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More experiments with microwave ovens

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Abstract
Microwave ovens can be used to perform exciting demonstrations that illustrate a variety of physics topics. Experiments discussed here show superheating, visualize the inhomogeneous heating that takes place in a microwave and also show how to use a mobile phone to detect radiation leaking from the oven. Finally eggs can give some spectacular (though messy) explosions. In all cases please note the safety advice given.

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Introduction

The physics of microwave ovens featured in two recent articles in *Physics Education* [1, 2]. Microwave ovens (often referred to here as just microwaves) are a part of students' everyday life and can be used to stimulate interest in physics [3]. Many of the experiments described here can be carried out with little additional equipment. However, some of these experiments use a thermal infrared camera [4] to visualize the temperature differences within various objects.

In order to visualize the processes within a microwave oven, we modified a commercial microwave by replacing part of the door with an infrared-transparent window. Microwave radiation does leak out and for safety reasons observers and cameras were some distance away. We have included details of these experiments in order to give an insight into the physics behind them. We do emphasize most strongly that this modified oven should not be built and experiments should not be repeated unless all necessary safety regulations have been followed.

Even some of the more straightforward experiments, such as the explosion of eggs, ignition of various substances and superheating of water, may be dangerous. We describe some of the experiments that have been carried out and reported upon, but accidents have happened. We indicate the dangers while describing the experiments, but if you choose to repeat them you do so at your own risk.

Chocolate bars

According to microwave mythology the principle of microwave cooking was discovered by Percy Spencer, who was working close to a powerful magnetron and realized that a chocolate bar in his pocket has melted [2]. In the early days of magnetron research, scientists were casual about being close to microwaves, but this quickly changed after the cooking effects were discovered!

This story can be easily tested by placing chocolate in a microwave. We used figures of Santa Claus or Easter bunnies made of chocolate, but as well as placing them inside an oven we also used our modified oven where part of the metal shielding in the door is replaced by an infrared-transparent window. The chocolate was placed directly in front of this window. The radiation

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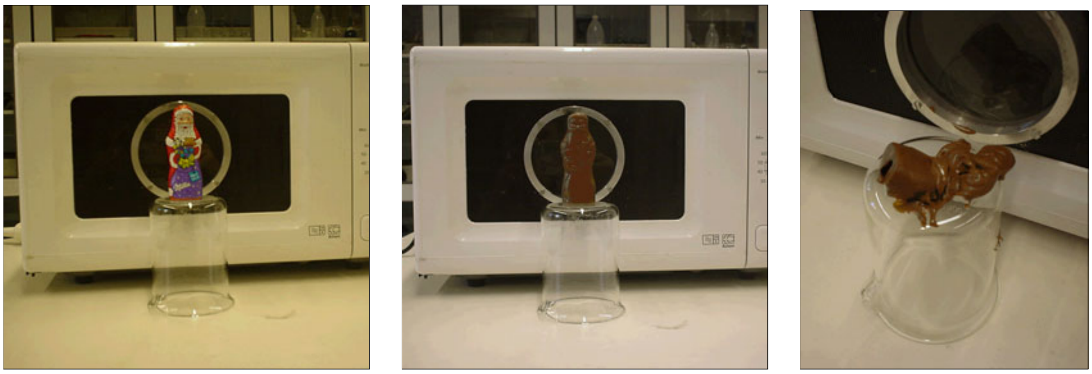


(*a*) (*b*) (*c*)

Figure 1. Christmas chocolate figure (*a*) with foil, (*b*) unwrapped and (*c*) after being exposed to microwaves for one minute.

leaks out, resembling Spencer's experimental set-up quite nicely.

First, it is necessary to get rid of the aluminium foil, since some foils are thicker than the penetration depth of the waves in the metal. Operating the empty oven at full power, e.g. 800 W, it takes a minute or so for the chocolate to melt (figure 1). The precise time depends on the water content (and hence the quality) of the chocolate. To reduce the melting time, you can inject water into the hollow stomach of the chocolate form using a syringe.

Superheating

Heating with microwaves easily produces superheated water. Very clean containers are usually needed, e.g. a glass with very smooth inner surfaces. When water is heated in a pan, it usually starts to boil at 100 °C. Small bubbles of steam form on the inside surfaces of the pan (which is where the water is hottest); here tiny scratches and crevices act as nucleation sites for the bubbles. As the bulk of the water reaches 100 °C bubbles may also form inside the liquid. For this to happen there need to be nucleation sites within the water in the form of impurities or small particles in the liquid. If there are no nucleation sites (or very few) superheating may occur, i.e. the water reaches temperatures above 100 °C without boiling. Adding impurities to a superheated liquid, e.g. by adding some powder, salt, sugar or tea to the water, may result in explosive boiling. Take care: boiling hot water may splash around. Sometimes, the originally full container is nearly empty afterwards!

If you want to demonstrate this phenomenon, you will find that normal boiling occurs in 99 out of 100 cases. The problem is to get rid of the nucleation sites. This can be done, in the microwave, by using a very clean glass container with distilled water and heating it to just below boiling temperature. Bubbles are formed and attach to the walls, since small crevices act as nucleation sites associated with the container. By slightly knocking the container, the bubbles become free. Heating the water several times and repeating the knocking procedure two or three times leads to fewer and fewer bubbles, though they grow bigger. Few nucleation sites are then present and the water may start to become superheated. The proper heating times must be found by trial and error—it may happen that explosive boiling also takes place within the microwave oven!

Using gloves and safety glasses, the container may be cautiously removed from the microwave. The effect may be demonstrated by, for example, inserting a thin wire (video 1)[1]. Boiling starts as soon as the wire touches the water. More impressive (but also dangerous) is to very rapidly add sugar or salt etc (video 2). We repeated the experiment at least 20 times and about half the time the water exploded in the oven. Very often the water was not superheated enough, but we were able to demonstrate the effect two or three times. Unfortunately, the best result, which led to a nearly empty glass, was not captured on video!

[1] Videos 1 and 2 are available from the online version of the journal at stacks.iop.org/physed/39/346.

Heating of baby food in bottles

Bottles used to feed babies are often rather tall. When heated up quickly in a microwave oven, there is the danger of very unevenly heated food due to the vertical modes within the oven. This is illustrated in figure 2, which shows infrared pictures of a tall narrow cylinder filled with 30 ml of water. It was placed in the centre of a microwave oven at about 800 W for 15 s. Obviously, there are large temperature differences of more than 20 °C between the bottom, middle and top of the glass. In the example, we found 76 °C at the top, 43 °C in the middle and 62 °C at the bottom of the glass. This measurement can also be performed with thermocouples.

Suppose that baby food is heated this way and that accidentally the cold part is on top—one may then erroneously assume that all the food is cool enough to eat.

Conclusion: all food in tall containers should be stirred before serving. This example also demonstrates that using the rotating turntable does not help if the food is placed in the centre—which is what most people do—because there the rotation does not move the food through the microwave fields. Check the effect yourself by placing the container at different positions on the turntable.

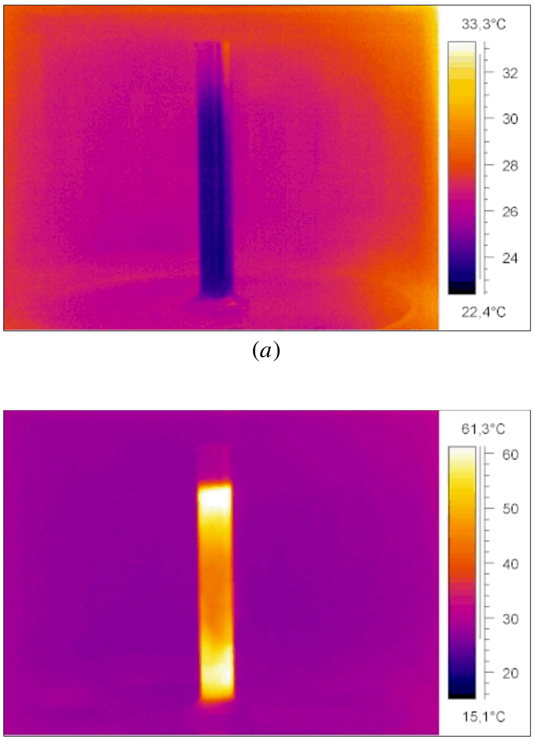


Figure 2. Water in a tall glass container (*a*) before and (*b*) after heating in the microwave. The heating introduces vertical inhomogeneities.

Leakage of radiation from a microwave?

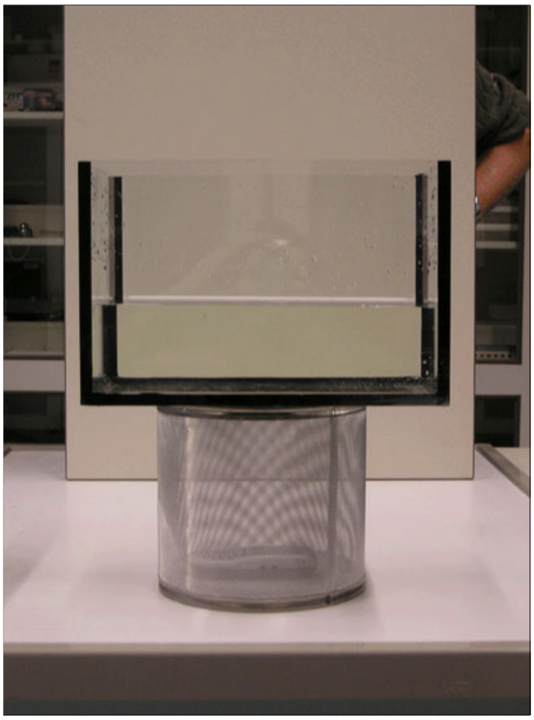
All parts of the body of a microwave oven, except the door, act as a Faraday cage. The glass or plastic doors contain a metal grid. The spacing of the grid allows visible light to pass through, but microwaves with wavelengths of about 12 cm are strongly suppressed, since the grid acts like two polarizers oriented perpendicular to each other. Obviously, little radiation can therefore leak out of an operating microwave and all commercial ovens fulfil strict regulations concerning the amount of leakage. Commercial microwave detectors such as Gunn diodes, however, are very sensitive and detect the leaking radiation. The remaining polarization of the radiation can then be tested by placing an additional polarizer in front of the detector. Another cheap way of detecting radiation leakage is to place a computer monitor next to the oven and watch for disturbances on the screen.

Still another possibility uses the most widely distributed and extremely sensitive detectors for microwaves: cell phones. The idea behind the experiment is that if radiation may leak out, then some radiation from outside may also leak in. Portable phones operate at typical frequencies of 900 MHz (D-band) or 1.8 GHz (E-band) in Germany, which correspond to wavelength of $\lambda_D = 33$ cm or $\lambda_E = 16.7$ cm. These are quite close to the conditions of microwave ovens with 2.45 GHz and $\lambda = 12.2$ cm.

In the demonstration, a cell phone is switched on and put in the microwave (figure 3(*a*)) and the door is closed. (Please ensure that the oven cannot be turned on—the phone would be dead within fractions of a second.) If there is not too much metal in the walls of the building, which already strongly attenuates the radiation, it is easily possible to call the phone within the oven and hear it ringing.

Cell phones can also be used to study microwave attenuation semi-quantitatively because of the absorption of water. For this purpose, the phone is placed in a Faraday cage that is open on top, such as a large metal can. A glass aquarium is placed on top of the can, and because glass does

(*a*)



(*b*)

Figure 3. (*a*) Portable phone in a microwave oven. (*b*) Testing the attenuation of microwaves by water.

not absorb microwaves, the phone should still ring when it is called (figure 3(*b*)). Water is then poured into the aquarium until the phone no longer rings when called. Students can measure the depth of water that reduces the signal such that it is no longer detected by the cell phone.

Eggs in the microwave

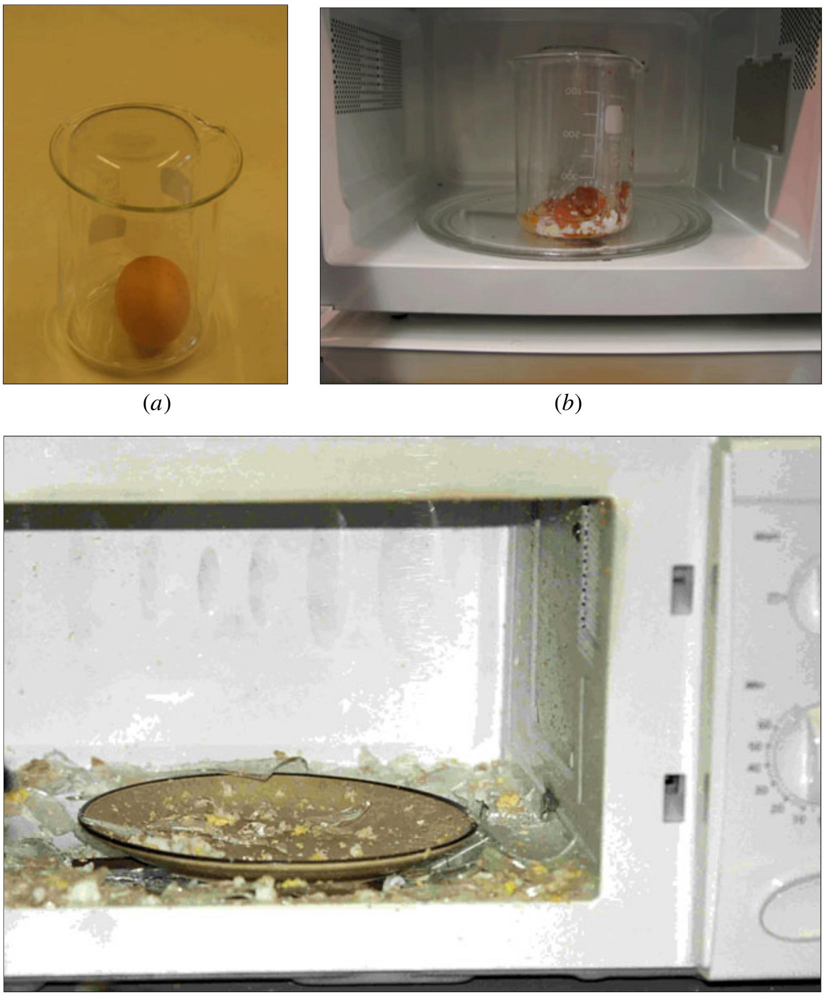
The most spectacular anecdotes involving microwave ovens usually have to do with eggs: fresh eggs, boiled eggs or even fried eggs. Eggs contain a lot of water, which gives rise to a lot of vapour pressure upon heating, so eventually the shell (or skin of fried eggs) cracks and the egg bursts or even explodes. We have not studied fried eggs in detail, so far. We presume that the skin of the yolk rapidly becomes strong and impermeable to water vapour. Therefore, the pressure might rise appreciably before the destruction of the egg.

So far, we have studied about 100 eggs, both fresh and boiled, while operating the microwaves at full power of typically 800 W. In order to minimize cleaning, we used two glass containers, the smaller one turned upside down on top of the egg (figure 4(*a*)). This worked well in about 90% of all cases, where the result is a very unspectacular cracking of the shell (figure 4(*b*)), usually happening within the first minute. Of the other ten eggs, eight exploded with a force that was strong enough to accelerate the upper container and crack it as it hit the interior top wall of the oven. The explosion of the 99th egg was even stronger and destroyed both glasses. Our record explosion is documented in figure 4(*c*). The container that hit the top dented the metal wall. The build-up of pressure in the egg was so high that both glasses were destroyed, the door burst open and the whole oven jumped a distance of several centimetres. The good news is that, in opening the door, the microwave turned itself off. The experiment is not really dangerous, but some cleaning-up may be needed afterwards!

One may guess the strength of the explosion by measuring the time. Good to very good explosions usually occur if the egg survives the first two to three minutes. This fact may be used to increase the tension in the audience.

Soap in the microwave: good smell and nice shapes

Soap (figure 5(*a*)) contains a lot of water, which will vaporize during heating. Many tiny pores with gas bubbles are formed within the soap, which will expand slowly, but continually. Depending on the quality of the soap, the skin may burst at many spots at the same time and just increase in volume, keeping its approximate shape (figure 5(*b*)), or



(*a*) (*b*) (*c*)

Figure 4. (*a*) Set-up for placing eggs in a microwave; (*b*) a typical result; (*c*) the scene after an explosion.

(*a*) (*b*) (*c*)

Figure 5. Soap: (*a*) before and (*b*) after heating in a microwave. Sometimes, very spectacular forms are generated (*c*), which may stimulate fantasies about the future (see text).

only at particular locations. In the latter case, very spectacular forms can be generated (figure 5(*c*)). They can even replace old customs like the so-called casting of lead, which is often done in Germany on New Year's Day. Usually, an alloy (not necessarily lead) that melts easily is heated on a spoon by the flame of a candle. After being melted it is quickly poured into cold water. Upon solidifying, very strange shapes result. According to old customs, one may interpret the forms to find out what will happen in the coming year. We suggest replacing the casting of lead by the microwaving of soap.

Careful: there will be an intense odour in the oven for a while. You should not do this experiment directly before heating food.

Miscellaneous

- Fill a balloon with 10 ml of water and knot it tightly. Heating it in the microwave will inflate the balloon (too much water will cause it to explode, which can also be a lot of fun).
- In 2003 American dentists performed the first tests on cleaning false teeth made of ceramics by using microwaves. They found that two minutes of microwave radiation killed germs that would normally survive the usual cleaning procedures for weeks.
- It is very dangerous to heat cold nail varnish-remover: the glass container may explode. In October 2003, a woman from Viernheim in Germany suffered severe injuries from glass splinters after trying this.

We hope to report on further experiments with microwave ovens in a future issue of *Physics Education*.

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References

[1] Vollmer M 2004 *Phys. Educ.* **39** 74–81
[2] Parker K and Vollmer M 2004 *Phys. Educ.* **39** 82–90
[3] Karstädt D, Möllmann K-P and Vollmer M 2004 *Physik in unserer Zeit* **35** (2) 90–6
[4] Karstädt D, Möllmann K P, Pinno F and Vollmer M 2001 *Phys. Teacher* **39** 371–6

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