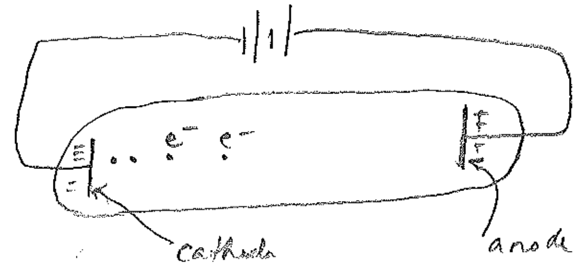
Cathode ray tubes



[19th century experiments:

Glass tube w/ electrodes sealed inside.

Place large voltage difference across them.

Higher voltage electrode = anode (pos. charge)
Lower voltage electrode = cathode (neg charge)

If voltage is large enough (~ kilovolts)
some electrons break free. (or if heated)
Because of voltage difference, acts as an electron gun,
which accelerates the electrons toward the anode.
Called "cathode rays" (discovery of electron by J.J. Thomson)
If there's gas inside tube it glows (neon lights)
If evacuate all gas, electrons will not be slowed down
but will accelerate until they hit the anode,
where they are brought to a sudden halt.
This sudden deceleration of charges causes emission of radiation]

Bremsstrahlung = braking radiation.

Bremsstrahlung is like an inverse photoelectric effect: the kinetic energy of the electron is converted to the energy of one or more photons.

Let V = voltage across electrodes

Potential energy difference of electron $\Delta U = qV$

Potential energy → kinetic energy → energy of photon

$$E_{photon} = \Delta U$$

$$hf = qV$$

$$f = \frac{qV}{h}$$

$$\lambda = \frac{c}{f} = \frac{hc}{qV} \approx \frac{1200 \text{ eV} \cdot \text{nm}}{qV}$$

If $V \gtrsim$ kilovolts, then $\lambda \lesssim$ nm ⇒ X-rays
1895 Röntgen

[Röntgen was experimenting.
Had a fluorescent screen across the room.
When the CRT was going, screen started to glow.
Not electrons which can't pass through glass.
Some strange emanation or radiation.
When he put his hand in front of screen, saw his bones
Called them X-rays. Not until later was it
recognized to be a form of EM radiation.]

Apr. 11, 1997 Brunswick Times Record

Brunswick, where Perley Watson was X-rayed

BY JOHN GOULD
Times Record Contributor

Every so often the story of Brunswick's participation in the development of the X-ray should be repeated. Now is the time. It was far from an unimportant participation, and revolves around two men; Dr. Charles Hutchins of the Bowdoin College department of physics and Gilbert M. Elliot, M.D., who owned the big house at the corner of Pleasant and Maine, long since swapped for a filling station. Dr. Hutchins lived on Federal Street, the lawn of his tidy little home running down to Market Lane.

When the Roentgen rays were discovered in Europe, there was no immediate thought that they would be applied to medicine, but great interest prevailed in the simple property that they could pass through even human flesh. There was wild surmise that a lady could no longer be safe on the streets, because now they had a machine that could defrock her in passing and reveal her rudely to the throngs. There was no basis for this entertaining thought, but people did believe it. Not long after the discovery of X-ray, a great medical magazine, the German counterpart of our American Medical Journal, had a story about X-rays, raising the question of what they would mean to physicians and surgeons, and public health.

Now, Dr. Elliot, here in Brunswick, subscribed to that German journal. Dr. Elliot was a big man, and had been a regimental physician in the Spanish-American War. He was utterly unschooled in the German language and couldn't read the German medical magazine. But it was a prestigious thing to have on his waiting-room table, and all his patients were impressed. And when the copy with the story on X-rays arrived, he thumbed through it before putting it on his table, and he was able to understand that an article was about these curious, penetrating, rays he had been reading about in the newspapers. He didn't know it, but the article included complete directions for making an X-ray tube. Now, something possessed Dr. Elliot to carry that magazine over and show it to Dr. Hutchins, who was a doctor of science rather than a doctor of medicine, and could read German.

Having the Bowdoin College physics lab and instrument-making shop at his disposal, Dr. Hutchins forthwith made an X-ray tube. Historically, it was some time before anybody else on this side of the Atlantic made an X-ray tube, and for some years the Bowdoin labs supplied them to other colleges. Dr. Hutchins had a monopoly.

And shortly, Dr. Hutchins asked Dr. Elliot if he'd like to come up to the Bowdoin lab some evening and see what he was doing with these interesting Roentgen rays.

Dr. Hutchins had one of his X-ray tubes positioned, with a photographic plate ready to make an X-ray photograph. At that time Dr. Hutchins, and many another photographer with him, was "flowing" his own glass plates, a tedious process Mr. George Eastman and the Stanley Brothers were to replace with dry glass plates and film. To demonstrate, Dr. Hutchins placed a hand of Dr. Elliot, his left hand, over the plate-holder, and made an X-ray exposure.

I have no idea where that picture is today, but I'd deplore the news that it is lost. It was framed and on the mantle in the Elliot waiting-room in the Pleasant Street home the last time I saw it. Dr. Elliot had retired and died, and Dr. C. Earl Richardson had bought the Elliot home and was practicing from Dr. Elliot's hallowed office. I would suggest the curious try the Pejepscot Historical people. It was plain black and white, and showed the bones of Dr. Elliot's fingers with his Masonic ring on the proper phalanx. It was not, however, a picture made for surgical purposes. That came later.

There was, at the time, a gentleman in Brunswick named Perley Watson who lived on McKeen Street and was employed by the Maine Central Railroad as a yard man. He came to see Dr. Elliot one evening, complaining about a kink in his back. Thinking Perley had perhaps popped a muscle while lifting at work, Dr. Elliot strapped him up and told him to come back in a week. But in a week Perley was no more comfortable, and he insisted he was suffering from serious complications. And Perley had heard about these miraculous Roentgen rays that would let you look right inside. "Why don't you take one of them there pictures," he said, "and find out?"

And that's where the era of X-ray medicine began. Dr. Hutchins said he wouldn't know about taking a picture right through a whole human body. He said he'd have to flow an enormous great plate. "How big a belly has this man got? he asked Dr. Elliot. And Perley was pleading for relief. Dr. Hutchins at last agreed to try, and Dr. Elliot brought Perley Watson to the lab.

Dr. Hutchins made things clear. He told Perley there would be no charge for the X-ray picture, but he would like to be reimbursed for the cost of the photographic materials, which might run to a considerable sum. Perley said to go ahead, all he wanted was to get rid of the kink in his back.

The picture required several exposures, trial and error. The first exposure was by no means long enough; the negative came out blank. They propped Perley with pillows, gave him a cigar to engage his attention, and tried again. And a third exposure was sufficient. It showed Perley's spine clear as a bell.

Dr. Elliot said the picture showed no blemishes, and convinced at last Perley Watson was satisfied. Dr. Hutchins said he thought $5 would be about right, and Perley paid him and went home. It was close, but still, the X-ray had not yet been used in surgery.

A week later Perley Watson was again in Dr. Elliot's office, this time complaining of an itch. His belly was all broken out. So it was! Dr. Elliot prescribed a salve, and the next day Perley was worse. His trouble, of course, was X-ray burns, and by this time Dr. Hutchins, also, know about them and had sustained them on his hands. Perley was in miserable pain for a long time, and nobody was just sure what should be done for X-ray burns. Perley kept harping on the $5 he paid for his misery.

It was the custom back then for physicians about the state to bring ambulatory patients to Brunswick for minor surgery at weekly clinics at the medical school connected with Bowdoin. Accordingly a porter at the Waterville railroad station was brought down to have a bullet extracted from his heel. Dr. Elliot didn't know just how this fellow got a bullet in his heel but as an observer at the clinic he suggested the operation would be simplified by an X-ray picture, which Dr. Hutchins could make next door in the physics lab.

This was done, and that was the first time X-ray was used in surgery. At least on this side of the Atlantic Ocean.

JOHN GOULD, *of Gorham, is the author of more than two dozen books. From 1931 to 1939 he was a reporter for The Brunswick Record.*

skipped T3-9 in FP6

Momentum of a photon

2 possible pedagogical approaches

In general, the energy and momentum of a particle is related by

$$E^2 = (pc)^2 + (mc^2)^2$$ ← relativistic energy-momentum relation

(E includes rest energy + kinetic energy)

If a particle is at rest, $p = 0 \Rightarrow E^2 = (mc^2)^2$

$E_{rest} = mc^2$

If $p \neq 0$, then $E > mc^2$; the difference $E - mc^2$ is kinetic energy.

A photon is a massless particle so

$E^2 = (pc)^2 \Rightarrow E = pc$

EM wave has energy density, also carries momentum

Electromagnetic wave
$\frac{\text{Energy density}}{\text{momentum density}} = c$

[units: $E \sim \frac{kg\,m^2}{s^2}$
$p \sim kg\,\frac{m}{s}$]

Energy of EM wave divided into discrete chunks

each photon $E_{photon} = hf$

also has momentum $p_{photon} = \frac{E_{photon}}{c}$

then $p_{phot} = \frac{hf}{c} = \frac{h}{\lambda}$

Now $p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$

(possibly mention radiometers / radiometer effect)

or just skip to here →

$$\boxed{p = \frac{h}{\lambda}}$$ de Broglie relation

~~[illegible]~~

Skip for now

Possibly Review:
1. Photoelectric: $f > \frac{\phi}{h}$, $\lambda < \frac{hc}{\phi}$
2. Bremsstrahlung $\longrightarrow \lambda > \frac{hc}{eV}$
3. Thermal $\longrightarrow \lambda_{peak} \sim \frac{hc}{5kT}$

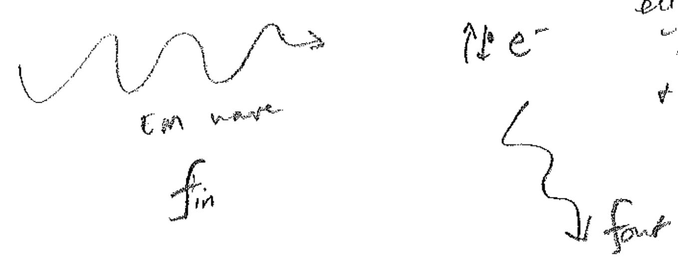
Skip

TU

4. Compton effect

Scattering of X-rays or γ-ray by electrons

classical picture



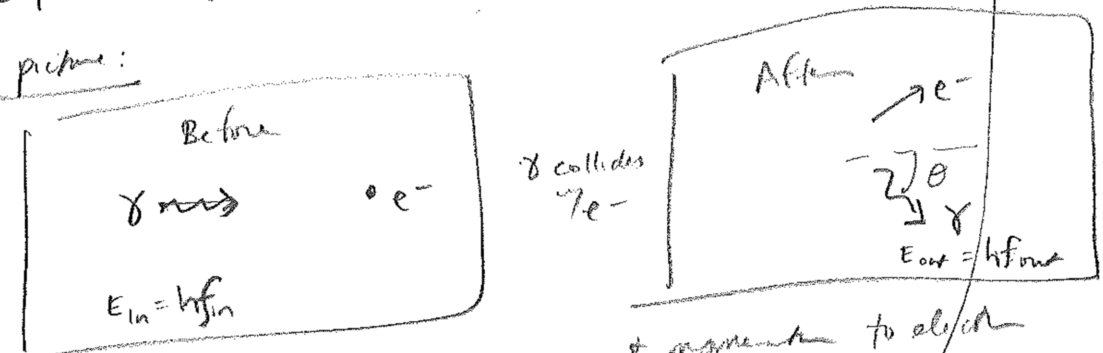
electron oscillates w/ frequency f_{in} + emits EMR w/ freq

$f_{out} = f_{in}$

Experimentally $f_{out} < f_{in}$. Why?

Quantum picture:

Photons carry energy $E = hf$ + momentum $p = \frac{h}{\lambda}$



photon loses energy + momentum to electron

so $E_{out} < E_{in}$

$f_{out} < f_{in}$

$\Rightarrow \lambda_{out} > \lambda_{in}$

Energy + momentum conservation can be used to show

$$\lambda_{out} = \lambda_{in} + \frac{h}{m_e c}(1 - \cos\theta)$$

Compton wavelength

$\frac{h}{m_e c} = 0.0004\,nm$ (Not noticeable except for X-rays, γ rays) $\rightarrow$ green light still green