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citation and DOI.Calculated spontaneous emission and blackbody-induced transition rates for rubidium Rydberg F states

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E-mail: m48luo@uwaterloo.ca and jddmartin@uwaterloo.ca**Keywords:** Rydberg states, radiative lifetimes, blackbody induced transitions, spontaneous emission

Abstract

We calculate the radiative transition rates of Rb nF Rydberg states due to both spontaneous emission and blackbody radiation (BBR), covering principal quantum numbers from $n = 4$ to $n = 65$, at temperatures of 0, 77, 300, and 520 K. The contribution of BBR-induced transitions to the total bound-to-bound transition rate is 24.6% for the $21F_{7/2}$ state at $T = 520$ K, indicating the contribution of BBR may have been underestimated in a previous study by Gounand *et al* (1980 *J. Phys. France* 41 119). We checked our calculation procedure for consistency with available theoretical and experimental data for the nS , nP , and nD series of Rb.

1. Introduction

Rydberg atoms have finite lifetimes due to spontaneous emission (SE) and blackbody radiation (BBR)-induced transitions between states [1]. The lifetimes of Rb Rydberg states are of particular interest because of the ease with which Rb can be laser-cooled and excited to Rydberg states. For example, lifetime measurements of Rb nS , nP , and nD Rydberg states were performed by Marcassa and co-workers [2–5] (principal quantum number $n = 26$ to 45, $T = 300$ K and 520 K). Branden *et al* [6] present lifetimes for the same Rydberg series with principal quantum number $n = 28$ to 45, at $T = 0$ K and 300 K.

At room temperature, BBR-induced transitions significantly affect the lifetime measurements presented in the works mentioned above [2–6]. Recently, Schlossberger *et al* [7] studied the BBR-induced transitions of Rb $32S_{1/2}$ atoms to nearby Rydberg states at temperatures near $T = 300$ K, and Archimi *et al* [8] presented measurements for the room-temperature BBR-induced transition rates of high-lying Rb nS , nP , and nD states ($n = 60$ to 110). While the previously mentioned studies [2–8] used selective-field ionization, Mack *et al* [9] have shown that the lifetimes of the nS and nD states of Rb may also be measured using an all-optical approach.

Although not as studied as the lower-angular momentum nS , nP , and nD series, the nF Rydberg states of Rb are of interest because of their almost hydrogen-like properties combined with the ease by which they can be optically excited; e.g. three-photon Doppler-free schemes [10, 11]. For example, application of a modest electric field can adiabatically convert the Rb nF states into the red-most Stark states, providing a route for circularization [12].

The nF series has hydrogen-like energies because the magnitude of its quantum defect is small compared to one. Specifically, $\delta_F \approx 0.02$ [13] in $E = (-1/2)/(n - \delta_\ell)^2$; whereas for the lower angular momentum states: $\delta_S \approx 3.13$, $\delta_P \approx 2.65$, and $\delta_D \approx 1.35$ [14]. However, despite their hydrogenic energy levels, the radiative lifetimes of the nF states cannot be accurately described by hydrogenic formulas as they predominantly decay into the nD states, which are distinctly non-hydrogenic ($\delta_D \approx 1.35$ [14]).

Surprisingly, the only experimental study of Rb nF state lifetimes is by Hugon *et al* [15]. These lifetimes were compared to theory, with the details appearing later in [16]. However, these calculations did not consider the contribution of BBR-induced transitions, which were discovered in the same year by Gallagher and Cooke [17]. Subsequently, the authors of the original study [15] applied Gallagher and Cooke's theory of BBR effects [18], correcting the former theoretical results, claiming that 'the blackbody correction is small for F levels ($10 \leq n \leq 21$)' [19].

Apart from [19], the only available theoretical study on lifetimes of Rb nF states that included BBR-induced transitions was conducted by Theodosiou [20]. However, as we mention later, at least one of their computed nF lifetimes appears to be anomalous.

We calculate the Rb nF series transition rates over a broad range of principal quantum numbers ($4 \leq n \leq 65$) due to SE and BBR-induced transitions between Rb Rydberg states using well-established methods [18, 21, 22]. We compare our results, at various temperatures, with other theoretical predictions [16, 19] and experimental data digitized from [19].

Although the bound-to-bound radiative transitions dominate the total transition rate, BBR-induced bound-to-free photoionization also makes a small contribution to the decay rate [23]. Since this contribution is not always considered, we provide separate estimates of it in section 3.2.

2. Theoretical approach

2.1. Energy levels

The nF Rydberg states have finite lifetimes due to both SE and blackbody-induced transitions. We consider fine-structure, but neglect hyperfine structure, so that the energy levels are described by the quantum numbers n , ℓ , and j .

Due to the selection rules, the transition channels of the initial Rydberg $n'F$ states are restricted to $n'F \rightarrow nD$ and $n'F \rightarrow nG$. The energy levels related to these transitions are taken from experimental measurements presented in the *NIST Atomic Spectra Database* [24]. However, the available experimental data are limited to Rb nD ($4 \leq n \leq 10$) and nF ($4 \leq n \leq 8$) levels. All other involved energy levels are calculated using the quantum defect model based on Han *et al* [13].

2.2. SE

The probability of SE per unit time from an initial level a (above) to a final level b (below) is given by the Einstein A coefficient [25]:

$$A_{a \rightarrow b} = \frac{4}{3} \frac{\alpha a_0^2 \omega_{a,b}^3}{c^2 (2j_a + 1)} |\langle b || D || a \rangle|^2, \quad (1)$$

where α is the fine-structure constant, a_0 is the Bohr radius, and $\omega_{a,b} = (E_a - E_b)/\hbar$ is the angular frequency corresponding to the transition. The reduced dimensionless electric dipole matrix element $\langle b || D || a \rangle$ follows the convention of [26]. For brevity we introduce the line strength as $S_{b,a} := |\langle b || D || a \rangle|^2$. Note that equation (1) gives the *total* emission rate for all transitions to magnetic sublevels of the final level b and is independent of the initial magnetic sublevel of a .

Since an excited atom can usually decay to several levels of lower energy, the total SE rate of level i is given by:

$$\Gamma_{\text{SE},i} = \sum_{E_b < E_i} A_{i \rightarrow b} \quad (2)$$

with the values of $A_{i \rightarrow b}$ given by equation (1).

We discuss the sources of the energy levels that appear in equation (1) in section 2.1 and the computation of the reduced dipole matrix elements in section 2.4.

2.3. BBR induced transitions

The BBR-induced bound-to-bound transition rate from level i can be computed using the A coefficients (equation (1)) and by summing the contributions due to both downwards ($E_b < E_i$) and upwards ($E_a > E_i$) transitions [17]:

$$\Gamma_{\text{BB},i} = \sum_{E_b < E_i} A_{i \rightarrow b} \bar{n}_{i,b} + \sum_{E_a > E_i} \frac{g_a}{g_i} A_{a \rightarrow i} \bar{n}_{a,i}, \quad (3)$$

where $g_a = 2j_a + 1$ and $g_i = 2j_i + 1$ are the sublevel degeneracies and the thermal photon occupation numbers are:

$$\bar{n}(\omega, T) = \frac{1}{\exp(\hbar\omega/kT) - 1}, \quad (4)$$

where T is the absolute temperature, k is Boltzmann's constant, and ω is the appropriate angular transition frequency.

For Rb Rydberg nF states ($4 \leq n \leq 65$), our calculations capture all of the BBR-stimulated downward transitions and upward transitions until $n' = 200$. Although transitions to states with arbitrarily high principal quantum number n' could be stimulated by BBR, it is infeasible to numerically perform a complete summation. Instead, following Farley and Wing [27], we replaced the discrete sum over high-lying states ($n' > 200$) with an analytical integral, which was obtained from fitting our calculated rates (Rb $52F_{7/2}$, at $T = 520$ K). The estimated error reduces the accuracy of BBR-induced transition rates by less than 0.1%.

Shortly after the discovery of BBR effects on bound-bound transition rates [17], experiments by Spencer *et al* [28] observed that BBR can stimulate the photoionization of sodium Rydberg atoms.

For Rb Rydberg states, the photoionization rate stimulated by BBR is numerically computed using [23, 28]:

$$\Gamma_{\text{PI},a \rightarrow b} = c \int_0^\infty \sigma_{a \rightarrow b}(\omega, T) d\omega. \quad (5)$$

Here, $\rho(\omega, T)$ is the thermal photon density per angular frequency derived from the Planck distribution:

$$\rho(\omega, T) = \frac{\omega^2 \bar{n}(\omega, T)}{\pi^2 c^3}, \quad (6)$$

where $\bar{n}(\omega, T)$ is the thermal photon occupation number (equation (4)). The photoionization cross sections $\sigma_{a \rightarrow b}$ between the bound (a) and continuum (b) states are:

$$\sigma_{a \rightarrow b} = \frac{4\pi^2 \alpha \hbar \omega}{3} \rho_{\text{box}}(\epsilon) \sum_{\ell_b = \ell_a \pm 1}^{\ell_{\text{max}}} \frac{\ell_{\text{max}}}{2\ell_a + 1} |R_{a \rightarrow b}|^2, \quad (7)$$

where $\hbar\omega$ is the photon energy, ℓ_{max} is the larger of the initial and final orbital quantum numbers, ℓ_a and ℓ_b , and $\rho_{\text{box}}(\epsilon)$ is the density of final states of the departing electron. The radial dipole matrix element $R_{a \rightarrow b}$ is:

$$R_{a \rightarrow b} = \int_0^L dr u_a(r) r u_b(r). \quad (8)$$

We normalize the continuum wavefunction $u_b(r)$ of the departing electron using an artificial sphere of radius L , so that $\rho_{\text{box}}(\epsilon) = L\sqrt{m/2\epsilon}/\pi\hbar$, where ϵ is the kinetic energy of the departing electron, and m is its mass.

The continuum wavefunction $u_b(r)$ is computed using Cooley's method [29] using the central potential from Marinescu *et al* [30]. The bound-state wavefunction $u_a(r)$ is obtained following the procedure by Zimmerman *et al* [21]. We choose L to be large enough so that the cross section given by equation (7) is independent of L .

2.4. Reduced dipole matrix elements

Some of the reduced dipole matrix elements required to evaluate the line strengths, $S_{b,a} := |\langle b || D || a \rangle|^2$ in equation (1), may be obtained from Kiruga *et al* [26]. Specifically, their calculations cover the necessary reduced dipole matrix elements for transitions between Rb Rydberg $n_a F$ and $n_b D$ levels (including fine structure), with principal numbers $4 \leq n_a \leq 11$ and $4 \leq n_b \leq 12$.

For other line strengths we use the technique of Zimmerman *et al* [21]. Specifically, we determine the radial dipole matrix elements using computed wavefunctions u_b and u_a for the single Rydberg electron, using:

$$R_{a \leftrightarrow b} = \int_0^\infty dr u_b(r) r u_a(r), \quad (9)$$

and obtain the reduced electric dipole matrix elements using Wigner's 6- j symbol [25]:

$$\begin{aligned} \langle b || D || a \rangle &= (-1)^{\ell_b + j_a + 3/2} [(2j_b + 1)(2j_a + 1)]^{1/2} \\ &\times \left\{ \begin{matrix} \ell_b & 1/2 & j_b \\ j_a & 1 & \ell_a \end{matrix} \right\} \langle b || r^{(1)} || a \rangle, \end{aligned} \quad (10)$$

where

$$\begin{aligned} \langle b \| r^{(1)} \| a \rangle &= (-1)^{\ell_b} [(2\ell_b + 1)(2\ell_a + 1)]^{1/2} \\ &\times \begin{pmatrix} \ell_b & 1 & \ell_a \\ 0 & 0 & 0 \end{pmatrix} R_{a \leftrightarrow b}, \end{aligned} \quad (11)$$

using Wigner's 3- j symbol [25].

For transitions between the highest n 's reported by Kiruga *et al* [26], we obtain good agreement between their reduced dipole matrix elements and the ones that we compute. For example, we find $\langle 12D_{5/2} \| D \| 11F_{7/2} \rangle \approx 298.9$ versus 298.5(32).

For transitions to lower n , where the valence electron penetrates the ion-core, e.g. $4D$ and $5D$, we do not expect the technique of Zimmerman *et al* [21] to be accurate. In these cases—when the line strength is not available in Kiruga *et al* [26] — we apply a slight correction. Specifically, we compute line strengths for $nF \rightarrow 4D$ (and $nF \rightarrow 5D$) using the method of Zimmerman *et al* [21] and then scale these line strengths by a constant factor for least squares agreement with the line strengths that are available from Kiruga *et al* [26] i.e. from $n = 4$ to $n = 11$ (see figure 2). Then as noted above, for the lower- n line strengths we use the results of Kiruga *et al* [26], but for higher- n where the line strength is not provided by Kiruga *et al.*, we apply the fitted scale factor:

$$|\langle b \| D \| a \rangle|^2 = f_{b,a} |\langle b \| D_Z \| a \rangle|^2, \quad (12)$$

where D_Z denotes calculations made using the method of Zimmerman *et al* [21]. For example, for $a = nF_{5/2}$ and $b = 4D_{3/2}$ we find $f_{b,a} \approx 0.89$. The scaling method introduces a fractional error of 1.0% to $S_{b,a}$.

3. Results

3.1. Bound-to-bound transitions

In this section, we will present the comparisons between our calculated results and available experimental measurements and theoretical results of the Rb Rydberg nF state bound-to-bound transition rates. For simplicity, any rates discussed in this section are associated with bound-to-bound transitions. The results of bound-to-free transitions will be in section 3.2.

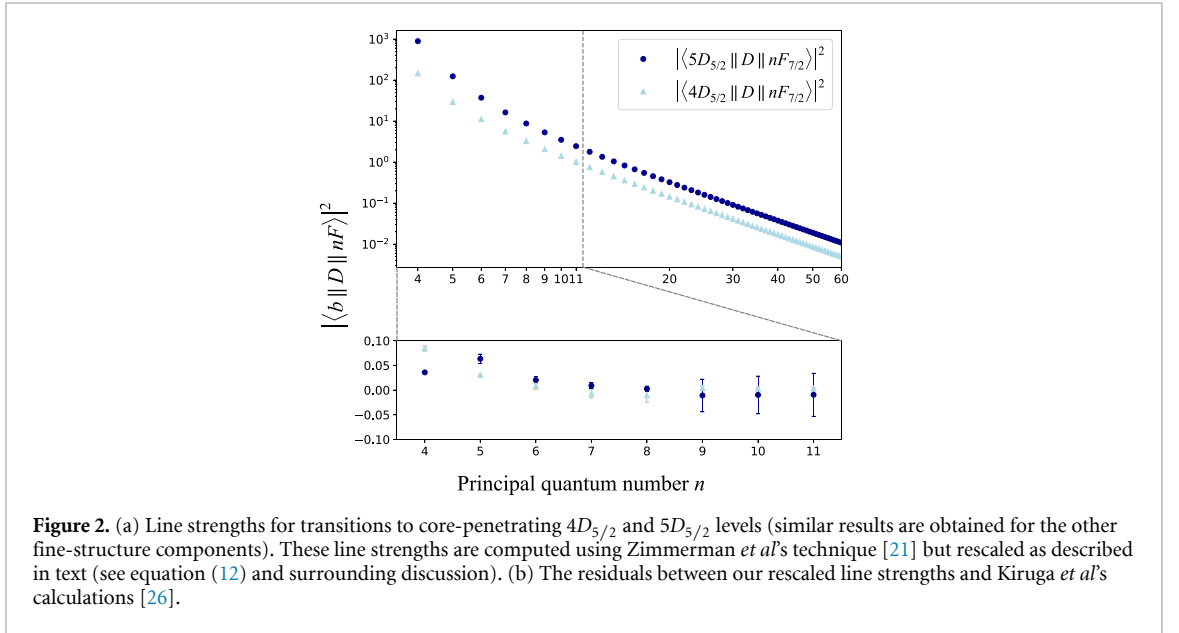
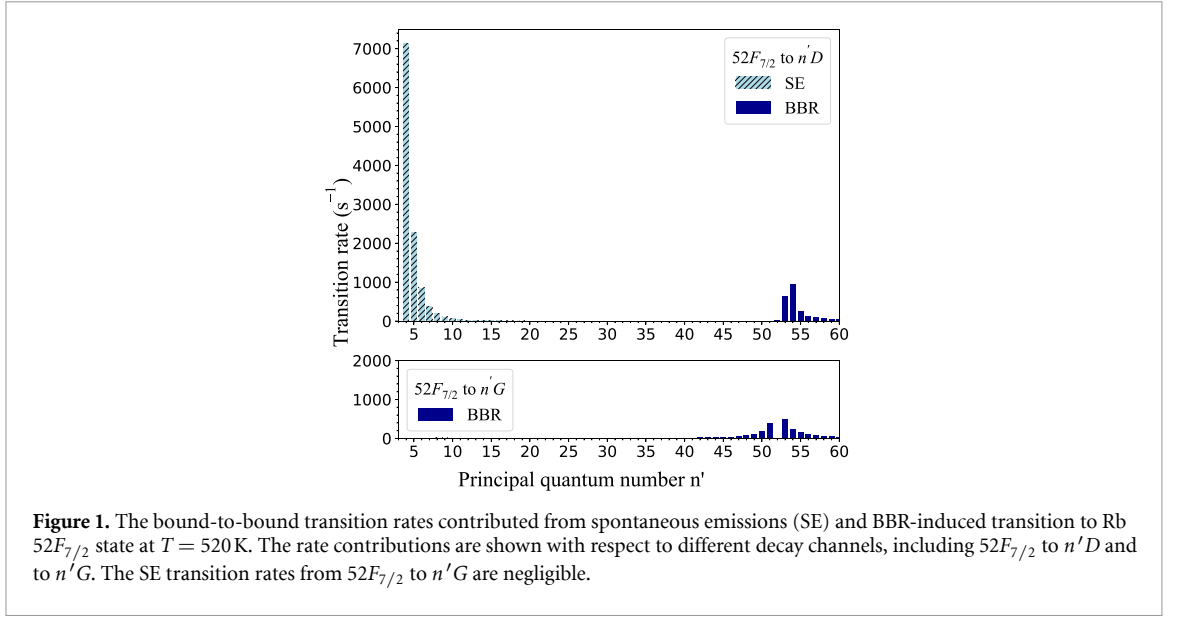
The total bound-to-bound transition rate is the sum of the SE and BBR-induced transition rates. These contributions to the rate for the Rb $52F_{7/2}$ state at $T = 520$ K are shown in figure 1, which illustrates the significant contribution from BBR-induced transitions to the total rate. The transitions from nF to $n'D$ dominate SE rates for low n' . Similar phenomena can also be found when calculating spontaneous transition rates for hydrogen Rydberg nF states [22].

In figure 3, the calculated transition rates for SE can provide accuracies better than 4%, agreeing with Gounand's numerical calculations (table I in [16]) within the range of $9 \leq n \leq 21$. The quantum defects δ applied in their calculations depend solely on the angular quantum number ℓ , while the values used in our calculations vary with both ℓ and j [13]. Gounand validated the calculations with experimental results at a temperature of $T = 520$ K by their group [15]. However, at the time when experimental results for the Rb Rydberg F state radiative lifetimes were published, the effects of BBR had not been fully appreciated. To investigate the effects of BBR on the total transition rate of Rb Rydberg nF states, we calculated the transition rates at temperatures of $T = 0, 77, 300$, and 520 K. Our results within the range of $(4 \leq n \leq 65)$ are presented in table 3. Note that the radiative transition rates of a Rb Rydberg state are only weakly dependent on the total angular momentum quantum number j .

A log-log plot for the transition rates of $nF_{7/2}$ series (figure 4) shows that BBR-induced transitions become more significant with increasing n . From least-squares fitting we find that the scaling of our calculated bound-to-bound transition rate ($9 \leq n \leq 65$) at $T = 0$ K can be described to within 5% by $\Gamma_{\text{cal}, 0K} = \Gamma_c(n^*)^{-\epsilon}$, with $\Gamma_c \approx 1.25 \times 10^9 \text{ s}^{-1}$ and $\epsilon \approx 2.97$. (In our results, the transition rate of $15F_{7/2}$ is lower than that of $14F_{7/2}$, which differs from the unusual variation shown in the work by Theodosiou [20] in which the $15F_{7/2}$ has a shorter lifetime than the $14F_{7/2}$ state.)

Note that the rate contribution of BBR-induced transitions is 24.6% for the Rb $21F_{7/2}$ state at $T = 520$ K, which is at odds with the results of Gounand *et al* [19]. Specifically, they corrected their calculations of Rb nS , nP , nD , and nF Rydberg states transition rates with Cooke and Gallagher's theory [18] of BBR effects:

$$\frac{1}{\tau_{\text{corr}}} = \frac{1}{\tau_{\text{th}}} + \frac{1}{\tau_b}, \quad (13)$$



where $1/\tau_{\text{th}} = \Gamma_{\text{th}}$ is the spontaneous transition rate by theoretical calculations [16], and $1/\tau_{\text{b}} = \Gamma_{\text{b}}$ is the BBR-induced transition rate. According to Gounand *et al* [19], ‘the black-body correction is small for F levels.’ To assess the validity of their conclusion, we manually digitized their plot in [19] and compared our calculated results ($nF_{7/2}$) with their theoretical and experimental data (nF), shown in table 1 and figure 3. Our calculated transition rates for Rb Rydberg nF states at $T = 520$ K are, on average, 1.74% lower than the theoretical values reported by Gounand *et al*. We then quantified the consistency between our calculations and their experimental data at $T = 520$ K using a chi-squared (χ^2) test [31]. The resulting chi-squared divided by the number of data points χ^2/N is 0.60, suggesting that the calculated rates are higher than the experimental uncertainties would predict.

It is worth noting that, while the BBR-induced rate contributions calculated by Gounand *et al* [19] do not show a systematic trend (between 8.9% and 14.7%), our results show that the rate contribution due to BBR-induced transition increases gradually with the principal quantum number n , from 7.75% ($n = 9$) to 24.6% ($n = 21$). This gradual increase of BBR-induced rate contribution could also be found in the theoretical calculations accounting for Rb nS , nP , and nD states by Gounand *et al* [19] (6.6% to 31.8% for nS , 27.5% to 53.5% for nP , and 11.9% to 31.8% for nD , $9 \leq n \leq 21$), and in other theoretical calculations [20, 32]. We also noticed that while the calculations for nS , nP , and nD states at $T = 520$ K by Gounand *et al* all have considerably lower rates compared to their experimental data at

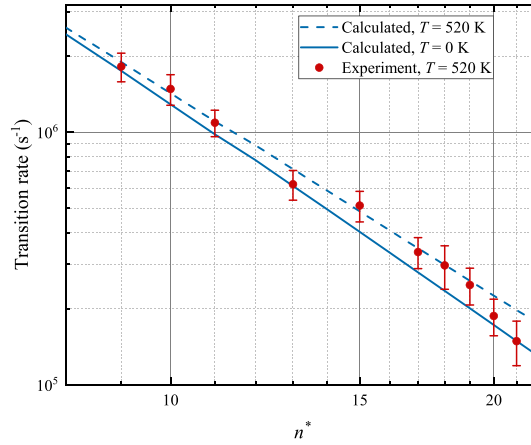


Figure 3. Transition rates of Rb nF ($9 \leq n \leq 21$) states, plotted versus the effective quantum number, n^* , in log-log scale. The data from Gounand *et al* [15, 16, 19] did not specify the total angular momentum quantum number j , and we used the calculated results of $nF_{7/2}$ states to compare with theirs.

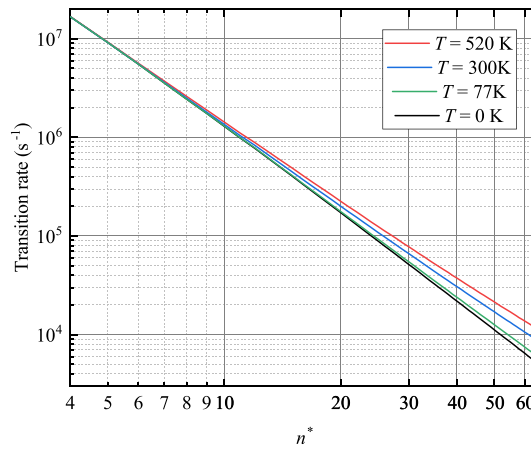


Figure 4. The total bound-to-bound transition rates Γ_{btb} (s^{-1}) for Rb Rydberg $nF_{7/2}$ states at temperatures $T = 0, 77, 300$, and 520 K, plotted versus the effective quantum number n^* .

$T = 520$ K, more than half of their calculations for $T = 520$ K nF states are similar to or higher than the experiment values. These anomalies raise concerns about the validity of their data.

3.2. Bound-to-free transitions

The BBR stimulated photoionization rates are numerically calculated and the results are shown in figure 5. Our calculations show that, at $T = 300$ K, the *fractional* contribution of BBR-induced photoionization to the total transition rate of Rb $nF_{7/2}$ states increases monotonically with principal quantum number n . Here, the total rate refers to the sum of the SE rate, the BBR-induced bound-to-bound transition rate, and the BBR-induced photoionization rate. At $T = 300$ K, the photoionization decay channel fraction rises from 0.01 % at $n = 10$ to 5.0 % at $n = 65$.

3.3. Uncertainties

Throughout the manuscript, we have indicated estimated uncertainties in the various contributions to the lifetimes. For convenience, table 2 summarizes these contributions for the total SE rates. The overall fractional error in the SE rate is 1.6 %. (Because of the small relative contribution of BBR-induced photoionization we do not estimate its error).

The uncertainty in the BBR-induced bound-to-bound transition rates is similar to that shown in table 2, except for another source of error, namely, the approximation of the high- n tail that was presented in section 2.3. Combining the 0.1% introduced by the high- n tail fitting, the estimated uncertainty of our calculated total bound-to-bound transition rate is 1.7%.

Table 1. Transition rates of Rb Rydberg nF states ($9 \leq n \leq 21$). On average, our results ($nF_{7/2}$) at $T = 520$ K are 1.74% lower than Gounand's total theoretical rates at 520 K ($\Gamma_{\text{th}} + \Gamma_{\text{b}}$), whereas they are 11.0% higher than Gounand's 0 K theoretical rates (Γ_{th}).

State	Transition Rate ($10^6 \times \text{s}^{-1}$)		
	Γ_{exp}	$\Gamma_{\text{th}} + \Gamma_{\text{b}}$	Γ_{btb}
9 F	1.819 ± 0.237	2.093	1.903
10 F	1.482 ± 0.205	1.550	1.433
11 F	1.091 ± 0.131	1.220	1.108
12 F			0.890
13 F	0.622 ± 0.084	0.769	0.717
14 F			0.587
15 F	0.512 ± 0.071	0.484	0.488
16 F			0.410
17 F	0.335 ± 0.047	0.353	0.348
18 F	0.297 ± 0.058	0.296	0.299
19 F	0.248 ± 0.041	0.249	0.259
20 F	0.187 ± 0.031	0.215	0.226
21 F	0.149 ± 0.030	0.188	0.198

^a Gounand *et al* experiments at $T = 520$ K [19].

^b Gounand *et al* theoretical calculations at $T = 520$ K [19].

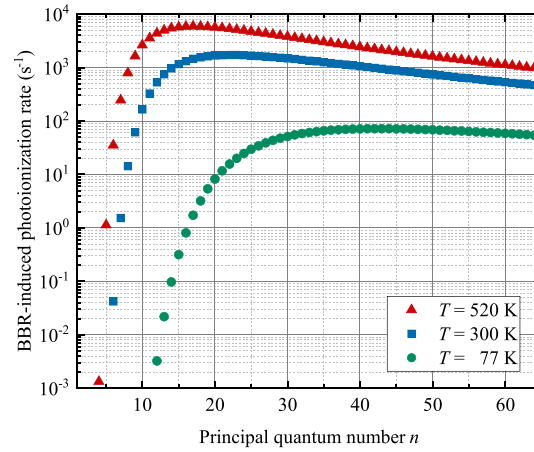


Figure 5. BBR-induced photoionization rates Γ_{PI} (s^{-1}) for Rb Rydberg $nF_{7/2}$ states at $T = 77, 300$, and 520 K versus the principal quantum number n , in semi-log scale. Rates are calculated using methods by Spencer *et al* [28] and Beterov *et al* [23].

Table 2. Contributions to the fractional uncertainties in the total spontaneous emission rates, $\Gamma_{\text{SE},i}$. The first column indicates the corresponding parameter in equation (1).

Parameter	Source	Source error	Contribution
$\omega_{a,b}$	[24]	$\sim 1.0 \times 10^{-6}$	$\sim 3.0 \times 10^{-6}$
	[13]	$\sim 1.0 \times 10^{-7}$	
$S_{a,b}$	[26]	$\sim 0.9 \times 10^{-2\text{a}}$	$\sim 1.6 \times 10^{-2}$
		$\sim 2.6 \times 10^{-2\text{b}}$	
	[21]	$\sim 5.5 \times 10^{-5\text{c}}$	

^a Estimated error for decay channels $nF \rightarrow 4D_{5/2}$, which have contribution of $\sim 60\%$ to $\Gamma_{\text{SE},i}$.

^b Estimated error for decay channels $nF \rightarrow 5D_{5/2}$, which have contribution of $\sim 22\%$ to $\Gamma_{\text{SE},i}$.

^c Estimated error for decay channels other than $nF \rightarrow 4D_{5/2}$ or $nF \rightarrow 5D_{5/2}$, which have contribution to $\Gamma_{\text{SE},i}$ of $\sim 18\%$.

Table 3. Rb $nF_{7/2}$ bound-to-bound transition rates, Γ_{bfb} ($10^3 \times \text{s}^{-1}$), and the total transition rates, Γ_{tot} ($10^3 \times \text{s}^{-1}$). The total rate combines Γ_{bfb} with the BBR-induced bound-to-free transition rate. The transition rates of the $nF_{5/2}$ states differ by less than the estimated fractional error of 1.7%.

n	$T = 0$ K	$T = 77$ K		$T = 300$ K		$T = 520$ K	
	Γ_{tot}	Γ_{btb}	Γ_{tot}	Γ_{btb}	Γ_{tot}	Γ_{btb}	Γ_{tot}
4	16 741	16 741	16 741	16 743	16 743	16 763	16 763
5	9142.0	9142.0	9142.0	9155.3	9155.3	9226.2	9226.2
6	5518.5	5518.6	5518.6	5551.2	5551.2	5652.6	5652.6
7	3569.8	3570.5	3570.5	3618.3	3618.3	3724.2	3724.4
8	2444.7	2446.3	2446.3	2501.5	2501.5	2600.3	2601.1
9	1755.3	1758.1	1758.1	1814.7	1814.8	1902.8	1904.4
10	1296.5	1300.4	1300.4	1355.3	1355.5	1432.8	1435.4
11	983.9	988.6	988.6	1040.2	1040.5	1108.0	1111.6
12	777.7	783.0	783.0	830.7	831.2	890.1	894.5
13	615.2	620.9	620.9	664.6	665.4	716.8	721.8
14	495.5	501.3	501.3	541.2	542.2	587.3	592.8
15	404.6	410.4	410.4	446.8	448.0	487.7	493.4
16	334.6	340.3	340.3	373.6	374.9	410.1	416.0
17	279.7	285.3	285.3	315.7	317.2	348.4	354.3
18	236.3	241.7	241.7	269.5	271.1	299.1	305.0
19	201.2	206.5	206.5	232.0	233.6	258.8	264.6
20	172.9	178.0	178.0	201.4	203.1	225.8	231.5
21	149.6	154.5	154.5	176.0	177.7	198.4	203.9
22	130.4	135.0	135.0	155.0	156.7	175.5	180.8
23	114.2	118.6	118.6	137.1	138.8	156.0	161.1
24	100.6	104.8	104.8	122.0	123.7	139.4	144.3
25	89.15	93.20	93.23	109.1	110.8	125.4	130.1
26	79.29	83.15	83.18	98.01	99.66	113.1	117.6
27	70.87	74.55	74.59	88.45	90.06	102.5	106.8
28	63.59	67.10	67.14	80.12	81.69	93.27	97.42
29	57.26	60.61	60.66	72.83	74.36	85.15	89.12
30	51.74	54.94	54.99	66.43	67.91	77.99	81.79
31	46.94	49.99	50.05	60.81	62.25	71.69	75.32
32	42.67	45.58	45.64	55.79	57.18	66.05	69.52
33	38.92	41.71	41.77	51.36	52.71	61.04	64.35
34	35.60	38.27	38.33	47.40	48.71	56.56	59.73
35	32.65	35.19	35.26	43.85	45.11	52.52	55.55
36	30.00	32.45	32.52	40.66	41.88	48.89	51.79
37	27.63	29.97	30.04	37.78	38.96	45.59	48.36
38	25.53	27.77	27.84	35.20	36.34	42.63	45.28
39	23.60	25.75	25.82	32.84	33.94	39.91	42.45
40	21.89	23.95	24.02	30.71	31.77	37.46	39.89
41	20.33	22.31	22.38	28.77	29.79	35.20	37.53
42	18.92	20.82	20.89	26.99	27.98	33.14	35.38
43	17.63	19.46	19.53	25.36	26.31	31.25	33.39
44	16.46	18.22	18.29	23.87	24.79	29.50	31.56
45	15.38	17.08	17.15	22.49	23.38	27.89	29.86
46	14.39	16.03	16.10	21.22	22.08	26.40	28.30
47	13.49	15.07	15.14	20.05	20.88	25.02	26.84
48	12.66	14.18	14.25	18.97	19.77	23.74	25.49
49	11.90	13.37	13.44	17.98	18.75	22.57	24.25
50	11.20	12.61	12.68	17.05	17.79	21.46	23.08
51	10.55	11.92	11.99	16.19	16.91	20.44	22.00
52	9.95	11.27	11.34	15.38	16.08	19.48	20.98
53	9.39	10.67	10.74	14.64	15.31	18.59	20.04
54	8.88	10.11	10.17	13.94	14.59	17.75	19.14
55	8.40	9.60	9.66	13.30	13.93	16.97	18.31
56	7.95	9.11	9.17	12.68	13.29	16.23	17.53
57	7.54	8.66	8.72	12.11	12.70	15.54	16.79
58	7.15	8.23	8.29	11.57	12.14	14.89	16.10
59	6.79	7.84	7.90	11.07	11.62	14.28	15.45

(Continued.)

Table 3. (Continued.)

60	6.45	7.47	7.53	10.59	11.12	13.70	14.83
61	6.13	7.12	7.18	10.15	10.67	13.15	14.24
62	5.83	6.79	6.85	9.73	10.23	12.64	13.69
63	5.55	6.49	6.55	9.33	9.82	12.15	13.17
64	5.30	6.20	6.25	8.96	9.43	11.69	12.67
65	5.05	5.93	5.98	8.60	9.06	11.25	12.20

4. Conclusion

We have calculated both spontaneous and BBR-stimulated transition rates for Rb Rydberg nF states over a wide range of principal quantum numbers ($4 \leq n \leq 65$). The calculated radiative transition rates showed good agreement with available theoretical data at $T = 0$ K [16]. For higher temperatures, our results showed that BBR-induced transitions cannot be neglected for Rb nF states (the rate contribution of BBR-induced transitions accounts for 24.6% for Rb $21F_{7/2}$ state at $T = 520$ K), while previous studies had considered the BBR-induced rate contribution for these states to be small [19].

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Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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