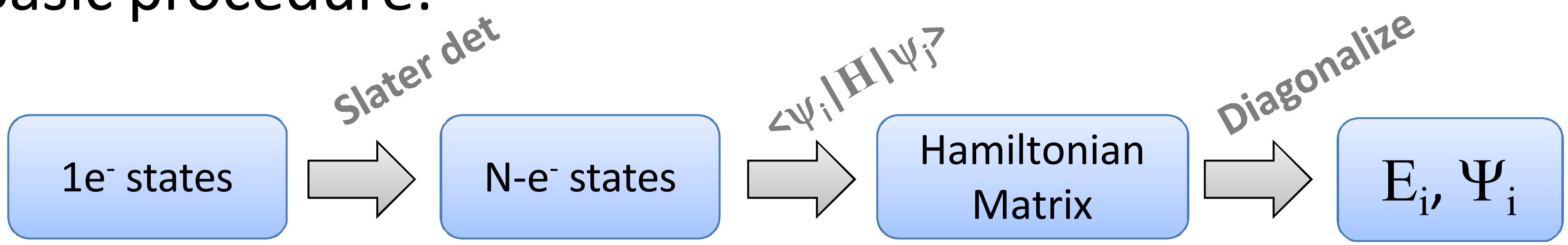
- **Initialization**, **manipulation**, and **read-out** are similar to the 2e case, and are **no harder to perform** (perhaps easier)
- They are **more robust to random charge** impurities & charge noise (they screen better)
- They may offer **richer control capability**, depending on the tunable range of the DQD, perhaps resulting in increased robustness to control noise.
- Caveat: dots cannot be *too* big (25-50nm diameter GaAs dots are borderline but ok; Silicon dots?)

Method: Configuration Interaction

- Solve many-electron Hamiltonian

$$\mathcal{H} = \sum_i^n \mathcal{H}_i + \sum_{i<j} \frac{e^2}{\kappa |r_i - r_j|} \qquad \mathcal{H}_i = \frac{(\vec{p} - e\vec{A})^2}{2m^*} + V(\vec{r}) + \frac{e}{m^*}\vec{S}\cdot\vec{B}$$

- Basic procedure:



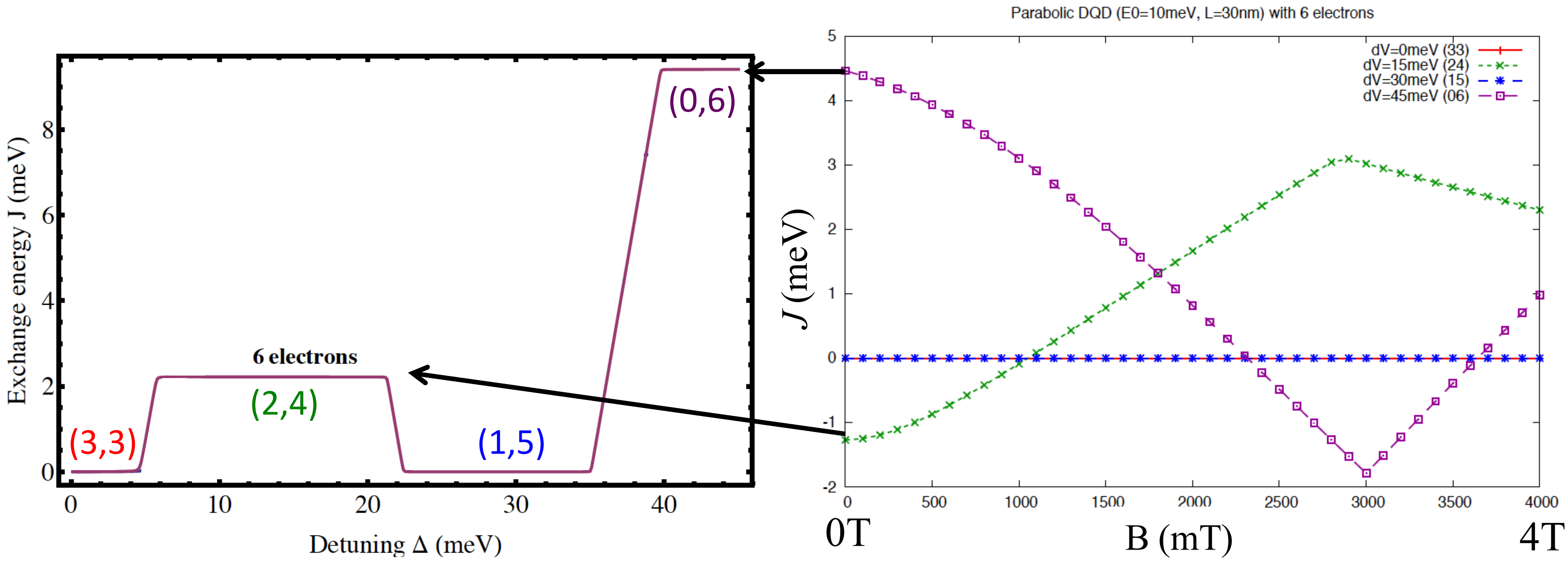
- We use two independent implementations:
  - **CI-1**: 1e- states = **Fock Darwin** states at dot center

$$\phi^{\pm}_{nm}(x,y) = \frac{1}{\ell_0}\sqrt{\frac{\left(\frac{n-|m|}{2}\right)!}{\pi\left(\frac{n+|m|}{2}\right)!}}\left(\frac{x \pm x_0 + iy\,\mathrm{sgn}\,m}{\ell_0}\right)^{|m|} \times e^{-\frac{(x\pm x_0)^2+y^2}{2\ell_0^2} \pm i\frac{x_0 y}{2\ell_B^2}} L^{|m|}_{\frac{n-|m|}{2}}\left(\frac{(x\pm x_0)^2+y^2}{\ell_0^2}\right)$$

  - **CI-2**: 1e- states = **s-type Gaussians** at different centers

$$g(x,y) = N e^{-\alpha_x (x-x_0)^2} e^{-\alpha_y (y-y_0)^2} \times e^{\frac{ieB}{2\hbar}(y_0 x - x_0 y)},$$

J-Plateaus: tunable with B-field

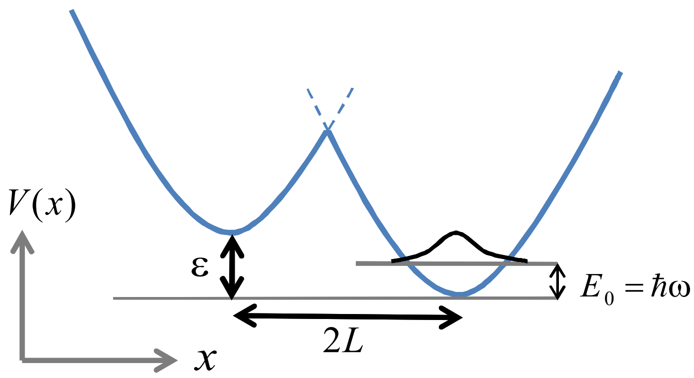


- Exchange energy **plateaus are tunable** by varying the magnetic field.
- **Two plateaus** could be useful for:
  - Separate **initialization** and **rotation plateaus** (want different O(magnitudes))
  - **Multiple speeds** of rotation = more possibilities for dynamical correction

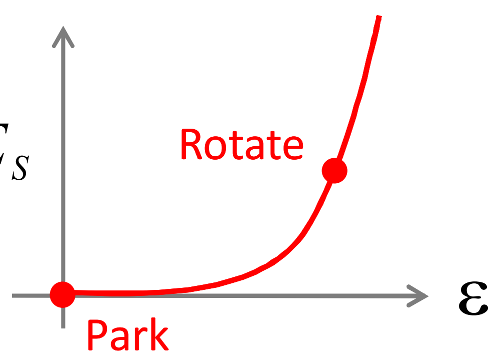
2-electron Spin DQD qubits

Splitting btwn $|S\rangle$ and $|T\rangle$ = **exchange energy *J*** = rate of qubit ***z*-rotation**

DQD potential (min of parabolas):



$$J = E_T - E_S$$



Example: E0 = 14.78meV, L=20nm, B=1.7T