# Temporal-Spatial Double Slit Interference of Photoelectron

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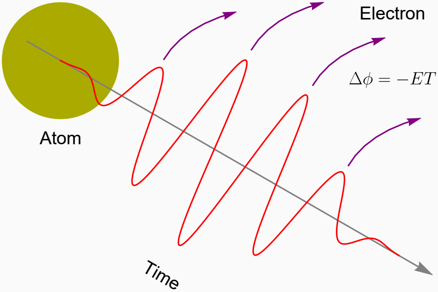
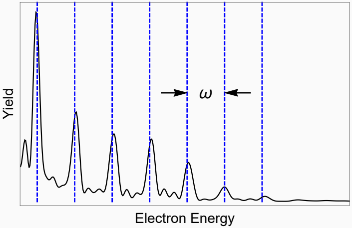
# Above Threshold Ionization

Electron ionized at each optical cycle⇒
Above threshold ionization peaks split by one photon energy.

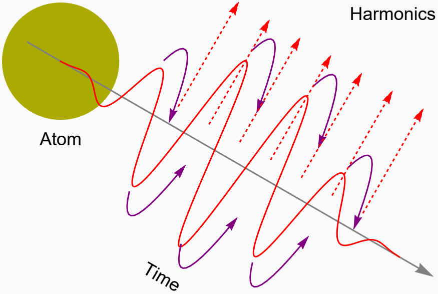


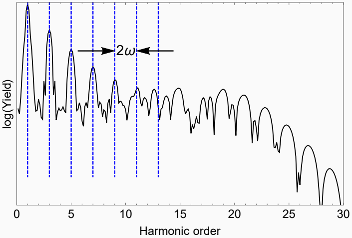




Grating in time domain.

# Harmonics Generation

Electron recollide with nuclear at each half cycle ⇒
Odd order harmonics split by two photon energy.

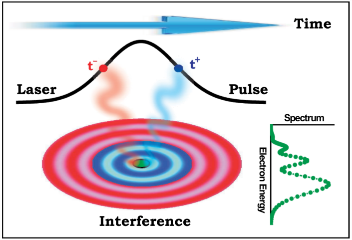



Grating in time domain.

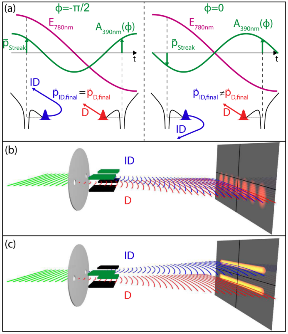
# Other types

Dynamic Interference:
two slits in the rising and falling part of pulse envelop.



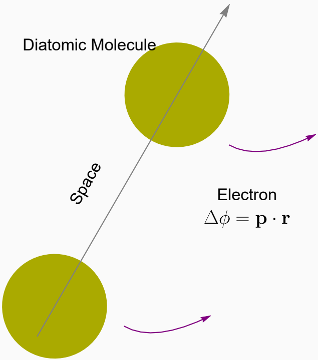

PRL **108**, 253001 (2012)
PRA **92**, 023419 (2016)
PRL **118**, 143202 (2017)
OE **26**, 019921 (2018)

Orthogonal Two-Color pulse:
manipulate inner-cycle interference.

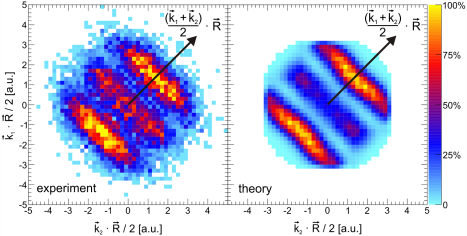



PRL **114**, 143001 (2015)
PRL **115**, 193001 (2015)
JPB **50**, 235604 (2017)

# Interference in spatial domain

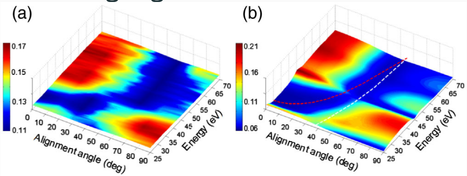



## One-photon region




Science **318**, 949 (2007) PNAS **108**, 7302 (2011)
Nat. Photon. **9**, 120 (2015) PRL **117**, 083002 (2016)

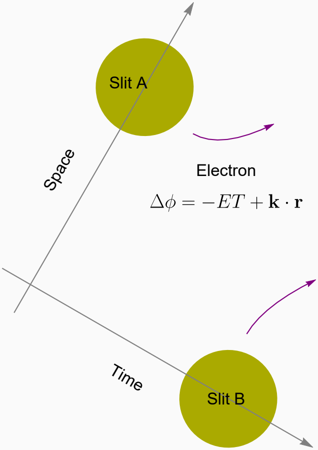
## Tunneling region




PRL **122**, 193202 (2019) Nat. Commun. **10**, 1 (2019)

# Temporal-Spatial Interference?

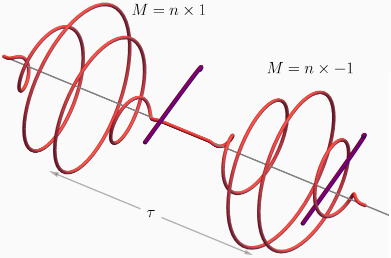
- Interference in Temporal domain ⇒ Patterns in Energy Spectra
- Interference in Spatial domain ⇒ Patterns in Momentum Spectra
- $E = \boldsymbol{p}^2/2$

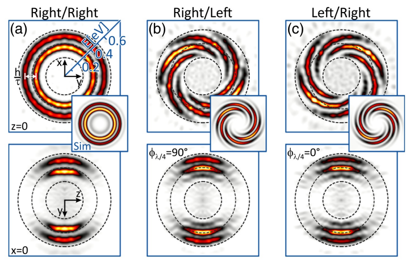



Can we see something special from the photoeletron momentum distribution?

# Electron Vortex

Two delayed counter-rotate circular polarized pulse ⇒ $2n$-fold Vortex structures in PMD



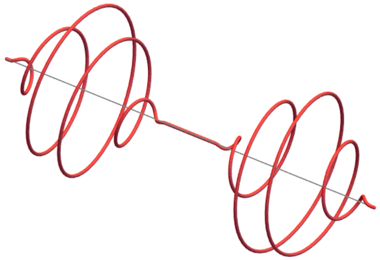



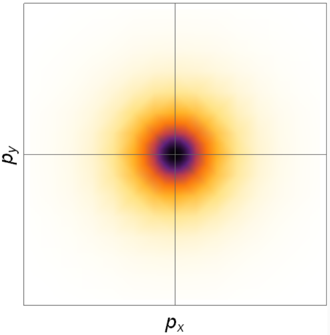

$$\Delta\phi = \underbrace{(p^2/2 + I_p)\tau}_{\approx n\omega,\ \text{Time delay}} + \underbrace{2n\phi}_{\text{Magnetic number}}$$

PRL **115**, 113004 (2015)
PRL **118**, 053003 (2017)
Nat. Commun. **10**, 658 (2019)

# Semiclassical explanation: Momentum Space

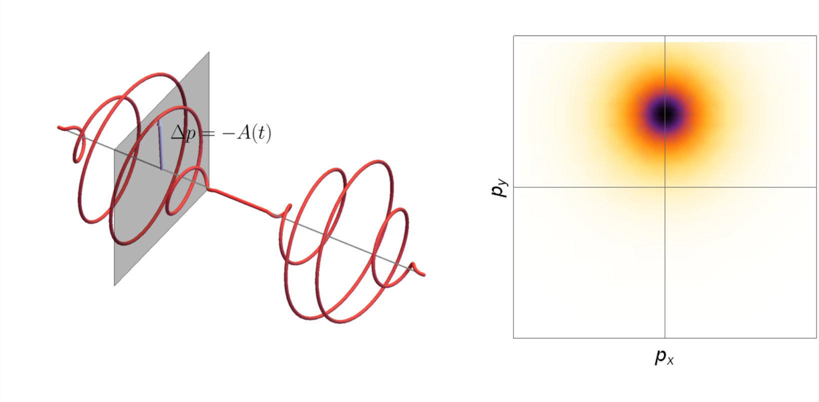
Momentum distribution of ground state center at origin.





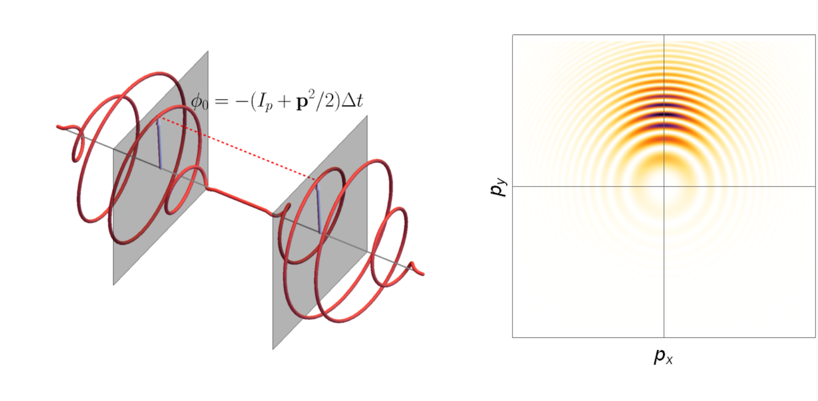
# Semiclassical explanation: Momentum Shift

If ionized at time $t_i$, PMD is shifted by $-\boldsymbol{A}(t_i)$.



# Semiclassical explanation: Double Slit

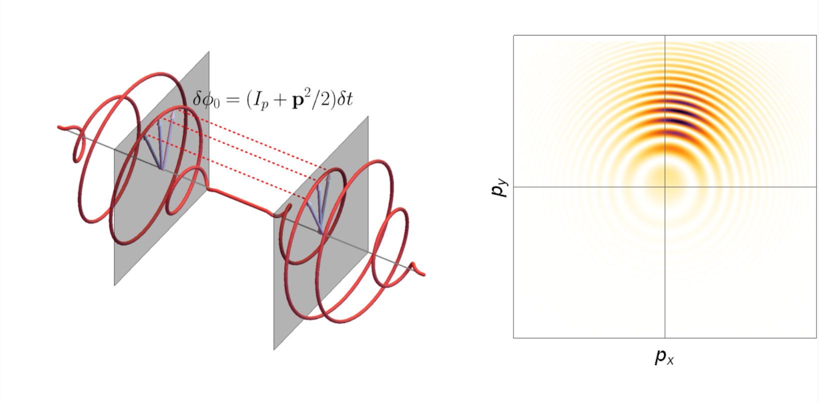
Interference occurs for the same vector potential of two pulses




$$\phi_0 = -(I_p + \boldsymbol{p}^2/2)(t_2 - t_1)$$

# Semiclassical explanation: Atto-Clock

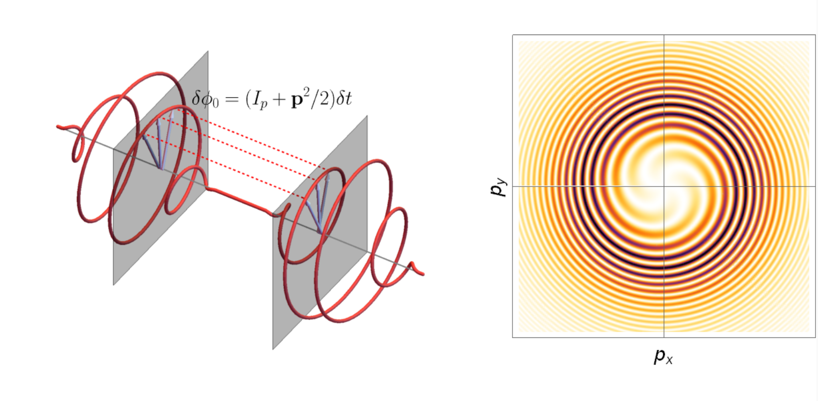
Change the two time points with vector potential being equal




$$\delta t_1 = -\delta t_2 = \delta\varphi/\omega$$

# Semiclassical explanation: Vortex

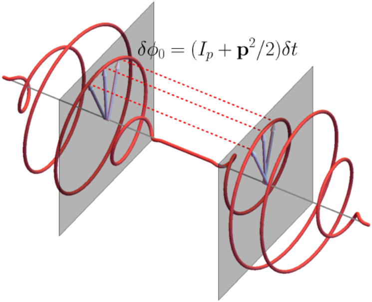
Integrate over $2\pi$ angle, vortex appears

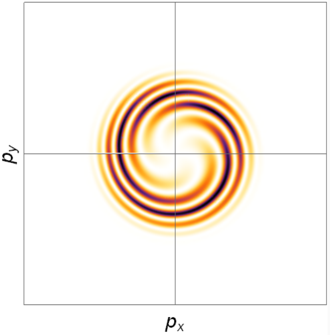



$$\delta\phi_0 = (2I_p + \boldsymbol{p}^2)\delta\varphi/\omega$$

# Semiclassical explanation: Resonance

Intercycle interference requires that $(p^2/2 + I_p) \approx n\omega$




$$\delta\phi_0 = 2n\delta\varphi$$

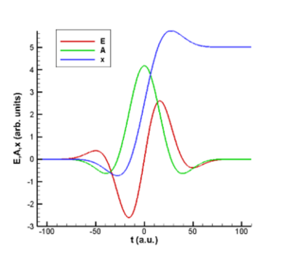
For a electron moving on the laser field

$$\boldsymbol{p}_{\text{mech}} = \boldsymbol{p}_0 + \boldsymbol{A}(t),$$

after integration

$$\boldsymbol{x}(t) = \boldsymbol{p}_0 t + \int A(\tau)\,\mathrm{d}\tau.$$

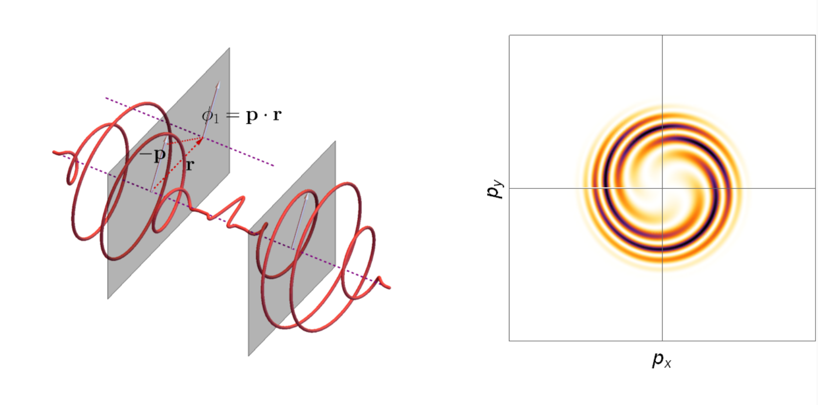
So, a short laser pulse would provide a net spatial shift for free electron




$$\boldsymbol{r} = \int A(\tau)\,\mathrm{d}\tau.$$

# Move one slit

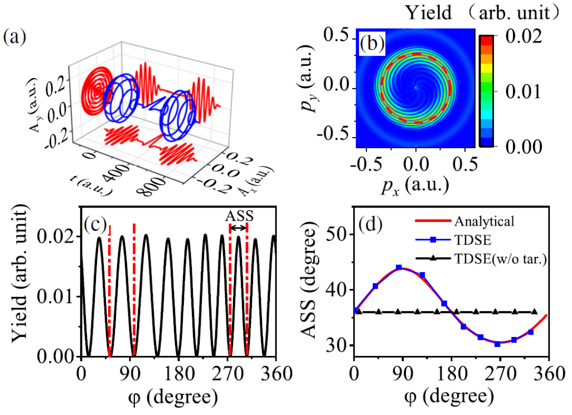
Insert a pulse to move the electron ionized by first pulse




$$\delta\phi = 2n\delta\varphi + \delta\boldsymbol{p} \cdot \boldsymbol{r}$$

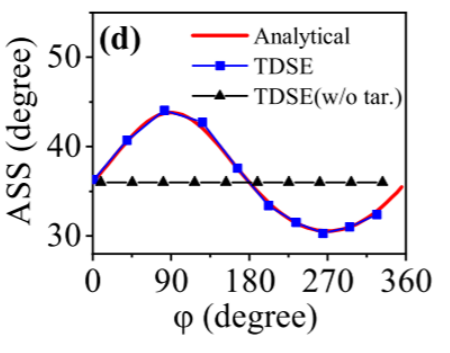
# Extract the phase shift

Plot angular distribution at $E_k = n\omega - I_p$, unevenly distributed angular stripes can be found




X.-R. Xiao, M.-X. Wang, H. Liang, Q. Gong, L.-Y. Peng*, *Phys. Rev. Lett.* **122** 053201 (2019)

# Angular Stripe Spacing




$$\text{ASS} = \delta\phi \text{ for } \delta\phi = 2\pi, \quad \Rightarrow \text{ASS} \approx \frac{2\pi}{2n + pr\sin(\phi - \phi_r)}.$$

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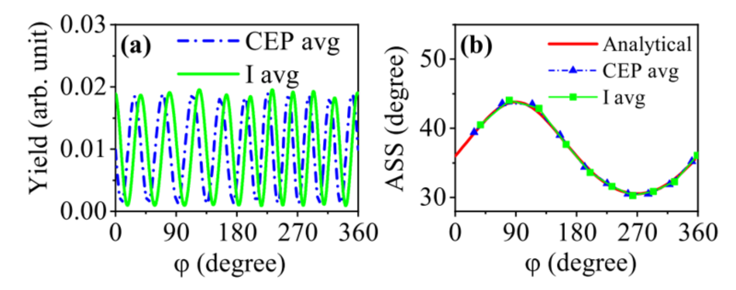
# Independent of intensity and CEP




One can fit displacement from TDSE result

$$(r, \varphi_r) = (5.26 \pm 0.21\,\text{a.u.}, 0.00 \pm 0.02\,\text{rad}).$$

Compare directly vector potential integral: $(5.03\,\text{a.u.}, 0)$.

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# Displacement & Phase shift

Look back into Volkov phase expression

$$\phi = -\frac{1}{2}\int (\boldsymbol{p} + \boldsymbol{A}(t))^2 \,\mathrm{d}t$$
$$= \underbrace{-\frac{1}{2}\boldsymbol{p}^2 t}_{\text{kinetic energy}} \underbrace{-\frac{1}{2}\int \boldsymbol{A}(t)^2 \,\mathrm{d}t}_{\text{ponderomotive energy}} -\boldsymbol{p}\cdot \underbrace{\int \boldsymbol{A}(t)\,\mathrm{d}t}_{\text{displacement!}}$$

- People always ignore the last term due to its fast oscillation behavior.
- But it does affect the results at least in this case.

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# Conclusion

- We proposed a way to demonstrate temporal-spatial double-slit interference of photoelectron.
- The displacement induced by a short pulse can be measured precisely in this way.
- The displacement is corresponding to the cross term in Volkov phase.

X.-R. Xiao, M.-X. Wang, H. Liang, Q. Gong, L.-Y. Peng*, *Phys. Rev. Lett.* **122** 053201 (2019)

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Thanks for your attention!

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Year 2019
Physics!
PKU School of Physics
I PLAY
TO WIN!

# If $\int A\,dt \neq 0$ could be true?

We know that for a realistic light pulse, the vector potential before and after the pulse should be the same (and we can set it to be zero). What about its integral?

We start from the retarded formula

$$\begin{aligned}\boldsymbol{A}(\boldsymbol{r},t) &= \int \frac{\boldsymbol{J}(\boldsymbol{r}',t-|\boldsymbol{r}-\boldsymbol{r}'|/c)}{|\boldsymbol{r}-\boldsymbol{r}'|}\,\mathrm{d}^3\boldsymbol{r}' \\ &\underbrace{\approx}_{\text{far field}} \frac{1}{r}\int \boldsymbol{J}(\boldsymbol{r}',t-r/c)\,\mathrm{d}^3\boldsymbol{r}' \\ &= \frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}t}\int \rho(\boldsymbol{r}',t-r/c)\boldsymbol{r}'\,\mathrm{d}^3\boldsymbol{r}',\end{aligned} \tag{1}$$

thus we have

$$\int \boldsymbol{A}(t)\,\mathrm{d}t = \frac{1}{r}\Delta\boldsymbol{p} \neq 0. \tag{2}$$