Positronium scattering by atoms and molecules at low energies

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The recent theoretical and experimental activities in positronium (Ps) scattering by atoms and molecules are reviewed with special emphasis at low energies. We critically compare the results of different groups – theoretical and experimental. The theoretical approaches considered include the R-matrix and close-coupling methods applied to Ps-H, Ps-He, and Ps-Li scattering, and a coupled-channel approach with a nonlocal model-potential for Ps scattering by H, He, H2, Ne, Ar, Li, Na, K, Rb, Cs, and Ps and for pickoff quenching in Ps-He scattering. Results for scattering lengths, partial, total and differential cross sections as well as resonance and binding energies in different systems are discussed.

1. INTRODUCTION

Due to the technical advancement in the preparation of the ortho positronium (Ps) beam, precise experimental results for the total cross section of Ps scattering by different atomic and molecular targets are now available [4]. Among recent experiments there have been measurements of total cross section by Laricchia's group for energies up to 100 eV for H2, He, and Ar [4,5]. Gidley's group provided results for low-energy (∼ 1 eV) elastic cross section for Ps scattering by H2, N2, He, Ar, Ne, isobutane, and neopentane [6]. They also studied the collisional quenching rate of ortho Ps at different temperatures for these targets as well as for ethane and methane [6]. Nagashima et al. provided cross section for Ps-He scattering at 0.15 eV [7]. Hyodo provided new results for quenching rate on different targets at this workshop [8]. Among the older experiments there are results for zero-energy Ps-He cross section and pickoff quenching [8,9] as well as low-energy cross-section of Ps scattering by noble gases [9]. There are several comprehensive reviews on this subject [9,10].

On the theoretical front, after the pioneering study of Ps-H scattering by Massey and Mohr in 1954 [11] using the first Born approximation with Oppenheimer exchange [12], there have been studies of Ps-H and Ps-He scattering using the static exchange approximation, respectively, by Fraser [13,14], and by Bransden [15,16] and their collaborators in the decades of 1960 and 1970. Drachman and Houston performed model calculations of Ps-H [20,21] and Ps-He [22] scattering in the decade of 1970. There are also accurate calculations of resonance [23,24] and binding energies [25,26] of Ps-H.

Extensive theoretical efforts on Ps-H and Ps-He scattering started in the decade of 1990 with the coupled channel R-matrix and close-coupling (CC) approaches by Walters [27,28,29] and Ghosh [30,31] and their collaborators. More recently, there has been successful calculation of Ps scattering by H, He, Ne, Ar, Li, Na, K, Cs, Rb, H2 and Ps using a model exchange potential in a coupled-channel formalism by Biswas and this author [32–34]. This latter study produced, in addition to cross sections, results for resonance and binding energies of different Ps-atom systems [35,36] as well as for pickoff quenching rate of the interaction of ortho Ps with He [37].

Of the different Ps-atom systems, Ps-He is the most studied system both theoretically and experimentally and hence deserves special attention in addition to the most fundamental Ps-H system on which there are some accurate results for PsH binding [33,34] and resonance energies [28–31]. However, there is considerable discrepancy among the different theoretical Ps-He cross sections at zero energy.

On the experimental front, there have been conflicting results for the low-energy Ps-He elastic cross section by Nagashima et al. [3], who measured a cross section of (13 ± 4)πa02 at 0.15 eV, by Coleman et al. [12], who reported 9πa02 at 0 eV, by Canter et al. [38], who found 8.47πa02 at 0 eV, and by Skalsey et al. [8], who measured (2.6 ± 0.5)πa02 at 0.9 eV. It is unlikely that all these findings could be consistent with each other.

The results for the total cross section of Ps-He scattering obtained from the coupled-channel calculation employing the model exchange potential [24,25] are in agreement with experiments of Refs. [1–5] at low energies as well as with a variational scattering length [30]. This model, while agrees [39,40] with the experimental total cross sections [41] in the energy range 0 to 70 eV, reproduces [42] successfully the experimental pickoff quenching rate [4,11]. All other calculations could not reproduce the general trend of cross sections of Ps-He scattering in this energy range and yielded a much too small quenching rate at low energies [23,24,25]. However, the very low-energy elastic cross sections of the model-potential calculation [43,44] are at variance with the experiments of Refs. [1–5].

In the Ps-H system there are no experimental results of scattering. However, there are theoretical calculations on Ps-H binding [35,36] and resonance energies [28–31] and scattering lengths [67]. These should be considered as guidelines for testing the coupled-channel calculations us-
ing the $R$-matrix, CC, and model-potential approaches. Of these only the model-potential calculation could provide nearly converged results for the binding and resonance energies of PsH.

Of the three coupled-channel methods only the model-potential approach has seen further successful applications in Ps scattering by Ne, Ar, Li, Na, K, Rb, Cs, H$_2$, and Ps [58]. There has been proposals of Bose-Einstein condensation using spin-polarized ortho-Ps atoms and a prior knowledge of Ps-Ps scattering length is of advantage. For Ne and Ar the low-energy results for elastic cross section are in agreement with recent experiment [58], whereas for the alkali-metal atoms new low-energy resonances have been predicted. For Ps scattering by H$_2$, good agreement with experimental total cross section has been obtained at low to medium energies [58,59].

II. MODEL-POTENTIAL APPROACH

The theory for the study of Ps scattering by $R$-matrix and CC approaches has appeared in the literature and we refer the interested readers to appropriate places. Here we only outline the model-potential approach for Ps-H scattering [55]. The modifications for more complex targets are straightforward and can be found elsewhere [57,58]. The following Lippmann-Schwinger scattering integral equation is considered in momentum space

$$f_{\mu'\nu',\mu\nu}(k', k) = B_{\mu'\nu',\mu\nu}^{\pm}(k', k)$$

\[ \sum_{\mu'\nu'} \int \frac{d k''}{2\pi^2} \frac{B_{\mu'\nu'\mu\nu}^{\pm}(k', k'')}{k''_{\mu'\nu'}/4 - k''^2/4 + i0} \]

(2.1)

where the singlet (+) and triplet (−) “Born” amplitudes $B^{\pm}$ are given by $B_{\mu'\nu'\mu\nu}^{\pm}(k', k) = B_{\mu'\nu'\mu\nu}^{D}(k', k) \mp B_{\mu'\nu'\mu\nu}^{E}(k', k)$, where $B^{D}$ and $B^{E}$ represent the direct and exchange Born amplitudes and $f^{\pm}$ are the singlet and the triplet scattering amplitudes, respectively. The quantum states $\mu$ and $\nu$ refer to the hydrogen and Ps atoms, respectively, $k, k'$ etc. are the appropriate momentum variables; $k_{\mu'\nu'}$ is the on-shell Ps-H relative momentum in the channel $\mu'\nu'$. We use atomic units (a.u.) $\hbar = m = e = 1$ where $m$ is the electron mass and $e$ its charge. The differential cross section for scattering from $k_{\mu\nu} \to k'_{\mu'\nu'}$ is given by

$$\frac{d \sigma}{d \Omega} = \left( \frac{k'}{4\pi} \right)^2 \frac{4|f^{+}_{\mu'\nu'\mu\nu}(k', k)|^2 + 3|f^{-}_{\mu'\nu'\mu\nu}(k', k)|^2}{2}.$$  

(2.2)

The Ps-H direct Born amplitude is given by

$$B_{\mu'\nu'\mu\nu}^{D}(k', k) = \frac{4}{Q^2} \int \frac{\phi^{*}_\mu(r)[1 - \exp(iQr)]\phi_\mu(r) dr}{d\Omega} \times \int \frac{\chi^{*}_{\nu}(t)2i\sin(Qt/2)\chi_\nu(t) dt}{d\Omega}.$$  

(2.3)

The Ps-H model exchange (Born) amplitude is a generalization of the electron-hydrogen model exchange potential of Ochkur [71] and Rudge [72] and is given by

$$B_{\mu'\nu'\mu\nu}^{D}(k', k) = \frac{4(-1)^{l+l'}}{D} \int \frac{\phi^{*}_\mu(r)\exp(iQr)\phi_\mu(r) dr}{d\Omega} \times \int \frac{\chi^{*}_{\nu}(t)\exp(iQt/2)\chi_\nu(t) dt}{d\Omega}$$

(2.4)

with

$$D = \frac{k'^2 + k^2}{8} + C^2 \left[ \frac{\alpha_\mu^2 + \alpha_{\mu'}^2}{2} + \frac{\beta_\nu^2 + \beta_{\nu'}^2}{2} \right].$$

(2.5)

where $\Omega$ and $\nu$ are the angular momenta of the initial and final Ps states; $Q = k - k'$; $\alpha_\mu^2/2$, $\alpha_{\mu'}^2/2$, $\beta_\nu^2$, and $\beta_{\nu'}^2$ are the binding energies of the initial and final states of H and Ps in a.u., respectively; and $C$ is the only parameter of the potential. Normally, this parameter is to be taken to be unity, which leads to reasonably good results. However, it can be varied slightly from unity to get a precise fit to a low-energy observable. After a partial-wave projection the coupled-channel scattering equations (2.1) are solved by the method of matrix inversion.

III. NUMERICAL RESULTS

A. Ps-H System

There are no experimental results for this system. Ps-H scattering has been studied with the static-exchange model by Fraser [19,20], with the pseudo-state $R$-matrix approach by McAlinden et al [43], with the CC approach by Ghosh and collaborators [14,47], using a model-potential by Drachman and Houston [25,22], and finally by the coupled-channel model potential approach by Biswas and this author [54,55]. In addition to these scattering calculations there exist variational calculations for PsH binding energy [32,33] and Ps-H scattering lengths [62,63]. There are calculations for PsH resonance energies and widths in different partial waves at low energies using the complex-coordinate rotation method [28,32].

The most accurate result for PsH binding (= 1.064661 eV) seems to be due to Frolov and Smith, Jr. [38]. Relativistic effects on PsH has also been studied [41] where a binding energy of 1.06404168 eV has been predicted. Shrader et al. confirmed the existence of PsH experimentally [40]. The S-wave resonances in the Ps-H system were studied by Drachman [32] and by Yan and Ho [28,37]. The most accurate results for 2S and 3S energies (widths) are 4.0058 ± 0.0005 eV (0.0592 ± 0.0011 eV) and 4.9479 ± 0.0014 eV (0.0585 ± 0.0027 eV) [28], respectively. The P- and D-wave resonances for this system were also studied by Drachman [25] and by Yan and Ho [29,30]. The most accurate values for the 2P and 3P resonance energies (widths) are 4.2850 ± 0.0014 eV (0.0435 ± 0.0027
eV) and 5.0540 ± 0.0027 eV (0.0585 ± 0.0054 eV) [29], respectively; that for the 3D wave is 4.710 ± 0.0027 eV (0.0925 ± 0.0054 eV) [30]. Ho and Yan [31] also studied resonances in higher partial waves.

In the absence of experiments on Ps-H scattering, the above accurate results could be critical tests for the different coupled-channel calculations. Campbell et al. [43] performed a 22-pseudo-Ps-state $R$-matrix calculation and predicted the following resonance energies (widths) in S, P and D waves, respectively: 4.55 eV (0.084 eV), 4.88 eV (0.058 eV), and 5.28 eV (0.47 eV). Compared to the resonances of Ho and Yan [28] the agreement is fair. The PsH binding energy of Campbell et al. [43] (0.634 eV) show similar convergence when compared with the accurate results 1.064661 eV [33]. Their singlet and triplet scattering lengths $a_s = 5.20a_0$ and $a_t = 2.45a_0$ is only in qualitative agreement with variational results: $a_s = (3.49 \pm 0.20)a_0$ [67] and 4.30$a_0$ [73], and $a_t = (2.46 \pm 0.10)a_0$ [67] and 2.20$a_0$ [73], respectively. Walters et al. presented new results for Ps-H scattering at this workshop in a (14 × 14) channel model containing 14 Ps states and 14 H states [74]. This preliminary calculation shows that their elastic cross sections are substantially reduced and the scattering lengths are in better agreement with variational results.

The CC calculations by Ghosh and collaborators [44,45,77] also exhibit slow convergence. No resonance or bound states have been reported by them. This makes the critical comparison difficult. Their singlet scattering lengths calculated with different basis states is always greater than 5.20$a_0$ of Campbell et al. [43] which demonstrates only fair agreement with the variational results [67,73]. However, they have recently emphasized the importance of including the hydrogen states in a coupled-channel calculation [44].

With an appropriate choice of the parameter $C(=0.784)$ in Eq. (2.5) using a five-state coupled-channel model Biswas and this author obtained 4.01 eV, 1.067 eV, 3.72$a_0$ for the singlet Ps-H resonance and binding energies and scattering length $a_s = 5.33a_0$, in better agreement with the corresponding variational results: 4.0058 eV [28], 1.064661 eV [33], and 3.49$a_0$ [67], respectively. The agreement with the variational singlet scattering length of Ref. [73] is only fair. They found that for obtaining good convergence of resonance and binding energies the inclusion of couple of hydrogen states in the expansion scheme was essential. They also calculated total, partial and differential cross sections at different energies [44,53]. The P-wave resonance of this model [44] at 5.08 eV agrees poorly with the calculation of Yan and Ho [28]. However, this shows a correlated behavior among the low-energy observables in the singlet S wave, which is expected for an effective Ps-H interaction of short-range. For an approximately fixed range of the effective Ps-H interaction, using the classic idea of the effective-range expansion, the low-energy Ps-H problem is expected to be determined by a single parameter – the strength of interaction. This means that once this parameter is adjusted to fit an observable of the low-energy S-wave singlet Ps-H system, a satisfactory description of other low-energy observables follows. As in the Ps-H system there are no experimental results, we next consider the problems of Ps-He and Ps-H$_2$ scattering where the above wisdom is turned to good advantage by fitting a low-energy data, e.g., the scattering cross section. Consequently, the model presents a faithful representation of Ps-He and Ps-H$_2$ scattering at low and medium energies.

## B. Ps-He System

There are no known resonance and bound state in the Ps-He system. The variational results for the scattering length are $1.0 \pm 0.1a_0$ and $1.61a_0$ corresponding to zero-energy cross sections of $4.0 \pm 0.8\pi a_0^2$ [25] and $10.4\pi a_0^2$ [24], respectively.

The static-exchange model by Sarkar and Ghosh [48], and by Blackwood et al. [14] yielded 14.38$\pi a_0^2$ (at 0.068 eV), and 14.58$\pi a_0^2$ (at 0 eV), respectively, for the zero-energy cross section. The inclusion of more states of Ps in the CC [18] and $R$-matrix [12] calculations does not change these results substantially. The static-exchange calculations by Barker and Bransden [13] yielded 13.04$\pi a_0^2$ and by Fraser [24] yielded 14.27$\pi a_0^2$ for zero-energy Ps-He cross section. The 22-pseudo-Ps-state calculation by McAlinden et al. yielded 13.193$\pi a_0^2$. These results are in good agreement with each other. However, in a recent study Ghosh and collaborators [50,51] have argued the importance of including excited He states in a CC calculation. By including a couple of excited states of He, they obtained a substantial reduction in the zero-energy Ps-He cross section to $7.40\pi a_0^2$ in good agreement with a model potential calculation by Drachman and Houston [27] which yielded 7.73$\pi a_0^2$. The coupled-channel model-potential calculation by this author [57] yielded $3.34\pi a_0^2$ calculated with the parameter $C = 0.84$ for the zero-energy Ps-He cross section in agreement with a variational result $(4.0 \pm 0.8)\pi a_0^2$ [60] and in total disagreement with another $10.4\pi a_0^2$ [24].

Now we present a discussion of the results for Ps-He total cross sections of the CC [19,41], $R$-matrix [12] and model-potential [50,57] approaches shown in figure 1. In the CC and model-potential approaches the Born cross sections for Ps ionization and higher excitation of the atom(s) are added to the result of the solution of the dynamical equation. In the 22-pseudo-state $R$-matrix approach the Ps excitation and ionization cross sections are obtained from the solution of the dynamical equation. In figure 1 we also plot the different experimental cross sections [11,12,25,73] as well as different zero-energy theoretical [23,73] cross sections. Of the experimental cross sections, the total cross sections of Garner et al [1] and Skalsey et al [1] can be accommodated in a smooth graph. Once that is done it is difficult to accommodate other experimental results in the same graph.
The model-potential cross section [56,57] is the only one which is in agreement with the results of Garner et al [13] and Skalsey et al [4] in the energy range 0 – 50 eV. The 22-pseudo-state \( R \)-matrix cross section [12] is in agreement with the cross section of Nagashima et al [4] at low energies. The CC cross section without He states [49] is also in agreement with the cross section of Nagashima et al at low energies. However, the CC cross section after including few He states [54,51] is significantly reduced and is in agreement with the theoretical model calculation of Ref. [25] and experimental cross sections of Coleman et al [12] and Canter et al [8] at low energies. Of the CC [49,51], \( R \)-matrix [42] and model-potential [56,57] total cross sections the \( R \)-matrix result is unique in not possessing a peak beyond the inelastic thresholds. The combined experimental results of Refs. 1,3 exhibit such a peak in the total cross section. To resolve the confusion in the low-energy cross section of we consider below the pickoff quenching rate in Ps-He scattering.

As the effective interaction for elastic scattering between Ps and He is repulsive in nature, a smaller scattering length as obtained in in Refs. [1,2] would imply a weaker effective Ps-He interaction. The scattering length of the \( R \)-matrix [42] and CC approaches without He states [49] is 1.90 a.u., model-potential coupled-channel approach [57] is 0.91 a.u., the CC approach with few He states [54,51] is 1.36 a.u., and a model calculation by Houston and Drachman [27] is 1.39 a.u. A small scattering length as in the model-potential coupled-channel approach [57] would imply a weaker ortho Ps-He interaction consequently, would allow the ortho Ps atom to come closer to He which would lead to a large pickoff quenching rate and a large \( ^1Z_{\text{eff}} \) (\( \sim 0.11 \)) in agreement with experiment [1,1] as shown in figure 2, where we plot \( ^1Z_{\text{eff}} \) of different theoretical approaches and compare with experiment. The static-exchange model leads to large low-energy cross sections and hence a much too small \( ^1Z_{\text{eff}} \) [53,54,21,65]. The CC [10] and \( R \)-matrix [42] models also yield a much too large scattering length corresponding to a stronger repulsion between Ps and He. Consequently, these models should lead to a much too small \( ^1Z_{\text{eff}} \) (\( \sim 0.04 \)) in disagreement with experiment [1,10]. This is addressed in detail in Ref. [15] where a correlation between the different scattering lengths and the corresponding \( ^3Z_{\text{eff}} \) is established. This correlation suggests that a small Ps-He scattering length as obtained in the model-potential [56,57] and variational [10] approaches is consistent with the large experimental \( ^1Z_{\text{eff}} \).

C. Ps-H\(_2\) System

The effective Ps-H\(_2\) interaction is also repulsive in nature and there are no known resonances in this system. There are two theoretical calculations of cross section: one using the Born-Oppenheimer approximation by Comi et al [72], and the other using coupled-channel calculation with model potential [3,60]. The two experimental results for total cross section in this case are due to Garner et al [13] and Skalsey et al [4] which can be combined in a smooth curve, as can be found from figure 3. The low-energy cross sections of Comi et al [72] are orders of magnitude larger than experiment. The theoretical total cross sections of Refs. [54,55] agree well with experiment in the low- to medium-energy region for energies less than 20 eV. In addition to the Ps(1s,2s,2p) excitations included in the coupled-channel approach [53,60], ionization and higher excitations of Ps and some excitations of H\(_2\) (\( ^3\Sigma_u^+ \) and \( ^3\Sigma_u^+ \) states) [61] are included in Refs. [70] using the first Born approximation.

D. Ps-Ne and Ps-Ar Systems

The only dynamical calculation including exchange interaction in these systems is the static-exchange calculation using the model potential [53]. The relevant experimental cross sections are reported by Zafar et al [3], Skalsey et al [4], and Coleman et al [12]. In this case the theoretical scattering length for Ps-Ar is 1.65 a.u., and for Ps-Ne is 1.41 a.u. The approximate experimental scattering length obtained by Coleman et al [12] for both systems is 1.5 a.u. in reasonable agreement with theory. The theoretical cross sections at low energies (0 to 5 eV) are in good agreement with the low-energy experiment of Skalsey et al [4].

E. Ps-alkali-metal Atom Systems

In Ps-alkali-metal atom systems so far there are no experiments. The CC method has been applied in the static-exchange [12] and two-Li-state models [54] for the Ps-Li system. There has also been a CC calculation by the Calcutta group reported at this workshop [76]. The coupled-channel approach with model exchange potential using Ps(1s,2s,2p) states has been applied successfully for Ps-Li [12], Ps-Na, Ps-K [13], Ps-Rb, and Ps-Cs [14] scattering. The CC calculation of Refs. [22,53] did not report results for PsLi binding and resonances. The most interesting aspects of the model potential calculation is the prediction for resonance and binding energies in all the Ps-alkali-metal atom systems as well as the cross sections. In all cases resonances were reported in singlet S, P and D waves near the lowest inelastic threshold. The binding energies of these model calculations are in agreement with other theoretical calculations [7,9]. As no other calculations or experiments are available for Ps scattering by these systems, we do not present a discussion of these results here and refer the interested readers to appropriate places.
F. Ps-Ps system

The model-potential \[28\] and the CC approaches \[79\] have been used in the three-Ps-state model for this system. There has also been elastic scattering results using a variational method \[28\]. In the overall singlet state the calculated scattering lengths are $7.46a_0$ \[58\], $5.85a_0$ \[73\], and $8.4a_0$ \[28\] and those for spin-polarized ortho Ps ortho Ps system are $1.56a_0$, $-49.43a_0$, and $2.95a_0$, respectively. The results of Refs. \[28,29,30\] are in reasonable agreement with each other. The calculation of Ref. \[73\] has produced a scattering length of wrong sign corresponding to an attraction between two spin-polarized ortho Ps atoms. The model potential calculation is unique in predicting resonances in the overall singlet channel in S and P waves at 3.35 eV and 5.05 eV of widths 0.02 eV and 0.04 eV, respectively \[28\]. Both the model-potential and the variational methods yield the correct result for Ps-Ps binding \[28,29,30\] $-0.44$ eV. The CC calculation underbinds the Ps-Ps system by a factor of 2 and leads to a Ps-Ps binding of 0.22 eV.

IV. SUMMARY AND FUTURE PERSPECTIVE

The experiments of Ps scattering by different atoms and molecules \[1–5,8,12,6\] have initiated a new era of theoretical calculations of Ps scattering using R-matrix \[24,25\], CC \[14,15\] and model exchange potential \[54–59\] approaches in a coupled-channel framework. Of these, the model-potential approach has been the most successful in a proper description of scattering in leading to total cross sections of Ps scattering, specially at low energies, in different systems (Ps-H, Ps-He, Ps-Ne, Ps-Ar, and Ps-H$_2$) in better agreement with experiment and variational calculations compared to the two other approaches. This approach has also led to a better description of binding and resonance energies in Ps-H, and Ps-alkali-metal atom systems.

Much remains to be done in both theoretical and experimental fronts. More exact calculations of low-energy elastic scattering are welcome. Experimentally, there are only results of total cross sections. The data for partial, differential, and ionization cross sections of Ps-He, and Ps-H$_2$ would help in the comparison of different calculations and will clearly reveal which of the theoretical approaches are providing a better description of Ps scattering. It would be better to concentrate at low energies below the lowest inelastic threshold, specially for Ps-He, Ps-H$_2$, Ps-Ne, Ps-Ar, and different Ps-alkali-metal atom systems. Precise measurements of Ps-He and Ps-H$_2$ elastic cross sections would provide a critical test for theoretical approaches. It would be also interesting to verify if the prominent resonances in Ps-alkali-metal atom systems in Refs. \[29,31\] can be observed experimentally from a measurement of cross section at low energies. Finally, one should be prepared to undertake the challenging theoretical study of pickoff quenching rates of ortho Ps interaction with different targets. The experimentalists are far ahead in this topic \[15\]. There is enough homework to be done till the next workshop.

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Figure caption:

1. Total cross section of Ps-He scattering: data from Ref. [1] □, from Ref. [4] •, from Ref. [8] △, from Ref. [12] *, from Ref. [5] ×; calculation of Ref. [27] +, of Ref. [66] + with error bar, of Ref. [57] full line, of Ref. [49] dashed line, of Refs. [51] dashed-double-dotted line.

2. $Z_{\text{eff}}$ for Ps-He: data from Ref. [8] □, from Ref. [7] ✷, from Refs. [9,10] +, from Ref. [11] ×, calculation of Ref. [23] full line, of Ref. [22] dashed line, of Ref. [22] dashed-dotted line.

3. Total cross section of Ps-H$_2$ scattering: data from Ref. [1] □, from Ref. [4] •, calculation of Ref. [23] with target excitation full line, without target excitation dashed line.
Figure 2

Ps-He

Energy (eV)

$1Z_{\text{eff}}$
Figure 3

Total Cross Section ($10^{-16}$ cm$^2$) vs. Energy (eV) for Ps-H$_2$.