Exp. Methods in Astroparticle Physics (SS 2020) - Problem sheet 4

Tutorial: Luisa Hötzsch (luisa.hoetzsch@mpi-hd.mpg.de)

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Direct Detection of Dark Matter, part I

4.1 Expected Dark Matter rates *6 Points*

Imagine you are an experimentalist in a collaboration working on the direct detection of dark matter. To detect possible WIMP scattering events, you are considering two different detector types. The first is based on a germanium target and the second has a xenon target. The characteristics of the two targets are listed below.

		Germanium	**Xenon**
Energy Threshold	E_t	$1\,\mathrm{keV/c^2}$	$5\,\mathrm{keV/c^2}$
Energy Interval	ΔE	$(1-40)\,\mathrm{keV/c^2}$	$(5-40)\,\mathrm{keV/c^2}$
Target Mass	M	$1\,\mathrm{kg}$	$35\,\mathrm{kg}$
Target Element Mass	m_A	$65\,\mathrm{GeV/c^2}$	$122\,\mathrm{GeV/c^2}$
Mass Number	A	73	131

Your goal is to provide the best possible limit on a theory predicting a

- light dark matter candidate $M_\chi = 5\,\mathrm{GeV/c^2}$,
- heavy dark matter candidate $M_\chi = 500\,\mathrm{GeV/c^2}$,

In both cases the commissioned runtime is $T = 100\,\mathrm{days}$.

a) Since the WIMP-nucleus relative speed is of order $100\,\mathrm{km/s}$, elastic WIMP scattering occurs in the extreme non-relativistic limit. Direct detection experiments are limited by the nuclear recoil energy threshold of the target material E_t . In terms of the velocity v of the dark matter particle and the center of mass frame scattering angle θ, the recoil energy E is given by

$$E = v^2 \frac{\mu_N^2}{m_A}(1 - \cos\theta), \tag{1}$$

in which the reduced mass is given by $\mu_N = \frac{m_A M_\chi}{m_A + M_\chi}$. Using equation 1, compute the minimal velocity v_{min} needed to generate a detectable energy deposit in the germanium and xenon detector, for the two dark matter masses given above (i.e. give four values of v). Note that v is given as a fraction of $c = 3 \cdot 10^5$ km/s using the units in the table.

b) Assume that the dark matter velocity distribution is isotropic, spherically symmetric and follows a Maxwell-Boltzmann distribution

$$f(\mathbf{v}) = N e^{-\mathbf{v}^2/v_0^2}, \tag{2}$$

with $v_0 = 220\,\mathrm{km/s}$ being the circular velocity of the dark matter halo and $N = 1/(\sqrt{\pi}v_0)^3$. Integrate out the angular dependencies so that you can sketch the function with respect to v. Indicate the values which you have derived in part a). Does it even make sense to consider very fast dark matter particles or should the velocity distribution be truncated at a certain speed v_{max}?

c) The expected rate for WIMP interactions can be expressed as

$$R \approx \frac{A^2}{2\mu_P^2\, M_\chi}\,\sigma_0\,\rho_\chi \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv \cdot \Delta E, \tag{3}$$

in which $\mu_P = \frac{m_N M_\chi}{m_N + M_\chi}$ is the reduced mass of the dark matter and a nucleon (either proton or neutron) $m_N \approx 1\,\mathrm{GeV/c^2}$. The local dark matter density $\rho_\chi = 0.3\,\mathrm{GeV/cm^3}$ and the velocity distribution given above are astrophysical inputs. The mass of the dark matter candidate and the cross section $\sigma_0 = 1 \cdot 10^{-45}\,\mathrm{cm}^2$ are quantities provided by your particle physics colleague. Compute the expected number of events $N = R \cdot T \cdot M$ for the two detectors and both the heavy and light dark matter candidate. (Make sure you are using consistent units!)

d) Explain the limiting features of the two detectors that were considered.

4.2 Gamma-ray background mitigation: Detector self-shielding *4 Points*

There are three main processes that lead to attenuation of photons as they propagate through matter: The photoelectric effect, Compton scattering and e^+e^- pair production. Each of these processes is dominant for photons of a given energy range. The gamma ray attenuation length of xenon at different photon energies is shown in Figure 1.

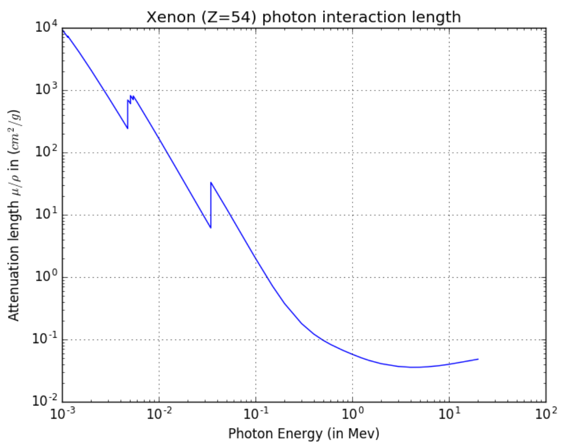


Figure 1: Photon attenuation length in xenon for different energies [1].

The intensity $I(x)$ of gamma rays after traversing a certain distance x within a medium can be computed using

$$I(x) = I_0 \cdot e^{-x\mu} \tag{4}$$

where I_0 is the initial intensity of the gamma radiation and μ is the absorption coefficient of the material.

[1] Data available at (`https://physics.nist.gov/PhysRefData/XrayMassCoef/ElemTab/z54.html`)

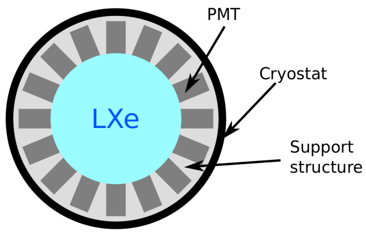
a) Some radioactive isotopes commonly found in detector materials are listed in the table below. Look up the energy of their (dominant) gamma emission line and estimate the corresponding attenuation length μ in liquid xenon ($\rho_{Xe} \approx 3\,\mathrm{g/cm^3}$) using Figure 1.

Isotope	^{137}Cs	^{208}Tl	^{40}K	^{214}Pb	^{60}Co$^{*)}$	^{60}Co$^{*)}$
Energy [MeV]						
$\mu\,[\mathrm{cm}^{-1}]$						

$^{*)}$ Find both characteristic lines

(*Hint: Commonly used databases with nuclear decay data can be found here:*
`http://nucleardata.nuclear.lu.se/toi/`
or here:
`https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html`)

b) You want to operate a liquid xenon detector with an active mass of 2 tons. For simplicity we assume a spherical detector, with a central liquid xenon (LXe) target and photo sensors (PMTs) which are fixed around it using a support structure.



Now consider that all detector materials except of the liquid xenon contain trace amounts of the above listed isotopes. To simplify further, assume that the photon emission is always directed towards the center and that they do not loose any energy before they reach the xenon volume.

In order to reduce the background from this gamma radiation for the dark matter search, we can "fiducialize" the data (discard events that happen in the outermost LXe layer). Assume that we need to reduce the gamma induced background by one order of magnitude and evaluate for each of the isotopes the fraction of the active LXe mass that remains after applying the fiducialization.

2 Bonus Points:

With the result of both problems on this sheet in mind, discuss which kind of detector you would choose to build. In order to increase the exposure of the detectors, consider whether you would either operate one larger detector or several smaller ones (assuming the same total target mass).