atoms

MDPI

Article

Photodetachment of the Positronium Negative Ion with Excitation in the Positronium Atom

Anand K. Bhatia

Heliophysics Science Division, NASA/Goddard Space Flight Center, Greenbelt, MD 20711, USA; Anand.K.Bhatia@nasa.gov

Received: 19 October 2018; Accepted: 22 December 2018; Published: 26 December 2018

Abstract: Lyman-α radiation ($2P \rightarrow 1S$) has been seen from astrophysical sources and the sun. The line shape of this transition has been measured recently in Ps atoms both inside and outside a porous silica target. In the photodetachment of Ps^-, the residual Ps atom can be left in the $2P$ state instead of the $1S$ state giving rise to positronium Lyman radiation at 2432 A^0. Photodetachment cross sections of Ps^- have been calculated when the Ps atom is left in nP states, n being 2, 3, 4, 5, 6 and 7, using the asymptotic form of the bound-state wave function and a plane wave for the final state wave function, following the approach of Ohmura and Ohmura [*Phys. Rev.* **1960**, *118*, 154] in the photodetachment of H^-.

Keywords: photoionization; photoabsorption; photodetachment

1. Introduction

The positronium atom (Ps), consisting of an electron and a positron, was predicted by Mohorovicic in 1934 [1] and discovered by Deutsch in 1958 [2]. It was shown by Wheeler [3] by a variational calculation that two electrons and a positron (Ps^-) have a bound state. Ps is particle stable and decays into gamma rays: the singlet state has a life time of 1.244×10^{-10} s and decays into two gamma rays while the triplet state has a lifetime of 1.4205×10^{-7} s and decays into three gamma rays. The energy and momentum conservation during the annihilation process can be utilized to study properties of solids. Thermal vacancies in metals have been studied by MacKenzie et al. [4] by using the behavior of positrons until annihilation. Mills [5] suggested that Ps^- could be used to generate positronium (Ps) beams of controlled energy by acceleration of Ps^- ions and detaching one electron. A positronium beam produced by the photodetachment of Ps^- ions has been observed by Michishio et al. [6,7]. They observed a shape resonance below the $n = 2$ level. This was the first observation of a shape resonance in Ps negative ion. The resonance position of the shape resonance of Ps negative ion below the $n = 2$ level of the Ps atom agrees with the results obtained by Ho and Bhatia [8] and Betoro and Green [9]. It is possible to study confined atoms, including Ps in porous materials. The constrained motion of such atoms allows for recoil and Doppler free spectroscopy. Cassidy et al. [10] have observed the $2P$ to $1S$ transition energy in Ps and narrowing of the line shape due to the confinement in the silica porous material. The observed energy of this transition is larger than that of a free Ps by 1.26 ± 0.06 meV. This transition can also be observed by photodetachment of Ps^- and leaving the residual atom in a $2p$ state. The annihilation of Ps, giving a 511 keV line, has been observed from the center of the galaxy [11,12]. The hydrogen Lyman-α radiation has been observed from Voyager measurements [13]. It might be possible to observe the positronium Lyman-α radiation due to the $2P$ to $1S$ transition in Ps. The $2P$ state can be excited by a positron or an electron impact from the $1S$ state or due to the photodetachment of Ps^-, leaving the positronium in the $2P$ state.

2. Calculations and Results

Bhatia and Drachman [14] calculated cross sections of such a process (photodetachment) when the residual atom is left in the $1S$ state by making two simplifications, namely, the initial state has a small binding energy [15] (E_B = 0.024010113 Ry) and is represented by an asymptotic form [16] whose normalization comes from the accurate Hylleraas wave function of the ion [15] and the final p-state (continuum) is represented by a plane wave. The cross sections obtained for photodetachment to the $1S$ state of positronium agreed fairly well with those obtained by Ward et al. [17], using the exchange approximation. Igarashi et al. [18] have calculated the photodetachment cross sections using the hyperspherical close-coupling method. Their results are lower than those of ref. [14] and agree with those obtained in ref. [17] at low photon energies. It is expected that the present results, when the positronium is in a P state, would be equally accurate. However, both the initial and final wave functions used here are not eigenfunctions of a single local effective Hamiltonian, therefore cross sections obtained in the length and velocity forms are not expected to be equal. Since we have used the asymptotic form of the initial wave function, we carry out the present calculation in the length form of the cross section. The length form emphasizes the long-range correlations while the velocity form emphasizes the short-range correlations. Therefore, it is appropriate to use the length form.

The initial state is represented by the following asymptotic form:

$$\Psi_i(R_2) = C\frac{e^{-\gamma R_2}}{R_2}\phi(r_1) \tag{1}$$

R_2 is the distance of the detached electron from the center of mass of the positronium, $R_2 = r_2 - (r_1)/2$ and r_1 and r_2 are the distances of two electrons from the positron. The nonlinear parameter γ is determined from

$$-\frac{1}{2\mu}\nabla_R^2\frac{e^{-\gamma R}}{R} = -E_B\frac{e^{-\gamma R}}{R} \tag{2}$$

where the reduced mass μ is $2m_e/3$ and $m_e = 1/2$ in Ry units. This gives $\gamma = 0.12651775$. The constant $C = 0.1856(2)$ is determined from the Hylleraas functions used in the calculation of the binding energy E_B, as indicated in ref. [14]. The final state wave function is given by

$$\Psi_f = \frac{1}{\sqrt{2}}[\phi_{np}(r_1)e^{ik\cdot R_2} + \phi_{np}(r_2)e^{ik\cdot R_1}] \tag{3}$$

The cross section in the length form is

$$\sigma_L = \frac{2}{9}k\omega\alpha a_0^2|\langle\Psi_f|Q_L|\Psi_i\rangle|^2 \tag{4}$$

where the dipole transition operator in the length form is

$$Q_L = \hat{k}\cdot(\vec{R} + \vec{r_1} + \frac{2}{3}\vec{R}_2)$$

where R is the coordinate of the center of mass. We find the cross section given below in this approximation [14] is

$$\sigma_L = (6.8115\times 10^{-20}\text{cm}^2)k(\gamma^2+k^2)\Big|M_L\Big|^2 \tag{5}$$

where the matrix element is given by

$$M_L = \sqrt{2}C\int d\vec{r_1}d\vec{R}e^{i\vec{k}R}\phi_{np}(\vec{r_1})|r_1\cos(\theta_1)|\frac{e^{-\gamma R}}{\vec{R}}\phi_{1s}(\vec{r_1}) \tag{6}$$

where $\phi_{1s}(\vec{r_1})$ and $\phi_{np}(\vec{r_1})$ are the positronium wave functions in the 1s and np states. Using the radial parts of ∣np> and ∣1s> functions, we can write M_L in the form

$$M_L = \sqrt{\frac{2}{3}} C \frac{4\pi}{(\gamma^2 + k^2)} \int_0^\infty dr r^3 R_{np}(r) R_{1s}(r) \tag{7}$$

The cross sections for various np states after the photodetachment are

$$\begin{aligned} \sigma(2p) &= 164.492C(k) \\ \sigma(3p) &= 26.3782C(k) \\ \sigma(4p) &= 9.1664C(k) \\ \sigma(5p) &= 4.3038C(k) \\ \sigma(6p) &= 2.3764C(k) \\ \sigma(7p) &= 0.2675C(k) \end{aligned} \tag{8}$$

where, $C(k) = \frac{10^{-20}k}{(\gamma^2 + k^2)}$ cm^2. The cross section for the photodetachment [14], when the final state is 1s, is

$$\sigma(1s) = \left(1.31744 \times 10^{-18}\text{cm}^2\right) \frac{k^3}{(k^2 + \gamma^2)^3} \tag{9}$$

This shows that the present cross sections are much smaller compared to the detachment to the 1S state and the maximum of these cross sections is at k = 0.13. The cross sections obtained are shown in Figure 1, where log (cross sections) vs. photon energies are given. It is noted that cross sections change considerably from n = 2 to n = 3, and again from n = 6 to n = 7.

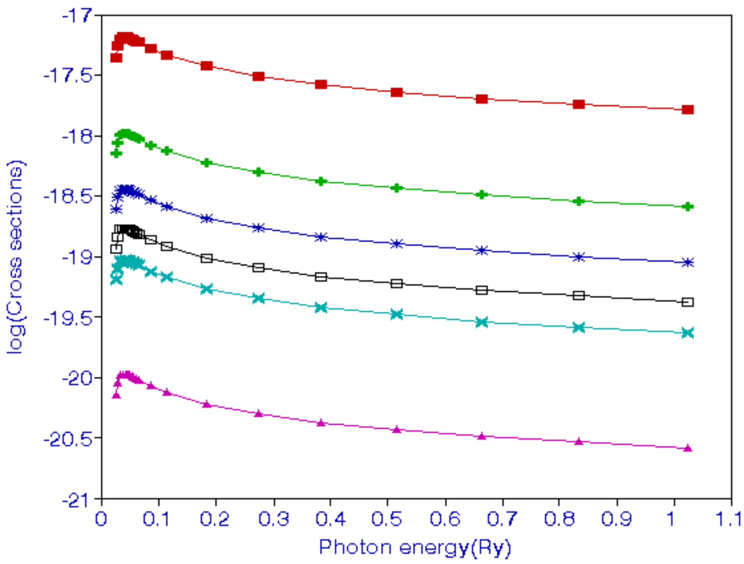

Figure 1. (Color online) The upper most curve represents photodetachment cross sections (units cm^2) on a $\log_{10}$ scale for n = 2. The curves below it are for n = 3, 4, 5, 6, and 7, also on a $\log_{10}$ scale.

3. Conclusions

Photodetachment of Ps^- to various P states of positronium has been calculated using approximations described in ref. [14] and the results are expected to be fairly accurate. It might be possible to observe Lyman-α Ps-radiation from the galactic center, where 0.511 keV lines have been observed and from other astronomical objects. It might be possible to observe radiation from higher np states to the 1s state of positronium as well, either in the laboratory or from astronomical sources.

Funding: This research received no external funding.

Acknowledgments: Thanks are extended to R. J. Drachman for helpful discussions and for critical reading of the manuscript.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Mohorovicic, S. Possibility of new elements and their meaning ifor astrophysics. *Astron. Nuchr.* **1934**, *253*, 93.
2. Deutsch, M. Evidence for the Formation of positronium in Gases. *Phys. Rev.* **1951**, *82*, 455. [CrossRef]
3. Wheeler, J.A. Polyelectrons. *Ann. N. Y. Acad. Sci.* **1946**, *48*, 221–238. [CrossRef]
4. Mackenzie, I.K.; Khoo, T.I.; Macdonald, A.D.; McKnee, B.T.A. Temperature Dependence of Positron Mean Lives in Metals. *Phys. Rev. Lett.* **1967**, *19*, 946. [CrossRef]
5. Mills, A.P., Jr. Observation of the Positronium Negative Ion. *Phys. Rev. Lett.* **1981**, *46*, 717. [CrossRef]
6. Michishio, K.; Kanai, T.; Kuma, S.; Azuma, S.; Azuma, T.; Wada, K.; Moch1zuki, I.; Hyodo, T.; Yagishita, A.; Nagashima, Y. Observation of a Shape resonance of the positronium ion. *Nat. Commun.* **2016**, *7*, 1160. [CrossRef]
7. Michishio, K.; Tachibana, T.; Terabe, H.; Igarashi, A.; Wada, K.; Kuga, T.; Yagishita, A.; Hyoda, T.; Nagashima, Y. Photodetachment of Positronium Negative Ions. *Phys. Rev. Lett.* **2011**, *106*, 153401. [CrossRef]
8. Ho, Y.K.; Bhatia, A.K. *P*-wave shape resonances in positronium ion. *Phys. Rev.* **1993**, *47*, 1497. [CrossRef]
9. Betoro, J.; Green, C.H. Resonant photodetachment of the positronium negative ion. *Phys. Rev. Lett.* **1986**, *56*, 1366. [CrossRef]
10. Cassidy, D.B.; Bromley, M.W.J.; Cota, L.C.; Hisakoda, T.H.; Tom, H.W.K.; Mills, A.P., Jr. Cavity Induced Shift and Narrowing of the Positronium Lyman-α Transition. *Phys. Rev. Lett.* **2011**, *106*, 023401. [CrossRef]
11. Leventhal, M.; MacMillum, C.J.; Stang, P.D. Detection of 511 keV Positron Annihilation Radiation. *Astrophys. Lett.* **1978**, *225*, L11. [CrossRef]
12. Bussard, R.W.; Ramaty, R.; Drachman, R.J. The annihilation of galactic positrons. *Astrophys. J.* **1979**, *228*, 928. [CrossRef]
13. Lallement, R.; Quemerais, E.; Bertaux, J.-L.; Sandel, B.R.; Izamodenov, V. Voyager Measurements of Hydrogen Lyman-α Diffuse Emission from the Milky Way. *Science* **2011**, *334*, 1665. [CrossRef]
14. Bhatia, A.K.; Drachman, R.J. Photodetachment of the positronium negative ion. *Phys. Rev. A* **1985**, *32*, 3745. [CrossRef]
15. Bhatia, A.K.; Drachman, R.J. New calculations of the properties of the positronium ion. *Phys. Rev. A* **1983**, *28*, 2523. [CrossRef]
16. Ohmura, T.; Ohmura, H. Electron-Hydrogen Scattering at Low Energies. *Phys. Rev.* **1960**, *118*, 154. [CrossRef]
17. Ward, S.J.; Humberston, J.W.; McDowell, M.R.C. The scattering of low-energy s-wave electrons by positronium. *J. Phys. B* **1985**, *18*, L525. [CrossRef]
18. Igarashi, A.; Shimamura, I.; Toshima, N. Photodetachment cross sections of the positronium negative ion. *New J. Phys.* **2000**, *2*, 17. [CrossRef]