

When the bubble chamber

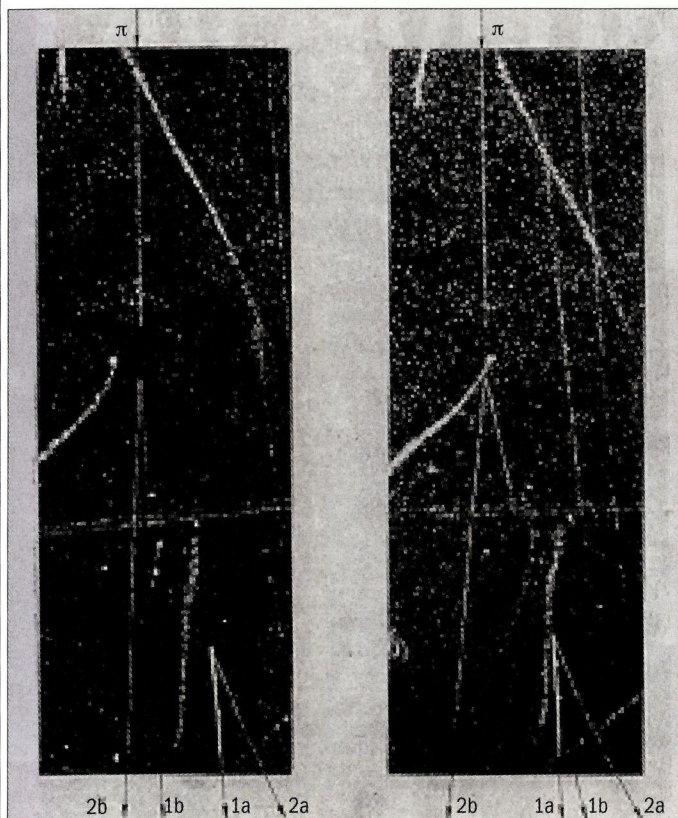


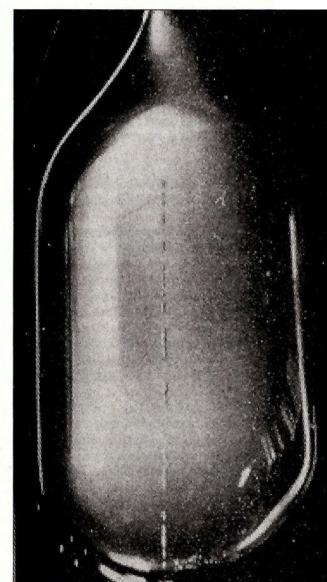
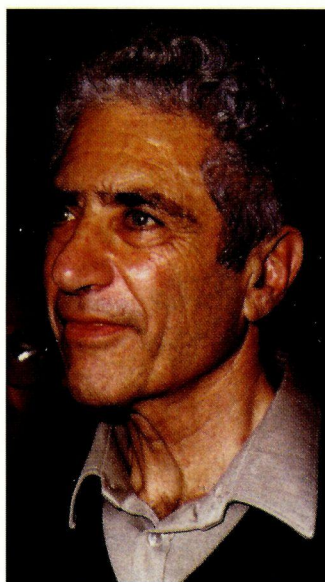
Fig. 1. Before the bubble chamber – Brookhaven Cosmotron diffusion chamber photograph of a 1.5 GeV negative pion producing two neutral V-particles, seen via their characteristic decays. Tracks 1a and 2a, believed to be a proton and a negative pion respectively, are the decay products of a Λ . A kaon is probably seen to decay into a positive and a negative pion (1b, 2b).

Strange particles were first seen in 1947 in a cloud chamber of Blackett, triggered by hadron showers produced by cosmic rays. Soon after, other strange particles, then called V particles, were also seen in nuclear emulsions. Progress in our understanding of these new particles was slow, partly because the experimental possibilities were limited to cosmic-ray observations, and partly because the phenomena were so totally outside of what was then known.

I remember in 1949, on a bulletin board at the Princeton Institute of Advanced Studies, a photomicrograph of a nuclear emulsion event, showing what is now known as a K-meson decaying to three pions. We all saw it. There could be no doubt that something interesting was going on, very different from what was then known, but it was hardly discussed because no-one knew what to do with it.

The copious production of these particles, indicative of the strong interaction, was at odds with their long lifetimes, indicative of the weak interaction. Pais noted in 1952 that this could be understood by inventing a feature of the strong interaction, a selection rule, which

On 25 May 2001, Jack Steinberger, who shared the Nobel Prize for his work on V particles, reaches his 80th birthday. His memoir *My Years in Nuclear Science* in 1997 (vol. 47, xiii). Jack is one of the few people in this article pulls together some episodes from the



Left: CERN stalwart Jack Steinberger. Right: Fig. 2. Track of a cosmic ray particle in Donald Glaser's first bubble chamber.

would permit their production but forbid their decay via the strong interaction. He implemented this in a mechanism that required the new heavy particles to be produced in pairs. This was extended some months later by Gell-Mann, who ingeniously combined the selection rule with the notion of isotopic spin. It required that the pair of Pais be composed of a "strange" and an "antistrange" particle.

Enter the accelerator

The arrival of accelerators of sufficient energy facilitated the study of these new particles enormously. The Brookhaven Cosmotron accelerated protons to 3 GeV, six times the energy of the highest energy cyclotron, and sufficient to produce the new particles in collisions on nuclei, and Ralph Shutt and colleagues had developed a new type of cloud chamber. The V particles produced in cosmic-ray showers had been observed in cloud chambers, but these were very inefficient for accelerator experiments because, once made sensitive by expanding the gas, they would require 1 min of relaxation before they could be expanded again. The accelerator cycle, however, was typically 1 s. The new "diffusion" cloud chamber, in contrast, was continuously sensitive and made it possible to demonstrate the production of strange particles in pairs and verify the hypothesis of Pais and Gell-Mann (figure 1).

er first burst onto the scene

ed the Nobel prize in 1988 and is one of CERN's
s of his early life were published in *Annual Reviews*
continuing to work on his reminiscences, from which
the bubble chamber era of the 1950s and 1960s.

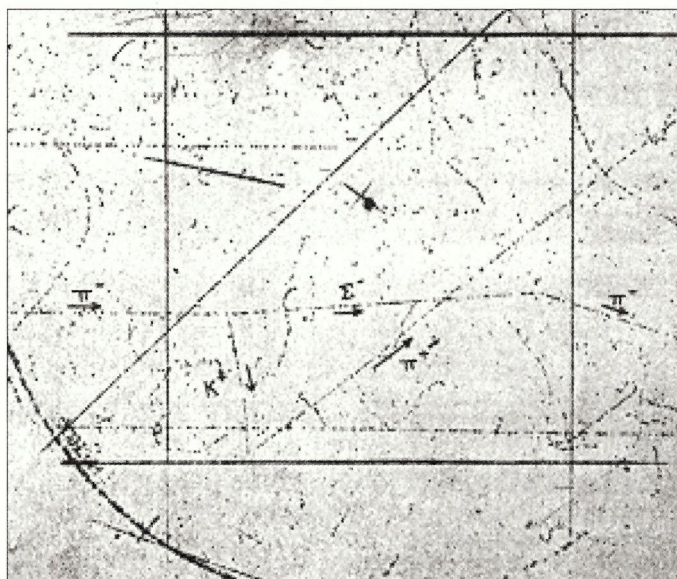


Fig. 3. An early Cosmotron bubble chamber photograph showing the associated production of two strange particles – a positive kaon and a Σ^- .

Two years later, in 1955, Gell-Mann and Pais noticed that the neutral kaon should exist in two versions, one strange and the other antistrange, one the antiparticle of the other. In addition to the known neutral kaon, there should be another one, with the same mass but with much longer lifetime and with different decays, with opposite symmetry under space inversion.

This idea, which seems obvious now, was not obvious at the time. It was not easy for me to understand or to accept this proposal when I read it, but a few days later T D Lee succeeded in explaining it to me. Once understood, the idea could not be rejected.

The experimental confirmation a year later by Lederman and Landé marked a big step forward. It was also carried out at the Cosmotron, and used what was, to my knowledge, the largest cloud chamber ever, 1 m in diameter. The large size made it more likely that the long-lived kaon, with a decay path of the order of 10 m, would decay inside. The chamber had been built at the Nevis laboratory some years before, but had never found any use. This, to my knowledge, was also the end of the long and glorious career of the cloud chamber in particle physics.

In 1953 Donald Glaser invented the bubble chamber, which went on to dominate particle physics, especially strange particle research, for the next 20 years. He showed that energetic particle trajectories



Fig. 4. A propane chamber with a magnet discovered the Σ^0 in 1956. A 1300 MeV negative pion hits a proton to produce a neutral kaon and a Σ^0 , which decays into a Λ^0 and a photon. The latter converts into an electron-positron pair.

can be made visible by photographing the bubbles that form within a few milliseconds after particles have traversed a suitably superheated liquid (figure 2).

The bubble chamber

The advantage of the bubble chamber over the cloud chamber at accelerators was two-fold: the higher density of the liquid proportionally increased the number of interactions produced in it, and it was faster to reactivate, matching the frequency of the accelerator cycle.

Within a year, John Woods, in the group of Alvarez at Berkeley, succeeded in producing tracks in liquid hydrogen. The chamber was a metal cylinder to which glass plates were attached, using indium ribbons as seals. In addition to being a major cryogenic technical achievement, this also demonstrated the crucial fact that for use with accelerators, where the expansion can be timed with respect to the accelerator cycle, the bubble chamber environment need not be as ultra-clean as was the glass vessel of Glaser, which permitted the liquid to survive in its superheated state for relatively long periods.

Three graduate students, John Leitner, Nick Samios, Mel Schwartz, and I began work at Nevis on the design of a practical

experimental bubble chamber to study strange particle production at the Cosmotron, I think early in 1954. By 1955 we had a 6 inch (15 cm) diameter liquid propane chamber. This was used at the Cosmotron in the first experiment using this new technique. The work profited a great deal from a generous collaboration as well as friendship with the inventor, who was working on a similar project at Brookhaven with his former student, David Rahm.

Rapid action

Our main technical contribution at Nevis was the discovery of a rapid action three-way gas pressure valve, the "Barksdale" valve. This made it possible to recompress the liquid within milliseconds after the expansion, and so to reduce the undesirable thermal effects that result if the pressure remains low for longer times and greater quantities of liquid boil.

As work progressed, we were joined by R Budde from the newly established CERN laboratory, who had been sent to learn about the new technique. The chamber had a serious flaw, which we nevertheless accepted in order to get experimental results – the liquid became clouded and lost its transparency after a few hours of operation. It was then necessary to empty and to refill the chamber, with a consequent loss of time.

The experiment used a pion beam of energy 1300 MeV, only slightly more than the minimum required to produce a strange particle pair. There was no magnetic field, so the particle momenta could not be measured. However, the information from the spatial directions of the observed particles, recorded stereoscopically, sufficed to permit the identification of Λ hyperon and neutral kaon decays, to distinguish collisions on hydrogen from those on carbon, and so identify the processes we wanted to study (figure 3).

The lifetimes of most of these particles are of the order of 10^{-10} s, and consequently their path length is typically some centimetres. The several dozen events obtained gave the first quantitative measure of the production probabilities and angular distributions for negative pion on proton reactions, giving a positive kaon and a Σ^- , and a neutral kaon and a Λ . In retrospect, the most interesting result was a precocious glimpse of parity violation, soon to be at the centre of the particle physics stage.

The development of bubble chambers went on apace. Within a year the 10 inch (25 cm) hydrogen chamber of Alvarez was in operation at the Bevatron, which was then, with 5 GeV protons, the world's highest-energy accelerator, and which had permitted the discovery of the antiproton by Chamberlain, Segrè, Wiegand and Ypsilantis in 1955. In 1959 this was superseded by the 72 inch (1.8 m) chamber, the workhorse of the Bevatron for more than a decade, which led to the discovery of several meson and hyperon resonances.

At Brookhaven the Shutt group made important technical advances. In 1958 its 20 inch (50 cm) chamber came into operation, followed in 1962 by the 80 inch (2 m) chamber. This went on to take 11 million photographs, and the results included the important discovery in 1964 of the triply strange Ω^- hyperon, confirming the SU(3) symmetry proposed by Gell-Mann to account for the multiplet structure and mass regularities of the observed strange particles, and which mothered the invention of the quark (figure 6).

At CERN a 30 cm hydrogen chamber came into operation in

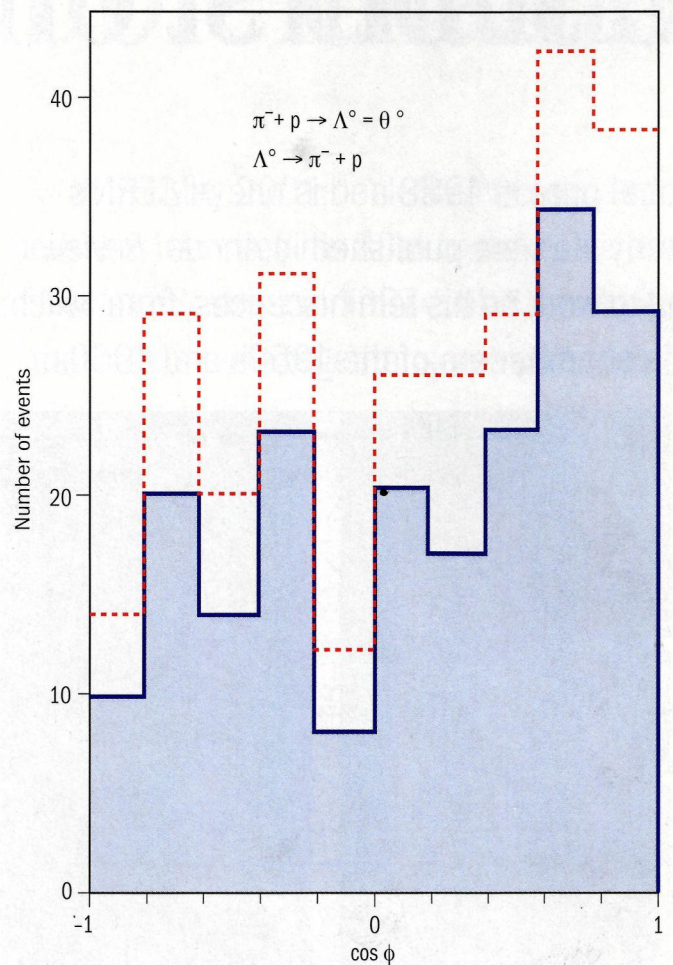


Fig. 5. 1957 – an early example of parity (left–right symmetry) violation. This shows the angular distribution in Λ decay. The shaded area contains events produced in the centre-of-mass angular region 30° – 150° . The asymmetry about 90° shows that parity is violated.

1960, and the 2 m hydrogen chamber in 1964. This became the main CERN tool for the study of resonant and strange particle physics for a decade and kept hundreds of physicists busy and happy. Gargamelle, a very large heavy-liquid (freon) chamber constructed at Ecole Polytechnique in Paris, came to CERN in 1970. It was 2 m in diameter, 4 m long and filled with freon at 20 atm. With a conventional magnet producing a field of almost 2 T, Gargamelle in 1973 was the tool that permitted the discovery of neutral currents.

These bubble chambers took pictures on film at the rate of about one per second. Many millions were produced. These had to be scanned, and the events of interest measured and reconstructed. At first we used the simple, manual techniques for scanning and measuring inherited from our cloud chamber predecessors: simple projection tables, protractors for angles, templates for the measurement of the track curvatures and manual computers.

However, just at that time commercial electronic computers were beginning to appear. We learned to construct digital measuring devices that would automatically punch the track co-ordinates onto cards, and to write increasingly sophisticated programs that utilized

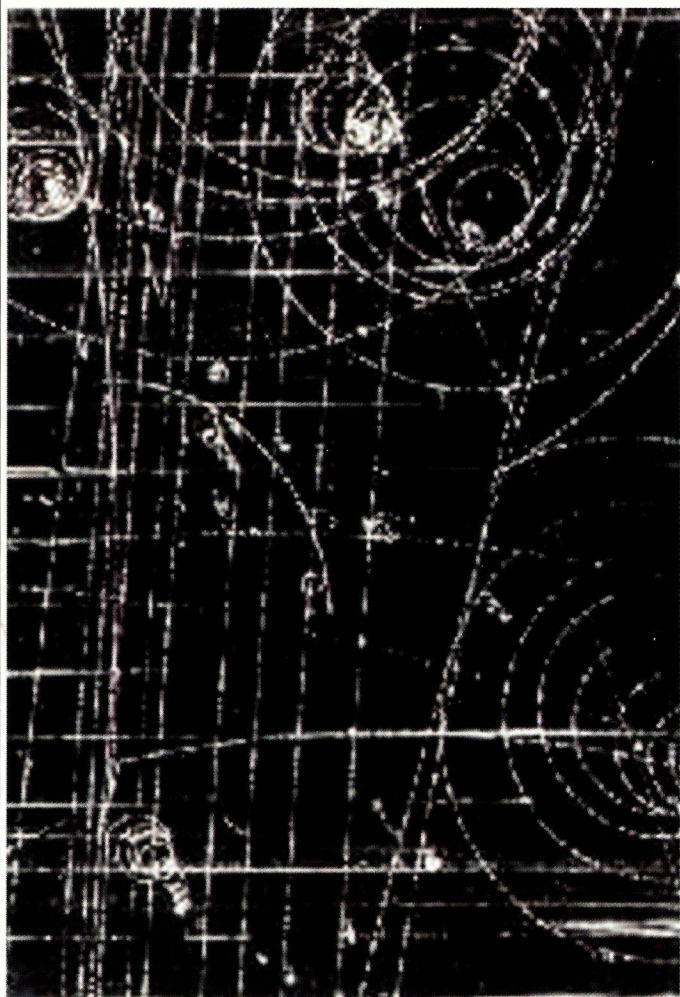


Fig. 6. 1964 – the bubble chamber classic, the production and decay of the Ω^- hyperon in Brookhaven's 2 m bubble chamber. This remarkable event permitted reconstruction of all particle momenta and the determination of the mass of the Ω^- .

the rapidly evolving power of computers to reconstruct interesting physical quantities. This was an essential element in the power that the technique developed. It was one of the early challenges to the evolving computer industry, and the bubble chamber community was able to contribute to the advancement of this technology.

At Nevis, in 1956, within a few months of the first chamber, we had our first chamber with a magnetic field. It was a propane chamber, 12 inches (30 cm) in diameter. The volume had increased eight-fold and the magnetic field was 1.3 T. One of the technical innovations was the introduction of a third camera, so that the field of view was photographed from three angles rather than two. This was essential to the automatic measurement and reconstruction of tracks parallel to the plane of two of the cameras.

In the first exposure we were able to discover the Σ^0 hyperon (figure 4) and measure its mass. Together with the previously known positively and negatively charged Σ s, the three formed an isotopic triplet, the first experimental evidence supporting the flavour SU(3) symmetry, later dramatically confirmed by the Ω^- .

The same magnet as well as optics also served our first hydrogen chamber, with dimensions similar to the propane one. This began

operation at the Cosmotron in 1957. The expansion of the liquid was accomplished with the help of stainless steel bellows, with the associated risk of rupture after many cycles of operation. This would have been an interesting accident involving substantial quantities of hydrogen. Nevertheless, I don't remember ever, at the time, trying to understand the likely consequences.

Soon after, Ralph Shutt at Brookhaven demonstrated that equally effective, but safer, expansion could be achieved with a piston sealed with teflon piston rings, and this was the method generally adopted afterwards. The 12 inch hydrogen chamber was used at the Cosmotron to continue the study of strange particle production, their decays and other properties. One of the first results was the demonstration of parity non-conservation in Λ decay, now with about 10 times as many statistics as with the premature experiment of 1956 (figure 5).

This combined the results obtained in the 12 inch propane and hydrogen chambers with those obtained in a somewhat smaller propane chamber by my mentor and inventor of the bubble chamber, Don Glaser. Similar results were also obtained by the Berkeley pioneers in the hydrogen bubble chamber development at the Bevatron.

This experiment was followed by a determination of the spins of the Λ and Σ hyperons. It was natural to assume these to be $1/2$, the same as those of the proton and neutron, in line with SU(3) symmetry, but this was not known experimentally.

One of the main interests of the bubble chamber community in the early 1960s was the discovery and study of meson and baryon resonances, and the determination of their properties and relationships to each other.

Resonances are excited states of hadrons that decay rapidly through the strong interaction, and therefore have poorly defined total energy or mass. The resonance "widths", or energy spread, are typically of the order of 100 MeV, corresponding to lifetimes of the order of 10^{-23} s.

Resonating properties

At the time, these resonances had the same right to be considered "elementary" as the stable hadrons. Now we understand all hadrons, stable or resonances, as bound states of quarks, and none is "elementary". The first meson resonance to be seen was the ρ , which decays into two pions, with a mass of about 750 MeV and a width of 150 MeV. It was discovered at the Cosmotron in 1962 by Erwin Walker *et al* in the 14 inch hydrogen bubble chamber of Adair-Leipuner, using beams of 1.89 GeV pions.

The first hyperon resonance was seen in Berkeley, which then had a 15 inch (38 cm) hydrogen chamber in operation at the Bevatron. Berkeley had also pioneered in the electrostatic separation of particle species, making use of the difference in velocity of particles previously selected to have the same momentum.

Using a negative kaon beam to produce $\Lambda\pi\pi$, the Berkeley group found a resonance in the $\Lambda\pi$ system with mass 1.38 GeV and width 37 MeV. The data favoured the assignment of spin $3/2$. Dozens of these resonances were found in rapid succession. This knowledge contributed to our understanding of the strong interaction, which crystallized in 1973 in the form of Quantum Chromodynamics.

At Nevis, in the meantime, we constructed two more chambers, again one using propane and one hydrogen. They were 30 inches (75 cm) in diameter, substantially larger than their

predecessors, but when they came into use, late in 1961, there were already larger chambers in operation. Some 12 million pictures were taken in the 30 inch hydrogen chamber.

In tune with the times, we did some work on the production and decay properties of resonances. In one set of measurements, antiprotons of a separated beam were brought to rest in the hydrogen chamber. The antiprotons combine with protons and annihilate, with many different possible final states, of different numbers of pions and kaons, and one could try to exploit these to gain some insights. One rather particular use we made of this exposure was the first determination of the widths of the ω and ϕ resonances. These were among the more interesting meson resonances that had been observed, and distinguished by the fact that their widths, or equivalently their inverse lifetimes, were too small to be measurable in the usual experiment.

In the case of the ω we were able to select a few proton-antiproton annihilations giving $\omega K^+ K^-$. Given the masses of the particles involved, the kaons are emitted with such small kinetic energy that they typically come to rest in the chamber. This made it possible to determine their energies very precisely from their ranges, and, by energy conservation, the mass of the accompanying ω . A similar procedure was used for the ϕ .

Searching for resonances at random was not my style, and I never looked for, nor found, a new one. I preferred to focus on something specific. In one experiment, negative kaons were stopped in the

chamber in order to study the relatively rare leptonic decays of Σ hyperons. In the same kaon exposure we could measure the relative parity of the Σ^0 and Λ hyperons.

Of these 30 inch chamber experiments, this was probably the one we valued most highly. This was also the thesis of a doctoral student who, in the meantime, had become my wife, after the first one had decided to throw in the towel in 1961.

End of an era

This was pretty much the end of my bubble chamber adventure. Since my first steps in physics in 1947, particle physics had advanced and changed very much. Cosmic rays had been entirely replaced by accelerators, experiments took more time, and were carried out by larger groups, more often 10 people than one or two. Quite a bit had been learned. Four elementary particles had swollen to dozens, the weak interaction had witnessed a wave of clarification in the wake of the discovery of parity violation, and particle detectors had advanced, with the advent of the scintillation counter and the bubble chamber.

I took great pleasure not only in contributing to our understanding of the physics, but also in the design and mechanical construction of the detectors: counters, liquid hydrogen targets, bubble chambers, even the electronics, where I did not shine particularly. ☐

• This article, fully annotated with references, is available at ["http://www.cerncourier.com/main/article/41/4/18"](http://www.cerncourier.com/main/article/41/4/18).

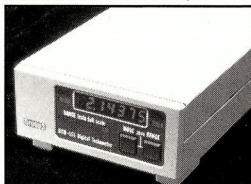
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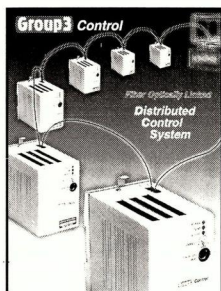


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