Fabrication of ZnO-PTFE material for use in the LUX-Zeplin (LZ) dark matter detection experiment to flag ^{210}Pb alpha decays through scintillation

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LUX-Zeplin is an experiment which aims to detect dark matter, primarily WIMPs (Weakly Interacting Massive Particles). The liquid and gaseous xenon housed in the Time Projection Chamber (TPC) of the LUX-Zeplin assembly commonly contains the ^{222}Rn isotope as an impurity. This isotope is part of a decay chain that results in the ^{210}Pb isotope. The alpha decay that creates this lead isotope can cause a false detection of a WIMP dark matter particle because the ^{210}Pb recoil can cause a signal-like flash in the xenon while the alpha particle goes into PTFE and escape detection. To address this, we have designed a scintillating PTFE (Polytetrafluoroethylene, more commonly known as Teflon) material using ZnO nanoparticles for the walls of the detector so the alpha particles entering the wall can be tagged. A dark box experiment set-up has been designed to test how well the ZnO-PTFE scintillates. Using the same photosensors called silicon photomultipliers, this dark box will measure the level of scintillation of the PTFE material while surrounded by radon gas. Thus, we aim to use this material in the TPC to help identify false detections of a WIMP caused by ^{222}Rn backgrounds near the PTFE wall. This will ultimately allow us to reduce backgrounds and achieve better dark matter detection results.

Keywords: dark matter, scintillating, PTFE, LUX-Zeplin

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1 What is dark matter?

Dark matter makes up about 80% of all matter in the universe and yet we have never directly detected it. The term dark matter refers to all the matter in the universe that we know exists but hasn't detected yet. Early evidence that dark matter exists, despite the lack of direct detection, was found in the 1930s through mass-to-luminosity ratios [1]. Discrepancies between the observed velocities of celestial bodies and their predicted velocities based on the observed mass of their galaxy indicated that said galaxy had much more mass than previously observed[1]. This directly unobservable mass was termed dark matter. These observations were later corroborated by many modern experiments and observations including the Bullet Cluster, an event where two galaxy clusters collided together [1].

Observing and understanding dark matter will lead to a deeper understanding of how galaxies move, form, and interact with each other and other celestial mass as well as the universe as a whole. Dark matter could also give insight into how the universe formed and its future. Directly observing dark matter will additionally fill in some gaps that arise in the Standard Model [2].

There are many theories about what dark matter may look like, but the particular kind the LUX-Zeplin experiment aims to detect is called a WIMP or Weakly Interacting Massive Particle. A WIMP is a massive particle that only interacts with other matter through gravitational forces and the weak force [2].

2 The LUX-Zeplin experiment

The LUX-Zeplin experiment is a dark matter detection experiment aimed primarily at detecting WIMPs. It uses a Time Projection Chamber or TPC to produce the three-dimensional coordinate of the interaction between an incoming particle and the atoms inside the detector [3]. The detector is filled with liquid and gaseous xenon, which is an effective scintillator, meaning the xenon emits photons when struck by another particle. This helps the detector identify when a collision happens.

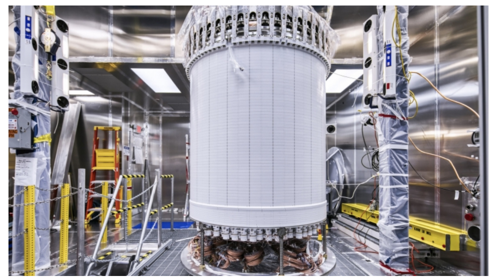

Figure 1: Image of the final TPC for the LUX-Zeplin experiment [5].

The TPC works by evaluating the time differential between two signals. The first signal happens when a particle comes into the detector and interacts with the xenon, causing it to scintillate. The second signal happens when the electrons broken from the xenon atom get carried up to the top of the detector by an electric field running vertically through the TPC and hit a set of photo sensors. The walls of the detector are made of PTFE (commonly known as Teflon) because of PTFE's high reflectivity of xenon scintillating light.

3 Radon impurity is causing false detections

A common impurity in the liquid xenon used in the detector is the ^{222}Rn isotope. Radon plated out on the TPC wall, originating from uranium, is a common background in such experiments. ^{222}Rn quickly decays into ^{210}Pb, which will continue to decay into less massive isotopes of lead with a half-life of 22 years. When an alpha decay from the Rn decay chain occurs on the wall, there are two directions it could go. In the first scenario, the ^{210}Pb daughter nucleus goes into the wall and the alpha particle goes out into the bulk xenon of the detector. This does not cause any problems because scintillating light caused by an alpha particle can easily be identified.

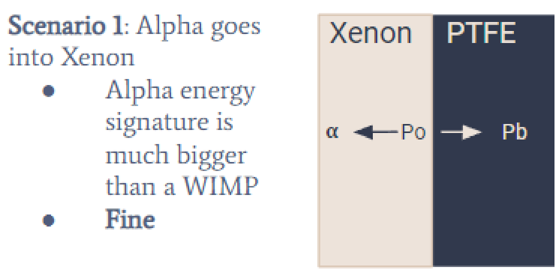

Figure 2: This figure shows one of two scenarios where a Po isotope alpha decays and the lead daughter nucleus goes into the wall and the alpha particle goes out into the detector.

However, in the second scenario, the alpha particle sometimes enters the wall and gets lost while the daughter nucleus goes out into the xenon. When the daughter nucleus hits a xenon atom, the nuclear recoil it generates is difficult to distinguish from a dark matter signal. Both WIMPs and Pb have nuclear recoils with xenon, which look very different from alpha, beta, and gamma particles making them easily mixed up. This *does* cause a problem. We would like our WIMP detections to be the real deal.

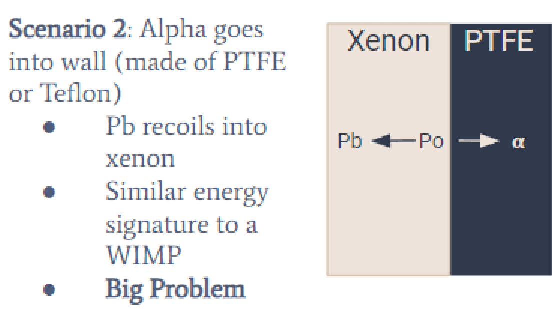

Figure 3: This figure shows one of two scenarios where the lead daughter nucleus goes out into the detector and the alpha particle goes out into the wall.

4 Zno-PTFE or scintillating teflon

The next big question is this: how do we address false WIMP detections caused by ^{210}Pb isotopes? Our proposed solution is to use a scintillating PTFE material in the walls of the TPC to tag the alpha particles going into the wall. We already know that PTFE works well as a material in the walls for the detector since it has worked well in previous experiments. If we add a scintillator to the PTFE, it would allow us to see when our alleged WIMP detection is not quite what it seems. When the lead daughter nucleus floats out into the detector and the alpha particle gets shot into the wall, the alpha particle would cause the scintillating PTFE material to emit photons. The photosensors that are already in the detector can be utilized to pick up when this happens and flag any suspicious WIMP detections that happened at the same time.

Photoluminescent zinc oxide nanoparticles (ZnO) were chosen to use in the walls of the detector because this is a very commonly used scintillator. ZnO comes in the form of a dangerous nanoparticle that needs to be handled with strict safety measures in place. When handling it, one should wear gloves and a mask and only handle it under a fume hood. Nanoparticles can permeate the blood-brain barrier and have unknown effects on the human body since they are a fairly new invention.

Both PTFE and ZnO can be purchased in a powdered form. The PTFE powder needs to be subjected to approximately 3000-4500 psi and 700 °F for it to properly form. Given the conditions that the PTFE and ZnO need to be handled in and subjected to, we needed to use a lab equipped with a hydraulic press capable of applying 4500 psi of pressure, an oven that can heat above 700 °F, and a fume hood. We were able to use a lab in the chemical sciences division at LBNL that met all of these requirements.

5 Instrumentation designs

5.1 The mold

The first piece of equipment that needed to be designed for this project was a mold capable of withstanding 3000-4500 psi and 700 °F for a small 1" diameter, 4-5 mm thick disk to test the efficacy of ZnO-PTFE for use in the LZ detector. We chose to use 304 stainless steel because of its resistance to deforming at the operating temperatures and loads of the mold.

The mold is made up of three components: the main body, the plunger piece, and the plug. The main body and plunger piece have an outer diameter of 3", and the plunger piece is designed to be used to get the PTFE disk out of the mold of the disk after it is formed. The mold's design was confirmed by loading models in Solidworks, which showed that the mold would not deform or yield and that the different components would not bond together.

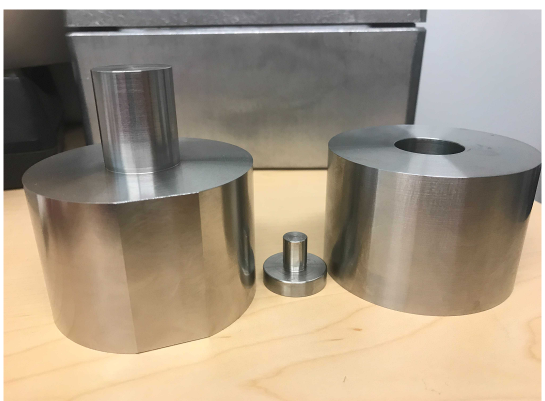

Figure 4: The image above shows the three manufactured components of the mold: the plunger (left), the plug (middle), and the body of the mold (right).

5.2 The dark box

After enough sample disks of PTFE and ZnO-PTFE are formed, they need to be tested. For this, we have designed a dark box that will house the PTFE disk as well as photosensors that will be connected to equipment outside of the box. It also needs to have gas feed-throughs so radon gas can be pumped into and then out of the box. A decently tight seal on the box is achieved with a large rubber ring that sits in a little groove along the edge of the top of the box to keep light from leaking in. Radon gas is used because a radon isotope is causing the problem, so we want to see how our ZnO-PTFE material reacts to it. The part inside the box that holds the PTFE disk and the photosensor is designed to be adjustable to allow for some variability in the thickness of the disks.

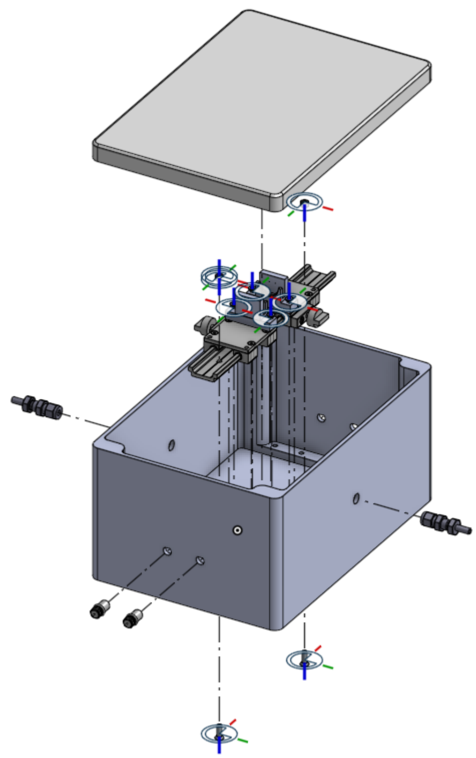

Figure 5: The image above shows an exploded view of the 3D model of the dark box design.

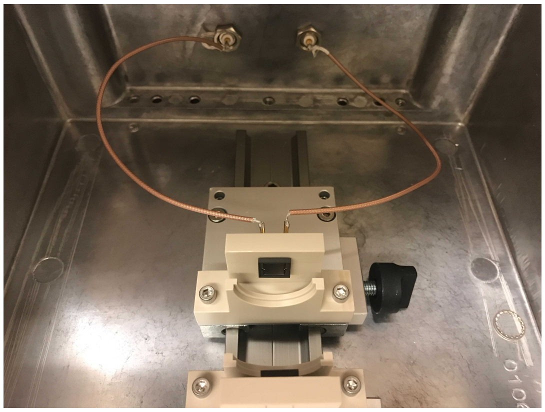

Figure 6: The image above shows the inner mechanism of the dark box as well as the photosensor.

6 PTFE fabrication

We fabricated a few different variations of the PTFE and ZnO-PTFE disks. The first disks we fabricated were pure PTFE so we could test the difference between that and ZnO-PTFE. We then combined the ZnO powder and PTFE powder in acetone to make a semi-homogeneous mixture with a 10% concentration of ZnO [4]. Next, we poured a thin layer (¡0.5mm) over an already formed plain PTFE disk. The last version of the disk we made was the same as the previous one except with a 1% concentration of ZnO. For each variation of the sample we made, we created both a fast and slow recipe version. This is just to see if there are any differences in the scintillation and reflectivity of the material between the fast and slow recipes. The fast recipe involves bringing the PTFE to a temperature of 380 °C in 38 minutes, holding for 30 minutes, and then cooling to 25 °C in 60 minutes. The slow recipe involves bringing the PTFE to 380 °C in 60 minutes, holding for 30 minutes, and then cooling to 25 °C in 12 hours.

7 Next steps

With all of the parts fabricated and the PTFE-ZnO disks formed, the next step is to test them. The first round of tests will be done with a Cary UV-Vis-NIR. This machine will be used to test the reflectivity of the material for xenon scintillating light in the vacuum ultra-violet (VUV) range. One anticipated issue is the range being far lower than what can be detected by the Cary UV-Vis-NIR. Based on preliminary testing, it is possible that the small amount of ZnO added to the surface of the PTFE is enough to reduce the reflectivity in the VUV range by a factor of two, though this may just be a calibration error since the reflectivity of the plain PTFE seems to be unusually low as well. We will later use the dark box to test the scintillating properties of the ZnO-PTFE. Radon gas will be circulated through the box to measure the scintillation light from alpha particles. However, after consulting with an expert in the field, we learned the amount of ZnO in the disks will likely not be enough to cause much scintillation. It is probable that we will have to make another round of ZnO-PTFE disks with a higher concentration of ZnO or start exploring the possibility of using a different photo-luminescent nanoparticle.

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