Elastic and Inelastic LSP-Nucleus Scattering on Medium-Heavy Nuclei

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TAUP2009 Conference, Rome, Italy, 1-5 July, 2009

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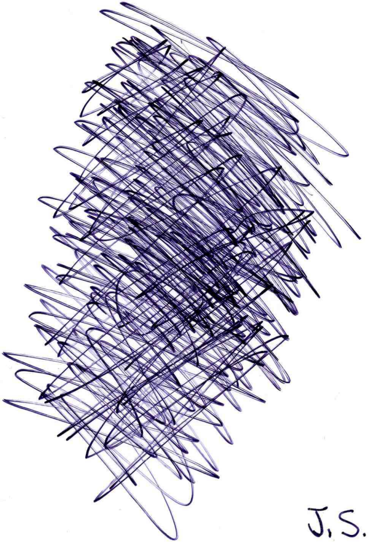
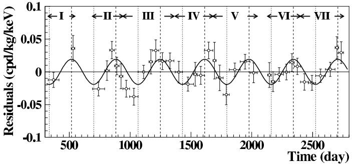
INTRODUCTION:

NUCLEAR
STRUCTURE
&
SEARCH
for the
CDM



Direct CDM Searches: Our Motivation



Our Motivation:
Contradiction between the DAMA and the rest

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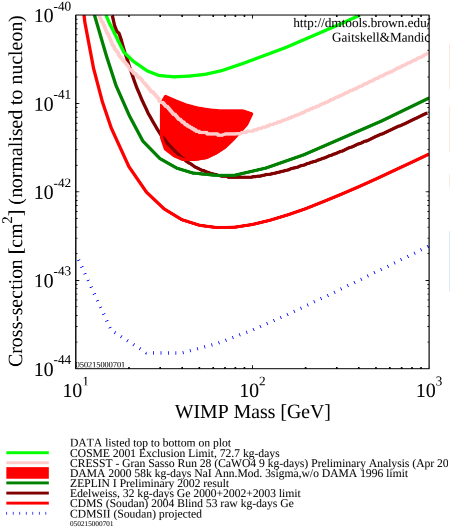
NUCLEAR-STRUCTURE EFFECT?

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

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



Theory of LSP-Nucleus Scattering: Cross Section

Cross section

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

v = relative velocity of the LSP and the detector

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

NOTE: $C_4 = 0$ for the inelastic channel

SUSY	$\leftrightarrow$	$f_{\mathrm{S,V,A}}^{\mathrm{isospin}}$
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

Large Scale Shell-Model Calculations

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

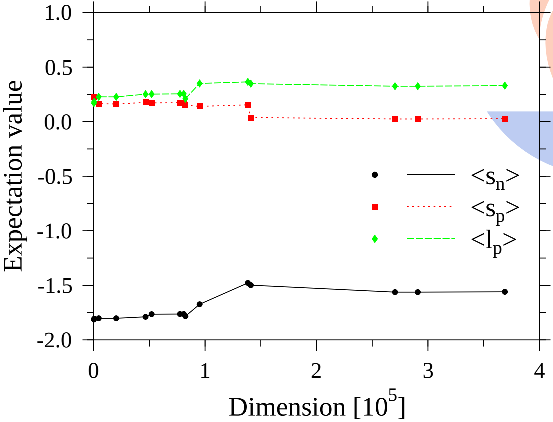
Nucleus	$\langle \mathbf{S_n} \rangle$	$\langle \mathbf{S_p} \rangle$	$\langle \mathbf{L_n} \rangle$	$\langle \mathbf{L_p} \rangle$	$\mu_{exp.}$	μ_{SM}	$\mu_{s.p.}$
^{73}Ge	0.4067	0.0048	3.7537	0.3348	-0.879	-1.194	-1.913
^{71}Ga	0.0382	0.3360	0.2810	0.8687	+2.562	+2.599	+3.793
^{23}Na	0.0199	0.2477	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

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)



Very Recent 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

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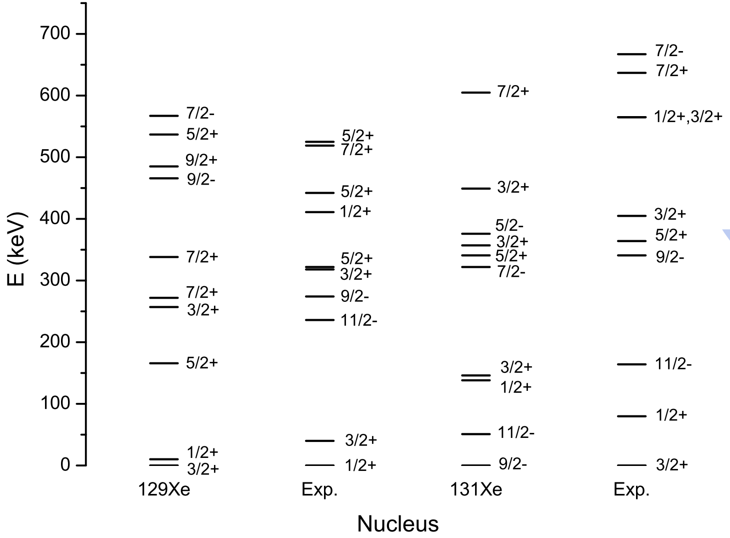
Event rates

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

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



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

Renormalization of Spin Operators

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

Published in

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

Results: Static Spin Matrix Elements

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

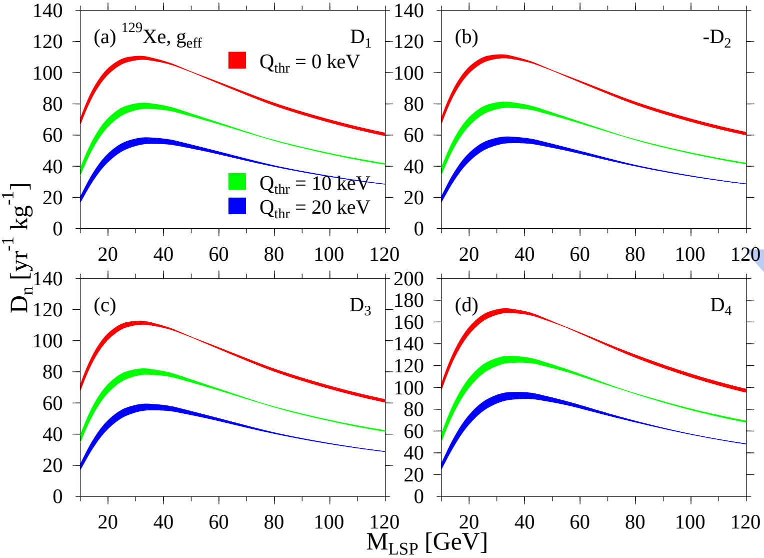
Integration limits depend on the scattering mode: elastic/inelastic

Results: Static Spin Matrix Elements

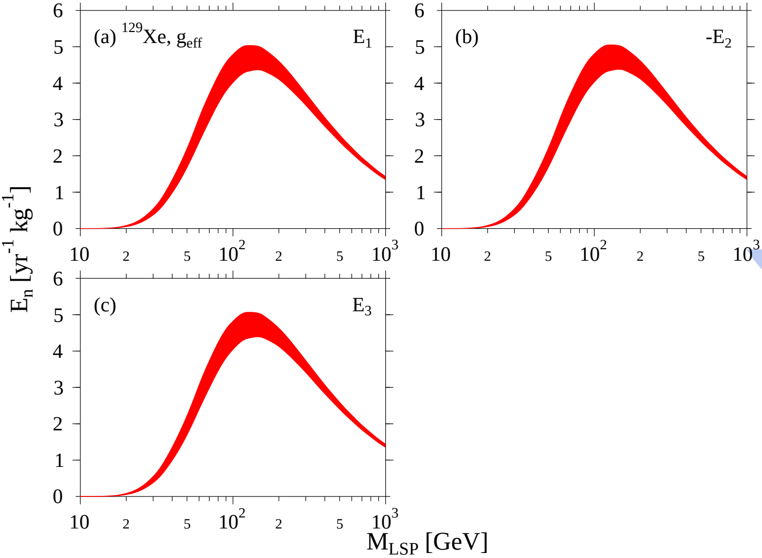
Table: Values of static spin matrix elements.

		Elastic		Inelastic	
Nucleus	g factors	Ω_0	Ω_1	Ω_0	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

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

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 $\overset{\text{future}}{\Longrightarrow}$ possible SUSY classification using spin-sensitive targets
- The **inelastic** channel is suppressed at least by a factor of 100 relative to the elastic channel