LSP-Nucleus Scattering for Medium-Heavy and Heavy Nuclei

Jouni Suhonen

Department of Physics University of Jyväskylä

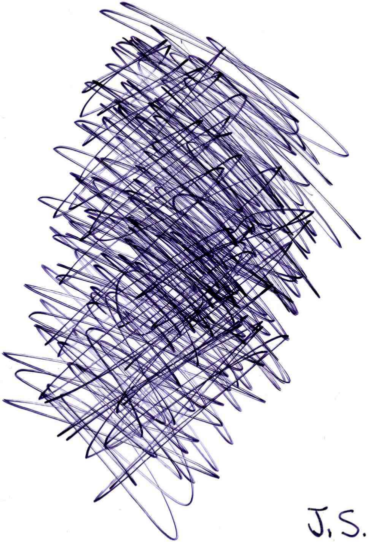
Direct Dark Matter Detection: Experiment Meets Theory, Garching, Germany, 6-8 March, 2017

Contents:

- Intro
- Past: Elastic Scattering
- Past: Inelastic Scattering
- Present and Future

INTRODUCTION:

NUCLEAR
STRUCTURE
&
SEARCH
for the
CDM



About 30% of the energy content of the Universe is:

Baryonic Matter

MACHOs
(Massive Compact
Halo Objects)

- brown dwarfs
- jupiters
- stellar black-hole remnants
- white dwarfs
- neutron stars

Nonbaryonic Matter

HDM
light ν's

CDM
axions
WIMPs:

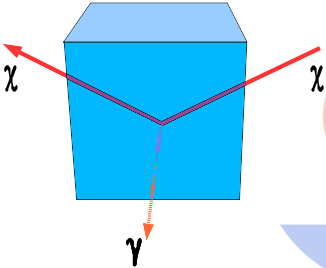
- heavy ν's
- **neutralinos**
- sneutrinos

HDM = Hot Dark Matter, relativistic light particles
CDM = Cold Dark Matter, slow very massive particles
WIMP = Weakly Interacting Massive Particles
neutralinos are neutral Majorana fermions of supersymmetric theories of particle physics (mixtures of the superpartners of Higg's bosons and weak bosons)

Detection of dark matter

Indirect detection:

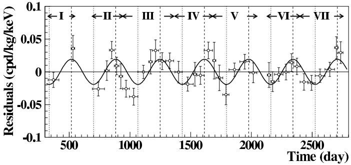
- rotation curves $v(r)$ of spiral galaxies (star velocities far from the galaxy center $v(r) \propto \text{const}$ and not $v(r) \propto r^{-1/2}$)
- Kinematics of galaxy clusters, x-ray emission of hot electron gas, gravitational lensing of the light of quasars
- Annihilation of WIMPs (e.g. in the Sun) and decay products of WIMPs



Direct detection:

WIMP-nucleon neutral-current scattering in the detector $\Rightarrow$ nuclear and electronic recoils $\Rightarrow$ Lattice phonons, electronic ionization, scintillation light

Direct CDM searches



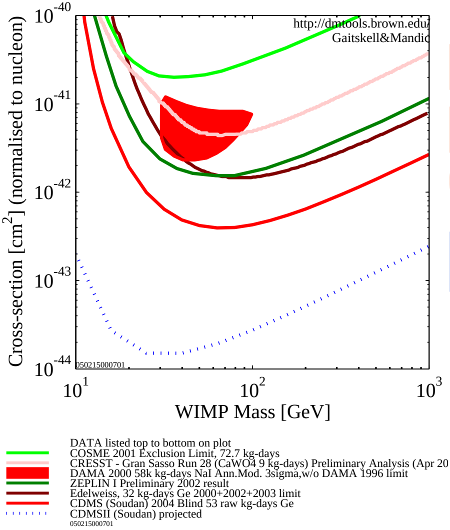
Our Motivation:
Contradiction between the DAMA and the rest

⇕

NUCLEAR-STRUCTURE EFFECT?

ASSUME: WIMP = LSP = Lightest Supersymmetric Particle (neutralino $\equiv \chi$)

$\chi = \alpha\tilde{\mathrm{B}} + \beta\tilde{\mathrm{W}}_3 + \gamma\tilde{\mathrm{H}}_1 + \delta\tilde{\mathrm{H}}_2$



ELASTIC LSP-NUCLEUS SCATTERING

ELASTIC LSP-nucleus scattering: cross section

Cross section

$$\sigma(v) = \frac{1}{2}\sigma_0 \left(\frac{1}{m_{\rm p} b}\right)^2 \frac{c^2}{v^2}\sigma_{\rm AS},$$

v = relative velocity of the LSP and the detector

$$\sigma_{\rm AS} = (f_{\rm A}^0)^2 C_1 + 2 f_{\rm A}^1 f_{\rm A}^0 C_2 + (f_{\rm A}^1)^2 C_3 + A^2 \left(f_{\rm S}^0 - f_{\rm S}^1 \frac{A-2Z}{A}\right)^2 C_4$$

NOTE: $C_4 = 0$ for the inelastic channel

SUSY	$\leftrightarrow$	$f_{\rm S,A}^{\rm isospin}$
nuclear structure	$\leftrightarrow$	C_i

LSP detection rate

Folding with Maxwellian velocity distribution of LSPs

$$\langle R \rangle = \frac{dN}{dt} = \frac{\rho(0)}{m_\chi} \frac{m_{\rm det}}{A m_{\rm p}} \int f(\mathbf{v} + \mathbf{v}_{\rm E})\, v\sigma(v) d^3 v,$$

$\mathbf{v}_{\rm E}$ = Earth's velocity with respect to the galactic center
$\mathbf{v} + \mathbf{v}_{\rm E}$ = LSP's velocity with respect to the galactic center

$\Downarrow$ Some calculation ...

$$\langle R \rangle = \left[(f_{\rm A}^0)^2 D_1 + 2 f_{\rm A}^1 f_{\rm A}^0 D_2 + (f_{\rm A}^1)^2 D_3 + A^2 \left(f_{\rm S}^0 - f_{\rm S}^1 \frac{A - 2Z}{A} \right)^2 D_4 \right] m_{\rm det}[\mathrm{kg}]$$

$D_i = D_i(m_\chi, Q_{\rm thr})$ Integrated nuclear factors

Adopted nuclear models

NUCLEAR-STRUCTURE MODELS:

for

$D_i(m_\chi, Q_{\text{thr}})$

MQPM

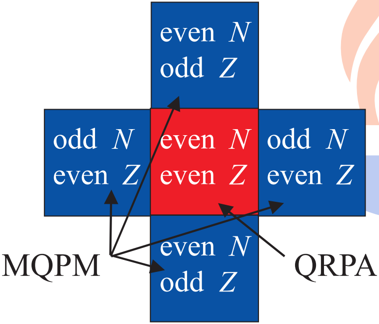
NUCLEAR SHELL MODEL

MQPM=Microscopic Quasiparticle-Phonon Model

BCS quasiparticles: $a^\dagger_\beta$

QRPA phonons: $Q^\dagger_\omega$

MQPM basis: $\{a^\dagger_{jm}, [a^\dagger_b Q^\dagger_\omega]_{jm}\}$



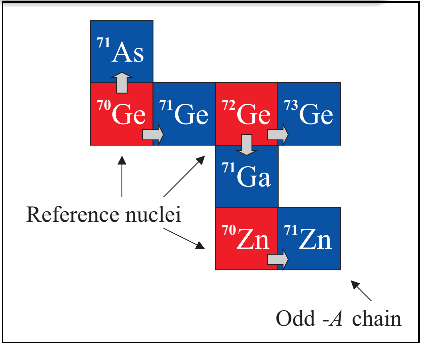
$$\Gamma^\dagger_i(jm) = \sum_n C^i_n a^\dagger_{njm} + \sum_{b,\omega} D^i_{b\omega}[a^\dagger_b Q^\dagger_\omega]_{jm}$$

Residual Hamiltonian with Bonn-A OBEP G-matrix

MQPM: Reference nuclei

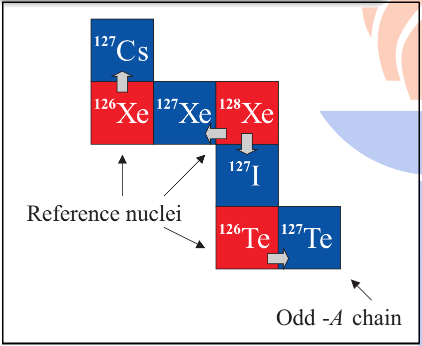
Medium masses

Gallium and Germanium

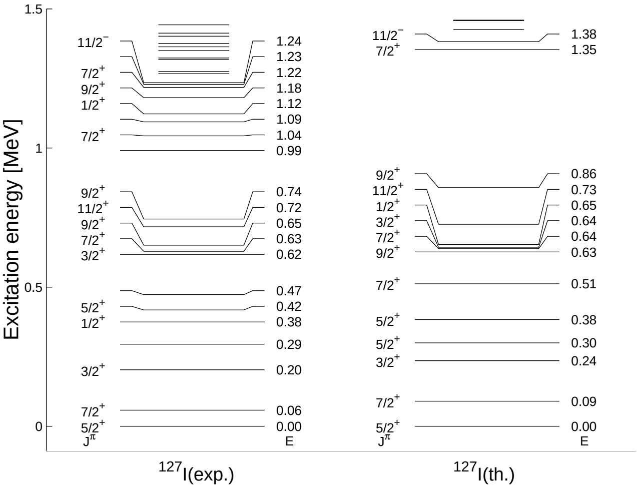


Heavy masses

Iodine



MQPM: Spectrum of ^{127}I



Experimental and theoretical spectra of ^{127}I

Theoretically

$^{127}\text{I} = {}^{128}\text{Xe} \otimes \mathbf{p}^{-1}$

Large-scale Shell-Model calculations (Bonn-CD G-matrix)

Nucleus	$< \mathbf{S_n} >$	$< \mathbf{S_p} >$	$< \mathbf{L_n} >$	$< \mathbf{L_p} >$	$\mu_{exp.}$	μ_{SM}	$\mu_{s.p.}$
^{73}Ge	0.4067	0.0048	3.7537	0.3348	-0.879	-1.194	-1.913
^{71}Ga	0.0382	0.3360	0.2810	0.8687	+2.562	+2.599	+3.793
^{23}Na	0.0199	0.2477	0.3207	0.9115	+2.218	+2.219	+3.793
^{127}I	0.0382	0.3299	0.7018	1.4301	+2.813	+3.127	+4.793

Studied nuclei: ^{23}Na, ^{71}Ga, ^{73}Ge, ^{127}I

MQPM

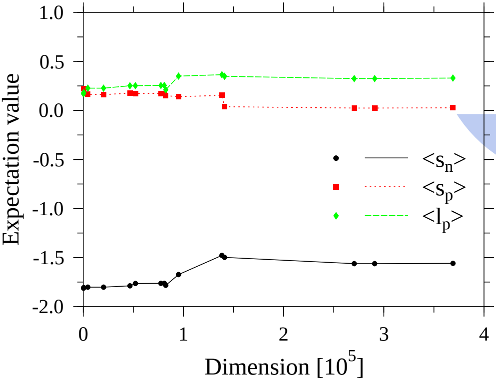
Detection rates in ^{71}Ga, ^{73}Ge and ^{127}I (Phys. Lett. B 584 (2004) 31-39)

LARGE-Scale EICODE calculations

Magnetic moments:

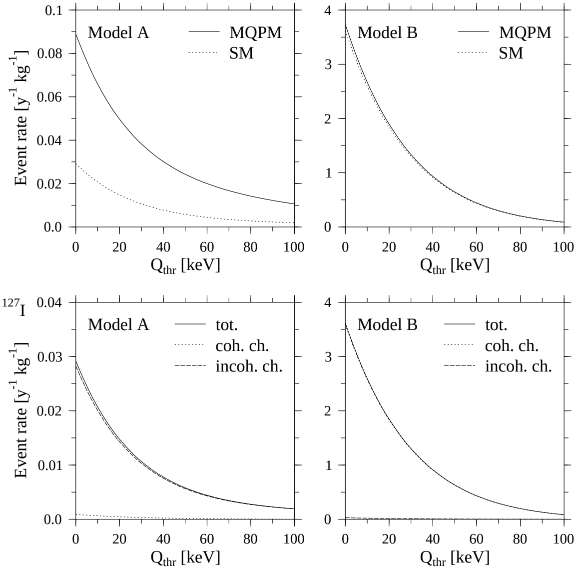
$\mu_{th} = -3.826\langle \mathbf{S}_n \rangle + 5.586\langle \mathbf{S}_p \rangle + \langle \mathbf{L}_p \rangle$

(Phys. Lett. B 632 (2006) 226-232)



Convergence for ^{73}Ge ($\langle \mathbf{s}_{p,n} \rangle = g_{p,n} \langle \mathbf{S}_{p,n} \rangle$)

^{127}I: MQPM ↔ Shell Model / coherent ↔ incoherent



Some conclusions from these studies

MQPM $\leftrightarrow$ Shell Model

The shell model reproduces the magnetic dipole moments of the ground states of the studied nuclei better than the MQPM

$\Downarrow$

Event Rates

Event rates differ substantially where spin-dependent incoherent channel dominates

Coherent $\leftrightarrow$ Incoherent channel

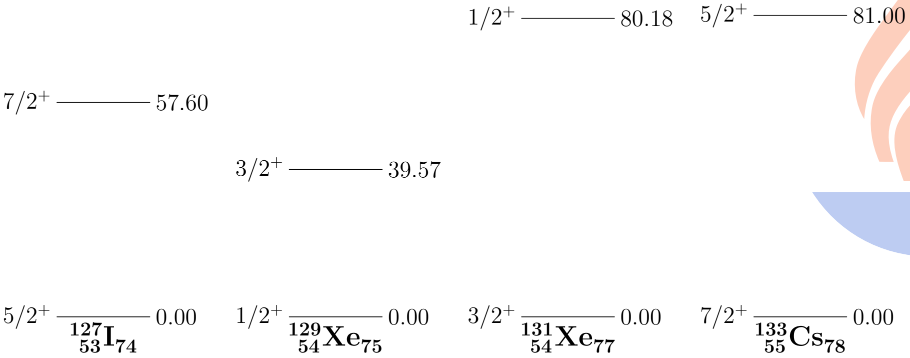
Sensitivity of the spin-dependent channel depends strongly on the adopted SUSY

$\Downarrow$

Relates to the DAMA mystery?

INELASTIC LSP-NUCLEUS SCATTERING

Interesting nuclei for WIMP inelastic scattering



Energies in keV

Next step of Shell-Model calculations

Renormalized realistic interaction

Based on the Bonn-CD G-matrix

Active orbitals

$0g_{7/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$ and $0h_{11/2}$

Fitted Effective *g* Factors

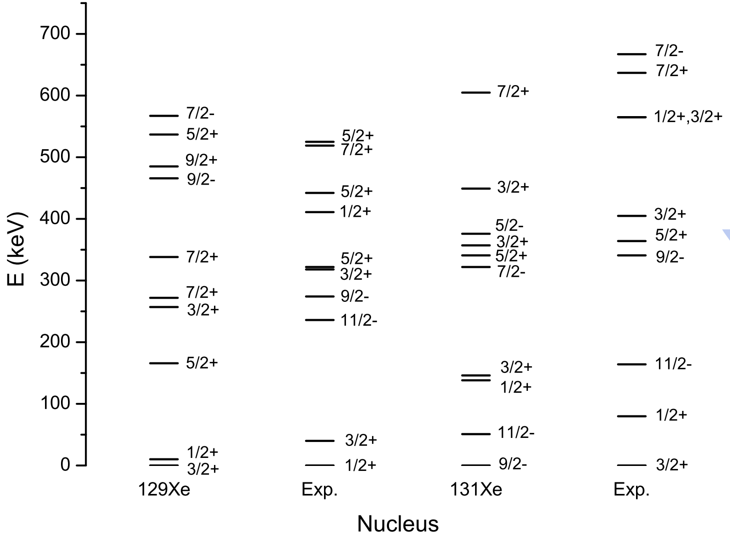
Linear least-squares fit of the ground-state and excited state magnetic moments for ^{127}I, ^{129}Xe, ^{131}Xe and ^{133}Cs

⇓

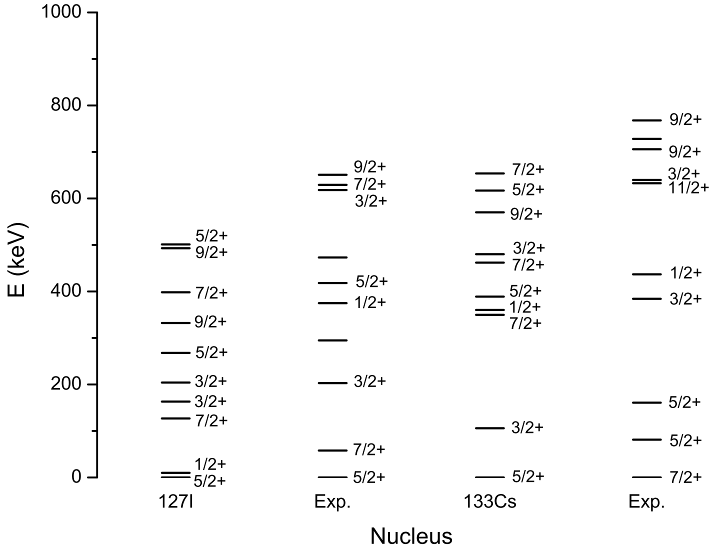
Event rates

Event rates for both elastic and **inelastic** scattering channels

Shell-Model calculations: ^{129}Xe and ^{131}Xe



Shell-Model calculations: ^{127}I and ^{133}Cs



Calculated magnetic dipole moments

Table: Experimental and calculated magnetic moments in units of μ_{N}/c.

		Present		Ressell *et al.* [1]	
State	Exp.	Fitted	Bare	Fitted	Bare
$^{127}\mathrm{I}(5/2^+_{\mathrm{g.s.}})$	2.81	2.74	3.55	2.47	2.77
$^{127}\mathrm{I}(3/2^+_1)$	0.97	0.66	-0.29	-	-
$^{127}\mathrm{I}(7/2^+_1)$	2.54	2.24	1.05	-	-
$^{129}\mathrm{Xe}(1/2^+_{\mathrm{g.s.}})$	-0.78	-0.80	-0.94	-0.63	-0.98
$^{129}\mathrm{Xe}(3/2^+_1)$	0.58	0.47	0.45	-	-
$^{129}\mathrm{Xe}(11/2^-_1)$	-0.89	-0.81	-1.17	-	-
$^{131}\mathrm{Xe}(3/2^+_{\mathrm{g.s.}})$	0.69	0.68	0.72	0.64	0.98
$^{131}\mathrm{Xe}(11/2^-_1)$	-0.99	-1.01	-1.37	-	-
$^{133}\mathrm{Cs}(7/2^+_{\mathrm{g.s.}})$	2.58	2.87	1.67	-	-
$^{133}\mathrm{Cs}(5/2^+_1)$	3.45	3.33	4.03	-	-
$^{133}\mathrm{Cs}(5/2^+_2)$	2.00	2.31	1.82	-	-

[1] M.T. Ressell and D.J. Dean, Phys. Rev. C 56 (1997) 535

Global fit: Obtained parameters

Gyromagnetic Factors

Bare: $g_{\mathrm{s,n}} = -3.826\,\mu_{\mathrm{N}}$ $g_{\mathrm{s,p}} = 5.586\,\mu_{\mathrm{N}}$ $g_{\mathrm{l,n}} = 0$ $g_{\mathrm{l,p}} = 1\,\mu_{\mathrm{N}}$
Fitted: $g_{\mathrm{s,n}} = -3.370\,\mu_{\mathrm{N}}$ $g_{\mathrm{s,p}} = 3.189\,\mu_{\mathrm{N}}$ $g_{\mathrm{l,n}} = 0.01903\,\mu_{\mathrm{N}}$ $g_{\mathrm{l,p}} = 1.119\,\mu_{\mathrm{N}}$

Renormalization of Spin Operators

$$\boldsymbol{\sigma}_{\mathrm{eff}}^{(p)} = r_{\mathrm{p}}\boldsymbol{\sigma}^{(p)}\ ,$$
$$\boldsymbol{\sigma}_{\mathrm{eff}}^{(n)} = r_{\mathrm{n}}\boldsymbol{\sigma}^{(n)}\ ,$$
$$r_{\mathrm{p}} = \frac{3.189}{5.586} = 0.571 \quad (\text{protons})\ ,$$
$$r_{\mathrm{n}} = \frac{3.370}{3.826} = 0.881 \quad (\text{neutrons})\ .$$

Published in

P. Toivanen et *al.*, Phys. Lett. B 666 (2008) 1 ; Phys. Rev. C 79 (2009) 044302

Global fit: Spin and orbital expectation values

State	$< \mathbf{S_n} >$	$< \mathbf{S_p} >$	$< \mathbf{L_n} >$	$< \mathbf{L_p} >$
$^{127}\mathrm{I}(5/2^+_{\mathrm{g.s.}})$	0.030	0.418	0.867	1.331
Kortelainen *et al.* [2006] (Bonn-CD)	0.038	0.330	0.702	1.430
Ressell *et al.* [1997] (Bonn-A)	0.075	0.309	0.779	1.338
Ressell *et al.* [1997] (Nijmegen)	0.064	0.354	0.664	1.418
Klos *et al.* [2013] (GCN5082)	0.031	0.342	-	-
$^{127}\mathrm{I}(7/2^+_1)$	0.056	−0.327	0.852	3.093
$^{129}\mathrm{Xe}(1/2^+_{\mathrm{g.s.}})$	0.273	−0.0019	0.113	0.115
Ressell *et al.* [1997] (Bonn-A)	0.359	0.028	−0.114	0.227
Ressell *et al.* [1997] (Nijmegen)	0.300	0.013	−0.185	0.372
Klos *et al.* [2013] (GCN5082)	0.329	0.010	-	-
$^{129}\mathrm{Xe}(3/2^+_1)$	−0.049	−0.0034	1.297	0.256
$^{131}\mathrm{Xe}(3/2^+_{\mathrm{g.s.}})$	−0.125	−0.00069	1.417	0.209
Ressell *et al.* [1997] (Bonn-A)	−0.227	−0.009	1.572	0.165
Ressell *et al.* [1997] (Nijmegen)	−0.217	−0.012	1.514	0.215
Klos *et al.* [2013] (GCN5082)	−0.272	−0.009	-	-
$^{131}\mathrm{Xe}(1/2^+_1)$	0.293	−0.0034	0.095	0.116
$^{133}\mathrm{Cs}(7/2^+_{\mathrm{g.s.}})$	0.021	−0.318	0.448	3.524
$^{133}\mathrm{Cs}(5/2^+_1)$	0.013	0.391	0.348	1.893

Results: Static spin matrix elements Ω_0 and Ω_1

Integrated Nuclear Factors

$$D_1 = \int_{-1}^{+1} \int_{\psi_{\min}}^{\psi_{\max}} \int_{u_{\min}}^{u_{\max}} G(\psi,\xi) F_{00}(u) {\Omega_0}^2 d\xi d\psi du \ ,$$

$$D_2 = \int_{-1}^{+1} \int_{\psi_{\min}}^{\psi_{\max}} \int_{u_{\min}}^{u_{\max}} G(\psi,\xi) F_{01}(u) \Omega_0 \Omega_1 d\xi d\psi du \ ,$$

$$D_3 = \int_{-1}^{+1} \int_{\psi_{\min}}^{\psi_{\max}} \int_{u_{\min}}^{u_{\max}} G(\psi,\xi) F_{11}(u) {\Omega_1}^2 d\xi d\psi du \ ,$$

$$D_4 = \int_{-1}^{+1} \int_{\psi_{\min}}^{\psi_{\max}} \int_{u_{\min}}^{u_{\max}} G(\psi,\xi) |F(u)|^2 d\xi d\psi du$$

Modulation function: $G(\psi,\xi) = \frac{\rho(0)}{m_\chi} \frac{\sigma_0}{Am_{\rm p}} \left(\frac{1}{m_{\rm p} b} \right)^2 \frac{e^{-\lambda^2}}{\sqrt{\pi}} \frac{c^2}{v_0} \psi e^{-\psi^2} e^{-2\lambda\psi\xi}$,

Integration limits depend on the scattering mode: elastic/inelastic

Results: Static spin matrix elements

Table: Values of static spin matrix elements.

Nucleus	g factors	Elastic Ω_0	Elastic Ω_1	Inelastic Ω_0	Inelastic Ω_1
^{127}I	Bare	1.001	0.868	0.098	0.066
	Effective	0.592	0.475	0.061	0.033
^{129}Xe	Bare	0.941	−0.954	0.306	−0.311
	Effective	0.831	−0.838	0.270	−0.273
^{131}Xe	Bare	−0.326	0.322	0.236	−0.224
	Effective	−0.286	0.284	0.206	−0.199
^{133}Cs	Bare	0.643	0.732	0.059	0.050
	Effective	0.353	0.432	0.035	0.027

Results: Spin structure functions

Integrated Nuclear Factors

$$D_1 = \int_{-1}^{+1} \int_{\psi_{\min}}^{\psi_{\max}} \int_{u_{\min}}^{u_{\max}} G(\psi,\xi) F_{00}(u) \Omega_0^2 d\xi d\psi du \ ,$$

$$D_2 = \int_{-1}^{+1} \int_{\psi_{\min}}^{\psi_{\max}} \int_{u_{\min}}^{u_{\max}} G(\psi,\xi) F_{01}(u) \Omega_0 \Omega_1 d\xi d\psi du \ ,$$

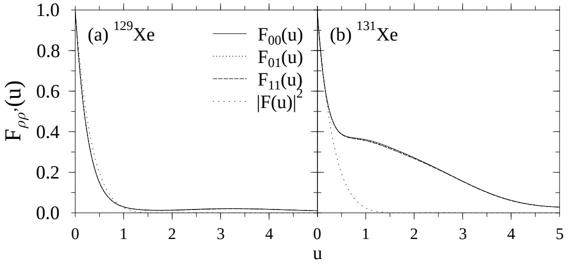
$$D_3 = \int_{-1}^{+1} \int_{\psi_{\min}}^{\psi_{\max}} \int_{u_{\min}}^{u_{\max}} G(\psi,\xi) F_{11}(u) \Omega_1^2 d\xi d\psi du \ ,$$

$$D_4 = \int_{-1}^{+1} \int_{\psi_{\min}}^{\psi_{\max}} \int_{u_{\min}}^{u_{\max}} G(\psi,\xi) |F(u)|^2 d\xi d\psi du$$

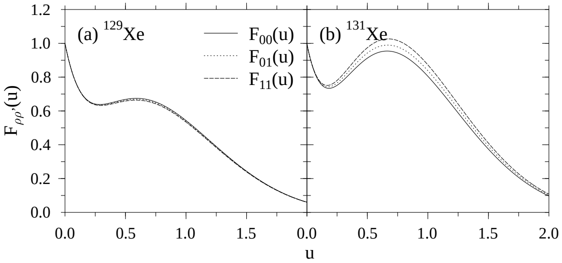
Spin structure functions: $F_{ij}(u)$; Nuclear form factor: $F(u)$

$u = q^2 b^2 / 2$, q is the transferred momentum in the LSP-nucleus scattering

Spin structure functions for the xenon isotopes

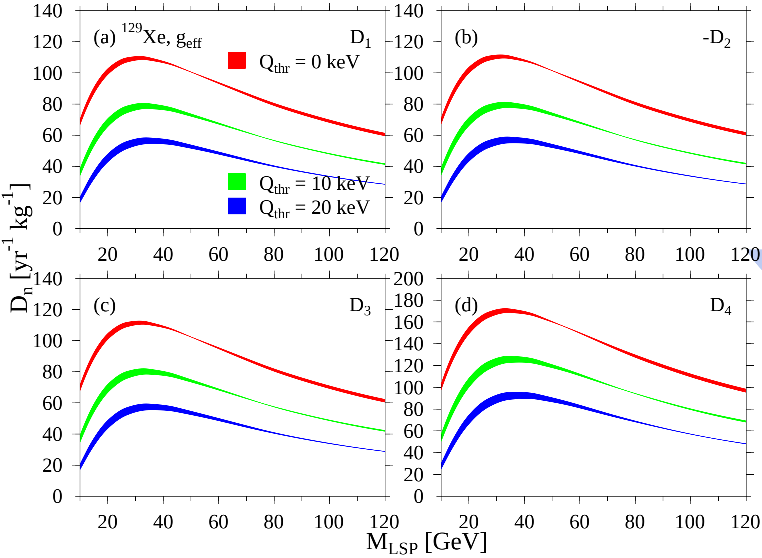


ELASTIC
scattering

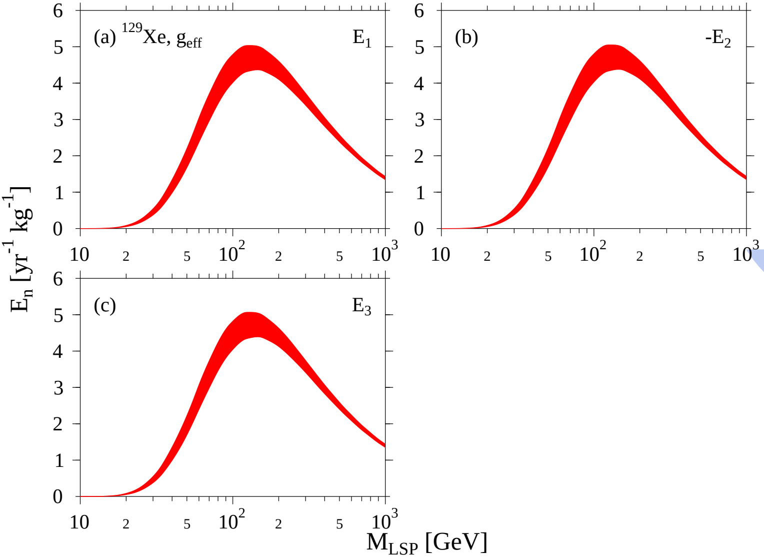


INELASTIC
scattering

Integrated nuclear factors for ^{129}Xe (elastic)



Integrated nuclear factors for ^{129}Xe (inelastic)



Example: Tabulated annual-averaged coefficients

Table: Computed auxiliary nuclear-structure coefficients $d_n(m_\chi)$ in units of $\mathrm{yr}^{-1}\mathrm{kg}^{-1}$ for the elastic LSP-nucleus scattering.

	m_χ [GeV]						α_n	β_n
	50	75	100	150	200	300		
^{129}Xe								
d_1	100.8	83.0	69.0	50.9	40.2	28.3	0.0241	0.000226
$-d_2$	101.6	83.7	69.5	51.2	40.5	28.5	0.0240	0.000229
d_3	102.5	84.4	70.1	51.6	40.8	28.7	0.0239	0.000232
d_4	160.5	133.7	111.0	81.0	63.2	43.7	0.0196	0.000267
^{131}Xe								
d_1	14.9	14.8	14.2	12.4	10.8	8.4	0.0302	−0.000213
$-d_2$	14.8	14.6	14.0	12.3	10.7	8.3	0.0302	−0.000212
d_3	14.7	14.5	13.9	12.2	10.6	8.2	0.0302	−0.000212
d_4	157.8	131.2	108.7	79.3	61.8	42.7	0.0195	0.000276

$$\bar{D}_n(m_\chi, Q_{\mathrm{thr}}) = e^{-(\alpha_n+\beta_n\mu_r)Q_{\mathrm{thr}}} d_n(m_\chi)\ , \ \mu_r = \frac{Am_{\mathrm{p}}m_\chi}{Am_{\mathrm{p}}+m_\chi}$$

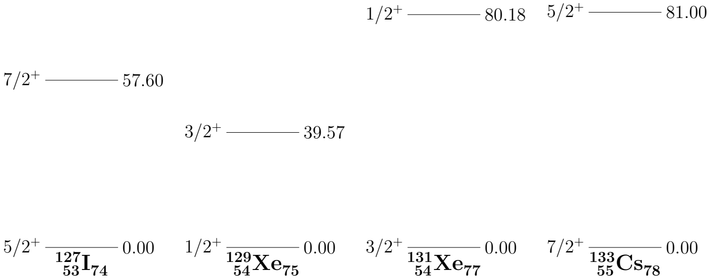
Example: the same for inelastic scattering

Table: Computed annual averaged coefficients $\bar{E}_n(m_\chi)$ in units of $\mathrm{yr}^{-1}\mathrm{kg}^{-1}$ for the inelastic LSP-nucleus scattering. $Q_{\mathrm{thr}} \equiv 0$.

	m_χ [GeV]					
	50	75	100	150	200	300
^{129}Xe						
$\bar{E}_1$	1.94	3.58	4.41	4.68	4.36	3.56
$-\bar{E}_2$	1.95	3.60	4.42	4.70	4.37	3.57
$\bar{E}_3$	1.96	3.61	4.44	4.72	4.39	3.58
^{131}Xe						
$\bar{E}_1$	0.086	0.359	0.625	0.904	0.970	0.905
$-\bar{E}_2$	0.086	0.359	0.625	0.907	0.973	0.908
$\bar{E}_3$	0.086	0.359	0.627	0.909	0.977	0.912

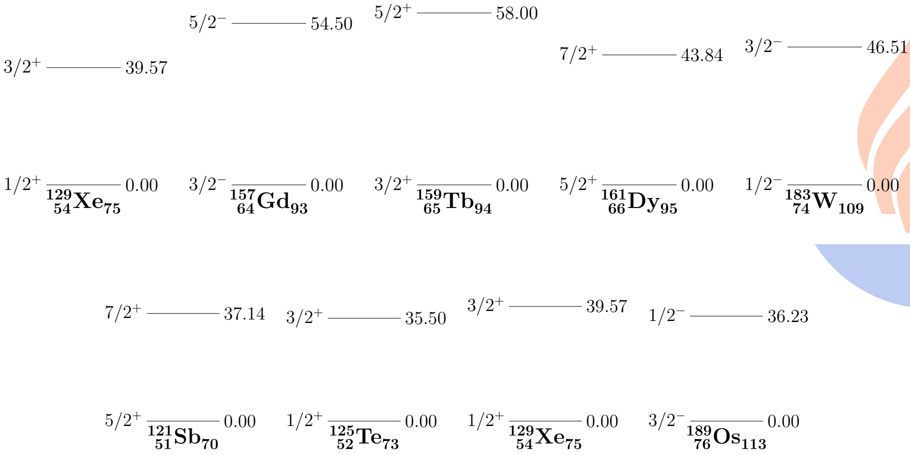
INELASTIC LSP-NUCLEUS SCATTERING FOR POTENTIALLY INTERESTING NUCLEI

Interesting nuclei for WIMP inelastic scattering



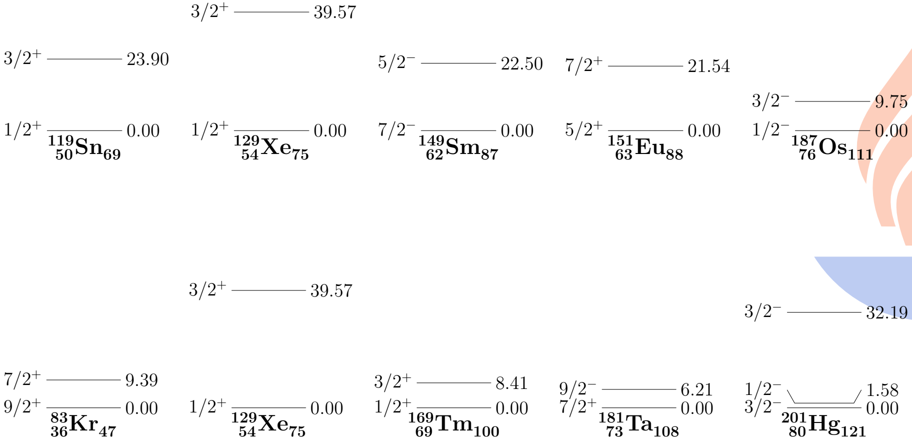
Energies in keV

Interesting nuclei (continues)



Energies in keV

Interesting nuclei (continues)



Energies in keV

CDM detection: Summary and conclusions

Folding

The computed LSP-nucleus cross sections are folded with the LSP velocity distribution

$\Downarrow$

Event Rates

Obtain event rates in units of events/year/kg

$\Downarrow$

Recent Results:

- Complete separation of the SUSY and nuclear-physics inputs
- Sensitivity of the spin-dependent channel depends strongly on the adopted SUSY $\stackrel{\text{future}}{\Longrightarrow}$ possible SUSY classification using spin-sensitive targets
- The **inelastic** channel is suppressed at least by a factor of 100 relative to the elastic channel

The spin-sensitivity leaves the DAMA results still valid?