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Simulation of the argon response and light detection in a dual-phase TPC

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Abstract: G4DS is the GEANT4-based Monte Carlo simulation for the DarkSide program, tuned on the data of the DarkSide-50 experiment. It includes: a tuned optical model, for the description of the detector non uniformities at the percent-level; the accurate simulation of the scintillation time profile, used for pulse shape discrimination; an effective model for the ionization and scintillation mechanism in liquid argon. This tool, combined with the additional data from dedicated calibration experiment, provides a comprehensive model to describe the response of liquid argon in dual-phase TPCs. This document reviews the calibration procedure and discuss some application for for the DarkSide experiments.

Keywords: Noble liquid detectors, Ionization and excitation processes, Dark Matter detectors

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1 Direct Detection of Dark Matter with a Liquid Argon Target

Earth-based direct detection experiments aim to detect galactic dark matter particles via their interaction with ordinary matter in an instrumented target. Noble liquid detectors, in the dual-phase layout, are particularly suitable for these searches, thanks to scalability, intrinsic radio-purity and good ionization and scintillation properties of the target. In this detector design, the active volume is immersed in a uniform electric field, to drift ionization electrons towards a gaseous region on top of the detector, where charges are accelerated to stimulate light production by electro-luminescence. Photo-detectors collect both the prompt scintillation (S1) and the delayed electro-luminescence light (S2), allowing for energy measurement and 3D vertex reconstruction, with typical resolution of 1 mm along the drift direction and 1 cm in the horizontal plane.

In addition to this, liquid argon (LAr) provides excellent rejection of the β and γ backgrounds, thanks to the pulse shape discrimination (PSD) technique. The DEAP-3600 [1] and DarkSide-50 [2] experiments recently published the results of background-free searches for dark matter in the form of WIMPs (*Weakly Interacting Massive Particles*). The DarkSide-50 experiment also provided the world-leading exclusion on dark matter candidates with lower mass ($<$ 6 GeV/c^2), demonstrating the potential of LAr in beyond the traditional WIMP paradigm [3]. The Global Argon Dark Matter Collaboration (GADMC) aims to perform the most sensitive dark matter search of the next decade, using a dual-phase TPC filled with 50 t of radio-pure argon extracted from underground (UAr): DarkSide-20k. This detector will be operated inside a 700 t LAr cryogenic bath and it is planned to start taking data in 2023. The future step of the program is foreseen to be Argo, a ~0.5 kt UAr detector.

Understanding, modeling and calibrating the response of LAr in the ROI for WIMP searches is therefore of capital importance to maximize the sensitivity of the current and the next generation of dark matter experiments employing LAr.

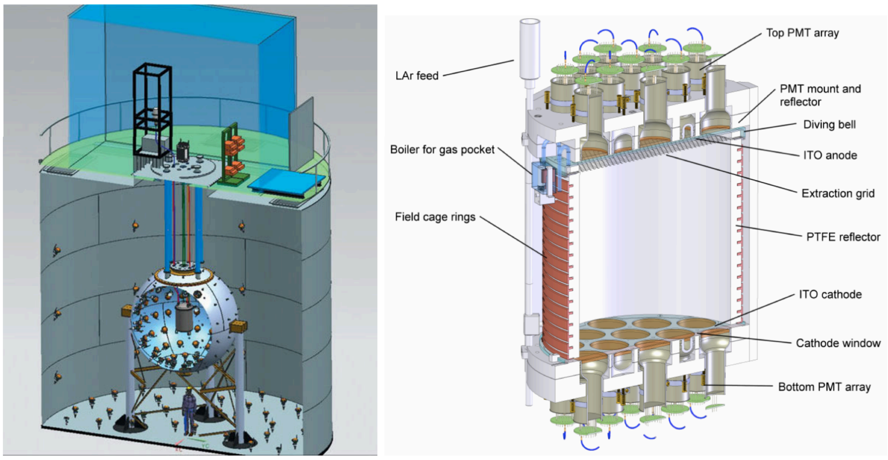

Figure 1. Left: the DarkSide-50 experimental apparatus, consisting of 3 nested detectors. Right: cutaway drawing of the TPC, filled with 50 kg of LAr.

2 The DarkSide-50 experiment

The DarkSide-50 experiment is running since 2013 at *Laboratori Nazionali del Gran Sasso* and it consists of three nested detectors, sketched in Figure 1: a 50 kg LAr TPC, the target for dark matter, is hosted inside a 30 t spherical liquid scintillator veto (LSV), which is in turn placed inside a 1 kt cylindrical water Cherenkov detector (WCD). The TPC is equipped with two arrays of 19 Hamamatsu R1165 PMTs, observing the active volume through quartz windows. The lateral walls of the TPC are made of 1” thick PTFE reflector. All the internal surfaces of the TPC are coated with TPB, to shift the wavelength of LAr scintillation light from the VUV (128 nm) to the visible.

A 1 cm thick gaseous argon layer is created on top of the detector, by heating the liquid. The electron drift system is made of a series of copper rings, surrounding the TPC barrel; two pairs of transparent ITO electrodes, coated on the quartz windows; and a steel mesh, placed $\sim$ 3 mm below the liquid surface. The active volume is immersed in a uniform electric field (200 V/cm), while above the grid the fields are 2.8 kV/cm and 4.2 kV/cm in the liquid and in the gas respectively.

The LSV is made of a solution of pseudocumene (PC, a scintillator), trimethyl borate (TMB, a borate compound) and diphenyloxazole (PPO, wavelength shifter) and it is equipped with 110 Hamamatsu R5912 PMTs. The high neutron capture cross section of boron makes the veto very efficient for capturing and tagging neutrons. The WCD, mounting 80 ETL 9351 PMTs, is designed to tag cosmic muons as they may produce neutrons along their path.

3 Tuning of G4DS, the DarkSide Simulation Tool

The response of the detector is modeled with a GEANT4-based tool, called G4DS [4], which includes the accurate geometry description of the detectors, an optical model for the propagation of scintillation and visible light, the calibration of the energy scales for nuclear and electronic recoils

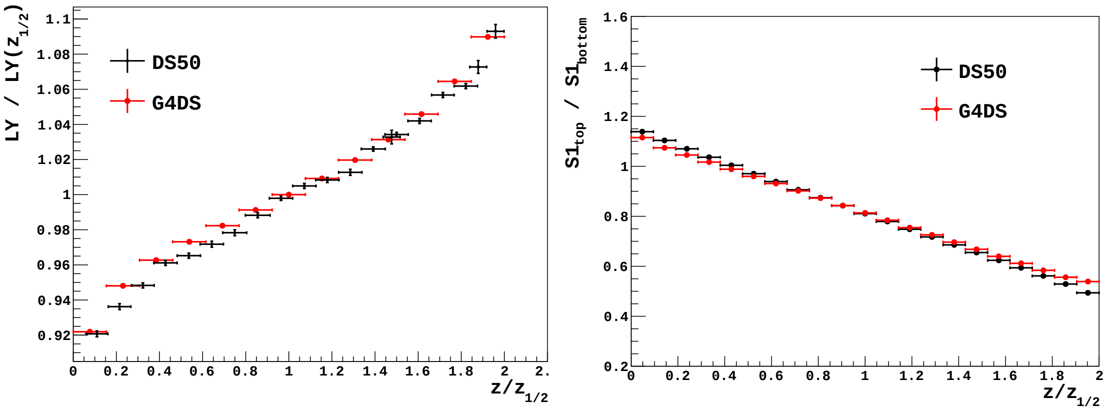

Figure 2. Left: relative light collection efficiency and right: top-bottom ratio as a function of the vertical position of the event. The normalization is relative to the center of the TPC, so that $z/z_{1/2} = 0$ corresponds to the top, $z/z_{1/2} = 2$ correspond to the bottom.

(NR and ER respectively), the tuned simulation of the PSD parameter distributions. In this work only the tuning of the optical model and the calibration of the energy scale will be covered.

The optical tuning has been performed using a set of relative quantities, such as the relative light yield as a function of vertical coordinate of the event, and the ratio between the amount of light collected by the top and bottom arrays of PMTs. More than 20 input parameters that affect the propagation of VUV and visible light in the detector were identified: refractive indexes, absorption and Rayleigh scattering lengths, wavelength shifter properties. These parameters were initially set to calculated or measured values. A large $O(10^4)$ matrix of simulations were produced, by simultaneously varying the parameters around nominal values to determine the configuration which better reproduced the real data. It was found that the agreement improves when a layer of LAr, possibly from condensation of the gas, is added on the underside of the top quartz window. The current status of the data-MC comparison is given in Figure 2.

The S1 energy scale is calibrated using a set of internal sources, uniformly distributed in the active volume: the β spectrum of ^{39}Ar, the 2.7 keV peak of ^{37}Ar and the 41.5 keV energy deposit of ^{83m}Kr decay. The energy deposited by the primary radiation is converted in numbers of excitons (N_{ex}) and electron-ion pairs (N_i) using constant work function ($W = 19.5$ eV) and $\alpha = N_{ex}/N_i = 0.21$. In addition to excitons, a fraction of ionization electrons undergoes recombination with ions and contributes to the S1 signal, while depleting S2. The recombination probability as a function of the recoil energy, which embeds possible non-linearities in the process described above, is extracted from real data. An analytical parameterization of this quantity, depending on 4 free parameters, was identified and fit to the data, in order to reproduce the observed S1 spectra for the chosen sources. Poisson fluctuations are assumed for the calculated number of emitted scintillation photons. The calibrated model was tested against independent datasets obtained with γ-ray sources external to the TPC (^{57}Co and ^{133}Ba), producing single and multiple-site interactions in the active volume, such as the ones shown in Figure 3. Full simulations of the calibration sources were then used to validate the calibration of the energy scale and the final resolution, due to the assumed statistical fluctuations combined with the simulated optical response.

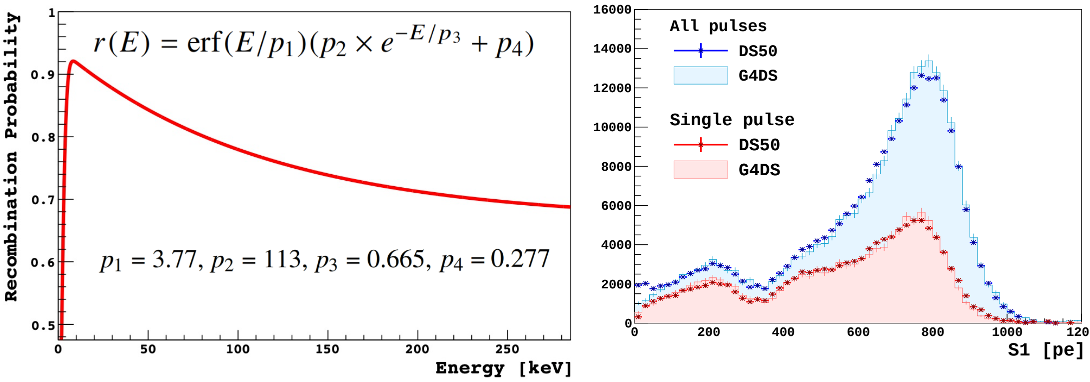

Figure 3. Left: recombination probability as a function of the ER energy extracted from DarkSide-50 data (left). Right: single and multiple scatter S1 spectra of ^{57}Co calibration source in DarkSide-50 data, after background subtraction, compared with a full G4DS optical simulation.

The ionization electrons which survive recombination are drifted upwards and they produce the proportional S2 light pulse by electroluminescence as they are accelerated in the gaseous region. The tuning of the S2 multiplication factor, g_2, takes into account the strong radial dependence observed in real data, with the mono-energetic ^{83m}Kr source. For similar S1, S2 is reduced by up to a factor of 4 at large radii compared to the TPC center, likely due to a non uniform thickness of the gas layer. In order to match the observed size of the S2 signal ($g_2^{DS50} \sim 23$ PE/e- at the center, in DarkSide-50), G4DS requires a larger multiplication factor ($g_2^{MC} \sim 43$ PE/keV). This is a consequence of the model assumptions on W and α. A more sophisticated work, out of the scope of the G4DS tuning, is required to correct this discrepancy.

A more detailed review of these calibrations and a description of additional features of G4DS is given in [4].

4 The ARIS Experiment for the Nuclear Recoil Calibration

The ARIS experiment was designed and conduced to measure the relative scintillation efficiency of NRs compared to ERs of the same energy, as a function of the recoil energy ($\mathcal{L}_{eff}(E)$). A small scale TPC, equipped with 7 1" PMT on top and 1 3" PMT on bottom was constructed at UCLA. It was then operated in single phase, with a nominal drift field of 200 V/cm, and exposed to a pulsed (2.5 MHz), collimated and nearly mono-energetic ($<E> = 1.453 \pm 0.085$ MeV) neutron beam produced by the p(^{7}Li,^{7}Be)n inverse reaction at the LICORNE facility at IPN of Orsay. The nuclear reaction is also a source of 478 keV γ-rays, from the de-excitation of ^{7}Be*. A set of 8, 20 cm diameter, liquid scintillator detectors were placed at different angles with respect to the beam axis, facing the TPC, to close the kinematics of neutrons and γ-rays interacting in the target. The angles and the corresponding mean recoil energies are listed in Figure 4. Pure samples of neutron and γ interactions of known energy are selected on the basis of time-of-flight (TOF) from the source to the TPC and from the TPC to the scintillator detectors.

An ER dataset including the γ-ray induced ERs and the data from external calibarion sources (^{241}Am, ^{133}Ba and ^{22}Na) were used to assess the linearity of the response of LAr at null drift

	Scattering Angle [deg]	Mean NR Energy [keV]	Mean ER Energy [keV]
A0	25.5	7.1	42.0
A1	35.8	13.7	75.9
A2	41.2	17.8	85.8
A3	45.7	21.7	110.3
A4	64.2	40.5	174.5
A5	85.5	65.4	232.0
A6	113.2	98.1	282.7
A7	133.1	117.8	304.9

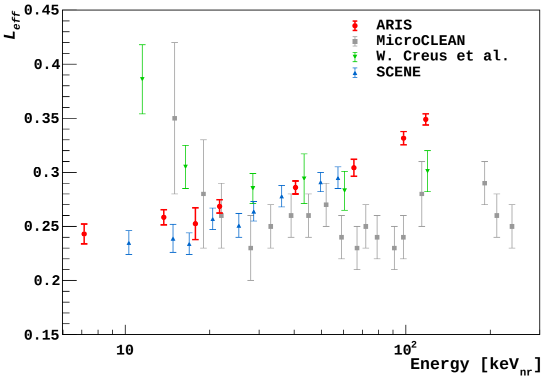

Figure 4. Left: mean scattering angle for each ND and corresponding mean ER and NR energies. Right: the ARIS measurement of $\mathcal{L}_{eff}$ compared with other datasets.

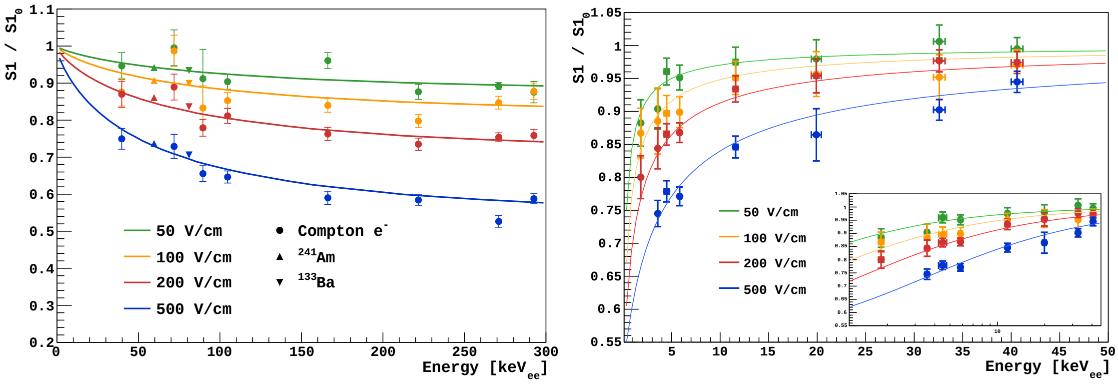

Figure 5. The effect of recombination for ER (left) and NR (right) for different electric drift fields. The fits are performed with the Doke-Birks parameterization and Thomas-Imel box model respectively.

electric field. Deviations from linearity are constrained at 1.6% in the [42, 511] keV energy range. Building on this, the NR dataset at null drift field is used for the measurement of the $\mathcal{L}_{eff}(E)$ parameter, summarized in Figure 4. The points represent the ratio between the S1 signal measured for NRs and for an ERs of the same nominal energy. The shown systematic uncertainties reflects the uncertainty on the correction for the trigger efficiency, on the beam kinematics, the errors on the relative position of detectors and on the model of the TPC optical response.

Both the neutron and γ-ray data taken at multiple electric drift fields are then used to extract a parameterization of the recombination probability as a function of the field and recoil energy. Each point in Figure 5 corresponds to the ratio between the S1 signal measured with and without drift electric field. The ER data is fit to the empirical Doke-Birks model, after fixing $\alpha = 0.21$. The data points at 200 V/cm provide an independent validation of the recombination model extracted from the DarkSide-50 data. The NR dataset is fit to the Thomas-Imel model, better suited to predict the recombination in the "short track" approximation, assuming $\alpha = 1.0$. The analytical expressions of the recombination probability for ERs and NRs, and of the best fit values are given in [5].

5 Conclusions

G4DS, the simulation tool for the experiments of the DarkSide program, features a model to describe the optical response of the LAr dual-phase TPC and the calibration of the energy scale, obtained using the DarkSide-50 data in combination with the data from the ARIS experiment. As a result, it provides a comprehensive model for the response of LAr to nuclear and electronic recoils in the energy range of interest for dark matter searches.

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