Interferometric Control of Photo-Chemical Reactions in ^{87}Rb Bose-Einstein Condensates

H. Esat Kondakci[1,*], **David B. Blasing**[1], **Chuan-Hsun Li**[1,2], **Yong P. Chen**[1,2]
[1] *Dept. of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA*
[2] *Dept. of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907, USA*
[*] *esat@purdue.edu*

Abstract: We report on an interferometric control of photo-chemical reactions in ^{87}Rb condensates, where the scattering channels behaves as if the arms of an interferometer. We control the relative phase between the scattering channels by exploiting the quadratic Zeeman shift at low magnetic field strengths.

OCIS codes: (020.1475) Bose-Einstein condensates; (020.2070) Effects of collisions; (120.3180) Interferometry;

Interferometry is one of the fundamental tools in physics and is used across various disciplines ranging from metrology to quantum information science. While traditional interferometry relies on superposing two electromagnetic fields where a relative delay between the superimposed fields creates an interferogram [1], the concept extends well-beyond electromagnetic waves. In most scenarios, however, the relative delay is usually a path difference resulting in an additional phase between the arms of an interferometer. This is also the case for the gravitational wave detector, where a gravitational wave squeezes or stretches the space such that a delay is introduced for an optical interferometry [2].

Here, we introduce a scheme to control rate of photoassociation (PA)–laser-induced molecular formation, by controlling the relative phase between different scattering (collision) channels. In our case, we photoassociate optically-trapped ultracold ^{87}Rb atoms into Rb_2 molecules. We utilize a Rb-87 Bose-Einstein condensate (BEC) apparatus where the condensates are prepared in superposition of different (pseudo-)spin components in the $F = 1$ hyperfine state of Rb condensates via RF coupling between different m_f spins. We select a PA line ($\lambda \approx 781.70$ nm) such that there are only two allowed scattering channels: between two atoms with $m_f = 0$ spin or between atoms with $m_f = +1$ and $m_f = -1$ spins [3]. Therefore, controlling the relative phase between the relevant coefficients for the photo-chemical reaction, we control the PA rate $k_{PA} \propto |C_0^2 - 2C_{+1}C_{-1}|^2$, where C_i is the coefficient for $m_f = i$ spin component [4].

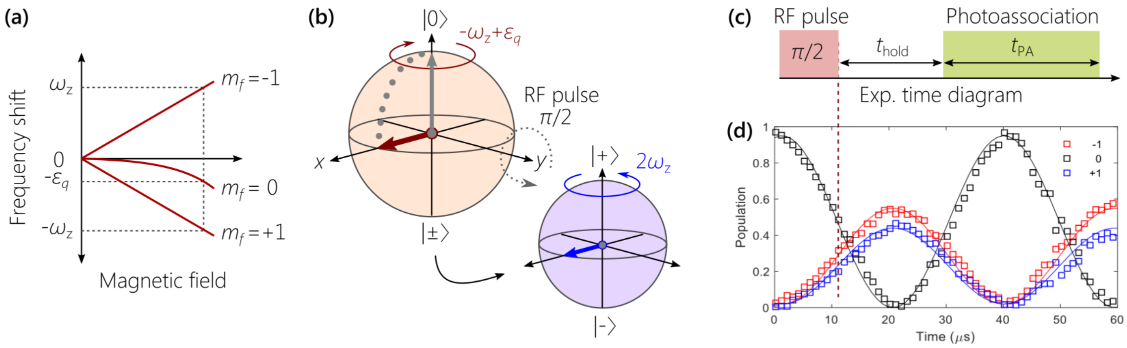

Fig. 1. (a) Schematic representation of Zeeman splitting under bias magnetic field (along z) for $F = 1$ manifold of ^{87}Rb atoms. For low magnetic field strengths, the quadratic dependence on the $m_f = 0$ spin state is orders of magnitude smaller than the linear frequency shift for the $m_f = \pm 1$ spin states. In the energy level diagram, the quadratic Zeeman shift is exaggerated for visibility. (b) A Bloch-sphere representation of three-level quantum state, requiring two spheres, for the Rb Bose-Einstein condensates created at the $F = 1$ hyperfine state splintting into 3 spin states under bias magnetic field. Initial state $|\, m_f = 0\rangle$ is coupled to the $|\, m_f = \pm 1$ states with an RF pulse that is perpendicular to the bias magnetic field (dotted path and dotted arrow depicting the rotation axis y). Rotation direction of the Bloch vectors under free evolution is shown by the circular arrows on top of the spheres. (c) Timing diagram for a typical PA experiment. During t_{hold} the quadratic Zeeman shift results in an additional phase in the relative scattering channels (see the main text for details). (d) A typical example for the population transfer between the m_f states due to RF coupling. Dashed line marks the $\pi/2$-pulse, for which the populations are approximately %25, %50, %25 for the $m_f = -1$, $m_f = 0$, $m_f = +1$ spin states, respectively.

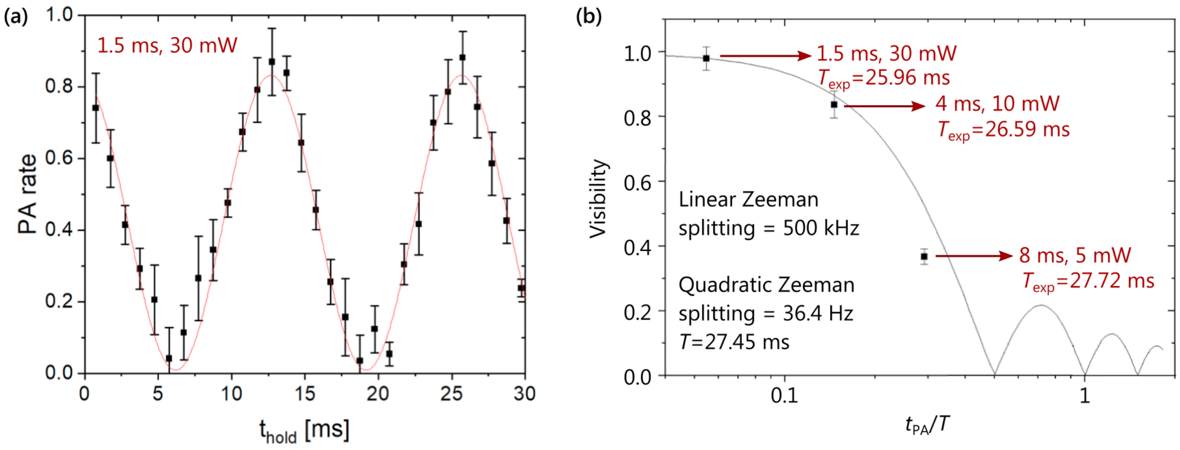

Fig. 2. (a) An interferogram of the photoassociation rate k_{PA} as a function of t_{hold}. PA laser with 30 mW and 1.5 ms of duration is impinged on the condensates. Experimentally obtained period of 25.96 ms matches well with the theoretical value (27.45 ms) for linear Zeeman energy splitting of 500 kHz. Error bars gives one standard deviation. Red line is a sinusoidal fit to the data. (b) Visibility as a function of ratio between the PA laser duration t_{PA} and the period for the quadratic Zeeman shift T. The black line gives the theoretical estimation.

To control the relative phase between C_0^2 and $C_{+1}C_{-1}$, we rely on the quadratic Zeeman shift at low bias magnetic field strengths [Fig. 1(a)]. The phase of the second term, which is due to the linear Zeeman splittings with opposite signs, cancels regardless of the bias field strength and the associated noise that might arise from instabilities in the bias magnetic field. The quadratic shift, then, results in a slowly varying phase between the two terms. We start our experiment by producing a BEC with bare $m_f = 0$ spin component. After coupling the spin states by a $\pi/2$-RF pulse [Fig. 1(b)] and selecting PA pulse duration t_{PA} that is shorter than the period T corresponding to the quadratic shift ε_q, we can control the PA rate by varying the t_{hold} [Fig. 1(c)]. Also note that for an ideal cancellation of PA process and high visibility, one needs to control the relative populations of the spin components based on the relevant Clebsch-Gordan coefficients for the allowed scattering channels [Fig. 1(d)].

Figure 2(a) depicts an interferogram of PA rate obtained by varying the free evolution time (t_{hold}) at a bias magnetic field corresponding to 500 kHz linear Zeeman splitting and 36.4 Hz quadratic shift with optimum populations for the spin states. PA pulse duration is set to be $t_{PA} = 1.5$ ms and power of 30 mW focused to $\approx$100 μm FWHM impingin on the BEC. Figure 2(b) shows the obtained visibilities for various configurations for the PA pulse duration and experimentally obtained periods, which are in good agreement with the theoretical calculation ($T = 27.45ms$).

In conclusion, we demonstrated a form of interferometric control for the PA rate in ultracold Rb condensates. The photo-chemical process strictly depends on the quadratic phase accumulated during the free evolution time. This study opens a novel way of characterizing PA scattering processes, where the chemical reactions partially or completely dependent on the spin compositions. In the case we studied, there are only two possible scattering channels, hence we obtained a near-perfect visibility. The question remains as to what happens when there are more than two possible channels available in a given PA line.

References

1. B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley, New York, 2007).
2. B. P. Abbott et al. “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral Phys. Rev. Lett. **119**, 161101 (2017).
3. C. D. Hamley et al., “Photoassociation spectroscopy of a spin-1 Bose-Einstein condensate, Phys. Rev. A **79**, 023401 (2009).
4. D. B. Balsing et al., “Observation of Quantum Interference and Coherent Control in a Photochemical Reaction, Phys. Rev. Lett. **121**, 073202 (2018).