BUBBLE CHAMBERS, TECHNOLOGY AND IMPACT ON HIGH ENERGY PHYSICS

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1. Introduction

Following its invention in 1953 by Donald Glaser, the bubble chamber provided important technological, sociological and pedagogical legacies, in addition to profoundly influencing the development of particle physics during the 20 years or more when bubble chambers were the dominant detectors. The aim of the article is to outline the evolution and impact of bubble chambers by following the parallel threads of selected technical developments and of some of the physics discoveries made using them. The field is so large, that justice cannot be done to all of its aspects. Therefore, the reader is referred to a comprehensive treatment given in *Bubbles 40*, the proceedings of a conference marking the 40th anniversary of the bubble chamber (Nuclear Physics B 36 (1994), edited by G.G. Harigel, D.C. Colley and D.C. Cundy). More emphasis is given here to design, new developments, operation of the whole range of chambers, and their hybridization, since it was the field where the author worked over three decades predominantly.

2. BUBBLE CHAMBERS AT PARTICLE ACCELERATORS

The invention of the bubble chamber by Donald Glaser goes back to the early fifties, to a time when interesting new particles were observed either by *Photographic Emulsion* or in *Cloud Chambers*. These particles were originally called *pothooks*, later *varitrons*, then *V-particles*, till they got their final name *strange particles.* They were detected during balloon flights or at particle accelerators in the few GeV-energy range. They represented truly new phenomena, unexpected and unexplained by theory. In cloud chambers on top of mountains they appeared only about once a day. Errors with these detectors were so large that a wide range of masses was reported. In order to get higher statistics for the study of their properties, a need arose for an energetically metastable system in which the tiny energy deposited by a minimum ionizing particle could trigger the growth of a recordable macroscopic effect. An additional requirement was that the detector should have high density and should be transparent.

Donald Glaser, at that time at the University of Michigan, studied systematically several options, starting with soluble chemicals and their transformation in insoluble products, and dielectric or photoelectric surfaces in high electric fields. The saga went around that he had the enlightening idea when he observed bubbles rising in a glass of beer. Actually he claimed it was much more of a systematic research than anything else, which led him to study superheated and supercooled fluids and solids, the groundwork for the bubble chamber. For technical reasons he concentrated his work on chemical compounds he could operate near ambient temperature, so that neither special heating nor cooling equipment were required. Diethyl ether was the liquid he put into a 3-cm^3-glass bulb, equipped with a simple mechanical expansion membrane to bring the liquid in a sufficiently superheated state. The ionizing particles would then deposit enough energy to act as seeds, to produce sub-nuclear bubbles. Once the bubble has reached a critical size, it is unstable against further growth and will continue to grow without any exogenous source of energy. When the bubble strings are large enough they are being photographed, showing the trajectory of the passing particle. With that device he could demonstrate sensitivity to ionizing cosmic rays. The news about the invention traveled in no time from lab to lab around the world and the building of so-called warm bubble chambers took place in almost all high-energy accelerator centers. However, physicists recognized immediately that systematic studies of interaction of high-energy particles should take place also on much simpler molecules, allowing for considerably easier explanation of results.

It was the group in Berkeley, chaired by Luis W. Alvarez, that demonstrated the feasibility to use liquid hydrogen as chamber liquid at cryogenic temperatures around 26 K, soon followed by liquid deuterium, one the simplest proton target, the other the simplest quasi-free neutron target.

Within ten years the volume of bubble chambers increased by a factor of a million. In the seventies giant chambers with almost 40 cubic meters volume began to operate successfully. Whereas a few hundred-litre chambers were well suited for doing hadron physics, a growth in volume and/or mass played an ever-increasing role in view of doing experiments successfully with accelerator produced neutrinos. Larger sizes required the development of innovative optic schemes. The smaller chambers were of the bath tub style and mostly worked with through illumination (dark-field). Large cryogenic chambers could no longer be built with this kind of optics due to the required size of windows, their resistance to thermal stress during cool-down and warm-up, and the necessary resistance to pressure variation during expansion and recompression. The invention of Scotchlite, a retro-directive material, with which the inside the chamber could be wallpapered, opened a way out of the difficulty. Bright-field illumination in combination with hemispherical windows, housing a wide-angle lens and flash tube, solved the problem.

Table 1. List of major bubble chambers.

	H_2	D_2	Ne/H_2	C_3H_8, Freon
US chambers (total > 50)				
Berkeley	2″, 4″, 6″, 10″, 15″, 25″			50 cm, 10″
	72″ (82″)			
SLAC	15″, 40″			
BNL	30/31″, 80″, 84″, 7′ (3.9 Mpx)			15 cm, 170 l
Argonne	30″ (4.7 Mpx), 12′ (7 Mpx)		30″, 12′	
Fermilab	15′ (2.9 Mpx)	15′	15′	Tohoku [Hologr.]
Wisconsin	30″[Scotchlite]			
European chambers (total > 50)				
German	85 cm (6.3 Mpx)	85 cm	85 cm	
French	80 cm (16 Mpx)			BP3, Garg. (4.7 M)
British	150 cm			Oxford He
Russian	Ludmilla Mirabelle (3.3 Mpx)		Ludmilla? Mirabelle?	1 m, 2 m, SKAT ITEP He, 700 l Xe
CERN	30 cm, 2 m (40 Mpx)	2 m		HOBC
	BEBC (6.3 Mpx)	BEBC	BEBC	
	LEBC (5.2 Mpx triggered)			

BEBC: Big European Bubble Chamber; LEBC: Lexan Bubble Chamber; *HOBC:* Holographic Bubble Chamber; Garg: Gargamelle Heavy Liquid Bubble Chamber; *Ludmilla:* Russian Heavy Liquid Bubble Chamber; *Mirabelle:* Bubble Chamber built in Saclay/France; Mpx: million pictures. Data in round brackets ( ) give the number of pictures taken with a chamber, those in straight brackets special features of the chamber.

Table 1 gives a list of the major bubble chambers, that provided new physics results. Chambers with special features, the *Hyperon Bubble Chamber* HYBUG, *Ultrasonic Bubble Chamber* development, *Track Sensitive Targets* (TST, a bubble chamber within a bubble chamber), and *some test chambers* (BIBC, HOLEBC) are not included in this table. Their characteristics and performance are described below.

Table 2. Properties of bubble chamber liquid.

Liquid	Temperature	Density	Radiation length
	[K]	[g/cm^3]	[cm]
H2	25	0.0645	968
D2	30	0.14	900
Ne	35	1.02	27
He	3.2	0.14	1027
Xe	252	2.3	3.9
C_3H_8	333	0.43	110
CF_3Br	303	1.5	11
Ar	135	1.0	20
N_2	115	0.6	65

Argon and nitrogen are liquids that were tested but not used for physics experiments.

Table 2 summarizes the essential features of bubble chamber liquids, which cover a wide range of radiation lengths and densities. Mixtures of propane with freons were used for neutrino physics in warm chambers. The huge cryogenic chambers, like BEBC at CERN, the 15-Foot Bubble Chamber at Fermilab, the 12-Foot Bubble Chamber at the Argonne National Laboratory, were originally conceived only for use of hydrogen or deuterium. However, an increasing demand for flexibility in the choice of radiation length for adaptation to various neutrino beams resulted in the investigation and use of neon/hydrogen mixtures. Chambers could now be filled with mixtures covering the range of three orders of magnitude in radiation length.

Increase in volume came from the demand for higher statistics in interactions with small cross-section, but also for better measuring accuracy. The latter was obtained by ever-stronger magnetic fields. To limit the operation costs for huge volume magnets, super-conducting coils had to be developed, pushing technology to the forefront.

3. PHYSICS OUTPUT

3.1. Stable particles

Table 3 gives an overview of stable particles detected with various techniques. Much work had been done by the photographic emulsion technique and cloud chamber–exposed to cosmic rays as well as accelerator based beams. The strength of the bubble chamber (coupled with newer and more powerful accelerators) was to verify, and reinforce with larger statistics, the existence of these states, to find some of the more difficult ones, mainly neutrals, and further to elucidate their properties, i.e. spin, parity, lifetimes, decay parameters, etc.

In the following only a few examples are shown, where the bubble chamber was first in detection of new particles in hadron beams and set the stage for higher statistics counter experiments.

The forte of the bubble chamber was evident in establishing the existence of Σ^0. The $\Sigma^+ \to \pi^+\mathrm{n},\ \mathrm{p}\pi^0$, and the $\Sigma^- \to \pi^-\mathrm{n}$ decays had been found and a counterpart of this isotropic triplet was expected on the basis of the Gell-Mann-Nishijima scheme of elementary particles. The expected mass and charge dictated that it should decay electromagnetically via $\Sigma^0 \to \Lambda^0\gamma$, and indeed this was observed.

Table 3. Stable particles with their source of production and method of detection. Detection methods: predominantly discovered by utilising cosmic rays.

Particle	Source of Radiation	Instrument
e^+	Cosmic ray	Cloud chamber
$\mu^\pm$	Cosmic ray	Cloud chamber
$\pi^\pm$	Cosmic ray	Nuclear emulsion
π^0	Accelerator	Counters
$K^\pm$	Cosmic ray	Nuclear emulsion
K^0	Cosmic ray	Cloud chamber
Λ^0	Cosmic ray	Cloud chamber
Σ^+	Cosmic ray	Nuclear emulsion
		Cloud chamber
Σ^-	Accelerator	Cloud chamber
Σ^0	Accelerator	*Bubble chamber*
Ξ^-	Cosmic ray	Cloud chamber
Ξ^0	Accelerator	*Bubble chamber*
Ω^-	Accelerator	*Bubble chamber*
Λ_c^+	Accelerator	*Bubble chamber*
p, n	Accelerator	Counters
B (Σ^+, Ξ^+, Ω^+)	Accelerator	*Bubble chamber*

With hydrogen bubble chambers the **associated production** of strange particles was demonstrated with π^- beams $\pi^- p \to \Lambda^0 \Theta^0$, $\pi^- p \to \Sigma^- K^+$, and $\pi^- p \to \Sigma^0\ K^+$.

One highlight of bubble chamber experiments was the proof of the existence of Σ^0. The expected mass and charge dictated that it should decay electromagnetically $\Sigma^0 \to \Lambda^0 \gamma$.

The Ξ^0 particle was expected from Gell-Mann-Nishijima scheme. The Alvarez group presented clear evidence for the Ξ^0 on the basis of one event. The reaction was

$$
\begin{array}{l}
K^- \pi \to \Xi^0 K^0 \\
\qquad\quad | \quad \lfloor\, \pi^+ \pi^- \\
\qquad\quad \lfloor\, \Lambda^0 \pi^0 \\
\qquad\qquad\ \lfloor\, p \pi^+
\end{array}
$$

The main features of this event are that the Λ^0 is not associated with the primary vertex and the K^0 is also observed: both force the hyperon to be a Ξ^0 (Fig. 1, schematic drawing).

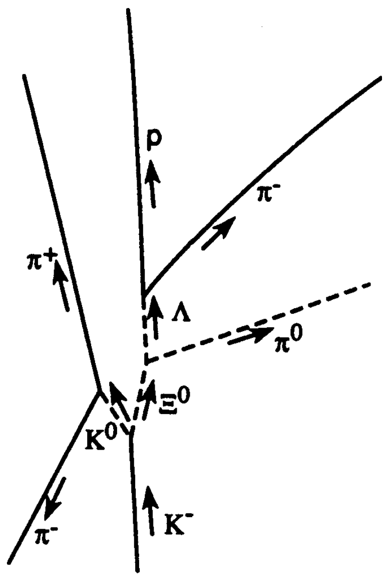

Figure 1: A Ξ^0 event from the 80″ bubble chamber at Brookhaven (schematic drawing).

Many techniques were used to determine the **spins** of these fundamental particles (production and decay angular correlation).

The first Ω^- **event** was found in the 80″ BNL chamber. It had a topology and a character that was completely unexpected, since the branching ratio into $\Xi^-\pi^0$, $\Xi^0\pi^-$, ΛK^- is 8%, 24% and 68%, respectively. The observed event, produced by a 5 GeV/c K^- beam, corresponds to the sequence (Fig. 2)

$$
\begin{array}{l}
K^- p \to \Omega^- K^+ (K^0) \\
\qquad\quad \lfloor \Xi^0 \pi^- \\
\qquad\qquad \lfloor \Lambda^0 \pi^0 \\
\qquad\qquad\;\, | \quad \lfloor \gamma \qquad \gamma \\
\qquad\qquad\;\, | \qquad \lfloor e^+e^- \lfloor e^+e^- \\
\qquad\qquad\;\, \lfloor \;\; p\pi^-
\end{array}
$$

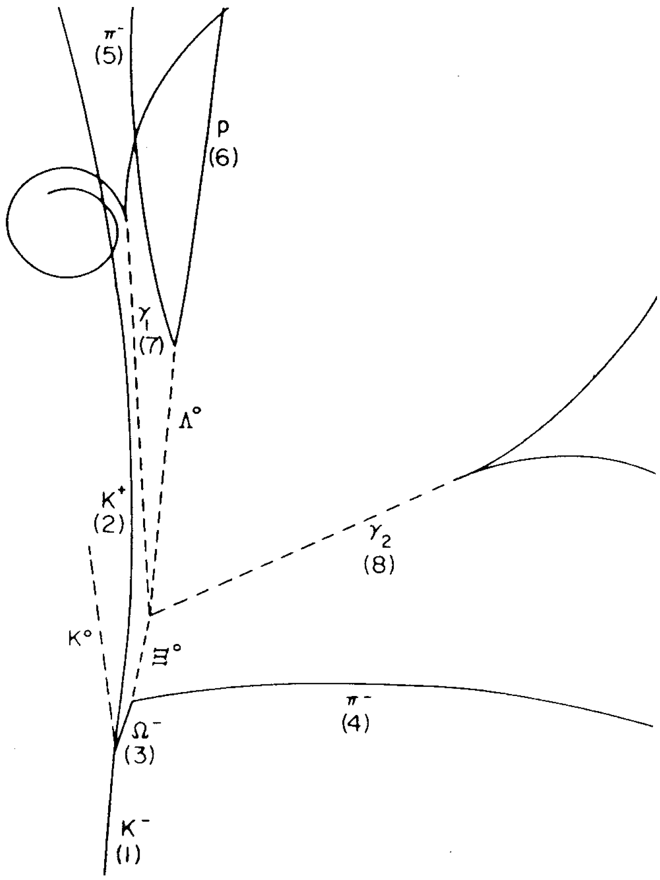

Figure 2: On the left is the photograph of the Ω^- event taken in the 80-inch bubble chamber with its reconstructed drawing on the right where neutral particles are indicated by broken lines. One of the several incoming K minus particles from the accelerator beam collided with a proton and created a neutral K zero meson (K^0), a K plus meson curving to the left, and an Omega minus (Ω^-) that after about 10^{-10} second decays into a Pi minus (π^-) and a neutral Xi zero (Ξ^0) particle. The Ξ^0 is identified by the disintegration of its neutral decay products; two gamma rays (γ_1 and γ_2) that give rise to positron-electron pairs, and a Lambda zero (Λ^0) that yields a π^- and a proton (p). Knowledge of the masses and momenta of the charged decay products of neutral particles that leave no tracks made it possible to identify the third particle emerging from the initial collision as a K^0.

The event has some unusual characteristics: (i) The Λ does not point to decay vertex, (ii) the transverse momentum of the decay π^- exceeds that expected from Ξ^- decay, (iii) the two gamma rays from π^0 decay materialize (probability 10^{-3}).

Shortly afterwards, in September 1964, a second Ω^- was found (Fig. 3). The reaction observed was

$$
\begin{array}{l}
\mathrm{K^-p} \to \Omega^-\mathrm{K}^+(\mathrm{K}^0) \\
\qquad\quad | \qquad\quad \lfloor \pi^+\pi^- \\
\qquad\quad \lfloor \ \Lambda^0\mathrm{K}^- \\
\qquad\qquad | \quad \lfloor \pi^-\pi^-\pi^+ \\
\qquad\qquad \lfloor \ \ \mathrm{p}\pi^-
\end{array}
$$

A clean example for the production of Σ^+, albeit not the first one, came from the 2-m hydrogen bubble chamber at CERN, exposed to a 10 GeV/c K^- beam (Fig. 4). The reaction observed was

$$\mathrm{K^-p} \to \Sigma^+\mathrm{K}^0\mathrm{K}^+\pi^0\pi^-\pi^- \ .$$

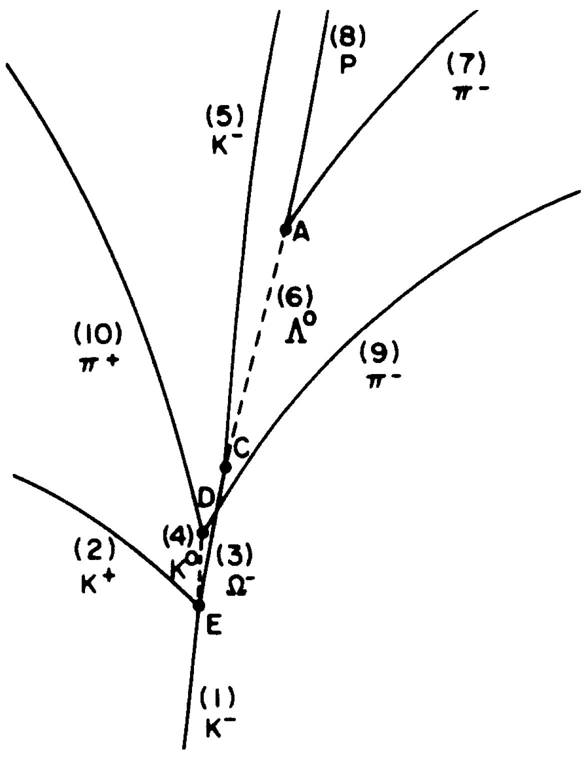

Figure 3: The second observation of an Ω^- event in the Brookhaven 80-inch hydrogen bubble chamber.

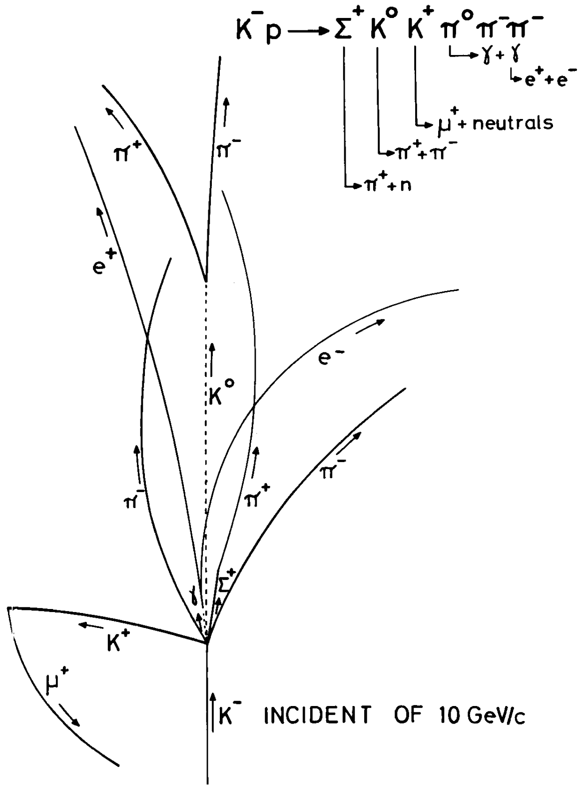

Figure 4: One of the first observations of a Σ^+ event in the CERN 2-m hydrogen bubble chamber.

The odd $\mathbf{K}\Lambda$ relative parity was obtained in a helium bubble chamber.

A beautiful bubble chamber experiment clearly demonstrated even $\Sigma\Lambda$ parity, which posed for a long time a problem.

With the advent of intense neutrino beams at Brookhaven, CERN and IHEP and the construction of huge bubble chambers, several new particles were found. A baryon charm stands out, that was found in the $7'$ bubble chamber at BNL (Fig. 5). The reaction chain was

$$\begin{aligned} \nu \mathrm{p} \to \mu^- \, & \Sigma_c^{++} \\ & \lfloor \Lambda_c^+ \pi^+ \\ & \quad \lfloor \Lambda^0 \pi^+ \pi^+ \pi^- \\ & \qquad \lfloor \mathrm{p} \pi^- \end{aligned}$$

With one event two new particles were discovered: Σ_c^{++} (cuu) and the Λ_c^+ (cud).

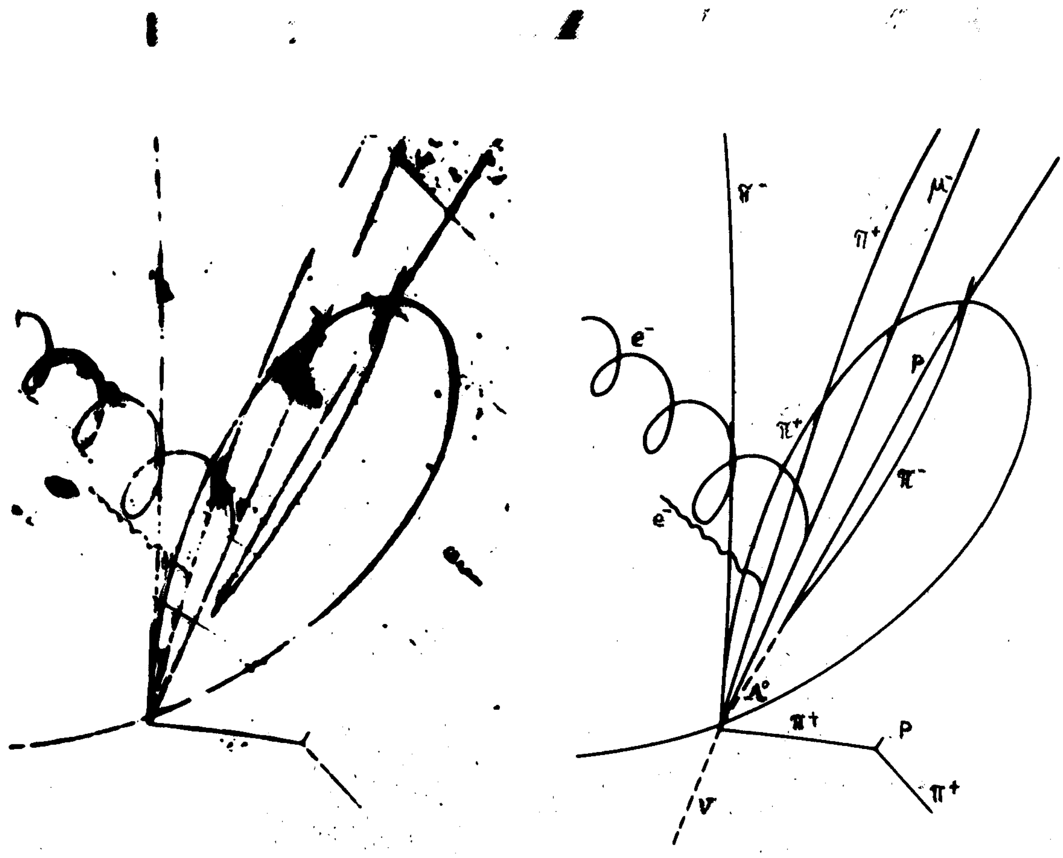

Figure 5: First evidence for a charmed baryon Σ_c^{++} produced by a neutrino in the 7-Foot hydrogen bubble chamber at Brookhaven.

3.2. Meson Resonance

Bubble chambers have played an immensely important role in developing our understanding of meson resonance. As a matter of fact, if we look at the four lowest lying meson nonets: O^{-+}, 1^{--}, 2^{++}, and 1^{++}, all the 27 states in the last three nonets were discovered via the bubble chamber technique. In addition, their spins and parities were determined in bubble chamber experiments. Experimental results were obtained on K*(892), ρ Resonance, ω Resonance, η Meson, φ Meson, and A_2 (split).

3.3. Baryon Resonance

Baryon resonance has been the most profitable among the wide range of subjects that the bubble chamber technique has covered. These resonances naturally subdivide among three known strangeness states:

S	=	-1	State (Alvarez 15″ hydrogen chamber, late 50s). Golden period 'bubble-chamber hyperon-resonance'. symbiosis
S	=	-2	State (premature demise of bubble chambers cut investigations. short)
S	=	0	State, understanding of inelastic channels.

No other technique could have achieved as much.

3.4. Weak Decays of Charged K-Mesons and Charmed Particles

The investigation of weak decays illustrates beautifully the versatility and the power what is called hermiticity, high granularity and high spatial resolution.

Most of the decay modes and branching fractions of K^+ were studied in bubble chambers. K^+ can be stopped in the bubble chamber and decay without interacting with the nuclei in the operating liquid. $K^+_{\ell_3}$ decays were first studied in the Xe bubble chamber at the Bevatron, then in other heavy liquid bubble chambers.

Large statistics experiments were done in the LRL-Wisconsin 30″ chamber at Fermilab, with 3 million stopping K^+ decays, and during the X2-experiment in the CERN 1.1-meter chamber, with 5 million stopping K^+ decays. Of particular interest was $K^+_{e_4}$ decays with very small branching ratios.

3.5. Charm: Rapid Cycling Bubble Chambers as Vertex Detectors in Spectrometers

The combination of relatively small-volume (a few litres), rapid-cycling bubble chambers with large spectrometers for downstream identification of particles played an important role in charm physics (European Hybrid Spectrometer, EHS, at CERN, Multi Particle Spectrometer, MPS, at Fermilab). The expected charm life times range between 0.1 ps and 1 ps, which span decay lengths from 1.2 mm to 12 mm at the CERN PS, and from 2.4 mm to 24 mm at the Fermilab Tevatron. These short decay distances require small bubble sizes and densities of more than 8 mm^{-1} to distinguish clearly charged from neutral charm particle. The target should not contain any neutrons to allow for unambiguous discrimination between charm decays and secondary interactions. Moreover to measure clearly charm production cross-sections requires material of atomic number A = 1.

Following these requirements, the detector specifications ask for liquid hydrogen as target material, and a bubble chamber as detector. The chamber should be able to cycle rapidly and accept a reasonable number of primary tracks in view of the small cross-section for charm production.

3.5.1. LEBC and HOBC

At CERN a 1-litre LEXAN bubble chamber had been constructed using a thermoplastic polycarbonate as chamber wall material (LEBC). It was operated with liquid hydrogen at an expansion rate of 30 s^{-1} in combination with the EHS at CERN. A high-resolution optic system allowed for photography of bubbles with diameters of 15 μm. There were 858 identified charm decays recorded during experiments at CERN and another 56 during an exposure at MPS at Fermilab.

A different approach was taken by a 2-litre heavy liquid bubble chamber (HOBC) at CERN with two optic windows for *in-line holography.* Using this advanced photographic technique allowed for higher resolution over a larger depth of focus than with classical optics, resulting in a resolution of 12 μm. Exposure in a 360 GeV/c π^- beam, typically 70 beam tracks per expansion, with a 10 Hz cycling rate resulted in 40 000 holograms. 298 charm candidates were found.

3.5.2. SLAC 40″ Bubble Chamber

Apart from the DESY 85-cm bubble chamber, the SLAC 40″ Rapid Cycling chamber was the only other chamber operated at an electron accelerator. The chamber cycling rate was 10 to 12 Hz. Like LEBC it was operated over many years as the target within a hybrid facility.

3.6. Neutral Kaon Decays — Weak Process

An interesting modification of the technology consisted in heaving a K_L^0 beam in a vacuum pipe running inside the 1.1-m heavy liquid CERN bubble chamber. This allowed studying the process of the CP violating $K_L^0 \to 2\pi^0$ decay. 24 ± 6.3 events showed the presence of this CP violating mode. The ratio $\eta_{00}/\eta_{+-} = 1.16 \pm 0.20$ confirmed the presence of a CP violation in weak interactions.

3.7. The Discovery of Weak Neutral Currents

One of the most important highlights of the bubble chamber era and an outstanding success story for CERN was the discovery of weak neutral currents. This was done in Gargamelle, a giant heavy liquid bubble chamber, filled with 10 tons of liquid and equipped with an external muon identifier. The chamber was exposed first to the neutrino beam at the CERN Proton Synchrotron (PS), where the decisive detection was made, and later in the neutrino beam at the Super Proton Synchrotron (SPS). Parallel with the operation of the chamber and the evaluation of the photographs from the PS exposure went detailed background calculations on neutron-induced events, which could simulate neutral currents. It turned out that this background was only 15% of the signal and so neutral currents were established.

3.8. Deep Inelastic Neutrino Interactions and Charm Production

The bubble chamber technique has made significant contributions to the study of deep inelastic neutrino interactions and charm production by neutrinos. The studies of inelastic neutrino interactions helped establish the quark structure of the nucleon and provided an early measure of the QCD forces between quarks. The observation of charm production by neutrinos helped establish the existence of charmed particles and provided evidence of the preferential coupling of charm to strangeness.

The two giant cryogenic bubble chambers, BEBC and the 15-Foot, as well as Gargamelle, were equipped with external muon identifiers (EMI). This combination of electronic and visual detector was crucial for unambiguous identification of the muon, after it had left the chamber liquid and had passed through thick absorber layers.

Dilepton production rate in neutrino bubble chamber experiments was dominated by an experiment in the 15-Foot Bubble Chamber at Fermilab, with a total of 659 dilepton events. This experiment established the ratio of 1.35 ± 0.24 strange particles/$\mu^- e^+$ event, and the ratio $\mu^- e^+/\mu^- = 0.45 \pm 0.04$. Dilepton production by *antineutrinos* in the same chamber resulted in a total of 16 events, and a ratio $\mu^+ e^-/\mu^+ = 0.20 \pm 0.06$.

Figures 6 and 7 give examples of a D^* and a Λ_c^+ produced by neutrinos in the BEBC chamber at CERN SPS. They show also the quality of optical registration and the cleanliness of pictures, which allows for precise reconstruction of the complete chain of reactions.

4. SPECIAL TECHNOLOGICAL DEVELOPMENTS

4.1. BEBC: technical challenges and performance

The Argonne 12-Foot Bubble Chamber, the Fermilab 15-Foot Bubble Chamber and the CERNs Big European Bubble Chamber (BEBC) have many features in common, so a detailed description of the latter can stand for the two other. Out of its total volume of 35 cubic metres some 20 cubic metres could be photographed simultaneously by four cameras.

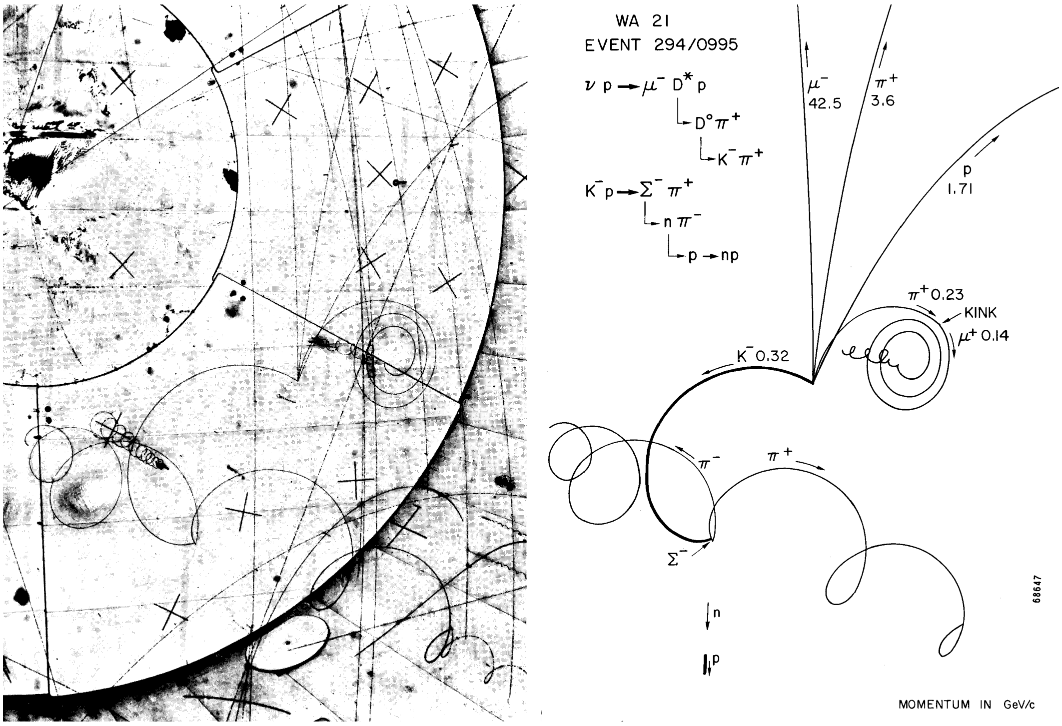

Figure 6: The production of a D* charmed particle by a neutrino in BEBC filled with hydrogen.

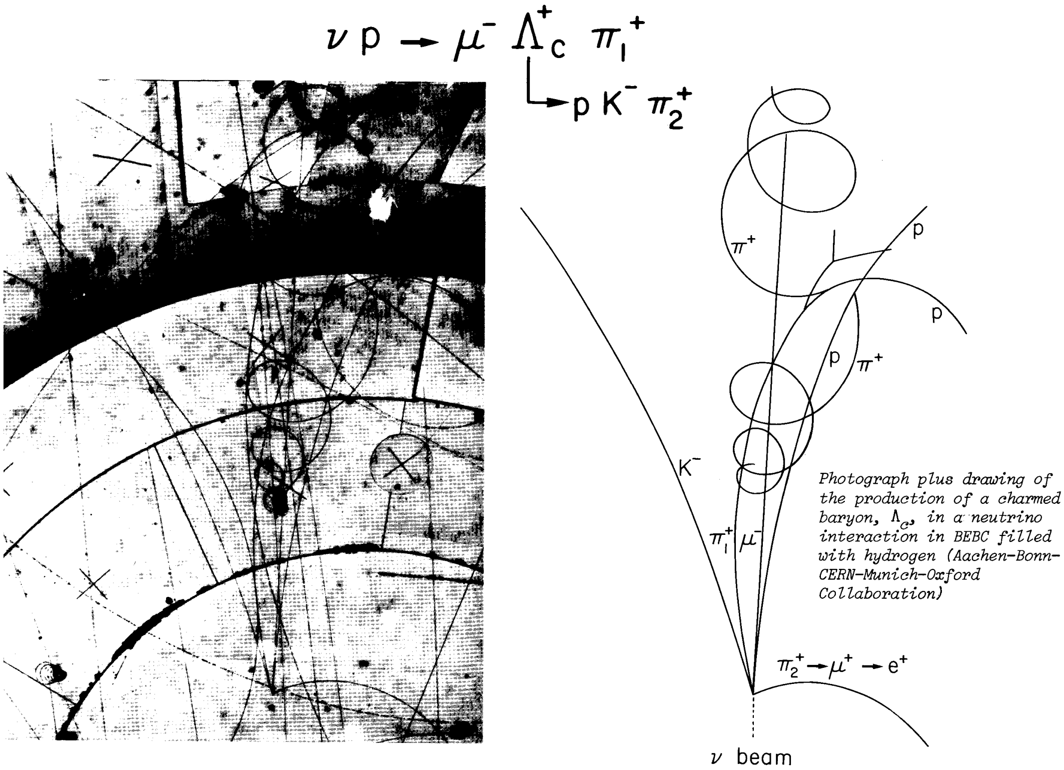

Figure 7: Production of a charmed baryon, Λ_c, in a neutrino interaction in BEBNC filled with hydrogen.

Careful pre-studies had shown, that the standard dark field illumination was no longer applicable to these dimensions, that flat windows could no longer manufactured of this size, and that the risk of failure due to thermal stress during cool-down to liquid hydrogen temperature became unacceptably high. A way out of this bottleneck was the use of Scotchlite, a retro-directive material, with which the chambers interior could be wall-papered. The chamber liquid was then seen by a wide-angle lens, surrounded by an annular flash tube, sending the light and photographing through three concentric hemispherical windows (Maxwells fisheyes). Light reflected from the Scotchlite was scattered by the bubble and can not reach the film, in this way registering the tracks as white strings on dark background. The largest window was in contact with the cryogenic liquid, the smallest had to be at ambient temperature. The demands on the reconstruction precision of tracks of better than 300 micrometres demanded a concentricity of the three hemispherical windows of 10 micrometres at the bubble chamber working temperature. The cameras had to work in a high magnetic stray field, so their film transport had to be done by hydraulic means.

Demands on the thermodynamics were equally important. The temperature gradient over a height of 4 metres was not allowed to exceed 0.1 K in order to avoid distortions of the track images.

The moving part of the expansion system had a weight of 2 tons. The piston with a diameter of 2 metres had to be displaced by 10 centimetres in 30 milliseconds downward and afterwards is 30 milliseconds upward, always synchronized with the arriving particle beam, demanding a jitter smaller than 1 millisecond. The upper part of the piston is in direct contact with the liquid at 25 K, the shaft and driving mechanism at ambient temperature. Triple pulsing in a 10.8-second long accelerator cycle was regularly obtained during combined runs in the hadron and neutrino beam. During the ten-year lifetime of BEBC 13 million expansions were performed and 6.3 million four-view photos were taken on 70-mm film (resulting in 3000 km total film length). Circa 150 publications appeared in scientific journals, the result of 22 experiments and the effort of 591 experimenters.

The combined Helium/Hydrogen refrigeration plant, one of the largest at the time in Europe, had a capacity of 25 kW at 22 K, which corresponds to the liquefaction of 1000 ℓ/hour on the hydrogen side, and 1.5 kW at 4.4 K (700 ℓ/h) on the helium side. The magnet surrounding the bubble chamber vessel was the largest sized one at the time of construction. It consisted out of two superconducting NbTi coils in Helmholtz arrangement, with an inner diameter of 4 metres, and a height of 4 metres, producing a field of 3.5 Tesla with a current of 5700 Amperes. The weight of the coils was 276 tons, the attraction force between them 9000 tons, and 740 MJ were stored when operational. The magnet was kept below liquid nitrogen temperature for about ten years, and had full current for 25 000 hours.

4.2. Track Sensitive Target (TST): A bubble chamber within a bubble chamber

Track sensitive targets combine the advantages of hydrogen/deuterium as target liquid with those of heavy liquid for efficient gamma conversion. Interactions of beam particles occur exclusively with free protons in hydrogen or quasi-free neutrons in deuterium, and neutral pions, which form 1/3 of the produced secondaries, are detected via the conversion of their decay gammas into electron-positron pairs in the neon/hydrogen mixture. Both liquids are separated by a transparent box (TST) where the flexible walls transmit the pressure reductions of the bubble chamber into the pure liquid hydrogen or deuterium in order to obtain track sensitivity simultaneously inside the TST and in the surrounding neon/hydrogen filling of the bubble chamber.

Successful feasibility tests of this innovative technology were made in the DESY 85-cm Bubble Chamber, first with a H_2-filled target in a 14 mole % Ne/H_2 mixture, and later with a D_2-filled target in a 95 mole % Ne/H_2 mixture.

Physics runs followed in the British National (150-cm) Bubble Chamber at Rutherford Laboratory in π^+ and p beams, and finally in BEBC with a 3-m^3 TST in ν, 70 GeV/c π^-, and 70 GeV/c p beams. Fig. 8 shows the first observation of the production and decay of a completely reconstructed Σ_c^+ by using this technology.

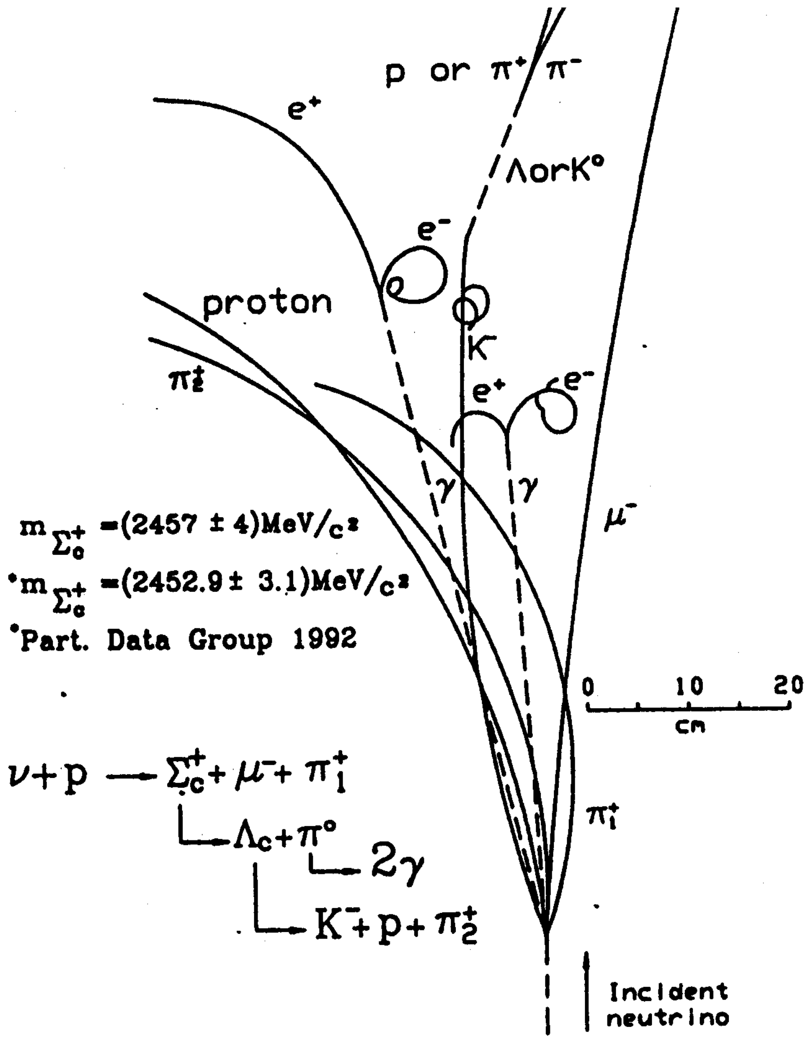

Figure 8: First observation of the production and decay of a completely reconstructed Σ_c^+.

4.3. Small holographic bubble chambers: BIBC, HOBC, and HOLEBC

Whereas huge bubble chambers found their application mainly in neutrino experiments, the domain of small (*holographic*) bubble chambers was in the precision measurement of rare decays with extremely low lifetimes. The Bern Infinitesimal Bubble Chamber (BIBC) was the first to try out in-line holography. A physics run was made with the 2-litre holographic heavy-liquid chamber (HOBC) at. The technology was also tried out with the modified LEBC. The success in small chambers encouraged developments of this technique for the giant chambers.

4.4. Holography in the 15′ Bubble Chamber

A major challenge for bubble chamber physicists working with giant instruments was the visual observation of the tau neutrino via its tau decay in a beam dump experiment. Two efforts were made: one by the Tohoku bubble chamber group that designed a heavy liquid chamber for Fermilab for this purpose, and another through the modification of the 15-Foot bubble chamber. Only the latter will be briefly described, where all the technical difficulties on the detector side were surmounted. However, the decisive experiment could not be done, since the budget for building the beam dump and its shielding did not get approval from the Department of Energy (DOE).

It was recognized from the very beginning that for big bubble chambers conventional and holographic photographs had to be used in combination. The recording of the same interaction with the two methods allows quick, efficient scan and the complete kinematical reconstruction of the entire events within the large volume, photographed in bright-field illumination with standard optics. The holograms with their enhanced resolution are used afterwards to study in more detail the vertex region for close-in decays. In order to make full use of holography the bubbles had to be illuminated with a laser beam shortly after their creation when they are still small. The conventional photographs are taken some milliseconds later, when the bubbles are much larger. A scheme was adapted which required that the laser beam enter the chamber from the bottom. It passes through a specially designed lens — a sophisticated beam splitter. Only the very small, center part of the laser light, the reference beam, reaches almost undisturbed one optic port on the top of the chamber. The rest of the beam illuminates the tracks within a conical volume. The intensity of this object beam is designed to increase at large angles to partially compensate for the decrease of light scattered by bubbles at this angle.

Multiple problems had to be overcome, a major one was that a Q-switched laser beam causes excessive parasitic boiling, not affecting the holograms, but disrupting the light needed for the conventional photos. Other anticipated disturbances were: (i) vibration of the equipment during the expansion of the chamber, (ii) movement/growth of bubbles during exposure, and (iii) multiple scattering of the laser light from the chamber wall, which adds unwanted, non-coherent light to the reference beam.

The main effort went into the design of a pulse-stretched ruby laser, to overcome the unwanted heating effect, and light absorbing baffles inside the chamber to protect against scattered light. The influence of the magnet stray field of the bubble chamber, and hydrogen safety were other obstacles during the eight-year development, done mostly on a part-time activity by hundred physicists/engineers. During physics run in the Quadrupol-triplet neutrino beam, with 800 GeV/c protons on target, 440 000 conventional three-view photos together with 220 000 holograms (110 000 good quality) were taken. Real and virtual image machines for the replay of holograms were successfully used for the analysis of this important, last neutrino run in 1987/88.

The Tohoku-MIT holographic bubble chamber ran successfully upstream in the same neutrino beam line.

4.5. The 11.4–Tesla Hyperon Bubble Chamber: HYBUC

The Hyperon Bubble Chamber, HYBUC, was a 50 Hz rapid cycling 30-cm high, 4-litre precision hydrogen chamber. HYBUC was the only successful high field chamber. Its superconducting magnet was operated at CERN at a magnetic field of 11 Tesla for more than 5000 hours. It had been built by a Vanderbilt-MPI Munich collaboration. 120 000 in flight Σ^- and Σ^+ decays were used to measure the lifetime, the Σ^+ nonleptonic decay branching ratio and the ratio of Σ^+ decay asymmetry parametres with unprecedented precision.

4.6. A Liquid Argon Hybrid Detector

The future of the use of bubble chamber at giant new accelerators, like the Superconducting Super Collider (SSC) in the United States, seemed still to be assured and bright at the beginning of the eightieth, and bubble chambers were not yet phased out. Therefore, a challenging aspect was the combination of the visual technique with electronic recording for fixed target physics at this kind of machine. One liquid 'argon' had never been tried as chamber liquid before, since it is a noble gas and seemed not to be suited. However, argon is particularly interesting because of its variety of properties. If its track sensitivity to ionizing particles could be shown during a bubble chamber expansion, then the possibility of drifting free electric charges (electrons) over large distances, and the strong scintillation signal produced by ionization when traversing the liquid, could be combined to a powerful hybrid detector. The author demonstrated that these features could be achieved and employed simultaneously with the well-known advantages of the bubble chamber technique. These features are the homogenous material, high resolution near the interaction vertex, curvature measurement in the magnetic field, energy range relation for slow particles, and particle identification from ionization via bubble density. Calorimetry offers charge collection for very energetic electron or hadronic showers, when measurements from tracks become tiresome or even impossible. The fast scintillation pulse provides another means for the measurement of total energy in dense showers. In addition the trigger derived from the scintillation signal can help to distinguish between the neutrino interaction and background events during long spills. Further advantages of liquid argon are that it is cheap (1% in the air we breeze), non-inflammable, and can be cooled with liquid nitrogen.

A chamber proposed on these principles was never realized, since high-energy physics took a turn away from fixed-target experiments at the planned SSC towards colliding beam experiments at the Tevatron at Fermilab and LEP at CERN.

5. DATA HANDLING

5.1. Measuring machines

Measurements on bubble tracks started manually using stereo projectors. Soon, the spatial reconstruction of the tracks made the use of computers imperative. The relevance of combining measuring equipment with computing capacity was recognized. The sociological aspect of decentralized measuring and computing was quite early understood. Bubble chambers were the first detectors where international collaboration came together then took their data in form of film rolls back to home institutions and did there the analysis. This was unprecedented for any of the counter experiments.

Many measuring machines were built, in the USA known under the names Frankenstein, POLLY, and PEPR, in Europe called MYLADY, HPD, Spiral Reader, and ERASME. Of the devices built for automating the measurement of bubble chamber tracks, the most successful was the Franckenstein, the first of which operated at LRL in 1956. The next step in the development was the Spiral Reader. It was the first machine where a digital computer was used to reject irrelevant data and to 'recognize' as such the digitisings belonging to each track. An operator was to remain at the center of the measurement process. In contrast, with the Hough-Powell Device or HPD, one set out to scan the film itself with a spot of light comparable in size to the bubble images and one separated the operator from the measurement process. ERASME was the final device built at CERN and copied by many European laboratories. It allowed to almost automatically measure hundreds of thousands of events per year.

5.2. Computers and programs

Bubble chamber data analysis started at a time when data processing was based on files mechanized on Hollerith cards and way before *Computer Science* existed. The concepts of how to organize big data processing had yet to be established. Physicists had to invent much of the instrumentarium of software for themselves. Most of the programs were written in FORTRAN for machines like the IBM 650. The size of the programs increased considerably with time, composed of geometry and kinematics parts.

It is often forgotten that Monte-Carlo Programs, now common tools all other high-energy physics had their roots in bubble chamber data analysis, mainly related since 1983 to neutrino experiments.

6. SOCIOLOGY, PEDAGOGICAL IMPACT, LEGACIES

Bubble chamber experiments brought physicists from almost all over the world closer together. The participants generally did not have the technical knowledge to run the chamber, since most of the chambers were considered facilities, operated by their designers at the accelerator laboratories. Data could be exchanged either by recordings on magnetic tapes or over the telephone line. Collaboration meetings were held, bringing experimenters together at various places. The size of collaborations varied, but in general did not exceed the hundred limits; mostly it was only half this number. The formation of 'large' collaborations, as we see it today at colliding beam machines, was not yet on the horizon when the bubble chamber technology had to give way to counter experiments. At colliding-beam machines the visual technique could not find any application.

Most of the counter physicists got their first training at bubble chambers, where they could 'see' the interaction of particles. They learned from this base how to design the electronic counter part, that would provide faster data accumulation, albeit sometimes with lower precision.

Education on the behavior and composition of elementary particle does not stop on the senior physicist level. Bubble chamber photographs are of immense value in education for lay person, starting with high school children.

The technological impact of bubble chambers on industry was many folds. The design of cryogenic bubble chambers gave a considerable boost to new developments, is it on the small scale in medicine or computer technology, be it on a large scale for instruments used in space research. In particular the advance in superconductivity can not be underestimated. The Tevatron, the future LHC, and other superconducting accelerators and their beam lines profit from the experience collected during the design of giant and small high-field superconducting magnets around bubble chambers.

Optic developments made big jumps forward, including holography and development of pulse stretched high power lasers.

Giant computer programs were written, together with instructions for a great variety of users. Data handling and data transmission made a great step forward and pointed to the development of the Internet.