1-1-2010

Mechanisms of x-ray emission from peeling adhesive tape

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Mechanisms of x-ray emission from peeling adhesive tape

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(Received 19 July 2010; accepted 7 September 2010; published online 29 September 2010)

It has previously been reported that x-rays are emitted when adhesive tape is peeled in a vacuum but no account of the dependence of the x-ray emission on the pressure of the environment has been given to date. In this paper we present detailed experimental data on the number and angular distribution of x-ray photons as a function of pressure. We find that x-rays are emitted for pressures between $p_0 = 10^{-3}$ and $p_1 = 10^{-2}$ mBar, with $\sim 10^6$ counts/(cm^2 s) recorded by a 256×256 pixel^2 silicon array sensor placed 35 mm from the tape. The main role of the tape is found to be the build-up of an acceleration potential sufficient to produce x-rays by bremsstrahlung of free electrons in a low-pressure gas. The source of the free electrons is the gas. Our model shows that the production rate of uncompensated tape charge and absorption of positive ions from the gas define p_1. The angular distribution of the radiation shows a pressure-independent 20° wide peak in the direction perpendicular to electron motion. Ordinary bremsstrahlung cannot describe this peak. [doi:10.1063/1.3493653]

Unpeeling adhesive tape has been shown to produce electromagnetic radiation at radio,[1] terahertz,[2] visible,[3,4] and x-ray[1,5] energies. X-ray emission by the tape is particularly intriguing, as the energy of x-ray photons is higher than the energy of the chemical bonds in the adhesive. The explanation was sought in terms of energy density focusing mechanisms.[1,6] Unlike the radio, terahertz and visible emission, x-ray radiation was reported to require a vacuum of $\sim 10^{-3}$ mBar,[1] but no information on the pressure dependence of the x-ray emission was given. We here present a detailed study of the pressure and angular dependence of x-ray radiation from peeling tape. A simple model for pressure dependence of the radiation points to its physical origins.

The experimental setup consisted of adhesive tape mounted on a feed spool and take-up spool driven by a variable speed electric motor. The tape speed was measured via the rotational speed of a roller of known diameter driven by the moving tape. An optical encoder was used to measure the roller speed. This was housed in a vacuum enclosure with sealed electrical feed-throughs and polypropylene window for measurement of the x-ray output. Three different x-ray sensors were used: a Geiger–Müller counter, an Ar filled proportional counter with Be window and a silicon sensor array consisting of 256×256 pixels^2 within an area of 14×14 mm^2 (Medipix-2). The vacuum in the enclosure was measured by combination pirani cold-cathode gauge (Pfeiffer).

Figure 1 shows the dependence of x-ray count on the pressure, measured by the Medipix sensor. The tape speed was 3 cm/s and the sensor was 35 mm from the source, taken to be the peeling vertex. Each point is the sum of all pixel counts over 1 s. There is a high-pressure threshold $p_1 = 10^{-2}$ mBar, below which x-ray radiation is emitted. The maximum is at $\sim 2.5 \times 10^6$ counts/s for pressure $p_{max} = 5 \times 10^{-3}$ mBar. Further decreasing the pressure results in a smaller count rate, which becomes negligible below $p_0 = 10^{-3}$ mBar.

Previous work shows that a significant charge separation occurs upon unwinding adhesive tape.[1,4,7] We confirm this, since the potential of the exposed core of a shielded cable changed by a few volts as it was moved by a few centimeters near the tape. Our measurements using a Geiger–Müller counter gave a substantial x-ray count only in the first second of unwinding. This was accompanied by a pressure increase of an order of magnitude in the first second. The pressure increase still occurred after removing air from the tape by repeated winding/unwinding under vacuum. We conclude the tape was releasing organic compounds, allowing substantial x-ray emission only when the pressure was still low within the first second of unwinding. After stopping the tape to restore the same vacuum as before, the original x-ray count was obtained.

Breaking of the adhesive bonds upon unwinding produces uncompensated charge on the tape. The most likely

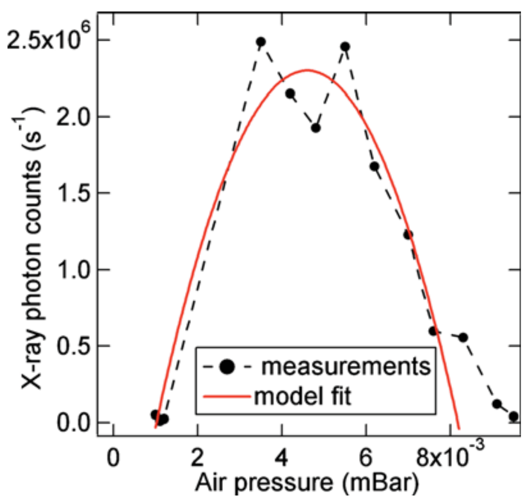

FIG. 1. (Color online) Pressure dependence of x-ray photon count rate measured over 1 s using a Medipix sensor at 35 mm from the source. The solid line is a quadratic fit using Eq. (2): $\Xi = -\mathrm{a}p^2 + \mathrm{b}p - \mathrm{c}$, with $\mathrm{a} = 1.800 \times 10^5$ mBar^{-2} s^{-1} $\mathrm{b} = 1.656 \times 10^6$ mBar^{-1} s^{-1}, and $\mathrm{c} = 1.509 \times 10^6$ s^{-1}.

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mechanism of x-ray emission is bremsstrahlung of electrons accelerated by the field due to this charge. Ions do not contribute to bremsstrahlung substantially because the bremsstrahlung power depends on the mass of charge carriers as m^{-6} for velocity parallel to acceleration.[8] The mean free path of electrons in ideal gas with a small proportion of ions and electrons is estimated as: $\lambda_e = 4kT/(\pi d^2 p)$, where k, T, d, and p are the Boltzmann constant, absolute temperature, diameter of gas atoms, and pressure, respectively.[9] Using $d \approx 3 \times 10^{-10}$ m of N_2 molecules, λ_e is 58 cm and 5.8 cm for pressures $p_0 = 10^{-3}$ and $p_1 = 10^{-2}$ mBar, respectively. Assuming that the x-ray emission occurs in approximately the same volume as the visible emission,[2] electrons travel ~ 1 mm between two oppositely charged parts of the tape. This is much less than λ_e for $p_0 < p < p_1$. For $\lambda_e = 1$ mm, one obtains $p = 58 \times 10^{-2}$ mBar. Therefore, electrons do not collide with gas atoms and can be accelerated by the full potential difference of the tape already for $p < 58 \times 10^{-2}$ mBar. This implies that acceleration potential is insufficient to produce x-rays at 58×10^{-2} mBar. Acceleration potential is decreased by absorption of free charge from the gas, which re-combines with the uncompensated charge on the tape. Concentration of free charge in the gas is proportional to its pressure. The effective tape charge becomes large enough to produce x-rays only for $p < p_1$. The source of the free charge traveling between the oppositely charged parts of the tape is the gas and not the tape itself. If the latter was the case, x-ray emission would not become zero below p_1 because the tape would emit free electrons even at $p = 0$. The observation that $p_0 > 0$ indicates that there is also a mechanism that excludes some free electrons from producing x-rays, as shown in the simple model below.

In our model, large charge accumulation occurs on the tape as it is unwound.[1] Because reported x-ray energies occur in the range of ~ 10 keV,[1] potential differences in excess of 10 kV have to be formed between the oppositely charged parts of the tape. Such large fields result in electron emission from the gas molecules.[10] These free electrons are accelerated toward the positive end of the tape, emitting x-rays by a bremsstrahlung process. The degree of ionization of the gas is small, so that λ_e does not change appreciably. Positive ions have a much smaller mobility than electrons. A proportion of them will in the same time reach the negative side of the tape recombining with some of the charge. Because of large mass of the ions, their bremsstrahlung emission is negligible. The only role of the gas in this model is to supply free electrons and ions by field emission. The only role of the tape is to produce an accelerating field for the free electrons. The number of uncompensated negative charges on the tape at a given time is $N_s - N_+$, where N_s and N_+ are the number of uncompensated surface charges produced by unwinding the tape and number of positive ions absorbed onto the tape, respectively. Maximum electron energy is proportional to $N_s - N_+$. Because the collisions between free electrons and the gas are negligible, a pressure independent portion of free electron energy is converted into x-ray photons. The number of emitted x-ray photons per unit time is then the following:

$$\Xi = \alpha(N_s - N_+)N_e, \tag{1}$$

where α and N_e are the pressure independent proportionality constant and number of free electrons which contribute to x-ray production, respectively. The same number of free electrons and ions is created in the gas, and this number is proportional to gas pressure. However only a small number of ions N_+ is absorbed on the tape surface and small number of free electrons N_0 does not contribute to detectable x-ray emission. We can write: $N_e = \tau N_+ - N_0$ and $N_+ = \mu p$, assuming N_0 is pressure-independent. τ and μ are pressure-independent proportionality factors. This gives the following:

$$\Xi = -\alpha[\tau\mu^2 p^2 - \mu(\tau N_S + N_0)p + N_S N_0]. \tag{2}$$

The threshold pressures are obtained from here as follows:

$$p_0 = \frac{N_0}{\tau\mu} \quad \text{and} \quad p_1 = \frac{N_S}{\mu}. \tag{3}$$

The solid line in Fig. 1 is fit to the experimental data using Eq. (2). The value of p_0 would be zero if $N_0 = 0$ or if N_0 was assumed proportional to p, contrary to the experiment (Fig. 1). Therefore, pressure threshold p_1 is defined by the competition between production rate of uncompensated charges on tape by unwinding (N_S) and absorption of positive ions from the gas. Pressure threshold p_0 is defined by the production rate of free electrons in gas (through μ and τ) and by exclusion of some free electrons from emitting detectable x-rays (through N_0). The exclusion mechanism could be the diffusion of free electrons away from the tape.

Similar pressure dependence of x-ray emission to ours was obtained by heating/cooling a pyroelectric $LiNbO_3$ crystal in low pressure gas.[11] The electric field produced by the temperature change of the pyroelectric crystal ionized the gas, resulting in bremsstrahlung radiation as the free electrons hit a Cu foil. That experiment also gave $p_0 > 0$. They proposed a model similar to ours, but without assuming a nonzero value of N_0. Their model gave $p_0 = 0$, contrary to the experiment.

One could assume that the x-ray count obtained by a given detector decreases for $p < p_{max}$ because N_+ decreases with decreasing p and the effective tape charge increases. This could result in increase of x-ray photon energies beyond the spectral sensitivity of the detector as pressure decreases. However, for $p < p_{max}$, $N_+ \ll N_S$. Any further reduction of already negligible N_+ will not change the accelerating potential substantially. This is supported by the experiments with pyroelectric crystal,[11] where no apparent shift to higher x-ray energies was observed as the pressure decreased below p_{max}.

It is reasonable to assume that the x-rays are emitted from the same volume around the unpeeling vertex of the tape as the visible light. From photography of visible emission,[2] this volume can be approximated by a cylinder ~ 1 mm in diameter with length equal to the width of the tape. In the case of isotropic emission, the same count rate would be obtained for any azimuthal angle for which there is no shading by the tape or window. This would give a homogenous count within the angle subtended by our 14×14 mm^2 Medipix sensor placed at 35 mm from the source. In the vertical direction this turns out to be the case, as the count-rate pattern is uniform across any vertical column of pixels (Fig. 2). However, x-ray radiation is substantially stronger within a narrow azimuthal angle (horizontal rows in Fig. 2).

Figure 3 shows the azimuthal angle distribution of the x-ray intensity for several different pressures. The definition of azimuthal angle θ is given in Fig. 4. The intensity sharply

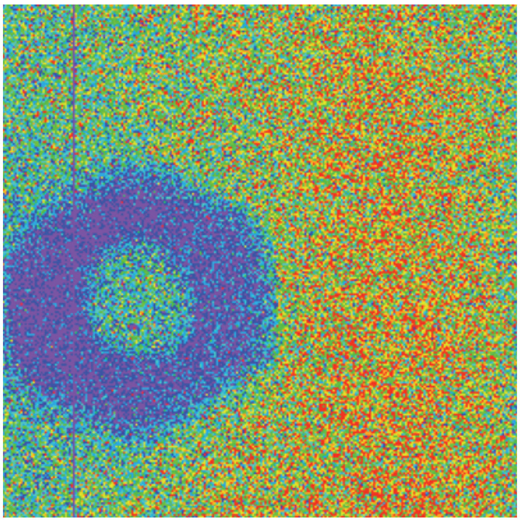

FIG. 2. (Color online) Image of x-ray emission from unwinding tape, obtained by Medipix sensor placed 35 mm from the unpeeling vertex of the tape. A hexagonal steel nut placed on top of the sensor is clearly distinguishable. The vertical line is a faulty sensor array.

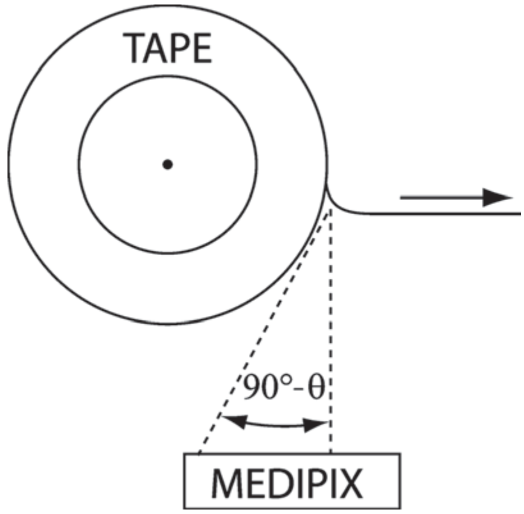

FIG. 4. Schematic showing the placement of Medipix sensor and defining the azimuthal angle θ. The diagram is not to scale, to help show θ more clearly.

increases by ~20% within 10° around the maximum, irrespective of the pressure. Shading by the tape spool or by the tape pulled away from the spool can be ruled out for such small angles, as for the visible emission.[2] This angular distribution may provide important clues about the bremsstrahlung mechanisms of radiation. The thick solid line is the angular distribution of x-ray emission expected from the ordinary bremsstrahlung process,[12] proportional to: $\sin^2\theta/(1-v/c\cos\theta)$,[5] where θ is the azimuthal angle. We assumed that non-relativistic charges move between the unpeeling end of the tape and the spool, giving a maximum in the direction perpendicular to their movement (θ=90°). Ordinary bremsstrahlung apparently cannot describe the observed angular distribution, even when the speed of charge carriers v approaches the speed of light c.

One possible mechanism of this x-ray emission may be the polarizational bremsstrahlung.[13] It occurs through the time-dependent change of polarization of atoms or molecules induced by charge carriers moving in their proximity. The angular dependence for combination of polarizational and ordinary bremsstrahlung was calculated for metal clusters and fullerenes to be[14] $[1-\eta P_2(\cos\theta)]$, where P_2 is the Legendre polynomial and η is a factor depending on the characteristics of the projectile charge carriers and target atoms. This angular dependence bears a general resemblance to the radiation obtained from the adhesive tape (Fig. 3): a peak in the intensity for θ=90° and a nonzero normalized intensity for θ=0° and 180°. This is rather different to the ordinary bremsstrahlung, where the intensities should vanish for θ=0° and 180°. However, the peak in Fig. 3 is still much narrower than the one obtained for polarizational bremsstrahlung of metal clusters (thick dashed line in Fig. 3). Our previous report shows that terahertz radiation is also emitted by unpeeling the tape.[2] Terahertz photons are of ~10^7 times lower energies than x-ray photons and the terahertz emission mechanism is most likely the breaking of chemical bonds of the adhesive.

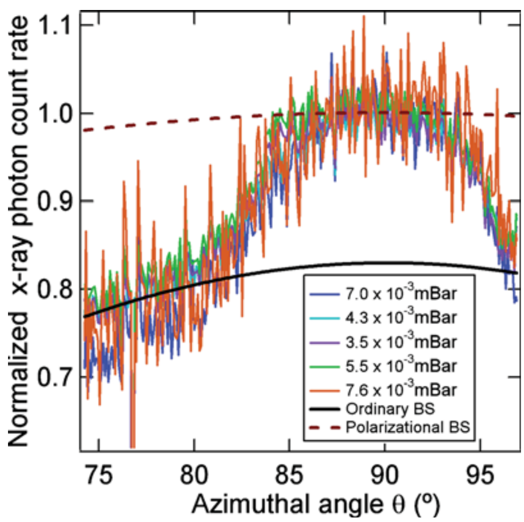

FIG. 3. (Color online) Angular dependence of x-ray emission from adhesive tape for different pressures, together with ordinary and polarizational bremsstrahlung fits. Measurements were performed using Medipix sensor.

We gratefully acknowledge help of Terry Braddock, Michael Lerch, and Michael Weaver in measurements of x-rays. This work was supported by Australian Research Council.

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