Creation of Particles from Plastic Containers: Beating up water bottles

I presented work at the ACS Fall National Meeting showing that simple mechanical distortion of plastic containers creates plastic micro- and nanoparticles. Optical microcopy and Rayleigh scattering are used to show particle creation inside sealed bottles by mechanically stressing the bottles. I also show that there are ways to reduce the amount of microparticles present in the water.

Background:
I began looking for environmental plastics largely after detecting polymers while rock collecting. In order to understand polymers observed in the environment, I developed method to produce suspensions of polymer particles so that I could better observe their behavior. This was reported at the Spring National Meeting. I used a Rayleigh scattering to assess and track presence of particles, including nanoparticles in water. In trying to better quantify concentrations, I began an unsuccessful search for particle-free water.

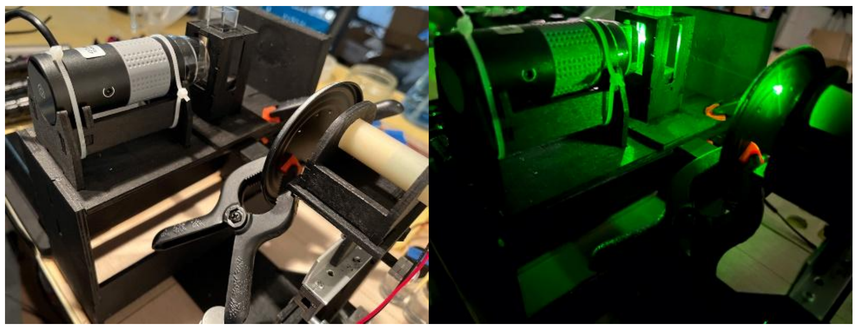
In purchasing purified water, both distilled and filtered, I noticed that water with the same lot numbers frequently had dramatically different levels of particles. All the water was packaged in plastic. There is already a body of literature showing that opening and closing screw-top bottles creates particles. I've observed this too. The literature and my experience also show that there are particles present coming from processing. These include particles generated from filters, valving and piping. When purchasing water in cases, the bottles on the outside and corners of the cases frequently had higher levels of particles.

I formed the hypothesis that mechanical stresses applied to sealed bottles was creating particles.

Methods and Observations:
Optical Microscopy: Data collected are videos of the water before and after mechanical insult under white light illumination and in the Rayleigh scattering apparatus. Still images, especially of the white light illumination, don't so clearly show the particles. Imperfections and dust on the bottles, which don't move, serve to hide the particles. Data consist of videos of samples, most commonly in 27 mm diameter vials, swirled and placed in front of a camera. Care is taken not to shake. Shaking can introduce air bubbles which interfere with the observation of particles. Illumination is from upper left to limit the reflected light. Cameras employed Sony low-light sensors at 2.1 and 4 megapixel resolution. These used the IMX 323 and IMX586 CMOS sensor. Both allowed the exposure to be set in software. Auto-ranging was not used. Lenses allowed exposure adjustments, in addition to focus and zoom.

One of the cameras used to observe particles in water.

Rayleigh Scattering: A home-built Rayleigh scattering rid was constructed. It consists of a digital microscope and perpendicular laser. The digital microscope selected allowed exposure to be set. Many auto-range and are unsuitable for measuring scattering. A 1 cm fluorescence cuvette was placed at the intersection. Cuvettes used were glass most commonly. Polystyrene cuvettes were also tested and found to yield identical results. Between the laser and the cuvette, a 1 mm drilled hole in thin sheet metal was used to provide a consistent viewing volume. A spatial filter would be preferred, but is too costly for self-funded experiments. The apparatus allows adjusting the location of the laser with a translation stage. Multiple interchangeable lasers can be used. Green gives the best performance, easily seen at low light and energetic enough to illuminate the smaller particles. The apparatus was modeled after one described in Ye, Yan, and David YH Pui. "Detection of nanoparticles suspended in a light scattering medium." Scientific reports 11, no. 1 (2021): 20268.



Rayleigh scattering rig under ambient light and in use with a green laser. The microscope and laser are at right angles. The cuvetter holder is positioned at the intersection. Microscope is a 2 MP Plugable USB microscope.

Rayleigh scattering is a useful method to study particle production from polymer surfaces. While scattering is incapable of determining composition, it is readily able to detect changes in particle concentration as conditions are varied. Results from a variety of commercial containers demonstrate that particle production occurs in use from a variety of polymers and in a variety of use patterns.

There are shortcomings. The major problem is laser stability. I can't count on an image taken today being equivalent to one tomorrow or even 30 minutes from now. The absolute observed "counts" can vary. To compensate, a sample is illuminated and the exposure adjusted to limit saturation.

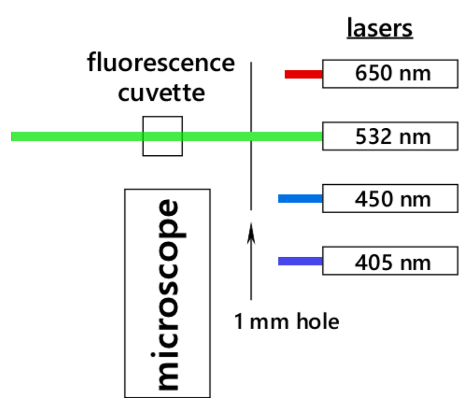


Diagram of the Rayleigh scattering apparatus showing the wavelength lasers available

Devices used to mechanically stress water bottles. From left to right, a commercial dryer operated on air-only (no heat) mode, an air-driven impact hammer, an impact massager and a group of students (the image is AI generated and does not show the student group at MSU Sustainability Day 2025)

Video is taken of sample and blank one after the other for comparison before the laser has changed significantly. Thus, scattering data are videos of sample and blank.

<u>New bottles:</u> Initial testing involved using drinking water purchased in 250 or 300 ml PET bottles. The bottles were thoroughly mixed, opened and a retainer sample taken. Water was then poured out leaving 150 ml in the bottle. This was accomplished by taring the balance with an empty bottle and removing water until 150 g (±2 g) remained. The now half-filled bottles were resealed and tape applied to cap to prevent loosening during testing. Testing involved dropping the bottles approximately 2 feet 1500, 3000 or 4500 times. The experiments were done using a 66 cm diameter cylindrical, baffled tumbler operating at 50 revolutions per minute. One of the reasons the bottles were tested half-full was to allow more distortion upon landing and to limit equipment damage. Less than half-filled bottles don't have sufficient mass to overcome the centripetal force and simply ride the baffles without ever falling.

The device used was an LG dryer operated in the air-only mode, no heat.

Subsequently, other means of impacting the bottle were also used. In all cases, retainers were kept and water poured out until only 150 g (±2 g) remained. The first was use of a commercial air hammer. Next, a commercially purchased impact massager was used. Lastly, multiple groups of students were handed a half-filled bottle and told to abuse is by any means at their disposal. These included, throwing it, repeatedly crushing it by hand, and rolling it under foot. In all cases, particles visible to the naked eye were created and Rayleigh scattering demonstrated a substantial increase in particles present.

Data collected are videos of the water before and after mechanical insult under white light illumination and in the Rayleigh scattering apparatus. Still images, especially of the white light illumination, don't so clearly show the particles. Imperfections and dust on the bottles, which don't move, serve to hide the particles. Data consist of videos of samples, most commonly in 27 mm diameter vials, swirled and placed in front of a camera. Care is taken not to shake. Shaking can introduce air bubbles which interfere with the observation of particles. Illumination is from upper left to limit the reflected light. Cameras employed Sony low-light sensors at 2.1 and 4 megapixel resolution. These used the IMX 323 and IMX586 CMOS sensor. Both allowed the exposure to be set in software. Auto-ranging was not used. Lenses allowed exposure adjustments, in addition to focus and zoom.

<u>Used bottles:</u> Particles were observed in many other commercial samples, such as contact solution and nasal saline. Both are in flexible bottles where flexing is an aspect of use. I also wanted to test reuseable bottles, cartons and more. The microscopy and Rayleigh scattering methods do not differentiate between inorganic, organic, biological or plastic particles. In order to test for particle generation by mechanical stressing, I had to use water of known purity. For this testing, bottles were thoroughly washed using Midland tap water. They were then triple rinsed using approximately 100 ml of purified water. After three rinses, 180 g (±2 g) water was added, swirled, and 30 g (±2 g) retained. Water, most commonly, was distilled water purchased in plastic bottles and confirmed to be low in particles. Attempts were made using commercial filtered water and home filtered water. All resulted in an increase in observable particles and increased particles were observed using Rayleigh scattering.

Additive experiments: MCT oil, another name for fractioned coconut oil and a lipophilic solid were introduced to new, 250 mL PET bottles freshly opened with all but 150 mL remaining. Water poured out was retained as a blank. To one bottle, 1 gram of MCT oil was added. The oil floated on the top of the meniscus. Then the bottle was vigorously shaken. The oil clung to the sides of the bottle and did not attempt to reform the oil layer on top of the water.

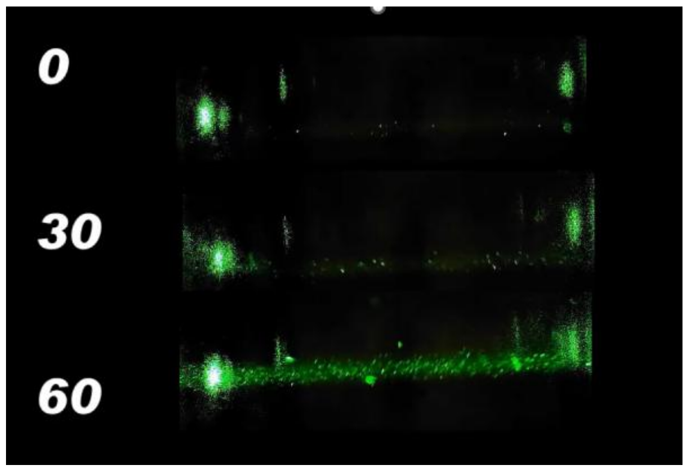
An identical bottle was similarly prepared except instead of oil, 1 gram of lipophilic gel was added.

A third bottle was prepared and nothing was added.

The three bottles were treated for 10 minutes each with the impact massager. They were allowed to sit for 30 minutes and then examined under visible light. The three samples were also examined with Rayleigh scattering.

Results:

The results show that all containers tested liberate particles into contained water when mechanically stressed by forces applied to the outside of the bottle. Further, the particles released can have major dimensions of over 1 mm. This was true with tumbling, use of the air hammer, use of an impact massager and through rough handling by hand. Materials tested included single-use PET water bottles, reuseable PET water bottle, HDPE jugs, PET beverage containers, polypropylene containers, PET contact lens solution bottle, HDPE nasal spray bottles, and cartons.



Capture from video showing the increasing particle levels with increasing time being tumbled at 50 Hz. The numbers are minutes tumbled. The cell width is 1 cm.

Results are videos comparing before and after water samples.

Videos used in presentation at ACS Fall National Meeting 2025 presentation PAPER ID: 4286177. These are in order of presentation during the talk.

Commercial water bottle showing visible particles made by opening and closing the screw-on lid: v01-PelligrinoWater.mp4

First experiments with tumbling 300 mL partially filled water bottles in a clothes dryer on air-only setting in November 2024 - v02-ShortTumbled.mp4

Illumination under UV light shows the characteristic stilbene fluorescence indicating the polymer particles are optically brightened PET, not the HDPE used in the lid - v03-UV_SixtyMinute.mp4

Images under white light of samples of water bottles mechanically stressed under a variety of ways. All are new water bottles, opened only to reduce amount in the bottle to 150 mL - v04-PET_Water_Bottles_01.mp4

Images under white light of water from a fresh water bottle showing the presence of some particles even in a fresh bottle - v05-Blank.mp4

Particles in a used water bottle after being mechanically stressed with an impact massager - v06-Pelligrino2.mp4

Images under white light of water from a used HDPE jug after 5 minutes of air hammer on the outside of the sealed container - v07-HDPE.mp4

Rayleigh scattering with a green laser of the same sample as above, used HDPE jug after 5 minutes of air hammer on the outside of the sealed container -v08-HDPE_scattering.mp4

Both white light illumination and Rayleigh scattering of a used PET iced tea container after 10 minutes mechanically stressing with an impact massager - v09-Tea.mp4 Note there is a likely release of some components of the tea leading to some cloudiness and a stronger than expected scattering.

White light illuminated water sample from a used carton treated with the air hammer for 10 minutes - v10-Carton.mp4

White light illuminated water sample from a reuseable PET container treated with the air hammer. Sample is illuminated in the container without opening. Sample is subsequently removed for Rayleigh scattering examination - v11-ReusablePETWithScatter.mp4

Multiple samples from used health-related containers under white light. Containers including IV bag, PET contact lens solution, HDPE nasal spray, and polypropylene electrolyte - v12-Health.mp4

Multiple samples from used health-related containers examined with Rayliegh scattering. Containers including PET contact lens solution, HDPE nasal spray, and polypropylene electrolyte - v13-HealthScatter.mp4

Capture of manufactured yellow fluorescent PET on a lipophilic solid - v14-CapturedParticlesSpoon.mp4

Comparison of three 250 ml water bottles treated identically with an impact massager. One has nothing added, one has 1 gram of MCT oil and one has a 1 g piece of lipophilic gel introduced as a thin, dime-sized piece - v15-Getter.mp4

Additional Videos:
Different fill levels in 250 mL partially filled water bottles in a clothes dryer on air-only setting in September 2025 - Dryer250903_white_light.mp4

Rayliegh scattering of particles produced by both abrasion and mechanical stressing. Stressing of 1-gallon HDPE bottle of distilled water begins at 1 minute - HunterSamples.mp4

Discussion:
The size of the particles produced inside a container when only the outside is contacted is surprising and remains to be fully explained.

The number of particles produced remains a bit of a mystery. The amount of particles observed both visually and with Rayleigh scattering increase with increasing number of blows to the outside of the containers. What remains uncertain is how the amount of water in the container impacts the particle counts. The current operating hypothesis, proving elusive to prove, is that the volume of water inside the bottles appears to inversely correlate with the particle concentration. That would be consistent with each mechanical deflection having a probability of producing particles. Those particles are completely transferred into the water. That would mean that doubling the amount of water halves the apparent concentration.

$$C\left[\frac{\text{particles}}{V}\right] = C_0 + \frac{\alpha I}{V}$$

Attempts to develop an equation describing the production of particles has proven elusive. The current operating hypothesis being tested is that each impact has a fixed probability of producing a particle. The observed concentration depends on the number of impacts, the initial concentration and the amount of water present.

Counting particles is difficult to do reproducibly creating measurement uncertainty. Additionally, the force of the impacts with all methods depends on the weight of the container. Work will continue and an additional technique, dynamic light scattering will be used in hopes of better quantitation.