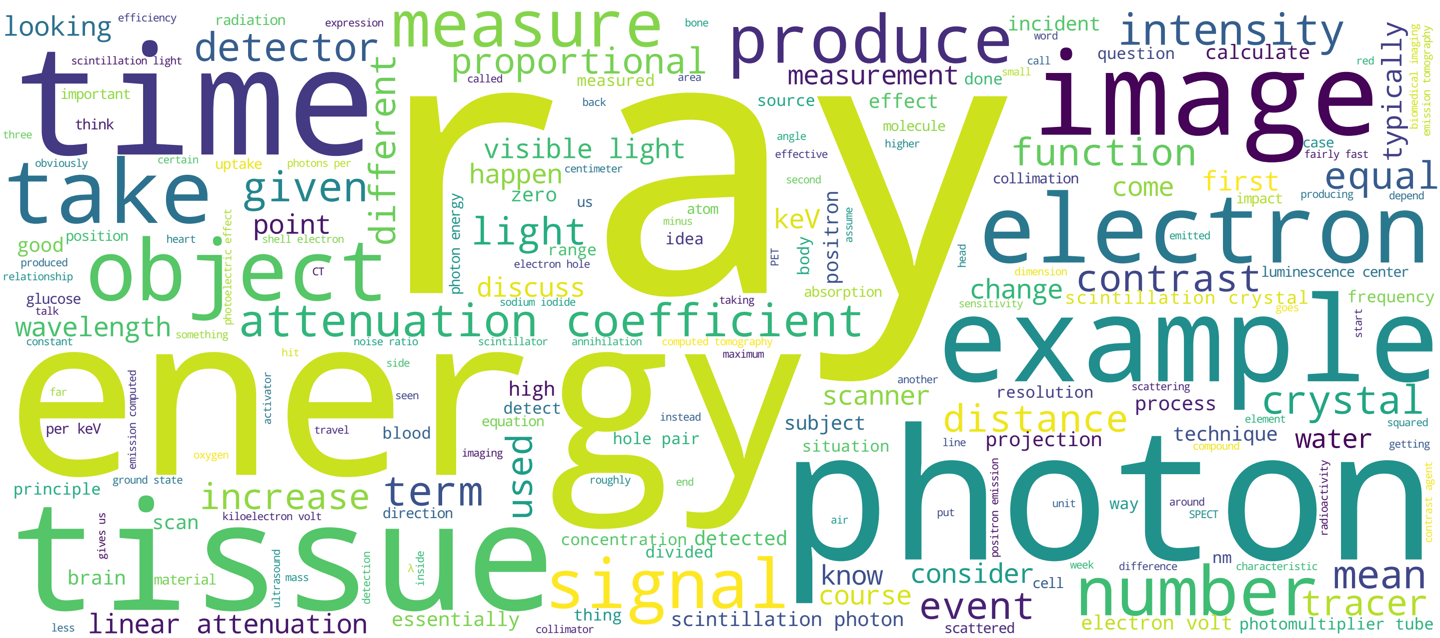
5.4 Principle of x-ray detection I: Scintillation

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



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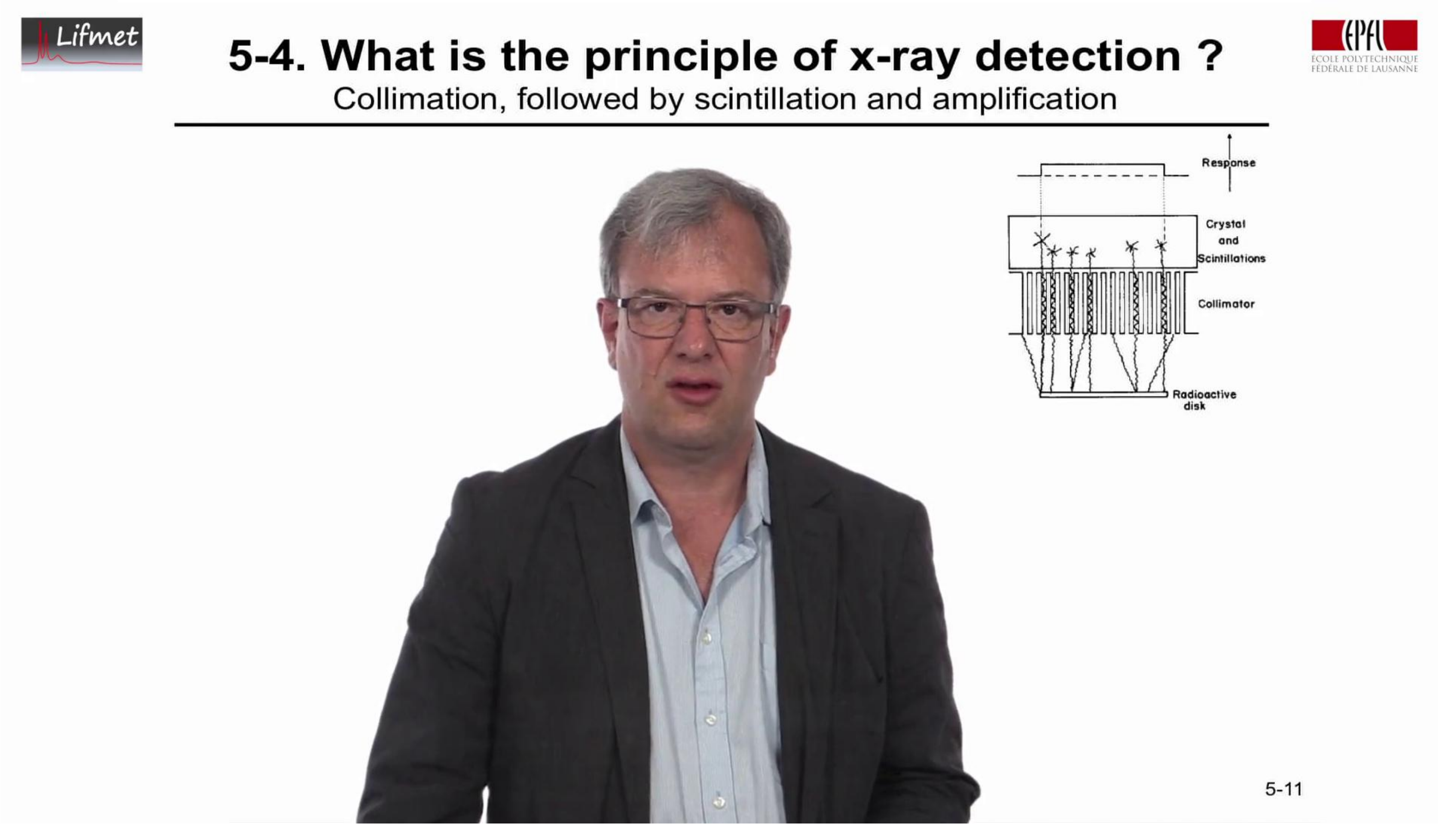


So far we have been pretending like we know how to measure x-rays, but I haven't really given you a full picture of how x-rays are being measured. We have dealt with the fact that we do collimation, but, how do we actually get an x-ray into a measured signal? And this is what I want to discuss in this section.

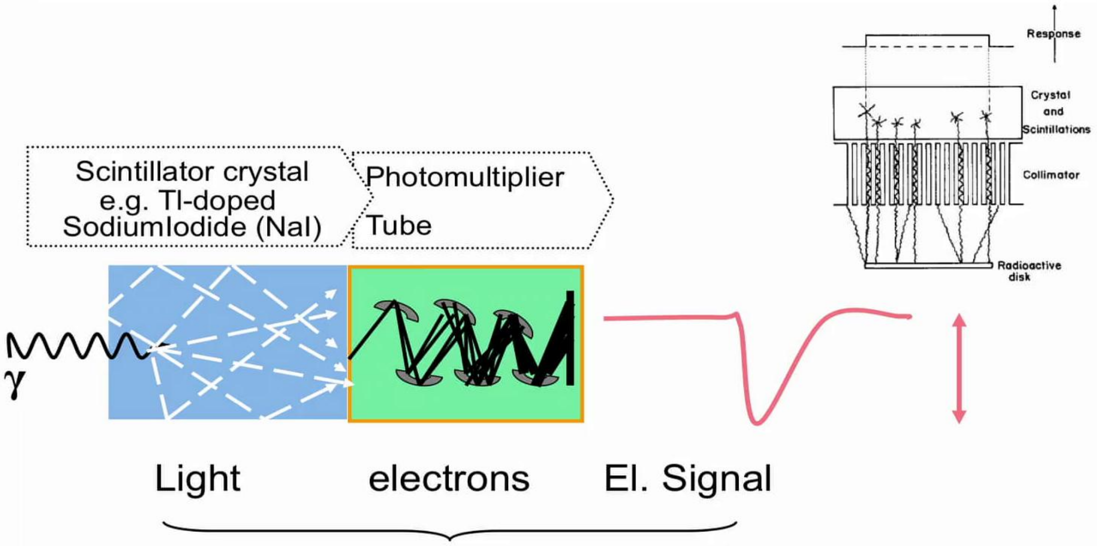
Notes

Summary

0m 04s

5-4. What is the principle of x-ray detection ?

Collimation, followed by scintillation and amplification



γ-energy ∝ # scintillation photons ∝ Signal

5-11

After collimation we have the detection that consists of a scintillation crystal. So, a typical example here is TI-doped SodiumIodide. We have the x-ray that hits this crystal, interacts with the crystal. What happens then is, visible light is being produced. This light then impacts on a photomultiplier tube which basically produces a lot of electrons, then multiplied, and this, in the end, produces an electrical signal. So this, schematically: we have x-ray interacting with the crystal, conversion to visible light, this visible light is amplified into an electrical signal using a photomultiplier tube. So, here's the complete process. Here we have the source, we have the collimator crystal, and scintillators, and then we have the photomultiplier tubes that produce the signal. One important feature of this detection process is that the energy of the gamma photon of the x-ray of 140 kV is one example. This energy is proportional to the number of scintillation photons, those are these guys here in white. And this, in the end, is proportional to the signal that we measure. So the intensity of the signal that we measure is a measure of the energy of the x-ray, and this is an important feature for the emission-computed tomography techniques that we're discussing this week and next week.

Notes

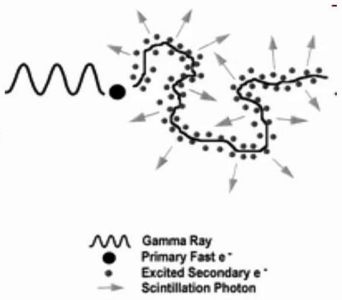
Summary

0m 26s

What is Scintillation ?

Sequence of events in scintillation crystal

1. Atom ionized by Compton interaction → Electron-hole pair
2. Hole ionizes activator, electron falls into activator



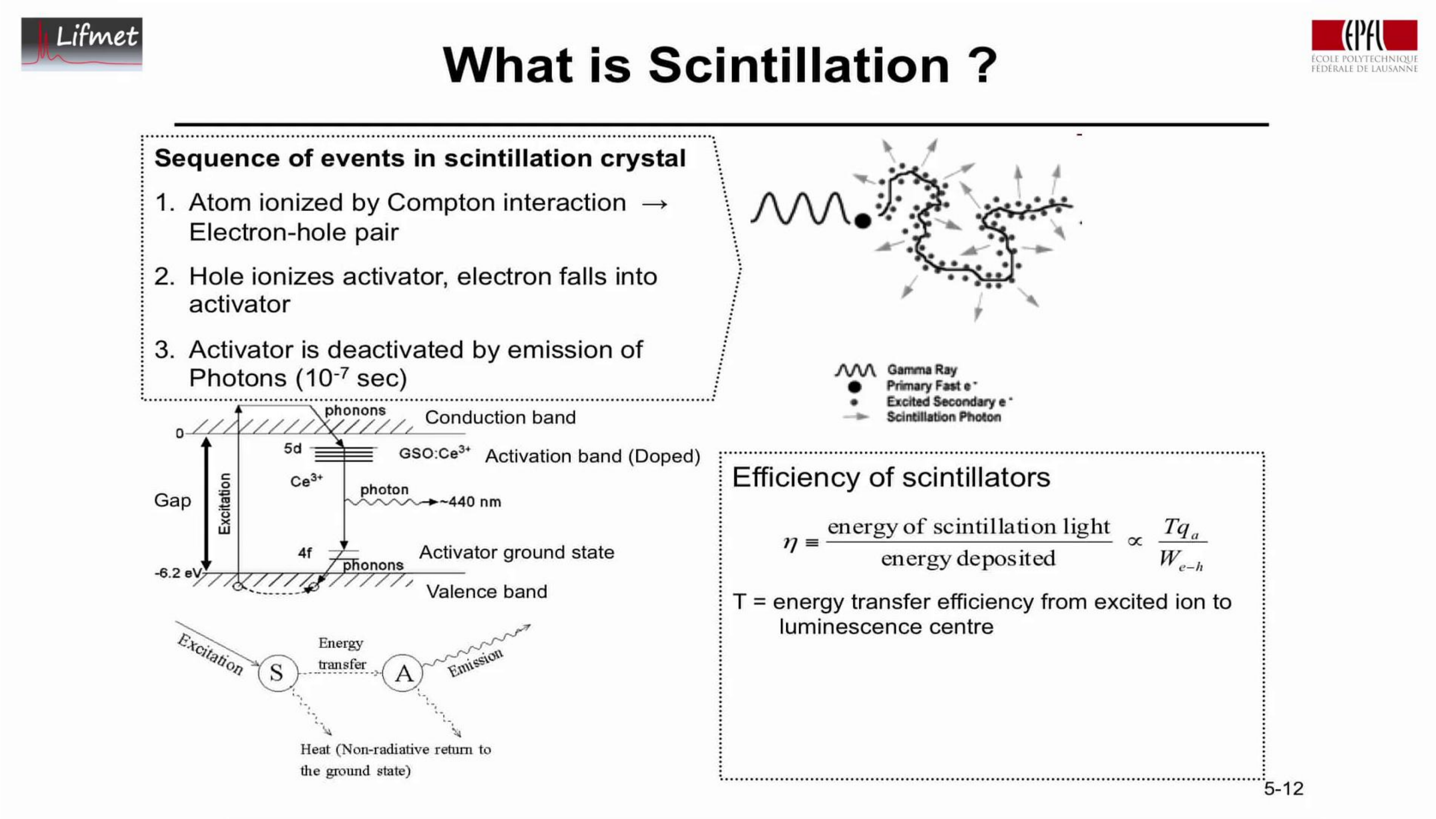
5-12

So, what is scintillation? What happens in a scintillation crystal? There are a sequence of events to consider. We'll have here the gamma ray, the x-ray that hits our thin crystal. It produces a primary fast electron. This can be an electron bumped out of an inner shell through the photoelectric effect. Or it can be an outer shell electron that's removed from the atom by Compton scattering. This electron in the crystal will then produce a number of excited secondary electrons and actually electron-hole pairs which, in the end, produces the scintillation photons. So it makes perfect sense if we have a higher energy x-ray that comes in. The kinetic energy of the liberated electron or electrons is higher, and therefore they are capable of producing more secondary electron-hole pairs, and therefore they will produce more scintillation photons. Hence the proportionality of the visible light to the energy of the incident x-ray. So we'll consider here that the atom is ionized by Compton interaction. This produces an electron-hole pair. The hole ionizes the activator, the electron falls into the activator, and so when the activator is deactivated and goes back to the ground state, it emits photons, and it does that fairly fast.

Notes

Summary

2m 08s

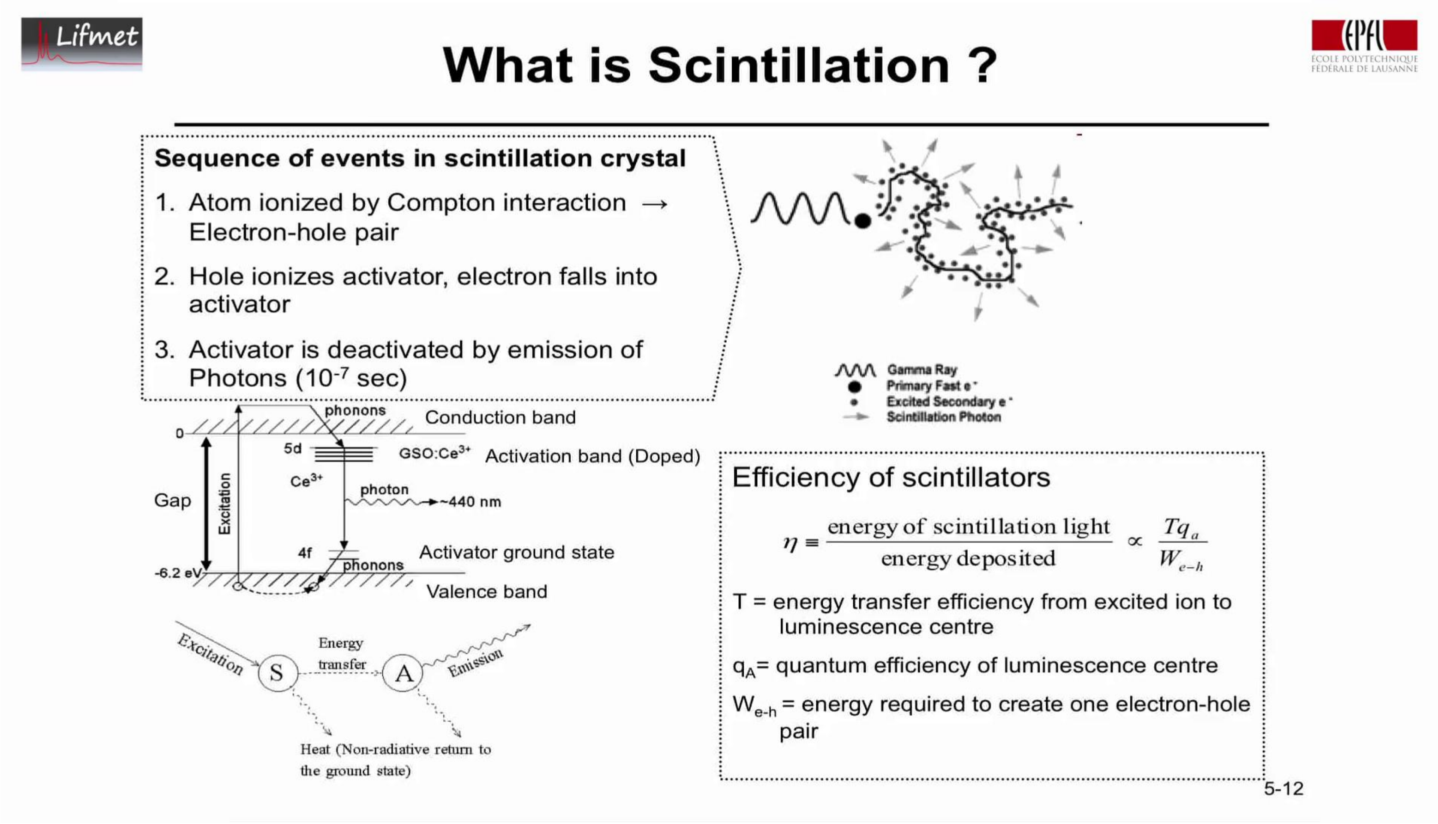


Here the example is on the order of a tenth of a microsecond. If you look at it from an objective standpoint we have a gap in the solid-state, we have the activator ground state, and we have the activation band. This band comes actually from the doping, so this is GSO, with the doping being here, indicated. I won't go into the details and the physics of scintillation. It's fairly complex, it's not a strict, precise description of it. What suffices for us to know is that we need an impurity in the crystal, and that the number of scintillation photons that are produced are proportional to the energy of the incident x-ray. So now, what we have is-- we have excitation, we have an energy transfer, and we have emission. But we have also quite some losses due to heat. And so, we're interested in characterizing scintillation materials and that's one thing is the efficiency of the scintillators. This is essentially the energy of the scintillation light. So, energy of the visible photons times the number of photons, divided by the energy deposited, typically the energy of the incident x-ray. And this is proportional to the energy transfer efficiency from the excited ion to the luminescence center.

Notes

Summary

3m 35s



So, how good are we in bringing that energy to the impurity ? We have the quantum efficiency of the luminescence center. How efficiently does it produce the light, and how much energy is required to generate an electron-hole pair? Again, what makes sense is if you need more energy created in a hole pair, the efficiency is lower, if we produce more photons from a luminescence center, the efficiency is better and if we can get the energy transferred to the luminescence center very efficiently, then the efficiency goes up, so these relationships make sense.

Notes

Summary

5m 02s

Lifmet

What elements characterize scintillation materials ?

Overview of some crystals

Scintillator	Density (g/cm^3)	Attenuation Coefficient (cm^{-1} @ 511 keV)	Light yield ph/keV	λ (nm)	τ (ns)	Z_{eff}	Refr. Index	Yield
$CdWO_4$	7.90	0.886	19	495	~10^4			
$Bi_4Ge_3O_{12}$	7.13	0.964	8,	480	300	73	2.15	13%
$(Y,Gd)_2O_3$:Eu,Pr	5.9	0.503 - 0.637	19	610	~10^6			
Gd_2O_2S:Pr,Ce,F	7.34	0.786	40	510	~10^3			
NaI:Tl	3.67	0.343	40	415	230	51	1.85	100%
Gd_2SiO_5:Ce	6.71	0.704	7,	430	300	59		
Lu_2SiO_5:Ce	7.4	0.869	30	420	40	66		79%
$LuAlO_3$:Ce	8.34	0.956	11	365	~17			
$LuPO_4$:Ce	6.53	0.735	17	360	25			

5-13

So, instead of going through the theory, I wanted to share with you some scintillation materials here, and the characteristics that typically are used to characterize them. So, there's a whole bunch of different materials here. What we notice is they are fairly heavy materials, so the density ranges between 3.7 for sodium iodide to around 8 for this compound here. The attenuation coefficient, obviously we'd like it to be high, so it's there somewhere between.3 and 1 per centimeter-- this is the attenuation coefficient at 511 keV. Then we have the light yield. So, how many scintillation photons are being produced per keV of the incident x-ray? Well we see here we're ranging between 70 and 40 photons per keV. So we have sodium iodide, which is among the most efficient here in terms of energy yield. Produces 40 photons per keV. The wavelength of the scintillation light here ranges between 360 and 600 nm. Here is a time constant τ given in nanoseconds-- this is the time it takes for the luminescence center to return back to the ground state after it has emitted a scintillation photon. This essentially gives you an idea of how fast is the scintillation crystal reset and ready to detect the next event.

Notes

Summary

5m 44s

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Requirements for scintillator

High yield

Good linearity

Small time constant τ

Transparent for scintillation light λ

5-13

This is important because if we increase-- if we have a lot of photons that are being detected we want a fairly fast crystal so we can measure fairly fast. If the crystal is not been reset back to its ground state, it cannot measure the next event, and so we lose that event from the measurement. Here are some ideas, what are the effective *Z* of the materials, the refraction index, and the yield that we have. So what ideally would we have for requirements for a scintillator? We want to have a high yield, we want to have good linearity. Obviously, we'll discuss more why that is. we want a small, time constant like I said. We want to be able to measure every event that impacts on the crystal as far, so we don't want to miss out on the second event. And if we have two events that come fairly short after each other, of course it should be transparent for scintillation light, there is no point in producing scintillation light that is mainly being absorbed by the crystal. Not to forget, it's a physical process for producing a mechanical camera, so it should have good mechanical properties and a refraction index close to 1.5, so that the light is being reflected through the crystal and is being detected by the photomultiplier tubes.

Notes

Summary

7m 19s

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Requirements for scintillator

- High yield
- Good linearity
- Small time constant τ
- Transparent for scintillation light λ
- good mechanical properties
- Refraction index close to 1.5

Most of the energy of the x-ray is lost as heat (to lattice), see

e.g. NaI(140keV)=40·140 =5600 photons at λ≅400nm

E_{400nm}[keV]=hc/λ = 1.2/λ [nm] =1.2/400 keV=3eV

5-13

So let's look here at the light yield, and the thing that we have to bear in mind is if we have a photon that impacts our scintillation crystal, most of its energy is lost to the lactis in the form of heat. So I'll give you here just an example. Let's say, we have a technetium, metastable technetium 99 scan. So the photons are at 140 keV, and we'll take the sodium iodide scintillated crystal-- that's this material here. So we have a yield of 40 photons per keV. So we have one of those x-rays impacting the crystal, we are producing 5600 photons with a wavelength of about 400 nm. It's 415, but this is good enough for our estimation here. So we have 5600 photons with a wavelength of 400 nm. Now the energy at 400 nm-- we can calculate that from the equation we've introduced in week two. So that's given by *hc / λ*, so it's *1.2 / λ*. If we give *λ* in nanometers, that's the energy in keV. So that's 1.2 keV divided by 400 nm. And so, the visible light photons, they have an energy of 3 electron volts. So, we are converting 140 keV into 5600 photons of 3 electron volts each. So 3 electron volts times 5600, we can say that's a little bit less than 20,000 electron volts in total energy, or it's less than 20 keV.

Notes

Summary

8m 39s

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<20keV or <120eV/keV

5-13

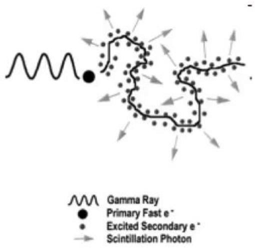
Or, in other words, this is roughly less than a seventh, or in other words, it's less than 120 electron volts per keV. So we're having here a conversion of the original energy into visible light, the energy we have in a visible light of around 12%.

Notes

Summary

10m 21s

Credits



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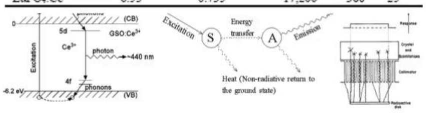

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Notes

Summary

10m 39s