Prospects for dark matter detection with inelastic transitions of xenon

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preliminary results — work in progress —

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• The original direct detection paper:

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Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

Aside from the detector proposed in Ref. 5, an interesting possibility is to detect dark-matter particles via inelastic rather than elastic scattering from nuclei.
An old idea... Inelastic scattering

• What is it?
• Why is it interesting?
• Why consider it now?

Can it ever be detected?
What is it?

**elastic** scattering:

DM → N → DM

measure: N’s recoil energy

**inelastic** scattering:

DM → N → N* → Y

measure: N’s recoil energy + photon energy
What is a good target?

Inelastic scattering *is not* coherently enhanced

- Hopeless to look for it with spin-independent interactions
  ➡ inelastic rate is $A^2 \approx 10^4$ smaller

- Spin-dependent interactions *are not* $A^2$ enhanced
  ➡ Elastic and inelastic scattering rates more comparable

★ Ideal target has good spin-dependent sensitivity
  …and a low lying excitation
What is a good target?

XENON
What is a good target?

- **Xenon**: two isotopes are sensitive to spin-dependent interactions:
  
  - $^{129}$Xe
    - Natural abundance: 26.4%
    - Lowest excitation: 39.6 keV
    - Lifetime: 0.97 ns
  
  - $^{131}$Xe
    - Natural abundance: 21.2%
    - Lowest excitation: 80.2 keV
    - Lifetime: 0.48 ns

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Previous studies

Limits on WIMP-\(^{129}\)Xe inelastic scattering

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Search for inelastic WIMP nucleus scattering on \(^{129}\)Xe in data from the XMASS-I experiment

- Previous searches with single phase-detectors
- **No limits or studies for two-phase detectors**
Why is it interesting?

- A detection would:
  - provide independent evidence for dark matter
  - point strongly to a spin-dependent interaction
  - help with mass reconstruction (because of different kinematics)

*Inferring properties of dark matter is difficult - why not search for a signal that will provide more information?*
We can accurately quantify the signal and background

- Precise calculation of structure functions available
- Future detector properties are more-or-less known
- Backgrounds are more-or-less known
Can it ever be detected?
• The form of the scattering rate is the same as usual:

\[
\frac{dR}{dE_R} = \frac{1}{m_A m_{DM}} \int_{v_{\text{min}}} d^3 \nu \nu f_{\text{DM}}(\vec{\nu} + \vec{\nu}_E) \frac{d\sigma}{dE_R}
\]

• \(v_{\text{min}}\) is higher
  (DM kinetic energy excites the nucleus and causes the recoil)

• This suppresses the inelastic rate
Structure functions

- Only consider axial-vector interaction: \( \mathcal{L} \propto -\bar{\chi} \gamma^\mu \gamma^5 \chi \cdot \sum_q A_q \bar{\psi}_q \gamma_\mu \gamma^5 \psi_q \)

- The form of the cross-section is the same...

\[
\frac{d\sigma}{dE_R} = \sum_{A=^{129}\text{Xe},^{131}\text{Xe}} \frac{4\pi m_A}{3} \frac{\sigma_n^0}{2} \frac{f_A}{\mu^2 v^2} \frac{E_R}{2J_A + 1} S_A^n(E_R)
\]

...but the **structure functions** are different: (\(u=1\) approx. \(E=60\) keV)

- This suppresses the inelastic rate

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Baudis et al 1309.0825
The rate

- Rate as a function of recoil energy (not directly measured)

- Inelastic rate **smaller** because of kinematics ($v_{\text{min}}$) and nuclear structure functions
• Express the signal in terms of measured quantities:

\[ S1 = g_1 n_\gamma \]

\[ S2 = g_2 n_e \]

• Drift field is also crucial
Mock detectors

- I’ll consider two scenarios:

  **XenonA180**
  \[ g_1 = 0.12 \text{ PE/}\gamma \]
  \[ g_2 = 12.5 \text{ PE/e} \]
  
  (50% extraction efficiency)
  
  drift field = 180 V/cm

  **XenonB1000**
  \[ g_1 = 0.18 \text{ PE/}\gamma \]
  \[ g_2 = 25 \text{ PE/e} \]
  
  (100% extraction efficiency)
  
  drift field = 1000 V/cm

- Model number of photons & electrons with NEST
Mock signals

- Include detector and recombination fluctuations

- For same energy, electronic recoils produce a much larger S1 and S2
Mock signals

• Looks like real data... 😊

Data from PandaX-I arXiv:1505.00771

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Scattering rate

• The scattering rate (for single phase)

![Graphs showing scattering rates for XenonA180 and XenonB1000 detectors.](image)

- Rates similar for both mock scenarios
- **Clear that discovery is always with elastic scattering**
• We need to model the backgrounds:

• 2-beta—2-neutrino decay of $^{136}$Xe dominates
Background versus signal

- Detecting this signal could be difficult…

...impossible for single phase (S1-only)?
Background versus signal

- Two-phase experiments help:
  - Some signal-to-background discrimination
  - Better for higher drift fields
• Quantify the sensitivity of future experiments with a ‘discovery limit’ Billard et al 1110.6079

The smallest cross-section at which 90% of experiments can make a $3\sigma$ detection of the signal

• Profile likelihood ratio:

$$
\lambda(0) = \frac{\mathcal{L}(\sigma_p = 0, \hat{R}_b, \hat{\nu})}{\mathcal{L}(\hat{\sigma}_p, \hat{R}_b, \hat{\nu})}
$$

- Include background and signal ($v_{\text{esc}}$) uncertainties
Discovery limit

• Compare discovery limit with current/future (elastic) constraints:

![Graph showing the discovery limit comparison between different detectors.]

- Better sensitivity for higher drift fields
- $^{131}\text{Xe}$ excitation is not detectable
- $^{129}\text{Xe}$ detectable if LUX/XENON1T make discovery in next run
Could have a larger exposure
  ➔ background dominated so only scales with the square root

Could reduce backgrounds
- Largest: 2-beta—2-neutrino decay of $^{136}$Xe
  ➔ Remove the $^{136}$Xe isotope

- Try to search for displaced the S2 signal from the recoil and photon?
• Dark matter can excite the $^{129}$Xe and $^{131}$Xe isotopes
  ➤ signal is nuclear recoil + photon

• Signal is always smaller than elastic rate
  ➤ Can it be detected?

  No: for $^{131}$Xe

  Yes: for $^{129}$Xe

  …need an (elastic) discovery signal
  in the next run of LUX or XENON1T
Thank you