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The scintillation and ionization yield of liquid xenon for nuclear recoils

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XENON10 Collaboration

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A B S T R A C T

XENON10 is an experiment designed to directly detect particle dark matter. It is a dual phase (liquid/gas) xenon time-projection chamber with 3D position imaging. Particle interactions generate a primary scintillation signal ($S1$) and ionization signal ($S2$), which are both functions of the deposited recoil energy and the incident particle type. We present a new precision measurement of the relative scintillation yield $\mathcal{L}_{\mathit{eff}}$ and the absolute ionization yield $\mathcal{Q}_y$, for nuclear recoils in xenon. A dark matter particle is expected to deposit energy by scattering from a xenon nucleus. Knowledge of $\mathcal{L}_{\mathit{eff}}$ is therefore crucial for establishing the energy threshold of the experiment; this in turn determines the sensitivity to particle dark matter. Our $\mathcal{L}_{\mathit{eff}}$ measurement is in agreement with recent theoretical predictions above 15 keV nuclear recoil energy, and the energy threshold of the measurement is ~4 keV. A knowledge of the ionization yield $\mathcal{Q}_y$ is necessary to establish the trigger threshold of the experiment. The ionization yield $\mathcal{Q}_y$ is measured in two ways, both in agreement with previous measurements and with a factor of 10 lower energy threshold.

1. Introduction

1.1. Expected signal in XENON10

There is abundant evidence for a significant cold dark matter (CDM) component in the universe [1–3], and perhaps the best-motivated candidate is the lightest neutralino from super-symmetric (SUSY) extensions to the Standard Model [4]. A neutralino is expected to be non-relativistic and stable, and is more generally classified as a weakly interacting massive particle (WIMP). The open question of the expected mass and cross-section of WIMPs is being addressed by numerous direct and indirect detection experiments [5–7], including XENON10.

The XENON10 detector is a liquid xenon time-projection chamber. It is designed to directly detect galactic WIMPs which scatter elastically from xenon nuclei. With velocities of order $10^{-3}c$, the recoil energy spectra WIMPs with a mass $100\,\mathrm{GeV}/c^2$ incident on xenon is predicted to be a featureless exponential falling one decade every 30 keV nuclear recoil energy (keVr). A particle interaction in liquid xenon creates both excited and ionized xenon atoms [8], which react with the surrounding xenon atoms to form excimers. The excimers relax on a scale of 10^{-8} s with the release of scintillation photons. This prompt scintillation light is detected and referred to as the $S1$ signal.

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An external electric field ($E_d = 0.73\,\mathrm{kV/cm}$) across the liquid xenon target causes a portion of the ionized electrons to be drifted away from an interaction site. The electrons are extracted into the gas phase by a stronger electric field ($\sim$10 kV/cm) and accelerated through a few mm of xenon gas, creating a secondary scintillation signal. This scintillation light is proportional to the number of ionized electrons and is referred to as $S2$. The amplification during proportional scintillation makes the recoil energy threshold for $S2$ lower than the threshold for $S1$. XENON10 discriminates between electron recoil background and the expected nuclear recoil WIMP signal via the distinct ratio of ionization ($S2$) to scintillation ($S1$) for each type of interaction.

1.2. Importance of these measurements

The energy threshold of XENON10 is determined by its total light collection efficiency for primary scintillation photons ($S1$), and by the effective scintillation yield of nuclear recoils ($\mathscr{L}_{eff}$). Because of the exponential slope of the expected signal, the detector energy threshold bears significantly on the ultimate sensitivity of XENON10. The sensitivity of XENON10 to spin-independent interactions [9] and spin-dependent interactions [10] are reported in separate letters, based on a constant $\mathscr{L}_{eff} = 0.19$. Several groups have measured $\mathscr{L}_{eff}$ using tagged neutron scattering, with a range of results [11,12].

In Section 3.1 we present an alternative method to measure $\mathscr{L}_{eff}$. We clearly establish the energy dependence of $\mathscr{L}_{eff}$ in the range of 4–100 keVr. The uncertainty is substantially reduced compared with previous measurements. In Sections 3.2–3.5 we make a careful assessment of possible systematic and statistical uncertainties affecting our measurement. The effect on the dark matter sensitivity of XENON10 is discussed in Section 5.

In Section 4 we report a measurement of the absolute ionization yield ($\mathscr{Q}_y$) of nuclear recoils in liquid xenon. Our results are in agreement with previous measurements, above 25 keVr [14]. To our knowledge, this is the first measurement of $\mathscr{Q}_y$ below 25 keVr. In Section 4.1 we also present a new method to determine the absolute ionization yield. This method provides a cross-check on our measurement of $\mathscr{L}_{eff}$.

2. Experimental apparatus

2.1. XENON10 detector and neutron calibration

XENON10 is a position-sensitive time-projection chamber. Two arrays of UV-sensitive photomultiplier tubes (PMTs) detect the $S1$ and $S2$ signals. The XENON10 instrument, including design, energy calibration and position-dependent corrections, is described in detail in Ref. [15]. The performance of the 3D position reconstruction is described in Ref. [16]. The XENON10 detector is shown schematically in Fig. 1.

The XENON10 detector was exposed for 12 h, with a live fraction 0.92, to a 3.7 MBq $\pm$15% AmBe source emitting 220 n/s. The neutron rate is based on a yield of 6×10^{-5} n/Bq [17]. The exposure occurred in low-background conditions at Laboratori Nazionali del Gran Sasso. With 3100 m water equivalent rock overburden, the cosmic muon flux is reduced by about 10^6 compared with surface conditions [18]. The instrument was shielded by 20 cm Pb outside of 20 cm high density polyethylene. The shield completely enclosed the detector. It reduced the cavern γ flux by more than 10^5, and the cavern neutron flux by about $10^{2.5}$ [15].

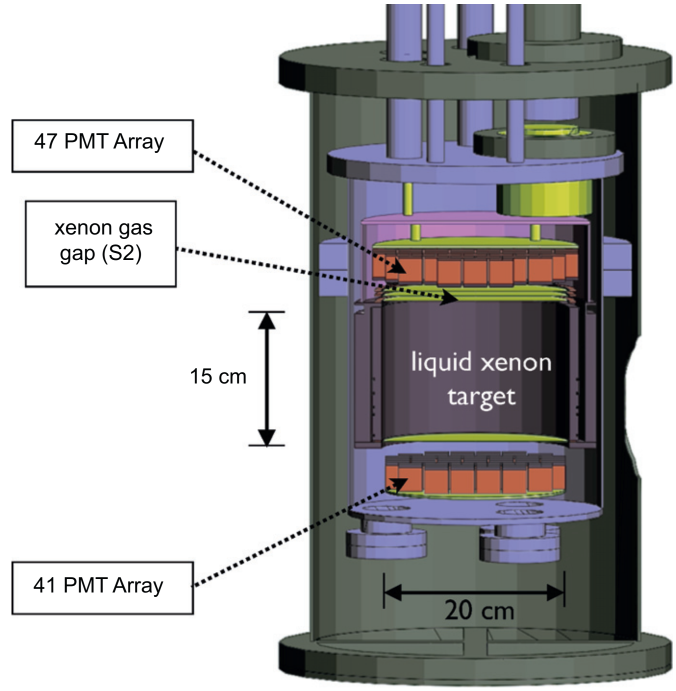

Fig. 1. A side view cut-away schematic of the XENON10 detector as rendered by the GEANT4 simulation. The liquid xenon target is 15 cm in height with a 20 cm diameter. Ancillary systems, cabling, shielding, etc. are omitted for clarity. The detector was completely enclosed by 20 cm Pb outside of 20 cm polyethylene shielding.

2.2. Neutron source and Monte Carlo simulation

The AmBe source was attached to a steel rod and inserted through a 7 mm diameter hole in the shield. It was positioned next to the detector cryostat, behind an additional 5 cm of Pb shielding. The active target of XENON10 had a 10 cm radius and 15 cm height, with a xenon mass of 13.7 kg. The analysis presented here uses only nuclear recoils which occurred in a 5.4 kg fiducial target, with 8 cm radius and 9.3 cm height. This is the same fiducial target used for the blind analysis of the WIMP-search data, as reported in Ref. [9], surrounded by a minimum of 2 cm of self-shielding xenon.

Initial neutron energies from the AmBe source ranged from below 0.1 to 11 MeV, with a mean at 4.3 MeV [19]. The neutron energy spectrum is known with an accuracy of $\pm$3% (per 0.1 MeV bin) for a source of this strength [20]. A detailed Monte Carlo simulation of the nuclear recoil spectrum in the xenon target was found to be insensitive to variations on this scale. Despite the features in the AmBe source energy spectrum [19], the spectrum of neutron energies as they enter the 5.4 kg fiducial target is a featureless exponential, falling 1 decade in 3.5 MeV.

The source also emitted 148γ/s at 4.4 MeV from the de-excitation of the ^{12}C final state. A 0.06 MeV γ with a branching ratio of 36% was not relevant due to the 5 cm of internal Pb shielding. The Monte Carlo simulation predicted a flat rate of single-scatter γ events in the fiducial target with $E < 100$ keV electron recoil equivalent energy (keVee). The predicted rate was reduced by $\times$40 by the 5 cm of internal Pb shielding, and by an additional $\times$3 due to the 2 cm of self-shielding xenon. Prior to $S2/S1$ discrimination, the single scatter γ rate in the energy range $E < 100$ keVee was measured to be $<$2 cts/0.25 keVee over the full exposure. In contrast, the single scatter elastic nuclear recoil rate was higher by as much as $\times$400, as shown in Fig. 2. Inelastic nuclear recoils on xenon cause additional prominent γ lines at