Coulomb's law / Image charge (Item No.: P2420401)

Curricular Relevance

Area of Expertise:	Education Level:	Topic:	Subtopic:	Experiment:
Physik	Hochschule	Elektrizität und Magnetismus	Elektrische Ladung und elektrisches Feld	Coulomb's law / Image charge

Difficulty	Preparation Time	Execution Time	Recommended Group Size
Intermediate	1 Hour	2 Hours	2 Students

Additional Requirements:

Experiment Variations:

Keywords:

Electric field, Electric field strength, Electric flux, Electrostatic induction, Electric constant, Surface Charge density, Dielectric displacement, Electrostatic potential

Overview

Short description

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.

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Fig. 1: Experimental set-up for measurement of the electrostatic force of attraction acting on the ball.

Equipment

Position No.	Material	Order 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	Conductor spheres, w. suspension	02416-01	2
5	Torsion dynamometer, 0.01 N	02416-00	1
6	DC measuring amplifier	13620-93	1
7	PHYWE Power supply, high voltage DC: 0... ± 25 kV, 0,5 mA	13671-93	1
8	Digital multimeter 2005	07129-00	1
9	Measuring tape, l = 2 m	09936-00	1
10	Connecting cord, 30 kV, 1000 mm	07367-00	1
11	Screened cable, BNC, l 1500 mm	07542-12	1
12	Adaptor, BNC socket/4 mm plug	07542-20	1
13	Connecting cord, 32 A, 750 mm, red	07362-01	1
14	Connecting cord, 32 A, 750 mm, blue	07362-04	1
15	Connecting cord, 32 A, 1000 mm, green-yellow	07363-15	2
16	Connecting cord, 32 A, 250mm, green-yellow	07360-15	1
17	Support base DEMO	02007-55	1
18	Barrel base PHYWE	02006-55	2
19	Right angle clamp PHYWE	02040-55	1
20	Support rod PHYWE, square, l = 1000 mm	02028-55	1
21	Holder for U-magnet	06509-00	4

Tasks

Duration: approx. 30 minutes for set-up, 60 minutes for performance and 30 minutes for evaluation

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.
3. Determination of the electric constant.

Set-up and procedure

Set-up

Set up the equipment as seen in Fig. 1 and 2. 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.

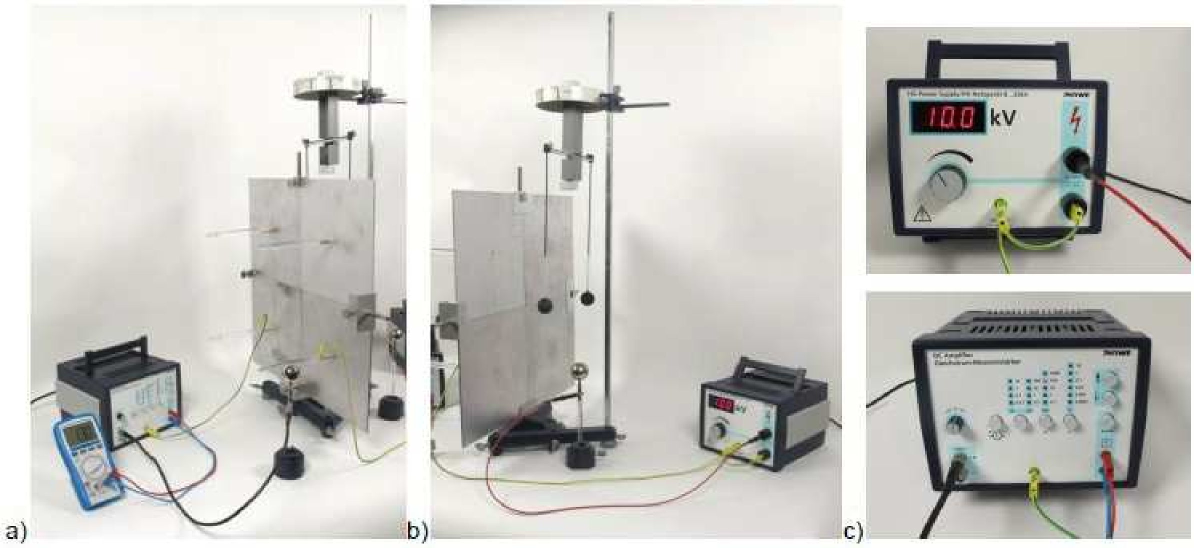


Fig. 2: Set-up of the metal plate, the torsion dynamometer with the conductor ball and the charge measurement (a) and the charging unit (b) respectively. Connections at the power supply and the DC amplifier (c).

One of the conductor ball 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.

The conductor ball on the insulating stem for measuring the charge is connected to the "I, Q" input of the DC measuring amplifier using the BNC cable with the adapter. 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.

While the acting force is 0 (Fig. 3, left), use the turning knob at the bottom of the torsion dynamometer (Fig. 3, mid) to set its arms to their initial position (Fig. 3, right). The arms of the torsion dynamometer should be mounted in a parallel way to the plate.

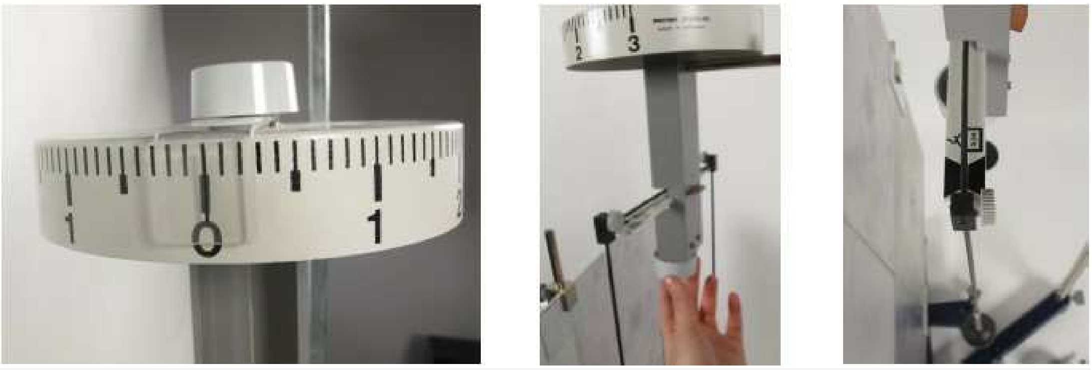
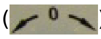


Fig. 3: Adjusting of the torsion dynamometer

The conductor ball on the insulating stem for charging is connected to the "+" port of the high voltage power supply using the high voltage connecting cord.

The conductor ball on the insulating stem for measurement the charge is connected to the "I, Q" input of the DC measuring amplifier using the BNC cable with the adapter. Connect the ground of the device with one of the plates.

Set the measurement range of the amplifier to Q and 100 nAs (i.e. the maximum output signal of 10 V is equal to 100 nAs). Select the measurement range of the multimeter to 20 V DC. Connect the blue cable to COM port and the red cable to the V port of the multimeter.

Press the discharging button () to discharge the measuring conductor ball. Use the zero adjuster () to set the reading on the multimeter to zero.

Procedure

Set the distance a between the center of the conducting sphere and the plates to 4 cm. Set the high voltage U to 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, press the discharging button of the DC amplifier to set the reading of the multimeter back to 0.

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 10 kV and repeat the steps mentioned above.

Perform the same procedure also for 15, 20 and 25 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 8 cm in steps of 1 cm and measure again for each step. At distances of 7 and 8 cm you may find no deflection at low voltages.

Theory and evaluation

Theory

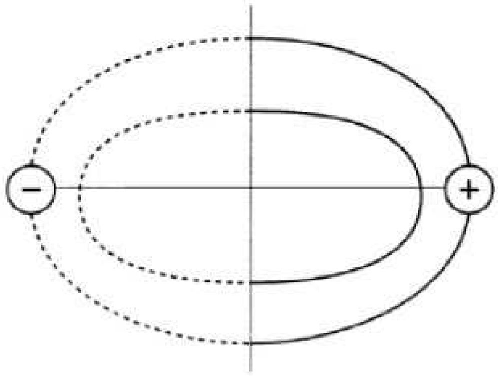


Fig. 4: Principle for Coulomb's law and image charge.

In accordance with Fig. 5 the electrostatic potential φ in the vicinity of two point charges of opposite polarity in the point P defined by $\vec{r}$ is

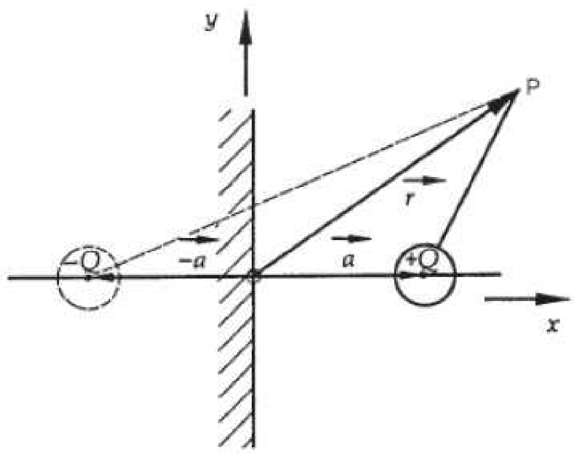


Fig. 5: Geometrical relationship in the plate/charge and image charge/charge system.

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

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

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

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

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

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

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

Evaluation

Task 1:

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.

Table 1: Measurement of charge Q and force F for different distances.
*For the distance $a = 8\,\mathrm{cm}$ the forces for the voltages 5 kV and 10 kV have been too small for measurement.

	Distance: 4 cm		Distance: 5 cm		Distance: 6 cm		Distance: 7 cm		Distance: 8 cm	
U in kV	*Q* in As	*F* in mN	*Q* in nAs	*F* in mN	*Q* in nAs	*F* in mN	*Q* in nAs	*F* in mN	*Q* in nAs	*F* in mN
5	5.1	0.03	4.4	0.04	4.5	0.02	4.5	0.02	-	-
10	10.2	0.18	9.2	0.09	8.2	0.08	8.3	0.08	-	-
15	15.5	0.39	13.8	0.19	13.2	0.12	12.4	0.11	12.4	0.07
20	20.1	0.65	18.0	0.32	17.1	0.19	16.8	0.16	16.0	0.11
25	23.8	0.94	21.8	0.46	23.0	0.36	21.0	0.24	20.9	0.16

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:

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.

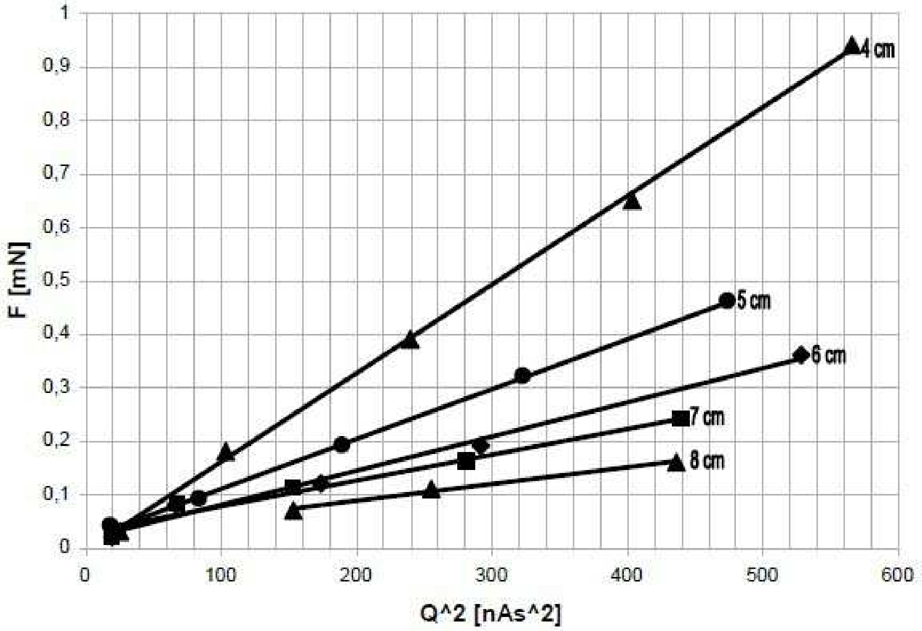


Fig. 6: Charge Q^2 and force F for different distances a

Pay attention to the right dimensions like changing the distance from cm to m. Especially, you should calculate A_a carefully, since its unit is $10^{-12}\,N/(C^2) = 10^{-12}\,\mathrm{V/(m\,As)}$.

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

Distance a in m	$1/a^2$ in $1/m^2$	Proportionality factor A_a in 10^{12} V (m As)
0.08	156	0.31
0.07	204	0.48
0.06	278	0.64
0.05	400	0.93
0.04	625	1.66

Task 3:

Finally from these proportionality factors the electric constant can be determined:

The inverse distance $1/a^2$ is plotted and the slope S of the graph is determined (Fig 7).

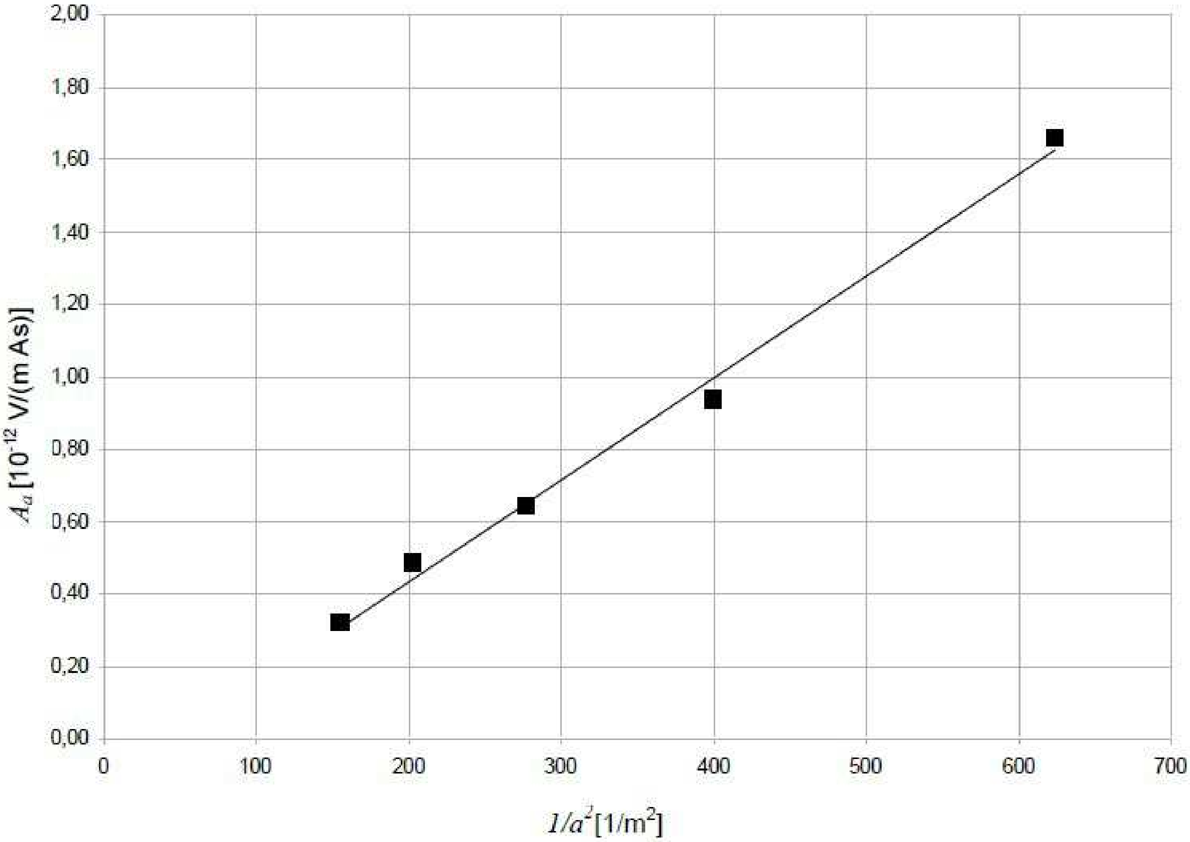


Fig. 7: Determination of the slope S

Slope $S = 0.0028 \cdot 10^{12}\,\mathrm{Vm/As}$

According to: $\varepsilon_0 = \dfrac{Q^2}{16\pi a^2 F}$ it follows: $\varepsilon_0 = \dfrac{1}{16\pi S} = 7.1 \cdot 10^{-12}\,\mathrm{As/Vm}$

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