Detector developing for directional dark matter search with nuclear emulsion

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Abstract. We are planning the directional dark matter search experiment with nuclear emulsion. Recoiled atoms inside of the emulsion fly several hundred nm, and it is too short to detect with usual emulsion. Fine crystal emulsion was needed to detect such tracks. We developed new method to produce them and succeeded to make crystals small as 20 nm at the minimum size. We also study several methods to improve sensitivity and reduce background noise to survey very interesting cross section region.

1. introduction

Recent results from several experiments indicate detection of WIMP signals. In addition to DAMA/LIBRA [1], Recent result of CoGeNT [3] also suggests annual modulation. Including CRESST excess events [2], their signals were observed at the near mass region from several GeV/c² to 100 GeV/c² and the near cross sections between $10^{-43}$ cm² and $10^{-39}$ cm². However, some other experiments suggest more lower cross section limit lines. For example, that of XENON 100 is two orders lower than the region [4]. In order to conclude this problem, a confirmation from other angle is very important. Directional dark matter search will provide good proof of this problem. We are trying it with nuclear emulsion.

The emulsion is a historical solid detector, and usually used as a film which is poured on a plastic support base, as is seen in section on the Figure 1. The emulsion is constructed from two parts, silver halide crystals and dispersion polymer. Each crystal can react to charged particles. When a charged particle passes through the emulsion, it exited electrons. Then exited electrons are captured by a certain spot of the crystal, and small silver grain is generated. A chemical process called developing can supply additional silver to this small grain, and it grow up to visible size. Each grains are lined where the charged particle passed, so finally we can get a track of visible silver grains (Figure 2.).

The flight length of recoiled nucleus from WIMP is estimated to be only several hundred nm. However, it had been proved that fine crystal emulsion can detect such extreme short tracks [5]. Fundamental readout method has also been established with direct expansion technique, and combination of optical microscope and X-ray microscope [6]. In addition to these studies,
improvement of resolution, sensitivity and background rejection are necessary to achieve dark matter detection. We have studied how to create our detector itself for these subject.

2. directional dark matter search with nuclear emulsion

The emulsion has several good features for direct dark matter search.

The spatial resolution of the emulsion is quite high. The reason is that dispersion of electrons from ionization is limited inside of each crystals, and initial position can be kept perfectly. Usual emulsion can detect track by micron order resolution, and our special emulsion for dark matter search can catch 100 nm order track.

On the other hand the emulsion does not have time resolution. The direction of WIMP wind is continuously changing by revolution and rotation of the earth, so astronomical information for each event is necessary. Instead of their time record, we can fix the emulsion to equatorial telescope, and follow the direction of WIMP wind.

The emulsion is also suit for the large mass experiment. The emulsion is used as a film, and their readout is same in anywhere. The detector mass affects time for readout linearly, however the readout efficiency is not depend on the mass. Additionally the detector volume will be compressed to relative small size because of solid state.
3. physics purpose
Our primary purpose is to survey of the interesting region with directional information. Figure 3 shows cross section plot of our experimental sensitivity. It was assumed zero background and 100% detection efficiency. In principle, our purpose is possible with the resolution which is higher than 100 nm.

Heavy atoms of target may give high crystal sensitivity and effective rejection of backgrounds for their high energy deposit. But most of them cannot fly more than 100 nm and a few events will be detected. To search this region, the detection of light mass atoms like Carbon, Nitrogen, and Oxygen is necessary. Our subject is how to get good sensitivity and background rejection power with these signals while keeping enough resolution. We will reach DAMA region with several ten kg target mass, if we get ideal detector condition.

4. research and development
4.1. production of the emulsion
We started to produce the emulsion by ourselves for rapid research and development. Our emulsion production machine can produce 100 g emulsion per one term in 4 hour. Additionally we are planning new machine which allows three times more rapid production, and we will be able to do at least 100 kg scale of the emulsion experiment.

Important subject for our experiment is how to detect very short tracks like several hundred nm. So first of all, we studied stabilize the size of micromized crystal. Archetype emulsion [5] had 40 nm crystals, and we could also produce it with our new machine. But reproducibility of the size of crystals was not good (Figure 4. left).

We tried to make it stable, and find new production method. Polyvinyl alcohol (PVA) can strongly covers surface of crystals and suppress their growing. Usually crystals are generated in gelatin solution, but we added PVA to this solution. This mixing solution makes crystal size very stable even with some additional chemical sensitivity control (Figure 4. right).

4.2. high sensitivity emulsion
We are trying to improve crystal efficiency for carbon track detection. Crystal size is strongly effect to sensitivity, so we have kept the size to relatively large size around 40 nm. When the size is 45 nm, average distance of crystals becomes about 85 nm. Considering our current optical analysis threshold, this size was enough for requirement of test run.
Figure 4. Comparison of crystal size distribution between two emulsion production method. Left is crystal size distribution with only gelatin production method. Right is the one with gelatin and PVA mixed production method. Red solid line and black dot line are using completely same recipe. Green broken line is added a typical chemical for noise reduction.

Preliminary result have showed that the crystal efficiency for carbon was about 50% without chemical sensitizing. Further sensitizing study will give very high efficiency for track detection. We started several methods of photographic sensitizing, like reducing recombine of electrons and holes, or disturbing dispersion of silver speck inside of crystal.

4.3. background rejection

Large mass experiments are suffering from many unexpected background signals like $\beta$ ray from carbon and proton from neutron recoil. We are trying to reject them with crystal sensitivity control. We expect that $\beta$ rays cannot leave tracks in ideal emulsion. Although protons will be kept sensitivity, we may distinguish it from other target atoms by length and their energy deposit.

The most critical background will be tracks made by chance coincidence. The emulsion generates unexpected silver grains at random with developing (Figure 5). If we define signals as two or more grains within 100 nm sphere, some of them are expected to make fake tracks. Our current emulsion has $0.1 - 1/1000$ um$^3$ noise grains, so $10^4 - 10^6$ fake tracks will be generated per kg in this case. They will limit experiment of sensitivity.

We are trying to reduce them by two ways. First plan is reduction of unexpected grains. Their amount is proportional to fake tracks by the square. All of Crystal quality, developing, readout efficiency are affect to them. They also affect to sensitivity, so careful study is required. The other way is changing signal definition as more than two grains. Of course signal range threshold will become worse with same crystal quality, however chance coincidence of fake tracks will be greatly reduced. It means the ratio between noise grains and fake tracks are changed from square to cubic. At the case of the definition that three grains are within 200 nm sphere, same noise grains make only $10^{-1} - 10^2$ fake tracks per kg. If $0.1/1000$ um$^3$ noise grain are assumed, we can run our experiment without this background up to about 10 kg (Figure 6).

4.4. micronized emulsion

If we use 3 grains background rejection, detectable track range becomes longer. Considering energy threshold, we have to reduce distance between crystals. Most effective way is making crystal size smaller. For example, 20 nm crystals have 76 nm of mean distance between 3 crystals, and it is less than the distance between 2 crystals of 45 nm crystals. In fact, we already
succeeded to make 24 nm stable crystals, and the best one is 18 nm (Figure 7.). These crystal allows further low energy threshold and noise reduction.

Instead of ideal range threshold, smaller crystal has low efficiency. We are planning to make up the loss by strong chemical sensitizing. Because the stability of the crystal size has become quite good, we may be able to sensitize crystals with very strong chemical treatment.

5. conclusion
We developed new fine grained nuclear emulsion to achieve directional dark matter search with large mass experiment. We succeed to produce very stable fine crystals with PVA, and theoretical resolution became enough range. Now we are trying to improve sensitivity and background reduction power. These will lead our experiment to 10 kg target mass order, and very interesting cross section region will be covered.

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