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NEWS: Nuclear emulsion WIMP search

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Summary. — The most convincing candidate as main constituent of the dark matter in the Universe consists of Weakly Interacting Massive Particles (WIMPs). WIMPs must be electrically neutral and interact with a very low cross-section ($\sigma < 10^{-40}\,\mathrm{cm}^2$) which makes them detectable in direct searches only through the observation of nuclear recoils induced by the WIMP rare scatterings. In the experiments carried out so far, recoiled nuclei are searched for as a signal over a background produced by Compton electrons and neutron scatterings. Signal found by some experiments have not been confirmed by other techniques. We propose an R&D program for a new experimental method able to observe the track of the scattered nucleus based on new developments in the nuclear emulsion technique. Nuclear emulsions would act both as the WIMP target and as the tracking detector able to reconstruct the direction of the recoiled nucleus. This unique characteristic would provide a new and unambiguous signature of the presence of the dark matter in our galaxy.

PACS 95.35.+d – Dark matter (stellar, interstellar, galactic, and cosmological).

1. – Introduction

The nature of dark matter remains one of the biggest questions in physics today. Weakly Interacting Massive Particles (WIMPs) are a particularly well motivated candidate for the missing matter that makes up 85% of the mass of the Universe. Many direct

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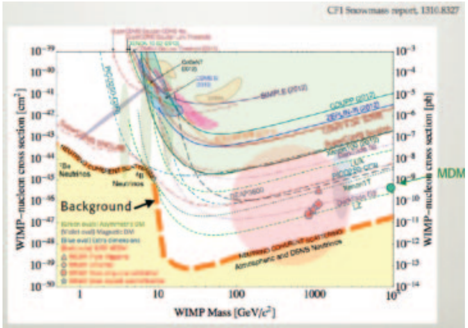

Fig. 1. – Present experimental limits and allowed regions in the WIMP cross-section and mass plane.

search experiments for WIMPs have been concluded, are currently being performed or are being planned. These detectors only measure the energy transferred to the nucleus through WIMP-nucleus scattering, thus the most distinct signal of WIMPs is the annual modulation of the energy spectrum. The results of an annual modulation observation reported by the DAMA/LIBRA [1] and the CoGeNT [2] collaborations are the only positive signatures ever reported. Although other groups have tried to confirm the these results with various types of detectors, no annual modulation signal has been observed yet (see fig. 1).

A distinct signature of WIMPs would result from the relative motion of the solar system with respect to the galactic halo. Assuming an isotropic WIMP motion, the WIMP flux should mostly come from the direction of solar motion, which happens to point toward the constellation Cygnus. The recoil rate would then peak in the opposite direction and this distribution would be a distinct and incontrovertible dark matter signal. Directional experiments would like to exploit this effect by sensing the vector direction of nuclear recoils, and thereby inferring the WIMP direction. So far most of the directional detection have focused on low-pressure gas time projection chambers. The actual limiting factor of directional experiments is the difficulty to achieve a sufficient gas target mass to be sensitive to the expected low rate WIMP interactions.

A novel detection technique to the directional dark matter search is based on the nuclear emulsion technology. Nuclear emulsions would act both as WIMP target and as tracking detector capable of measuring the direction of the nuclear recoil. This unique feature can provide an unprecedented sensitivity in WIMP directional searches.

2. – NEWS: a novel approach to directional dark matter search

Nuclear emulsions consist of AgBr crystals immersed in an organic gelatin made mainly of carbon, oxygen and nitrogen. The passage of charged particles becomes visible through a chemical amplification of the atomic-scale perturbations induced by energy losses of ionizing particles. The emulsions currently used in particle physics have grains with linear dimensions of 200 nm and the linear density of silver halide crystals produced by incident particles is about 2.3 AgBr/μm. This resolution is not enough for directional dark matter search since the nuclear recoil produced by WIMP scattering with the heavy nuclei of the detector are expected to have a few hundred nanometers length. In 2007 OPERA collaborators from the Nagoya University have completed a first phase of an R&D project aimed at the development of films with nanometric grains, producing the

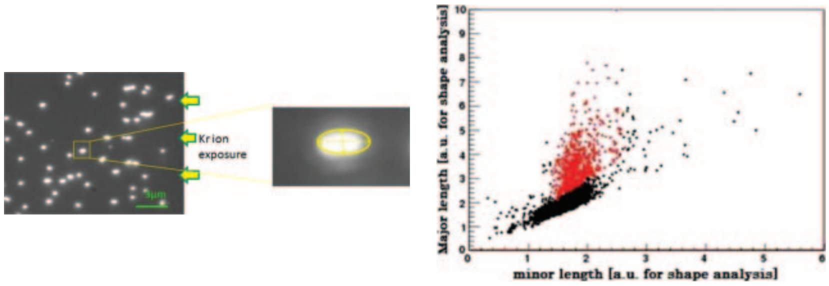

Fig. 2. – Left: Eexpanded Kr ion tracks analyzed with optical microscope. The selection of candidate tracks is based on the elliptic fit of the clusters. Right: scatter plot of major and minor axis lengths for clusters with elliptical shape analysis. Signal tracks are represented as red dos, fog grains as black dots.

so-called Nano Imaging Trackers (NIT) with grain size of about 40 nm and linear density of crystals about 11 crystals/μm [3]. A further R&D on the NIT technology has recently led to the production of the emulsion films with grain size of the order of 18 nm, the so called Ultra Nano Imaging Tracker (U-NIT) [4]. The sensitivity of an experiment using NIT strongly depends on the minimum detectable track length: the path length of the recoiled track depends 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. WIMP with a mass about 100 GeV/c^2 prefers Ag and Br as target, producing a Br recoil with an average kinetic energy of 47 KeV.

To observe tracks in NIT emulsions a two step approach for the readout method is required: optical automated microscopes are used to to preselect the signal and X-ray microscopes are employed to detect single grains that make up the trajectory for a very much reduced sample from the previous selection.

Optical automated microscope systems for high speed nuclear emulsion scanning have been developed in the framework of the OPERA experiment with the European Scanning system (ESS) [5, 6] and the S-UTS in Japan [7]. In order to recognize the direction of the submicron tracks with an optical microscope, NIT emulsions undergo an *expansion* process. It consists in the elongation of submicron tracks via a constrained expansion of the emulsion film after the development treatment, using the swelling characteristics of the film [8]. An expansion by a factor of two of the emulsion surface along the incident direction can make tracks a few hundred nanometers and therefore comparable with the resolution of optical microscopes ($\sim$ 200 nm). The sequence of several grains making such tracks will therefore appear as a single cluster. The key element to distinguish clusters made of several grains from clusters made of a single grain produced by thermal excitation is the analysis of their shape. A cluster made of several grains tends 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.

In order to prove the capability of the optical microscope to observe submicron tracks, a test with low velocity Kr ions (200 keV and 400 keV) was performed [9]. An image of expanded submicron tracks is shown in fig. 2. Although silver grains belonging to Kr tracks are not distinguishable and are seen as a single cluster, the elongated form of the cluster is visible. An elliptic fit of the clusters shape therefore allows a clear separation between fog grains and signal tracks, expected to have ellipticity greater than 1.5 (see fig. 2) [10].

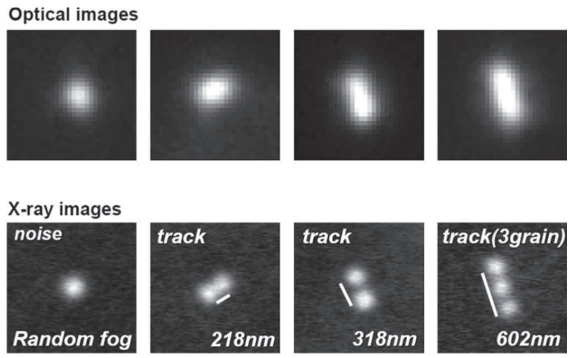

Fig. 3. – Comparison between reconstructed tracks of a few hundred nanometers length with the optical microscope and with the X-ray microscope.

The angular resolution of the readout system is about 36° and the minimum track length 200 nm. For expanded NIT emulsion, this corresponds to a real track length of 100 nm. After the scanning of NIT emulsions with an optical microscope, the selected candidate tracks, *i.e.* clusters with elliptical shape, are checked using X-ray microscope. Having the possibility to resolve tracks with higher resolution (~ 50 nm), it allows a non-destructive observation of the emulsion (this is not possible using an electron microscope).

Measurements have been done at Spring8 (Japan) using BL47XU X-ray line operating at 8 keV to demonstrate the technology. Using a phase difference method, a high contrast is obtained. A photo mask pattern is used to define a common coordinate system between optical and X-ray microscope and select the area where the candidate track is. The optical images of some candidate tracks compared with the X-rays images obtained using X-ray microscope is shown in fig. 3.

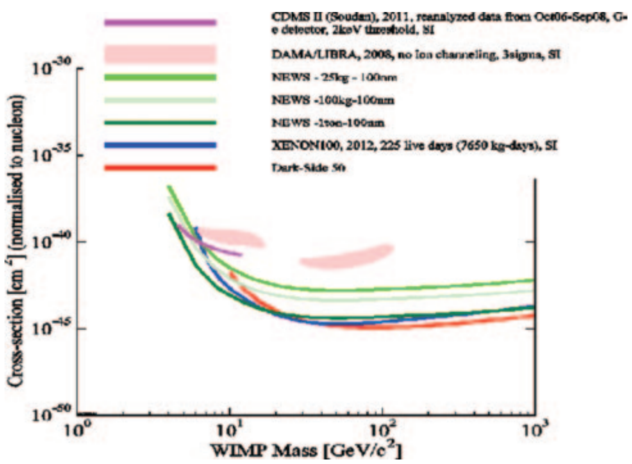

Fig. 4. – Sensitivity projection at 90% CL for a NIT detector with an exposure of 25, 100 and 1000 kg × year respectively, a threshold of 100 nm, in the zero background hypothesis and without including the directionality information.

Elliptical clusters are clearly resolved in grains. The analysis performed on 579 candidate tracks has demonstrated a successful matching rate of 99% between tracks selected with optical microscope and confirmed using X-ray microscope [11]. The angular resolution measured with X-ray microscope is found to be 16°.

The sensitivity for an experiment with an exposure of 25, 100, 1000 kg $\times$ year of NIT emulsions respectively, with a minimum detectable track length equal to 100 nm and in the zero background hypothesis, is shown at 90% C.L. in fig. 4. Even not including the directionality discrimination of the signal and assuming to reach a negligible background level, such an experiment would cover the parameter space indicated by the DAMA/LIBRA results with a rather small (25 kg) detector mass. Increasing the detector mass up to 1 ton it would be able to explore signals possibly coming from current dark matter experiments, but using a powerful and complementary approach.

3. – Conclusions

The evidence for the existence of dark matter comes from cosmological observations. A final confirmation of the existence of Dark Matter should come from direct or indirect detection of dark matter candidates. One of the commonly used approaches is the search for elastic WIMP scatterings on ordinary nuclei. The expected signal is difficult to be separated from background in particular from neutron interactions induced either by cosmic rays or by natural radioactivity. An unambiguous proof of dark matter could come from experiments able to measure the direction of the nuclear recoils induced by WIMP interactions with ordinary matter. The use of the nuclear emulsion technology combines the capability to detect sub-micrometric tracks with the possibility to build large mass detectors, thus achieving a very high sensitivity to WIMPs. The NEWS project would open a new window in the dark matter field: an experiment based on the use of the novel NIT technology could lead to confirm or disprove, with a complementary and alternative approach, signals possibly coming from current non-directional dark matter experiments.

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