Nanosecond Spin-dependent Kicks on a Hyperfine Manifold

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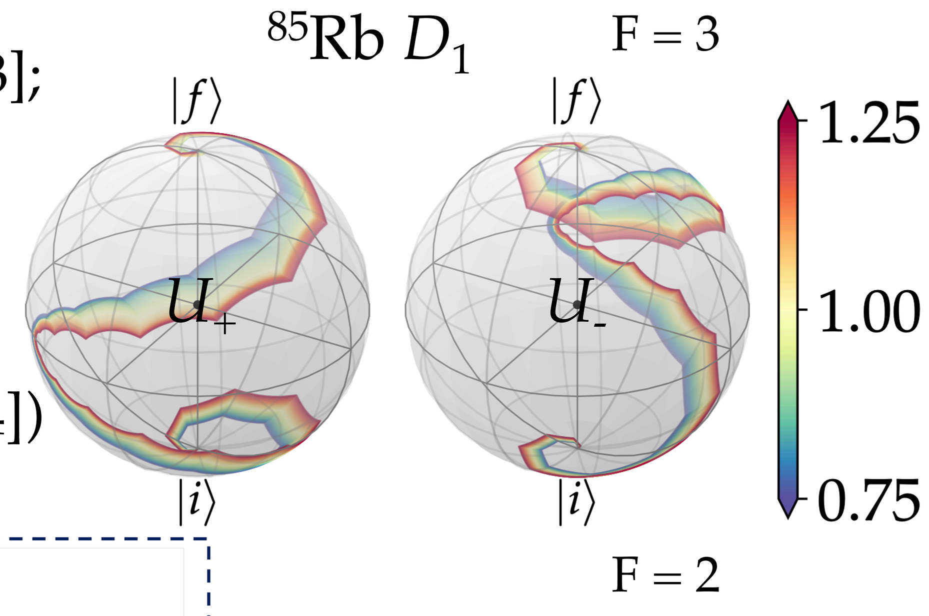
Motivation

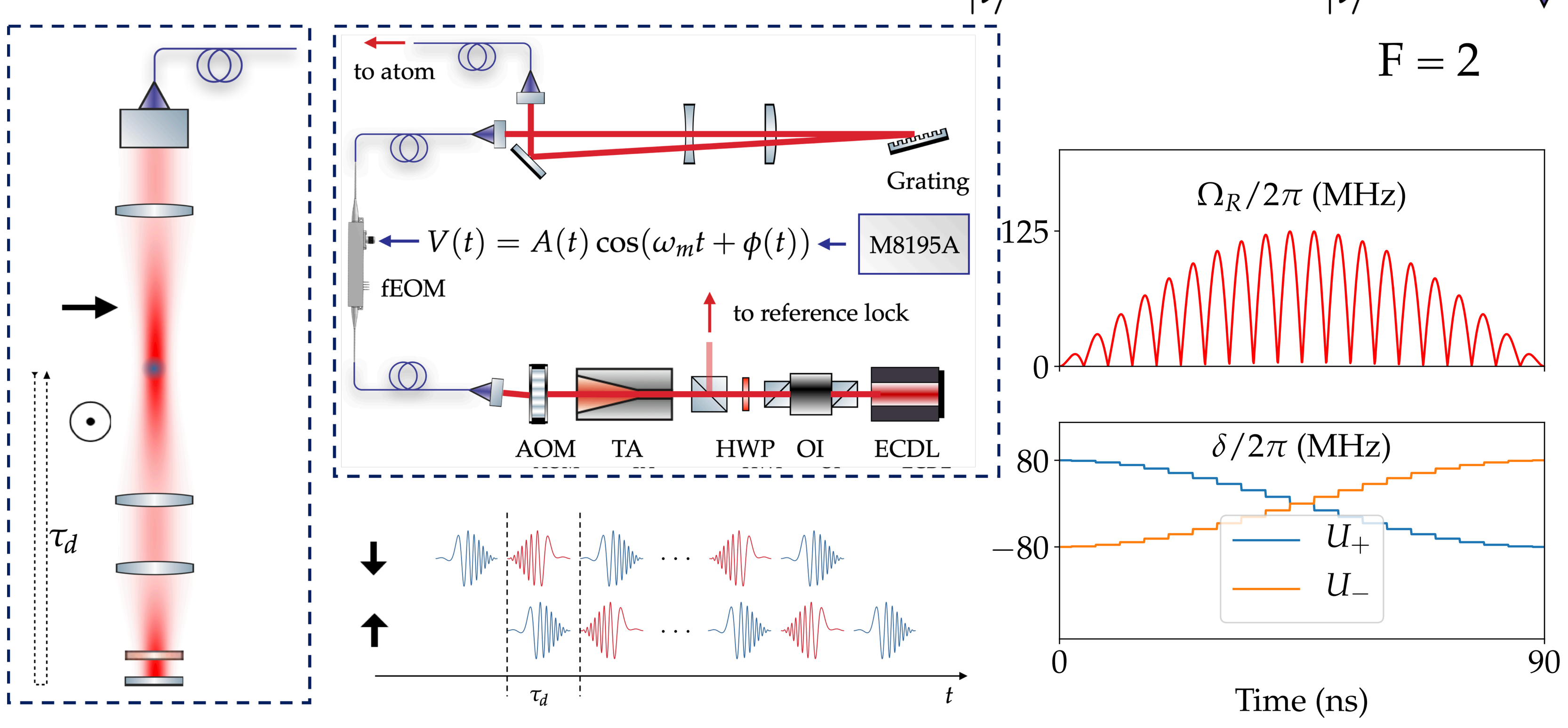
- Transfer of photon recoil momentum to atoms via Raman transition is a common technique for steering matterwave dynamics, with wide range of applications (AI [1], QC [2], …).
- Instantaneous "kicks": applying transient spin-dependent force within a time scale when other dynamics such as atomic motion or interactions are negligible – preciseness & scalability.
- **This work**: toward high speed, high fidelity SDK beyond traditional regime.

Methods

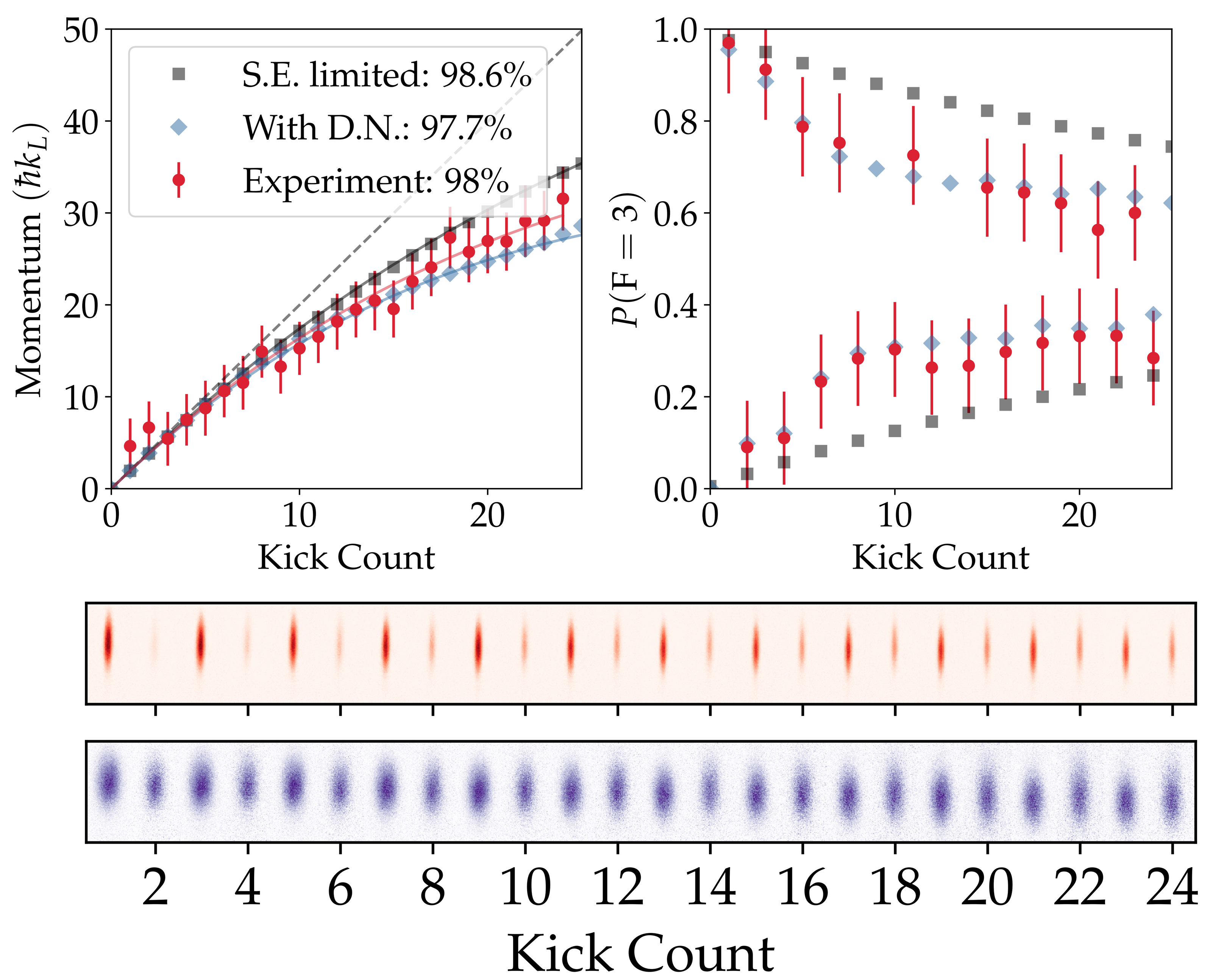
Experimental
- Wide band laser modulation [3];
- SDK on an optical delay line.

Theoretical
- Full-level simulation;
- Pulse optimization (GRAPE [4])





Results

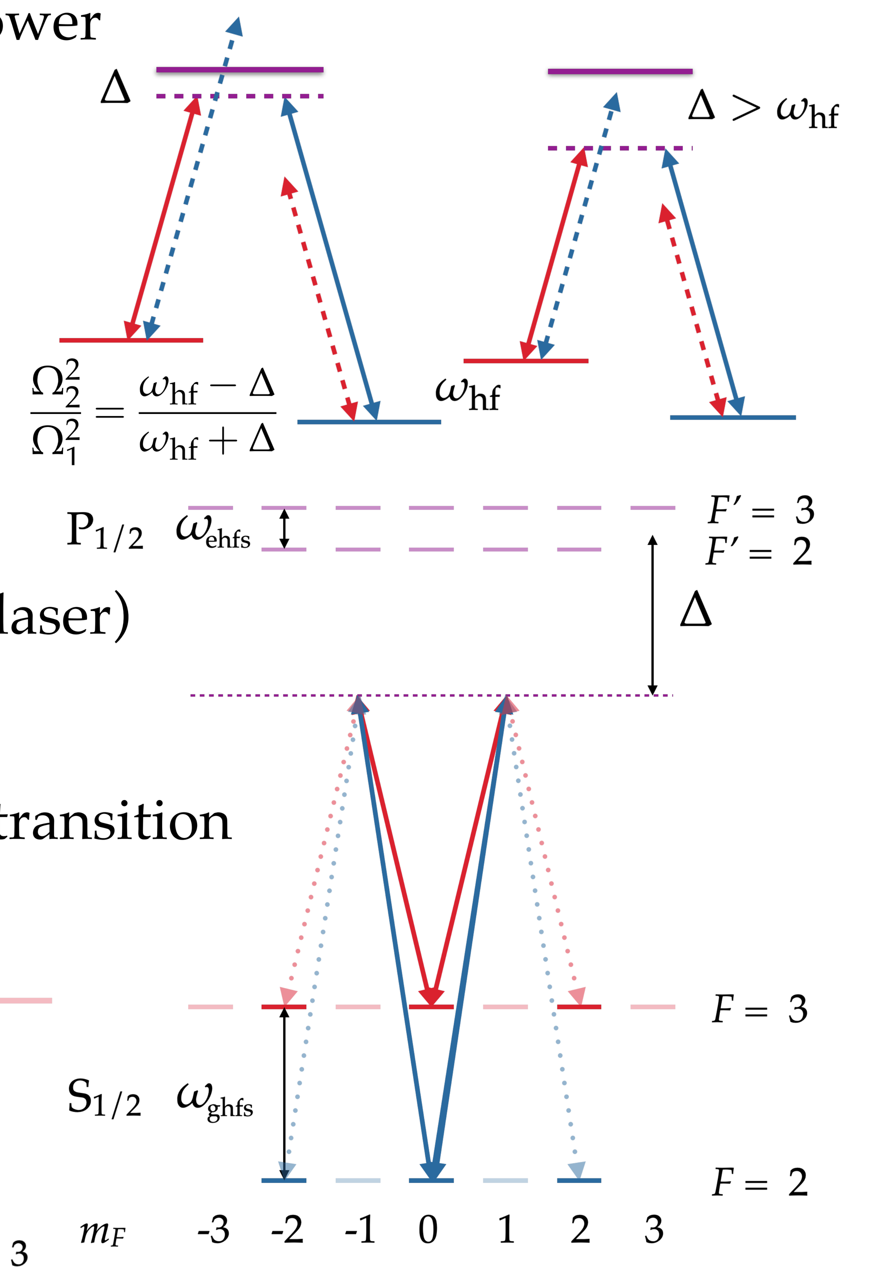


- Momentum transfer efficiency ~ 97% .
- We know how to improve further.
- Can we manage unwanted hyperfine dynamics for precision measurements?

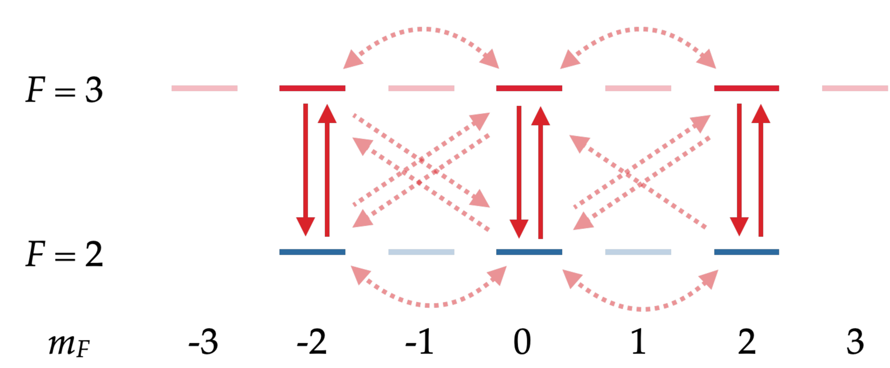
What is limiting ns SDK?

Speed limit: in general, spin-motion entanglement operation is limited by hyperfine splitting; practically, it is usually limited by the driving laser intensity / power

$$\Omega_R = \frac{\Omega_1\Omega_2^*}{2\Delta} \sim \frac{\Omega^2}{\Delta^2}\Delta$$

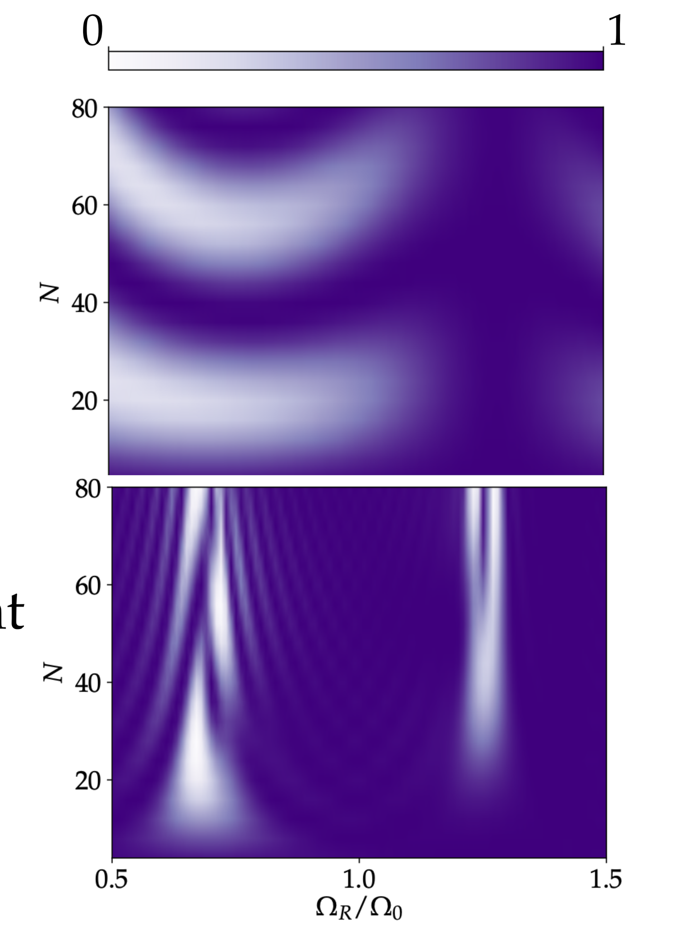


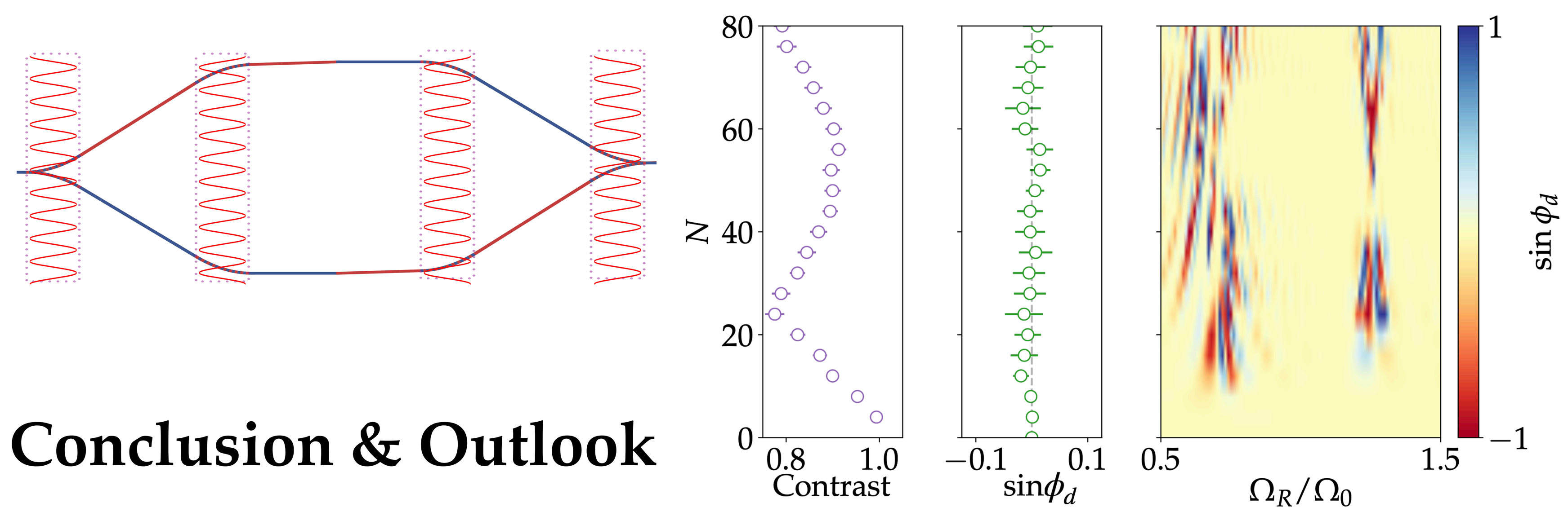
Fidelity limit:
- Spontaneous emission: $R_{sc} \sim \frac{\Omega^2}{4\Delta}\Gamma\tau \sim \frac{m\pi}{2}\frac{\Gamma}{\Delta}$
- Dynamic phase (by a focused laser)
- **"Qubit leakage":** $\Delta m = \pm 1, 2$ transition



AI with multiple nanosecond SDK (LMT)

- Large detuning, strongly focused laser;
- Dynamic phase cancelation: $U_+U_+U_+U_+$ and $U_+U_-U_-U_+$;
- Management of the intensity-dependent "leak";
- Recovering high contrast, faithful AI interference near a strong laser focus.





Conclusion & Outlook

- $2\hbar k$/100ns, largest Raman SDF for macroscopic samples!
- High fidelity, nanosecond SDK within a strongly focused laser
- Discovery of nontrivial hyperfine leakage dynamics
  – Negative impacts appear mitigatable;
  – Positive applications?

Reference

[1] K. Kotru *et al.*, *Phys. Rev. Lett.* **115**, 103001 (2015); M. Jaffe *et al.*, *Phys. Rev. Lett.* **121**, 040402 (2018).

[2] J. Mizrahi *et al.*, *Phys. Rev. Lett.* **110**, 203001 (2013); C. Flühmann *et al*, Nature **566**, 513 (2019).

[3] Y. He *et al.*, *Phys. Rev. Res.* 2, 043418 (2020).

[4] N. Khaneja *et al.*, *J. Magn. Reson.* **172**, 296 (2005).