Spinor Matter-Wave Control with Nanosecond Spin-Dependent Kicks

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➢ Motivations

Ultra-precise control of spinor matterwave is instrumental to atom interferometry and other ultra-cold experiments for achieving quantum enhanced performances. Traditionally, precise Raman control requires the differential light shifts to be nullified at proper sideband intensity ratios [1], at the expense of significant spontaneous emission. On the other hand, the THz-level ``magically detuned” Spin-dependent kicks (SDK) for ion traps [2-3] is too power-demanding for large samples.

Here, we propose and demonstrate an adiabatic SDK technique, operated in an intermediate regime of detuning, for achieving deeply subwavelength-resolved spinor phase gates in a laser power-efficient manner. We show in presence of the multi-level couplings in such regime, the coherent spin leakage and Stark shifts can nevertheless be well-controlled. Experimentally, we break the detuning-dependent SDK speed barrier by spatially resolving nanosecond Raman pulses on an optical delay line, for the first time [4].

➢ Adiabatic SDK on a Hyperfine Manifold

- **SDKs on a hyperfine manifold**

$$H(\mathbf{r},t)=\sum_{m=-F_b}^{F_b} H_0^{(m)}(\mathbf{r},t)+H'(\mathbf{r},t)$$

$$H_0^{(m)}(\mathbf{r},t)$$
$$=\hbar\left(\frac{\delta_0}{2}\sigma_z^{(m)}+\frac{\Omega_R^{(m)}}{2}e^{i\mathbf{k}_R\cdot\mathbf{r}}\sigma_+^{(m)}+h.c.\right)$$

- **f_{SDK} and $\varepsilon_{\mathrm{leak}}$ for non-ideal SDK**

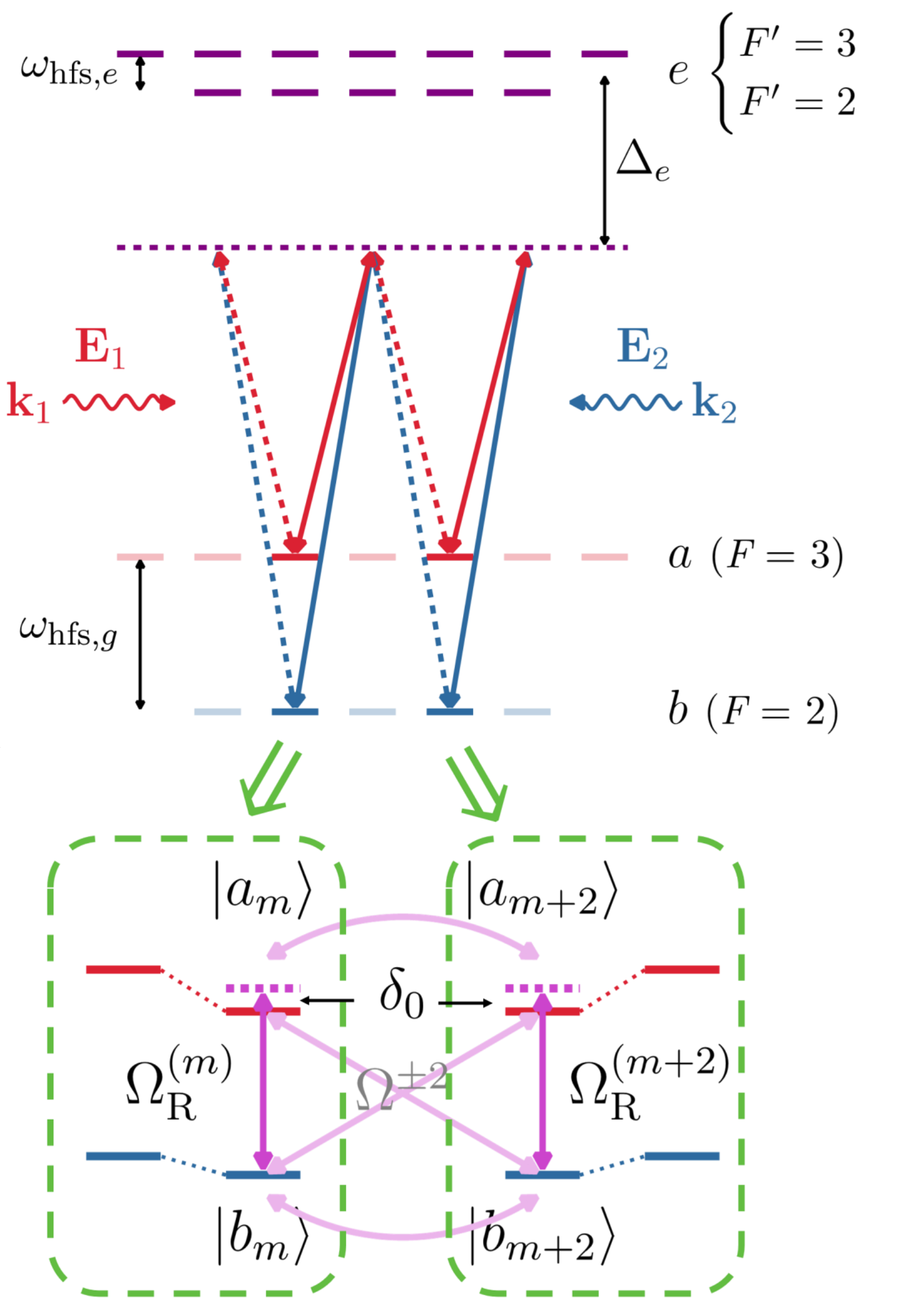
$$f_{\mathrm{SDK}}=\left\langle\left|\langle c_m|U_K^{+}(\mathbf{k}_{\mathrm{R}})\widetilde{U}(\mathbf{k}_{\mathrm{R}};\eta)|c_m\rangle\right|^2\right\rangle_{\eta,c_m}$$

$$\varepsilon_{\mathrm{leak}}=\varepsilon_{\mathrm{sp}}+\varepsilon_{\Delta m}$$

1) Spontaneous emission

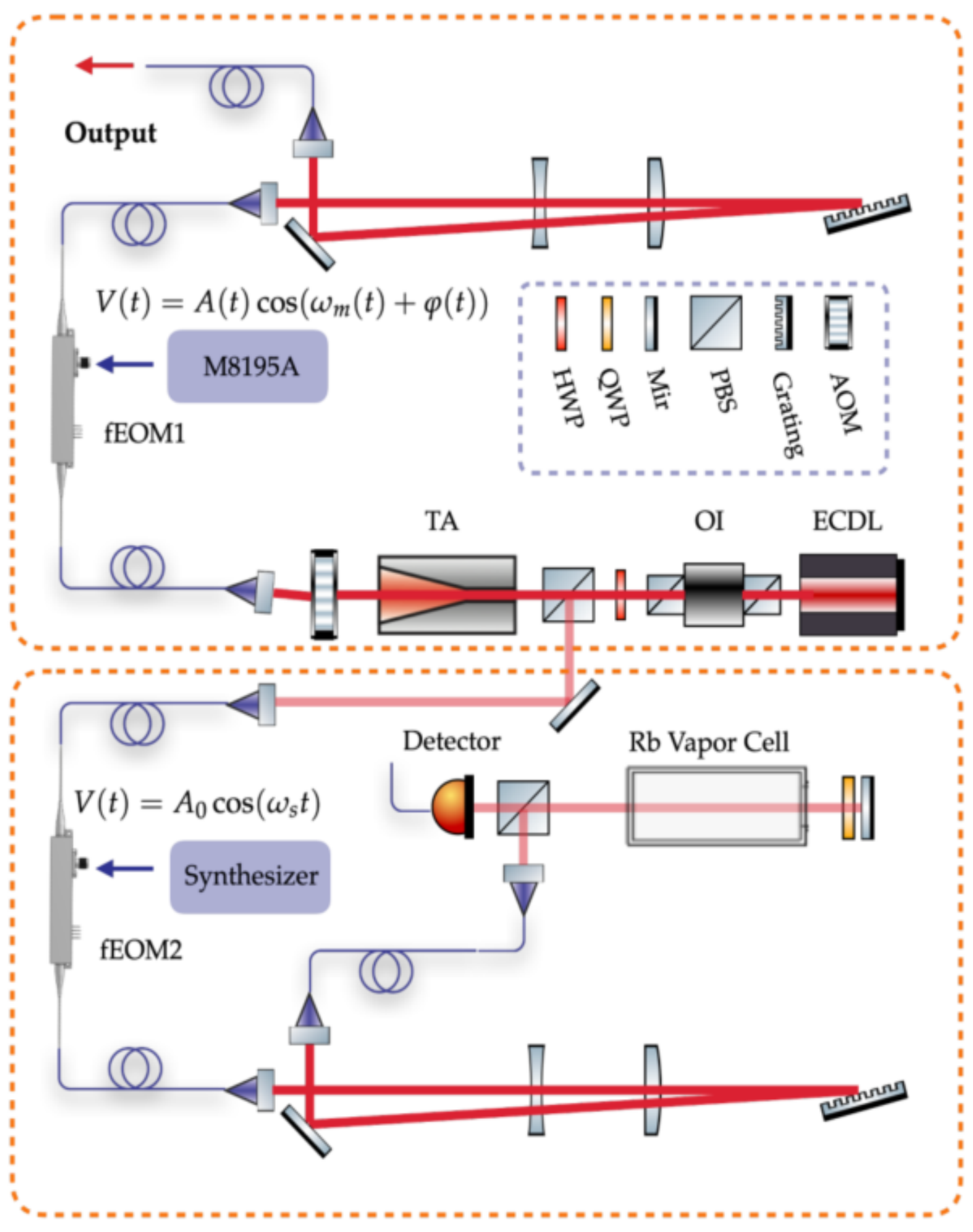
2) Coherent leakage ($\Delta m=\pm 2$)

$$\varepsilon_{\Delta m}\propto\frac{\omega_{\mathrm{hfs},e}^2}{\Delta_e{}^2},\ \Omega^{\pm 2}=O\left(\frac{\omega_{\mathrm{hfs},e}}{\Delta_e}\right)\Omega_R$$

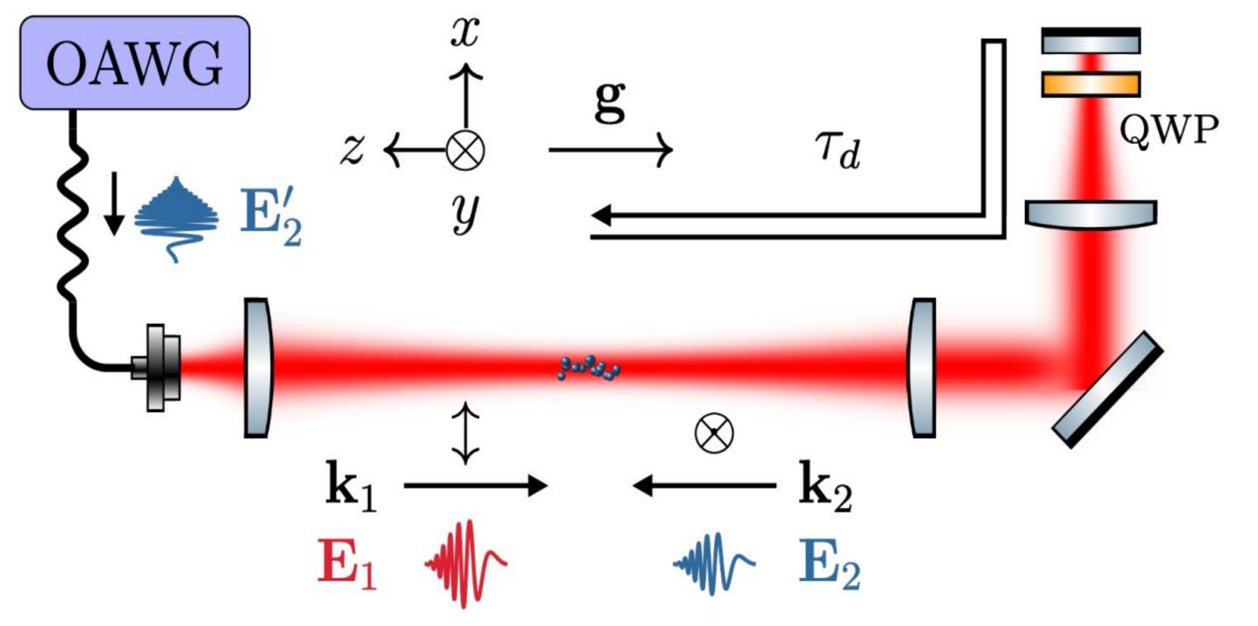


➢ Delay-line Based Nanosecond SDKs

- **D1 line quantum control pulse generation setup**



- **Nanosecond SDKs on an optical delay line**



☐ frequency-chirped optical waveforms are programmed by an OAWG
☐ 140ns optical delay line, long enough to spatially resolve nanosecond pulses (shorter in the future)
☐ cross-linear, multi-Zeeman control

➢ Conclusion

We extend the Raman adiabatic SDK technique into the nanosecond regime. Counter-propagating frequency-chirped laser pulses are programmed on an optical delay line to parallelly drive five Δm=0 hyperfine Raman transition of ^{85}Rb atoms within τ=40ns. An average SDK fidelity of $f_{\mathrm{SDK}}\approx 97.6\%$ is inferred from spin-dependent momentum transfer and Raman population measurements, combined with precise numerical modeling.

➢ Pulse Sequence

- **Adiabatic rapid passage (ARP)**

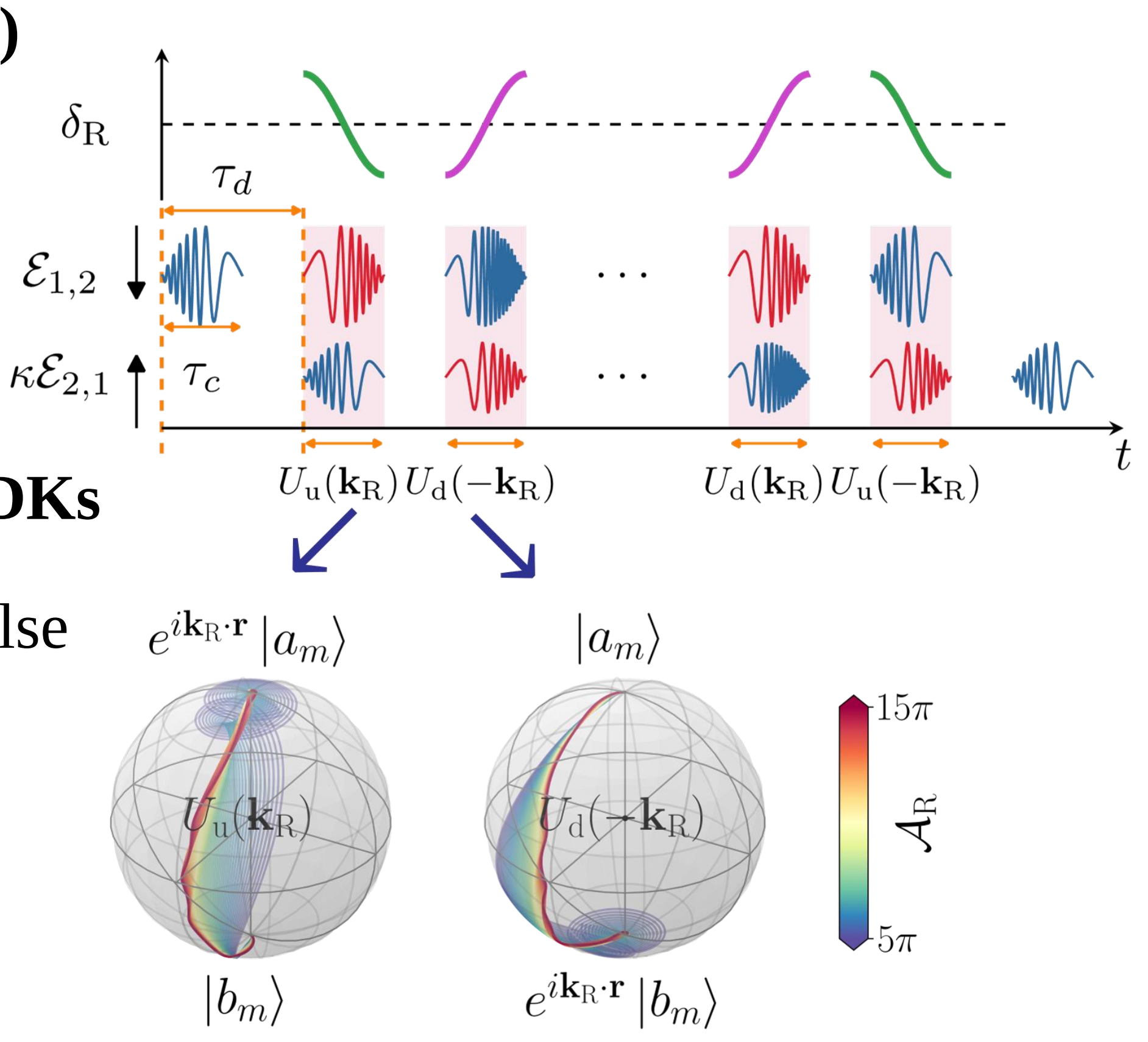
$$\begin{cases}\Omega_R(t)=C_R^{(0)}\sin(\pi t/\tau_c)\\ \delta_R^b(t)=\delta_{\mathrm{swp}}\cos(\pi t/\tau_c)\end{cases}$$

- **Chirp-alternating adiabatic SDKs**

1) Positive and negative chirped pulse

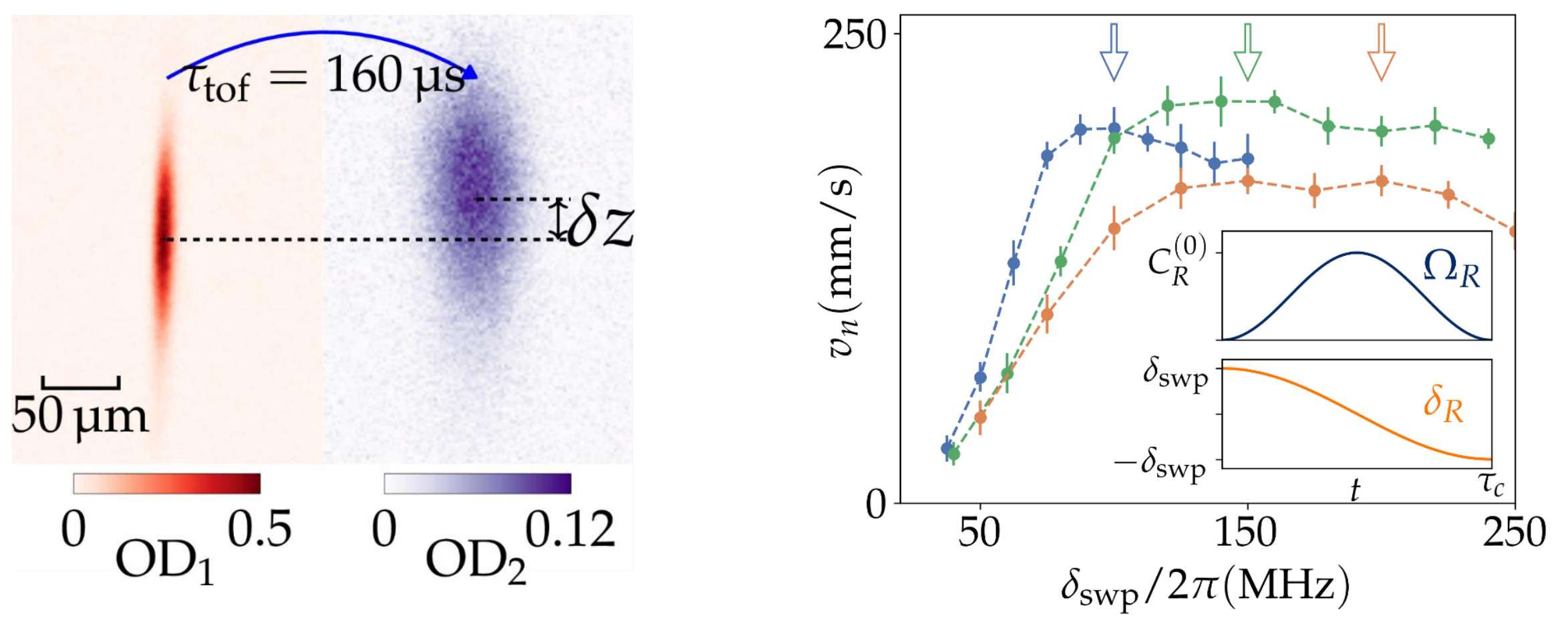
$$\begin{cases}\delta_{R,\mathrm{u}}^b(t)=\delta_{\mathrm{swp}}\cos(\pi t/\tau)\\ \delta_{R,\mathrm{d}}^b(t)=-\delta_{\mathrm{swp}}\cos(\pi t/\tau)\end{cases}$$

2) $\widetilde{U}_{\mathrm{uddu}}^{(4N)}(\mathbf{k}_R)=\widetilde{U}_{\mathrm{u}}(\mathbf{k}_R)\widetilde{U}_{\mathrm{d}}(-\mathbf{k}_R)\widetilde{U}_{\mathrm{d}}(\mathbf{k}_R)\widetilde{U}_{\mathrm{u}}(-\mathbf{k}_R)$



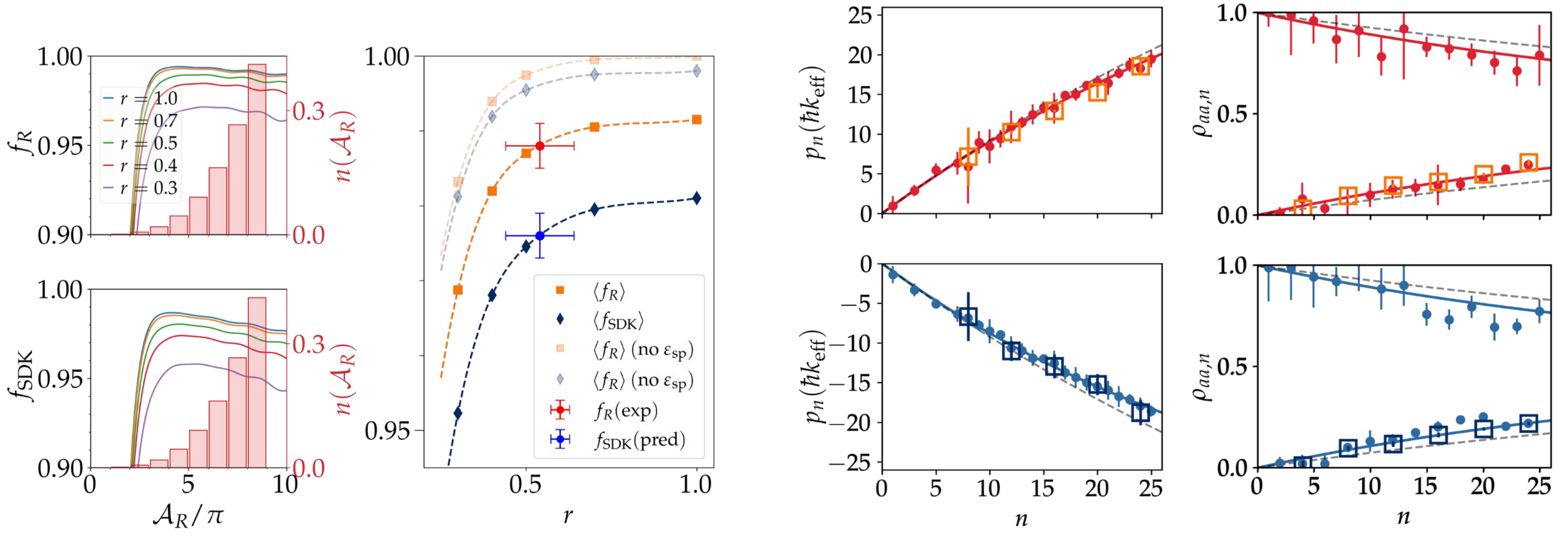
➢ Experimental Results

- **Momentum transfer measurement**



Optimizing $\mathcal{V}_n$ by sweeping δ_{swp} in different pulse area

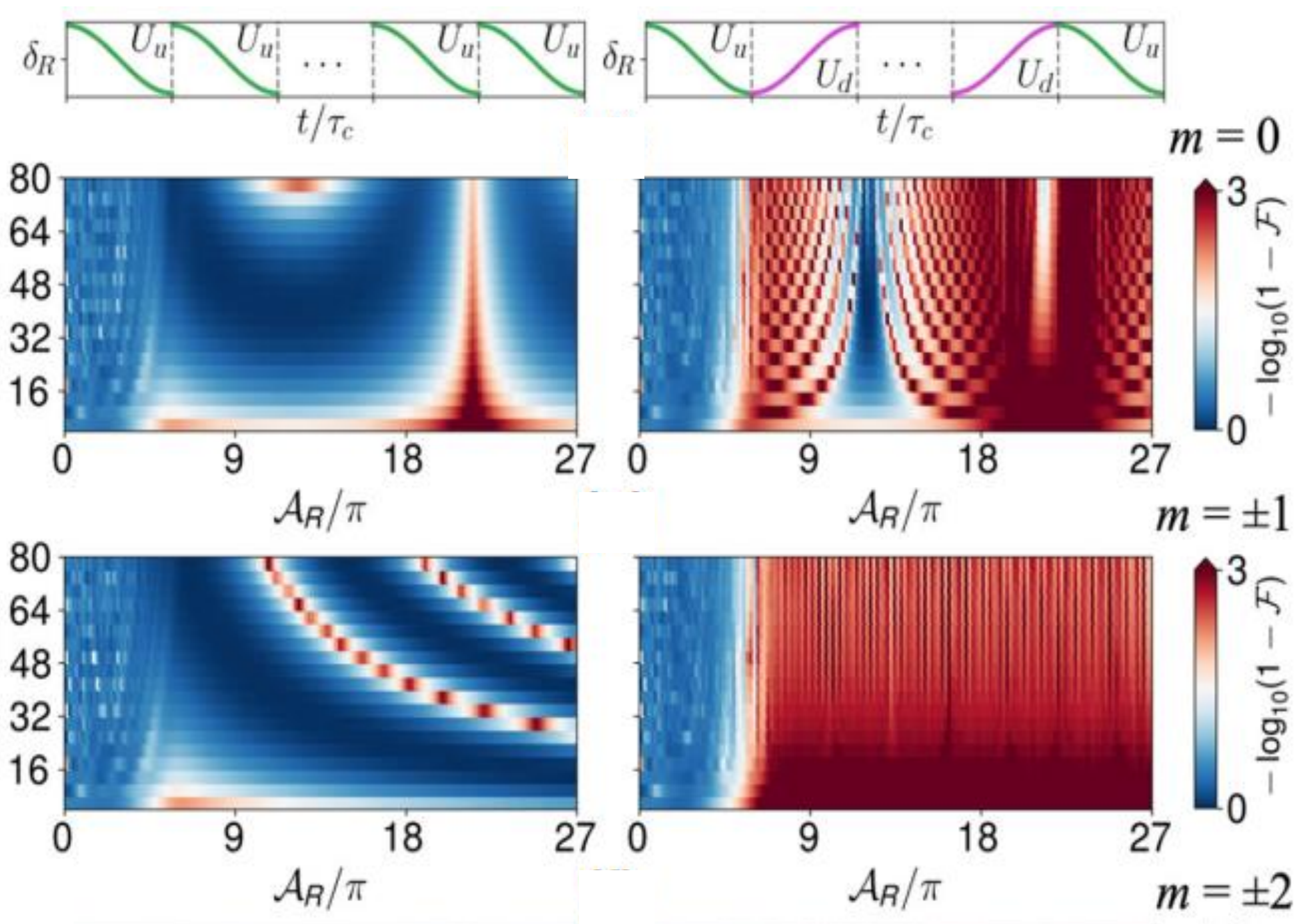
- **Inference of f_{SDK}**



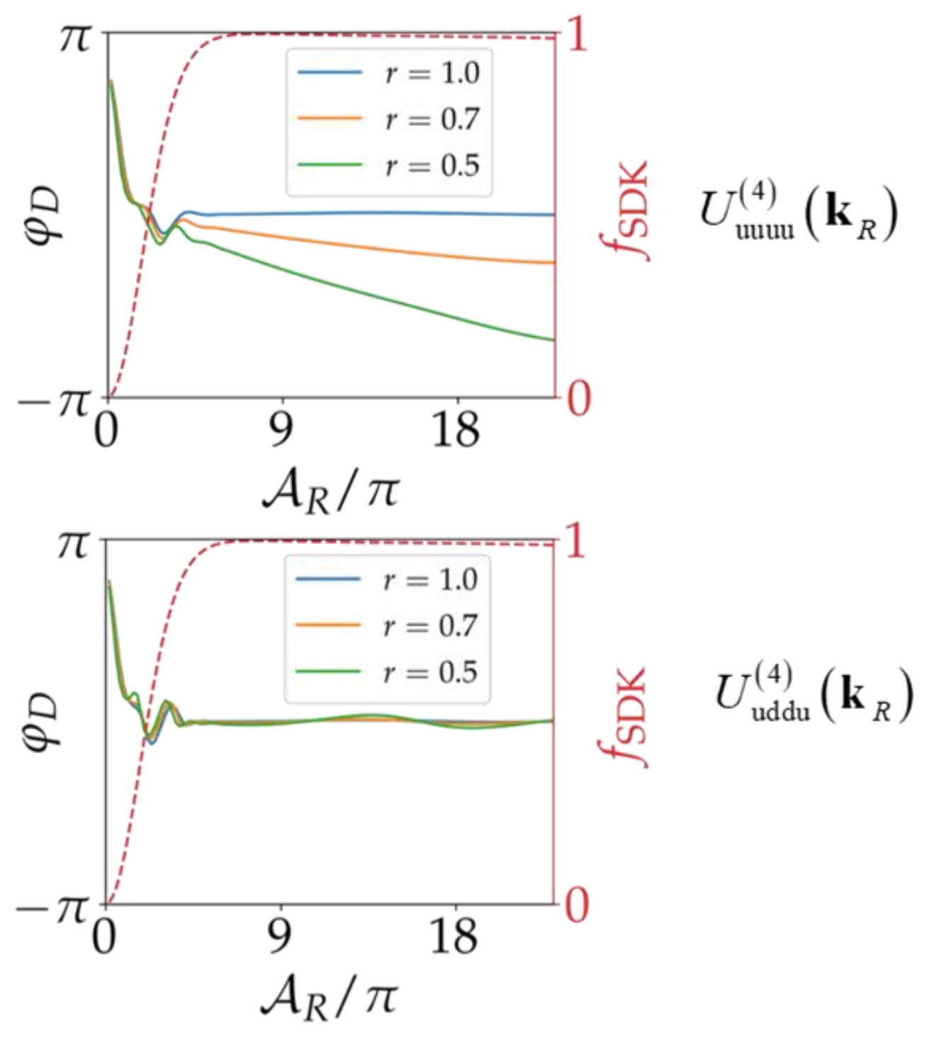
Raman transfer efficiency $f_{\mathrm{R}}\approx 98.8\%$ $f_{\mathrm{SDK}}\approx 97.6(3)\%$

➢ Geometric Spinor Matterwave Control

- **Numerical results of Phase gate infidelity**



- **Robust cancellation of dynamic phase**



➢ Reference

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4.Qiu, L. & Ji, L. & Hu, J. et al. PRX Quantum.3.040301 (2022).

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