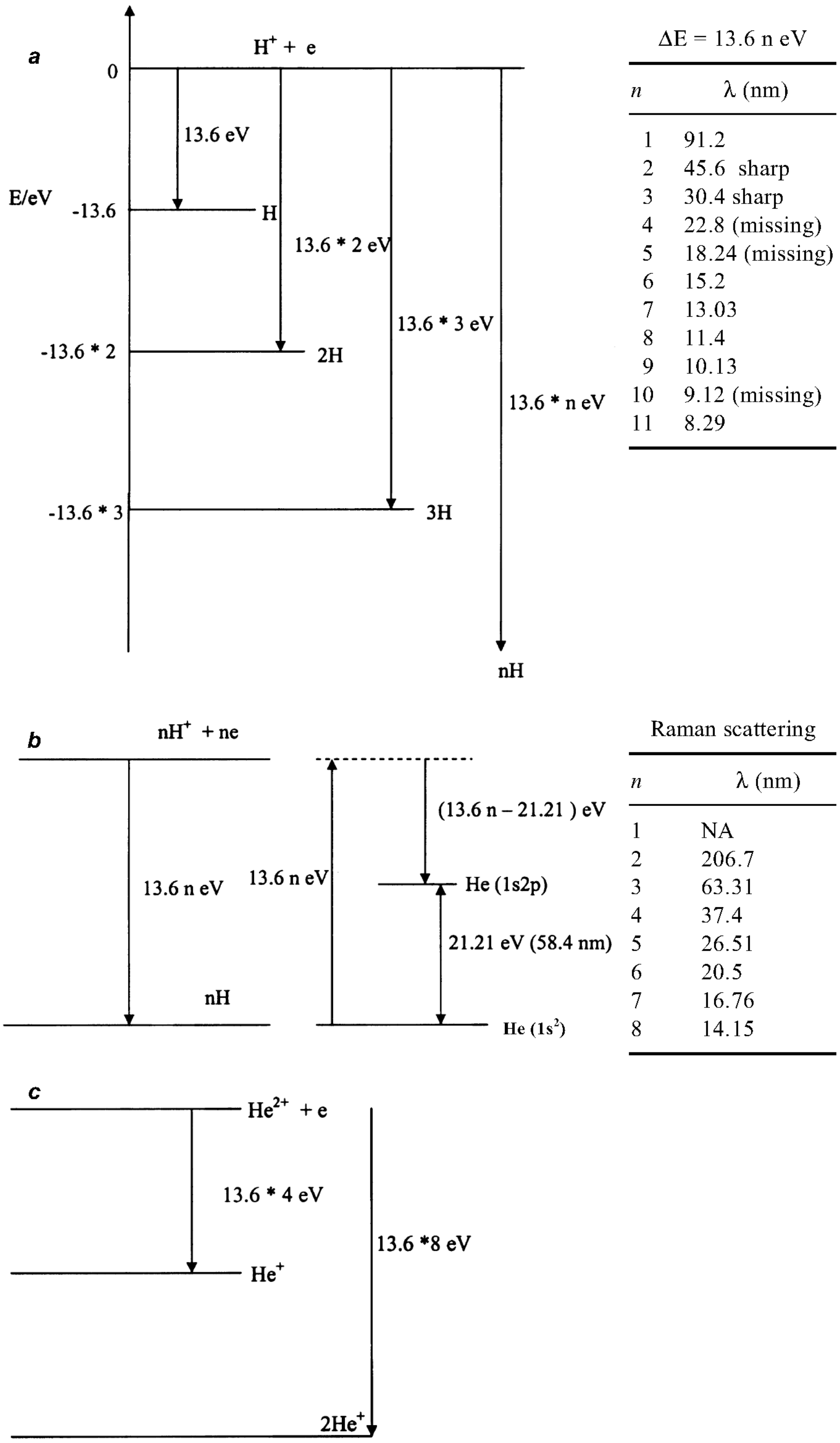
Possible explanation for the extended UV emission lines from helium–hydrogen plasma*

Absorption/emission spectrum of hydrogen atom resulting from electric and microwave discharges has been studied for more than a century now. Efforts to interpret it correctly led to the development of quantum theory and quantum mechanics and quantum electrodynamics eventually. Interestingly, there seem to be still some parts of it that remain to be understood. Recently, Mills and coworkers[1,2] have reported the observation of some novel emission lines in the extreme ultraviolet (EUV) region from helium–hydrogen (98/2%) plasmas. They showed that they corresponded to 13.6 n eV, where n = 1, 2, 3, 7, 9 and 11 and {13.6 n – 21.21} eV, with n = 4, 6 and 8. They interpreted their results in terms of states of H atom that could be assigned fractional quantum numbers and invoked a catalytic mechanism for the observation of emission lines resulting from nonradiative states.

In this paper, we point out a simple way in which their results could be interpreted.

The energy (E_g) of the ground state of H atom is known to be – 13.6 eV. On recombination of a proton and an electron in a discharge plasma, one can expect an emission line corresponding to 13.6 eV. If there are several H atom recombinations taking place simultaneously, under favourable circumstances, there could be emissions corresponding to integral (n) multiples of 13.6 eV, as illustrated in Figure 1 *a*. In addition to emission corresponding to $n = 1$ at $\lambda = 91.2$ nm, which is standard (not shown in their paper) prominent emission corresponding to $n = 2$ and 3 at $\lambda = 45.6$ and 30.4 nm, respectively can be readily seen as sharp lines in figures 7, 10 and 12 of ref. 1 and they are several orders of magnitude less intense than the lines observed beyond (>) 50 nm. Lines of much less intensity corresponding to $n = 9$ and 11 at $\lambda =$ 10.13 and 8.29 nm are clearly identifiable in figure 12 of ref. 1. The line corresponding to $n = 7$ at $\lambda = 13.03$ nm can be barely made out in figure 12 of ref. 1. The lines corresponding to other values



ΔE = 13.6 n eV

n	λ (nm)
1	91.2
2	45.6 sharp
3	30.4 sharp
4	22.8 (missing)
5	18.24 (missing)
6	15.2
7	13.03
8	11.4
9	10.13
10	9.12 (missing)
11	8.29

Raman scattering

n	λ (nm)
1	NA
2	206.7
3	63.31
4	37.4
5	26.51
6	20.5
7	16.76
8	14.15

Figure 1. Illustration of (*a*) harmonic generation by hydrogen atom recombination in helium–hydrogen plasma, (*b*) Raman scattering involving the harmonic emission and the ground and the first excited states of He and (*c*) light emission resulting from (He^{2+}, e) recombination and its second harmonic.

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*Dedicated to Prof. S. Ramaseshan on his 80th birthday.

of n (4, 5, 6, 8 and 10) are not evident in their reported spectrum. Either they are buried in the noise or there is a reason for their absence.

If indeed there are harmonic emissions corresponding to 13.6 n eV, $n = 2$–11, these lines could be scattered inelastically by the He atoms that are abundant in the plasma, as illustrated in Figure 1 *b*. The most likely inelastic transition in He is $1s^2 \rightarrow 1s2p$ and this involves an energy difference of 21.21 eV. Therefore, the observed Raman (inelastic scattering of the harmonics shown in Figure 1 *a*) lines would be expected at ($13.6\,n$–21.21) eV, $n = 2$–11. For $n = 1$, the energy of the photon is much less than that required for the electronic excitation in He. For $n = 2$ and 3, the Raman lines would be expected at 206.7 and 63.31 nm, respectively and they fall outside the region of the EUV spectrum reported in refs 1, 2. For $n = 4$, the Raman line would be expected to occur at $\lambda = 37.4$ nm, and it is clearly seen as a prominent peak in figures 7, 10 and 12 of ref. 1. The other lines corresponding to $n = 6$ and 8 occur, as expected, at $\lambda = 20.5$ and 14.15 nm, respectively. The lines corresponding to $n = 5$ and 10 are clearly missing (or are not above the noise level).

Clearly there is a complementarity between the observed harmonics and the Raman lines. For $n = 2$, 3, 9 and 11, the harmonics are clearly noticeable and for $n = 4$, 6 and 8 the Raman lines are clearly noticeable. For some reason, lines corresponding to $n = 5$ and 10 are missing, on both counts.

There could also be emission resulting from the recombination of He^{2+} and an electron to yield He^+ in its ground state, at $\lambda = 22.8$ nm and this could be inelastically scattered by He ($1s^2$), accounting for the line at $\lambda = 37.4$ nm, as illustrated in Figure 1 *c*. In addition, there could be the emission corresponding to the second harmonic of the (He^{2+}, e) recombination and concomitant Raman scattering by He ($1s^2$) resulting in emission at $\lambda =$ 14.15 nm (see Figure 1 *c*). In principle, one could resolve the components of emission at $\lambda = 22.8$ nm and 14.15 nm arising from the harmonics of (H^+, e) recombination and (He^{2+}, e) recombination, based on the differences in the reduced mass of the electron relative to the hydrogen nucleus and the helium nucleus. In practice, this is not possible at the present level of spectral resolution.

Mills and Ray[1,2] have clearly pointed out that the emission lines mentioned above are not observed when pure He or H_2 is used in the discharge, or when other gases such as Ne, Ar, Kr, Xe, N_2, O_2 and CO_2 are used along with H_2.

Why only the helium–hydrogen (98/2%) plasma leads to EUV emission remains to be understood. One has to examine the origin of the harmonics emission. There could be some aspects of the plasma that make this possible.

One might argue about our usage of the expression 'Raman scattering', which is usually used in the context of vibrational/rotational inelastic transition. This is because the usually available visible light sources do not have sufficient energy to cause electronic transitions. There is no reason why electronic Raman cannot occur, if suitable light source is available and the corresponding selection rules are obeyed[3]. It is not clear as to why emission lines corresponding to $n = 5$ and 10 are missing and also why there is a complementarity between the emission corresponding to $n = 2$, 3, 7, 9 and 11 and Raman scattering with emission corresponding to $n = 4$, 6 and 8.

These are clearly issues that need further investigation and we hope to take up some of them in the immediate future.

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2. Mills, R. L., Ray, P., Dhandapani, B., Nansteel, M., Chen, X. and He, J., *J. Quant. Spectrosc. Radiat. Transfer*, 2003, **76**, 117–130.
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A rapid method for measuring olfactory responses of *Drosophila* larva*

The olfactory responses of *Drosophila* larvae are measured by following its chemotactic movements on a petri dish. Several variants of this test have been employed. In the commonly used version of the experiment[1–3], diluted odorant is placed near the edge of the dish and a spot of the diluent diametrically opposite. After 5 min, the larvae on the two halves of the dish, the odour side (*O*) and the control side (*C*) are counted, and the response index is computed as $O - C/O + C$. This method of measuring olfactory response suffers from certain disadvantages. The test is slow; since the odour spreads on the dish by diffusion, it takes a few minutes for the larvae on the farther side of the odour source to respond. On the other hand, the larvae near the source respond early and, if the concentration of the odorant is high, they become desensitized and wander-off. We describe here a modification of the larval test, which enables us to assess the attraction response rapidly by measuring the initial rate of entry in a zone around the odour source.

CsBZ flies were grown on standard cornmeal yeast medium at 24°C and

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