Annual Modulation in DM Direct Detection

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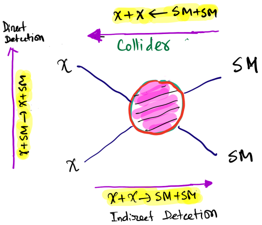
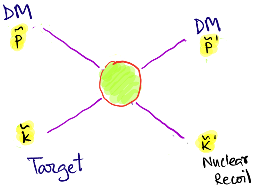
Outline

Experimental constraints on dark matter scenarios

- the main experiment types: dark matter direct and indirect detections, and collider searches.





- 2 body scattering has two possiblities.
  - Elatic Scattering
  - Inelastic Scattring

Events Kinematics at LEGEND

k is the number of target nuclei per kg, σ DM-nuclei scattering cross section

- Events rate R

$$R = k \cdot \phi \cdot \sigma$$

- DM flux ϕ

$$\phi = n_0 v_{DM} = \frac{\rho_{DM} v_{DM}}{m_\chi}$$

- $\sigma = 10^{-41} cm^2, v_{DM} = 220 km/s, Target\,^{76}Ge, 1000 kg$

$$R = 4 - 5\,Events/year$$

- LEGEND can be interesting for RoI less than 10 GeV DM

Recoil Energy?

The relevant physics can be identified if we examine the kinematics of DM-Nucleus scattering more closely.

- Initial K.E, $E_i = \frac{p^2}{2m_\chi}$
- Final K.E, $E_f = \frac{p'^2}{2m_\chi} + \frac{q^2}{2m_T}$
- Momentum Conservation $p + k = p^{'} + q$, q=momentum transfer

Deposited energy (Recoil energy of the nucleus) is

$$E_R = \frac{q^2}{2m_T} = \frac{\left(\vec{p} - \vec{p'}\right)^2}{2m_T}$$

Max momentum transfer

$$|q|_{max} = \frac{2\mu_T |p|}{m_\chi}$$

- For Ge-76, $|q|_{max} = 140 MeV \Rightarrow \boxed{E_R|_{max} = 140 KeV}$

Elastic Scattering Process

$$a(p) + b(k) = a(p') + b(k')$$

$$DM + Target = DM + NR$$

a=DM , b=Target

Differential Scattering Cross-Section

- COM Frame

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} \frac{|\vec{p_a'}|}{|\vec{p_a}|} |\bar{M}|^2$$

$$d\Omega = d\cos\theta d\phi$$

- For a scattering process we need to find

$$\vec{p_a}, \vec{p_a'}, s, d\Omega$$

- NR-EFT gives matrix elemnts M and Kinematics gives the pre-factor!

Non-Relativistic Limit

From DM velocity distribution, DM speed is (220-235)km/s i.e $v_{DM} \gg c$, NR limit works well!

- COM Energy

$$\sqrt{s} = E_p + E_k = m + \frac{p^2}{2\mu_T} + m_T$$

$$s = E_p + E_k = \left(m + m_T + \frac{p^2}{2\mu_T}\right)^2 = (m+m_T)^2\left(1 + \frac{p^2}{2\mu_T(m+m_T)}\right)^2$$

- Taking leading order term the COM energy becomes,

$$s \overset{NR}{\approx} (m + m_T)^2$$

$$|\vec{p_a}| = |\vec{p_a}^{\,\prime}| = \mu_T V_{rel}$$

$$V_{rel} \equiv V_{DM} - V_{Target}$$

Physical Process

$$\frac{d\sigma}{d\cos\theta d\phi} = \frac{1}{64\pi^2(m+m_T)^2}|\bar{M}^2|$$

"We make substitutions:"

- Spin Independent Interaction,

$$|\bar{M}|^2 \stackrel{NR}{=} 16m^2 m_T^2 \left(Zf_p + (A-Z)f_n\right)^2 F_{SI}^2(E_R)$$

, $F_{SI}^2(E_R)$ is Helm Factor.

- $d\phi = 2\pi$
- $d\cos\theta$ can be obtained from energy recoil

$$E_R = \frac{\mu_T^2 v^2}{m_T}(1-\cos\theta) \Rightarrow \boxed{\frac{d\sigma}{dE_R} = \frac{m_T}{2\pi v^2}\left[Zf_p + (A-Z)f_n\right]^2 F_{SI}^2(E_R)}$$

Rate Spectrum

Boltzmann Equation for photon distribution in presence of collision with plasma in a galaxy cluster or any other medium,

$$[Zf_p + (A - Z)f_n]^2 = \frac{\sigma_o \pi}{\mu_T^2} \tag{1}$$

$$\frac{dR(E_R, t)}{dE_R} = \frac{\zeta_T}{m_T} \frac{\rho}{m} \int_{v \geq v_m in(E_R)} \frac{d\sigma}{dE_R} v f_E(v, t) d^3 v \tag{2}$$

$$\frac{dR(E_R, t)}{dE_R} = \sum_T \zeta_T \frac{\rho}{m} \frac{\sigma_p}{2\mu_N^2} \left[Z + (A - Z)\frac{f_n}{f_p} \right]^2 F_{SI}^2(E_R)\, \eta_0\, (v_{min}, t)$$

Velocity Integral

When $t = 0$, we set $V_E = v_{ini}$ km/s and for v_{min} we can have choice of values

$$R_0 = \frac{N_A \times 10^3}{A}\frac{\rho}{m}\sigma_0 v$$

R_0 usually denoted in evts/kg/day

Then R can be written as,

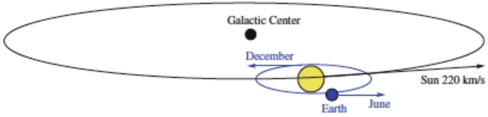
$$\frac{dR(E_R,t)}{dE_R} = \frac{R_0 \times m_T}{2\mu_T^2 A^2 v}\left[Z + (A-Z)\frac{f_n}{f_p}\right]^2 F_{SI}^2(E_R)\,\eta_0\left(v_{min},t\right)$$

With Standard Halo Model DM velocity distribution,

$$\eta_0(v_{min},t) = \int_{v \geq v_{min}}^{v_{esc}=\infty} \frac{f_E(v,t)}{v} d^3v = \frac{1}{2V_E}\left[erf\left(\frac{v_{min}+V_E}{v}\right) - erf\left(\frac{v_{min}-V_E}{v}\right)\right]$$

Earth motion around the Sun

The velocity integral and scattering rate depends on time through the variation of the DM flux on earth due to the earth's motion around the sun.



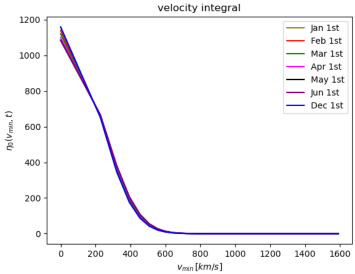
A good approximation one can represent the annual modulation of the orbit of the Earth around the sun by,

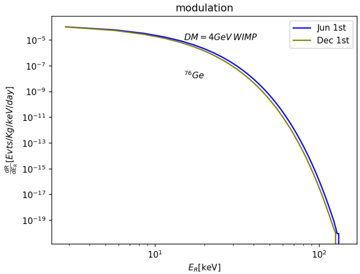
$$V_E(t) = 232 + 15\cos\omega\,(t - 152.5\,days)\ km/s$$

$$V_E(t) = V_E = 232 + 15\cos\left(2\pi\frac{t - 152.5\,days}{1\,Yr.}\right) km/s$$

$$1\,Yr = 365.25\,days$$

Modulation





- When $v_{min} \gg V_E$ $E_R \gg 10KeV$, the population of WIMP with a high velocity is Boltzmann suppressed, diffrential rate which mainly depends on velocity integral $\eta_0(v_{min}, t)$ rapidly converges to zero.
- We notice that DM less than 10 GeV gives a measureable spectrum at very low energy recoil 0-20 KeV.

Comments

- Need to integrate the rate spectrum including the detector's efficiency and cut acceptance,the experimental threshold, and an upper E_R value
- Bayesian analysis and MC sampling is interesting to study the parameter space i.e mass-cross section plot(ref. Prof.Laura Baudis's paper).
- Need to compute rate spectrum for other velocity distributions and compare it with each other to see their effect on rate spectrum for Ge-76.

Comments

Thank You and Suggestions