PHYSICAL REVIEW A VOLUME 28, NUMBER 6 DECEMBER 1983

Radiative lifetimes of ^1S and ^1P Rydberg levels of He

M. Larsson, B. Mannfors, and W. R. Pendleton, Jr.*
Research Institute of Physics, S-104 05 Stockholm 50, Sweden
and Physics Department, Royal Institute of Technology, S-100 44 Stockholm 70, Sweden
(Received 18 April 1983)

Radiative lifetimes of four ^1S levels ($n=6$–9) and seven ^1P levels ($n=7$–13) of He I have been measured using the high-frequency deflection technique. The ^1S lifetimes, with estimated limiting errors of about 3–7 %, agree well for $n=6$–8 with theoretical lifetimes based on transition probabilities computed from central-field wave functions with exchange and configuration interaction. An apparent discrepancy between theory and experiment in the case of the $9\,^1S$ measurement is largely removed when blackbody-radiation-induced emission and absorption processes are included in the theoretical lifetime. Radiative lifetimes for the ^1P levels were determined under conditions where, in favorable cases ($n=8$–12), the zero-pressure lifetimes differed by no more than 10–20 % from the values measured at low pressures. In these cases, the estimated accuracy of the measurements is comparable to that of theory, and the agreement is deemed within the combined uncertainties. Quenching cross sections for the $n\,^1S$ levels are also reported.

I. INTRODUCTION

Radiative lifetime determinations based on the high-frequency deflection (HFD) technique are reported here for several ^1S and ^1P Rydberg levels of He. This technique has previously been used to determine a large number of atomic and molecular lifetimes with a limiting precision of about 0.5% in favorable cases.[1] In the present case, the statistical uncertainty in each *effective* level lifetime determination was typically $<2\%$. However, extrapolations to zero pressure were required to deduce the radiative lifetimes, resulting in estimated precisions in the range 3–7 % and 7–20 %, respectively, for the ^1S and ^1P measurements. In the case of the ^1S measurements, the estimated precision is slightly better than that of critically compiled theoretical results, while the precision of the ^1P measurements is comparable to or slightly poorer than that of theory.

Very precise (uncertainty $\leq 1\%$) transition-probability calculations exist for only a few transitions in helium. Theoretical He I transition probabilities for radiative transitions from the $n\,^1S$ and $n\,^1P$ terms are of special interest to this study. The most extensive tabulations of theoretical results for these levels are found in the publications of Wiese *et al.*,[2] Green *et al.*,[3] and Gabriel and Heddle.[4] Several of the critically compiled He $n\,^1S$ and $n\,^1P$ transition probabilities in Ref. 2 have estimated accuracies $\leq 3\%$, but most fall in the $\leq 5\%$ and $\leq 10\%$ categories, especially for the more highly excited terms.

Computations of He I lifetimes from the critically compiled tabulation are frequently complicated by incomplete information for terms with $n>5$. In such cases one is forced to extrapolate and/or interpolate the tabulated values in computing lifetimes. However, the He I oscillator strengths of Green *et al.*[3] are complete through $n=9$ for the $n\,^1S$ terms and through $n=8$ for the $n\,^1P$ terms and provide a self-consistent set for computing true theoretical lifetimes for many of the levels of interest to this study.

Recent experimental studies have raised serious questions concerning the reliability of the theoretical $n\,^1S$ lifetimes. In particular, the beam-foil He I lifetime studies of Bukow *et al.*[5] have produced ^1S lifetimes for $n=3$–5 which depart significantly from the theoretical values. This discrepancy is about 10% at $n=3$ and systematically increases with n to about 30% at $n=5$, with experimental values smaller than corresponding theoretical values. A recent study by Hitachi *et al.*[6] has also yielded He($n\,^1S$) radiative lifetimes which are significantly shorter than the theoretical results. In particular, these investigators report zero-pressure lifetimes for the $6\,^1S$ and $8\,^1S$ terms which differ from the theoretical values by about 15% and nearly 200%, respectively, although they report agreement with theory for $n\leq 5$. Earlier precise determinations of He($n\,^1S$) radiative lifetimes are restricted to $n\leq 6$ and tend to agree with the theoretical values.

The apparent discrepancy between experimental and theoretical He($n\,^1S$) radiative lifetimes, especially in the case of the $8\,^1S$ term, was a factor which contributed to our decision to investigate the radiative properties of $n\,^1S$ terms with $n=6$–9. A lower limit of $n=6$ provides adequate overlap with previous investigations, while an upper limit of $n=9$ coincides with that of available theoretical results. In addition to the He($n\,^1S$) measurements, we report radiative lifetime determinations for $n\,^1P$ levels with $7\leq n\leq 13$. We are unaware of previous experimental work with which to compare these results, but sufficient theoretical results are available to permit a meaningful comparison except in the case of the $13\,^1P$ term.

II. EXPERIMENTAL

A careful consideration of the effects of He concentration on the measured lifetimes proved essential to the determination of accurate "zero-pressure" values. Toward this end, a systematic investigation of the effective lifetime of each level was carried out for several pressures in the range $1 \leq p(\text{He}) \leq 50$ mTorr. Effective lifetimes were measured using the HFD technique. This technique is basically a refined version of the conventional multichannel delayed-coincidence method. Principles of the technique have previously been given,[1] as has a complete description of a basic HFD system similar to the one used in the present study.[7] For present purposes, we mention the essential features of the experiment.

Excited helium atoms were produced by bombarding a He($1\,^1S$) target with periodic pulses of 20-keV electrons. The current pulses were about 30 mA in amplitude and $(\tau/5)$ in duration with τ the effective lifetime of the level of interest. Target pressures were monitored with a Leybold-Heraeus IONIVAC IM 10 ionization gauge which was compared with an MKS Instruments Model 110 capacitance manometer. This procedure resulted in pressure measurements with an estimated accuracy of about $\pm 10\%$. The base pressure in the target chamber was typically $< 10^{-5}$ Torr. Prepurified helium was introduced into the chamber by means of a precision variable leak valve.

A 2-m Czerny-Turner scanning monochromator, equipped with a cooled EMI 9789 SQ photomultiplier, was used to select and detect the He I $n\,^1S \rightarrow 2\,^1P$ or $n\,^1P \rightarrow 2\,^1S$ transition of interest. A spectral slit width < 1 Å was used for the measurements. This resolution ensured isolation of the transition of interest from neighboring helium lines under worst-case conditions. We note that the viewing geometry for the experiment resulted in negligible net loss of excited atoms from the field of view for the longest lifetimes of interest (~ 1 μsec), thus effectively eliminating thermal-escape effects.[8]

The time scale of the multichannel delayed-coincidence system used to accumulate the decay curves was calibrated to an accuracy of better than 1% by means of precision delays. Repeated checks of the system time calibration yielded results which were consistent to about 0.5%.

A nonlinear, least-squares curve-fitting routine was used to extract the lifetime information from the raw data. Both one- and two-component reductions were carried out, and the best result, based on statistical criteria, was selected. In the case of the He($n\,^1S$) measurements, the reciprocal lifetime varied linearly with pressure for the full pressure range of the measurements at $n=6$ but exhibited distinctly nonlinear behavior above $\sim 10^{-2}$ Torr for $n>6$. The pressure dependence of the He($n\,^1P$) lifetimes was more complex as a result of the combination of the radiation-imprisonment and collisional effects which control the effective decay rate of this species. Least-squares procedures, described below, were implemented to extract the "zero-pressure" lifetimes and quenching rate constants from the data.

In the case of the $n\,^1S$ measurements, the pressure dependence of the effective decay rate was examined for each level to determine the linear region. A linear least-squares analysis was then carried out to determine the "best-fit" values for the zero-pressure lifetime (τ_0) and the collisional destruction-rate coefficient (Γ) in the linear equation

$$(1/\tau_{\text{eff}}) = (1/\tau_0) + \Gamma p \;, \tag{1}$$

where p is the He pressure.

A more complex analysis was required to extract the information of interest from the He($n\,^1P$) data. As previously noted, the pressure dependence of the effective decay of this species is controlled, under present experimental conditions, by a combination of radiation trapping and collisional quenching. For sufficiently low pressures ($p \leq 20$ mTorr), the effective decay rate of He($n\,^1P$) was accurately described by the relationship

$$1/\tau_n = \alpha_n + \beta_n g_n(k_0\rho_{\text{eff}}) + \gamma_n p \;, \tag{2}$$

where $1/\tau_n$ is the decay rate, $(\alpha_n, \beta_n, \gamma_n)$ and $g_n(k_0\rho_{\text{eff}})$ are discussed below, and p is the helium pressure.

The parameters $(\alpha_n, \beta_n, \gamma_n)$ are identified, respectively, with the resonance-trapped decay rate in the absence of collisional loss, the Einstein coefficient for the $n\,^1P \rightarrow 1\,^1S$ resonance transition, and the collisional loss-rate coefficient. The so-called "escape factor" $g_n(k_0\rho_{\text{eff}})$ enables one to approximate the impact of radiation imprisonment on the measured lifetime by a single parameter $k_0\rho_{\text{eff}}$, the product of the absorption coefficient at line center k_0, and the effective imprisonment radius ρ_{eff}. This approximation to the complex radiative transfer problem has recently been reviewed by Irons[9,10] who compares various theoretical results for g_n and notes that the results of Phelps[11] are accurate for both small and large $k_0\rho_{\text{eff}}$.

An effective imprisonment radius for the collision chamber used in this study was determined by the well-established technique[12,13] of precisely measuring the effective decay rate of He($3\,^1P$) over a wide range of optical depths. This study, which has recently been reported,[14] yielded $\rho_{\text{eff}} = 1.60 \pm 0.10$ cm, the value adopted for each n of interest in Eq. (2). Following Heddle and Samuel,[15] we used the $g^>$ results of Phelps[11] in determining ρ_{eff}. An extensive study of the impact of imprisonment effects on the radiative properties of He($3\,^1P$) resulted in their conclusion that the $g^>$ model of Phelps was consistent with the data provided ρ_{eff} was identified with the distance from the observed axial region to the closest wall.

We note that the fitting parameter β_n, which is identified with the transition probability $A(n\,^1P \rightarrow 1\,^1S)$, also appears in g_n through the product $k_0\rho_{\text{eff}}$. Under the assumption of Doppler line broadening, the line-center (wavelength λ_0) absorption coefficient k_0 (units of cm^{-1}) is given at 300 K by

$$k_0 = (1.942 \times 10^7)[\lambda_0^3 A(n\,^1P \rightarrow 1\,^1S)]p \;, \tag{3}$$

where λ_0, A, and p are expressed, respectively, in cm, s^{-1}, and mTorr. Hence, Eq. (2) is nonlinear in the parameter β_n. A least-squares curve-fitting routine was developed and used to extract best-fit values for $(\alpha_n, \beta_n, \gamma_n)$ from the pertinent set of lifetime measurements. Values of α_n, extracted from the analyses, were $\sim 10^{-2}\beta_n$ and were not well determined. However, the zero-pressure lifetimes, which are given by the sum $\alpha_n + \beta_n$, were accurately established by these analyses. The parameters γ_n in the collision term of Eq. (2) were also well determined from the analyses and have formed the subject of a previous publication.[14]

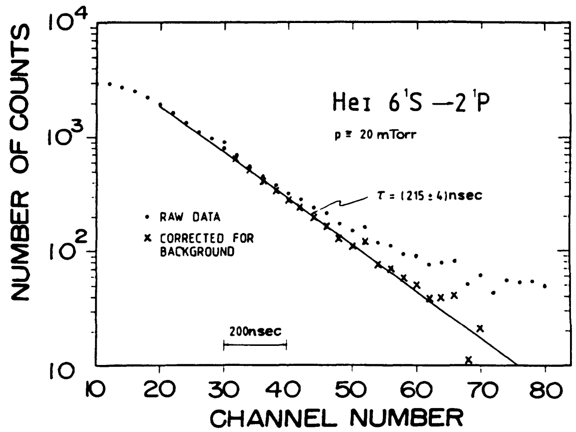

FIG. 1. Experimental decay curve for He($6\,^1S$) at a target pressure of 20 mTorr. The solid line reflects the best-fit exponential component obtained from an analysis of the tail region.

III. RESULTS

The results of the present measurements for the radiative mean lifetimes of $n\,^1S$ and $n\,^1P$ levels of helium and for the collisional destruction of He($n\,^1S$) in collisions with He($1\,^1S$) at $\approx$300 K are presented in this section. In what follows, the results pertinent to the $n\,^1S$ and $n\,^1P$ measurements will be separately introduced. A comparison of these results with other measurements and with theory will be deferred until Sec. IV.

A. He($n\,^1S$) measurements

A typical decay curve for He($6\,^1S$) is presented in Fig. 1. The removal of background counts from the raw data results in a decay curve which appears simple. Computer analyses confirmed that the best-fit model in this case consisted of a single exponential component and a constant background. Analyses of the He($6\,^1S$) data, over the pressure range of the measurements, consistently indicated the presence of only one statistically significant component in the decay. However, it was determined that the decay curves for the higher ^1S terms became complex at the higher pressures used in the investigation. The probable cause for the deviation from a single-component decay is collisional angular momentum mixing with the higher angular momentum states of the same n, as discussed below.

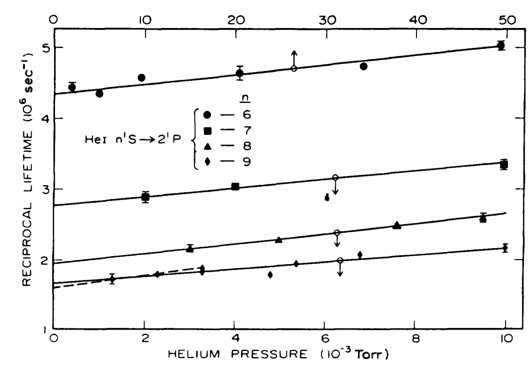

FIG. 2. Dependence of the decay rates of He($n\,^1S$) on target pressure. The upper scale applies to the $n=6$ measurements. The error bars are typical and include only statistical error.

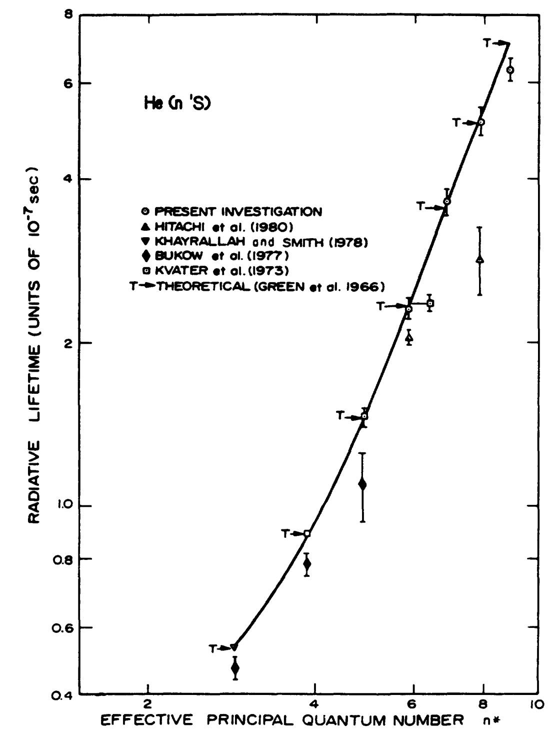

FIG. 3. Log-log plot of experimental and theoretical He($n\,^1S$) lifetimes. The cited works are as follows: Hitachi *et al.*, Ref. 6; Khayrallah and Smith, Ref. 16; Bukow *et al.*, Ref. 5; Kvater *et al.*, Ref. 17.

In Fig. 2, the pressure-dependent He($n\,^1S$) lifetime re-

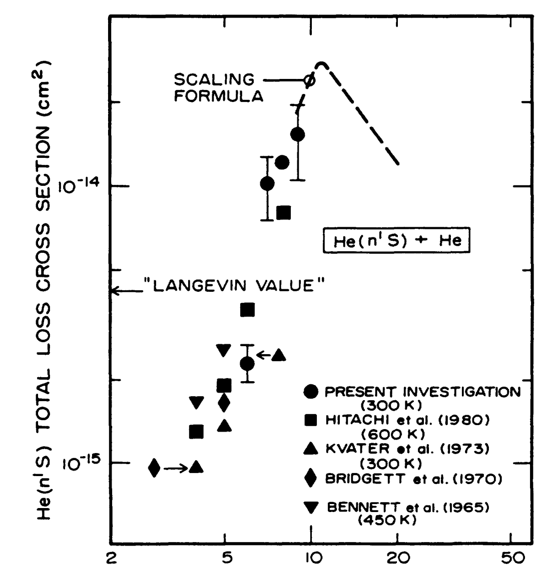

FIG. 4. Total loss sections for He($n\,^1S$) in thermal collisions with He. The cited works are as follows: Hitachi *et al.*, Ref. 6; Kvater *et al.*, Ref. 17; Bridgett *et al.*, Ref. 18; Bennett *et al.*, Ref. 19.

TABLE I. Radiative lifetimes of ^1S and ^1P Rydberg levels of He.

	Experimental				
Term	$[\tau(p_m)/\tau(0)]^a$	$\tau(0)$ (nsec)^b	Theoretical lifetimes (nsec)		
6^1S	0.97	230(7)	239(9)[c]	233[e]	240[f]
7^1S	0.93	360(18)		351	356
8^1S	0.81	513(30)		508	52_0
9^1S	0.87	625(40)		710	
7^1P	1.31	22.7(3.4)	[19][d]	21.0	20.4
8^1P	1.16	31.7(4.0)	[28]	31.1	30.5
9^1P	0.87	43.6(3.1)	[40]		
10^1P	0.91	54.9(3.8)	[52]		
11^1P	0.79	71.4(7.1)	[73]		
12^1P	0.83	90.9(9.1)	[91]		
13^1P	0.40	125(20)			

[a]Ratio of effective lifetime $\tau(p_m)$ at minimum pressure p_m to extrapolated zero-pressure lifetime $\tau(0)$.
[b]Extrapolated zero-pressure (radiative) lifetimes. The numbers in parentheses are estimated uncertainties which reflect a combination of the following: (1) time-calibration uncertainties, (2) statistical uncertainties, and (3) extrapolation uncertainties.
[c]Reference 2. A value for $A(6\,^1S \rightarrow 5\,^1P)$ was scaled from the results in Ref. 3.
[d]He($n\,^1P$) lifetimes based on the critically compiled, dominant $A(n\,^1P \rightarrow 1\,^1S)$ transition probabilities of Ref. 2 and estimates of the small ($\leq 6\%$) amount of branching to other terminal levels.
[e]Lifetime values in this column are based on the He I oscillator strengths documented in Ref. 3.
[f]Lifetime values in this column are based on the He I transition probabilities documented in Ref. 4.

sults are presented to illustrate the data sets which were used in the linear-least-squares fits. Results of the fits to Eq. (1) are reflected in the solid lines through the data points. The dashed line illustrates the results of a least-squares fit to the lowest pressure data for the $9\,^1S$ level, where a slight disparity between theory and experiment prompted special consideration of the data. Radiative (zero-pressure) lifetimes for the $n\,^1S$ levels are presented in Fig. 3, and numerical results are summarized in column 3 of Table I. The ratio of the $n\,^1S$ lifetime measured at the lowest pressure of the experiment to the inferred zero-pressure value is also given in column 2 of the table. These ratios illustrate the very small extrapolations required at $n=6,7$ and the modest extrapolations required

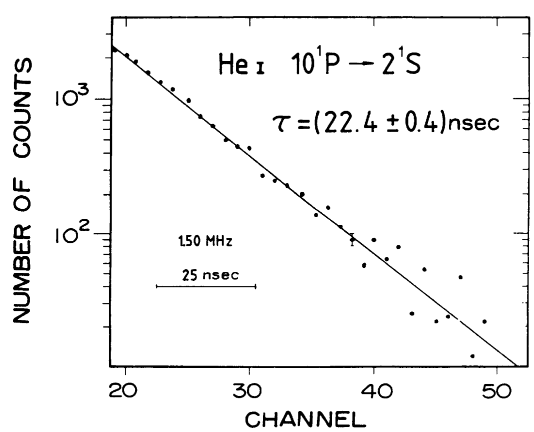

FIG. 5. Experimental decay curve for He($10\,^1P$) illustrating the simple exponential decay observed under short-pulse conditions. Background counts have been removed in preparing the figure.

for the higher levels. Theoretical lifetimes are summarized in columns 4—6. Results for the He($n\,^1S$) collisional-loss measurements are given in Fig. 4 where they are compared with similar measurements by other investigators and with predicted values.

B. He($n\,^1P$) measurements

A decay curve for He($10\,^1P$) is presented in Fig. 5 to illustrate the single-exponential behavior observed for these higher $n\,^1P$ levels under conditions where the excitation period was short compared to the l-mixing time. (This important interpretational consideration has been discussed in a previous publication.[14]) Data in channels greater than 70 suggested a constant background on the time scale of the measurements, as evidenced by the form of the best-fit analyses of the data. In accord with this observation, a constant background was removed from the raw data in preparing the figure.

In Fig. 6, pressure-dependent He($n\,^1P$) lifetime results are presented for $n=3,7,8,11,12$ to illustrate the trend from a radiation-trapping-controlled decay at low n to a collision-dominated decay at higher n. The solid curves through the sets of data points reflect the results of least-squares fits to Eq. (2). Precise fits were realized except at the higher pressures of the experiment ($p>20$ mTorr) where reciprocal-transfer effects tend to become important. No attempt was made to modify the collisional-radiative model to include reciprocal-transfer effects since the information of interest was readily obtained from the lower-pressure data, which are deemed essentially free of such effects. The statistical uncertainty of the $n=3$ measurements is within the displayed dots. As previously noted, our determination of $\rho_{\rm eff}$ was based on these $n=3$ re-

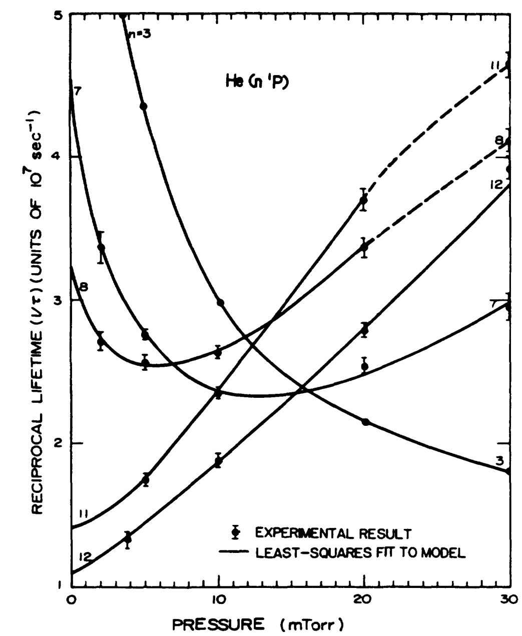

FIG. 6. Dependence of the decay rates of He($n\ ^1P$) on target pressure. The solid lines reflect best-fit analyses using a collisional-radiative model.

sults which are presented in greater detail in Ref. 14. A highly favorable fit of the collisional-radiative model to these precise measurements throughout the range of pressures critical to the present investigation lends confidence to our treatment of the trapping of the resonance transitions from the higher $n\ ^1P$ levels.

A log-log presentation of the zero-pressure lifetime results for the $n\ ^1P$ levels is given in Fig. 7, and numerical values are summarized in column 3 of Table I. The precise result of Astner *et al.*[20] for the radiative lifetime of He($3\ ^1P$) is also shown in Fig. 7 since it was combined with our lower-precision, higher-n measurements in determining the best-fit line through the data points in the figure. We note that Table I includes, in column 2, lifetime ratios which reflect the magnitude of the extrapolation from the lowest pressure of the experiment to zero pressure. In the most favorable cases ($n=9,10$), the zero-pressure result differs from the value measured at the minimum pressure by only about 10%, whereas in the least-favorable case ($n=13$), the zero-pressure result is larger than the "minimum-pressure result" by a factor of 2.5. These ratios provide an important indication of the reliability which one might expect for the zero-pressure extrapolations. Theoretical He($n\ ^1P$) lifetimes are summarized in columns 4–6 of Table I.

IV. DISCUSSION

In attempting to compare the He $n\ ^1S$ and $n\ ^1P$ lifetime measurements with theory, it was ascertained that the critically compiled He I transition probabilities of Wiese *et al.*[2] are incomplete for $n>5$. As a result, it proved necessary to use theoretical results of uncertain reliability in effecting the comparison. We have adopted the set of He I oscillator strengths computed by Green *et al.*,[3] although we have also drawn on the slightly less extensive and incompletely documented tabulation of A coefficients by Gabriel and Heddle.[4]

The oscillator strengths of Ref. 3 agree at the 1% level with the very accurate computations of Schiff and Pekeris[21] for the $1\ ^1S$-$2\ ^1P$ and $1\ ^1S$-$3\ ^1P$ transitions. Also,

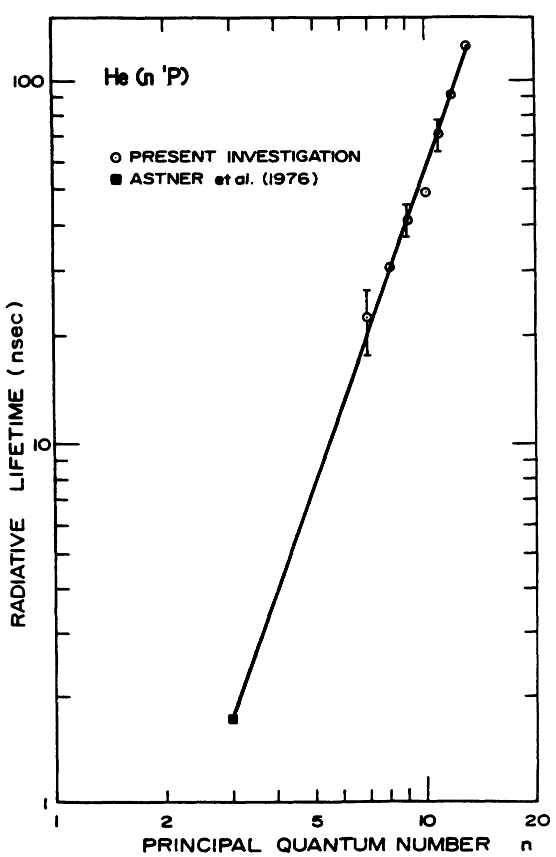

FIG. 7. Log-log plot of the experimental He($n\ ^1P$) radiative lifetimes. The solid line reflects a best-fit analysis assuming a power-law model.

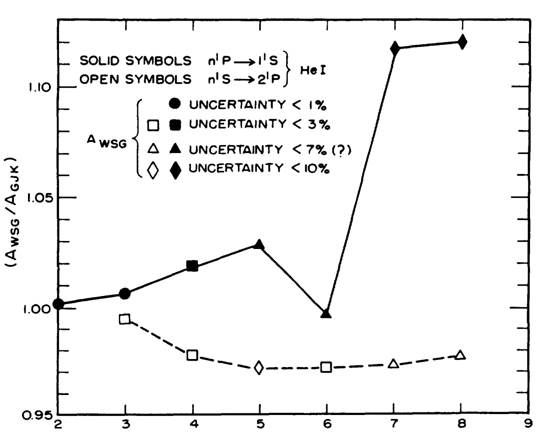

FIG. 8. Comparison of critically compiled He I transition probabilities ($A_{\rm WSG}$, Ref. 2) with values deduced from the oscillator strengths of Green *et al.* ($A_{\rm GJK}$, Ref. 3).

their $n\,^1S$-$n'\,^1P$ results computed by the dipole length and velocity expressions agree to $\leq 2\%$ for nearly all of the transitions of interest to the present study. In order to strengthen confidence in the use of these theoretical oscillator strengths, we have compared pertinent Einstein coefficients deduced from the oscillator strengths with values from the critical data compilation of Ref. 2, as described below.

A comparison of theoretical transition probabilities from Green *et al.*[3] ($A_{\rm GKG}$) with those from the critically compiled set of Wiese *et al.*[2] ($A_{\rm WSG}$) is presented in Fig. 8 for both the $n\,^1S \rightarrow 2\,^1P$ and $n\,^1P \rightarrow 1\,^1S$ series. In the case of the $n\,^1S \rightarrow 2\,^1P$ series, the ratio of transition probabilities lies in the range 0.97–1.00 for $3 \leq n \leq 8$. The trend illustrated in the figure suggests that the Einstein coefficients of Ref. 3 for the $n\,^1S \rightarrow 2\,^1P$ series are probably reliable to within 5% over the full range of n. (Note that the critically compiled set involves computational results from two independent sources.) A comparison in the case of the $n\,^1P \rightarrow 1\,^1S$ transitions is favorable (agreement to within about 3%) for $n \leq 6$; however, the unfavorable comparison for $n = 7,8$ is consistent with the decrease in reliability of the critically compiled data. The trend suggests that the He I $n\,^1P \rightarrow 1\,^1S$ Einstein coefficients of Ref. 3 should be reliable to somewhat better than 10%, especially for $n \leq 6$.

A. He($n\,^1S$) measurements

We note from Table I and Fig. 3 that our $n\,^1S$ lifetimes agree with the theoretical results of Green *et al.*[3] to within 3% for $n = 6$–8. In sharp contrast, the $n = 9$ result differs from the theoretical value by about 12%. The trend in Fig. 3 suggests that this experimental result is indeed systematically low since it departs significantly from the power-law scaling established by the theoretical and experimental lifetimes in the range $5 \leq n \leq 8$.

In view of the evidence suggesting a systematic error in the $n = 9$ result, an effort was made to identify a possible source. The influence of background spectra was examined and found to have negligible impact on the measurements. The possibility that the pressure dependence of $(1/\tau_{\rm eff})$ was not closely linear in the region used for the least-squares fit was also considered. However, the correlation coefficient was found to be greater than 0.98, and this source of error was deemed too small to account for the disparity.

Although systematic error in the $n = 9$ measurement is still a possibility, it is suggested that a contributing factor to the apparent disagreement between theory and experiment is the neglect of induced emission and absorption processes in the theoretical lifetime. In the presence of a radiation field, it is, of course, necessary to make proper allowances for induced transitions. Gallagher and Cooke[22] have recently shown that such effects indeed have an important impact on the effective decay rate of Rydberg levels under typical experimental conditions. These effects are expected to manifest themselves, in favorable cases, when the condition $(h\nu/kT) \leq 1$ is satisfied, i.e., when the transition energy is comparable to or less than the product kT with T the effective blackbody temperature of the radiation field. In the case of thermal equilibrium at 300 K, rates associated with transitions for which $h\nu \leq 200$ cm^{-1} are expected to be significantly altered by these effects.

We have estimated the magnitude of these blackbody effects in the case of the He($n\,^1S$) lifetime measurements and find them to be small at 300 K ($\approx 2\%$ at $n = 9$). However, the effective radiation field in the excitation cavity of the high-power electron-impact facility used in the investigation probably differs somewhat from that of a 300-K blackbody. The correction factor is a sensitive function of the effective temperature and is estimated to approach 10% at $n = 9$ for an effective temperature of 600 K. Hence, it would appear that the appropriate $n = 9$ theoretical lifetime might be several percent shorter than the spontaneous radiative value in the table. One then finds reasonable agreement between theory and experiment at $n = 9$, in keeping with the good agreement for smaller n.

In comparing the measurements in Fig. 3, we note that our $n = 6$ result compares favorably with that of Kvater *et al.*[17] but differs from that of Hitachi *et al.*[6] by about 15%. Thompson and Fowler[23] have also reported a precise value of 210 ± 4 nsec for the radiative lifetime of this level, in agreement with Hitachi *et al.* The source of the modest disparity in these experimental results is not clear but may stem from systematic differences in effecting zero-pressure extrapolations. Kvater *et al.*[17] have emphasized the need for careful extrapolations to obtain accurate radiative lifetimes for the ^1S levels, in keeping with the results of this investigation. Neither Hitachi *et al.* nor Thompson and Fowler provide enough information to permit an assessment of this point.

It appears the $n = 8$ measurement of Hitachi *et al.*[6] is the only available precise measurement with which to compare our $n > 6$ results. Our result exceeds that of Ref. 6 by about a factor of 2. The source of this disparity cannot be identified with certainty, but a systematic difference in extrapolating to zero pressure is considered a possibility. Under the conditions of the present experiment, an extrapolation to zero pressure from the region above 20 mTorr would have yielded a zero-pressure lifetime of about 350 nsec, whereas an extrapolation based on measurements in the region 2–10 mTorr yielded the value 513 nsec in Table I.

Prior to discussing the He($n\,^1P$) lifetime results, we briefly consider the He($n\,^1S$) collisional-loss measurements in Fig. 4. Our results compare favorably with similar measurements by other investigators when experimental differences and uncertainties are considered. The trend in the figure is consistent with the suggestion of Hitachi *et al.*[6] that collisional l mixing is the principal loss mechanism for the $n\,^1S$ terms with $n \geq 5$. In keeping with this idea, we have estimated the l-mixing cross sections for these highly excited ^1S states by means of a recently introduced scaling relationship.[24] The large energy defects for the $n\,^1S$ levels with $n < 9$ prevent a valid prediction using the scaling formula. However, it is clear from Fig. 4 that the $n = 9$ result is of the magnitude expected for the l-mixing process and that the value expected in the case of a dominant core-perturber interaction (Langevin value) is significantly smaller than the measured value. It is also of interest to note that the n dependence of our total loss cross section is similar to that reported by Freund *et al.*[25] in the case of cross sections for the transfer process $n\,^1S \rightarrow n\,^1D$. Our total loss cross sections exceed these partial cross sections by roughly a factor of 5 at each n.

B. He($n\,^1P$) measurements

Lifetime results for the $n\,^1P$ levels are compared with theory in Table I. Measurements at $n=7,8$ agree well with the theoretical values of Green *et al.*[3] Agreement with the other theoretical values is less favorable, but it is deemed satisfactory when the uncertainties are considered. Above $n=8$, theoretical results are limited to estimates based on the dominant $n\,^1P \rightarrow 1\,^1S$ transition probabilities in the compilation of Wiese *et al.*[2] The comparison is again favorable, with experimental- to theoretical-lifetime ratios in the range 0.98–1.09.

The log-log plot of the ^1P lifetimes in Fig. 7 illustrates the satisfactory fit of the data to the expected n^x behavior. A least-squares analysis yielded $x=2.9\pm0.1$.

ACKNOWLEDGMENTS

The authors wish to thank Professor P. Erman and Professor G. Witt for their interest in the studies and for helpful comments. The contribution of I. L. Davis to data analyses is acknowledged with gratitude. Also, one of us (W.R.P.) would like to express his appreciation to the Swedish Natural Science Research Council and to the Division of Research at Utah State University for providing funds toward his stay in Sweden. The hospitality of Professor Erman and Professor Witt, as extended through the Research Institute of Physics and the Meteorological Institute of the University of Stockholm, respectively, is gratefully acknowledged by W.R.P.

*Permanent address: Department of Physics, Utah State University, Logan, UT 84322.

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