

Triboluminescence and X-Rays

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ABSTRACT: Triboluminescence is shown to produce X-rays from the nanoparticles (NPs) that form as the sticky acrylic adhesive of Scotch tape is peeled from the polyethylene (PE) roll in a vacuum. Prior to peeling, atoms in the adhesive are not under electromagnetic (EM) confinement and have full thermal kT energy. But upon peeling, the atoms in NPs that form in the gap between adhesive and PE are under EM confinement at vacuum ultraviolet (VUV) frequencies that by quantum mechanics (QM) are restricted to vanishing kT energy. Momentarily, the NP atoms therefore have kT energy in excess of that allowed by QM. But the specific heat of NPs at VUV frequencies also vanishes, and therefore the excess kT energy cannot be conserved by an increase in temperature. Since the NPs have EM confinement frequencies at VUV levels, and since the lowest frequency allowed in the NP is at its EM frequency, the low frequency kT energy is frequency up-converted to VUV levels by quantum electrodynamics (QED). Conservation then proceeds by a burst of VUV radiation that by the photoelectric effect charges the adhesive positive while the liberated electrons charge the PE negative. Charge accumulates during peeling by the VUV radiation from a continual supply of NPs until the breakdown of voltage is reached across the gap between the adhesive and the PE. Electrons from the PE then are accelerated to velocities of about 10^8 m/s in gaps up to 1000 microns. Upon collision with the adhesive, electron bremsstrahlung produces x-rays from 15 to 100 keV.

KEYWORDS: Triboluminescence, tape, x-rays

I. TRIBOLOLUMINESCENCE

Wikipedia explains the light emission in triboluminescence: "electrical fields are created; separating positive and negative charges that then create sparks while trying to reunite." The light emission is thought [1] to occur as crystalline materials are scratched, crushed or rubbed. The name triboluminescence comes from the Greek *tribein* ("to rub") and the Latin *lumen* ("light"). Observations of light emission have a long history. In 1620, Francis Bacon in *Novum Organum* stated:

"It is almost certain that all sugar, whether refined or raw, provided only it be somewhat hard, sparkles when broken or scraped with a knife in the dark."

Light may be observed if you chew fresh, dry Wint-O-Green candies in a dark room -- or snap them in two using a pair of pliers -- you see a spark of visible (VIS) light having a green/blue color. But how this occurs is debated to this day.

It is commonly thought [1] the VIS light from crushing "Life Savers" is caused by the collision of electrons with nitrogen molecules in the air because excited nitrogen is known to emit green/blue VIS light. But this is unlikely because electrons cannot be removed from atoms by crushing. Einstein showed with the photoelectric effect that EM and not mechanical energy is required to free an electron from an atom. The electron is bound to the atom far tighter than the atoms are bound to each other, and therefore crushing cannot excite the electrons to produce the VIS light upon collision with nitrogen.

Instead, crushing is likely to only form particles of neutral clusters of atoms. Given that VIS light is observed on crushing, it can only be concluded that the particles that form somehow produce EM radiations at the VUV levels necessary to excite nitrogen.

Another explanation for the VIS light in crushing "Life Savers" is fluorescent methyl salicylate that gives you the flavor of wintergreen oil. Fluorescence means VUV light is absorbed and then is emitted as light of a longer wavelength which for methyl salicylate is similar to the VIS light from nitrogen. Of importance is not the emission of VIS light from any specific chemical species, but rather that VUV radiation is somehow produced in particles.

VUV radiation from particles is similar to that produced by QED induced EM radiation [3]. But not all particles produce EM radiation at the VUV levels necessary to excite chemical species. Only NPs do so. Micron particles (MPs) are induced by QED to emit in the infrared (IR), but chemical species are generally not excited with IR radiation.

II. X-RAYS IN TRIBOLOGY

In 1930, x-rays from triboluminescence were first reported [4] by Obreimoff. Splitting of mica by a wedge in an evacuated glass vessel under 1 – 0.1 mm mercury vacuum produced x-rays similar to a Geissler tube. Only VIS light was observed by splitting mica at atmospheric pressure.

Triboluminescence in mica and adhesive tape [5] were observed in 1939 by Harvey:

“It is not possible to prove that mica sheets or tire tape, surgeons’ tape or Scotch tape are oppositely charged as a whole when pulled apart, but there are no doubts local positive and negative regions developed, the discharge between them giving rise to luminescence”.

Triboluminescence without x-rays in the peeling of tape was studied by many researchers. Seminal work by Dickenson, et al. included bursts of light having nanosecond duration [6] in 1988 and measurement of current flow [7] from tape peeled from metal surfaces in 1995. Also Miura et al. in 1997 correlated [8] the electrical discharge with the fracture of adhesive filaments in tape. In these seminal works any x-rays that accompanied the observed triboluminescence from peeling tape were not reported.

In this regard, it is worthwhile to note that x-rays were discovered [9] by Röntgen in 1895 while experimenting with the cathode ray tube (CRT). CRTs are devices which the positive anode attracts electrons from the negative cathode in a vacuum. The electrons upon collision with the anode emit x-rays by bremsstrahlung.

Recently, x-rays were reported [10] by Camara, et al., at UCLA by peeling 3M brand Scotch tape at steady 3 cm/s in a vacuum. The tape did not emit x-rays continuously, but in short nanosecond bursts – accumulating enough energy to produce an x-ray image of a finger in a second. Most brands of clear adhesive tape also give off x-rays, albeit with a different spectrum of energies, although why duct tape does not emit X-rays is not explained.

But how are x-rays produced in splitting mica or peeling tape?

Both split mica and peeled tape are similar to the CRT in that a gap forms between the surfaces, so if one surface is charged positive and the other negative, electrons may be accelerated to high velocities. Provided the accumulated charge produces a high voltage across the gap, both split mica and peeled tape act as a CRT in producing x-rays. The problem is Röntgen charged the CRT with external voltage while the mica and tape must somehow be charged in the process by which they are formed.

Long-standing tribology holds that charging in peeling tape [10] occurs by the abrupt separation of the sticky adhesive from the PE, the adhesive charged positive with the PE negative charged. However, this is unlikely. For if it was, steady x-rays would be emitted and not the in nanosecond bursts as observed.

Instead, the charging accumulates non-uniformly on the adhesive from VUV induced from NPs that form as adhesive fractures. In fact, x-ray emission correlates (Fig.2b of [10]) with the collapse of the stick-slip peeling force. Many local discharges therefore occur that are not uniform over the separation as a whole. In this regard, Harvey’s statement is still applicable.

“It is not possible to prove that mica sheets ...or Scotch tape are oppositely charged as a whole when pulled apart.”

Tribocharging by accumulated charge is suggested because of the nanosecond x-ray bursts observed in peeling Scotch tape.

Recently, McCarty et al. proposed [11] a theory of contact electrification based on ion transfer making the undeniable argument that to transfer an electron from nylon in contact with PE requires energies of 5-10 eV while the available kT energy of atoms at ambient temperature is only 0.0258 eV. However, other electron transfer mechanisms were not considered.

In this paper, tribological charging is based on the electron transfer by QED induced EM radiation [3] applicable to a wide range of tribology including peeling Scotch tape, splitting mica, and crushing “Life Savers.” By this theory, the 5-10 eV necessary to remove electrons from nylon cited by McCarty et al. only requires the formation of NPs upon rubbing against PE. Any ion transfer is likely insignificant.

Applications of QED induced EM radiation in tribology are limitless, and to cite a few:

Over 2000 years ago, the Greeks discovered static electricity upon rubbing an amber rod with a cloth. QED induced EM radiation [12] explains the charging by the amber NPs that form upon rubbing. Numerous observations [3] of photons and electrons find origin in the formation of NPs. Indeed, the microplasma in tribochemistry [13] having electron emission [14] from a few eV to 1 keV is explained by photochemistry driven by QED induced EM radiation from NPs that form during the rubbing and scratching of surfaces.

III. THEORY

X-rays by QED induced EM radiation rely on VUV emission from NPs to charge the adhesive positive while the liberated electrons move to the electronegative PE. Upon breakdown the PE electrons are accelerated to velocities of about 10^8 m/s that upon collision with the adhesive are decelerated to generate 15 to 100 keV x-rays by bremsstrahlung as illustrated in Fig. 1.

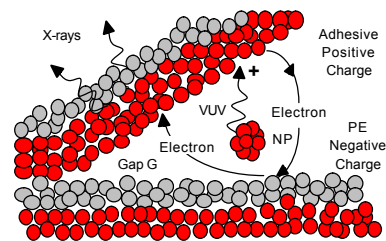


Fig. 1 X-rays from Scotch Tape Conserving Excess kT Energy by X-ray Emission

A. QM Restrictions

QM restricts the kT energy of atoms depending on the EM confinement wavelength λ of the NPs. At 300 K, the Einstein-Hopf relation [15] for the harmonic oscillator gives the kT energy as shown in Fig. 2.

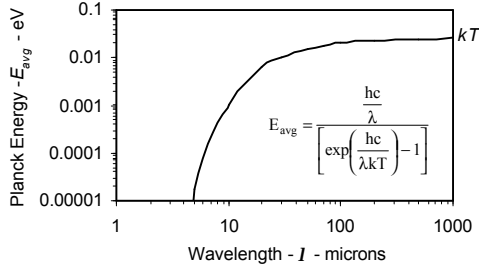


Fig. 2 Harmonic Oscillator at 300 K

In the inset, h is Planck's constant, and c the speed of light.

Prior to peeling, the atoms in the adhesive are not under EM confinement and have full kT energy; whereas, the NP atoms under EM confinement have small kT energy. Fig. 2 shows full kT energy ~ 0.0258 eV for $\lambda > 100$ microns in the FIR and $kT \sim 1 \times 10^{-5}$ eV at EM confinement of $\lambda \sim 5$ microns. Hence, NPs under EM confinement at VUV wavelengths $\lambda < 0.050$ microns have vanishing small $kT \ll 1 \times 10^{-5}$ eV.

B. EM Confinement Frequencies

For NPs having $D \ll \lambda$, the EM confinement is analogous [13] to the QM analogy of creating photons of wavelength λ by supplying EM energy to a QM box with walls separated by $\lambda/2$. For NPs of diameter D and refractive index n_r , the EM confinement frequency f and Planck energy E_p ,

$$f = \frac{c}{\lambda}, \quad \lambda = 2n_r D, \quad \text{and} \quad E_p = \frac{hc}{\lambda} = \frac{hc}{2n_r D} \quad (1)$$

C. Vanishing Specific Heat

Classical heat transfer conserves absorbed EM energy by an increase in temperature, but is not applicable to NPs because of the QM restrictions on thermal kT energy. Equivalently, the specific heat of NPs vanishes. But the Einstein specific heat for the NP atoms as harmonic oscillators is modified for thermal photons under EM confinement.

Einstein assumed the atoms in solids are harmonic oscillators vibrating independent of each other. But the thermal photons as oscillators vibrate not only coherently at the EM confinement frequency having the shape of a spherical box of photons, but at optical instead of atomic frequencies. Taking one thermal photon for each degree of freedom, the energy U of a NP with N atoms,

$$U = 3N \frac{\frac{hc}{\lambda}}{\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1 \right]} \quad (2)$$

For the specific heat C given by $\partial U / \partial T$, the dimensionless specific heat C^* is,

$$C^* = \frac{C}{3Nk} = \frac{\left(\frac{hc}{\lambda kT}\right)^2 \exp\left[\frac{hc}{\lambda kT}\right]}{\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1 \right]^2} \quad (3)$$

At 300 K, C^* vanishes for $\lambda = 2n_r D < 5$ microns. For $n_r = 1.2$, the absorbed EM energy is therefore conserved for $D > 2$ microns by a temperature increase while EM emission occurs for $D < 2$ microns.

IV. ANALYSIS

A. NP Charge

In peeling Scotch tape, the atoms in NPs that form from the adhesive have the same kT energy as that prior to fragmentation. The energy U of a NP is,

$$U = \frac{\pi}{6} \left(\frac{D}{\Delta}\right)^3 3kT = \frac{\pi}{2} \left(\frac{D}{\Delta}\right)^3 kT \quad (4)$$

where, Δ is the cubic spacing between NP atoms at solid density, $\Delta \sim 0.3$ nm. Lacking specific heat, the NP conserves the energy U in a burst of VUV radiation that by Einstein's photoelectric effect electrifies the surroundings. The charge q is,

$$q = N_p Y_e = \frac{U}{E_p} Y_e = \pi kT \left(\frac{D}{\Delta}\right)^3 \frac{n_r D}{hc} Y_e \quad (5)$$

where, N_p is the number of QED photons induced in the NPs at Planck energy E_p . Charging is optimum for $D \sim 100$ nm [13]. For the adhesive having $n_r = 1.2$, $\lambda = 240$ nm and $E_p > 5$ eV where most materials [16] have yields $Y \sim 0.1$ electrons/VUV photon. Here, each NP is taken to produce charge $q \sim 4.8$ fC / NP.

B. NPs and Electrical Voltage and Field

For NPs that form in the gap G between the adhesive and PE, the voltage V and field F ,

$$V = \frac{q N_{np}}{4\pi\epsilon_0 G} \quad \text{and} \quad F = \frac{V}{G} \quad (6)$$

where, N_{np} is the number of NPs that form and G is the gap.

Electrical breakdown for the adhesive depends on the surface asperities and is not known. The typical breakdown field F in a vacuum [17] is about 2.5×10^7 V/m that is bracketed here by $F = 10^8$ V/m. Fig. 3 shows breakdown voltage V and the number N_{np} of 100 nm NPs necessary for a given gap G . For $G = 150$ and 300 microns, $V = 15$ and 30 keV with $N_{np} = 46,000$ and 184,000, respectively.

C. Rate and Number of NPs for Breakdown

The number N_{np} of NPs produced in the peeling of Scotch tape is not known. An estimate of the rate of NPs necessary to balance the measured X-ray emission Q is,

$$q \frac{dN_{np}}{dt} = Q < \frac{wv}{\Delta^2} kT \quad (7)$$

The spectrum of x-ray energies (Fig. 3 of [10]) during peeling at velocity $v = 3$ cm/s gives $Q = 2$ nW, and therefore $dN_{np}/dt \sim 4.16 \times 10^5$ /s. This is reasonable provided Q is a small fraction of the rate of kT energy available in the adhesive surface atoms. For tape width $w = 20$ cm, Q is upper bound by 2.76×10^{-5} W so Q is about 10^{-5} of the available surface kT energy.

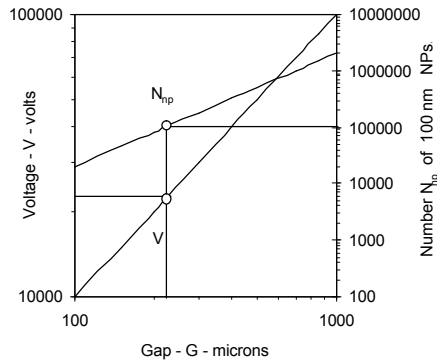


Fig. 3 X-rays from Peeling Scotch Tape

The number N_{np} of NPs necessary for charge to accumulate to breakdown may be estimated from the rise time Δt for the force (Fig. 2b of [10]). Taking $\Delta t = 0.25$ s, $N_{np} = (dN_{np}/dt) \cdot \Delta t \sim 1 \times 10^5$. Fig. 3 shows the corresponding breakdown voltage $V \sim 23,000$ volts at field $F = 10^8$ V/m occurs at gap $G \sim 230$ microns.

D. Electron and X-ray Energy

Conservation of the electron potential energy eV with the kinetic gives its velocity v_e ,

$$v_e = \sqrt{2eV/m} \quad (8)$$

where, m is the electron mass. For $V = 27,000$ volts, $v_e = 1.2 \times 10^8$ m/s. The Planck energy E_p of the x-ray upon bremsstrahlung is, $E_p = 27$ keV.

V. SUMMARY

X-rays in the peeling of Scotch tape follow the physics of CRTs. The separation gap between the adhesive and PE in a vacuum allows electrons from the PE to be accelerated to high velocities at electrical breakdown. Upon collision with the adhesive, the x-rays are produced by bremsstrahlung.

The x-ray production relies on electron transfer by the photoelectric effect. The Planck energy at VUV levels necessary to charge the adhesive by removing electrons is induced from the thermal kT energy of atoms in NPs by QED induced EM radiation. Only

NP diameters less than 100 nm have the necessary EM confinement to induce VUV radiation.

The simulation of x-rays is described through simple calculations based on the production of 100 nm NPs. Smaller NPs and MPs are ignored, although they also will be produced in peeling tape. Experimental data on the number and distribution of NPs is required to complement the x-ray calculations.

X-rays from Scotch tape and not duct tape is explained by NPs less than 100 nm that produce VUV radiation are more likely to form in the thin Scotch tape while MPs are likely to form in duct tape.

The generality of QED induced EM radiation not only allows x-rays to be inherent in tribology but that all of electrostatics may be unified through NPs, e.g., static electricity from NPs that form in rubbing of solids, and atmospheric electricity from ice NPs that form from frosted surfaces of upward moving water droplets in the draft of a thunderstorm.

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