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An exciting prospect: detecting inelastic transitions of xenon caused by dark matter

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Abstract. Dark matter can scatter and excite the xenon isotopes ^{129}Xe and ^{131}Xe to a low-lying excitation in a direct detection experiment. This signature is distinct from the canonical elastic scattering signal because the inelastic signal also contains the energy deposited from the subsequent prompt de-excitation of the nucleus. A measurement of the elastic and inelastic signal will allow a single experiment to distinguish between a spin-independent and spin-dependent interaction. In this paper, I will discuss the prospects of detecting this inelastic signal with up-coming tonne-scale two-phase xenon direct detection experiments.

1. Introduction

Direct detection experiments are arguably the most promising way of detecting the non-gravitational interaction of particle dark matter. A positive detection will provide information on the dark matter particle's mass, the size of the dark matter-nucleon cross-section and will give input into the dark matter-quark interaction. Although there have been hints of a detection at a few separate experiments [1, 2, 3, 4], the majority of the direct detection community now attributes these signals to background processes [5, 6, 7, 8]

Two-phase xenon experiments are currently the most sensitive searches for dark matter particles heavier than 10 GeV. This is expected to remain the case in the coming decade as much larger, multi-tonne experiments come online. Multi-tonne xenon experiments bring new opportunities to search for rare signals. This paper is concerned with the search for one such rare signal: the excitation and subsequent decay of the ^{129}Xe and ^{131}Xe isotopes caused by dark matter.

The canonical direct detection search is for elastically scattering dark matter particles, where the interaction causes the xenon nucleus to recoil with an energy in the range $1-100$ keV. This is an interesting energy range since many nuclear isotopes have excitations in this range. For this reason, it was long ago proposed that these nuclear excitations could also play a role in the detection of dark matter [9, 10].

For xenon, the two isotopes of interest, ^{129}Xe and ^{131}Xe, which make up 26.4% and 21.2% of natural xenon and have an excitation energy and lifetime of 39.6 keV and 80.2 keV, and 0.97 ns and 0.48 ns, respectively. If a dark matter particle excites one of these isotopes, some part of the dark matter's kinetic energy causes the excitation of the nucleus while the other part causes the nucleus to recoil. The excited nucleus then decays emitting a gamma-ray, so that the total measured signal is the recoil of the nucleus together with the de-excitation gamma-ray.

Although a number of *single-phase* xenon experiments have searched for the 39.6 keV de-excitation from the ^{129}Xe isotope [11, 12, 13], no studies have been performed with the more sensitive *two-phase* xenon experiments. Single-phase experiments are generally less sensitive than two-phase experiments because they are substantially less able to distinguish between nuclear and electromagnetic events. This paper provides a succinct discussion of the sensitivity of upcoming tonne-scale two-phase xenon detectors to the inelastic scattering process. The reader is referred to [14] for a more detailed discussion.

2. Modelling inelastic recoils of xenon

The differential event rate for inelastic scattering of dark matter with mass $m_{\rm DM}$ with a xenon nucleus of mass m_A in the detector frame may be written in the usual form:

$$\frac{dR}{dE_{\rm R}} = \frac{1}{m_A}\frac{\rho_{\rm DM}}{m_{\rm DM}}\int_{v_{\rm min}} d^3v\, v f_{\rm DM}(\vec{v}+\vec{v}_{\rm E})\frac{d\sigma}{dE_{\rm R}}\ , \tag{1}$$

where $E_{\rm R}$ is the recoil energy of the xenon nucleus, $\rho_{\rm DM} = 0.3$ GeV/cm^3 is the local dark matter density [15], v and $\vec{v}$ are the dark matter speed and velocity, and $f_{\rm DM}(\vec{v}) \propto \exp\left(-v^2/v_0^2\right)$ is a Maxwell-Boltzmann distribution in the galactic frame with a hard cut-off at the galactic escape speed $v_{\rm esc}$, for which we assume $v_{\rm esc} = 550$ km/s [16]. We boost from the galactic frame to the detector rest frame with $\vec{v}_{\rm E} = (0, v_0, 0) + \vec{v}_{\rm pec} + \vec{v}_{\rm e}$, where $v_0 = 220$ km/s, $\vec{v}_{\rm pec} = (11.1, 12.2, 7.3)$ km/s [17] and we use the expression for $\vec{v}_{\rm e}$ from [18].

The minimum speed to recoil with an energy $E_{\rm R}$ additionally depends on the excitation energy E^*:

$$v_{\rm min} = \sqrt{\frac{m_A E_{\rm R}}{2\mu_A^2}} + \frac{E^*}{\sqrt{2 m_A E_{\rm R}}}\ , \tag{2}$$

where μ_A is the nucleus-dark matter reduced mass. The minimum speed is larger for bigger E^* since part of the kinetic energy of the incoming dark matter particle is required to excite the nucleus.

In this paper we only consider axial-vector interactions of the type

$$\mathcal{L} \propto -\bar{\chi}\gamma^\mu\gamma^5\chi \cdot \sum_q A_q \bar{\psi}_q \gamma_\mu \gamma^5 \psi_q\ , \tag{3}$$

where χ is the dark matter (here assumed to be a fermion), ψ_q are the light-quark fields ($q = u, d, s$) and A_q are the (model-dependent) dark matter-quark coupling constants. The total spin-dependent differential cross-section applicable for this operator can generally be written as

$$\frac{d\sigma}{dE_{\rm R}} = \sum_{A={}^{129}{\rm Xe},\,{}^{131}{\rm Xe}} \frac{4\pi}{3}\frac{m_A}{2\mu_n^2}\frac{\sigma_n^0}{v^2}\frac{f_A}{2J_A+1} S_A^n(E_{\rm R})\ , \tag{4}$$

where μ_n is the nucleon-dark matter reduced mass, the sum is over the isotopes that have spin, f_A is the fractional abundance of the xenon isotope, J_A is the ground-state spin of the isotope ($J_{129} = 1/2$ and $J_{131} = 3/2$) and σ_n^0 is the elastic cross-section to scatter off a point-like neutron in the limit of zero-momentum transfer. The structure factors $S_A(E_{\rm R})$ describe how the dark matter interacts with the nucleus and depend on the isotope. We take the central values of the one + two-body expressions from [19] and [20] for elastic and inelastic scattering respectively. In both cases we only consider the neutron structure factors $S_A^n(E_{\rm R})$ since the proton structure factors are always at least a factor of 10 smaller.

The recoil spectra as a function of the xenon nucleus's recoil energy $E_{\rm R}$, assuming $m_{\rm DM} = 1000$ GeV and $\sigma_n^0 = 10^{-39}$ cm^2, is shown in the left panel of figure 1. The total elastic and

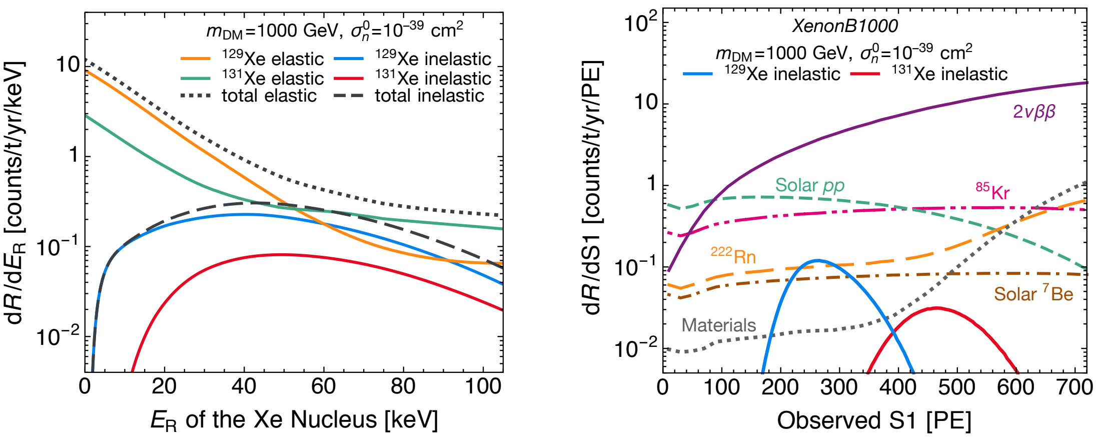

Figure 1. The left panel shows the recoil spectra for the elastic and inelastic processes. We remind the reader that $E_{\rm R}$ is not directly measured in a two-phase xenon detector, rather, it is the scintillation signals S1 and S2. The right panel shows the inelastic differential event rate in terms of S1 and a comparison with the main backgrounds.

inelastic spectrum are shown by the black dotted and black dashed lines respectively. The orange and green lines show the contribution of ^{129}Xe and ^{131}Xe to the elastic spectrum, while the blue and red lines show the contribution of ^{129}Xe and ^{131}Xe to the inelastic spectrum. The elastic spectrum is always larger implying that for the axial-vector interaction, a discovery of dark matter will always first be made with the elastic scattering process.

Two-phase xenon detectors do not directly measure the energy. Instead, a particle interacting in the fiducial volume of the liquid xenon produces two measurable signals referred to as the S1 and S2 signal. An interaction in the liquid xenon produces ions and excitons which produce photons and electrons. The quantity S1 is a measure of the number of photoelectrons (PE) from the prompt scintillation due to the photons in the liquid xenon. The electrons are drifted in an electric field to the xenon gas phase, where they are extracted and accelerated. These extracted electrons create a secondary scintillation, denoted as S2. For an energy deposition E, the expectation values for S1 and S2 can be expressed as $\langle \mathrm{S1}\rangle = g_1\langle n_\gamma(E)\rangle$ and $\langle \mathrm{S2}\rangle = g_2\langle n_e(E)\rangle$ respectively, where the measurement gains g_1 and g_2 relate the number of produced photons $n_\gamma(E)$ and electrons $n_e(E)$ to the expected number of detected PEs. The gain g_1 is the probability that a photon produced at the centre of the detector strikes a photomultiplier tube (PMT) and is converted to a PE. The gain $g_2 = \epsilon \times Y$ is the product of the probability of extracting an electron from the liquid to the gas (ϵ) and the amplification factor (Y) converting a single ionisation electron to photoelectrons. The S2 signal measured from the bottom PMTs ($\mathrm{S2_b}$) is usually used because the light collection efficiency is more homogeneous on these PMTs. We therefore use $\mathrm{S2_b}$ and assume that it is related to the total S2 signal by $\mathrm{S2_b} = 0.43 \times \mathrm{S2}$, as found in XENON100 [21] and LUX.

In this paper we show results for a single benchmark scenario, *XenonB1000*, whose parameters agree with the expectation of tonne-scale experiments: *XenonB1000* corresponds to a detector with a drift field of 1000 V/cm and the parameters $g_1 = 0.12$ PE/γ, $\epsilon = 100\%$, $Y = 50$ PE/e so that $g_2 = 50$ PE/e. Our benchmark exposure is 15 tonne-years and we assume that all measurement efficiencies are 100% since the signals of interest are far from thresholds.

The right panel of figure 1 shows the inelastic differential event rate in terms of S1 for $m_{\rm DM} = 1000$ GeV and $\sigma_n^0 = 10^{-39}$ cm^2 for the *XenonB1000* benchmark scenario. Unlike in the left panel, the inelastic spectrum now has two distinct peaks whose origin should be clear. The first peak is the signal containing the 39.6 keV de-excitation photon from the ^{129}Xe isotope

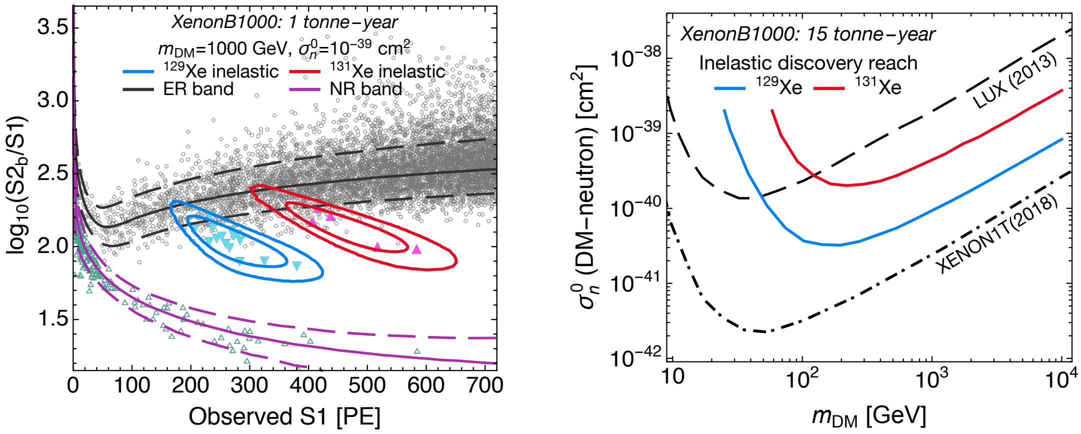

Figure 2. The left panel show a simulation of the background and signal regions for the *XenonB1000* benchmark scenario. Two-phase xenon experiments allow for some discrimination between the inelastic signal and the background events because the signal region extends below the electronic recoil band. The right panel shows the discovery reach for scattering and exciting the ^{129}Xe and ^{131}Xe isotopes, respectively. Also shown is the LUX exclusion limit and the projected exclusion limit from XENON1T.

while the second peak is the signal containing the 80.2 keV de-excitation photon from the ^{131}Xe isotope.

3. Characterising the detection sensitivity

Our aim is to assess the discovery potential of the inelastic signal. We will do this by calculating the 'discovery limit', introduced in [23], or as we will call it, the *discovery reach*. The discovery reach is the smallest cross-section for which 90% of experiments make at least a 3σ discovery of the signal under consideration.

To assess the discovery reach, we must first consider background processes. In the signal range of interest, the background rates that dominate in order of decreasing importance are the $2\nu\beta\beta$-decay of ^{136}Xe, elastic neutrino-electron scattering from *pp* and ^{7}Be solar neutrinos, decays of ^{85}Kr and ^{222}Rn and finally, radioactivity from detector materials. All of these backgrounds are beta-electronic sources. The background rates for the *XenonB1000* scenario are shown in the right panel of figure 1. The main point to take away from the right panel of figure 1 is that the signal rate is always at least 30 times smaller than the background rate. This demonstrates that observing this signal with a single-phase xenon experiment that only measures the S1 signal will be very challenging.

Two-phase experiments provide additional information in the form of the S2 signal. In the left panel of figure 2 we plot the signal and background distributions in the $\log_{10}(\mathrm{S2_b/S1})$ – S1 plane traditionally used by two-phase xenon experiments. The black and purple lines show the electronic and nuclear recoil bands, respectively. The blue and red contours indicate where 68% and 95% of events occur for inelastic scattering off the ^{129}Xe and ^{131}Xe isotopes for $m_{\mathrm{DM}} = 1000$ GeV and $\sigma_n^0 = 10^{-39}$ cm^2, respectively. Finally, the circles and triangles show the simulated events expected for an exposure of one tonne-year and the dark matter parameters mentioned above. The open grey circles show the electronic background events, the filled blue and filled red triangles show the inelastic events from the 39.6 keV and 80.2 keV de-excitation after scattering off the ^{129}Xe and ^{131}Xe isotopes and the open green triangles show the events from elastic scattering off xenon.

The left panel of figure 2 shows that the signal and background distributions are slightly displaced; the inelastic signal region lies below the electronic recoil band. This displacement is crucial as it allows for some discrimination between signal and background events. This means that two-phase xenon detectors should have a significantly better sensitivity than single-phase detectors.

4. Main result and conclusions

The right panel of figure 2 contains the discovery reach for the *XenonB1000* benchmark scenario for an exposure of 15 tonne-years. The discovery reach of the inelastic signal is below the current LUX exclusion limit for a dark matter mass greater than ~ 100 GeV. This means that for dark matter particles that are heavier than this, it is possible for the inelastic signal to be detected by a future two-phase xenon detector that collects an exposure of 15 tonne-year (such as LZ or XENONnT). The parameter space where the inelastic signal may be detected is populated by many dark matter models, including neutralino scenarios where the higgsino component is large (see e.g. [24, 25, 26]). XENON1T [27] is expected to be significantly more sensitive than LUX and will probe all of the parameter space where the inelastic signal may be detected with a 15 tonne-year exposure. Therefore, if the inelastic signal is ever to be detected with this exposure, XENON1T should find evidence for the elastic scattering dark matter signal by 2018.

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