

Discovery potential for directional dark matter detection with nuclear emulsions

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Abstract. Direct Dark Matter searches are nowadays one of the most exciting research topics. Several Experimental efforts are concentrated on the development, construction, and operation of detectors looking for the scattering of target nuclei with Weakly Interactive Massive Particles (WIMPs). In this field a new frontier can be opened by directional detectors able to reconstruct the direction of the WIMP-recoiled nucleus thus allowing to extend dark matter searches beyond the neutrino floor. Exploiting directionality would also give a proof of the galactic origin of dark matter making it possible to have a clear and unambiguous signal to background separation. The angular distribution of WIMP-scattered nuclei is indeed expected to be peaked in the direction of the motion of the Solar System in the Galaxy, i.e. toward the Cygnus constellation, while the background distribution is expected to be isotropic. Current directional experiments are based on the use of gas TPC whose sensitivity is limited by the small achievable detector mass. In this paper we show the potentiality in terms of exclusion limit of a directional experiment based on the use of a solid target made by newly developed nuclear emulsions and read-out systems reaching sub-micrometric resolution.

1. Introduction

The most (~26%) of the matter in the Universe is in the form of non-baryonic cold Dark Matter [1]. The evidence for the existence Dark Matter came from the observation that various luminous objects move faster than one would expect if they only felt the gravitational attraction of other visible objects. The existence of such matter requires new particles beyond the standard model of particle physics. Among the several possibility the most discussed one are weakly interacting massive particles (WIMPs). They are neutral stable particles that were in thermal equilibrium in the early universe and have to be non-baryonic, cold, and nearly non-interacting. A large, and growing, experimental effort are devoted to detect and characterize WIMPs.

The most promising experimental method for the detection of WIMPs is the direct detection of the recoil energy deposited by elastic scattering of WIMPs on the target nuclei. Although new generation detectors are capable of measuring the direction of a nuclear recoil track, resulting from the elastic scattering of a target nucleus by an incoming WIMP, they are commonly limited in sensitivity by background. Neutrino interactions are an irreducible source of background since no detector can be shielded from the flux of incident neutrinos. However, even in the presence of irreducible backgrounds, directional detection can still provide an unambiguous observation of dark matter interactions. The motion of our solar system around the galactic center should produce an apparent dark matter wind which is detectable as diurnal modulations of the magnitude and direction of a dark matter interaction signal in a terrestrial detector. In contrast, backgrounds are expected to be relatively isotropic.



Since the track length of the recoil nucleus is too short, direct searches requires a very high spatial resolution. The length of a WIMP-induced nuclear recoil depends on the recoil energy and density of the target material. For example, a nucleus recoiling with energy 100 keV travels 100 nm in a solid. For the direct detection of Dark Matter there are several approaches [2] based on different technologies like Multi-Wire Proportional Chambers (MWPCs), Micro Pattern Gaseous Detectors (MPGDs), optical readouts, and nuclear emulsions. Each technology has its own advantages and disadvantages. For example, experiments based on low pressure gaseous Time Projection Chambers (TPCs) is hardly scalable to very large detectors masses needed to reach a good sensitivity to the Spin-Independent (SI) case. They are only sensitive to the Spin-Dependent (SD) coupling of WIMPs with less than 1 kg mass detectors. However, the use of a solid target for directional searches would overcome the mass limitation of gaseous detector thus allowing to reach an high sensitivity in the low cross section sectors of the SI case. Nevertheless, in a solid medium, the track of the WIMP-scattered nuclear recoil will have the length of a nuclear recoil of the order of a few hundred nanometers, much shorter than in the case of a gaseous target where the recoil length is expected to be of the order of a few millimeters. The nuclear emulsion based techniques proposed by NEWSdm Collaboration [3] fullfils both conditions i) high spatial resolution and ii) massive target. Emulsions consist of silver-halide crystals dispersed in a polymer layer, typically gelatin. Silver-halide crystals are semiconducting with a band gap of 2.6 eV, and work as a sensor to detect charged particles. The size of a silver grain after development is typically around 50 nm. A nuclear recoil can be reconstructed by imaging sets of these silver grains.

In this paper, we report the discovery potential of WIMPs using an emulsion-based detector.

2. Experimental concept

The detector exploits new generation nuclear emulsions with nanometric grains. An R&D conducted by the Nagoya University in collaboration with the Fujifilm Company has established the production of films with nanometric grains. The so-called Nano Imaging Trackers (NIT) and Ultra-Nano Imaging Trackers (U-NIT), have grains of 45 and 18 nm diameter respectively (see figure 1) [4,5]. The detector is conceived as a bulk of NIT 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, i.e. toward the Cygnus constellation. The angular distribution of the WIMP-scattered nuclei is therefore expected to be strongly anisotropic with a peak centered in the forward direction.

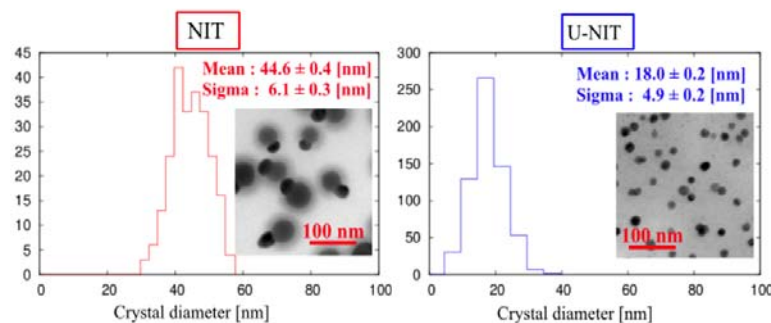


Figure 1: Distribution of the crystal diameter measured with an electron microscope for NIT (left) and U-NIT (right) emulsions [3].

The presence of both light and heavy nuclei in the emulsion gel results in a good sensitivity to WIMPs with both light and heavy masses. Figure 2 shows the correlation between the track length of the recoiled nucleus and its kinetic energy for the different target nuclei. Although Ag and Br are the most effective targets for WIMP masses in this range, the detection capability is reduced since their ranges are shorter than lighter elements at the same energy. Instead, for a WIMP with a mass around 10 GeV/c², the

kinematics favours lighter nuclei that, for a given kinetic energy, have a longer range. Therefore, the contribution of the C, N and O ions is essential for WIMP masses around $10 \text{ GeV}/c^2$.

The estimated WIMP rates are of the order of 1 event/kg/year, much lower than the usual radioactive backgrounds. For this reason, the detector has to be placed underground to be protected from cosmic-ray induced background. Moreover, a careful control of the radioactive contamination of the materials used for the detector construction and a precise estimation of the corresponding induced background are needed.

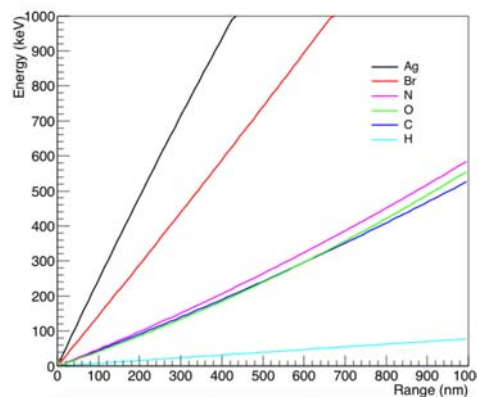


Figure 2: Correlation between the track length of the recoiled nuclei and their kinetic energy, for different target nuclei in NIT emulsions [3].

2.1. Read-out technique

Fast automatic optical microscopes are used to read out nuclear emulsions. After the exposure, the search for signal candidates requires the scanning of the whole emulsion volume. The analysis of NIT emulsions is performed with a two-step approach: a fast scanning, based on techniques developed for the OPERA experiment [6] for the signal preselection: an ellipse is fitted to the optically reconstructed track, and candidate events are selected by applying a cut on the ratio of the lengths of the major and minor axes. After elliptical shape recognition with optical microscopy candidate events are confirmed by super-high resolution microscopy techniques.

In order to simulate the effect of a WIMP-induced nuclear recoil and to measure the efficiency and the resolution of the optical microscope, a Kr ion beam at different energies was exposed NIT films. When analysed with the optical microscope, submicrometric tracks produced by Kr ions appear as shown in figure 3.

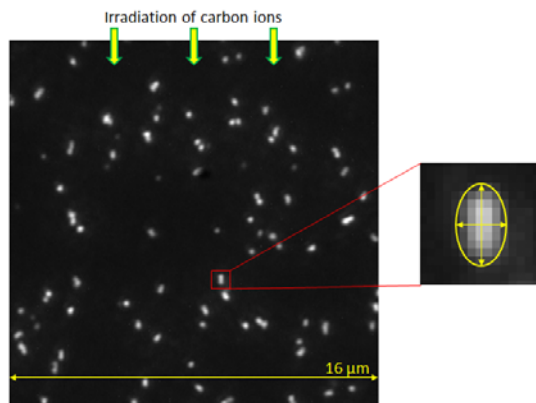


Figure 3: Kr ions implanted on NIT films. The image is taken with an optical microscope. The selection of candidate tracks is based on the elliptic fit of the clusters [3].

3. Discovery Potential

The final sensitivity of low-energy rare event searches is strongly limited by the background induced by radioactivity. Two main categories have to be taken into account: the environmental or external background and the intrinsic one. The main background sources α , β , γ -rays and neutron induced recoils, while NIT are essentially not sensitive to minimum ionizing particles (MIP). α originating from U and Th isotopes having energies of the order of MeV, can be identified by measuring the track length. Moreover, γ -rays and β 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, therefore they are considered as reducible background. However, the contribution from neutrons is usually considered as irreducible, since they induce nuclear recoils as WIMPs do. The directional detection has the unique capability of distinguishing the WIMP signal from the background by exploiting the feature of the signal, expected to be peaked in the direction of motion of the Sun. On the contrary, there is no reason for the neutron-induced nuclear recoil spectrum to present the same feature. In particular, the neutron background is expected to be isotropically distributed. Neutrons in underground laboratories originate either from cosmic muon interactions, or from environmental radioactivity, or from spontaneous fissions and (α, n) reactions. The first two sources can be reduced by an appropriate shielding; the latter one, coming from the intrinsic radioactivity of the target materials, is associated with an isotropic distribution in the laboratory frame.

The 90% C.L. upper limit in case of null observation is shown in figure 4 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 [3]. 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.

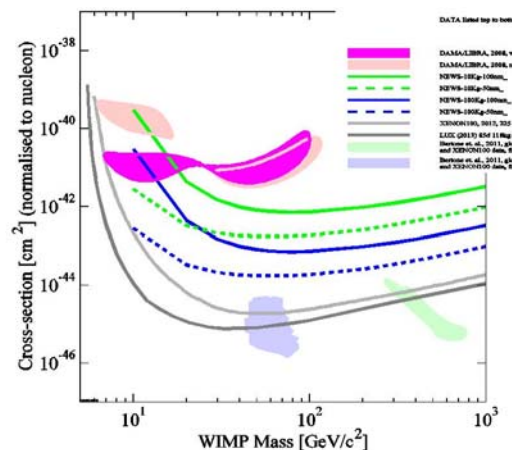


Figure 4: Sensitivity at 90% C.L., in the zero background hypothesis for an experiment with a mass of 10 kg (green) and 100 kg (blue) for two value of detection threshold: 100 nm (dashed lines) and 50 nm (solid line) [3].

References

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