NEWSdm: an emulsion-based directional Dark Matter experiment

N. Di Marco for the NEWSdm Collaboration
INFN - Laboratori Nazionali del Gran Sasso, I-67010 Assergi - Italy
E-mail: natalia.dimarco@lngs.infn.it

Abstract. In the field of direct Dark Matter search, a variety of experiments have been developed over the past decades aiming at detecting Weakly Interactive Massive Particles (WIMPs) via their scattering in a detector medium and, in the last years, several experimental efforts are concentrated on the directionality approach: the observation of the incoming apparent direction of WIMPs would in fact provide a new and unambiguous signature and the proof of the galactic origin of Dark Matter. Furthermore the directionality appears as the only way to overcome the neutrino background that is expected to finally prevent standard techniques to further lower cross-section limits. The NEWSdm experiment has been proposed to measure the direction of WIMP-induced nuclear recoils by using a novel emulsion technology with improved spatial resolution. In this paper we will present the status of the experiment, the performances of the newly developed read-out systems reaching sub-micrometric resolution and we will discuss the expected sensitivity and discovery potential.

1. Introduction
The evidence of the existence of Dark Matter (DM) is nowadays well supported by several astrophysical measurement [1]. In the sector of direct DM search, the experimental signature is the detection of the nuclear recoil scattered-off by a WIMP. The analysis is based on the measurement of an excess of events over the expected background or on the detection of an annual modulation of the event rate due to the motion of the Earth-based detector in the DM Halo. A different experimental approach would consist in the detection of the direction of the recoiled nuclei: 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 itself (i.e. toward the Cygnus costellation). First proposed by Spergel [2] in 1988, the detection of the anisotropy of the recoiled nucleus direction, with respect to the isotropically distributed background, would provide a strong signature and an unambiguous proof of the galactic origin of DM particles.

Current directional DM projects are mainly based on the use of a large TPC [3]: 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 NEWSdm project, using very high resolution nuclear emulsions as solid target and novel technologies for their read-out, would overcome this problem.
Figure 1. Left: correlation between the track length of the recoiled nuclei and their kinetic energy, for the different target nuclei contained in NIT emulsions. Right: 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. For a detailed study on the NEWSdm sensitivity the reader is referred to [4].

2. Directional Dark Matter Searches: the NEWSdm approach

In the NEWSdm (Nuclear Emulsion for WIMP Search, directional measurement) project, 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 target is 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 [5]. The angular distribution of the WIMP-scattered nuclei is therefore expected to be strongly anisotropic with a peak centered in the forward direction.

In order to reach the extremely high spatial resolution needed to detect the submicrometric track left by a WIMP-scattered nucleus in a solid medium, the target is planned to be instrumented with the so-called Nano Imaging Tracker (NIT) [6] consisting of silver halide crystals with diameters down to a few tens of nm, an order of magnitude smaller than conventional emulsions (like the ones used in the OPERA [7] experiment). 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 ∼ 80% for AgBr and ∼ 20% for CNO.

The correlation between the track length of the recoiled nucleus and its kinetic energy is shown in Figure 1 for the different target nuclei.

The read-out of the target emulsion films is based on a two-step approach and is performed by using an improved version [8, 9, 10] of the optical microscope used for the scanning of the OPERA films [11] with an intrinsic spatial resolution of the order of 200 nm. In the first step a fast pre-selection of candidate signal tracks is performed on the basis of the so-called shape-analysis [12]: a signal-like 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 background cluster, produced by a single grain, tends to have a spherical shape. An elliptical fit of the cluster shape allows to perform a first separation between background grains and signal tracks.

In the second read-out step, a pin-point check of preselected candidates is needed in order to resolve the grains belonging to a track. A microscope system using polarized light and with the capability of extending the nanometric resolution to all 3 axes, has been designed and tested [13]. The basic idea is to exploit the resonance effect occurring when nanometric metal grains are dispersed in a dielectric medium [14]. The polarization dependence of the resonance frequencies strongly reflects the shape anisotropy and can be used to infer the presence of non-spherical nanometric grains. Images of the same cluster taken with different polarization angles will then
show a displacement of the position of its barycenter. The analysis of the displacements allows to distinguish clusters made of a single grain from those made of two (or more) grains thus resulting in a clear signal to background track discrimination.

In order to measure efficiency and resolution of the new scanning system, a test beam with low velocity ions was performed. Kr ion beam with energies of 200 and 400 keV [15] and a C ion beam with energies of 60, 80 and 100 keV were used. The results are reported in [12] and [5]. As shown in Figure 2 the unprecedented accuracy of about 10 nm has been achieved. Moreover, in order to evaluate the intrinsic angular resolution of the scanning system we exposed a NIT sample to a 2.8 MeV neutron beam at the Fusion Neutronics Source (FNS-JAEA) in Japan. An intrinsic angular resolution of 230 mrad was achieved, by far the best resolution achieved with direction sensitive detectors in this energy range [5].

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, can be identified by measuring their range in emulsion ($O(10) \mu m$), 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 being possible to rejected it by properly regulating the emulsion sensitivity through a chemical treatment, 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. 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 contribution, a detailed study including evaluation of the activities of U and Th in the emulsion components via spectroscopic methods and a SOURCES [16]/GEANT4 MC simulation, was performed. We found that the detectable neutron-induced background would be $0.02 \div 0.03$ per year per kilogram. The reader is referred to [17] for further details.

3. Status and perspectives

At present, a technical test with a 10 g NIT sample was performed in a shielded environment in the underground Hall B of the Laboratori Nazionali del Gran Sasso (LNGS). In parallel, the construction of the underground infrastructure for emulsion production and development is ongoing together with the studies of the final detector design.
We plan to perform a pilot exposure with a target mass of 1 kg and the corresponding analysis of the data on a time scale of five years: in Fig. 1 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 detector mass, using a powerful and complementary approach.

A detailed simulation was performed to take into account the scattering effect of nuclear recoils together with a study of the NEWSdm potentialities in terms of sensitivity and discovery potential assuming a given background budget and including the directionality information. The reader is referred to [4] for details.

4. Conclusions
The aims of the NEWSdm project is to realize the first directional DM experiment with high sensitivity in the spin-independent case. A Letter of Intent [17] was presented in 2015 to INFN and to the Scientific Committee of the National Gran Sasso Laboratories. The project was founded for the first three years of operation.

The idea to exploit fine-grained nuclear emulsions and an innovative read-out system has to be proven successful thanks to a campaign of measurements carried out by implanting low energy ions simulating nuclear recoils with track lengths of the order of few hundred of nm and with neutron test beams. We demonstrated to be able to reconstruct track as long as the one expected for WIMP-scattered nuclei (\(< 1 \mu m\) even for large \((O(\text{TeV}))\) WIMP masses) with the impressive resolution of 10 nm in position and 13° in angle. These results constitute a breakthrough in the sector of tracking detectors.

A technical test with a low-mass (10g) sample has been already realized and a pilot experiment with 1 kg mass is foreseen on a time scale of 5 years. The actual intrinsic radioactive level allows to scale the target mass and exposure time up to one order of magnitude. A careful selection of the emulsion components and a better control of their production could further increase the radiopurity and reduce the thermal background (typically referred as fog), thus allowing larger detector mass. Recent developments in optical microscopy envisage the possibility to lower the threshold down to 50 nm and achieve scanning speeds suitable for the analysis of ton scale emulsion detectors in the near future.

References
[1] Bertone G, Hooper D and Silk J 2005 Phys. Rept. 405 279–390 (Preprint hep-ph/0404175)
[2] Spergel D N 1988 Phys. Rev. D37 1353
[3] Battat J B R et al. 2016 Phys. Rept. 662 1–46 (Preprint 1610.02396)
[4] Agafonova N et al. (NEWSdm) 2017 (Preprint 1705.00613)
[5] Aleksandrov A et al. (NEWS) 2016 (Preprint 1604.04199)
[6] Natsume M et al. 2007 Nucl. Instrum. Meth. A575 439–443
[7] Acquafredda R et al. 2009 JINST 4 P04018
[8] Alexandrov A et al. 2015 JINST 10 P11006
[9] Alexandrov A et al. 2016 JINST 11 P06002
[10] Alexandrov A et al. 2017 Nature Scientific Reports 7
[11] Armenise N et al. 2005 Nucl. Instrum. Meth. A551 261–270
[12] Kimura M and Naka T 2012 Nucl. Instrum. Meth. A680 12–17
[13] Alexandrov A et al. patent N. 102016000132813
[14] Tammaru H, Kuwata H, Miyazaki H T and Miyano K 2002 Applied Physics Letters 80 1826–1828
[15] Naka T et al. 2012 EAS Publ. Ser. 53 51–58 (Preprint 1109.4485)
[16] Wilson W B et al. Submitted to: American Nuclear Society/Radiation Protection and Shielding Division, 12th Biennial Topical Meeting, Santa Fe, NM, April 14-18, 2002
[17] Alexandrov A et al. 2016 Astropart. Phys. 80 16–21 (Preprint 1507.03532)