

运动里德堡原子多体纠缠与自旋压缩的研究

1. 绪论
2. 物理背景与理论基础
3. 运动里德堡原子的三体纠缠与量子关联
4. 运动里德堡原子的多体纠缠与量子关联
5. 光与里德堡原子相互作用的自旋压缩与退相干行为
6. 基于海森堡算符的自旋压缩与退相干行为

论文总结

参考文献

第一章

量子信息
量子计算

第二章

量子纠缠
自旋压缩
里德堡原子
分子运动
塔利算法

运动里德堡原子

$$|\pi_n\rangle \equiv |s\cdots p\cdots s\rangle$$

$$H(\mathbf{R}) = -\sum_{n=1}^N \frac{\nabla_{\mathbf{R}_n}^2}{2M} + H^{\text{el}}(\mathbf{R})$$

$$H^{\text{el}}(\mathbf{R}) = \sum_{nm} V_{nm}(R_{nm}) |\pi_n\rangle \langle \pi_m|$$

$$V_{nm}(R_{nm}) = (-1)^n \frac{\mu^2}{R_{nm}^3}$$

$$H^{\text{el}}(\mathbf{R}) |\varphi_k(\mathbf{R})\rangle = U_k(\mathbf{R}) |\varphi_k(\mathbf{R})\rangle$$

$$|\varphi_k(\mathbf{R})\rangle = \sum_m c_{km}(\mathbf{R}) |\pi_m\rangle$$

$$|\Psi(t=0)\rangle = |\varphi_{\text{rep}}(\mathbf{R})\rangle \prod_{n=1}^N \phi_G(\mathbf{R}_n)$$

$$\phi_G(\mathbf{R}_n) = \mathcal{N} \exp\left(-|\mathbf{R}_n - \mathbf{R}_{0n}|^2 / 2\sigma_0^2\right)$$

$$i \frac{\partial}{\partial t} |\Psi\rangle = H |\Psi\rangle$$

$$|\Psi(\mathbf{R})\rangle = \sum_{n=1}^N \phi_n(\mathbf{R}) |\pi_n\rangle$$

$$\mathrm{i}\frac{\partial}{\partial t}\phi_n(\mathbf{R})=\sum_{m=1}^N\left[-\frac{\nabla_{\mathbf{R}_{\mathfrak{m}}}^2}{2M}\phi_n(\mathbf{R})+V_{nm}\left(R_{nm}\right)\phi_m(\mathbf{R})\right]$$

$$|\Psi(\mathbf{R})\rangle = \sum_{k=1}^N \tilde{\phi}_k(\mathbf{R}) \big| \varphi_k(\mathbf{R}) \big\rangle$$

$$\tilde{\phi}_k(\mathbf{R}) = \sum_n O_{kn}(\mathbf{R}) \phi_n(\mathbf{R})$$

$$n(R)=\sum_{j=1}^N\sum_{m=1}^N\int\mathrm{d}^{N-1}\!\mathbf{R}_{\{j\}}\left|\phi_m(\mathbf{R})\right|^2$$

$$|\Psi(\mathbf{R},t)\rangle = \sum_{k=1}^N \tilde{c}_k(t) \big| \varphi_k(\mathbf{R}) \big\rangle$$

$$\mathrm{i}\frac{\partial}{\partial t}\tilde{c}_k=U_k(\mathbf{R})\tilde{c}_k-\mathrm{i}\sum_{q=1}^N\dot{\mathbf{R}}\cdot\mathbf{d}_{kq}\tilde{c}_q$$

$$\mathbf{d}_{kq}=\left\langle \varphi_k(\mathbf{R})\Big|\nabla_{\mathbf{R}}\Big|\varphi_q(\mathbf{R})\right\rangle$$

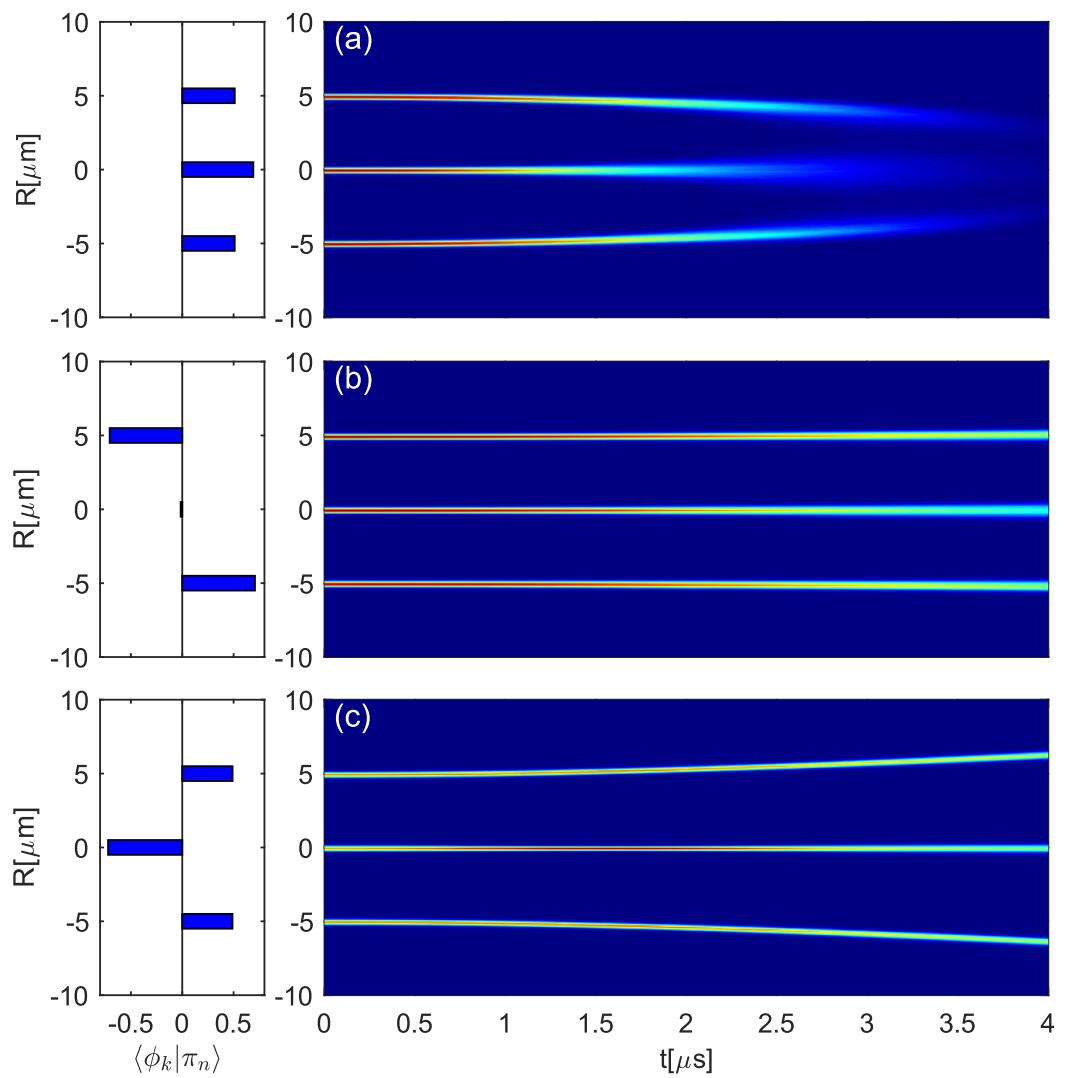
$$M\ddot{\mathbf{R}}=-\nabla_{\mathbf{R}}\bar{U}(\mathbf{R},t)$$

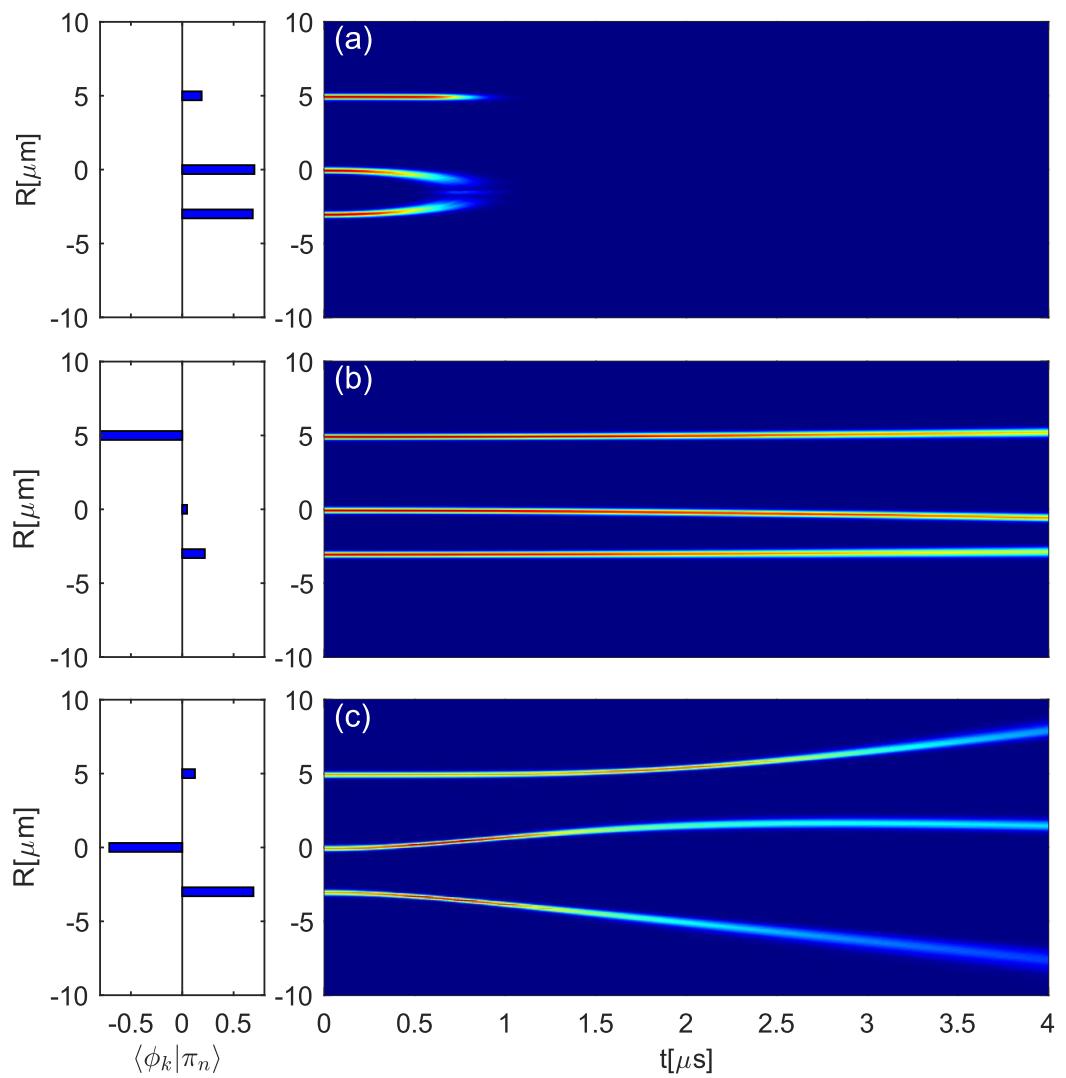
$$\bar{U}(\mathbf{R},t)=\left\langle \Psi(\mathbf{R},t)\Big|H^{\text{el}}(\mathbf{R})\Big|\Psi(\mathbf{R},t)\right\rangle=\sum_k\left|\tilde{c}_k(t)\right|^2U_k(\mathbf{R})$$

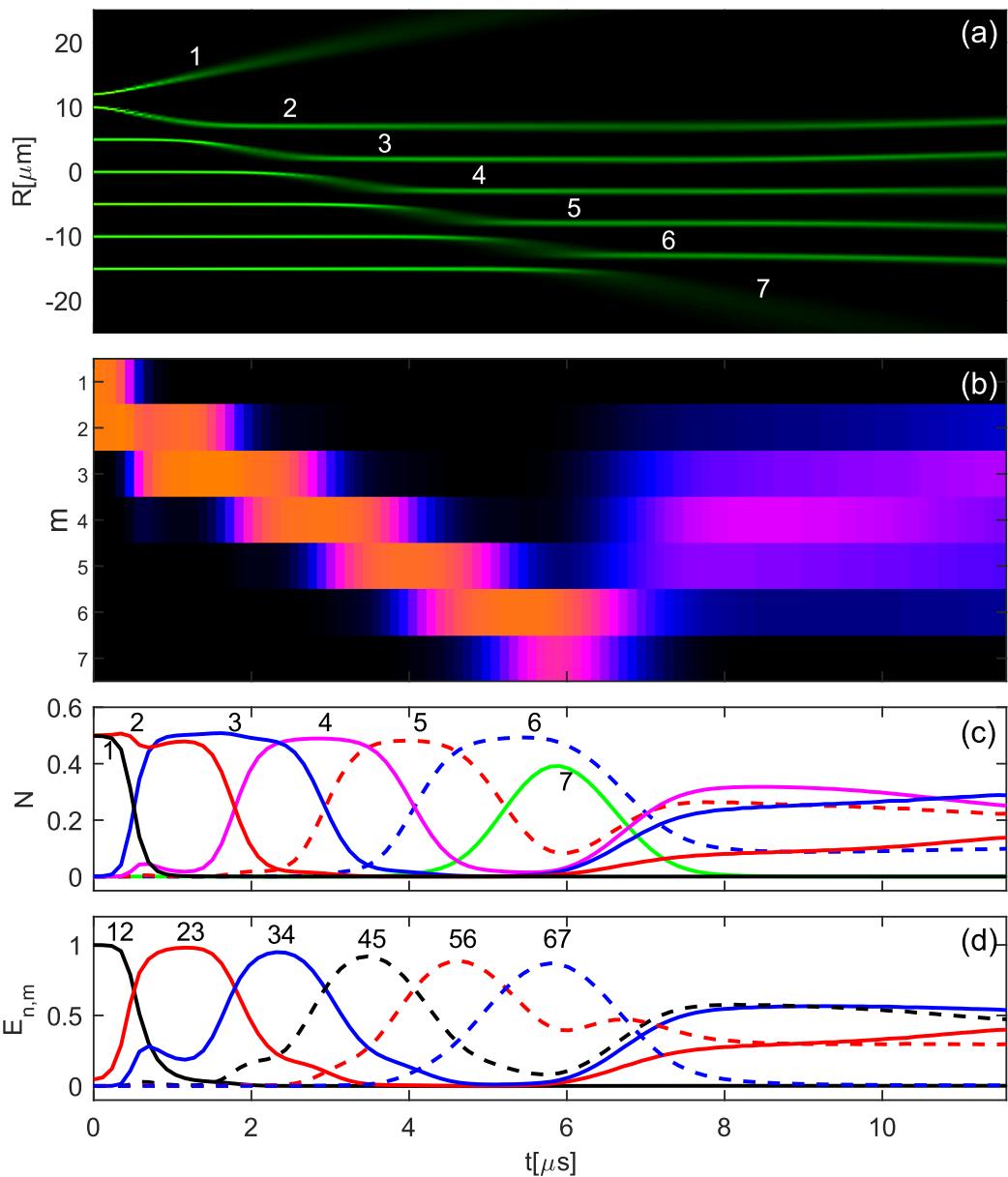
$$M\ddot{\mathbf{R}}=-\nabla_{\mathbf{R}}U_k(\mathbf{R})$$

$$\hat{\sigma}=\sum_{n,m}\sigma_{nm}\left|\pi_n\right\rangle\left\langle\pi_m\right|$$

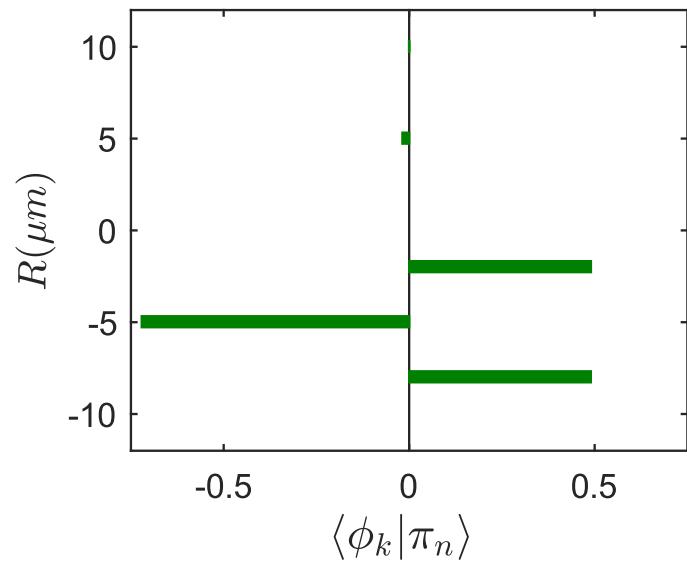
$$\sigma_{nm}=\begin{cases}\int\mathrm{d}^N\!\mathbf{R}\phi_n^*(\mathbf{R})\phi_m(\mathbf{R})\\ \overline{c_n^*c_m}\end{cases}$$

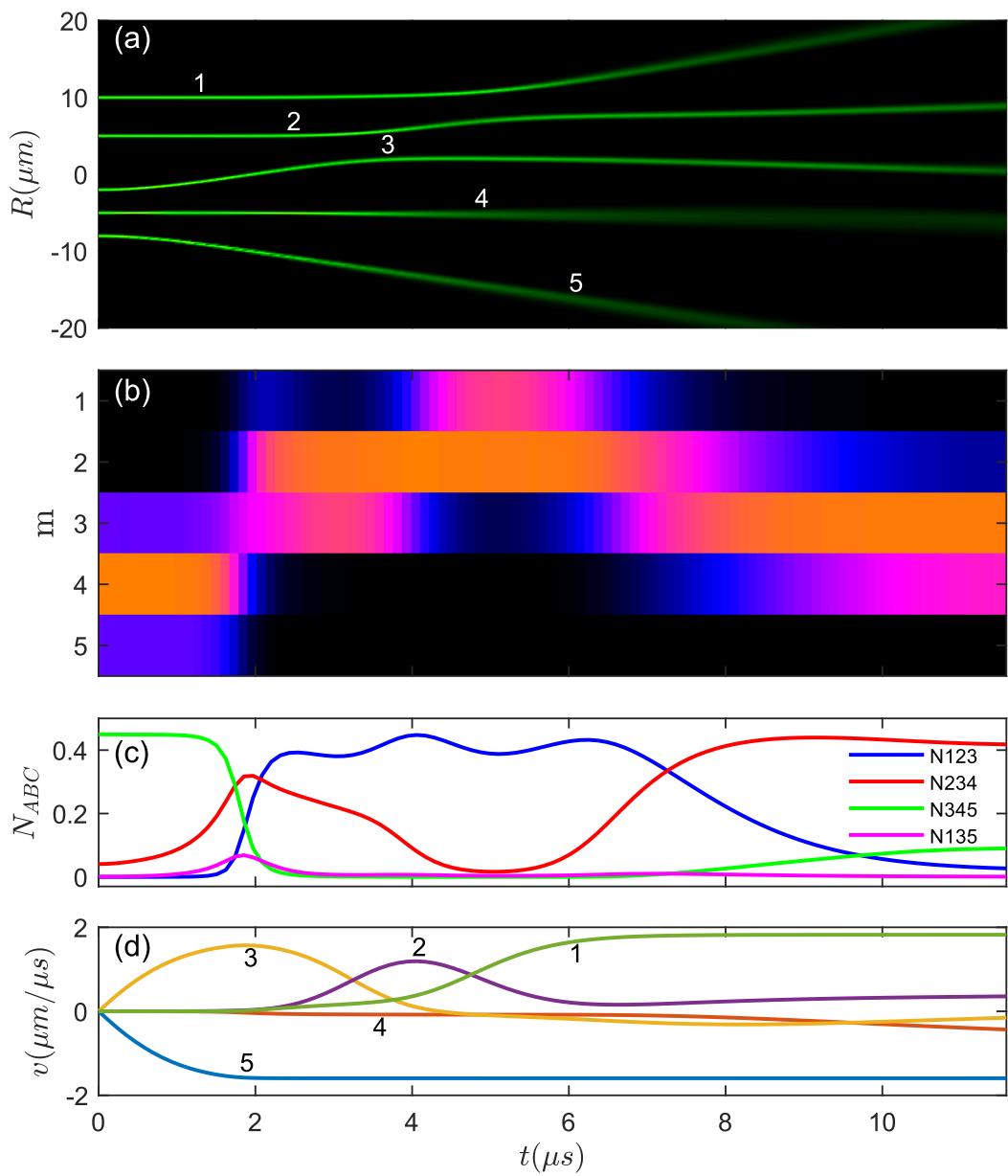


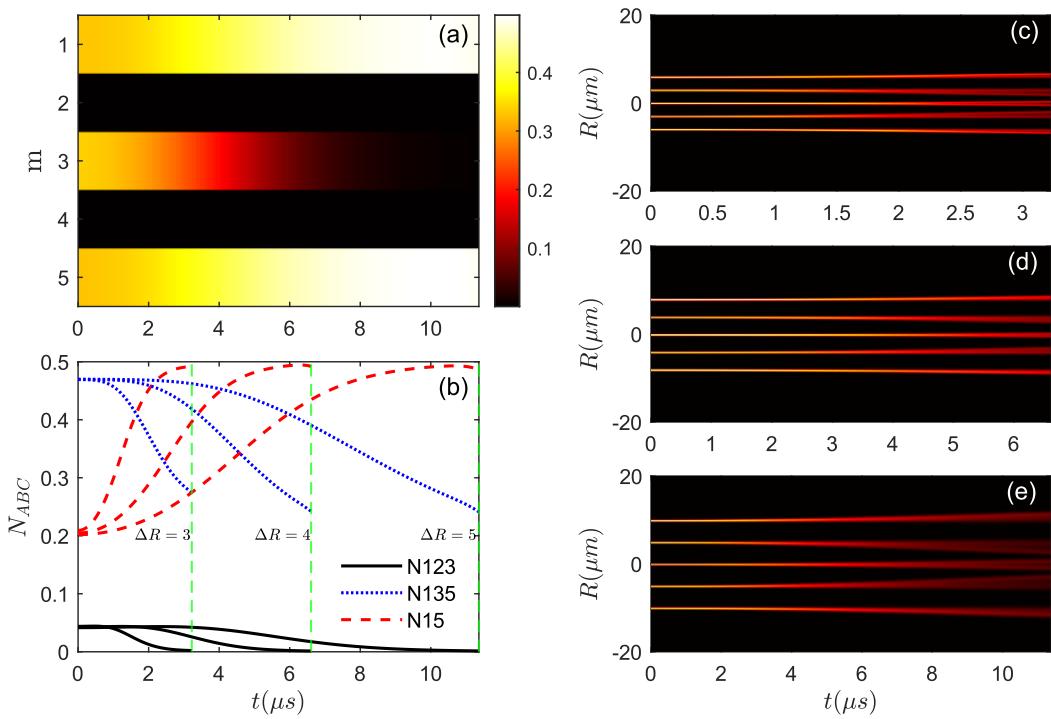
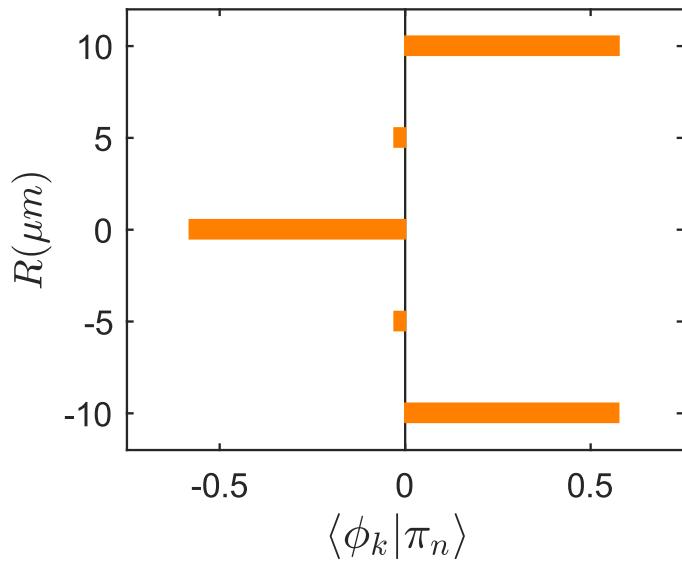


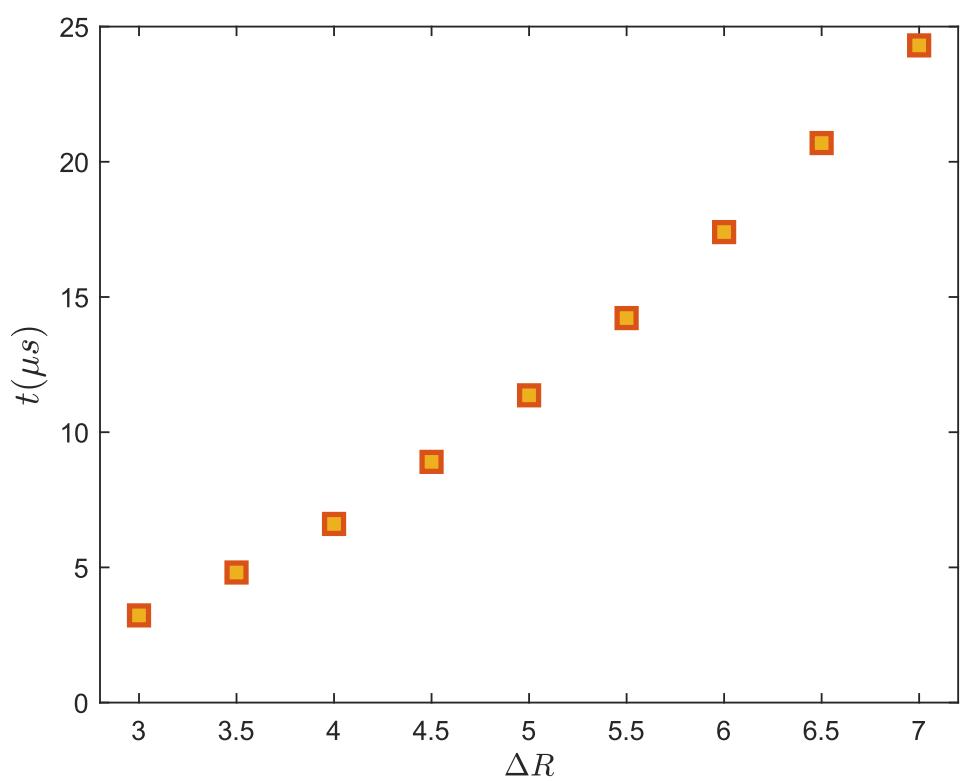


第三章









第四章

在前面的介绍中，量子纠缠是区别微观粒子与宏观世界的重要特性。量子多体问题是量子力学中的重要问题，而多体纠缠又是量子多体问题中最基本的问题之一，它在量子信息技术中有着重要的应用，如量子密码学，量子保密通信，量子计算等等[1]。

在度量多体纠缠的许多方法中，负熵(Negativity)是应用比较广泛的一种方法，它的定义为：

$$N_{\alpha,\beta\gamma\delta\epsilon} = \left\| \rho_{\alpha,\beta\gamma\delta\epsilon}^{T_\alpha} \right\| - 1, \quad N_{\alpha\beta,\gamma\delta\epsilon} = \left\| \rho_{\alpha\beta(\gamma\delta\epsilon)}^{T_{\alpha\beta}} \right\| - 1, \quad N_{\alpha,\beta} = \left\| \rho_{\alpha\beta}^{T_\alpha} \right\| - 1,$$

其中 $N_{\alpha,\beta\gamma\delta\epsilon}$ ， $N_{\alpha\beta,\gamma\delta\epsilon}$ 和 $N_{\alpha,\beta}$ 分别表示为 1-4 缠结，2-3 缠结和 1-1 缠结。表达式

$\left\| \rho_{\alpha(\beta\gamma\delta\epsilon)}^{T_\alpha} \right\|$ ， $\left\| \rho_{\alpha\beta(\gamma\delta\epsilon)}^{T_{\alpha\beta}} \right\|$ 与 $\left\| \rho_{\alpha\beta}^{T_\alpha} \right\|$ 分别代表密度矩阵部分转置迹的范数。通常来说，

任意厄密算符 A 的迹与其本征值之和相等， $\|A\| = \text{tr} \sqrt{A^\dagger A}$ ，则：

$$\|M\| - 1 = 2 \sum_{i=1}^N |\lambda_M^{(-)}|^i,$$

其中 $\lambda_M^{(-)}$ 表示矩阵 M 负的本征值。应该指出的是，这些负性的计算是非常复杂和耗时的。

我们使用 π 缠结来度量多体纠缠，它的定义为：

$$\pi_A = N_{A,BCDE}^2 - N_{A,B}^2 - N_{A,C}^2 - N_{A,D}^2 - N_{A,E}^2,$$

$$\pi_B = N_{B,ACDE}^2 - N_{B,A}^2 - N_{B,C}^2 - N_{B,D}^2 - N_{B,E}^2,$$

$$\pi_C = N_{C,ABDE}^2 - N_{C,A}^2 - N_{C,B}^2 - N_{C,D}^2 - N_{C,E}^2,$$

$$\pi_D = N_{D,ABCE}^2 - N_{D,A}^2 - N_{D,B}^2 - N_{D,C}^2 - N_{D,E}^2,$$

$$\pi_E = N_{E,ABCD}^2 - N_{E,A}^2 - N_{E,B}^2 - N_{E,C}^2 - N_{E,D}^2,$$

从中我们可以计算出整体剩余纠缠 π_5 缠结，它的代数平均表示为：

$$\pi_5 = (\pi_A + \pi_B + \pi_C + \pi_D + \pi_E) / 5,$$

它的几何平均表示为：

$$\Pi_5 = (\pi_A \cdot \pi_B \cdot \pi_C \cdot \pi_D \cdot \pi_E)^{\frac{1}{5}}.$$

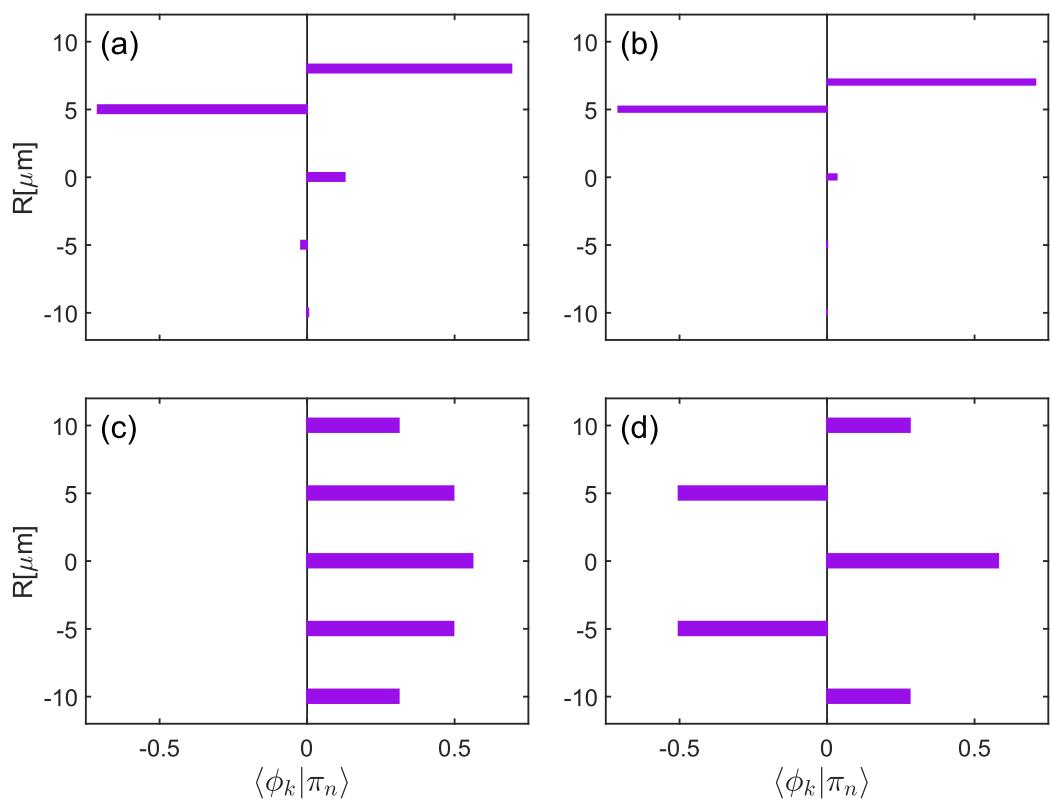


图 4-1

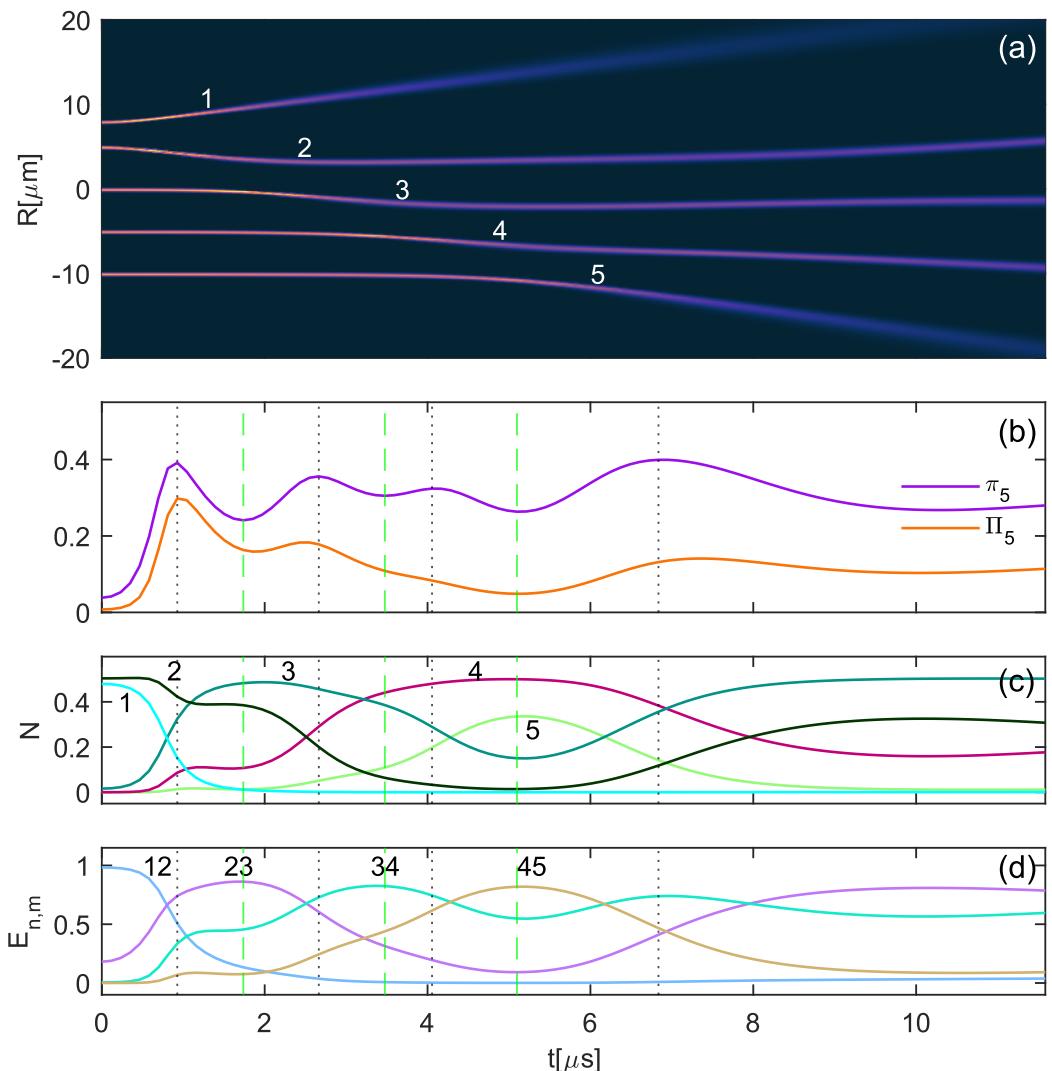


图 4-2 原子间距离不等的五个里德堡原子一维运动。图(a)原子总密度与原子运动轨迹。图(b)五个里德堡原子运动时随时间演化的多体纠缠。图(c)每个原子在绝热面上的透热激发概率。图(d)相邻两个原子的纠缠。

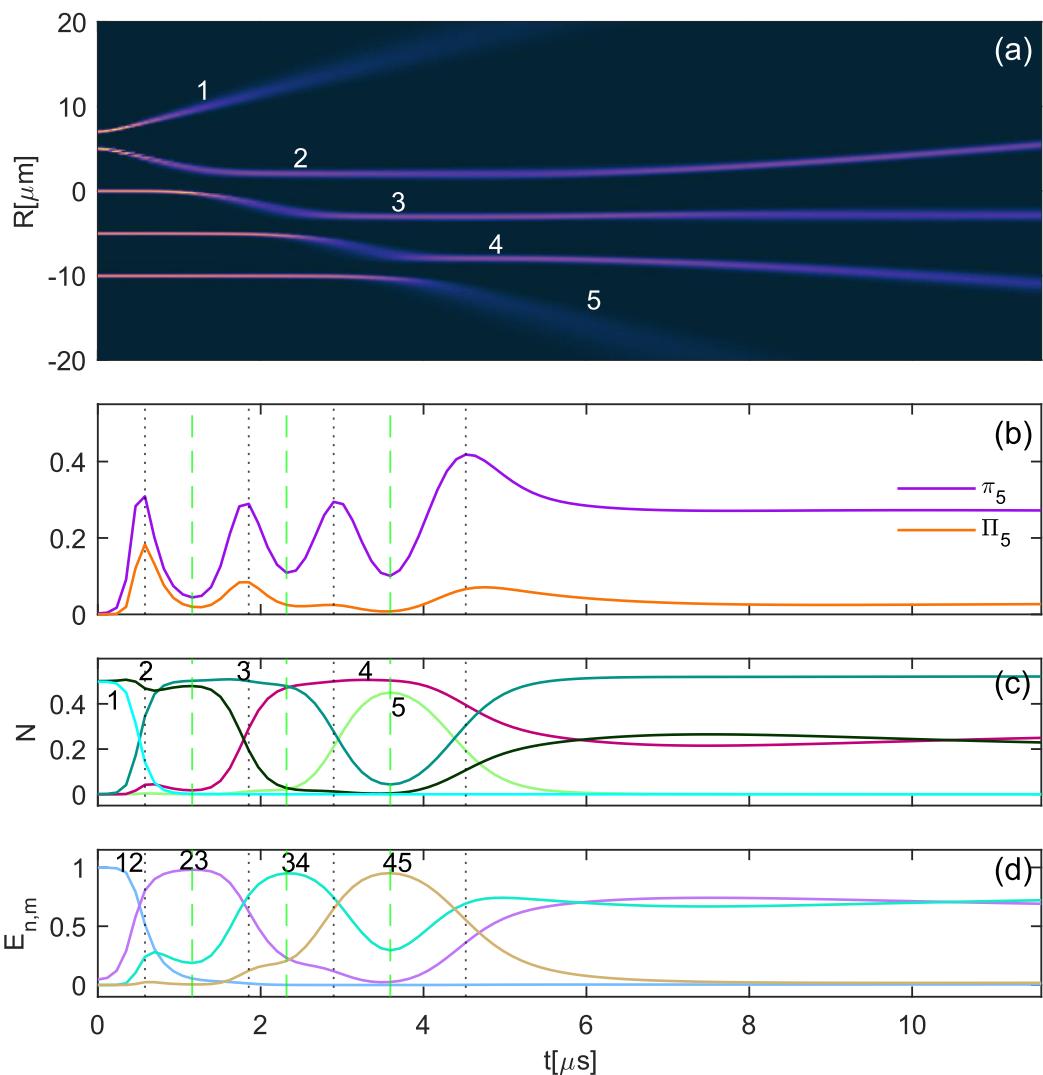


图 4-3 原子间距离不等的五个里德堡原子一维运动。图(a)原子总密度与原子运动轨迹。图(b)五个里德堡原子运动时随时间演化的多体纠缠。图(c)每个原子在绝热面上的透热激发概率。图(d)相邻两个原子的纠缠。

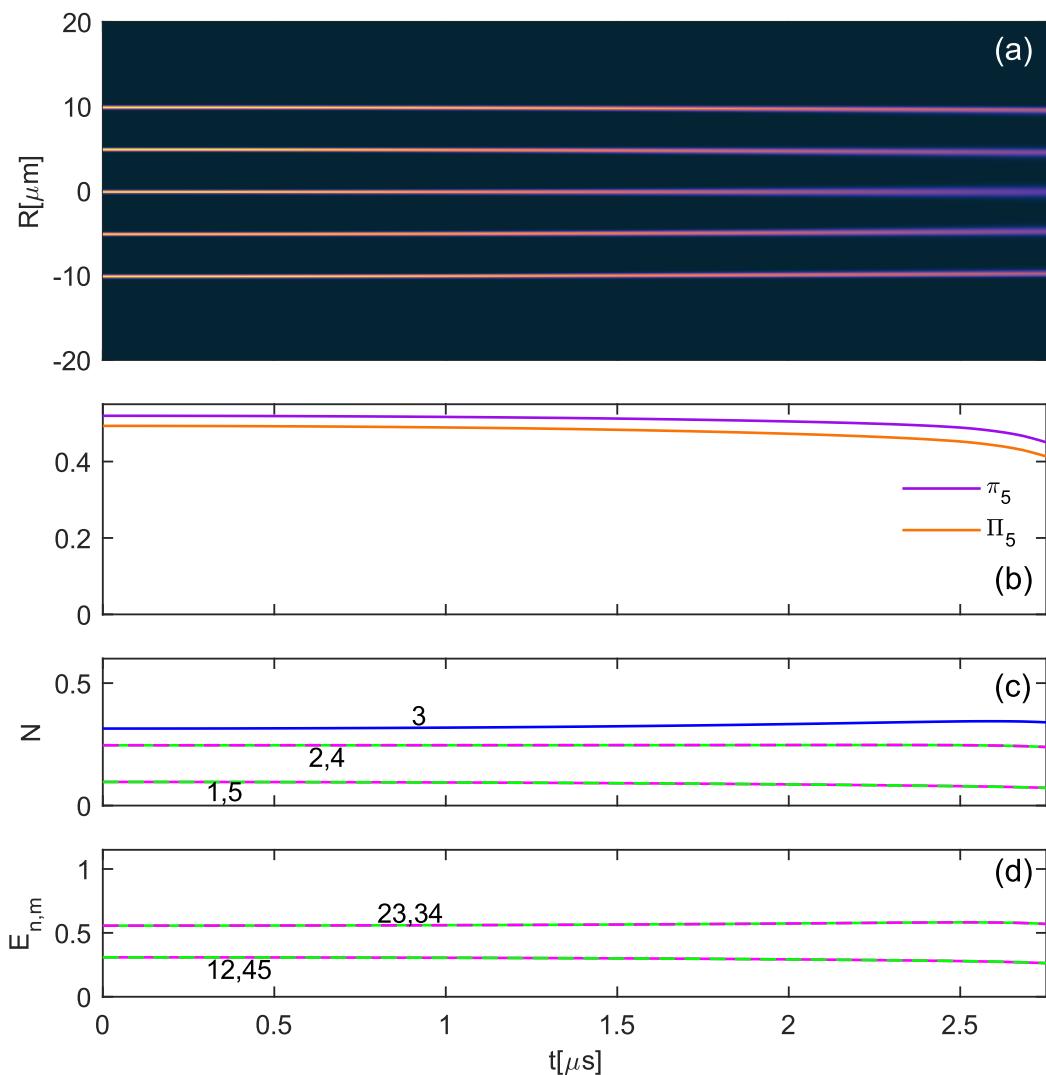


图 4-4 原子间距离相等的五个里德堡原子一维运动。图(a)原子总密度与原子运动轨迹。图(b)五个里德堡原子运动时随时间演化的多体纠缠。图(c)每个原子在绝热面上的透热激发概率。图(d)相邻两个原子的纠缠。

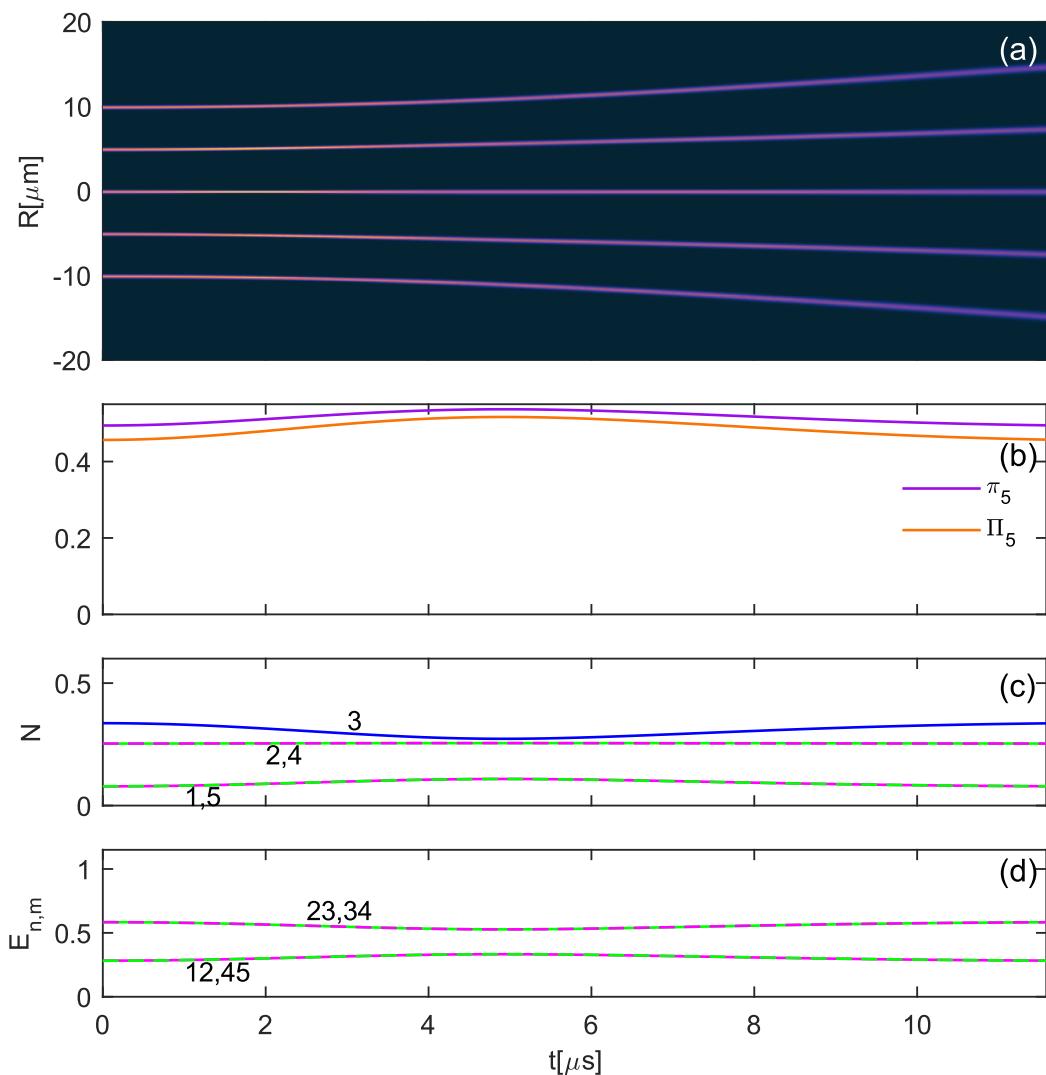
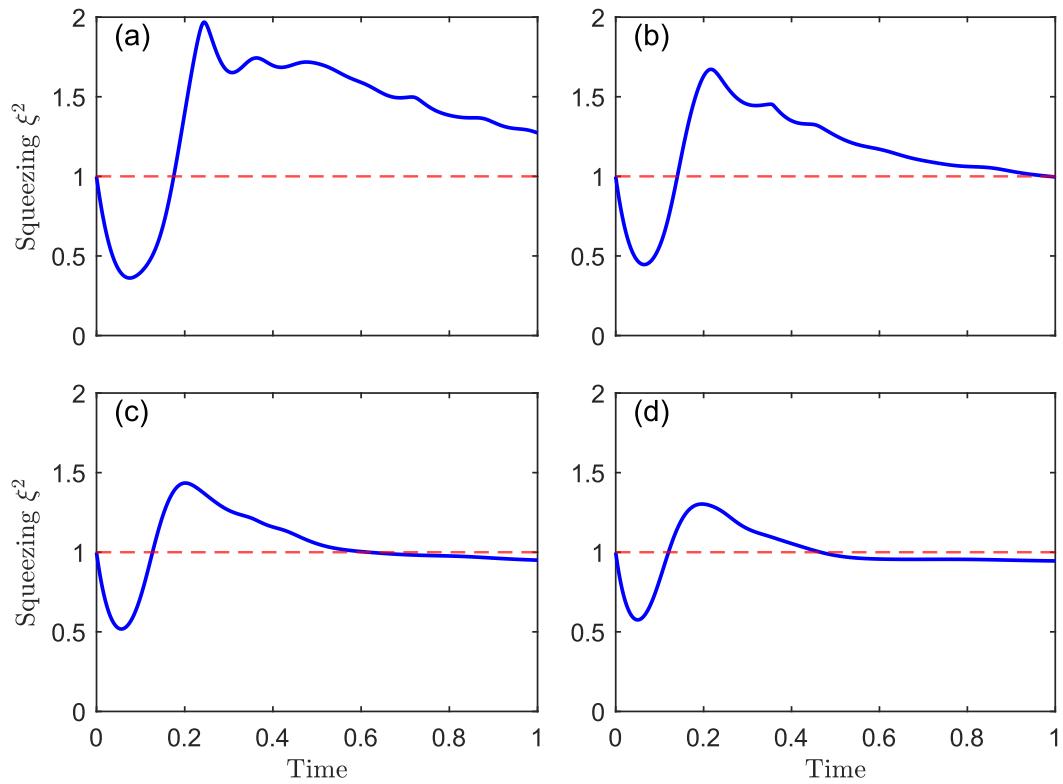
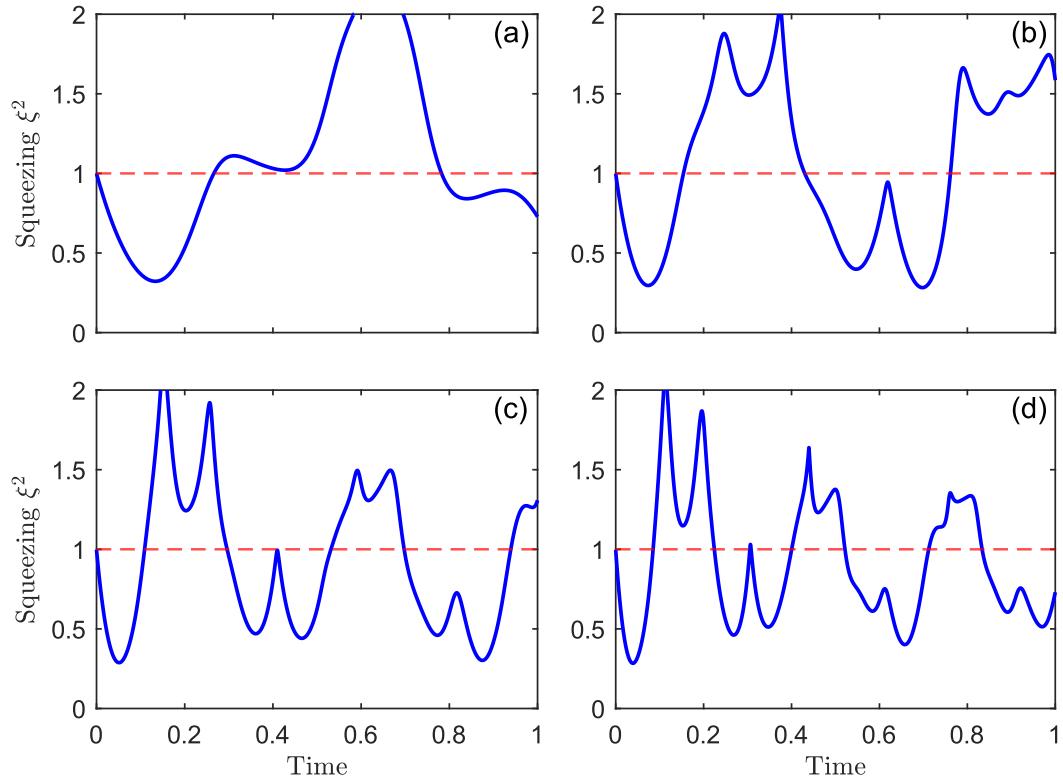
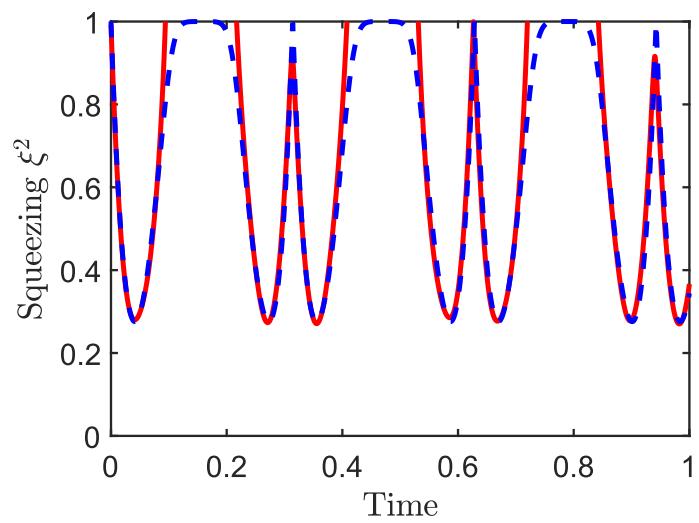
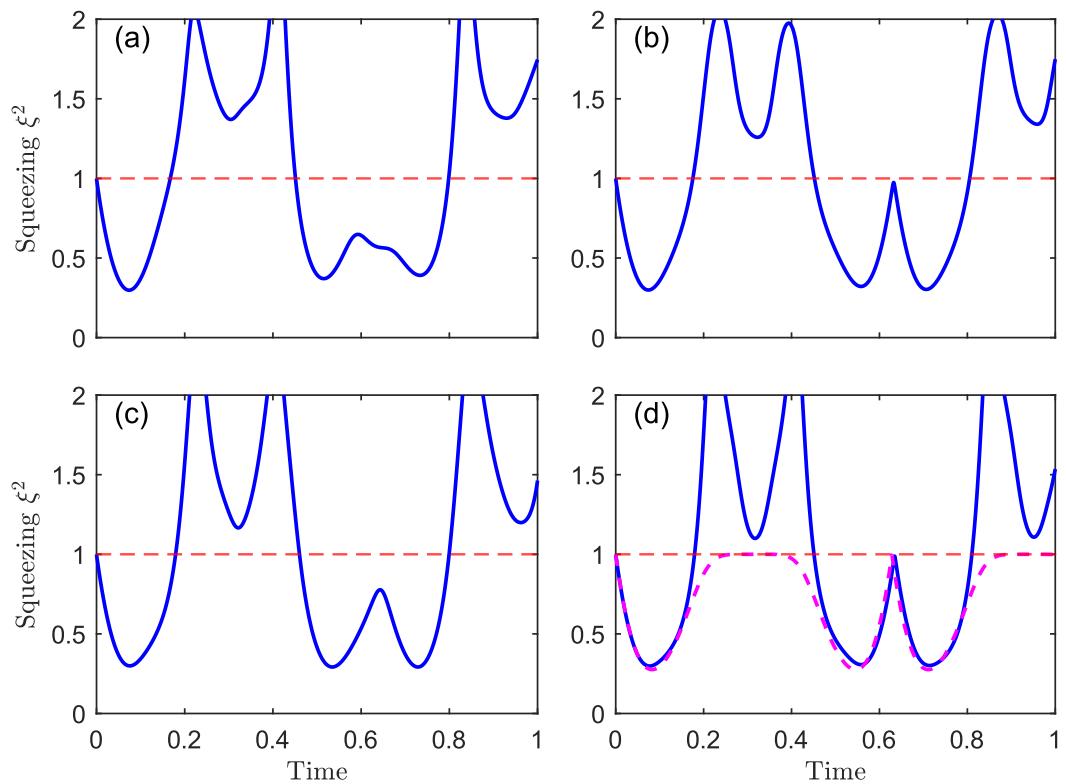
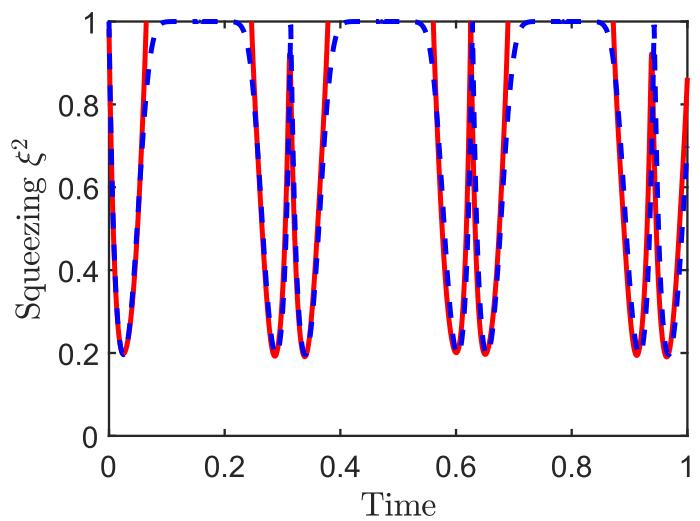


图 4-5 原子间距离相等的五个里德堡原子一维运动。图(a)原子总密度与原子运动轨迹。图(b)五个里德堡原子运动时随时间演化的多体纠缠。图(c)每个原子在绝热面上的透热激发概率。图(d)相邻两个原子的纠缠。

第五章



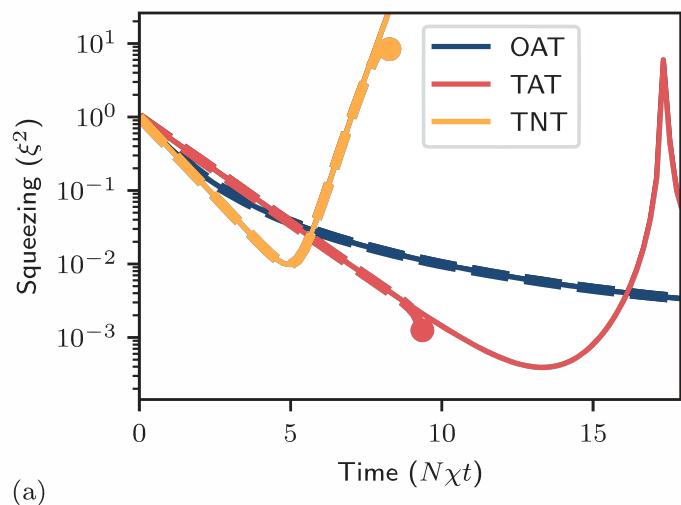




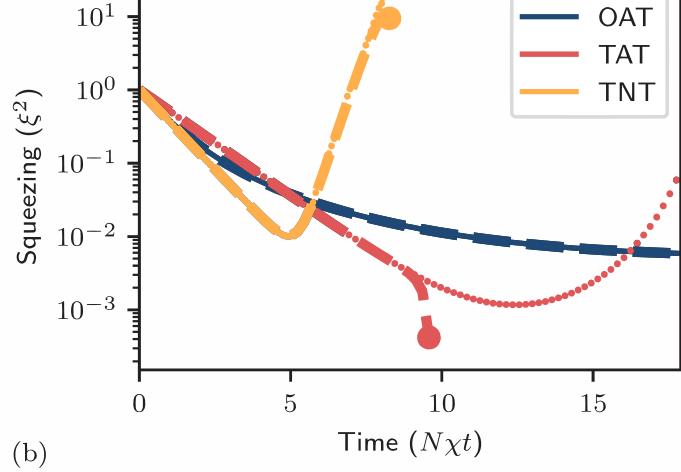
第六章

展开算法

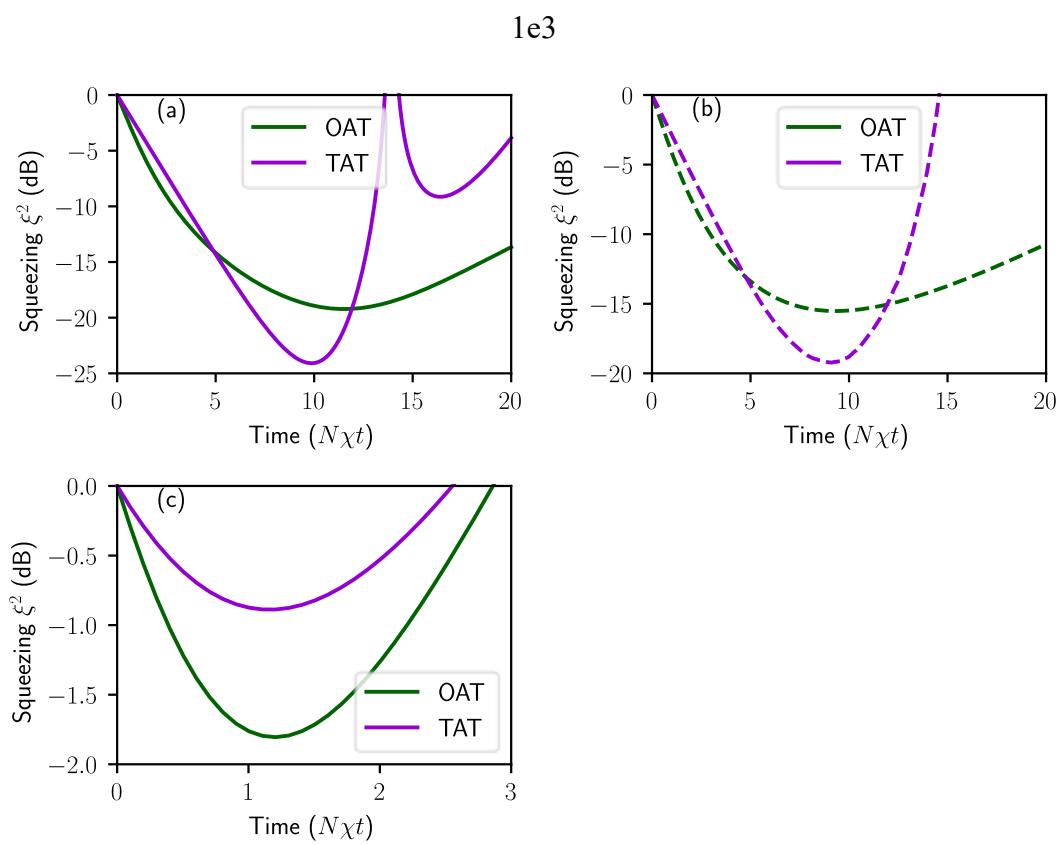
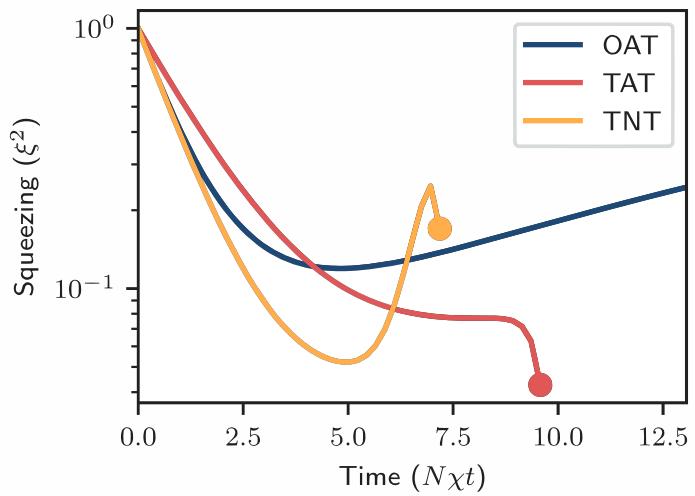
$$\mathcal{O} = \sum_m \mathcal{O}_m \mathcal{S}_m,$$



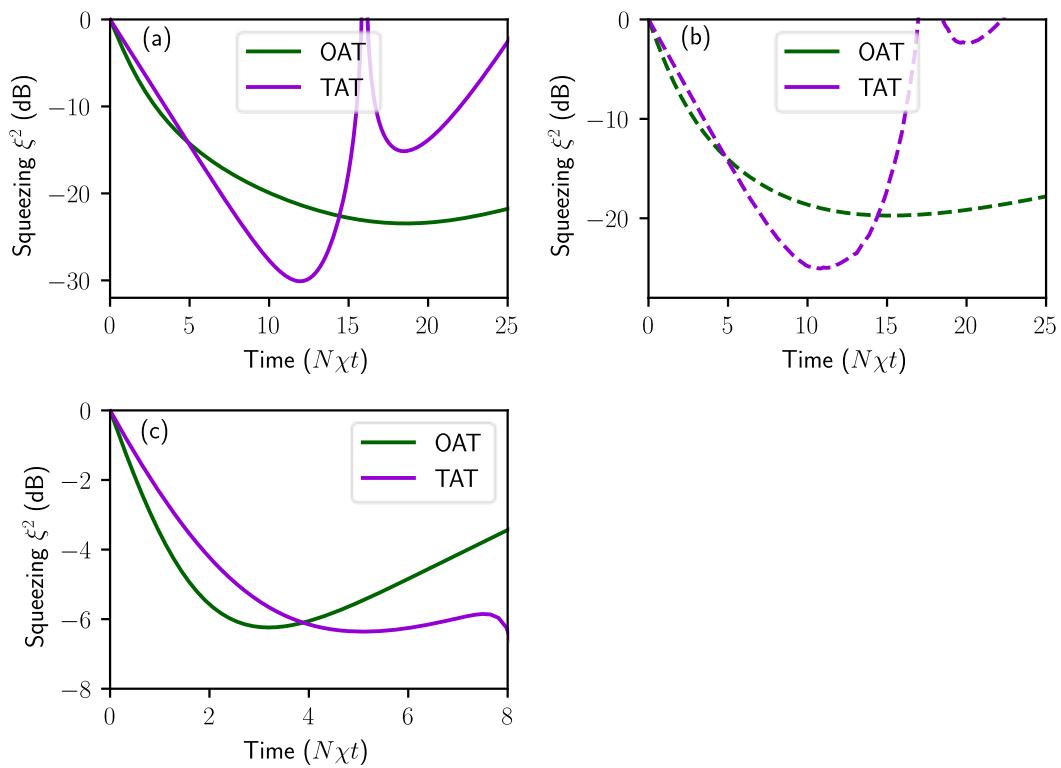
(a)



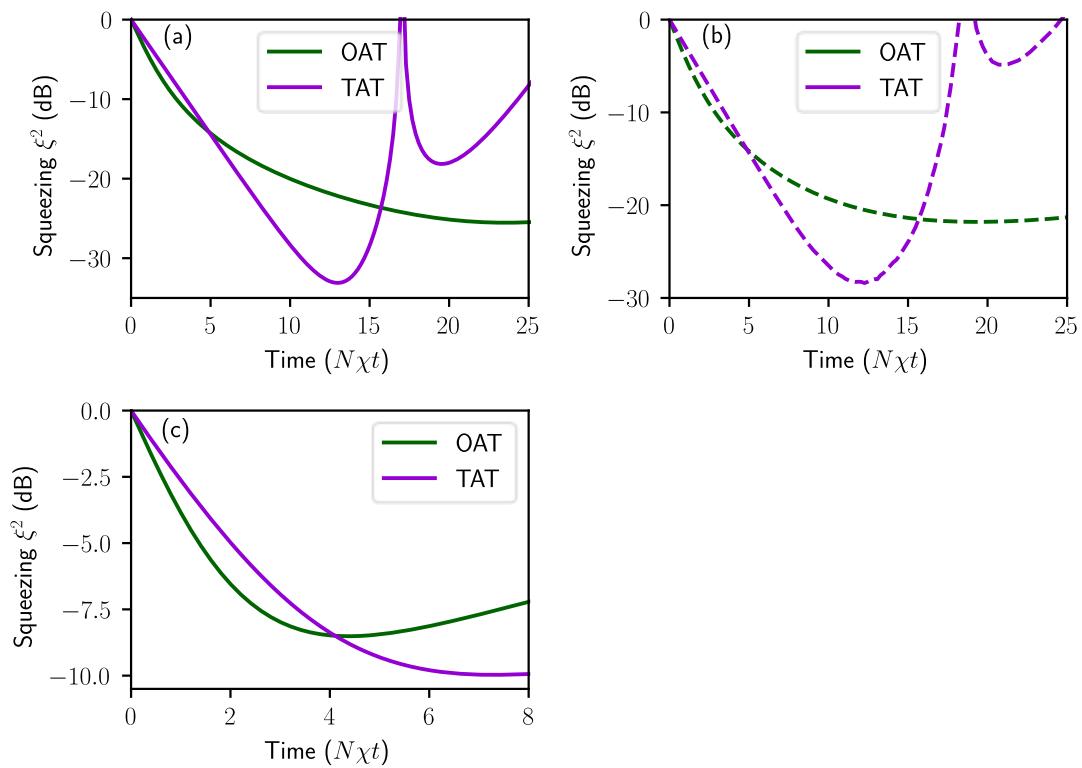
(b)

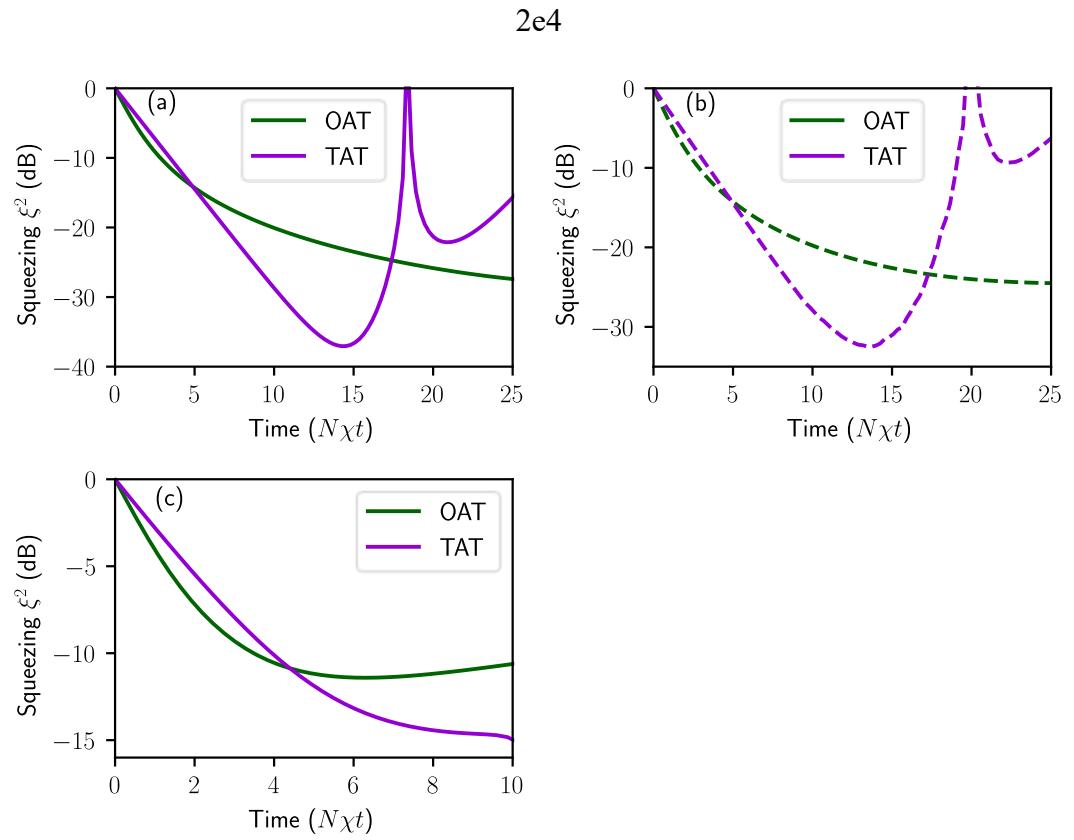


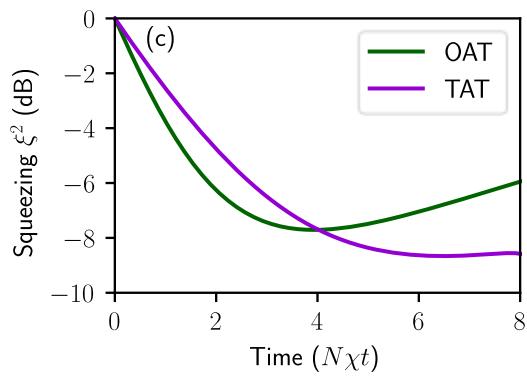
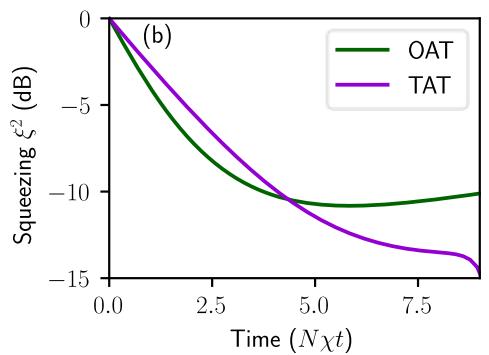
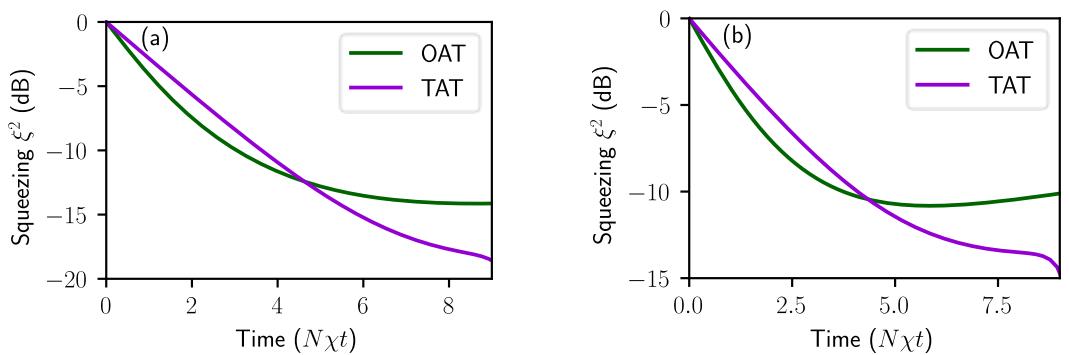
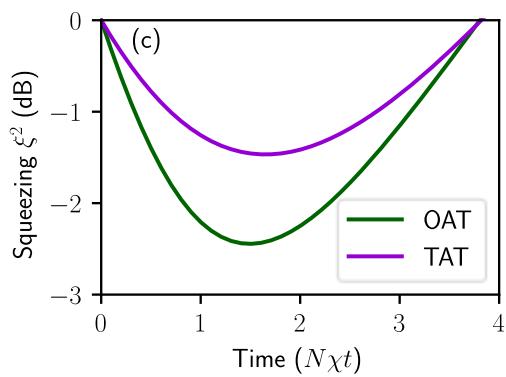
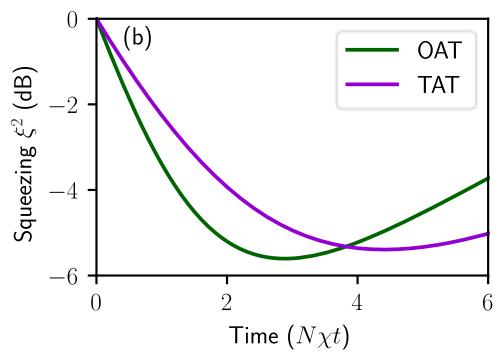
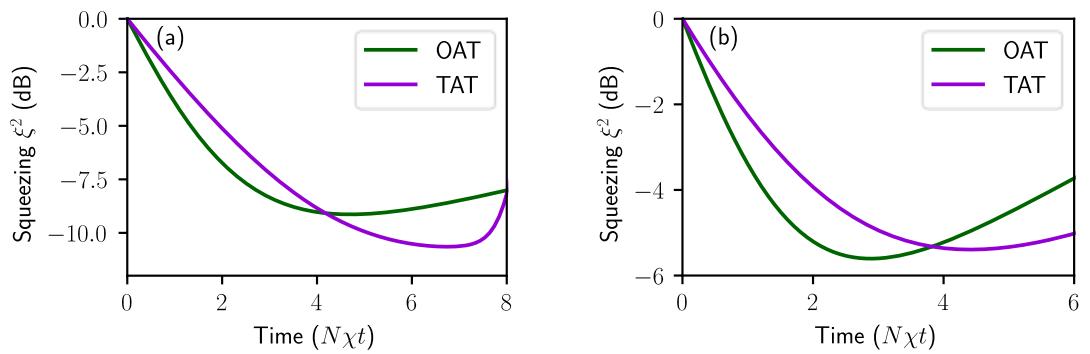
$4e3$



$8e3$







结论

参考文献