X-ray Test Facility Calculations

Prof. George F. SMOOT
Extreme Universe Laboratory
Moscow State University SINP
Chaire Blaise Pascal Univesite Paris, Diderot
Institute for the Early Universe at
Ewha Advanced Institute and Ewha Womans Univesity Seoul
Berkeley Center for Cosmological Physics
LBNL & Department of Physics, University of California, Berkeley, USA 94720

1 Introduction

Here are some assigned calculations about considerations for an X-ray test facility.

1.1 Attenuation of X-rays in dry air

Estimate the attenuation of 5 keV X-rays in 5 meters path of air. Can you make a rough graph of attenuation versus energy from 5 keV to hard X-rays or to 100 MeV?

Looking in the NIST tables of X-ray mass attenuation coefficients for dry air we find the mass attenuation for 5 keV X-rays in dry air is about 40 cm^2/g. The attenuation is given as:

$$I/I_0 = e^{-(\mu/\rho)x}$$

For this case: 5 keV in dry air and 5 m = 500 cm path length and a density of air of about $\rho_{air} \sim 1.21 \times 10^{-3}$ gm/cm^3 at standard temperature and pressure.

$$I/I_0 = e^{-(\mu/\rho)x} = e^{-40\times1.21\times10^{-3}\times500} = e^{-24} \simeq 4 \times 10^{-11}$$

That is to say less than one in ten billion get through.

2 X-ray Attenuation in Air and Needed Vacuum Levels

2.1 95% Transmission for 5 keV at 10 meters

What level vacuum would be needed for 95% or greater transmission of 5 keV X-rays

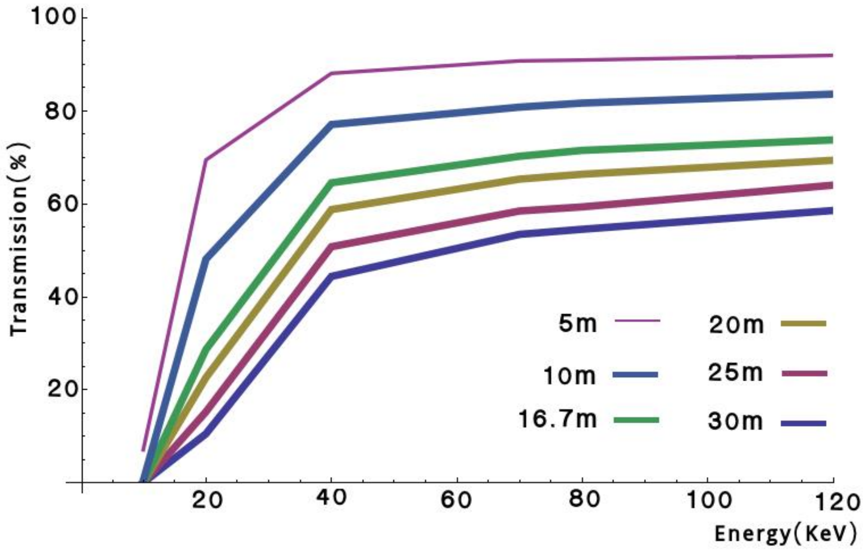


Figure 1: Rough Figure showing attenuation of X-rays as a function of energy for selected path lengths in dry air. Just sample points used. One can simply read into the computer the tables of mass attenuation and compute and plot. I did not have them handy so did some by hand.

through 10 meters?

$$I/I_0 = e^{-(\mu/\rho)x} = e^{-40\times v\times 1.2\times 10^{-3}\times 1000} = e^{-48v} = 0.95$$

The solution to this is $v \leq 0.001$ or a vacuum less than one thousandth of atmospheric pressure will do.

Can you make a rough graph of attenuation versus energy from 5 keV to hard X-rays or to 100 MeV?

The answer is yes with computers. See Figure 2. One can include the cut off of the window or filter on the source like a quarter mm of copper and 5 m of dry air. In that case one can conclude that for energies below about 10 keV there are no real safety issues as the X-rays will not get out of the vacuum tank or through a lot of air.

2.2 Source Halo of X-rays from Scattering in Residual Air

What would the halo around a hypothetical point source of X-rays be? How does it depend upon vacuum level if more than 95% of the X-rays make it to the designated target? Here we are going to be very rough with our estimation since we just want

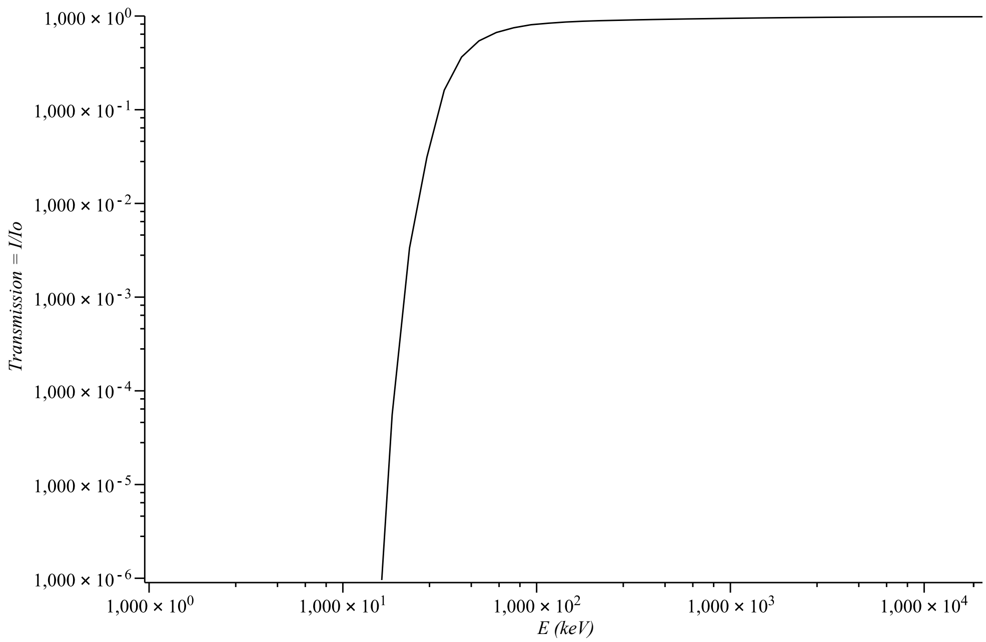
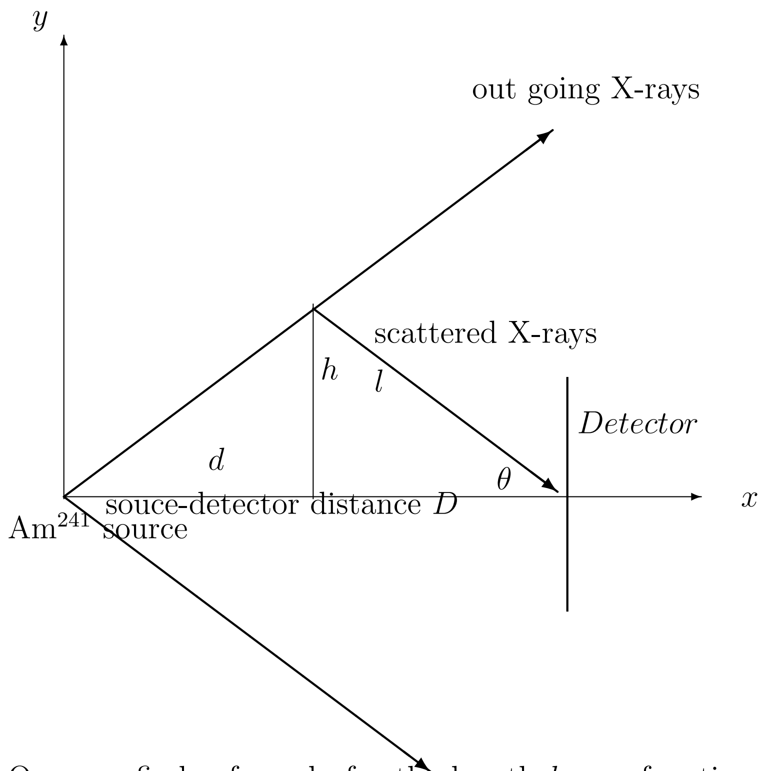


Figure 2: Figure showing the attenuation of X-rays though a copper filter and then 5 m of air. Again the , is the decimal point so the plot goes from 1 keV to 10 MeV and one can easily see it will approach unity at 100 MeV.)

an idea. To be more accurate we would have to do a computer generated integration or simulation. This was discussed in person to give an example of how to do an order of magnitude calculation.

The X-rays come out of the source with a wide beam represented in the figure as an outgoing cone. Any where in the cone a stray air molecule could scatter an X-ray toward the detector. E.g. any where along the vector of length $l$marked "scattered X-rays" that goes to the center of the detector along angle θ. There are very roughly similar lengths for any location on the detector (to order of magnitude).

If the scattering is incoherent (see the iron plot) then the angular distribution is roughly a dipole and we approximate that as isotropic to get a rough estimate of the effect. (Coherent scattering will be forward peaked and give an additional peak closer to the original beam direction.) For incoherent scattering the signal will be roughly proportional to the length of l



One can find a formula for the length l as a function of the incoming angle θ given the source opening angle θ_S. We can find the length l by trigonometric definitions:

$$h = l sin\theta = (D - d) tan\theta = (D - h/tan\theta_S) tan\theta = (D - l sin\theta/tan\theta_S) tan\theta$$

grouping the l on the same side of the equation and dividing through by its coefficient we have

$$l = D/[cos\theta(1 + tan\theta/tan\theta_S)] = D/[cos\theta + sin\theta/tan\theta_S]$$

There is a $cos\theta$ factor for the projection of the area of the detector giving us $f = l cos\theta = D/(1 + tan\theta/tan\theta_s)$. This formula is plotted in Figure 3 for representative numbers. One in principle should be integrating along the vector $\vec{l}$ using the differential scattering cross section. The plot is surpressed a bit at large angles compared to the formula.

We can estimate relative amplitude of the total halo except for the coherent portion, therefore at the larger angles as being roughly integrated to about one sixth of the scattered fraction of the main beam that intercepts the detector. That is less than about 1% of the direct beam for a 5% scattered beam. The large angle scattering should simply scale down as the fraction of the original beam scattered (attenuated). The forward spike could come up to about 70% of the scattered beam.

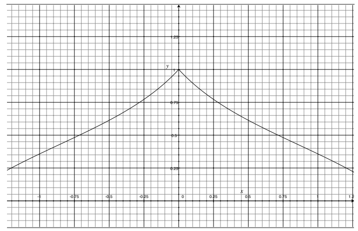


Figure 3: Figure schematically showing the X-ray halo from scattering of the residual air. X-axis is angle $\pm 90^o$. The intensity versus the entrance angle in radians. The total under the curve should be less then 5% of the main beam flux with solid angle factors. The total amplitude will scale with the total scattering which is linear for this low level of scattering. The incoherent part of the scattering is nearly independent of angle (dipole pattern) but the coherent scattering is generally peaked in the forward (small scattering angles) direction and thus the halo will peak around the direction of the beam.

2.3 What other considerations are important here?

What if you would like to have a polarized source to check that you can measure polarization of the sources? *Next week give reasons for measuring the polarization and then a scheme for a polarized source for the test system.*

What if you wanted to test a detector in the UV (ultraviolet)? What bands would make sense and how good a vacuum would one need?

2.4 Radiation Shielding for Operator

What about shielding of the test chamber operator? What range of X-rays will come out to irradiate the users. See the attached file for 0.56 mm thick copper though one should use the graph for iron (Fe) above since the walls of the vacuum chamber are likely to be stainless steel which is primarily made of iron. (note the Cu (copper) curve has the European style of , instead of . for the decimal point.) What additional shielding or effort is required if a 4 MeV gamma source is used? (see below) E.g. how thick a lead shield would you want?

Figure 2 makes it clear as long as the X-ray source is operated below about 20 keV maximum energy there is sufficient shielding with the vacuum vessel and some distance (order 5 m) through the air. Below 10 keV is clearly no issue. X-rays above 30 keV would be a serious problem and the range between 20 and 30 keV requires extra shielding.

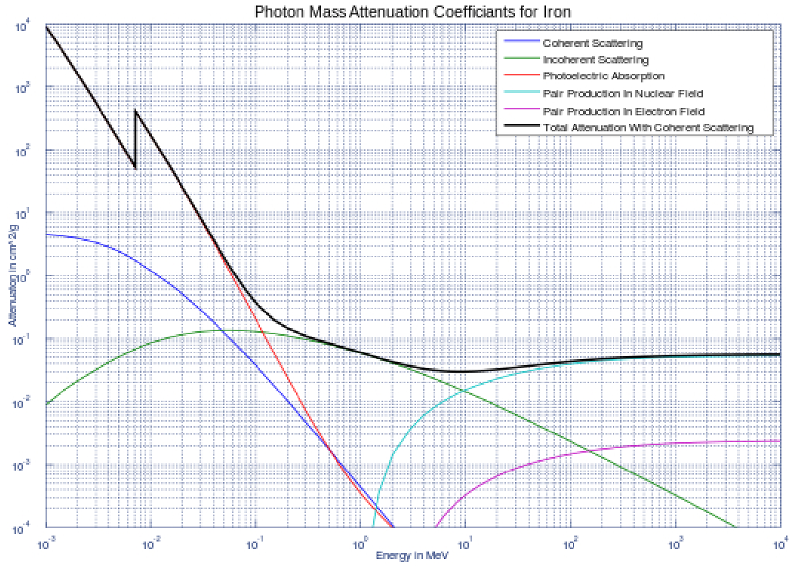


Figure 4: Figure showing X-ray mass attenuation coefficients for iron.

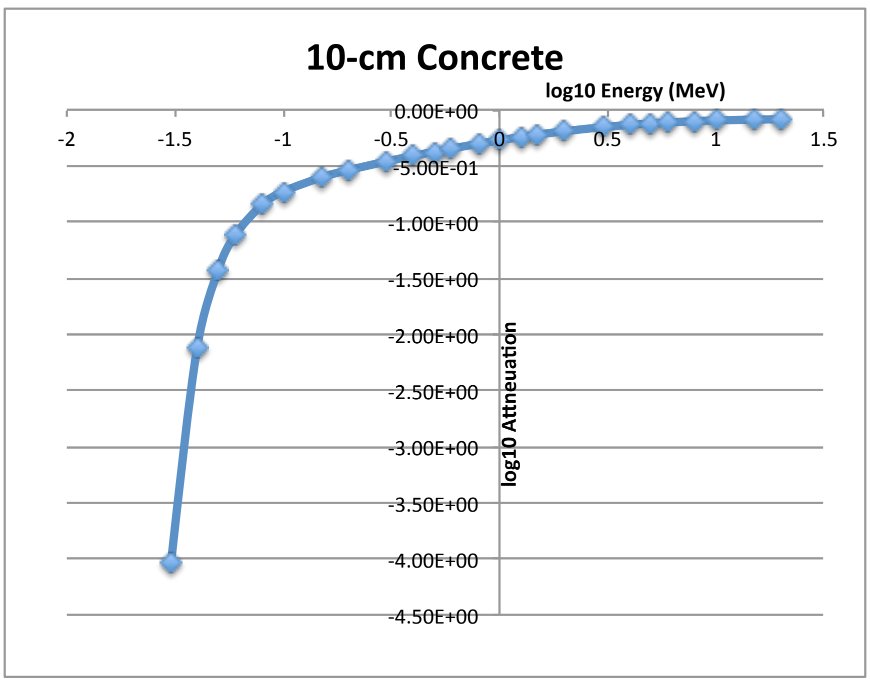


Figure 5: Figure showing X-ray attenuation from about 10 keV (log10 (E in MeV) = -2) to nearly 30 MeV shown as log10 of the attenuation. I.e. about 10^{-4} (-4) at 30 keV.

What does the shielding of 1-cm of iron (Fe) do for the operator? The density of stainless steel is about 8 gm/cm^3 which is slightly more than plain iron. We can estimate the attenuation due to 1-cm iron using the simple formula

$$I/I_0 = e^{-(\mu/\rho)x} = e^{-\mu(E)\times 8\times 1} = e^{-8\mu\ g/cm^2}$$

and simply look on the chart of figure 4 to find $\mu(E)$ for the energy we want. Fo example the mass attenuation of 15 keV X-rays by iron is about 100 cm^2/gm giving a net attenuation of $e^{-800} = 10^{-347}$, while for 100 keV X-rays the mass attenuation is about 0.35 cm^2/gm yielding a net attenuation of about $e^{-2.8} = 10^{-1.2}$ or about 10% getting through which is much too high. The break point is some where around 40 keV which has a mass attenuation coefficient of about 3.5 cm^2/gm and thus an attenuation of about $e^{-28} = 10^{-12}$, which is likely to be enough.

Likewise, when we look at a concrete wall or floor to protect others in the building or an unshielded source we find that for 30 keV X-rays or lower 10-cm thickness of concrete is sufficient. See figure 4 which assumes normal concrete with a density of 2.4 gm/cm^3.

If one needed more shielding for more energetic gammas, see next question, then one could make the concrete containing higher-Z materials or make lead or other dense high-Z special liners. *Problem for those working there is how much is actually needed?*

2.5 What is needed length of X-ray vacuum test chamber?

Ideally one would want a very long distance to have the X-rays appear to come approximately from astronomical distances. However the size of the vacuum chamber is necessarily limited by space available and other costs such as vacuum pipes and pumps to create sufficient vacuum.

For a detector at a distance D from the source which is finite, what is the consequence? The effective wavefront instead of being a plane wave will be curved. This matters for any system with optical focusing and also for any coded mask or occulting system.

For example, consider a detector on the scale of $w = 0.5$ meters in cross section. It will extend $w/2 = 0.35$ m from the center line transverse to a source on axis. At a distance D from the front to the source, the wave front will make an angle α with $sin\alpha = w/2D$ for our example of $w = 0.5$ m and $D = 5$ m, $sin\alpha = w/2D = 0.05$, the small angle approximation is good and $\alpha \simeq 0.05 radians = 2.86°$. This does not seem too bad. At half the distance (2.5 m) the effect is roughly twice as large. This is enough to make the grazing incidence optics not function.

Consider the effect on software for a coded mask which first needs to be modified to take into account the effective magnification of the coded mask on the detector plane of roughly 5 per cent from zero at the center to the full 5% at the detector edge fort 5 meters and with secondary effects of the slight change in mask shape at the varying illumination angle. Again at $D = 5$m this seems reasonable. At half the distance, the effect is twice as large and less of a test of the flight software and instrumentation. It could be manageable, if space is tight but it is better to design a longer test chamber when possible.

3 Gamma Ray Source Considerations

What is the gamma-ray flux from a standard Americium source? That is how many gamma rays per unit time per unit area. For a raw strong source exposed the x-ray plus gamma flux is about a million photons per second. If it is put in a collimating pipe so that the gammas must pass out through the end of the tube and then go to reach the detector, only a faction of these photons reach the detector. See attached figure for collimator design How does that depend upon the distance of the source from the detector? How does that compare to background of cosmic rays? How close would you need to move the source to get a good ratio of signal to noise? Make a sketch of the test set up design. Does it need to be in a vacuum test chamber? Remember that a standard source is set by safety requirements.

A standard Americium 241 source has an activity level of about 10^6 gammas per second. By far the largest and most widespread use of americium-241 is as a component in household and industrial smoke detectors, where a small amount is used in an ionization chamber inside the detector. It is the radiation source for a number of applications: medical diagnostic devices, research, fluid-density gauges, thickness gauges, aircraft fuel gauges, and distance-sensing devices, all of which utilize its gamma radiation.

A mixture of americium-241 and beryllium provides a neutron source for industrial devices that monitor product quality. Two examples are devices for nondestructive testing of machinery and gauges for measuring the thickness of glass and other products. Some properties are: Half Life: 432 Years, Primary Emission: Neutron, Primary Energy: 2-10 MeV.

The amount of Americium in a typical new smoke detector is 1 microcurie (37 kBq) or 0.28 microgram. (One Curie is 3.7×10^{10} decays per second. So a micro curie is about 3.7×10^4 decays per second.) To get to 10^6 per second one would need a source 30 times stronger.

Consider the source in the Choi et al design shown in the accompanying Figure

6, where the resultant answer is shown. The source is in a long copper cylinder with a lead (Pb) plug in the end with a small 1 mm hole in the end and and over all effective length of about 230 mm. The solid angle is about $\Omega = 1mm \times 1mm/(230mm)^2 = 1/53000 = 1.9 \times 10^{-}5$ radian squared. This is to be compared to the total solid angle of a sphere of 4π sterradians or a ratio of 1.5×10^{-6}. Thus if the bare source had a decay rate of 10^6/sec one would expect about 1.5 coming in the direction of the exit. The measured rate is 0.33 photons per second. This is probably about right given the various issues and internal scattering.

This is a low rate as cosmic rays at sea level appear at roughly the rate of a few per second for a 20-cm square detector.

Why would one have the source reduced to such a small solid angle (except for radiation shielding to those in the lab)? There are times when one wants to know the gamma-rays to come from a well-defined angle or distance. That low flux compared to the cosmic ray rate is an issue.

If one has a 20-cm width detector and the source is 5 meters away, then the solid angle (round or roughly square detector) would be about $\Omega = (0.2/5)^2 = 1.6 \times 10^{-3}$ or about 1000 times greater or about 300/sec. This would be enough to allow the user to deal with the cosmic ray background as a nuisance background.

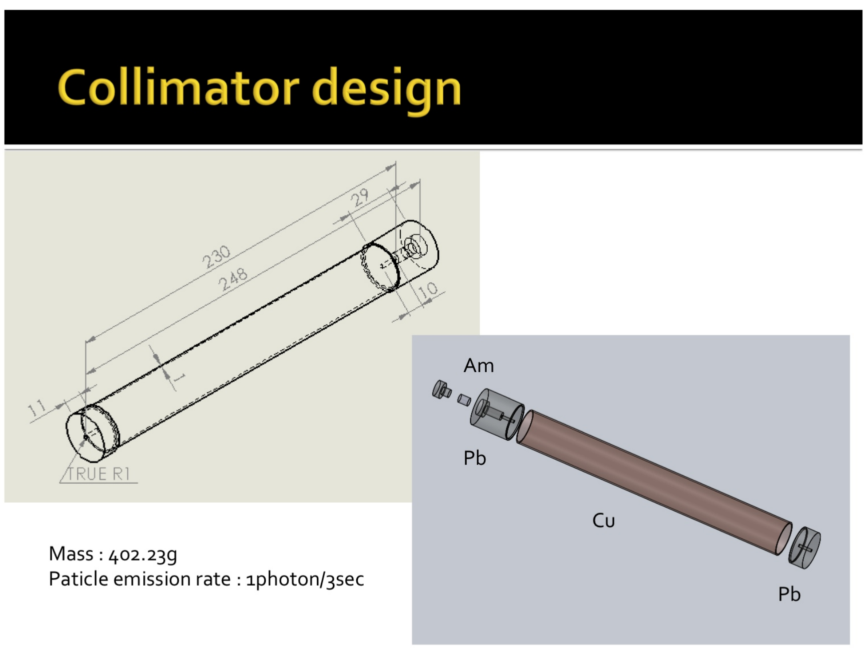


Figure 1: Americium 241 Source and Collimator Design from Choi et al.

Figure 6: Figure Americium 241 collimated source design from Choi et al..