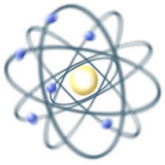
Atomic Modeling in the Early 20th Century: 1904-1913



Charles Baily
University of Colorado, Boulder
Oct 12, 2008

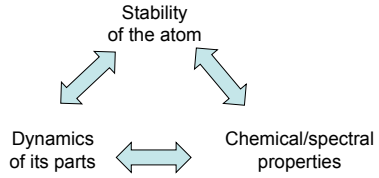
"Do not all fix'd bodies, when heated beyond a certain degree, emit Light and shine; and is not this Emission perform'd by the vibrating motion of its parts?"

-Newton, Opticks, Query 8

"[C]onditions which must be satisfied by an atom … permanence in magnitude, capability of internal motions or vibrations…"

-Maxwell, Encyclopedia Britannica, "Atom" (1875)

Key Themes to Atomic Modeling



"It is perhaps not unfair to say that for the average physicists of the time, speculations about atomic structure were like speculations about life on Mars – very interesting for those who like that sort of thing, but without much hope of support from convincing scientific evidence and without much bearing on scientific thought and development."

-Abraham Pais

J.J. Thomson (1904)
"Plum Pudding" Model

Hantaro Nagaoka (1904)
"Saturnian" Model

Ernest Rutherford (1911)
Nuclear Model

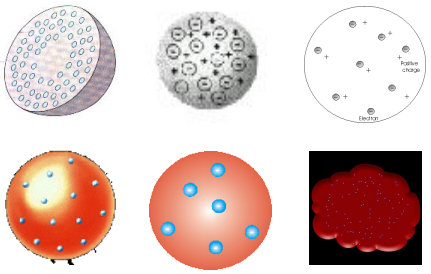
Niels Bohr (1913)
Quantum Model

J.J. Thomson

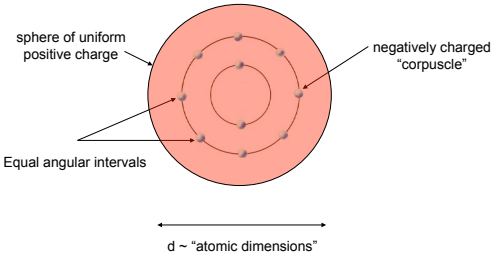
- 1897: Electrons are charged particles.
- 1900: β-rays are electrons.

<u>Conclusion:</u>
Electrons are constituents of matter

Various Depictions of the "Plum Pudding Model"



Thomson's Atomic Model* (1904)



* Joseph J. Thomson, "On the Structure of the Atom"
Philosophical Magazine and Journal of Science, Series 6, Vol. 7, No. 39, pp. 237-265

(From Thomson 1904, p. 254)

n	5	6	7	8	9	10	15	20	30	40
p	0	1	1	1	2	3	15	39	101	232

N	3	11	15	20	24	30	35	40	45	50	55	60
	3	8 3	10 5	12 7 1	13 8 3	15 10 5	16 12 6 1	16 13 8 3	17 14 10 4	18 15 11 5 1	19 16 12 7 1	20 16 13 8 3

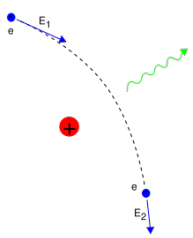
Li (Z= 3)
Na (Z=11)
K (Z=19)
Rb (Z=37)
Cs (Z=55)

(From Thomson 1904, p. 258)

N	59	60	61	62	63	64	65	66	67
	20 16 13 8 2	20 16 13 8 3	20 16 13 9 3	20 17 13 9 3	20 17 13 10 3	20 17 13 10 4	20 17 14 10 4	20 17 14 10 5	20 17 15 10 5

He	**Li**	**Be**	**B**	**C**	**N**	**O**	**F**	**Ne**
Ne	**Na**	**Mg**	**Al**	**Si**	**P**	**S**	**Cl**	**Arg**

Accelerated Charges Radiate!



$$P = \frac{e^2 a^2}{6\pi\varepsilon_0 c^3}$$

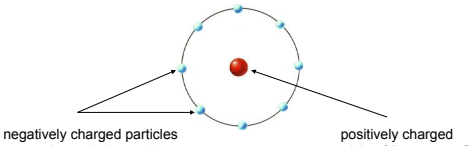
J.J. Larmor (1897)

Radiative Instability

"… in consequence of the radiation from the moving corpuscles, their velocities will slowly – very slowly – diminish; when, after a long interval, the velocity reaches the critical velocity, there will be what is equivalent to an explosion of the corpuscles."

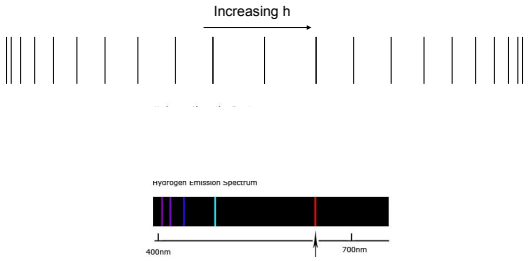
Hantaro Nagaoka (1904)

Nagaoka's "Saturnian" Model* (1904)



*Hantaro Nagaoka, "Kinetics of a System of Particles illustrating the Line and the Band Spectrum and the Phenomena of Radioactivity," *Philosophical Magazine and Journal of Science*, Series 6, Vol. 7, No. 41, pp. 445-455

Frequency (h) = $a_0 + a_1h^2 + a_2h^3 + \ldots$
h=0,1,2,…



*Hantaro Nagaoka, "Kinetics of a System of Particles illustrating the Line and the Band Spectrum and the Phenomena of Radioactivity," *Philosophical Magazine and Journal of Science*, Series 6, Vol. 7, No. 41, pp. 445-455

Ernest Rutherford
(1906)

- Radiation is scattered by matter.

"From measurements of the width of the band due to the scattered α-rays, it is easy to show that **some have been deflected from their course by an angle of about 2 degrees**. **It is possible that some were deflected through a considerably greater angle**, but if so, their photographic action was too weak to detect on the plate."

Ernest Rutherford
(1906)

- Powerful electrical fields in atoms.

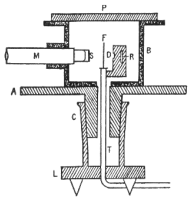
"This would require over that distance an average transverse field of about 100 million volts per centimeter. Such a result brings out clearly the fact that **atoms of matter must be the seat of very intense electrical forces**."

- Geiger (1908) – Deflection of α-particles is not an artifact of previous experimental methods.

"One day Rutherford came into the room where [Geiger and I] were counting α-particles, turned to me and said, "See if you can get some effect of α-particles directly reflected from a metal surface." I do not think he expected any such result. To my surprise, I was able to observe the effect looked for. I remember well reporting the result to Rutherford a week after, when I met him on the stairs."

-Ernest Marsden

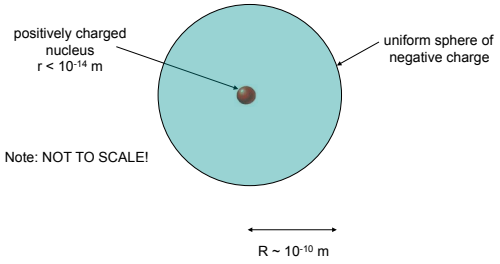
Schematic Diagram of Geiger and Marsden's Experimental Setup



From "The Laws of Deflexion of α Particles through Large Angles," Hans Geiger and Ernest Marsden, *Philosophical Magazine and Journal of Science*, Series 6, Vol. 25, p. 607

- Geiger (1908) – Deflection of α-particles is not an artifact of previous experimental methods.
- Geiger and Marsden (1909) – 1 in 8000 alpha particles are "diffusely reflected".
- Geiger (1910) – Most probable angle of deflection is 1/200th of a degree.

Rutherford's Atomic Model* (1911)



* Ernest Rutherford, "The Scattering of α- and β-Particles by Matter and the Structure of the Atom," *Philosophical Magazine and Journal of Science*, Series 6, Vol. 21, No. 125, pp. 669-688

$$\text{Prob}(r,\theta) = \frac{Qntb^2}{16r^2 \sin^4\left(\frac{\theta}{2}\right)}$$

$$b \approx \frac{2kZe^2}{\frac{1}{2}m_\alpha v_\alpha^2} \rightarrow \text{Prob}(r,\theta) \sim Z^2$$

$$\rightarrow$$ **The quantity Prob(r,θ)*A$^{1/2}$*Z^{-2} should be independent of the scattering material**

$$nt \sim \frac{1}{A^{1/2}} \rightarrow \text{Prob}(r,\theta) \sim A^{-1/2}$$

Substance	Atomic Weight A	N	$N*A^{-3/2}$ (10^{-4})
Aluminum	27.1	3.4	243
Iron	56	10.2	250
Copper	63.6	14.5	225
Silver	107.9	27	241
Tin	119	34	226
Platinum	195	63	232
Gold	197	67	242
Lead	207	62	208
Average			233
Standard Deviation			13
Coefficient of Variation			5.6%

Data from Rutherford 1911, p. 681

"The question of the stability of the atom proposed need not be considered at this stage, for this will obviously depend upon the structure of the atom, and on the motion of the constituent parts."

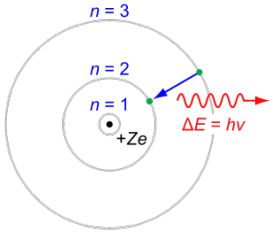
Niels Bohr
(1913)

"…introduce a hypothesis for which there will be given no attempt at a mechanical foundation (as it seems hopeless)."

"It was in the air to try to use Planck's ideas in connection with such things."

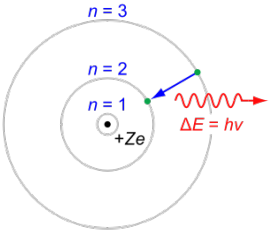
J.W. Nicholson (1910)

"…obtained a relation to Planck's theory showing that the ratios between the wavelength of different sets of lines in the coronal spectrum can be accounted for with great accuracy by assuming the ratio between the energy of the system and the frequency of rotation of the ring of charges is equal to an entire multiple of Planck's constant."



"Electrons occupy discrete **orbits of constant energy**. These orbits are described using the ordinary mechanics, while **the passing of the system between different stationary states cannot be treated on this basis**"

* Niels Bohr, "On the Constitution of Atoms and Molecules"
Philosophical Magazine and Journal of Science, Series 6, Vol. 26, No. 151, pp. 1-25

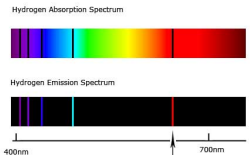


"In making a transition between stationary states, a **single photon** will be radiated…"

* Niels Bohr, "On the Constitution of Atoms and Molecules"
Philosophical Magazine and Journal of Science, Series 6, Vol. 26, No. 151, pp. 1-25

$$E_{orbit} = \frac{-13.6eV}{n^2}$$

Balmer's Formula: $\nu_{ab} = R_1\left(\frac{1}{b^2} - \frac{1}{a^2}\right)$



Absorption and Emission Spectrum of Hydrogen

"I think I discussed the paper with someone … that was Professor Hansen … I just told him what I had, and he said, "But how does it do with the spectral formulae?" And I said I would look it up. I didn't know anything about it, then I looked it up in the book of Stark. Other people knew about it, but I discovered it for myself."