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Excessively bright hydrogen–strontium discharge light source due to energy resonance of strontium with hydrogen

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Abstract. A plasma formed with a low field ($1\,\mathrm{V\,cm^{-1}}$) at low temperatures (e.g. $\approx 10^3\,\mathrm{K}$) from atomic hydrogen generated at a tungsten filament and strontium which was vaporized by heating the metal. Strong extreme ultraviolet emission was observed, but not when sodium, magnesium or barium replaced strontium or with hydrogen or strontium alone. Characteristic emission was observed which supported a resonant energy-transfer mechanism. Significant Balmer α line broadening corresponding to an average hydrogen atom temperature of 23–45 eV was observed for glow discharges of strontium–hydrogen, helium–hydrogen, argon–hydrogen, strontium–helium–hydrogen and strontium–argon–hydrogen compared with ≈ 3 eV for pure hydrogen, krypton–hydrogen, xenon–hydrogen and magnesium–hydrogen. To achieve the same optically measured light output power, hydrogen–sodium, hydrogen–magnesium and hydrogen–barium mixtures required 4000, 7000 and 6500 times the power of the hydrogen–strontium mixture, respectively. A glow discharge plasma formed for hydrogen–strontium mixtures at an extremely low voltage of about 2 V compared with 250 V for hydrogen alone and sodium–hydrogen mixtures, and 140–150 V for hydrogen–magnesium and hydrogen–barium mixtures.

1. Introduction

Suitable hydrogen plasma light sources and spectrometers have been developed that permit observations in the vacuum ultraviolet (VUV). Developed sources that provide a suitable intensity are high-voltage glow discharges, synchrotron devices, inductively coupled plasma generators [1], and magnetically confined plasmas [2]. In contrast with the high electric fields, power densities and temperatures of prior sources, it has been reported that intense VUV emission was observed at low gas temperatures (e.g. $\approx 10^3\,\mathrm{K}$) with a very low field ($1\,\mathrm{V\,cm^{-1}}$) from atomic hydrogen and certain atomized elements or certain gaseous ions that singly or multiply ionize at integer multiples of the potential energy of atomic hydrogen, $m \cdot 27.2$ eV [3–14]. The so-called resonant transfer or rt-plasma forms by a resonant energy transfer mechanism involving the species providing a net enthalpy of a multiple of 27.2 eV and atomic hydrogen.

The enthalpy of ionization of Cs to Cs^{2+} has a net enthalpy of reaction of 27.05135 eV, which is equivalent to $m = 1$ [15]. And, the reaction Ar^+ to Ar^{2+} has a net enthalpy of reaction of 27.63 eV, which is equivalent to $m = 1$ [15]. Emission

was previously reported from a continuum state of Cs^{2+} and Ar^{2+} at 53.3 and 45.6 nm, respectively [7]. The single emission feature with the absence of the other corresponding Rydberg series of lines from these species confirmed the resonant energy transfer of 27.2 eV from atomic hydrogen to atomic caesium or Ar^{+}. The product hydride with the caesium atom or Ar^{+} as a reactant was predicted to have a binding energy of 3.05 eV and was observed spectroscopically at 407 nm [7]. In addition, He^{+} ionizes at 54.417 eV which is 2×27.2 eV, and novel extreme ultraviolet (EUV) emission lines were observed from microwave and glow discharges of helium with 2% hydrogen that corresponded to the catalysis product [5].

The second and third ionization energies of strontium are 11.03013 and 42.89 eV, respectively [15]. The ionization reaction of Sr^{+} to Sr^{3+}, then, has a net enthalpy of reaction of 53.92 eV, which is about 2×27.2 eV; thus, Sr^{+} may serve as a catalyst to form an rt-plasma from atomic hydrogen generated at a tungsten filament and strontium vaporized by heating the metal. Ar^{+} and He^{+} formed by glow discharge of the corresponding noble gas–hydrogen mixture were anticipated to serve as catalysts as well. Thus, plasma formation studies, VUV spectroscopy, line broadening and optical power balance measurements were performed on hydrogen plasmas with at least one of strontium, argon and helium present. The results were compared with those of mixtures of hydrogen and chemically similar controls that do not have electron ionization energies which are a multiple of 27.2 eV. Four different light sources were used to form and characterize the rt-plasmas under a range of plasma conditions.

2. Experimental

2.1. VUV spectroscopy

Owing to the extremely short wavelength of this radiation, 'transparent' optics do not exist for VUV spectroscopy. Therefore, a windowless arrangement was used wherein the source was connected to the same vacuum vessel as the grating and detectors of the VUV spectrometer. Windowless VUV spectroscopy was performed with a vacuum ultraviolet spectrometer that was mated with the cell. Differential pumping permitted a high pressure in the cell compared with that in the spectrometer. This was achieved by pumping on the cell outlet and pumping on the grating side of the collimator that served as a pin-hole inlet to the optics. The cell was operated under gas flow conditions while maintaining a constant gas pressure in the cell. The gas pressure inside the cell was maintained at about 300 mtorr with a hydrogen flow rate of 5.5 sccm controlled by a 0–20 sccm range mass flow controller with a readout.

The experimental set up of a type I light source shown in Fig. 1 comprised a quartz cell which was 500 mm in length and 50 mm in diameter. A Pyrex cap sealed to the quartz cell with a Viton O ring and a C-clamp incorporated ports for gas inlet, outlet and photon detection. A tungsten filament (0.508 mm in diameter and 800 cm in length, total resistance $\sim 2.5\,\Omega$) heater and hydrogen dissociator were in the quartz tube as well as a cylindrical titanium screen (300 mm long and 40 mm in diameter) that served as a second hydrogen dissociator in the case of the hydrogen gas experiments. A new dissociator was used for each hydrogen gas experiment. The filament was coiled on a grooved ceramic tube support to maintain its shape when heated. The return lead passed through the inside of the ceramic tube. The titanium screen was electrically floated. Power was applied to the filament

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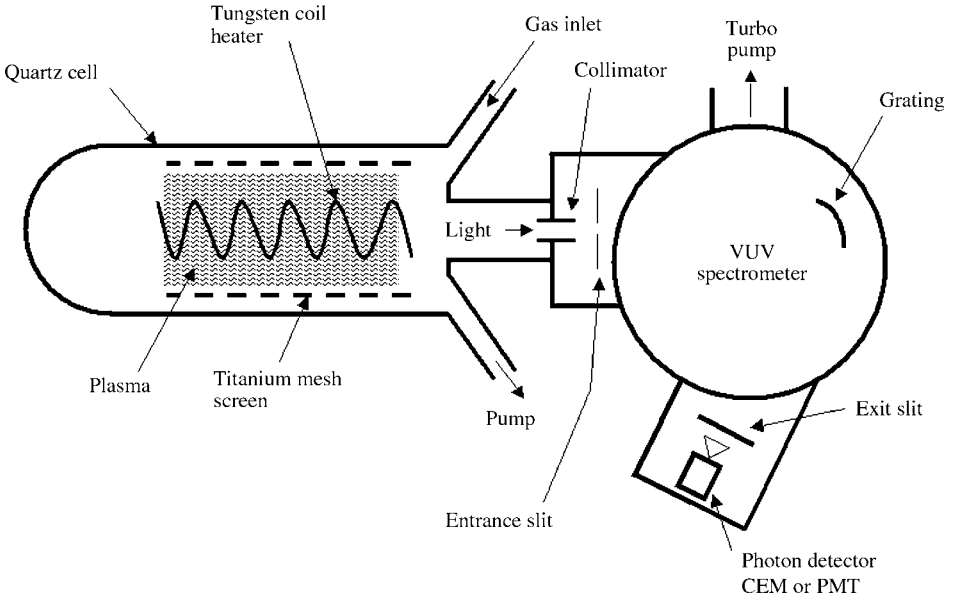

Figure 1. The experimental set up of a type I light source comprising a gas cell light source and a VUV spectrometer which was differentially pumped.

by a DC power supply, which was controlled by a constant power controller. The temperature of the tungsten filament was estimated to be in the range 1100–1500 °C. The external cell wall temperature was about 700 °C. The entire quartz cell was enclosed in an alumina insulation package. Several K-type thermocouples were located in the insulation. The thermocouples were monitored with a multichannel computer data acquisition system.

In the present study, the light emission phenomena was studied for: (1) hydrogen, argon, neon and helium alone; (2) sodium, magnesium, barium and strontium metals alone and (3) sodium, magnesium, barium and strontium with hydrogen. 1 g of the pure metal (Alfa Aesar 99.95%) of sodium, magnesium, barium or strontium was placed in the centre of the cell under 1 atm of dry argon in a glovebox. The cell was sealed, removed from the glovebox and connected to VUV spectrometer. Each metal was vaporized by the filament heater. The power applied to the filament was 300 W in the case of strontium and up to 600 W in the case of sodium, magnesium or barium metal. The voltage across the filament was about 55 V and the current was about 5.5 A at 300 W. For each control, sodium, magnesium or barium metal, the cell temperature was increased to the maximum permissible with the power supply.

The light emission was introduced to a VUV spectrometer for spectral measurement. The spectrometer was a 0.2 m monochromator (McPherson Model 302) equipped with a 1200 lines mm^{-1} holographic grating with a platinum coating. The wavelength region covered by the monochromator was 20–560 nm. A channel electron multiplier (CEM) was used to detect the VUV light. The wavelength resolution was about 0.2 nm (FWHM) with an entrance and exit slit width of 50 μm. The vacuum inside the monochromator was maintained below 5×10^{-4} torr by a turbo pump. The VUV spectrum (40–160 nm) of the cell emission with strontium present was recorded at about the point of the maximum Lyman α emission.

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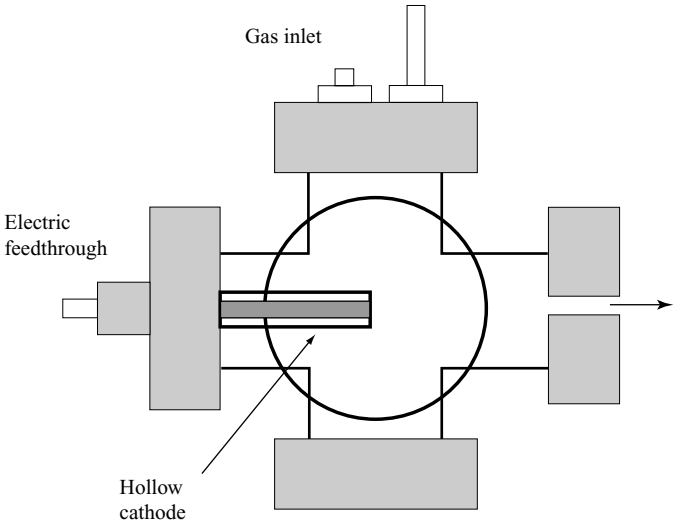

Figure 2. Cross-sectional view of a type II light source comprising a glow discharge cell.

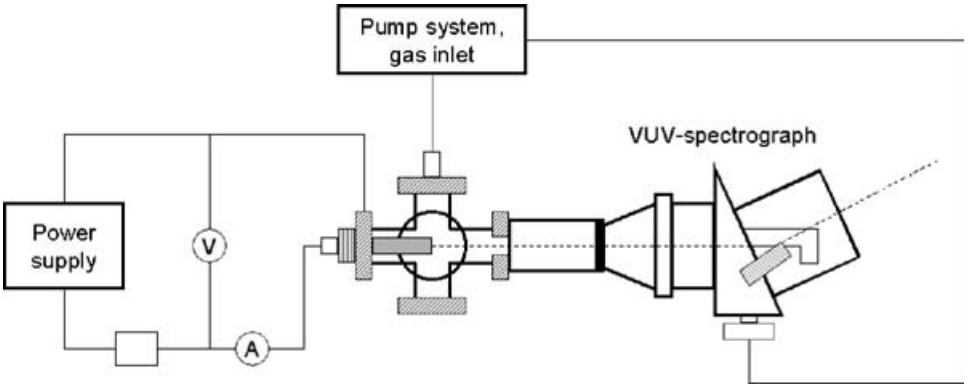

Figure 3. The experimental set up comprising a type II discharge gas cell light source and a VUV spectrometer which was differentially pumped.

The UV/visible spectrum (40–560 nm) of the cell emission with hydrogen alone was recorded with a photomultiplier tube (PMT) and a sodium salicylate scintillator. The PMT used had a spectral response in the range of 185–680 nm with a peak efficiency at about 400 nm. The scan interval was 0.4 nm. The inlet and outlet slit were 500 μm, with a corresponding wavelength resolution of 2 nm.

2.2. Helium–hydrogen glow discharge emission spectrum

A diagram of a type II light source comprising a hollow cathode discharge plasma cell is given in Fig. 2. The hollow cathode and VUV spectrograph were aligned on a common optical axis using a laser. The experimental setup for the discharge measurements is illustrated in Fig. 3. The vacuum ultraviolet emission spectrum was obtained for hydrogen and helium–hydrogen (5/95%) plasma with a gas discharge cell that comprised a five-way stainless steel cross that served as the anode with

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a hollow stainless steel cathode. The plasma was generated at the hollow cathode inside the discharge cell. The hollow cathode was constructed of a stainless steel rod inserted into a steel tube, and this assembly was inserted into an alumina tube. A flange opposite the end of the hollow cathode connected the spectrometer to the cell. It had a small hole that permitted radiation to pass to the spectrometer. An AC power supply (0–1 kV, 0–100 mA) was connected to the hollow cathode to generate a discharge. The AC voltage and current at the time the VUV spectrum was recorded were 200 V and 40 mA, respectively. A Swagelok adapter at the very end of the steel cross provided a gas inlet and a connection with the pumping system, and the cell was pumped with a mechanical pump. Valves were located between the cell and the mechanical pump, the cell and the monochromator, and the monochromator and its turbo pump. The five-way cross was pressurized with 400 mtorr of gas, which was maintained by flowing hydrogen or helium–hydrogen (5/95%) while monitoring the pressure with a 1 torr absolute pressure gauge.

2.3. Balmer line broadening and visible spectra recorded on rt-plasmas by high-resolution visible spectroscopy

The method of Videnovic et al. [16] was used to calculate the energetic hydrogen atom densities and energies from the intensities and width of the 656.3 nm Balmer α line emitted from glow discharge and microwave plasmas. The full half-width $\Delta\lambda_G$ of each Gaussian results from the Doppler ($\Delta\lambda_D$) and instrumental ($\Delta\lambda_I$) half-widths:

$$\Delta\lambda_G = \sqrt{\Delta\lambda_D^2 + \Delta\lambda_I^2} \tag{2.1}$$

where $\Delta\lambda_I$ in our experiments was 0.025 nm or $\pm$0.006 nm. The temperature was calculated from the Doppler half-width using the formula

$$\Delta\lambda_D = 7.16 \times 10^{-7}\lambda_0 \left(\frac{T}{\mu}\right)^{1/2} \text{(nm)} \tag{2.2}$$

where λ_0 is the line wavelength in nm, T is the temperature in K (1 eV = 11, 605 K) and μ is the atomic weight (= 1 for hydrogen). In each case, the average Doppler half-width that was not appreciably changed with pressure varied by $\pm$4%, corresponding to an error in the energy of $\pm$4%. The corresponding number densities for noble gas–hydrogen mixtures varied by $\pm$8% depending on the pressure.

The width of the 656.3 nm Balmer α line was recorded on light emitted from a hydrogen glow discharge performed according to methods reported previously [17] and maintained in the cylindrical stainless steel gas cell comprising a type III light source shown in Fig. 4 that served as a control for measurements recorded on light emitted from rt-plasmas of hydrogen with strontium maintained in type I cells. The inorganic test materials were coated on a titanium screen dissociator by the method of wet impregnation. The screen was coated by dipping it in a 0.6 M $SrCO_3$/10% H_2O_2, and the crystalline material was dried on the surface by heating for 12 h in a drying oven at 130 °C.

The plasma emission from the hydrogen glow discharge (type III light source) and each rt-plasma maintained in the filament-heated cell (type I light source) was fibre-optically coupled through a 220F matching fibre adapter positioned 2 cm from the sapphire window or cell wall, respectively, to a high-resolution visible spectrometer with a resolution of $\pm$0.006 nm over the spectral range 190–860 nm.

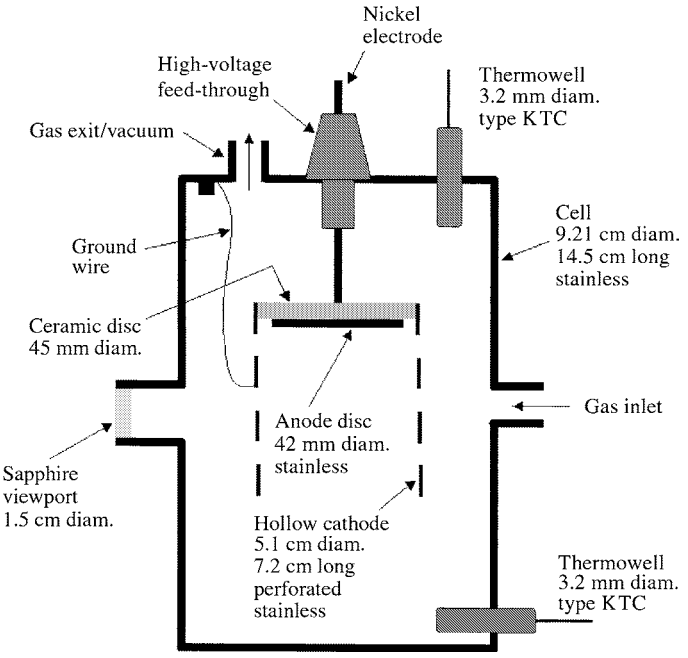

Figure 4. Type III light source comprising a cylindrical stainless steel glow discharge cell for studies of the broadening of the Balmer α line emitted from gas discharge plasmas of pure hydrogen alone or with strontium or magnesium or a mixture of 10% hydrogen and helium, argon, krypton or xenon.

The spectrometer was a Jobin Yvon Horiba 1250 M with 2400 groves mm^{-1} ion-etched holographic diffraction grating. The entrance and exit slits were set to 20 μm. The spectrometer was scanned between 655.5 and 657 nm using a 0.01 nm step size. The signal was recorded by a PMT with a stand-alone high-voltage power supply (950 V) and an acquisition controller. The data was obtained in a single accumulation with a 1 s integration time. The high-resolution visible spectrum (400–410 nm) was also recorded on the strontium plasma to record Sr and Sr^+ lines.

In addition, the width of the 656.3 nm Balmer α line emitted from gas discharge plasmas having atomized hydrogen from pure hydrogen alone, hydrogen with magnesium or strontium, a mixture of 10% hydrogen and helium, argon, krypton or xenon, a mixture of 10% hydrogen and helium or argon with strontium, and argon with strontium was measured with a high-resolution visible spectrometer with a resolution of $\pm$0.025 nm over the spectral range 190–860 nm. The plasmas were maintained in a type III light source.

The 304-stainless steel cylindrical cell was 9.21 cm in diameter and 14.5 cm in height. The base of the cell contained a welded-in stainless steel thermocouple well (1 cm OD) which housed a thermocouple probe in the cell interior approximately 2 cm from the discharge and 2 cm from the cell axis. At the middle height of the cell wall was a welded-flush stainless steel tube (0.95 cm diameter), which was connected to a flexible stainless steel tube (100 cm in length) that served as a vacuum line from the cell and the line to supply the test gas. The top end of the cell was welded to a high-vacuum 11.75 cm diameter conflat flange. A silver-plated copper gasket was placed between a mating flange and the cell flange. The two flanges

were clamped together with 10 circumferential bolts. The mating flange contained two penetrations comprising (1) a stainless steel thermocouple well (1 cm OD) also housing a thermocouple probe in the cell interior approximately 2 cm from the discharge and 2 cm from the cell axis and (2) a centred high-voltage feedthrough which transmitted the power, supplied through a power connector, to a hollow cathode inside the cell.

The axial hollow cathode glow discharge electrode assembly comprised a stainless steel plate (42 mm diameter, 0.9 mm thick) anode and a circumferential stainless steel cylindrical frame (5.08 cm OD, 7.2 cm long) perforated with evenly spaced 1 cm diameter holes. The cathode was attached to the cell body by a stainless steel wire and the cell body was grounded.

A 1.6 mm thick UV-grade sapphire window with 1.5 cm view diameter provided a visible light path from inside the cell. The viewing direction was normal to the cell axis.

Strontium (99.9%) or magnesium (99.98%) metal was coated on to the cathode in a glovebox under a dry argon atmosphere. The cell was sealed in the glovebox, removed, and then evacuated with a turbo vacuum pump to a pressure of 4 mtorr. The gas was ultrahigh-purity hydrogen or noble gas–hydrogen mixture (90/10%) at 2 torr total pressure. The pressure of each test gas comprising a mixture with 10% hydrogen was determined by adding the pure noble gas to a given pressure and increasing the pressure with hydrogen gas to a final pressure. The partial pressure of the hydrogen gas was given by the incremental increase in total gas pressure monitored by a 0–10 torr absolute pressure gauge. The discharge was carried out under static gas conditions. The discharge was started and maintained by a DC electric field supplied by a constant-voltage DC power supply at 275 V, which produced a current of about 0.2 A. In the case of strontium–hydrogen and argon–hydrogen plasmas, the voltage was increased at 50 V increments from 275 to 475 V, and the high-resolution visible spectra were recorded to observe the effect of voltage on the Balmer α line broadening.

The plasma emission from the glow discharges of pure hydrogen and noble gas–hydrogen mixtures was fibre-optically coupled to the spectrometer through a 220F matching fibre adapter. The entrance and exit slits were set to 20 μm. The spectrometer was scanned between 656 and 657 nm using a 0.01 nm step size. The signal was recorded by a PMT with a stand-alone high-voltage power supply (950 V) and an acquisition controller. The data was obtained in a single accumulation with a 1 s integration time.

The electron density and temperature of the rt-plasma was determined using a compensated Langmuir probe according to the method given previously [18].

2.4. Power cell apparatus and procedure

Plasma studies with (1) hydrogen alone and (2) hydrogen with strontium, sodium, magnesium or barium were carried out in the cylindrical stainless steel gas cell comprising a type IV light source shown in Fig. 5. The experimental setup for generating a glow discharge hydrogen plasma and for optically measuring the power balance is shown in Fig. 6. The cell was heated in a 10 kW refractory brick kiln as shown in Fig. 6. The cell was evacuated and pressurized with hydrogen through a single 0.95 cm feedthrough. The discharge was started and maintained by an alternating current electric field in the 1.75 cm annular gap between an axial electrode and the cell wall. The cylindrical cell was 9.21 cm in diameter and 14.5 cm

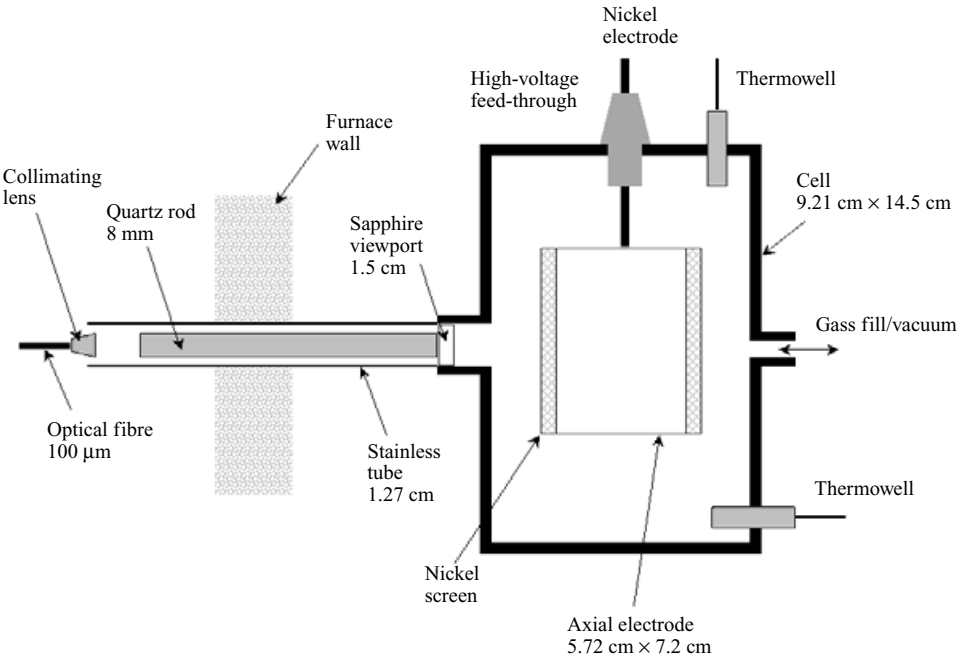

Figure 5. Type IV light source comprising a cylindrical stainless steel gas cell for plasma studies with (1) hydrogen alone and (2) hydrogen with strontium, sodium, magnesium or barium.

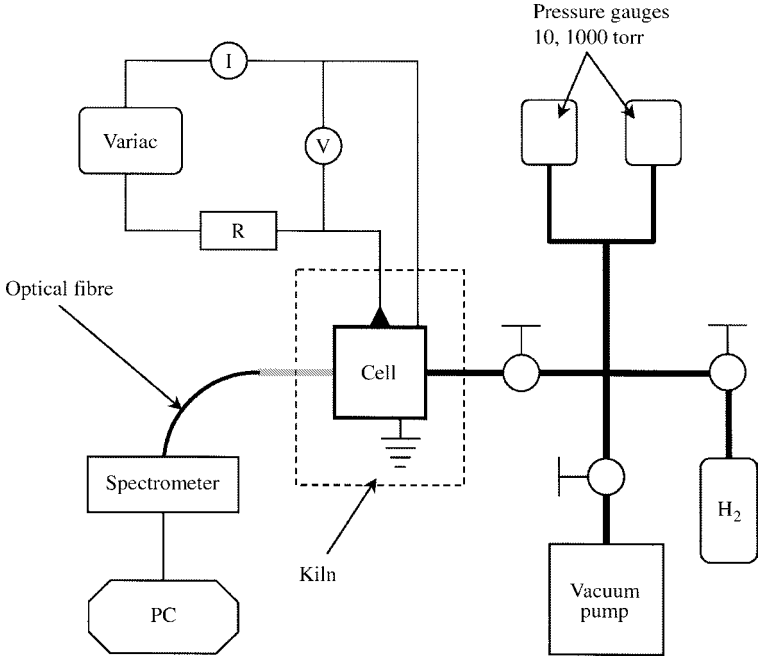

Figure 6. The experimental setup for generating a glow discharge hydrogen plasma and for optically measuring the power balance of the type IV light source.

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in height. The axial electrode was a 5.08 cm OD by 7.2 cm long stainless steel tube wound with several layers of nickel screen. The overall diameter of the axial electrode was 5.72 cm. Optical access to the cell was as described in Sec. 2.3 except that an 8 mm quartz rod channelled the light from the view port through a stainless tube to a collimating lens that was focused on a 100 μm optical fibre located outside the furnace. Spectral data were recorded with a visible spectrometer and stored on a personal computer.

The field voltage was controlled by a variable voltage transformer operating from 115 VAC, 60 Hz. A step-up transformer was used when necessary. The true rms voltage at the axial electrode was monitored by a digital multimeter. A second multimeter in series with the discharge gap was used to indicate the current. The cell temperature was measured by thermocouple probes located in the cell interior as described in Sec. 2.3. Pressure in the hydrogen supply tube outside the furnace was monitored by 10 and 1000 torr absolute pressure gauges. In the absence of gas flow, the gas supply tube pressure was essentially the cell pressure.

Strontium (99.9%), sodium (99.95%), magnesium (99.98%) or barium (99.99%) metal was loaded into the cell under a dry argon atmosphere. The cell was evacuated with a turbo vacuum pump to a pressure of 4 mtorr during most of the heating process. During the heat-up the cell was periodically pressurized with hydrogen (99.999% purity) to approximately 100 torr and subsequently evacuated to purge gaseous contaminants from the system. When the cell temperature stabilized hydrogen was added until the steady pressure was approximately 1 torr. The field voltage was increased until breakdown occurred. This was confirmed by the spectrometer response to visible light emitted from the cell. The hydrogen pressure was adjusted, as much as possible, to maximize the light emission from the cell. The voltage was maintained at the minimum level that resulted in a stable discharge during data acquisition.

The spectrometer system comprised a 100 μm optical fibre and visible spectrometer. To correct for the nonuniform response of the spectrometer system as a function of wavelength and the dependence of energy on wavelength, the system was calibrated against a reference light source. A spectral calibration factor was applied to the count rate data at each wavelength to yield the irradiation of the detector in units of energy/time/area/wavelength. The total visible radiant flux incident on the detector was calculated by integrating the spectral irradiation between 400 and 700 nm.

3. Results

3.1. VUV spectroscopy

The cell was operated without any test material present to establish the baseline of the spectrometer. No emission was observed except for the low-level blackbody filament radiation at the longer wavelengths. The intensity of the Lyman α emission as a function of time and the UV/visible spectra (40–560 nm) was observed at 700 °C from the gas cell comprising a tungsten filament, a titanium dissociator and: (1) hydrogen, argon, neon or helium alone; (2) sodium, magnesium or barium metal; (3) sodium, magnesium or barium metal with 300 mtorr hydrogen with a flow rate of 5.5 sccm. No emission was observed in any case. The maximum filament power was greater than 500 W. A metal coating formed in the cap of the cell over the course of the experiment in each case with a metal vaporized by filament heating.

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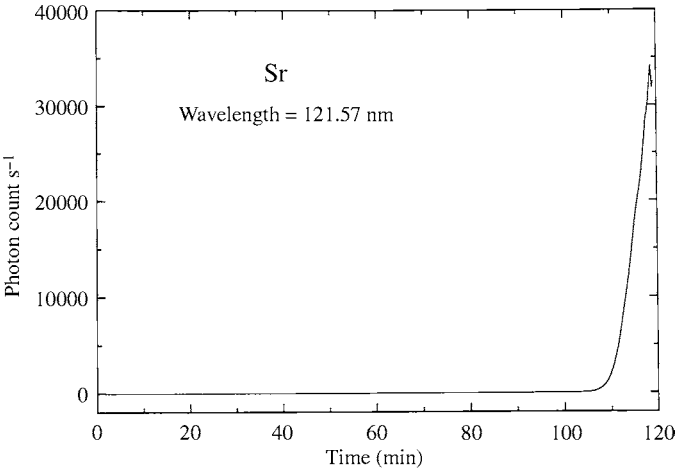

Figure 7. The intensity of the Lyman α emission as a function of time from the type I light source. The gas cell at a cell temperature of 700 °C comprised a tungsten filament, a titanium dissociator, vaporized strontium metal and 300 mtorr hydrogen, recorded with a CEM.

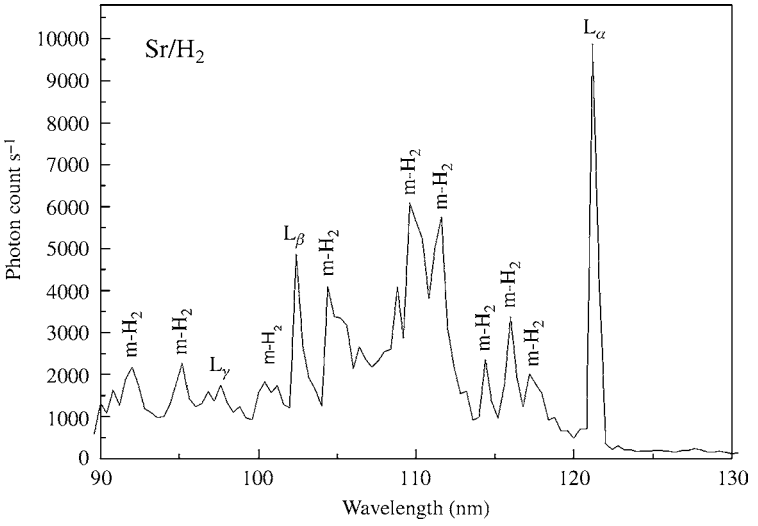

Figure 8. The VUV spectrum (90–130 nm) of the type I light source emission recorded at about the point of the maximum Lyman α emission. The gas cell at a cell temperature of 700 °C comprised a tungsten filament, a titanium dissociator, vaporized strontium metal and 300 mtorr hydrogen, recorded with a CEM.

The intensity of the Lyman α emission as a function of time from the gas cell at a cell temperature of 700 °C comprising a tungsten filament, a titanium dissociator, vaporized strontium metal and 300 mtorr hydrogen at a flow rate of 5.5 sccm is shown in Fig. 7. Strong emission was observed from vaporized strontium and hydrogen. The VUV spectrum (90–130 nm) of the cell emission recorded at about the point of the maximum Lyman α emission is shown in Fig. 8. No emission was observed in the absence of hydrogen flow. A metal coating formed in the cap of the cell over the course of the experiment.

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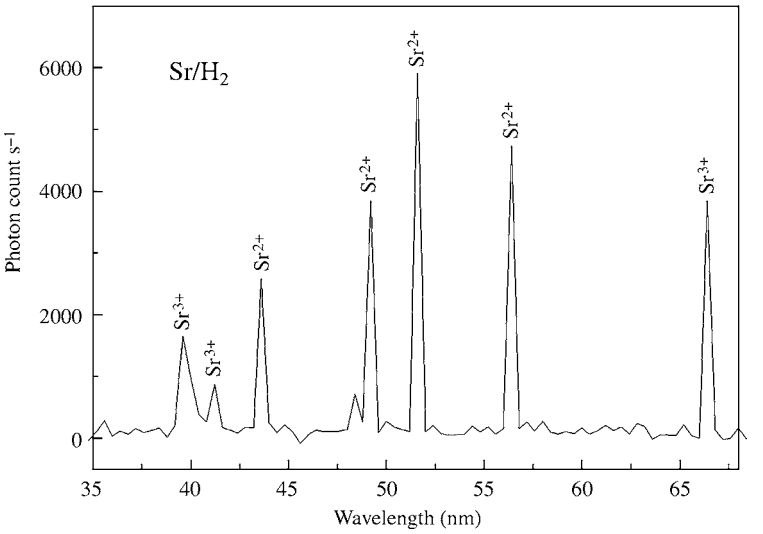

Figure 9. The VUV spectrum (35–67 nm) of a strontium rt-plasma type I light source emission. Line emission corresponding to Sr^{3+} confirmed the catalyst mechanism was observed at 66.4, 41.35 and 39.6 nm. Sr^{2+} was observed at 56.3, 51.4, 49.2 and 43.7 nm.

3.2. Emission of Sr^+ catalyst

The second and third ionization energies of strontium are 11.03013 and 42.89 eV, respectively [15]. The ionization reaction of Sr^+ to Sr^{3+}, then, has a net enthalpy of reaction of 53.92 eV, which is about 2×27.2 eV; thus, Sr^+ may serve as a catalyst to form an rt-plasma. The VUV spectrum (35–67 nm) of the emission of a strontium rt-plasma type I light source is shown in Fig. 9. Line emission corresponding to Sr^{3+} that confirmed the catalyst mechanism was observed at 66.4, 41.35 and 39.6 nm, which matched NIST tables [19]. Sr^{2+} was observed at 56.3, 51.4, 49.2 and 43.7 nm. The presence of the Sr^+ catalyst was confirmed by the Sr^+ line emission shown in Fig. 10 at 407.77 nm, which matched NIST tables [19].

3.3. Helium–hydrogen glow discharge emission spectrum

The VUV spectra (110–180 and 400–520 nm) of the type II light source emission from the hydrogen plasma (dotted line) and the hydrogen plasma to which 5% helium was added (solid line) are shown in Figs 11 and 12, respectively. Upon the addition of 5% helium, the hydrogen Lyman and Balmer line emission intensity approximately doubled, which is indicative of a higher plasma temperature.

3.4. Line broadening measurements type I cells

The results of the 656.3 nm Balmer α line width measured with a high-resolution ($\pm$0.006 nm) visible spectrometer on light emitted from rt-plasmas of hydrogen with $SrCO_3$ maintained in a type I cell are shown in Fig. 13. From the Balmer α line intensity and width, the energetic hydrogen atom density and energy given in Table 1 were calculated using the method of Videnovic et al. [16]. Significant line broadening of 14 eV and an atom density of 8×10^{11} atoms cm^{-3} were observed from an rt-plasma of hydrogen formed with a strontium catalyst.

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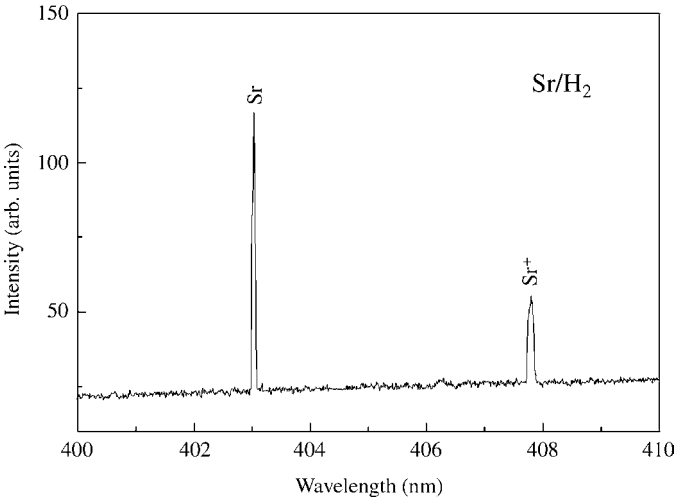

Figure 10. The high-resolution visible spectrum (400–410 nm) of a strontium rt-plasma type I light source emission. Line emission corresponding to Sr^+ was observed at 407.77 nm. Sr was observed at 403.03 nm.

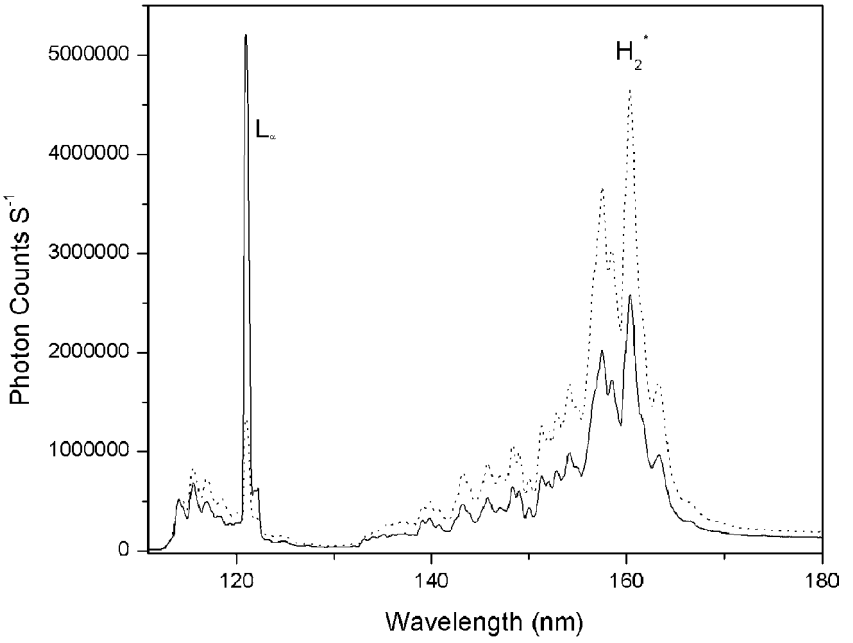

Figure 11. The VUV spectra (110–180 nm) of type II light source emission from the hydrogen plasma (dotted line) and the hydrogen plasma to which 5% helium was added (solid line), which shows the increase in hydrogen L_α emission.

3.5. Line broadening measurements on type III cells

The 656.3 nm Balmer α line width was measured on type III light sources normal to the applied electric field direction with a high-resolution($\pm$0.025 nm) visible

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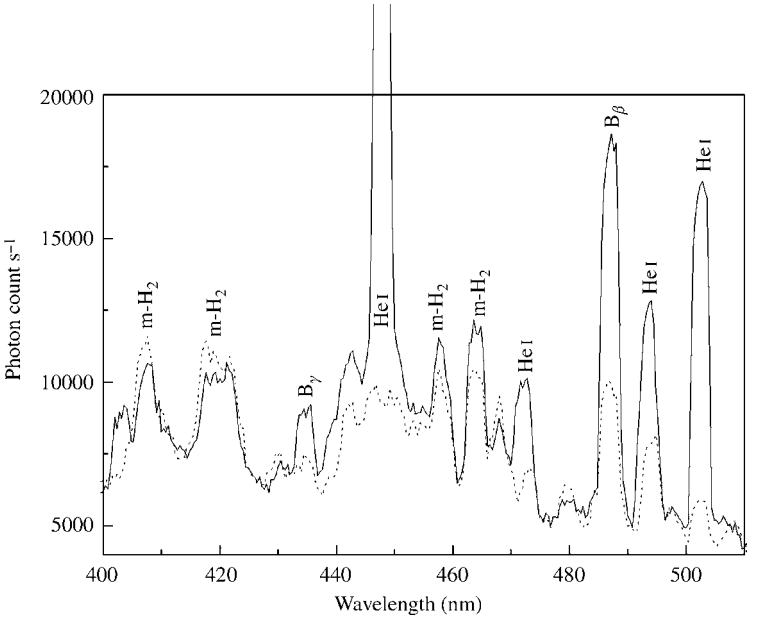

Figure 12. The VUV spectra (400–520 nm) of the type II light source emission from the hydrogen plasma (dotted line) and the hydrogen plasma to which 5% helium was added (solid line) which shows the increase in hydrogen B_β and B_γ emission.

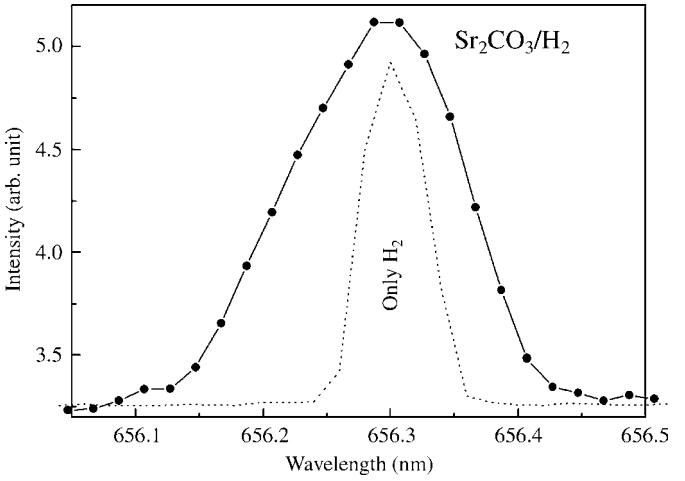

Figure 13. The 656.3 nm Balmer α line width recorded with a high-resolution ($\pm$0.006 nm) visible spectrometer on the type I light source emission of a hydrogen–strontium rt-plasma. Significant broadening was observed corresponding to an average hydrogen atom temperature of 14 eV.

spectrometer. The discharge was started and maintained at 2 torr total pressure by a DC electric field supplied by a constant-voltage DC power supply at 275 V, which produced a current of about 0.2 A. The results of the gas discharge plasmas of a mixture of 10% hydrogen and 90% xenon, strontium with hydrogen, a mixture of 10% hydrogen and 90% helium or argon, 10% hydrogen with helium or argon

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Table 1. Energetic hydrogen atom densities and energies for rt-plasmas and ordinary hydrogen plasmas maintained in type I and type III light sources.

Plasma gas	Light source type	Hydrogen atom density[a] (10^{12} atoms cm^{-3})	Hydrogen atom energy[b] (eV)
H_2	III	50	3–4
Mg/H_2	III	60	4–5
Kr/H_2	III	10	2.5–3.5
Xe/H_2	III	10	3–4
Sr/H_2	I	0.8	13–15
Sr/H_2	III	100	20–25
Ar/H_2	III	30	30–35
He/H_2	III	30	33–38
$Sr/Ar/H_2$	III	40	35–40
$Sr/He/H_2$	III	40	40–45

[a]Calculated after [16], (1) and (2).
[b]Calculated after [16], (1) and (2).

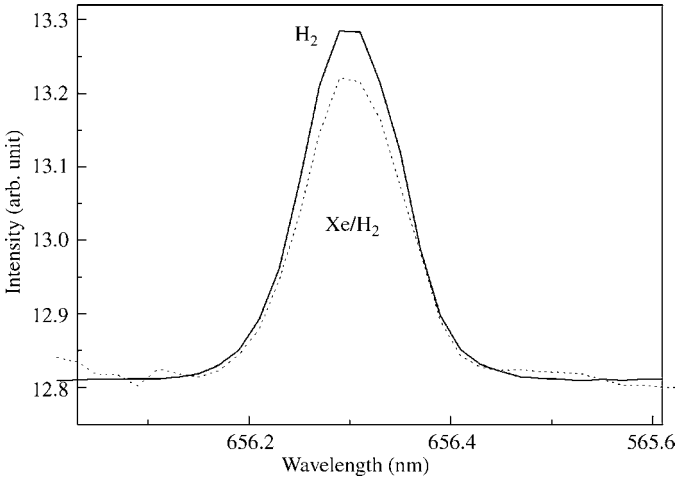

Figure 14. The 656.3 nm Balmer α line width recorded with a high-resolution ($\pm$0.025 nm) visible spectrometer on a xenon–hydrogen and a hydrogen gas discharge plasma of a type III light source. No line excessive broadening was observed corresponding to an average hydrogen atom temperature of $\approx$3 eV.

and strontium each compared to control hydrogen alone are given in Figs 14–19, respectively. In addition, the emission of a strontium–argon plasma in the region of the Balmer α line was recorded as also shown in Fig. 19. Sr I emission was observed at 655 nm, but, no emission was observed in the region of the Balmer α line, which eliminated the possibility that a strontium line close to the Balmer α line was the source of the line broadening with strontium present. The Balmer α line intensities and width were used to calculate the energetic hydrogen atom densities and energies are given in Table 1. It was found that strontium–hydrogen, helium–hydrogen, argon–hydrogen, strontium–helium–hydrogen and strontium–argon–hydrogen plasmas showed significant broadening corresponding to an average hydrogen atom temperature of 23–45 eV; whereas, pure hydrogen,

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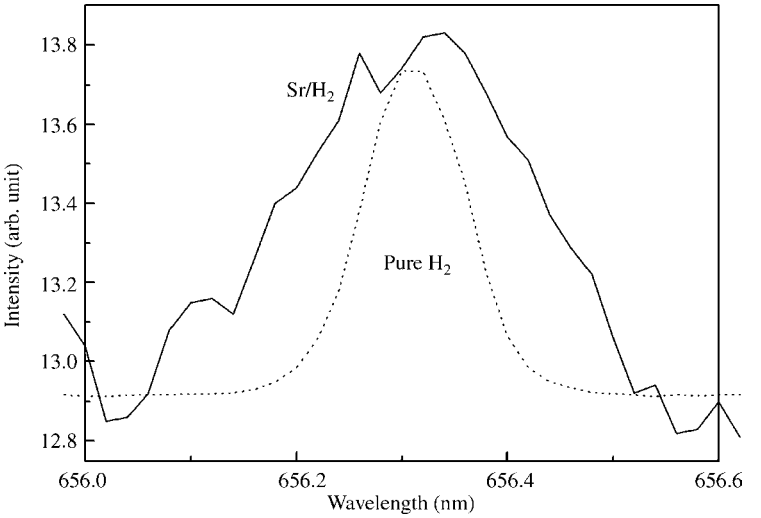

Figure 15. The 656.3 nm Balmer α line width recorded with a high-resolution ($\pm$0.025 nm) visible spectrometer on a strontium–hydrogen and a hydrogen gas discharge plasma of a type III light source. Significant broadening was observed corresponding to an average hydrogen atom temperature of 20–25 eV.

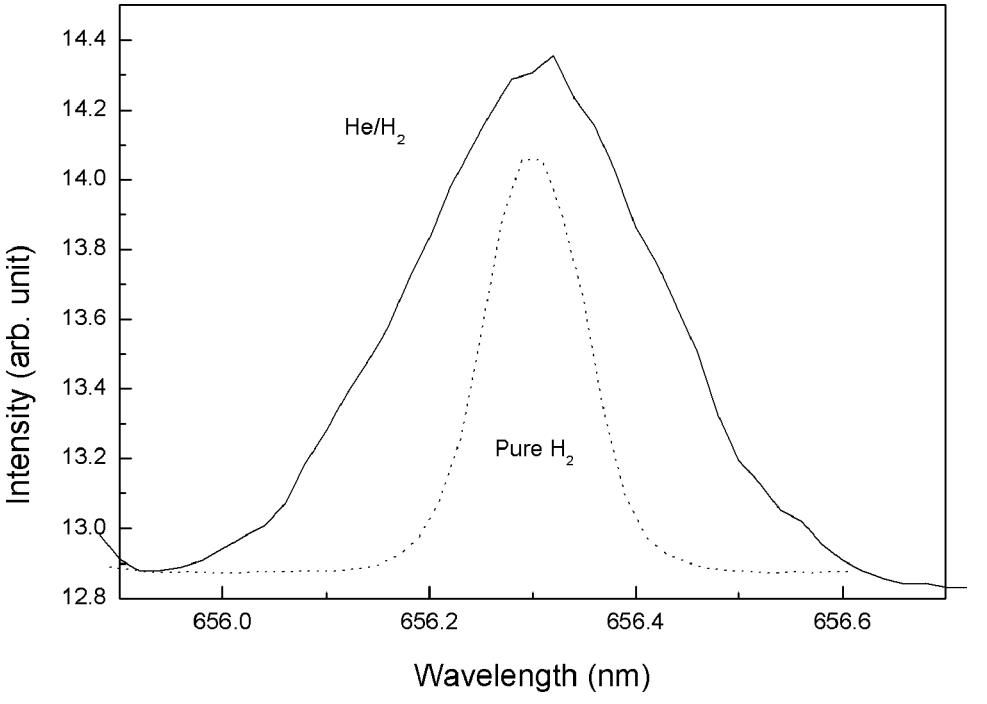

Figure 16. The 656.3 nm Balmer α line width recorded with a high-resolution ($\pm$0.025 nm) visible spectrometer on a helium–hydrogen and a hydrogen gas discharge plasma of a type III light source. Significant broadening was observed corresponding to an average hydrogen atom temperature of 33–38 eV.

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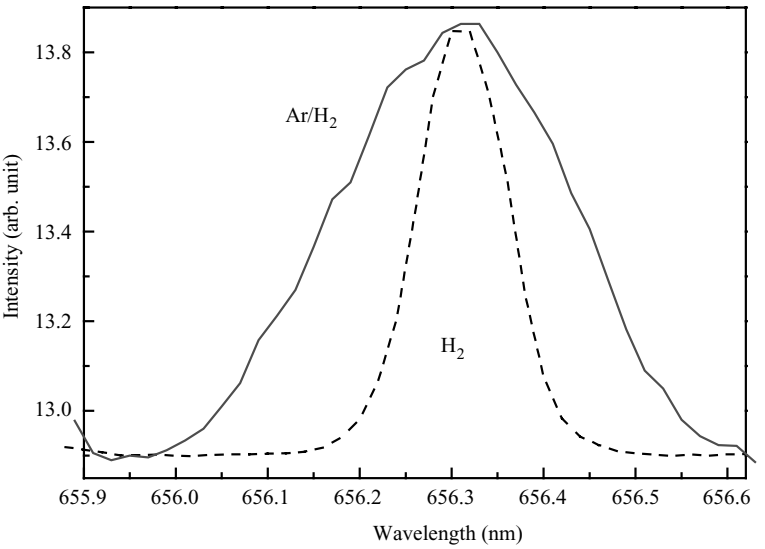

Figure 17. The 656.3 nm Balmer α line width recorded with a high-resolution ($\pm$0.025 nm) visible spectrometer on an argon–hydrogen and a hydrogen gas discharge plasma of a type III light source. Significant broadening was observed corresponding to an average hydrogen atom temperature of 30–35 eV.

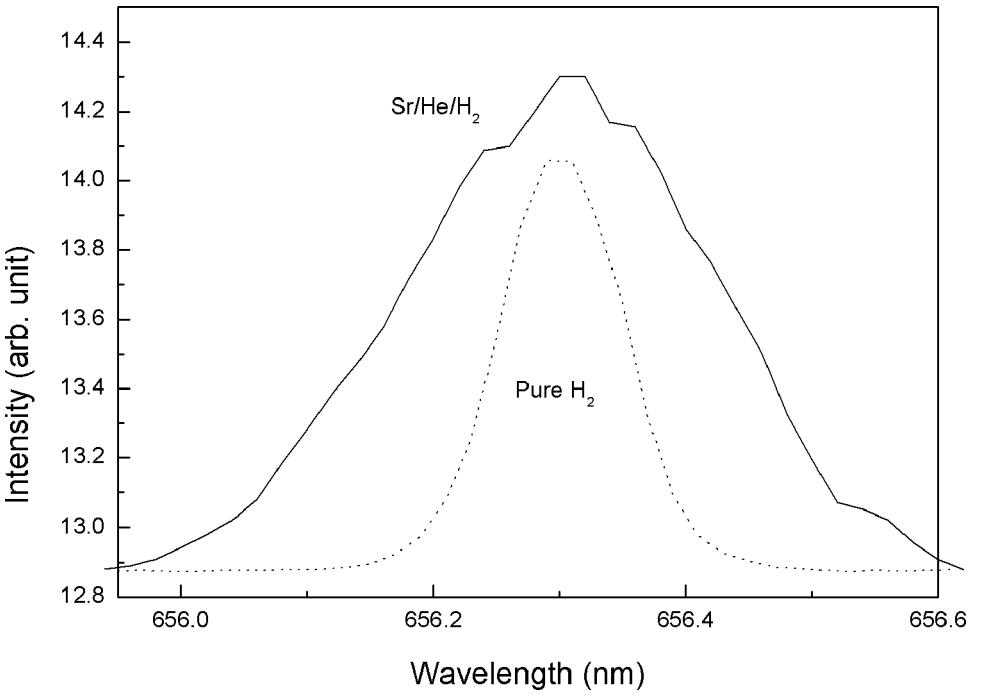

Figure 18. The 656.3 nm Balmer α line width recorded with a high-resolution ($\pm$0.025 nm) visible spectrometer on a strontium–helium–hydrogen and a hydrogen gas discharge plasma of a type III light source. Significant broadening was observed corresponding to an average hydrogen atom temperature of 40–45 eV.

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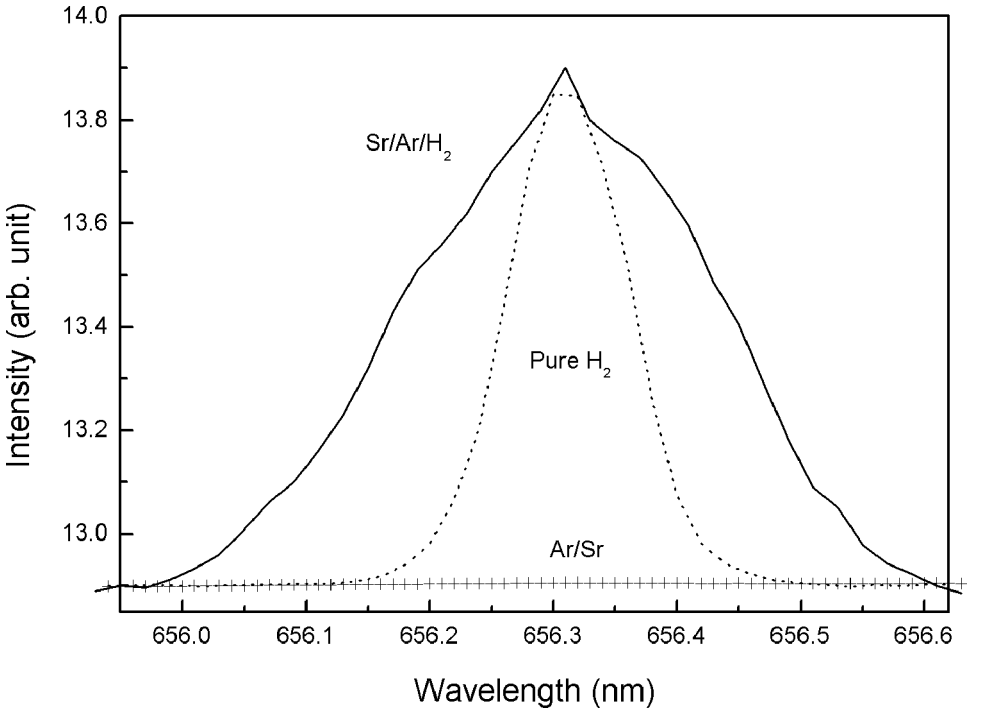

Figure 19. The 656.3 nm Balmer α line width recorded with a high-resolution ($\pm$0.025 nm) visible spectrometer on a strontium–argon–hydrogen, strontium–argon, and a hydrogen gas discharge plasma of a type III light source. Significant broadening was observed corresponding to an average hydrogen atom temperature of 35–40 eV.

krypton–hydrogen, xenon–hydrogen and magnesium–hydrogen showed no excessive broadening corresponding to an average hydrogen atom temperature of $\approx$4 eV. No voltage effect was observed with the argon–hydrogen and strontium–hydrogen plasmas.

3.6. Optically measured power balance

The count rate and spectrometer system irradiation of the background spectrum of hydrogen and strontium vapour over the wavelength range $400 \leqslant \lambda \leqslant 700$ nm in the absence of power applied to the electrode and in the absence of a discharge were measured. These data were collected during cell evacuation following the test with strontium and hydrogen at a cell temperature of 664 °C. The maximum visible irradiation of 0.004 μW cm^{-2}/nm occurred at the red end of the visible spectrum. The results are summarized in Table 2, where T is the temperature, P_{hyd} is the hydrogen partial pressure and P_v is the equilibrium metal vapour pressure calculated from standard curves of the vapour pressure as a function of temperature [20].

Power was applied to the electrode to achieve a bright plasma in the strontium–hydrogen mixture and the controls of hydrogen alone, and sodium–hydrogen, magnesium–hydrogen and barium–hydrogen mixtures for cell temperatures in the range 335–666 °C. In each case, the spectral radiant flux at the spectrometer system was recorded. If possible, the power driving the controls was adjusted such that the peak spectrometer system spectral irradiation was about 0.1 μW cm^{-2}/nm in each

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Table 2. Discharge conditions and comparison of the driving power to achieve a total visible radiant flux of about 1 μW cm^{-2}.

	T (°C)	P_{hyd} (torr)	P_v (torr)[a]	Voltage (V)	Current (mA)	Integ. time (ms)	Detector irradiation (μW cm^{-2})	Power (W)
$H_2 + Sr$	664	–	0.270	2.20	3.86	768	1.17	0.0085
H_2	664	1.0	–	224	110	1130	2.08	24.6
$H_2 + Na$	335	1.0	0.051	272	124	122	1.85	33.7
$H_2 + Na$	516	1.5	5.3	220	68	768	0.40	15.0
$H_2 + Na$	664	1.5	63	240	41	768	0.41	9.84
$H_2 + Mg$	449	4.0	0.016	153	380	500	1.7	58
$H_2 + Mg$	582	4.2	0.6	233	290	500	0.16	68
$H_2 + Mg$	654	3.0	2.8	250	400	1000	0.18	100.0
$H_2 + Ba$	666	2.0	0.025	138	730	716	0.03	55[b]
Bkgnd	664	–	0.270	0	0	768	0.20	0

[a]Calculated [20].
[b]Power input differs from volt amperes due to nonunity power factor.

case. The integrated visible irradiation levels were of the order of 1 μW cm^{-2}. One exception was the case of hydrogen–barium. In this case, the maximum spectral irradiation levels and integrated visible irradiation levels were only of the order of 0.01 μW cm^{-2}/nm and 0.03 μW cm^{-2}, respectively.

The power required to maintain a plasma of equivalent optical brightness with strontium present was 4000, 7000 and 6500 times less than that required for the sodium, magnesium and barium control, respectively. A driving power of 33.7 and 58 W was necessary to achieve a total visible radiant flux of about 1 μW cm^2 from a sodium–hydrogen mixture and a magnesium–hydrogen mixture, respectively. For a hydrogen–barium mixture, a power input of about 55 W was required to achieve a total visible irradiation of about 0.03 μW cm^{-2}. Whereas, in the case of a strontium–hydrogen mixture, a power input of 8.5 mW resulted in a plasma with a total visible radiant flux of about the same optical brightness as sodium and magnesium. A plasma formed at a cell voltage of about 250 V for hydrogen alone and sodium–hydrogen mixtures, and 140–150 V for hydrogen–magnesium and hydrogen–barium mixtures; whereas, a plasma formed for hydrogen–strontium mixtures at the extremely low voltage of about 2 V. The results are summarized in Table 2.

The count rate and the spectrometer system irradiation for a mixture of hydrogen and strontium vapour at 664 °C is shown in Fig. 20. Optimal light emission was observed after several hours of cell evacuation. The hydrogen partial pressure was unknown under these conditions. The calculated equilibrium vapour pressure of strontium at 664 °C is approximately 270 mtorr. The measured breakdown voltage was approximately 2 V. The maintenance voltage for a stable discharge was 2.2 V and the input power was 8.5 mW. Spectral characteristics are noted in Table 3. The hydrogen Balmer α and β peaks were obscured by strong strontium emission near 654.7 and 487.2 nm, respectively.

The spectrometer system irradiation for a hydrogen discharge at a cell temperature of 664 °C and 1 torr is shown in Fig. 21. The breakdown voltage was approximately 220 V. The field voltage required to form a stable discharge was 224 V. The input power was 24.6 W. Spectral features are tabulated in Table 4. The peak at

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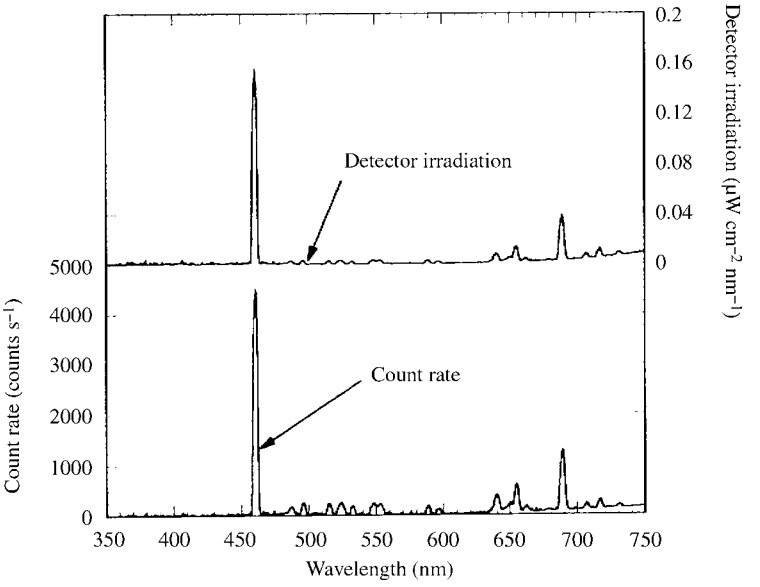

Figure 20. The count rate and the spectrometer system irradiation of a type IV light source with a mixture of hydrogen and strontium vapour at 664 °C.

Table 3. Spectral features of hydrogen and strontium at 664 °C.

Measured wavelength (nm)	Spectrometer system irradiation (μW cm^{-2}/nm)	Published emission data [21] (nm)
460.6	0.156	460.73 (Sr I)
487.2	0.002 90	487.25 (Sr I), 486.13 (H I)
639.8	0.008 13	638.82 (Sr I)
654.7	0.0139	654.68 (Sr I), 656.29 (H I)
689.4	0.0386	689.26 (Sr I)

589.1 nm may be due to sodium contamination from a previous experimental run. The minor peaks at 518.2 and 558.7 nm have not been identified.

The spectrometer system irradiation for mixtures of hydrogen and sodium vapour are shown in Figs 22(a)–(c) for temperatures of 335, 516 and 664 °C, respectively. Corresponding hydrogen pressures are 1, 1.5 and 1.5 torr, respectively. The calculated sodium vapour pressure was 51 mtorr, 5.3 and 63 torr at 335, 516 and 664 °C, respectively. At least 200 V was required to maintain a discharge. The input power for a stable discharge ranged from approximately 10 W at 664 °C to 34 W at 335 °C. Spectral features corresponding to 335 °C are summarized in Table 5. Strong emission observed near 656–657 nm was probably due, in part, to hydrogen. The relative contribution to the intensity was masked by strong sodium emission at a slightly shorter wavelength. The peak at 486.2 nm could only be due to hydrogen emission. Sodium does not have emission lines in the neighbourhood of this wavelength. The intensity of this peak diminishes relative to the more prominent sodium peaks with increasing temperature as shown in Figs 22(a)–(c). This may have been due to a decreasing hydrogen concentration as the sodium vapour pressure increased.

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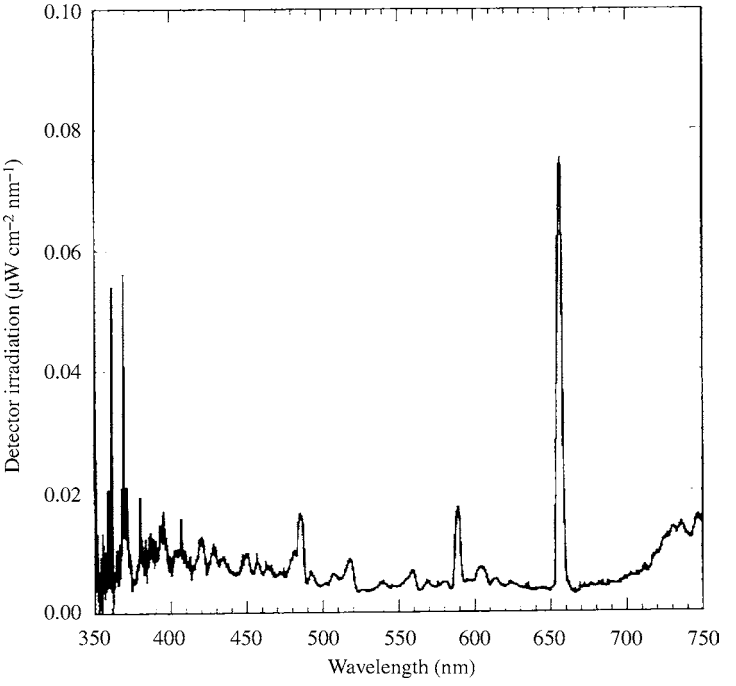

Figure 21. The spectrometer system irradiation for a hydrogen discharge of a type IV light source at a cell temperature of 664 °C and a hydrogen pressure of 1 torr.

Table 4. Spectral features of hydrogen at 664 °C.

Measured wavelength (nm)	Spectrometer system irradiation (μW cm^{-2}/nm)	Published emission data [21] (nm)
485.8	0.0165	486.13 (H I)
518.2	0.008 94	
558.7	0.006 94	
589.1	0.0174	589.00 (Na I), 589.59 (Na I)
656.7	0.0752	656.29 (H I)

The spectral response for mixtures of magnesium vapour and hydrogen are shown in Figs 23(a)–(c) for temperatures of 449, 582 and 654 °C, respectively. The corresponding hydrogen pressures are 4, 4.2 and 3 torr, respectively. A minimum of 150 V was required to maintain a discharge. The minimum input power required to maintain a stable discharge was 58 W at 449 °C. Spectral features corresponding to 449 °C are summarized in Table 6. Both hydrogen and magnesium spectral features are observed. The modest sodium emission at 588 nm may be due to sodium contamination from previous control experiments.

The spectral response for a mixture of barium vapour and hydrogen at 666 °C is shown in Fig. 24. The hydrogen partial pressure and barium vapour pressure are 2 torr and 25 mtorr, respectively. It was not possible to achieve a total visible irradiation level of 1 μW cm^{-2} even with voltages approaching 150 V. The voltage and power input corresponding to Fig. 24 are 138 V and 55 W, respectively. Spectral

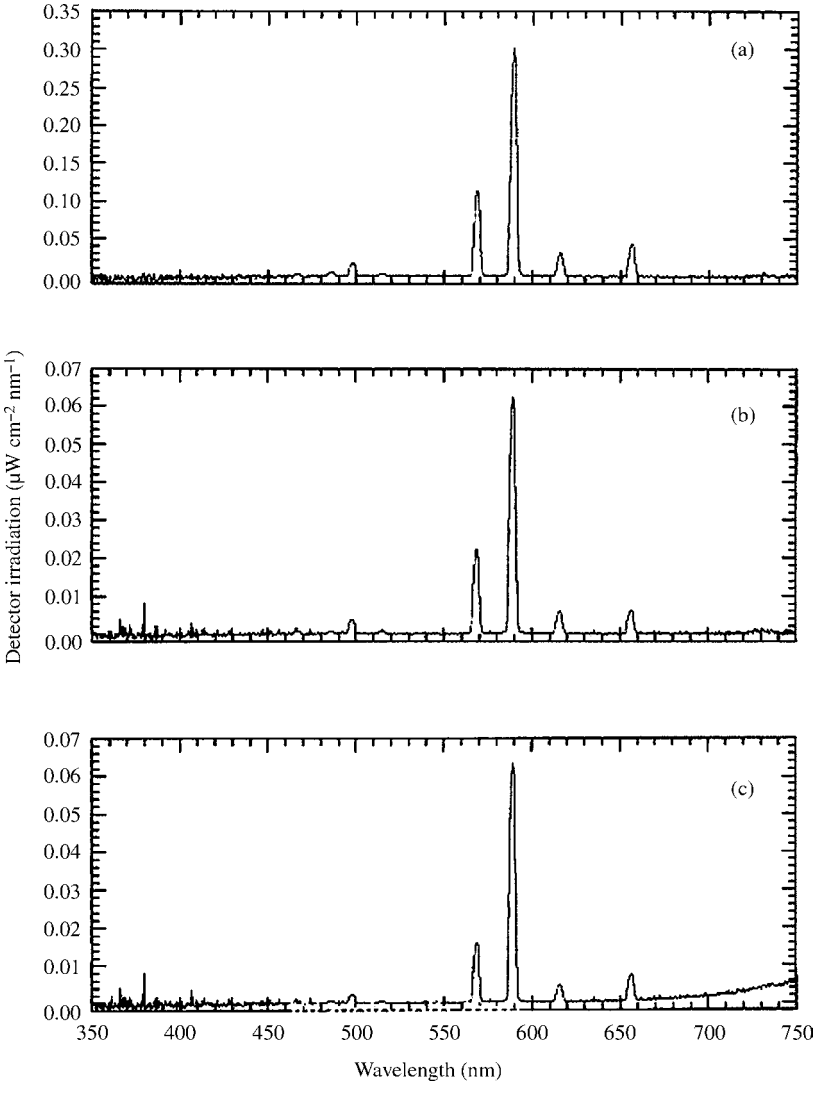

Figure 22. The spectrometer system irradiation of a type IV light source with a mixture of hydrogen and sodium vapour at (a) 335, (b) 516 and (c) 664 °C.

features are summarized in Table 7. Both barium and hydrogen spectral features are observed as well as sodium features, which are presumably due to contamination. The peak at 493 nm has not been identified.

4. Discussion

Intense VUV emission was observed at low temperatures (e.g. $\approx 10^3$ K) from atomic hydrogen and strontium, which ionizes at integer multiples of the potential energy of atomic hydrogen to generate a resonant transfer plasma. In the cases where Lyman α emission was observed, no possible chemical reactions of the tungsten filament, the dissociator, the vaporized strontium and 300 mtorr hydrogen at a

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Table 5. Spectral features of hydrogen and sodium at 335 °C.

Measured wavelength (nm)	Spectrometer system irradiation ($\mu W\,cm^{-2}/nm$)	Published emission data [21] (nm)
467.2	0.004 00	466.86 (Na I)
486.2	0.0055	486.13 (H I)
498.4	0.0176	498.28 (Na I)
516.1	0.003 80	515.34 (Na I)
569.0	0.114	568.82 (Na I)
589.3	0.302	589.00 (Na I), 589.59 (Na I)
615.9	0.0310	616.07 (Na I)
656.0	0.0422	656.29 (H I), 655.24 (Na II)
657.0	0.0421	656.29 (H I)

cell temperature of 700 °C could be found to account for the hydrogen α line emission. In fact, no known chemical reaction releases enough energy to excite Lyman α emission from hydrogen. The emission was not observed with hydrogen alone or with helium, neon or argon gas. Intense emission was observed for strontium with hydrogen gas, but no emission was observed with hydrogen or strontium alone. This result indicates that the emission may be due to a reaction of hydrogen. The increase in intensity with the formation of He^+ and the equal dependence of the emission on the presence of both He^+ and atomic hydrogen indicates a reaction between these species.

Other studies support the possibility of a novel reaction of atomic hydrogen which produces an rt-discharge under extraordinary low field conditions. It has been previously reported that intense vacuum ultraviolet emission was observed from atomic hydrogen and certain atomized elements or certain gaseous ions [3–14] with incandescent heating at low temperatures (e.g. $\approx 10^3$ K). The only pure elements that were observed to emit VUV were those wherein the ionization of t electrons from an atom to a continuum energy level is such that the sum of the ionization energies of the t electrons is approximately $m \cdot 27.2$ eV, where t and m are each an integer. Sr^+ ionizes at an integer multiple of the potential energy of atomic hydrogen and caused emission, whereas the chemically similar metals sodium, magnesium and barium, do not ionize at integer multiples of the potential energy of atomic hydrogen and caused no emission.

In our studies, rt-plasmas were formed by helium, argon and strontium catalysts [>]. He^+ ionizes at 54.417 eV [15], which is $2 \cdot 27.2$ eV. While the ionization energy of Ar^+ to Ar^{2+} is 27.6 eV [15] and the ionization of Sr^+ to Sr^{3+} has a net enthalpy of reaction of 53.92 eV [15], an electric field may adjust the energy of ionizing Ar^+ to Ar^{2+} and Sr^+ to Sr^{3+} to match the energy of 27.2 eV and $2 \cdot 27.2$ eV, respectively.

The characteristic emission from Sr^+ and Sr^{3+} confirmed the resonant nonradiative energy transfer of $2 \cdot 27.2$ eV from atomic hydrogen to Sr^+. Atomic strontium may serve as a catalyst as well, which may initiate the rt-plasma and form Sr^+ [9]. With a highly conductive plasma, the voltage of the cell was about 20 V, and the field strength was about 1–2 V cm^{-1}, which was too low to ionize Sr^+ to Sr^{3+} which requires at least 53.92 eV, rather a resonant energy transfer explains the observations.

Line broadening of the hydrogen Balmer lines provides a sensitive measure of the number and energy of excited hydrogen atoms in a plasma. To further characterize

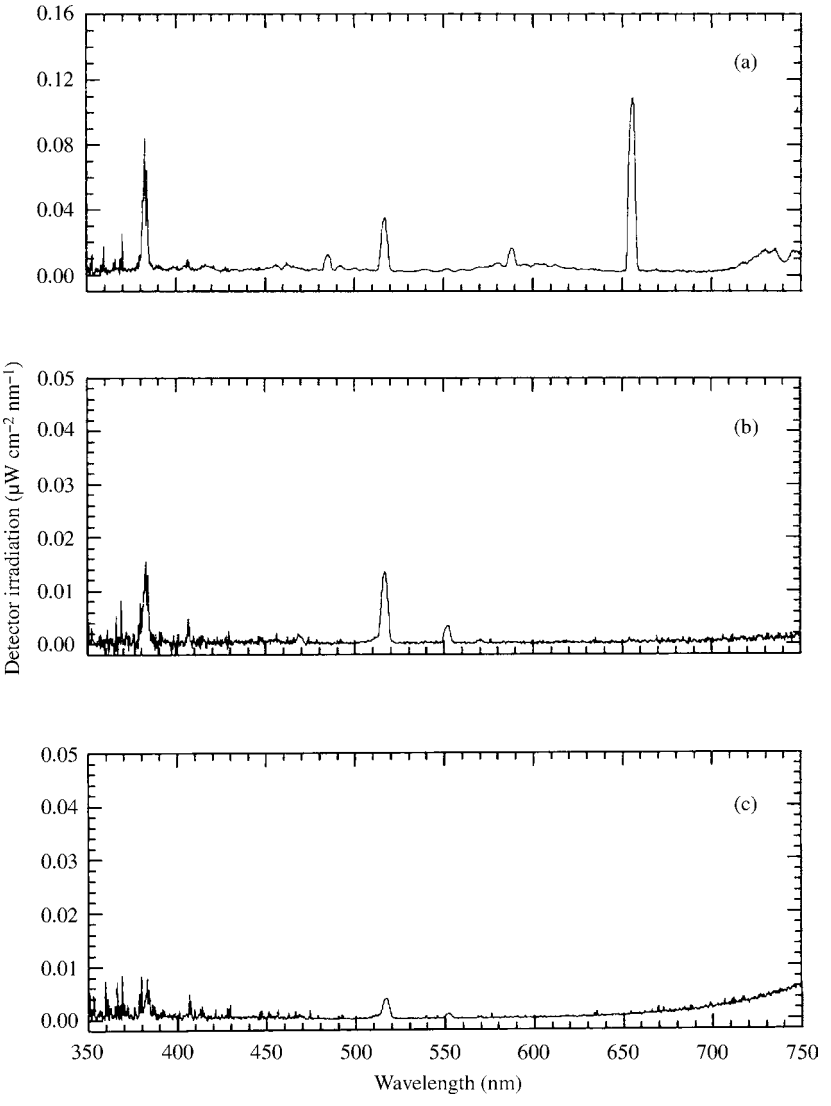

Figure 23. The spectrometer system irradiation of a type IV light source with a mixture of hydrogen and magnesium vapour at (a) 449, (b) 582 and (c) 654 °C.

Table 6. Spectral features of hydrogen and magnesium at 449 °C.

Measured wavelength (nm)	Spectrometer system irradiation (μW cm^{-2}/nm)	Published emission data [21] (nm)
382.6	0.0843	382.93 (Mg I), 383.23 (Mg I)
384.0	0.0643	383.83 (Mg I)
485.2	0.0122	486.13 (H I)
517.3	0.0353	517.27 (Mg I), 518.36 (Mg I)
588.1	0.0167	589.00 (Na I), 589.59 (Na I)
655.8	0.109	656.29 (H I)

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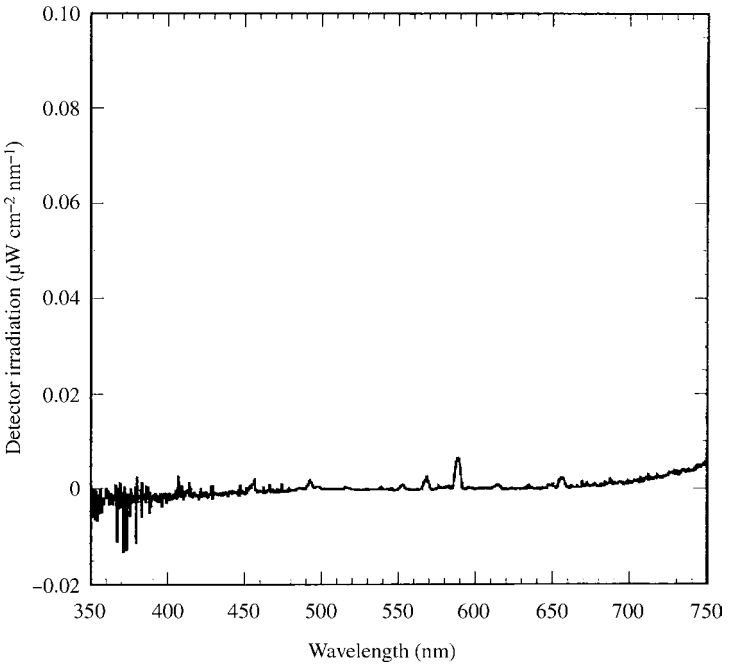

Figure 24. The spectrometer system irradiation of a type IV light source with a mixture of hydrogen and barium vapour at 666 °C.

Table 7. Spectral features of hydrogen and barium at 666 °C.

Measured wavelength (nm)	Spectrometer system irradiation ($\mu W\,cm^{-2}/nm$)	Published emission data [21] (nm)
456.2	0.0021	455.40 (Ba II)
492.6	0.002	
552.7	8.4×10^{-4}	553.55 (Ba I)
568.4	0.003	568.26 (Na I)
588.8	0.006	589.00 (Na I)
614.7	9.0×10^{-4}	614.17 (Ba II)
655.9	0.002	656.29 (H I)

the plasma parameters of rt-plasmas, the width of the 656.3 nm Balmer α line was recorded on light emitted from rt-plasmas formed from hydrogen with a gaseous ion which ionizes at integer multiples of the potential energy of atomic hydrogen. The energetic hydrogen atom densities and energies were determined from the intensity and broadening, and it was found that significant line broadening of 14 eV and an atom density of 8×10^{11} atoms cm^{-3} were observed from an rt-plasma of hydrogen formed with strontium. Whereas, a glow discharge of hydrogen maintained at the same total pressure with an electric field strength that was at least two orders of magnitude greater than the 1 V cm^{-1} field of the filament cell showed no excessive broadening corresponding to an average hydrogen atom temperature of $\approx$3 eV.

In the characterization of argon–hydrogen (97/3%) Grimm-type plasma discharges with a hollow anode, Kuraica and Konjevic [24] and Videnovic et al.

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[16] analysed the broadening data in terms of Stark and Doppler effects, wherein acceleration of charges such as H^+, H_2^+ and H_3^+ in the high fields (e.g. over $10\,kV\,cm^{-1}$) which were present in the cathode fall region was used to explain the Doppler component. In our experiments with type I cells, the measured field of the incandescent heater was extremely weak, $1\,V\,cm^{-1}$, corresponding to a broadening of much less than 1 eV. Thus, we have assumed that Doppler broadening due to thermal motion was the dominant source in the rt-plasmas to the extent that other sources may be neglected. In general, the experimental profile is a convolution of a Doppler profile, an instrumental profile, the natural (lifetime) profile, Stark profiles, van der Waals profiles, a resonance profile and fine structure. The source of broadening was confirmed to be Doppler alone by considering each possible source according to the methods described previously [25, 26]. For example, using a compensated Langmuir probe [18], the electron density was measured to be $n_e < 10^{10}\,cm^{-3}$, which is at least five orders of magnitude too low to invoke Stark broadening as discussed previously [25, 26].

It was reported previously [25, 26] that microwave helium–hydrogen and argon–hydrogen plasmas showed extraordinary broadening corresponding to an average hydrogen atom temperature of 180–210 and 110–130 eV, respectively. Whereas, pure hydrogen and xenon–hydrogen microwave plasmas showed no excessive broadening corresponding to an average hydrogen atom temperature of ≈4 eV. No hydrogen species, H^+, H_2^+, H_3^+, H^-, H or H_2, responds to the microwave field; rather, only the electrons respond. But, the measured electron temperature was about 1 eV, which requires that $T_H \gg T_e$. This result cannot be explained by electron or external Stark broadening or electric field acceleration of charged species. The electron density was five orders of magnitude too low [25, 26] for detectable Stark broadening. And, in microwave-driven plasmas, there is no high electric field in a cathode fall region ($> 1\,kV\,cm^{-1}$) to accelerate positive ions as proposed previously [16, 27–29] to explain significant broadening in hydrogen-containing plasmas driven at high-voltage electrodes. It is impossible for H or any H-containing ion which may give rise to H, to have a higher temperature than the electrons in a microwave plasma. The observation of excessive Balmer line broadening in a microwave-driven plasma requires a source of energy other than that provided by the electric field. The formation of fast H was explained by resonant energy transfer between hydrogen atoms and Ar^+ or He^+ of an integer multiple of the potential energy of atomic hydrogen, 27.2 eV. Similarly, the excessive line broadening in the strontium and argon–strontium rt-plasmas is explained by an energetic reaction caused by a resonant energy transfer between hydrogen atoms and strontium or Ar^+ catalysts.

An rt-plasma with hydrogen–potassium mixtures has been reported in an experiment identical to the present VUV experiments [13] with type I cells. In this experiment and that treated in [12], an rt-plasma formed with hydrogen–potassium mixtures wherein the plasma decayed with a 2 s half-life when the electric field was set to zero [12]. This was the thermal decay time of the filament that dissociated molecular hydrogen to atomic hydrogen. This experiment showed that hydrogen line emission was occurring even though the voltage between the heater wires was set to and measured to be zero and indicated that the emission was due to a reaction of potassium atoms with atomic hydrogen. Potassium atoms ionize at an integer multiple of the potential energy of atomic hydrogen, $m \cdot 27.2$ eV. The enthalpy of ionization of K to K^{3+} has a net enthalpy of reaction of 81.7426 eV, which is equivalent to $m = 3$. The observation of K^{3+} has been reported previously [6].

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As reported previously, an rt-plasma of hydrogen and certain alkali ions formed at low temperatures ($< 10^3$ K) the H plasma was confirmed by VUV spectroscopy and hydrogen Balmer and alkali line emissions in the visible range [13]. The observed plasma formed from atomic hydrogen generated at a tungsten filament that heated a titanium dissociator and one of potassium, rubidium, caesium and their carbonates and nitrates. These atoms and ions ionize to provide a net enthalpy of reaction of an integer multiple of the potential energy of atomic hydrogen ($m \cdot 27.2$ eV, m = integer) to within 0.17 eV and comprise only a single ionization in the case of a potassium or rubidium ion. Whereas, the chemically similar atoms of sodium and sodium and lithium carbonates and nitrates, which do not ionize with these constraints, caused no emission. To test the electric dependence of the emission, a weak electric field of about 1 V cm^{-1} was set and measured to be zero in $< 0.5 \times 10^{-6}$ s. An afterglow duration of about 1–2 s was recorded in the case of potassium, rubidium, caesium, K_2CO_3, $RbNO_3$ and $CsNO_3$. Hydrogen line or alkali line emission was occurring even though the voltage between the heater wires was set to and measured to be zero. These atoms and ions ionize to provide a net enthalpy of reaction of an integer multiple of the potential energy of atomic hydrogen to within less than the thermal energies at $\approx 10^3$ K and comprise only a single ionization in the case of a potassium or rubidium ion. Since the thermal decay time of the filament for dissociation of molecular hydrogen to atomic hydrogen was similar to the rt-plasma afterglow duration, the emission was determined to be due to a reaction of atomic hydrogen with each of the atoms or ions that did not require the presence of an electric field to be functional.

The width of the 656.3 nm Balmer α line emitted from gas discharge plasmas having atomized hydrogen from pure hydrogen alone, hydrogen with magnesium or strontium, a mixture of 10% hydrogen and helium, argon, krypton or xenon, and a mixture of 10% hydrogen and helium or argon with strontium was also measured with a high-resolution (± 0.025 nm) visible spectrometer on light emitted from type III cells. The energetic hydrogen atom densities and energies were determined from the Balmer α line intensities and broadening, and it was found that strontium–hydrogen, helium–hydrogen, argon–hydrogen, strontium–helium–hydrogen and strontium–argon–hydrogen plasmas showed significant broadening corresponding to an average hydrogen atom temperature of 23–45 eV, whereas, pure hydrogen, krypton–hydrogen, xenon–hydrogen and magnesium–hydrogen showed no excessive broadening corresponding to an average hydrogen atom temperature of ≈ 4 eV. Thus, line broadening was only observed for the atoms and ions which provided a net enthalpy of reaction of a multiple of the potential energy of the hydrogen atom.

In our normal glow discharge studies with argon–hydrogen plasmas, the voltage was increased at 50 V increments from 275 to 475 V, and the high-resolution visible spectra were recorded to observe the effect of voltage on the Balmer α line broadening. In contrast to an increase in broadening with voltage predicted by Kuraica and Konjevic [24], no voltage effect was observed. Also, no voltage effect was observed with the strontium–hydrogen plasma, which supports the rt-plasma mechanism of the low-voltage strontium–hydrogen plasma reported in the optically measured power balance section.

Since line broadening is a measure of the plasma temperature, and a significant increase was observed for strontium with hydrogen, the power balance of a gas cell having vaporized strontium and atomized hydrogen from pure hydrogen was

Table 8. Glow discharge parameters from von Engel [22] and Naidu and Kamaraju [23].

Gas	Minimum starting voltage (V)	Pressure-discharge gap product at minimum starting voltage (cm torr)
N_2	251	0.67
H_2	273	1.15
Air	327	0.567
CO_2	420	0.51
Ar	137	0.9
He	156	4.0
Hg	520	2
Na	335	0.04

measured by integrating the total light output corrected for spectrometer system response and energy over the visible range. A cylindrical nickel mesh hydrogen dissociator of a gas cell also served as an electrode to produce an essentially uniform radial electric field between the dissociator and the wall of the cylindrical stainless steel gas cell. Power was applied to the electrode to achieve a bright plasma which was recorded over the wavelength range $400 \leqslant \lambda \leqslant 700$ nm. Control experiments were identical except that sodium, magnesium or barium replaced strontium. In the case of hydrogen–sodium, hydrogen–magnesium and hydrogen–barium mixtures, 4000, 7000 and 6500 times the power of the hydrogen–strontium mixture was required, respectively, in order to achieve the same optically measured light output power. A plasma formed at a cell voltage of about 250 V for hydrogen alone and sodium–hydrogen mixtures, and 140–150 V for hydrogen–magnesium and hydrogen–barium mixtures; whereas, a plasma formed for hydrogen–strontium mixtures at the extremely low voltage of about 2 V. This is two orders of magnitude lower than the starting voltages measured for gas glow discharges, cf. Table 8.

The observation of plasmas formed with strontium and hydrogen at 1% of the theoretical or prior known voltage requirement with a light output per unit power input up to 7000 times that of the control standard light source has implications for an advanced light source based on a resonant energy transfer between hydrogen atoms and strontium.

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