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Microwave oven experiments with metals and light sources

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Abstract

'Don't put metal objects in the microwave' is common safety advice. But why? Here we describe demonstration experiments involving placing household metallic objects in a microwave oven. These allow a better understanding of the interaction of microwaves with materials. Light bulbs and discharge lamps can also be used in instructive demonstrations.

M This article features online multimedia enhancements

Introduction

The physics of microwave ovens and cooking with microwaves has been the topic of three recent articles [1–3]. A selection of demonstrations has already been included in the second and third of these; however, microwave ovens (abbreviated hereafter as microwaves) allow a huge variety of other experiments which may serve as lecture demonstrations in the classroom [4]. There are also many related websites with images and sometimes video clips (e.g. [5–7]), each giving further links. Since microwaves are part of many students' everyday lives, they are a suitable topic to raise and/or stimulate interest in physics. Many of the experiments can be performed with little additional equipment. Some, however, use a thermal infrared camera [8] to visualize temperature differences in extended objects.

In order to visualize the processes within a microwave oven, we also modified a commercial microwave by replacing part of the door with an infrared-transparent window. Since part of the metal grid is absent some radiation will leak out. For safety reasons a large distance is required between the observers and the camera/microwave. We have still included some of these experiments in order to give an insight into the physics. We emphasize that this modified oven should not be rebuilt and experiments should not be repeated unless all necessary safety regulations are obeyed.

Most experiments were performed with just the objects mentioned being placed in the microwave. The experiments should also work if you place an additional small glass with water in the microwave, although they may take a little bit longer. This ensures that no radiation is coupled back into the magnetron, thus extending its lifetime. Some of the easy hands-on experiments may be dangerous, for example the explosion of light bulbs or the sudden ignition of cigarettes or CD-ROMs. We will attempt to indicate the dangers while describing the experiments, but all repetition of the experiments described here is done at your own risk.

Metals in microwave ovens?

One often hears the statement that metals or objects with metallic parts should never be put into the microwave (see also [2]). Physicists know about the origin of this 'wisdom', but they also know about its limited range of validity.

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When microwaves interact with metals, they are effectively absorbed, but the metals also reradiate most of the energy [1]. Since metals have good thermal conductivity (according to the Wiedemann–Franz law, it is proportional to the electrical conductivity) the fraction of the energy that is absorbed is rapidly distributed over the whole metallic body. If this body is very massive—like the walls of the microwave oven—then the new equilibrium state, which depends on the absorbed power, the heat capacity and heat losses, corresponds to a very small warming. The behaviour of smaller metal parts, however, depends strongly on their shape and mass. Very thin metal sheets or similar bodies have only a very small heat capacity and can warm up quickly. This can even lead to glowing and evaporation, e.g. from plates with golden edges. One should never put such plates in a microwave, unless you wish to remove the golden edges.

Thin metal wires: miracle candles

The rapid warming up of thin pieces of metal by several hundred degrees within seconds can easily be demonstrated with miracle candles. We recommend using cork as the base for the candle. Depending on their length, the candles may need to be bent in order to fit in the microwave (figure 1).

The metal wire in the microwave rapidly heats up and this leads to self-ignition. The candle may not ignite at the top and ignition may even start at two different points simultaneously (see video 1 accompanying the electronic version of this article).

If thin metal wires are used in an otherwise empty microwave, the electric fields at the end of the wires can become larger than the breakdown potential in air of about 10^6 V m^{-1}. In this case, sparks may be formed and discharges occur (see also below with cigarettes).

Thin metal films: coatings on CD-ROMs and coated glass spheres

Unwanted advertising CD-ROMs are perfect cheap samples for showing the rapid warming up of thin metal films. Alternatively, one could use Christmas tree decorations that are coated metal spheres. Figure 2 depicts a CD-ROM before and after treatment in a microwave. The thin metal coating warms up very rapidly. Depending on the local distribution of the electric fields, structures are burnt into the CD while part of the metal evaporates (and condenses somewhere else in the microwave). Safety note! If the CD-ROM stays too long in the oven, it may start to burn! We

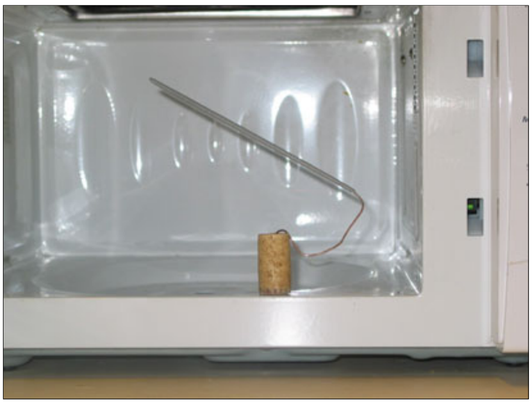


Figure 1. Miracle candle before treatment in the microwave oven.

Figure 2. CD-ROM before and after heating in the microwave.

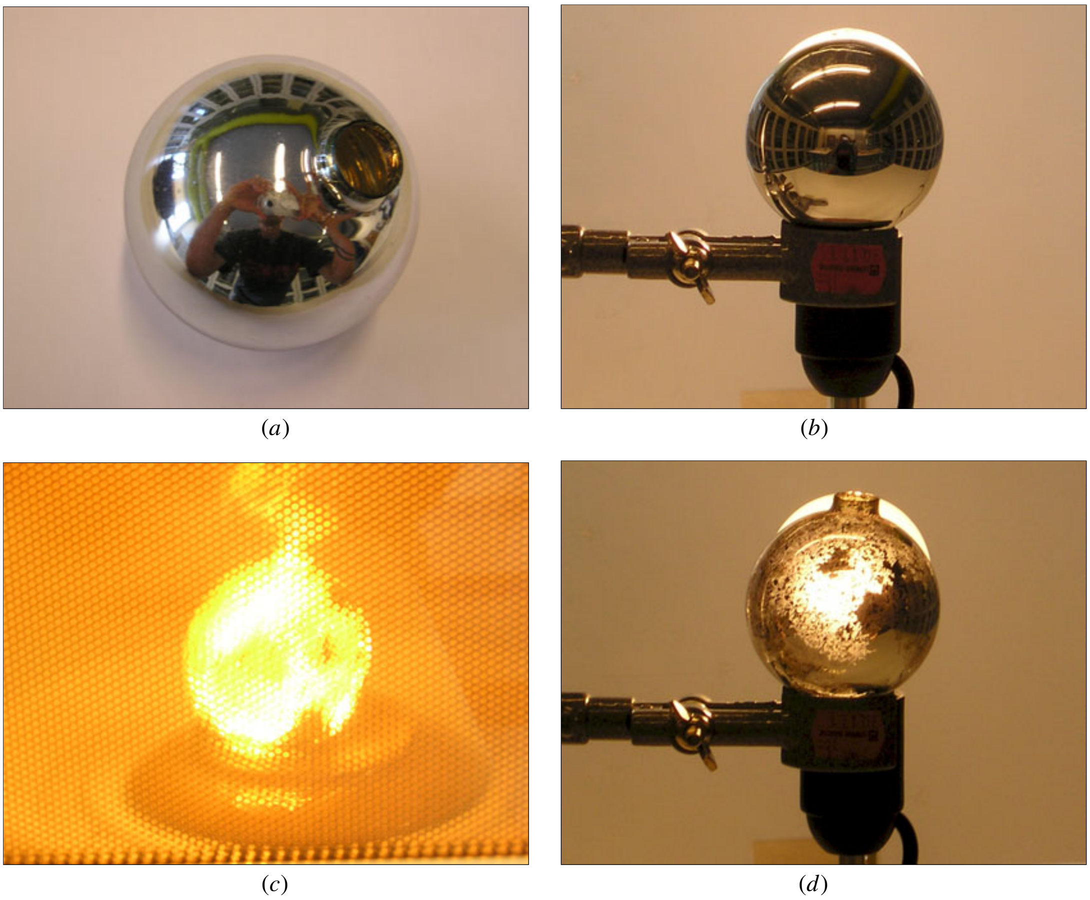


Figure 3. (*a*) Coated open glass sphere, usually used as a decoration on Christmas trees. Parts (*b*) to (*d*) correspond to the situation before (*b*), during (*c*) and after (*d*) treatment in the microwave. In the set-up of (*b*) and (*d*) the sphere is placed in front of an operating light bulb in order to demonstrate that in (*d*) a large part of the coating has evaporated, since the sphere has become transparent.

usually stop the experiment after, say, 3–5 seconds.

Even more convincing are the Christmas tree decorations (figure 3(*a*)). The metal films are very thin and may evaporate to a large extent. The spheres are open at one spot such that a clamp may be attached to them. Figure 3(*b*) shows a sphere (clamp opening pointing downward and not seen) in front of a 100 W light bulb. The coating is thick enough that only the upper rim of the light bulb is observable. If put in the microwave, the metal film starts to evaporate within seconds, and associated with this is a bright glow that moves over the surface (figure 3(*c*)). The photograph was taken through the door and thus shows the structure of the door's grids. After a few seconds, most of the coating has gone and one can usually see through the sphere (figure 3(*d*)).

Aluminium foil and more massive metal objects

Other experiments may be performed with aluminium foil. Thin strips can show spark formation and heat up quickly. Foil can be used without harmful effects if there is good thermal contact to another body, which may absorb some of the thermal energy (compare figure 8 in [2]).

Similarly, other metal objects may be used within an operating microwave if they have good thermal contact to another more massive body, for example a glass of water. Hence, a metal spoon in a mug full of water, tea or coffee may of course be used without problem. Figure 4 depicts the experimental set-up where the mug was replaced by a glass. The upper 1–2 cm of the spoon were painted with a black paint that is suitable for use at high temperatures. This

Figure 4. Glass containing water and a metal spoon.

was necessary in order to simultaneously measure the temperature of the glass and the spoon with infrared thermal imaging. (The temperatures found by measuring the thermal radiation with the IR camera depend on the emissivity ε; metals usually have much lower emissivities than glass and images are usually displayed for constant emissivity. If temperatures are measured conventionally, e.g. with thermocouples, this painting is not necessary.)

Figure 5 gives examples of the different behaviour of the spoon alone in a glass compared with the spoon in water. The microwave was operated for 30 s each time at 700 W. Figure 5(*a*) shows the situation before heating and figure 5(*b*) after heating the spoon in the otherwise empty glass. The initial spoon temperature at its blackened end did rise by about 26 K from about 29 °C to 55 °C while, at the same time, the glass temperature rose from 29.5 °C to a maximum of about 66 °C (where the spoon touched it inside at the bottom). This result should be compared with the situation where the glass was filled with about 60 ml of water. Figures 5(*c*) and 5(*d*) show the results for the same parameters, the only difference being a slightly different initial temperature of the tap water. Now, the spoon temperature rose by about 15.5 K from 28 °C to 43.5 °C while at the same time the water was heated from 25.5 °C to 60 °C. Obviously, the spoon is much colder than the water and its temperature rose by much less than it did without the water. This is due to its high thermal conductivity, which allows the thermal energy within the spoon to be easily transferred to

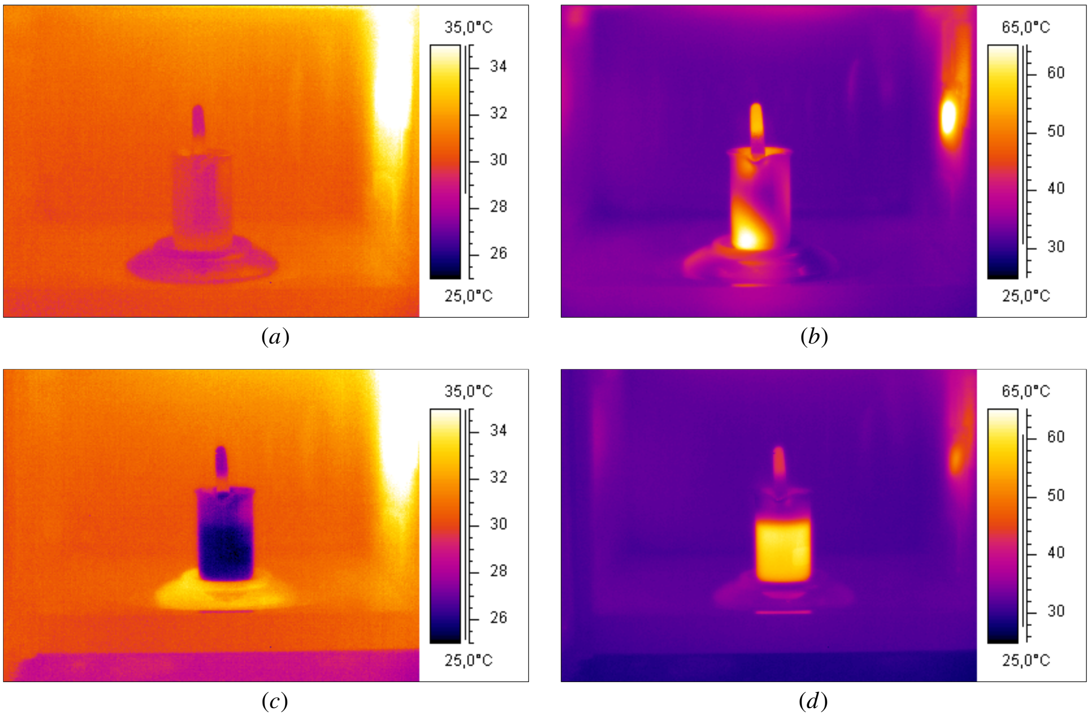


Figure 5. IR images of a spoon in a glass without water (top row) before (*a*) and after (*b*) heating, as well as with water (bottom row) before (*c*) and after (*d*) heating. Note the change in temperature scale between left and right.

Figure 6. A glowing cigarette is attached to a piece of cork using a toothpick. If this is unstable, the cork may be squeezed into a holder.

the water. This set-up has the additional advantage of avoiding superheating [3], since the spoon offers many nucleation sites.

Discharges: a new method for cigarette disposal

Thin metal wires exhibit spark and discharge formation. This can be demonstrated even more effectively and easily by using glowing cigarettes. Figure 6 shows the experimental set-up.

A glowing cigarette is placed in the microwave and the microwave is turned on. The glowing tobacco leads to preionization of the air, which enhances the formation of discharges (see video 2). Because the fan causes the air inside the microwave to move, the discharge is not stable but continually changes position and size.

Light sources in microwave ovens?

At first thought, it sounds absurd to discuss how light sources behave within microwaves; however, when a microwave is turned on, the interior, i.e. the microwave cavity into which the food is placed, is usually illuminated. On looking more closely (i.e. opening the housing), it is obvious that the light bulb is not within the cavity but behind a metal grid (figure 7). Since the cavity acts as a Faraday cage, very little microwave radiation from inside can reach the light bulb outside the cavity. However, the much smaller wavelength of visible radiation easily allows the light from the bulb to illuminate the inside.

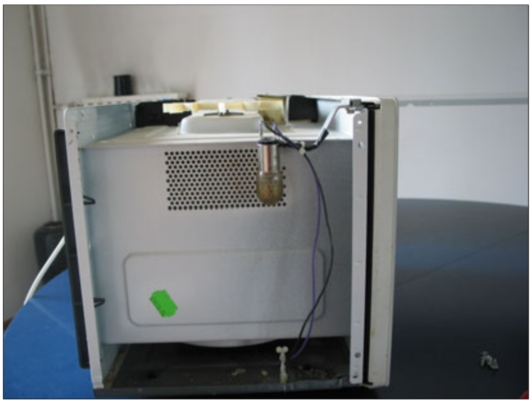


Figure 7. A microwave oven is illuminated by a light bulb behind a metal grid, e.g. at the side of the cavity (in this case, the microwaves are coupled in from the top).

Naturally the question arises as to what would happen if the light bulb were not shielded. Therefore, in the following some simple experiments [5–7] with light sources in microwave ovens are described.

Light bulbs

Light bulbs are available as vacuum lamps, lamps filled with noble gases or the smaller lamps filled with noble gases and halogens. The operating temperature of the filament depends on the filling and usually ranges between 2300 K (vacuum lamps) and 3400 K (halogen lamps). Obviously, only the filament, the support wires and the electrical metallic contacts in the socket of the lamp (figure 8) may react to the microwave radiation. In particular, the thin metal wires should heat up very rapidly.

Since the heating of the filament is responsible for the emission of the incandescent radiation, light bulbs usually light up inside a microwave within several seconds. We used 700 W and just placed the light bulb on a dish in the oven. The light emission is not restricted to the filament, but may also take place at the metallic contacts (see figure 9 in [2]). During the heating of the metallic parts, the gas also starts to heat up. This enhances the formation of discharges in gas-filled lamps. It may be helpful to try out lamps from several manufacturers. We were able to see wonderful violet and greenish discharge colours. Depending

Figure 8. The filament as well as support wires and contacts in a light bulb are made of metal.

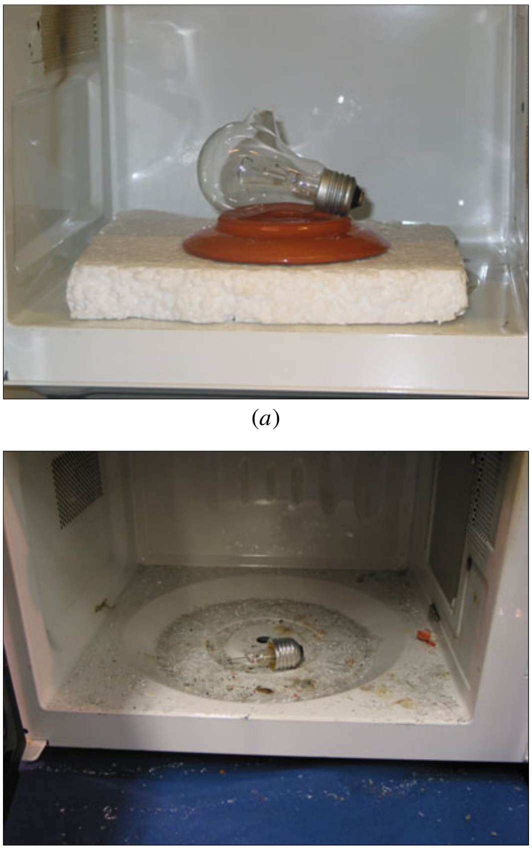
on the quality of the lamp, one may be able to use them for typically 20 s to 40 s before the bulb explodes. The explosion may take place in various ways (similar to the eggs used in [3]). Most often, the glass turns soft at just one spot and some kind of bulge forms (figure 9(*a*)). Sometimes, however, the glass is so uniform that a very large stress can build up, leading to a more destructive explosion (figure 9(*b*)). Safety note! Never open a microwave with a light bulb in before it explodes or else wait long enough for it to cool down again.

Sometimes, discharges and the explosion take place close to the metal socket. This may be prevented by putting the lamp with the socket facing towards the bottom, inside a glass filled with enough water to cover the socket.

Safety note! Light bulbs treated in a microwave oven are usually damaged and should not be used in the conventional way afterwards.

Why do the lamps explode? Vacuum light bulbs are produced with internal pressures of less than 10^{-3} mbar (0.1 Pa) and light bulbs filled with noble gases and halogens as treated here are sold with internal gas pressures at room temperature in the mbar range. The explosion does, however, require pressures well above 1 bar.

There are two contributions to the internal pressure while operating the lamp. First, the gas pressure within the bulb increases while heating up. If treated as an ideal gas at constant volume and assuming a very large initial pressure of 10 mbar at room temperature, even a gas temperature of 3000 K would result only in a pressure of 100 mbar. Hence, the pressure must come from a different source. Figure 10 gives a clue. It shows an exploded light bulb. The filament and large parts of the support metal wires look like they may have evaporated. A quick estimate shows that this is easily sufficient to raise the internal pressure above atmospheric pressure. If, for example, 10 mm^3 of metal evaporate, this corresponds to the order of 10^{21} atoms for iron. For a volume of the light



(*a*)

(*b*)

Figure 9. Various types of exploded light bulbs.

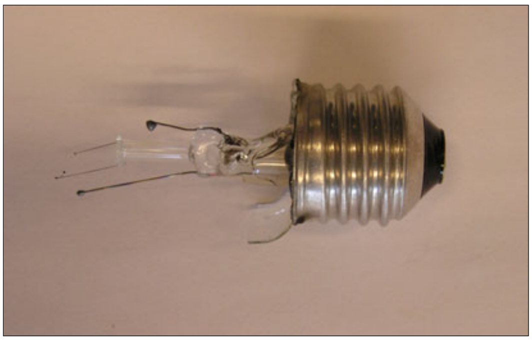


Figure 10. The filament and large parts of the support wires have evaporated.

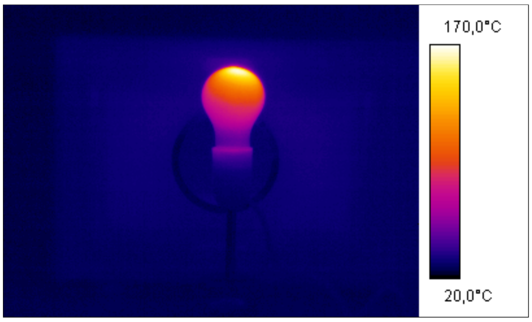


Figure 11. A 100 W light bulb after two minutes of operation.

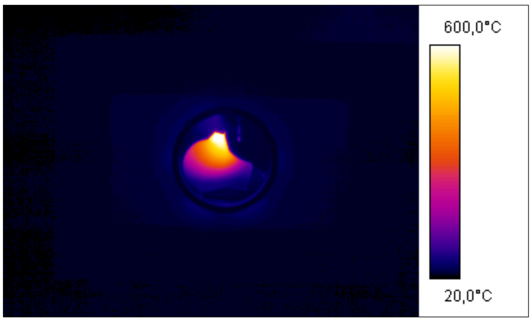


Figure 12. Infrared image directly after the explosion with surface temperatures at the top being above 620 °C.

bulb of, say, 100 cm^3, and with the approximation that the vapour behaves like an ideal gas, we find $p(\text{Pa}) \approx 140T$, where T is given in kelvin. For a temperature of 1000 K, one readily obtains about 1.4 bar, which can be sufficient to destroy the light bulb, as is shown below.

A quantitative analysis of the temperature of light bulbs before explosion was made with clear 100 W bulbs. First, figure 11 shows a 100 W bulb (*in front* of our modified microwave) after two minutes of operation. At the top, the maximum temperature is about 170 °C. This is of course too hot to touch, but much too low for the glass to become soft.

In contrast, figure 12 shows the same light bulb after treatment and explosion within the modified microwave. The bulb was positioned in such a way that it could be directly observed through the IR-transparent window. Within about 20 seconds of operation at 700 W, the maximum surface temperature of the bulb just before the explosion reached more than 620 °C.

This high surface temperature leads to a local softening of the glass. Since the internal pressure rises to values above atmospheric pressure the glass bulges outwards and explodes with a result similar to figure 9(*a*). In the infrared video (video 3) one can clearly see the gradual change before the explosion.

Many other things may be done with light bulbs. For example, they may be used to study the defrost mechanism. At the very low powers of this mode of operation, the filament and other metal wires may just start to glow for, e.g., 10 s on-periods, which are followed by, say, 20 s off-periods. Usually, the power is too low for evaporation and destruction, hence the bulb turns on with a time delay of 1–2 s and is only lit during the on-periods. Similarly, one may try to use the rotating turntable and place the bulb off centre. With luck, the light bulb will turn on and off, depending on the field distribution within the cavity.

Discharge lamps: the phenomenon

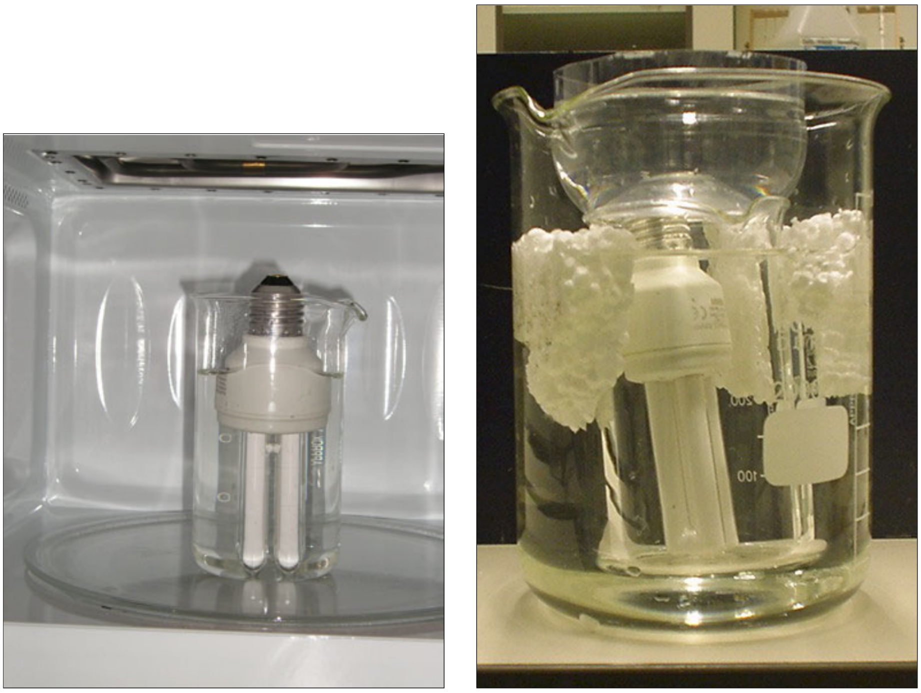
Finally we will discuss some experiments with discharge lamps. As was seen already with the cigarettes or the gas-filled light bulbs, it is very easy to initiate discharges in a microwave. This also works for commercial discharge lamps (see figure 13) as has been reported elsewhere (see, e.g., [6, 7]).

Safety note! In contrast to long discharge tubes, which will not fit into the microwave, energy-saving lamps usually have some electronics in their socket. The metal wires therein are destroyed by the microwaves and the lamp will not work in a conventional way after being in the microwave. One could try to postpone this effect by placing the lamps with the socket downward in a glass of water that covers the socket. The water strongly attenuates the radiation (see below). We suggest that you demonstrate the lighting of the discharge for intervals of only 10–15 s. In this way, the lamp will live longer. Some energy-saving lamps survived 5–10 demonstrations of this kind, others 20 to 30.

Discharge lamps: demonstrating the attenuation of microwaves by water

Since the lamps are used while placed in beakers, we filled the beakers with water. This can either be done directly with the set-up of figure 14(*a*) or—if you want to avoid water touching the lamp—by

Figure 13. A discharge lamp (energy-saving lamp) during operation of the microwave.



(*a*) (*b*)

Figure 14. Set-up for studying the attenuation of microwaves by water with one or two beakers.

placing the beaker with the lamp inside into a larger beaker, partially filled with water (figure 14(*b*)). Some Styrofoam may be used to ensure a more or less equal thickness of water surrounding the lamp. Placing the whole thing into the microwave resulted in no discharge if the thickness of water was larger than about 1 cm. This corresponds nicely to the attenuation length of microwaves in water [1].

This method is also suitable for semi-quantitative measurements. We used our modified microwave, placed the lamp in front of it and observed from the side. The radiation leaking out of the window was sufficient for a discharge (figure 15).

This set-up allowed us to study the absorption of water by placing different thicknesses of water between the opening and the lamp. Not

Figure 15. Discharge lamp in front of the modified microwave. The leaking radiation was strong enough to produce a discharge.

surprisingly, a water tank that is 10 cm thick strongly attenuates the microwaves (video 4); however, even a very small amount of water with a thickness of 1 cm and dimensions similar to the lamp is sufficient to suppress the discharge (video 5). As mentioned in the introduction, this set-up should be used only under strict safety regulations since the leaking radiation is dangerous. The sideways scattering of the radiation becomes visible in the videos as image distortions. They vanish immediately after the water tank is placed in front of the opening.

Finally, discharge lamps are also suitable for visual demonstration of the partial polarization of the microwave radiation that leaks out of the cavity. Rather than placing water tanks between the lamp and microwave, we use a microwave polarizing grid, as is usual for microwave (not microwave oven) demonstration experiments in physics. The excitation of the discharge depends on the orientation of the polarizing filter (video 6).

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