## G S <br> S I

## INTIUM

## Second year report

Feasibility of solar neutrino measurement with the CYGNO/INITIUM experiment

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## Introduction

- CYGNO is a TPC with optical readout, developed for directional DM searches


Primary ionization


Amplification + light production


Light detection

- Under the hypothesis of WIMP permeating the galaxy, a dipolar angular distribution of nuclear recoil in galactic coordinate can be the signature to positively identify DM



## Neutrino background for DM searches

- Solar neutrinos represent an irreducible background for DM experiment
- Neutrinos can mimic DM interaction through the Coherent Elastic NeutrinoNucleus Scattering (CELNS)
- Increasing sensitivity of DM experiments the "neutrino-floor" is reached, here the $\mathrm{CE} \nu \mathrm{NS}$ cross-section becomes comparable with the DM one
- Below the neutrino floor a DM signal is harder to distinguish from a neutrino one
- This limit can be overcome with directionality by backtracking the direction of the incoming particle


solar neutrinos

WIMPs


## Solar neutrino with CYGNO/INITIUM

- Neutrino from the sun can be object of study with large TPC
 through $\nu-e^{-}$scattering as proposed in '90:
Seguinot, Jacques \& Ypsilantis, Thomas \& Zichichi, Antonino. (1992). A high rate solar neutrino detector with energy determination.
- Directional detection $\rightarrow$ capability of discriminating particles from different sources through directionality


Electron track detected with CYGNO/INITIUM sCMOS

- Fixed kinematic relationship between the neutrino energy, recoil energy, and scattering angle: a directional measurement allows the event-by-event reconstruction of the initial neutrino Energy
- Expected rate @I atm: $\left.R=N_{e} \sum_{i} \varphi\left(E_{i}\right)\left(P_{e e} \sigma_{\nu_{e}}\left(E_{\nu, i}\right)+P_{e \mu} \sigma_{\nu_{\mu}}\left(E_{\nu, i}\right)\right)\right) \Delta E=2.9 \cdot 10^{-8} \frac{\text { events }}{\mathrm{s} \cdot \mathrm{m}^{3}}=0.9 \frac{\text { events }}{y \cdot \mathrm{~m}^{3}}$
- With a CYGNO PHASE 2 detector of $30 m^{3}$ active volume we expect: $\sim 90$ events in $3 y$
- The goal of my thesis is to establish the exposure needed to claim detection of solar neutrino with a CYGNO PHASE 2 detector, and therefore demonstrate the feasibility of solar neutrino spectroscopy with this TPC technology



CYGNO 1 Cubic Meter

## Evaluation of expected angular distribution

I. Random neutrino energy from the flux extracted, with random $\cos \theta$ value according to the differential cross section

$$
T_{e}^{\prime}(\theta)=\frac{2 E_{\nu}^{2} m_{e} \cos ^{2}(\theta)}{\left(E_{\nu}+m_{e}\right)^{2}-E_{\nu}^{2} \cos ^{2}(\theta)}
$$

2. Calculation of the $e^{-}$kinetic energy given $E_{\nu}$ and $\cos (\theta)$ $\rightarrow$ kinematic closed
3. Smearing of energy and angle according to the resolutions:
4. Reconstruct the energy of the neutrino with $E_{e^{-}}$and $\cos \theta$ smeared

- $\cos (\theta)$ distribution for two different threshold: $20-100 \mathrm{keV}\left(E_{\nu} 80-220 \mathrm{keV}\right)$
- Very low signal regions available for background characterisation
- With 100 keV threshold sharper peak but $R \sim 0.3 \mathrm{ev} /\left(m^{3} \cdot y\right)$

$$
E_{\nu, \text { Reco }}=\frac{-m_{e} T_{e}-\sqrt{T_{e}^{2} m_{e}^{2} \cos (\theta)^{2}+2 T_{e} m_{e}^{3} \cos (\theta)^{2}}}{\left(T_{e}-T_{e} \cos (\theta)^{2}-2 m_{e} \cos (\theta)^{2}\right)}
$$



## Study of low-energy electron reconstruction performances

## Track images production

- Tracks imaged are produced as they would appear in the CYGNO PHASE I and PHASE II with module:
- 50 cm drift length
- $33 \times 33 \mathrm{~cm}^{2}$ readout area
- Triple GEM amplification
- Light collected by sCMOS + 4 PMTs
- Electron tracks produced using GEANT4 at the center of the detector in $\mathrm{He}: \mathrm{CF}_{4}$ 60:40 at I atm
- Tracks are then digitized in images simulating
- Fluctuation in primary ionization
- GEM gain and light production variation
- sCMOS granularity and solid angle
- Carriers diffusion (at random Z for each track )
- Noise from real pedestal is superimposed




## The track reconstruction code - superclustering

- The algorithm applies an iterative version of DBSCAN (iDBSCAN)
- Originally developed to reconstruct ${ }^{55} \mathrm{Fe}$ electron recoils, AmBe nuclear recoils, and cosmics, it perform 3 iteration for different ionization patterns: high density (NR), light spot (Fe), long tracks
- Once the clusters are found they are merged into a single supercluster with the geodesic active contour (GAC)
- GAC uses the light profile gradient of the image to reconstruct tracks, not suitable for $e^{-}$
- Noticing GAC not able to reconstruct $e^{-}$, I found Chan-Vese and optimized its parameters for $e^{-}$ The Chan-Vese algorithm. Rami Cohen.
- Chan-Vese exploit the global light density of the image to segment images, suitable for $e^{-}$



## Dataset

- Electrons generated at the center of the detector


## 30 keV electron @ 25 cm

- Angular distribution isotropic on theta and phi, with original information saved
- Electron energies simulated in range [20-60] keV with step of 2 keV
- Diffusion simulated uniform in $5-45 \mathrm{~cm}$
- All tracks reconstructed with same reconstruction algorithm parameters


## Reconstruction efficiency and energy resolution

- Reconstruction efficiency @ E>20 keV = I00\%

Capability of reconstructing the whole track >99\% below $50 \mathrm{keV}, 95 \%$ and $90 \%$ at 50 and 60 keV


- Data e Montecarlo in agreement on energy resolution
- Once track energy is known the directionality algorithm parameters can be optimised for the energy

The directionality algorithm

## How the algorithm works:Track main axis

- Algorithm adapted from X-ray polarimetry:

```
"Measurement of the position resolution of the Gas Pixel Detector" Nuclear Instruments and Methods in Physics Research Section A, Volume 700, 1 February 2013, Pages 99-105
```

- This first steps have the purpose of finding the beginning of the track
- Calculation of the track barycenter weighting pixels with light

$$
x_{c}=\frac{\sum_{i} Q_{i} x_{i}}{\sum_{i} Q_{i}} \quad y_{c}=\frac{\sum_{i} Q_{i} y_{i}}{\sum_{i} Q_{i}}
$$




- Calculation of the main axis of the track:
- Line passing from the barycenter, such that the RMS of the histogram resulting from the projection of the track points on the line is maximum (lime)

$$
\begin{aligned}
& M_{2}(\Phi)=\frac{\sum_{i} Q_{i} x_{i}^{\prime 2}}{\sum_{i} Q_{i}}=\frac{\sum_{i} Q_{i}\left[\left(x_{i}-x_{c}\right) \cos \Phi+\left(y_{i}-y_{c}\right) \sin \Phi\right]^{2}}{\sum_{i} Q_{i}} \\
& \frac{d M_{2}(\Phi)}{d \Phi}=0 \Longrightarrow \Phi_{0}=-\frac{1}{2} \arctan \frac{2 \sum_{i} Q_{i}\left(x_{i}-x_{b}\right)\left(y_{i}-y_{b}\right)}{\sum_{i} Q_{i}\left[\left(y_{i}-y_{b}\right)^{2}-\left(x_{i}-x_{b}\right)^{2}\right]}
\end{aligned}
$$

$\Phi$ angle of the line respect to the x-axis

## How the algorithm works:The skewness



- Calculation of the skewness of the track along the main axis respect to the barycentre

$$
M_{3}=\frac{\sum_{i} Q_{i} x_{i}^{\prime 3}}{\sum_{i} Q_{i}}=\frac{\sum_{i} Q_{i}\left[\left(x_{i}-x_{b}\right) \cos \Phi_{\max }+\left(y_{i}-y_{b}\right) \sin \Phi_{\max }\right]^{3}}{\sum_{i} Q_{i}}
$$

- Third momentum of the distribution contains the information on the Bragg Peak (end of the track)


Negative Skew
Positive Skew

## How the algorithm works:Track beginning

Calculation of the interaction region as points such that:

1. The point is on the other side of the Bragg peak

$$
\frac{x_{i}^{\prime}}{M_{3}}<0 \Longrightarrow \frac{\left(x_{i}-x_{c}\right) \cos \Phi_{\max }+\left(y_{i}-y_{c}\right) \sin \Phi_{\max }}{M_{3}}<0
$$

2. The distance of the point from the barycentre is greater than $r$ :
$r<d_{c m} \quad d_{c m}=\sqrt{\left(x_{i}-x_{c}\right)^{2}+\left(y_{i}-y_{c}\right)^{2}}$


- Where $r$ taken in order to include $N_{p t}$ within in the interaction region through an iterative procedure in which $r$ is progressively increased

$$
\begin{aligned}
& N_{p t} \text { parameter of } \\
& \text { the model }
\end{aligned}
$$

## How the algorithm works: Interaction point

- The interaction point (IP) calculated as the barycenter of the interaction region
- IP $\neq$ extremity of the track due to diffusion



## How the algorithm works: Directionality axis determiantion

- Directionality information contained at the beginning of the track
- Intensity of the pixel re-weigth for the distance from the IP to weight less pixels far from the IP

$$
W\left(d_{i p}\right)=\exp \left(-d_{i p} / w\right)
$$

$w$ parameter of the model

- Find the line passing from the IP such that the RMS of the histogram resulting from the projection of the track points rescaled on the line is maximum (Orange line in the plot below)




## How the algorithm works: Giving an orientation

- $r$ (Slide 14) is calculated with an iterative process increasing it progressively until the correct number of points is selected for the interaction region
- The barycentre is calculated for a previous iteration $\left(\mathrm{IP}_{p}\right)$
- Two line perpendicular to the direction line passing from IP and $I P_{p}$ are built


$$
\begin{gathered}
\theta_{\text {meas }}=-21.32^{\circ}<0 \\
\& \\
q_{I P_{p}}>q_{I P}
\end{gathered} \longrightarrow \theta=158.68^{\circ}
$$

## When the algorithm fails

## $\star$ Real interaction point

Calculated interaction point


## Parameter scan

- The parameters of the algorithm ( $N_{P t}$ and $\left.w\right)$ for each energy are not known a priori

Ang. resolution vs parameters at 30 keV


Best value $N_{P t}=65 \quad w=2.5$

## Results on angular resolution

- Sigma of the distributions as a function of the energy
- Parameter tuned on 2030405060 keV
- For intermediate energy the average of the neighbour energies parameters is used


- Non gaussian tails due to physics:
- Tracks perpendicular to the gem plane (spot-like)
- Tracks overlapping with themselves
- Immediate backscattering
- Non gaussian tails due to algorithm:
- When the algorithm fails
- Fail in track reconstructions


## Scenarios comparison on directionality capability

- Worst case scenario: Isotropic tracks at random diffusion
- Ideal inclination scenario:Tracks produced along the positive direction of $x$ axis @ 25 cm diffusion

- In the best case scenario the resolution is comparable to the one hypothesised before


## Considerations on directionality application

- At the moment we don't have a PMT simulation for 3D tracking
- Angular resolution studied on sCMOS images (2D detector)
- This will be used in the sensitivity evaluation in two ways:
I. PMT doesn't help at all with 3D reconstruction: use the distribution obtained with 2D and I study the feasibility in 2D

2. PMT resolution comparable with the sCMOS one: feasibility study in 3D with the same angular resolution on $\theta$ and $\phi$

## Experimental studies

- In November 2020 we set up our laboratory overground at LNGS with the MANGO prototype
- I contributed to the setup of the laboratory, to the data acquisition system, and to the studies of different gas mixtures and GEMs
- Moreover I performed a GEANT4 simulation of ${ }^{133} \mathrm{Ba}$ to test directionality, background rejection, and simulation.


z_hits:x_hits:y_hits \{energyDep>4 \&\& energyDep<5\}

z hits:x hits:y hits \{energyDep>29 \&\& energyDep<31\}



## Conclusions \& outlook

- The TPC approach can be very powerfull for solar neutrino study exploiting the feature of the directionality
- CYGNO PHASE2 could be the first experiment to demonstrate the possibility of performing neutrino spectroscopy with event by event energy determination, exploring lower neutrino energies than the one reached by Borexino.
- I have performed preliminary studies on the expected interaction rate of solar neutrino from the pp-cycle in our gas mixture at atmospheric pressure, and on the kinematic of the process with slightly optimistic angular and energy resolution
- I developed an algorithm to measure the directionality of low energy electrons
- The next step will be to develop a fist estimation of the exposure needed to claim detection of solar neutrino from the pp-flux
- I will try to further improve the directionality, improving the superclustering algorithm and testing different directionality algorithms


## Backup

I calculated the expected rate for pp-flux neutrino on 60:40 $\mathrm{He} / \mathrm{CF}_{4}$ gas mixture @ Iatm

$$
\begin{aligned}
\sigma_{\nu_{e}}\left(E_{\nu}\right) & =\frac{G_{F}^{2} m_{e}}{2 \pi}\left\{\left(g_{V}+g_{A}+2\right)^{2}\left[\frac{2 E_{\nu}^{2}}{\left(m_{e}+2 E_{\nu}\right)}-T_{e, T h r}^{\prime}\right]+\right. \\
& -\left(g_{V}-g_{A}\right)^{2} \frac{E_{\nu}}{3}\left[\left(1-\frac{2 E_{\nu}}{m_{e}+2 E_{\nu}}\right)^{3}-\left(1-\frac{T_{e, T h r}^{\prime}}{E_{\nu}}\right)^{3}\right]+ \\
& \left.-\left(g_{V}-g_{A}\right)\left(g_{V}+g_{A}+2\right) \frac{m_{e}}{2}\left[\frac{4 E_{\nu}^{2}}{\left(m_{e}+2 E_{\nu}\right)^{2}}-\frac{T_{e, T h r}^{\prime}}{E_{\nu}^{2}}\right]\right\}
\end{aligned}
$$

$$
E_{\nu, \text { Reco }}=\frac{-m_{e} T_{e}-\sqrt{T_{e}^{2} m_{e}^{2} \cos (\theta)^{2}+2 T_{e} m_{e}^{3} \cos (\theta)^{2}}}{\left(T_{e}-T_{e} \cos (\theta)^{2}-2 m_{e} \cos (\theta)^{2}\right)}
$$

$$
\theta: \text { angle of } e^{-} \text {recoil respect to sun direction }
$$

Cross section I obtained as a function of $E_{\nu}$ with fixed threshold on $e^{-}$energy

- Average oscillation probability considered in the calculation

$$
\begin{aligned}
& P\left(\nu_{e} \rightarrow \nu_{\mu}\right)=P_{e \mu}=\frac{1}{2} \sin ^{2}\left(2 \theta_{12}\right) \\
& P\left(\nu_{e} \rightarrow \nu_{e}\right)=P_{e e}=1-\frac{1}{2} \sin ^{2}\left(2 \theta_{12}\right)
\end{aligned}
$$

- Solar pp flux tabulated from Bahcall:

| $\mathrm{q}[\mathrm{MeV}]$ | $\mathrm{P}(\mathrm{q})$ | $\mathrm{q}[\mathrm{MeV}]$ | $\mathrm{P}(\mathrm{q})$ | $\mathrm{q}[\mathrm{MeV}]$ |
| :--- | :--- | :--- | :--- | :--- |
|  |  |  |  |  |
| 0.00504 | 0.0035 | 0.11089 | 1.2477 | 0.21675 |
| 0.01008 | 0.0138 | 0.11593 | 1.3417 | 0.22179 |
| 0.01512 | 0.0307 | 0.12097 | 1.4370 | 0.22683 |
| 0.02016 | 0.0538 | 0.12601 | 1.5335 | 0.23187 |
| 0.02520 | 0.0830 | 0.13106 | 1.6310 | 0.23691 |
| 0.03024 | 0.1179 | 0.13610 | 1.7291 | 0.24195 |
| 0.03528 | 0.1582 | 0.14114 | 1.8278 | 0.24699 |
| 0.04032 | 0.2038 | 0.14618 | 1.9267 | 0.25203 |
| 0.04537 | 0.2543 | 0.15122 | 2.0258 | 0.25707 |

Expected rate: $\left.R=N_{e} \sum_{i} \varphi\left(E_{i}\right)\left(P_{e e} \sigma_{\nu_{e}}\left(E_{\nu, i}\right)+P_{e \mu} \sigma_{\nu_{\mu}}\left(E_{\nu, i}\right)\right)\right) \Delta E=2.9 \cdot 10^{-8} \frac{\text { events }}{s \cdot m^{3}}=0.9 \frac{\text { events }}{y \cdot m^{3}}$
I. Random neutrino energy from the flux extracted, with random $\cos \theta$ value according to the differential cross section


2. Random $\cos \theta$ value according to the differential cross section for extracted neutrino energy






## The track reconstruction code - clusterization

- The official CYGNO reconstruction code in based on the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm after noise subtraction

A density-based clustering algorithm for the CYGNO data analysis E. Baracchini et AI.

- DBSCAN identifies high density regions in the image based on two parameters:
- $\epsilon$ : radius of research region
- MinPts : minimum amount of points to form a cluster

- Pixels divided into:
- Core points: point that as at least MinPts over threshold within $\varepsilon$
- Border points: point within $\varepsilon$ from a core point but doesn't have MinPts around
- Noise points: neither a core point or a border point


## Preliminary steps in directionality analysis

- Tracks rebinned to be less sensitive to noise fluctuations

- Improvement in signal identification (rebinning)
- Improvement in impact point calculation (noise reduction)

- A very basic filter to remove noise is applied:

Point removed from the track if it doesn't have at least I neighbour

- Filter can still be optimized



## Gaussian tails and IP resolution




- Presence of two gaussian components in IP distribution at higher energies
- IP resolution behaviour to be studied in deep


## Check multiple scattering formula in $\mathrm{CF}_{4}$



[2] Arpesella, C., C. Broggini, and C. Cattadori. "A possible gas for solar neutrino spectroscopy." Astroparticle Physics 4.4 (1996): 333-341.

- The figure on the left shows angular resolution on the first 2 cm of recoil tracks for 3 methods (Degrad simulations Vs. PDG formula Vs. Ref. [2] )
- The PDG formula underestimate angular resolution
- The dashed accounts for energy loss over the 2 cm range, this effect is negligible

$$
\sigma_{\Psi_{\mathrm{plane}}}=\frac{1}{\sqrt{3}} \frac{13.6 \mathrm{MeV}}{\mu \beta c p} \sqrt{\frac{x}{X_{o}}}\left[1+0.038 \ln \frac{x}{X_{o} \beta^{2}}\right]
$$

Lynch and Dahl obtain these parameters by fitting to RMS values for nuclear recoils distributions with Geant. They fit to different values of $x$ and $Z$ (X_o), for singly charged $(z=1)$ heavy particles with beta = 1
[1] Lynch, G., \& Dahl, O. (1990). Approximations to Multiple Coulumb Scattering. Nuclear instruments and methods in physics research B, 58. LBNL Report \#: LBL-28165. Retrieved from https://escholarship.org/uc/item/2h34c3ms

Slides by Majd
Ghrear (University of Hawaii)



We fit the parameters to our Degrad simulations varying $x$ and Energy.

Best Fit:
13.6 --> 27.7 +/- 1.7
0.038 --> $0.0605+/-0.0033$

$$
\sigma_{\Psi_{\text {plane }}}=\frac{1}{\sqrt{3}} \frac{27.7 \mathrm{MeV}}{\beta c p} \sqrt{\frac{x}{X_{o}}}\left[1+0.0605 \mathrm{n} \frac{x}{X_{o} \beta^{2}}\right]
$$



