Title: Indirect spin-spin interactions with Rydberg molecules

Speakers: Hossein Sadeghpour

Collection: Cold Atom Molecule Interactions (CATMIN)

Date: July 14, 2022 - 9:40 AM

URL: https://pirsa.org/22070005

Abstract: Simulation of quantum magnetism with AMO systems is now a fully fledged enterprise. In this talk, I will discuss how Rydberg molecular interactions can be exploited to simulate indirect spin-spin coupling, with Rydberg atoms acting as localized impurities. Engineering chiral spin Hamiltonians with Rydberg atoms is also described.

Indirect quantum magnetism

H. R. Sadeghpour

CATMIN- Waterloo, July 14, 2022

Indirect quantum magnetism

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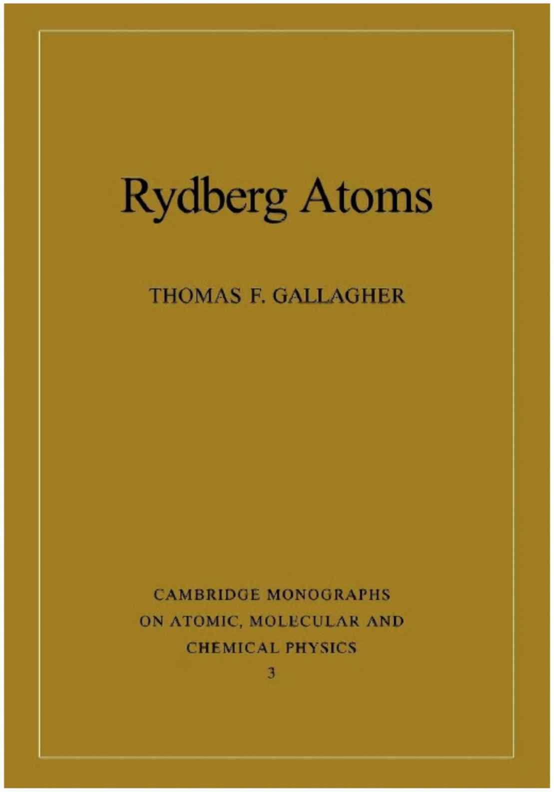
Rydberg Atoms
THOMAS F. GALLAGHER
CAMBRIDGE MONOGRAPHS
ON ATOMIC, MOLECULAR AND
CHEMICAL PHYSICS
3

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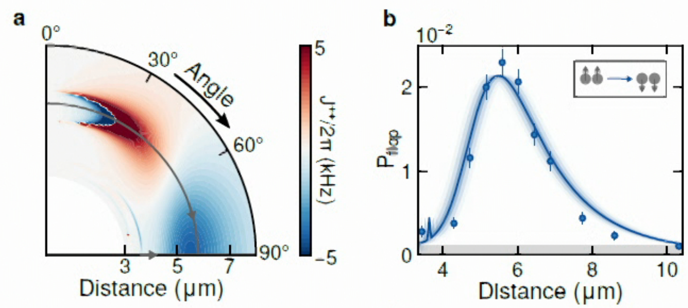
Spatially programmable spin interactions in neutral atom arrays

Lea-Marina Steinert,[1,2,3,*] Philip Osterholz,[1,2,3] Robin Eberhard,[1,2] Lorenzo Festa,[1,2]
Nikolaus Lorenz,[1,2] Zaijun Chen,[1,2] Arno Trautmann,[1,2,3] and Christian Gross[1,2,3]

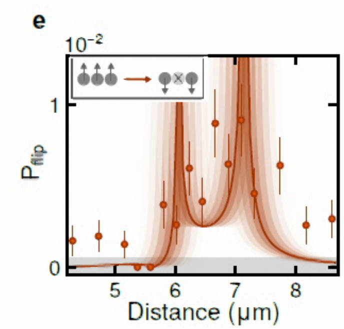
$$\hat{H}_{\mathrm{XYZ}} = \hbar \sum_{i<j} (J_{ij}^{z} \hat{\sigma}_i^z \hat{\sigma}_j^z + J_{ij}^{++} \hat{\sigma}_i^+ \hat{\sigma}_j^+ + J_{ij}^{+-} \hat{\sigma}_i^+ \hat{\sigma}_j^-) + h.c.$$

J_{ij}^{z} diagonal (Ising)

J_{ij}^{++} off – diagonal (flop – flop)



J_{ij}^{+-} off – diagonal (flip – flop)

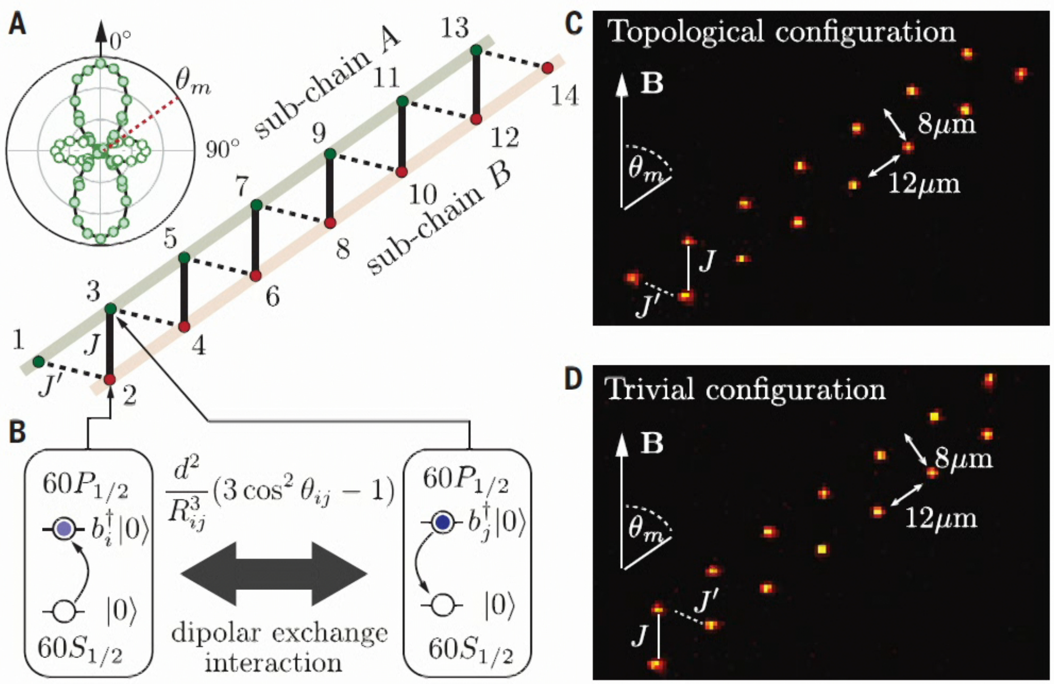


RESEARCH ARTICLE

QUANTUM SIMULATION

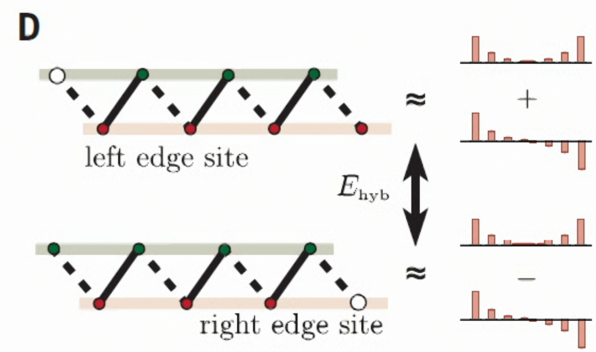
Observation of a symmetry-protected topological phase of interacting bosons with Rydberg atoms

Sylvain de Léséleuc[1*†], Vincent Lienhard[1*], Pascal Scholl[1], Daniel Barredo[1], Sebastian Weber[2*], Nicolai Lang[2*], Hans Peter Büchler[2], Thierry Lahaye[1], Antoine Browaeys[1]

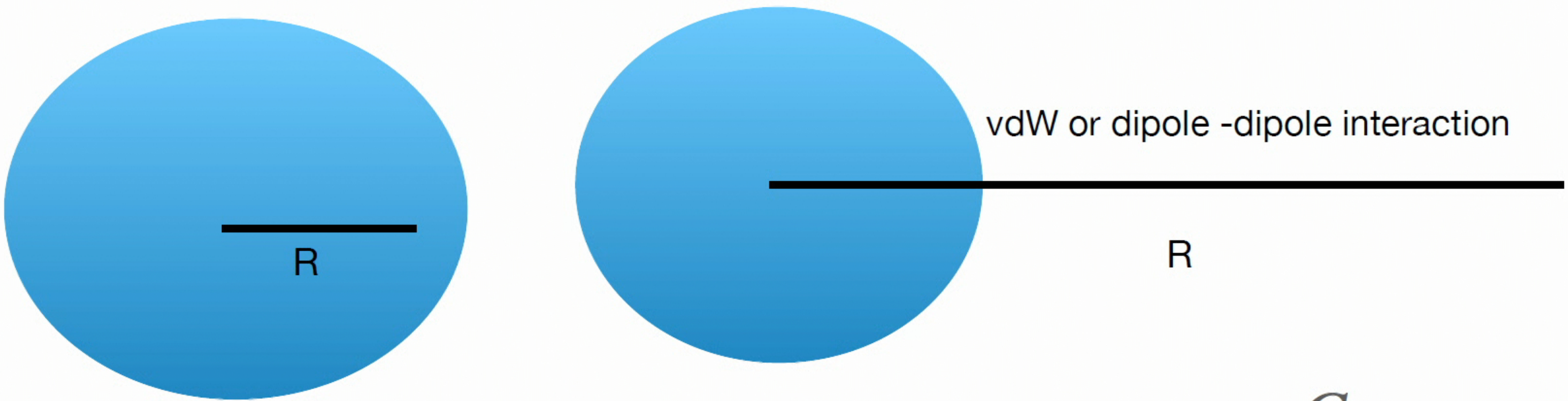


XY Hamiltonian

$$H = -\sum_{i\in A, j\in B} J_{ij}[b_i^\dagger b_j + b_j^\dagger b_i]$$



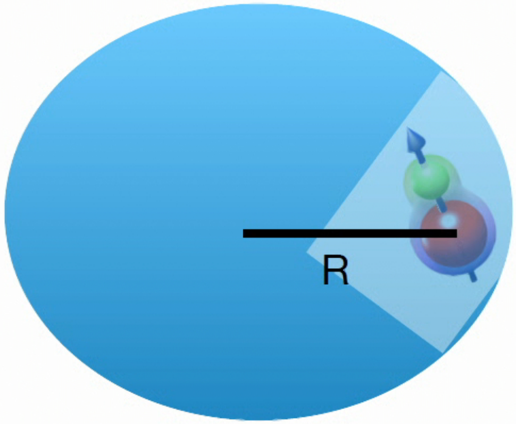
NO has a small permanent electric dipole moment, d~0.15 D

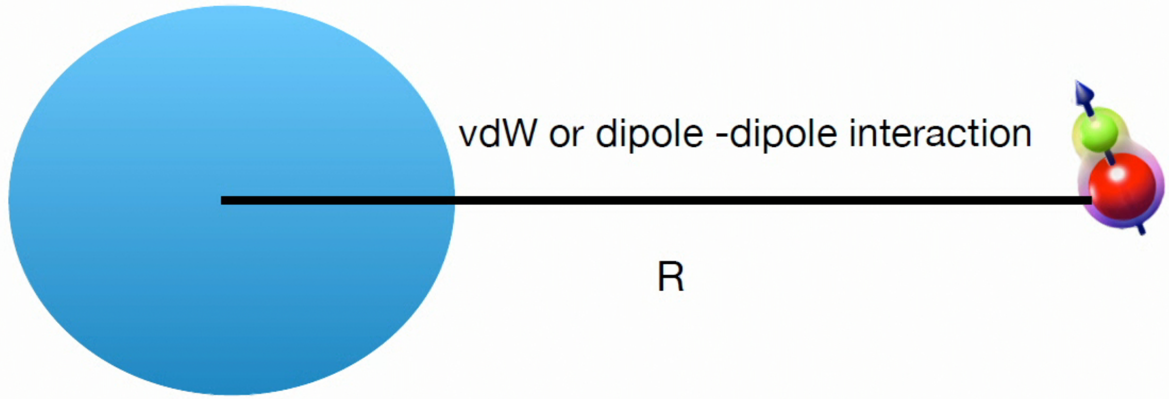


Netural and charged scattering occur

$$\frac{C_6}{R^6}$$

NO has a small permanent electric dipole moment, d~0.15 D

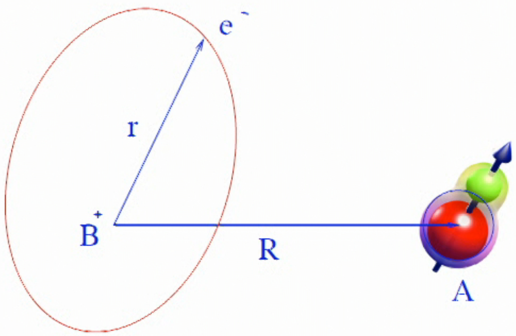


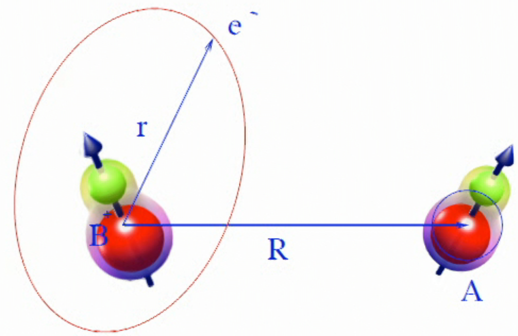


Netural and charged scattering occur

$$\frac{C_6}{R^6}$$

Rydberg orbit interactions





e- - dipole interaction

$$V_{ed}(\mathbf{r}-\mathbf{R}) = B\mathbf{N}^2 - \mathbf{d}\cdot\mathbf{F}(\mathbf{r}-\mathbf{R})$$

$$F = \frac{\mathbf{d}\cdot(\mathbf{R}-\mathbf{r})}{|\mathbf{R}-\mathbf{r}|^3}$$

- long-range anisotropic interaction

Electron scattering

$$2\pi a_S(k)\delta(\mathbf{r}-\mathbf{R}) + 6\pi a_P^3(k)\delta(\mathbf{r})\overleftarrow{\nabla}\cdot\overrightarrow{\nabla}$$

- short-range channel interaction

Rosario will elborate much more later today ….

$$\sum_{i\neq j\alpha,\beta=x,y,z} J_{ij}^{\alpha\beta}\,\hat{S}_i^{\alpha}\,\hat{S}_j^{\beta}$$

Symmetric:

$$\sum_{i\neq j\alpha,\beta=x,y,z} \frac{J_{ij}^{\alpha\beta}+J_{ij}^{\beta\alpha}}{2}\left(\hat{S}_i^{\alpha}\hat{S}_j^{\beta}+\hat{S}_i^{\beta}\hat{S}_j^{\alpha}\right)$$

[Heisenberg, XXZ, RKKY (Ruderman–Kittel–Kasuya–Yosida)]

Anti-symmetric:

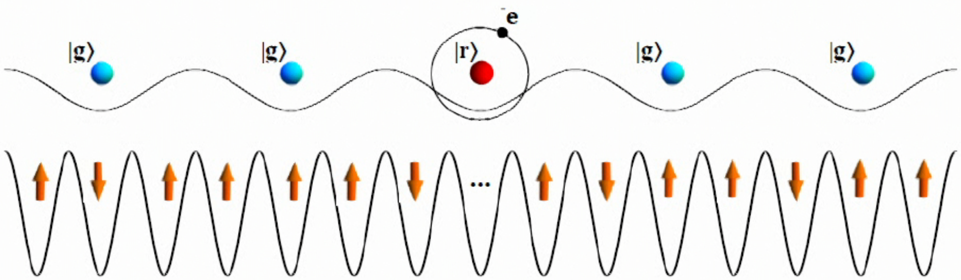
$$\sum_{i\neq j\alpha,\beta=x,y,z} \frac{J_{ij}^{\alpha\beta}-J_{ij}^{\beta\alpha}}{2}\left(\hat{S}_i^{\alpha}\hat{S}_j^{\beta}-\hat{S}_i^{\beta}\hat{S}_j^{\alpha}\right)$$

[Dzyaloshinsky–Moriya] …. Spin texture, chirality, …

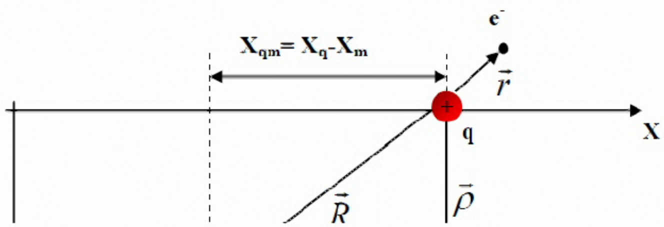
Lena Kuznetsova

Seth Rittenhouse

Susanne Yellin



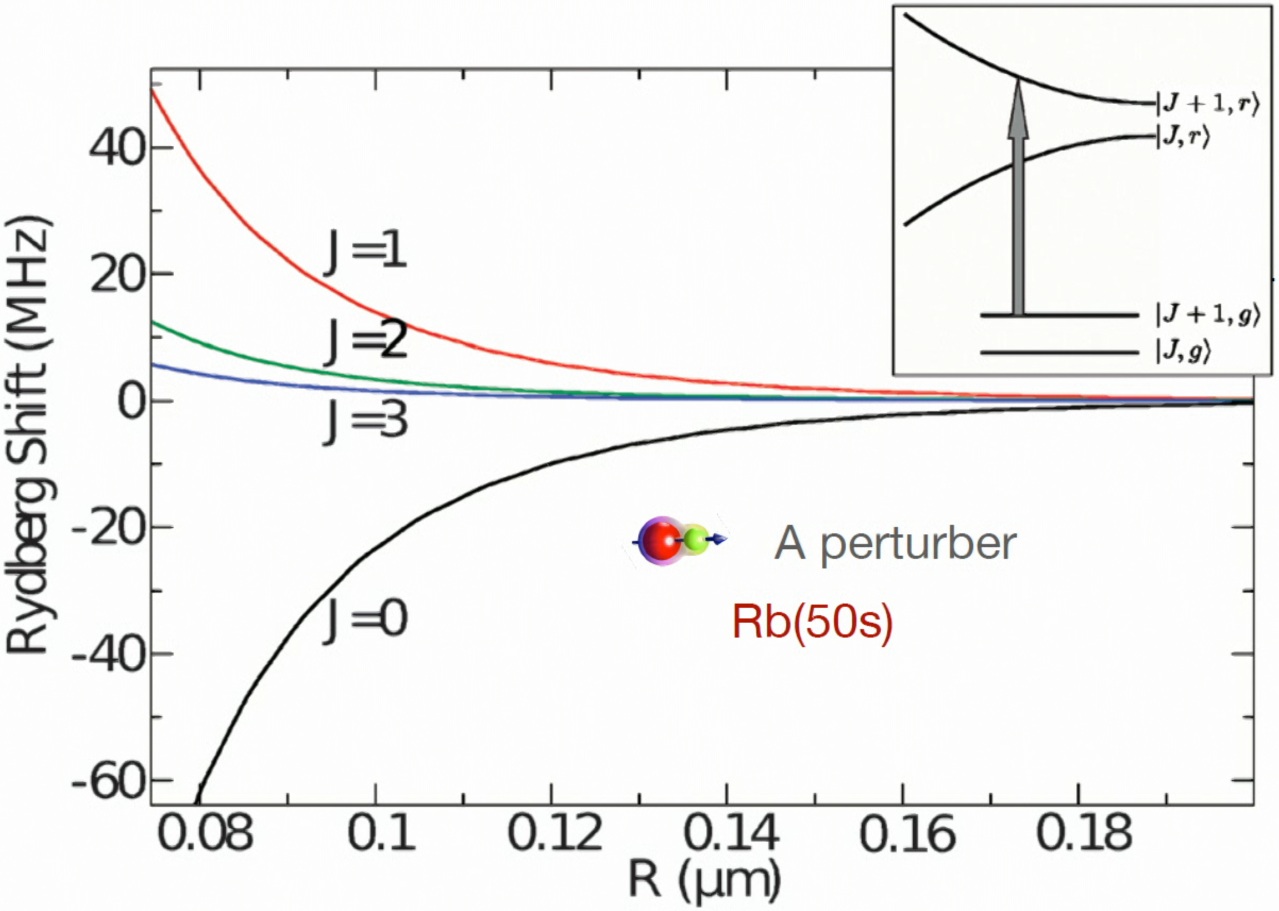
(a)



$$H_{JJ'} = B\frac{J(J+1)}{2}\delta_{J,J'} - \langle J|\vec{F}_{\rm Ryd}\cdot\vec{d}_0|J'\rangle$$

$$\vec{F}_{\rm Ryd} = e\hat{z}\left\langle \psi_{\rm ns}\left|\frac{\cos\theta_{\vec{R},\vec{r}}}{|R\hat{z}-\vec{r}|^2}\right|\psi_{\rm ns}\right\rangle$$

- condition this interaction on the state of Rydberg atom



… a typical polar molecule interacting with a non-degenerate Rydberg atom

$$d_0 \sim 1\ D$$

Quadratic shift of rotational energies

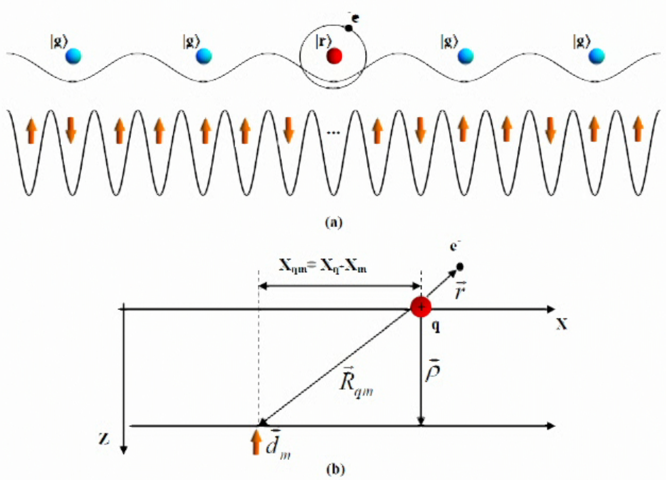
…

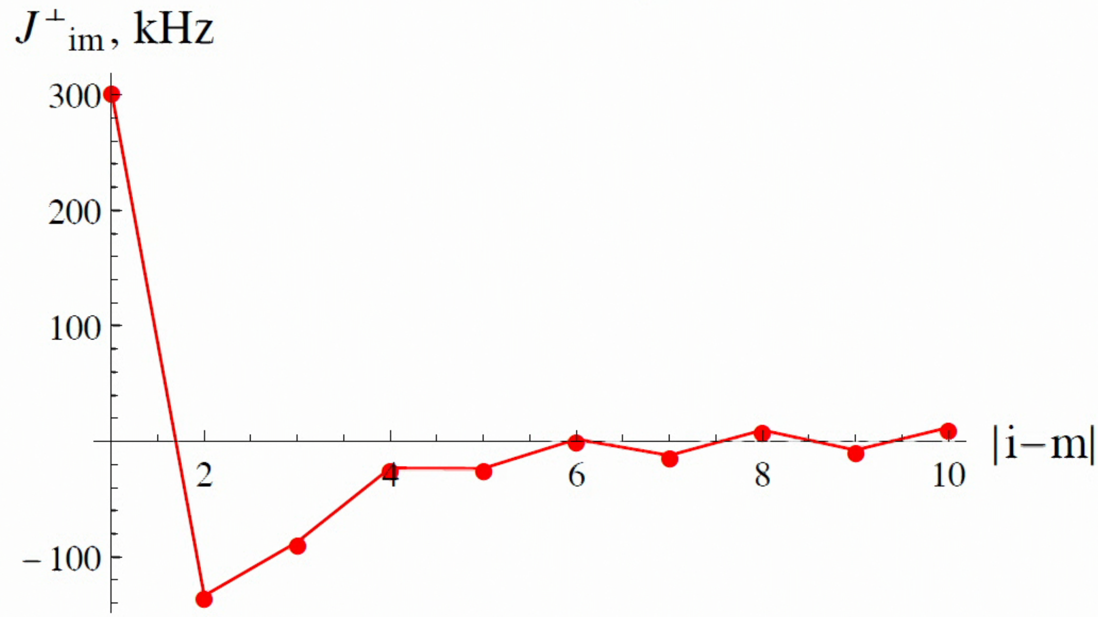
(No rotational mixing)

Simulating “RKKY” Hamiltonian with Rydberg molecules

$$\hat{V}^{ns}_{\text{eff spin}} = \sum_{i,m=1}^{N} \left(J^{zz}_{im} \hat{S}^z_i \hat{S}^z_m + \frac{J^{\perp}_{im}}{2} \left(\hat{S}^+_i \hat{S}^-_m + \hat{S}^-_i \hat{S}^+_m \right) \right) + \sum_{i=1}^{N} b^z_i \hat{S}^z_i,$$

... random magnetization, frustration, etc.

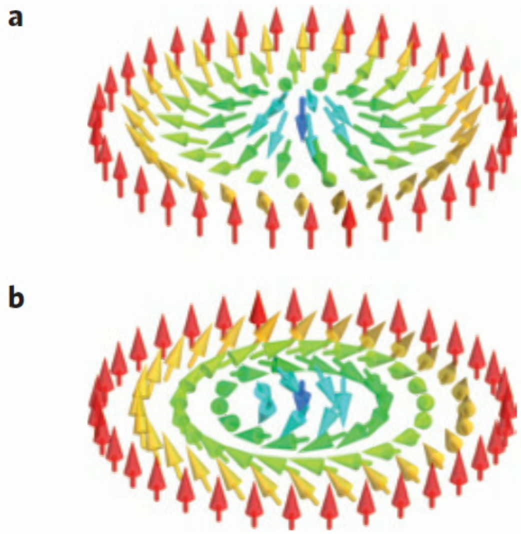


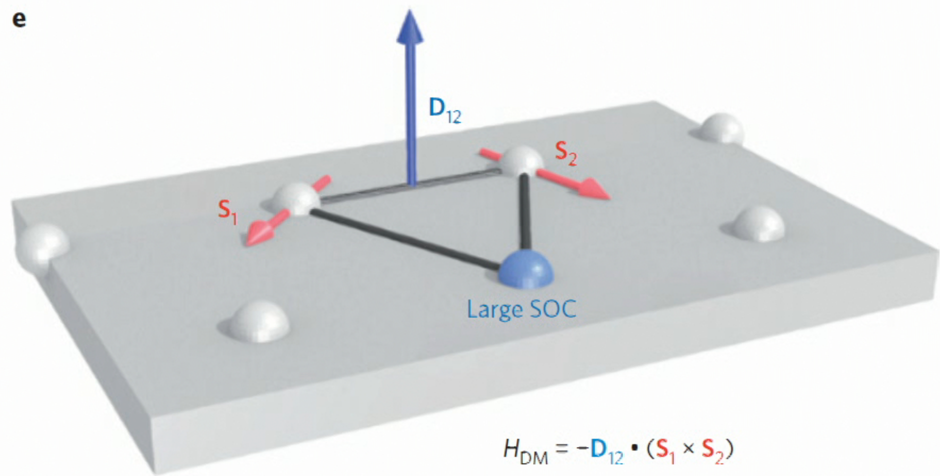


DOI: 10.1103/PhysRevA.98.043609

Quantum magnetization with chiral DMI interaction

Magnetic Skyrmions are chiral spin structures which topologically protected. This is because Skyrmions cannot be continuously deformed into FM or other magnetic states.





Spin chain quantum magnetization with chiral DMI interaction

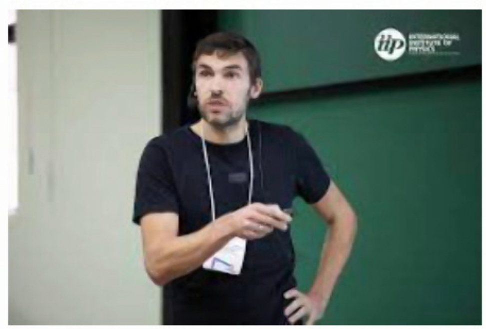
$$H = -J\sum_{i=1}^{N}(\vec{\sigma}_i \cdot \vec{\sigma}_{i+1}) - \vec{D}\cdot\sum_{i=1}^{N}(\vec{\sigma}_i \times \vec{\sigma}_{i+1}) - h\sum_{i=1}^{N}\sigma_i^z,$$

A) DMI with $\overrightarrow{D} = (D_x, 0, 0)$

B) DMI with $\overrightarrow{D} = (0, 0, D_z)$

iRyd

Igor Lesanovsky (Tübingen)

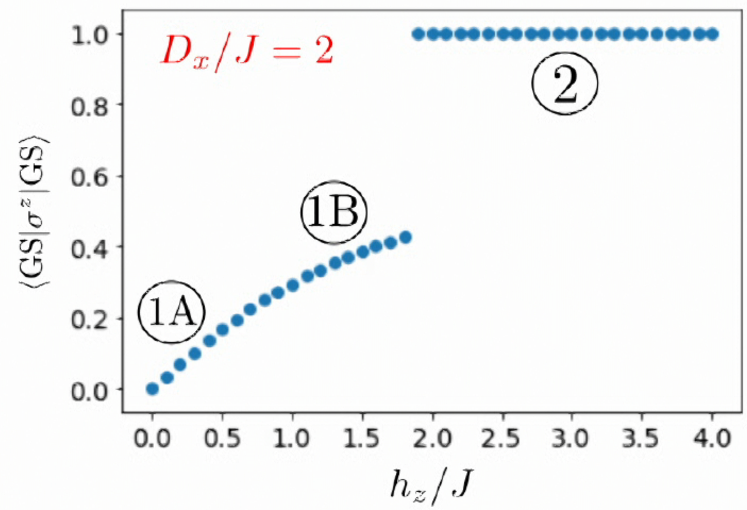


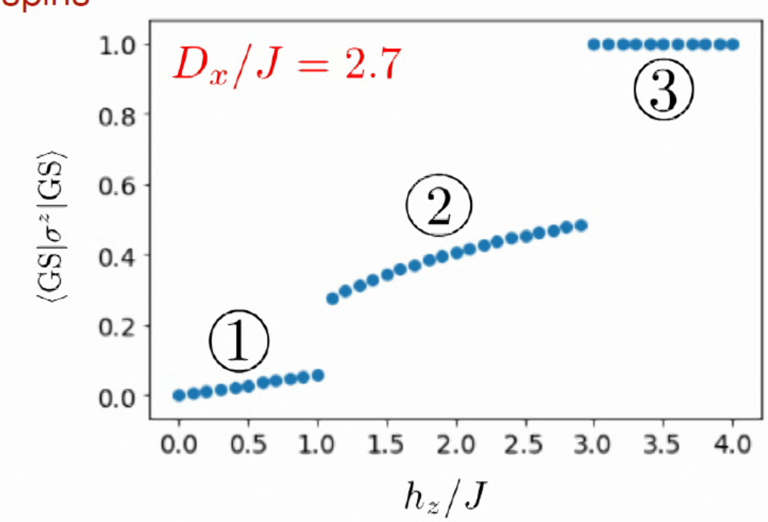
Matteo Magoni - Tübingen/ITAMP

Simos Mistakidis - ITAMP

$$H = -\sum_{i=1}^{N}(\sigma_i^x\sigma_{i+1}^x + \sigma_i^y\sigma_{i+1}^y + \sigma_i^z\sigma_{i+1}^z) - D_x\sum_{i=1}^{N}(\sigma_i^y\sigma_{i+1}^z - \sigma_i^z\sigma_{i+1}^y) - h\sum_{i=1}^{N}\sigma_i^z$$

N=8 spins





(1A) $\propto |\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\rangle$: 2 domain walls

(1B) $\propto |\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\rangle$: 2 domain walls

(2) = fully polarized state

(1) $\propto |\uparrow\uparrow\downarrow\downarrow\uparrow\uparrow\downarrow\downarrow\rangle$: 4 domain walls

(2) $\propto |\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\rangle$: 2 domain walls

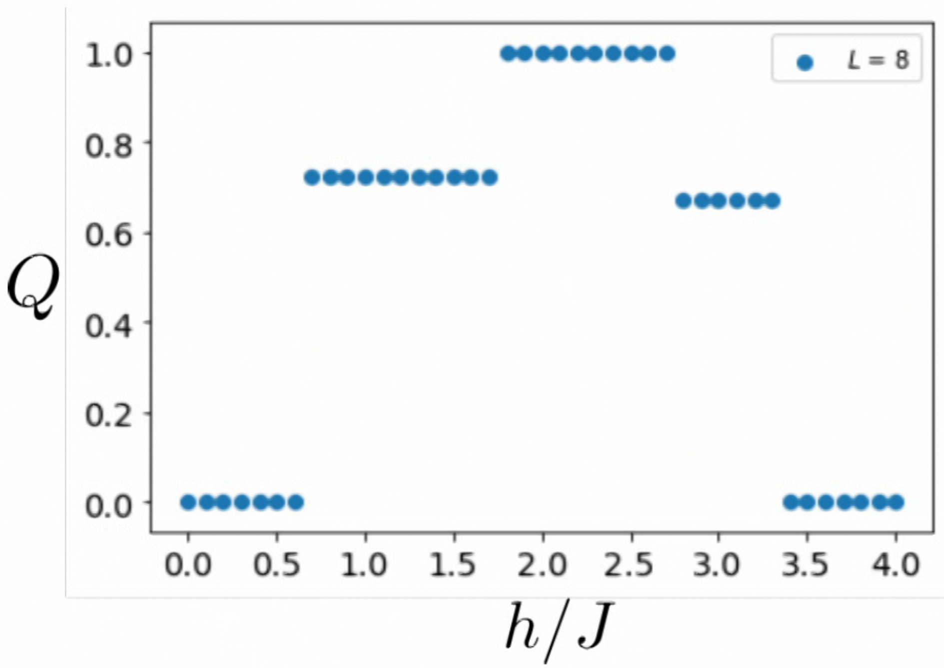
(3) = fully polarized state

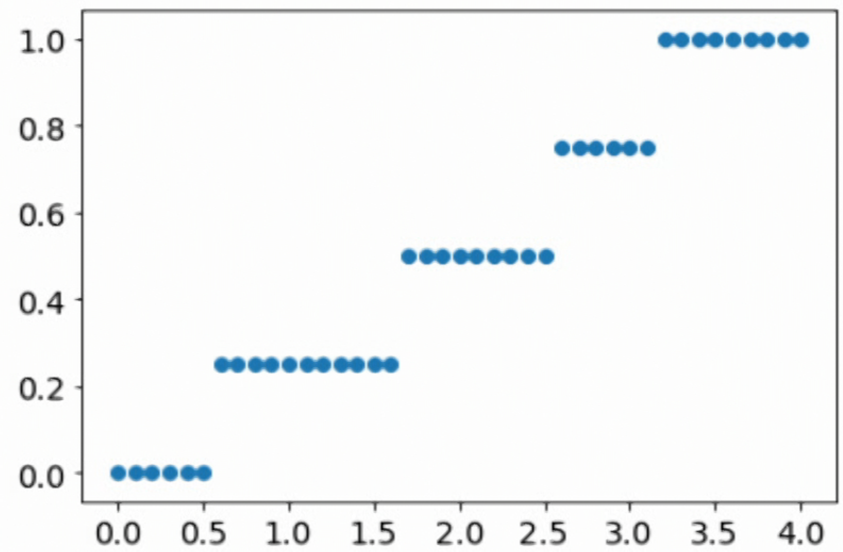
B) DMI with $\overrightarrow{D} = (0,0,D_z)$

$$H = -\sum_{i=1}^{N}(\sigma_i^x \sigma_{i+1}^x + \sigma_i^y \sigma_{i+1}^y + \sigma_i^z \sigma_{i+1}^z) - D_z \sum_{i=1}^{N}(\sigma_i^x \sigma_{i+1}^y - \sigma_i^y \sigma_{i+1}^x) - h \sum_{i=1}^{N} \sigma_i^z$$

… a measure of chirality

$$Q = \overrightarrow{\sigma}_i \cdot (\overrightarrow{\sigma}_j \times \overrightarrow{\sigma}_k)$$





Same as XY hamiltonian with h_z, but then Q=0

Friedel (1952)

“The distribution of electrons round impurities in monovalent metals”

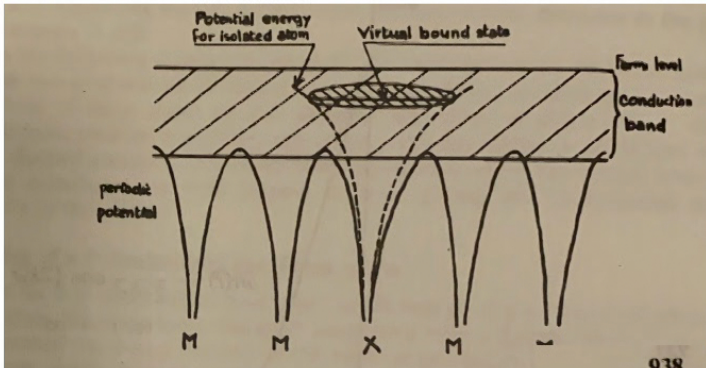


Fig. 2. Virtual d level on X in MX.

Virtual bound states

10.1. General

LOCALIZED STATES IN DILUTE ALLOYS

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J. Friedel

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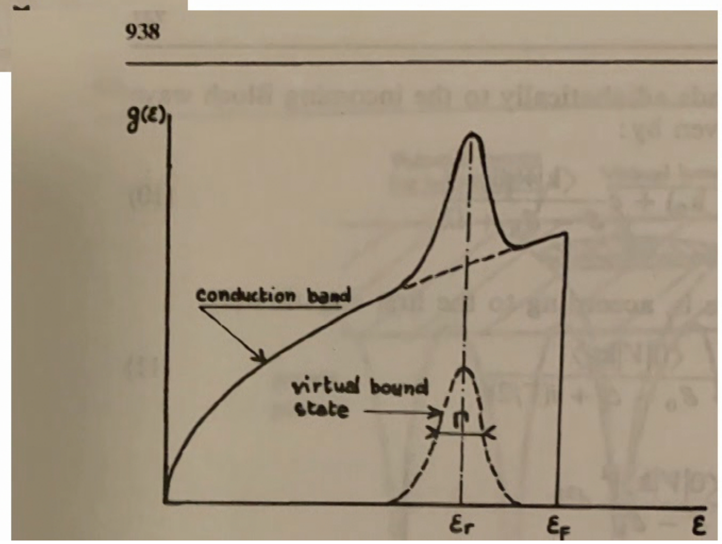
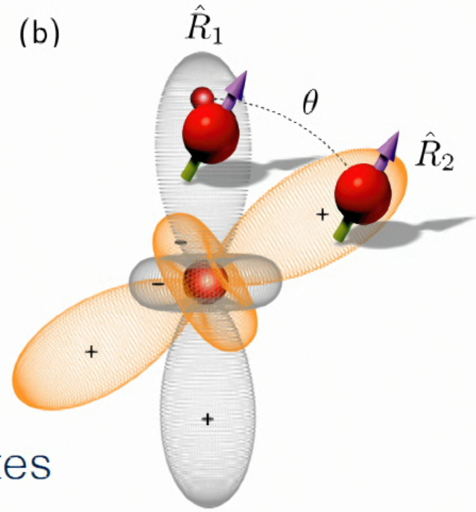
Orsay, France



$$H_{DMI} = -\Gamma\delta(r - R_1)s\cdot S_1 - \Gamma'\delta(r - R_2)s\cdot S_2 + \gamma l\cdot s$$

(broken inversion symmetry)



Anisotropic coupling is due to spin interactions which depend on $\vec{R}_1 \times \vec{R}_2$

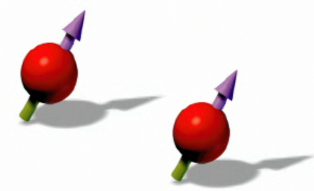
Friedel virtual bound states

$$\phi_{\vec{k}} \sim e^{i\vec{k}\cdot\vec{r}} + e^{i\eta_2(k)} sin\eta_2(k)\frac{<d|V|k>}{\Delta}\Sigma_m\phi_{2m}(r)Y_{2m}(\hat{k})$$

$$V(k_1, k_2, k_3) \propto \iiint \Gamma_1 < \delta(\vec{r} \cdot \overrightarrow{R}_1)\vec{s} \cdot \overrightarrow{S}_1 > \Gamma_2 < \delta(\vec{r} \cdot \overrightarrow{R}_2)\vec{s} \cdot \overrightarrow{S}_2 > < \lambda\vec{s} \cdot \vec{l} >$$

$$V(k_1, k_2, k_3) \propto (\overrightarrow{R}_1 \cdot \overrightarrow{R}_2)(\overrightarrow{R}_1 \times \overrightarrow{R}_2) \cdot (\mathbf{S_1} \times \mathbf{S_2})$$

$$V(k_1, k_2, k_3) \propto \overrightarrow{D}(R_{12}) \cdot (\mathbf{S_1} \times \mathbf{S_2})$$

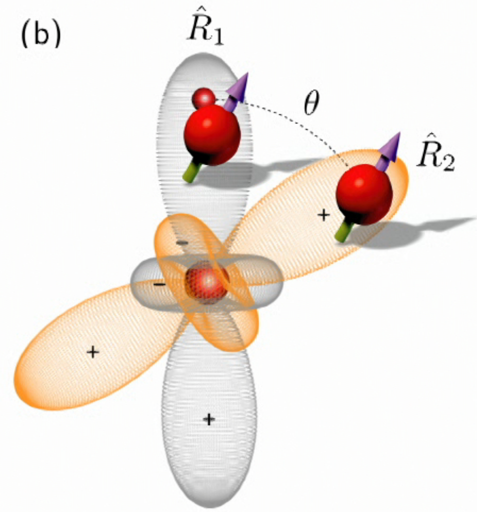


$$V(k_1, k_2, k_3) \propto \iiint \Gamma_1 < \delta(\vec{r} \cdot \vec{R}_1)\vec{s} \cdot \vec{S}_1 > \Gamma_2 < \delta(\vec{r} \cdot \vec{R}_2)\vec{s} \cdot \vec{S}_2 > < \lambda \vec{s} \cdot \vec{l} >$$

$$V(k_1, k_2, k_3) \propto (\vec{R}_1 \cdot \vec{R}_2)(\vec{R}_1 \times \vec{R}_2) \cdot (\mathbf{S_1} \times \mathbf{S_2})$$

$$V(k_1, k_2, k_3) \propto \vec{D}(R_{12}) \cdot (\mathbf{S_1} \times \mathbf{S_2})$$

(b)

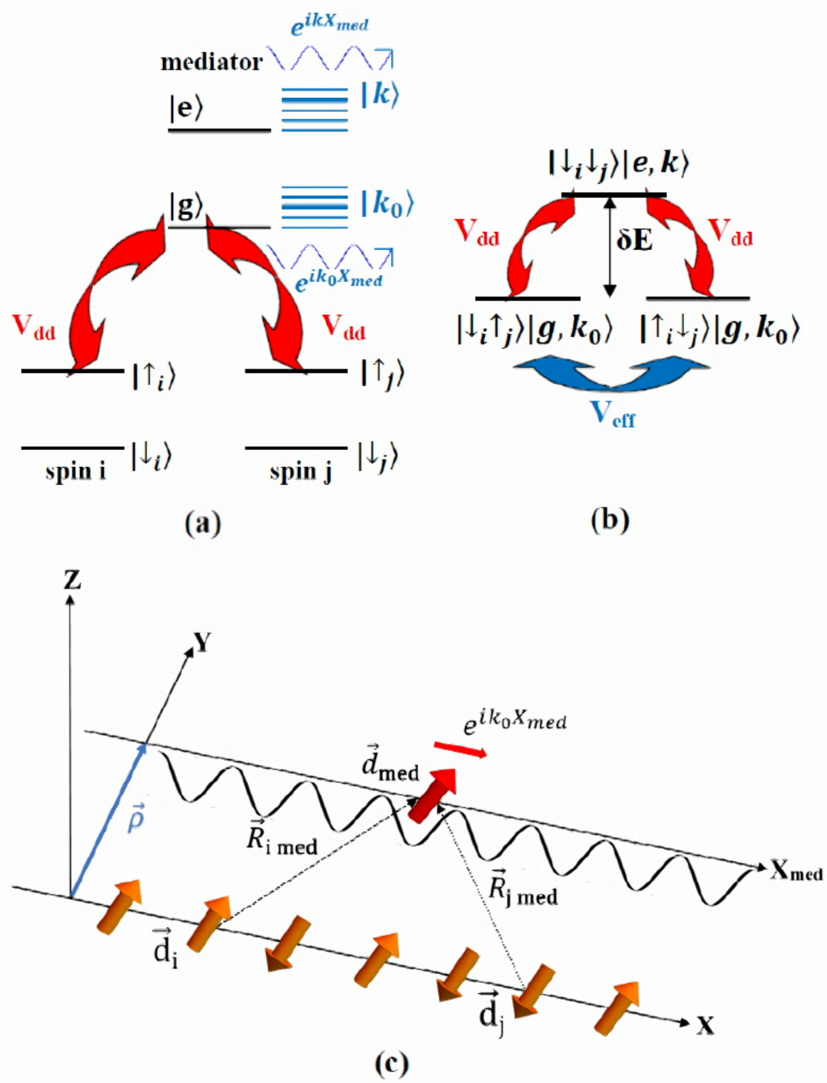


Lena Kuznetsova (with Seth Rittenhouse and Susanne Yellin)

$$\hat{V} = \Sigma_k \frac{< g, k_0 | V | e, k > < e, k | V^{\dagger} | g, k_0 >}{\delta E}$$

$$\delta E = E_e + \frac{k^2}{2} - (E_g + \frac{k_0^2}{2}) - (E_{\uparrow} - E_{\downarrow})$$

$$V_{dd\ (or)\ ed} << \delta E$$



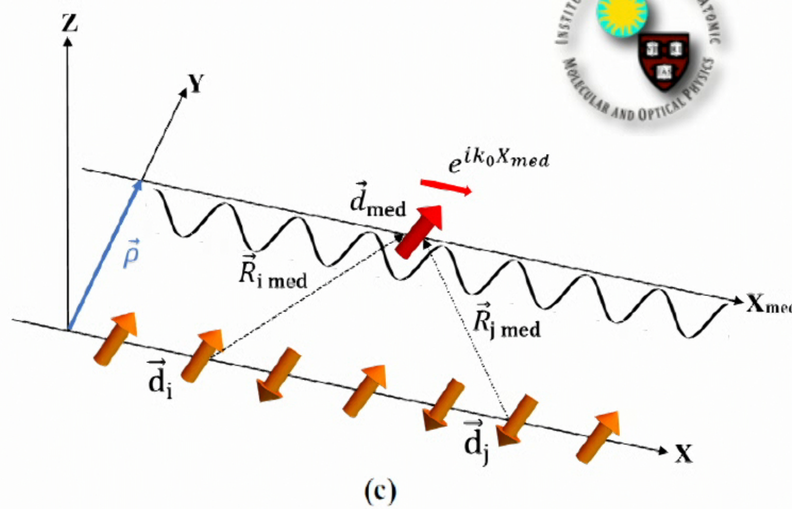
$$V \sim \Sigma_i \mathscr{V}(R_{imed}) S_i^+ s_{med}^-$$

$$< k_0 | V | k > \sim \mathscr{V} e^{i\delta k X_{med}}$$

$$\hat{V} \sim \Sigma_{ij} J_i^{+-} S_i^+ S_j^-$$

Looks like the Heisenberg spin interaction

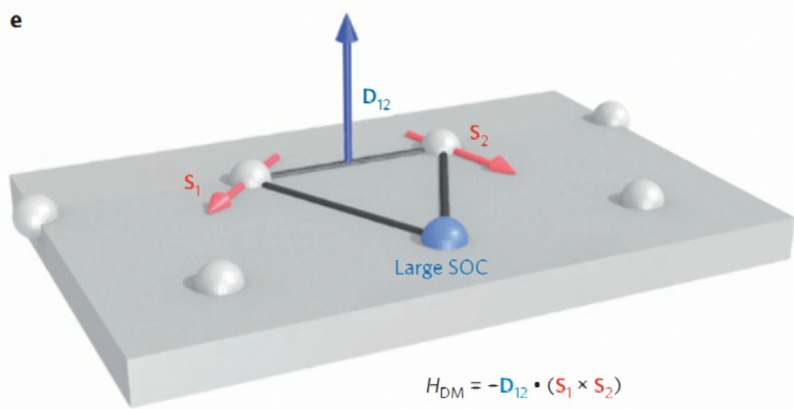
$$J_{ij}^{+-} \sim \Sigma_k \frac{|\mathscr{V}|^2 e^{i\delta k X_{ij}}}{\delta E}$$



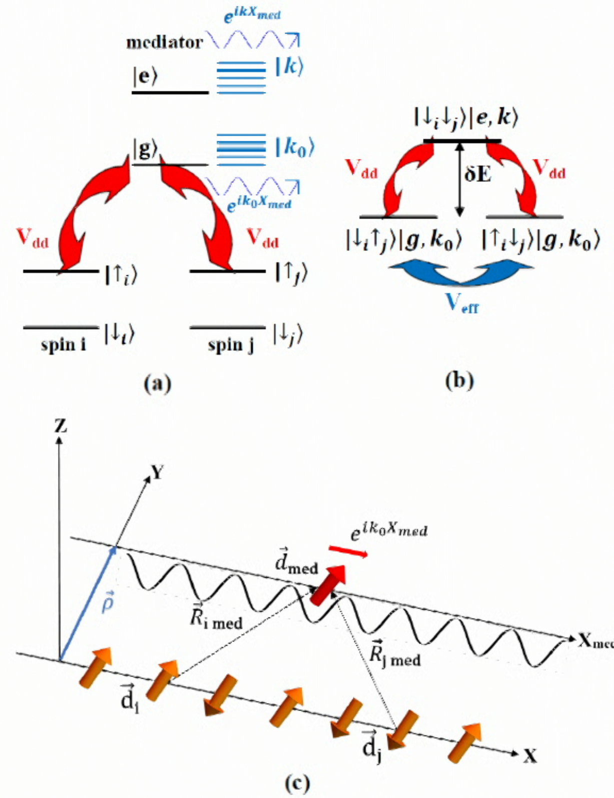
$$V = \frac{J_{ij}^{\perp}}{2}(S_i^+ S_j^- + S_i^- S_j^+) + D_{ij} \cdot (S_i \times S_j)$$

$$J_{ij}^{\perp} = 2ReJ_{ij}^{+-}$$

$$D_{ij} = (0,0,2ImJ_{ij}^{+-})$$



$H_{DM} = -\mathbf{D}_{12} \cdot (\mathbf{S}_1 \times \mathbf{S}_2)$



··· simulate variety of indirect (and chiral) interactions with Rydberg excitations

··· calculate from first principles the RKKY and DMI couplings