PHYS 1444 – Section 002
Lecture #12

Wednesday, Oct. 11, 2017

Dr. Jaehoon Yu

- Chapter 24 Capacitance etc..
  - Electric Energy Storage
  - Effect of Dielectric
  - Molecular description of Dielectric Material
- Chapter 25
  - Electric Current and Resistance
  - The Battery
  - Ohm's Law: Resisters, Resistivity
  - Electric Power

Announcements

- Mid Term Exam
  - In class next Wednesday, Oct. 18
  - Covers CH21.1 through what we cover in class Monday, Oct. 16 + appendix
  - Bring your calculator but DO NOT input formula into it!
    - Cell phones or any types of computers cannot replace a calculator!
  - BYOF: You may bring a one 8.5x11.5 sheet (front and back) of **handwritten** formulae and values of constants
  - No derivations, word definitions or solutions of any kind!
  - No additional formulae or values of constants will be provided!
- Triple credit colloquium 3:30pm today in NH100
  - Dr. Michael Turner of U. of Chicago, National Academy of Science member

The Department of Physics Colloquium Series presents

Λ-CDM: "Much more than we expected, but now less than what we want."

3:30 p.m., Wednesday, October 11

Nedderman Hall, Room 100

A reception will follow the talk at 4:30 p.m. in the Nedderman Hall Atrium

Abstract:
The Λ-CDM (Lambda Cold Dark Matter) cosmological model is remarkable. With just six parameters it describes the evolution of the Universe from a very early time when all structures were quantum fluctuations on subatomic scales to the present, and it is consistent with a wealth of high-precision data, both laboratory measurements and astronomical observations. However, the foundation of Λ-CDM involves physics beyond the standard model of particle physics: particle dark matter, dark energy and cosmic inflation. Until this "new physics" is clarified, Λ-CDM is at best incomplete and at worst a phenomenological construct that accommodates the data. I discuss the path forward, which involves both discovery and disruption, some grand challenges and finally the limits of scientific cosmology.

Michael Turner, *Ph.D.*

Dr. Michael Turner is a theoretical cosmologist and is the Bruce V. & Diana M. Rauner Distinguished Service Professor at the University of Chicago. He is a member of the National Academy of Sciences and coined the term "dark energy" in 1998. He helped establish the interdisciplinary field that combines together cosmology and elementary particle physics to understand the origin and evolution of the Universe. Dr. Turner served as president of the American Physical Society in 2013 and from 2003-06 served as assistant director for the National Science Foundation's Division of Mathematical and Physical Sciences. He has won numerous awards for his research, including the Helen B. Warner Prize from the American Astronomical Society. He received his Ph.D. in Physics from Stanford University in 1978.

UNIVERSITY OF TEXAS ARLINGTON | COLLEGE of SCIENCE

SCIENCE WEEK

OCTOBER 9-14, 2017

Electric Energy Density

- The energy stored in a capacitor can be considered as being stored in the electric field between the two plates
- For a uniform field E between two plates, V=Ed and $C=\varepsilon_0 A/d$
- Thus the stored energy is

$$U = \frac{1}{2}CV^2 = \frac{1}{2}\left(\frac{\varepsilon_0 A}{d}\right)(Ed)^2 = \frac{1}{2}\varepsilon_0 E^2 Ad$$

- Since Ad is the gap volume V, we can obtain the energy density, stored energy per unit volume, as

$$u = \frac{1}{2}\varepsilon_0 E^2$$

Valid for any space that is vacuum

Electric energy stored per unit volume in any region of space is proportional to the square of E in that region.

Dielectrics

- Capacitors have an insulating sheet of material, called dielectric, between the plates to
  - Increase breakdown voltage greater than that in air (3MV/m)
  - Apply higher voltage to the gap without the charge passing across
  - Allow the plates get closer together without touching
    - Increases capacitance (recall $C=\varepsilon_0 A/d$)
  - Increase the capacitance by the dielectric constant

$$C = KC_0$$

  - Where C_0 is the intrinsic capacitance when the gap is vacuum

Dielectrics

- The value of dielectric constant K varies depending on the material (Table 24 – 1)
  - K for vacuum is 1.0000
  - K for air is 1.0006 (this is why permittivity of air and vacuum are used interchangeably.)
  - K for paper is 3.7
- **Maximum electric field before breakdown** occurs is called the **dielectric strength**. What is its unit?
  - V/m
- The capacitance of a parallel plate capacitor with a dielectric (K) filling the gap is

$$C = KC_0 = K\varepsilon_0 \frac{A}{d}$$

Dielectrics

- A new quantity of the **permittivity of a dielectric material** is defined as **$\varepsilon = K\varepsilon_0$**
- The capacitance of a parallel plate capacitor with a dielectric medium filling the gap is

$$C = \varepsilon \frac{A}{d}$$

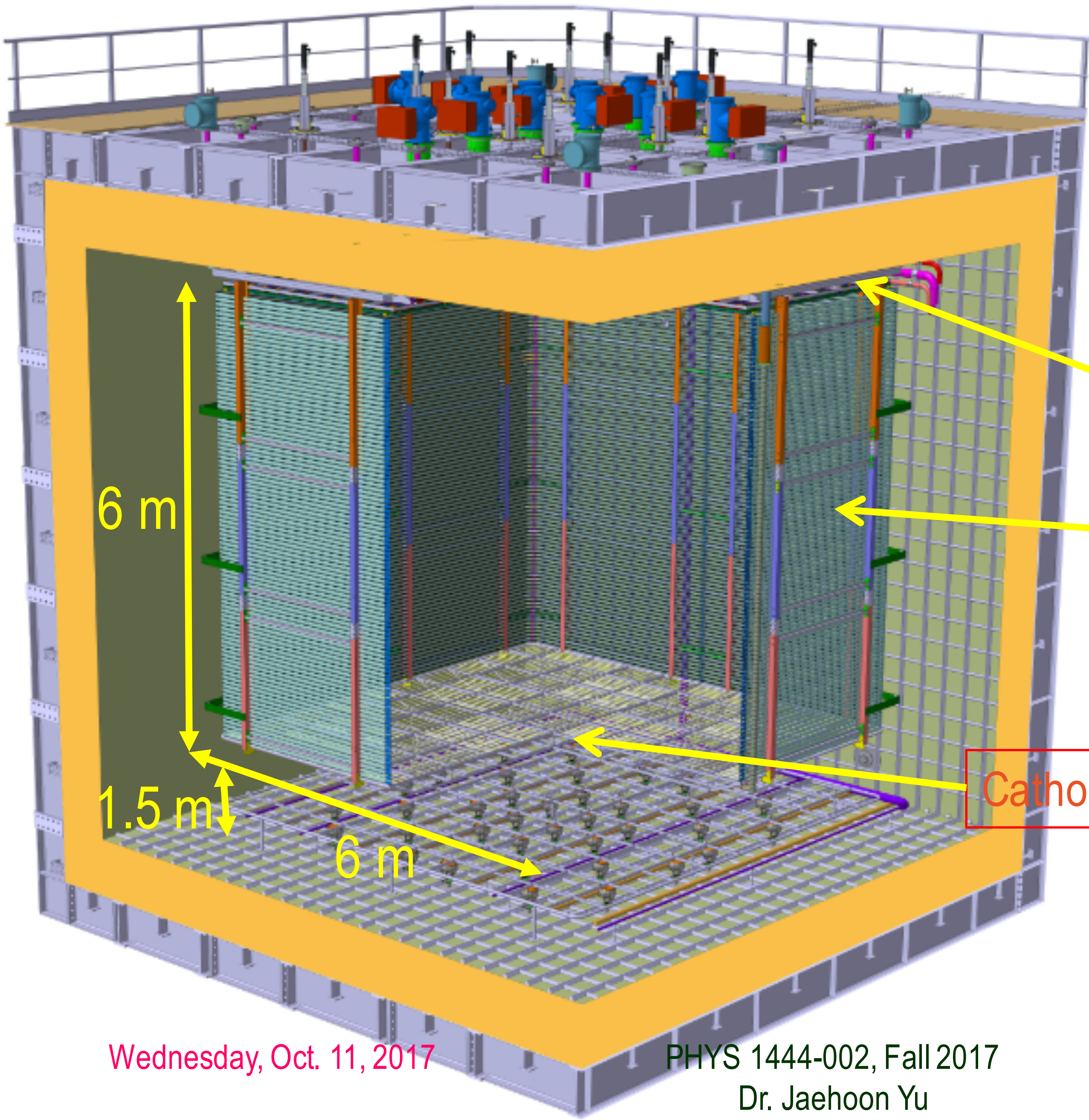
- The energy density stored in an electric field E in a dielectric is

$$u = \frac{1}{2} K\varepsilon_0 E^2 = \frac{1}{2}\varepsilon E^2$$

Valid for any space w/ dielectric w/ permittivity ε.

What is the stored energy in between ProtoDUNE cathode (-600kV) plate (6mx6m) and the cryostat wall (0V), d=1.5m, LAr K=1.6?

ProtoDUNE Dual Phase

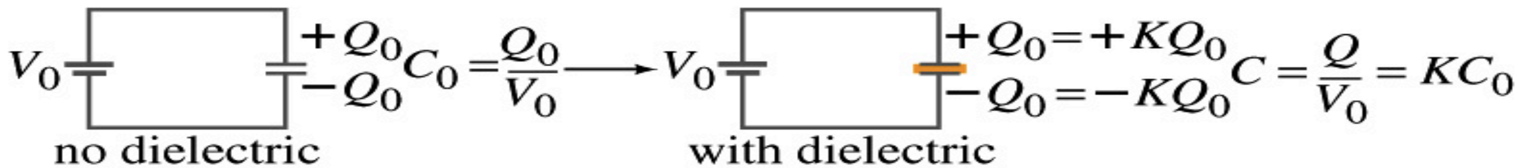


- Field Cage and cathode hangs off of the ceiling
- Essential to have light yet sturdy structure
- Based on modular concept as SP

Effect of a Dielectric Material on Capacitance

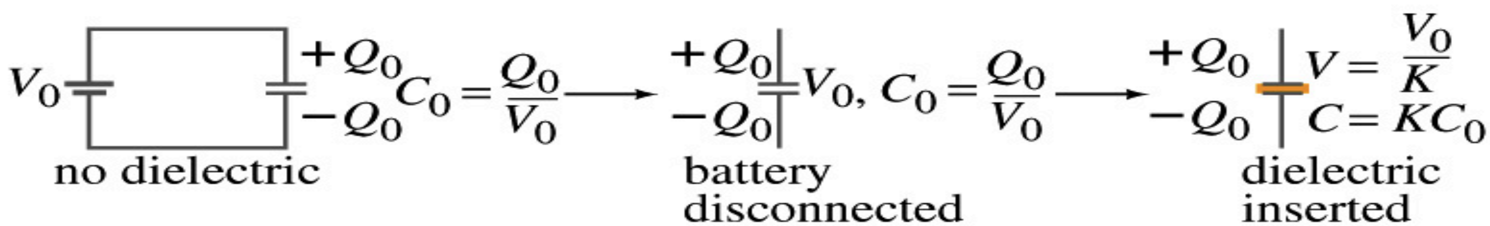
- Let's consider the two cases below:

Case #1 : constant V



(a) Voltage constant

Case #2 : constant Q



(b) Charge constant

- Constant voltage: Experimentally observed that the total charge on the each plate of the capacitor increases by K as a dielectric material is inserted between the gap ➔ $Q=KQ_0$
  - The capacitance increased to $C=Q/V_0=KQ_0/V_0=KC_0$
- Constant charge: Voltage found to drop by a factor K ➔ $V=V_0/K$
  - The capacitance increased to $C=Q_0/V=KQ_0/V_0=KC_0$

Effect of a Dielectric Material on Field

- What happens to the electric field within a dielectric?
- Without a dielectric, the field is

$$E_0 = \frac{V_0}{d}$$

  - What are V_0 and d?
    - V_0: Potential difference between the two plates
    - d: separation between the two plates
- For the constant voltage, the electric field remains the same
- For the constant charge: the voltage drops to $V=V_0/K$, thus the field in the dielectric is

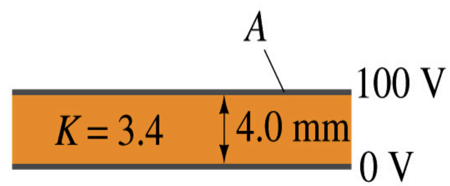
$$E = E_D = \frac{V}{d} = \frac{V_0}{dK} = \frac{E_0}{K}$$

  - The field in the dielectric is reduced.

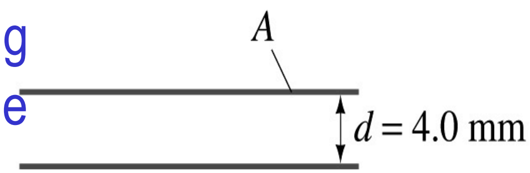
$$E_D = \frac{E_0}{K}$$

Example 24 – 11

Dielectric Removal: A parallel-plate capacitor, filled with the dielectric of K=3.4, is connected to a 100-V battery. After the capacitor is fully charged, the battery is disconnected. The plates have area $A=4.0m^2$, and are separated by d=4.0mm. (a) Find the capacitance, the charge on the capacitor, the electric field strength, and the energy stored in the capacitor. (b) The dielectric is carefully removed, without changing the plate separation nor does any charge leave the capacitor. Find the new value of capacitance, electric field strength, voltage between the plates and the energy stored in the capacitor.



(a)



(b)

(a) $$C=\frac{\varepsilon A}{d}=\frac{K\varepsilon_0 A}{d}=\left(3.4\times 8.85\times 10^{-12}\,C^2/N\cdot m^2\right)\frac{4.0m^2}{4.0\times 10^{-3}\,m}=3.0\times 10^{-8}\,F=30nF$$

$$Q=CV=\left(3.0\times 10^{-8}\,F\right)\times 100V=3.0\times 10^{-6}\,C=3.0\mu C$$

$$E=\frac{V}{d}=\frac{100V}{4.0\times 10^{-3}\,m}=2.5\times 10^{4}\,V/m$$

$$U=\frac{1}{2}CV^2=\frac{1}{2}\left(3.0\times 10^{-8}\,F\right)\left(100V\right)^2=1.5\times 10^{-4}\,J$$

Example 24 – 11 cont'd

(b) Since the dielectric has been removed, the effect of dielectric constant must be removed as well.

$$C_0 = \frac{C}{K} = \left(8.85\times10^{-12}\,C^2/N\cdot m^2\right)\frac{4.0m^2}{4.0\times10^{-3}\,m} = 8.8\times10^{-9}\,F = 8.8nF$$

Since charge is the same ($Q_0 = Q$) before and after the removal of the dielectric, we obtain

$$V_0 = Q/C_0 = K\,Q/C = KV = 3.4\times100V = 340V$$

$$E_0 = \frac{V_0}{d} = \frac{340V}{4.0\times10^{-3}\,m} = 8.5\times10^4\,V/m = 84\,kV/m$$

$$U_0 = \frac{1}{2}C_0V_0^2 = \frac{1}{2}\frac{C}{K}(KV)^2 = \frac{1}{2}KCV^2 = KU = 3.4\times1.5\times10^{-4}\,J = 5.1\times10^{-4}\,J$$

Where did the extra energy come from?

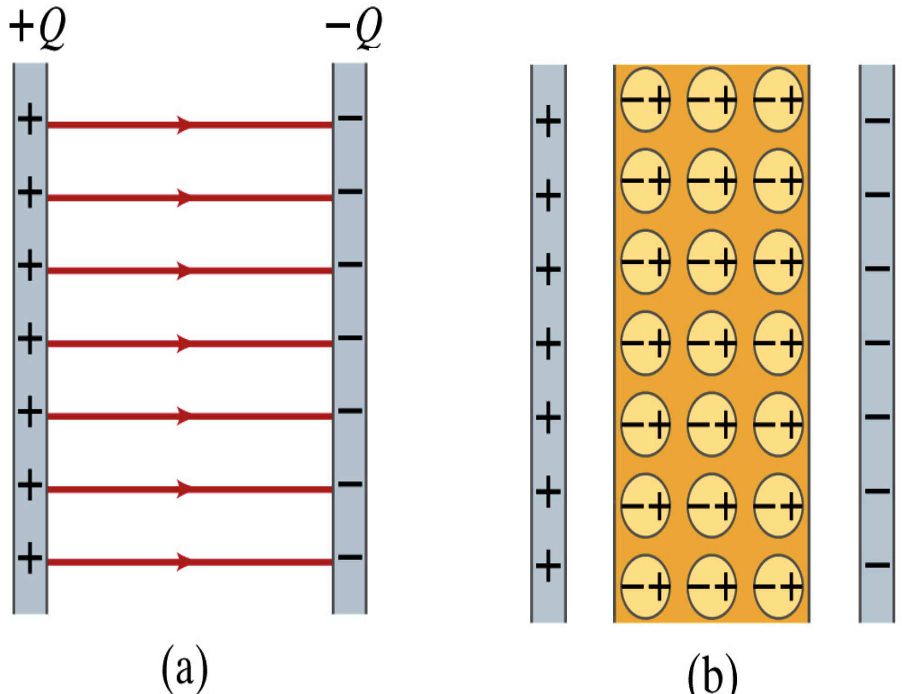
T… ergy conservation law is violated in elec… ??

Wrong!
Wrong!
Wrong!

An external force has done the work of 3.6×10^{-4}J on the system to remove dielectric!!

Molecular Description of Dielectric

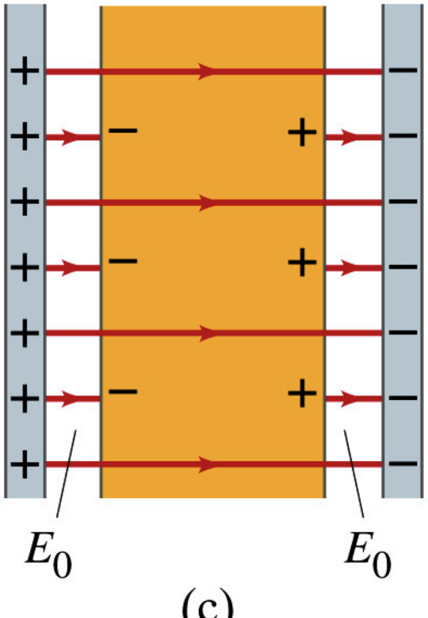
- So what in the world makes dielectrics behave the way they do?
- We need to examine this in a microscopic scale.
- Let's consider a parallel plate capacitor that is charged up $+Q(=C_0V_0)$ and $-Q$ with air in between.
  - Assume there is no way any charge can flow in or out



- Now insert a dielectric
  - Dielectric can be polar ➔ could have permanent dipole moment. What will happen?
- Due to the electric field molecules will be aligned.

Molecular Description of Dielectric

- OK. Then what happens?
- Then effectively, there will be some negative charges close to the surface of the positive plate and positive charge on the negative plate
  - Some electric field do not pass through the whole dielectric but stops at the negative charge



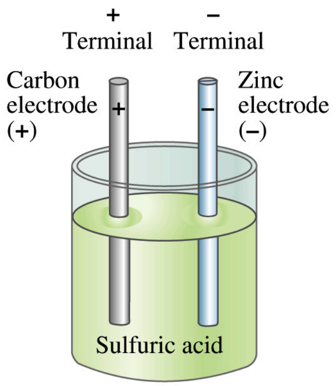
  - So the field inside dielectric is smaller than the air
- Since electric field is smaller, the force is smaller
  - The work need to move a test charge inside the dielectric is smaller
  - Thus the potential difference across the dielectric is smaller than across the air

Electric Current and Resistance

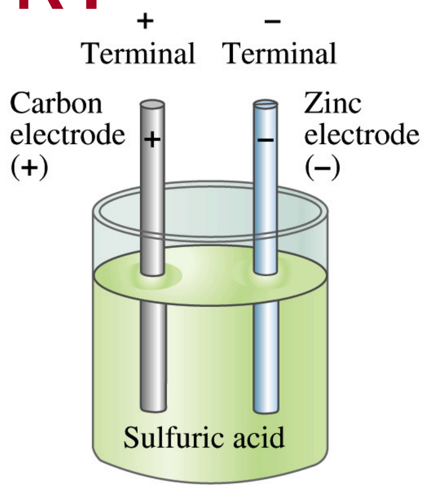
- So far we have been studying static electricity
  - What is the static electricity?
    - The charges so far has not been moving but staying put at the location they are placed.
- Now we will learn dynamics of electricity
- What is the electric current?
  - A flow of electric charge
  - A few examples of the things that use electric current in everyday lives?
- In an electrostatic situation, there is no electric field inside a conductor but when there is current, there is field inside a conductor. Why?
  - Electric field is needed to keep charges moving

The Electric Battery

- What is a battery?
  - A device that produces electrical energy from the stored chemical energy and produces electricity ➔ Maintains potential difference!
- Electric battery was invented by Volta in 1790s in Italy
  - It was made of disks of zinc and silver based on his research that certain combinations of materials produce a greater electromotive force (emf), or potential, than others
- Simplest batteries contain two plates made of dissimilar metals called electrodes
  - Electrodes are immersed in a solution, the electrolyte
  - This unit is called a cell and many of these form a battery
- Zinc and Iron in the figure are called terminals



How does a battery work?



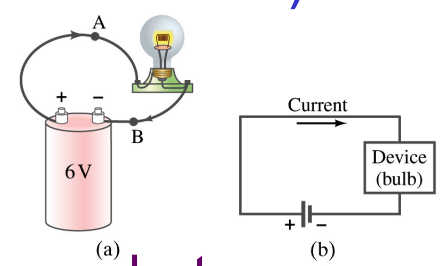
- One of the electrodes in the figure is zinc and the other carbon
- The acid electrolyte reacts with the zinc electrode and dissolves it.
- Each zinc atom leaves two electrons in the electrode and enters into the solution as a positive ion → zinc electrode acquires negative charge and the electrolyte (the solution) becomes positively charged
- The carbon electrode picks up the positive charge
- Since the two terminals are oppositely charged, there is a potential difference between them

How does a battery work?

- When the terminals are not connected, only the necessary amount of zinc is dissolved into the solution.
- How is a particular potential maintained?
  - If the terminals are not connected, as too many of zinc ion gets produced,
    - zinc electrode gets increasingly charged up negative
    - zinc ions get recombined with the electrons in zinc electrode
- Why does battery go dead?
  - When the terminals are connected, the negative charges will flow away from the zinc electrode
  - More zinc atoms dissolve into the electrolyte to produce more charge
  - One or more electrode get used up not producing any more charge.

Electric Current

- When a circuit is powered by a battery (or a source of emf) the charge can flow through the circuit.



- Electric Current: Any flow of charge
  - Current can flow whenever there is a potential difference between the ends of a conductor (or when the two ends have opposite charges)
    - The current can flow even through the empty space under certain conditions
  - Electric current in a wire can be defined as the net amount of charge that passes through the wire's full cross section at any point per unit time (just like the flow of water through a conduit.)
  - Average current is defined as: $\bar{I} = \Delta Q / \Delta t$
  - The instantaneous current is: $I = dQ/dt$
  - What kind of a quantity is the current? Scalar

Unit of the current?

C/s

1A=1C/s

In a single circuit, conservation of electric charge guarantees that the current at one point of the circuit is the same as any other points on the circuit.

Example 25 – 1

Current is a flow of charge: A steady current of 2.5A flows in a wire for 4.0min. (a) How much charge passed by any point in the circuit? (b) How many electrons would this be?

Current is total amount charge flown through a circuit in a given time. So from $\Delta Q = I\Delta t$ we obtain

$$\Delta Q = I\Delta t = 2.5\times 4.0\times 60 = 600C$$

The total number of electrons passed through the circuit is

$$N_e = \frac{\Delta Q}{e} = \frac{600C}{1.6\times 10^{-19}C} = 3.8\times 10^{21}\,electrons$$