

SPECTROSCOPY / ATOMIC STRUCTURE EXERCISE: IDENTIFYING LINES IN THE SOLAR SPECTRUM¹

Background and Theory: The brightest star in our sky is the Sun. Absorption lines in the solar spectrum were first noticed by an English astronomer in 1802, but it was a German physicist, Joseph von Fraunhofer, who first measured and cataloged over 600 of them about 10 years later. These lines are now known collectively as the "Fraunhofer lines." In the 1800's, scientists did not know that these lines were chemical in origin. Thus, the letters used by Fraunhofer to identify the lines have no relation to chemical symbols nor to the symbols used to designate the spectral types of stars. Today's astronomers use some of the designations simply for convenience and ease in identifying lines.

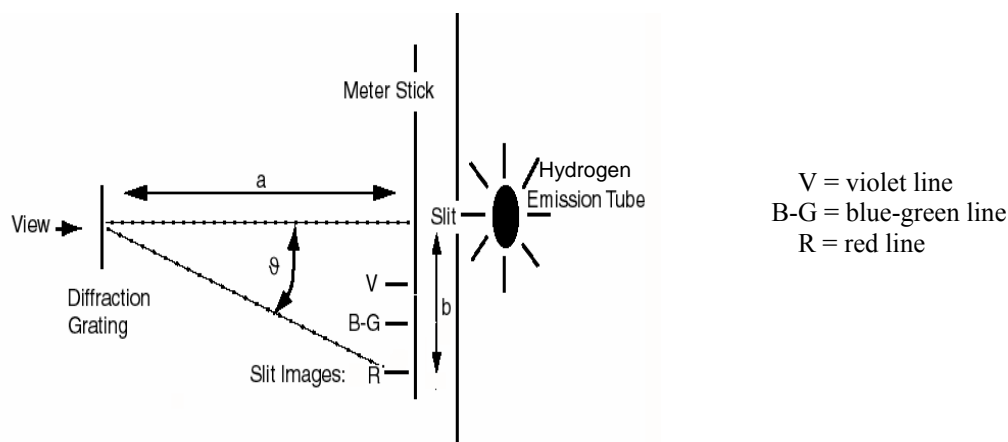
Now we know that each absorption line is caused by a transition of an electron between energy levels in an atom. Each element has a distinct pattern of absorption lines. Once the pattern of the lines of a particular element have been observed in the laboratory, it is possible to determine whether those elements exist elsewhere in the universe simply by pattern matching the absorption lines.

The strongest Fraunhofer lines of the Sun can easily be seen with even the most primitive spectroscope. In this exercise, we work with the solar spectrum between approximately 390 and 660 nm (3900 - 6600 Angstroms) and identify some of the strongest Fraunhofer lines. The spectrum was obtained under conditions that prevented the observation of most of the weak lines.

When an electron in an atom undergoes a transition from a higher energy level to a lower energy level, the atom emits light at a discrete frequency and wavelength determined by the energy difference between the levels. The emission frequency, ν , and wavelength, λ , are related to the transition energy, ΔE , by the Planck equation

$$\Delta E = h \cdot \nu = \frac{h \cdot c}{\lambda}$$

where h is Planck's constant, $h = 6.6261 \times 10^{-34}$ J·s, and c is the speed of light, $c = 2.9979 \times 10^8$ m/s. Because the separation between the energy levels depends on the type of atom, the emission spectrum is characteristic of the element. Hydrogen atoms, if excited by an electrical discharge, emit a series of lines in the visible region called the Balmer series. This series corresponds to transitions from several different excited states to the $n = 2$ level. Three or four lines of the Balmer series can be observed with the unaided eye. The schematic diagram shows how the wavelengths of the red, blue-green, and violet emission lines of the Balmer series are determined.



A diffraction grating is a transparent film ruled with a number of closely spaced grooves. It is used to separate the light from the source according to its wavelengths. If light from an incandescent lamp is directed onto the grating, a continuous spectrum of colors is formed. The grating produces an image of the light for each color emitted; because all colors are emitted, these images blur together and appear as a continuous band (like a rainbow). When a hydrogen lamp is viewed through the grating, only three images of the light will appear, each in a different color. These correspond to the individual emission lines of the Balmer series, each with a different wavelength. Because they are separated in space, the images appear distinct. The wavelengths of these emission lines are determined by the diffraction equation

$$\lambda = d \cdot \sin \theta$$

where d is the separation between the grooves on the grating, and the angle θ is determined by the geometry of the schematic as shown above. Measurements of the distances shown will provide the angle θ , because $\tan \theta = b/a$. Note that the geometric

¹ Adapted in part from "Identifying Lines in the Solar Spectrum", University of Washington Astronomy Department, <http://www.astro.washington.edu/labs/clearinghouse/labs/Solarspec2/sunspec.html>, accessed 1 August 2005.

relations hold on both the left and right side, as one views the lamp through the grating. Thus the pattern of a continuous band or set of discrete images appears on each side.

The overall solar spectrum is basically a continuous spectrum, because the layer we can see, called the photosphere, has been heated until it glows (incandescens) by nuclear reactions occurring in the core of the Sun. The heat is conveyed to the surface by convection, conduction, and radiation. The surface emits a black-body (continuous) spectrum that is characteristic of a temperature of about 6000 K. (An ordinary incandescent light bulb produces a black-body spectrum characteristic of about 2500 K.) Above the surface is a very thin gas of atoms, ions, and a few molecules which are much cooler than the surface. These “cold” particles absorb the light at characteristic wavelengths, creating the dark lines identified by Fraunhofer superimposed on the continuous spectrum.

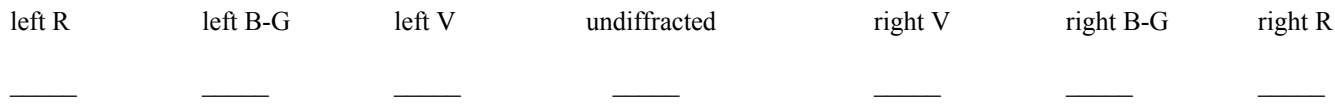
The spectrum of an atom or molecule is characteristic of that substance because the wavelengths absorbed or emitted depend only on the energy differences between allowed levels. For a given substance, those differences are the same for both absorption and emission, so the wavelengths observed in an emission (bright-line) spectrum and absorption (dark-line) spectrum are the same. In this exercise, we will experimentally determine the emission wavelengths of the H atom, and then use these to identify H absorption lines in the solar spectrum. Absorption features caused by other atoms will also be identified from tabulated values.

Procedure:

Part A. Determining the Wavelengths of the Balmer Series of Hydrogen

1. Your instructor will demonstrate the difference between continuous and line spectra, and absorption and emission spectra. Hand-held spectroscopes may also be available.

2. Your instructor will set up the hydrogen lamp to display the line spectrum of the H atom on the projector screen. The display includes a ruler you can use to identify the positions of the various lines. You should see three colored lines – red (R), blue-green (B-G), and violet (V) - on each side of the undiffracted bluish-white image at the center. Record the positions of each of those images, measured to the nearest 0.1 mm. (Read at the center of the image. Don’t guess! Walk up to the screen and look at it carefully!)



3. Calculate the absolute values of the distances between the left red line and the undiffracted central line _____, and between the right red line and the undiffracted central line _____. Average the values in mm. Repeat for the other two colors. These are the values identified as “b” in the diagram above.

average distance between red lines and central image: _____

average distance between blue-green lines and central image: _____

average distance between violet lines and central image: _____

4. Your instructor will provide you the value identified as “a” in the diagram. (This depends on how he or she set up the demonstration.) Record the value, in mm. _____

5. Your instructor will provide you with a value of the number of lines/mm on the grating: _____. Given this value, what is the distance “d” between the lines, in mm? _____. What is the distance “d” in nm? _____

6. Complete the table below, using the distances “a” and “b” identified in the diagram, the distance “d” just determined, and the diffraction equation provided above. Remember that $\tan \theta = b/a$. You can use degrees or radians for the angular functions, but you must be consistent! You are encouraged to work in degrees for ease of comparison.

Line	a (mm)	b (mm)	$\tan \theta$	θ	$\sin \theta$	d (nm)	λ (nm)
red							
blue-green							
violet							

7. The wavelengths λ that you determined for the H atom spectrum should be within 10% of the following: red, 656.3 nm; blue-green, 486.1 nm; violet, 434.1 nm. Calculate your % error for the red line.

Part B. Identifying Elements in the Solar Spectrum

8. Look at the simplified solar spectrum supplied to you. The large upper-case letters at the top represent lines of known elements; some of these will be used to determine the scale. For example, line B is known to be due to terrestrial oxygen atoms in the upper atmosphere; this line appears at 686.7 nm. Line E has been shown by laboratory experiments to be due to neutral Fe atoms; it appears at 527.0 nm. Carefully measure the distance in mm between these two lines, and determine the scale factor of the spectrum, in nm/mm. (One would actually do this for many pairs of known lines, and average the values, but this will suffice for our purposes.)

scale factor: _____ nm/mm

9. The numbered lines beneath the spectrum correspond elements in the Sun which we would like to identify. They are all done by the same procedure:

- a) measure the distance (in mm) between the unknown line and a known line, e.g., line E.
- b) use the scale factor to convert the distance just determined to a difference in wavelengths.
- c) add or subtract the difference in nm to the known wavelength of line E (527.0 nm), to determine the wavelength of the unknown line.
- d) use the table of laboratory spectra to identify the element associated with the spectral line.

Perform the steps described above to identify the element associated with the following lines:

line 1

line 2

line 3

line 4

line F

line 7

line 9

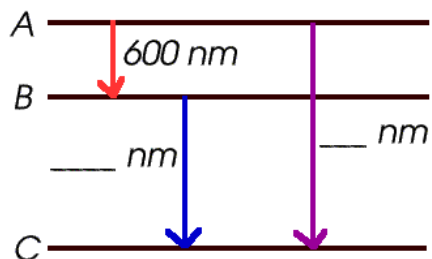
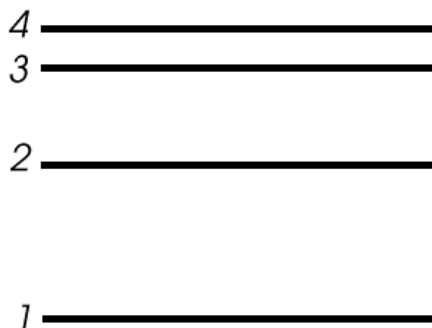
line 12

line C

Exercises²

Consider just four of the energy levels in a certain atom, as shown in this diagram:

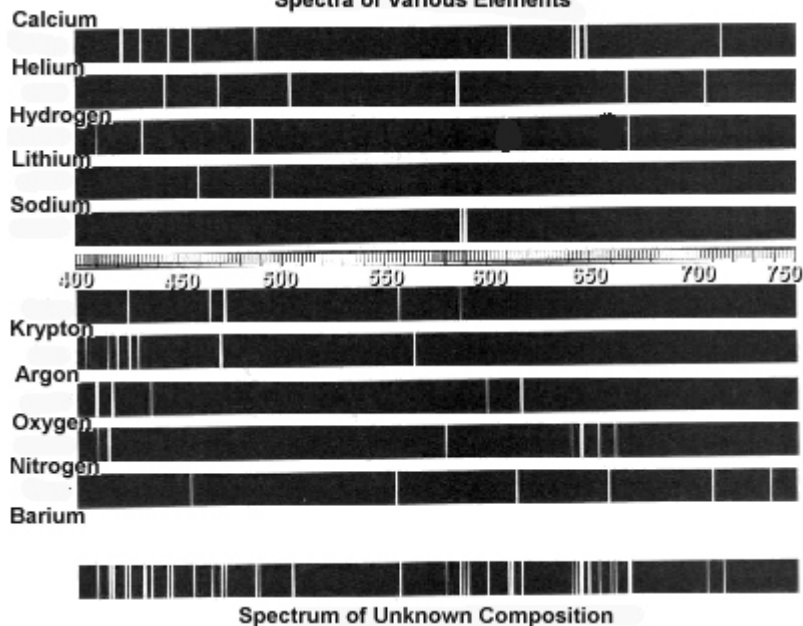
- Assume an emission spectrum and draw arrows indicating all of the possible transitions.
- How many spectral lines will result from all possible transitions among these levels? _____
- Which transition corresponds to the highest frequency (shortest wavelength) light emitted?
From $n =$ _____ to $n =$ _____.
- Which transition corresponds to the lowest frequency (longest wavelength) light emitted?
From $n =$ _____ to $n =$ _____.



In this diagram, the energy difference between states B and C is twice the energy difference between states A and B. In a transition (quantum jump) from A to B, an atom emits a photon of wavelength 600 nm.

- What is the wavelength emitted when the electron jumps from B to C? _____
- When it jumps from A to C? _____

Spectra of Various Elements



Use the spectra of the known elements to identify atomic components in the unknown spectrum at the bottom.

Elements present in unknown:

² From "Spectra Analysis", University of Washington Astronomy Department, <http://www.astro.washington.edu/labs/clearinghouse/labs/Spectanalysis/spectanalysis.html>, accessed 1 Aug. 2005.

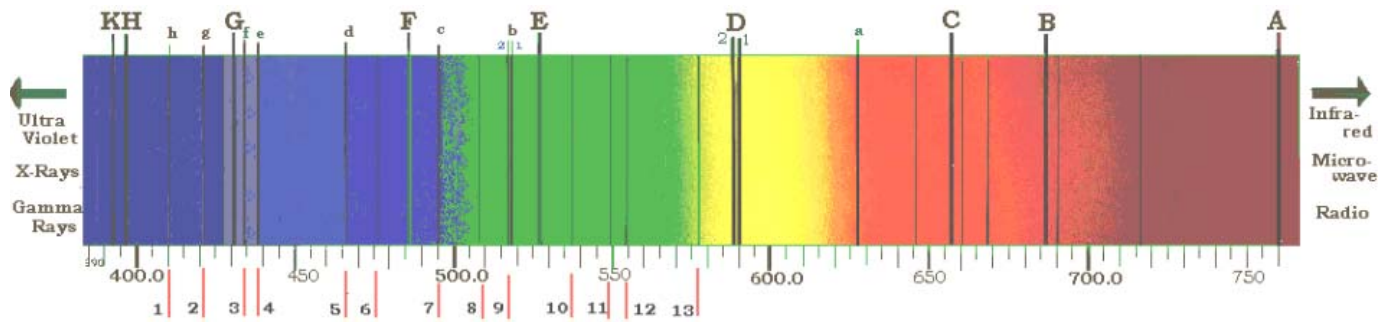


Table 4

Adapted from *Learning Astronomy by Doing Astronomy* by Ana Larson

Wavelength (nm)	Line Width (nm)	Element	Wavelength (nm)	Line Width (nm)	Element
393.3682	2.0253	Ca ⁺	440.4761	0.0898	Fe
394.4016	0.0488	Al	441.5135	0.0417	Fe
396.1535	0.0621	Al	452.8627	0.0275	Fe
396.8492	1.5467	Ca ⁺	455.4036	0.0159	Ba ⁺
404.5825	0.1174	Fe	470.3003	0.0326	Mg
406.3605	0.0787	Fe	486.1342	0.3680	H
407.1749	0.0723	Fe	489.1502	0.0312	Fe
407.7724	0.0428	Sr ⁺	492.0514	0.0471	Fe
410.1748	0.3133	H	495.7613	0.0696	Fe
413.2067	0.0404	Fe	516.7327	0.0935	Mg
414.3878	0.0466	Fe	517.2698	0.1259	Mg
416.7277	0.0200	Mg	518.3619	0.1584	Mg
420.2040	0.0326	Fe	525.0216	0.0062	Fe
422.6740	0.1476	Ca	526.9550	0.0478	Fe
423.5949	0.0385	Fe	532.8051	0.0375	Fe
425.0130	0.0342	Fe	552.8418	0.0293	Mg
425.0797	0.0400	Fe	588.9973	0.0752	Na (D ₂)
425.4346	0.0393	Cr	589.5940	0.0564	Na (D ₁)
426.0486	0.0595	Fe	610.2727	0.0135	Ca
427.1774	0.0756	Fe	612.2226	0.0222	Ca
432.5775	0.0793	Fe	616.2180	0.0222	Ca O
434.0475	0.2855	H	630.2499	0.0083	Fe
438.3557	0.1008	Fe	656.2808	0.1020	H