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Phase sensitive measurements of order parameters for ultracold atoms through two particles interferometry

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The concept of order parameter, which characterizes states with spontaneously broken symmetries, has been successfully applied to a wide range of physical phenomena such as the Higgs mechanism in high energy physics 11, superfluidity in neutron stars 2, superconductivity 3, gaseous Bose-Einstein condensates 4 and charge and spin ordering in electronic systems 5. Recent works on condensed matter systems emphasized that order parameters can often be characterized by non-trivial orbital symmetries. For example, in contrast to conventional superconductors, which have isotropic s-wave electron pairing, high Tc cuprates exhibit d-wave pairings 6, while superfluidity of 3He or superconductivity in Sr2RuO4 exhibit triplet p-wave pairings 7. Other examples of order parameters with non-trivial orbital symmetries discussed in the literature are high angular momentum Pomeranchuk instabilities of electron systems 8 and unconventional charge and spin density wave states 9. Despite of the interests of such exotic states, the experimental verifications of these states are yet a challenging problem. Standard thermodynamic and transport properties can be used to observe the modulation in the magnitude of quasiparticle gaps, but not the change of the sign of the order parameters 10. Only phase sensitive experiments, such as the observations of Josephson effects in corner SQUID junctions 11 and τ-ring tricrystal experiments 11, have been considered as the definitive proof of the unconventional pairing for both cuprates and ruthenates 12. In the case of states with anisotropic charge and spin orderings, the lack of experimental tests is one of the main reasons that their existence remains an open question.

During the last few years, a considerable progress has been achieved in creating analogues of strongly-correlated electron systems, using ultracold atoms in optical lattices (see refs. 13 for reviews). One of the most challenging problems, which could be addressed in the future experiments, is the search for d-wave pairing in the repulsive Hubbard model 14. Realizations of other exotic states in cold-atom systems, such as d-density wave states 15, have been theoretically proposed. These states are characterized by order parameters with non-trivial angular dependence of the relative phase between the components of the entangled wavefunction. Hence, it is important to understand how tools of atomic physics can be used to perform tests of such quantum many-body states of ultracold atoms 16.

In this paper, we discuss a scheme for performing such phase sensitive measurements. It is based on the analysis of atom-atom correlations resulting from two-particle interference 17. Our proposal builds on the theoretical ideas 18 of using noise-correlations in atomic density to characterize many-body states, and on the experimental demonstration to measure atom-atom correlations, or atomic density noise spectroscopy with ultracold atoms 19–22. This method should provide an unambiguous evidence for non-trivial pairings, including p- and d-wave 14, 23, 24, as well as for non-trivial particle-hole correlations such as in a d-density wave state 14, 15. It should also allow the direct observation of two particle coherence and nontrivial angular momentum of ultracold diatomic molecules. For example, for p-wave Feshbach molecules realized in JILA 25, our approach should distinguish between px + ipy and px − ipy states 24.

We start by considering a Feshbach molecule, which consists of a pair of atoms, and has the center of mass momentum equal to zero

\[ |\Psi_{\text{mol}}\rangle = \int \frac{d^3k}{(2\pi)^{3/2}} \psi(k) c_{\uparrow_1} c_{\uparrow_2} |0\rangle. \]  

(1)

The two atoms making up the molecule can be either bosons or fermions. For concreteness, in this paper we focus on the case of two fermions in different hyperfine states labeled by σ = ↑, ↓, in analogy with states of a spin 1/2 particle. Here \( \psi(k) \) is the wavefunction of a molecule, \( c_{\sigma k} \) is a creation operator of a fermion atom in the state...
FIG. 1: Illustrations of using two-atom interference to measure the relative phase between different components of molecules after dissociation. a) Scheme I: Free propagating atoms are reflected in mirrors and mixed in beam splitters denoted by S. Coincidences are counted between detectors on opposite sides, e.g. D1 and D3. b) Bragg pulses with wavevectors \( \mathbf{G} = \mathbf{p} - \mathbf{q} \) and \(-\mathbf{G}\) are used to exchange (atomic mirrors) or mix (atomic beam-splitters, S) components \( \mathbf{q} \uparrow \) and \( \mathbf{p} \uparrow \), as well as \(-\mathbf{q} \downarrow \) and \(-\mathbf{p} \downarrow (|\mathbf{q}| = |\mathbf{p}|)\). In scheme II, the Bragg pulse applied at the beginning of expansion carries out reflections on mirrors andmixings in beam splitters in a single operation.

with momentum \( \mathbf{k} \) and hyperfine state \( \sigma \). The symmetry of \( \psi(\mathbf{k}) \) determines the nature of the paired state. We assume that the potential binding the two atoms is removed instantaneously and the released atoms subsequently evolve as free particles. Experimentally this can be achieved either by changing the magnetic field abruptly near a Feshbach resonance or by applying an RF pulse[21,22]. The released pair of atoms are in a superposition of momentum \((\mathbf{k}, -\mathbf{k})\) pairs with amplitudes \( \psi(\mathbf{k}) \). Our goal is to find a method to measure the relative phases between \( \psi(\mathbf{k}) \) for different \( \mathbf{k} \).

**Scheme I.** We first explain the main idea through the scheme of Fig. 1, analogous to the quantum optics scheme of [20]. Atomic mirrors and beam splitters are used to reflect and mix states with momenta \( \mathbf{p} \) and \( \mathbf{q} \) on one side, \( -\mathbf{p} \) and \( -\mathbf{q} \) on the other side. Time and space resolved detectors in opposite sides (e.g. D1 and D3) allow measurements of correlations resulting from the interference between \( \psi(\mathbf{p}) \) and \( \psi(\mathbf{q}) \), and thus, can reveal the relative phase between these components. The atomic mirrors and beam splitters are based on Bragg diffractions from laser beams which make standing waves with wave vectors \( \pm \mathbf{G} \), and they couple states with the same spin and magnitude of momenta \((|\mathbf{q}| = |\mathbf{p}|)\) but whose momenta differ by \( \mathbf{p} - \mathbf{q} = \pm \mathbf{G} \). For simplicity, we consider long Bragg pulses where a perfect Bragg diffraction can be achieved, i.e. no other diffraction order is involved. Later, we demonstrate that the phase sensitive measurements can also be carried out with short and strong Bragg pulses which can introduce higher diffraction orders. The atomic mirrors in Fig. 1 can be realized through Bragg pulses whose amplitudes and durations are chosen to produce \( \pi \) pulse so that it converts \( \pm \mathbf{p} \) into \( \pm \mathbf{q} \) and vice versa. On the other hand, a \( \pi/2 \) pulse introduces mixing between states with momenta \( \pm \mathbf{p} \) and \( \pm \mathbf{q} \), realizing a beam splitter (denoted by \( \mathbb{S} \) in Fig. 1). We can express the original fermion operators in terms of the operators after the mixing as follows:

\[
e^{-i\mathbf{q}_1 \cdot \mathbf{c}_\uparrow} \mathbf{c}_\uparrow = \cos \beta d_1^\dagger - i \sin \beta e^{i \chi_\uparrow} d_2^\dagger,
\]

\[
e^{-i\mathbf{p}_1 \cdot \mathbf{c}_\uparrow} \mathbf{c}_\uparrow = -i \sin \beta e^{-i \chi_\uparrow} d_1^\dagger + \cos \beta d_2^\dagger,\]

\[
e^{-i\mathbf{q}_1 \cdot \mathbf{c}_\downarrow} \mathbf{c}_\downarrow = -i \sin \beta e^{i \chi_\downarrow} d_1^\dagger + \cos \beta d_2^\dagger,\]

\[
e^{-i\mathbf{p}_1 \cdot \mathbf{c}_\downarrow} \mathbf{c}_\downarrow = \cos \beta d_1^\dagger - i \sin \beta e^{-i \chi_\downarrow} d_2^\dagger,\]

Here \( d_i^\dagger \) are creation operators for particles observed in detectors \( D_i \) (\( i = 1,\ldots, 4 \)). The mixing angle \( \beta \) (of the order of \( \pi/2 \)) and spin-dependent phases \( \chi_\sigma \) can be controlled through the amplitudes, durations and relative phases of the Bragg laser pulses. We denote by \( \theta_{\mathbf{k}\sigma} \) the phase accumulated by an atomic component with momentum \( \mathbf{k} \) and spin \( \sigma \) during the propagation between the source and the beam splitters.

If we assume that molecular wavefunctions for wave vectors \( \mathbf{q} \) and \( \mathbf{p} \) differ only in phase, i.e. \( \psi(\mathbf{k}) = e^{i\phi_{\mathbf{k}}} \psi(\mathbf{q}) \), we find the following expressions for the coincidence counts of \( n_i = d_i^\dagger d_i \):

\[
\langle n_1 n_3 \rangle_c = |\psi|^2 \sin^2(2\beta) \cos^2 \left( \frac{\phi_{\mathbf{q}} - \phi_{\mathbf{p}} + \Phi_I}{2} \right),
\]

\[
\langle n_1 n_4 \rangle_c = |\psi|^2 \left[ 1 - \sin^2(2\beta) \cos^2 \left( \frac{\phi_{\mathbf{q}} - \phi_{\mathbf{p}} + \Phi_I}{2} \right) \right],
\]

\[
\Phi_I = \theta_{\mathbf{q}\uparrow} + \theta_{\mathbf{q}\downarrow} - \theta_{\mathbf{p}\uparrow} - \theta_{\mathbf{p}\downarrow} + \chi_\uparrow - \chi_\downarrow,
\]

and similarly for \( \langle n_2 n_3 \rangle_c \) and \( \langle n_2 n_4 \rangle_c \). The oscillatory behavior of the correlation as a function of \( \Phi_I \) probes the coherence of pairing in the molecule. To vary \( \Phi_I \), one can, for instance, change the phases \( \chi_\sigma \). Moreover, if we know the precise value of \( \Phi_I \), such coincidence signals yield the relative phase \( \phi_{\mathbf{q}} - \phi_{\mathbf{p}} \) between different molecular components. In the absence of precise knowledge of \( \Phi_I \), the phase difference \( \phi_{\mathbf{q}} - \phi_{\mathbf{p}} \) could be extracted through a scheme analogous to white light fringes in classical optics, whose pattern and shape can reveal the existence of fundamental phase factors[27]. Note, however, that \( \mathbf{k} \) dependence of the phase factors acquired during the propagation and the reflection may render these methods unreliable. Thus, we consider a second scheme which avoids such a problem.

**Scheme II.** In this alternative scheme, we apply a \( \pi/2 \) Bragg pulse at the very beginning of the expansion to mix atomic components with momenta \( \mathbf{q} \uparrow \) and \( \mathbf{p} \uparrow \), as well as \(-\mathbf{q} \downarrow \) and \(-\mathbf{p} \downarrow \). This realizes, in a single operation, reflections on the mirrors and mixing on the beam splitters. In scheme II, there is a common mode propagation after the Bragg pulse, and phases acquired during the expansion do not affect interference. Two atom interference is revealed by coincidence counts with point detectors just as in the previous scheme. The scheme can be generalized to many-body case by replacing coincident
counts between point detectors with density imaging and studying noise correlations between patterns registered on opposite sides (see below).

To discuss scheme II, we start again with the example of a dissociated Feshbach molecule, described by the wavefunction in Eq. (1). We consider the case in which the Bragg pulses for spin up and down atoms differ only in the phase, and such pulses are created by the potentials $V_{\sigma}(r) = 2V_0 \cos(G \cdot r - \chi_{\sigma})$. Here we assume again a perfect Bragg diffraction. Detectors $D_i$ ($i = 1, 2, 3, 4$) detect atoms with momenta and spins $\uparrow$, $\uparrow$, $\downarrow$, $\downarrow$, respectively. The only difference between this scheme and scheme I is the absence of phase factors $e^{i\phi_{\sigma\sigma'}}$. As a result, coincidence counts have forms similar to Eq. (4), with $\Phi$ replaced by $\Phi_{II} = \chi_{\uparrow} - \chi_{\downarrow}$. Therefore, provided that we know the phase difference $\chi_{\uparrow} - \chi_{\downarrow}$ associated with the two Bragg pulses, atom-atom coincidence counts directly reveals $\phi_\uparrow - \phi_\downarrow$, i.e. the pairing symmetry in Eq. (4).

Many-body state analysis. We now apply scheme II to a BCS state of fermions $|\Psi\rangle = \prod_k (u_k + v_k c_{k\uparrow}^\dagger e^{-ik\cdot r})|0\rangle$. This BCS wavefunction is general and can describe weakly-coupled BCS paired states as well as a condensate of tightly-bound molecules. Here, we consider the generic diffraction pulse that can mix states whose momenta are separated by any integer multiple of $G$. The effect of the mixing pulse is described by the transformation of particle creation operators: $a_{k\sigma}^\dagger \rightarrow \tilde{a}_{k\sigma}^\dagger = \sum_{\alpha} \tilde{\alpha}_{0\alpha} e^{-im_\sigma \chi} c_{k+mG\uparrow}^\dagger$, and analogously for $c_{k\downarrow}^\dagger$ and $\tilde{c}_{k\downarrow}^\dagger$, which is the quantity we are interested in. Space- and time-resolved single atom detection [19, 22, 23] permits direct measurements of atom-atom correlations for specific momenta, corresponding to Eq. (4). Alternatively, one may look for noise correlation in absorption images after time of flight [13]. In this case, absorption imaging, as well as finite resolution of detectors, result in the integration of the atomic density. In order to take into account these effects, we have integrated Eq. (4) over ranges of momenta as shown in Fig. 2a. We present in Fig. 2b the numerical result of this integration, which displays noise correlation in integrated density vs. the phase difference $\chi_{\uparrow} - \chi_{\downarrow}$ of the diffraction pulses. Here we took the integration range to be $|\Delta k_\perp| = |G|/10$, $|\Delta k_x| = |G|/10$, $|\Delta k_z| = 5|G|$ and the pairing gap to be $\Delta \approx 0.1E_F$. The diffraction pulse amplitude is set to $V_0/E_F = 2$ where $E_R = |G|^2/8m$ is the recoil energy, and its duration is chosen to have the maximum oscillation of the signal. We assume that the integration range is sufficiently small that the phases of the Cooper pairs $\phi_\uparrow$ and $\phi_{-G}$ are constant in the integration range.

The signature of non-trivial pairing of the BCS wavefunction shows up in the angular dependence of the phase $\phi_\uparrow$ in $v_k = |v_k|e^{i\phi_\uparrow}$. In order to probe the relative phase $\Delta \phi = \phi_\uparrow - \phi_{-G}$ between pairs with momenta $k$ and $-G$, we consider the following density noise correlation after the integration:

$$\delta N_{\uparrow\downarrow} = \langle d_{n\uparrow}^\dagger d_{n\downarrow} \rangle - \langle d_{n\uparrow} \rangle \langle d_{n\downarrow} \rangle$$

$$= |v_k|^2 |v_{-G}|^2 \sum_{j,m} |\tilde{\alpha}_{0j}^\dagger |^2 \sum_{\alpha} \tilde{\alpha}_{0\alpha}^\dagger e^{-i\alpha k_\perp} + v_k v_{-G}^\ast \sum_{\alpha} \tilde{\alpha}_{0\alpha}^\dagger e^{-i\alpha k_\perp} - (|v_k|^2 - |v_{-G}|^2) \sum_{\alpha} \tilde{\alpha}_{0\alpha}^\dagger e^{-i\alpha k_\perp}$$

In analogy with the case of a Feshbach molecule, the first line in the RHS of Eq. (4) contains an interference term which depends on the relative phase $\Delta \phi$ as well as on $\Phi_{II} = \chi_{\uparrow} - \chi_{\downarrow}$.

![FIG. 2: (a) In order to take into account the finite resolution of detectors and the integration in absorption imaging, the density noise correlation is integrated over the cylinders shown in the figure. (b) Integrated density noise correlations $\langle \delta N_{\uparrow\downarrow} \rangle$ as a function of phase difference $\chi_{\uparrow} - \chi_{\downarrow}$ for a strong diffraction pulse of amplitude $V_0/E_R = 2$ and a duration $\tau$ which yields the maximum oscillation of the signal. Blue, Green(dash-dotted line) and Red(dashed line) curves correspond to $\Delta \phi = \phi_\uparrow - \phi_{-G} = 0, \pi/2$ and $\pi$, respectively.](image-url)
In Fig. 4b, two Bragg pulses couple k and \( k' + Q \), and the correlation function \( \langle \delta n_k \delta n_{k'} \rangle \) contains the term \( \psi_{ph}(k') \psi_{ph}(k) \). In Fig. 4c, a Bragg pulse couples k and \( k' \), and the correlation function \( \langle \delta n_k \delta n_{k+Q} \rangle \) contains the term \( \psi_{ph}^*(k) \psi_{ph}(k') \). When combined, these information should not only provide evidence of the angular dependence of CDW, but also allow one to distinguish site and band centered density wave states.

Conclusion. In this paper, we have proposed a new method for performing phase sensitive measurements of non-trivial order parameters in systems of ultra-cold atoms, with a view toward studying open problems in strongly correlated systems. Note that in contrast to scheme I, which was introduced in analogy to a scheme first introduced in Photon Quantum Optics, scheme II is specific to Quantum Atom Optics, and takes advantage of the unique features of cold atom systems.

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