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# DELAYED CHOICE QUANTUM COHERENT CONTROL

## HOW TO CERTIFY QUANTUMNESS OF COHERENT CONTROL RIGOROUSLY?

We show how a certain coherent control process can be proven to be the quantum-coherent interference of mutually exclusive dynamical path alternatives. This is a challenging task because quantitative agreement with a quantum description **CANNOT** serve as a proof that an observed phenomenon is indeed quantum in nature. Rather, one has to exclude **ALL** classical explanations. To this end, we employ a Bell test that distinguishes rigorously nonclassical from classical statistics. This distinction is device-independent, which means that it is based on observed statistical data only and devoid of prior assumptions or knowledge on the devices and processes involved, in particular, their nonclassicality.

Wave-particle complementarity of a photon, an electron, a spin, etc. is demonstrated by these experimental situations:

For **PARTICLE** statistics, the interference is absent. Path knowledge is available (in principle if not in practice) by measurement.

If interference is displayed, the statistics are **WAVE**-like. Full path knowledge cannot be aquired (not even in principle).

## QUANTUM INTERFERENCE EXPOSED

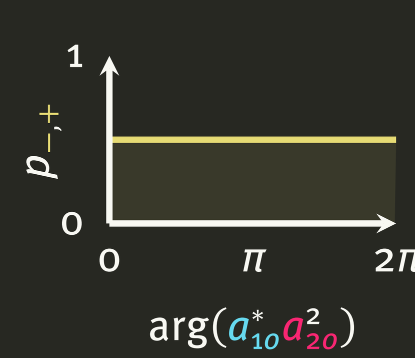
The individual situations can be described classically. In Wheeler's **DELAYED CHOICE** gedanken experiment, the decision between them is postponed (and randomized) in such a way that the property of the interfering object (wave or particle) is not causally linked to the experimental setup before it enters it. Still, the observations can be accounted for by a classical model. **QUANTUM DELAYED CHOICE** is an interference effect that is demonstrably quantum. Here, complementarity is observed in a single experimental setup that is in a coherent superposition between the two situations above. The choice between them is conditioned coherently on an ancillary d.o.f. such that even perfect knowledge of the total system state does not give away knowledge on the property of the interfering object. This total state is nonclassical and can violate a Bell inequality. The nature of the interference experiment cannot be predetermined and is guaranteed to be random.

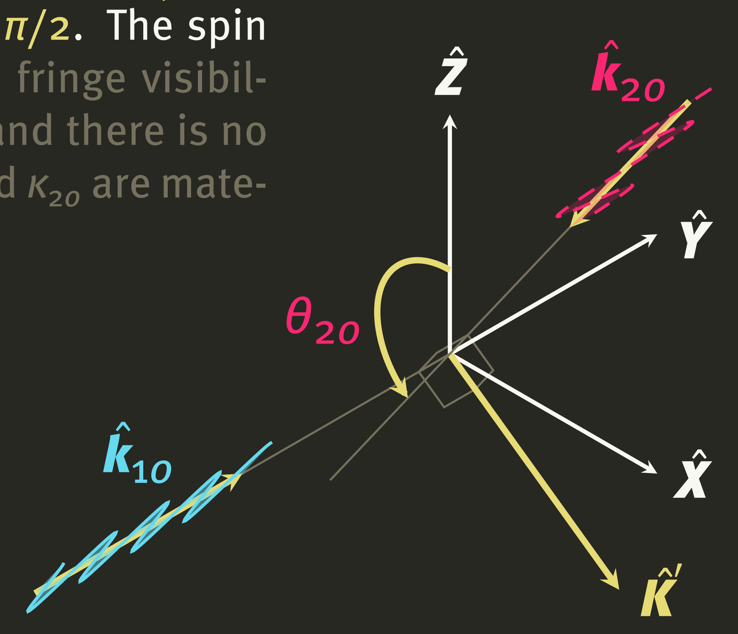
## AN EXAMPLE: SPIN CONTROL IN PHOTOIONIZATION

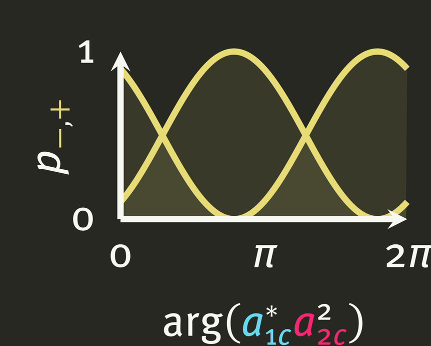
We certify quantumness of the phase coherent control over the photoelectron spin in the ionization of heavy, tightly trapped alkali atoms by weak bichromatic coherent radiation. Let the continuum states $|\boldsymbol{K}' m_s'^{+}\rangle$ at energy $E' = (\hbar K')^2/2m$ be reached from the ground state $|i\rangle = |nS½\,\text{-}½\rangle$ mainly by two pathways (in agreement with 2nd order perturbation theory): Absorption of 1 photon of energy $\hbar\omega_2 = E' - E(nS½)$ or of 2 photons each with energy $\hbar\omega_1 = \hbar\omega_2/2$. The ground state is spin-½ and constitutes the interferometer's two input ports. Here, we restrict ourselves to the port $m_j = $ -½. The photoelectron's final spin projection $m_s' = \pm½$ is identified with the two output ports.

We define two configurations of the radiation field that realize each a different process.

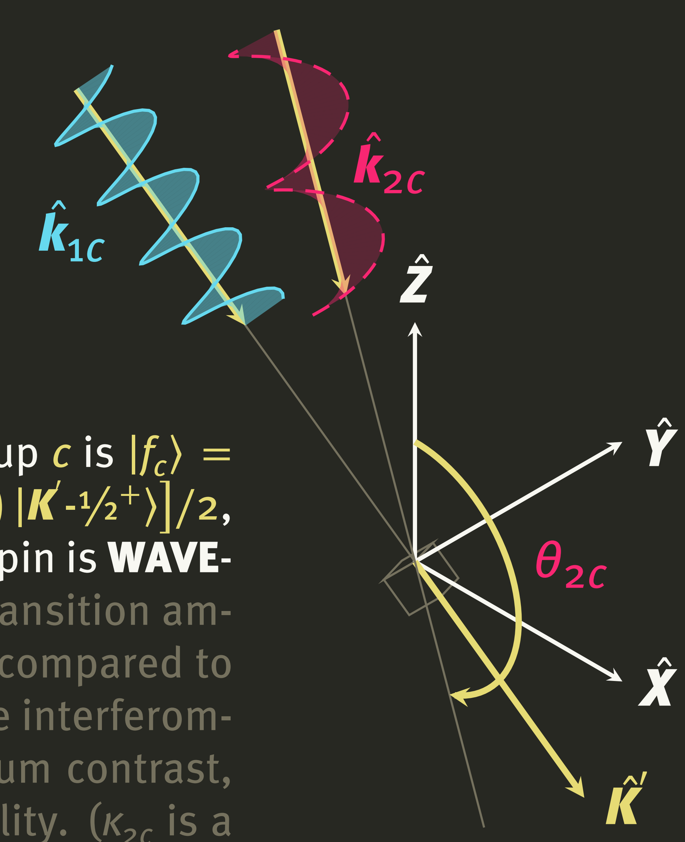
In the open configuration $o$, 1- and 2-photon ionization are distinguishable by their outcomes: $|f_o\rangle = -(\mathrm{i}|\boldsymbol{K}' ½^{+}\rangle + \mathrm{e}^{\mathrm{i}\phi}|\boldsymbol{K}' \text{-}½^{+}\rangle)/\sqrt{2}$, $\arg(a_{1o}^{*}a_{2o}^{2}) = \phi + \kappa_1 - \kappa_{2o} - \pi/2$. The spin behaves like a **PARTICLE**. The fringe visibility vanishes on both outputs and there is no phase coherent control. ($\kappa_1$ and $\kappa_{2o}$ are material phases, $\theta_{2o} = -\sqrt{2/3}$.)



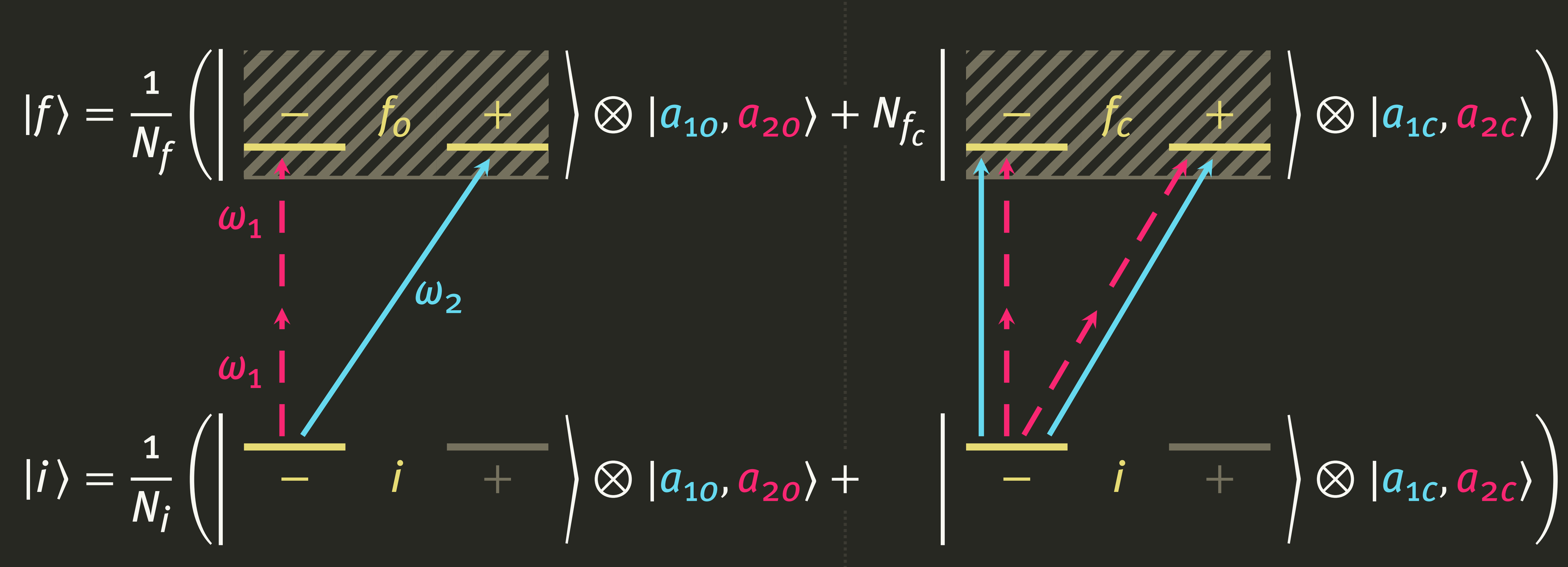




The final state in the closed setup $c$ is $|f_c\rangle = [(\mathrm{e}^{-\mathrm{i}\phi} - 1)\,|\boldsymbol{K}' ½^{+}\rangle + (\mathrm{e}^{-\mathrm{i}\phi} + 1)\,|\boldsymbol{K}' \text{-}½^{+}\rangle]/2$, $\arg(a_{1c}^{*}a_{2c}^{2}) = \phi + \kappa_1 - \kappa_{2c}$. The spin is **WAVE**-like. We assume here that the transition amplitude to $j' = 2½$ is negligible compared to $j' = 1½$. If the $|a_k|$ are tuned, the interferometer is unbiased, shows maximum contrast, and offers maximum controllability. ($\kappa_{2c}$ is a material phase, $\theta_{2c} = -2\sqrt{2}/3$.)




## CONTROL CONDITIONED ON NONCLASSICAL CORRELATIONS BETWEEN MATTER AND RADIATION

By preparing a coherent superposition between $o$ and $c$ (entangled coherent states), the choice between the spin's wave and particle property (and thus control) is conditioned on the radiation field.

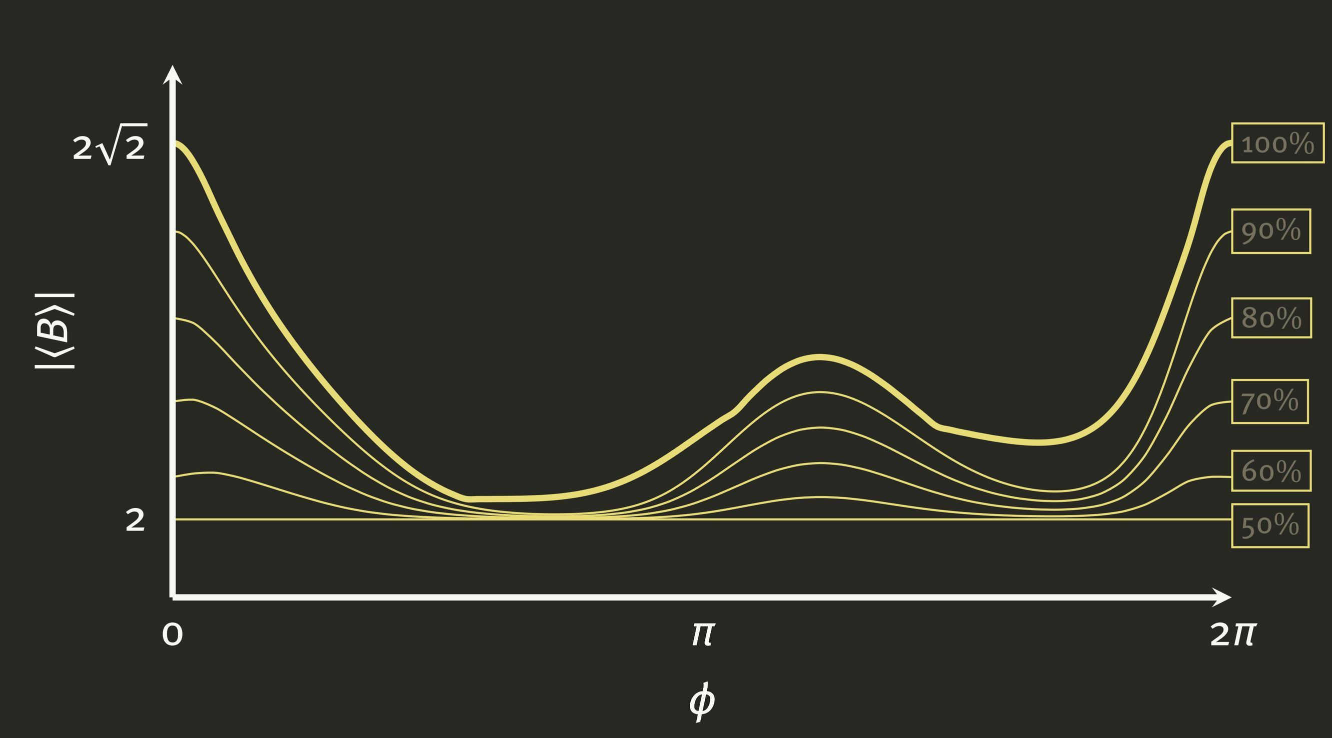



The state $|f\rangle$ describes nonclassical correlations between matter and radiation. However, we still owe a test that certifies the nonclassicality of an actual experiment. Such test is provided by a certain Bell inequality.

## BELL TEST VIOLATION HAS NO CLASSICAL EXPLANATION

For the Bell test of $|f\rangle$, we define two families of dichotomic measurement operators: $\Gamma(\zeta) = R(\zeta)^{\dagger}\sigma_z R(\zeta)$ with the rotation $R(\zeta) = \exp(\zeta\sigma_{+} - \zeta^{*}\sigma_{-})$ measures the spin in the direction of space defined by $\zeta$. The Pauli operators $\sigma_z$, $\sigma_{\pm}$ are defined with respect to the basis $\{|\boldsymbol{K}' ½^{+}\rangle, |\boldsymbol{K}' \text{-}½^{+}\rangle\}$. $A(\boldsymbol{\beta}) = \otimes_k D_k(\beta_k)^{\dagger}\cdot(2|0\rangle\langle 0| - \mathbb{1})\cdot\otimes_{k'} D_{k'}(\beta_{k'})$ with the displacements $D_k(\beta_k) = \exp(\beta_k a_k^{\dagger} - \beta_k^{*}a_k)$ is a joint photon threshold measurement over all modes $k = 1o, 1c, 2o$, and $2c$.

We have calculated numerically the maximally achievable violation of the Bell-CHSH inequality $|\langle B\rangle| = |\langle\Gamma(\zeta)\otimes A(\boldsymbol{\beta})\rangle + \langle\Gamma(\zeta')\otimes A(\boldsymbol{\beta})\rangle + \langle\Gamma(\zeta)\otimes A(\boldsymbol{\beta}')\rangle - \langle\Gamma(\zeta')\otimes A(\boldsymbol{\beta}')\rangle| \leq 2$ by measurements on $|f\rangle$ as a function of $\phi$ for different photon detection efficiencies. Classical explanations can be refuted for all $\phi$. The maximum violation, the optimized complex phases of $\boldsymbol{\beta}$ and $\boldsymbol{\beta}'$ as well as the optimal choices for $\zeta$ and $\zeta'$ are independent of $|a_k|$.




## CONCLUSION

We proposed a coherent control experiment within which quantum delayed choice can be rigorously displayed. By virtue of a Bell test, control can be confirmed to be due to the quantum interference of dynamical pathways.

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