



From Quanta to Quarks

Anna Binnie

Macquarie University

(email abinnie@laurel.ocs.mq.edu.au)

Introduction

This workshop will cover the theory and practical work required for the new Elective unit, Quanta to Quarks. The structure of this paper will follow the headings and outline as set out in the syllabus. This paper will give some background information on areas of physics that are new to the HSC Syllabus. Some aspects of this unit which should be familiar to Physics teachers will not be covered, specifically the parts of this unit which were in the old "Nuclear Physics" Unit will *not* be treated.

Problems with the Rutherford model of the atom led to the search for a model that would explain the observed phenomena

The discovery by Geiger and Marsden that not all projectile α -rays traveled through gold foil, led Rutherford to hypothesize the existence of a dense centrally located atomic nucleus. The fact that the majority of these rays passed through the foil undeflected indicated that the atom was also mostly empty space. Hence the Rutherford Model of the atom showed a central positive nucleus around which electrons orbited. The number of electrons in orbit around this nucleus was equivalent to the atomic number of the atom. This model had a number of major problems, these included the following:

1. Since any charged particle will radiate energy when accelerated, an orbiting electron would continually lose energy, and hence spiral down into the nucleus emitting a continuous spectrum of light. Equating the force due to electrostatic attraction between nucleus and electron to the force due to centripetal acceleration yields:

$$\frac{1}{4\pi\epsilon_0} \frac{e^2}{r^2} = \frac{m_e v^2}{r}$$

$$v = e \sqrt{\frac{1}{4\pi\epsilon_0 m_e r}}$$

where e is the charge on the electron, m_e is the mass of the electron, v is the speed of the electron and r the radius of the electron's orbit. ϵ_0 is the permittivity of free space. The period is $T = 2\pi r/v$, hence

$$T = 2\pi \frac{r^{3/2}}{e} \sqrt{4\pi\epsilon_0 m_e}$$

$$f = \frac{e}{r^{3/2} \sqrt{4\pi\epsilon_0 m_e}}$$

Since $f = 1/T$, using the equation for the period above gives:

Since the radius changes continuously, the frequency of radiation it emits will also change continuously.

2. It did not sufficiently describe the location of electrons that are involved in chemical reactions. It is easier to remove some electrons than it is others. For example, compare chlorine, neon and potassium; while there is only one electron difference between Cl and Ne and between Ne and K they all have significantly different reactive abilities.
3. The model did not explain the presence of unique emission and absorption spectra of elements.



4. The model did not explain the Zeeman effect. The Zeeman effect is the change in spectral lines that occurs in the presence of a magnetic field. The presence of a magnetic field has the effect of splitting a spectral line into two or more adjacent but distinct lines and this occurs in both emission and absorption spectra.

In 1900 Planck investigated the relationship between the intensity and the frequency of the radiation emitted by hot objects. It was found that the maximum intensity of light emitted by these objects was directly related to the temperature of the object; specifically an object emitting a maximum intensity in the blue range was hotter than an object whose emission maximum intensity was in the red range. Planck hypothesised that the energy of the light emitted was linked to the frequency of that light and that this light was emitted in little bursts or quanta. He suggested that the relationship between the energy and the frequency of these light quanta could be expressed as;

$$E = hf$$

where h is a constant term now called the Planck Constant.

In 1905, Einstein made an extension of Planck's theory of light quanta by suggesting that these bursts of light could be regarded as "particles" of light or "photons" and as such must have momentum. This resulted from his work into the Photoelectric effect. When light is shone on some metals a current starts to flow. The frequency of the light determines the magnitude of the current and if the frequency is below the cut-off frequency no electrons flow. From this it could be seen that the following relationship holds:

$$\begin{aligned} p &= \frac{E}{c} \\ &= \frac{hf}{c} \\ &= \frac{h}{\lambda} \end{aligned}$$

Bohr, in an attempt to reconcile empirical evidence with a model of the atom focused his attention on the hydrogen atom. He made the following postulates:

1. The hydrogen atom must have certain stable orbits in which the electrons can be found and that these electron orbits are circular.
2. In its normal state each hydrogen atom would have its electron in the lowest stable orbit.
3. As the hydrogen gas is heated, atoms collide, sometimes violently, causing electrons to be knocked up into higher orbits. The electrons would stay in this higher orbit for some time and then would jump down to the lower orbit, emitting a quantum of light of a frequency determined from the Planck equation.

From these postulates and the previous experimental results Bohr was able to develop a mathematical model for the Hydrogen spectrum. (See appendix 1 for the mathematical details).

The Bohr model worked well for an atom with only one orbiting electron. For elements with higher atomic numbers, the interactions between the orbiting electrons and their positions and the interactions between the orbiting electrons and the nucleus had to be taken into account. As a result the neat mathematical model did not fit exactly with observation and hence a new model, or more correctly a refinement to this model, was required.

The practical work for this section could include:

- viewing the spectra of a variety of gases using a handheld spectroscope.
- use a table spectroscope and either a glass prism or a diffraction grating with a hydrogen gas emission tube to calculate the wavelength of the spectra of hydrogen in the visible region
- place a pair of strong magnets near a hydrogen gas emission tube and use a handheld spectroscope to view the hydrogen spectrum. Repeat this with other gases. A pair of thin spectral lines should now replace those previously seen. This is the Zeeman Effect.

The limitations of Classical Physics gave birth to Quantum Physics

In 1925 Louis de Broglie submitted his thesis in which he had formulated the basis of wave-particle duality. In his thesis, de Broglie starts with Einstein's model for the particle nature of light waves, i.e. the energy and momentum relationships of Special Relativity, and suggested that it holds not only for photons but also for particles such as electrons. He further, suggests that if this premise is correct then electrons should also behave as waves. Thus he



suggested that electrons should exhibit diffraction patterns. de Broglie's ideas were so unusual that his thesis was shown to Einstein for a comment. Einstein in turn approved of the young man's work and de Broglie graduated in 1925.

de Broglie's prediction of electron diffraction patterns were verified in 1927 by two groups working independently, C. Davisson and L. Germer, and G. Thomson (son of J.J. Thomson) and A. Reid. It is of interest to note that while J.J. Thomson worked to establish the particle nature of electrons, his son George confirmed the wave properties of electrons. Both father and son won Nobel Prizes for their work.

The atomic electrons could now be regarded as standing wave patterns that only occur at predetermined positions around the central nucleus. These predetermined positions for standing wave patterns coincide with the energy levels that have already been discussed. This led to the situation that subatomic electrons could now be regarded as both waves and as particles. Once the idea of the wave-particle duality of matter was suggested, a new atomic model was required to explain both these two disparate sets of properties for the single entity, the electron. (See appendix 1 for the mathematical developments).

The practical work in this section is based on the student's research. They should find the contributions made by both Heisenberg and Pauli. Heisenberg's equation is a wave equation and is based on the wave properties of electrons (is also called the Uncertainty Principle). Pauli produced his famous Exclusion Principle. The students should gain an understanding of the importance of these contributions. There is a number of history of science books (some dating from the 1960s) which could be useful or use any of the modern US College Physics texts (non-calculus).

Quantum Physics is used in a range of technologies

An application of the wave characteristics of the electron is the electron microscope. There are essentially two types of electron microscope, the transmission and the scanning electron microscope. The transmission electron microscope produces two-dimensional images and most resembles the light microscope. The lenses to focus the beams of electrons are produced by magnetic fields, (see diagram A at end).

The scanning electron microscope produces three dimensional images since the beam of electrons travels in lines across the sample, producing secondary electrons which are then detected and produce the "picture" (see diagram B at end).

The scanning tunneling electron microscope is a development of the scanning electron microscope. The tip of the scanning probe sits about a nanometer away from the surface that is scanned, a small voltage between the probe and the surface causes electrons to flow out from the surface to the probe, this flow is called the tunneling current and is very sensitive to the size of the gap between the probe and the surface and hence the probe can be adjusted to follow the surface of the specimen very closely.

The Practical work in this section could best be done by obtaining electron microscope images from the web or from the Key centre for Microscopy and Microanalysis at the University of Sydney. (See section by Prof. Dave McKenzie in this proceedings.)

The work of Chadwick and Fermi in producing artificial transmutations led to practical applications of radiation

The discovery of radioactivity by Bequerel in 1896 opened the door to another aspect of research into the structure of the atom. The phenomenon of radioactivity produced rays that were emitted from only some select materials. Work in this area was conducted by Bequerel, the Curies, Rutherford and others, who by the turn of the century had determined that these rays were of three types. α -rays were discovered to have a charge of twice that of the electron and a mass four times that of hydrogen. In 1909 Rutherford proved that these rays were the nuclei of helium. β -rays were shown to be electrons and γ -rays were shown to carry no charge or mass and were found to be electromagnetic radiation of very short wavelength.

In 1902 Rutherford and Soddy discovered that with every radioactive emission of either an α -ray or β -ray a new element was formed. Thus one element would change into another. The term "transmutation" was thus coined for this process. α emissions resulted in nuclei of atomic number 2 less and mass number 4 less than the original nucleus while a β emission produced an atomic number of 1 greater than the original nucleus. By 1919 Rutherford, who was now at



the Cavendish, was using high-energy α -rays to bombard nitrogen nuclei, producing hydrogen and oxygen. The first instance of artificially induced transmutation had just taken place. During the period 1920-25 Rutherford and others induced transmutation in a number of light elements, all by the energetic bombardment of α -rays. Hydrogen was often one of the resultant products in such reactions. Consequently, physicists concluded that this positively charged hydrogen nucleus was one of the fundamental building blocks of the nucleus and was named the proton.

It became apparent that the proton did not carry all the mass of the nucleus but only approximately half. Rutherford had assumed that if an electron and proton formed a closer link than that of an ordinary atom of hydrogen, a composite particle would be formed of the mass of a proton and with a neutral charge. The term "neutron" was first termed at the Cavendish and the search for it commenced, a search that lasted almost 12 years.

While members of the Cavendish laboratory were trying to find evidence for the formation of the neutron by attempting a variety of reactions between protons and electrons, the Joliot-Curies were continuing with their work on the artificial transmutation of elements bombarded by high-energy α -rays. In 1930 two German physicists Walther Bothe and Herbert Becker reported that when beryllium is exposed to α emissions from polonium, "new radiations are produced". They assumed these radiations were α -rays. In 1932 the Joliot-Curies discovered that if this radiation struck materials containing hydrogen, such as paraffin, protons were emitted. Within weeks of the Joliot-Curie paper reaching the Cavendish, Chadwick had performed his own experiments and concluded that the radiation emitted from beryllium was the long sought after neutron and hence Chadwick discovered the neutron. The Joliot-Curies came close but never quite identified the neutron.

Experiments on induced radiation continued well into the 1930s. The target nuclei included not only the light atoms that Rutherford and his team had used but also included the heavy uranium atom. Uranium has a property akin to many other atoms, that of possessing a number of isotopes. "Isotope" is the term used to refer to nuclei of the same type of atom (i.e. those with the same number of protons) but with different atomic masses (i.e. with different numbers of neutrons). By June 1934, Enrico Fermi (1901-1954) and his team in Rome had discovered that when uranium was bombarded by neutrons a number of induced activities occurred including what appeared to be the formation of a new element whose atomic number was greater than that of uranium. This in itself was a startling discovery since uranium is the heaviest naturally occurring atom. The new element that Fermi and his team had produced was man-made and later played a major role in nuclear physics. This new element became known as plutonium.

Hahn (1879-1968) and Strassmann (1902-1980) continued with these neutron-uranium collision experiments, but in analysing the results discovered that many of the uranium nuclei split into two lighter nuclei such as barium. These results were totally baffling until Otto Frisch (1904-1979) spent the Christmas of 1938 with his aunt, Lise Meitner (1878-1968). During a walk in the woods they came across the idea that some uranium nuclei may behave like wobbly unstable drops which will divide at the least provocation, and a neutron could trigger this. This splitting process could be likened to the process of cell division and hence was termed nuclear fission. Meitner and Frisch calculated the energy released in one such reaction was much greater than anything that had previously been observed.

Hahn and Strassmann continued with their work and by January 1939 discovered that when an atom of uranium undergoes fission, not only is a great deal of energy released, but the process releases more neutrons. This implied that the reaction could in theory become self-sustaining – the extra neutrons produce a chain-reaction. Neils Bohr (1885-1962) proposed that only one isotope of uranium was responsible for this reaction, that of U^{235} . What was now required was uranium in which the amount of the relatively rare U^{235} isotope could be increased in an amount of uranium; so the need for a process of uranium enrichment was established.

Practical work for this section could include:

- an excursion to ANSTO to obtain the data on the use of isotopes.
- set library research tasks on Pauli, Fermi and Chadwick.

An understanding of the Nucleus had led to many applications

This is essentially a repetition of a part of the old "Nuclear Physics" Unit from the old Syllabus. The practical work in this section is also a repetition of sections of the old syllabus.

Our attempts to understand the structure of matter is an ongoing process

The development of Quantum Mechanics and Relativistic Electrodynamics allowed the mathematical models that eventually lead to the "subatomic zoo". The following does not attempt to develop the Quantum Mechanics that



underlies much of the theoretical developments in this area. Instead a brief overview will be presented to allow a broad understanding of the issues involved behind the theoretical developments and the subsequent discoveries in subatomic physics. What appears to be a rather messy chronological exposition only highlights the number of discoveries, proposals and models which were developed over an extremely short time frame of approximately 40 years. Many of the chief protagonists play more than one part in this drama and complete justice cannot be done due to the limitations of time and space.

Studies of β decay indicated that conservation of energy, momentum and angular momentum (of the nucleus and its decay products) were not conserved. Consequently, in 1929 Austrian physicist Wolfgang Pauli proposed the existence of an additional neutral particle that was released in β decay. This new particle was called the neutrino. The existence of the neutrino was not demonstrated experimentally until 1956 with the direct detection of the e-neutrino in β decay (see also Dr Tim Bedding's article in these proceedings). This was followed by the discovery of the μ -neutrino in 1962.

The theoretical existence of the neutrino and the mounting evidence that neutrons were not composed of a proton and an electron, led Enrico Fermi in 1933 to develop his theory of β decay. His theory is that during this decay process a proton, electron and neutrino come into existence at the moment of the decay as a result of a new type of force. This new type of force has since become known as the weak interaction. The weak interaction was later incorporated with electromagnetism into the electroweak theory, which was developed to explain the decays of the newly discovered particles (found in cosmic rays eg pions and muons). This electroweak theory was developed independently by Weinberg and Salam during 1962-3.

The problem now arose as to how the nucleus of an atom could remain intact without disintegrating due to Coulomb repulsion – a new mechanism was required. In 1935 the Japanese physicist H. Yukawa published his theory on the existence of a strong nuclear force acting on the nucleons (protons and neutrons) of an atom. This strong nuclear force acts over extremely short distances and could, under certain circumstances, create subatomic particles. Yukawa went on to determine the properties of these subatomic particles called muons (or μ mesons). In 1942-3 other Japanese physicists proposed the existence of a second type of mesons, the pions (π mesons). These particles were discovered in 1947 (pions) and 1950 (muons) in photographs of the tracks of cosmic rays and their decay products.

As a result of accelerator experiments and more sensitive cosmic ray detection, the number of so-called fundamental subatomic particles had increased to almost 200 in total by the 1960s. This necessitated the classification of subatomic particles into groups or even a periodic table of subatomic particles. In 1964 Murray Gell-Mann proposed the idea that all matter was composed of fundamental particles called quarks, of which there are three. Quarks have electric charges that are fractions of the charge on the electron, and together with their antiparticles combined to form all other subatomic particles. However it was found that a few particles could not have been made up of these quarks; the electron, the muon and their neutrinos could also be considered as being fundamental. This class of particles was called leptons. Further, it was found that in some subatomic particles it is possible to find two or more identical quarks (this would violate the Pauli Exclusion Principle) and so another quantum number was assigned to quarks, colour; red, blue and green. The interaction or the forces acting only between "coloured" particles became known as chromodynamics and the theory behind this was quantum chromodynamics or QCD. This force is transmitted by particles known as gluons.

Again as the theory was modified it was found necessary to introduce yet more quarks, hence another three were incorporated into the model and were later joined by two new leptons.

The Standard Model is a description of the behaviour of subatomic fundamental particles and forces that make up matter. This is by necessity a summary of what the model is at present. The Standard Model divides fundamental particles into two types, leptons and quarks. Both these types of particles are fermions, ie they have a spin of 1/2. The difference between leptons and quarks lies in the way in which they are affected by strong forces. Quarks are affected by the strong force, QCD, while leptons are not. Leptons and quarks can be arranged into families of increasing mass and occur in pairs. For each pair of leptons and quarks there is a corresponding pair of antiparticles. The basic interactions or forces between elementary particles are "carried" by another set of particles called the bosons (with integer spin). These include photons for the electromagnetic force, the massive W^+ , W^- , Z^0 for the weak nuclear force and for QCD the carriers are the gluons.

QUARKS	LEPTONS
Down, Up	Electron, e-neutrino
Strange, Charm	Muon, μ -neutrino
Bottom, Top	τ , τ -neutrino



The Standard Model also attempts to join all the known types of forces together. So far it has managed to combine the electromagnetic, the nuclear weak force and the nuclear strong force. The Grand Unified Theory (GUT) which hopes to also include gravitation has not yet been developed. As it stands the Standard Model is under constant review and modification.

It is now believed that the processes observed in the far outer reaches of the Universe and hence in the young Universe were the processes that allowed matter as it is seen today, to form. The beginnings of the Universe, as in the "Big Bang" Theory suggest that as the Universe cooled and condensed, matter was formed. The first "particles" to come into existence were the building blocks of matter. High Energy Physics, which studies the debris from the collisions in huge accelerators, attempts to find these building block of matter. Hence both Cosmology and High Energy Physics study at the fundamental building blocks of matter.

The practical work for this section could include a search on the internet or literature eg "New Scientist" as to the latest advances in Physics.

Appendix 1

From Bohr's first postulate, a single electron moving in a stable circular orbit, of radius r_n has angular momentum

$$L = mvr_n$$

$$= n \frac{h}{2}$$

which, on rearranging, gives $n \frac{h}{2 mr_n}$.

From the previous work on the forces acting on the electron in this orbit we have;

$$r_n = \frac{e^2}{4 m_e v^2}$$

Substituting for v we get the following relationship for the radius of a stationary orbit;

$$r_n = n^2 \frac{h^2}{m_e e^2}$$

We must now consider the energy of the electron while it is in orbit, it has both kinetic energy and electric potential energy, hence the total energy of the electron may be obtained from;

$$E_{potential} = \frac{e^2}{4 r_n}$$

$$E_{kinetic} = \frac{mv^2}{2}$$

$$E_{total} = \frac{mv^2}{2} - \frac{e^2}{4 r_n}$$

If we now substitute for v and r_n we get;

$$E_{total} = -\frac{m_e e^4}{8 h^2 n^2}$$

Thus for any stable orbit in a hydrogen atom, the electron has an easily calculated energy.

If an electron now moves from one energy level to another its change in energy can be described as;



$$E_{\text{final}} - E_{\text{initial}} = -\frac{m_e e^4}{8 \hbar^2} \frac{1}{n_{\text{final}}^2} - \frac{1}{n_{\text{initial}}^2}$$

$$E = hf$$

$$= \frac{hc}{\lambda}$$

$$\frac{1}{\lambda} = -\frac{m_e e^4}{8 \hbar^2 c} \frac{1}{n_{\text{final}}^2} - \frac{1}{n_{\text{initial}}^2}$$

$$\text{ie } \frac{1}{\lambda} = -R \frac{1}{n_{\text{final}}^2} - \frac{1}{n_{\text{initial}}^2}$$

where the term R is called the Rydberg Constant. The negative sign is related to the definition of potential energy that was initially used, ie the potential energy of the electron would be zero if it was placed at an infinite distance from the nucleus.

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Figures from: Quantum Physics is used in a range of technologies

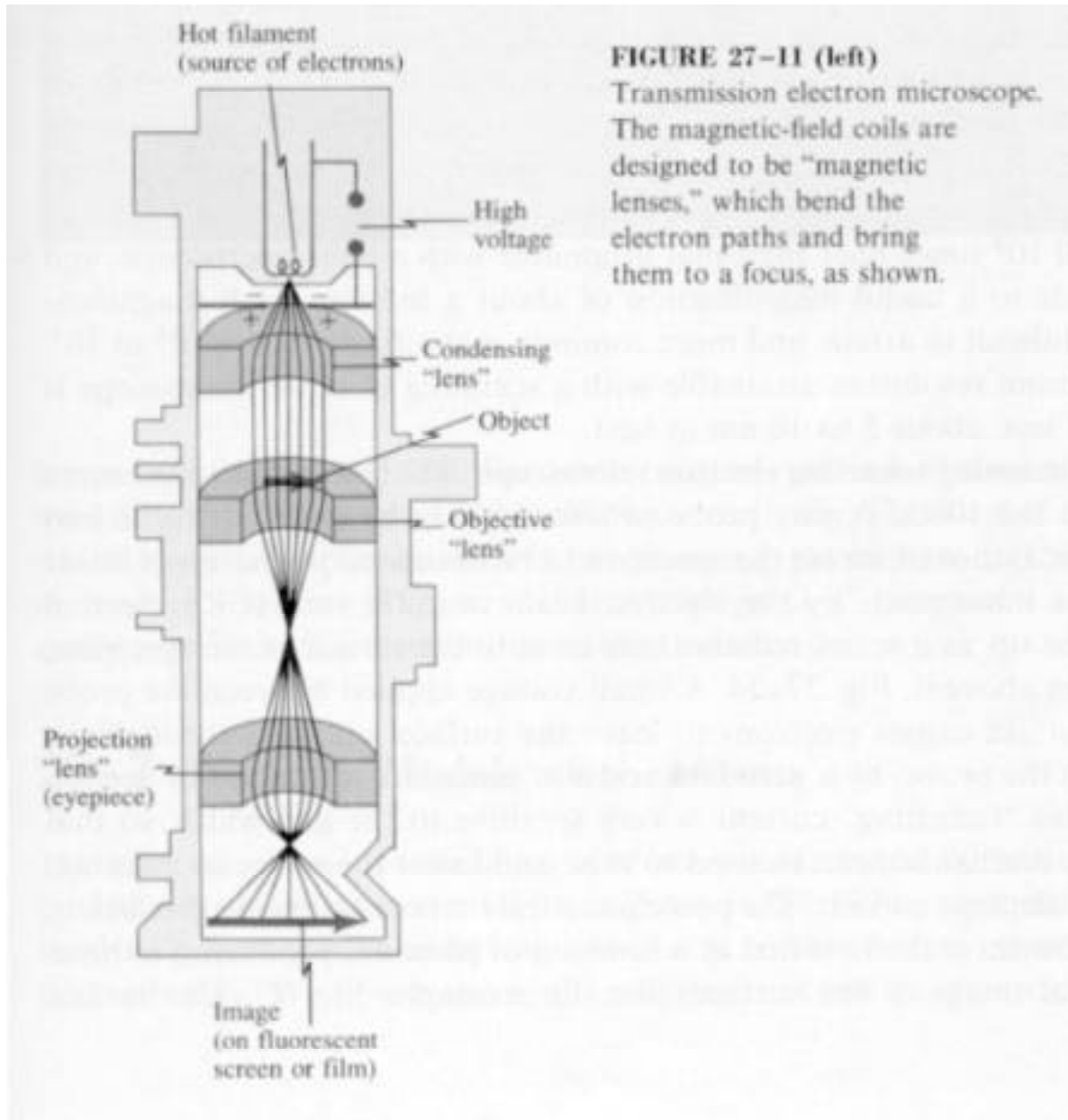


FIGURE 27-11 (left)
Transmission electron microscope. The magnetic-field coils are designed to be "magnetic lenses," which bend the electron paths and bring them to a focus, as shown.

Diagram A (from Giancoli)



Scanning electron microscope.
Scanning coils move an electron beam
back and forth across the specimen.
Secondary electrons produced when
the beam strikes the specimen are
collected and modulate the intensity of
the beam in the CRT to produce a picture.

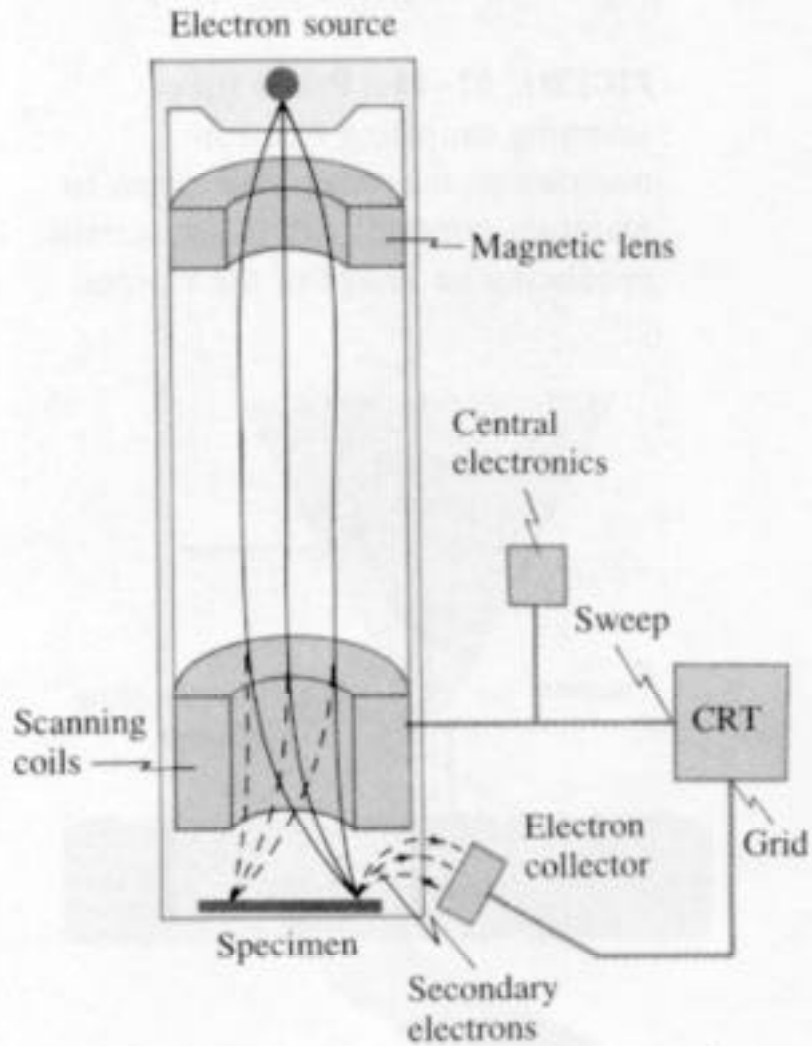


Diagram B (from Giancoli)