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Emission spectrum of a depleted neon–mercury positive column

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Under certain discharge conditions, radial cataphoresis causes significant mercury depletion in a low-pressure neon–mercury positive column. This depletion can result in the addition of neon radiation to the emission spectrum of the column. The addition of neon radiation can be used to change the color of fluorescent lamps. In order to investigate the radial cataphoresis process, we performed spatially resolved emission measurements. For the relevant spectral lines of mercury and neon, the emission coefficient is determined, along with the density of the upper state of the corresponding transition. Absorption measurements are performed to check the amount of self-absorption of the spectral lines. We present emission and density profiles for various discharge conditions. The obtained results can be understood using an approximate description of the radial cataphoresis process. © 2000 American Institute of Physics. [S0021-8979(00)03916-5]

I. INTRODUCTION AND THEORY

In the past, several authors proposed fluorescent lamps capable of changing color during operation; see, for instance, the papers by Itatani et al.\textsuperscript{1} and by Ravi and Maya.\textsuperscript{2} In a recent paper, we presented a way of changing the color of a fluorescent lamp.\textsuperscript{3} This method is based on the depletion of mercury in the center of a neon–mercury positive column. We have shown that it is possible to add neon radiation to the emission spectrum of the positive column of a low-pressure neon–mercury discharge. In this article we will investigate the emission spectrum of such a discharge more thoroughly. We performed spatially resolved emission spectroscopy on a depleted neon–mercury positive column.

A fluorescent lamp is filled a few milligrams of mercury and a noble gas or a mixture of noble gases. The mercury pressure is approximately 1 Pa. The temperature of the coldest part of the discharge tube determines this pressure. The noble gas pressure is a few hundred Pa. Under these conditions, mercury dominates the positive column of the discharge. The rare gas only acts as a buffer gas. The main function of the buffer gas is to limit the mean free path of the electrons. In the mercury rare-gas positive column, there is always some depletion of ground state mercury. This is due to the process of radial cataphoresis. This radial cataphoresis is the net transport of ground state mercury to the walls of the discharge. Ambipolar diffusion results in a flux of mercury ions and electrons to the walls. At the walls, these ions and electrons recombine. The neutral mercury that is produced by this recombination diffuses back into the bulk region of the discharge. However, this diffusion is associated with a much smaller diffusion coefficient than ambipolar diffusion. Therefore, there will be a net transport of mercury to the wall, which builds up a gradient in the neutral mercury density directed to the wall. When this gradient is large enough, the flux of neutral mercury $\Gamma_0$ from the wall will be in equilibrium with the ambipolar flux $\Gamma_a$. By equating the two diffusional fluxes we obtain

$$\nabla(D_a \cdot n_+) = -\nabla(D_0 \cdot n_0).$$

(1)

In cylindrical coordinates, this expression results in

$$n_+(r) = \frac{1}{D_a(r)} \cdot [D_0(r) \cdot n_0(r) - D_0(r) \cdot n_0(0)].$$

(2)

where we assumed the mercury ion density at the wall to be equal to zero, i.e., we have total recombination at the wall. The mercury density at the wall is fixed. We assume the wall to be the coldest part of the discharge, the cold spot. Expression (2) can be rewritten in the definition for the degree of mercury depletion $\chi$:

$$\chi = [1 - \frac{T_0(R)}{T_0(0)}] + \frac{T_0(R)}{T_0(0)} \cdot \left[ e^{-\frac{\mu_+}{\mu_0} \cdot \frac{1}{p_{Hg}} \cdot \hat{T}_e \cdot n_+(0)} \right].$$

(3)

In deriving this expression, we used the Einstein relation for the diffusion coefficients and the ideal gas law for mercury. In expression (3), $\mu_+$ is the mercury ion mobility, $\mu_0$ is the mobility of neutral mercury, $\hat{T}_e$ is the electron temperature expressed in eV, $T_0$ is the heavy particle temperature in K, and $p_{Hg}$ is the mercury pressure at the wall, as determined by the wall temperature. The first term in expression (3) results from the nonuniform temperature profile in the tube. This “depletion” due to temperature differences is also present in the neon atom density profile.

It is clear from expression (3) that an increase in the mercury ion density or the electron temperature will result in a higher degree of depletion. On the other hand, when the mercury pressure is high, then the degree of depletion will be low. In physical terms, the first conclusion results from the fact that a higher ambipolar flux has to be compensated for by a higher degree of depletion. The second conclusion re-
results from the fact that at higher mercury pressures the amount of mercury on the tube axis is high in comparison with the amount transported to the walls. The degree of depletion is not an explicit function of all the relevant discharge parameter. The degree of depletion is an implicit function discharge parameter like the current and the neon pressure. Their influence is felt in the electron density and the electron temperature. We need a complex discharge model to calculate this influence. However, the trends in the electron density and temperature were measured by Verweij in a 36 mm diam argon–mercury discharge. Qualitatively, the neon–mercury discharge is similar to the argon–mercury discharge. Therefore, we can assume that the trends Verweij found also hold for the neon–mercury discharge. The following trends are important in our range of experimental conditions:

1. the electron density is proportional to the current;
2. the electron density is approximately constant with changing mercury pressure;
3. the electron density increases with increasing argon pressure;
4. the electron temperature is approximately constant in the current range in which we investigate the discharge;
5. the electron temperature decreases with increasing mercury pressure;
6. the electron temperature decreases with increasing argon pressure.

When the mercury density is low, then the energy loss to inelastic collisions of electrons with mercury will be smaller than at a high mercury density. This results in an increase of the electron temperature. This increase enables the electrons to excite neon atoms, resulting in neon emission from the discharge column. In this article we describe an investigation of the spatially resolved emission spectrum of the mercury–neon positive column.

II. EXPERIMENTAL SETUP

We now describe the experimental setup we used for measuring the spatially resolved emission spectrum of the neon–mercury positive column. In Sec. II A, the emission measurements are described. In Sec. II B we discuss the absorption measurements done in order to check whether the spectral lines we measured are optically thin.

A. Emission measurements

The setup consists of a discharge tube, a diaphragm, two lenses, an optical fiber, and an optical multichannel analyzer. Figure 1 shows the setup schematically. The discharge tube diameter is 26 mm. It is filled with 5 mg mercury and neon at 3, 10, or 15 mbar. The temperature of the discharge tube is controlled by a transparent water jacket. The temperature of the inner wall of the discharge tube at the position of the water jacket determines the mercury pressure in the tube. However, we can only control the outer wall temperature. Since there is some heat transport through the glass tube, the inner wall temperature will be somewhat higher than the outer wall temperature. This temperature difference is of the order of 0.5 °C. The water jacket is connected to a Haake FE thermostat bath. The water jacket is a 80 mm diam Perspex cylinder. The discharge is sustained by a Philips BRC 411/01 35 kHz ballast.

The diaphragm has a diameter of 4 mm. It determines the solid angle of the emission that is captured by the detector. The focal distance of the first lens is 200 mm. The axis of the discharge tube is positioned in the focal plane of this first lens. The second lens has a focal distance of 300 mm. The aperture of the optical fiber is positioned in the focal plane of this second lens. The aperture is circular, with a diameter of 1 mm. This optical system composed of a diaphragm and two lenses captures the radiation emitted in the detection cone as shown schematically in Fig. 1. It makes an image of this captured radiation on the aperture of the optical fiber. The solid angle in which the radiation is detected is 3 × 10^{-4} sr. The spatial resolution in the focal plane is 0.67 mm. However, since the detection cone widens when moving away from the focal plane, the real spatial resolution is approximately 1 mm. The position of the discharge tube can be changed in order to measure a lateral profile of the plasma emission. The plasma emission is measured through the transparent water jacket. The optical axis is perpendicular to the axis of the tube. On the one hand, in the plane constructed by the optical and the tube axis, the solid angle and the image size do not change. On the other hand, in the plane perpendicular to the tube axis the water jacket acts as a negative lens. However, it can be shown that the absolute emission measurements are not affected by this negative lens; see the Appendix.

The optical multichannel analyzer consists of an EG&G Princeton Applied Research 1461 detector interface and a
coefficient tral lines. We determined the radial profile of the emission of mercury and the neon atom, along with these measured spectral lines. Figure 2 shows the energy scheme of the measured spectrum is integrated in a 5 nm band around the relevant spectral lines. The transitions are labeled with the corresponding wavelength.

The intensity calibration is performed by replacing the discharge tube with a calibrated Osram Wi 17/G tungsten ribbon lamp. During the calibration, the tungsten ribbon is positioned in the focal plane of the first lens. The optical system is not changed after the calibration procedure, except for the water jacket that is placed around the fluorescent lamp. The transmission of the lamp with this water jacket is measured in a separate experiment using a tungsten ribbon lamp and a helium–neon laser. For these measurements, we turned the fluorescent lamp off. It is difficult to get an absolute value for the transmission of the water jacket using a tungsten ribbon lamp since the jacket acts as a strong negative lens. Therefore, we measured a normalized transmission profile at the tube axis with the tungsten ribbon lamp, and scaled this profile to the measurement with the helium–neon laser. This transmission profile can be used to correct the emission measurements. However, in the transmission measurements, Fresnel reflection losses are present at the surfaces. On the other hand, in the emission measurements these reflection losses are not present. Although the radiation emitted in the direction of the detector is partly reflected at the tube and the water jacket, this reflection has no influence. The reflection loss is counterbalanced by the extra contribution of the radiation emitted in the opposite direction, which is reflected in the direction of the detector. It can be shown that this holds for all the lateral positions. We corrected the transmission profile of the water jacket for these reflection losses.

From the measured spectra, the line-of-sight integrated intensity for several spectral lines is determined. The measured spectrum is integrated in a 5 nm band around the relevant spectral lines. Figure 2 shows the energy scheme of the mercury and the neon atom, along with these measured spectral lines. We determined the radial profile of the emission coefficient \( \varepsilon_{yi}(r) \) from the lateral profile of the line integrated emission coefficient \( I(y) \) using two different methods. In the first method, we used a fifth order polynomial function as a model for the radial profile. The lateral profile that corresponds to this radial profile is calculated using the following Abel type equation:

\[
I(y) = 2 \int_{y}^{R} \varepsilon(r) \frac{r}{\sqrt{r^2 - y^2}} \, dr.
\]

This lateral profile is then fitted to the measurements. We assumed the intensity gradient at the cylinder axis equal to zero. In the second method, we used expression (4) to obtain the radial profile of the experimental data directly. The noise was reduced by applying a fast Fourier transform (FFT) filter to the raw data, which eliminates spatial structures narrower than 1 mm. Using the transition probabilities given in the National Institute of Standards and Technology database, we can calculate the density \( n_k \) of the levels from which the radiation originates. In order to do this, we use

\[
n_k = \frac{4 \pi \lambda}{hc \cdot \Delta \varepsilon_{ki}} \cdot \varepsilon_{ki},
\]

where \( \lambda \) is the wavelength of the transition. Note that \( \varepsilon_{ki} \) is expressed in W/sr m\(^3\), so the density is expressed in m\(^{-3}\). The uncertainty in the transition probabilities is 10% for the lines of neon and 10%–50% for the lines of mercury.

In order to visualize the emission in the lamp, we recreated the radial profile of the total visible spectrum by using the radial profiles of the emission coefficients for the spectral lines of mercury and neon. From the constructed spectra, the chromaticity coordinates \( x \) and \( y \) are calculated. These chromaticity coordinates can be transformed into red, green, and blue (RGB) values that can be used to create a bitmap containing the radial profile of the color of the visible emission. The chromaticity coordinates of the red, green, and blue color are equal to the ones used in the European PAL television standard. The RGB values are maximized, conserving their mutual ratios. Therefore, the cross sections of the tube we construct do not contain intensity information.
B. Absorption measurements

It is important to realize that we cannot use the Abel transformation as given in expression (4) when the spectral lines are not optically thin. In order to check whether the spectral lines we used are optically thin, we measured the transmission of one lamp for the radiation produced by a second, similar lamp. Both lamps are operated under the same experimental conditions using a Philips BRC 411/01 ballast, and their temperature is controlled by the same thermostat bath. A chopped beam of 1 mm diameter, produced by the first (source) lamp is guided through the second (probe) lamp. We used a Princeton Applied Research model 191 variable speed chopper at a frequency of 1.8 kHz. The transmission is measured at \( y = 0 \), i.e., the axis of the lamp. The radiation is detected by a Radio Corporation of America type 1P28 photomultiplier. This photomultiplier is mounted on an Oriel model 7240 monochromator. The chopped radiation produced by the source lamp is discriminated from the radiation produced by the probe lamp by an EG&G Princeton Applied Research model 5209 lock-in amplifier. The transmitted radiation when the probe lamp is on is divided by the transmitted radiation when the probe lamp is off, giving the transmission of the plasma. When this transmission is high enough, then the line is optically thin. When the absorption in the tube is linear, then the maximum error we make in the radial profile of the emission coefficient is one minus the square root of the measured transmission.

We measured the transmission for some of the spectral lines of mercury and neon in a lamp with a neon pressure of 10 mbar, cold-spot temperatures of 18 and 30 °C, and an electric current of 400 mA. We will start with the mercury lines at a cold-spot temperature of 18 °C. Table I shows the measured transmission of several spectral lines of the mercury atom. It is clear that the spectral lines corresponding to the transitions to the resonant levels \( 6^1P_1 \) (576.96 nm) are optically thin. The two transitions to the metastable levels (546.07 and 404.66 nm) are not optically thin. However, the density of the \( 7^3S_1 \) level can be obtained from the 435.83 nm line. The 546.07 and 404.66 nm lines originate also from this \( 7^3S_1 \) level, so we can construct these lines from the \( 7^3S_1 \) density. The density of the resonant and the metastable levels increases with increasing electric current through the lamp. Therefore, we can assume that the transitions to the resonant levels are optically thin for currents lower than 400 mA. At a cold-spot temperature of 30 °C, the situation is quite different. Only the transitions resulting in the \( 6^1P_1 \) level are optically thin. The density of the \( 7^3S_1 \) level cannot be obtained at this cold-spot temperature. Based on calculations by Vriens et al., who used the results of Koedam et al., we can assume that, at different neon pressures and a cold-spot temperature of 18 °C, the transitions to the \( 6^1P_1 \) level are optically thin.

The absorption of the neon lines is measured at a cold-spot temperature of 18 °C. Table I also shows the transmission for several neon lines. We used the Paschen notation for identification of these lines. Figure 3 shows the measured transmission as a function of

\[
\kappa = A_{ki} \cdot \lambda^2 \cdot \frac{g_s}{g_i},
\]

which scales with the absorption coefficient. In this expression, \( A_{ki} \) is the transition probability, \( \lambda \) is the wavelength of the transition, and \( g_s \) and \( g_i \) are the statistical weights of the upper and the lower levels, respectively. We separated the spectral lines into four groups. These groups correspond to the four lower levels of the transitions, either \( 1S_2, 1S_3, 1S_4 \), or \( 1S_5 \). For every lower level, we measured at least one spectral line. We assumed the absorption coefficient to correlate positively with \( \kappa \). Therefore, we can give a maximum value for the absorption of lines which have a lower \( \kappa \) than

---

<table>
<thead>
<tr>
<th>( \lambda ) (nm)</th>
<th>Transition</th>
<th>( A_{ki} ) (10^9 s^-1)</th>
<th>( t_{18 \degree C} ) (%)</th>
<th>( t_{30 \degree C} ) (%)</th>
<th>( I \leq 400 \text{ mA} )</th>
<th>( T_{cold} = 18 \degree C )</th>
<th>( p_{neon} ) (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg</td>
<td>404.66</td>
<td>( 7^3S_1 ) - ( 6^3P_0 )</td>
<td>0.21</td>
<td>90</td>
<td>75</td>
<td>No</td>
<td>No</td>
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<tr>
<td></td>
<td>435.83</td>
<td>( 7^3S_1 ) - ( 6^3P_1 )</td>
<td>0.557</td>
<td>100</td>
<td>86</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td></td>
<td>546.07</td>
<td>( 7^3S_1 ) - ( 6^3P_2 )</td>
<td>0.487</td>
<td>68</td>
<td>48</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>576.96</td>
<td>( 6^1D_2 ) - ( 6^1P_1 )</td>
<td>0.236</td>
<td>100</td>
<td>95</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>491.61</td>
<td>( 8^3S_0 ) - ( 6^3P_1 )</td>
<td>0.058</td>
<td>100</td>
<td>95</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Ne</td>
<td>588.19</td>
<td>( 2p_{21} - 1s_3 )</td>
<td>0.115</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td></td>
<td>594.48</td>
<td>( 2p_{22} - 1s_3 )</td>
<td>0.113</td>
<td>96</td>
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<td>614.31</td>
<td>( 2p_{21} - 1s_3 )</td>
<td>0.282</td>
<td>93</td>
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<td>?</td>
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<tr>
<td></td>
<td>640.22</td>
<td>( 2p_{21} - 1s_3 )</td>
<td>0.514</td>
<td>93</td>
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<td>?</td>
<td>?</td>
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<tr>
<td></td>
<td>609.62</td>
<td>( 2p_{21} - 1s_3 )</td>
<td>0.181</td>
<td>94</td>
<td>No</td>
<td>?</td>
<td>?</td>
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<td></td>
<td>650.65</td>
<td>( 2p_{21} - 1s_3 )</td>
<td>0.300</td>
<td>90</td>
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<td>?</td>
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<td></td>
<td>724.52</td>
<td>( 2p_{10} - 1s_4 )</td>
<td>0.0935</td>
<td>Yes</td>
<td>Yes</td>
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<td></td>
<td>626.65</td>
<td>( 2p_{11} - 1s_4 )</td>
<td>0.249</td>
<td>87</td>
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<td>?</td>
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<td></td>
<td>585.25</td>
<td>( 2p_{11} - 1s_4 )</td>
<td>0.682</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td></td>
<td>534.11</td>
<td>( 4d_{5} - 2p_{10} )</td>
<td>0.110</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td></td>
<td>748.89</td>
<td>( 3d_{5} - 2p_{10} )</td>
<td>0.349</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
the lines for which we measured the transmission. When the transmission of a line is higher than 95%, then we assume the line to be optically thin.

We also measured the emission of two very weak lines at 534.11 and 748.89 nm corresponding to transitions to the $2p_{10}$ level. The density of the $2p_{10}$ level can be estimated from the emission of the spectral lines that originated from this level. This density is low enough to assume the 534.11 and the 748.89 nm lines to be optically thin.

At lower electric currents and at higher cold-spot temperatures, the neon emission is lower. This is because of the fact that the degree of depletion is lower. Therefore, we can assume that the density of the metastable and the resonant states is also lower. So for the absorption of the neon spectral lines, the 400 mA, 18 °C measurements are the worst case. For different neon pressures we can still use the 534.11 and the 748.89 nm lines. Table I gives a summary of the conclusions drawn in Sec. II B.

III. RESULTS

A. Spatially resolved emission: Cross section of the discharge for several currents

We will start with the emission of the lamp with 10 mbar neon, a cold-spot temperature of 18 °C, and electric currents of 100, 150, 200, and 400 mA. The radial profile of this emission is converted into a bitmap containing the color distribution cross section of the discharge, described in Sec. III. The radial profile of the mercury emission spectrum is constructed using the emission coefficients for the spectral lines of mercury. The neon spectrum is constructed by using the $y=0$ spectrum and scaling it to the 588.2 nm spectral line. This construction saves a lot of calculation time. It can be used since the shape of the normalized neon spectrum stays constant within 10%. Note that the influence of self-absorption on the intensity is also of the order of 10%. These errors are negligible for the construction of the cross sections of the discharge. There are two reasons for this. First, we do not give intensity information in the cross section. Furthermore, the color of monochromatic radiation with a wavelength in the range of 620–775 nm is virtually the same. Small changes in the shape of the neon spectrum will therefore not result in a different color.

The cross sections of the discharge are given in Fig. 4. The cross sections show the development of a red area in the middle of the discharge. The size of this area increases with increasing current. This is due to the fact that, at higher currents, the mercury density profile gets more depleted in the middle part of the discharge. The development of the red area causes the overall color of the lamp to shift towards red.

B. Atomic state density profiles

We can obtain the density of the upper state of the transitions from the emission coefficient $e_{ij}$ using expression (5). For the 10 mA neon discharge with a cold-spot temperature of 18 °C and a current of 400 mA, we can use the 435.83, the 576.96, and the 491.60 nm spectral lines to obtain the density of the $7^1S_1$, the $6^3D_2$, and the $8^1S_0$ levels, respectively. For the optically thin lines of neon we can do the same calculation. All the neon lines show the same behavior. Figure 5 shows the density of the $7^1S_1$, the $6^3D_2$, and the $8^1S_0$ levels of mercury, and the $2p_1$, the $2p_2$, the $2p_{10}$, the $3d_3$, and the $4d_5$ levels of neon, as obtained from the emission measurements. The lines represent the first lateral-to-radial transformation method, the markers represent the second method. Along with these densities, the mercury $6^1S_0$ (ground state) density is shown in Fig. 5. This mercury ground state density is obtained by ultraviolet absorption measurements, discussed in Ref. 3.

The electron density in the discharge is expected to have a somewhat flattened Bessel profile. This profile and the
mercury ground state density explain the shape of the excited state density profiles of mercury. For the production of excited mercury atoms, ground state mercury and electrons are needed. Since the ground state Hg density profile is hollow, the excited state density profiles will also be hollow. Furthermore, since the electron density is approximately zero at the walls, the excited state density profiles will also be approximately zero at the wall.

The excited state density profiles for neon are bell shaped. The main reason for this is the fact that the 2p states are mainly populated from the 1s states. Therefore, for the production of neon atoms excited to the 2p states, electrons and neon in one of the 1s states are needed. The density profile of both of these particles is approximately Bessel shaped, so the 2p state density will be bell shaped. A second reason for the bell shaped profile is the fact that the resonant states will also have a bell shaped density profile due to radiation trapping. The third reason for the bell shaped profile can be the quenching of neon metastable atoms due to Penning ionization of mercury, which results in a bell shaped density profile of metastable neon.

In the remainder of Sec. III, we will only give the 6D$_2$ density of mercury, along with the 2p$_2$ density of neon, since they can be obtained for all the experimental conditions.

C. Hg 6D$_2$ density and the Ne 2p$_2$ density: Current dependency

The Hg 6D$_2$ density and the Ne 2p$_2$ density can be obtained from the emission measurements. We measured this emission using a discharge with 10 mbar neon and a cold-spot temperature of 18 °C at currents of 100, 150, 200, and 400 mA. The results of these measurements are given in Fig. 6, where the two excited state densities are given. It is clear that the Hg 6D$_2$ density profile becomes more hollow when the current increases. This is due to mercury depletion, which is more pronounced at higher currents. The 6D$_2$ density gradient at the wall increases with increasing current.
This means that the mercury ground state density gradient and the mercury ion density gradient also increase with increasing current.

The neon $2p_2$ density has a bell shaped profile. The normalized shape of the profiles is constant with changing current. This proves that neon excitation is not a threshold process which occurs when the mercury density is low enough.

**D. Hg $6^3D_2$ density and the Ne $2p_2$ density: Mercury pressure dependency**

The mercury pressure can be set by choosing the right water temperature in the water jacket. We measured the emission spectrum of the discharge at four different cold-spot temperatures: 18 (square), 22 (circle), 27 (triangle), and 30 °C (inverted triangle). The results of these measurements are shown in Fig. 7, where the two excited state densities are given. It is clear that the mercury depletion is more pronounced at lower mercury pressures. This is due to the fact that a decrease of the mercury density has more effect when the mercury density is low than at a high mercury density. Note that the gradient in the $6^3D_2$ density is approximately the same for all the mercury pressures. This means that the gradient in the mercury ground state density and the mercury ion density are approximately constant at changing mercury pressures. The neon $2p_2$ density profile is bell shaped for all the mercury pressures. The normalized neon $2p_2$ density profiles are approximately the same for different mercury pressures.

**E. Hg $6^3D_2$ density and the Ne $3d_3$ density: Neon pressure dependency**

We have measured the emission spectrum of three different lamps. The neon pressure in these lamps was 3, 10, and 15 mbar. The current through the lamp was 400 mA, and the cold-spot temperature was 18 °C. The Hg $6^3D_2$ density profile and the Ne $3d_3$ density profiles are given in Fig. 8 for
the three neon pressures, 3, 10, and 15 mbar. It is clear that the production of neon radiation is much more efficient at high neon pressures. This is probably due to a higher electron density in the discharge at higher neon pressures. For mercury radiation the opposite is true. The higher the neon pressure, the less mercury radiation. This is probably due to the increase of the energy loss in elastic collisions of electrons with neon atoms.

IV. DISCUSSION

Spatially resolved emission measurements are performed for several spectral lines under several experimental conditions. Using absorption measurements, the influence of re-absorption is checked. For several conditions this re-absorption cannot be neglected. The density profiles of several excited states of neon and mercury are obtained from the emission coefficients of optically thin spectral lines. We estimate the error in the shape of the density profiles to be of the order of 5%–10%. The error in the absolute value of the densities is estimated to be of the order of 25%–50%. This large error is due to uncertainties in the intensity calibration and the transition probabilities. The results for the excited state density profiles can be explained qualitatively using the mass balance for mercury. In future research we will investigate the electron energy distribution function in the discharge using Thomson scattering. The quantities missing in this article are the electron temperature and density. Combining the Thomson scattering measurements with these, we hope to obtain a more complete, in-depth picture of the depleted neon–mercury positive column.

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APPENDIX

Here we describe how it can be shown that a water jacket around the tube does not change the emission measurements. We assume the water jacket and the tube to have an infinitely small thickness. Then there is no influence of the walls, and we have a tube with a cylinder around it, like in Fig. 9. In Fig. 9, the definitions of the angles $\alpha_1$, $\alpha_2$, $\alpha_3$, and $\alpha_4$, the tube radius $R_1$, the cylinder radius $R_2$, $y$, $y^*$, the indices of refraction $n_0$ and $n_1$, and the line $l$ are shown. We assume the discharge to have cylindrical symmetry.

The two lenses make an image of a certain surface of the focal plane of the first lens. From this surface, we capture the radiation within a certain solid angle. The emission measurements are not affected by the cylinder around the tube when the surface area, the solid angle, and the lateral position of this surface are not changed. We will start with this lateral position.

1. Conservation of the lateral position

We have to show that the cylinder around the tube does not change the lateral position $y$ inside the tube. So, using the definitions given in Fig. 9, we have to show that $y^*=y$. In order to do this, we have to apply Snell’s law to the boundaries where the index of refraction changes. Furthermore, we have to use the sine rule in order to find a relation between $\alpha_2$ and $\alpha_3$. The result is

$$y = R_2 \sin(\alpha_1) = R_2 \frac{n_1}{n_0} \sin(\alpha_2)$$

$$= R_2 \frac{n_1}{n_0} \frac{R_1}{R_2} \sin(\alpha_3) = R_1 \sin(\alpha_4) = y^*.$$

So the coaxial boundary rotates the beam; however, since we assumed cylindrical symmetry, this has no influence.

2. Conservation of the solid angle

The solid angle in which the radiation is captured is determined by the focal distance of the first lens $f$, along with the radius of the diaphragm. We have to prove that inside the cylinder on line $l$, we capture the radiation in the very same solid angle. Note that this is in general not the case for radiation captured by a negative lens like the cylinder. In order to show that in our case the solid angle is not changed by the cylinder, we consider a small volume on line $l$. We assume this volume to radiate isotropically. The radiation, which is emitted within the solid angle $\delta\Omega$ has to be within the same solid angle after passing the cylinder. In order to show that this is the case, we consider the beam drawn in Fig. 9. When we rotate this beam over an angle $\delta\alpha$ around the intersection of line $l$ and the beam itself, we constructed a second beam which we will call the rotated beam. We now have to show that the angle between the rotated beam and the original beam is $\delta\alpha$, even outside the cylinder. Because of the fact that the solid angle $\delta\Omega$ is very small, we can use the first order Taylor expansion, i.e., a linearization, for the sine, cosine, and tangent of $\delta\alpha$. This can be done in a very simple way, since it can be shown that the equivalent of $\alpha_4$ for the rotated beam is equal to $\alpha_4$ when using the linearization. So the angle between the two beams is always equal to $\delta\alpha$. Therefore, we can conclude that all the radiation and only the radiation emitted in the solid angle $\delta\Omega$ will be captured by the optical system, independent of the lateral position. An important implication is that line $l$ is positioned in the focal plane of the first lens. This focal plane is different for different lateral positions.
3. Conservation of the imaged area

In order to show that the imaged surface area is also unaffected by the cylinder, we rotate the beam in Fig. 9 over the angle $\delta \beta$ around the point where it intersects with the first lens. The angle $\delta \beta$ is dependent of the size of the aperture of the optical fiber. This aperture determines the maximum imaged area. For this rotated beam, we calculated the equivalents of $\alpha_1$, $\alpha_2$, $\alpha_3$, and $\alpha_4$. Using these angles, we can calculate the positions of the intersections of the rotated beam with the cylinder, and with line $l$. We used the same linearization for $\delta \beta$ as we did for $\delta \alpha$. It can be shown that the intersection of the rotated beam with line $l$ is a distance $f \times \delta \beta$ away from the intersection of the original beam with the line $l$. This is the same distance as we would have without the cylinder. However, the angle between the original beam and the rotated beam does change. The cone in which we capture the radiation widens a little. This decreases the spatial resolution of the measurements. However, this does not affect the amount of radiation we capture.