Position Reconstruction for DEAP-3600

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WHAT IS DARK MATTER?

The existence of invisible, non-standard model matter, or "dark matter" has become well-established in recent decades. Perhaps the most well-known evidences are the distribution of the velocities of stars within galaxies as they revolve around the centre, and the velocities of the galaxies themselves as they revolve around the centre of galactic clusters. These stars and galaxies travel much faster than the gravitational force of the observable mass of these galaxies would allow. This led to speculation of extra invisible "dark matter" within the galaxies that would produce the extra gravitational force [1]. Other evidences, such as the collision of the Bullet Cluster (in which actual pockets of dark matter were observed through gravitational lensing), lend weight to this theory as opposed to a modification of Einstein's law of gravity [2].

Searches for MAssive Compact Halo Objects (such as stray planets, black holes, etc.), also known as MACHOs, have shown that there aren't enough of these in the galaxy to explain the missing mass [3].

Big Bang nucleosynthesis has shown that if dark matter is baryonic, the higher initial density of baryons during the Big Bang that would have been necessary to account for this extra matter would have resulted in a relative abundance of light elements that is inconsistent with the observed abundances. In fact, the observed abundances are consistent with Big Bang nucleosynthesis models that assume that dark matter is non-baryonic [1].

Models of the evolution of the universe show that the gravitational collapse of hot gas into stars and galaxies, the gas was so energetic that it would not have been possible to form the structures seen today without the presence of cold dark matter to effectively "boost" gravity [1].

Lastly, measurements of the multipole moments in the Cosmic Microwave Background (CMB) have also shown evidence for a non-baryonic dark matter component in the universe [4]. These observations have led to the conclusion that some particle (or particles) that is not included in the Standard Model is responsible.

Summary

Position reconstruction is used in DEAP-3600 WIMP dark matter search experiment to discriminate impostor events from the detector surface and to locate candidate events.

SEARCHING FOR DARK MATTER WITH DEAP-3600

There is no evidence for any kind of interaction between dark matter and normal matter except through gravity. The fact that dark matter is invisible and appears to not interact with gases around it (such as in the Bullet Cluster), implies that it does not interact electromagnetically. If it interacted via the strong force, either protons would decay into it, or it would decay hadronically, depending on its mass. Since these interactions have not been observed, it appears that dark matter does not interact via the strong force.

However, the weak force is not ruled out. Weakly Interacting Massive Particles (WIMPs) are a leading theoretical candidate for dark matter [1]. If they exist they would interact very rarely with normal matter and would release very little energy in an interaction. So to make detection possible, it is necessary to construct an experiment that maximizes the probability of interaction, while minimizing the backgrounds that would mask or mimic the signal from the interaction. Noble gases are good targets for WIMP searches, due to their stability over time, lack of chemical reactivity, and good scintillation response.

DEAP-3600 is located 2 km underground at SNOLAB, in Sudbury, Ontario [5,6]. It uses liquid argon as the target mass, and is primarily an 85 cm acrylic sphere filled with liquid argon. The idea is that a dark matter particle will find its way into the liquid argon and scatter with an argon nucleus. This nuclear recoil will generate scintillation photons within the liquid argon. These photons will be emitted isotropically from the interaction site and propagate to the edge of the sphere, where acrylic light guides will transport the wavelength shifted argon scintillation light to the 255 photo-multiplier tubes (PMTs) that surround the acrylic vessel. To shift the 128 nm scintillation light to blue light that can travel through acrylic, a layer of tetraphenyl butadiene (TPB) coats the inner surface of the acrylic vessel. See Fig. 1 for a diagram of the detector and

1. Carl Rethmeier received 1st place in the CAP Best Student Poster Presentation competition at the 2017 CAP Congress at Queen's University in Kingston, ON.

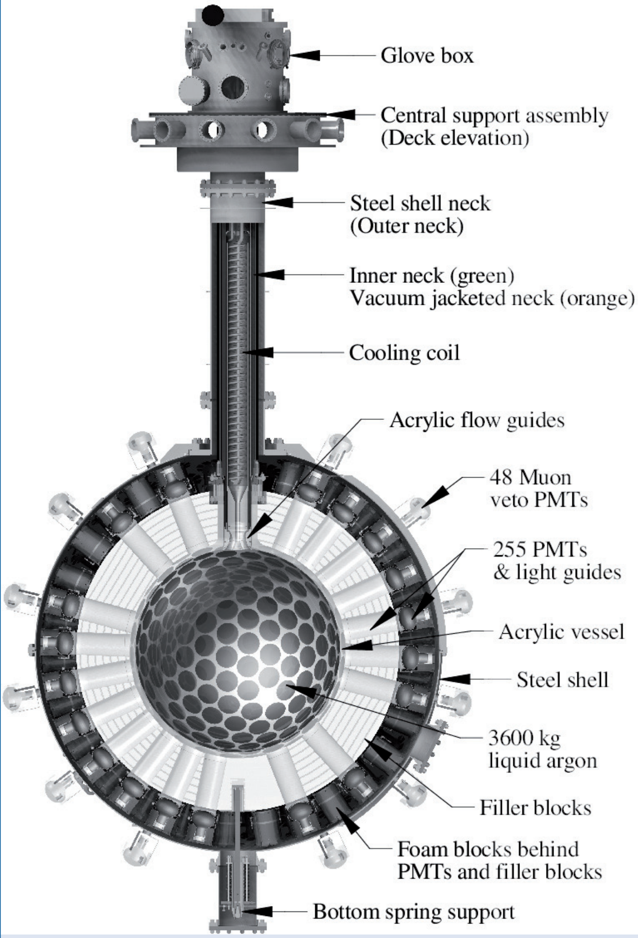

Fig. 1 Annotated cross-section of the 3D CAD schematic of the DEAP-3600 detector, showing the acrylic vessel, light guides, and PMTs.

[7] for more details on the TPB, including its deposition, testing, and performance.

The primary observable in DEAP-3600 is the distribution of charge collected by the PMTs, which is proportional to the number of photons detected. For the WIMP events DEAP-3600 is sensitive to, this is expected to be approximately 80-240 photons.

POSITION RECONSTRUCTION

Motivation

When particles interact with liquid argon they excite the argon atoms into long-lived triplet (1600 ns) and short-lived singlet (6.7 ns) spin states. The ratio of singlet to triplet states depends on whether a given incoming particle recoiled off an electron (via an electromagnetic interaction) or the nucleus (as WIMPs are expected to do). This allows for a very strong discrimination of electron recoil background events. This is essential for argon dark matter searches, since the naturally occurring radioactive ^{39}Ar (a beta emitter) would otherwise drown out any dark matter signal.

However, there will always be some level of radioactivity within the detector from alpha decays. Alpha particles tend to recoil off the nuclei of argon atoms. This is not normally an issue, as alpha particles release orders of magnitude more energy when they scatter than a WIMP would. An exception to this is the case when an alpha particle is produced in the TPB or acrylic bulk. Occasionally, the alpha particle will lose just enough energy in the TPB before entering the argon that it ends up producing a nuclear recoil in the energy range of interest for the WIMP search.

Fortunately, these alphas don't penetrate very far into the liquid argon volume. They can therefore be excluded from the WIMP search data by ignoring all events that occur within a certain distance from the surface of the acrylic vessel. In order to accomplish this, it is necessary to have a reliable position reconstruction algorithm to find the positions of events within the detector.

Fitters

There are three preliminary position reconstruction fitters currently being evaluated by the collaboration. They are: "Centroid", "MBLikelihood", and "ShellFit". These fitters have shown promise in terms of both their resolution and accuracy. Monte Carlo studies have shown that the resolution is better than 20 cm throughout the detector, and is even better near the edge.

CENTROID

Centroid is not as much a fitter as a weighted average. The charge on each PMT is scaled up by a power, *f*.

$$Q_{scaled} = Q^f \tag{1}$$

This power factor is pre-set, and is intended to be tuned on ^{39}Ar calibration data. As it loops through the PMTs, the scaled charge is multiplied by the PMT position (**P**) and added to an overall Centroid position vector (**C**).

$$C = \sum_{i=1}^{nPMT} P_i \times Q_{scaled,i} \tag{2}$$

Once this is done, **C** is divided by the total scaled charge, resulting in a final weighted average for the location of the charge. This is the value returned by Centroid. Centroid's simple algorithm makes it well suited for sanity checks of the Monte Carlo, as any unexpected artefacts in the spectrum of reconstructed position are unlikely to originate from defects in the algorithm. It is currently being used to further calibrate the Monte Carlo optical model, for example. The power, *f*, has been calibrated on ^{39}Ar data, and a value of 3 was found to give the highest position resolution. A good resolution increases the effectiveness of using this tool to calibrate the Monte Carlo.

MBLIKELIHOOD

MBLikelihood is a negative log likelihood fit of the charge distribution. A Monte Carlo based tuning algorithm creates the likelihood function that is used by this fitter. This depends on the state of the Monte Carlo model at the time of tuning, so it is necessary that the Monte Carlo is calibrated as well as possible.

SHELLFIT

ShellFit performs Monte Carlo simulations on an event-by-event basis to determine the position of events within the detector. It uses Centroid to get a position estimate for an event, and then generates a series of Monte Carlo events in that region. A negative log likelihood minimization is then used to converge on the most likely position of an event.

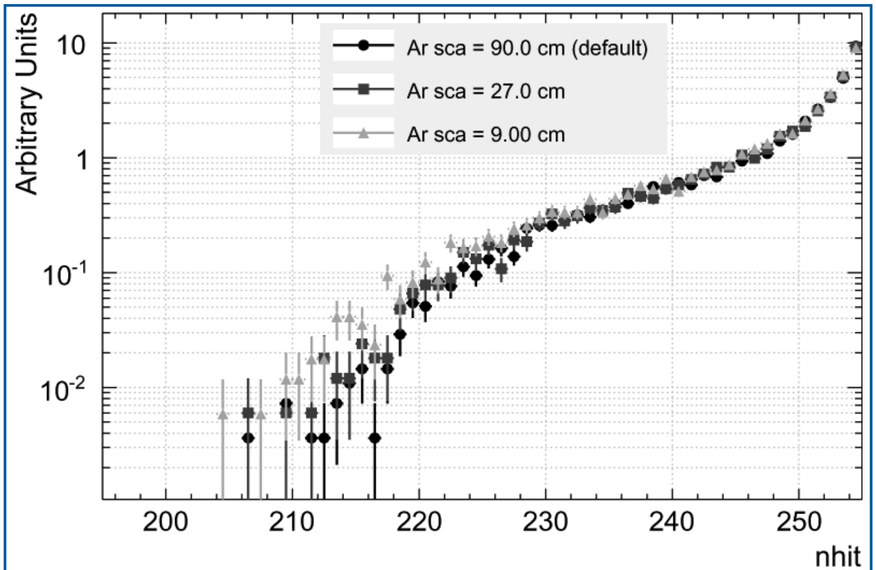

Fig. 2 Effect of scattering length on the total number of PMTs hit.

POSITION RECONSTRUCTION - CALIBRATION

Monte Carlo studies have also shown that the fitters perform well in discriminating events that occur near the acrylic surface. All that is needed, therefore, is to ensure that the algorithms perform as well on surface events in data as they do on Monte Carlo.

To ensure that the Monte Carlo is a sufficiently good representation of the data, it will be necessary to calibrate the models used in the Monte Carlo using various calibration sources. Calibration sources include a laser ball, the "Acrylic and Aluminium Reflector and Fibre optic-System" (AARF), external AmBe and 22 Na sources, and the radioactive internal ^{39}Ar that exists naturally in the liquid argon that fills the detector.

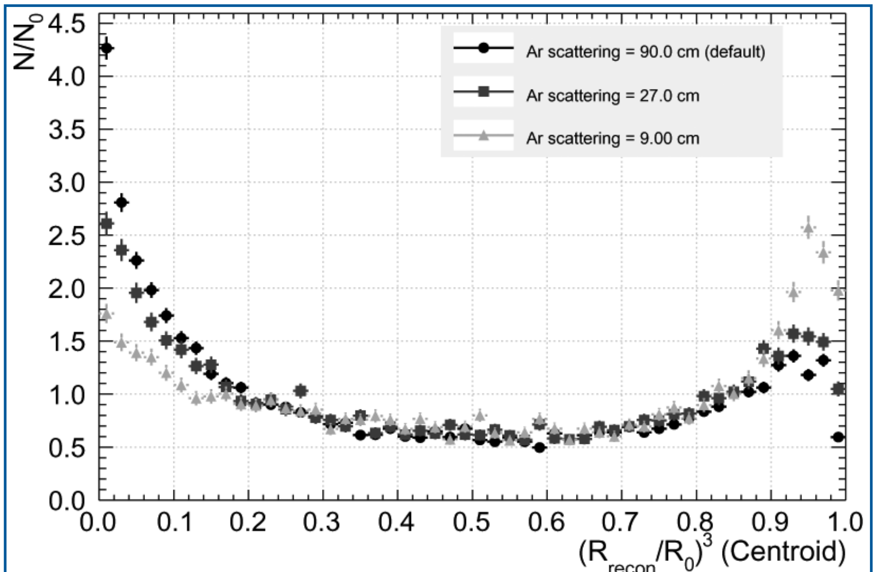

Fig. 3 Effect of scattering length on the reconstructed positions using the Centroid algorithm.

We will focus here on the ^{39}Ar, as it is a high rate background that is always present in the data. This allows for an in-situ comparison between the data and Monte Carlo model at any point in time while argon is in the detector.

This distribution is characterized by several variables used in the analysis. One such variable is "nhit", which is the number of PMTs that record pulses during an event.

By comparing the characteristics of the ^{39}Ar events seen in data with simulated ^{39}Ar events it will be possible to test and tune various parameters of the Monte Carlo model. One such parameter is the argon scatttering length. The argon absorption length depends strongly on the purity level of the argon, making measurements of the scattering length very difficult. Since this affects the diffusivity of light within the argon, getting this parameter (or others like it) wrong could bias the reconstructed positions of events.

All parameters used in the DEAP-3600 analysis are initially based on values found in the literature. Tuning these parameters on data is mostly a matter of trying extreme values for a given parameter and seeing whether changing this parameter will bring about a closer match between the simulated calibration events and actual calibration events. Figures 2 and 3 show how the scattering length affects nhit and Centroid. These figures show how different extreme values of a given parameter might affect the characteristics of the observed signal.

An actual calibration would consist of a similar approach, with the main difference being that all parameters would need to be investigated in order to properly understand how the calibration of the Monte Carlo would affect the final analysis.

CONCLUSION

Once the development and calibration of these fitters is complete, DEAP-3600 will gain a significant boost in sensitivity, as this will enable it to utilize much more of its argon volume while still excluding radioactive surface backgrounds. These techniques might also be applied in future large scale WIMP searches, and may one day contribute to the discovery of these mysterious particles.

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