Some Physics and Medicine
Monday April10, 2006

Medical Lasers

We have previously discussed how laser beams are created. We require a quantum system in which we can excite the ground state to some excited state A, which then decays to a lower excitation energy, but long lived, excited state B. In these conditions, it is possible to excite the system enough so that the population of B is larger than the ground state population. In this case, a decay photon from one of the quantum systems can stimulate decays of others. Leading to many photons of the same energy. By enclosing the system in a reflective cavity, with a partially reflective mirror at one end, it is possible to generate a beam of photons that is essentially collinear and monochromatic.

For medical use, we now have to consider how they interact with the body and are used for medical purposes. There are three main molecules that absorb visible and near visible light.

First, let us consider interactions of light with water. Water is fairly transparent to visible light – you can see though several m of *clear* water – but much more strongly absorbs shorter (UV) and longer (infrared) wavelengths. So a visible light laser has little interaction with the water in your body, but infrared for example will be absorbed in the water, heating it up.

Melanin is the dark pigment in skin that absorbs UV and also visible light. In general, anything that looks dark is a good absorber of visible light, whether it is melanin or ink used in tattoos.

Another common component of your body is the hemoglobin in blood. This has a complicated absorption pattern, strongly dependent on wavelength, and most transparent to yellow light. Blood of course generally has a red appearance, indicating dominant reflection of red light, when oxygen rich. Oxygen deficient blood tends toward blue.

In addition to absorption, your body tissues scatter light. Blue light tends to be scattered more. As a result, transmitted light is mostly red. (Try shielding a bulb with your fingers.)

So, what can lasers be used for? Here are several examples, and some more included physics asides.

CO_2 lasers produce 10,600 nm light, with high power. This wavelength is too long to have good transmission in optical fibers, so it is used with articulated arms and mirrors. The energy from the laser is rapidly absorbed by water in the body, heating it up. A short intense pulse will convert water to steam, vaporizing it. A small crater surrounded by a thin layer of dead tissue, is created. The surrounding area is heated momentarily, but conduction and convection with blood vessels cool the region in of order 1 ms. Thus, high intensity CO_2 lasers essentially act as replacements for scalpels. Lower intensities provide heat without vaporization.

Nd:YAG lasers emit 1064 nm light, in the near infrared region. They tend to penetrate deeper into tissue than CO_2 lasers. Some applications include using short pulses for hair or tattoo removal. In the first case, the hair follicle is killed by the heat. In the second case, the ink pigments absorb the light and are heated and destroyed. The body then naturally removes the foreign substances.

The most common application nowadays would seem, from television adds, to be excimer lasers used in LASIK eye surgery, which will be discussed in a presentation later.

More Lasers

Since lasers provide an intense light source, they can also be used in Photodynamic Therapy. Here a photosensitive drug is given to a person. For treatment of tumors, prophyrin is given, and is preferentially absorbed into the tumor cells due to their high metabolic rate. Porphyrins absorbs light in the 400 – 650 nm range, converting the energy in the light into freeing single, and thus highly reactive, oxygen atoms. Oxygen atoms react with and destroy molecules in cells – think of all the advertisements and recommendations for anti-oxidents such as vitamin C, vitamin E, ... – leading to cell death if there is enough oxygen.

Interaction of light with Tissue - Microwaves

So far we have discussed the interactions of high energy photons – X-rays and gamma rays – with tissues, and of light with tissue. Higher energy photons can directly ionize atoms and break molecules, leading to cancer in some cases. Ultraviolet light, between the energy of visible light and X-rays, is well known to promote skin cancer, more so in people with lower levels of melanin. What happens with lower energy / longer wavelength light? This takes us to the question of cooking.

Infrared is well known as a heat source, often used in food warming lamps – intended to keep food from cooling off. It tends to be absorbed in the surface layers.

Radio frequencies, particularly microwaves at f = 2.45 Ghz, or 12 cm, are more penetrating. These frequencies largely excite water molecules into rotational states, but friction converts the rotation into general heating of whatever medium the water is in. The result is that, rather than heating food, and making it crispy, from the outside in, you are steaming food more or less uniformly throughout the food. Of course, this is not something you want to do to yourself. In principle is is done by users of cordless / cell phones regularly, since these operate at GHz frequencies, but the power levels of phones are far below the kW power levels of microwave ovens.

Extreme low frequency fields (ELF)

As a result of sensationalist, nonscientific, trashy journalism several years ago, many people remain under the impression that low frequency, 60 Hz power lines are potentially dangerous to people's health. In fact, your body is largely transparent to these low energy fields. The result has been billions of dollars of money searching for ever smaller effects, and no robust evidence of anything. The main effect appears to be statistics. If you look at a cause of nothing, and search for enough potential effects, just from statistical fluctuations some of them will appear to be statistically significant.

Here is an example of how statistics work. The rate of childhood acute lymphocitic leukemia (ALL), is about 4000 per year in the US, so a community of 100,000 people expects about 1.4 cases. One year they get 7 cases. The rate is 5 times too high. Clearly something is wrong and someone should be sued, right?

The expected number of cases, given these small rates, can be estimated from Poisson statistics. $P(x,n) = e^{-x} x^n / n!$, where x is the expected number and n is the number observed. So, given about 3000 100,000 people communities in the US, we expect about 740 with 0 cases, 1040 with 1 case, 720 with 2 cases, 340 with 3 cases, 120 with 4 cases, 33 with 5 cases, 8 with 6 case, 1.5 with 7 cases, and 0.3 with 8 cases! We can only infer some localized causal effect if the distribution is non-probabilistic.

Looking at the number of communities with 4 cases, about 3 times the expected rate, you can see that there is about a 3 % chance of this happening. So if you study a community for about 30 rare diseases, it is likely that there is one in which the rate is significantly elevated. The more diseases that are studied, the greater the likelihood of a false positive.

HOMEWORK

Assume that 10 % of the Rutgers students fall in some particular category. We have 20 students in Physics 397. What is the probability that we have 0, 1, 2, 3, 4, 5, or 6 of those students in our class?

Radiation and Cancer Treatment

Perhaps the most common way to treat cancer with radiation is using x-ray and gamma-ray sources to irradiate and kill tumors. Some radiation soucres are introduced to the body i chemical form, and concentrated in some metabolically active tissue, which they then kill. Overactive thyroids are killed this way, by radioactive iodine, and then people take hormones to replace those the thyroid would normally produce.

Alternatively, x-ray or gamma-ray sources are used to illuminate the tumor. The problem is that photons are exponentially attenuated as they pass through the body, so, for internal tumors, more surface areas receive a higher and more deadly radiation dose. The solution is to vary the direction the radiation comes through the body to intersect the tumor. That way the tumor can receive a large dose, while surrounding tissue receives lower and less damaging dosages. A prime example of this is a device called the gamma knife. It is a helmet with about 200 directional cobalt-57 sources in it. It is mounted on a person's head, with the sources all aimed towards a brain tumor.

When charged particles pass through matter, they lose energy largely through knocking atomic electrons free. Nuclear interactions occur, but they are uncommon. The energy loss per unit distance traveled through materials like organic tissue is about 2 MeV/cm for GeV energy charged particle like protons, antiprotons, and pions, decreasing to about half this as the momentum is lowered, then finally having a sharp rise at very low momenta, below a few hundred MeV/c, up to 10s of MeV/cm. As a result, if you look at energy deposited as a high energy charged particle moves through tissue, a small amount of energy is loss per unit distance, but the amount tends to increase with distance, and a large amount of energy is lost close to the point at which the charged particle stops.

For treating cancer by depositing lots of energy to disrupt cells, this behavior is ideal. The beam energy can be adjusted, either by adjusting the energy of the accelerator, or by using a fixed beam energy but putting absorbers before the body so there is energy loss before entering the tissue. Then, the charged particles deposit a large fraction of their energy is the diseased tissue, and relatively little in the healthy tissue. This is technically superior to (but more expensive than) the use of conventional X-rays.

For even more “bang”, two techniques have been considered. The idea for the improvement is to use charged particle other than protons, which then decay upon being stopped. Two good candidates – both of which require highly energetic accelerators – are pions and anti-protons. The ~140 MeV pions stop and naturally decay with a few ns to ~105 MeV muons and nearly massless muon neutrinos – one of these is an anti-particle; which one is depends on whether the pion is positively or negatively charged. The muon then decays in about 2 μs, to an electron, and electron and muon neutrinos. The neutrinos tend to simply escape, but the muon and decay electron will lose additional kinetic energy in the tissue, further damaging cancerous cells.

For anti-protons, the stopped anti-protons will quickly drop into “atomic” orbits with some local nucleus, and then annihilate with a proton. The proton-anti-proton annihilation produces pions, typically three of them which lose energy as indicated above. The exception is the neutral pion, which decays in fs to two ~70 MeV photons. These photons rapidly lose energy as they pass through tissue, though the production of electron-positron pairs. Also, the nucleus may be disrupted by the proton-anti-proton annihilation, leading to added particles that lose energy in the cancer site. (Of course, the total energy is reduced a little in disrupting the nucleus, but the larger number of lower energy particles results in a more localized energy distribution.)

Accelerators

All of the substances given are proton rich isotopes. Thus they decay by positron emission to nuclei with a more even number of protons and neutrons. The most common isotopes of these nuclei are ^{12}C, ^{14}N, ^{16}O, and ^{19}F. All of these short lived isotopes can be produced by sending in a several MeV proton beam, to pick up a neutron with the A(p,d)A-1 reaction for example. How are the proton beams accelerated?

The simplest acceleration schemes simply generate the protons
from hydrogen gas at high voltage, which then accelerates them to ground, we have already discussed. Typical accelerators of this type (often called van der Graafs, after the Nobel prize winning inventor) often go to about 1 MV. There is a similar electrostatic type of accelerator called the Cockcroft-Walton, after its inventors. A refinement is the tandem accelerator. Here one forms H- ions that are accelerated to a high central voltage. At the high voltage terminal, the H- beam passes through a thin foil, or a small amount of gas. The interactions of the beam and the gas tend to strip the electrons from the beam, and the protons are then accelerated back to ground.

How is the high voltage generated? Low voltage batteries use the different electro-negativities of different compounds to generate a potential difference. For high voltage power lines, transformers use the magnetic fields generated from one coil to induce an emf in a second coil. By varying the ratio of number of turns in the two coils, it is possible to step the voltage up or down. Van der Graafs operate more like petting a cat. The mechanical rubbing of one material against another can transfer electrons. A nonconducting rubber belt can have electrons continuously added to it at one end, which it can then transport and give to the more negative voltage terminal, increasing the voltage difference. The mechanical motion of the belt adds energy to the electrons, so that when they reach the negative terminal they are at the same potential as it is. The metallic high voltage structures are mechanically supported by insulating ceramics, and almost the entire assembly is enclosed in a large tank, surrounded by insulating gas (uranium hexaflouride).

A more common technique in medical physics is the cyclotron. Consider a region of constant magnetic field. The time it takes a particle to complete a circular orbit is $t = d/v = 2\pi r/v$. For a particle in circular motion, recall $mv^2/r = qvB$, so $r = mv/qB$. Thus, the orbital period becomes $t = (2\pi/v)(mv/qB) = 2\pi m/qB$. The orbital period is independent of the momentum / velocity. (As the particles become relativistic, there is a factor of γ in the orbital period, so this is no longer true.)

Thus the scheme of the cyclotron is to have a region of constant field in which the protons will have circular orbits. The protons will orbit between electrodes over which one puts a time varying voltage $V = V_0 \cos\omega t$. By setting $\omega=2\pi/t=qB/m$, the proton passes each way through the electrodes in phase with the electric field accelerating it. For B = 1 T, $f=\omega/2\pi\sim 16$ Mhz. As the protons are accelerated to higher energy, the radius of the orbit increases, and shaping the electrodes can compensate for the increase in γ.

The use of RF cavities in acceleration of particles is now common; it appears in linear accelerators, microtrons, and synchrotrons (the biggest machines, at CERN and Fermilab). The idea is to use a klystron to generate RF fields – this is crudely speaking a similar device to the magnetron in your microwave oven – which are then directed by a waveguide to a cavity. Consider a cavity that is ½ wave length long, with a resonating electric field in it. The field as a function of time will be proportional to cos(wt), and as a function of position can be proportional to cos(kx). If a proton is sent through the cavity at the right phase, it will see a maximal acceleration. Protons enough out of phase will be de-accelerated.

For ``slow'' particles, one might use an ``Alvarez'' type drift tube linac. Here there is a large tank full of RF fields, and small field shielding assemblies in the middle along the beam path. The tubes have varying length, so that particles are between the tubes being accelerated, then in the tubes for the time that the RF field has reversed direction. For faster particles, with v~c, it is more common to use cavities of equal length, since in acceleration one adds energy but only insignificant speed to the particles.

The fields in the cavities will not be perfect, and will accelerate electrons in the metal cavity surfaces. Resistivity drains the energy, heating the metallic surface, making the cavity expand, and possibly detuning it – making it a non-integral number of wavelengths. Thus the most modern high energy accelerators use superconducting cavities, to lower the resistivity to 0, and keep the energy from draining. The problem remains that electrons can occasionally be pulled from the cavity walls, particularly if the structure is not smooth, and accelerated to another part of the cavity, hitting and knocking out other electrons, leading to arcing and a drain of energy. Once the energy drains, the arc stops and the cavity can be turned back on. One method of further smoothing the cavity is to introduce a light contaminant gas – helium – which then gets accelerated to the surface, hitting the high points on the surface and ``blasting'' them down. (Because the cavities are cooled to liquid helium temperatures, other gases would simply freeze to the cavity surfaces too soon.)

Modern RF cavities can store high electric fields, leading to accelerations of several MV/m. There are several novel schemes being tested to improve acceleration to ~GeV/m. These include wake-field acceleration and laser acceleration. I will not (unless I get requests) reproduce here the notes on how Maxwell's equations lead to traveling RF fields (photons) in free space, and how a focused laser beam can lead to GeV/m magnitudes of accelerations.