Direct Detection Models with Distinct Direct Detection Signatures

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PPC17, May. 25th, 2017
simplest WIMP DM is running out of room

[Liu, Chen, Ji '17]

(not shown: latest Xe100 (1609.06154) and XENON1T (1705.06655) results)
simplest WIMP DM is running out of room
third direction: inelasticity
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\[ \chi = DM \]

**DM–nucleon cross-section**

**Limits on Dark Matter from Direct Detection**

- CRESST (2015)
- CDMSlite (2015)
- PandaX (2016)
- LUX (2016)

**Dark Matter Mass [GeV]**

- \( \nu \) Floor
- \( Xe \)

**mass splitting**
Inelastic DM

\[ \delta = m_{\chi'} - m_{\chi} \]

\[ E_R \text{ recoil} \]

[L. J. Hall, T. Moroi and H. Murayama '97, Tucker-Smith, Weiner '01]
Inelastic DM

\[ \delta = m_{\chi'} - m_{\chi} \]

(target-dependent) minimum velocity required to scatter

\[ KE_{\chi} \geq \delta \left( 1 + \frac{m_{\chi}}{m_N} \right) \]

\[ \sigma_{inelastic} = \sqrt{1 - \frac{2\delta}{\mu_{\chi N} \nu^2} \sigma_{elastic}} \]

[L. J. Hall, T. Moroi and H. Murayama '97, Tucker-Smith, Weiner '01]
Inelastic DM

\[ \delta = m_{\chi'} - m_{\chi} \]

popularized to reconcile DAMA with CDMS (2001-)
required \( \delta \sim 100 \text{ keV} \) for \( m_{\chi} \sim 100 \text{ GeV} \)

forgetting DAMA, range of \( \delta \) is wide open

for canonical DM velocity distribution, available KE \( \approx 650 \text{ keV} \)
How to make an inelastic DM model

1.) Dirac fermion + some interaction that we can connect to SM

$$\mathcal{L} \supset V_\mu (\chi_1^\dagger \bar{\sigma}^\mu \chi_1 + \chi_2^\dagger \bar{\sigma}^\mu \chi_2) + M (\chi_1 \chi_2 + h.c.)$$
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\[ m_{\chi'} - m_{\chi} \sim \delta m \]
Inelastic DM: inelastic DM poster child

(nearly) pure Higgsinos: $\tilde{H}_u^0, \tilde{H}_d^0 \rightarrow \tilde{H}_1^0, \tilde{H}_2^0$ once we turn on EWSB
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\[
\tilde{H}_1^0 \quad \tilde{H}_2^0 \quad Z
\]

\[
\delta_{\tilde{H}} \approx m_Z^2 \left( \frac{\sin^2 \theta_W}{M_1} + \frac{\cos^2 \theta_W}{M_2} \right) + \mathcal{O} \left( \frac{1}{M_{1,2}^2} \right) = \\
\left\{ \\
192 \text{ keV} \left( \frac{10^7 \text{ GeV}}{M_1} \right) \quad M_2 \gg M_1 \gg \mu \\
640 \text{ keV} \left( \frac{10^7 \text{ GeV}}{M_2} \right) \quad M_1 \gg M_2 \gg \mu \\
\right. 
\]

Z-exchange inelastic (see 1405.3692)
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$\tilde{H}^0_1 \quad \tilde{H}^0_2 \quad Z$

$\delta_{\tilde{H}} \simeq m_Z^2 \left( \frac{\sin^2 \theta_W}{M_1} + \frac{\cos^2 \theta_W}{M_2} \right) + O\left( \frac{1}{M_{1,2}^2} \right) =$

\[
\begin{cases}
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\sigma_{\tilde{H}, \text{inelastic}} \sim (\text{velocity factor}) \times 10^{-39} \text{ cm}^2 \times A^4
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Inelastic DM: inelastic DM poster child

elastic scattering at loop level: suppressed by $m_n$ or $E_R$

![Diagrams showing elastic scattering processes](attachment:image.png)

[Hisano et al '11, Hill+Solon '13]

further suppressed by accidental cancellations

![Graph showing cross sections vs. mass](attachment:graph.png)
Inelastic DM: inelastic DM poster child

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\[ \tilde{H}_1^0 \quad \tilde{H}_2^0 \quad \tilde{H}_1^0 \]
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\[ \tilde{H}_1^0 \quad \tilde{H}_1^\pm \quad \tilde{H}_1^0 \]

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further suppressed by accidental cancellations

Just one example: many others, both fermion and scalar

[C. Arina and N. Fornengo '07]
[Batell, Pospelov, Ritz '09]
[Y. Cui, D. E. Morrissey, D. Poland and L. Randall '09]
[K. R. Dienes, J. Kumar, B. Thomas and D. Yaylali '14]
Distinct Signals from inelastic DM

Two possibilities, depending on the lifetime of excited state: $\tau_{\chi'}$

1.) $v_{\text{DM}} \tau_{\chi'} \gg 1$ m: direct detection at high recoil

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2.) $v_{\text{DM}} \tau_{\chi'} \lesssim 1$ m: detecting excited state decay, $\chi' \rightarrow \chi + \gamma$

[Pospelov, Yavin, Weiner 1312.1363]
Direct Detection at High Recoil: Inelastic Kinematics

inelasticity changes nuclear recoil energy spectrum

rate

elastic

\( E_R \)
Direct Detection at High Recoil: Inelastic Kinematics

inelasticity changes nuclear recoil energy spectrum

Inelasticity changes the nuclear recoil energy spectrum.

The rate drops as we go into less phase space.

The recoil spectrum shifts to higher values.
Direct Detection at High Recoil: Inelastic Kinematics

Experimental **signal windows** focused on low $E_R$

![Graph showing rate versus $E_{R,\text{expt}}$ and $E_R$]

as a result, blind to sufficiently inelastic DM, even if $\sigma_{XN}$ is large
Direct Detection at High Recoil: Inelastic Kinematics

Experimental **signal windows** focused on low $E_R$

as a result, blind to sufficiently inelastic DM, even if $\sigma_{\chi N}$ is large
The predicted number of neutron backgrounds primarily come from radioactivity of the detector components and from intrinsic radioactivity in the LXe target, such as the detector components and from the detector components in proximity to the active volume and from the combination of internal components and the combination of internal components and detector components in proximity to the active volume.

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After unblinding, two events were observed in the background model used in the PL analysis. The fit is made over the parameter of interest plus the contributions to neutron backgrounds primarily come from radioactivity of the detector components and from intrinsic radioactivity in the LXe target, such as the detector components and from the detector components in proximity to the active volume.

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BUT: experiments are sensitive to high recoil events

ex. LUX 1403.1299

Xenon100 1101.3866
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CRESST 1509.01515
**BUT: experiments are sensitive to high recoil events**

Ex. **LUX 1403.1299**

CRESST 1509.01515

Present: inelastic DM could be lurking in high nuclear recoil data of existing experiments: go and look!
BUT: experiments are sensitive to high recoil events

ex.  LUX  1403.1299

CRESST  1509.01515

present: inelastic DM could be lurking in high nuclear recoil data of existing experiments: go and look!

future: don’t limit searches to low-recoil
Direct Detection at High Recoil: Inelastic Kinematics

\[
E_R = \frac{\mu_{\chi N}}{m_N} \left( (\mu_{\chi N} v^2 \cos^2 \theta_{lab} - \delta) \pm (\mu_{\chi N} v^2 \cos^2 \theta_{lab})^{1/2} (\mu_{\chi N} v^2 \cos^2 \theta_{lab} - 2\delta)^{1/2} \right)
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Direct Detection at High Recoil: Inelastic Kinematics

\[ E_{\text{min}} = \frac{\mu_{\chi N}}{m_N} \delta \]

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Direct Detection at High Recoil: Inelastic Kinematics

Figure 1: The shaded region is the available range of recoil energies on a nuclear target, for a given DM mass splitting and incoming DM speed in the laboratory frame. The contours indicate mass splitting \( \delta = 0 \) in solid, \( \delta = 100 \), \( \delta = 200 \), \( \delta = 300 \), \( \delta = 400 \), and \( \delta = 500 \) keV in dashed, dotted-dashed, dotted, long-dashed, and fine dotted, respectively. The dashed grey horizontal lines indicate the maximum recoil energy windows used by collaborations including CDMS [26,27], DarkSide [28], PICO-60 [29], Xenon Experiments (LUX [30], PandaX II [31], XENON100 [32]), and CRESST II [33]. Note that the maximum incoming terrestrial dark matter speed is expected to be 780 \( \pm 54 \) km/s, Ref. [34].
Direct Detection at High Recoil: Inelastic Kinematics

Figure 1: The shaded region is the available range of recoil energies on a nuclear target, for a given experiment. The dashed grey horizontal lines indicate the maximum recoil splitting.

- CDMS
- DarkSide
- PICO-60
- Xenon Experiments (LUX, PandaX II, XENON100, CRESST II)

Note that the incoming terrestrial dark matter speed is expected to be 780 km/s.
high recoil data can probe farthest in $\delta$ for heavy targets
and for $m_X \gg m_N$
Direct Detection at High Recoil: Inelastic Kinematics

The total rate is the combination of energy range, DM velocity spectrum (MB here), and nuclear form factors.
Direct Detection at High Recoil: Inelastic Kinematics

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\[ E_{\text{min}} = \frac{\mu_{\chi N}}{m_N} \delta \]

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(MB her)
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form factor zeros
Putting everything together

The figure 3 shows the rate for dark matter nucleon scattering assuming a DM-nucleon cross-section $\sigma_n = 10^{-40}$ cm$^2$ and a target made purely of $^{132}$Xe. Blue (red) lines indicate $dR/dE$ for $m_X = 1$ TeV ($= 10$ TeV) inelastic dark matter, with $\delta = 0, 100, 200, 300$ keV mass splittings between dark matter states, as indicated. The vertical line marks the maximum recoil energy considered by LUX in [30].

The exact rate will be sensitive to the tail of the velocity distribution and large $E_R$ part of form factors.
bounds with current data, $m_X = 1 \text{ TeV}$

exposure (tonne-day)

LUX: 1.4, PICO: 1.3, CRESST: 0.05
bounds including high recoil, current exposure: $m_X = 1$ TeV

including data up to **500 keV**
(assuming no new observed events)
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including data up to \( 500 \text{ keV} \) (assuming no new observed events)
through dark photon mediation [16, 17]. The mass splitting between the VEV of a scalar field that spontaneously breaks a gauge symmetry and is also responsible for pertinent constraints. Inelastic scattering cross sections for the DM-nucleus interaction is different, i.e.

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Note also that for a mass splitting of $\delta = 300$ keV, as shown, the velocity sensitivity $\rightarrow$ large modulation effects. Modulation could be used to improve S/B and help pin down $\delta$.

- $^{132}$Xe target: 200 kgs, 30 days
  - $m_\chi = 1$ TeV
  - $\sigma_n = 10^{-40}$ cm$^2$
  - $\delta = 300$ keV

- $^{184}$W target: 10 kgs, 30 days
  - $m_\chi = 1$ TeV
  - $\sigma_n = 10^{-40}$ cm$^2$
  - $\delta = 300$ keV
Recent progress at high recoil! : XE100 1705.02614

considered recoil energies out to 240 keVnr

limit on ‘weak strength’ DM pushed out to $\delta \gtrsim 260$ keV
Distinct Signals from inelastic DM

Two possibilities, depending on the lifetime of excited state: $\tau_{\chi'}$

1.) $v_{DM} \tau_{\chi'} \gg 1$ m: direct detection at high recoil
   [Bramante, Fox, Kribs, AM 1608.02662]

2.) $v_{DM} \tau_{\chi'} \lesssim 1$ m: detecting excited state decay, $\chi' \rightarrow \chi + \gamma$
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So far, we’ve ignored the excited state coming out of the inelastic collision… but it can be a discovery tool!
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If $\chi'$ lifetime is short and $\chi' \rightarrow \chi \gamma$ exists, can hunt for, $\chi'$ decay via $\sim$ **monochromatic** photon
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Two-step detection

FIG. 1. A schematic of the search proposal. An incoming WIMP scatters in the shield and can scatter in the shield and against a lead target Pb. The excited state then travels some distance before de-exciting by emitting an x-ray photon. We emphasize that the decay occurs spontaneously and is independent of the detector material.

1.)

<table>
<thead>
<tr>
<th>( \chi^* )</th>
<th>Pb</th>
<th>( \chi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering against lead nucleus</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Two-step detection

2.)

\[ \chi \rightarrow \gamma \rightarrow \chi^* \]

Detector

1.)

\[ \chi \rightarrow \gamma \rightarrow \chi^* \rightarrow \text{Pb} \]

Scattering against lead nucleus
Two-step detection

Need: detector sensitive $E_\gamma \sim 100’s$ of keV - MeV
\[ \therefore 1312.1363 \text{ focused on } 0\nu\beta\beta \text{ experiments (CUORE)} \]

$E_\gamma$ comes from decay, so independent of detector material
Two-step detection

\(\chi'\) dir, \(\gamma\) dir. highly correlated with WIMP wind dir.

1.)

\[ \chi \rightarrow \chi^* \rightarrow \gamma \]

2.)

Need: detector sensitive \(E_{\gamma} \sim 100's\) of keV - MeV
\[ \therefore \ 1312.1363 \text{ focused on } 0\nu\beta\beta \text{ experiments (CUORE)} \]

\(E_{\gamma}\) comes from decay, so independent of detector material
Model requirements present in magnetic inelastic DM (MiDM)

$$\mathcal{L} \supset \left( \frac{g_M e}{8 m_\chi} \right) \chi_2 \sigma_{\mu \nu} \chi_1 F^{\mu \nu}$$

[Chang, Weiner, Yavin '10]

interaction with nuclei through photon exchange

interaction with nuclei through photon exchange

momentum dependent
Model requirements present in magnetic inelastic DM (MiDM)

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interaction with nuclei through photon exchange

\[ \chi_1 \quad \text{γ} \quad \chi_2 \]

momentum dependent

\[ \chi_2 \text{ lifetime: } \frac{10^{-4} \text{ s}}{g_M^2} \times \left( \frac{100 \text{ keV}}{\delta} \right)^3 \times \left( \frac{m_X}{\text{TeV}} \right)^2, \text{ easily have } \nu_{\text{DM}} \tau \approx m \]
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Relic abundance, UV completions explored in Weiner & Yavin 1209.1093
Two-step detection

Correlated directions mean asymmetries in detector design (amt. of Pb shielding) lead to modulation in signal on a daily basis.
Two-step detection

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Two-step detection

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Can be exploited to separate signal from background
Two-step detection

estimates of rates

\[ \nu_{\text{esc}} = 554 \text{ km/sec}, \nu_{\text{rot}} = 220 \text{ km/sec} \]

\[ \delta = 75 \text{ keV} \] - Dashed
\[ \delta = 100 \text{ keV} \] - Solid
\[ \delta = 125 \text{ keV} \] - Dotted

\[ \mu X = 0.9 \times 10^{-2} \mu N \]
\[ \mu X = 0.6 \times 10^{-2} \mu N \]
\[ \mu X = 0.3 \times 10^{-2} \mu N \]

mX (GeV)

cpd

estimates of modulation

Rate (counts/hour)

\[ m_\chi = 150 \text{ GeV} \]
\[ \delta = 100 \text{ keV} \]

Solid - \( \mu_\chi = 0.9 \times 10^{-2} \mu N \)
Dashed - \( \mu_\chi = 0.6 \times 10^{-2} \mu N \)
Dotted - \( \mu_\chi = 0.3 \times 10^{-2} \mu N \)

CUORE-0 with extra shield

Rate/\langle Rate \rangle

hour

(Here limits quoted in terms of fractions of \( \mu_N = e/2m_p \))
ever, this does not necessarily imply a greater sensitivity in the next section. Using the more precise cubical geometry of the CUORE setup is indeed somewhat closer to being as those of the CUORICINO and CUORE-0 setups [42].

For example, in Fig. 4 we show the event rate in a spherical geometry. As we note that the maximum angle that would reach the detector after the initial collision. If the exited the detector, we can model the detector as a sphere of radius $r$.

The lifetime of the WIMP is given in Eq. (15) above. The probability of the excited state to decay inside the detector, which is determined by the geometry of the different WIMP models parametrized by $\mu = v_{\text{esc}}$, is divided by the average rate for the same parameters.

The direction of the sidereal daily modulations of the signal can be increased by plotting the hourly rate divided by the average rate for the same parameters. The expected diurnal modulations by plotting the hourly rate.

The direction of the modulations depends on the existence of dark matter. Given the relatively low cost to pursue the existence of dark matter, it is worthwhile to explore the discovery of such particles. (Here limits quoted in terms of fractions of $\mu_N = e/2m_p$)

Recently studied by Xe100 1704.05804 (both steps). DAMA region excluded but lots of open space left to explore.
Conclusions

Explore the inelastic direction! Motivated models with sizable $\sigma_{X-N}$ within easy reach

Distinct signals!

1.) scattering at high nuclear recoil energy
   - current techniques work, just enlarge $E_R$ signal regions;
   - most sensitive to heavy DM using heavy targets;
   - sensitive to tails of DM velocity distribution

2.) excited state decay
   - targets inelastic scenarios with short $\tau_\chi$ and $\chi'\chi\gamma$ interaction;
   - monochromatic $\gamma$, daily modulating signal
   - searches can be done with little/no modification to existing experiments ($0\nu\beta\beta$, Xe)
EXTRAS
What other models could lie in high recoil data?

Dark photon + dark charged DM: [Batell, Pospelov, Ritz '09]

\[\mathcal{L} = \mathcal{L}_{\text{SM}} + |D_\mu \Phi|^2 - V(\Phi) - \frac{1}{4} V_{\mu \nu}^2 + \epsilon V_{\mu} \partial_{\nu} F^{\mu \nu} + \bar{\psi} (i D_\mu \gamma_\mu - m_\psi) \psi + (\lambda_D \Phi \psi^T C^{-1} \psi + \text{h.c.}) \]

\(U(1)_D\) breaking splits Dirac DM (\(\psi\)) \(\rightarrow\) 2 Majorana (\(\chi_1, \chi_2\))

annihilation \(\chi_1 \chi_1 \rightarrow \gamma_D \gamma_D\) yields correct relic abundance for

\[\alpha_D \sim 0.04 \left( \frac{m_{\chi_1}}{\text{TeV}} \right) \]

\(\chi_1 \quad \chi_2\)

\[\gamma_{\text{dark}}\]

\[\gamma\]

inelastic scattering via kinetic mixing

\[\sigma_{\chi, \text{inelastic}} \approx 10^{-30} \text{ cm}^2 \times \epsilon^2 \times \left( \frac{m_\chi}{\text{TeV}} \right) \left( \frac{\text{GeV}}{m_V} \right)^4 \times (\text{velocity factor}) \times A^4 \]
Dark photon + dark charged DM:

high recoil studies probe parameter space other methods can’t (though more model dependent)
Dark photon + dark charged DM:

high recoil studies probe parameter space other methods can’t (though more model dependent)
Dark photon + dark charged DM:

\[ \chi_1 \rightarrow \gamma \rightarrow \gamma_{\text{dark}} \]

\[ \gamma_{\text{dark}} \rightarrow \gamma \rightarrow \gamma_{\text{dark}} \]

high recoil studies probe parameter space other methods can’t (though more model dependent)
PICO?

PICO-60  CF$_3$I  1510.07754

smaller fiducial volume than Xe experiments (& similar mass element). .. but NO upper limit on search window
of the MiDM model: the excited WIMP de-excites with a lifetime 
\[ \tau = \frac{\pi}{3} \left( \frac{\mu^2}{\mu_s} \right) \tau_{O}(\mu_s) \] (for the values of \( \mu \) and \( \mu_s \) considered in this analysis). During this period, the WIMP propagates a distance of \( O(100\,\text{keV}) \) given the mean velocity of the Sun with respect to the WIMP halo. The de-excitation leads to the emission of a \( O(100\,\text{keV}) \) photon which will interact with the target as well, inducing an electronic recoil signal. This unique combination of a low-energy nuclear recoil followed by a significantly larger electronic recoil provides the means for the first search for dark matter-induced interactions in double-scatter signatures.

For the analysis presented here, we use data from the science run II of the XENON100 dark matter experiment, previously used for various analyses [11–14]. The data was acquired between February 28, 2011 and March 31, 2012 comprising a total live time of 224.6 days. XENON100, a liquid xenon time projection chamber (LXe TPC) described in detail in [15], is located at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN in Italy. The TPC is instrumented with two arrays of photomultipliers (PMTs, Hamamatsu R8520), one below the 62 kg LXe target in the cryogenic liquid and one above in the xenon gas phase. A particle interaction inside the TPC leads to a prompt scintillation signal (S1) and liberates free ionization electrons, that are drifted towards the liquid-gas interface by an electric field of 0.53 kV/cm. A stronger electric field (\( \sim 12 \, \text{kV/cm} \)) extracts them into the gas phase, where they create a secondary scintillation signal (S2), which is proportional to the ionization charge [16]. The interaction vertex can be spatially reconstructed using the time separation of the two signals and the S2-signal spatial distribution on the top PMT array. The ratio of scintillation light and ionization charge signal depends on the interacting particle. This allows the discrimination of backgrounds, which produce electronic recoils (ER), from nuclear recoils (NR) that are expected from WIMP interactions.

The size of the cylindrical XENON100 TPC (\( \sim 30 \, \text{cm diameter and height} \)) allows a first-ever search for the distinct MiDM signature of a primary nuclear recoil followed by the photon emission.
A. Comparison for spin-dependent WIMP scattering

The interaction of WIMPs with nuclei can be also SD reflecting the coupling of the spin of the WIMP to nucleons. The even-mass xenon isotopes are practically insensitive to SD scattering due to their \( J = 0 \) ground state, so that only the odd-mass xenon isotopes \( ^{129}\text{Xe} \) and \( ^{131}\text{Xe} \) are relevant. In previous work [11, 12], we have calculated SD structure factors for xenon, also including two-body currents in chiral effective field theory.

To complete the study of WIMP scattering on xenon, we also compare these calculations to the results obtained by Fitzpatrick et al. in Ref. [15]. This provides a test of the calculations and explores the sensitivity of SD WIMP scattering to nuclear structure.

The SD structure factor is naturally decomposed in terms of the isospin couplings \((a_0 + a_1 \times \sigma_3)/2\). However, experimental results are commonly presented in terms of “neutron-only” \((a_0 = a_1 = 1)\) and “proton-only” \((a_0 = a_1 = 1)\) structure factors \(S_n(u)\) and \(S_p(u)\), because these coupling combinations are more sensitive to neutrons and protons, respectively. For vanishing momentum transfer, \(q = 0\) (\(u = 0\)), and considering only one-body currents, the SD “neutron-only” and “proton-only” structure factors are proportional to the square of the expectation values of the neutron and proton spins [14].

These are given for both calculations in Table III. Because xenon has an even proton number, \( S_n \) \( S_p \), the “neutron-only” structure factor dominates over the “proton-only” one.

This hierarchy of “neutron-only” versus “proton-only” structure factors manifests itself in Figs. 21 and 22, where we show the calculated SD structure factors for \( ^{129}\text{Xe} \) and \( ^{131}\text{Xe} \). Note that the absolute scale of the SD structure factors is \( \sim 10^{-4} \) smaller than for SI scattering, because in the SD case, due to pairing, the contributions from different nucleons do not add coherently.

In Refs. [11, 12], we included one- and two-body currents in the WIMP-nucleon interaction Lagrangian. However, for a direct comparison, Figs. 21 and 22 restrict the results to the one-body level, even though two-body currents are important because they reduce the “neutron-only” structure factors by about 20% for xenon, and significantly enhance the “proton-only” structure factors.

### Table III. Proton/neutron spin expectation values

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( h S_p )</th>
<th>( h S_n )</th>
<th>( h S_p )</th>
<th>( h S_n )</th>
</tr>
</thead>
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<td>( ^{129}\text{Xe} )</td>
<td>0.007</td>
<td>0.009</td>
<td>0.005</td>
<td>0.019</td>
</tr>
<tr>
<td>( ^{131}\text{Xe} )</td>
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<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
</tr>
</tbody>
</table>