NEWS: Nuclear Emulsions for WIMP Search

Natalia Di Marco on behalf of the NEWS Collaboration
INFN - Laboratori Nazionali del Gran Sasso, I-67010 Assergi (LAquila), Italy
E-mail: natalia.dimarco@lngs.infn.it

Abstract. In the field of direct Dark Matter search a different and promising approach is the directionality: the observation of the incoming apparent direction of WIMPs would in fact provide a new and unambiguous signature. The NEWS project is a very innovative approach for a high sensitivity experiment aiming at the directional detection of WIMPs: the detector is based on a novel emulsion technology called NIT (Nano Imaging Trackers) acting both as target and tracking device. In this paper we illustrate the features of a NIT-based detector and the newly developed read-out systems allowing to reach a spatial resolution of the order of 10 nm. We present the background studies and the experimental design. Finally we report about the time schedule of the experiment and the expected sensitivity for DM searches.

1. Introduction
There are nowadays compelling evidences about the existence of Dark Matter [1]. Current direct search techniques are based on the detection of the nuclear recoil scattered-off by a WIMP. The analysis is based on the detection of an excess of events over the expected background or on the detection of an annual modulation of the event rate. The detection of the direction in the lab frame of the apparent WIMP flux, first proposed by Spergel [3] in 1988, would provide a different and strong DM signature: the motion of the Sun inside the galaxy causes in fact a peak in the nuclear recoils induced by WIMPs in the direction opposite to the motion of the Sun in the galaxy (i.e. toward the Cygnus costellation). The detection of the anisotropy of the recoiled nucleus direction with respect to the isotropically distributed background, would provide an unambiguous proof of the galactic origin of DM particles with only few tens of events.

Current directional DM projects are mainly based on the use of a large TPC [4]: in low pressure gaseous detectors the nuclear recoils are long enough (O(mm)) to be reconstructed as tri-dimensional tracks, but the target mass is rather small being limited by the low gas density. The sensitivity of such experiments is therefore quite poor. The use of a solid target would allow to explore low cross section sectors in the phase space covered by recent direct search experiments, the challenge being the shorter track length (O(100 nm)) resulting in the WIMP-nucleus scattering. The ground-breaking approach of the NEWS project, using very high resolution nuclear emulsions as solid target, would overcome this problem.

2. Directional Dark Matter Searches: the NEWS approach
NEWS is based on a very innovative approach for a high sensitivity experiment aiming at the directional detection of WIMPs. The detector is conceived as a bulk of nuclear emulsions, acting both as a target and as a tracking device, surrounded by a shield to reduce the external background. The detector is then placed on an equatorial telescope in order to absorb the earth
rotation, thus keeping fixed the detector orientation with respect to the incoming apparent WIMP flux. The angular distribution of the WIMP-scattered nuclei is therefore expected to be strongly anisotropic with a peak centered in the forward direction.

The emulsion target is based on recent developments of the nuclear emulsion technology. The so called Nano Imaging Tracker (NIT) \[5\] consists of silver halide crystals with linear dimension of \(\sim 40\) nm, an order of magnitude smaller than conventional emulsions (like the ones used in the OPERA\[6\] experiment). This feature allows to reach the extremely high spatial resolution needed to detect the submicrometric track left by a WIMP-scattered nucleus. The silver halide crystals are immersed in an organic gelatin: NIT therefore contains both heavy (Ag, Br) and light nuclei such as C, N and O with weight fractions of \(\sim 80\)% for AgBr and \(\sim 20\)% for CNO.

The presence of different target nuclei allows to enhance the sensitivity to both light and heavy WIMP masses. The sensitivity indeed strongly depends on the minimum detectable track length. The path length of the recoiled track depends in turn on the kinetic energy of the scattered nucleus, being the kinematics determined both by the mass of the incident WIMP and by that of the target nucleus. Therefore, the contribution of the light ions (CNO) is essential for WIMP masses around 10 GeV/c\(^2\). The correlation between the track length of the recoiled nucleus and its kinetic energy is shown in Figure 1 for the different target nuclei.

_2.1. Read-out technique_

Soon after the exposure, the target emulsion films will be developed and the whole detector volume will be analyzed by using fully automated scanning systems. The read-out is based on a two-step approach.

In the first phase a fast pre-selection of candidate signal tracks is performed by means of an improved version of the optical microscope used for the scanning of the OPERA films (\[7, 8\]): the new prototype developed allows to reach a spatial and angular resolution of the order of 200 nm and 13° respectively, with a scanning speed of the order of 20 mm\(^2\)/h. In this phase, being the spatial resolution too low to resolve grains belonging to a submicrometric track, the so called _shape analysis_ is applied \[9\]. A cluster made by several grains tends indeed to have an elliptical shape with the major axis coincident with the direction of the trajectory, while a cluster produced by a single grain tends to have a spherical shape. An elliptical fit of the cluster shape allows a clear separation between background grains and signal tracks.

In the second read-out phase a further scanning of the pre-selected candidates is needed in order to resolve the grains belonging to a track thus enhancing the signal to background ratio.
2.2. Expected background

Background sources for dark matter searches are $\alpha$ and $\beta$ particles, $\gamma$-rays and neutron induced recoils, while NIT are essentially not sensitive to minimum ionizing particles (MIP). $\alpha$-particles, originating from U and Th radioactive chains and having energies of $\sim$MeV, can be identified by measuring the track length. Their range in emulsion is indeed of the order of tens of microns, by far longer than WIMP-induced nuclear recoils ($<1\mu$m). The $\gamma$ radiation due to environmental radioactivity constitutes a non-negligible contribution to the total background budget as well as $\beta$-rays produced in $^{14}$C decay. This kind of background is anyway less critical for NIT emulsion with respect to other sources: $\gamma$-rays and $\beta$-particles can be rejected by properly regulating the emulsion response, in terms of number of sensitized crystals per unit path length (i.e. the sensitivity), through a chemical treatment of the emulsion itself. Moreover possible improvements in the rejection power can be achieved exploiting the response of $\beta$-rays to the polarized light scattering or performing a cryogenic exposure and by exploiting the phonon effect.

Neutron induced recoils are the main background source: they are not distinguishable from the expected WIMP signal, except for the isotropic angular distribution and for the typical track length. Indeed, while neutron-induced proton recoils can be as long as few hundred microns, the maximum length of a WIMP-induced nuclear recoil is smaller than $1\mu$m even for large ($O$(TeV)) WIMP masses. While the external neutron flux can be reduced to a reasonable level with an appropriate shielding, the intrinsic emulsion radioactivity would be responsible of an irreducible neutron yield through ($\alpha$, n) and $^{238}$U spontaneous fission reaction. In order to estimate this

![Figure 3. Track length for proton (left) and nuclear (right) recoils produced by radiogenic neutron scattering. Figure from [11].](image-url)
contribution, the activities of U and Th in the emulsion components has been measured with the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and with the γ-spectrometry. The total activity has been estimated to be 23 ± 7 mBq kg⁻¹ for the the ²³⁸U activity and 5.1 ± 1.5 mBq kg⁻¹ for the ²³²Th one [11]. By using a dedicated MC simulation based on the SOURCES code [12], the corresponding neutron yield has been estimated to be of the order of 1.2 ± 0.4 n/yr/kg. The neutron energy spectrum, as calculated with SOURCES, was then used as the input for a GEANT4-based simulation in order to estimate the fraction of interacting neutrons inside the emulsion itself. We found that only 20.4% of neutrons originating from the intrinsic radioactivity interact producing either a proton or a nuclear recoil with track length distributions shown in Figure 3: only a small fraction of interacting neutrons (from 5% to 10%), i.e. tracks with lengths above the read-out threshold and below 1 µm, contributes to the background. A further reduction of ∼ 70% can be achieved exploiting the directionality information with the cut −1 < φ < 1. Under these assumptions, the detectable neutron-induced background would be 0.02 ÷ 0.03 per year per kilogram.

2.3. Experimental set-up
At present two possible experimental set-ups are under study [13]. In Figure 4 a schematic view of the first option for the detector structure is shown: a stack of NIT films is placed at the center of a plexiglass sphere with a diameter of 30 cm. A sphere of 50 cm-thick polyethylene will act as a shield against the external neutron background. The addition of a thin (1 ÷ 2 cm) layer of Cadmium to capture thermalised neutrons is under study. Both the passive shield and the emulsion target are enclosed in a sealed plexiglass box maintained in High Purity (HP) Nitrogen atmosphere in slight overpressure with respect to the external environment to prevent radon contamination. The target and the shielding are installed on the equatorial telescope. Thanks to the high NIT electron rejection power, the use of high-Z shielding materials (Pb and Cu) against the external γ radiation is not foreseen at the moment.

Figure 5 shows a preliminary view for the second detector option: the emulsion target is hermetically enclosed inside a spherical container made of low-Z material (teflon or polyethylene) with a diameter of 55 cm. The inner volume is flushed with N₂. The container is mounted on a long shaft and positioned in the center of a tank (diameter 5 m, height 5 m) filled with ultrapure water. The shaft, made of light, low-radioactive material (i.e. aluminum) is aligned with Earth’s rotation axis and rotate with the period of one sidereal day. The second solution can be more flexible and cheaper, allowing to hold much larger masses without changing neither the mechanics of the telescope nor the shielding. A detailed simulation of the shielding and a study of the mechanics requirements, together with an estimation of the costs, are ongoing.
3. Conclusions
The neutron-induced background due to the intrinsic radioactive contamination allows the design of an emulsion detector with an exposure up to 10 kg year. We plan to perform the first exposure with a target mass of 1 kg and the corresponding analysis of the data on a time scale of six years. The first two years of the project will be devoted to the realization of a pilot exposure of 10 gr in order to confirm the estimations of the overall background budget of the experiment. In parallel, a full detector simulation will be realized in order to design the final experimental set-up. The third and fourth year of the project will be devoted to the construction of the infrastructures, the production of the emulsion target and of the detector shield. The exposure of 1 Kg detector is foreseen by the beginning of 2020 and will last one year. We plan to get first analysis results by the end of 2021. A Letter of Intent was recently submitted by the NEWS Collaboration to the Scientific Committee of the National Gran Sasso Laboratories [13].

In Figure 6 the 90% C.L. upper limit, in case of null observation for an exposure of 1 kg ⋅ year of NIT emulsions, with a minimum detectable track length ranging from 200 nm down to 50 nm and in the hypothesis of zero background, is shown. Even not including the directionality discrimination of the signal and assuming to reach a negligible background level, such an experiment would cover a large part of the parameter space indicated by the DAMA/LIBRA results with a small (1 kg) detector mass, using a powerful and complementary approach.

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Figure 6. The 90% C.L. upper limits for a NIT detector with an exposure of 1 kg × year, a threshold ranging from 200 nm down to 50 nm, in the zero background hypothesis. The directionality information is not included.