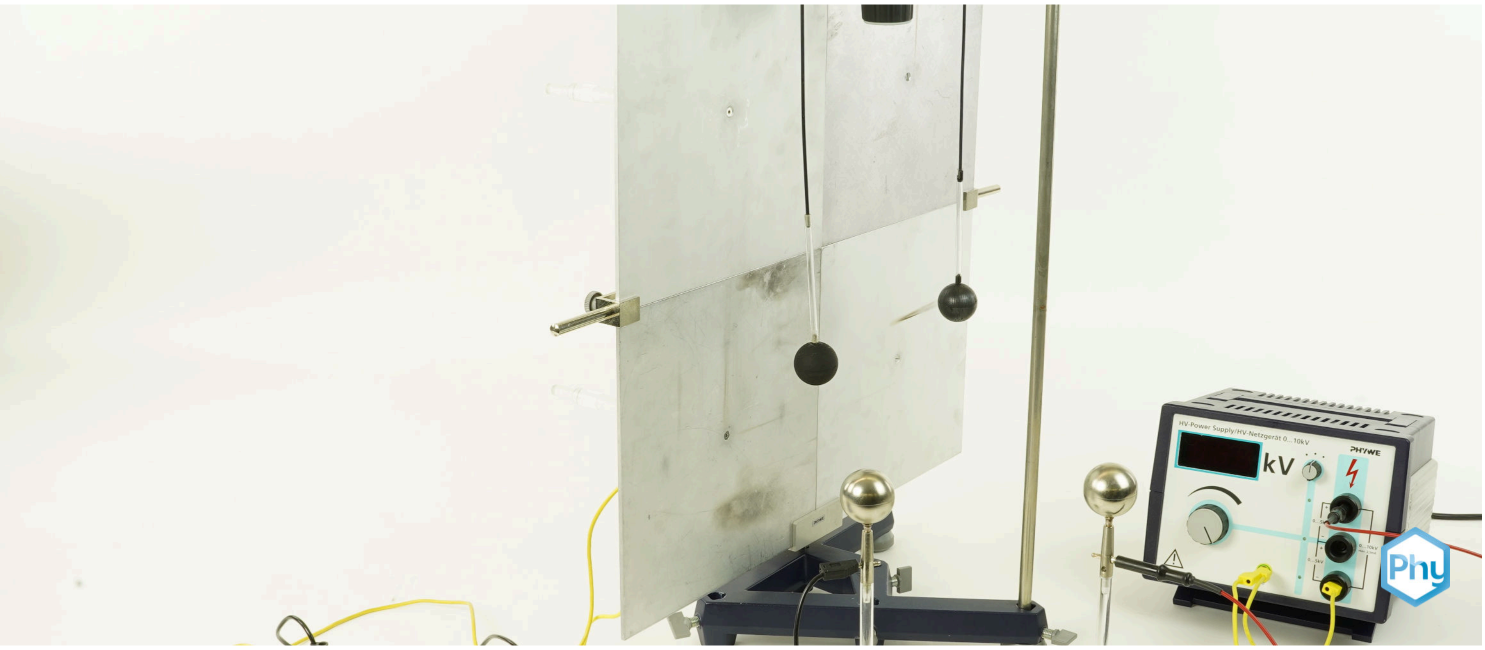
Coulomb's law/ image charge



Physics | Electricity & Magnetism | Electrostatics & electric field

Difficulty level	Group size	Preparation time	Execution time
medium	2	45+ minutes	45+ minutes

This content can also be found online at:

http://localhost:1337/c/62f619d9cde5dd0003298b89

General information

Application

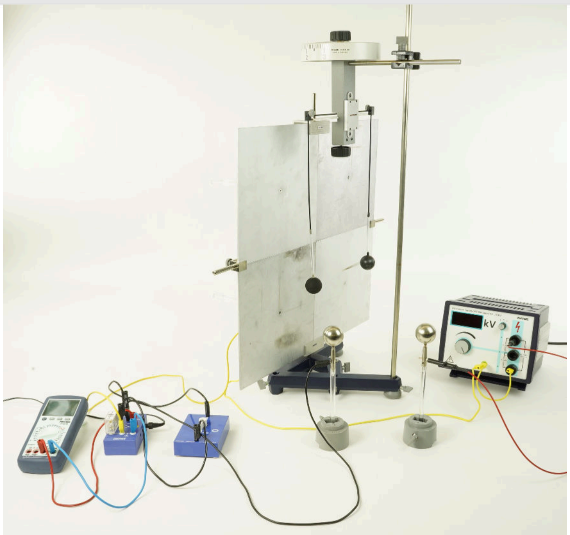


Fig.1: Experimental set-up

Coulomb's law is fundamental in all fields that use electric fields such as electrostatic and electrodynamics.

This experiment offers the opportunity to gain a first understanding of Coulomb's law.

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Other information (1/2)

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Prior knowledge

The prior knowlege required for this experiment is found in the theory section.

Main principle

A small electrically charged ball is positioned at a certain distance in front of a metal plate lying at earth potential. The surface charge on the plate due to electrostatic induction together with the charged ball forms an electric field analogous to that which exists between two oppositely charged point charges.

The electrostatic force acting on the ball can be measured with a sensitive torsion dynamometer.

Other information (2/2)

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Learning objective

The goal of this experiment is to investigate Coulob's law and the phenomenon of image charge.

Tasks

1. Establishment of the relation between the active force and the charge on the ball.
2. Establishment of the relation between force and distance, ball to metal plate.

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Theory (1/3)

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In accordance with Fig. 3 the electrostatic potential φ in the vicinity of two point charges of opposite polarity in the point P defined by $\vec{r}$ is

$$\varphi(\vec{r}) = \frac{Q}{4\pi\varepsilon_0|\vec{r}-\vec{a}|} - \frac{Q}{4\pi\varepsilon_0|\vec{r}+\vec{a}|} = \frac{Q}{4\pi\varepsilon_0\sqrt{(x-a)^2+y^2}} - \frac{Q}{4\pi\varepsilon_0\sqrt{(x+a)^2+y^2}}$$

where Q represents the amount of charge and ϵ_0 the electric constant. To prove this spatial potential distribution in the plate/ball system, it is advisable to relate the electrostatic potential to a certain locus (e. g. 1/2\vec a). We obtain

$$\varphi(\vec{r}) = \frac{3}{4}\varphi\left\{\frac{1}{2}\vec{a}\left(\frac{a}{\sqrt{(x-a)^2+y^2}} - \frac{a}{(x+a)^2+y^2}\right)\right\}$$

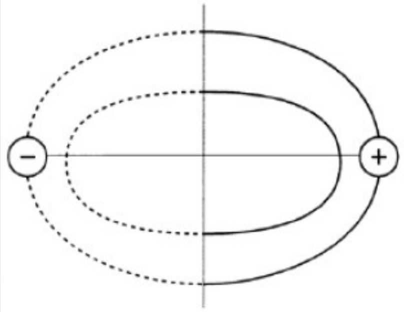

Fig. 2: Principle for Coulomb's law and image charge.

Theory (2/3)

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In an example of measurement there is a potential of 1000 V with respect to earth potential on the conductor ball. One obtains for the reference point in this case.

$$\varphi(\tfrac{1}{2}\vec{a}) = 175\ \mathrm{V}$$

See experiment P2420100 "Electric fields and potentials in the plate capacitor". From

$$\vec{E}(\vec{r}) = -\mathrm{grad}\frac{-Q}{4\pi\varepsilon_0|\vec{r}-\vec{a}|}$$

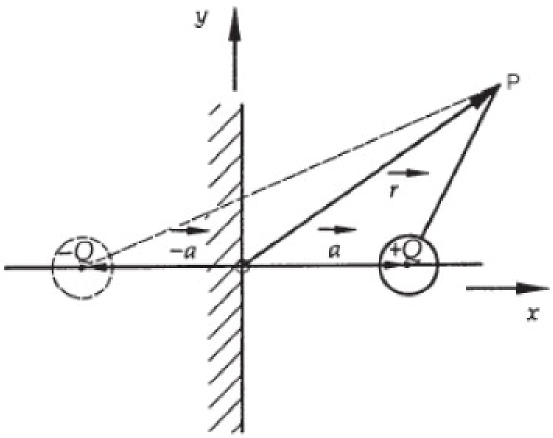

Fig. 3: Geometrical relationship in the plate/charge and image charge/charge system.

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Theory (3/3)

The electrostatic field produced by the image charge becomes

$$\vec{E}(\vec{r}) = -\frac{-Q}{4\pi\varepsilon_0|\vec{r}+\vec{a}|^3}(\vec{r}-\vec{a})$$

Hence the electrostatic force acting on the charge at the locus

$$\vec{F} = Q(\vec{E}(\vec{a})) = -F\frac{\vec{a}}{a}$$

with $F = \frac{Q}{16\pi\varepsilon_0 a^2}$

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Equipment

Position	Material	Item No.	Quantity
1	Plate capacitor, 283x283 mm	06233-02	4
2	Insulating stem	06021-00	2
3	Conductor ball, d 40mm	06237-00	2
4	Torsion dynamometer, 0.01 N	02416-00	1
5	PHYWE High voltage power supply with digital display, 10 kV DC: 0... ± 10 kV, 2 mA	13673-93	1
6	PHYWE Digital multimeter, 600V AC/DC, 10A AC/DC, 20 MΩ, 200 µF, 20 kHz, −20°C…760°C	07122-00	1
7	Measuring tape, l = 2 m	09936-00	1
8	Connecting cord, 30 kV, 1000 mm	07367-00	1
9	Connecting cord, 32 A, 1000 mm, green-yellow	07363-15	2
10	Connecting cord, 32 A, 250mm, green-yellow	07360-15	1
11	Support base DEMO	02007-55	1
12	Barrel base expert	02004-00	2
13	Right angle clamp expert	02054-00	1
14	Support rod, stainless steel, 1000 mm	02034-00	1
15	Plate holder, opening width 2 - 35 mm	06509-00	4
16	Connecting cord, 32 A, 250 mm, black	07360-05	2
17	Connecting cord, 32 A, 1000 mm, black	07363-05	1
18	Connecting cord, 32 A, 500 mm, red	07361-01	1
19	Connecting cord, 32 A, 500 mm, blue	07361-04	1
20	Capacitor 100 nF/250V, G1	39105-18	1
21	PHYWE Electrometer amplifier	13621-00	1
22	brigde plug	06027-07	1
23	Conductor spheres, w. suspension	02416-01	2
24	On/off switch	06004-00	1
25	Power supply 12V AC/500 mA	11074-93	1

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Setup and Procedure

Setup (1/3)

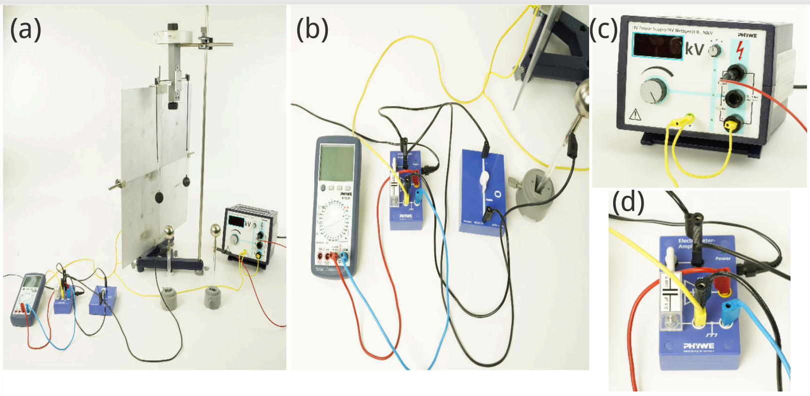

Fig. 4: Set-up of the metal plate, the torsion dynamometer with the conductor ball and the charge measurement (a) and the charging unit (b) respectively. Connections at the power supply (c) and the electrometer amplifier (d).

Set up the equipment as seen in Fig. 1 and 4. The manual includes two conducting spheres, that hang from the dynamometer and two conductor balls that are placed on insulating stems. Both of the conductor spheres are attached to the torsion dynamometer. The one in the center in front of the plate is used for the measurement, the other one acts only as a counterbalance.

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Setup (2/3)

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One of the conductor balls on the insulating stem is used for charging the conductor sphere. It is connected to the "+" port of the high voltage power supply using the high voltage connecting cord. It is used to charge the conductor sphere that is hanging from the dynamometer. To do so, touch the conductor sphere with the charged conductor ball. As soon as the conducting sphere is charged the conductor ball is placed somewhere on the table.

Connect the connector of the electrometer amplifier to the power supply. Put the bridge ("short-circuit plug") and the 100 nF capacitor between as shown in the picture. Keep the electrometer amplifier's input earthed by connecting the bottom row of sockets to the ground of the HV power supply.

Keep any high voltage away from the electrometer amplififer, its input is for up to 10 V, only!

The conductor ball on the insulating stem for measuring the charge is connected to the top row of sockets of the electrometer amplifier. It is used to measure the charge at the conducting sphere after the experiment. To do so, touch the charged conductor sphere with this conductor ball for measurement.

Setup (3/3)

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Connect the on/off switch to the electrometer amplifier as indicated. By closing the switch, the capacitor will be discharged after each measurement. Keep the switch always closed and open it only when collecting and measuring the charge of the suspended sphere.

While the acting force is 0 (Fig. 5, left), use the turning knob at the bottom of the torsion dynamometer (Fig. 5, mid) to set its arms to their initial position (Fig. 5, right). The arms of the torsion dynamometer should be mounted in a parallel way to the plate.

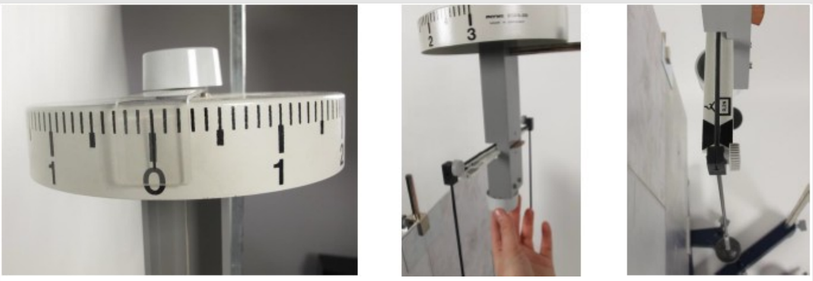

Fig. 5: Adjusting of the torsion dynamometer

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Procedure (1/2)

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Set the distance a between the center of the conducting sphere and the plates to 3 cm. Set the high voltage U to 2.5 kV. After charging the conducting sphere, it moves toward to the plate (for theoretical background please refer to the LEP version of this experiment).

Now bring the arm of the dynamometer back to its initial position using the upper turning knob to apply a counterforce. After restoring the initial position measure immediately the charge Q of the conducting sphere (remember: 10 V = 100 nAs, i.e. 1 V = 10 nAs) and read the applied force F. Note all values.

After noting the value of the charge, close the switch to discharge the capacitor setting the reading of the multimeter back to 0.

Procedure (2/2)

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Measuring the charge means also discharging of the conducting sphere. For that reason it moves away from the plate. Keep this position and increase the voltage to 5 kV and repeat the steps mentioned above.

Perform the same procedure also for 7.5 and 10 kV.

After completing set the applied force back to 0 and check if the initial position for the discharged conducting sphere is still the same.

Increase the distance to 6 cm in steps of 1 cm and measure again for each step. At 6 cm you may find no deflection at low voltages.

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Evaluation

Task 1 (1/2)

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The pairs of values of force and charge found for different distances a between the conductor ball and the condenser plate in a measurement example are listed in Table 1.

Q

Distance a [cm]	3		4		5		6	
U [kV]	Q [nAs]	F [mN]	Q [nAs]	F [mN]	Q [nAs]	F [mN]	Q [nAs]	F [mN]
2,50	4,2	0,07	4	0,03	-	-	-	-
5,00	8	0,12	10	0,08	7	0,02	-	-
7,50	13	0,26	15	0,18	13	0,05	-	-
10,00	19	0,44	23	0,32	16	0,12	17	0,02

Table 1: Measurement of charge Q and force F for different distances.

*For the distances a = 5 cm & 6 cm the forces for lower voltages have been too small for measurement.

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Task 1 (2/2)

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The force F is proportional to the square of the charge:

$$F = A_a X Q^2 + b$$

The intercept b is needed for a flexible fit of the data and can be neglected. In an ideal or theoretical case, b = 0.

Task 2 (1/2)

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The relationship between electrostatic force F and the square of the charge Q is plotted and the proportionality factors A_a between F and Q^2 for each distance a is determined form the slope of the straight line. It is a function of the distance a between condenser plate and ball.

Distance a [m]	1/a² [1/m²]	A_a [10^{12} mAs]
0,03	1111	1,08
0,04	625	0,56
0,05	400	0,47

Table 2: Distances a and the related proportionality factors A_a:

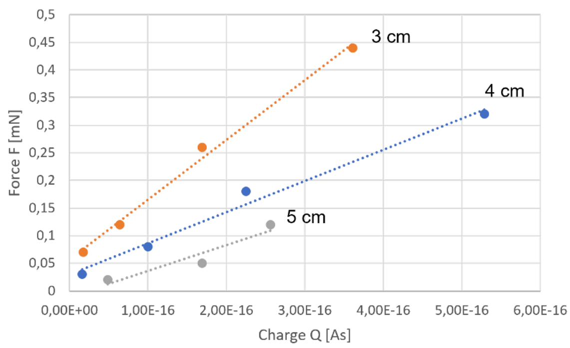

Fig. 6: Charge Q^2 and force F for different distances a

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Task 2 (2/2)

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From these proportionality factors the relation between force and distance of Coulomb's law can be confirmed:

The inverse distance a is plotted against Aa, showing a linear dependency.

Using the slope S of the fit, it is possible to estimate the dielectric constant:

$$\varepsilon_0 = \frac{Q^2}{16\pi a^2 F} = \frac{1}{16\pi S}$$

The literature value is $\varepsilon_0 = 8.8542 \cdot 10^{-12}\ \mathrm{As/Vm}$

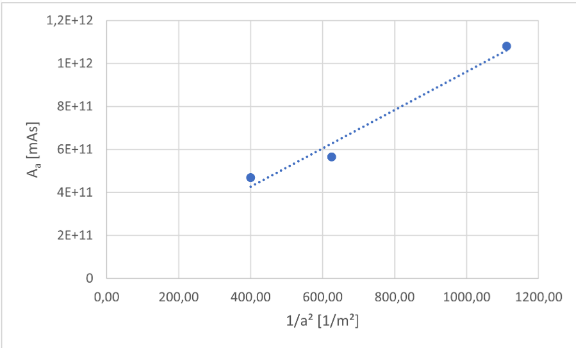

Fig. 7: Confirming the relation between force and distance of Coulomb's law

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