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Latest nuclear emulsion technology

Production, readout and interaction analysis

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Abstract. Nuclear emulsion is a extremely high-resolution 3D tracking detector. Since the discovery of the pion by C.F. Powell et al. in 1946, experiments with nuclear emulsions have contributed to the development of particle physics. (e.g. the OPERA collaboration reported the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode in 2015) The technology of nuclear emulsion still keeps making progress. Since 2010, we have introduced a system of nuclear emulsion gel production to our laboratory in Nagoya University, and have started self-development of the new gel, instead of from the photographic film companies. Moreover, a faster automated emulsion scanning system is developed. Its scanning speed reaches 4000 cm^2/h, and the load for analyzing becomes more and more lighter. In this presentation, we report the status of nuclear emulsion technologies for cosmic ray experiments.

1. Introduction

Nuclear emulsion is an ultra high-precision position-sensitive detector. It consists of mostly gelatin and crystals of silver bromide (AgBr). The crystals penetrated by a charged particle grow up to silver grains (the diameter is about 0.8 μm) via a chemical development process, then we can observe the trajectory of the particle as a line of black points using optical microscopes. The intrinsic position accuracy is expected to be $200/\sqrt{12} = 56$ nm. In addition, although typical electronic trackers consist of readout channels in two or more independent projections for 3D reconstruction, nuclear emulsion directly gives 3D position information of the trajectory.

S. Kinoshita discovered that the radiation of alpha decay is a "track" of a charged particle by the observation of nuclear emulsion in 1915 [1]. C. F. Powell and his colleagues discovered the decay chain of $\pi \rightarrow \mu + \nu$ in nuclear emulsions exposed to cosmic rays [2].

Double-side poured nuclear emulsion plate realizes a precise measurement of incident angle. In the 1950's, a Japanese group developed a chamber, called Emulsion Cloud Chamber (ECC), that had a sandwich structure of nuclear emulsion and other material plates (carbon, lead, etc.). ECCs mounted on balloons or airplanes enabled to measure angles of jet particles from high-energy cosmic-ray interactions. A fire ball model of multiple meson production in nucleon-nucleon collisions [3] and the discovery of charmed meson in cosmic-ray interactions [4] were produced by the observation of ECCs in the era when no accelerator was in Japan.

Though the observation and the measurement of tracks in nuclear emulsion had been done by human eyes and microscopes, the realization of fully automated scanning systems enabled high resolution and large-scale experiments which use the advantages of nuclear emulsion. For example, the OPERA experiment discovered $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode on the basis of these technologies [5].

Here, we report the recent improvements of the nuclear emulsion technology since 2010.

2. Emulsion gel production

In 2010 we introduced a system of emulsion gel production to the laboratory in Nagoya University, and started to supply the new gel instead of relying on photographic film companies. Figure 1 shows a nuclear emulsion gel produced in Nagoya on the left, and an image of AgBr crystals captured by SEM after removing gelatin on the right.

Our self-production system enables us to develop ambitious nuclear emulsion gels. We succeeded in the development of a high-sensitive nuclear emulsion by increasing the occupancy of AgBr crystals from typically 30–35% to 55%. Figure 2 shows a comparison of microscopic images between two type of nuclear emulsion. The grain density (the average number per unit length) of the silver particles of this new type of gel is two times higher than that of a typical gel.

The size control of AgBr crystals is also studied. 200 nm-diameter crystal has been used for detection of minimum ionization particles for a long time. Recently, we produced various-sized crystals according to the purposes of experiments. The minimum-sized crystals (the diameter is 30–40 nm) are being developed for dark matter directional searches [6], and the maximum-sized crystals (~800 nm) for the long term observation requesting the stability of the latent image [7].

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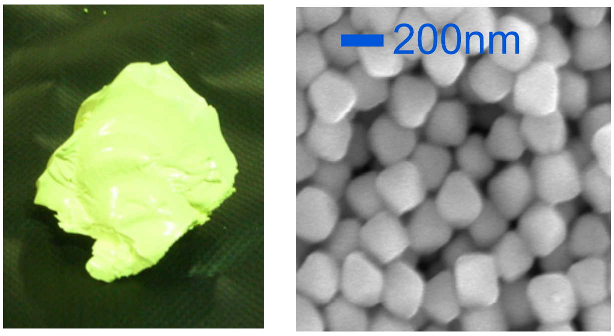

Figure 1. Nuclear emulsion gel produced in Nagoya on the right, and SEM image of AgBr crystals after removing gelatin on the left.

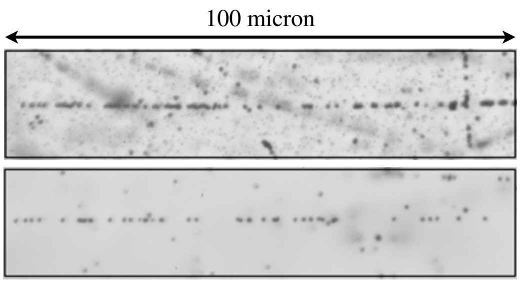

Figure 2. Microscopic view of highly sensitive film (upper) and typical film (lower).

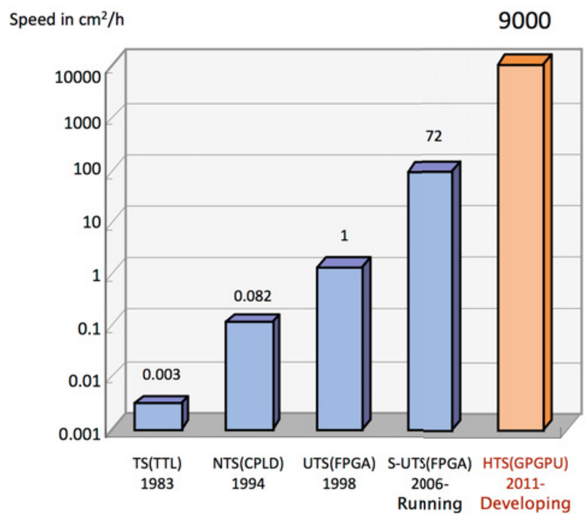

Figure 3. Evaluation of scanning speed by generations of Track Selector.

The environment of the mass production of films is constructed in the laboratory. We have already produced the nuclear emulsion film at a speed of 100 m^2/year and supplied several experiments. In a few years, the production speed will increase to about 1000 m^2/year for accelerator neutrino experiments, balloon-borne experiments, muon radiography projects, etc.

3. Emulsion readout system

The concept of fully automated emulsion readout system, Track Selector (TS), was invented by K. Niwa [8], and was

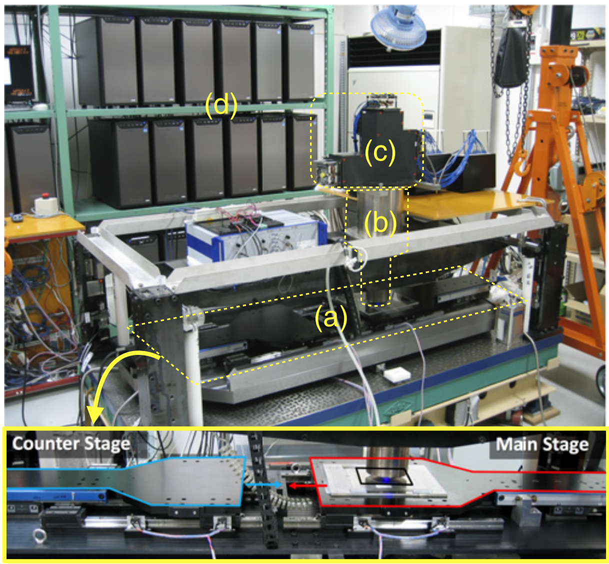

Figure 4. Picture of HTS. It consists of (a) precision stages which move to the next view precisely and quickly after capturing, (b) a huge objective lens that realizes a 5 mm × 5 mm-size FOV, (c) 72 mosaic CMOS sensors that cover the large FOV (each 2M pixels, 340 fps.), and (d) 36 PSs for realtime process of track-recognizing with 27 GB/s image data.

put to practical use in the 1990's. The latest TS is called Hyper Track Selector (HTS). HTS has been developed in Nagoya University since 2011. Figure 3 shows scanning speed by generations of TS, and HTS is designed for 0.9 m^2/hour.

HTS consists of precision stages, a huge objective lens, 72 mosaic CMOS sensors, and 36 PSs. These are shown in Fig. 4. The most characteristic point of HTS is a very wide field of view (FOV), 5 mm × 5 mm. The FOV of HTS is 600 times larger than that of the previous system, S-UTS. To cover its FOV with 0.4 μm-pitch pixel, the image is divided into six imaging planes through prisms, and 12 CMOS sensors (each 2M pixels, 340 fps) capture it at each plane. The image data from 72 sensors are sent to 36 PCs, then the track recognition and the calculation (angles, positions, etc.) are processed immediately. A motor-driven XY axes stage moves to the next view precisely and quickly. At that time, the counter stage moves in the opposite direction from the main stage to cancel acceleration.

Figure 5 shows the pulse height distribution obtained by the high-sensitive film and HTS. TS recognizes a track from 16 images (32 images in a double-side poured film) captured over changing a focal plane, and the number of hit layers in a signal track is called the pulse height. By improvement of the grain density, clear signals were observed. Figure 6 shows the track-finding efficiency obtained by the high-sensitive film and HTS. At each incident angle from $\tan\theta = 0.0$ (a vertical angle) to $\tan\theta = 2.0$, more than 95% was evaluated [9].

The operation of HTS was started in 2015 at half of the designed speed. Nuclear emulsion films employed in the GRAINE-2015 balloon experiment were scanned as the first practical data taking of HTS, and it took three months to finish 41 m^2 in total [10].

Table 1. Candidates of previous emulsion experiments for the archive project.

Experiments	Original purpose	Total Area for Scanning
RUNJOB (balloon experiment)	primary cosmic-ray observation	$120\,m^2$
JACEE (balloon experiment)	primary cosmic-ray observation	$900\,m^2$
CHORUS (accelerator ν experiment)	search for $\nu_\mu \to \nu_\tau$ oscillations	$400\,m^2$
DONUT (accelerator ν experiment)	detection of ν_τ	$100\,m^2$

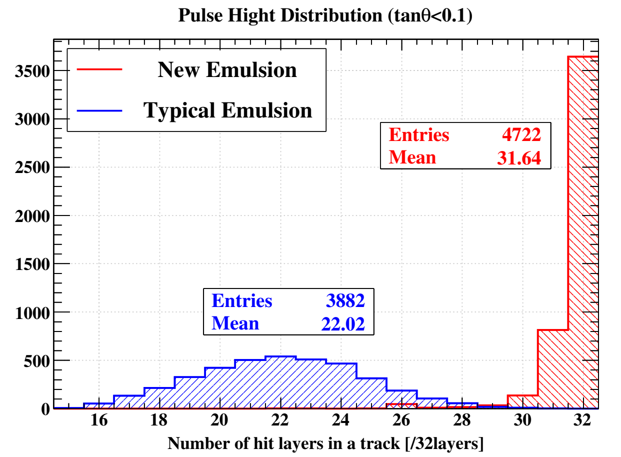

Figure 5. Pulse height distributions. Red histogram was given by high-sensitive emulsion film and HTS. Blue histogram was given by typical emulsion film (OPERA type).

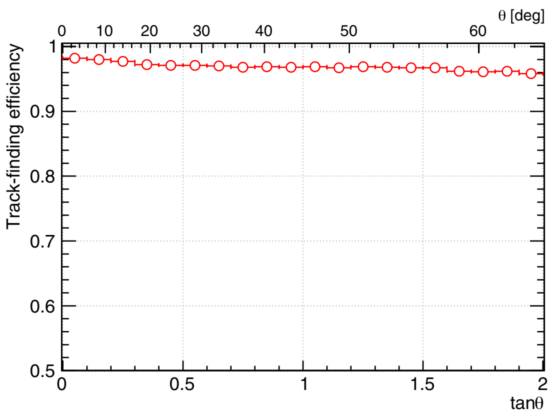

Figure 6. Track-finding efficiency as a function of incident angle obtained by the high-sensitive film and HTS.

4. Applications for cosmic-ray experiments

4.1. Balloon-borne gamma-ray telescope

GRAINE is a project aimed at a precise observation of gamma-ray sources (the energy region is sub-GeV/GeV) with a balloon-borne nuclear emulsion chamber. The gamma-ray telescope with the original timestamp technique [11,12] has the following advantages: high angular resolution (0.1deg at 1 GeV); polarization sensitive; large aperture area($> 10\,m^2$). Recently, a small-scale observation was made to demonstrate the performance of the detector [13].

4.2. Emulsion archives project

We also plan to archive "digital" data of emulsion plates of past experiments and to make it public. In previous (accelerator and cosmic-ray) emulsion experiments, the analysis was performed by focusing on special interesting events. A re-scan data set of the whole of the detector volume provides for minimum-bias and no-dead-time analysis without an event trigger of another detector (electronic counters or X-ray films). We will start a test scan of old emulsion plates (see Table 1) and discuss about a standard data format etc, toward opening archive data to the public.

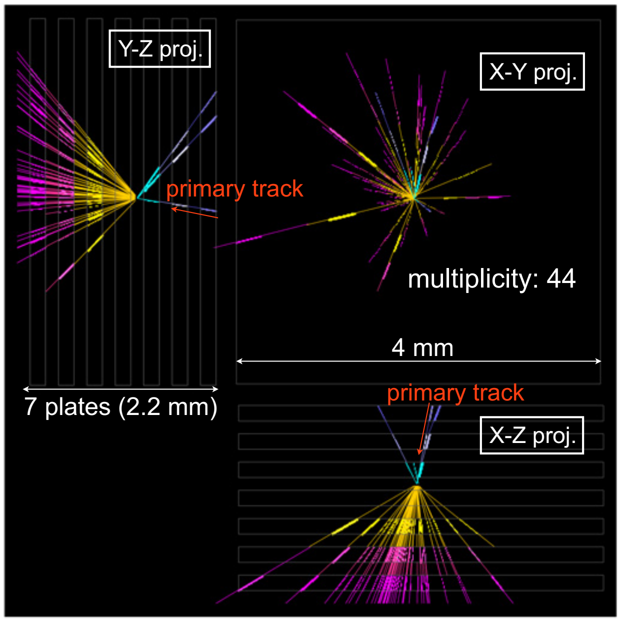

Figure 7. Cosmic-ray interaction event recorded in a balloon-borne chamber. It was detected by an offline analysis method under development.

4.3. Study for cosmic ray interactions

We are developing an offline analysis method to detect hadronic interactions recorded in the emulsion chamber. Figure 7 shows a sample event recorded in a balloon-borne chamber. If a systematic analysis flow is established, it is possible to search for short-lived particles from a large number of cosmic-ray interactions, and to measure the production rate of charmed particles at balloon altitudes. In accelerator experiments, the measurement of differential cross section of D_s mesons produced in proton interactions is starting at the CERN SPS. Nuclear emulsions can record all tracks emitted from the vertex with 4-π angular acceptance, and cover the wide range of rapidity in the laboratory frame. A precise comparison of the topological values between hadron interaction models will also be tried.

5. Conclusion

We report the status of nuclear emulsion technologies for cosmic ray experiments. The highest quality emulsion films became available by introducing self-gel production system to the laboratory level. The emulsion readout systems are getting increasingly faster and the next generation system is being planned. These innovations of nuclear emulsion technology will lead cosmic ray physics to the next stage.

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References

[1] S. Kinoshita and H. Ikeuti, Philosophical Magazine and Jounal of Science Ser. 6, **29**, 171, pp. 420-425 (1915)
[2] C.M.G. Lattes, G.P.S. Occhialini and C.F. Powell, Nature **160**, 453 (1947)
[3] K. Niu et al., Nuovo cimento **10**, p. 994, (1958)
[4] K. Niu et al., Progress of theoretical physics **46**(5), 1644–1646 (1971)
[5] N. Agafonova et al. Physical review letters **115**(12), 121802 (2015)
[6] T. Naka et al., Nuclear Instruments and Methods A **718**, 519–521 (2013)
[7] T. Ariga et al., Journal of Instrumentation **11**(03), P03003 (2016)
[8] K. Niwa et al., Proc. Int. Cosmic Ray Symp. High Energy Phenomena, Tokyo, p. 149 (1974)
[9] K. Ozaki et al., Journal of Instrumentation **10**(12), P12018 (2015)
[10] H. Rokujo et al., Proc. of ISVHECRI 2016, Moscow (2016)
[11] S. Takahashi et al., Nuclear Instruments and Methods A **620**, 192 (2010)
[12] H. Rokujo et al., Nuclear Instruments and Methods A **701**, 127 (2013)
[13] S. Takahashi et al., Prog. Theor. Exp. Phys. **2015**, 043H01 (2015)