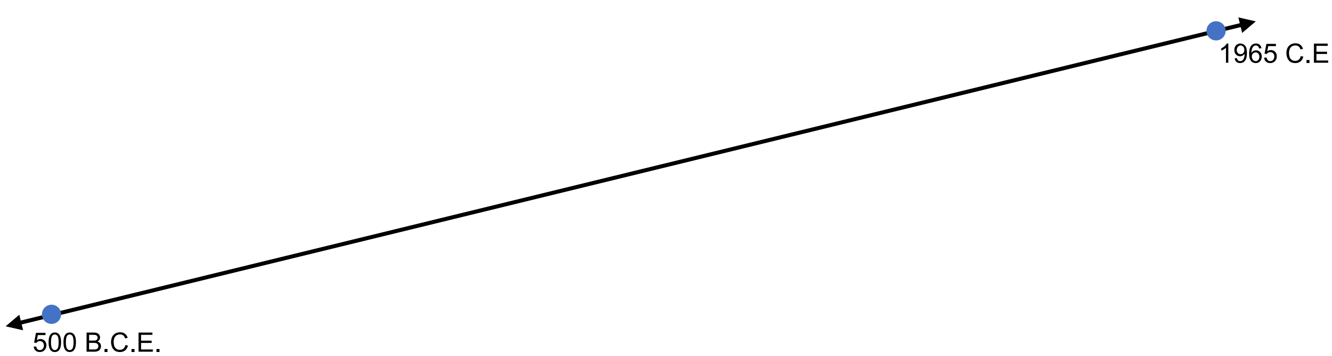
Activity Handout

The Evolution of Atomic Theory

Section 1: What do you know?

Using only your prior knowledge and context clues from their discoveries and innovations, sort the following people onto the timeline below. The innovations listed all occurred between 500 B.C.E. and 1965 C.E., but it's up to you to figure out where they fit.

Name	Innovation
John Dalton	Different substances are made of different kinds of atoms.
Erwin Schrödinger	Electrons are quantized and exist in regions, not orbits.
J.J. Thomson	Electrons (at the time called cathode rays) are an electrical component of an atom.
Michael Faraday	Atoms involve electricity somehow.
Ernest Rutherford	Atoms have a dense nucleus surrounded by electrons.
Robert Millikan	Quantized charge and mass of an electron.
Democritus	Atoms make up everything.
Niels Bohr	Electrons travel around the nucleus in distinct orbits based on their emission energy.
Henry Moseley	Organized the periodic table based on properties of atoms.



Section 2: Scientific Discoveries
This section includes real excerpts from groundbreaking papers in atomic theory. Read them and see how scientists made their discoveries, as well as the timeline on which these discoveries were made.

Thomson, J.J. "Cathode Rays." *Philosophical Magazine*, vol. 44, 1897. pp. 302-303.

As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter. The question next arises, What are these particles? are they atoms, or molecules, or matter in a still finer state of subdivision? To throw some light on this point, I have made a series of measurements of the ratio of the mass of these particles to the charge carried by it. To determine this quantity, I have used two independent methods. The first of these is as follows: Suppose we consider a bundle of homogeneous cathode rays. Let m be the mass of each of the particles, e the charge carried by it. Let N be the number of particles passing across any section of the beam in a given time; then Q the quantity of electricity carried by these particles is given by the equation

$$Ne = Q.$$

We can measure Q if we receive the cathode rays in the inside of a vessel connected with an electrometer. When these rays strike against a solid body, the temperature of the body is raised; the kinetic energy of the moving particles being converted into heat; if we suppose that all this energy is converted into heat, then if we measure the increase in the temperature of a body of known thermal capacity caused by the impact of these rays, we can determine W, the kinetic energy of the particles, and if v is the velocity of the particles,

$$\frac{1}{2}Nmv^2 = W.$$

If ρ is the radius of curvature of the path of these rays in a uniform magnetic field H, then

$$\frac{mv}{e} = H\rho = I,$$

where I is written for $H\rho$ for the sake of brevity. From these equations we get

$$\left(\frac{1}{2}\right)\left(\frac{m}{e}\right)v^2 = \frac{W}{Q}.$$

$$v = \frac{2W}{QI},$$

$$\frac{m}{e} = \frac{I^2Q}{2W}.$$

Thus, if we know the values of Q, W, and I, we can deduce the values of v and $\frac{m}{e}$.

Photograph by D. Schoenberg, courtesy AIP Emilio Segrè Visual Archives, Bainbridge Collection.
J.J. Thomson (L) and Ernest Rutherford (R).

Rutherford, Ernest. "The Scattering of α and β Particles by Matter and the Structure of the Atom." *Philosophical Magazine*, vol. 21 no. 6, May 1911. p. 686.

A narrow pencil of homogeneous α rays was used as a source. After passing through the scattering foil, the total number of α particles are deflected through different angles was directly measured. The angle for which the number of scattered particles was a maximum was taken as the most probable angle. The variation of the most probable angle with thickness of matter was determined, but calculation from these data is somewhat complicated α particles in their passage through the scattering material.

The scattering data for […] the α rays indicate that the central charge in an atom is approximately proportional to its atomic weight. This falls in with the experimental deductions of Schmidt. In his theory of absorption of β rays, he supposed that in traversing a thin sheet of matter, a small fraction α of the particles are stopped, and a small fraction β are reflected or scattered back in the direction of incidence. […] This is exactly the relation to be expected on the theory of single scattering if the central charge on an atom is proportional to its atomic weight.

In comparing the theory outlined in this paper with the experimental results, it has been supposed that the atom consists of a central charge supposed concentrated at a point, and that the large single deflexions of the α and β particles are mainly due to their passage through the strong central field. […] It does not seem possible from dynamic considerations that an α particle can be deflected through a large angle by a close approach to an electron, even if the latter be in rapid motion and constrained by strong electrical forces. It seems reasonable to suppose that the chance of single deflexions through a large angle due to this cause, if not zero, must be exceedingly small compared with that due to the central charge.

Millikan, Robert. "On the Elementary Electrical Charge and the Avogadro Constant." *Physics Review*, vol. 11 no. 2, August 1913. p. 109.

Photograph by Harris & Ewing, AIP Emilio Segrè Visual Archives, W. F. Meggers Gallery of Nobel Laureates Collection.
Robert Millikan.

The experiments herewith reported were undertaken with the view of introducing certain improvements into the oil-drop method of determining e [the charge on a single electron] and N [the number of electrons in a single oil drop] and thus obtaining a higher accuracy than had before been possible in the evaluation of these most fundamental constants.

In the original observations by this method such excellent agreement was found between the values of e derived from different measurements that it was evident that if appreciable errors existed they must be looked for in the constant factors entering into the final formula rather than in inaccuracies in the readings or irregularities in the behavior of the drops. Accordingly a systematic redetermination of all these constants was begun some three years ago. The relative importance of the various factors may be seen from the following review.

As is now well known the oil-drop method rested originally upon the assumption of Stokes's law and gave the charge e on a given drop through the equation

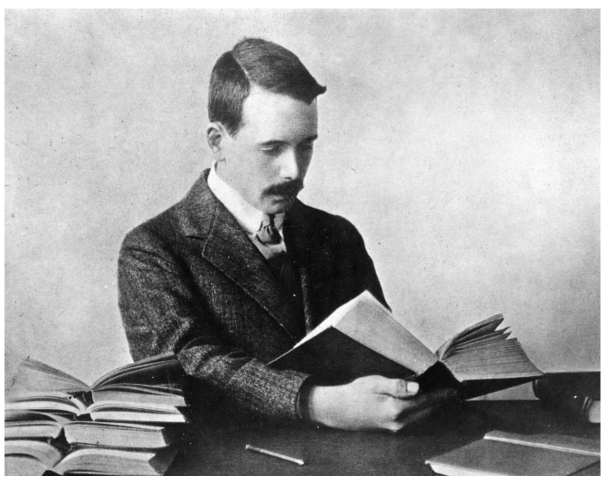
$$e_n = \frac{4}{3}\pi\left(\frac{9\eta}{2}\right)^{\frac{3}{2}}\left(\frac{1}{g(\sigma-\rho)}\right)^{\frac{1}{2}}\frac{(v_1+v_2)v_1^{1/2}}{F},$$

in which η is the coefficient of viscosity of air, σ the density of the oil, ρ the density of the air, v_1 the speed of descent of the drop due to gravity and v_2 its speed of ascent under the influence of an electric field of strength F.

The essential feature of the method consisted in repeatedly changing the charge on a given drop by the capture of ions from the air and in thus obtaining a series of charges with each drop. These charges showed a very exact multiple relationship under all circumstances—a fact which demonstrated very directly the atomic structure of the electric charge.

Moseley, Henry. “The High-Frequency Spectra of the Elements.” *Philosophical Magazine*, vol. 27, 1914. pp. 712-713.

[A note: this is the latter of Moseley’s two publications on the subject. The former was published in early 1913.]



National Bureau of Standards, courtesy AIP Emilio Segrè Visual Archives.
Henry Moseley.

Now [Ernest] Rutherford has proved that the most important constituent of an atom is its central positively charged nucleus, and [Antonius] van den Broek has put forward the view that the charge carried by this nucleus is in all cases an integral multiple of the charge on the hydrogen nucleus. There is every reason to suppose that the integer which controls the X-ray spectrum is the same as the number of electrical units in the nucleus, and these experiments therefore give the strongest possible support to the hypothesis of van den Broek. [Frederick] Soddy has pointed out that the chemical properties of the radio-elements are strong evidence that this hypothesis is true for the elements from thallium to uranium, so that its general validity would now seem to be established.

1. Every element from aluminum to gold is characterized by an integer N which determines its X-ray spectrum. Every detail in the spectrum of an element can therefore be predicted from the spectra of its neighbours.
2. This integer N, the atomic number of the element, is identified with the number of positive units of electricity contained in the atomic nucleus.
3. The atomic numbers for all elements from Al to Au have been tabulated on the assumption that N for Al is 13.
4. The order of the atomic numbers is the same as that of the atomic weights, except where the latter disagrees with the order of the chemical properties.
5. Known elements correspond with all the numbers between 13 and 79 except three. There are here three possible elements still undiscovered.
6. The frequency of any line in the X-ray spectrum is approximately proportional to $A(n-b)^2$, where A and b are constants.

Bohr, Niels. "On the Constitution of Atoms and Molecules." *Philosophical Magazine*, vol. 26, July 1913. p. 24.

Photograph by J. Ehrenfest, Jr. Courtesy AIP Emilio Segrè Visual Archives, Weisskopf Collection.
Niels Bohr at a Copenhagen conference.

Proceeding to consider systems of a more complicated constitution, we shall make use of the following theorem, which can be very simply proved:

"In every system consisting of electrons and positive nuclei, in which the nuclei are at rest and the electrons move in circular orbits with a velocity small compared with the velocity of light, the kinetic energy will be numerically equal to half the potential energy."

By help of this theorem we get—as in the previous cases of a single electron or of a ring rotating round a nucleus— that the total amount of energy emitted, by the formation of the systems from a configuration in which the distances apart of the particles are infinitely great and in which the particles have no velocities relative to each other, is equal to the kinetic energy of the electrons in the final configuration.

Schrödinger, Erwin. "An Undulatory Theory of the Mechanics of Atoms and Molecules." *Physical Review, vol. 28 no. 6, December 1926*. pp. 1058-1059.

Photograph by Francis Simon, courtesy of AIP Emilio Segrè Visual Archives.
Erwin Schrödinger.

The only [energy]-values, for which […] solutions exist, that are continuous, finite and single valued throughout the whole space are the following ones

(1) $E > 0$

(2) $E = -\frac{2\pi^2 me^2}{h^2 n^2}, n = 1, 2, 3, 4, \ldots$

The first set corresponds to the hyperbolic orbits in ordinary mechanics. It is the general view, that according to ordinary quantum theory that the hyperbolic orbits are not submitted to quantization. In our treatment this turns out quite spontaneously from the fact that every positive value of E leads to finite solutions. The second set corresponds exactly to Bohr's stationary energy levels of the elliptic orbits.

[…]

Any one of the above mentioned solutions (consisting of a product of a spherical surface-harmonic and a function of r [the radius] only) greatly resembles a fundamental vibration of an elastic sphere, with a finite number of (1) spheres, (2) cones, (3) planes as "node surfaces." But it is surely not permissible to think that the wave-motion constituting the atom is, in general restricted to one of these solutions, the special selection and separation of which is very much influenced by the choice of coordinates.

Section 3: What do you know *now*?

Using knowledge you gained from this lesson, sort the following people onto the timeline below again. Then talk about your answers with your classmates!

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