

Spectroscopy of Hydrogen, Helium, Neon and Mercury Low-Pressure Discharge and a Barcode-like Periodic Table Based on Energy Levels

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Strong spectral lines in the visible range are obtained from luminescence generated by low-pressure gas discharge tubes of hydrogen, neon, helium, and mercury. Although the spectrum of neon is complicated at first glance, the energy levels are degenerate and clustered; this means that the level statistics differ from the Wigner surmise, which is closely related to level repulsion and quantum chaos. We present a visualization of the lower 99 energy levels of each atom in a barcode-like periodic table.

Key words: Gastube, Discharge, Periodic Table, Energy Level

1. Introduction

One of the authors (YM) has studied “secondary real images” in the framework of the Super Science High School (SSH) project [1], which aims to nurture talented Japanese students in the field of science and technology. The secondary real image, which is distinct from the universal real image, is formed by multiple reflections and refractions inside the lens. This image is formed near the lens, and may provide a method of ghost photography. Such interests in the research field of geometrical optics are hereafter expanded to spectroscopy.

Luminescence was generated by applying 5000 V across glass tubes containing low-pressure hydrogen, helium, neon, and mercury gas. The pressure of each gas was about 1/100 atmospheres. The resulting luminescence is shown in Fig. 1.

It is well established that the geometric construction of phase space for classical dynamical systems (*islands* of periodicity embedded in a *sea* of chaos) is reflected in the statistical property of energy levels in quantum systems [2]. It may be considered as a *Science on Form*. Wigner introduced random matrices to describe nuclei of heavy atoms [3]. He compared the spacings between the lines in the spectrum of a heavy atom nucleus to the spacings between the eigenvalues of a random matrix. The level spacings of neon, which is not so heavy though, are somewhat complicated, as shown later. In this study, we first obtained a distribution of the nearest-neighbor energy level spacings of neon and compared these with spacing distribution calculated according to the Wigner surmise [3]. With the help of an atomic-spectroscopic database, we then illustrate en-



Fig. 1. Luminescence of H, Ne, He, and Hg (from left to right).

ergy levels near the ground states as barcodes in the periodic table.

In the second section, luminescence of hydrogen, helium, neon, and mercury is spectroscopically analyzed. The spectrum of neon is compared with the Wigner surmise. In the third section, a barcode-like periodic table is presented. The final section is devoted to concluding remarks.

2. Luminescence of H, He, Ne, and Hg

A visible-light spectrometer supplied by Kyoto Nijikoubou LLP was used to obtain the wavelength and relative intensity of strong spectral lines. The wavelength calibration accuracy for the instrument is about 2 nm in the vicinity of 600 nm wavelength, and the wavelength resolution $\lambda/\Delta\lambda$ is nearly equal to 300. The results are shown in Fig. 2. As expected, the Balmer series is observed in the case of hydrogen.

In the case of neon, a relatively complicated spectrum is obtained as shown in Fig. 2. Figure 3 compares our data with a neon spectrum from *The Basic Atomic Spectroscopic Data* [4], supplied by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce.

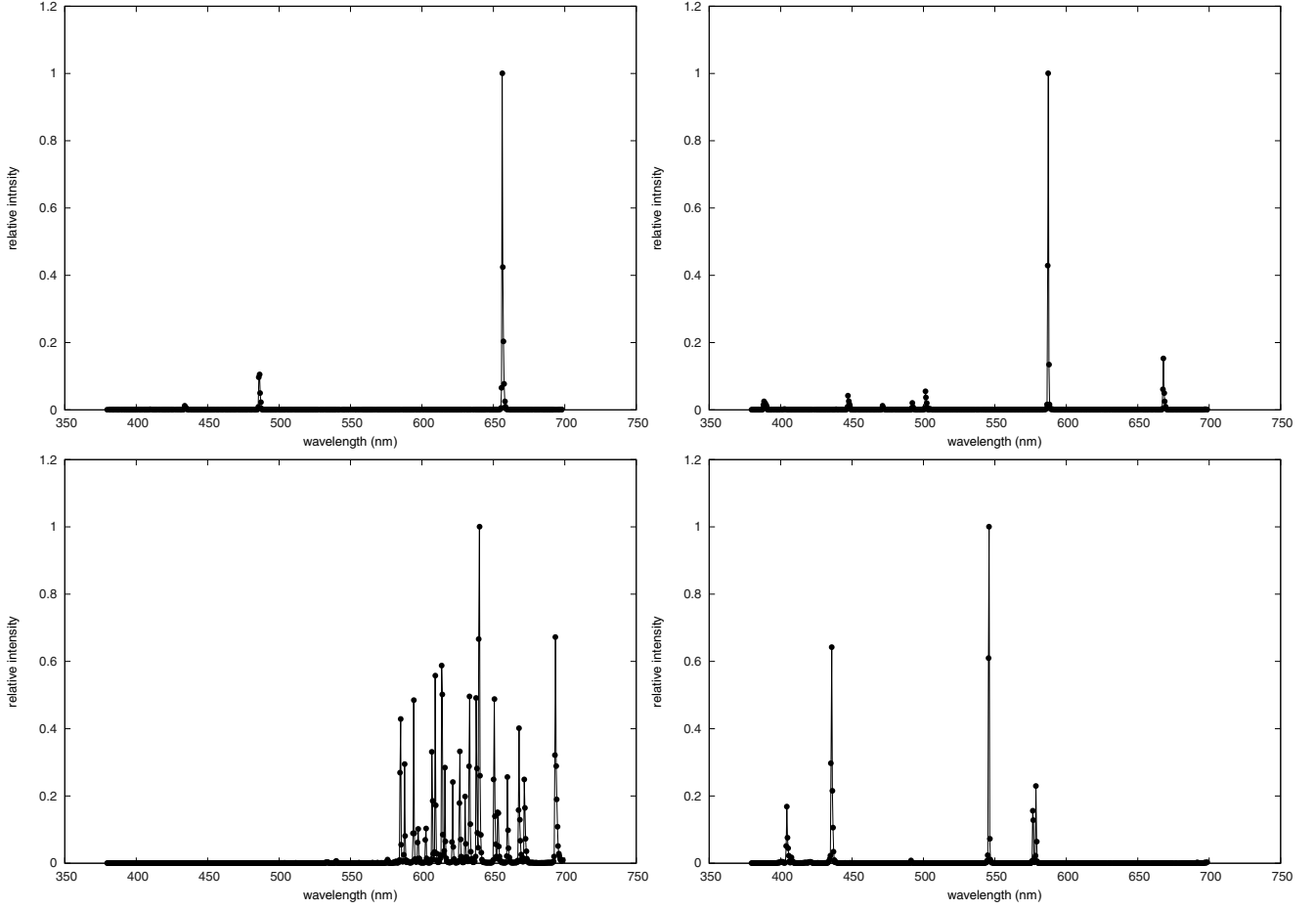


Fig. 2. Atomic spectra of H, He, Ne, and Hg: relative intensity if plotted against wavelength (nm).

We observe that the agreement between these datasets is relatively good about the positions of the strong lines. The atomic energy levels of the NIST data [4] are illustrated as a bar code in the left panel of Fig. 4. (In [4], the data of Neon is supplied by [5] only.) In the right panel of Fig. 4, the probability distribution function of the measured nearest-neighbor spacing normalized by the average spacing is plotted (+) and compared with the cumulative probability density function

$$\int_0^x p_w(y)dy = 1 - \exp\left(-\frac{\pi}{4}x^2\right)$$

of the Wigner surmise

$$p_w(y) = \frac{\pi}{2}y \exp\left(-\frac{\pi}{4}y^2\right)$$

[3] (solid line). The Wigner surmise originates from level repulsion, in which matrix elements of the operator such as Hamiltonian is assumed to be random satisfying some basic symmetries e.g. Hermitian property only. Highly excited heavy atomic nuclei, Hydrogen atoms in a strong magnetic field, elastic modes of elastomechanical eigenfrequencies of irregularly shaped quartz blocks, and many other examples show the universal level spacing statistics approximately given by the Wigner surmise. On the contrary, the left panel of Fig. 4 shows that the energy levels of neon are highly clustered. It is quite natural that this disagreement

appears, since all the energy levels of Neon shown in Figs. 2 and 4 are identified, and the configuration such as $2p^6$, the term such as 1S , and other quantum properties are specified. This clustering, along with the deviation of energy level statistics from the Wigner surmise, implies the absence of quantum chaos in the low-pressure neon gas, despite the seemingly complicated spectrum shown in the lower left panel of Fig. 2. Thus, this result implies that the lower energy levels reflect characteristics of individual atoms. In the next section, the barcode-like presentation of the energy levels shown in Fig. 4 will be obtained in the form of a periodic table.

3. Barcode-like Periodic Table

The lower 99 energy levels of each atom [2] in units of cm^{-1} are plotted against atomic number in Fig. 5. For example, energy levels of Hydrogen are plotted along a vertical line at the value of 1 of abscissa. Distances between the lowermost point and the other points correspond to the Lyman series. Distances between the second-lowest point and the other upper points correspond to the Balmer series. It is interesting that the discontinuities in Fig. 5 reflect the construction of the periodic table. The range of energy levels of Li (atomic number 3) locates much lower than that of He (atomic number 2). Such drops are also found between atomic numbers 10 and 11, 18 and 19, 36 and 37, 54 and 55. Both sides of the drops belong to the columns

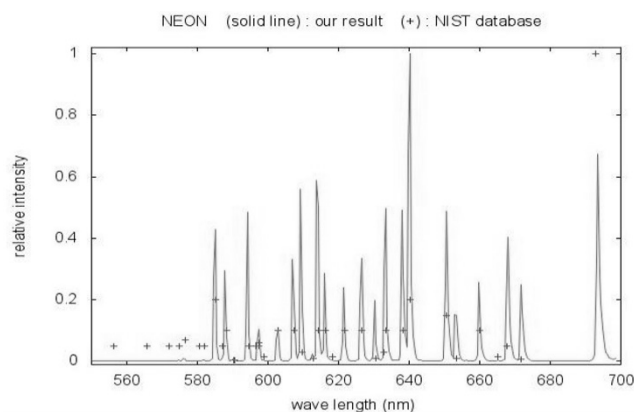


Fig. 3. Visible Ne spectrum. NIST data (+), measured data (solid line).

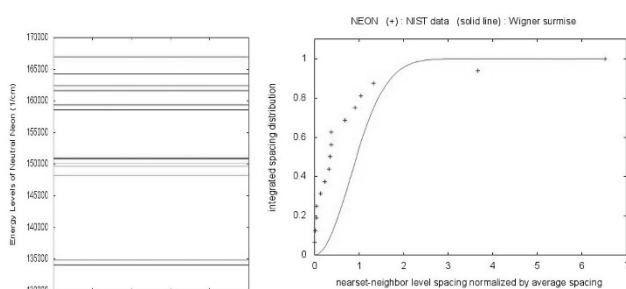


Fig. 4. Energy levels of neon shown as a bar code (left). Cumulative nearest-neighbor spacing statistics (+) compared with a theoretical line derived from the Wigner surmise (right).

of the alkali metal and the noble gas in the periodic table. Between the neighboring drops, the center of the range of the energy levels monotonically increases, roughly speaking. Using the pattern set out in the left panel of Fig. 4, we can construct a barcode-like periodic table as shown in Fig. 6.

4. Concluding Remarks

Strong spectral lines in the visible range were obtained from low-pressure gas discharge tubes of hydrogen, neon, helium, and mercury. Our experimental data are in agreement with the Balmer series and the NIST database [4].

The spectrum of neon is at first glance complicated. The energy levels are degenerate and clustered, however, so that the level statistics differ from the Wigner surmise, which is closely related to level repulsion and quantum chaos. The lower 99 energy levels of each atom were visualized in a barcode-like periodic table.

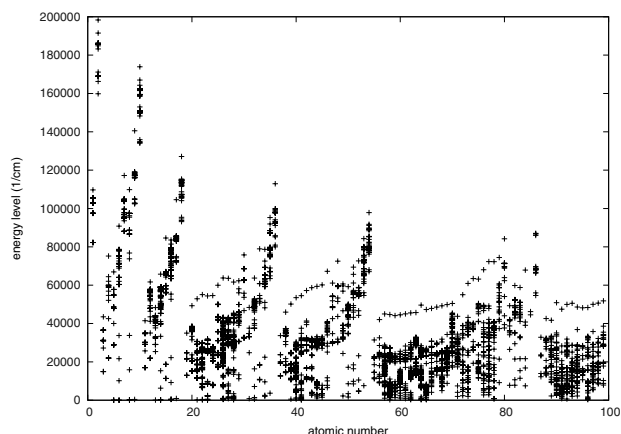


Fig. 5. The lower 99 energy levels of each atom (cm^{-1}) plotted against the atomic number.

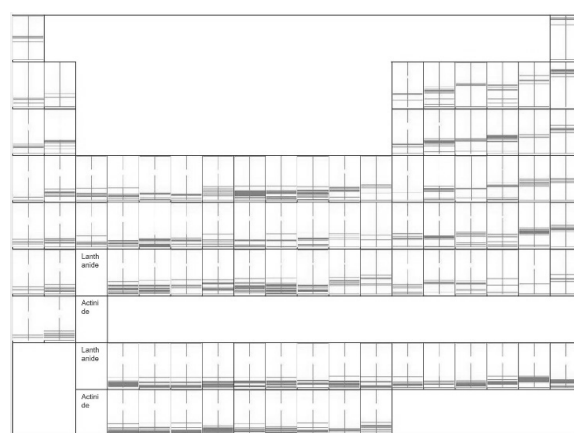


Fig. 6. The data from Fig. 5 is shown as a barcode-like periodic table.

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References

- [1] Super Science Highschool <http://www.jst.go.jp/cpse/ssh/index.html> (written in Japanese) [accessed on 23 May 2018].
- [2] Haake, F. (2010) *Quantum Signatures of Chaos*. Springer Series in Synergetics 54, Springer-Verlag Berlin Heidelberg.
- [3] Wigner, E. (1955) Characteristic vectors of bordered matrices with infinite dimensions, *Annals of Mathematics*, **62**(3), 548–564; doi:10.2307/1970079.
- [4] Handbook of Basic Atomic Spectroscopic Data <https://www.nist.gov/pml/handbook-basic-atomic-spectroscopic-data> [accessed on 23 May 2018].
- [5] Saloman, E. B. and Sansonetti, C. J. (2004) *J. Phys. Chem. Ref. Data*, **33**, 1113.