DIRECT DARK MATTER DETECTION

I) physics of WIMP direct detection

II) annual modulation and WIMP direct detection techniques

III) particle physics uncertainties : cross section

IV) channeling effect

Main References :

I) ISAPP 2008 lectures (http://dark.ft.uam.es/isapp2008/)
→ Stefano Scopel

Bernabei, Dark Matter Search, Lectures given at the Summer School on Astroparticle Physics and Cosmology, Trieste 17 June - 5 July 2002

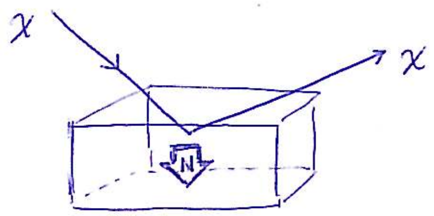
II) ISAPP 2008 lectures
→ Rita Bernabei talk
→ Maria Luisa Sarsa

III) Jungman et al., Phys. Reports 267 (1996) 195 - 373

Bottino et al., Astroparticle Physics 18 (2002) 205 - 211

IV) Bernabei et al., Eur. Phys. J. C 53, 205 - 213 (2008)

Physics of WIMP direct detection: main formules



Elastic recoil of non relativistic halo WIMPs off the nuclei of an underground detector

WIMP differential detection rate:

$\rightarrow \# \cdot \frac{\#}{cm^3} \cdot \frac{cm}{s} \cdot \frac{cm^2}{E} = \frac{1}{s \cdot E}$ ok|

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{v_{max}} \underbrace{d^3\vec{v}\; f(\vec{v})}_{\text{normalized}} \; |\vec{v}| \; \frac{d\sigma(\vec{v}, E_R)}{dE_R}$$

$\rightarrow$ dependence $\frac{1}{v^2}$

E_R = nuclear energy
N_T = # of nuclear targets
v = WIMP velocity in the Earth's rest frame

Astrophysics

ρ_χ = WIMP local density
$f(v)$ = WIMP velocity distribution function

Particle and nuclear physics

$$\frac{d\sigma}{dE_R} = \left(\frac{d\sigma}{dE_R}\right)_{coherent} + \left(\frac{d\sigma}{dE_R}\right)_{spin\text{-}dependent}$$

$\propto$ (atomic #)^2 $\Rightarrow$ dominant contribution.

$\Rightarrow$ The RECOIL ENERGY of the nucleus is given by:

$$E_R = \frac{1}{2} m_W v^2 \quad \frac{4 m_W m_N}{(m_W + m_N)^2} \quad \frac{1-\cos\theta^*}{2}$$

kinetic energy of incoming WIMP

"mass-matching" factor

angular factor
θ^* = angle between the WIMP and the nucleus in the center of mass

- A detector containing a light nuclear target is more sensitive to lighter WIMPs.

- $E_R^{max} = \frac{1}{2} m_W v^2 \frac{4 m_W m_N}{(m_W + m_N)^2}$
  when $\theta^* = 1$
  head-on recoil

The WIMP incoming velocity is $v \sim 10^{-3} c$

$$E_R^{max} = \frac{1}{2} m_W \cdot 10^{-6} \frac{4 m_W m_N}{(m_W + m_N)^2} = 2 \left(\frac{m_W}{m_W + m_N}\right)^2 \cdot \left(\frac{m_N}{GeV}\right) \text{ keV}$$

The expected energy is of the order of keV.

CROSS SECTION

isotropy of the cross section

$$\frac{d\sigma}{d\cos\theta^*} = \frac{\sigma}{2} = \text{constant} \qquad \left(E_R = E_R^{max} \frac{1+\cos\theta^*}{2}\right)$$

$$\frac{d\sigma}{dE_R} = \frac{d\sigma}{d\cos\theta^*} \cdot \frac{d\cos\theta^*}{dE_R} = \frac{\sigma}{2} \cdot \frac{2}{E_R^{max}} = \frac{\sigma}{E_R^{max}}$$

Form factor:

$$\sigma \rightarrow \sigma_0 \cdot F^2(q)$$

$q = \sqrt{2 m_N E_R}$ momentum transfer

$$\Rightarrow \frac{d\sigma}{dE_R} = \frac{\sigma_0}{E_R^{max}} \cdot F^2(E_R)$$

HELM FORM

$$F(q^2) = \frac{3 j_1(r_0)}{q r_0} e^{-1/2 q^2 s^2}$$

$r_0 = (r^2 - 5s^2)^{1/2}$ $\quad r = 1.2 A^{1/3}$ $\quad s \simeq 1$ fm, thickness of nucleus surface

The differential rate become:

$$\frac{dR}{dE_R} = N_T \frac{\rho_W}{m_W} \cdot \int_{v_{min}} f(v) \cdot v \frac{d\sigma}{dE_R} d^3\vec{v} = \frac{N_T \rho_W}{m_W} \cdot \int_{v_{min}} f(v) \cdot v \frac{\sigma_0}{E_R^{max}} \cdot d^3\vec{v} =$$

$$= N_T \frac{\rho_W}{m_W} \cdot \int_{v_{min}} f(v) \cdot \cancel{v} \, \sigma_0 \frac{m_N}{2 m_{WN}^2 v^{\cancel{2}}} d^3\vec{v} = N_T \frac{\rho_W}{m_W} \cdot \sigma_0 \frac{m_N}{2 m_{WN}^2} \cdot \int_{v_{min}} \frac{f(v)}{v} d^3\vec{v}$$

$= \mathcal{J}(v_{min})$, contains the dependence from the velocity distribution

$$E_R^{max} = \frac{m_W^2 m_N \cdot 2}{(m_W + m_N)^2} \cdot v^2$$

$$m_{WN} = \frac{m_W m_N}{(m_W + m_N)}$$

$$E_R^{max} = \frac{2 m_{WN}^2}{m_N} \cdot v^2$$

$f(v)$ is usually assumed to be a Maxwellian distribution at rest in the Galactic system. ($\rightarrow$ the assumption is an isothermal spherical model for the halo)

$$f_{gal}(v) = \begin{cases} N\left[\exp\left(-\frac{v^2}{\bar{v}^2}\right) - \exp\left(-\frac{v_{esc}^2}{\bar{v}^2}\right)\right] & v < v_{esc} \quad ; \; N = \text{normalization} \\ 0 & v > v_{esc} \end{cases}$$

v → $v_{WIMP}^{\text{Galactic reference frame}}$

$\bar{v} = 220 \; \frac{km}{s}$

$v_{esc} = 650 \; \frac{km}{s}$ → WIMP Maxwellian must be truncated at the escape velocity, because WIMPs faster than v_{esc} are not trapped by the galactic gravitational potential well (otherwise leading to an infinite mass)

WIMP velocity distribution in the Earth rest frame:

$$f_{\oplus}(v,t) = f_{gal}(v + w(t))$$

v → $v_{WIMP}^{\text{Earth ref. frame}}$; $w(t)$ → $v_{Earth}^{\text{Galactic ref. frame}}$

$$w(t) = v_{\odot} + v_{orb} \cos\gamma \cos[\omega(t - t_0)]$$

$$\begin{cases} v_{\odot} \simeq 220 \; \frac{km}{s} & \text{(Sun velocity in the halo)} \\ v_{orb} \simeq 30 \; \frac{km}{s} & \text{(Earth velocity around the Sun)} \\ \gamma = \pi/3 & \text{(the ecliptic is inclined by} \sim 60° \text{ from the galactic plane)} \\ \omega = \frac{2\pi}{T} \;, & T = 1 \text{ year} \\ t_0 = 2^{nd} \text{ of June} & (w(t) \text{ is maximal}) \end{cases}$$

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v_{min} → from E_R ~~threshold~~

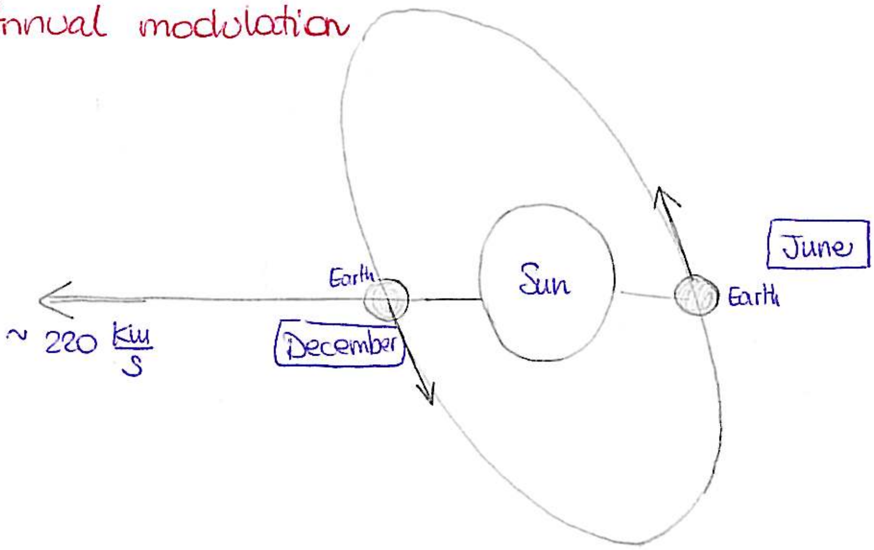
$$E_R^{max} = \frac{1}{\cancel{2}} m_w v^2 \frac{\cancel{4}^{\,2} m_W m_N}{(m_W + m_N)^2}$$

$$\boxed{v_{min} = \frac{m_W + m_N}{m_W} \cdot \sqrt{\frac{E_R}{2 m_N}}}$$

v_{max} → maximal WIMP velocity in the halo (v_{esc}) evaluated in the Earth frame

$$\mathcal{I} \equiv \int_{v_{min}(E_R)}^{v_{max}} d^3v \; \frac{f(v)}{v}$$

Annual modulation



A WIMP-induced seasonal effect must simultaneously satisfy all the following requirements:

1) The rate must contain a component modulated according to a cosine function with one year period
2) a phase that peaks around 2^{nd} of June
3) this modulation must be found in a low energy range where WIMPs induced recoils can be present
4) it must apply just to single hit events, since the WIMP multi-scattering probability is negligible
5) The modulation amplitude must be $\leq 7\%$

↳ Difficult that systematic effects can fulfill all these requirements

The motion of the Earth around the Sun produces a modulation in the dark-matter count rate.

↳ This predicted MODULATION is NOT the result of our assumed velocity distribution → we expect this effect for any velocity distribution that has a cutoff at high velocity.

$$w_{\oplus}(t) = v_{\odot} + v_{orb} \cos\gamma \cos(\omega(t-t_0))$$

↳ the expected rate in given energy bin changes because the annual motion of the Earth around the Sun, moving in the Galaxy)

$$S_k = \int_{E_k} \frac{dR}{dE_R}\, dE_R \simeq S_{0,k} + S_{m,k} \cos(\omega(t-t_0))$$

Few percent effect : $\frac{S_{m,k}}{S_{0,k}} \sim 5 \div 10\ \%$

If $N = \#$ events, assuming a 5% effect a 5σ discovery requires:

$$\underbrace{\frac{5}{100}}_{\text{modulation amplitude}} \cdot N > 5 \cdot \underbrace{\sqrt{N}}_{\text{Poissonian fluctuation}}$$

$\hookrightarrow N > 10'000$ events

Expected events

$$N_T\, n_\chi\, \sigma\, v_\chi \simeq 6{,}02 \cdot 10^{23} \frac{1}{10^{-3}\,kg} \cdot \frac{0{,}3\ GeV/cm^3}{50\ GeV} \cdot \overbrace{10^{-6}\,pb}^{10^{-42}\,cm^2} \cdot 10^{-3} \cdot 3 \cdot 10^{10}\,\frac{cm}{s} \simeq$$

$$\simeq \underbrace{\frac{6{,}02 \cdot 0{,}3 \cdot 3}{50}}_{0{,}1} \cdot \underbrace{10^{23+3-42-3+10} \cdot \frac{1}{1{,}157 \cdot 10^{-5}}}_{0{,}864 \cdot 10^{-4}} \cdot \frac{1}{kg \cdot day} \simeq$$

$$\underbrace{\simeq 0{,}08 \cdot 10^{-4}\ \frac{1}{kg \cdot day}}_{\text{(there is also a dependence on A !)}}$$

$$\sigma_{\chi S} = A^2 \cdot \sigma_{\chi N} \cdot \left(\frac{(\cancel{m_\chi}\, m_S)\ (m_\chi + m_p)}{(m_\chi + m_S)\ \ \cancel{m_\chi}\, m_p} \right)^2 \simeq A^2\ \sigma_{\chi N}$$

mass number : A
atomic # : Z

$$N_T^S = \frac{6{,}02 \cdot 10^{23}\ \frac{1}{mol}}{A\ (g/mol)} = \frac{N_T^N}{A}$$

WIMP Direct Detection techniques

WIMP detectors → low threshold
→ ultra low background
→ high mass detector

When a WIMP interacts with a nucleus, the nuclear recoil can induce different signals: heat, ionization and scintillation

We have also HYBRID detectors that profit from the simultaneous measure of two channels

CHARGE <=> LIGHT

⇖⇘ HEAT ⇙⇗

light & ionization detectors: ZEPLIN, XENON, WARP, ArDM

ionization — scintillation

phonon

heat & ionization bolometers: CDMS, EDELWEISS

light & heat bolometers: CRESST

PURE SCINTILLATION experiments → DAMA/LIBRA
→ KIMS 3 keVee threshold
→ ANAIS 2 keVee threshold

+ other experiments for neutrinoless $\beta\beta$ decay (GERDA, CUORE, ...)

<u>IONIZATION detectors</u>: collect the charge carriers produced by a particle interaction

<u>SCINTILLATION detectors</u>: collect the light produced by a particle interaction

<u>THERMAL detectors</u>: directly sensitive to the heat (phonons, lattice vibrations) produced by a particle interaction

<u>BUBBLE CHAMBERS</u>: superheated liquids where heat released by a particle is able to produce the nucleation of a vapor phase.
COUPP
PICASSO

Background

↳ separation of nuclear recoils from electron recoils

↳ neutrons background:

Thorium Th, Uranium U, potassium K

- low energy neutrons (< 10 MeV) from fissions and (α, n) reactions in the surrounding rocks and concrete of the laboratory
- low energy neutrons from fission in the shielding material and experimental set up.
- high-energy neutrons induced by muons in the rock or in the shielding material

  ↳ Two main reactions of muons with nuclei:

  - μ^- capture: muons stopped in matter either decay $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$ or are captured by a nucleus
    $\mu^- + p \to n + \nu_\mu$
    the energy transfered to the nucleus is $E \sim 15\text{-}20$ MeV
    ↳ above the neutron emission threshold.
  - DIS of μ^- on nuclei: virtual γ radiated from cosmic muons interact with a nucleus and can produce one or more high-energetic spallation neutrons

Scattering cross section

The differential cross section of the WIMP-nucleus elastic processes can be written as:

$$\frac{d\sigma}{dE_R} = \left(\frac{d\sigma}{dE_R}\right)_{SI} + \left(\frac{d\sigma}{dE_R}\right)_{SD}$$

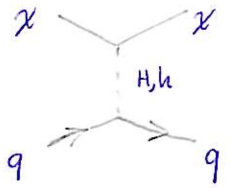
Among SI contribution: <u>scalar interaction</u>

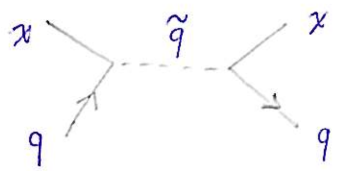
$$\mathcal{L}_{scalar} = f_q\, \bar{\chi}\chi\, \bar{q}q$$

Matrix element

$\hookrightarrow$ $\langle \chi | \bar{\chi}\chi | \chi \rangle \longrightarrow 1$ spinor normalization

$\hookrightarrow$ quarks scalar interaction:
in the case of Neutralino the main contributions arise from squark exchange and Higgs exchange.





$\Leftrightarrow$ coupling proportional to

$m_q \langle N | \bar{q}q | N \rangle$ $\longrightarrow$ can be related to the nucleon mass (see part on hadronic uncertainties)

(N: nucleon)

(this part do not distringuish between proton and neutron, because it depends from the content of quark s and heavy quarks in the nucleon)

$$m_q \langle N | \bar{q}q | N \rangle \longrightarrow \underbrace{g_q}_{\text{function of the nucleon mass}}\ \underbrace{\bar{\Psi}_N \Psi_N}_{\text{nucleon wave function}} \longrightarrow \langle \underbrace{\mathcal{N}}_{\text{nuclei}} | \bar{\Psi}_N \Psi_N | \mathcal{N} \rangle \longrightarrow \underbrace{A}_{\text{number of nucleons inside the nucleus}}$$

The matrix element for scalar interaction will be:

$$\mathcal{M}^{(coh)} = \langle N, \chi | \underset{\substack{\downarrow \\ \text{low energy} \\ \text{effective lagrangian}}}{\mathcal{L}_{eff}^{(coh)}} | N, \chi \rangle = \sum_{\substack{q= \\ s,c,b,t}} C_q^{(coh)} \, g_q \, A$$

$C_q^{(coh)}$: couplings arised from the particle physics model

g_q: contains nucleon mass, $\sigma_{\pi N}$, σ_0, ...

Cross section:

$$\frac{d\sigma_{elastic}}{dE_R}(v, E_R) = \underbrace{\frac{d\sigma}{dE_R}(v, 0)}\, F^2(E_R)$$

$F^2(E_R)$: nuclear form factor

$$\hookrightarrow \frac{d\sigma}{dE_R}(v,0) = \frac{\sigma}{E_R^{max}}$$

$$E_R^{max} = \frac{2 m_{red}^2 v^2}{m_N} \qquad m_{red} = \frac{m_N \, m_\chi}{(m_N + m_\chi)^2} \quad \text{nucleus}$$

$$\sigma_{el}^{(coh)} = \frac{m_{red}^2}{\pi} A^2 \sum_q \left(C_q^{(coh)} g_q \right)^2$$

m_{red}: with mass of the nucleus

SD contribution: <u>axial-vector interaction</u>

$$\mathcal{L}_{AV} \propto (\bar{\chi} \gamma^\mu \gamma_5 \chi)(\bar{q} \gamma_\mu \gamma_5 q)$$

Matrix element

$$\hookrightarrow \langle \chi | (\bar{\chi} \gamma_\mu \gamma_5 \chi) | \chi \rangle \longrightarrow \propto 2 \langle \chi | (\bar{\chi} \vec{S}_\chi \chi) | \chi \rangle$$

$\hookrightarrow$ quarks axial-vector interaction:

$$\underset{\text{nucleon}}{\langle N |} (\bar{q} \gamma_\mu \gamma_5 q) | N \rangle \longrightarrow \propto 2 \, S^{(N)} \, \Delta q^{(N)}$$

$S^{(N)}$: spin of the nucleon

$\Delta q^{(N)}$: fraction of the nucleon spin carried ~~from~~ by the quark q.

Nuclear matrix element: evaluation of the matrix elements of the nucleon spin operators in the nuclear state.

At zero momentum transfer ⇒ calculate the average spins for neutrons and protons in the given nucleus

Nonzero momentum transfer ⇒ there is also a form-factor suppression (calculated from nuclear wave functions)

↳ $\langle N | \vec{S}_p | N \rangle$ and $\langle N | \vec{S}_n | N \rangle$ (**)

These quantities are calculated with nuclear shell model or the "odd-group" model (this last model assumes that all the nuclear spin is carried by the proton or the neutron, whichever is most unpaired. In this case only one of either $\langle S_n \rangle$ or $\langle S_p \rangle$ is non zero)

Usually in literature (**) are written as a function of the spin of the nucleus $\vec{J}$:

$$\langle N | \vec{S}_{p,n} | N \rangle = \lambda \langle N | \vec{J} | N \rangle$$

The matrix element for axial-vector interaction is:

$$\mathcal{M}^{(spin)} = 4 \sum_{\substack{q \\ u,d,s}} \underbrace{C_q^{(spin)}}_{\text{contains also } \langle \chi | \vec{S}_\chi | \chi \rangle} \Delta q \; \lambda \langle N | \vec{J} | N \rangle$$

Cross section:

$$\sigma^{(spin)} = \frac{m_{red}^2}{\pi} 4 \lambda^2 J(J+1) \sum_q \left(C_q^{spin} \Delta q \right)^2$$

contains Δq, different for protons and neutrons

$\sigma_{\chi N}^{SI} = \dfrac{M_{red}^2(M_{nucleus})}{M_{red}^2(M_p)} \cdot A^2 \cdot \sigma_{\chi p}^{SI}$	$\sigma_{\chi N}^{SD} = \dfrac{M_{red}^2(M_{nucleus})}{M_{red}^2(M_p)} \cdot \dfrac{J(J+1)\lambda^2}{J_p(J_p+1)} \cdot \sigma_{\chi p}^{SD}$ $3/4$

We could also have pure vector interaction, but in the case of NON Majorana particle. Indeed a Majorana particle does not have a vector current, since

$$\underbrace{\bar{\nu}^c \gamma_\mu \nu^c}_{\substack{\shortparallel \\ \bar{\nu} \gamma_\mu \nu}} = - \bar{\nu} \gamma_\mu \nu$$

for Majorana particle

WIMP-nucleon cross section : hadronic uncertainties

Let's consider the neutralino case as example.

$\downarrow$

The neutralino- nucleon scalar cross section $\sigma^{(nucleon)}_{scalar}$ is due to:

1) exchanges of two CP-even Higgs boson : h, H (t - channel)
2) squark - exchanges (s- and u- channels)

For the case 1), we have that the couplings between the Higgs bosons and the nucleons may be written as:

$$I_{h,H} = \sum_q \underbrace{K_q^{h,H}}_{\text{supersymmetric parameters}} \; \underbrace{m_q}_{\text{quark mass}} \; \underbrace{\langle N | \bar{q} q | N \rangle}_{\text{scalar density of the quark } q \text{ in the nucleon}}$$

Evaluation of the quantities $m_q \langle N | \bar{q} q | N \rangle$

For the calculation of the quantities $m_q \langle N | \bar{q} q | N \rangle$, it is useful to express them in terms of the pion- nucleon sigma term

$$\sigma_{\pi N} \equiv \frac{1}{2} (m_u + m_d) \langle N | \bar{u}u + \bar{d}d | N \rangle ,$$

of the quantity σ_0 (related to the size of SU(3) symmetry breaking)

$$\sigma_0 \equiv \frac{1}{2} (m_u + m_d) \langle N | \bar{u}u + \bar{d}d - 2\bar{s}s | N \rangle ,$$

and of the ratio

$$r = \frac{2 m_s}{m_u + m_d} .$$

Assuming isospin invariance for quarks u and d, we can write

$$\begin{cases} m_u \langle N | \bar{u}u | N \rangle \simeq m_d \langle N | \bar{d}d | N \rangle \simeq \frac{1}{2} \sigma_{\pi N} \\ m_s \langle N | \bar{s}s | N \rangle \simeq \frac{1}{2} r (\sigma_{\pi N} - \sigma_0) \end{cases}$$

For the quarks c, b, t, one can use the heavy quark expansion and obtain:

$$m_c \langle N|\bar{c}c|N\rangle \simeq m_b \langle N|\bar{b}b|N\rangle \simeq m_t \langle N|\bar{t}t|N\rangle \simeq$$

$$\simeq \frac{2}{27}\left(\underset{\text{nucleon mass}}{m_N} - \sigma_{\pi N} + \frac{1}{2} r\left(\sigma_{\pi N} - \sigma_0\right)\right).$$

We can now express the quantities $I_{h,H}$ as: $I_{h,H} = K^{h,H}_{u\text{-type}}\, g_u + K^{h,H}_{d\text{-type}}\, g_d$

with

$$\begin{cases} g_u \simeq m_{light} \langle N|\bar{l}l|N\rangle + 2 m_{heavy} \langle N|\bar{h}h|N\rangle \\ \quad \simeq \frac{4}{27}\left(m_N + \frac{19}{8}\sigma_{\pi N} - \frac{1}{2} r\left(\sigma_{\pi N} - \sigma_0\right)\right) \\ g_d \simeq m_{light} \langle N|\bar{l}l|N\rangle + m_s \langle N|\bar{s}s|N\rangle + m_{heavy} \langle N|\bar{h}h|N\rangle = \\ \quad \simeq \frac{2}{27}\left(m_N + \frac{23}{4}\sigma_{\pi N} + \frac{25}{4} r\left(\sigma_{\pi N} - \sigma_0\right)\right) \end{cases}$$

<u>Problem</u>: The three quantities $\sigma_{\pi N}$, σ_0 and r are all affected by sizable uncertainties which affect the determination of the coefficients g_u, g_d.

<u>Range of $\sigma_{\pi N}$</u>:

$41\ \text{MeV} \lesssim \sigma_{\pi N} \lesssim 57\ \text{MeV}$; $55\ \text{MeV} \lesssim \sigma_{\pi N} \lesssim 73\ \text{MeV}$

↳ calculated by Koch ; ↳ calculated by TRIUMF group

- from experimental data of π-N scattering
- heavy quarks chiral perturbation theory
- lattice calculation

<u>Range of σ_0</u>:

$\sigma_0 = 30 \div 40\ \text{MeV}$

- from octet baryon masses
- with chiral perturbation theory

<u>Range of r</u>:

$r = 29 \pm 7$

$m_s = (175 \pm 25)\ \text{MeV}$ lattice simulation

$m_u + m_d = (12 \pm 2.5)\ \text{MeV}$

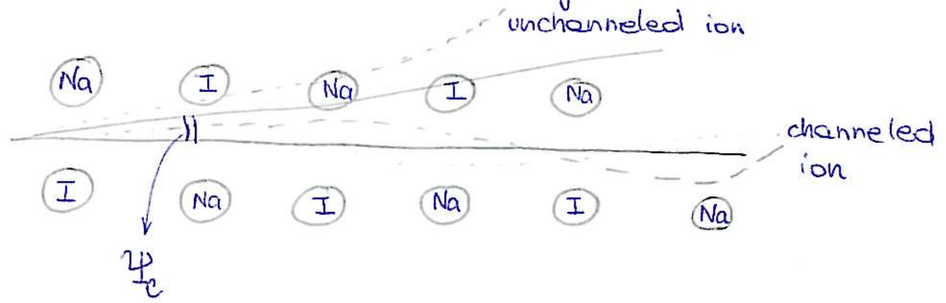
Channeling Effect

Ions (→ recoiling nuclei) move in a CRYSTAL in a different way than in amorphous materials.

↓

Ions moving quasi-parallel to crystallographic axes or planes fell the "channeling-effect"

↳ anomalous penetration into the lattice of the crystal



channeled ions:

a) ranges much longer than the unchanneled ions

b) energy losses are mainly due to the electronic contributions

⇓

a channeled ion transfers its energy mainly to electrons rather than to the nuclei in the lattice

↳ the quenching factor ← ratio between the detected energy in KeV electron equivalent (KeVee) and the kinetic energy of the recoiling nucleus in KeV.

approaches the unity

⇒ This effect is important for WIMP direct detection experiments, but commonly the quenching factors are assumed to be constant values without considering their energy dependence and usually WIMP analysis does not account for the channeled events.

↳ impact of the channeling effect in NaI(Tl) ~~detectors~~ crystals has been discussed by the DAMA collaboration.

Basic physics of channeling effect

The stopping power of an ion is given by the sum of two effects:
↳ interaction with nuclei
↳ interaction with the binding electrons

$$\frac{dE_{ion}}{dx}(E) = \frac{dE_{ion-n}}{dx}(E) + \frac{dE_{ion-e}}{dx}(E)$$

E: energy of the ion at any point x along the path

for SCINTILLATOR detectors, the detectable light produced by a charged particle (electron or ion) mostly arise from the energy loss in the electronic interactions.

↓

Differential luminosities in scintillators:

$$\begin{cases} \frac{dL_e}{dx} = \alpha \frac{dE_{e-e}}{dx} \\ \frac{dL_{ion}}{dx} = \alpha \frac{dE_{ion-e}}{dx} = \alpha \frac{dE_{ion}}{dx} \cdot q'(E) \end{cases}$$

$$q'(E) = \frac{\frac{dE_{ion-e}}{dx}(E)}{\frac{dE_{ion-n}}{dx}(E) + \frac{dE_{ion-e}}{dx}(E)}$$

differential quenching factor

Total detected luminosities $L = \int_{path} \frac{dL}{dx} dx$

$$\begin{cases} L_e = \alpha E_e & \text{for electrons} \\ L_{ion} = \alpha\, q_1(E_{ion}) \cdot E_{ion} & \text{for recoils} \end{cases}$$

↳ $q_1(E) = \int_0^E q'(E')\, dE'$ light quenching factor

for crystal ⇒ the luminosity depends on whether the recoiling nucleus is quasi-parallel to the crystallographic axis or planes or not.

↓

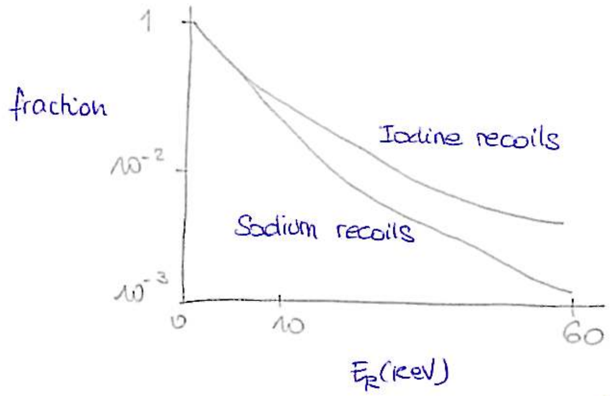
in this case: energy losses due to electronic contributions, penetration of ions is larger and the quenching factor approaches 1.

for a given nucleus A with recoil energy E_R, the responce of a detector is written usually (in most cases of dark matter direct detection):

$$\frac{dN_A}{dE_{det}}(E_{det} | E_R) = \delta(E_{det} - q_A E_R)$$

with q_A = costant value of quenching factor of the unchanneled A nucleus

but $\frac{dN_A}{dE_{det}}$ has been calculated by the DAMA collaboration using a Monte Carlo code that includes also the channeling effect.



fraction of events with quenching factor ≃ 1 that is fully channeled events as a function of the energy of the recoiling nuclei.

$(A_I = 121 ; A_{Na} = 23)$

$\longrightarrow$ # of fully channeled ($q \sim 1$) events decreases when increasing the recoil energy.

$\Rightarrow$ The expected differential counting rate of recoils induced by WIMP nucleus elastic scatterings has to be evaluated in given astrophysical, nuclear and particle physics scenario + channeling effects must be considered as an additional uncertainties

No enhancement can be present in liquid noble gas (XENON, WARP)

No 〃 is possible for bolometer experiments.

Similar situation for purely ionization detectors, Ge

$\hookrightarrow$ channelling effect change the region allowed in the plane (σ, m_χ)

Parameterization for fraction f of channeled events relevant for DAMA:

$$f_{Na}(E_R) \approx \frac{e^{-E_R/18}}{1 + 0.75\, E_R} \qquad f_I(E_R) \approx \frac{e^{-E_R/40}}{1 + 0.65\, E_R}$$

Spectrum in DAMA is:

$$R_{DAMA}(E) = \sum_{X = Na, I} \frac{M_X}{M_{Na} + M_I} \cdot \left\{ \left(1 - f_X\left(\frac{E}{q_X}\right)\right) R_X\left(\frac{E}{q_X}\right) + f_X(E)\, R_X(E) \right\}$$