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Light detection and the wavelength shifter deposition in DEAP-3600

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Abstract: The Dark matter Experiment using Argon Pulse-shape discrimination (DEAP) uses liquid argon as a target medium to perform a direct-detection dark matter search. The 3600 kg liquid argon target volume is housed in a spherical acrylic vessel and viewed by a surrounding array of photomultiplier tubes. Ionizing particles in the argon volume produce scintillation light which must be wavelength shifted to be detected by the photomultiplier tubes. Argon scintillation and wavelength shifting, along with details on the application of the wavelength shifter to the inner surface of the acrylic vessel are presented.

Keywords: Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Noble liquid detectors (scintillation, ionization, double-phase); Dark Matter detectors (WIMPs, axions, etc.)

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Contents

1 Introduction

DEAP-3600, shown schematically in figure 1, is a single phase liquid argon dark matter search experiment located 2 km underground at SNOLAB in Sudbury, Canada [1]. It utilizes the pulse shape discrimination (PSD) characteristics of the argon scintillation signal to distinguish nuclear recoil events from electromagnetic background events. 3600 kg of liquid argon (LAr) is contained in a spherical acrylic vessel (AV) and viewed by 255 inward-facing 8" Hamamatsu R5912 HQE photomultiplier tubes (PMTs) coupled through 50 cm light guides. Filler blocks made from alternating layers of foam and high-density polyethylene occupy the space between the light guides. Both the filler blocks and light guides provide neutron shielding from the PMTs and thermal insulation of the cryogenic volume. The instrumented AV is surrounded by a spherical stainless steel pressure vessel inside an 8 m diameter veto water tank. The spherical detector module is connected above to the central support assembly which contains hermetically sealed PMT feedthroughs routing to the data acquisition system. The inner surface of the AV was resurfaced with a robotic sander after construction to remove diffused-in radio-contaminants in the acrylic from atmospheric exposure during construction. The inner surface of the acrylic was then evaporatively coated with the organic wavelength shifter 1,1,4,4-tetraphenyl-1,3-butadiene (TPB). A liquid nitrogen fed cooling coil was installed in the inner neck, which maintains the argon near 87 K.

With a 1000 kg fiducial mass, DEAP-3600 aims to perform a spin-independent dark matter search targeted at a WIMP-nucleon cross section of 10^{-46} cm^2. The projected sensitivity from a background free, 3 tonne-year exposure with both natural and depleted argon is shown in figure 2, along with the current dark matter limits from the CDMS-II [2], PICO-60 [3], XENON100 [4], LUX [5], and DarkSide-50 [6, 7] experiments.

2 Optical processes

Argon scintillates in the vacuum ultraviolet (VUV) spectrum from decaying dimer states resultant of particle interactions. Nuclear and electromagnetic recoil events can both produce singlet (excited) and triplet (ionized) dimer states. However, there is a difference in the ratio of singlet to triplet state production for nuclear and electromagnetic recoil events due to the density of energy deposited in each type of interaction. Nuclear recoil events, as expected for dark matter interactions, have a higher probability of singlet state production with a lifetime of 6 ns, while electromagnetic events

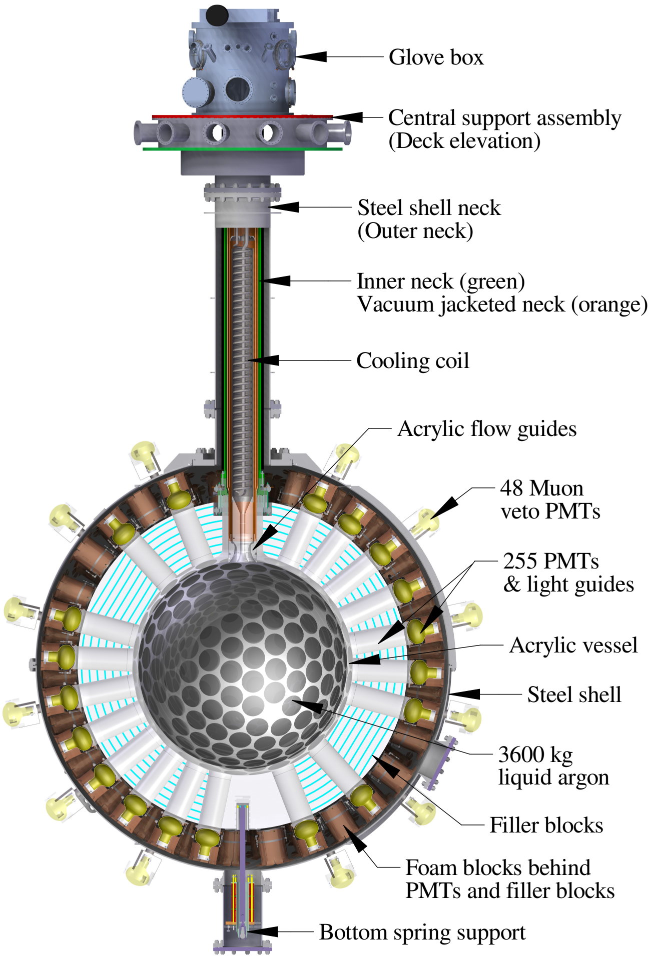

Figure 1. Schematic of the DEAP-3600 detector. An acrylic vessel with an inner radius of 85 cm is viewed by 255 Hamamatsu R5912 HQE PMTs through 50 cm acrylic light guides. The wavelength shifter TPB (not shown) was deposited over the inner surface of the AV before installation of the cooling coil in the neck.

have a higher probability of triplet state production, with a lifetime around 1.5 µs [8]. Both singlet and triplet state decay modes result in a 128 nm photon, as can be seen in equation (2.1) and (2.2). The ratio of the scintillation light intensities for singlet (I_1) and triplet (I_3) states for nuclear and electromagnetic recoils, along with other argon optical properties, are presented in table 1 [9].

Excitation: Ar^*

$$\begin{aligned} Ar^* + Ar + Ar &\rightarrow Ar_2^* + Ar \\ Ar_2^* &\rightarrow 2Ar + \gamma \end{aligned} \tag{2.1}$$

Ionization: Ar^+

$$\begin{aligned} Ar^+ + Ar &\rightarrow Ar_2^+ \\ Ar_2^+ + e^- &\rightarrow Ar^{**} + Ar \\ Ar^{**} &\rightarrow Ar^* + \text{heat} \\ Ar^* + Ar + Ar &\rightarrow Ar_2^* + Ar \\ Ar_2^* &\rightarrow 2Ar + \gamma \end{aligned} \tag{2.2}$$

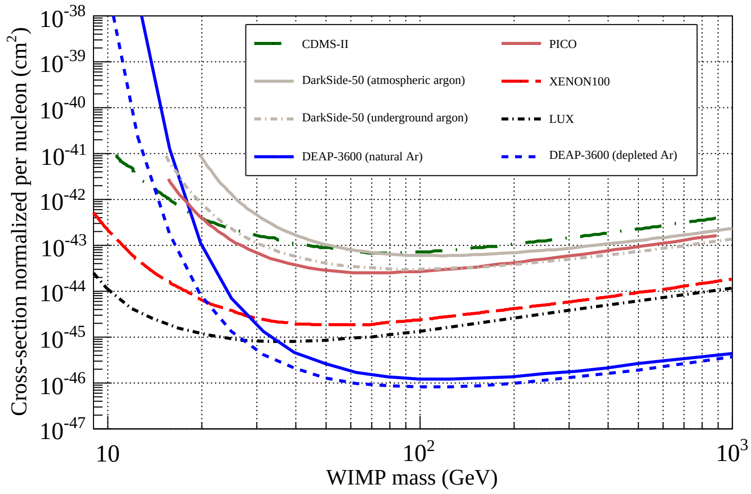

Figure 2. Dark matter sensitivity expressed as a limit on the spin-independent WIMP-nucleon scattering cross-section. Shown are the current experimental limits from CDMS-II [2], PICO-60 [3], XENON100 [4], LUX [5], and DarkSide-50 (atmospheric [6] and underground argon [7]). The expected DEAP-3600 sensitivity is also shown for a background free, 3 tonne-year exposure with natural liquid argon at a 15 $\mathrm{keV_{ee}}$ threshold, and with a 12 $\mathrm{keV_{ee}}$ threshold for low-radioactivity argon that has been depleted in ^{39}Ar by a factor of 100.

The subscript "2" in equation (2.1) and (2.2) indicates the dimer states, and the "heat" refers to a non-radiative transition.

Table 1. Liquid argon optical properties.

parameter	value
Light Yield	40 000 γ/MeV
Prompt τ_1	6 ns
Late τ_3	1.5 µs
I_1/I_3 for electronic recoil	0.3
I_1/I_3 for nuclear recoil	3
Peak Emission Wavelength	128 nm
Rayleigh Scattering Length	60 cm [10]

The difference in lifetimes leads to a powerful PSD capable of separating nuclear recoil events from electromagnetic backgrounds. The discriminating variable, F_{prompt}, is a ratio of the number of prompt photoelectrons (PE) (−50 ns to 150 ns about the leading edge of the pulse) to the total number of PE for an event (−50 ns to $\simeq$ 10 µs about the leading edge) [11].

The F_{prompt} distribution for tagged ^{22}Na data taken on surface and underground in DEAP-1 is shown in figure 3. One event is within the 90% nuclear recoil acceptance region ($F_{prompt} > 0.7$), while the probability of one or more detected background events from random pile-up is 0.37. An upper limit is set on the electromagnetic recoil misidentification factor at 2.8×10^8 (90% C.L.) for the 120–240 PE search region of interest. The projection for DEAP-3600 gives the suppression factor on order 10^{10} [1].

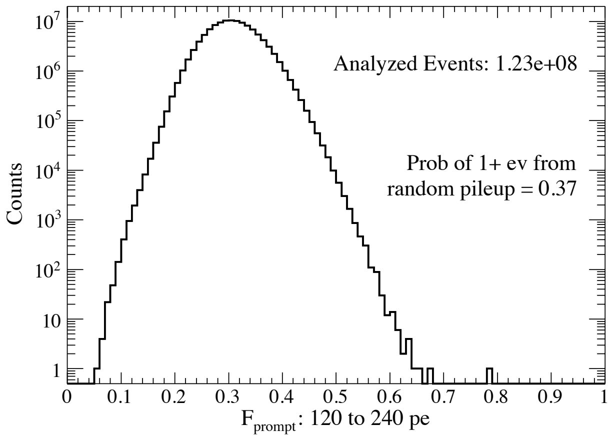

Figure 3. The combined DEAP-1 PSD dataset containing tagged ^{22}Na γ events from surface and underground runs at ~2.7 PE/keV for 120–240 PE range [1]. One event is detected inside of the 90% nuclear recoil acceptance window (F_{prompt} >0.7), while the probability of detecting one or more background events from random pile-up is 0.37. The resulting upper limit on electron recoil misidentification fraction is $< 2.8 \times 10^8$ (90% C.L.) for 44–89 keV_{ee} region of interest.

As VUV light is efficiently absorbed by most optical media (acrylic, PMT glass), information from the deposition of energy in the LAr volume must be wavelength shifted to be recorded by the PMTs. TPB absorbs VUV light and re-emits at a peak wavelength of 420 nm [12]. Under vacuum, the TPB was evaporatively deposited over the inner surface of the AV prior to filling with argon.

3 TPB deposition

The TPB evaporation source is shown in figure 4. TPB is evaporated from a crucible inside the source, and the generated gas is kept at a pressure to sufficiently scatter the molecules inside the perforated sphere creating an isotropic distribution of escaping trajectories. The exiting TPB molecules travel from the source to the inner AV surface in a sufficiently low vacuum to prevent scattering en route. The source is made of 316 stainless steel and the inner crucible holding the TPB powder, of copper. The crucible is radiatively heated by the externally-wrapped coil heater. Additional information on the development of the evaporation source and final performance can be found in [13].

Several considerations motivated the target thickness of the TPB coating. Complete coverage of the acrylic was paramount to avoid bare acrylic which would lead to a source of background. Complicating this was the underlying acrylic surface morphology. Roughness features from the resurfacing process ranged from 1–2 µm. Additionally, as TPB scintillates under alpha excitation [14], active background mitigation can be performed. With increasing thickness, more of the signal resultant from ^{210}Po alpha decays on the TPB surface can be boosted out of the dark matter search energy region of interest [15].

The inner surface of the acrylic vessel was slowly brought to approximately 50°C under vacuum in preparation for the TPB deposition. This vacuum bake addresses outgassing water from the acrylic, improving the overall achievable vacuum in the AV and liberating H_2O which can quench the argon scintillation signal.

Figure 4. Final stainless steel TPB deposition source. The coil heater is held in thermal contact with the stainless steel sphere by compressed stainless tabs. A stainless steel top hat was machined from which the inner copper crucible is attached.

At the intersection of the AV sphere and neck, an acrylic stage was deployed to act as a sensor and sample mount, bumper, and baffle to prevent TPB coating further up the neck.

Two evaporations, 29.4 ± 0.2 g in combined total mass, were performed on the DEAP-3600 acrylic vessel. Given the inner surface area of the AV and this deposited mass, a uniform coating is estimated to be $3.00 \pm 0.02\,\mu$m thick. A quartz deposition monitor, located on the neck stage, was used for real-time feedback and control of the deposition. Additionally, data from this monitor can provide a rough thickness measurement at this sampling point, shown in figure 5. A fault occurred in the deposition monitor during the first evaporation. The measured thickness of the second deposition was then scaled based on the ratio of deposited mass between the two coatings to estimate the thickness of the first deposition (dotted blue) at this sampling point. The combined final thickness from this sample point direct measurement is 2.30 μm, which given the extrapolation and shadowing of the deposition monitor's line-of-sight of the source due to the power cables and deployment system, agrees within a few percent of the 20% thickness non-uniformity target across the detector.

4 Summary

The DEAP-3600 experiment aims to perform a spin-independent dark matter search targeted at a WIMP-nucleon cross section of 10^{-46} cm^2. Utilizing the pulse shape discrimination characteristics of argon, the suppression of electromagnetic background events is projected at the level of 10^{10}. Wavelength shifting is necessitated from the efficient absorption of the VUV argon scintillation signal from the cryogenic volume by the surrounding acrylic vessel. At an ambitious scale for

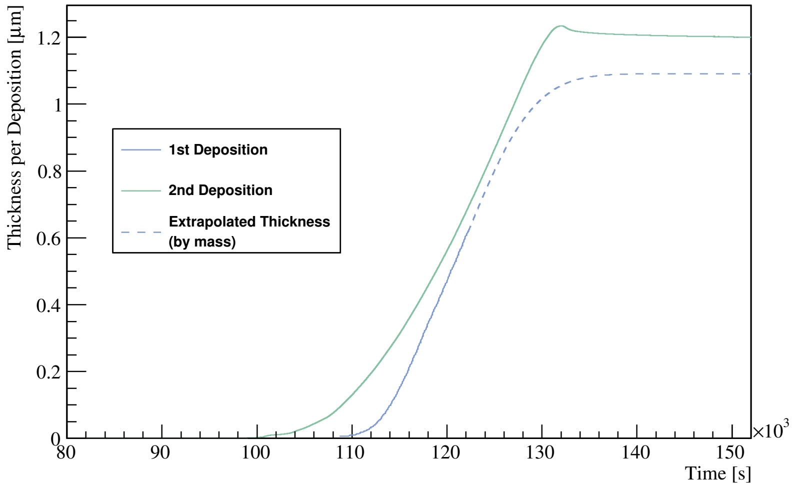

Figure 5. Measured TPB thickness per deposition at the sampling point in the neck. Blue: first deposition thickness curve (solid) and by-mass extrapolated final value (dotted). Green: full second deposition thickness curve. Shadowing of the deposition monitor's line-of-sight from the power cables and deployment system bias this measurement low.

vacuum deposition in an experimental physics application, a $3.00 \pm 0.02\,\mu$m thick coating of the wavelength shifter 1,1,4,4-tetraphenyl-1,3-butadiene was evaporatively deposited over the $9\,m^2$ inner surface of the acrylic vessel.

Acknowledgments

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