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Ionization and scintillation of nuclear recoils in gaseous xenon

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ABSTRACT

Ionization and scintillation produced by nuclear recoils in gaseous xenon at approximately 14 bar have been simultaneously observed in an electroluminescent time projection chamber. Neutrons from radioisotope α-Be neutron sources were used to induce xenon nuclear recoils, and the observed recoil spectra were compared to a detailed Monte Carlo employing estimated ionization and scintillation yields for nuclear recoils. The ability to discriminate between electronic and nuclear recoils using the ratio of

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ionization to primary scintillation is demonstrated. These results encourage further investigation on the use of xenon in the gas phase as a detector medium in dark matter direct detection experiments.

1. Introduction

Xenon has been the detection medium of choice in multiple experiments searching for rare physics events due to its favorable properties as a detection medium [1,2] including the availability of two channels of energy measurement, scintillation and ionization, that can be accessed simultaneously in a single detector. In particular, recent experiments have employed liquid xenon in searching for interactions of WIMP (weakly interacting massive particle) dark matter [3–5], and neutrinoless double-beta ($0\nu\beta\beta$) decay [6]. Both of these processes have strong implications in fundamental physics. WIMPs are strong candidates to be a possible constituent of cold dark matter (see for example [7]), thought to make up the majority of matter in the universe. The observation of $0\nu\beta\beta$ decay (see for example [8]) would establish the Majorana nature of the neutrino and provide information on the absolute value of the neutrino masses and the neutrino mass hierarchy.

WIMPs interact via the electroweak force, allowing them to elastically scatter off nuclei, and so the signature of a WIMP in a pure xenon detector would be the recoil of a xenon nucleus, in which the energetic nucleus excites and ionizes xenon atoms to produce primary scintillation photons and electron–ion pairs. Nuclear recoils have been observed and well-characterized in liquid xenon. In particular, it is known that the scintillation and ionization yields of nuclear recoils are lower, or quenched, relative to those of energetic electrons (electronic recoils) of the same kinetic energy. A model that predicts these yields based on the existing measurements has been constructed in [9]. Experiments in liquid xenon have also clearly shown that the amount of quenching in both scintillation and ionization is not the same, enabling one to discriminate between electronic recoils and the nuclear recoil signals of interest to dark matter detection by using the ratio of ionization to primary scintillation (see for example [10–12]).

The use of xenon in the gas phase may provide several advantages that would imply greater sensitivity in searches for dark matter and $0\nu\beta\beta$ decay. In particular, the gas phase offers improved energy resolution [13] over the liquid phase, largely due to the observed significant fluctuation in energy deposition between the ionization and scintillation channels [14] in liquid Xe. Though this can be corrected by combining both channels to recover some of the lost energy resolution, as done in [6], the inability to achieve light collection efficiencies beyond $\sim 20\%$[3] limits overall resolution in the combined signal due to Poisson fluctuations inherent to the detection of a relatively small amount of primary scintillation. In the gas phase, good energy resolution is realizable using only the *S*2 signal. Better energy resolution could lead to improved electron/nuclear recoil discrimination. Under the right conditions and possibly with the addition of a molecular additive to the pure xenon gas, the amount of electron–ion recombination in nuclear recoil tracks may show a dependency on the orientation of the drift electric field relative to the orientation of the track, thereby providing information about the direction of the incident WIMP [15,16].

Here we report data on the ionization and scintillation of nuclear recoils in gaseous xenon. Further details of this study can be found in [17,18]. In addition, scintillation and ionization of nuclear recoils were previously presented in [19]. The experiment was performed with a high pressure xenon gas time projection chamber (TPC) constructed as a prototype for NEXT (neutrino experiment with a xenon TPC), called the NEXT prototype for research and development towards detection of neutrinoless double beta and dark matter (NEXT-DBDM). NEXT will search for $0\nu\beta\beta$ decay with an electroluminescent TPC containing 100 kg of enriched (91% ^{136}Xe) xenon. Should potential advantages be found in using gaseous xenon to search for dark matter, one could comtemplate a simultaneous $0\nu\beta\beta$ and dark matter search with a ton-scale gaseous xenon detector. A clear understanding of nuclear recoils in gaseous xenon is a critical first step in this direction.

[3] The LUX experiment (see Ref. [3]) achieved an average detection efficiency of 14% for primary scintillation.

2. Experimental setup and calibration

2.1. Detector hardware and operation

The NEXT-DBDM detector is described in detail in [20]. Here we summarize this description and describe the modifications made for this study. Fig. 1 gives an overview of the experimental setup and source locations.

The main hardware of the TPC consists of a stainless steel cylindrical pressure vessel (20 cm diameter, 33.5 cm length) with one end closed in an ellipsoidal shape and the other sealed via a ConFlat flange to a stainless steel lid to which the internal components forming the TPC are attached. The internal hardware consists of a hexagonal field cage separated into a drift (active) region of length 8 cm and an amplification region of length 5 mm by grids of wire mesh stretched tightly across metal frames. The active region is enclosed by PTFE panels with copper strips attached to their outer surfaces which are connected via resistors to grade the drift field. The panels are supported by thin plastic frames, and the PTFE surfaces facing the active region were coated with tetraphenyl butadiene (TPB) by dissolving the TPB in toluene and spraying it directly onto the surface using an airbrush. An array of 19, 1-in. diameter Hamamatsu photomultiplier tubes (PMTs) arranged in a hexagonal pattern is located at the end opposite to the amplification region. High voltages for the wire meshes are fed into the pressure vessel through the lid via commercial feedthroughs rated to 20 kV at 17 bar and connected via PTFE-coated wire to the mesh frames. The lid is connected by a long tube to a stainless steel octagon with 8 ConFlat ports, several of which are occupied by multi-pin feedthroughs through which PMT high voltages are input to the interior of the detector and through which the PMT signals are output. An opening of diameter 1.7 cm extends through the center of the octagon and down the tube to a 2 mm source entrance window to the interior of the pressure vessel. An external sodium iodide (NaI) scintillator coupled to a PMT was used to tag gamma rays emitted in coincidence with the neutrons or gamma rays of interest. The tagging procedure mostly served to identify events of interest but also provided some time-of-flight information (see Section 3.1).

The pressure vessel is connected to a gas system allowing for full system pump-down to pressures on the order of 5×10^{-5} Torr. The gas system also permitted reclamation/reintroduction of the xenon gas used in operation to/from a steel cylinder and constant