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Surprising electroscope experiments help students think like physicists

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Abstract
In this paper, we present activities that help students deepen their understanding of basic electrostatics using an electroscope in combination with the photoelectric effect. The students investigate the behaviour of an isolated electroscope when the metal housing of the electroscope is charged. The activities follow the framework of the Investigative Science Learning Environment (ISLE) approach to learning and teaching. ISLE helps students learn fundamental physics concepts by engaging them in processes that mirror those used by physicists when they develop new knowledge and use it for practical applications.

Keywords: electroscope, photoelectric effect, ISLE, active learning, electrostatics

1. Introduction

Did it ever happen to you that you wanted to discharge an electroscope by touching the metal part on the top but the leaves (or the needle) instead of going down remained deflected or maybe the deflection even increased? When such things happen, we usually blame the weather, clothes and shoes that we wear, or all of these. Fortunately, the reason for such strange behaviour is often simpler and allows some easy ways to avoid it, as you will learn by the end of this paper. However, the main goal of this paper is not to describe surprising experiments and give explanations, but to present the activities that we conducted with our students and teachers (we shall call them all students from now on) and the steps that they took when investigating the surprising outcomes of the experiments with an electroscope. We included the descriptions of the experiments in the activities and presented the explanations the way they evolved through the students' work. To our best knowledge, there are no reports in the literature about the experiments that we describe here.

In designing the activities, we followed the theoretical framework of the *Investigative Science Learning Environment* (ISLE) approach to learning and teaching physics. The ISLE approach helps students learn fundamental physics concepts by engaging them in processes that mirror those that physicists use to develop new knowledge and use it for practical applications [1, 2]. ISLE-based examples of activities have been described in many papers [3–9] and the whole approach has been implemented in a published textbook [10] and accompanying collection of activities [11]. In this paper, we describe ISLE-based activities that are suitable for students who already have

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Figure 1. Future high-school physics teachers (left) and in-service high-school physics teachers (right) while working on the activities described in this paper.

a basic knowledge of electrostatics and photoelectric effect and wish to deepen their knowledge. We piloted the activities with the students in our physics education program (future high-school physics teachers) and with the in-service physics teachers who attend our continuing education program (figure 1).

In order to be successful in the activities that follow, students need to know that:

- The same sign charges repel and opposite sign charges attract.
- Movable charges in metals are negative (electrons).
- Interactions of charged and uncharged conductors and dielectrics can be explained microscopically.
- The charges of a charged conductor are located on its surface.
- There is no electric field inside a conductor, and the electric field lines outside a charged conductor have a specific shape.

In addition, the students need to be familiar with the construction of an electroscope and the basics of its operation.

In the activities described in this paper, we use an electroscope with a metal needle mounted in a metal housing (see figure 2(a)). Note that the metal support with the needle is isolated from the metal housing. Let us call the metal support with a needle 'the indicator'. There are numerous experiments in introductory physics that all involve manipulating charges on the indicator. Although rarely explicitly stated, in all these experiments, the metal housing is assumed to be connected to the ground (i.e. have the same potential as Earth). Below we present student handouts for three activities (not-indented) with typical student responses and our comments indented). In all activities, students worked in small groups (typically four per group) using white boards.

It should be noted that if the indicator is not well isolated from the housing, the experiments might not succeed. A well-known difficulty is high air humidity. Blowing a hot hairdryer over the electroscope can help, as well as using a dehumidifier [12]. Another difficulty is charge leakage between the indicator and the housing, which can happen due to poor isolation, or because the two are too close together either at the top or at the bottom. In our case, the distance between the lower tip of the indicator and the housing is about 2 cm. In case an appropriate electroscope is not available, we present in figure 2(b) a homemade electroscope from aluminium foil, styrofoam and copper wire, with which we have been able to reproduce the experiments.

2. Activity 1—Investigating an unconventionally charged electroscope

2.1. Activity 1 handout

For this activity, you need the following equipment: an electroscope, a metal sphere or plate, a thick block of styrofoam, a plastic rod and a piece

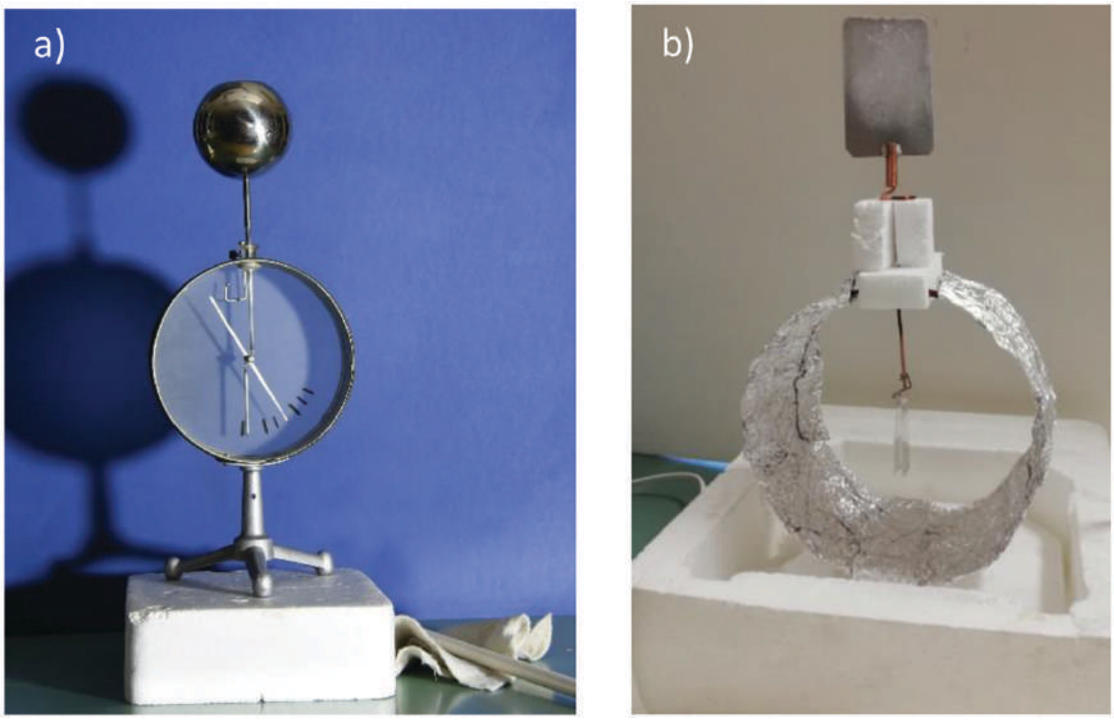


Figure 2. (a) Electroscope used in our activities. The diameter of the housing is 20 cm. (b) Simple homemade electroscope with which we were able to reproduce the experiments. The diameter of the housing is 17 cm.

of felt (we know that a plastic rod becomes negatively charged when rubbed with felt), and a cable that can be connected to an object of zero electric potential—the ground (for example, to a water tap or to 'earth' of the mains).

> We purposefully do not give students the source of positive charge (such as glass + silk) because switching the charge can result in transient unpredicted outcomes that may confuse students. This limitation did not pose any problem for our students; they were able to conduct all testing experiment ideas using only the equipment listed above.

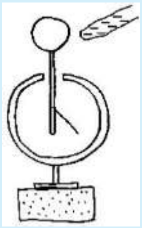
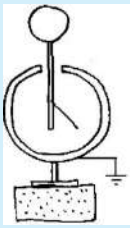
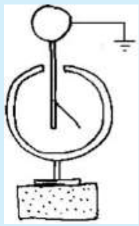
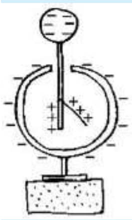
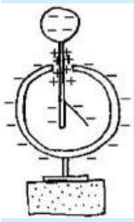
a. Put the electroscope on the styrofoam block. Put the metal sphere on the indicator. Make sure the electroscope is discharged. Touch the *metal housing* of the electroscope with the negatively charged plastic rod (do not touch the indicator or the sphere!) and then remove the rod. Observe what happens and describe the outcome of the experiment.

> Students will observe that the needle of the electroscope deflects. The housing of some electroscopes can be covered with a layer of paint that is a poor conductor. If this is the case, tell students to touch the metal connector that is usually mounted on the housing or to remove the paint at some place.

b. Propose different explanations for the observed outcome. Draw sketches of the experimental setup and indicate any charges that are relevant for your explanations.

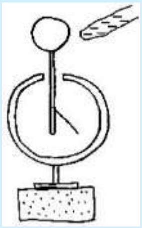
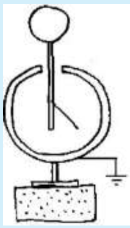
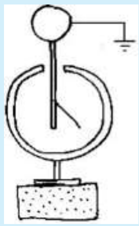
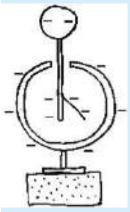
> Our students proposed the following explanations (see also sketches in table 1).
>
> E1: The negatively charged housing repels the electrons on the

Table 1. Summary of typical student proposals for explanations (including sketches), testing experiments, predictions and judgments. In all cases, students assumed that the charge is not leaking from the electroscope to the ground or air. Note that the students were given only the rod that charges negatively after rubbing.

	 **TE1:** Bring a negatively charged object close to the top part of the electroscope, without touching it.	 **TE2:** Connect the metal housing to the ground potential[a].	 **TE3:** Connect the metal sphere to the ground potential.
 **Explanation 1:** Negatively charged housing makes the electrons on the indicator move to the outside part, away from the housing. The needle becomes positively charged.	The deflection of the needle should *decrease,* because some electrons move towards the needle, making it less positively charged.	The deflection of the needle should go to zero, because the indicator is neutral.	The deflection of the needle should *not change,* because the indicator is neutral.
 **Explanation 2:** Negatively charged housing makes the electrons move to the extreme parts of the indicator. The needle and the sphere become negatively charged.	The deflection of the needle should *increase,* because some electrons move towards the needle, making it even more negatively charged.	The deflection of the needle should go to zero, because the indicator is neutral.	The deflection of the needle should *not change,* because the indicator is neutral.

(Continued)

Table 1. (Continued)

	 **TE1:** Bring a negatively charged object close to the top part of the electroscope, without touching it.	 **TE2:** Connect the metal housing to the ground potential[a].	 **TE3:** Connect the metal sphere to the ground potential.
 **Explanation 3:** Some negative charge from the housing leaks or 'jumps' to the indicator.	The deflection of the needle should *increase,* because some electrons move towards the needle, making it even more negatively charged.	The deflection of the needle should be larger than zero, because the indicator is charged.	The deflection of the needle should *decrease* (some say it should go to zero), because the excess negative charges will move from the indicator to the ground.
Outcomes of the testing experiments	The deflection of the needle decreases.	The deflection of the needle goes to zero.	The deflection of the needle *increases.*
Judgments	**Reject 2 and 3**	**Reject 3**	**None**

[a]The idea is to turn the electroscope into the familiar 'mode of operation'. Students know from their earlier experiences with grounded electroscope housing that the needle deflects if there is a net charge on the indicator and that the deflection is zero if the indicator is neutral.

sphere and on the part of the indicator outside the housing, pushing them away from the housing. As a result, the sphere becomes negatively charged and the needle inside the housing becomes positively charged, therefore deflects.

E2: The negatively charged housing repels the electrons on the indicator. As a result, the electrons move to the sphere and to the needle while the part of the indicator near the housing becomes positively charged. Because the needle becomes negatively charged, it deflects.

E3: Some negative charge from the housing leak or 'jump' to the indicator, therefore charging it negatively. Because the needle inside the housing becomes negatively charged, it deflects.

c. Propose several testing experiments that you can use to test your explanations. You may use the following equipment: connecting wire, plastic rod.

Our students proposed the following testing experiments (TE) (see table 1).

TE1: Bring a negatively charged rod close to the top part of the electroscope without touching it.

TE2: Connect the metal housing to the ground.

TE1 and TE2 were proposed by all groups. In addition, some groups proposed the following testing experiment:

TE3: Connect the sphere at the top of the electroscope to the ground.

d. Make predictions of the outcomes of each testing experiment based on the explanations that you proposed in b. Indicate any assumptions that you made and think how you can verify them.

Table 1 summarizes student predictions for the testing experiments, the outcomes and judgments as given by the students. In all cases, the students assume that the charge is not leaking from the electroscope to the ground or air. To verify this assumption the students can observe the deflection of the electroscope for long time (in our case the needle remained deflected for more than an hour).

Explanation 1 includes the assumption that the negative charges reside mostly on the outside surface of the housing. Students may want to verify this assumption by fixing a small metal foil leaf on the electroscope housing (if correct, the leaf should deflect when housing is charged, which is exactly what happens, see figure 3).

e. Perform the testing experiments that you proposed in c. Compare the outcomes of the experiments with the predictions and make judgments about the proposed explanations.

After comparing the outcomes of the testing experiments with the predictions, the students realized that they could reject explanations 2 and 3 but they could not reject explanation 1 (see table 1).

Figure 3. The aluminium foil leaf indicator that shows the presence of the excess charges on outside surface of the electroscope housing.

TE3 needs additional comments. The outcome of TE3 did not match any prediction given by our students, which surprised them greatly. When making predictions for the outcomes, the students thought that if we connect the metal object to the ground it would always become neutral and if the metal object is charged, the excess charges would flow to the ground. The students realized that their understanding of the outcome of TE3 was incomplete and that they probably made some assumptions that were not valid. Because other testing experiments allowed them to reject explanations 2 and 3, the students decided to accept explanation 1 as the correct one and leave the testing experiment 3 for later consideration. During the whole class discussion at the end of the activity, the students reconciled their ideas and (with some prompts from the instructor) proposed the following improved explanation for the outcome of TE3. The excess electrons on the housing are repelling the electrons on the sphere, therefore they move away from the housing as far as possible. As long as the indicator is isolated, the electrons cannot move farther than to the top of the sphere. When we connect the indicator to the ground, the electrons can move farther away (to the ground), leaving the indicator positively charged. Note that the strange outcome of the experiments that we mentioned at the very beginning of the paper can be explained using the same reasoning (see the summary of the activity below).

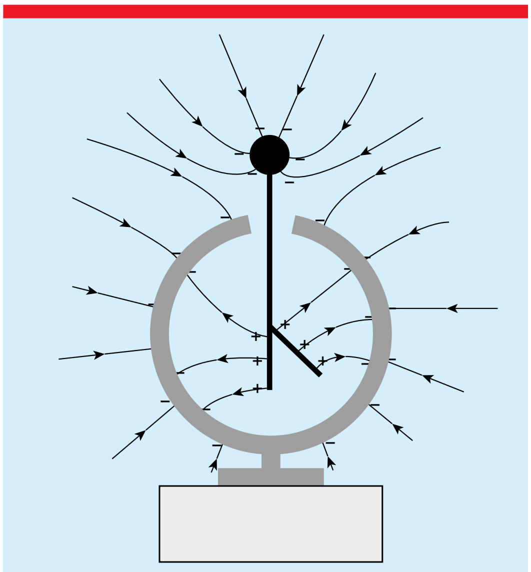


Figure 4. Charge distribution and electric field lines for an isolated electroscope when the electroscope housing is negatively charged.

End of activity 1

Let us summarize the main finding from this activity, which is also the answer to the questions posed in the introduction: if we charge an isolated housing of an electroscope and keep the indicator uncharged, then the part of the indicator outside the housing acquires the charge of the same sign as the housing and the part inside the housing acquires equal charge of the opposite sign. As a result, the needle deflects, while the indicator as a whole remains neutral. The majority of charges that we brought to the housing reside on the outer surface of the housing. Note that some charges should reside on the inner surface of the housing, to terminate the electric field lines that originate from the charges on the needle, as there should be no electric field inside the metal (see figure 4). This last idea did not appear spontaneously to our students but only after some hints from the instructor.

3. Activity 2—Investigating what happens when we add a photoelectric effect

Activity 1 introduces students to the experiments and explanations related to the charging of the housing of an isolated electroscope and prepares them for two more challenging activities that are described in this and in the following section where we combine two topics: electrostatics and photoelectric effect. In addition to students' previous knowledge in electrostatics, we also assume that the students are familiar with the photoelectric effect and with the experiments with an electroscope that are often used at the beginning of the exploration of photoelectric effect (see for example [10], chapter 27). Specifically, that a negatively charged electroscope with the top made of zinc can be discharged using UV light. Again, we present below student handout and common student responses and our comments.

3.1. Activity 2 handout

For this activity, you need the following equipment: an electroscope, a thick block of styrofoam, a plastic rod and a piece of felt (we know that the plastic rod becomes negatively charged if rubbed with felt), a cable that can be connected to the ground, zinc plate, sand paper and a UV light source (do not look into the light!).

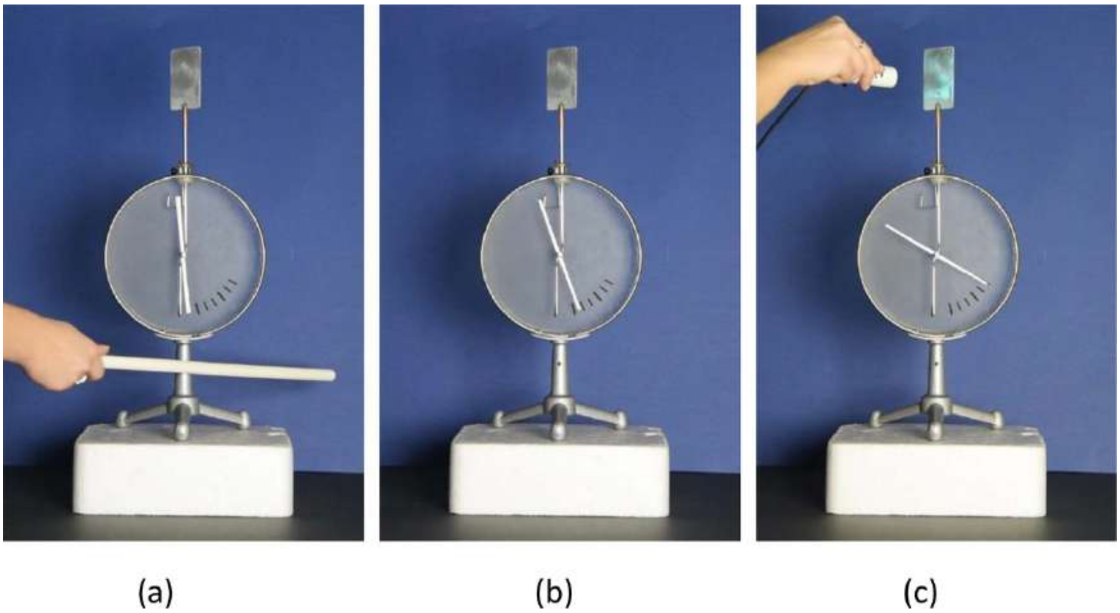


Figure 5. The housing of an isolated electroscope is negatively charged (a), (b). As UV light shines on the zinc plate, the deflection of the needle increases (c).

a. Put an electroscope on the styrofoam block. Put a freshly sanded zinc plate on the indicator. Make sure the electroscope is discharged. Touch the metal housing of the electroscope with the negatively charged plastic rod so that the needle of the electroscope deflects. Shine a UV light on the zinc plate. Describe the outcome of the experiment.

> Students will observe that when the needle of the electroscope is exposed to UV light, the deflection of the needle starts increasing until it reaches the maximum deflection (figure 5).

b. Explain the outcome of the experiment using what you have learnt so far. Draw sketches of the experimental setup and indicate any charges that are relevant for your explanation. Indicate any assumptions that you made and think how you can verify them.

> After completing the previous activity, all groups of students were able to construct the correct explanation using the following reasoning.
>
> We know from the previous activity that initially the zinc plate is negatively charged, the needle is positively charged and the indicator as a whole is neutral. When we expose the zinc plate to UV light, UV photons kick out the electrons from the plate. Because the plate is negatively charged, these electrons fly away from the plate. As the result, the indicator becomes more positively charged and therefore the deflection of the needle increases. It is crucial to realize that negatively charged housing keeps the zinc plate negatively charged (allowing the photoelectrons to keep leaving the plate) although the indicator as a whole is becoming positively charged (see figure 6).
>
> Note that as the positive charge inside the electroscope increases,

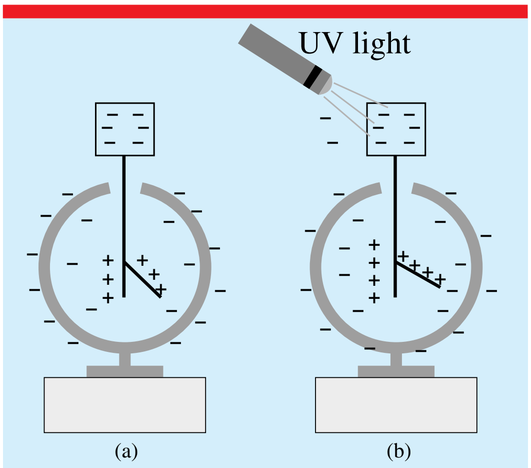


Figure 6. The charge distribution after the housing of an isolated electroscope is negatively charged (a) and after UV light kicks out some electrons from the zinc plate (b).

some negative charges should move from the outside to the inside surface of the housing (to compensate for extra positive charge), therefore the density of the negative charges on the outside part of the housing should decrease. Our students did not spontaneously think about the charges on the inner surface of the housing but after we encouraged them with additional questions, they were able to improve their explanations to account for these effects.

c. How can we test this explanation? Propose one or more testing experiments and make predictions for their outcomes based on the explanation that you devised before.

Building on the experience and knowledge from activity 1, students usually propose the following testing experiments and make corresponding predictions.

TE1: Ground the housing of the electroscope. *Prediction*: If the explanation above is correct and we ground the housing, the needle of the electroscope should remain deflected, because the indicator should have net positive charge.

Students often propose two follow-up testing experiments to test the hypothesis that the net charge on the indicator is positive.

TE1a: Bring a negatively charged rod close to the zinc plate (keep the housing grounded). *Prediction*: If the indicator is positively charged, the deflection of the needle should decrease. (Some students also predict that if we bring the negatively charged object even closer to the plate, the deflection will start to increase, because the negative charge repelled from the plate will exceed the positive charge on the needle.)

In addition, students may want to test the hypothesis that the negative charge that accumulates on the outside surface of the housing decreases while the deflection of the needle increases. Students can test this idea by fixing a small metal foil leaf on the electroscope housing (if the hypotheseis is correct then the deflection of the leaf should decrease while we are shining UV light on the zinc plate, which is exactly what happens).

d. Perform testing experiments that you proposed in c. Compare the outcomes of the experiments with the predictions and make judgments about the proposed explanation.

The outcomes of the experiments match all the predictions, therefore we accept the proposed explanation.

At the end, we also asked the students what they can say about the charges on the zinc plate when the needle reaches maximum deflection and stops moving.

Some students correctly said that at this moment there was no excess charge on the plate, but some students thought that the plate is positively charged. If this happens in your class, remind the students that in the original experiments on photoelectric effect using a grounded electroscope, we never observed that the neutral zinc plate would get charged after being illuminated with UV light. As soon as the electrons are kicked out from the neutral plate, the plate becomes positively charged, bringing those electrons back to the plate due to mutual attraction [13].

End of activity 2

Let us summarize the main findings. When the housing of the electroscope is negatively charged and the indicator with a zinc plate on top is neutral, the indicator inside the housing (including the needle) becomes positively charged and the zinc plate negatively charged (follows from activity 1). When we shine UV light on a zinc plate, the UV photons eject electrons by the photoelectric effect and these electrons fly away from the plate, making space for new electrons to arrive from the needle. Thus, the needle becomes even more positively charged and the deflection increases. The process ends when the zinc plate is neutral. When the process ends, the indicator as a whole is positively charged.

4. Activity 3—Applying what we have learnt so far

For this activity, you need the same equipment as for activity 2. Note: in this activity, the students will first predict the outcome of the experiment based on what they have learnt so far and only then run the experiment.

We will use the same setup as in the previous experiment (an isolated electroscope with a zinc plate on the top of the indicator). We will charge both the metal housing of the electroscope *and* the indicator using the plastic rod negatively. Then we will shine UV light on the zinc plate for a long enough time so that any movements of the needle stops.

a. Predict what will happen to the needle throughout this experiment using what you have learnt so far. Explain how you came up with your prediction. Draw sketches of the experimental setup and indicate any charges that are relevant to your explanation.

Several groups correctly predicted that the deflection of the needle would first decrease and then increase, until it reaches some maximum deflection. In order to be able to construct the correct and complete explanation on which this prediction is based, the students need to apply carefully the findings from previous activities (we present this explanation below). Some groups might come up with the same prediction for the outcome but their explanation can be incomplete. In this case, you might want to let them observe the outcome and then encourage them to improve their explanation by drawing sketches and indicating any charges that are relevant for their explanation.

Explanation: Initially the indicator is negatively charged (figure 7(a)). When we shine UV light on the zinc plate, the electrons start to leave the plate and fly away from the zinc plate. Consequently, the negative charge density on the needle decreases and so does the deflection of the needle (figure 7(b)). After a while, the part of the indicator near the needle becomes neutral. In this moment, the deflection of the needle is zero (figure 7(c)). However, at this time, the zinc plate is still negatively charged (due to interaction with negatively charged housing) and therefore the UV light continues

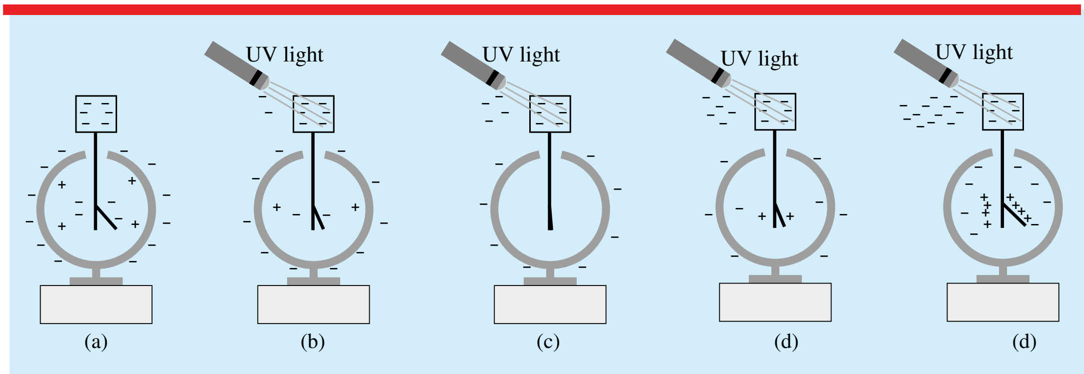


Figure 7. The charge distribution after the housing of an isolated electroscope and the zinc plate are negatively charged (a) and after the zinc plate is illuminated with UV light (b)–(e).

to kick out electrons from the zinc plate. As a result, the needle and the part of the indicator near it become positively charged and the deflection of the needle starts increasing (figure 7(d)). Note that while this is happening, the charge on the zinc plate remains negative. At some point, the net charge of the indicator becomes zero (no excess charges). Note that at this point, the situation is exactly the same as the initial situation in activity 2 and therefore we can continue with the explanation described before. As long as the interaction between the negatively charged housing and the zinc plate is able to keep the zinc plate negatively charged, UV light keeps kicking the electrons out from the zinc plate and the deflection of the needle increases (figure 7(e)). The needle stops moving when the excess negative charge on the zinc plate becomes approximately zero. At this point, the net charge of the indicator has maximal positive value and the needle stops moving.

It is instructive to discuss with the students what happens to charges on the outside of the electroscope housing during this experiment. If you discussed this issue in the previous activity, then the students would be able to explain that the density of the negative charge on the housing is decreasing through the whole experiment (again, students can test this hypothesis by fixing a small metal foil indicator on the outer side of the electroscope).

Some groups in our pilot predicted that the deflection of the needle would only decrease explaining, that UV light would remove the negative charge from the zinc plate. We let them observe the outcome and then encouraged them to revise their explanation so that it would account for the observed outcome. It is important that to be successful the students need to draw sketches including relevant charges.

Based on what they have learnt in activity 1, some students predict that if we add negative charges gradually on the indicator (that is initially neutral), the deflection should first decrease, become zero and then increase. In order to test this idea, they have to rub the plastic rod only slightly and repeat the charging process several times. Seeing that their prediction matches the outcome of the experiment makes students feel successful and more self-confident.

b. Perform the experiment. Does your prediction match the outcome? If it does not, resolve any discrepancies. If necessary, perform additional experiments to construct an explanation about the outcome of this experiment that is consistent with what you learnt so far and with the previous experiments.

The students observe that the deflection of the needle first decreases, reaches zero deflection and then increases, until it reaches some maximum deflection. If students fix a small metal foil indicator on the housing, they observe that the leaf is continually decreasing.

The students may also want to test that the total charge on the indicator at the end of the experiment is positive. They can do this in a usual way, by grounding the electroscope and bringing the negatively charged rod close to the top. The outcome confirms that the indicator is indeed positively charged (the deflection of the needle first decreases).

End of activity 3

Let us summarize the findings from this activity. We place a zinc plate on the indicator and negatively charge both the indicator and the housing. When we shine UV light on the zinc plate, UV light ejects electrons making the indicator less and less negatively charged. As a result, the deflection of the needle decreases. Due to the interaction between the charges on the housing and on the indicator, the plate is more negatively charged than the needle. At some point, the needle becomes neutral and its deflection is zero. At this moment, the zinc plate is still negatively charged and therefore the electrons continue leaving the plate due to the photoelectric effect. While this is happening, the needle is becoming more and more positively charged and the deflection starts increasing again. As in the previous experiment, the process ends when the zinc plate becomes neutral.

4.1. Summary

We presented the sequence of three ISLE-based activities that all involve experiments with an isolated (not grounded) electroscope. The goal of the first activity is to investigate the basic behaviour of the isolated electroscope when the metal housing of the electroscope is charged. In the second activity, students investigate how the photoelectric effect affects the discharging of the zinc plate on top of the isolated electroscope with the previously charged housing. In the final activity, students apply what they have learnt in the first two activities to predict the outcome of a new experiment that combines the isolated electroscope and the photoelectric effect. All activities were piloted with students−future high-school teachers and with in-service high-school teachers. In both cases, the participants worked on the activities in small groups using white boards to present their findings. All groups successfully completed all three activities. Several participants said that these activities helped them deepen their understanding of the experiments with an electroscope and the knowledge of electrostatics in general. In addition, the explanations and findings presented in this paper may help physics teachers avoid some unwanted phenomena when using an electroscope in traditional experiments. In this case, the most important advice is: make sure that the electroscope housing is grounded.

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