Review

Discovery of naked charm particles and lifetime differences among charm species using nuclear emulsion techniques innovated in Japan

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Abstract: This is a historical review of the discovery of naked charm particles and lifetime differences among charm species. These discoveries in the field of cosmic-ray physics were made by the innovation of nuclear emulsion techniques in Japan. A pair of naked charm particles was discovered in 1971 in a cosmic-ray interaction, three years prior to the discovery of the hidden charm particle, J/Ψ, in western countries. Lifetime differences between charged and neutral charm particles were pointed out in 1975, which were later re-confirmed by the collaborative Experiment E531 at Fermilab. Japanese physicists led by K.Niu made essential contributions to it with improved emulsion techniques, complemented by electronic detectors. This review also discusses the discovery of artificially produced naked charm particles by us in an accelerator experiment at Fermilab in 1975 and of multiple-pair productions of charm particles in a single interaction in 1987 by the collaborative Experiment WA75 at CERN.

Keywords: naked charm particle, hidden charm particle, emulsion chamber, pellicle stack, 2-fold emulsion tracker, hybrid emulsion electronic detector

1. Introduction

Nuclear emulsions have aided in the study of nuclear physics and elementary particle physics because of their high spatial resolving power of better than 1 μm. Fig. 1 shows a photograph of the tracks of charged particles in an electron-sensitive nuclear emulsion. The grains in the tracks have a diameter of about 1 micron. With the aid of a microscope, we can observe the full behavior of any charged particle. The practical thickness of a single emulsion layer had been restricted to less than 0.6 mm for technical reasons: the working distance of the objective lens of a microscope as well as the difficulty in uniformly developing thick emulsion films.

In 1910, S. Kinoshita observed individual tracks of α particles in an emulsion for the first time.[1] The techniques using pure nuclear emulsions were improved to their highest level during 1930–1940s under the direction of C.F. Powell. The most fundamental contribution of emulsion techniques to particle physics was the discovery of $\pi \rightarrow \mu$ decay by C.M.G. Lattes *et al.* in 1947.[2] This $\pi \rightarrow \mu$ decay is shown in Fig. 2. This was achieved by a highly sensitive nuclear emulsion, named Ilford C2. In fact, in 1935 H. Yukawa predicted that the π was the quantum of a nuclear field,[3] and in 1943 S. Sakata predicted that the μ was its daughter.[4] Powell was awarded the Nobel Prize for Physics in 1950 for his discovery using nuclear emulsion techniques. A.E. Lindh, a member of the Nobel Committee for Physics, paid tribute to Powell in his 1950 Presentation Speech: "Discoveries of fundamental importance can still be made with simplest apparatus—nuclear emulsion and microscopes. He brought the photographic method to undreamt of perfection and has made it one of the most efficient aids of modern nuclear physics."[5] The study of new particles with nuclear emulsions continued in the cosmic-ray field for the following several years.

However, L. Leprince-Ringet stated in his welcome address to the 17th International Cosmic Ray conference in 1981: "After the war, we also began the discovery of new particles, the mesons and the first hyperons, with balloon-borne emulsions and Wilson Chambers at mountain altitudes.

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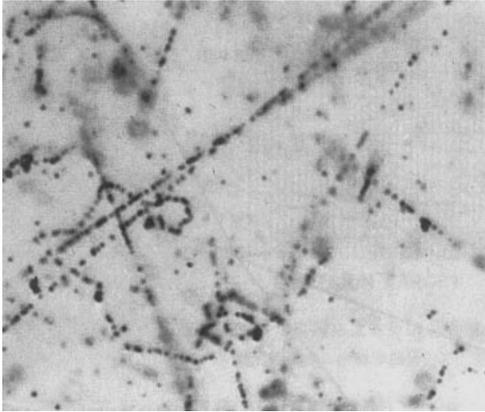
Fig. 1. Micro-photograph of tracks of charged particles in an electron-sensitive nuclear emulsion. Curved dotted line: electron. Straight dotted line: energetic single charged particle. Diameter of each dot: about $1\,\mu$m.

But, the Bangneres conference in 1953 was the swan song of this period. And soon, particle accelerators relayed the cosmic rays."[6] After particle accelerators began to more commonly relay cosmic rays, nuclear emulsion techniques were generally discarded in western countries. Nuclear emulsion techniques were discarded because of the inefficiency in processing the enormous amount of data coming out of accelerator experiments. There is an adage that says 'what is its strength is also its weakness.' This could be applied to the case of nuclear emulsions.

At the same conference I countered Leprince-Ringet's statement in my Rapporteur presentation: "That was true; however, only for the study of 'old' new particles. At the beginning of the 1970's a breakthrough in elementary particle physics again took place in the cosmic-ray field."[7] Fig. 3 shows an essential part of the 1971 breakthrough. This

discovery was made in a nuclear interaction produced by super high-energy cosmic rays. This event contained a pair of kinks and a co-planarity relation, suggesting a two-body decay of a charged particle. This event was observed by using a new emulsion technique, that I developed. Before going into the details of this prominent event, I give a brief history of the development of emulsion techniques in Japan and the compact emulsion chamber. These innovations helped us to discover naked charm particles.

2. Innovations of nuclear emulsion techniques in Japan

In Japan, the use of nuclear emulsion techniques began after 1950 for the study of higher energy interactions by cosmic rays. Japanese physicists wished to improve the techniques to reach a level of scientific ability to that of the already advanced countries. To improve and to overcome the shortage of research funds available at that time, Japanese physicists had to find a better way to study these higher energy interactions. As the flux of cosmic rays in the higher energy region became lower, a larger effective area/volume detector was the most important equipment to study interactions of such particles. Two ways were possible to improve the detecting capability. One way was to simply use a very large pure emulsion (pellicle) stack being used in western countries. It was a stack of pure emulsion films stripped of their glass supports in order to observe tracks of high-energy particles as long as possible—following them pellicle by pellicle. When using the large pellicle stack, extra processing of the emulsion was needed. It was also necessary to strip the emulsion from its backing glass support and then later to
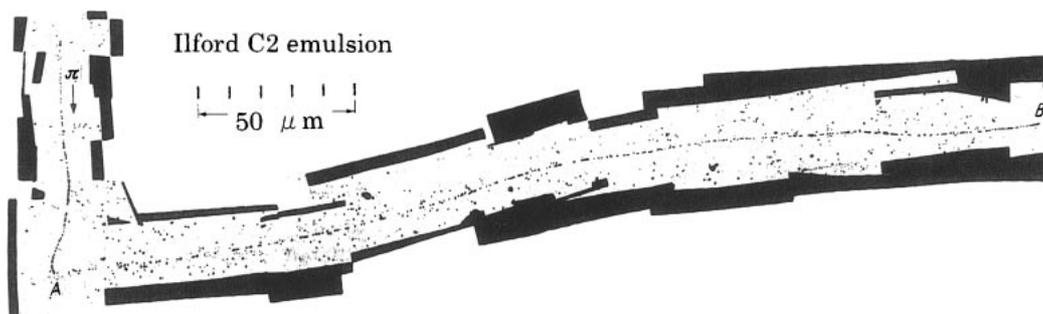
Fig. 2. $\pi \to \mu$ decay, discovered in the nuclear emulsion, named Ilford C2. π stopped and decayed into μ at A. μ was emitted at A, and decayed at B. Lattes, Muirhead, Occhialini, Powell (1947) Nature **159**, 694.

PLATE NUMBER
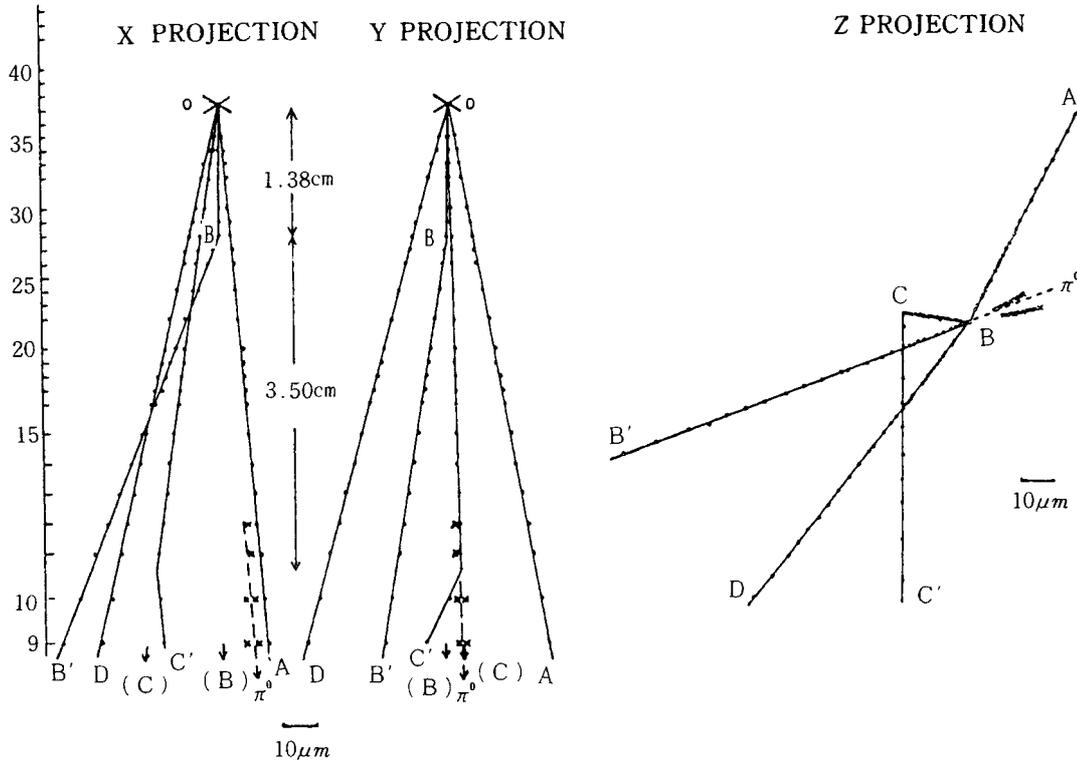
Fig. 3. Pair production and decay of naked charm particles discovered in 1971 in a cosmic-ray interaction. Particle B decayed at B into B′ and a π^0. Two γ rays, daughters of the π^0, initiated electron showers at plate no. 12 and no. 10, respectively. Particle C decayed at C into C′ and unseen neutral hadron(s). Niu, Mikumo, Maeda (1971) Prog. Theor. Phys. **46**, 1644.

remount it. This stripping and remounting caused greater distortion.

The second way was to use a new type of detector, called the Emulsion Cloud Chamber (ECC). The first design of the ECC was a sandwich of a brass plate and thin emulsion plates. By using the ECC, an emulsion plate was placed perpendicular to incoming particles as a track detector. When using the emulsion plate as a track detector, it was possible to have a spatial resolution of up to 1 μm. This type of detector was first developed by M.F. Kaplon *et al.*, and was used very effectively to study heavy primaries.[8] The ECC was also very cost-effective because most of the chamber's volume consisted of metal plates and backing glass, which were far cheaper than nuclear emulsion material. Moreover, J. Nishimura predicted the potential in the ECC to regulate the development of electron showers from π^0 decays by choosing plates made from the most appropriate material.[9] Our group, led by J. Nishimura, felt that this potential was the

most important advantage of the ECC, which could not be realized with conventional homogenous pellicle stacks.

Our improved design of the ECC combined low- and high-z materials in order to observe two γ rays from a π^0 decay as laterally separated electron showers initiated by these γ rays in the detector. A nuclear emulsion chamber consisting of a layer for producing cosmic-ray interactions and a layer for observing secondary electron showers was constructed. The former was a sandwich of low-z material (carbon) plates and emulsion plates, while the latter was a sandwich of high z-material (lead) plates and emulsion plates. Since that time, our group has called this type of detector an Emulsion Chamber. Our group specialized in placing the emulsion plate perpendicular to incoming particles as a track detector to take advantage of the 1 μm spatial resolution of emulsion plates. This resolving power is still unsurpassed by any other type of track detector. In 1956, seventeen emulsion chambers
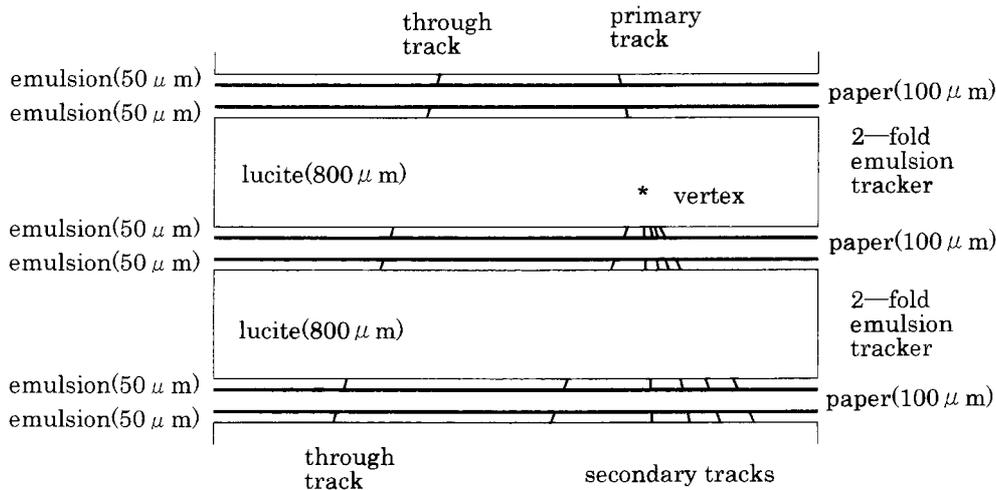
Fig. 4.   2-fold emulsion tracker.

were launched with balloons at a level altitudes of 25 ± 2 km to observe super high-energy cosmic rays. Fourteen clean interactions in the TeV range were observed. From an analysis of the 43 π^0s we determined the average transverse momentum to be 390 ± 20 MeV/c.[10] At the time, this was considered to be a very important result in order to investigate the mechanisms of multiple productions of mesons. The results were confirmed to be accurate enough within an error of 10%, when almost the same results were obtained after several years by a high-energy accelerator at CERN. Through these experiments, we succeeded to move toward the forefront of elementary particle physics.

However, the above study of cosmic ray interaction was restricted to the neutral secondary (π^0), while a simultaneous study of charged hadron components had not been made. A lack of emulsion trackers in the producing layer of interactions and a lack of accuracy in the alignment of the chamber prevented tracing the individual secondary hadron tracks up to a primary vertex in the producing layer of interactions. To carry out a complete analysis of both charged and neutral secondary particles in each interaction, another breakthrough in emulsion techniques was needed.

Stimulated by a suggestion of M. Koshiba, I developed a new type of emulsion plate in collaboration with the Fuji Photo Film, Co., Ltd. I decided to call this new type of emulsion plate a '2-fold emulsion tracker.' It was an emulsion plate with an 800 μm thick transparent plastic base,

coated on both sides with 50 μm of a nuclear emulsion material. An illustration of this new emulsion plate is shown in Fig. 4. By utilizing a longer lever arm made available by the thick base, this type of '2-fold emulsion tracker' served as a vector tracker with a relative angle resolution as high as 1 mrad. Because the bulk of the plate material was a low-z-plastic material, a stack of these "2-fold emulsion trackers" could be used as the target of cosmic rays, where we could analyze in detail the behavior of charged secondary particles, and thus minimize any disturbances due to the development of electron showers. To clearly observe sub-micron sized grains and tracks, which were registered in both emulsion layers—both before and after passing through the thick plastic base, we had to solve two problems. First, we needed a plastic plate with good optical quality, that should be compatible with nuclear emulsions. We adopted a meta-acrylic (Lucite) plate in order to overcome this first problem. Secondly, we needed a high-power objective lens with ideal optical performance and a working distance of more than 1 mm. This second problem was solved by the efforts of the Chiyoda Optical Co., Ltd.

3. The study of cosmic-ray interactions by a compact emulsion chamber

Fig. 5 shows the concept of a compact emulsion chamber that was exposed to cosmic rays at high (airplane) altitude. It consists of three parts: a veto on showers from the upper atmosphere, a target for
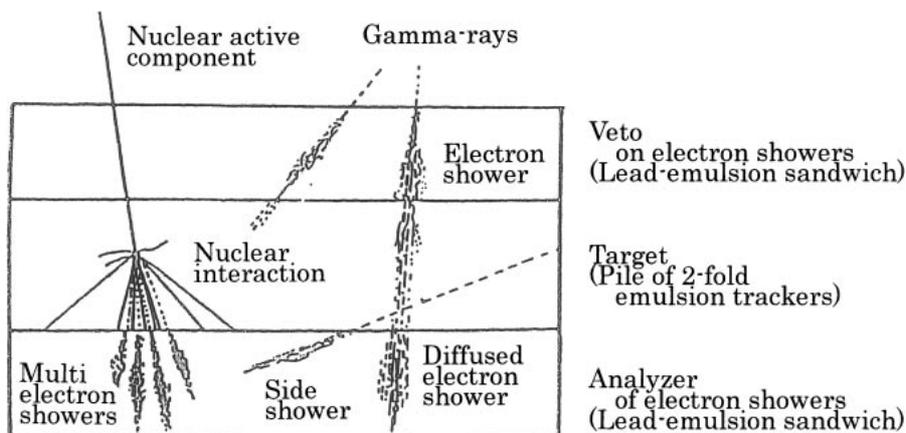
Fig. 5.   Schematic illustration of the compact emulsion chamber used at airplane altitude.
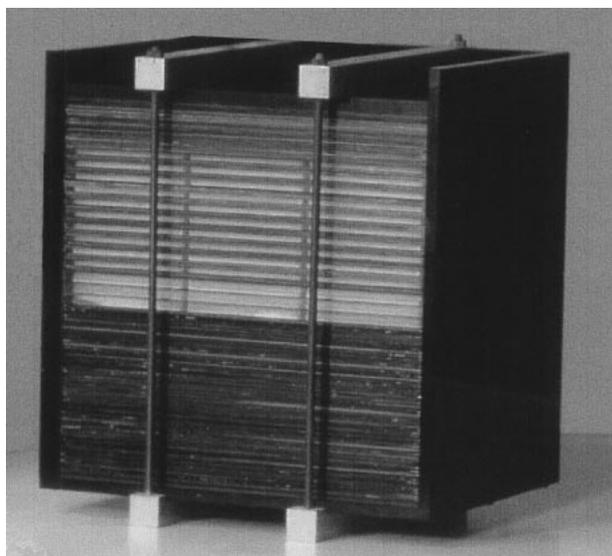
Fig. 6.   Photograph of the compact emulsion chamber used at airplaine altitude.

cosmic rays (which also served as an analyzer of the charged secondary particles of the interactions), and an analyzer of electron showers from $\pi^0 \to 2\gamma$ decays. A photograph of the compact emulsion chamber is shown in Fig. 6. It was this compact emulsion chamber design that made it possible to discover naked charm particles. The target part of the chamber was a pile of 49 '2-fold emulsion trackers' plus five, 1 mm thick, lead plates. The total thickness of the target was 7.3 cm, which corresponded to a 0.1 interaction mean-free path. It was possible to observe a cross-sectional view

of secondary tracks at each millimeter along the shower axis. Any kink or trident (three prong vertex), due to decays of charged hadrons, and any vee (two prong vertex) or wee (four prong vertex), due to decays of neutral hadrons, could be examined up to the place of several centimeters from the primary vertex. The analyzer was a multiple sandwich of lead plates, '2-fold emulsion trackers,' and X-ray films. Even a single ionizing track passing through the top part of the analyzer could be observed at each 0.2 radiation length. Either an incoming electron or a γ ray could be clearly determined by inspecting the electron showers, which began in this part of the chamber. The incoming electron or a γ ray's energy could be estimated by analyzing each electron shower they initiated. To tag unwanted cosmic-ray interactions from the upper atmosphere, we also put multiple sandwiches, similar to the lower analyzer on top of the chamber. The assembly of all the compact emulsion chamber elements was precisely carried out, and X-rays were applied to the four sides of the chamber through fine, linear slits. The alignment of the chamber was found to be accurate to more than $50\,\mu$m when we compared the rectilinear X-ray marks with sharp edges. The chamber weighed approximately 50 Kgs and had dimensions of $25 \times 20 \times 19\,\mathrm{cm}^3$ (L $\times$ W $\times$ D). Exposures of these emulsion chambers to high-energy cosmic rays were carried out at a pressure of approximately $260\,\mathrm{g/cm}^2$ between August and December, 1969 using a jet cargo airplane from Japan Air Lines. In all, 12 compact emulsion chambers were each exposed for 500 hours.
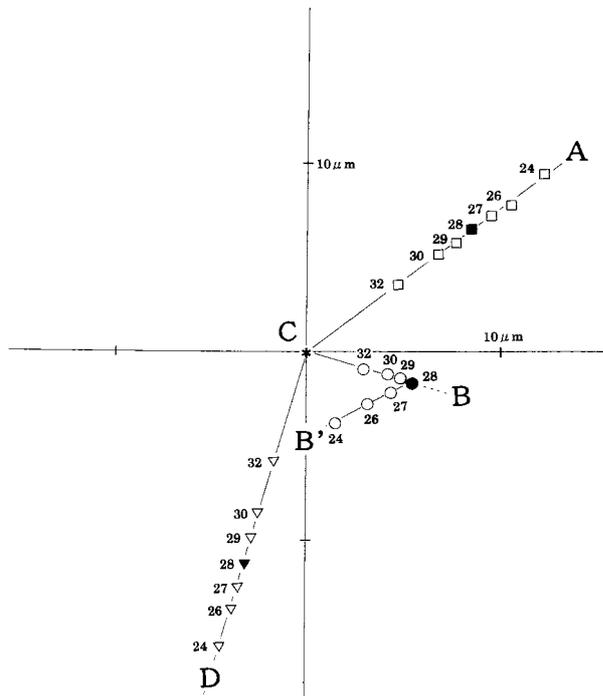
Fig. 7. Sudden pattern change in successive target diagrams (plates from no. 32 to no. 24, track C as the reference).

Fig. 8. Micro-photograph of the cosmic ray interaction (19+70)n, in which a pair of naked charm particles were discovered. A neutral primary particle (not seen) flied in from left with large incidence angle to the plane. It collided with a nucleus on the plane, and produced a big event of type (19+70)n. Black tracks scattering from the center are those of evaporated particles from the target nucleus. A short fan-shaped dense core toward right down off the plane is a bundle of 70 high-energy secondary particles.

We observed the cosmic-ray interactions step by step. At first, we scanned the X-ray films of the analyzer with naked eyes to pick out dark spots due to multi-γ ray events. Using this observation method we found interactions with $\Sigma E\gamma$ higher than 1 TeV. Secondly, we rejected side showers, and those showers already seen in the veto pile. Then, the penetrating showers were followed back along their initial trajectory to detect the primary vertex in the target part of the chamber. During this process, switching from tracks of shower electrons to charged secondary hadron tracks was performed at the boundaries between the analyzer and the target. After detecting the primary vertex of each nuclear interaction, the behavior of secondary charged particles was inspected with special attention, being paid to drawing target diagrams plate by plate. It was during this part of the process that E. Mikumo found one event with a sudden pattern change, as shown in Fig. 7.

4. The discovery of pair production and the decay of new particles

Fortunately, the primary vertex of this unusual event was in a thin emulsion layer of the lower

surface of a '2-fold emulsion tracker.' A microphotograph of this event is shown in Fig. 8. The event was produced by the collision of a neutral cosmic-ray particle with a heavy element in the emulsion—a nucleus of either Silver (Ag) or Bromine (Br). The collision emitted as many as 70 charged secondary particles plus 19 evaporated tracks. At the downstream of this event we observed 23 electron showers initiated by γ rays belonging to this event. A target diagram of these electron showers at 6.63 cm below the primary vertex is shown in Fig. 9. A + mark shows the energy-weighted center of γ rays. Among these 23 electron showers, 4 marked by ○ were identified as nuclear interactions produced by secondary charged particles. In Fig. 9, we show the possible combinations of γ rays marked by ● into π^0 mesons, whose production height coincided with that of the primary vertex within an error of 10%. Most of the couples are consistent with a π^0 emitted from the primary vertex. This confirmed for us that our method of energy estimation was sufficiently reliable.

Fig. 10 shows a graph of energy versus angle (log.tan θ) for γ rays with the angular distribution of charged secondary particles. The most impressive feature of this event was the fact that two γ rays, tagged by arrows, whose energy are one order higher than the others, were emitted in the most forward part of this event. This extraordinary phenomenon excited us, and we made an exhaustive
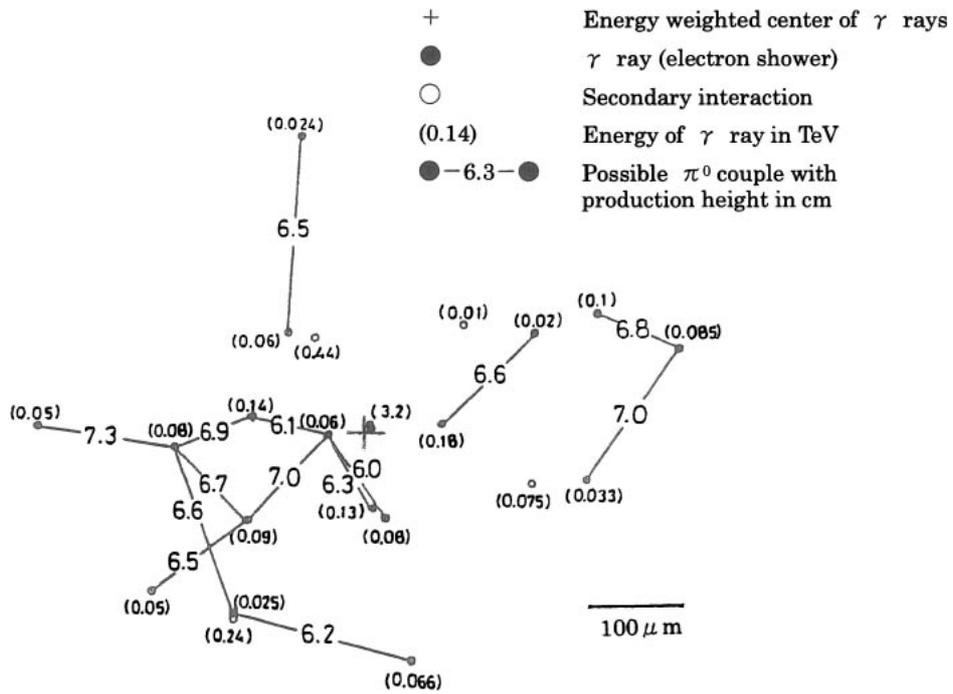
Fig. 9.   Target diagram of electron showers at 6.63 cm down from the origin of the event.
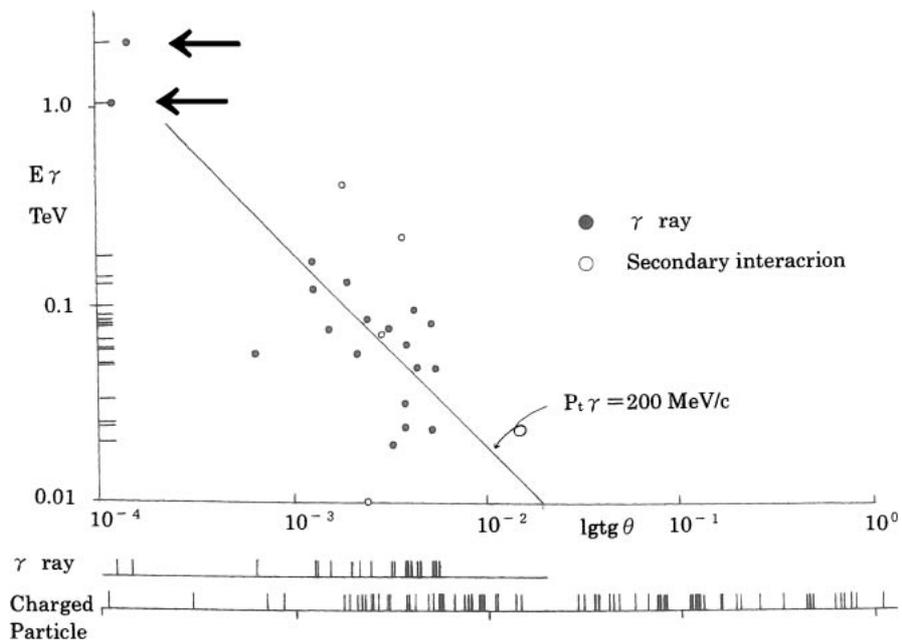
Fig. 10.   Energy and angular distribution of γ rays and angular distribution of charged secondary particles. Two γ rays tagged by arrows are isolated from the main group, both in energy and angle.

investigation of this event. The relative distance between those two γ rays was $3.4\,\mu$m at the plane 5.14 cm below the primary vertex, and the energy sum of these two γ rays was estimated to be 3.2 TeV. A kinematical study to couple these two γ rays into a π^0 resulted in the production height of this π^0 being 3.8 ± 0.5 cm above the studied plane, and it was unable to reach the primary vertex. Therefore, by combining both charged and neutral particles, we reconstructed a 3-dimensional view of the most forward part of this event as seen in Fig. 3. The two charged tracks found had kinks of 1.07 mrads and 1.50 mrads at 1.38 cm and 4.88 cm, respectively, from the primary vertex. When one looks at the Z projection, in which the emitted direction of the track B was perpendicular to the plane, one can easily recognize that the two electron showers from the π^0 appear just opposite of the track B′ after the kink. This meant that the tracks B, B′, and the flight path of the π^0 satisfied a co-planarity condition. The emitting angle of the π^0 from the kink point of B is 0.196 mrad. The B′ and C′ tracks after the kinks were attributed to hadrons, because they simply passed through seven radiation lengths without any cascading. No other associated charged track pointing to the kink points was observed.

Based on the co-planarity condition, it was possible to attribute this event to a 2-body decay of the parent particle B into the charged hadron B′ and the π^0 meson. The transverse momentum of the π^0 meson was estimated to be 627 ± 90 MeV/c from its emitting angle and observed energy. The momentum of the charged hadron B′ was estimated to be 0.59 ± 0.1 TeV/c, assuming the Pt balance. Table 1 gives estimated mass and decay times of the parent particle B, assuming the identity of its daughter B′ to be either π, k, p, or Σ. Due to the Pt value of B′, high above the maximum possible Pt

Table 1. Mass and decay time of the X-Particle

Parent X	Assumed decay mode	M_x GeV	T_x sec
OB	$X \to \pi^0\pi^{\pm}$	1.78	2.2×10^{-14}
	$X \to \pi^0 k^{\pm}$	2.15	2.7×10^{-14}
	$X \to \pi^0 P^+$	2.95	3.6×10^{-14}
	$X \to \pi^0 \Sigma^{\pm}$	3.5	4.2×10^{-14}
OC	$X \to ?^0?^{\pm}$		$< 1.5 \times 10^{-12}$

for strange particles, the parent particle B could not have been a strange particle. In addition, because the decay time was an order of 10^{-14} seconds, it could not have been a resonance particle suffering strong decay. In addition, the kink of track C should have been attributed to a decay of hadron C, with a lifetime similar to B, into hadron C′ and other neutral hadrons. These facts convinced us that this event showed the pair production and decay of new particles with a new quantum number or new degree of freedom. We named the new particle an X-particle. We reported that we had discovered the pair (X and $\bar{\text{X}}$) production and decay of a new type of particle at the 12th International Cosmic Ray Conference held in Hobart, Australia, in 1971.[11]

5. The attribution of the new particle to the fourth quark (charm), and related work in the cosmic-ray field before the discovery of J/Ψ, including a study of their lifetimes

Immediately after the discovery of this new particle, S. Ogawa, who led a branch of S. Sakata's school of thought, pointed out that this new particle might comprise the fourth quark, p′.[12] This idea was first introduced into the New Nagoya model in 1962[13] and was now called "charm" after being named by B.J. Bjorken and S.L. Glashow in 1964.[14] The discovery of our event in 1971 created a certain excitement among Japanese physicists and in the Cosmic Ray Physics Community. Stimulated by this experimental evidence, many Japanese theoretical groups discussed and refined models–including SU(4). During the three years after our discovery, a total of 24 papers[15] were published in Progress of Theoretical Physics that referred to this event. Incidentally, only a few theoretical papers from western countries referred to this discovery; among them was one by J. Shwinger.[16] In contrast to our progress, the field of experimental charm physics had not progressed in the High Energy Physics Community until a later discovery of the hidden charm particle J/Ψ in 1974.[17] A major reason for this lack of progress may have been a lack of confidence in the work using emulsion techniques once discounted by western scientists. Another reason may be because this work was carried out in the cosmic ray field, reported to the Cosmic Ray Conference, and was published in the Far East, where no remarkable experimental high-

energy physics activity by accelerators had yet been recognized.

However, encouraged by Japanese theoretical groups—mainly from S. Sakata's school, the study and the hunting of the X-particles containing the fourth quark had been actively continued in Japan by cosmic ray physicists. The design of the compact emulsion chamber was improved and refined so as to better determine the decay of short-lived particles. Those compact emulsion chambers were exposed to super high-energy cosmic rays, not only at airplane altitudes, but also at balloon altitudes. Additional examples of naked charm particles steadily accumulated.[18] The most complete pair of charm particles were observed in a balloon-borne emulsion chamber in 1974 by H. Sugimoto et al.[19] Their report was published in 1975 in the Progress of Theoretical Physics. Further evidence had been unearthed by a re-analysis of certain anomalous events observed before 1971 in the ECC type of detectors. Among these anomalies, the T-star observed by M.F. Kaplon et al.[20] in 1952 bore the closest resemblance to our 1971 discovery. They observed two π^0 mesons produced in the same event with much higher energy than the others. The energy was measured to be 1.6 TeV and 2.4 TeV, respectively. Each decayed into two γ rays, 2.5 cm and 7 cm, respectively, from their primary origin. Kaplon et al. reported that they observed delayed decays of π^0 mesons with lifetimes of the order of 10^{-14} seconds. We re-analyzed their data, and found that it could be naturally interpreted as pair production and the decay of X-particles.[21] Their data was impressive, since they had observed events very similar to ours by means of the ECC exposed to cosmic rays nearly 20 years earlier.

In 1974, the year J/Ψ was discovered, there were 20 observed charm decays on record. Most of them were observed as pairs. These 20 observations were made from new exposures and from re-analyses of older events. Based on those statistics, we concluded that the production rate of charm particles at the 10 TeV range was one pair per 20–40 observed inelastic interactions. In addition, we recognized that the lifetimes of charged and neutral charm particles seemed to be different by a factor of 2∼3. Fig. 11 shows the integral distribution of the decay times of both components. Fig. 11 shows that the lifetimes of the charged particles were $(1$–$1.5)\times10^{-12}$ seconds, but those of neutral parti-
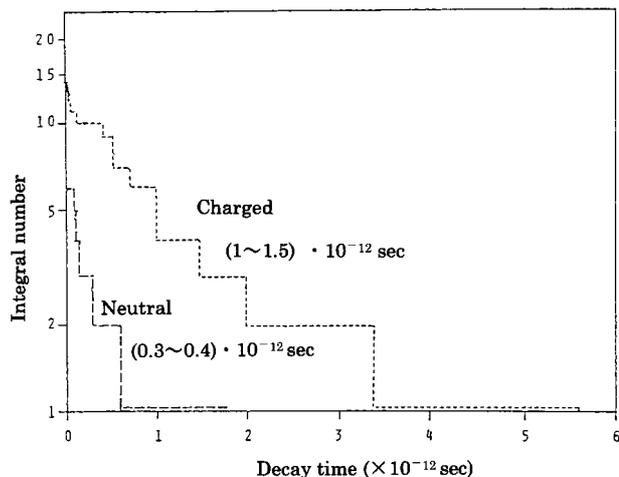
Fig. 11. Lifetime difference between charged and neutral naked charm particles observed in cosmic-ray experiments.

cles were $(3$–$4)\times10^{-13}$ seconds. We reported this result at the 14th International Cosmic Ray Conference held in Munich in 1975.[22] However, it was too early to generate any excitement in the High Energy Physics Community. Unfortunately, the referees of some scientific journals did not accept our results. However, a decade later, our results regarding the lifetime differences between charged and neutral particles were confirmed by accelerator experiments. I believe that the Japanese emulsion group once again made critical contributions to these developments.

6. The study of naked charm particles by compact emulsion chambers in accelerators

In 1972, just after the discovery of naked charm particles, my colleagues and I took part in accelerator experiments following a suggestion by S. Hayakawa. We thought that the search for, and the study of, charm particles would move to accelerator laboratories with the development of the hadron accelerators in the sub-TeV energy region at Fermilab and CERN. This situation seemed very similar to the case of 'old,' new particles. However, nuclear emulsions would remain the most powerful detectors with a resolving power of sub-μm. This resolving power must be indispensable to directly observe both production and decay vertices of charm particles with lifetimes of approximately 10^{-13} seconds. We improved the design of the emulsion chamber so as to inspect the behavior of charged and neutral secondary particles more
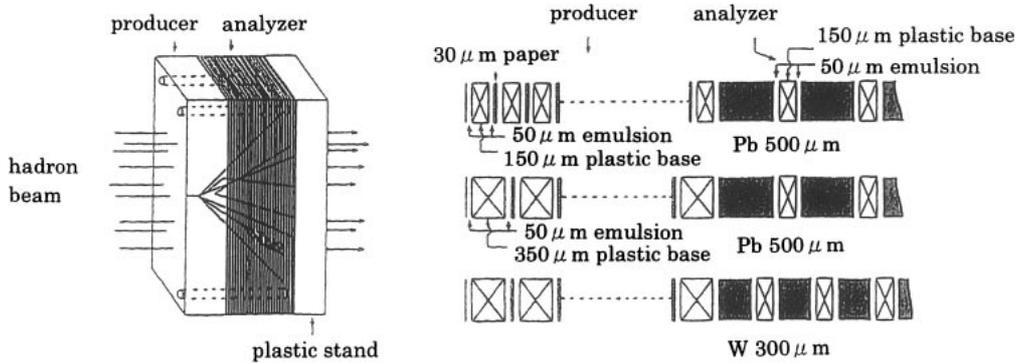
Fig. 12.   Setup of various compact emulsion chambers used for accelerator experiments.

precisely in the energy region two orders of magnitude lower than that of cosmic rays. As shown in Fig. 12, a thinner base for the '2-fold emulsion tracker' and thinner plate materials for the analyzer were used as components of the compact emulsion chambers for the accelerator experiments. By using this type of emulsion chamber, it was possible to estimate the momentum of a charged particle that penetrated the analyzing part by means of the relative scattering method.[23] High-precision measurements of the relative distance of secondary tracks to the beam tracks, with known momentum, and high scattering signals due to lead nuclei, made it possible for us to apply the method to the tracks of sub-TeV region. Following the development of higher energy hadronic accelerators at Fermilab and CERN, this type of detector was successively exposed to accelerated hadron beams with momentum in the sub-TeV region. Due to the higher intensity beams of accelerators, the efficiency in collecting charm particles increased greatly when compared to those in cosmic-ray experiments. Our group discovered the first artificially produced naked charm particles in 1975.[24] These discoveries were achieved by using a compact emulsion chamber exposed to proton beams with a momentum of 205 GeV/c at Femilab. Sketch of one event is shown in Fig. 13. Details of this event is described in the reference 24). Among secondary particles of this event, we observed a neutral particle that suffered two body decay at the point V, 809 μm down from the origin of this event O. The invariant mass and flight time of this particle OV, was estimated from the opening angle and the momenta of particles Vm and Vn, assuming the identity of both particles. The results excluded the possibility to be kown
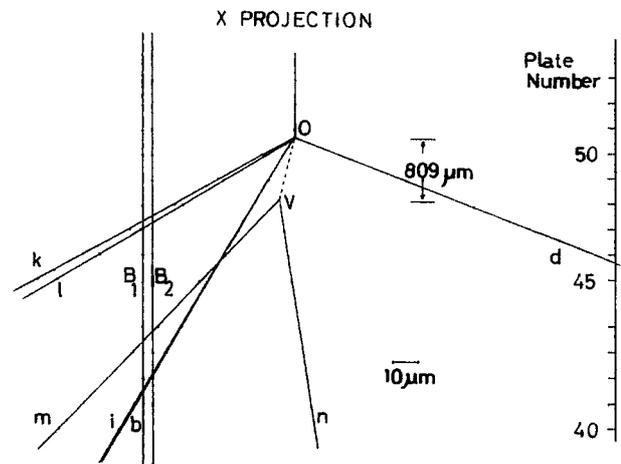
Fig. 13.   First artificially produced naked charm particle (neutral particle connecting O-V), discovered in 1975 in a compact emulsion chamber exposed at Fermilab. Hoshino *et al.* (1975) Prog. Theor. Phys. **53**, 1859.

particles, and were quite consistent with the charm particles observed thus far in cosmic-ray experiments.

Along with the experiments in the accelerator field, our group introduced and developed two new emulsion techniques: the coating facility of nuclear emulsions and the semi-automatic scanning system of emulsion plates. To obtain suitable types of emulsion trackers at suitable times, K. Hoshino and our group[25] constructed a coating factory at Nagoya University in collaboration with the Fuji Photo Film Co., Ltd. Fuji Photo supplied us with the gel-type emulsion. Subsequently, we were able to fabricate any type of emulsion tracker by ourselves when needed. K. Niwa and our group also developed a semi-automatic scanning system in

1974 to reduce tedious labour, expertise and inefficient manual scanning.[26] This system of development has been considered to be very significant, and has made steady progress since its inception.

The last experiment using only compact emulsion chambers was carried out at CERN in 1979.[27] These compact emulsion chambers were exposed to negative-pion beams of 340 GeV/c. The scanning and analysis of the pion interactions were carried out by applying semi-automatic scanning machines in a practical way. In total, 4323 events were located and analyzed in a few months—among which four charm pairs, five neutral charm particles, and three charged charm particles were detected. All five neutral particles were consistent with the $D^0/(\bar{D}^0)$ hypothesis, and we estimated the mean lifetime to be $\tau = (3.1^{+2.0}_{-1.6}) \times 10^{-13}$ seconds. We also estimated the production rate to be $\sigma(\pi N \to c\bar{c}X) = 44 \pm 22\,\mu b$. The mean lifetime and inclusive production rates were consistent with the present-day values, but for some time we felt that we needed more precise results, and to reduce the statistical error. To proceed to the next step of a higher statistical study of charm particles, we needed to improve our experimental techniques.

7. Confirmation of the lifetime differences among charm species by a high-statistics study of charm particles with hybrid emulsion-electronic detectors

Great strides in collecting charm particles were made by using neutrino beams to produce charm particles. Our group adopted a hybrid method of emulsion chambers and electronic detectors as well as the automation of scanning and measuring systems. Neutrino beams proved to be the most effective method of creating charm particles in terms of the production rate per interaction— about 7% of the charged current cross section. To observe enough neutrino interactions, we needed to run the experiment for a long time with a very high-intensity neutrino beam because neutrinos interact with nuclear particles only via the weak force. Artificial neutrinos are produced by an accelerated proton beam as its grandchild with muons, $P \to \pi \to \mu + \nu$. Therefore, a high-intensity neutrino beam inevitably associates itself with high-intensity muons. Thus, we had to work with a high-intensity muon background.

The chief shortcoming of emulsion-only detec-

tors had been the time required to scan a large volume of detectors. Ways to shorten this time were examined by E.H.S. Burhop *et al.*[28] They felt that the solution was to restrict the scanning volume of the pellicle stack by predicting an event vertex using external tracking detectors. Their results were rather disappointing, because the results suffered from a low detection efficiency. We analyzed possible causes of the low locating rate of tagged events in the emulsion. Our conclusion was that the deficit in detecting vertices in the emulsion was inevitably connected with the use of their volume scanning method to search for events in a conventional pellicle stack. To overcome this deficit, we intended to find a more efficient predicting algorithm for the event, and a more reliable tracking method using improved emulsion chambers as an extension of techniques developed thus far in Japan.

We performed some preliminary experiments to develop our new systems. We also needed to find a counter group willing to collaborate with us. We asked T. Yamanouchi at Fermilab to mediate collaboration with a worthy North American counter group. After some studies and discussion, we decided to collaborate with N.W. Reay's group at Ohio State University, Canadian University of Ottawa, and others. We proposed to test a new "scan back method." We attempted to reach the event vertex following a single track from an external detector back up to the emulsion chamber. At first, the external detector did lead us to the point and angle of a track associated with the event on the downstream surface of the emulsion chamber. Next, we scanned the most downstream '2-fold emulsion tracker' utilizing a more advanced semi-automatic scanning system that we developed. The spatial resolution and angle resolution of a '2-fold emulsion tracker,' almost 1 μm and 1 mrad, were sensitive enough to identify a candidate track. We then traced the track in reverse, plate by plate, up to the event vertex in a stack of '2-fold emulsion trackers.'

This new method was tested in a short run in the M5 test beam using 30 GeV/c π^- beams at Fermilab.[29] As a result, this method was confirmed to be very effective, minimizing losses from three sources. First, we minimized the loss of events with few or no heavily ionizing tracks, because the followed track ends automatically at the event
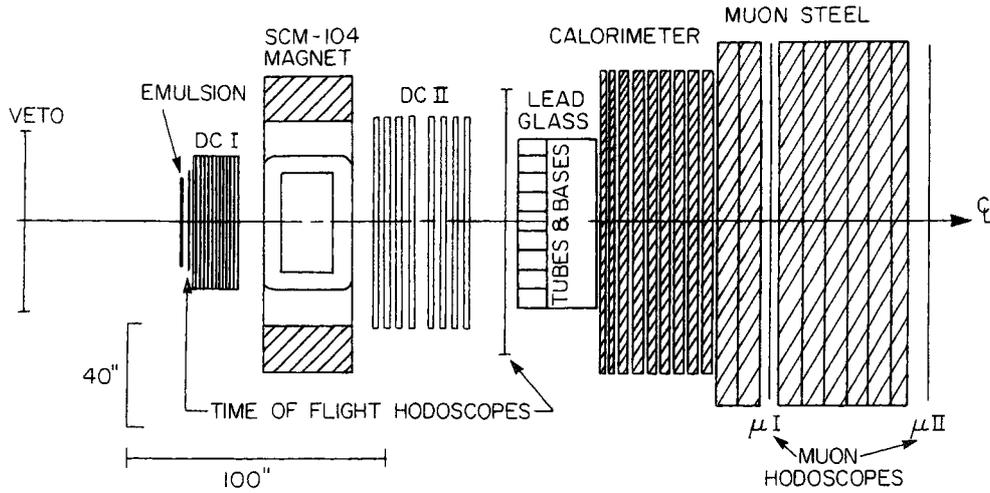
Fig. 14.   Plan view of Experiment E531.

vertex, itself, and we needed no additional information. Second, we minimized the losses of events with low multiplicity, since a single secondary track was enough to locate the vertex. Finally, we minimized any problems due to the multiple scattering of tracks in the emulsion because external detectors predicted the positions and angles at the downstream faces of the target. Moreover, we found that the scanning time needed was far shorter than that of the conventional volume scanning method.

Applications of our new techniques were carried out in Experiment E531 at Fermilab to study charm life-times.[30] The experimental set-up is shown in Fig. 14. The neutrino beam, produced by 350 GeV/c protons, was incident from the left. Secondary particles from interactions in the emulsion target were tracked in a high-resolution drift chamber spectrometer. The identification of charged and neutral particles was made by ionization loss in the emulsion, time of flight (TOF), a lead glass and a steel (for μ) hodoscope. Events were recorded when no signal is seen in the veto hodoscope upstream of the target, two or more charged particles leave the emulsion, and these particles were detected in the TOF hodoscope downstream of the magnet. Scanning for neutrino interactions was done with the aid of the downstream spectrometer, which pointed out the exit coordinate and angle of the secondary tracks.

As for the emulsion part of this experiment, our collaboration consisted of two groups. One was our
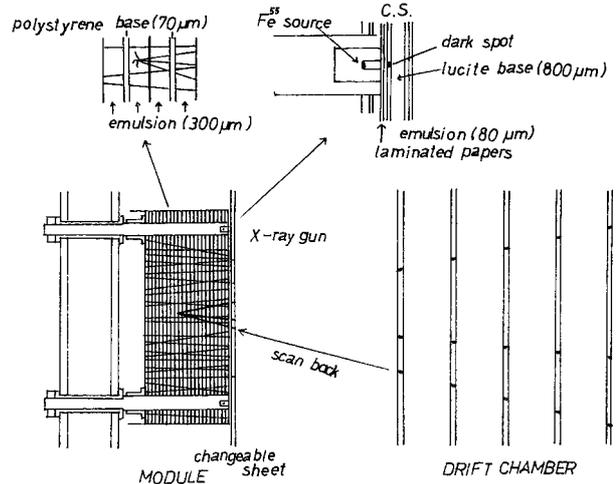
Fig. 15.   "Vertical" emulsion target of Experiment E531.

group using emulsion chambers, plus new techniques. The other was a group using conventional pellicle stacks. We used 22.6 liters of Fuji ET7B-type of nuclear emulsion to make the 27 emulsion chamber modules and 12 pellicle stacks that were installed on the target board. The emulsion chamber module of this target is shown in Fig. 15. Once again, new emulsion techniques specifically developed for Experiment E531 were put to practical use. Five new techniques were key to the success of Experiment E531.

1) Changeable sheet. This was an indispensable element to realize the "scan back" method under actual conditions with an extremely high muon

background. This changeable sheet was an emulsion plate doubly coated on an $800\,\mu$m thick Lucite sheet with an area of $40 \times 90\,\mathrm{cm}^2$, enough to cover all of the modules, and was placed immediately downstream of the emulsion targets. It was changed every two days during an experiment run of several months. The most important function of this fiducial sheet was to serve as a low-background interface to couple drift-chamber tracks to those seen in the emulsion module. Muon and other backgrounds were kept sufficiently low to pick up a single minimum track predicted by drift chambers on this sheet.

2) Thick emulsion tracker. This was fabricated by coating both sides of a $70\,\mu$m polystyrene sheet with $330\,\mu$m of emulsion. A stack of thick emulsion trackers was used as a position detector of tracks transversing the film bases as well as an analyzer of 3-dimensional topology of the event in the thick emulsion layers. This minimized any concealment of the event vertex by the base sheets. Sixty-eight layers of $9 \times 12\,\mathrm{cm}^2$ thick trackers stacked on four Lucite posts were exposed perpendicularly to the neutrino beam. By an analogical expression, this was compared with a super multi-layer counter assembly with a spatial resolving power of sub-microns.

3) On-site coating and developing of emulsion sheets. To keep the changeable emulsion sheets fresh, field factories for coating and developing the emulsion sheets were constructed near the experiment site. Well-experienced physicists coated and developed the emulsion sheets. We purchased a gel-type emulsion from Fuji Photo Film Co., Ltd. and transported it via surface to North America to avoid any possible heavy background tracks from cosmic rays at high (airplane) altitude during the flight. The main emulsion target was coated and developed at Canadian University of Ottawa.

4) X-Ray guns. To calibrate the relative position of the changeable sheet and emulsion modules with an accuracy of $50\,\mu$m, we imbedded Fe^{55} fluid in each mounting post of the emulsion modules. As shown in Fig. 15, the marks left on the changeable sheet recorded the relative positions of all modules.

5) "Origami packing". In order to minimize troublesome neutrino interactions in the materials surrounding the emulsion target, the mass of packing materials should be minimized. We thus intended to 'vacuum pack' each emulsion module in a thin laminated sheet of $135\,\mu$m thick, which consisted of nylon, paper, aluminum and polyethylene. This sheet had been used commercially to preserve flat X-ray films. To apply this sheet for a solid emulsion module, we made an open box and a lid folding the sheet by "Origami method". Each emulsion module was enclosed into a sheet-box in a vacuum vessel using specially developed sealing equipment for this purpose. By this method, during the several-months long experiment run, the emulsion modules were safely shielded from light, humidity, and chemicals with the minimum amount of packing materials.

Data recording of Experiment E531 began on November 18, 1978 and ended on February 7, 1979. During the 1250 hours of the experiment running time, 7.2×10^{18} protons were incident on the production target. A total estimated flux of 1.7×10^{15} neutrinos/m^2 passed through the $0.49\,\mathrm{m}^2$ emulsion target. In total, 1751 events were predicted by the tracking detector in the emulsion volume. Among them, 1257 events were actually found. The detection efficiency of neutrino interactions in the emulsion chamber modules was 88% using the "scan back" method. However, the detection efficiency was only 42% by volume scanning in the pellicle stack. The latter was somewhat improved to 51% when the "scan back" method was applied to the pellicle stack. A decay search for all detected neutrino interactions yielded 22 charged and 21 neutral multi-prong charm decay candidates, and 49 single prong or kink events. As shown in Table 2, Experiment E531 yielded the most successful results to measure the lifetimes of each charm state.[31] It was noted that the lifetimes of charm particles were quite different to the early and simplest theoretical expectations that they were equal.

In Fig. 16, the integral lifetime curve of neutral and charged charm particles from Experiment E531 are overlaid on the results from the cosmic-ray

Table 2.   Summary of charm lifetimes from E531

Particle	No. of decays	Lifetime (10^{-13} sec)	World Average (1988) (10^{-13} sec)
D^0	58	$4.3^{+0.7-0.5}_{+0.1-0.2}$	4.28 ± 0.11
$D^\pm$	23	$11.1^{+4.4}_{-2.9}$	$10.69^{+0.14}_{-0.12}$
$Ds^\pm$	6	$2.6^{+1.6}_{-0.9}$	$4.36^{+0.39}_{-0.32}$
Λc^+	13	$2.0^{+0.7}_{-0.5}$	$1.79^{+0.23}_{-0.17}$
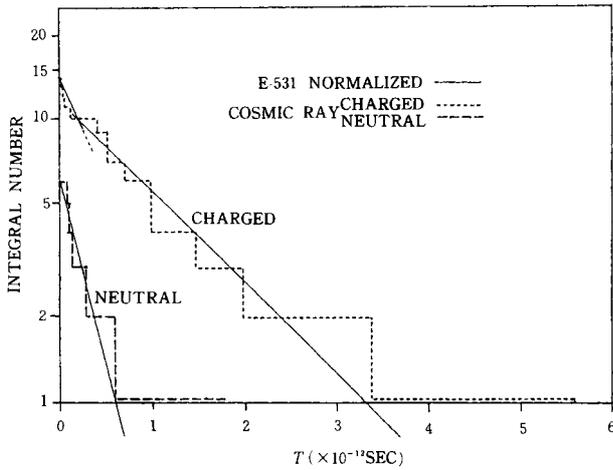
Fig. 16. Comparison of lifetime curves from cosmic-ray experiments (up to 1975) and those from Experiment E531 at Fermilab.

studies shown in Fig. 11. The Experiment E531 data and the data from the cosmic-ray studies showed similar results. This similarity in results generated confidence in the pioneering cosmic-ray work made on charm lifetimes.

Finally, I would like to briefly discuss the discovery of the simultaneous production of two pairs of charm particles in a single event.[32] A sketch of this is shown in Fig. 17. We discovered two primary interactions—each of which contained 4 charm particles, subsequently decaying in the emulsion. These two events were found among

200 cases of single-pair productions of charm particles during a study of hadronically produced beauty particles at CERN with the WA75 hybrid apparatus. A simple mechanism, like two successive processes in the intra-nuclear cascade, gave rise to a ratio of, at most, 10^{-3} in 200 events. The large observed production rate is in disagreement with the results of any current theoretical expectation. Although we need confirmations from other high statistical experiments, this is a very interesting experimental result to study the mechanism of production of heavy flavor particles by hadrons.

8. Conclusion

The majority of this report has been a historical review on the discovery and studies of naked charm particles with compact emulsion chambers carried out in Japan. The 1971 discovery of a pair of naked charm particles was made three years in advance of the discovery of the hidden charm particle J/Ψ in western countries. The lifetime differences among charm species was discovered just after the discovery of J/Ψ in 1975 based on data accumulated from cosmic-ray studies. This was confirmed a decade later by our collaborative Experiment E531 work with North American physicists at Fermilab, in which we made critical contributions. The discovery of artificially produced naked charm particles in a compact emulsion chamber exposed at Fermilab was published in 1975. The discovery of multiple-pair production of
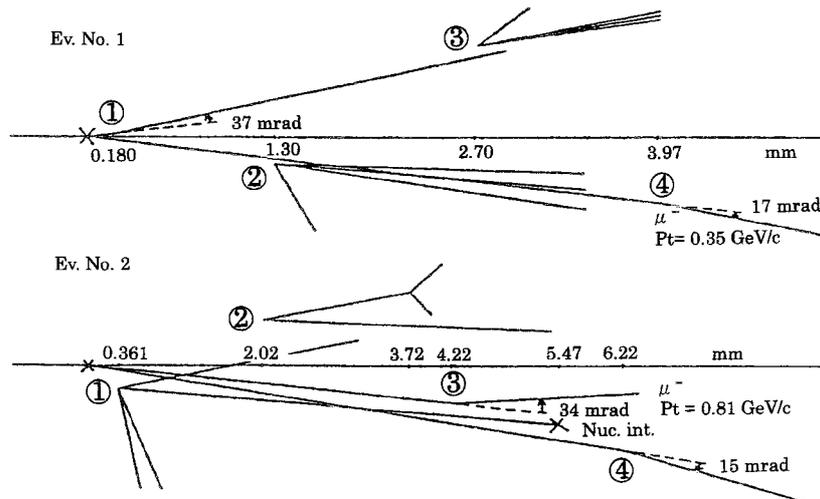
Fig. 17. Sketch of two events each containing the simultaneous production of two pairs of naked charm particles from the experiment WA75 at CERN. Aoki et al. (1987) Phys. Lett. **B187**, 185.

charm particles was made in 1987 by another hybrid emulsion-electronic detector with European physicists at CERN in the collaboration WA75. All of these discoveries were prominent and significant ones in the history of elementary particle physics. They could not have been obtained without making use of the most advanced emulsion techniques, that we developed—including the semi-automatic machine for scanning and measuring.

9. Acknowledgements

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Profile

Kiyoshi Niu was born in 1925. Before the end of the last world war in 1944, when he was a student of the First Higher School, he was drafted for one year as an assistant of the Nishina Laboratory in the Institute of Physical and Chemical Research. There, he engaged in the observation of cosmic ray, and that experience helped him to fix his future to work in the field of particle physics. He graduated from the School of Physics, Nagoya University in 1953.

While attending the Graduate Course of Physics, Nagoya University, in 1954 he detected a strange meson for the first time in Japan in an emulsion plate exposed at high altitude. This plate had been donated to a Japanese emulsion group by the California Institute of Technology. He subsequently proposed the "Two fireball model" of multiple meson production in super high-energy cosmic-ray interactions in 1956, and published it in 1958. He received in 1959, a Degree of Doctor of Science from Nagoya University, and in 1961, he received the Nishina Memorial Prize for his "Two fireball model". During 1956 to 1964, he was Research Associate at the Institute for Nuclear Study, University of Tokyo, and he contributed to establish balloon and emulsion chamber techniques for cosmic-ray experiments at balloon and mountain altitudes. Being recommended by Prof. S.Tomonaga in 1963, he made an inspection tour, as an UNESCO Fellow, around European institutes and laboratories to study nuclear and cosmic-ray physics.

Being promoted to Associate Professor, Institute for Nuclear Study, University of Tokyo, he developed a new type of emulsion tracker for cosmic-ray studies at airplane altitude. He discovered naked charm particles by his new techniques in 1971. Just after that, he moved to Nagoya University as Professor to establish an emulsion group to investigate new elementary particles. Collaborating with younger physicists, he developed further emulsion techniques, such as the self-coating of emulsion plates and a semi-automatic scanning system, to be used for studies of particle physics in the accelerator field. His group has been refreshing nuclear emulsion techniques in the study of particle physics. In 1989, he retired from Nagoya University, and was granted the title of Emeritus Professor of Nagoya University. In 1993, he stayed at CERN for 6 months as a Guest Professor, invited by Prof. C. Rubbia, Director General.

He is the recipient of 2005 the Order of the Sacred Treasure, Gold Rays with Neck Ribbon.