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Directional detection of dark matter with a nuclear emulsion based detector

A. Alexandrov(*) on behalf of the NEWSdm Collaboration

INFN, Sezione di Napoli - I-80126 Napoli, Italy

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Summary. — Cosmological observations indicate that the major part of our Universe is composed of dark matter (DM). The DM in the form of Weakly Interacting Massive Particles (WIMP) can be detected directly through its scattering inside the detector. Most direct detection experiments measure only the energy of recoiled nuclei. The NEWSdm experiment is the first directional DM search experiment with a solid-state detector: the use of nano-grained nuclear emulsions both as a target material and as a nanometric-resolution tracking device will enable overcoming the so-called neutrino floor and will provide an unambiguous proof of the galactic origin of DM.

1. – Introduction

A variety of experiments have been developed over the past decades, aiming at detecting WIMPs via their scattering in a detector medium [1]. Doubling their sensitivity roughly every 18 months, ultimately, direct detection experiments will start to see signals from coherent scattering of solar, atmospheric and diffuse supernova neutrinos. Hence, direct DM searches below the so-called "neutrino floor" will eventually require background subtraction or directional capability in WIMP direct detection detectors to separate neutrinos from the dark matter signals. Therefore, the directionality becomes particularly valuable when the residual background energy spectrum mimics the one from a possible WIMP signal [2]. Directional detection is a next-generation strategy that offers a unique opportunity to conclusively identify WIMP events and aims to reconstruct both the energy and the track direction of a recoiling nucleus following a WIMP scattering.

(*) E-mail: `andrey.alexandrov@na.infn.it`

2. – The NEWSdm experiment

The NEWSdm experiment (Nuclear Emulsions WIMP Search with directional measurement) [3] proposes an innovative approach for a high-sensitivity experiment for directional WIMP detection. The detector is based on innovative nuclear emulsions with an extremely high spatial resolution allowing to see the direction of the recoiled nuclei. Nuclear emulsions act both as target and as tracking detector with nanometric resolution to reconstruct the direction of the recoiled nucleus. Nuclear emulsions are unique detectors for the measurement of WIMP direction: given the extremely higher sensitivity and density compared to gas detectors, they are the ideal candidates to stand out in the landscape of the direct dark matter searches with the directionality approach. If placed on an equatorial telescope pointed at the Cygnus constellation an emulsion detector becomes capable of distinguishing the WIMP signal from other backgrounds whose directional distributions are expected to be essentially uniform in the laboratory frame.

The energy loss of ionizing particles crossing the films induces along its path atomic-scale perturbations that, after a chemical treatment, produce a sequence of visible grains in the emulsion. The so-called Nano Imaging Trackers (NIT) and Ultra-Nano Imaging Trackers (U-NIT) [4], have grains of 44 and 24 nm diameter, respectively. NIT emulsions with controllable grain size and shape open a possibility to take advantage of the Localized Surface Plasmon Resonance (LSPR) optical phenomenon, generated by an interaction of an incident light wave and silver nano-grains inside emulsion [5, 6]. A non-spherical shape of silver nano-grains leads to a strong polarization effect, which is used to improve the optical resolution of a microscope and overcome the diffraction limit, thus enabling the measurement to be carried out with a nanometric accuracy. The NEWSdm Collaboration has developed and patented [7] the LSPR-based super-resolution method and an optical microscope capable of measuring recoil tracks with lengths down to 100 nm and 50 nm in NIT and U-NIT emulsions, respectively.

The measured neutron-induced background due to the intrinsic radioactive contamination allows the design of an emulsion detector with an exposure of about 10 kg× year [8]. 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 [9].

3. – Conclusions and outlook

Both innovative NIT emulsions and the fast super-resolution microscopy are key ingredients for next-generation directional DM searches. Study of new phenomena and technologies is now ongoing: an R&D on sintetic polymer emulsions is started to eliminate the intrinsic radioactivity; NIT and U-NIT emulsions are being tested under low temperature conditions to reduce thermal excitation; the optical readout is being extended to provide both the 3D and wavelength information; novel techniques of computational microscopy are under testing to boost the readout; a dedicated deep learning analysis method is under development to provide a gain in sensitivity, background discrimination and head-tail sense recognition.

As a result of the continuous improvements in the field of nuclear emulsion technologies and super-resolution readout, relevant progresses in the reduction of the track length threshold are foreseen in the near future, thus allowing the NEWSdm experiment to start building a few kg mass detector as a demonstrator of a technology scalable to multi-ton masses.

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