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Antihydrogen formation in laser-assisted positron-antiproton scattering

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Antihydrogen formation in the laser-assisted positron-antiproton (nonrelativistic) radiative recombination is investigated. The state of incident positron is given by the Coulomb-Volkov wave function. The perturbative dressed wave function of the atom is obtained in the soft-photon approximation. Our calculation shows that for a geometry of laser polarization parallel to the incident direction, the formation cross section of antihydrogen is greatly reduced. Especially at high impact energy, the reduction is remarkable. [S1050-2947(98)06008-9]

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The production and detection of the bound states of antimatter has attracted great interest in recent years [1–4], because the investigation of such bound states provides an experimental test of the correctness of the CPT theorem in the standard quantum field theory. In experiment the only available stable bound state of antimatter is the antihydrogen, the atomic state of an antiproton and a positron. The simplest reaction to form an antihydrogen atom is the radiative capture collision between a positron and an antiproton. Suppose that such a reaction is embedded in a linearly polarized laser field $\boldsymbol{\varepsilon}=\boldsymbol{\varepsilon}_0\sin\omega_0 t=(\omega_0/c)\mathbf{A}_0\sin\omega_0 t$, which is weak compared to the Coulomb field in antihydrogen although strong enough by laboratory standards. Then the S matrix for capture into the dressed ground state of antihydrogen (in atomic units $e=\hbar=m=1$) is

$$S=-i\int_{-\infty}^{\infty}dt\langle\psi_0^{\bar{H}}(\mathbf{r},t)|\mathbf{a}\cdot\nabla e^{-i(\mathbf{k}\cdot\mathbf{r}-\omega t)}|\chi^{e^+}(\mathbf{r},t)\rangle, \quad (1)$$

in which $\mathbf{a}$ is the polarization vector of the final-state radiation, ω is the corresponding frequency. χ^{e^+} is the Coulomb-Volkov wave function of the incident positron [5,6],

$$\chi^{e^+}(\mathbf{r},t)=(2\pi)^{-3/2}\Gamma(1-i\xi)F(i\xi,1,i(pr-\mathbf{p}\cdot\mathbf{r}))\times e^{i(\mathbf{p}\cdot\mathbf{r}+\mathbf{k}\cdot\alpha_0\sin\omega_0 t-Et+\pi\xi/2)}, \quad (2)$$

where $\xi=1/137p$, $\alpha_0=\varepsilon_0/\omega^2$, and $E=\frac{1}{2}p^2$. $\psi^{\bar{H}}$ is the dressed ground state of antihydrogen. In the soft photon approximation, a perturbative solution can be obtained [7],

$$\begin{aligned}\psi_0^{\bar{H}}(\mathbf{r},t)&=e^{-iW_0^{\bar{H}}t}\left\{\phi_0^{\bar{H}}(\mathbf{r})+\frac{1}{2}\sum_{n\neq0}\left[\frac{e^{i\omega_0 t}}{\omega_{n0}+\omega_0}+\frac{e^{-i\omega_0 t}}{\omega_{n0}-\omega_0}\right]\langle n|\frac{1}{c}\mathbf{A}_0\cdot\mathbf{p}|0\rangle\phi_n^{\bar{H}}\right\}\\&\approx e^{-iW_0^{\bar{H}}t}\left\{\phi_0^{\bar{H}}(\mathbf{r})+\frac{1}{\omega_0}\varepsilon_0\cos\omega_0 t\sum_{n\neq0}\frac{1}{\omega_{n0}}\langle n|\mathbf{p}|0\rangle\phi_n^{\bar{H}}\right\}\\&=e^{-iW_0^{\bar{H}}t}\left(1+\frac{i}{\omega_0}\varepsilon_0\cdot\mathbf{r}\cos\omega_0 t\right)\phi_0^{\bar{H}}(\mathbf{r}),\end{aligned} \quad (3)$$

where $\phi_0^{\bar{H}}$ is the ground state of antihydrogen, $W_0^{\bar{H}}$ is the ground-state energy. In obtaining Eq. (3) we have used the relation $\Sigma_{n\neq0}|n\rangle\langle n|\mathbf{p}|0\rangle=i\mathbf{r}|0\rangle$. Summing over all the final-state polarization and all the photons exchanged between the scattering system and the laser field, the S matrix of Eq. (1) gives the laser-modified radiative capture cross section.

In Table I we display the laser-modified total radiative capture cross section for a geometry $\varepsilon_0\|\mathbf{p}$ with the field strengths $\varepsilon_0=5.0\times10^7$ V/cm and photon energy $\hbar\omega_0$

TABLE I. Total cross sections of antihydrogen formation in the laser-assisted e^+-$\bar{p}$ radiative capture collision. σ_{t0}: result for laser free. $\sigma_{t\varepsilon}$: laser-modified result for a geometry $\varepsilon_0\|\mathbf{p}$, with field strength $\varepsilon_0=5.0\times10^7$ V/cm, and photon energy $\hbar\omega_0=1.17$ eV.

E (eV)	σ_{t0} (a.u.)	$\sigma_{t\varepsilon}$ (a.u.)
10^1	8.8×10^{-1}	1.1×10^{-1}
10^2	2.5×10^{-2}	1.2×10^{-3}
10^3	1.1×10^{-4}	2.0×10^{-5}
10^4	3.8×10^{-7}	2.4×10^{-9}

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$=1.17$ eV. It is shown that the cross section is greatly reduced with the application of the laser field. With the impact energy increasing, the reduction becomes increasingly remarkable. As a matter of fact, the radiative capture process is extremely unstable, a small disturbance from laser may destroy such a capture process, thus the probability of antihydrogen formation is seriously reduced. As the impact energy increases, it becomes more and more difficult to form a bound state; therefore, the laser modification becomes increasingly notable.

Unlike other laser-assisted electron capture processes in ion-atom collisions where the cross section is mostly promoted by a laser [8–10], for laser-assisted radiative capture scattering, the cross section is lowered in general. The same mechanism applies to electron-proton radiative capture or similar reactions. This suggests that it is hardly workable to use a laser to improve the efficiency of antihydrogen production in such a radiative capture process. On the contrary, one can use a laser to remove the unneeded radiative capture processes in some collisions.

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