Emergence and Change of the Entanglement in the Pair of H(2p) Atoms Produced in the Photodissociation of an H_2 Molecule

We have for the first time demonstrated the emergence of entanglement in the pair of H(2p) atoms produced in the photodissociation of H_2. It is remarkable that the entanglement is efficiently changed by the reaction of the entangled pair of H(2p) atoms with an H_2 molecule: the cross section amounts to approximately one hundred times those of the reactions of a single H(2p) or H(2s) atom with an H_2 molecule. The entanglement in the pair of H(2p) atoms is fragile.

Entanglement is a fundamental concept in quantum mechanics and plays a central role in quantum information technologies. The generation of entangled pairs of massless photons and massive quantum particles has been widely investigated [1, 2, 3]. Compared with photons, massive quantum particles have the advantage that they can remain stationary, but they have the disadvantage that their entanglement is easily changed by interaction with the environment. It is therefore important to investigate the change of entanglement in massive quantum particles by interaction with surrounding atoms or molecules. In the present study [4] we have for the first time demonstrated that an entangled pair of H(2p) atoms is produced in the photodissociation of an H_2 molecule and its entanglement is efficiently changed by the reaction of the entangled pair of H(2p) atoms with an H_2 molecule.

The process of interest is shown below [5]:

$$\begin{aligned} H_2(X\,^1\Sigma_g^+) + h\nu &\rightarrow H_2(Q_2\,^1\Pi_u(1)) \\ &\rightarrow H(2p) + H(2p) \\ &\rightarrow H(1s) + H(1s) + 2\,\text{Lyman-}\alpha\text{ photons.} \quad (1) \end{aligned}$$

A pair of $H(2p_0)$ and $H(2p_{\pm1})$ atoms is produced from an H_2 molecule in the $^1\Pi_u$ state, where the lower subscripts 0 and ±1 are the magnetic quantum numbers m with respect to the internuclear axis. Miyagi et al. [6] in our group showed that the pair is entangled as expressed by

$$\begin{aligned} \left|{}^1\Pi_u^+\right\rangle = \frac{1}{2\sqrt{2}}\Big(&\left|2p_1^a(1)2p_0^b(2)\right\rangle + \left|2p_1^a(2)2p_0^b(1)\right\rangle - \left|2p_0^a(1)2p_1^b(2)\right\rangle \\ &- \left|2p_0^a(2)2p_1^b(1)\right\rangle - \left|2p_{-1}^a(1)2p_0^b(2)\right\rangle - \left|2p_{-1}^a(2)2p_0^b(1)\right\rangle \\ &+ \left|2p_0^a(1)2p_{-1}^b(2)\right\rangle + \left|2p_0^a(2)2p_{-1}^b(1)\right\rangle\Big), \end{aligned} \quad (2)$$

where two protons are labeled *a* and *b* and two electrons are labeled 1 and 2. The entangled pair of H(2p) atoms in equation (2) emits an entangled pair of Lyman-α photons. Miyagi et al. [6] calculated the angular distribution of two Lyman-α photons and demonstrated strong anisotropy as shown in Fig. 1. The detectors *c* and *d* are placed on the plane perpendicular to the incident light beam. The directions of *c* and *d* are specified by angles Θ_c and Θ_d, respectively, measured from the unit polarization vector of the linearly polarized incident light. We have measured the angular distribution of a pair of Lyman-α photons to probe the entanglement in the pair of H(2p) atoms in process (1).

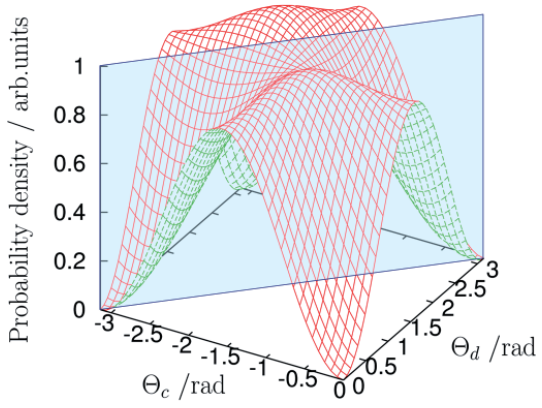

Figure 1
The calculated angular distribution of two Lyman-α photons in the photodissociation of H_2 [6].

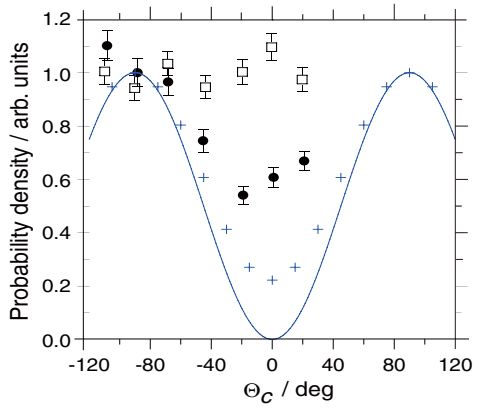

Figure 2
Angular distribution of two Lyman-α photons in the photodissociation of H_2. □: experimental results at 33.66 eV incident photon energy and at 0.40 Pa hydrogen gas pressure, ●: those at 0.13 Pa, solid line: the cutting plane of Figure 1, +: convoluted result of the solid line with the angular resolution.

The pair of Lyman-α photons was counted with a standard delayed-coincidence system while changing Θ_c but keeping the relation $\Theta_d = \Theta_c + \pi$. This means measuring the cutting plane of the angular distribution as a function of Θ_c (Θ_d) as seen in Fig. 1.

Figure 2 shows the angular distributions of two Lyman-α photons in the photodissociation of an H_2 molecule measured at the incident photon energy of 33.66 eV and at the hydrogen gas pressures of 0.40 Pa (□) and 0.13 Pa (●). The theoretical prediction, the cutting plane of Fig. 1 [6], is also shown (solid line). It was convoluted with the angular resolution of the apparatus (+). The experimental angular distributions approach the theoretical prediction (+) with decreasing pressure. There still exists a discrepancy between the experimental one at 0.13 Pa (●) and the theoretical prediction (+), which is probably because the pressure was still too high and the incident light was not completely polarized. Figure 2 shows that i) the entangled pair of H(2p) atoms in equation (2) is generated in the photodissociation of H_2, ii) the entanglement is more changed at 0.40 Pa than at 0.13 Pa, iii) the change of entanglement is not due to the reactions of an H(2p) or H(2s) atom but the reaction of the entangled pair of H(2p) atoms with an H_2 molecule, referred to as the entangled atom-pair reaction, and iv) the cross section of the entangled atom-pair reaction is roughly two orders of magnitude larger than those of the reactions of a single H(2p) or H(2s) atom with an H_2 molecule. The entangled atom-pair reaction is unexpectedly efficient.

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