Should have photos of each of a variety of detector types

Timing issues? How do you get microsecond resolution? Tradeoffs?

Detection of high-energy photons and particles

Chapters 6 and 7 of volume 1 of Longair

Ask class: what are some of the different challenges they could imagine related to detection of high-energy photons, particles, neutrinos, and gravitational waves, compared to optical photons? Start with high-energy photons. Atmosphere is opaque, so it is mandatory that the detector be lifted above at least most of the atmosphere (in a balloon or sounding rocket) if not the whole atmosphere (in a satellite). Very high-energy photons are extremely penetrating, meaning that for gamma rays the detectors must be very thick (leading to weight limitations, since it's on a satellite! For particles, it depends on the energy. As we'll see, mildly relativistic particles must be detected by balloon experiments because the atmosphere stops them. However, for ultrasuperduperrelativistic particles like really high-energy cosmic rays, vast number of secondary particles are created, either Cerenkov light or as an air shower (TeV and up photons also create air showers). For neutrinos, main problem is that the interaction cross section is so small. Therefore, need enormous volume of detector, hence thousands of gallons of cleaning fluid or water, or 1 km^3(!) ice caps. For gravitational waves, signal is really, really weak (nothing detected yet) and the noise is overwhelming.

Now, let's examine some of the specific detector types used.

Proportional counters

These are gas-filled chambers with a voltage applied across the chamber. A high-energy particle (an X-ray, let's say) comes through and ionizes some of the molecules. The ionized electrons then drift towards the end of the chamber (because of the voltage), where they are collected and measured. Xenon is often used as the gas. For X-rays with energies about 1 keV, there is typically an electron ionized for every 30 eV of energy. That means that the number of electrons, which is a measure of the energy of the X-ray, is a stochastic quantity. **Ask class:** if the number of electrons for a given X-ray energy is Poisson distributed around the mean, how do they expect the energy resolution to go with photon energy? Say that there are $N \gg 1$ photons emitted on average. Then the standard deviation is $\sigma \sim \sqrt{N}$. Since $N \propto E$, where E is the photon energy, that means that $\Delta E \propto \sigma \propto \sqrt{E}$. Therefore, the fractional energy resolution improves with higher photon energies.

Ask class: my good friend Dr. I. M. N. Sane doesn't see why Xenon should be used, and he has submitted a proposal for a new concept in proportional counters. Instead of Xenon, his chamber is filled with Fluorine gas. What's the problem with this? Really reactive! The gas would all bond to the sides of the chambers. Better to use a gas that will mind its own business!

One problem with proportional counters is that their efficiency scales as the ionization cross section. Since that goes like ω^{-3}, at high energies the chambers have to be really big (costing lots of weight) or you just have to resign yourself to low efficiency.

Solid-state detectors

More recently, solid-state detectors have been used more frequently. Here, a photon knocks out an electron (creating an electron-hole pair) by the photoelectric effect instead of creating an electron-ion pair by ionization. The energy to knock out the electron is only ~ 3 eV for silicon or germanium, so ten times as many electrons are produced for the same incident X-ray energy. **Ask class:** what should that mean for the energy resolution? It's about 3x better (square root of 10).

These are now being used at low energies, but historically these have played a role in scintillators. In such a detector, a scintillation crystal is hit by a gamma-ray, then the electrons produced make photons, which make more electrons, which are then amplified and read out at an anode. These are rugged devices, but unfortunately the scintillating material converts only about 3% of the gamma-ray energy into electrons, and only about 10-20% of the photons produce an electron. This decreases the available energy resolution. Instead of a crystal, a pure semiconductor can be used (germanium is good). The drawback is that Compton scattering competes with the photoelectric effect at the energies of interest, so that although the energy resolution is high, so is the background.

Microcalorimeters

A new concept, which would have first flown on Astro-E (RIP), is that of microcalorimeters. The "calorimeter" bit means that to get the enegy of a photon you actually measure the *heat* deposited when it hits the detector. The way this is done is to maintain the detector material at a temperature just at the boundary of superconductivity, then constantly measure the electrical resistance of the material. If the temperature goes up just a little bit, the resistance increases sharply. This is expected to produce extremely good energy resolution, at least ten times better for X-rays than had been possible before. One potential problem, though, is that it is dicey to observe bright sources with such a detector. If too many photons hit, the detector stays hot and the sensitivity and resolution drop like a rock.

Focusing mirrors

One thing that has been missing so far, that is present in optical telescopes, is mirrors. Mirrors are extremely helpful for increasing signal to noise, and also for getting good positional information. **Ask class:** what would be the special challenge in using mirrors for

X-rays, as opposed to optical photons? X-rays are much more penetrating, so straight-on reflection is unlikely. Instead, grazing incidence must be used, which is the principle behind Chandra and why it has such fantastic spatial resolution ($< 1''$!) compared to its predecessors.

Microchannel plates, lobster-eye optics

An approach now under construction uses focusing mirrors, except that not all incident light is focused to the same spot. This is the principle behind lobster-eye optics: light from many different directions can be focused, allowing an all-sky monitor with good spatial resolution. To do this and save weight, microchannel plates are used. These are plates with small-diameter (microns) holes in them, so that excellent collimation is possible with something that only has to be a few mm long. To get the lobster-eye effect, you take a plate and warm it up until it becomes slightly molten, then place it over a form with the right curvature. The plate then slumps over the form, giving the correct focus. This is a largely untried concept, but future instruments could benefit greatly from it. One of the reasons that people are enthusiastic about this concept is that when one stretches glass, it becomes very smooth (only a few Angstroms roughness). That means that the required tolerance for micron-sized holes can in principle be achieved without too much difficulty. TBD whether this works in practice and in space, of course!

Cerenkov detectors

If a particle moves faster than the local speed of light in a medium, it emits Cerenkov light. This provides a means by which to construct threshold detectors, which give a signal only if a particle moving faster than some velocity comes through. If weakly relativistic particles are of interest, one can use something with a high index of refraction, like lucite. If faster particles are important, you need something with an index very close to one, so gases are often used. A neat new approach for low index materials is aerogels. These are solid, but have densities just a few times that of air(!). They are relatively sturdy, which is a plus, and they don't leak out like a gas would.

Air shower arrays

Neutrino detectors

Gravity wave detectors