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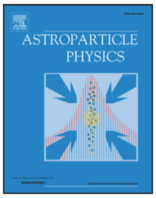

Measurement of the scintillation time spectra and pulse-shape discrimination of low-energy β and nuclear recoils in liquid argon with DEAP-1

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ABSTRACT

The DEAP-1 low-background liquid argon detector was used to measure scintillation pulse shapes of electron and nuclear recoil events and to demonstrate the feasibility of pulse-shape discrimination down to an electron-equivalent energy of 20 $\mathrm{keV_{ee}}$.

In the surface dataset using a triple-coincidence tag we found the fraction of β events that are misidentified as nuclear recoils to be $< 1.4 \times 10^{-7}$ (90% C.L.) for energies between 43–86 $\mathrm{keV_{ee}}$ and for a nuclear recoil acceptance of at least 90%, with 4% systematic uncertainty on the absolute energy scale. The

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discrimination measurement on surface was limited by nuclear recoils induced by cosmic-ray generated neutrons. This was improved by moving the detector to the SNOLAB underground laboratory, where the reduced background rate allowed the same measurement to be done with only a double-coincidence tag.

The combined data set contains 1.23×10^8 events. One of those, in the underground data set, is in the nuclear-recoil region of interest. Taking into account the expected background of 0.48 events coming from random pileup, the resulting upper limit on the level of electronic recoil contamination is $< 2.7 \times 10^{-8}$ (90% C.L.) between 44–89 $\mathrm{keV_{ee}}$ and for a nuclear recoil acceptance of at least 90%, with 6% systematic uncertainty on the absolute energy scale.

We developed a general mathematical framework to describe pulse-shape-discrimination parameter distributions and used it to build an analytical model of the distributions observed in DEAP-1. Using this model, we project a misidentification fraction of approximately 10^{-10} for an electron-equivalent energy threshold of 15 $\mathrm{keV_{ee}}$ for a detector with 8 PE/$\mathrm{keV_{ee}}$ light yield. This reduction enables a search for spin-independent scattering of WIMPs from 1000 kg of liquid argon with a WIMP-nucleon cross-section sensitivity of 10^{-46} cm^2, assuming negligible contribution from nuclear recoil backgrounds.

1. Introduction

The ability to separate electron-recoil ($\beta - \gamma$) interactions from nuclear-recoil interactions is critical for many nuclear and particle astrophysics experiments, including direct searches for dark matter particles. Liquid argon provides very sensitive pulse-shape discrimination based on scintillation timing [1], and it is a favourable target for dark matter particle searches since it can be used to construct a very large target mass detector. It is the target of choice in ArDM [2], MiniCLEAN [3], DarkSide [4], and WArP [5] detectors. In this paper we present results on the pulse-shape discrimination of $\beta - \gamma$ events from nuclear recoils with the DEAP-1 liquid argon detector, substantially extending the initial analysis [6].

Argon has many desirable properties as a scintillator, among them a high light yield of approximately 40 photons per keV [7] and ease of purification, so that it can meet the radio-purity requirements of a rare-event search experiment. However, argon that is condensed from the atmosphere is known to contain cosmogenically-produced $^{39}\mathrm{Ar}$, which undergoes β-decay at a rate of approximately 1 Bq per kg [8,9]. The scintillation properties of liquid argon provide a method for discriminating these β-decays from WIMP interactions in the detector [1].

Scintillation in argon is a result of the formation of excited dimers after exposure to ionizing radiation [10]. These occur in singlet and triplet states. On decaying to the ground state, they emit light at a peak wavelength of 128 nm, lower in energy than the lowest excited atomic state [11,12]. The scintillation light can thus pass through pure argon without being absorbed.

The scintillation yield of nuclear recoils in liquid argon is quenched to about 0.25(2) [13] of the yield for electron recoils.[7] When referring to energies of nuclear recoils, units of either $\mathrm{keV_{ee}}$ ("electron equivalent") or $\mathrm{keV_r}$are used, with the latter being the full energy of the recoil, and $[\mathrm{keV_r}] = 0.25 \cdot [\mathrm{keV_{ee}}]$.

The two argon dimer states have vastly different lifetimes, about 6 ns for the singlet and approximately 1.5 µs for the triplet state [12]. Moreover, the relative population of singlet and triplet states is determined by the linear energy transfer (LET), such that fewer triplet excimers are produced at higher LET, and by the track structure of the exciting radiation [12,16]. With the large difference in lifetimes, the percentage of light signal in the first few tens of nanoseconds is a good estimate for the relative population of the singlet state, allowing for an effective way to discriminate between particles of different LETs, such as low-energy electrons and nuclei. The exact value of the triplet state lifetime is debated in the literature and values as low as 1110 ns [17] and as high as 1590 ns [12] have been reported (for a review of recent results see Ref. [18]).

Measurements of the pulse-shape discrimination of $\beta - \gamma$ events from nuclear recoils in liquid argon have also been reported in [19] and [4]. In this work the upper limit on the $\beta - \gamma$ event misidentification probability is improved by a factor of ~ 5, due to higher statistics. A new improved analytic model for the pulse-shape discrimination parameter distribution, presented in Section 5, is consistent with the data and provides a more general framework than the previously used ratio-of-Gaussians model from Ref. [6]. It has been applied to the case of a much larger detector.

2. Experimental apparatus

The target volume of the DEAP-1 detector (shown in Fig. 1) is a cylinder 28 cm in length and 15 cm in diameter, containing 5.1 L (7 kg) of liquid argon at about 87 K. It is defined by a 1/4-inch thick polymethyl-methacrylate (PMMA) sleeve and two PMMA windows, which were coated on the inside, using standard vacuum deposition techniques, with a roughly 0.1 $\mathrm{mg/cm^2}$ thick layer of the wavelength-shifter 1,1,4,4-tetraphenyl-1,3-butadiene (TPB) [20]. The TPB shifts the 128 nm liquid argon scintillation light to the visible range so that it may pass the glass and acrylic windows. In order to increase scintillation light collection efficiency, the outside of the acrylic sleeve is coated in $\mathrm{TiO_2}$ paint (Bicron BC-620) for the first two datasets presented here and wrapped in Gore® Diffuse Reflector for the third dataset.

The target volume is contained inside a cylindrical stainless steel ultra-high vacuum shell with a 6-inch diameter glass window on each end. An 8-inch long cylindrical PMMA light guide rests against each glass window. The stainless steel shell and part of each light guide are located inside a 12 inch diameter PMMA acrylic vacuum chamber, and further thermally insulated by multi-layer super-insulation. The light guides are o-ring sealed to PMMA flanges on the insulating acrylic vacuum chamber, and the outer light guide face is at laboratory atmosphere and room temperature. A ETL5" 9390B photo multiplier tube (PMT) is coupled to each lightguide using Bicron BC-630 optical gel and operated at room temperature.

The light guides allow the PMTs to be operated at room-temperature by thermally insulating them from the liquid argon target volume (the measured heat load in this configuration is approximately 7 W per light guide) while at the same time transporting visible light from the target volume. The light-

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[7] We are aware of more recent results of approximately 0.29[14,15], which is slightly higher. Changed quenching factor does not affect our conclusions significantly.