Two photon optical shielding of collisions between ultracold polar molecules

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Introduction

Research focusing on the formation of ultracold atomic and molecular quantum gases is a continuously expanding field due to its envisioned applications such as quantum-controlled chemistry or quantum simulation. The aim of our theoretical work is to find ways to suppress inelastic or reactive processes between colliding particles in ultracold quantum gases [1]. We propose a method to engineer repulsive long-range interactions between ultracold ground-state molecules using optical fields, thus preventing short-range collisional losses. It maps the microwave coupling recently used for collisional shielding [2,3,4] onto a two-photon transition and takes advantage of optical control techniques. In contrast to one-photon optical shielding [5], this scheme avoids heating of the molecular gas due to photon scattering. The proposed protocol, exemplified for $^{23}Na^{39}K$, should be applicable to a large class of polar diatomic molecules.

Principle of EM shielding of collisions

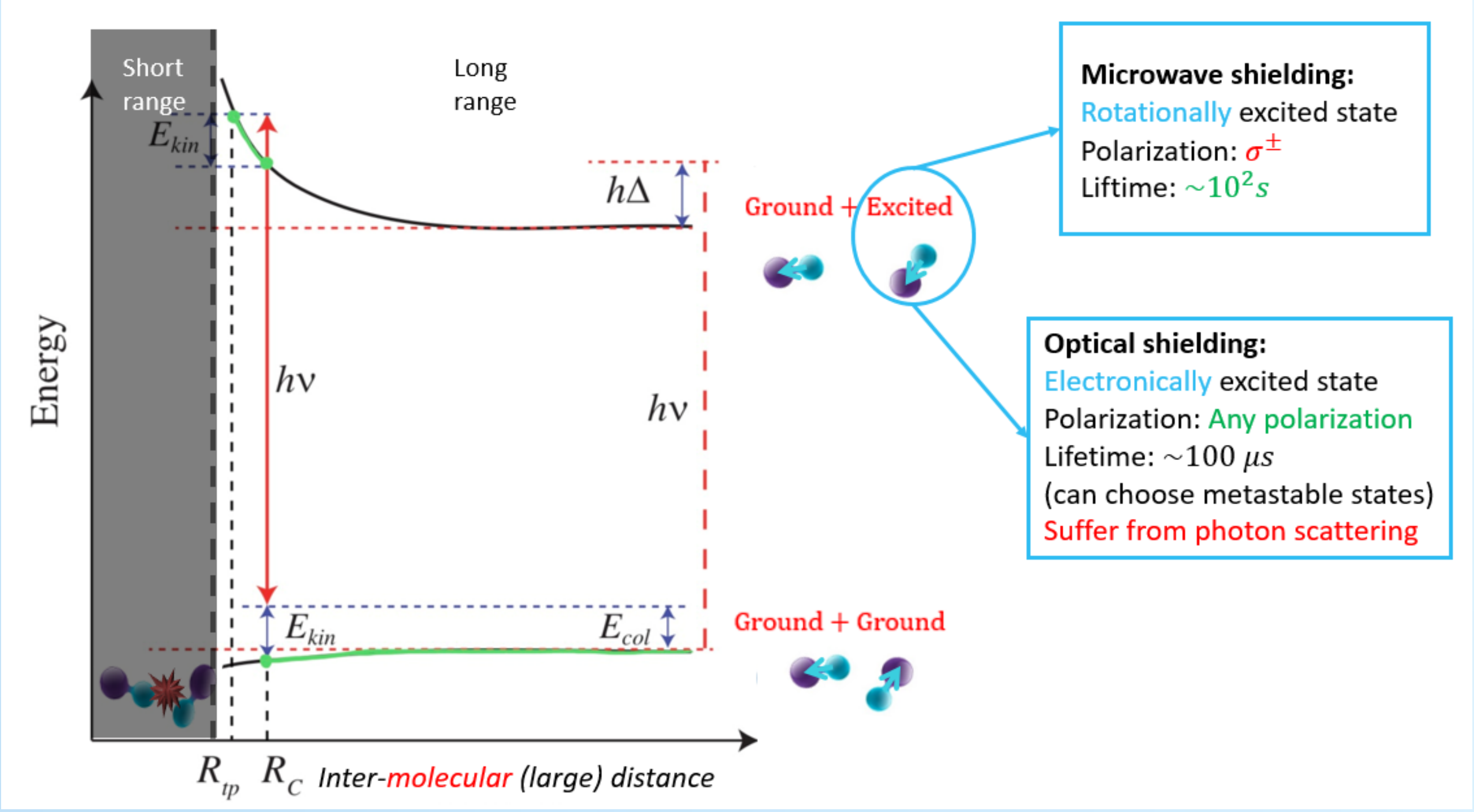


Fig.1: General schematic representation of the electromagnetic shielding of collisions between ultracold molecules. By using a **blue detuned** photon by respect to the transition between the **ground attractive** state of the two molecules to a **repulsive excited** state, we prevent the molecules from reaching the "loss region" labeled as short range in the scheme. The effect of the different EM source on the shielding process are also summarized for both one photon optical shielding **(1-OS)** and microwave shielding **(MW-S)**.

Field free long range PECs and dipole-dipole interaction

Ground manifold
$^{23}Na^{39}K$ + $^{23}Na^{39}K$

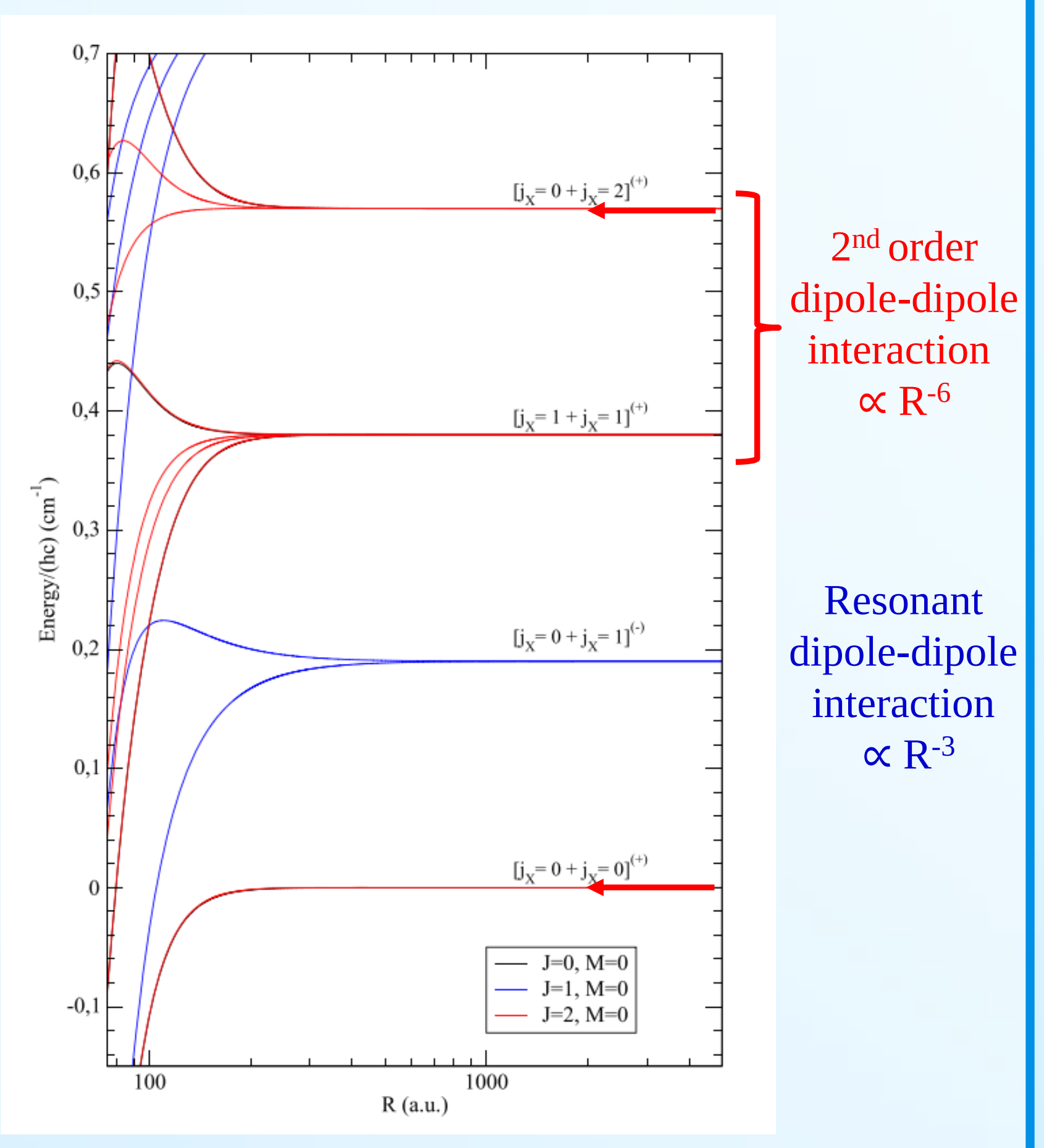


Fig.2: Adiabatic long-range potential energy curves of **two** $^{23}Na^{39}K$ molecules in the $v_X = 0$ level of their electronic $\mathbf{X^1\Sigma^+}$ for the lowest combinations of internal rotational states j_X, and for J=0,2 with M=0.

Two photon optical shielding (2-OS)

Three level system → Adiabatic elimination → Effective two level system

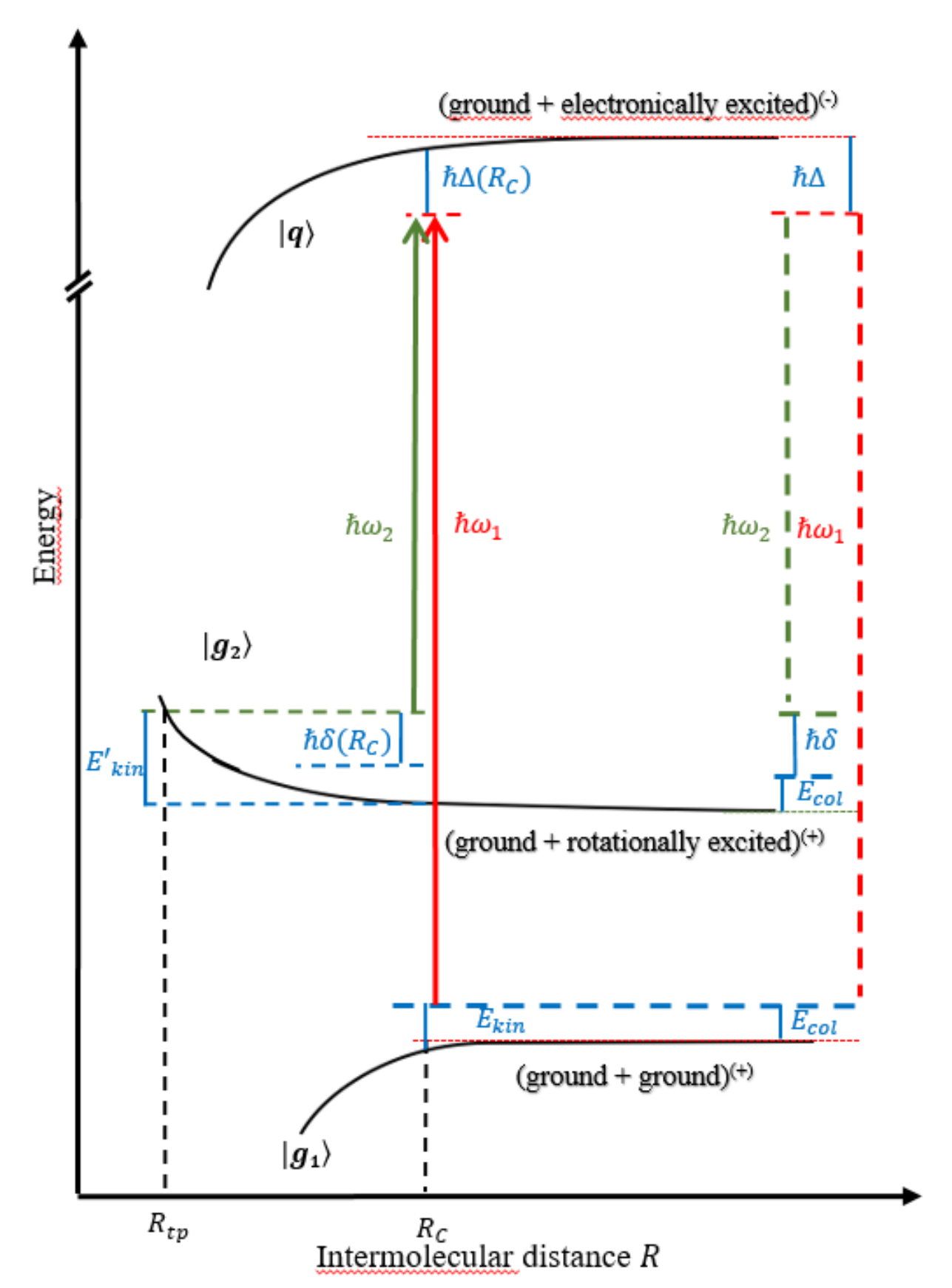
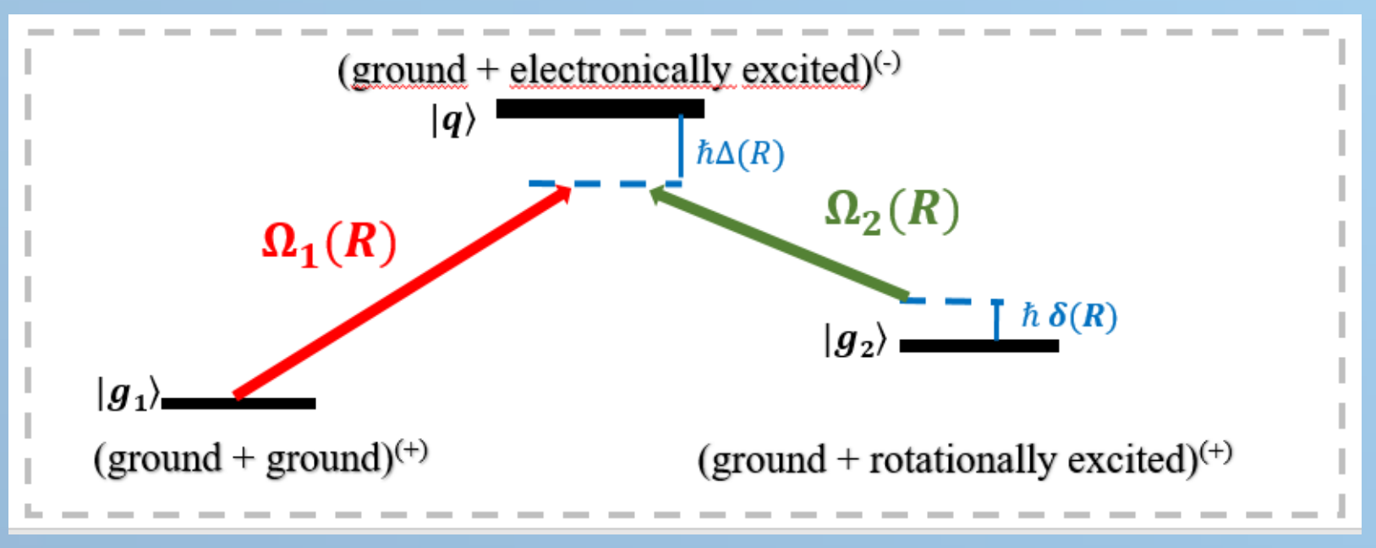


Fig.3: Schematic view of the proposed two-photon optical shielding (energies not to scale). Sketch of the long-range adiabatic potential energy curves (PECs), describing the interaction between two polar molecules in their ground rovibrational state and rotationally excited state of their electronic ground state (X), and a ground state molecule and a molecule in an electronically-excited one in state e.

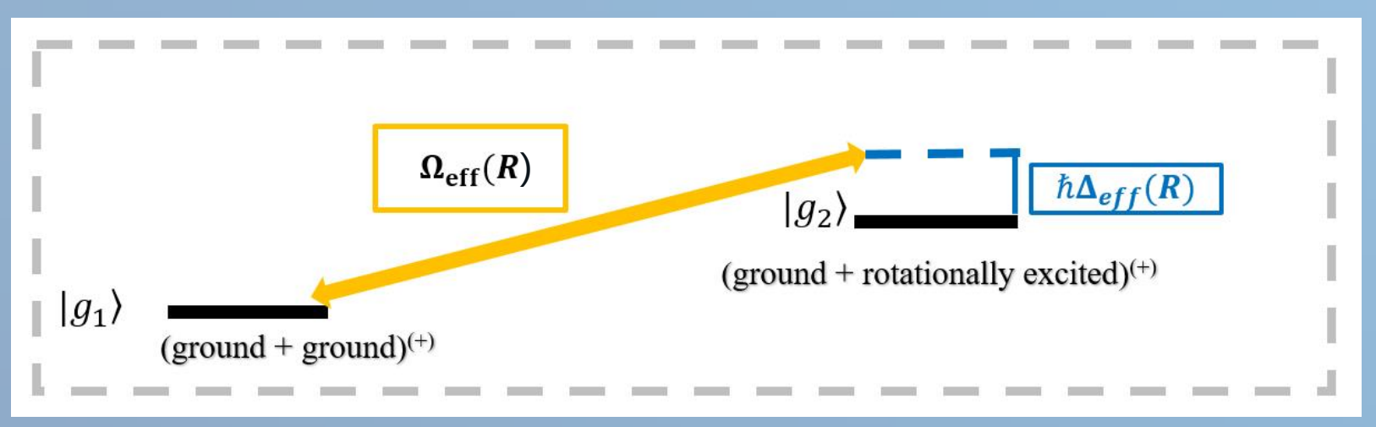
Hamiltonian of a 3 level system
In dressed basis $\{|\tilde{g}_1\rangle, |\tilde{g}_2\rangle, |\tilde{q}\rangle\}$

$$H^I = \hbar \begin{pmatrix} 0 & 0 & \Omega_1/2 \\ 0 & \delta & \Omega_2/2 \\ \Omega_1/2 & \Omega_2/2 & \Delta \end{pmatrix}$$



Adiabatic elimination of $|\tilde{q}\rangle$
$\Delta \gg \Omega_1, \Omega_2, \Gamma_q$

$$H^I_{\text{eff}} = \hbar \begin{pmatrix} 0 & -\Omega_{\text{eff}}/2 \\ -\Omega_{\text{eff}}/2 & \Delta_{\text{eff}} \end{pmatrix}$$



With

$$\Delta_{\text{eff}} = \delta + \frac{\sqrt{\Omega_1^2 - \Omega_2^2}}{4\Delta} ; \Omega_{\text{eff}} = \frac{\Omega_1 \Omega_2}{2\Delta}$$

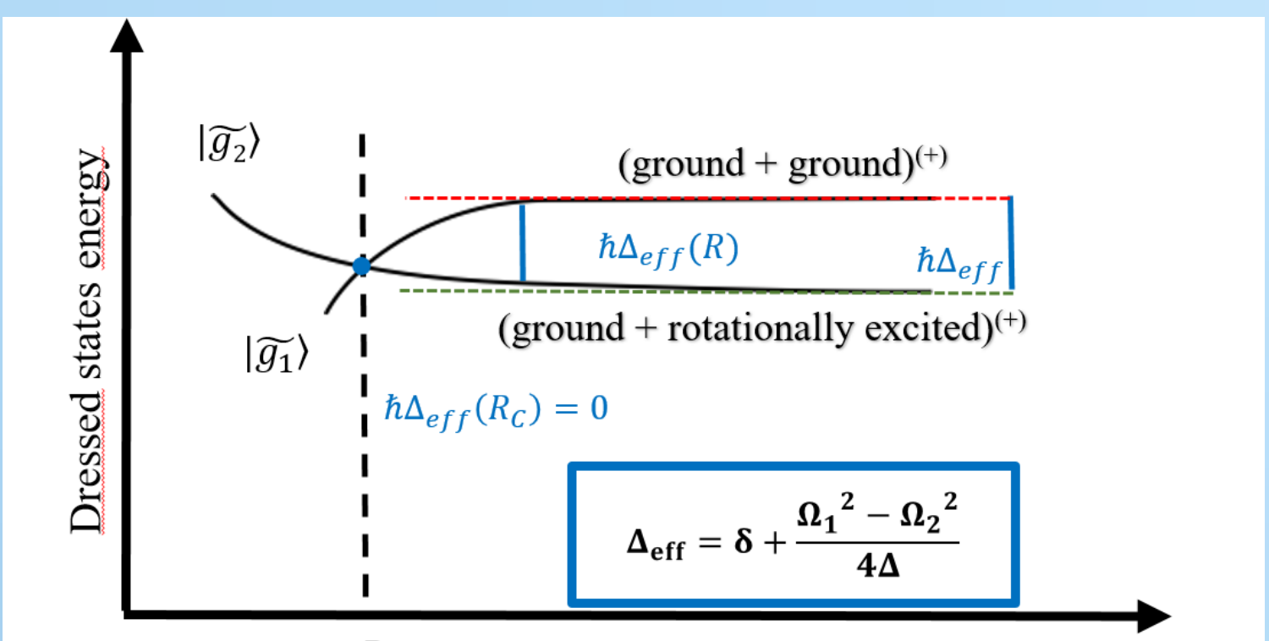


Fig 4: The PECs of Fig,3 in the dressed-state framework involving the states $|\widetilde{g_1}\rangle$ and $|\widetilde{g_2}\rangle$: R_C is the crossing point between the attractive and repulsive PECs, resulting from the effective detuning Δ_{eff} at infinity.

↓
From crossing to avoided crossing
↓

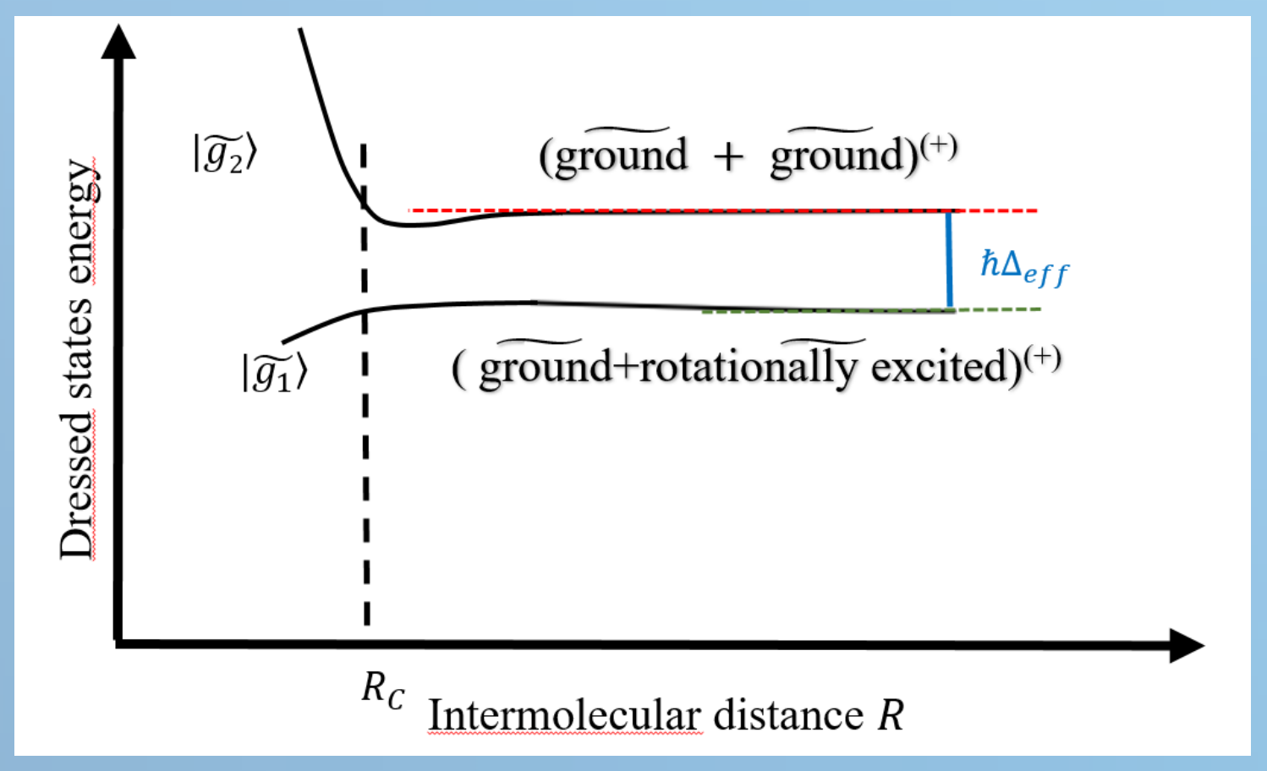


Fig 5: The dressed PECs of Fig.4 after adding the light and matter interaction term and diagonalizing.

Mapping MW-S with 2-OS

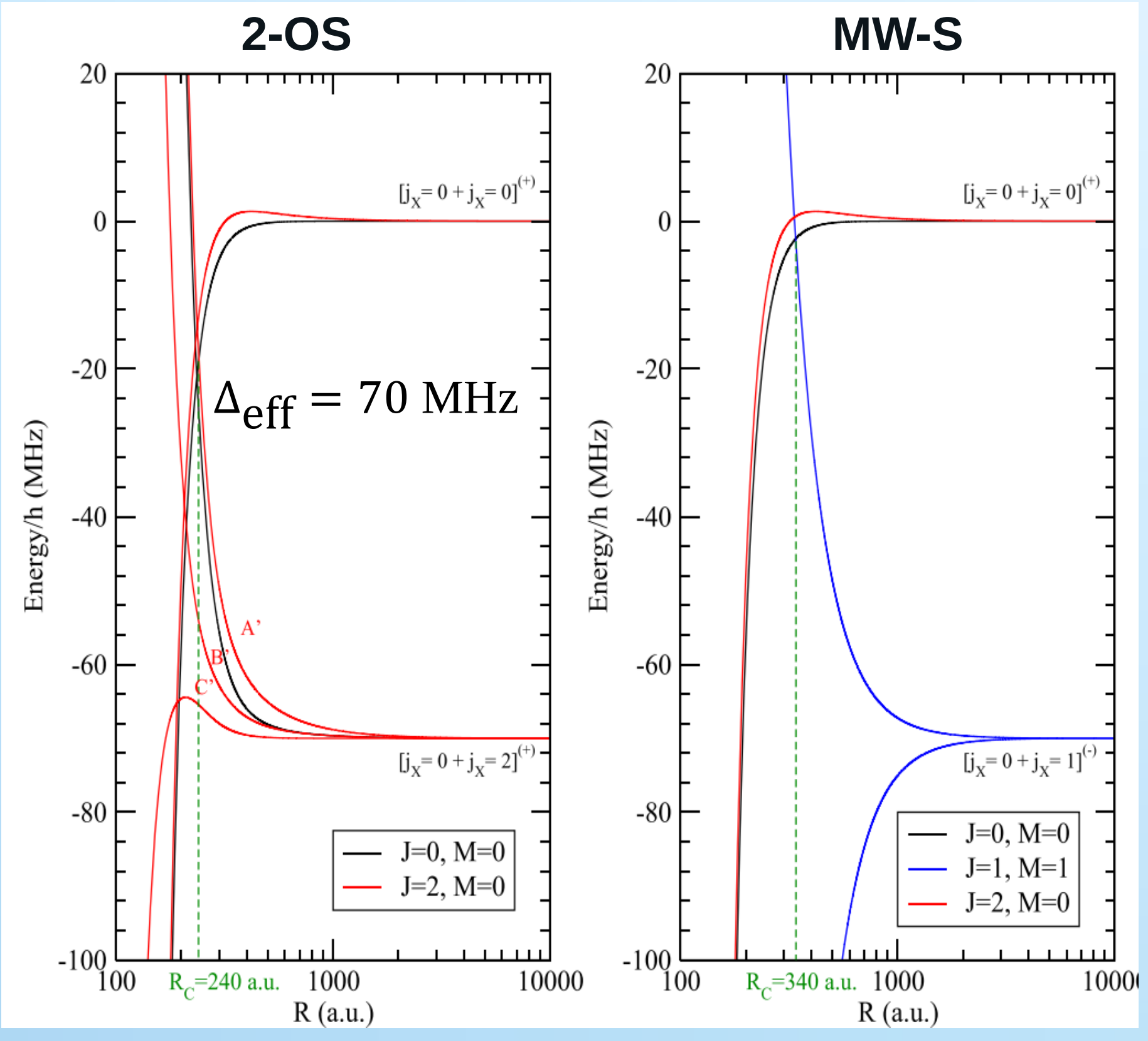


Fig.6: (a) The two-optical-photon **diabatic dressed** PECs for two ground state $^{23}Na^{39}K$ molecules in R_C=240 a.u., (or $\Delta_{\text{eff}} = 70$ MHz). (b) The one-mw-photon dressed PECs for the same detuning of $\Delta_{\text{mw}} = 70$ MHz following [2].

Dressed adiabatic PECs

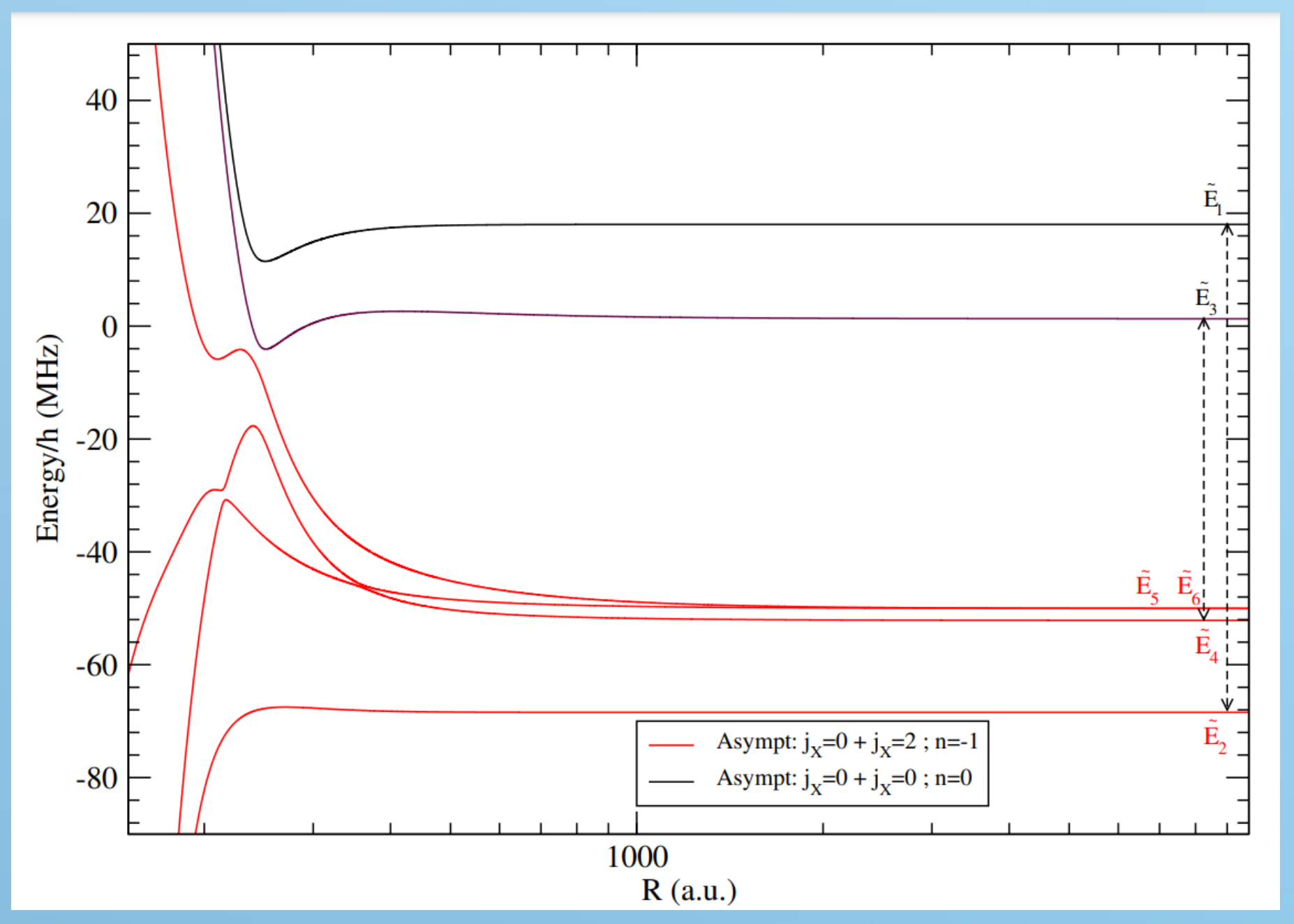


Fig.6: (a) The two-optical-photon **adiabatic dressed** PECs for two ground state $^{23}Na^{39}K$ molecules in for $\Delta_{\text{eff}} = 70$ MHz. [4].

Discussion and Conclusion

The proposed scheme can be generalized to any intermediate state $|\tilde{q}\rangle$, excited electronic states with large TEDM can be readily used, allowing for moderate laser intensities I_1 and I_2. For example, coupling via the $A^1\Sigma^+$ state in $^{23}Na^{39}K$ yields the desired $\Omega_{\text{eff}}/(2\pi)$ ~10 MHz with an estimated I_2(>>I_1) on the order of 10^4 W/cm^2 for Ω_1/Ω_2 ~ 10^{-2}, and a loss probability due to off-resonant scattering below 10^{-6} per collision.

In this scheme, we propose a new shielding scheme that:

- Maps the MW-S using **lasers**
- does **not suffer** from **photon scattering**
- with **flexible** choice of the electronic state.
- with **Any** laser **polarization**.

Arxiv link:
arXiv:2211.08950v2

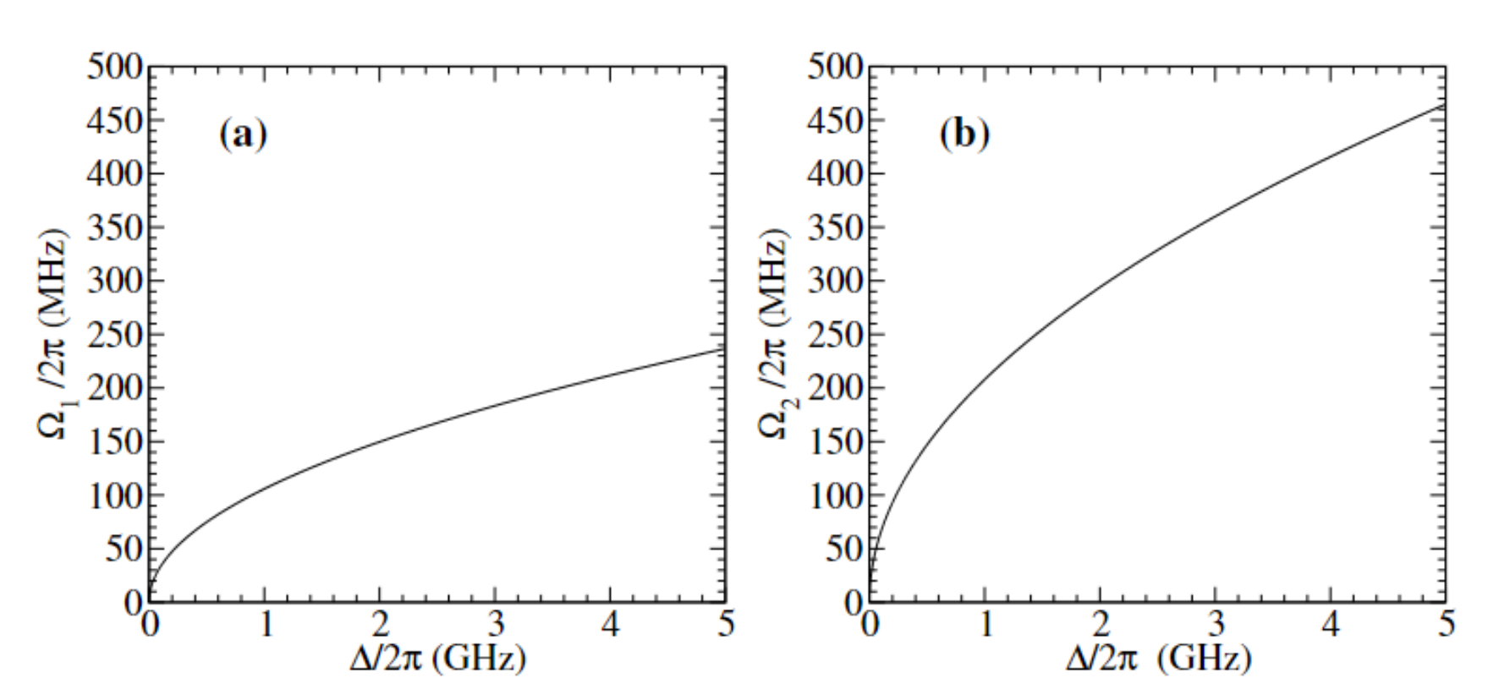


Fig.7: The one-photon Rabi frequency (a) $\Omega_1/2\pi$ and (b) $\Omega_2/2\pi$ as functions of the one-photon detuning $\Delta/2\pi$, with $\delta = 0, \Omega_{\text{eff}}/2\pi = 11$ MHz and $\Delta_{\text{eff}}/2\pi = 8$ MHz, identical to the experimental values of [4] for the mw shielding.

References

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