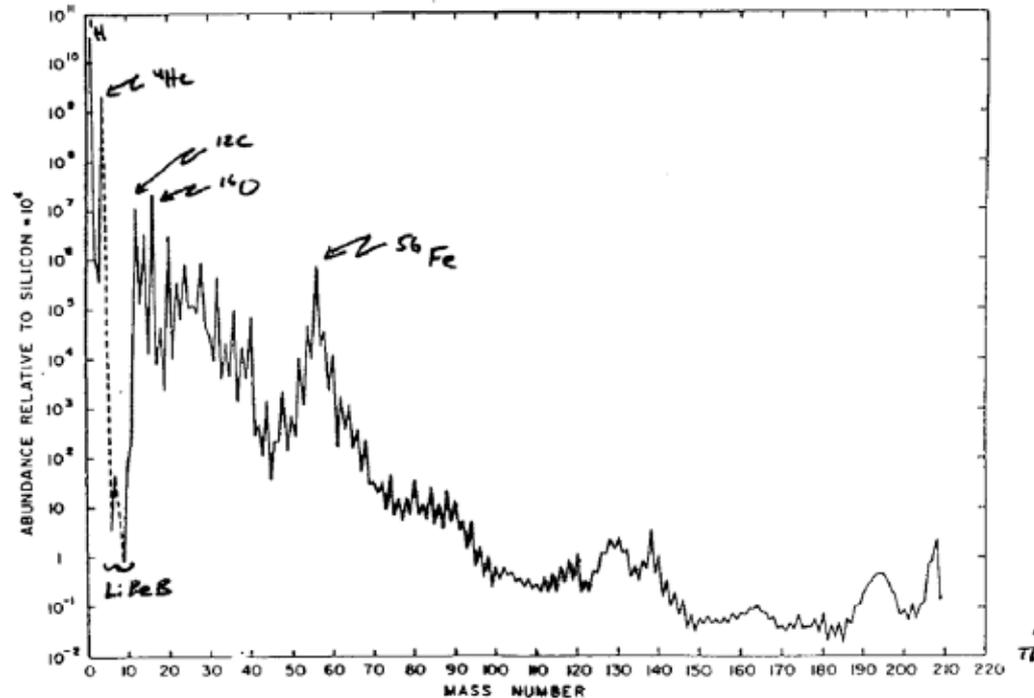


Lecture 1: Radioactivity, Radiation and the Structure of the atom

Consider the periodic Table. Atoms combine (form bonds) to make molecules in compounds. Molecules have shape and can react to form other molecules. Atomic reactivity is a consequence of electronic structure. All molecules inorganic, organic, and biological have atoms as their building blocks. Where did the building blocks come from?

Solar System abundances



Why does one have the peaks and valleys (structure)?

You have no doubt heard that at the “heart of every atom” is a nucleus.

- How did this picture emerge?
- What is the structure of the nucleus?
- What reactions do nuclei undergo?
- What are the biological effects of radiation?
- What are the “facts” regarding nuclear power?

These are some of the questions we will address in this course !

Nuclear chemistry today is active as basic science, an analytic tool, a therapeutic tool.

RADIOACTIVITY IS A SPONTANEOUS PROCESS.

We are constantly bombarded with radiation from above (Cosmic rays) and below (ores in the earth).

Let's begin with Henri Becquerel. About 1880 he prepared potassium uranyl sulfate: $\text{K}_2\text{UO}_2(\text{SO}_4)_2 \cdot 2\text{H}_2\text{O}$ and experimented with it. He was exploring the phenomenon of **fluorescence**.

On Feb. 24, 1896 Henri Becquerel reported his first results. After exposure to bright sunlight, the crystals emitted a radiation that blackened a photographic plate after going through black paper, glass, and other substances.

Subsequently he found the effect had nothing to do with the sunlight. Other uranous salts, solutions containing uranium, and even what was believed to be uranium metal all exhibited the same behavior. [*Chance favors the prepared mind.* - Louis Pasteur]

On the invisible rays emitted by phosphorescent bodies.

[read before the French Academy of Science 2 March 1896 (*Comptes Rendus* **122**, 501 (1896)) translated by Carmen Giunta]

In the previous session, I summarized the experiments which I had been led to make in order to detect the invisible rays emitted by certain phosphorescent bodies, rays which pass through various bodies that are opaque to light.

I was able to extend these observations, and although I intend to continue and to elaborate upon the study of these phenomena, their outcome leads me to announce as early as today the first results I obtained.

The experiments which I shall report were done with the rays emitted by crystalline crusts of the double sulfate of uranyl and potassium

[$\text{SO}_4(\text{UO})\text{K}+\text{H}_2\text{O}$], a substance whose phosphorescence is very vivid and persists for less than $\frac{1}{100\text{th}}$ of a second. The characteristics of the luminous rays emitted by this material have been studied previously by my father, and in the meantime I have had occasion to point out some interesting peculiarities which these luminous rays manifest.

One can confirm very simply that the rays emitted by this substance, when it is exposed to sunlight or to diffuse daylight, pass through not only sheets of black paper but also various metals, for example a plate of aluminum and a thin sheet of copper. In particular, I performed the following experiment:

A Lumière plate with a silver bromide emulsion was enclosed in an opaque case of black cloth, bounded on one side by a plate of aluminum; if one exposed the case to full sunlight, even for a whole day, the photographic plate would not become clouded; but, if one came to attach a crust of the uranium salt to the exterior of the aluminum plate, which one could do, for example, by fastening it with strips of paper, one would recognize, after developing the photographic plate in the usual way, that the silhouette of the crystalline crust appears in black on the sensitive plate and that the silver salt facing the phosphorescent crust had been reduced. If the layer of aluminum is a bit thick, then the intensity of the effect is less than that through two sheets of black paper.

If one places between the crust of the uranium salt and the layer of aluminum or black paper a screen formed of a sheet of copper about 0.10 mm thick, in the form of a cross for example, then one sees in the image the silhouette of that cross, a bit fainter yet with a darkness indicative nonetheless that the rays passed through the sheet of copper. In another experiment, a thinner sheet of copper (0.04 mm) attenuated the active rays much less.

Phosphorescence induced no longer by the direct rays of the sun, but by solar radiation reflected in a metallic mirror of a heliostat, then refracted by a prism and a quartz lens, gave rise to the same phenomena.

I will insist particularly upon the following fact, which seems to me quite important and beyond the phenomena which one could expect to observe: The same crystalline crusts, arranged the same way with respect to the photographic plates, in the same conditions and through the same screens, but sheltered from the excitation of incident rays and kept in darkness, still produce the same photographic images. Here is how I was led to make this observation: among the preceding experiments, some had been prepared on Wednesday the 26th and Thursday the 27th of February, and since the sun was out only intermittently on these days, I kept the apparatuses prepared and returned the cases to the darkness of a bureau drawer, leaving in place the crusts of the uranium salt. Since the sun did not come out in the following days, I developed the photographic plates on the 1st of March, expecting to find the images very weak. Instead the silhouettes appeared with great intensity. I immediately thought that the action had to continue in darkness, and I arranged the following experiment

At the bottom of a box of opaque cardboard I placed a photographic plate; then, on the sensitive side I put a crust of the uranium salt, a convex crust which only touched the bromide emulsion at a few points; then, alongside, I placed on the same plate another crust of the same salt but separated from the bromide emulsion by a thin pane of glass; this operation was carried out in the darkroom, then the box was shut, then enclosed in another cardboard box, and finally put in a drawer.

I did the same with the case closed by a plate of aluminum in which I put a photographic plate and then on the outside a crust of the uranium salt. The whole was enclosed in an opaque box, and then in a drawer. After five hours, I developed the plates, and the silhouettes of the crystalline crusts appeared in black as in the previous experiments and as if they had been rendered phosphorescent by light. For the crust placed directly on the emulsion, there was scarcely a difference in effect between the points of contact and the parts of the crust which remained about a millimeter away from the emulsion; the difference can be attributed to the different distance from the source of the active rays. The effect from the crust placed on a pane of glass was very slightly attenuated, but the shape of the crust was very well reproduced. Finally, through the sheet of aluminum, the effect was considerably weaker, but nonetheless very clear.

It is important to observe that it appears this phenomenon must not be attributed to the luminous radiation emitted by phosphorescence, since at the end of $\frac{1}{100\text{th}}$ of a second this radiation becomes so weak that it is hardly perceptible any more.

One hypothesis which presents itself to the mind naturally enough would be to suppose that these rays, whose effects have a great similarity to the effects produced by the rays studied by M. Lenard and M. [Röntgen](#), are invisible rays emitted by phosphorescence and persisting infinitely longer than the duration of the luminous rays emitted by these bodies. However, the present experiments, without being contrary to this hypothesis, do not warrant this conclusion. I hope that the experiments which I am pursuing at the moment will be able to bring some clarification to this new class of phenomena.

1898: Pierre and Marie Curie concluded that the uranium rays were an atomic phenomenon (due to the element uranium) and not its chemical or physical state. They introduced the term “radioactivity”.

Understanding the emissions

Radiochemistry : Field started as separation of different radioactive species from ores and one species from another. Discovery of Polonium (Po) a new element; Separation of radium from pitchblende (75% U_3O_8). Some of the uranium undergoes fission. One of the products of the fission is barium, which can be separated by precipitation. From the barium one can separate radium. All of this early work in the field involved (radio)chemical separation techniques. Hence this area is called radiochemistry.

Types of radiation: Based on the ability of the radiation to ionize air (as measured by an electroscope/electrometer) J.J. Thomson and others; Absorption by metal foils placed between the radioactive source and the electroscope.

Alpha rays (α) : stopped by a few thousandths of Al foil.

Beta rays (β): required 100 times more Al to be absorbed.

Gamma rays (γ): even more penetrating

Names provided by Rutherford

Deflection in electric and magnetic fields led to the realization that α and β rays were in fact streams of high speed particles and allowed determination of the charge and charge to mass ratio.

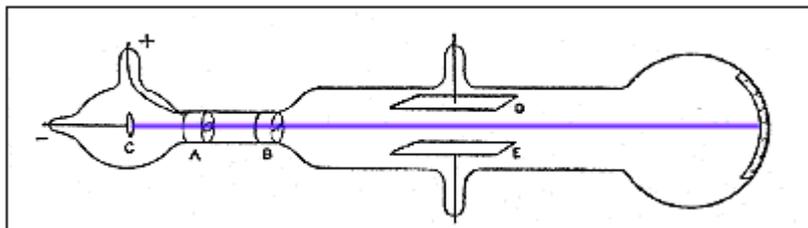
Particle	Charge	Mass (rest)	Comment	
β	e= chg. On electron	$9.1091 \times 10^{-28} \text{g}$	Same as electron	
α	$-2e$	Same as He^{2+}	Same as He^{+2}	
γ	0	0		

Lorentz Force:

$$\vec{F} = q(\vec{E} + (\vec{V} \times \vec{B}))$$

arrows indicate vector quantities

What do these quantities mean?



J.J. Thomson, "Cathode Rays," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, Fifth Series, October 1897. p. 296

Schematic drawing of Thomson's apparatus in the second experiment. Rays from the cathode (C) pass through a slit in the anode (A) and through a slit in a grounded metal plug (B). An electrical voltage is established between aluminum plates (D and E), and a scale pasted on the outside of the end of the tube measures the deflection of the rays.

Cathode rays (electrons) could be bent by placing a voltage between the plates labeled D and E generating an electric field.

$$\vec{E} = \frac{V}{d} \quad \text{where } V \text{ is the voltage and } d \text{ is the distance between the plates}$$

Alternatively, the electrons can be deflected by a magnetic field. Key to making the experiments work was evacuating the gas in the tube as much as possible.

Discovery of neutron (existence predicted by Rutherford in 1920)

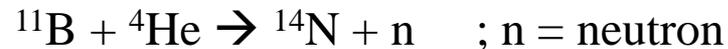
By J. Chadwick, F.R.S.

Proc. Roy. Soc., A, **136**, p. 692-708

(Received May 10, 1932)

Bombarded a sample of beryllium with a source of alpha particles. The result was a penetrating radiation they called 'beryllium rays' that required 200 mm of lead to be stopped. In contrast, a proton required only 1 mm of lead to be stopped. Chadwick showed that the 'beryllium rays' were in fact uncharged particles and could not be gamma rays.

For example,



First Law of Radioactivity and Concept of half-life

$$\frac{dN}{dt} = -\lambda N$$

from observation; λ is a constant known as the **decay constant**.

$$\frac{dN}{N} = -\lambda dt$$

$$\int \frac{dN}{N} = \int -\lambda dt$$

$$\ln(N) = -\lambda t + a ; a \text{ is a constant of integration}$$

When $t=0$, we have N_0 initial # of nuclei of the radioactive substance. Therefore we get,

$$\ln\left(\frac{N}{N_0}\right) = -\lambda t$$

$$N(t) = N_0 e^{-\lambda t}$$

Let $t_{1/2}$ be the time it takes for N_0 nuclei to decay into $N_0/2$ nuclei.

$$\ln\left(\frac{N_0/2}{N_0}\right) = -\lambda t_{1/2} \quad \text{so} \quad \ln(1/2) = -\lambda t_{1/2} \quad \text{or} \quad t_{1/2} = \frac{\ln(2)}{\lambda} = \frac{0.69315}{\lambda}$$

Half-lives are a characteristic of a particular decay. For example,

^{40}K undergoes β decay with a half-life of 1.27×10^9 years to transform itself into ^{40}Ca

UNITS

1. Time: s – seconds
2. Energy: E – electron Volt
 $1 \text{ MeV} = 1.6 \times 10^{-6} \text{ ergs} = 3.8 \times 10^{-14} \text{ cal} = 11.6 \times 10^9 \text{ }^\circ\text{K}$
3. Mass: M – u – atomic mass unit
 $1 \text{ u} = 1.6705655 \times 10^{-24} \text{ g}$
4. Length: r, d, R
$$\frac{1 \text{ fm} = 10^{-13} \text{ cm}}{\text{Fermi}} = \frac{10^{-15} \text{ m}}{\text{femtometer}}$$
5. Electric charge – e
 $e = 0, \pm 1, \pm 2 \dots$ integral
6. Angular Momentum – \hbar (AM)
s – intrinsic spin
l = orbital
 $I = \text{total} = \vec{s} + \vec{l}$
 $I\hbar = 0, 1/2, 1, 3/2, 2 \dots n/2$

NOTATION

“Nuclide” is any combination of neutrons and protons

Z = # of protons = Atomic Number

N = # of neutrons = Neutron Number

$A = (Z+N)$ = # of Nucleons = Mass Number

ALWAYS
INTEGERS



← Atomic ionization state = Z -# of electrons

Definitions --

Isotopes: Z is constant (e.g. ^{12}C , ^{13}C , ^{14}C)

Isotones: N is constant (e.g. ^{11}B , ^{12}C , ^{13}N)

Isobars: A is constant (e.g. ^{14}C , ^{14}N)

NOTE: The mass of a nucleus is NOT its mass number!

Coulomb's Law, Rutherford scattering, and the model of the atom

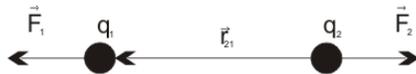
Coulomb's Law :

$$V(r) = \frac{q_1 q_2}{r}$$

The potential energy, V , between two charges is proportional to the product of their charges (q_1 and q_2 respectively) and inversely proportional to the distance between them (r). Notice that opposite charges repel and opposite charges attract..

Notice the similarity and difference between Coulomb's Law and the equation for gravitational potential

$$V(r) = -G \frac{m_1 m_2}{r}$$

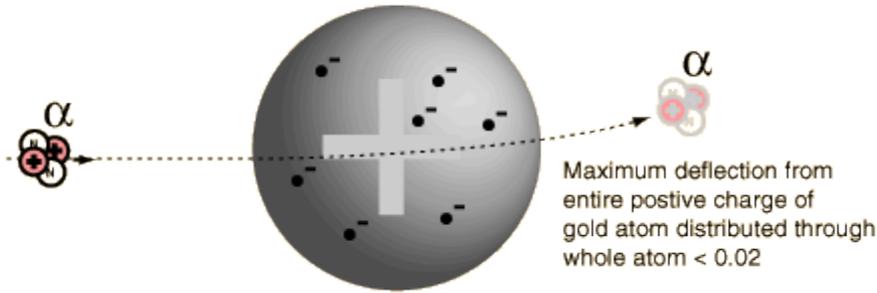


Force is the negative of the derivative of the potential with respect to position (r).

$$F = -\frac{dV}{dr}$$

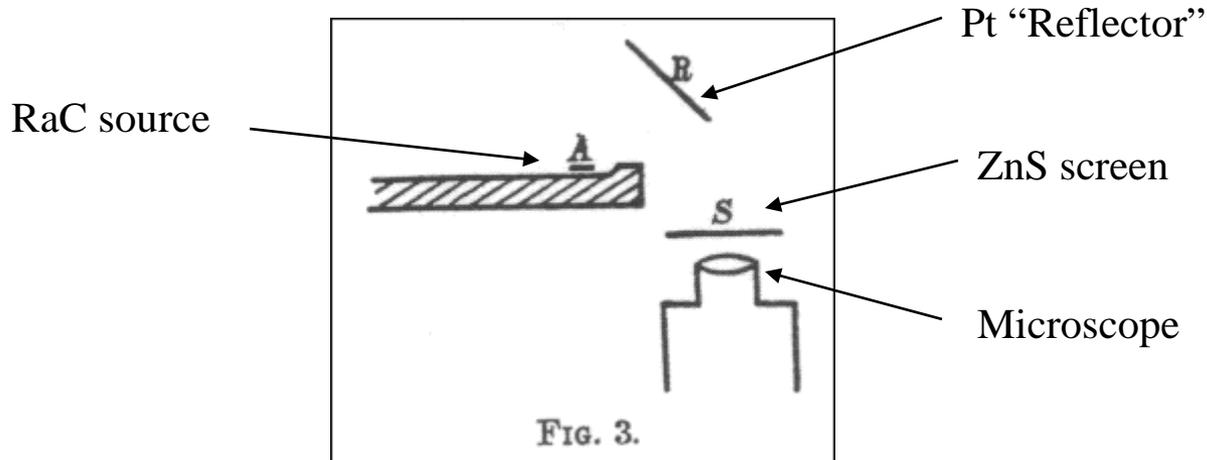
Therefore the Coulomb interaction between two charges q_1 and q_2 is:

$$F(r) = \frac{q_1 q_2}{r^2} \quad ; \text{ notice that a positive force is repulsive and a negative force is attractive!}$$



Thomson
model of the
atom

Geiger and Marsden (Phil. Mag. 25, 605 (1913)) scattered α particles of different foils.



About 1 in 8000 incident alphas was scattered to a large angle and observed on the screen.

Conclusion: The experiments indicated that **the nucleus is a densely charged object**, otherwise these large deflections would not be possible.

$$n(\phi) = n_0 \frac{Nt}{16r^2} \left(\frac{Ze.Z_\alpha e}{\frac{1}{2}M_\alpha V_\alpha^2} \right)^2 \frac{1}{\sin^4\left(\frac{\phi}{2}\right)}$$

$n(\phi)$ = number of alpha particles falling on a unit area at a distance r from the scattering point to the scattering angle ϕ .

n_0 = number of incident alpha particles

t = thickness of the scatterer

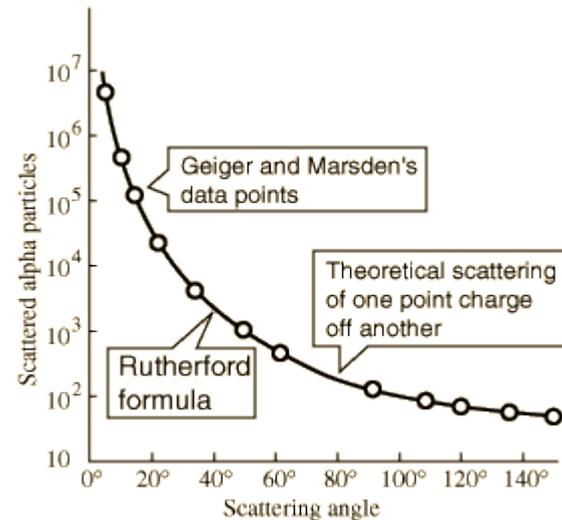
N = number of nuclei per unit volume scatterer

M_α = mass of the alpha particle

V_α = initial velocity of the alpha particle

$Z_\alpha e$ = charge of the alpha particle

Ze = charge of the scatterer



What's happening physically?

