Introductory helium atomic spectrum analysis

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We present a spreadsheet that introduces undergraduate students to the analysis of helium atomic spectrum data. © *2009 American Association of Physics Teachers.*
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I. INTRODUCTION

The measurement and analysis of the visible hydrogen spectrum is a standard experiment performed by nearly every undergraduate physics major. Students measure the four visible lines of the Balmer series, and the analysis includes verifying Balmer's formula and measuring the Rydberg constant. The hydrogen spectrum experiment is ideal because the spectral data were key ingredients in the development of quantum mechanics and can be understood using a simple relation.

The spectra of other atoms are not as simple to analyze. Adding just one more proton to the nucleus and one more orbiting electron to the atom for helium results in the complications of shielding and the effects of indistinguishable particles on the energy level structure. The energy levels of helium are discussed in upper level quantum mechanics courses as an example of identical fermions,[1] and an analysis of the helium spectrum data is usually not done by undergraduate physics students. If it is done at all, the experiment often consists of the students measuring the emitted wavelengths and using tables to identify the corresponding atomic transitions.[2] Although this experiment introduces the students to terminology in atomic physics, a quantitative analysis is absent.

In this note we present a spreadsheet calculation to be used in the laboratory to analyze the helium spectrum data. By tabulating the difference in the photon energies of helium and hydrogen, the students can measure the singlet-triplet splitting of the $2p$ level in helium and identify the d level transitions to this state.

II. HELIUM SPECTRUM EXPERIMENT

After carrying out the hydrogen spectrum experiment students collect data from helium. In both experiments data are collected using a spectrometer interfaced to a personal computer.[3] The students begin by calibrating the spectrometer using a standard source.[4] The hydrogen spectrum yields four strong lines plus one weak line of the Balmer series. The wavelengths[5] in nanometers of the Balmer lines are listed in the top row of Table I, along with the initial principal quantum number of the electron, n_i. The final quantum number for the Balmer series is $n_f=2$.

The students collect the helium spectra by first using a short collection time of 10 μs. The spectrum is taken from a helium discharge tube with a glass container. The collection time is chosen so that the most intense line, 587.6 nm, fits on the display. Although the glass absorbs in the ultra-violet, the students can identify 14 spectral lines, which are the first 14 lines listed in Table I. Figure 1 is a plot of the 10 μs helium spectrum. After measuring the wavelengths of the short collection time data, the students collect data for a longer time to observe and measure less intense emissions. The last four emission lines in Table I, listed in italics, can be observed with a 5 s collection time. In Fig. 2 we display part of the helium spectrum for a 5 s collection time, where we label the spectral lines in units of nanometers. The weakest line at 414.4 nm is small but measurable. The first column of Table I is a list in order of intensity of the 18 helium emission lines observed with our spectrometer.

III. DATA ANALYSIS

After the students have measured the helium wavelengths, we begin a discussion on how to analyze the data. We start by proposing a model for an excited helium atom. We assume that an excited state of helium consists of one electron, the screening electron, in the lowest energy level, the $1s$. The second electron, or valence electron, is in an excited state. When a transition occurs, the energy of the emitted photon is

Table I. The differences in energy of the measured hydrogen and helium visible radiation. The entries in the table are $(1240/\lambda_{He}-1240/\lambda_H)$ eV with the wavelengths in nanometers. The uncertainty of each entry in the table is 0.006 eV. The last four rows are in italics to point out that these lines are weak and need a long collection time to be observed. The bold numbers are the transitions from the corresponding d levels to the $2p$ singlet and triplet final states.

n_i (hydrogen):	3	4	5	6	7
λ (nm) H→	656.3	486.1	434.0	410.2	*397.0*
He↓					
587.6	**0.22**	−0.44	−0.75	−0.91	−1.01
706.5	−0.13	−0.80	−1.10	−1.27	−1.37
667.8	**−0.03**	−0.69	−1.00	−1.17	−1.27
388.9	1.30	0.64	0.33	0.17	0.07
501.6	0.58	−0.08	−0.39	−0.55	−0.65
728.1	−0.19	−0.85	−1.15	−1.32	−1.42
447.1	0.88	**0.22**	−0.08	−0.25	−0.35
492.2	0.63	**-0.03**	−0.34	−0.50	−0.60
471.3	0.74	0.08	−0.23	−0.39	−0.49
402.6	1.19	0.53	**0.22**	0.06	−0.04
396.5	1.24	0.58	0.27	0.10	0.00
438.8	0.94	0.27	**−0.03**	−0.20	−0.30
382.0	1.36	0.70	0.39	**0.22**	0.12
318.8	2.00	1.34	1.03	0.87	0.77
412.1	0.12	0.46	0.15	−0.01	−0.11
370.5	1.46	0.80	0.49	0.32	**0.22**
361.8	1.54	0.88	0.57	0.40	0.30
414.4	1.10	0.44	0.14	**-0.03**	−0.13

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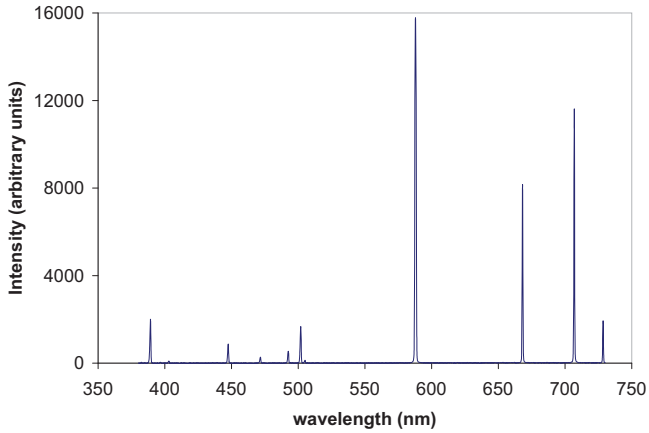

Fig. 1. A plot of the helium spectrum for a collection time of 10 μs. All the spectral lines except the last four in Table I can be observed. The data were collected using the spectrometer of Ref. 3.

approximately equal to the energy lost by the valence electron as it goes from one level to another. This model is only an approximation, because the state of the screening electron depends on the state of the valence electron. In addition, the two electrons are not independent, but satisfy the properties required of indistinguishable particles. In the extreme case that the screening electron completely screens out the nucleus, the valence electron would have the same energy levels as an electron in hydrogen.

The analysis begins by having the students perform a spreadsheet calculation. The hydrogen wavelengths are entered in the first row of the spreadsheet according to their initial principal quantum number, n_i. The helium wavelengths are entered in the first column of the spreadsheet according to their relative intensity. The students fill the spreadsheet with the energy differences ΔE_{ij} between all combinations of the emitted photons of hydrogen and helium by computing the following quantity to examine if there are any patterns in the energy differences:

$$\Delta E_{ij} = hc\left[\frac{1}{\lambda_i(\mathrm{He})} - \frac{1}{\lambda_j(\mathrm{H})}\right] = 1240\left[\frac{1}{\lambda_i(\mathrm{He})} - \frac{1}{\lambda_j(\mathrm{H})}\right]\ \mathrm{eV}, \tag{1}$$

where $\lambda_i(\mathrm{He})$ is the helium wavelength (in nm) in the ith row and $\lambda_j(\mathrm{H})$ is the hydrogen wavelength (in nm) in the jth column. Note that i and j are not indices for the ith or jth energy level. In Table I we display the results of the calculation of ΔE_{ij}.

The students are then asked to identify any patterns in the ΔE_{ij} array. As seen in Table I, 0.22 eV occurs five times and −0.03 eV occurs four times, once in each column indicated in bold. The interpretation of these results leads to the following discussion. Consider first the 0.22 eV difference, which is the same value for n_i=3, 4, 5, 6, and 7 in hydrogen with n_f=2. One way to have the same energy difference for these five lines is to have the binding energy of the valence electron in helium for n_i=3, 4, 5, 6, and 7 be the same as in hydrogen and the n_f=2 level for the valence electron in helium be shifted 0.22 eV compared to hydrogen. The orbital quantum number ℓ plays an important role. For larger values of ℓ the electron's location is farther from the nucleus. Because $\Delta\ell=1$ for dipole radiation, the largest values of ℓ for the transitions are $7d\rightarrow 2p$, $6d\rightarrow 2p$, $5d\rightarrow 2p$, $4d\rightarrow 2p$, and $3d\rightarrow 2p$. The five values of 0.22 eV in Table I can be understood if the $\ell=2$ (d) states for the valence electron in helium have the same energy to the accuracy of our measurements as the corresponding states for the electron in hydrogen. That is, for the $\ell=2$ states of the helium valence electron, the screening electron successfully screens the nucleus so that the valence electron experiences the potential from just one proton. The 0.22 eV shift is therefore due to the shift of the $2p$ level of the valence electron from that of the $2p$ level of hydrogen.

The −0.03 eV differences can be similarly understood if the $2p$ level of helium's valence electron is shifted up 0.03 eV from the energy of the $2p$ level of hydrogen. Thus,

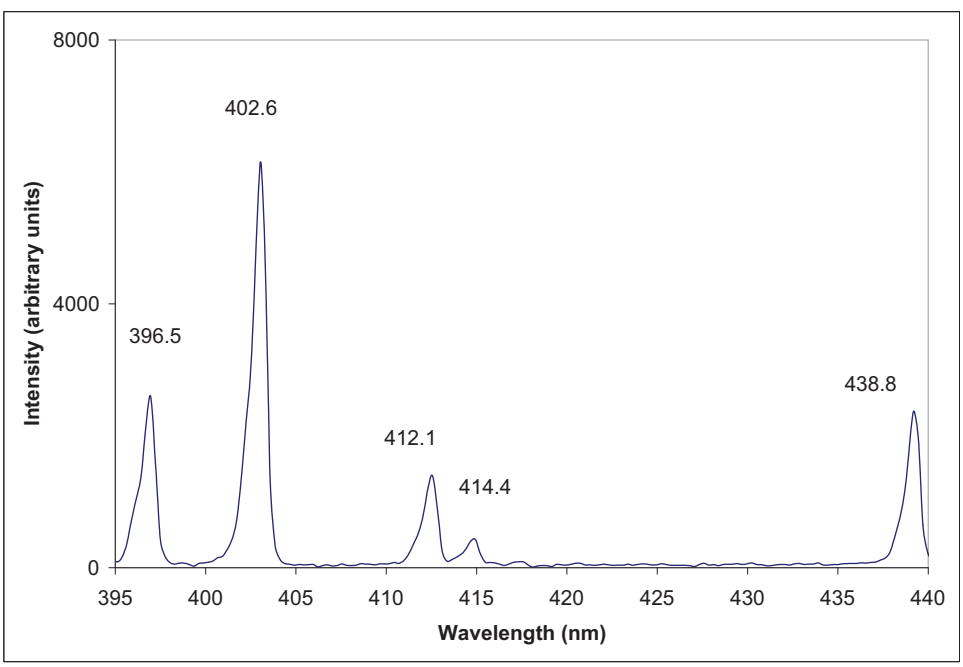

Fig. 2. A plot of part of the helium spectrum for a collection time of 5 s.

the multiple occurrences of 0.22 eV and −0.03 eV in Table I can be explained if the $\ell=2$ energies of helium's valence electron are not shifted significantly from the corresponding levels in hydrogen, and the $2p$ level for helium's valence electron is split: one state being 0.22 eV lower than the corresponding hydrogen state and the other 0.03 eV higher. We note that the expected −0.03 eV singlet entry in the $n_i=7$ column corresponds to a wavelength of 400.93 nm. This wavelength in the helium spectrum is not observable with our spectrometer because the $7d\rightarrow 2p$ singlet transition is very weak and is obscured by the much stronger $5d\rightarrow 2p$ triplet line at 402.6 nm.

The problem concludes with a discussion of the splitting of the $2p$ valence electron level in helium. The largest contribution to the splitting is due to the exchange interaction, which is a consequence of the collective properties of the identical electrons.[6] It is also referred to as singlet-triplet splitting. The triplet level, or orthohelium, has a lower energy than the singlet level, or parahelium. The total splitting measured in the experiment is 0.25 eV and agrees with the published value for the $1s2p$ level splitting in helium.[5]

It is important to have adequate resolution of the wavelengths for the experiment to be successful. An accuracy of ± 0.5 nm for the wavelength is desirable. An uncertainty of ± 0.5 nm is $\approx 0.1\%$ error in λ and consequently 0.1% error in the energy of the emitted photon. The largest photon energies are 3 eV, so the uncertainty in the photon energies is around 0.003 eV. Because the entries in Table I are the difference of two photon energies, their uncertainties are around ± 0.006 eV. This resolution is enough to recognize the pattern of 0.22 eV, but insufficient to see any further splitting of the levels. The spectrometers of Ref. 3 are rated to have an uncertainty of 0.7 nm in wavelength and are ideal for the experiment.

In conclusion, the experiment allows students to identify nine of the helium spectral lines: $1s\ n_id\rightarrow 1s2p$ triplet for $n_i=3$, 4, 5, 6, and 7, and $1s\ n_id\rightarrow 1s2p$ singlet for $n_i=3$, 4, 5, and 6. This problem is ideal for an upper division physics laboratory and can also be used in a sophomore level atom physics laboratory.

[1] R. L. Liboff, *Introductory Quantum Mechanics*, 3rd ed. (Addison-Wesley, Reading, MA, 1998).

[2] M. C. Lo Presto, "A closer look at the spectrum of helium," Phys. Teach. **36**, 172–173 (1998).

[3] We use the Ocean Optics HR4000 spectrometer.

[4] We use a standard source provided by the HR4000 spectrometer. Alternatively, we could use the accepted values of the Balmer lines of hydrogen to calibrate the spectrometer.

[5] The NIST Atomic Spectra Data website is ⟨physics.nist.gov/PhysRefData/ASD/lines-form.html⟩.

[6] A. Goswami, *Quantum Mechanics*, 2nd ed. (Brown, Dubuque, IA, 2001).

Evolution and the second law of thermodynamics

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Skeptics of biological evolution often claim that evolution requires a decrease in entropy, giving rise to a conflict with the second law of thermodynamics. This argument is fallacious because it neglects the large increase in entropy provided by sunlight striking the Earth. A recent article provided a quantitative assessment of the entropies involved and showed explicitly that there is no conflict. That article rests on an unjustified assumption about the amount of entropy reduction involved in evolution. I present a refinement of the argument that does not rely on this assumption. © *2009 American Association of Physics Teachers.*

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I. INTRODUCTION

Styer recently addressed the claim that evolution requires a decrease in entropy and therefore is in conflict with the second law of thermodynamics.[1] He correctly explained that this claim rests on misunderstandings about the nature of entropy and the second law. The second law states that the total entropy of a closed system must never decrease. However, the Earth is not a closed system and is constantly absorbing sunlight, resulting in an enormous increase in entropy, which can counteract the decrease presumed to be required for evolution. This argument is known to those who defend evolution in evolution-creationism debates,[2] but it is usually described in a general, qualitative way. Reference 1 filled this gap with a quantitative argument.

In the following I present a more robust quantitative argument. We begin by identifying the appropriate closed system to which to apply the second law. We find that the second law requires that the rate of entropy increase due to the Earth's absorption of sunlight, $(dS/dt)_{\text{sun}}$, must be sufficient to account for the rate of entropy decrease required for the evolution of life, $(dS/dt)_{\text{life}}$ (a negative quantity). As long as

$$\left(\frac{dS}{dt}\right)_{\text{sun}}+\left(\frac{dS}{dt}\right)_{\text{life}}\geqslant 0, \tag{1}$$

there is no conflict between evolution and the second law.

Styer estimated both $(dS/dt)_{\text{sun}}$ and $(dS/dt)_{\text{life}}$ to show that the inequality (1) is satisfied, but his argument rests on an unjustified and probably incorrect assumption about $(dS/dt)_{\text{life}}$.[1] I will present a modified version of the argument, which does not depend on this assumption and which shows that the entropy decrease required for evolution is orders of magnitude too small to conflict with the second law of thermodynamics.

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