

# He Metastable Concentration Measurements in a Glow Discharge

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## **Abstract**

The density of the metastable He atoms in the positive column of a glow discharge is determined using two techniques involving a Fourier Transform spectrometer. The techniques are the traditional self-absorption method and the newly reported Doppler shift technique. The two results agree well within the experimental errors.

# 1 Introduction

The ability to remotely measure concentrations of molecular species is important in many areas of science and technology. However the challenges are enormous and it is unlikely that any one technique will be universally applicable. In the preceding paper, a new technique of concentration measurement, Doppler Shifted Fourier Transform Spectroscopy (DSFTS) has been theoretically described.[1] This technique may be useful for measuring concentrations whenever a combination of lower state population and absorption strength causes the probability to exceed a few percent for a photon being absorbed before it leaves the medium.

A typical application might be weakly ionized gases or plasmas, be they in the laboratory, involved in materials processing, in the upper atmosphere, or interstellar space. A particularly interesting example is the glow discharge or plasma which has numerous applications in industry such as plasma assisted integrated circuit fabrication and various other chemical deposition and etching processes[2, 3, 4, 5]. The densities of metastable atoms in these plasmas are of significant importance to the chemistry within the discharge. They are involved in many chemical reactions such as Penning ionization, laser action as in He/Ne mixtures, as well as various other energy-transfer and fragmentation processes.

The low pressure D.C. or glow discharge also offers an opportunity to directly compare the results from the new technique of DSFTS with the more traditional method of measuring densities, self absorption using the Fourier Transform spectroscopy (SAFTS). If the DSFTS method is experimentally

validated by the self-absorption measurements in the glow discharge, then it can be applied with some confidence to systems where traditional density measurements are impractical.

## 2 Experimental

The discharge cell used for this experiment was a U type quartz tube in which two 8mm i.d. side arms are connected to a 2mm i.d., 3 cm long capillary tube, as shown in Fig. (1). The capillary part of the cell, in which the metastable density is measured in these experiments, (marked by a dotted rectangle in Fig. (1)) is shown in more detail in Fig. (2) with some of the key physical parameters indicated. The electrodes are unmodified 0.5 inch i.d. Cajon stainless steel vacuum fittings and are positioned off-axis to make it easy to collect the photons from the capillary into the spectrometer. The chemical and the physical behavior of the plasma and its emission near the cathode and anode are very different from that of the positive column of the discharge[5]. Therefore, only the light from the capillary region consisting of the positive column is collected by the spectrometer.

Many other experiments with the glow discharge have been performed using copper or other metal electrodes[6]. However we found that stainless steel electrodes are superior in terms of stability and were used throughout the experiments. Copper electrodes sputtered much more easily and left Cu deposits on the discharge wall after a short period of operation.

The windows are epoxied to the discharge cell using Torrseal (Varian Co.). The gas mixture is introduced symmetrically via small holes located

near the end of the tube as shown in Fig. (1). The distance between the two inlet holes define the length of the plasma which is represented as  $L_3$  in the Fig. (2). This arrangement ensures that the pressure in the capillary plasma is uniform. The pressure was measured at the center, marked  $P$  in Fig. (1), of the capillary with a MKS #122AA capacitance manometer.

The discharge tube was evacuated by mechanical pump Sargent-Welch model # 1397 (pumping speed: 500 lpm) through the side arms of the discharge cell, where the electrodes are located. The discharge current is supplied by Hewlett Packard power supply DC#6522A and was maintained at 30mA throughout the experiment, which corresponds to a current density of  $0.95\text{A}/\text{cm}^2$  in the capillary.

To achieve our comparisons between the SAFTS and the DSFTS methods, we have performed two sets of experiments. The experimental setup for the self absorption experiment is shown schematically in Fig. (1). The light from the discharge cell is collected by the spectrometer with and without mirror M1. The mirror, whose reflectivity as a function of frequency is known, is aligned along the axis connecting the central part of the discharge tube and the aperture of the spectrometer so as to reflect the light from the discharge back into the cell. An iris was placed in front of the discharge cell with an adjusted diameter at 2mm to ensure that only light from the capillary is collected. After the iris diaphragm, a 1.5 inch diameter 12cm focal length quartz lens was used to maximize the light reaching the spectrometer.

Fig. (2) shows the physical parameter for the experiment.  $L_3$  is the length of the plasma defined by the two inlet holes at the end.  $L_2$  and  $L_4$  are the short, equal distances between the end of the plasma and the windows W1

and W2 respectively.  $L_1$  is the distance from the end of the discharge cell to the mirror and  $L_5$  is the distance from the front end of the discharge tube to the iris.  $L_6$  and  $L_7$  are the distances between the iris and the lens and between the lens and the aperture on the spectrometer, respectively. The actual values in cm for the parameters in all our experiments are as follows:  $L_1=0.5$ ,  $L_2=1.0$ ,  $L_3=3.0$ ,  $L_4=1.0$ ,  $L_5=19$ ,  $L_6=55$  and  $L_7=14$ .

For the DSFTS measurements, the mirror is removed and light from the central part of the capillary region is collected and collimated by lens  $f_1$  ( $F=40\text{cm}$  and then focused by another lens  $f_2$  onto the entrance aperture of the spectrometer. The lens  $f_2$  has a diameter of 5 cm with focal length of 25 cm. An iris is also placed at the end of the capillary tube as an aperture. Alignment of the optical axis is checked by a He-Ne laser beam which is installed at the detector port of the spectrometer. The laser beam passes through the centers of all optical elements from the detector side of the spectrometer to the emission source. To additionally insure that the light from the center of the discharge tube is correctly imaged to the spectrometer, a thin wire is placed at the center of the capillary and the discharge cell position adjusted until a clear image is seen at the spectrometer aperture. A Bruker IFS-120HR Fourier transform spectrometer is used to collect and record the emission from the positive column which is physically the same discharge cell as is used in the self-absorption experiments. As we have described previously[7, 8, 9] we record paired FTS spectra with opposite discharge polarities but with otherwise identical discharge conditions. Doppler shifts are then determined by comparing the position of lines in the two spectra ( $\Delta\nu$ =half the distance between the two oppositely shifted lines). For these

experiments the spectrometer instrumental resolution was  $0.03 \text{ cm}^{-1}$ .

## 3 Theory

### 3.1 Self absorption method

For the density determination by the self absorption technique, we have adopted the approach used by others[10, 11, 12]. Consider the experimental arrangement shown in Fig. (2) in which the intensity is  $I_0(\nu)$  for photons of frequency  $\nu$ , emitted along the axis from a plasma region at position  $z$  with thickness  $dz$ . The photon intensity after travelling a distance,  $z$ , filled with absorbing atoms, becomes[13]

$$I_z(\nu) = I_0(\nu) \exp(-K_{12}(\nu)z) \quad (1)$$

where  $K_{12}(\nu)$  is the absorption coefficient for a transition between states 1 and 2 at frequency  $\nu$ .

The net radiation at an aperture along the  $z$  axis is not only determined by the absorption but also by the solid angle defined by

$$\Omega(z) = \frac{\Theta}{(z + L_4 + L_5)^2} \quad (2)$$

where  $\Theta$  is the cross section of the aperture of the iris. The light passing through the iris is focused into the spectrometer by the collection lens. If we integrate over the frequency and the position in the plasma, the total amount of light ( $I_F$ ) reaching the spectrometer, is given in the absence of the mirror, by

$$\begin{aligned}
I_F &= \int_0^\infty \int_0^{L_3} F_2(\nu) I_z(\nu) \Omega(z) dz d\nu & (3) \\
&= \int_0^\infty \int_0^{L_3} (F_2(\nu) I_0(\nu) \exp(-K_{12}(\nu)z)) \frac{\Theta}{(z + L_4 + L_5)^2} dz d\nu \\
&= F_W \Theta \int_0^\infty \int_0^{L_3} \frac{I_0(\nu) \exp(-K_{12}(\nu)z)}{(z + L_4 + L_5)^2} dz d\nu
\end{aligned}$$

where  $F_2(\nu)$  is the transmittance of the window, W2, at frequency  $\nu$ . The  $\nu$  dependence of  $F_2(\nu)$  is small over the region considered and is neglected in the last equality where  $F_2(\nu) \equiv F_W$ .

When the mirror (M1) is in place, the amount of light reaching the spectrometer increases. The additional amount of light,  $I_R$ , reflected by the mirror can be calculated by recognizing the fact that the light that originated at a point  $+t$  from the mirror is reflected by the mirror as if it originated at a point  $-t$ . (see Fig. (2)).

By following the same logic as above, the reflected light intensity  $I_R$  reaching the spectrometer can be written in terms of  $I_z^r(\nu)$ , and its solid angle  $\Omega^r(z)$ . Ergo, the intensity,  $I_R$ , is

$$\begin{aligned}
I_R &= \int_0^\infty \int_0^{L_3} [F_W^3 F_M I_z^r(\nu) \Omega^r(z)] dz d\nu & (4) \\
&= F_W^3 F_M \Theta \int_0^\infty \int_0^{L_3} \left[ \frac{I_0(\nu) \exp[-K_{12}(\nu)(2L_3 - z)]}{[2(L_1 + L_2 + L_3) + L_4 + L_5 - z]^2} \right] dz d\nu
\end{aligned}$$

where  $F_M$  is the reflectivity of the mirror and we have assumed the transmittance of each window is  $F_W$ , since they are of identical size and material. In the last equality,  $\Omega^r(z)$  is easily obtained from the equation for  $\Omega(z)$  by considering the geometry illustrated in Fig. (2).

Since Doppler broadening dominates in this experiment, the intensity distribution,  $I_0(\nu)$ , can be written as a Gaussian of the form

$$I_0(\nu) = I_0(\nu_0) \exp(-x^2) \quad (5)$$

where

$$x = \frac{2\sqrt{\ln(2)}(\nu - \nu_0)}{\Delta w} \quad (6)$$

and  $\Delta w$  is the line width(full width at half maximum).

In a similar way the frequency dependence of the absorption coefficient  $K_{12}(\nu)$  can be expressed

$$K_{12}(\nu) = K_{12}(\nu_0) \exp(-x^2) \quad (7)$$

where the absorption coefficient  $K_{12}(\nu_0)$  at the line center is given by([13])

$$K_{12}(\nu_0) = \lambda_{12}^3 \left( \frac{A_{21}}{\bar{u}} \right) \left( \frac{g_2}{g_1} \right) N_r \quad (8)$$

Here  $\lambda_{21}$  is the transition wavelength,  $g_i$  the degeneracy of state  $i$ ,  $\bar{u}$  the thermal velocity, and  $A_{21}$  the spontaneous emission coefficient..  $N_r$  is the reduced number density which is related to the lower state density  $N_1$  by

$$N_r = N_1 \left( 1 - \frac{g_1 N_2}{g_2 N_1} \right) \quad (9)$$

When the lower state is long-lived i.e., a ground or metastable state, the second term of the right hand side of the equation usually becomes negligible

and  $N_r \approx N_1 \equiv N$ . We will therefore use reduced number density and lower state density without distinction hereafter.

Using Eqs. (3), (4), (5) and (7), the intensity ratio  $I_R/I_F$  can be given

$$\frac{I_R}{I_F} = F_W^2 F_M \frac{\int_0^\infty \int_0^{L_3} e^{-x^2} e^{[-K_{12}(\nu_0)e^{(-x^2)}(2L_3-z)]} / (2(L_1 + L_2 + L_3) + L_4 + L_5 - z)^2 dz d\nu}{\int_0^\infty \int_0^{L_3} e^{-x^2} e^{[-K_{12}(\nu_0)e^{(-x^2)}z]} / (L_4 + L_5 + z)^2 dz d\nu} \quad (10)$$

It is useful to define the quantity,  $R$ , by

$$R = \frac{I_R}{I_F F_W^2 F_M} \quad (11)$$

Since numerical values are known for  $F_W$  and  $F_M$ ,  $R$  can be determined directly from experimental measurements of  $I_F$  (without  $M1$ ) and  $I_F + I_R$  (with  $M1$ ).

### 3.2 Doppler Shift Method

Theoretical details of the Doppler shift method for the density determination have been given in the preceding paper[1]. Therefore only the elements of the theory directly applicable to our experimental measurements are given here. The observed Doppler shift  $S = \left\langle \frac{\Delta\nu}{\nu} \right\rangle$ , under a given set of trapping conditions can be written

$$S = \left\langle \frac{\Delta\nu}{\nu} \right\rangle = \beta \left\langle \frac{\Delta\nu}{\nu} \right\rangle_0 \quad (12)$$

where  $\langle \frac{\Delta\nu}{\nu} \rangle_0$  represents the Doppler shift without radiation trapping. The quantity  $\beta$  is known as the diminuation factor and is directly measured experimentally by determining  $\langle \frac{\Delta\nu}{\nu} \rangle_0$  for an untrapped transition and then in the same sample  $\langle \frac{\Delta\nu}{\nu} \rangle$  for the transition that is trapped by the state of interest. If two transitions (denoted with and without a prime) suffer equal trapping ( $\beta = \beta'$ ) in the same volume, then the absorption coefficients,  $K_{12}$  and  $K'_{12}$ , must be equal and we have

$$\lambda_{12}^3 \left( \frac{A_{21}}{\bar{u}} \right) \left( \frac{g_2}{g_1} \right) N = \lambda_{12}'^3 \left( \frac{A'_{21}}{\bar{u}} \right) \left( \frac{g_2'}{g_1'} \right) N' \quad (13)$$

Eq. (13) allows the determination of the density,  $N'$ , providing the density  $N$  and the numerical factors (defined after Eq. (8)) are known, which will usually be the case for an atomic transition. Eq. (13) holds whether there is one or multiple transitions from the upper level 2, if  $A_{21} \gg A_{2i} (i \neq 1)$ .

## 4 Results and Discussion

A series of experiments have been performed to compare measurements of the metastable  $2s^3S_1$  He densities in the plasma with the newly-proposed DSFTS method to those obtained by the more traditional SAFTS technique. In the following, we describe the results of our SAFTS and DSFTS measurements, and then compare the concentrations obtained by the two techniques.

## 4.1 SAFTS concentration measurements

For the SAFTS experiments, metastable  $2s^3S$  He concentrations were monitored by the transition  $2s^3S - 3p^3P(388.9 \text{ nm})$  with absorption coefficient,  $K_{12} = 0.2023 \times 10^{-12} N_r \text{ cm}^{-3}$ . One can obtain an  $R$  value, from experimental measurements of  $I_R$  and  $I_F$  and Eq. (11) using  $F_M = 0.90$  and  $F_W = 0.96$ ,

$$R(388.9 \text{ nm}) = 1.21 \frac{I_R}{I_F} \quad (14)$$

The  $R$  value in turn can be related to the metastable He concentration using Eq. (8) and performing numerically the integrations in Eq. (11). The result of the evaluation is given in Fig.(3) where  $R$  is plotted vs metastable He concentration.

Fig. (4) showed the experimentally determined values of  $R$  for the 388.9 NM transition from the measurement of  $I_F$  (with the mirror) and  $I_T$  (without the mirror) plotted against total He pressure in the discharge. By comparison of Fig. (3) and Fig. (4), a He metastable density can be determined for each discharge condition.

As a test of the validity of our theoretical analysis and the resulting plot of Fig. (4), we have monitored another transition,  $2p^3P - 6s^3S(386.8 \text{ nm})$  with  $K_{12} = 0.0055 \times 10^{-12} N_r \text{ cm}^{-3}$ . This transition should be free of self-absorption due to a combination of low oscillator strength and very small population in the  $N_r$  state,  $2p^3P$ . Using  $F_W = 0.97$  (for this wavelength), and Eq. (11), we obtain a theoretical value of  $R = 0.58$  for our geometry. This compares well with an experimentally measured value of 0.56(2) independent of discharge condition for the untrapped  $2p^3P - 6s^3S$  transition. The marginal

discrepancies in these two results can be accounted for by assuming less than perfect optical alignment. While not of real significance, our reported metastable densities are determined using the experimentally determined  $R$  without any correction for slight optical misalignment.

## 4.2 Doppler shift concentration measurements

To determine metastable concentration via the DSFTS method, the average number of radiation trapping cycles needs to be determined by finding the ratio of the Doppler shift of the transition with and without radiation trapping, i.e., determining  $\beta$ . If two transitions show the same  $\beta$  value ( $\beta = \beta'$ ), the transitions must have the same absorption coefficients,  $K = K'$ . Thus if we can measure  $\beta = \beta'$  for any two transitions observed from the same plasma volume, we can determine  $N'$  for the metastable  $2s^3S$  state provided we know  $N$ . In a He atom system, radiation trapping would be expected to occur between the ground state and excited states optically connected to it. Since the ground state density is easily determined by a simple pressure measurement and is essentially unaffected by the discharge we choose it for  $N$ .

### 4.2.1 Ground State Radiation Trapping

Fig. (5a) illustrates the transitions that we choose for observing radiation trapping by the ground  $1^1S_0$  state with the emitting upper level  $3p^1P_1$ . The  $3p^1P_1$  state is optically connected to both the ground and the  $2s^1S_0$  state. This constitutes a three-level system with radiation trapping occurring on

the  $3p^1P_1-1^1S_0$  transition which results in a reduction of the Doppler shift of the  $3p^1P_1-1^1S_0$  emission. Fortunately, the radiative decay rate<sup>14</sup> is  $5.66 \times 10^8$  for  $3p^1P_1-1^1S_0$  and  $1.34 \times 10^7$  for  $3p^1P_1-2s^1S_0$ , satisfying the condition  $A_{21} \gg A_{23}$ . As shown previously[1] this means that the observed Doppler shift diminution on the  $3p^1P_1-2s^1S_0$  transition is determined by the radiation trapping of the ground state *via* the  $3p^1P_1-1^1S_0$  transition.

The  $3p^1P_1-1^1S_0$  emission is in the VUV frequency region (53.7 nm), which is not observable with our spectrometer, while the  $3p^1P_1-2s^1S_0$  transition lies in the easily accessible visible region (501.6 nm). These transitions provide a good example of how a three-level system provides convenience for a study of radiation trapping. Experimentally, we measured the Doppler shifts of the  $3p^1P_1-2s^1S_0$  He emission, and for comparison, the shift of the  $3d^1D_2-2p^1P_1$  emission, whose Doppler shift is undiminished by radiation trapping. The two emission wavelengths (501.6 nm vs. 492.2 nm) are close enough that they can easily be obtained under identical spectrometer conditions.

The measurement was accomplished for discharges of  $H_2/He$  mixtures with the  $H_2$  pressure fixed at 0.4 torr while varying the He partial pressure from 2-20 mtorr. The  $H_2$  is necessary to maintain the discharge since the He partial pressures must be chosen to give comparable radiation trapping to that observed for the metastable state in the discharge. Although the  $2s^1S_0$  state is also a metastable, at these He partial pressures the density of the  $2s^1S_0$  state is extremely low and radiation trapping on the  $3p^1P_1-2s^1S_0$  transition is negligible. Fig. (6) gives the results of our measurements, showing that while the Doppler shift of the  $3d^1D_2-2p^1P_1$  transition remains almost constant, that of the  $3p^1P_1-2s^1S_0$  transition decreases rapidly with

increasing He partial pressure, i.e., with radiation trapping as the  $1^1S_0$  density increases. Fig. (7) shows the value of  $\beta$ , deduced from Fig. (6), plotted vs partial pressure of He.

#### 4.2.2 Metastable State Radiation Trapping

Under discharge conditions where the density of metastable He( $2^3S_1$ ) is appreciable, radiation trapping on the transitions between the metastable state  $2^3S_1$  and more highly excited triplet states is also observable. In a second set of DSFTS experiments in a pure He discharge at 0.4 torr, we have chosen, as shown in Fig. (5b), the emissions  $2^3P_0$ - $2^3S_1$  and  $3^3S_1$ - $2^3P_0$  for observation. In this case, we have a simple two-level system with radiation trapping between  $2^3P_0$  and  $2^3S_1$  and a reduction of the Doppler shift of the same transition. The Doppler shift of the  $3^3S_1$ - $2^3P_1$  transition, which is not affected by the trapping, serves as a reference. The two lines again have wavelengths, respectively, of 1083 nm and 706.5 nm, in proximate spectral regions. We choose a triplet transition now for a reference for  $\left\langle \frac{\Delta\nu}{\nu} \right\rangle_0$  since it has previously been shown[9] that singlet and triplet transitions show slightly different intrinsic Doppler shifts in the discharge.

The experimentally measured Doppler shifts of the two transitions are shown in Fig. (8) and their calculated Doppler shift ratio  $\beta$  is shown in Fig. (9). Fig. (9) shows that the ratio  $\beta$  decreases sharply in the low pressure region, but it remains approximately constant at pressures higher than 1 torr.

### 4.3 The observed metastable state densities

To obtain the  $2s^3S_1$  metastable density at a given discharge condition by the DSFTS method one matches the  $\beta$ 's in Fig. (7) and Fig. (9) to find a ground state He pressure which gives an equivalent Doppler shift. One then uses Eq. (13) and the atomic transition probabilities to derive, at equal  $\beta$ , the following relationship, between the metastable density  $N'(2s^3S_1)$  and the (ground  $1s^1S_0$  state) pressure  $p$  in the He discharge (Fig. (7)).

$$N'(2s^3S_1) = 0.068N(1s^1S_0) = 1.0 \times 10^{12} p(\text{mtorr}) \quad (15)$$

For this result the temperature of the discharge is taken to be 650K (from the measured Doppler-broadened linewidth) and that temperature is used to convert number density to pressure.

One then uses this pressure and Eq. (15) to calculate the density of the  $2s^3S_1$  state which is plotted in Fig. (10) vs total He discharge pressure. As discussed earlier, the He metastable density can be independently determined by the SAFTS method, by reading an experimental  $R$  value from Fig. (4) and converting it to a concentration via Fig. (3).

Fig. (10) plots vs total He pressure the metastable densities obtained by both the DSFTS and SAFTS experiments and shows good agreement between the densities obtained by the two methods. The metastable state densities can be seen to gradually increase with total pressure, starting from  $1.3 \times 10^{12}$  atoms/cm<sup>3</sup> at 0.4 torr and reaching a maximum of  $\approx 6 \times 10^{12}$  atoms/cm<sup>3</sup>, a value which appears roughly constant in the  $\approx 1$ -5 torr region.

Our present experimental measurements of metastable densities are not

only self-consistent using the SAFTS and DSFTS methods, but they are also in reasonably good agreement with data taken under similar discharge conditions by Brown and Dunn.[14] Their experiments used a 50% larger 3mm diameter cell with a slightly larger current density of 1.0A/cm<sup>2</sup>. They observed a maximum metastable density at 2 torr He of  $9 \times 10^{12}$  atoms/cm<sup>3</sup>, with a slow decrease to higher and lower pressures. The approximately 50% increase in He metastable density compared to the present experiments is probably attributable to slightly increased production by the higher current density and significantly decreased quenching of metastables in the larger diameter cell.

## 5 Conclusion

We have determined the densities of the metastable state  $2s^3S_0$  He by two different techniques, DSFTS and SAFTS. By selecting the appropriate transitions, we have found that the DSFTS method can be a useful and reliable technique to determine the densities of states giving rise to observable radiation trapping.

For measuring the densities of atoms or molecules via the DSFTS method the following criteria should be met:

- i) The molecule/atom should be light enough in mass to show appreciable Doppler shift under the given source conditions. Clearly this criteria is a strong function of the source but may also be dependent upon the spectrometer's resolution

- ii) The signal should be strong enough to allow the measurement of the Doppler shift with reasonably high precision.
- iii) There must be an untrapped reference transition to determine the magnitude of the Doppler shift with and without trapping and hence calculate  $\beta$ .

The Doppler shift method can be especially useful in measuring the population densities of atomic or molecular states when other methods are not suitable. A good example might be astrophysical plasmas where other techniques cannot be employed. However, any situation where access to the sample is restricted or prohibited, but from which observable emission is obtained, might be a candidate for the DSFTS technique. A laboratory example of the latter would be geometrically constricted discharge cell such as was used to study dissociation reactions[15].

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## Figure Captions

1. Schematic representation showing the discharge cell and the optical setup, which includes the mirror ( $M1$ ), windows ( $W1$  and  $W2$ ), and the collection lens. The  $z$  axis coincides with both the spectrometer axis and the plasma electric field. Gases are introduced through small holes at both ends of the horizontal capillary tube and the pressure is measured at point  $P$ , which is at the center of the discharge tube. The region enclosed by the marked dotted lines is shown in more detail in Fig. (2).
2. Detailed diagram of the experimental setup showing details of plasma region and the definitions of the several important geometrical parameters, which include the mirror ( $M1$ ), the capillary part of the discharge tube defined by the two windows ( $W1$  and  $W2$ ) and several distances represented by  $L_i$  ( $i = 1, 2, 3, \dots$ ) (see text). The shaded area, marked as  $L_3$ , contains the positive column of the discharge. The image of the discharge is formed by the reflective mirror  $M1$  and is shown with dotted lines behind the mirror. The image behaves like an additional light source. The solid angle  $\Omega(z)$  is defined by the distance from the light source to the iris.
3. Theoretical  $R$  values vs absolute metastable density (units of  $10^{11}$  atoms/cm<sup>3</sup>) from Eqs. (8) and (11). The strong distance dependence of the solid angle  $\Omega$  limits the maximum  $R$  to about 0.6 in this experimental arrangement (see text for details).

4. The measured  $R$  value of the  $2s^3S - 3p^3P$  transition vs ground state He pressure in Torr.
5. Schematic diagram showing the energy levels of He and the transitions monitored in the DSFTS. Panel (a) illustrates ground state trapping and (b) illustrates metastable state trapping.
6. The measured Doppler shift,  $S$ , in ppm, of the  $3^1P - 2^1S$  and  $3^1D - 2^1P$  transitions for different He partial pressures in a 0.4 torr H<sub>2</sub> discharge. The former is the transition suffering radiation trapping and the latter is free of trapping.
7. The diminution factor ( $\beta$ ) for the  $3^1P - 2^1S$  transition at different He partial pressures in a 0.4 torr H<sub>2</sub> discharge. The curve is a fit of the data points to the empirical formula,  $\beta = 0.6794(1/6)^{0.1272P} + 0.3091$  where  $P$  is the He partial pressure in mtorr.
8. The measured Doppler shift,  $S$  in ppm, of the  $2^3P - 2^3S$  and  $3^3S - 2^3P$  transitions. The former represents the transition suffering radiation trapping and the latter is from the radiation-trapping-free transition.
9. The diminution factor( $\beta$ ) for the transition  $2^3P - 2^3S$  vs total He pressure.
10. The density in units of  $10^{12}$  atoms/cm<sup>3</sup> of the metastable He ( $2^3S$ ) as a function of total He pressure. The solid circles are the data points determined by the SAFTS method using the results displayed in Figs.

(4), (5) and (4) and the open circles are by the DSFTS method via from Eq.(15) and the data of Fig. (7).

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