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Cite this article: Virot E, Ponomarenko A. 2015 Popcorn: critical temperature, jump and sound. *J. R. Soc. Interface* **12**: 20141247. http://dx.doi.org/10.1098/rsif.2014.1247

Received: 10 November 2014
Accepted: 16 January 2015

Subject Areas:
biomechanics

Keywords:
fracture, thermodynamics, biomechanics

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Electronic supplementary material is available at http://dx.doi.org/10.1098/rsif.2014.1247 or via http://rsif.royalsocietypublishing.org.

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Popcorn: critical temperature, jump and sound

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Popcorn bursts open, jumps and emits a ‘pop’ sound in some hundredths of a second. The physical origin of these three observations remains unclear in the literature. We show that the critical temperature 180°C at which almost all of popcorn pops is consistent with an elementary pressure vessel scenario. We observe that popcorn jumps with a ‘leg’ of starch which is compressed on the ground. As a result, popcorn is midway between two categories of moving systems: explosive plants using fracture mechanisms and jumping animals using muscles. By synchronizing video recordings with acoustic recordings, we propose that the familiar ‘pop’ sound of the popcorn is caused by the release of water vapour.

1. Introduction

Popcorn is the funniest corn to cook, because it jumps and makes a ‘pop’ sound in our pans. Some other types of corn also produce flakes, such as flint corn or dent corn, but in a far less impressive extent [1]. In this article, we will focus on one type of corn (popcorn) for discussing the physical properties of popping. Early studies have focused on conditions required for successful popping of popcorn [1–3], conditions that are closely related to the fracture of the pericarp (outer hull) [4]. In this way, popcorn has been bred over the years for improving popping expansion [5]. When the popcorn temperature exceeds 100°C, its water content (moisture) boils and reaches a thermodynamic equilibrium at the vapour pressure, as in a pressure cooker [6]. Above a critical vapour pressure, the hull breaks. At the same time in the popcorn endosperm, the starch granules expand adiabatically and form a spongy flake of various shapes [7–10], as shown in the insets of figure 1. Then, the popcorn jumps a few millimetres high to several centimetres high and a characteristic ‘pop’ sound is emitted. To the best of our knowledge, the physical origin of these observations remains elusive in the literature. Here we discuss the possible physical origins with elementary tools of thermodynamics and fracture mechanics.

Recently, many biological material fractures have been highlighted: these fractures allow plants and fungi to disperse their seeds and spores, respectively [11–15], or corals to colonize new territories by their own fragmentation [16,17]. Mammals do usually not need fracture for moving: they can use instead their legs as springs and form a single projectile with their whole body [18]. *Equisetum* spores have a similar mechanism for catapulting themselves with their elaters [19].

2. Warm-up: the critical temperature

To first understand the origin of the temperature at which popcorn pops, micro-waveable pieces of popcorn from a single lot (Carrefour, ‘Popcorn’) are placed in an oven at temperatures increasing by increments of 10°C and lasting 5 min. We observe in figure 1 that only 34% of popcorn are popped at 170°C (17 out of 50). Instead, 96% of popcorn are popped at 180°C (48 out of 50), suggesting a well-defined critical temperature close to 180°C. This is consistent with previous measurements [6,20,21], i.e. in the range 177–187°C.

We consider that the temperature is critical when the orthoradial stress induced in the hull exceeds the hull ultimate strength. At the rupture point, the hull has an ultimate strength $\sigma_c \sim 10$ MPa [9,10,22,23]. Using a micrometer screw gauge, the

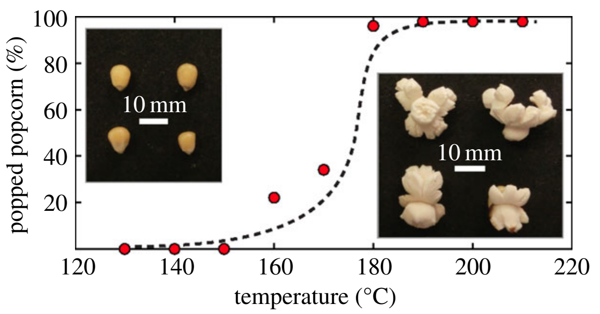

Figure 1. Percentages of popped popcorn in an oven at increasing temperature (50 tests); the dashed line is a guide to the eyes. The critical temperature T_c is approximately 180°C. (Insets) Snapshots of unpopped popcorn (kernels, left) and popped popcorn (flakes, right). (Online version in colour.)

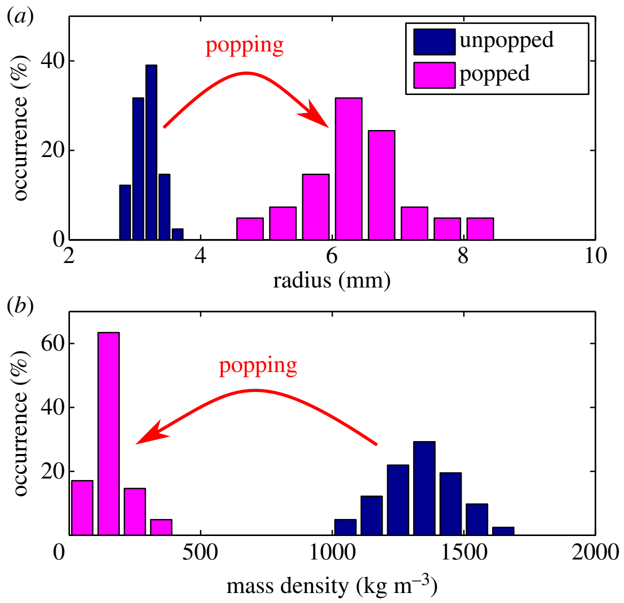

Figure 2. Change in the properties of popcorn. (*a*) Distribution of popcorn radius before and after popping. (*b*) Distribution of mass density; popcorn becomes two times larger and eight times less dense. (Online version in colour.)

mean radius of the popcorn before and after popping is measured (an average of three directions) as well as the hull thickness (figure 2 and table 1). The critical pressure in the popcorn satisfies $p_c = 2t/R_k \times \sigma_c \simeq 1/10 \times \sigma_c$, where t is the mean hull thickness and R_k is the mean kernel radius [24], leading to $p_c \sim 10$ bar. Pieces of popcorn contain around 20 mg of water [1]. In the conditions of pressure and temperature just before explosion, only a small part (less than 1 mg) is in the vapour phase, which means that there is also a liquid phase in the popcorn before explosion. Then, considering the water vapour as an ideal gas in this range of pressure, the corresponding temperature T_c is given by the Clausius–Clapeyron relation [25]

$$T_c = \frac{T_0}{1 - (\mathcal{R}T_0/ML_v)\ln(p_c/p_0)}, \tag{2.1}$$

with ($p_0 \simeq 1 bar$, $T_0 = 100$°C) the standard boiling conditions of pure water, $\mathcal{R} \simeq 8.3$ J mol^{-1} K^{-1} being the ideal gas constant, $L_v \simeq 2.3 \times 10^6$ J kg^{-1} is the heat of vaporization of pure water and $M \simeq 18$ g mol^{-1} is the molar mass of pure water. Equation (2.1) gives a consistent order of magnitude $T_c \sim 180$°C, which

Table 1. Popcorn properties before popping (kernel) and after popping (flake). Mean values ±s.d. on 41 measurements.

parameter	kernel	flake
hull thickness t (μm)	160 ± 40	—
radius R (mm)	3.1 ± 0.2	6.5 ± 0.8
mass density (kg m^{-3})	1300 ± 130	160 ± 60
mass m (mg)	172 ± 30	165 ± 26

logarithmically depends on the popcorn properties: a 100% underestimation of p_c (i.e. of σ_c or t/R_k) only results in a 15% underestimation of T_c (°C). This explains why the pieces of popcorn pop at the same temperature, as evidenced in figure 1. Note that the critical temperature $T_c \simeq 180$°C is high compared with the ambient one, say 20°C. This reminds us that it would be almost impossible to see popped popcorn without the human contribution.

3. Break dance: the popcorn jump

To explore further the dynamic of popcorn during its transformation, a piece of popcorn laid on a hot plate is recorded with a high-speed camera Phantom v9 at 2900 frames per second. The hot plate is set at 350°C whereas the room temperature is 20°C, so that the popcorn is partly heated at the required temperature $T_c = 180$°C. A flake is formed after approximately 1 min of rest on the hot plate. An example is reported in figure 3*a*. After the fracture of the popcorn hull and the beginning of starch expansion (see the snapshot at 6.9 ms), we observe the formation of a ‘leg’ which is compressed on the plate (at 13.8 ms). This leg bounces and the popcorn jumps (at 20.7 ms). We do not observe motion during the ejection of vapour (no rocket effect).

Let us study further the somersault of popcorn shown in figure 3*a*. The rotation angle observed is $\theta \simeq 490°$ (see also the electronic supplementary material, figure S1, for the statistical analysis of the rotation angle). This is slightly better than the somersault of a running gymnast [26], with an angle of about 300°, as shown in figure 3*c*. Presumably, the popcorn stores thermal and elastic energy during its warm-up, which is partially released into the kinetic energy of the leg. The energy assigned to the jump is actually reduced because of many dissipative processes, such as the popcorn fracture, the ‘pop’ sound emission or the inelastic rebound of the leg. Nevertheless, as shown in figure 3*a*, the jump energy of popcorn is split into horizontal, vertical and rotary kinetic energy, $E_0 = (1/2)m_k(v_{x0}^2 + v_{z0}^2) + (1/2)I\omega_0^2$, where the kernel mass is $m_k \simeq 170$ mg and where the moment of inertia is approximately the one of a ball $I = (2/5)m_k R_k^2$. As reported in figure 3, the initial horizontal velocity is $v_{x0} \simeq 0.12$ m s^{-1}, the initial vertical velocity is $v_{z0} \simeq 0.39$ m s^{-1} and the initial rotation rate is $\omega_0 \simeq 120$ rad s^{-1} (i.e. 19 Hz). The jump energy is then $E_0 \sim 20$ μJ. The initial acceleration of the popcorn is approximately 200 m s^{-2}. By comparison, a flea of approximately 1 mm in size jumps at a velocity of approximately 1 m s^{-1} with an acceleration of approximately 1000 m s^{-2} [27,28] and the explosive plant *Hura crepitans* launches its seeds of approximately 1 cm in size at a velocity of approximately 70 m s^{-1} with an acceleration of approximately 40 000 m s^{-2} [29].

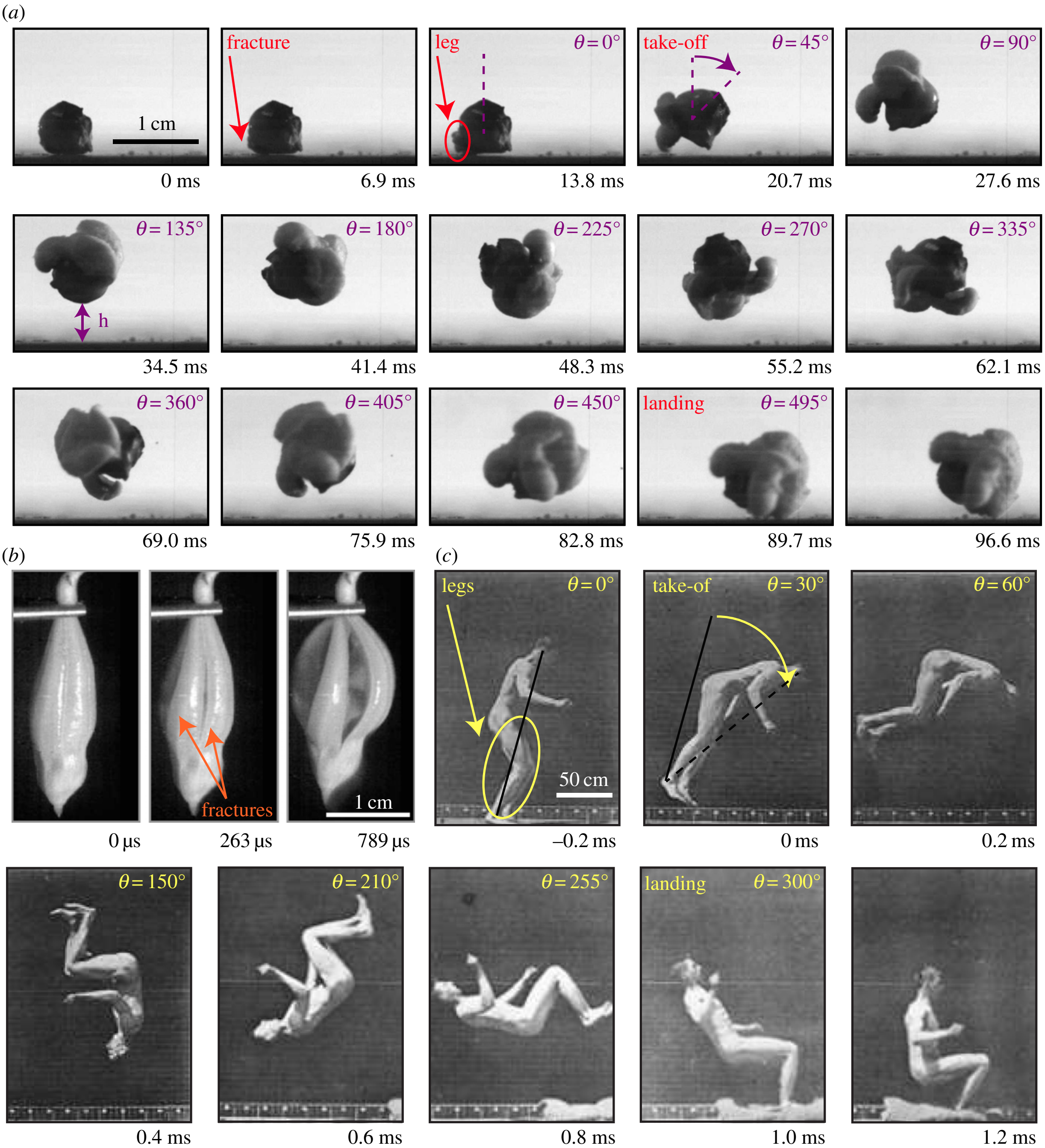

Figure 3. Fractures and jumps. (*a*) Snapshots of the somersault of a piece of popcorn while heated on a hot plate, 350°C (see electronic supplementary material, movie S1). We assume that the displacement in the *y*-direction is small compared to the displacements in the *x*–*z* plane because the kernel stays in the depth of field of the camera which is about 3 mm. (*b*) The fracture of *Impatiens glandulifera* seedpod, adapted from Deegan [13]. (*c*) The snapshots of the somersault of a gymnast, adapted from Muybridge [26]. (Online version in colour.)

In order to appreciate quantitatively the popcorn's performance, let α be the ratio of the initial vertical kinetic energy to the total kinetic energy E_0. In the range of Reynolds number reached by the popcorn ($20 < Re < 80$), the drag force is reasonably negligible compared to the gravitational force [18]. If the height were the objective (as for a high jump), with $\alpha = 1$ for maximizing the vertical flight time and $E_0 \sim 20\ \mu\text{J}$, the popcorn would jump with an initial vertical velocity $v_{z0} = \sqrt{2E_0/m_k} \sim 0.5\ \text{m s}^{-1}$, it would reach a height $h = E_0/(m_k g) \sim 1$ cm and the jump would last $T = 2v_{z0}/g \sim 100$ ms. These orders of magnitudes are consistent with our observations. If the angle of rotation were the objective (as for an optimal somersault), a remaining part of the leg energy $(1-\alpha)E_0$ is converted into rotary kinetic energy for increasing the rotation rate, i.e. $(1/2)I\dot{\theta}^2 = (1-\alpha)E_0$, where the moment of inertia would be at least $I = (2/5)m_k R_k^2$. A simple integration gives

$$\theta(\alpha) = 2\sqrt{10}\sqrt{\alpha(1-\alpha)}\frac{E_0}{m_k g R_k}. \qquad (3.1)$$

This expression has a maximum θ_m for $\alpha = 1/2$, i.e. when the available energy is shared equally among vertical and rotary kinetic energy

$$\theta_m = \sqrt{10}\frac{E_0}{m_k g R_k}. \qquad (3.2)$$

We have $E_0 \sim 20\ \mu\text{J}$ and $R_k \sim 3$ mm, leading to $\theta_m \sim 700°$, a value larger than the one observed. However, the somersault of figure 3*a* is not perfect because $\alpha \simeq 0.7$ and because

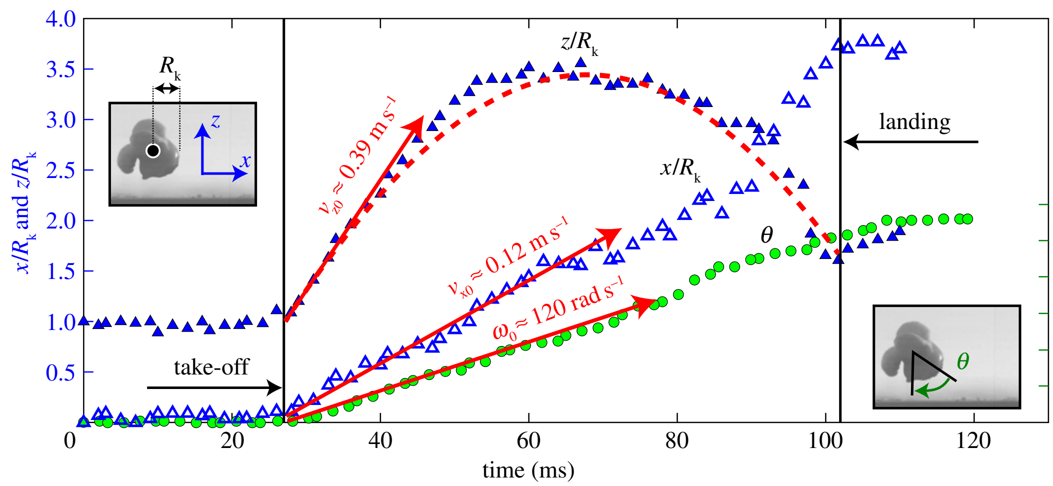

Figure 4. Dimensionless coordinates of the mass centre (x/R_k, z/R_k) and evolution of the angle of rotation θ for the jump of figure 3*a*. Initial velocities are indicated with arrows. The dragless Galilean parabola (dashed line) fits well the trajectory. (Online version in colour.)

5% of the energy is lost in horizontal motion (see electronic supplementary material, figure S2, for the statistical analysis of the parameter α). In this situation, we find theoretically $\theta_m \sim 500°$, perfectly consistent with our observations. We can check in figure 4 that the dragless Galilean parabola (with a deceleration 9.81 m s^{-2}) fits well the trajectory of the popcorn's centre of mass. In figure 5, we can appreciate that the measured angles of rotation are correctly predicted by equation (3.1).

By comparison, the gymnast's best high jumps involve the elevation of a mass $M \simeq 80$ kg on $H \simeq 2$ m, thus the available energy is approximately $E_0 \simeq 1600$ J. If this energy is now dedicated to a somersault, say for a 'spherical gymnast' of size $R \simeq 1$ m, then equation (3.2) gives consistently $\theta_m \simeq 360°$. Note that gymnasts take advantage of angular momentum conservation to increase their rotation rate [30], as shown in figure 3*b*, whereas popcorn does not because its size increases, as shown in figure 3*a*. However, it can be seen in figure 4 that the popcorn rotation rate is almost constant. This suggests that the popcorn is denser in its centre during the jump.

Since the maximum rotation angle $\theta_m \sim E_0/(\rho g R^4)$ is also a dimensionless number which compares the energy E_0 released by the legs to a characteristic gravitational energy of the body of mass density ρ and size R, we can use it as a rough indicator of performance. In the situation of a jump done with muscles, we have $E_0 = F_m \times l_m$, where $F_m \sim R^2$ stands for the muscle force (proportional to the number of muscle fibres in the body section) and $l_m \sim R$ being the muscle elongation proportional to the body size. Consequently, the performance θ_m of a jump executed with muscles should scale inversely with the body size. However, the popcorn is thousand times smaller than gymnast though they have rather the same performance θ_m. As already pointed out, the jump of popcorn relies on a highly dissipative mechanism instead of muscle elasticity.

4. Pop music: the popcorn sound

To the best of our knowledge, little attention has been paid so far to the origin of the characteristic 'pop' sound. In our scenario, this sound could be caused by (i) the crackling fracture, (ii) the rebound on the ground or (iii) the release of pressurized water vapour.

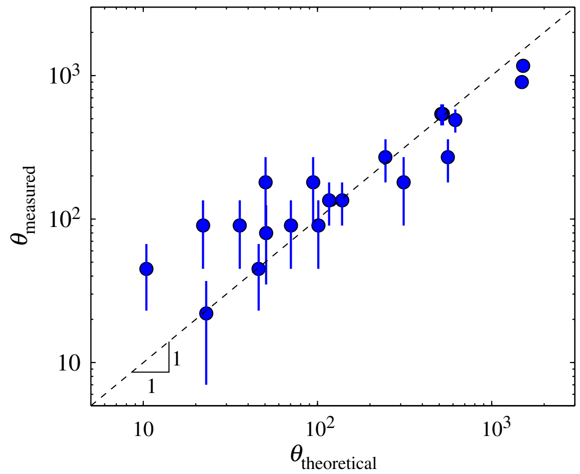

Figure 5. Rotation angles (in deg.) measured as a function of the predicted one, equation (3.1). The data collapse on a straight line of slope 1 in logarithmic scales. (Online version in colour.)

To understand the origin of the 'pop' sound, a microphone Neumann KM 84 (40–16 000 Hz) is added to our experimental set-up. The microphone is set 30 cm away from a piece of popcorn laid on a hot plate. The acoustic recording is synchronized with a high-speed camera Phantom Miro 4 (2000 frames per second) by the break of a pencil lead, for an error less than 1 ms.

As shown in figure 6*a*,*b*, the popcorn first opens part of the starch without emitting any sound. Then, after 100 ms, a second fracture starts (figure 6*c*), followed by the start of the 'pop' sound 6 ms later (figure 6*f*). Both fractures enlarged, while the leg of starch continues its course towards the hot plate. The 'pop' sound, starting at 106 ms, lasts approximately 50 ms, without a clear dominant frequency, but with sharp bursts at 110, 115 and 121 ms (figure 6*f*).

We first see that the 'pop' sound is not caused by the rebound because it occurs before any jump. Careful observations also discriminate crackling noises because the most part of fractures on the pieces of popcorn are not correlated to any sound (see also [31]). Then, it is reasonable to hypothesize that the 'pop' sound is triggered by the vapour release. More precisely, the pressure drop excites cavities inside the popcorn as if it were an acoustic resonator. Such a scenario has been applied to volcano acoustics and to the 'pop' of champagne bottle cork [32]. The bursts observed in figure 4*f* can then be interpreted as successive

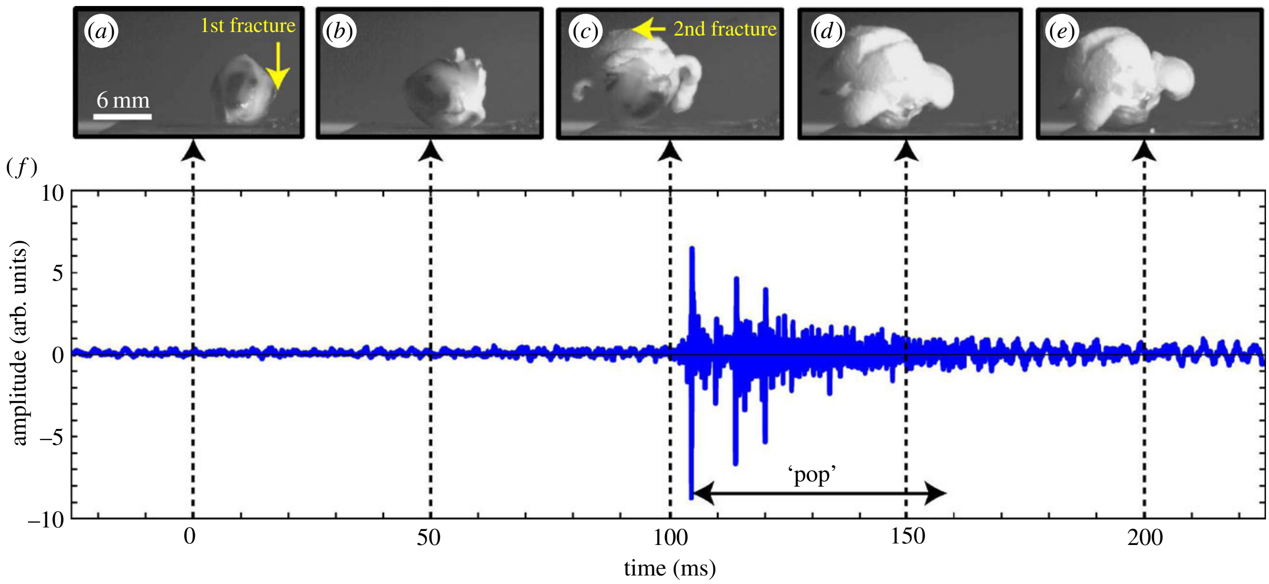

Figure 6. 'Pop' sound recording synchronized with high-speed imaging (see electronic supplementary material, movie S2). (*a*–*e*) The snapshots of the piece of popcorn are separated by 50 ms. (*f*) A 'pop' sound is observed during the fracture of the popcorn and before any jump. (Online version in colour.)

releases of pockets of pressurized water vapour triggering successive excitations. Also, since the room where experiments are performed has reflective surfaces a few metres from the popcorn, the successive bursts can irremediably be associated with recurring artefacts from echoes. The short time delay of 6 ms between the fracture and the 'pop' sound can be interpreted as the time needed to reach and release the first pocket of vapour. The absence of a dominant frequency in our acoustic recordings remains surprising but it mirrors the drastic modifications of the properties of popcorn during its transformation.

5. Conclusion

We reported a series of experiments evidencing the physical origin of the critical temperature, the jump and the 'pop' sound of popcorn. Concerning the critical temperature of popcorn, we have shown that an elementary pressure vessel scenario gives the good order of magnitude $T_c \simeq 180°C$, and explains why the critical temperature weakly depends on the resistance and geometry of the pericarp. Concerning the jump, we found that a leg of starch is responsible for the observed motion. We note that the popcorn dynamic is twofold: the popping relies on a fracture as for explosive plants, while the jump relies on a leg as for animals. Concerning the 'pop' sound, we synchronized acoustic and video recordings: the scenario of an excitation by the water vapour release is consistent with our observations.

Acknowledgements. Hearty thanks to Christophe Clanet for encouragements and enlightening suggestions. We wish to thank Stéphane Douady, Sébastien Moulinet and Mokhtar Adda-Bedia for helpful discussions. We warmly thank Gaspard Panfiloff for the microphone Neumann KM 84 and we are grateful to Loïc Tadrist and Karina Jouravleva for valuable comments on the manuscript.

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