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First measurement of surface nuclear recoil background for argon dark matter searches

Jingke Xu,[1,*] Chris Stanford,[1,†] Shawn Westerdale,[1,‡] Frank Calaprice,[1] Alexander Wright,[2] and Zhiming Shi[1,§]

[1] *Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*

[2] *Department of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, Ontario, Canada.*

One major background in direct searches for weakly interacting massive particles (WIMPs) comes from the deposition of radon progeny on detector surfaces. A dangerous surface background is the ^{206}Pb nuclear recoils produced by ^{210}Po decays. In this letter, we report the first characterization of this background in liquid argon. The scintillation signal of low energy Pb recoils is measured to be highly quenched in argon, and we estimate that the 103 keV ^{206}Pb recoil background will produce a signal equal to that of a ∼5 keV (30 keV) electron recoil (^{40}Ar recoil). In addition, we demonstrate that this dangerous ^{210}Po surface background can be suppressed, using pulse shape discrimination methods, by a factor of ∼100 or higher, which can make argon dark matter detectors near background-free and enhance their potential for discovery of medium- and high-mass WIMPs. We also discuss the impact on other low background experiments.

Noble liquid detectors have demonstrated exceptional sensitivity in direct searches for weakly interacting massive particles (WIMPs), a candidate for dark matter. Over the past decade, xenon-based experiments including XENON [1, 2], LUX [3], and PandaX-II [4] have achieved the highest sensitivities in this field. Recently, argon-based experiments have also developed key technologies necessary for sensitive WIMP searches, as demonstrated by the DarkSide-50 experiment [5, 6]. The DEAP-3600 experiment [7] and the DarkSide-20K experiment [8] are expected to achieve a comparable dark matter sensitivity to that of current xenon experiments for medium- to high-mass WIMPs. With the powerful pulse shape discrimination (PSD) capability of argon, argon dark matter searches at multi-tonne scales can be free of electron recoil backgrounds from solar neutrinos [9] and from radioactive decays of radon progeny and ^{85}Kr [10], all of which compromise the sensitivity of xenon experiments.

Due to the low expected interaction rate between WIMP dark matter and ordinary matter, it is critical for WIMP search experiments to achieve a very low background rate, especially for nuclear recoil background that can mimic a WIMP interaction. One such nuclear recoil background can result from the exposure of detector surfaces to radon that is naturally present in the environment, specifically in air and in ground water. Through the following decay sequence,

$$\begin{aligned} {}^{222}\mathrm{Rn} &\xrightarrow{3.8\,d} {}^{218}\mathrm{Po} \xrightarrow{3.1\,m} {}^{214}\mathrm{Pb} \xrightarrow{26.8\,m} {}^{214}\mathrm{Bi} \\ &\xrightarrow{19.9\,m} {}^{214}\mathrm{Po} \xrightarrow{164.3\,\mu s} {}^{210}\mathrm{Pb} \xrightarrow{22.2\,y} {}^{210}\mathrm{Bi} \\ &\xrightarrow{5.0\,d} {}^{210}\mathrm{Po} \xrightarrow{138.4\,d} {}^{206}\mathrm{Pb} \end{aligned}$$

^{210}Po and other radon progeny can be produced and become attached to detector surfaces. The decay of ^{210}Po produces a ^{206}Pb recoil and an α particle.

$$^{210}\mathrm{Po} \xrightarrow{138\,d} {}^{206}\mathrm{Pb}\ (103\,\mathrm{keV}) + \alpha\ (5.3\,\mathrm{MeV})$$

For bulk ^{210}Po-decays, the recoiling ^{206}Pb nucleus does not make a low-energy WIMP search background because of the high energy deposition by α-particles in the active detector region. However, if the decay occurs on the detector wall and only the ^{206}Pb hits the active volume it will make a very dangerous background. What makes this surface ^{206}Pb nuclear recoil background more dangerous is the long half-life (∼22 years) of ^{210}Pb, which can produce the ^{206}Pb recoil background many years after radon exposure.

^{206}Pb recoils have been identified as one of the most important backgrounds in several major dark matter experiments, such as LUX [3, 11], SuperCDMS [12, 13], CoGeNT [14], and CRESSTII [15]. For example, a surface ^{210}Po α-decay rate of ∼35 mHz was detected in the LUX experiment [16], and ^{206}Pb recoils are believed to be a major WIMP search background near the detector walls [3]. In experiments with position reconstruction capability, the surface background can usually be suppressed with a fiducial cut at the cost of active volume loss. For argon-based dark matter experiments like DarkSide-50 and DEAP-3600, position sensitivity as accurate as that in xenon detectors has not been achieved, which makes these experiments more vulnerable to surface background contamination or large loss of fiducial mass. Indeed, the ^{206}Pb problem has been considered the most dangerous background for the DEAP-3600 experiment [17].

This paper presents a study of the surface ^{206}Pb nuclear recoil background for argon dark matter experiments. We will report the first scintillation measurement of low energy Pb recoils in liquid argon, and then characterize the full surface background by taking into consideration the signals induced by the α particles accompanying the Pb recoils. Because argon experiments usually use a wavelength shifter (WLS) coating on the interior

* Corresponding author, xu12@llnl.gov; Current Address: Lawrence Livermore National Laboratory, Livermore, California 94550, USA

† Jingke Xu and Chris Stanford contributed equally to this work.

‡ Current Address: Department of Physics, Carleton University, Ottawa, Ontario, K1S 5B6, Canada

§ Current Address: Google Inc., Mountain View, California 94043, USA

detector surfaces for the detection of vacuum ultraviolet (VUV) argon scintillation light, the α particles can produce additional scintillation photons in the WLS. With this scintillation signal, we demonstrate that this surface background in argon dark matter experiments can be significantly suppressed. The impact of this research on DarkSide-50, DEAP-3600 and other low-background experiments will be discussed.

Although the ^{206}Pb recoils from ^{210}Po decays are produced at a relatively high energy (103 keV), most of the energy is non-radiatively dissipated as heat and cannot be detected in argon detectors. Due to the low detectable energy and the lack of signal tagging methods, no definitive characterization of this ^{206}Pb recoil signal has been reported to date. In this work, we took an alternative approach of studying the ^{210}Pb recoils in the α decays of ^{214}Po. ^{214}Po can be produced by the β decay of ^{214}Bi in the ^{222}Rn chain; the short half life ($\sim$164 μs) of ^{214}Po means that the ^{214}Bi and ^{214}Po decays will be in delayed coincidence, and this ^{214}Bi-^{214}Po coincidence can be used to efficiently tag ^{214}Po decays. ^{214}Po decays through the reaction

$$^{214}\mathrm{Po} \xrightarrow{164\,\mu s} {}^{210}\mathrm{Pb}\ (146\,\mathrm{keV}) + \alpha\ (7.7\,\mathrm{MeV})$$

The slightly higher ^{210}Pb recoil energy makes the direct measurement more viable; at the same time, one does not expect the scintillation efficiency of argon for ^{206}Pb recoils to differ significantly from that for ^{210}Pb.

In this experiment, we first collected ^{222}Rn progeny onto a VUV-reflective mirror (>85% reflectivity for argon scintillation light at 128 nm [18]) by exposing its reflective side to a radon-argon gas mixture with a ^{222}Rn activity of $\sim$2 MBq [19]. The VUV mirror consists of a highly reflective aluminum coating on a quartz substrate and a 25$\pm$10 nm MgF_2 protective layer to prevent the aluminum from oxidizing. During the exposure, the progeny of ^{222}Rn plated out on the VUV mirror and ^{214}Pb quickly accumlated due to its relatively long half life (27 min). After about 3 hours, this VUV mirror was removed from the radon collection chamber and deployed into a specially designed liquid argon detector as illustrated in Fig. 1. The detector was then pumped and purged for several cycles to remove electronegative impurities, cooled down to 87 K with an external liquid argon bath, and filled with purified argon for scintillation measurements.

When ^{214}Po decayed on the surface of the VUV mirror, the daughter ^{210}Pb nucleus may recoil into the liquid argon and produce VUV argon scintillation light while the accompanying α particle went into the mirror. Due to the thinness of MgF_2, the α particle will only deposit negligible energy in the MgF_2 and not produce significant amount of light. The ^{210}Pb light was efficiently collected by a photomultiplier (PMT) through the use of the VUV mirror and a WLS coating on the Spectralon reflector. Due to the 27 min lifetime of ^{214}Pb, the ^{214}Bi-^{214}Po coincidence rate became negligible within several hours of the initial radon exposure. The whole measurement therefore had to be completed within 6–8 hours.

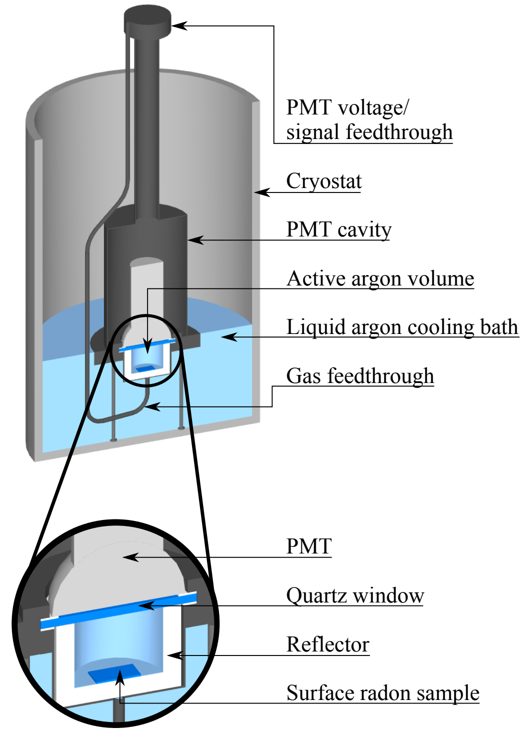

FIG. 1. Illustration of the single-phase liquid argon detector used in this study. The lower chamber (Φ72 mm$\times$48 mm) hosts a Spectralon reflector cell that contains the radon sample in purified liquid argon; the upper chamber hosts a Hamamatsu R11065 photmultiplier tube (PMT). The two chambers are hermetically sealed with a quartz window. The reflector cell and the quartz window are coated with a WLS for argon light collection. An external liquid argon bath provides the needed cooling power.

The energy spectrum of the ^{214}Po decay events, identified by the ^{214}Bi-^{214}Po coincidence, is shown in Fig. 2 (dotted blue). The energy scale is given by the number of photoelectrons (p.e.) detected by the PMT, which is proportional to the number of scintillation photons produced. Due to the presence of electronegative impurities in the liquid argon, a small fraction of the triplet argon scintillation was lost [20]; a correction for this effect [19] was made based on the measured triplet scintillation lifetime and singlet-to-triplet ratio. Two groups of events were observed in the ^{214}Po decays. The high energy events around 20,000 p.e. were easily identified as α particles and the low energy events below 100 p.e. can be attributed to ^{210}Pb recoil nuclei. The rates of the two event groups are approximately equal, which confirmed the explanation of their origins.

However, the ^{210}Pb energy spectrum exhibited a broad distribution with a high-energy cutoff instead of a mono-energetic peak. This was explained by a fraction of ^{214}Po decays that were embedded in the surface of the VUV mirror. Some of the ^{214}Po precursors could have recoiled into the VUV mirror as a result of momentum conserva-

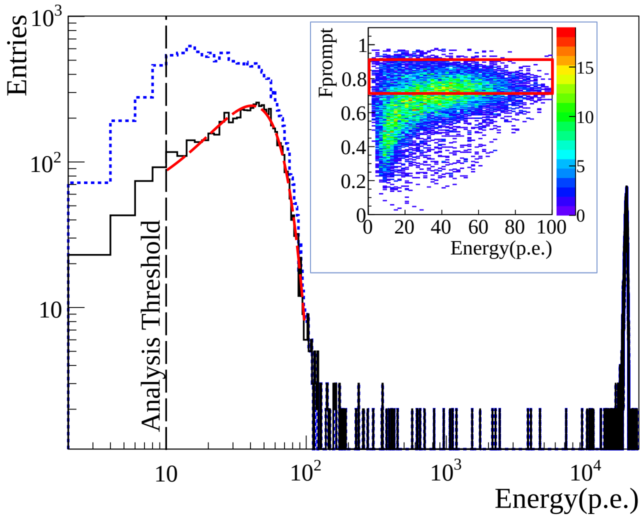

FIG. 2. Scintillation spectra of liquid argon excited by ^{214}Po decays with (solid black) and without (dotted blue) F_{prompt} cut. The ^{210}Pb recoils are observed below 100 p.e. and the α events are observed around 20,000 p.e.. The inset figure shows the F_{prompt} distribution of ^{210}Pb recoils. The F_{prompt} cut selected events within 2σ above the most probable F_{prompt} value, and a Gaussian fit to the spectrum is also shown.

tion in α-decays, and when these ^{214}Po nuclei decayed the energy of the recoiling ^{210}Pb nuclei would be degraded by the energy loss under the reflector surface. In addition to having a lower observable energy, the embedded events also exhibited lower F_{prompt} values, a pulse shape parameter defined as the fraction of scintillation within the first 90 ns, as shown in the inset of Fig. 2. This trend is similar to that of ^{40}Ar recoils measured by [21], possibly explained by the increasing linear energy transfer to argon for low energy nuclear recoils. SRIM simulations [22] predict that ^{210}Pb nuclei produce scintillation mostly through imparting energy to argon nuclei, which then cause scintillation, rather than directly exciting/ionizing argon atoms. Therefore, the observed F_{prompt} behavior for ^{210}Pb may have the same physical origin as that observed for ^{40}Ar in [21].

To calculate the argon scintillation light yield for ^{210}Pb recoils with the maximum energy deposition (146 keV), we selected the ^{210}Pb events with relatively high F_{prompt} values, as shown in the inset of Fig. 2, so the contribution from the embedded events (low energy, low F_{prompt}) could be suppressed. The resulting spectrum exhibited a Gaussian-like distribution peaked at 41.2±0.6 p.e., as determined with a χ^2 fit. The uncertainty originating from the F_{prompt} cut, evaluated by varying the F_{prompt} cut range, is included in later analysis. The data acquisition threshold in the measurement was set to an equivalent amplitude of ∼1.5 p.e., and the trigger efficiency is expected to be 100% above the analysis threshold of 10 p.e. (integral). The full energy ^{210}Pb light output was corrected to 45.7±2.3 p.e. based on a geometric calculation. In this simple correction model, we assumed that the upwards emitted light was collected with a certain efficiency but the downwards emitted light suffered an additional loss corresponding to the reflectivity of the aluminum mirror. Based on specificiations from the manufacturer, we used an effective reflectivity of 80%±10%, with a relatively large uncertainty to account for the simplicity of the correction model. A second measurement with a non-VUV-reflective silver foil as the radon backing material, using the same analysis technique, yielded a corrected ^{210}Pb light output of 42±4 p.e. (systematics not fully evaluated), consistent with the VUV mirror measurement.

Using the measured scintillation light yield of 6.2±0.2 p.e./keV for 59.5 keV ^{241}Am γs, we can obtain an electron-equivalent energy of 7.4±0.4 keV_{ee} for the 146 keV ^{210}Pb recoils. This result indicates a scintillation quenching factor of 19.7±1.2 relative to gammas/electrons and 6.2±0.5 relative to ^{40}Ar nuclear recoils, extrapolated from [23]. Simulations using the SRIM software [22] indicate that the stopping power of ^{210}Pb recoils in liquid argon is ∼5 times higher than that of ^{40}Ar recoils. This high stopping power can cause 1) a high fraction of the ^{210}Pb energy to be dissipated as heat, decreasing the Lindhard factor, and 2) a high argon dimer decay rate through non-radiative channels, strengthening the Birks quenching. The SRIM simulations, however, under-predict the amount of quenching, possibly due to Lindhard model breaking down for Pb recoils at low energies, as suggested in [24].

Assuming that the scintillation efficiency of liquid argon is the same for ^{210}Pb recoils (146 keV), measured in this work, and for ^{206}Pb recoils (103 keV) produced by ^{210}Po, the surface ^{206}Pb recoil background would produce only a modest ∼5 keV_{ee} signal, similar to a ∼30 keV ^{40}Ar recoil. This background is below the energy threshold of current argon dark matter experiments [5]. However, since argon detectors usually use WLS coatings on the inner detector surfaces, when a surface ^{206}Pb nucleus enters liquid argon, the α particle will enter the WLS and produce additional scintillation light. This α signal will contribute to the overall scintillation light, and make the ^{206}Pb recoils more likely to become a background in argon-based dark matter experiments.

Therefore, we carried out a direct, *in situ* surface background measurement that combined scintillation signals from both the Pb recoils and the accompanying α particles. The measurement used a similar technique to the ^{210}Pb recoil experiment described earlier. However, instead of depositing the ^{222}Rn daugters on a VUV mirror, we deposited them on a quartz slide with a WLS coating. This way, when the ^{214}Po nucleus decayed and sent a ^{210}Pb nucleus recoiling into the argon, the α particle would produce scintillation light as it traveled through the WLS, as occurs in argon dark matter detectors. Again, we used the ^{214}Bi-^{214}Po coincidence signal to tag the surface ^{214}Po events. In this study, two WLS chemicals were investigated: tetraphenyl-butadiene (TPB), the most widely used WLS in argon dark matter experiments, and 1,4-Diphenylbenzene (pTP, or p-Terphenyl). To ensure consistency in the comparison, we applied approximately the same coating thickness for both WLSs (∼0.3-0.4 mg/cm^2), which was chosen to match that used in dark matter experiments.

The energy spectra of ^{214}Po decay products, selected with the ^{214}Bi-^{214}Po coincidence, are shown in Fig. 3. As expected, two peaks are observed in each spectrum. The higher energy peak contains the full energy α signals in argon and the Pb recoils in the WLS. The lower energy peak contains the ^{210}Pb recoil signals in argon together with the α-induced signals in the WLS. Due to the additional WLS scintillation, the light output of the low energy peak greatly increased in comparison to that in Fig. 2. The different amount of increase observed with the two WLSs agrees well with studies of WLS scintillation properties under α excitation [19, 25–27]. Due to the mix of argon scintillation and WLS scintillation in this measurement, the argon scintillation loss due to impurities is not corrected for, but the effect on the overall energy scale is estimated to be less than 5%.

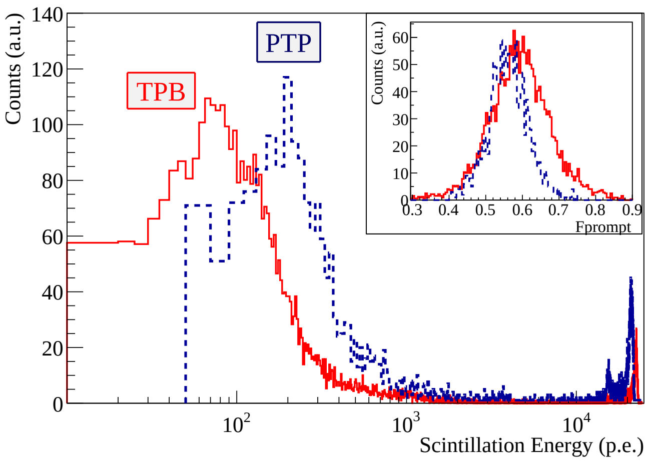

FIG. 3. The scintillation energy spectra of ^{214}Po-induced surface events measured in argon, using TPB (∼0.4 mg/cm^2) and pTP (∼0.3 mg/cm^2) as the WLS, respectively. The low energy events (∼100 p.e.) contain the ^{210}Pb signals in argon and the α signals in WLS; the high energy events (∼20,000 p.e.) are dominated by α signals in argon. The inset shows the F_{prompt} distribution (15μs maximum integral window) for the low energy surface events. For comparison, the 50% F_{prompt} value for ^{40}Ar is 0.69 at 88 p.e. (the TPB measurement) and 0.72 at 192 p.e. (the pTP measurement) [5].

The peak signals from the low energy surface background events were observed at 88 p.e. and 192 p.e. for TPB and pTP, respectively. Both fall in the dark matter search window as used in DarkSide-50 [5, 6]. The fact that this background has not been observed in DarkSide-50 could be partially explained by the relatively low statistics, and more importantly by the low ionization collection efficiency on the detector surfaces, which cause surface events to fail the analysis cuts, similar to that observed in LUX [16]. Single phase argon dark matter experiments like DEAP-3600, on the other hand, only collect the scintillation signals and are therefore more vulnerable to surface background contamination [17].

The surface background, however, can be suppressed using the pulse shape discrimination (PSD) method. The inset of Fig. 3 shows the overall F_{prompt} distribution of the low energy surface background events. Owing to the relatively slow WLS scintillation under α excitation [26, 27], the overall F_{prompt} distribution of surface background events is pushed towards lower values than those of pure ^{40}Ar nuclear recoils (0.69 at 88 p.e. and 0.72 at 192 p.e.) [5]. Using the simple F_{prompt} PSD method, we estimate that the surface background can be suppressed by a factor of ∼10 (100) for TPB (pTP) at 50% (90%) ^{40}Ar recoil acceptance for coatings of the investigated thicknesses. Although TPB exhibits a low background rejection power using the simple F_{prompt} method, a newly discovered long decay component in TPB under α excitation [26] could improve the PSD situation, which topic is under active investigation by the authors [27]. As for pTP, the rejection power against the Pb recoil background can also be further improved by increasing the coating thickness, which will lower both the central value and the spread of the F_{prompt} distribution for the combined surface background events. Optimization of the surface background rejection power for argon dark matter experiments is beyond the scope of this paper; interested readers can find more on this topic in references [19] and [27].

We point out that the surface background suppression power presented here is conservative for two reasons. First, we left out the correction for the loss of argon triplet scintillation due to impurities, and such a correction will lower the overall F_{prompt} values for the surface background events. Second, the F_{prompt} value of ^{206}Pb recoils will be lower than that of ^{210}Pb due to the lower recoil energy, especially for those embedded under the detector surfaces. Both factors will increase the separation of the surface background from the nuclear recoil values in F_{prompt} distributions and enable stronger background rejection. A full evaluation of the ^{210}Po background in argon dark matter experiments requires extrapolation from the measured ^{214}Po results, but we expect the background suppression factor to be at the same order of magnitude.

Finally, we comment that this method of rejecting surface backgrounds by detecting the α particles has potential applications beyond argon-based dark matter experiments. For example, coating the reflector surfaces of xenon experiments like LUX with a thin layer of MgF_2 or LiF, which can produce significant scintillation [28, 29] under α excitations and which are transparent to xenon scintillation light, can help reject surface nuclear recoil backgrounds. For double-beta decay experiments like CUORE, the dominant surface background arises from α particles with partial energy deposition in the crystals [30]. Similarly, the α particles may be detected with a thin coating of scintillating material on the surfaces of the crystals and supporting structures, which would allow this background to be suppressed.

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