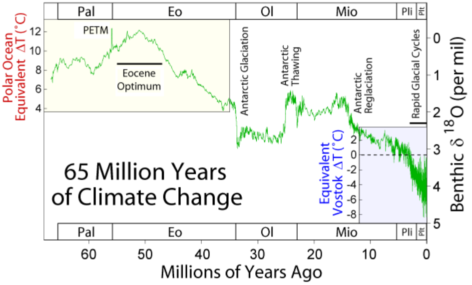
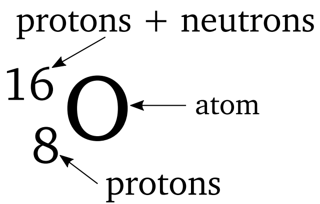
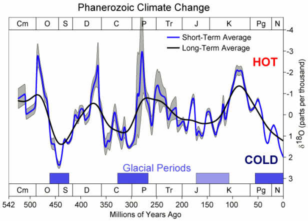
Climate change has been a somewhat (!) controversial topic driven, in part, by our understanding of temperatures from deep time (*i.e.*, long ago). The plot below shows the temperature 'anomaly' extracted from glaciers and foraminifera (one-celled critters that live in shells) from the ocean floor. The 'thermometer' is based on the relative amount of a particular isotope of oxygen $^{18}\mathrm{O}$ (see below). In two regions of time, $\approx 35 - 65$ *Mya* and $\approx 0 - 15$ *Mya*, the time-temperature relationship is known, but that is not true in the middle region.



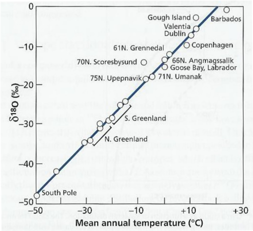


How did ^{18}O become a thermometer? 2



1. It's all about water and oxygen isotopes.
2. Vapor pressure of $H_2{}^{16}O$ ('normal' isotope of oxygen) is 1% higher than vapor pressure of $H_2{}^{18}O$ (replace ^{16}O with ^{18}O) which has two more neutrons.
3. Evaporation creates vapor poorer in the heavier isotope ^{18}O leaving the remaining water enriched in ^{18}O.
4. Water vapor is carried over polar regions where the $H_2{}^{18}O$ molecules condense more readily than $H_2{}^{16}O$ so rain is enriched in the heavy isotope and vapor is depleted even more. The temperature proxy is

$$\delta\,^{18}O = \left(\frac{^{18}O/^{16}O_{\text{measured}}}{^{18}O/^{16}O_{\text{standard}}} - 1 \right) \times 1000$$



5. The plot shows the $\delta\,^{18}O$-T connection.

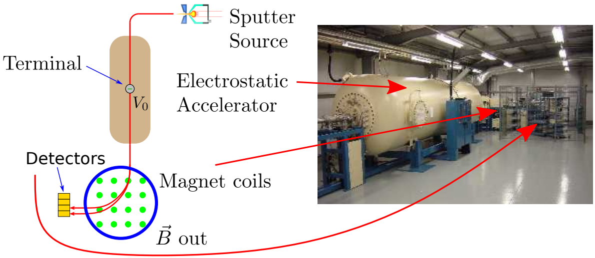
1. The temperature proxy is

$$\delta\,^{18}\mathrm{O} = \left(\frac{^{18}\mathrm{O}/^{16}\mathrm{O}_{\mathrm{measured}}}{^{18}\mathrm{O}/^{16}\mathrm{O}_{\mathrm{standard}}} - 1\right) \times 1000$$

where $^{18}\mathrm{O}$ and $^{16}\mathrm{O}$ are the amounts of different oxygen isotopes extracted from ice or ocean floor drilling cores.

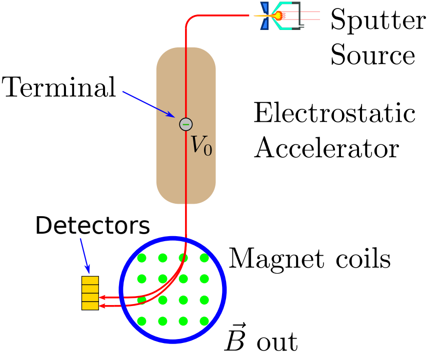
2. The chemistry of the two oxygen isotopes is very similar making it difficult to precisely separate them.
3. The masses of the two isotopes are significantly different so use electric and magnetic forces to do the separation.

A Mass Spectrometer

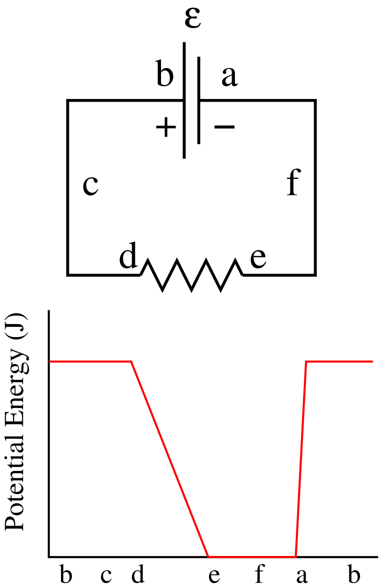


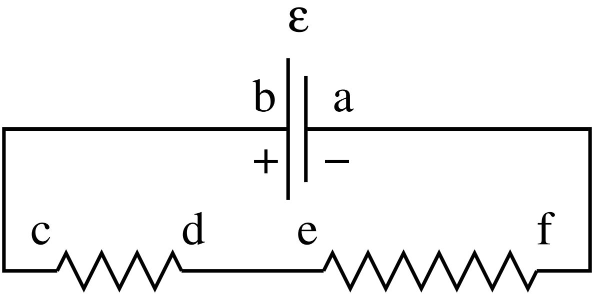
Taking the Ocean Temperature a Million Years Ago

Isotopes of oxygen, $^{16}\mathrm{O}$ and $^{18}\mathrm{O}$, are accelerated twice across a potential difference $V_0 = 5.0 \times 10^6\ V$. Each atom carries an extra electron initially, but that electron and three others are stripped off the oxygen in the accelerator by a thin foil at the terminal. The oxygen has a charge $+3e$ and is moving horizontally when it enters a uniform magnetic field pointing straight up with $B = 3.0\ T$. The positively-charged atoms follow a circular path before striking detectors that measure their position. The variation in the trajectory of each atom leads to an uncertainty in their final position of about $\pm 0.014\ m$. Will the spectrometer be able to separate the isotopes?

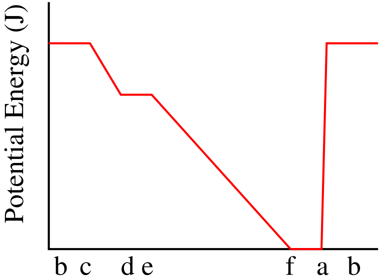


Electric Circuits - 1

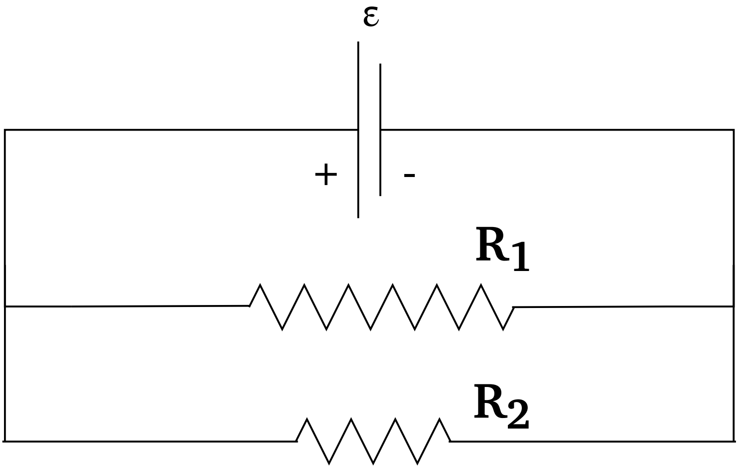


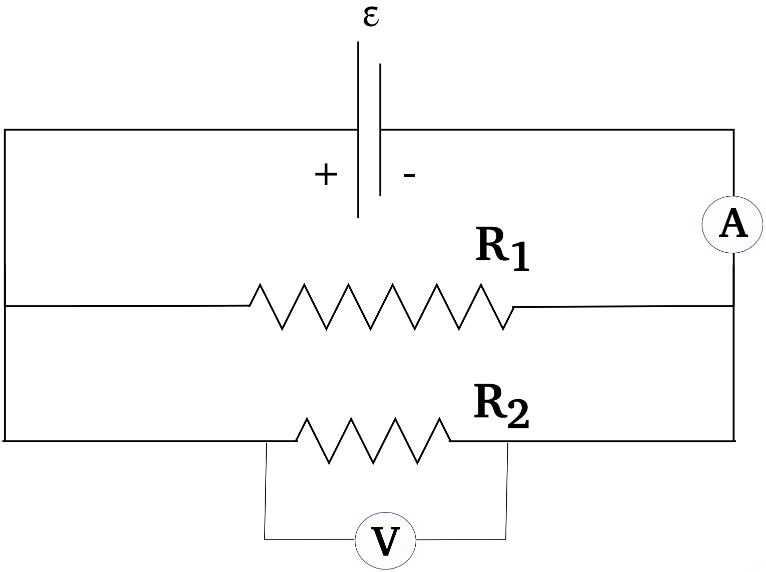


ε
b
a
+
−
c
d
e
f



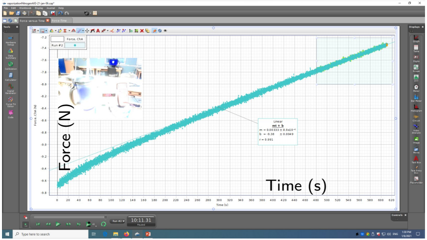
Potential Energy (J)
b c d e f a b

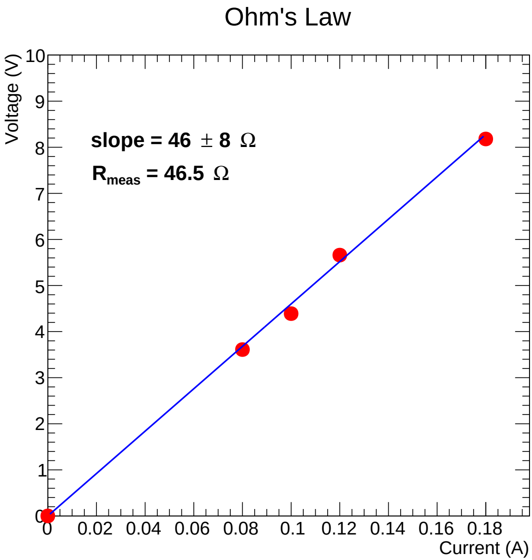

ε
+
-
R1
R2


ε
+
-
A
R1
R2
V

In our study of thermodynamics you measured the latent heat of vaporization L_V of liquid nitrogen by heating an open container of liquid nitrogen with a resistor with current $\mathcal{I}$ and voltage $\mathcal{V}$. See the figure below. The electrical power generated in the resistor by the current heated the liquid nitrogen by a known amount. What is the relationship between power and the properties of the circuit $\mathcal{I}$ and $\mathcal{V}$? Using the values below compare the power dissipated in the circuit with the thermal energy needed to evaporate the liquid nitrogen. Do they agree?

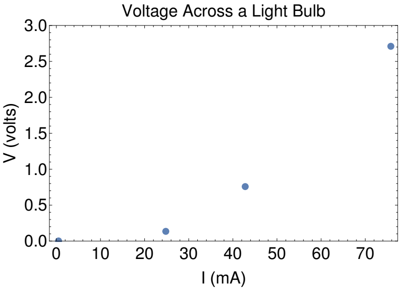
slope (current on)	$0.0035 \pm 0.0002\ N/s$
slope (current off)	$0.0012 \pm 0.0003\ N/s$
L_V (accepted)	$1.99 \times 10^5\ J/kg$
current $\mathcal{I}$	$2.01\ A$
voltage $\mathcal{V}$	$23.23\ V$

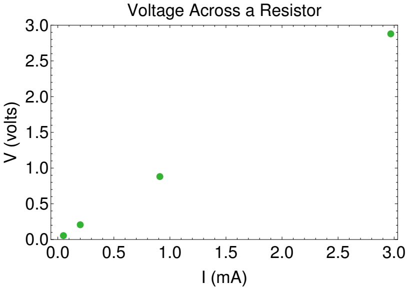




Ohm's Law
slope = 46 ± 8 Ω
R_{meas} = 46.5 Ω
Voltage (V)
0
1
2
3
4
5
6
7
8
9
10
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
Current (A)

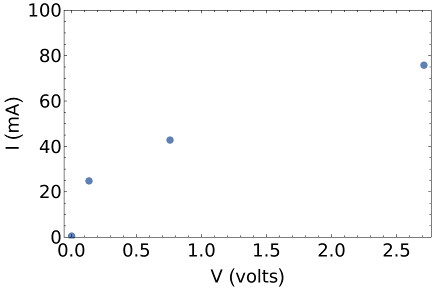
Ohm's Law Results

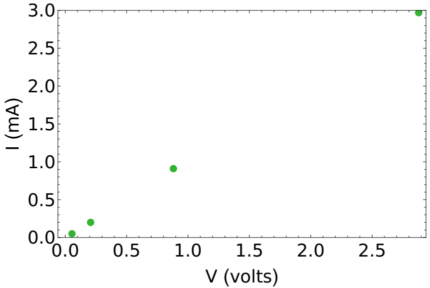


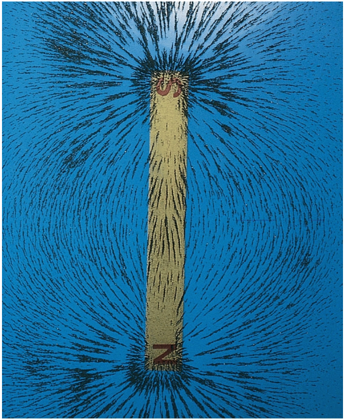


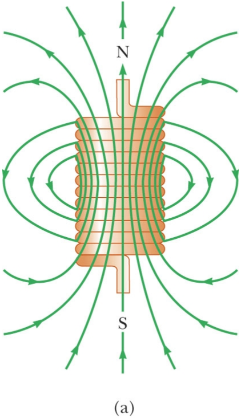
Note difference in horizontal scales.

Ohm's Law Results

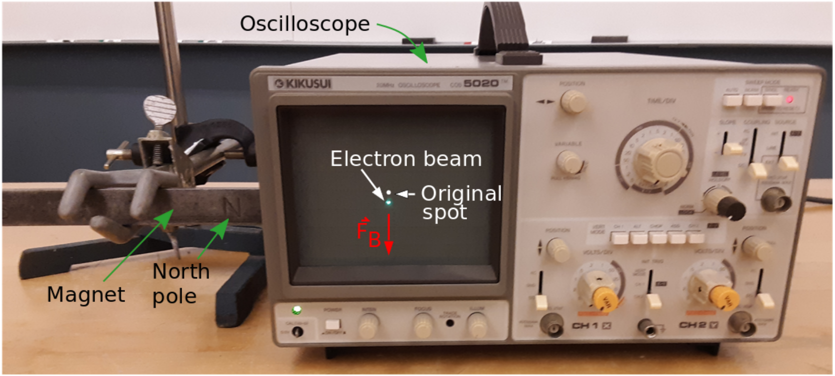




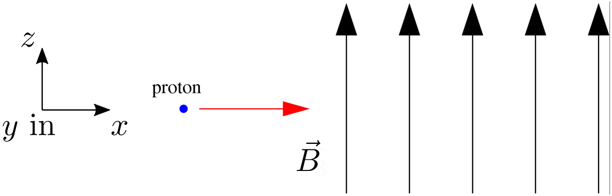




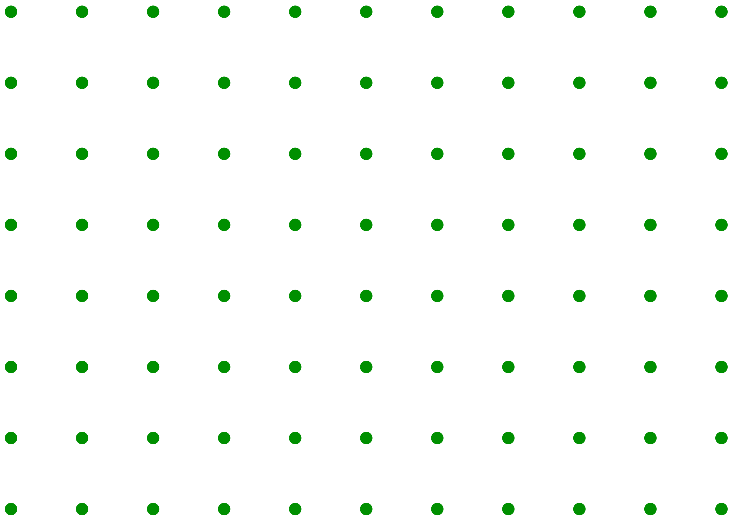
(a)


Oscilloscope
KIKUSUI
5020
Electron beam
Original spot
$\vec{F}_B$
Magnet
North pole

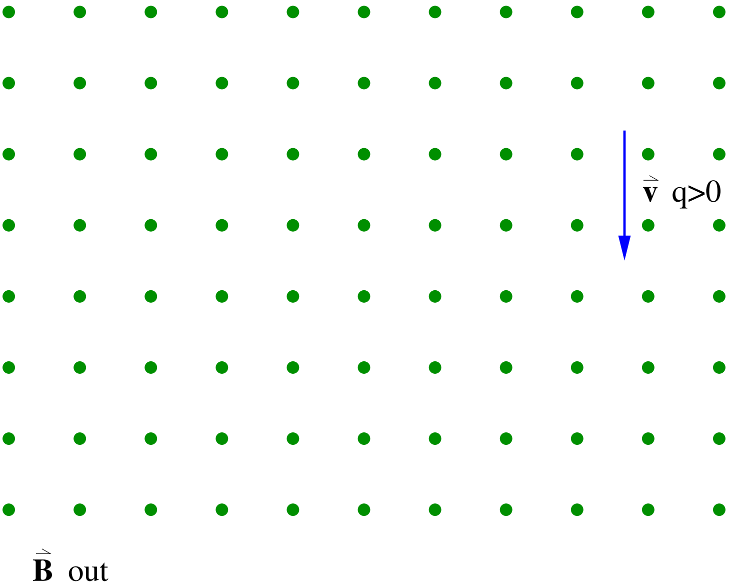
A uniform magnetic field has a magnitude $|\vec{B}| = 1.2\ T$ and points straight up. A proton with velocity $\vec{v} = 3.2 \times 10^7\ \hat{i}\ \ m/s$ enters the field moving horizontally. What is the magnitude and direction of the force on the proton? How would the force change for an electron moving with the same initial velocity? Describe the trajectory of the particle.

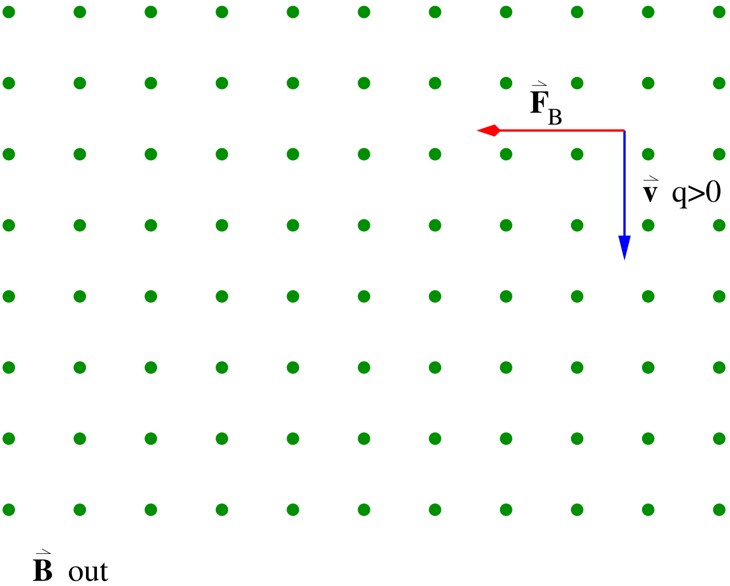


The Magnetic Force $\rightarrow$

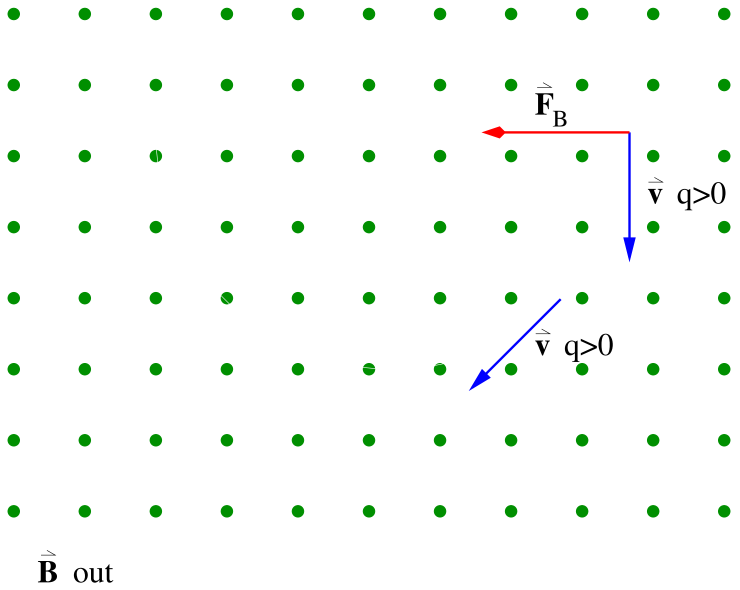


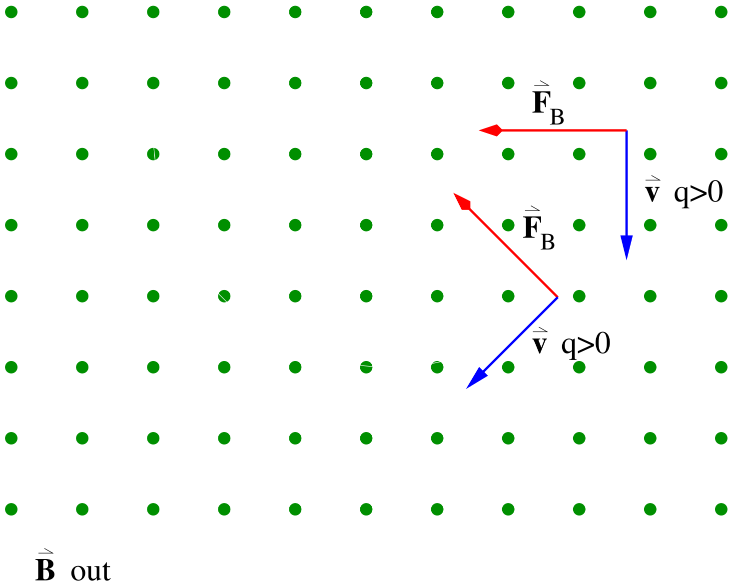
$\vec{\mathbf{B}}$ out


$\vec{\mathbf{v}}$ q>0
$\vec{\mathbf{B}}$ out

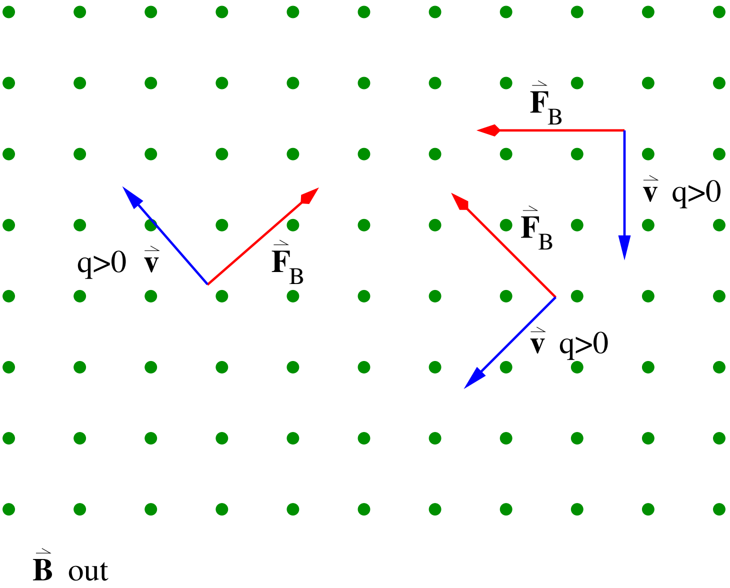


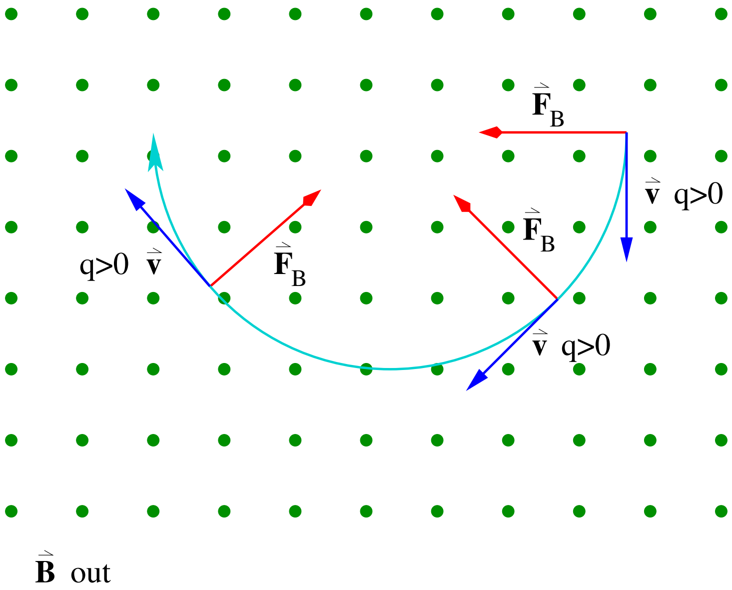
$\vec{\mathbf{F}}_B$
$\vec{\mathbf{v}}$ q>0
$\vec{\mathbf{B}}$ out


$\vec{\mathbf{F}}_B$
$\vec{\mathbf{v}}$ q>0
$\vec{\mathbf{v}}$ q>0
$\vec{\mathbf{B}}$ out

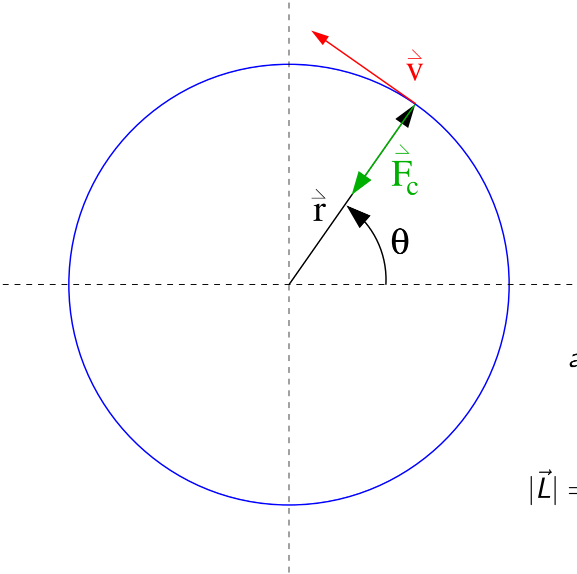


$\vec{\mathbf{F}}_B$
$\vec{\mathbf{v}}$ q>0
$\vec{\mathbf{F}}_B$
$\vec{\mathbf{v}}$ q>0
$\vec{\mathbf{B}}$ out


$\vec{F}_B$
$\vec{v}$ q>0
q>0 $\vec{v}$
$\vec{F}_B$
$\vec{F}_B$
$\vec{v}$ q>0
$\vec{B}$ out



$\vec{F}_B$
$\vec{v}$ q>0
$\vec{F}_B$
q>0 $\vec{v}$
$\vec{F}_B$
$\vec{v}$ q>0
$\vec{B}$ out



$$\vec{F}_c \perp \vec{v} \qquad \vec{F}_c \parallel \vec{r}$$

$$\vec{a}_c \perp \vec{v} \qquad \vec{a}_c \parallel \vec{r}$$

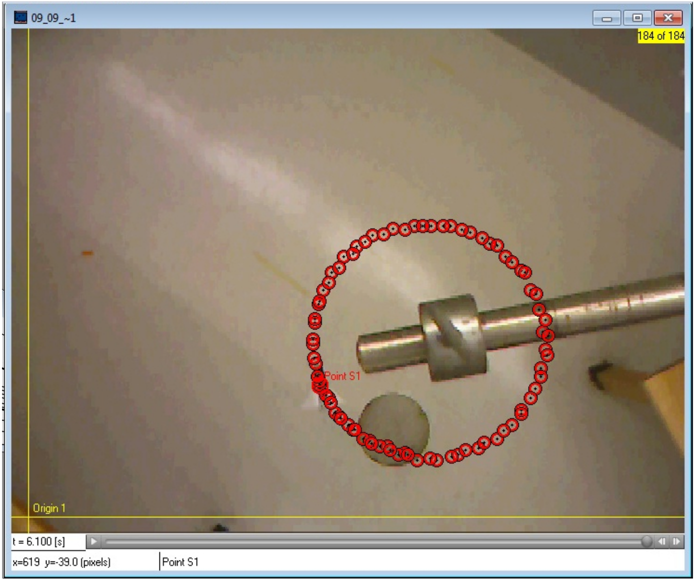
$$\vec{v} \perp \vec{r}$$

$$a_c = \frac{v^2}{r} \qquad |\vec{F}_c| = \frac{mv^2}{r}$$

$$|\vec{L}| = mvr = I_L\omega \quad I_L = \sum mr_i^2$$

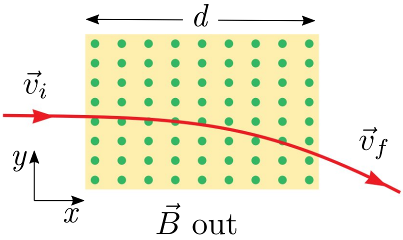
$$C = 2\pi r$$

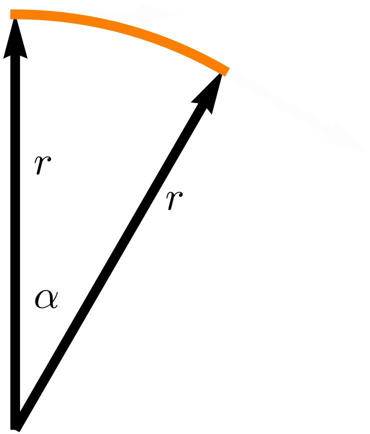
09_09_~1
184 of 184
Origin 1
t = 6.100 [s]
x=342 y=171 (pixels)
Point S1

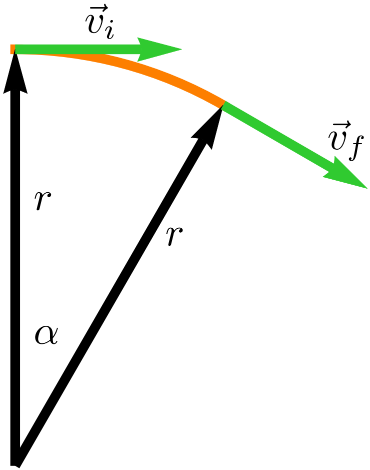

09_09_~1
184 of 184
Point S1
Origin 1
t = 6.100 [s]
x=619 y=-39.0 (pixels)
Point S1

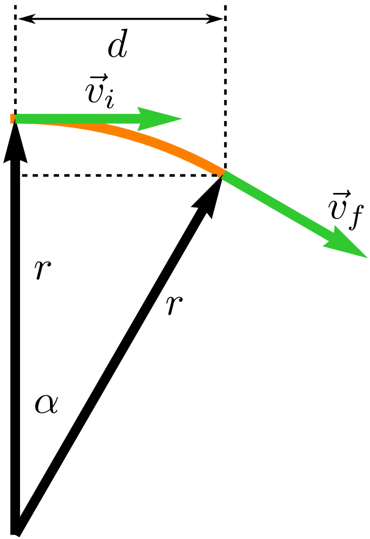
Protons in a Magnetic Field - 1

Protons having an initial speed of $v_i = 3.1 \times 10^7\ m/s$ are moving in the positive x direction and enter a magnetic field $\vec{B} = 0.05\ \hat{k}\ T$ directed out of the plane of the page and extending a horizontal distance $d = 1.0\ m$ as shown in the figure. (a) What is the radius of the arc the proton follows? (b) Find the angle α between the initial velocity vector $\vec{v}_i$ of the proton beam and the final velocity vector $\vec{v}_f$ after the beam emerges from the field. Ignore relativistic effects and note that $1\ eV = 1.60 \times 10^{-19}\ J$.




r
r
α

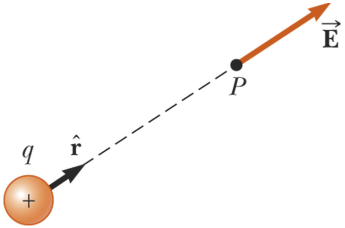

$\vec{v}_i$
$\vec{v}_f$
r
r
α



d
$\vec{v}_i$
$\vec{v}_f$
r
r
α

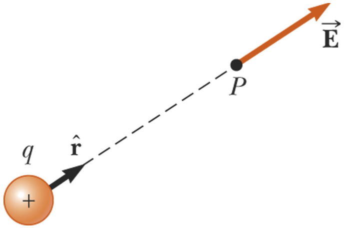
Coulomb's Law

$$d\vec{E} = k_e \frac{dq\hat{r}}{r^2} = \frac{1}{4\pi\epsilon_0}\frac{dq\hat{r}}{r^2}$$



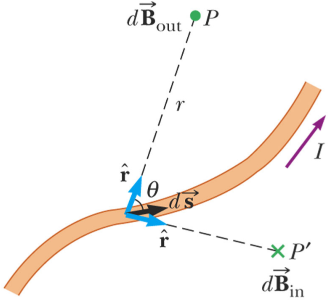
Coulomb's Law

$$d\vec{E} = k_e \frac{dq\hat{r}}{r^2} = \frac{1}{4\pi\epsilon_0}\frac{dq\hat{r}}{r^2}$$

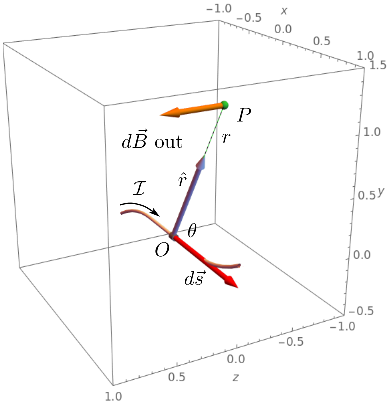


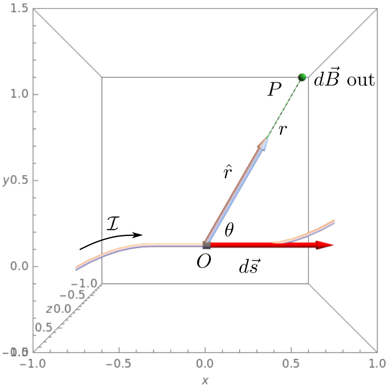
Biot-Savart Law

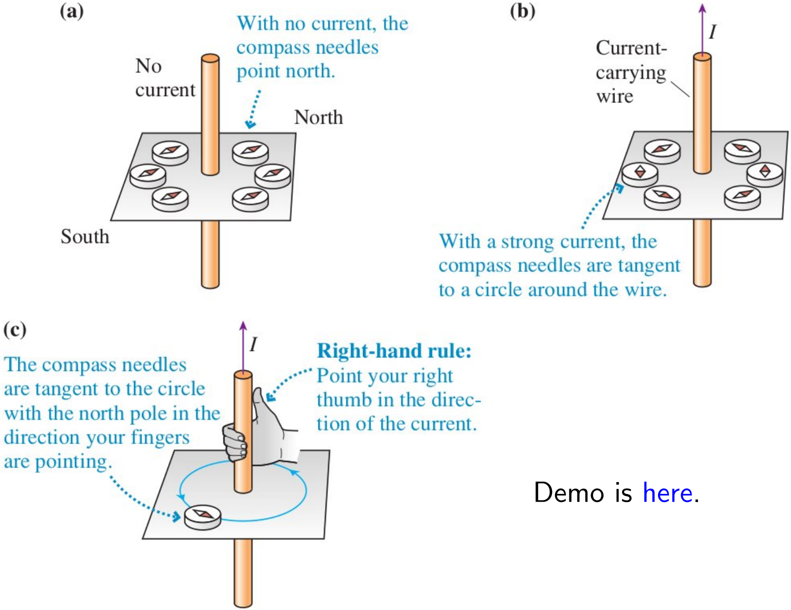
$$d\vec{B} = k_m \frac{Id\vec{s}\times\hat{r}}{r^2} = \frac{\mu_0}{4\pi}\frac{Id\vec{s}\times\hat{r}}{r^2}$$



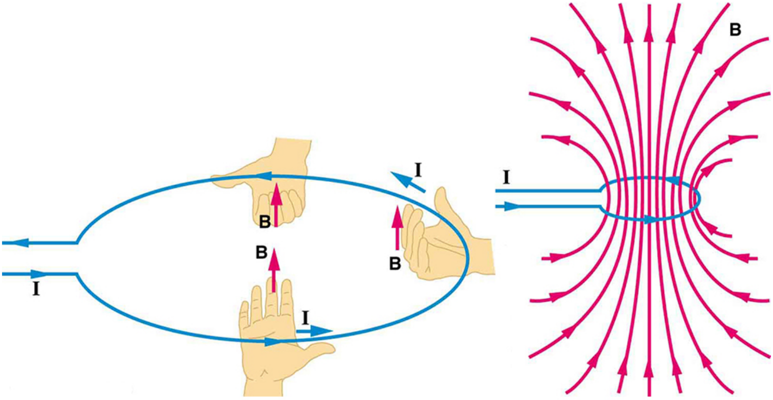
The figures show two views of a segment of a current. What is the magnetic field $d\vec{B}$ at the point P due to the infinitesimal chunk of current at O in terms of the current $\mathcal{I}$, $d\vec{s}$, r, and the angle θ?






(a)
No current
With no current, the compass needles point north.
North
South
(b)
I
Current-carrying wire
With a strong current, the compass needles are tangent to a circle around the wire.
(c)
I
The compass needles are tangent to the circle with the north pole in the direction your fingers are pointing.
Right-hand rule:
Point your right thumb in the direction of the current.

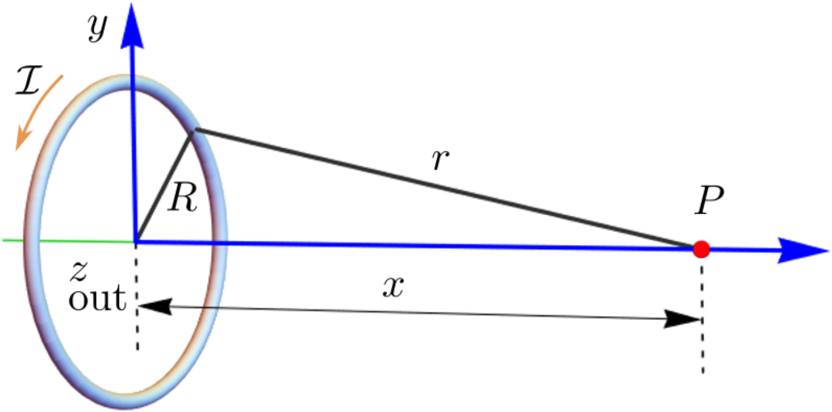
Demo is here.



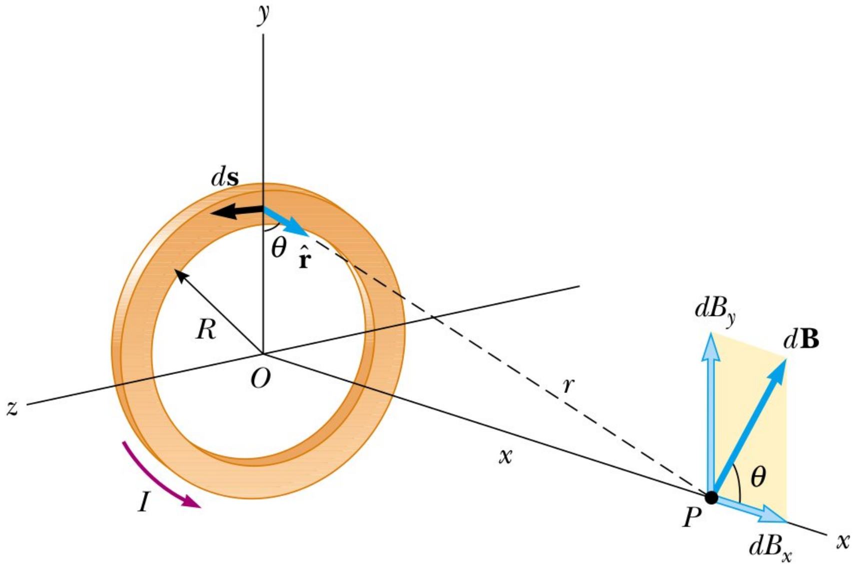
(a) (b)

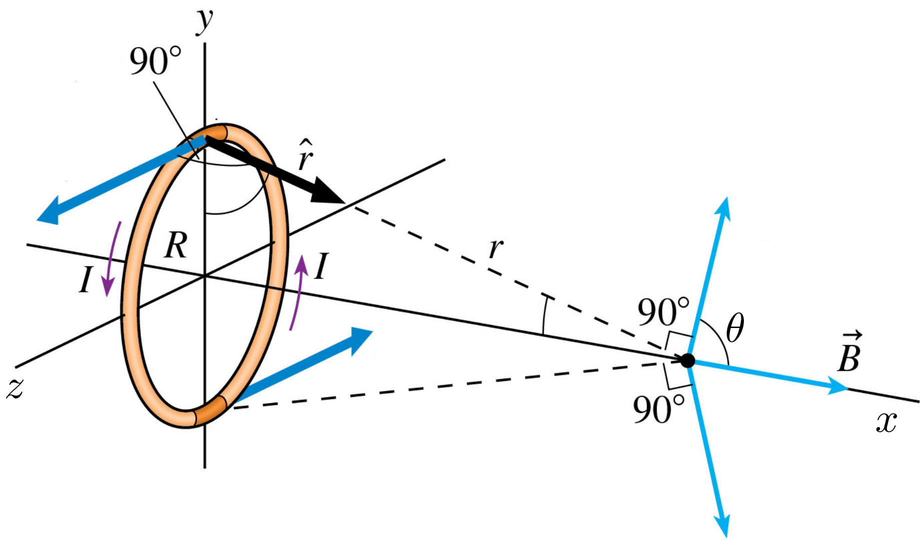
Demo is here.

A ring of radius R as shown in the figure has a current $\mathcal{I}$. Calculate the magnetic field $\vec{B}$ along the axis of the ring at a point lying a distance x from the center of the ring. Get your answer in terms of R, x, $\mathcal{I}$.

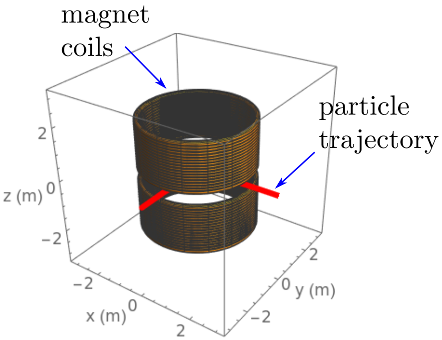


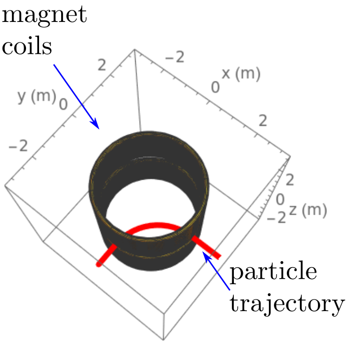
Demo is here.


y
ds
θ
r̂
R
O
z
I
x
r
dB_y
dB
θ
P
dB_x
x


y
90°
$\hat{r}$
R
I
I
r
90°
θ
$\vec{B}$
90°
z
x

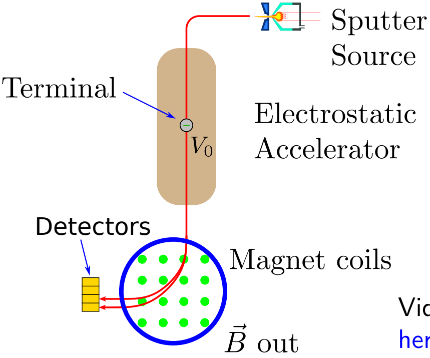
Usually many loops are used to reach the desired field as shown in the figure. What is the field for $R = 0.3\ m$, $I = 1116\ A$, an average distance from the center of each loop of $\langle x \rangle = 0.10\ m$, and the number of loops $N = 1116$? Assume the field inside the loops is the same as we calculated for the center and use $\langle x \rangle$ for the position along the center of the loop.



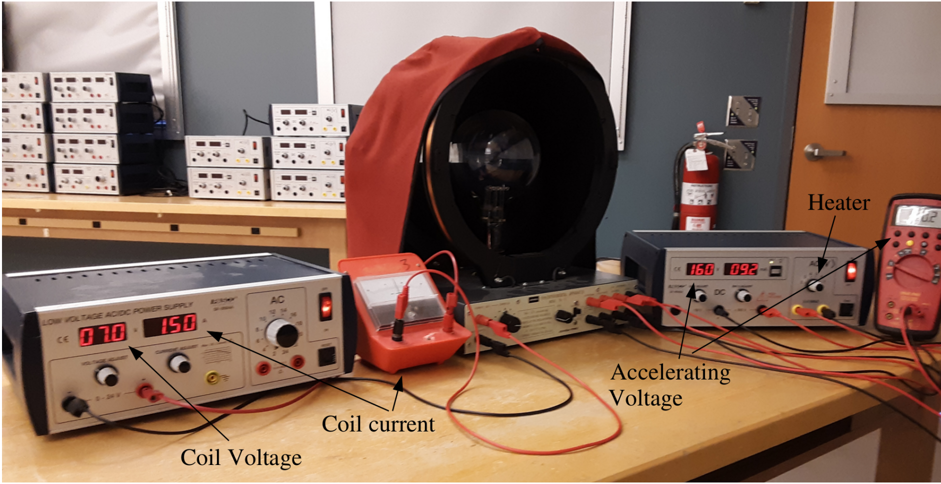


Taking the Ocean Temperature a Million Years Ago

Isotopes of oxygen, $^{16}\mathrm{O}$ and $^{18}\mathrm{O}$, are accelerated twice across a potential difference $V_0 = 5.0 \times 10^6\ V$. Each atom carries an extra electron initially, but that electron and three others are stripped off the oxygen in the accelerator by a thin foil at the terminal. The oxygen has a charge $+3e$ and is moving horizontally when it enters a uniform magnetic field pointing straight up with $B = 3.0\ T$. The positively-charged atoms follow a circular path before striking detectors that measure their position. The variation in the trajectory of each atom leads to an certainty in their final position of about $\pm 0.014\ m$. Will the spectrometer be able to separate the isotopes?



Video is here.



LOW VOLTAGE AC/DC POWER SUPPLY
070
150
AC
160
092
DC
Heater
Coil current
Coil Voltage
Accelerating
Voltage

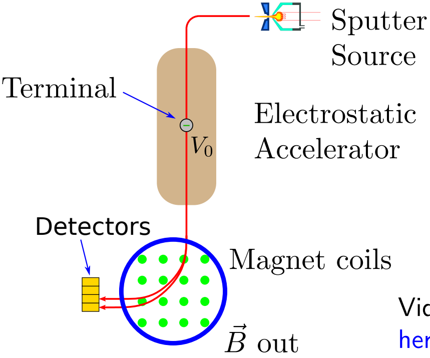
Demo is here.

For Activities 5.b-5.d

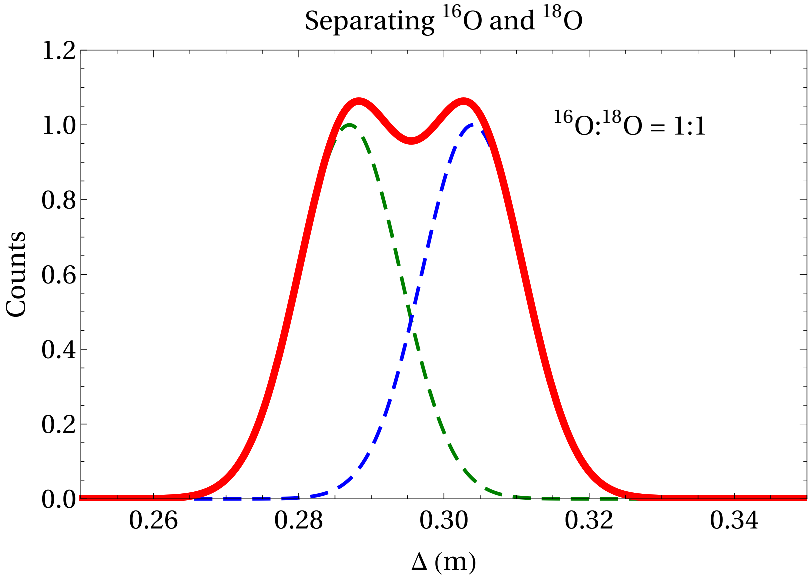
1. Get the electron mass m_e for each entry in the table.
2. Get the average and standard deviation for m_e.
3. State your final result for $m_e \pm \delta m_2$ in Activity 5.d. Does the accepted value fall within your range?

Taking the Ocean Temperature a Million Years Ago

Isotopes of oxygen, $^{16}\mathrm{O}$ and $^{18}\mathrm{O}$, are accelerated twice across a potential difference $V_0 = 5.0 \times 10^6\ V$. Each atom carries an extra electron initially, but that electron and three others are stripped off the oxygen in the accelerator by a thin foil at the terminal. The oxygen has a charge $+3e$ and is moving horizontally when it enters a uniform magnetic field pointing straight up with $B = 3.0\ T$. The positively-charged atoms follow a circular path before striking detectors that measure their position. The variation in the trajectory of each atom leads to an certainty in their final position of about $\pm 0.007\ m$. Will the spectrometer be able to separate the isotopes?

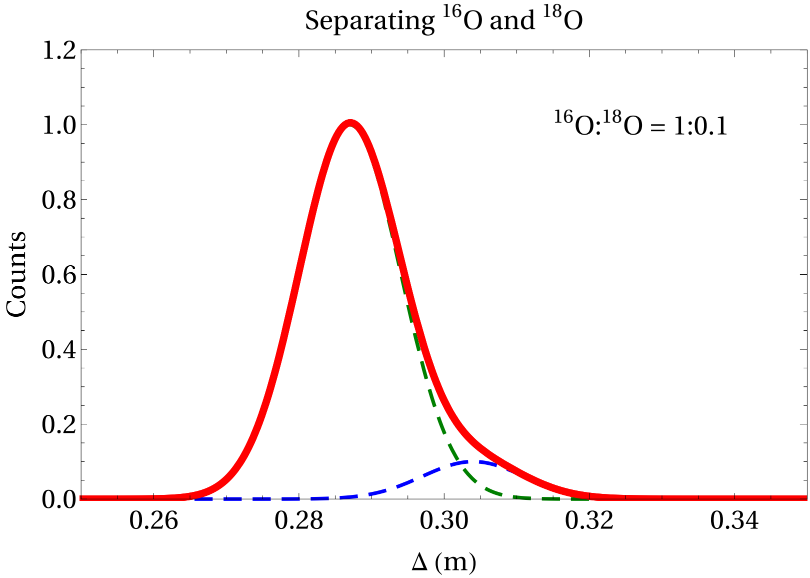


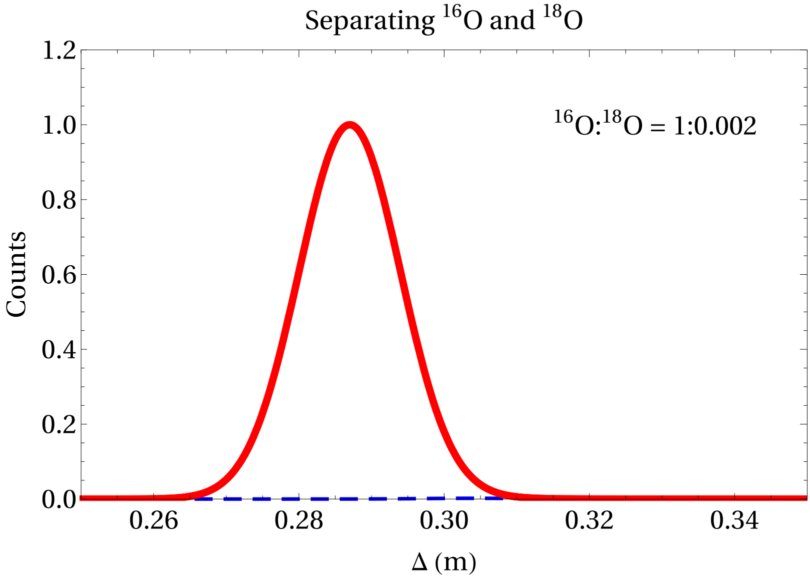
Video is here.

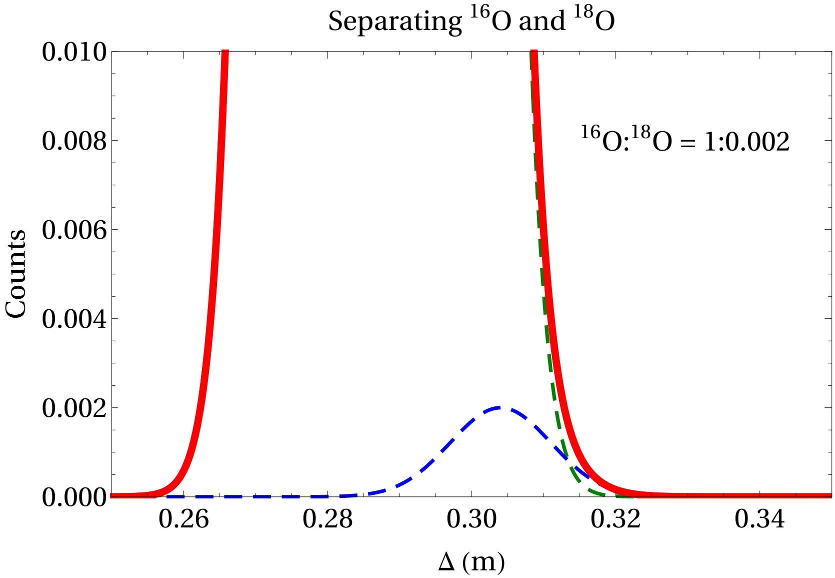


Separating ^{16}O and ^{18}O
^{16}O:^{18}O = 1:1
Counts
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.26
0.28
0.30
0.32
0.34
Δ (m)

Mass Spectrometry

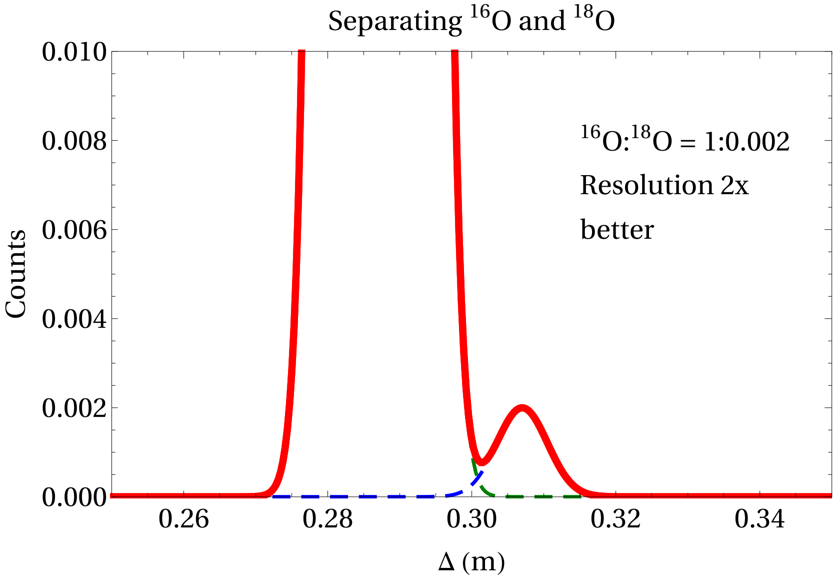


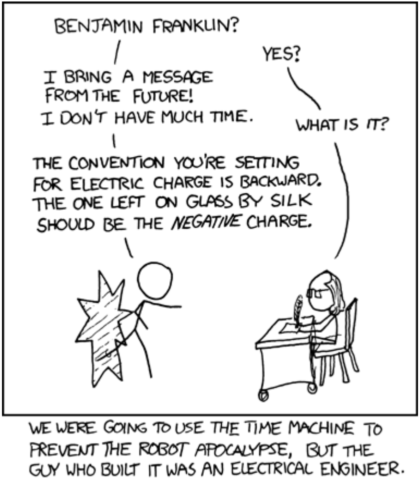

Separating ^{16}O and ^{18}O
^{16}O:^{18}O = 1:0.002
Counts
Δ (m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.26
0.28
0.30
0.32
0.34



Separating ^{16}O and ^{18}O
^{16}O:^{18}O = 1:0.002
Counts
0.010
0.008
0.006
0.004
0.002
0.000
0.26
0.28
0.30
0.32
0.34
Δ (m)

Mass Spectrometry - More realistic ^{18}O ratio





Cueball tells Franklin that the charge left on a glass rod by rubbing it with silk should be the negative charge, not the positive charge, because the friction removes electrons from the rod. This would not have been intuitive to Franklin, because the electron had not as of yet been discovered. Yet by telling Franklin to reverse the positive and negative conventions, this would ultimately result in an alternate universe where electrons are assigned a positive charge. One can only speculate what other changes this reversal of convention would lead to, as small changes tend to cascade into huge ones. Would the positron have been instead named the negatron? And would this affect the success of the Transformers franchise?

567: Urgent Mission by xkcd