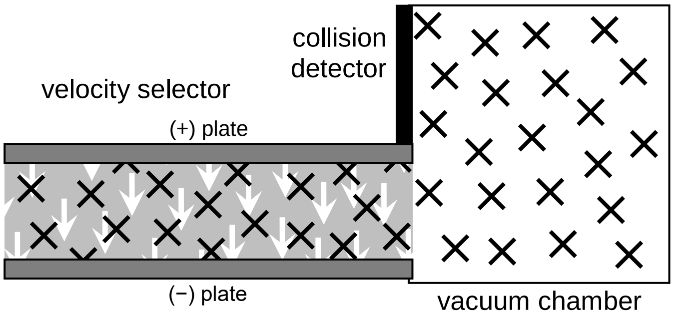
Physics 0993 Learning Centre

VANCOUVER COMMUNITY COLLEGE

Electromagnetism

The Mass Spectrometer

A **mass spectrometer** is a device that uses electric and magnetic fields to separate particles of different masses. It's in two parts: a velocity selector and a vacuum chamber.



The **velocity selector** is just a parallel-plate capacitor; it has a uniform electric field from its positive plate to its negative plate (white arrows). A positively charged particle fired into the selector will be deflected towards the negative plate. The entire device is also in a magnetic field, perpendicular to the electric field (black X's, into the page). There's a "current" of a positive charges moving to the right in this magnetic field, so the particles experience a magnetic force deflecting it towards the positive plate. The field strengths are tuned so that if the speed of the particle is correct, then the two forces balance out; the particle isn't deflected in either direction. If the particle isn't travelling at the right speed, it won't get through — it will be deflected into one plate if it's too fast and the other if it's too slow. The selector ensures that all the particles that leave have the same velocity.

$$F_E = F_B$$
$$qE = qvB$$
$$v = \frac{E}{B}$$

Particles leave the selector and enter the **vacuum chamber**, which only has a magnetic field (possibly with a different strength from that in the velocity selector). Without the counterbalancing effect of the electric field, the stream of particles will move on a circular path. The formula for the **cyclotron radius** of this path is shown. The radius depends on B, the magnetic field strength; q, the particles' charge; v, the particles' velocity (all of which we have already ensured will be constant); and m, the mass of each particle. Since the mass is the only quantity that can vary, the radius depends directly on mass. Particles of different masses, such as isotopes of the same element, will travel different paths. The positions at which the particles strike the wall of the chamber are recorded, and how often, and this data can be analysed to determine what percentage of the particles have which masses.

$$r_{cyc} = \frac{mv}{qB_{\perp}}$$

Example 1: A mass spectrometer has a velocity selector with a plate separation of 30.00 mm, with a potential difference of 250.0 V between the plates. The uniform magnetic field in the velocity selector is 12.30 mT, and in the vacuum chamber, 1.050 T. If singly charged cations of carbon-12 and carbon-14 are fired into the spectrometer, at what distances along the collision detector would they be expected to collide?

Solution: The distances along the detector are the diameters of the path, so we need the radius of each particle's path. "Singly charged" means a charge of 1, the

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cations are C^+. We know mass, charge and local field strength, so we need to know the velocity of the velocity selector.

The velocity is the ratio of the electric field strength to the magnetic field strength in the capacitor (which we are given). The first step is finding the electric field in the capacitor.

$$E = \Delta V / s = 250.0\ \mathrm{V} \div 0.03000\ \mathrm{m} = 8.3333... \times 10^{3}\ \mathrm{V/m}$$

$$v_{sel} = E / B_{sel} = 8.3333 \times 10^{3}\ \mathrm{V/m} \div 0.01230\ \mathrm{T} = 6.7751\ldots \times 10^{5}\ \mathrm{m/s}$$

The mass of carbon-12 is defined to be 12 amu, or $12 \div N_A = 1.9926\ldots \times 10^{-26}$ kg. The mass of carbon-14 will be two masses of neutrons more, or $2.3276\ldots \times 10^{-26}$ kg. [*] We can use these masses to calculate the diameters:

$$d_{C12} = 2 \times r_{C12} = 2 \times \frac{m_{C12}v}{qB_{vac}} = \frac{2(1.9926\text{E}{-26})(6.7751\text{E}5)}{e(1.050\ \mathrm{T})} = 0.16050\ldots\ \mathrm{m}$$

$$d_{C14} = 2 \times r_{C14} = 2 \times \frac{m_{C14}v}{qB_{vac}} = \frac{2(2.3276\text{E}{-26})(6.7751\text{E}5)}{e(1.050\ \mathrm{T})} = 0.18748\ldots\ \mathrm{m}$$

We expect the carbon-12 particles to collide at a distance of 16.05 cm and the carbon-14 particles to collide at a distance of 18.75 cm.

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[*] Wolfram Alpha reports these as 1.993×10^{-26} kg and $2.32529304 \times 10^{-26}$ kg.

EXERCISES

A. Refer to the diagram of page 1 of this worksheet. If a negatively charged particle is travelling too fast, will it strike the negative plate or the positive plate?

B. In cases where the magnetic field in the velocity selector is a different strength from the one in the vacuum chamber, the one in the vacuum chamber is much higher. Can you suggest a reason why? [*Hint:* The vacuum chamber is only so big.]

C. Particles of an ore believed to contain a heavy metal are ionized to become singly charged cations and fired into the mass spectrometer shown on page 1. The velocity selector has a plate separation of 25.00 mm, a voltage across the plates of 200.0 V, and lies in a magnetic field of strength 0.0825 T; the vacuum chamber has a field of 1.761 T. Two isotopes emerge: 99.2% of collisions occur at a distance of 13.59 cm and the other 0.8% occur at 13.41 cm. Identify the metal.

SOLUTIONS

A: Negative. The particle's velocity affects its magnetic force, so the magnetic force will be higher than the electric force. The electric field would direct the anion into the positive plate. The anion would therefore collide with the negative plate.

B: Magnetic field strength is inversely proportional to radius in the cyclotron motion equation. If the particles are so large that they miss the detector because their path is on too big a circle, increasing the field will reduce the radius so they can be detected.

C: The masses of the particles turn out to be 3.95E^{-25} kg and 3.90E^{-25} kg, or 238 amu and 235 amu. By recognition, or by looking on the periodic table for a naturally occurring metal with an atomic weight of around 238, it's uranium.