

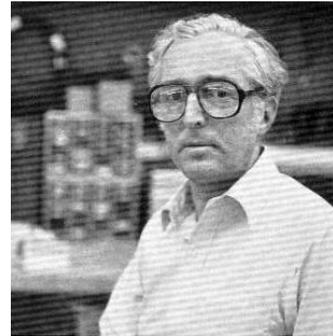
## Chapter 16 Experimental Particle Physics - CWRU

In 1965, after proposals seeking Science Development Program (SDP) grants had been made to the National Science Foundation by both CIT and WRU, there was increased pressure from various quarters (including the NSF) for the merger of the two institutions. Ultimately, the NSF granted \$3.5 million *each* to CIT and WRU, essentially contingent on their eventual federation. Of this, a total of \$2.6 million was assigned to the two physics departments. It took several years for the combined department to reach equilibrium. There were some bumps in the road. To put it simplistically, these were rooted in the differences between the “pure physics” research, “university” atmosphere, and the BA degree at WRU and the “applied physics” research, “tech school” atmosphere, and the BS degree at CIT. The two departments had a total of 31 faculty in 1963, which grew to 53 by 1966. By 1971, four years after federation, this number had dropped back to 34, following the departure of such established players as Reines, Smith, Kisslinger, Weinberg, Zilsel, Klein, Reichert, as well as the non-reappointment of several young tenure-track assistant professors who had been hired around the time of federation. There were no new hires between 1974 and 1980. (*Thanks to Chandrasekhar for his compilation of these numbers.*)

### Jenkins, Blanpied, Frisken, Sullivan: accelerator physics - counters

In the allocation of the SDP funds, it had been agreed that three new experimental, accelerator-based, particle physics groups would be formed. The groups were referred to as the “counter group” (Jenkins, Frisken), the “bubble chamber group” (Keith Robinson, Fickinger), and the “intermediate energy group” (Willard, Bevington).

**Thomas Jenkins**, whom we met in Chapter 8 when he was working on neutrinos with Fred Reines, put together the “counter group”. His picture, taken around 1980, is shown in **Fig. 16-1**. Similar “counter groups” sprang up in the 1950’s and 1960’s at accelerator laboratories and universities across the world. Geiger counters, wire chambers, Čerenkov counters, scintillation counters, and spark chambers were the building blocks for experiments in which interactions involving specific particles traveling in specific directions were being studied. This technique was in contrast to experiments using bubble-chamber detectors. The latter allowed more of a “fishing expedition”, with particles traveling in all directions. The two approaches complemented one another. In some cases, counters looking for certain signals were used to trigger a bubble chamber in “hybrid” experiments.



**Fig. 16-1.** Tom Jenkins

Jenkins was joined in 1966 by **William R. Frisken** who had been doing counter physics at Brookhaven National Laboratory. He is the fellow on the left in **Fig. 16-2**, squatting in front of an array of wire chambers. Frisken was born in 1933 in Ontario. He earned a BS and MS at Queens University in Kingston, Ontario. He completed his



**Fig. 16-2.** Bill Frisken (left)

doctorate at the University of Birmingham in 1960, having studied proton-proton and proton-neutron scattering at the new Birmingham synchrotron. "Isotopic Spin Dependence of Nucleon-nucleon Cross Sections between 600 and 1000 MeV" *Nuovo Cim.* **21** 581 1961. He then spent two years at the Radiation Lab of McGill University where he did some nuclear physics, specifically, looking at protons coming from long-lived levels in  $^{25}\text{Si}$  produced at the 100 MeV proton accelerator. Frisken moved on to Brookhaven National Lab, where, for two years he worked with a Cornell counter-physics group.

Frisken was appointed associate professor in the Case department in 1966, just before the departure of Fred Reines and federation. He continued to work with his collaborators at Brookhaven on a series of accelerator-based high energy counter experiments. This work led to a series of papers on the elastic scattering by protons of pions, kaons, and antiprotons, beams of which had just become available at the Alternating Gradient Synchrotron (AGS). The measurements established the role of baryon exchange processes, i.e. collisions which are almost head-on in which the particles essentially reverse directions in the center of mass. "Backward Peaks in Elastic  $\pi$  p Scattering" *Phys. Rev. Lett.* **19** 460 1967. "High-Energy  $\pi$  p, K p and pbar-p Elastic Scattering" *Phys. Rev. Lett.* **21** 387 1968.

Jenkins and Frisken, along with two young post-doctoral colleagues, **Alan Strelzoff** (b. 1937; PhD Columbia 1964) and **Charles Sullivan**, (b. 1934, PhD Vanderbilt 1966) and three graduate students, constructed a large array of spark chamber detectors which they installed in the  $\pi^-$  beam at the Zero Gradient Synchrotron (ZGS) at Argonne National Laboratory near Chicago.

*A spark chamber consists of a set of parallel metal plates, a few centimeters apart, with a high voltage between them. When a charged particle crosses the gap between the plates, a visible spark appears in the gap. Cameras are triggered by nearby scintillation counters, and the pattern of sparks in the gaps is photographed. The film is then scanned for interesting events either by trained technicians or, as in the case of the Jenkins experiment, by an electronic scanning device controlled by an IBM 1802 computer (This refrigerator-sized computer had 16K of RAM (yes, K not M) and cost about \$200K.)*

In a run at the Argonne National Lab ZGS accelerator, using a beam of negative pions at 5.9 GeV/c momentum, the Jenkins group measured the differential cross section for charge exchange scattering ( $\pi^- p \rightarrow \pi^0 n$ ) at large center-of-mass angles. They detected both the neutron (which rescattered in their chambers) and the two photons from

the decay of the  $\pi^0$ . For the 5.9 GeV sample, 946,000 photos were scanned for acceptable candidates. Of around 6000 such, 782 passed all cuts. The authors compared the results with  $\pi^- p$  *elastic* scattering. In the forward direction, both channels are dominated by meson exchange, where the target proton emits a virtual meson (a  $\rho$  meson in this case) which is struck by the incident pion. In the backward direction, one sees baryon exchange, where the target nucleon takes on most of the momentum of the incident particle. Interference among the various exchange channels produces interesting structure in the angular distributions. The charge-exchange experiment at the ZGS was later extended to lower incident pion momenta, 3.7 and 4.8 GeV/c. "Measurement of the Reaction  $\pi^- p \rightarrow \pi^0 n$  at Large Momentum Transfers" *Phys. Rev. Lett.* **26** 527 1971; "Measurement of High Momentum Transfer  $\pi^- p \rightarrow \pi^0 n$  at 5.9 GeV/c" *Phys. Lett.* **51B** 390 1974.

These experiments are typical of the period, as many interactions involving two-body to two-body channels were being described theoretically in terms of scattering by a virtual particle ("one-particle-exchange model").



**Fig. 16-3.** Bill Blanpied

In anticipation of the generous NSF SDP money, the Case department added **William A. Blanpied** to its particle physics program in 1966. Born in Rochester in 1933, Blanpied received his PhD from Princeton in 1959. His photo is in **Fig. 16-3**. At Princeton he had studied polarization effects in the scattering of protons at 17 MeV. Blanpied was briefly on the faculty at Yale, working with Vernon Hughes on photoproduction experiments at the Cambridge Electron Accelerator. During his first two years at Case, he worked as part of a collaboration with a counter group at Harvard, looking at muon pairs at the Brookhaven AGS accelerator. "Observation of Muon Pairs Produced by High-energy Negative  $\pi$  Mesons" *Phys. Rev.* **18** 929 1967. (It later turned out that important advances in particle physics would derive from the study of muon pairs with the Nobel prize winning discovery of charmonium in 1974.)

In another AGS experiment, (in collaboration with Harvard and McGill), Blanpied and his student Larry Levit looked at the decays of neutral K mesons into three pions. They were especially interested in whether there were any differences between the momentum distributions of the  $\pi^+$  and  $\pi^-$  in the decay  $K_L^0 \rightarrow \pi^+ \pi^- \pi^0$ . This was a very hot topic at the time, as the kaon had recently been shown to violate CP conservation in an earlier Brookhaven experiment. (*CP non-conservation is that subtle imbalance in Nature which could account for the fact that there seem to be more protons than antiprotons in the Universe. As a consequence, a few remain after the rest have annihilated, leaving us and something for us to study.*) In the Blanpied *et al.* measurement, the momenta of all three pions were measured and the transverse momentum distributions of the two charged

pions were compared. No differences were observed. "Search for a CP-Nonconserving Asymmetry in the Decay  $K_L^0 \rightarrow \pi^+ \pi^- \pi^0$ " *Phys. Rev. Lett.* **21** 1650 1968.

Both Argonne and Brookhaven established boards of overseers which were responsible for the operation of the labs. Membership on these boards included representatives from affiliated universities. Since the experimental particle physicists at CWRU made use of the accelerator facilities at both of these labs, the university participated in MURA (Midwest Universities Research Association) and AUI (Associated Universities, Inc.).

Bill Frisken left CWRU in 1971, returning to Canada to take a position at York University in Toronto. He has continued in accelerator based particle physics as well as becoming active in environmental physics. His colleague, Bill Blanpied left in 1972, taking a position with the public sector programs division of the AAAS and later with the National Science Foundation, where he became Senior International Analyst. Both Frisken and Blanpied had been awarded tenure at CWRU and their departures depleted the experimental particle physics program. Their two tenure slots were not regained by that program. Tom Jenkins subsequently hooked up with Glenn Frye on the next generation of balloon (and satellite) borne detectors, as described at the end of Chapter 8.

### Willard, Bevington, Baer: nuclear & intermediate energy

**Harvey Willard (Fig. 16-4)** was hired to set up the second SDP-supported particle physics group. After Martin Klein and Chandrasekhar stepped down as interim co-chairmen of the newly formed CWRU physics department, the 42-year-old Willard was selected as its first chairman in May of 1967. It would become his disagreeable responsibility to pare down the size of the combined department. Within four years after federation, between 15 and 20 faculty would have to leave. No new tenure-track faculty would be hired until 1980, leaving the department with a generation gap which would not be rectified until the 1990's.

Willard had completed his PhD at MIT in 1950. Using the proton beam from the MIT electrostatic accelerator, Willard studied (p,n), i.e. proton-in, neutron-out, reactions on the lithium nucleus. He continued this type of nuclear physics at the van de Graaff accelerator of Oak Ridge National Laboratory in Tennessee from 1951 until 1967. He was on the faculty of the University of Tennessee from 1963 until 1967. Among his several dozen publications from Oak Ridge, we shall mention two (because they are sort of interesting).



**Fig. 16-4.** Harvey Willard

In the first, the object was to check on the reversibility of time in nuclear reactions. If the physics of an interaction does not depend on the direction in which time "flows", then one would expect reversed reactions like  $d O \rightarrow \alpha N$  and  $\alpha N \rightarrow d O$  to be identical if kinematic corrections are made to compensate for the difference in masses.

Willard's experiment at Oak Ridge showed that in this reaction this was true to the one-half percent level. "Test of Time-reversal Invariance in the Reaction  $^{16}\text{O}(d,\alpha)^{14}\text{N}$  and Its Inverse" *Phys. Rev. Lett.* **21** 447 1968 and *Phys. Rev.* **C3** 1065 1971.

In the second, Willard looked at some short-lived nuclear states. When a proton is shot at a  $^{14}\text{N}$  nucleus, it can become incorporated in the nucleus which then becomes  $^{15}\text{O}$ . The probability for this happening depends very much on the energy of the incident proton, with peaks where the total energy of the new oxygen nucleus matches one of its excited states. One can scan through a range of beam energies to find these excited states, and then deduce some of their properties (like spin) by looking at the angular distribution of the  $\gamma$ 's which shoot out when the nucleus returns to its ground state. Willard *et al.* presented evidence for 14 such states in  $^{15}\text{O}$ . "Level Structure in  $^{15}\text{O}$  from the Proton Bombardment of  $^{14}\text{N}$ " *Phys. Rev.* **179** 1047 1969. *Experiments like these, done at many energies and with many projectiles and target nuclei, formed the basis for our understanding of the atomic nucleus. They were done at reactors and accelerators by hundreds of research groups worldwide.*

Willard began his research at CWRU with an experiment which used the deuteron beam from the department's van de Graaff accelerator. Recall that Erwin Shrader (Chapter 7), who was instrumental in getting this machine up and running, had worked with a 3 MeV deuteron beam in 1963 and Rolf Scharenberg had done nuclear physics using the van de Graaff's beams in the mid 1960's. A key player in the van de Graaff program was the machine's operator, technician Larry Hinckley (Chapter 11) who had come from MIT with the machine. Bob Lescovec, the engineer introduced in Chapter 7, was a major contributor to the design and construction of detectors and electronic logic circuits. Both Shrader and Scharenberg had left the department by the time Willard started using the van de Graaff.

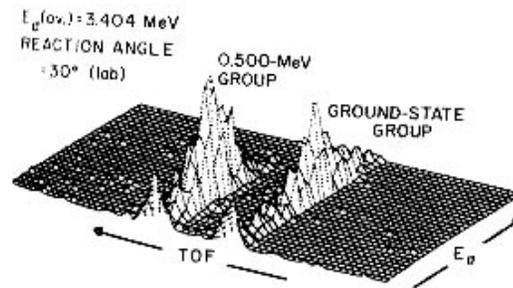
### Nuclear Physics at the van de Graaff

Willard studied the reaction  $d + ^{16}\text{O} \rightarrow n + ^{17}\text{F}$ . In this reaction, the deuteron leaves its proton behind in the target nucleus, which thus becomes  $^{17}\text{F}$ . The residual neutron continues on to be subsequently detected. The  $^{16}\text{O}$  nucleus consists of neatly filled spherical shells of 8 protons and 8 neutrons, while the  $^{17}\text{F}$  has these shells as a core and a loose proton running around the outside. The  $^{17}\text{F}$  nuclei were produced about half the time in the ground state and half the time in the first excited state.

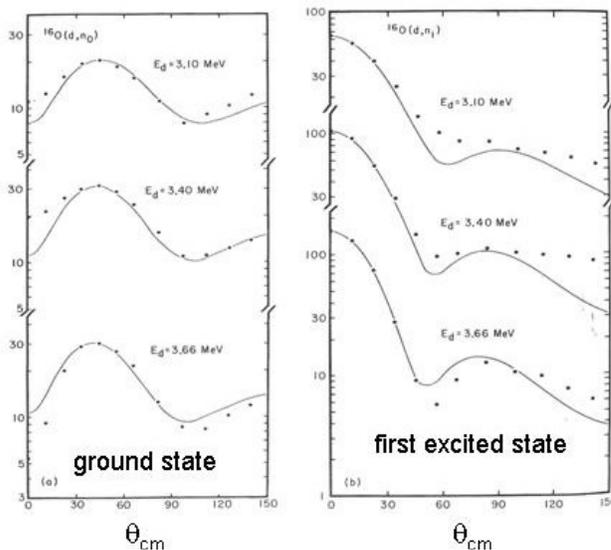
Recall that the van de Graaff provided a pulsed beam of deuterons, with a 1.2 ns-long bunch arriving every microsecond. Because the *time* of the collision was known, time-of-flight measurements on the neutron could give its speed and energy. In this experiment, the neutrons were detected in a "polarimeter". In the polarimeter, the neutron scatters off a helium nucleus and the recoil  $\alpha$  particle's (i.e. the helium nucleus) direction and energy are recorded. Left-right asymmetries of the recoil  $\alpha$  give a measure of the degree of polarization of the neutrons (i.e. whether the spin of the neutron had a preferred direction). For each run, a deuteron beam energy was selected, and the scattering angle of the neutron was fixed by placement of the polarimeter. For each event, the neutron

time of flight was determined along with the energy deposited in the polarimeter by the  $\alpha$  particle. The  $\alpha$  was detected by one of two scintillators, one to the left and one to the right of the neutron direction, so that the average left-right asymmetry could be determined for each run.

The **Fig. 16-5** shows the number of counts as a function of neutron time-of-flight versus the energy deposited by the  $\alpha$  in the polarimeter. The two mountain ranges correspond to the two  $^{17}\text{F}$  states, the ground and the first excited. The second plot, **Fig. 16-6**, shows the angular distribution of the neutrons for three incident deuteron energies for events in the ground state (on the left) and the excited state (on the right). The curves are the theoretical predictions of a Born approximation model, i.e. a model in which only single scattering is considered."  $^{16}\text{O}(d,n)$  Polarizations and Cross Sections from 3 to 4 MeV" *Phys. Rev.* **C6** 1513 1972.



**Fig. 16-5.**  $\alpha$  energy vs. neutron time-of-flight in  $(d,n)$  reaction on  $^{16}\text{O}$ .



**Fig. 16-6.** Neutron angular distributions for two  $^{17}\text{F}$  states in  $(d,n)$  reaction on  $^{16}\text{O}$ .

In 1970, **Philip R. Bevington** joined Willard as the second member of the "intermediate energy" group. Born in New York City in 1933, Bevington completed his AB at Harvard and then earned his doctorate at Duke University in 1960. His photo is shown in **Fig. 16-7**. Bevington remained at Duke for an additional three years, doing van de Graaff based nuclear physics. He then spent four years as assistant professor at Stanford University, where he became an expert in the use of computers in the analysis of nuclear physics experiments. Bevington was severely injured in an automobile accident before coming to CWRU,

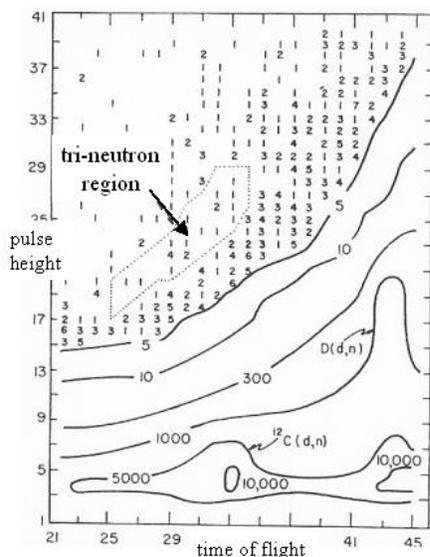
and was confined to a wheelchair until the time of his death in 1980. In spite of his disability, he was a successful teacher and was instrumental in setting up a state-of-the-art PDP9 computer facility for use by many members of the department. One can see Phil Bevington's hand in Fig. 16-5 for the Willard van de Graaff experiment. It was surely he who produced the multi-dimensional plots with the aid of the PDP9.

*Les Foldy gave me his file of Bevington memos for the PDP9. Memo #1, February 1969, describes the machine: central processor – 8192 words of 18 bits each (i.e. 8K RAM), 1.5  $\mu$ sec cycle time; paper-tape reader and punch; hardware multiplier; memory expansion to 16,383 words (temporarily leased for 18 months), two DEC magnetic tape drives; X-Y oscilloscope display with Light Pen; price \$46,100 on delivery with \$20,000 more in 18 months. Around \$200,000 in 2002 dollars, and imagine, no monitor, not even a mouse!)*



**Fig. 16-7.** Phil Bevington

In a paper published just before his arrival at CWRU, Bevington presented a user-friendly programming system, written in Fortran. "Real-time Reduction of Nuclear Physics Data" *IBM J. Res. Develop.* 1969. The system allowed the user to identify and fit structure in experimental spectra, using the latest techniques in curve-fitting and error analysis. One of Bevington's longest-lasting accomplishments is his widely used book on computerized data analysis. Keith Robinson, whom we shall meet later in this chapter, has expanded and updated this book over the past two decades. (The 3<sup>rd</sup> edition appeared in 2002; *Data Reduction and Error Analysis for the Physical Sciences*, McGraw Hill.)



**Fig. 16-8.** Search for tri-neutron.

At CWRU, Bevington set up an experiment using the van de Graaff accelerator in a rather interesting search for a new nucleus which some theorists thought might exist. The three-nucleon system has two bound states:  $^3\text{H}$  (pnn) and  $^3\text{He}$  (ppn). These are held together by the attractive nuclear force, in spite of (in the case of  $^3\text{He}$ ) the repulsion between the two protons. Some calculations indicated that the  $^3\text{n}$  (nnn) state might also be bound, in spite of the fact that the Pauli principle requires that one of the neutrons would have to be in the second energy shell. Bevington and graduate student Kenneth Koral used the pulsed neutron beam from the van de Graaff incident on a target of  $^7\text{Li}$ . The proposed reaction was  $n + ^7\text{Li} \rightarrow ^3\text{n} + ^5\text{Li}$ . The tri-neutron would be detected in a helium filled detector where the arrival time and recoil energy of the helium nucleus would be recorded. The **figure 16-8** shows a scatter-plot of time-of-flight (running from right to left) versus pulse height. The vast majority of hits (tens of thousands) comes from single neutrons, while an insignificant handful of events falls into the zone marked "TRINEUTRON REGION". The authors conclude that there is no evidence for the  $^3\text{n}$ . "A Search for the Bound Tri-neutron from  $^7\text{Li} + n$  Reactions" *Nucl. Phys.* **A175** 156 1971.

The versatility of the van de Graaff was again exploited when the helium isotope,  $^3\text{He}$ , was accelerated and delivered in short pulses to a nuclear target. Bevington and his student S. K. Bose studied the reaction in which the incident  $^3\text{He}$  nucleus left its two protons behind in a  $^{20}\text{Ne}$  nucleus, leaving a lone neutron and a  $^{22}\text{Mg}$  nucleus in the final state. Runs were made with  $^3\text{He}$  energies ranging from 2.6 to 4.0 MeV. Measurement of the neutron time-of-flight allowed the determination of the total energy of the excited  $^{22}\text{Mg}$  nucleus. Analysis of the energy dependence of the reaction cross-section and the angular distribution of the outgoing neutrons provided a test for theoretical models. It was found, for example, that in this reaction both “direct interaction” (when the projectile just grazes the target) and “compound nucleus” (when the projectile is absorbed by the target which later decays) processes contribute. *Nucl. Phys.* **A219** 115 1974. A similar study was made of the excited states in  $^{30}\text{S}$  with graduate student Alberto Kogan. *Jour. of Phys. G: Nucl. Phys.* **4** 422 1975.

Bevington, along with two grad students, B.D. Anderson and Frank Cverna, worked on the development of a new type of multiwire proportional chamber. They found that they could use a plane of thin metal foil as the electron-emitting cathode, rather than a series of parallel thin wires. The wires of the anode would be enough to signal the location of the ionizing particle. They reported that such chambers could be used at higher voltages than the usual (wire-cathode) type and would result in higher efficiencies over a broad range of operating voltages. “Investigation of some properties of multiwire proportional chambers with planar cathodes” *Nucl. Inst. and Meth.* **129** 373 1975. A second paper on detector instrumentation was written with Bob Lescovec. “CWRU Multiwire Proportional Counter Readout System” *Nucl. Instr. and Meth.* **147** 431 1977.

### Intermediate energy experiments: Los Alamos

Four years later, in 1974, a third member of the “nuclear/intermediate energy” group joined Willard and Bevington. **Helmut Baer** was born in China in 1939, the son of American missionary parents. He completed his doctorate at the University of Michigan in 1967 where he did experimental nuclear physics at the Cyclotron Lab. He came to CWRU after several years at the Lawrence Berkeley Lab. A photo of Baer is shown in **Fig. 16-9**.

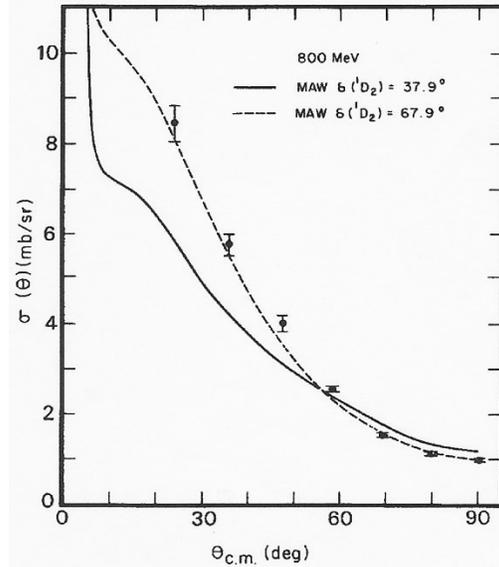


**Fig. 16-9.** Helmut Baer

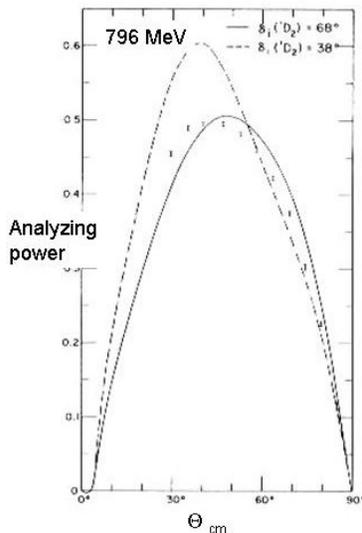
At Berkeley, Baer used the pion beam from the 184-inch cyclotron to measure radiative capture reactions, i.e. reactions in which a negative pion is absorbed by a nucleus and a photon is subsequently emitted. He and his colleagues at Lawrence published a 100 page review of this work in an article which began: “The central question to be addressed in this article is: What can be learned about nuclear structure by stopping negatively charged pions in targets of nuclei from various regions of the periodic table and examining the emitted photon spectra between 50 and 150 MeV with a resolution of  $\leq 2$  MeV?” The authors review their work and that of other groups on pion capture by nuclei

from hydrogen to lead. One area of interest was pionic atoms, in which the pion goes into electron-like orbits around the nucleus, and where its wave function reaches deep into the nucleus. The principal goal, however, was the study of nuclear states which are excited when the pion disappears into the nucleus. “Radiative pion capture in nuclei” *Advances in Nucl. Phys.* **9** 177 1977.

The first “intermediate energy” experiment mounted by the CWRU group was the study of proton-proton elastic scattering at the Los Alamos Meson Physics Facility (LAMPF). The list of authors included Willard, Bevington, and Baer. **Fig. 16-10** shows the resulting differential cross section from the 800 MeV data, along with the predictions of a phase shift analysis done by a group at Lawrence Radiation Lab in Livermore. The authors found that there was better agreement (dashed curve) with the data if one of the phase angles was changed from the Rad Lab value. “Absolute differential cross section measurements for proton-proton elastic scattering at 647 and 800 MeV” *Phys. Rev.* **C14** 1545 1976.



**Fig. 16-10.** Phase shift analysis, 800 MeV pp elastic scattering.

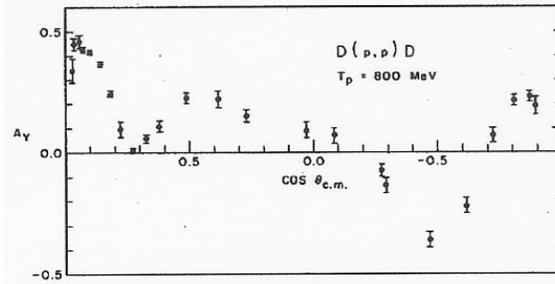


**Fig. 16-11.** Analyzing power in pp scattering.

This work was followed by a similar experiment, but this time the incident protons were polarized, i.e. with spins preferentially oriented. A polarized ion source had been installed at the LAMPF accelerator and the group wanted to exploit it to perform a more complete measurement of the phase shift parameters. “In this experiment a beam of protons with transverse polarization up to 0.92 was obtained from the LAMPF accelerator and focused (typically 4 mm diam) onto a CH<sub>2</sub> target.” Both protons were detected in the wire chambers built by Bevington and Lescovec so that elastic proton scatters on hydrogen could be identified. The beam polarization direction was flipped every three minutes. Data were taken at scattering angles from 30 to 90° in the center of mass (cms) and the quantity  $\varepsilon = (L-R)/(L+R)$  was determined, i.e. the difference between scatters to the left and those to the right, over the total. This quantity equals the product of the polarization analyzing power of the pp scattering and the beam polarization,  $\varepsilon = A_y(\theta) P_{\text{beam}}$ . **Fig. 16-11** shows the resulting analyzing power as a function of the cms scattering angle. The dashed curve shows the predictions for the analyzing power as calculated from published phase shifts, and the solid curve includes the modification of one of the phase shifts described in the previous paper. The authors suggest that

because the beam polarization  $P_{\text{beam}}$  is so well measured at LAMPF and most probably more difficult to measure at other accelerators, other experimenters could use these  $A_y$  results along with their own measurement of the pp asymmetry  $\varepsilon$  to deduce the polarization of their beam. “Polarization Analyzing Power  $A_y(\theta)$  in pp Elastic Scattering at 643, 787, and 796 MeV” *Phys. Rev. Lett.* **41** 384 1978. *Phys. Rev.* **C23** 838 1981.

Bevington and Willard followed this with a study of 800 MeV protons scattered by *deuterons*. They once again measured polarization analyzing powers as well as differential cross sections. This was a natural next-step after the proton-proton experiment, as now there would be two nucleons in the target, and the interferences between scatters off of the proton, the neutron, or successive scatters by each, would provide meaningful tests of the models. **Fig. 16-12** shows the terribly complicated structure in the measured analyzing power. “Proton-deuteron elastic scattering at 800 MeV” *Phys. Rev.* **C21** 2535 1980.



**Fig. 16-12.** Analyzing power in pd scattering.

The next step in this progression of experiments, from pp elastic to polarized incident protons to deuteron targets, was to look at some inelastic channels, in particular single and double pion production in pp scattering. A magnetic spectrometer based on multi-wire proportional chambers was set up at the Los Alamos facility to identify and measure the momentum of  $\pi^+$  and  $\pi^-$  mesons. The reactions  $pp \rightarrow pn\pi^+$  and  $pp \rightarrow pp\pi^+\pi^-$  were studied and the momentum and angular distributions of the outgoing pions compared to several current models. These channels had been studied in detail twenty years earlier in bubble chamber experiments, as will be described in the next section of this chapter. Why then would one repeat the study? Counter experiments usually measure vector momenta of hundreds of thousands of individual particles resulting from high energy collisions. Bubble-chamber experiments, on the other hand, typically measure all the particles produced in each collision, but only a few thousand events. It's a question of more statistics versus more details. “Single and double pion production from 800 MeV proton-proton collisions” *Phys. Rev.* **C23** 1698 1981.

Helmut Baer left CWRU in 1978 after fewer than five years in the department, taking a position at LAMPF. The tenure-track during this period in the CWRU physics department was a dead-end. After a productive decade of research at LAMPF, Baer tragically died of cancer in 1991 at age 52. His death has been coupled with those of at least two other LAMPF experimentalists, resulting in a wrongful death suit against the lab. A 1998 Court of Appeals decision found in favor of the defendant, the University of California, which operates the lab.

In 1980 Phil Bevington succumbed to complications from his old injuries. His computer software expertise had been vital to many of his colleagues in the department.

Harvey Willard held the position of Dean of Science from 1970 until 1976. Left without a research group, he decided in 1981 to accept a permanent position at the NSF as Section Head for Nuclear Science. Two of the SDP-funded experimental “sub-atomic” programs – the “counter group” and the “intermediate energy group”, had for various reasons enjoyed somewhat truncated lifetimes.

### **Robinson, Kikuchi, Fickinger, Eisner: bubble chambers**

The third group to be set up under the NSF grant was initiated on the WRU side of the fence with the hiring of **D. Keith Robinson**. Its history would be somewhat longer than the other two groups. If this section of the narrative seems more detailed than some of the earlier parts, the reason is obvious.



Robinson was born in 1932, raised in Nova Scotia, graduated from Dalhousie in Halifax and went to Cambridge for his doctorate. When his advisor, Dennis Wilkenson, moved to Oxford, Robinson went with him and completed his degree there in 1960, writing on the properties of hyperfragments. These states, occasionally produced in high energy collisions, are nuclei in which a nucleon has been replaced by a  $\Lambda$  or  $\Sigma$  strange baryon (or, on a different level, a down-quark by a strange-quark). Robinson studied their production and disintegrations as recorded in nuclear emulsions. (We described the emulsion technique in Chapter 7.) Robinson’s picture is shown in **Fig. 16-13**.

**Fig. 16-13.** Keith Robinson

In 1960 Robinson took a position at Brookhaven National Laboratory in the newly organized bubble-chamber group of E.O. Salant. He was responsible for the analysis software written for the new IBM 700-series supercomputers (32K RAM, programming language: assembler or Fortran, punch card input). He developed a data summary system (“Corregram”) which was subsequently used for years by bubble-chamber groups at many labs. His first experiment at Brookhaven was the study of 2 GeV kinetic energy protons striking protons in the Brookhaven 20-inch hydrogen-filled bubble chamber. The proton beam was produced by the Cosmotron synchrocyclotron.

**William Fickinger** (your narrator) was born in 1934, raised in New York City and Rhode Island, and graduated from Manhattan College. He spent the summer after his junior year in Salant’s lab at Brookhaven, learning about nuclear emulsions. He later went to Yale for his PhD. Working under Horace Taft and Earle Fowler, he and fellow grad student Jim Sanford planned to do an experiment at the Cosmotron using positive pi mesons ( $\pi^+$ ) incident on the 20-inch hydrogen bubble chamber. To create a beam of  $\pi^+$ s the team built an electromagnetic beam separator. This device was a 20-ft long, 4-ft diameter, stainless steel, evacuated cylindrical tank containing two long parallel plate electrodes, 2-in apart, with a potential difference between them of 500,000 V, all sitting in a transverse magnetic field of 700 Gauss. What a toy to give two 24 year-old grad stu-

dents! It worked just fine. The incoming beam was a mix of protons and  $\pi^+$ 's, all with the same momentum, so the lighter  $\pi^+$ 's were traveling faster than the protons. The crossed electric and magnetic fields were adjusted in strength so that the fast  $\pi^+$ 's would pass through undeflected, and the slower protons would be nudged slightly aside. Fickinger was responsible for the vacuum system – based on titanium ion pumps. This was the first "separated beam" at BNL. The students and their toy are shown in **Fig. 16-14**.

*(An aside for graduate students: Somehow it was my job to make the drawings for the 20-foot long stainless steel tank. By copying the notation I found on other drawings, I seem to have specified that the 4-foot diameter end-plates must be parallel to one another to something like two thousandths of an inch across the diameter. The manufacturer in Pittsburgh phoned to say that would be impossible, so I said make it half-an-inch. He found that pretty funny.)*



**Fig. 16-14.** Jim Sanford, Bill Fickinger and the beam separator.

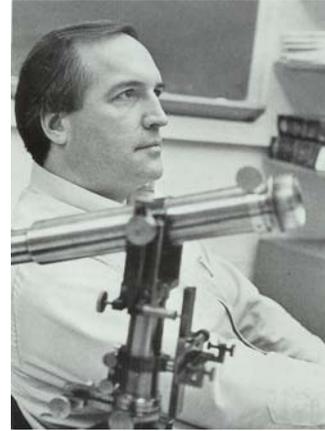
### Early work at Brookhaven

Before the Yale group had the chance to run their  $\pi^+$  experiment, the "pole-face" magnets of the Cosmotron burned up, shutting down that machine for a year: the type of delay dreaded by any graduate student. Earle Fowler took Fickinger over to see Salant and somehow talked him into turning over half of the film from the 2 GeV proton run for analysis at Yale (and for a dissertation for Fickinger). Robinson was livid! Thus began the Fickinger-Robinson collaboration which was to play for forty years.

The first paper, on the production of  $\Delta$  baryons by one-pion-exchange, was based on that exposure and analyzed by Horace Taft's reconstruction and fitting programs and Robinson's data summary programs. The Yale and BNL sets of data for the reaction  $p p \rightarrow p n \pi^+$  were merged and the paper written on the lawn of Robinson's house overlooking Long Island Sound. "One Pion Exchange in p-p Collisions at 2 BeV" *Phys. Rev. Lett.* **7** 196 1961. "p-p Interactions at 2 BeV, I. Single-pion Production" *Phys. Rev.* **125** 2082 1962. "Evidence for a Two-Pion Decay Mode of the  $\omega$  Meson" *Phys. Rev. Lett.* **10** 457 1963.

Armed with state-of-the-art software and some experience in using it, Fickinger went off like Johnnie Appleseed, installing the bubble-chamber analysis software on the computers of the University of Kentucky, the Centre d'Études Nucléaire de Saclay in France, and then Vanderbilt University.

Robinson remained at Brookhaven, working in collaboration with Mark Sakitt, and with Arnold Engler's group from Carnegie-Mellon University. They produced a series of important papers on the properties of K-mesons, a very hot topic at the time. "Measurement of the  $K^0$ - $K^+$  Mass Difference" *Phys. Rev.* **168** 1534 1968. "Measurement of the Lifetime of the Short-Lived Neutral K Meson" *Phys. Rev.* **171** 1418 1968. "Study of the  $\Delta S = \Delta Q$  Rule in the Leptonic Decays of the Neutral K Meson" *Phys. Rev.* **D1** 3031 1970. "Search for  $K_S \rightarrow \pi^+ \pi^- \pi^0$ " *Phys. Rev.* **D3** 1557 1971. Partnerships with Sakitt and his group at Brookhaven and Engler's group at Carnegie were to play an important role in the work of the CWRU group for the following 20 years.

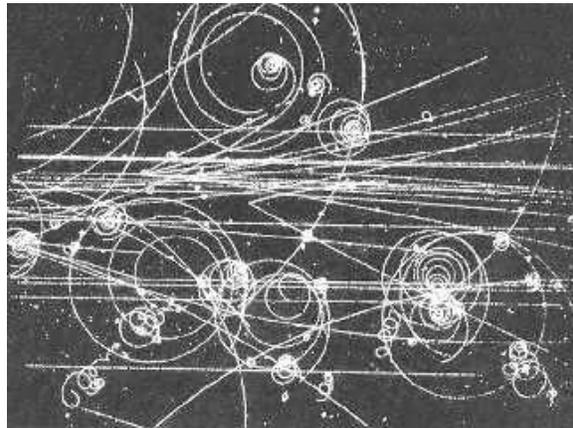


**Fig. 16-15.**  
Bill Fickinger.

In 1966, Robinson accepted a position in the Western Reserve physics department where he set up the third of the NSF-SDP programs. Projection machines to measure the bubble-chamber pictures were built by the WRU machine-shop, scanners trained, and the PDP8 data-acquisition system developed. In the fall of 1967, Fickinger joined Robinson at CWRU. He was interviewed by two chairmen (Martin Klein and Chandrasekhar) and by two deans, and was probably the first appointee to the faculty of the new CWRU department. His photo is in **Fig. 16-15**.

### About bubble chambers

What is a "bubble chamber experiment"? First, a proposal is made to the program committee of the accelerator lab, asking for a certain number of pictures with a certain target liquid (propane, hydrogen, deuterium, methyl iodide), a certain beam and beam energy, giving physics arguments for the exposure. Often several university groups would join forces, and share the film, each selecting specified types of "events". The physicists, grad students and technicians would go to the accelerator laboratory for a few weeks, help set up the beam (magnets, counters, collimators), and sit in (24/7) on the run, while the laboratory physicists and technicians would tend to the chamber itself. The film, often hundreds of thousands of pictures, would be developed at the lab and taken back to the home institutions for scanning and measuring.



**Fig. 16-16.** A typical hydrogen bubble-chamber picture.

A bubble chamber is a container of liquid which is at a pressure and temperature just below the boiling point. Shortly before the beam is shot into the chamber, a piston drops, lowering the pressure on the liquid, leaving it in a superheated state. Bubbles form



**Fig. 16-17.** Donald Glaser BS '56 and Polykarp Kusch. BS '31.

along the ionized path of the moving charged particles. **Fig. 16-16** shows a typical bubble chamber photograph. The bubbles are allowed to grow to optimum size for photography (for about a millisecond) and then flash lamps illuminate the chamber. Three or more cameras record the strings of bubbles as seen from different angles. The chamber is usually inside a strong electromagnet – with a 10 to 20 kilogauss field. Measurement of the curvature of a track gives the momentum of the particle which caused it. A former Case undergraduate, Donald Glaser (BS 1946) won the Nobel Prize for inventing the bubble chamber. He is shown in **Fig. 16-17** with Polykarp Kusch, another Nobelist with a Case physics degree (BS 1931), when they visited the CWRU campus.

A team of trained "scanners" examines the pictures at "measuring tables" equipped with movable crosshairs attached to digitizers (forerunners of today's mouse). A series of x-y coordinates are recorded along each track, in each stereo view. This is the "data acquisition phase", controlled by small computers. Robinson designed and maintained this system. The group employed 4 to 8 full-time scanners, working two shifts on four measuring machines. In **Fig. 16-18**, Robinson hovers over Gracie Broadway.

In the "data analysis phase", the x-y coordinate pairs are combined to make a three-dimensional track which is fitted with a curve, allowing for optical distortions, energy loss, and magnetic field inhomogeneities. The resulting vector momenta are fed to a second, "kinematic analysis" program which assigns trial masses to each track, and then checks to see how well relativistic energy and momentum are conserved by a given mass assignment. In this way, each event may be associated with a particular reaction, for example,  $p p \rightarrow p n \pi^+$ . Because there are four energy-momentum conservation equations to work with, it is possible to determine the momentum of one *unobserved* neutral particle (in this reaction, the neutron). Fickinger was principally concerned with the analysis phase, and maintained the resulting data base of hundreds of 2400-ft magnetic tapes. Over the course of about 15 years, this procedure was applied to about five major experiments, mostly in collaboration with friends at Carnegie Mellon University.



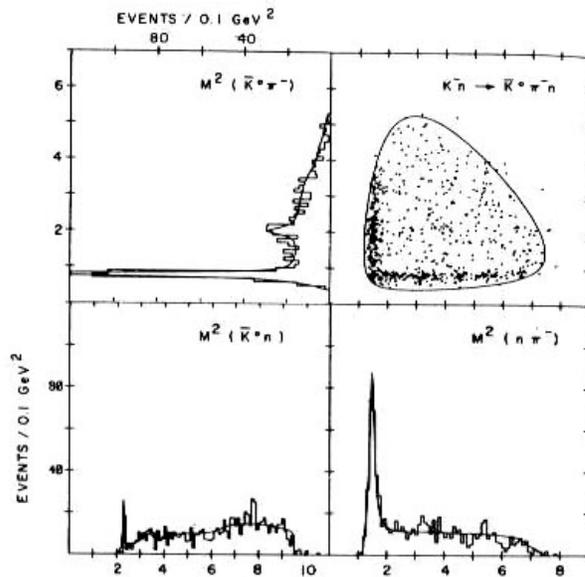
**Fig. 16-18.** Gracie Broadway measuring bubble chamber events.

As early as their period on the staff at Brookhaven, Robinson and Fickinger became associated with the use of deuterium as the target liquid in the bubble chamber. The idea was that one could study interactions with the neutron in events in which the proton was just a spectator to the collision. This allowed the study of some multi-particle states not accessible with a hydrogen target.

The first set of film measured and analyzed at CWRU was a continuation of the K-meson work which Robinson had begun with the Brookhaven and Carnegie-Mellon groups. Robinson was joined by three new colleagues, instructors **Tadashi Kikuchi** and **Clarence Tilger** and RA **Walter Carnahan**. The experiment was based on an exposure of the Brookhaven 30-inch deuterium filled bubble chamber to 600 MeV/c  $K^+$ . “Determination of the Sign of the  $K_L^0 - K_S^0$  Mass Difference” *Phys. Rev.* **D4** 7 1971.

### Bump hunting (a.k.a. building the Standard Model)

The next bubble chamber experiment tackled by the new CWRU group was an exposure of the Brookhaven 80-inch deuterium-filled chamber. The beam was  $K^-$  mesons at momentum 4.9 GeV/c. The run produced 100,000 sets of photos taken with four cameras. The object was to study interactions of the  $K^-$  with the neutron, especially those including neutral particles in the final state: e.g.  $K^-n \rightarrow \Lambda\pi^-$  or  $\Lambda\pi^-\pi^0$  or  $K^0\pi^-n$ . The measurements were recorded on punchcards and analyzed on the CWRU Univac 1108 computer.



**Fig. 16-19.** Dalitz plot and projections for the  $K^0\pi^-n$  final state.

The physics was similar to that studied in the proton-proton experiment at Brookhaven. In the former case the properties of non-strange baryonic resonances were studied, for example,  $p p \rightarrow \Delta^{++}(1238) n \rightarrow p \pi^+ n$ . In the  $K^-$  experiment, reactions like  $K^- n \rightarrow K^{*0}(890) n \rightarrow K^0 \pi^- n$  or  $K^- n \rightarrow \Sigma^{*0}(1385) \pi^0 \rightarrow \Lambda \pi^- \pi^0$  yielded information on strange mesons and baryons, like the  $K^*(890)$  and the  $\Sigma(1385)$ . The figure (one of 42 in the paper) shows a Dalitz plot for the  $K^0\pi^-n$  final state. The scatter plot in **Fig. 16-19** has one dot per event located at the intersection of the  $Kp$  and the  $np$  effective masses (squared). If the three outgoing particles are uncorrelated, this plot would be uniformly populated. The two highly populated re-

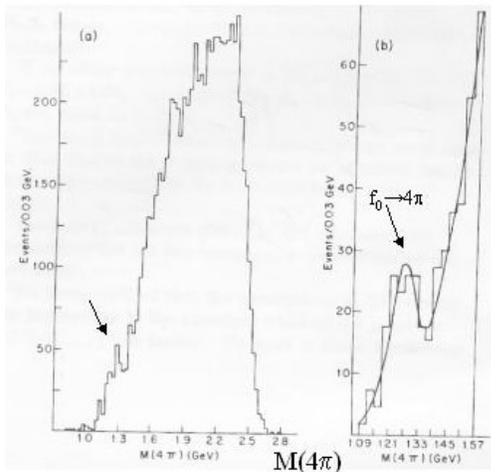
gions correspond to the  $\Sigma(1385)$  and  $\Lambda(1238)$  resonant states, as can be seen in the two tall peaks in the projections. Cross sections and angular distributions for these strongly decaying states were measured. All these data are included in the Particle Data Group

Tables which are published each year by a world-wide consortium. The PDG compilation is the raw data for the quantum chromodynamics part of the Standard Model. This experiment was done entirely by the CWRU group, including three grad students (Bernard Burdick, John Korpi, and Sergei Al Gourevitch), and was published in a single 45-page paper. “K<sup>-</sup>d Interactions at 4.9 GeV/c” *Nucl. Phys.* **B41** 45 1972.

### Multipion resonances

In collaboration with Carnegie-Mellon, the group next tackled a 930K picture exposure to a beam of 6 GeV/c  $\pi^+$  of the deuterium filled 30-inch bubble chamber at Argonne National Laboratory. This very large exposure was to occupy both the CWRU and the CMU groups’ measuring capacity for at least three years. Of particular interest were those reactions in which the neutron became a proton, and the incident  $\pi^+$  became a new neutral heavy meson which decayed into two or more pions. Events with more than one neutral particle in the final state cannot be analyzed (too many unobserved momentum components). The reactions studied included  $\pi^+ n \rightarrow p \pi^+ \pi^-$ ;  $\pi^+ n \rightarrow p \pi^+ \pi^- \pi^0$ ;  $\pi^+ n \rightarrow p \pi^+ \pi^- \pi^+ \pi^-$ ;  $\pi^+ n \rightarrow p \pi^+ \pi^- \pi^+ \pi^- \pi^0$ , thus giving access to neutral multipion systems of 2, 3, 4, and 5 pions. As a result, the experiment produced many contributions to the PDG compilation. This is the stuff of which the quark picture of the Standard Model is made. The masses, widths, angular distributions, decay channels, etc. all enter into the establishment of the quark constituents of the state. The literally hundreds of baryonic and mesonic states, discovered mostly in bubble chamber experiments in the 1960's and 1970's, were shown to be combinations of three quarks or a quark and an antiquark. More impressive is the fact that **no** so-called “exotic” particle has been found, i.e. one which does not fit that picture – not, certainly, for the lack of looking. (The hunt was not

abandoned, however, and three decades later, in 2003, convincing evidence was reported by laboratories in Osaka, Moscow, Virginia and Bonn for a  $qqqq$ - $q\bar{q}$  baryon, called the  $\Theta^+$ , with mass 1540 MeV.)



**Fig. 16-20.** Four-pion mass distributions

As an example, the effective mass distribution of the three-pion system  $\pi^+ \pi^- \pi^0$  contained about 800 examples of the  $\omega$  meson (mass 780 MeV). This large sample of events allowed the determination of the “spin-density matrix elements”, that is, the factors which describe how the three-pion system breaks up. The data were compared with models based on the exchange of various spin-one mesons. “Study of the Reaction  $\pi^+ n \rightarrow p \omega$  at 6.0 GeV/c” *Phys. Lett.* **45B** 165 1973.

The  $\pi^+ \pi^- \pi^+ \pi^-$  system has an enhancement in the region of the 1272 MeV  $f^0$  meson which previously had been only known to decay to  $\pi^+ \pi^-$ . The left hand side of **Fig. 16-20** shows the four-pion effective mass for all events and the right hand figure

shows how one could pull out the signal for the  $f^0$  by selecting events in which the “quadri-pion” traveled along the same direction as the incident pion (i.e. in a peripheral interaction). The ratio of the four-pion to two-pion decay rates was  $3.7 \pm 0.7 \%$ . The breakup of the  $f^0$  into four pions was further analyzed in a search for possible intermediate steps, e.g. via 3-pion or 2-pion states. Theoretical models predicted such possibilities as a  $\rho^0\rho^0$  intermediate state, and the data were found to agree rather well with that picture. "Observation of the Decay  $f^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ " *Phys. Rev. Lett.* **31** 562 1973.

There was even evidence for two states which decay into five-pions, and, as has been found for many of these massive mesons, the decay proceeded in sequential steps:  $A_2 \rightarrow \omega \pi^- \pi^+$  followed by  $\omega \rightarrow \pi^- \pi^+ \pi^0$ . "Evidence for the  $\omega\pi\pi$  Decay Modes of the  $A_2$  and  $\omega(1675)$ " *Phys. Rev. Lett.* **32** 260 1974. The  $\pi^+n$  experiment yielded a variety of results in addition to the multipionic states. Because the exposure was rather large (for the time) and the statistics quite good, one could look at the details of some rare processes. During this period the group included assistant professor Charles Sullivan, who had earlier worked with Tom Jenkins. Graduate student David Matthews and research associates Frank DiBianca (Carnegie Mellon), John Malko (Ohio University), and José Diaz Bejarano (CERN) were essential to the success of the program. "Backward Production of  $\rho$  and  $\phi$  Mesons in  $\pi n$  Interactions at 6 GeV/c" *Phys. Lett.* **50B** 275 1974. "Features of the  $\pi d \rightarrow \pi \pi \pi d$  Reaction at 6 GeV/c" *Phys. Rev.* **D12** 1272 1975. " $\pi\pi$  Scattering in the Energy Region 0.5 to 1.42 GeV" *Phys. Rev.* **D10** 2070 1974. "Resonant Structure in the  $\pi^+ \pi^+ \pi^- \pi^-$  System between 1.5 and 1.9 GeV" *Phys. Rev.* **D23** 595 1981.

In 1974, a new member joined the group as assistant professor. **Robert Eisner** had completed his doctorate at Purdue University and had been working with a bubble chamber group at Brookhaven Lab. He pointed out the possibility of combining the CWRU data on  $\rho^0$  production with data from his former group concerning a related reaction in which a strange meson, the  $K^*$ , is produced. The resulting papers stressed the similarities between the angular distributions for production and decay of these two spin-one mesons. "A Study of Inclusive Vector Meson Production" *Phys. Lett.* **63** 461 1976 and *Nucl. Phys.* **B119** 1 1977. Eisner and CWRU post-doc J. F. Owens built further on the collaboration with the Brookhaven group, publishing a series of papers on resonance production by pion and kaon-induced collisions.

### Polarized Protons at Argonne

The next major experiment for the CWRU-Carnegie Mellon collaboration was based on two 120K photograph exposures of the enormous (12-foot diameter) Argonne hydrogen bubble chamber, one at 6 GeV/c and the other at 12 GeV/c beam momentum. Many proton-proton experiments had been done, but these were different in that the incident beam was about 50% polarized. The expectation was that several spin-dependent features of the collisions could be explored. This turned out to be true for high-statistics *counter* experiments done with Argonne's ZGS polarized beam, but the limited statistics of a bubble-chamber experiment made it difficult to extract significant information. Nevertheless, three papers were published in which a few standard deviations worth of polarization-dependent effects were coaxed out of the data. Specifically, the 6 GeV/c

events of  $p \uparrow p \rightarrow n \Delta^{++}$  in which the  $\Delta^{++}$  is produced backward in the center of mass (i.e. the target proton becomes the  $\Delta$ ), showed a polarization-induced decay asymmetry of  $30 \pm 10\%$  in a particular range of momentum transfer. Such effects arise from interference between the amplitudes for various production channels. (A technical note: to avoid asymmetries caused by scanning or other experimental biases, the direction of polarization of the beam protons was reversed on each accelerator pulse, and its sign was imprinted on the film.)

The events in which the strange particles,  $K^0$ 's or  $\Lambda$ 's, were produced also showed some tantalizing effects, such as the forward-produced  $K^0$ 's which presented "the rather remarkable experimental situation in which 70% of the  $K^0$ 's traveled to the right and 30% to the left." These effects would have to wait for counter experiments, preferably with both polarized beam **and** target, for confirmation and exploitation. " $\Lambda$  and  $K^0$  production in  $p \uparrow p$  interactions at 6 GeV/c" *Nucl. Phys.* **B123** 361 1977; "Study of the reaction  $p \uparrow p \rightarrow n \Delta^{++}$  at 6 GeV/c with polarized beam" *Phys. Rev.* **D20** 596 1979; and "Effects of beam polarization on  $\Lambda$  and  $K^0$  inclusive production in pp interactions at 12 GeV/c" *Phys. Rev.* **D21** 10 1980.

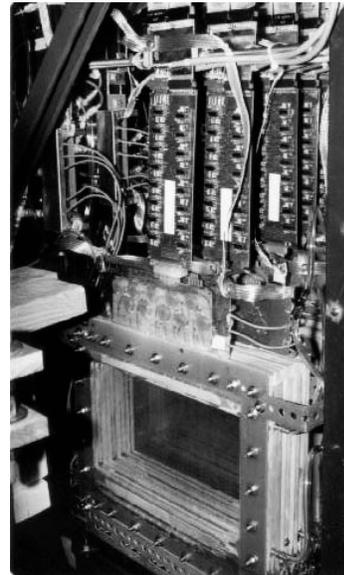
By 1980, it was time to get out of the bubble chamber business. Most other bubble chamber groups were switching over to counter experiments. The labor-intensive, one event at a time, photographic technology was being replaced by reaction specific all-electronic methods. The funding agencies (DOE, NSF) no longer wanted to support teams of "scanners". Fickinger and Robinson had been chasing strings of bubbles for twenty years, and the time had come to switch to electronic detection.

### Counter experiments at Brookhaven

During the following decade or so, Fickinger and Robinson were part of three "counter-physics" collaborations at Brookhaven: with BNL's Mark Sakitt, with Syracuse's Ted Kalogeropoulos, and with Boston University's Lee Roberts.

#### The $K^+n$ system

The first experiment with Sakitt was a search for a previously reported resonant state in the  $K^+n$  system. This state, called the S-hyperon, has *positive* strangeness; it cannot be constructed from only three quarks, because positive strangeness is carried only by an antiquark. This then would be one of the "exotic" particles mentioned above. The experiment involved scattering a  $K^+$  off a neutron (one which had been sitting comfortably in a deuteron for billions of years). The interaction point in the liquid deuterium target would be found by detecting the *spectator* proton. The neutron must then enter a second target, this one filled with liquid hydrogen, and



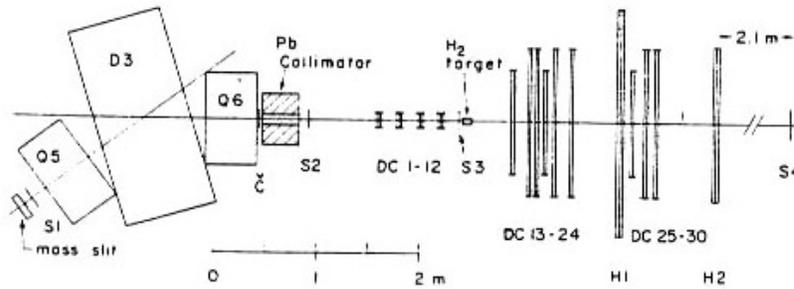
**Fig. 16-21.** Wire chambers built at CWRU.

scatter off a proton. This recoiling proton must then be detected, indicating whether the neutron scattered to the left or right. Any asymmetry gives the neutron polarization, whose value depends on the existence of the S-hyperon. Once again, the group would be working with liquid deuterium (i.e. neutron) targets and with polarization effects.

Twelve planes of wire chambers, one of which is pictured in **Fig. 16-21**, defined the incident beam. They were built by Larry Hinckley (the van de Graaff man) at CWRU. All the reconstruction and analysis of the data was done at CWRU. It eventually became clear that, in spite of the valiant analysis efforts of graduate student Oscar Rondon Aramayo and post-doc V. A. Sreedhar, the combination of limited spatial resolution, limited statistics, and large background would preclude a meaningful result. The moral of the story may be that one can never do too many Monte Carlo studies before attempting an experiment of this complexity.

### The pbar-p system

The second counter experiment with Sakitt had three parts: antiprotons bouncing off protons, a search for a pbar-p bound state, and antiprotons bouncing off nuclei. The Low Energy Separated Beam (LESB) at the AGS was “partially separated”, i.e. the antiproton to negative pion ratio was enhanced by electromagnetic separation; the antiprotons were subsequently tagged by



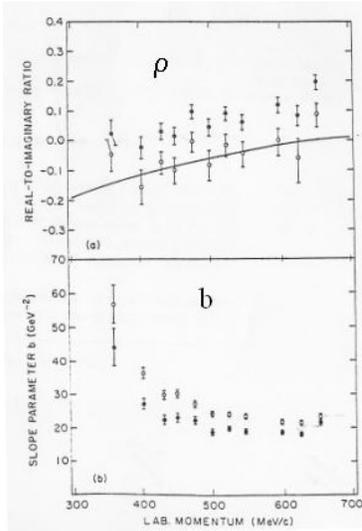
**Fig. 16-22.** Experimental setup for antiproton-proton scattering.

time-of-flight and pulse height signals. The beam provided on the order of 1000 antiprotons per accelerator pulse. **Fig. 16-22** shows a drawing of the experimental layout.

A liquid hydrogen target was placed in this beam and a measurement was made of pbar-p elastic scattering. Runs were made at eleven different incident momenta, and the angular distributions were fitted to a combination of Coulomb and nuclear terms, including interference between them. Two parameters were extracted from the data: the  $b$  which appears in the  $e^{-bt}$  part of the nuclear term and the  $\rho$  which is the ratio of the real to imaginary parts of the p-pbar scattering amplitude. Plots of  $\rho$  and  $b$  are shown in **Fig. 16-23** for two different analyses: one including the possibility of spin-flip (open circles), the other without (solid circles). The results favored the theoretical model for pbar-p scattering advanced by the “Paris Group”. “Measurement of the Real-to Imaginary Ratio of the pbar-p Forward-Scattering Amplitudes” *Phys. Rev. Lett.* **54** 518 1985.

One feature of pbar-p scattering which was of great interest was whether or not there are any pbar-p bound states. Between 1974 and 1985, there were more than a dozen

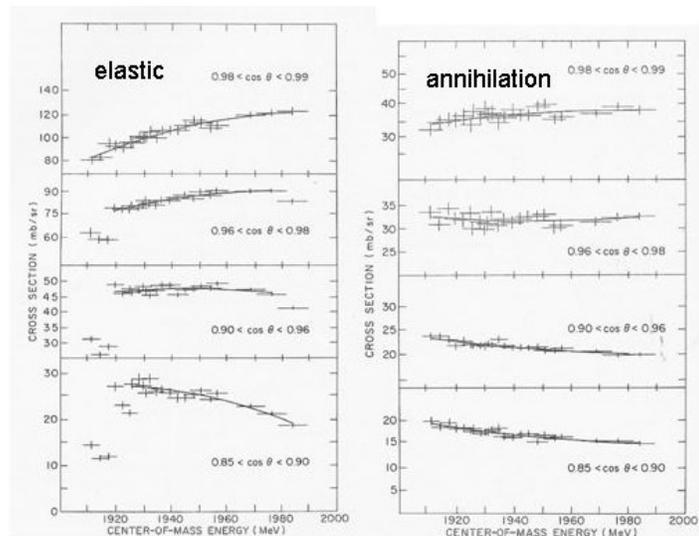
experiments which looked for such states, either in the elastic channel or in annihilations into pions. There were several claims of rather narrow (10-20 MeV) peaks with rather large cross sections, but there were enough “non-observations” to raise some doubts. A new measurement was needed, and the AGS beam was waiting. The same beam layout was used as just described, with a liquid hydrogen target which had Mylar walls only 15 mils thick.



**Fig. 16-23.**  $\bar{p}$  p elastic scattering.

Eleven beam momenta were chosen (387 to 682 MeV/c), corresponding to  $\bar{p}$ -p effective masses from 1914 to 1988 MeV. Again, all the analysis was done at CWRU. There were 2000 2400-ft 1600 bits-per-inch magnetic tapes. That’s 11 Gigabytes on two tons and \$85K-worth of tape! The PDP 11/40 (16 kilobyte RAM, 2 Megabyte disk) was run continuously for more than one year. The results shown in **Fig. 16-24** indicate no structure between 1930 and 1980 MeV in the elastic channel (left) or in the pion-producing annihilation channel (right). The earlier claims for an “S-meson” at 1938 MeV would have made a bump many error-bars tall. (The figure has more than eleven points because the target could be divided into three slices of antiproton energy when the energy loss in the hydrogen is considered.) This experiment put an end to the controversy: no  $\bar{p}$ -p bound state. The non-existence of the S-meson was a significant contribution to the picture of how quarks can arrange themselves: seemingly not as two quarks with two antiquarks. Graduate student Richard Marino wrote his dissertation on this experiment. “Search for the S meson in antiproton-proton interactions” *Phys. Rev.* **D34** 3332 1986.

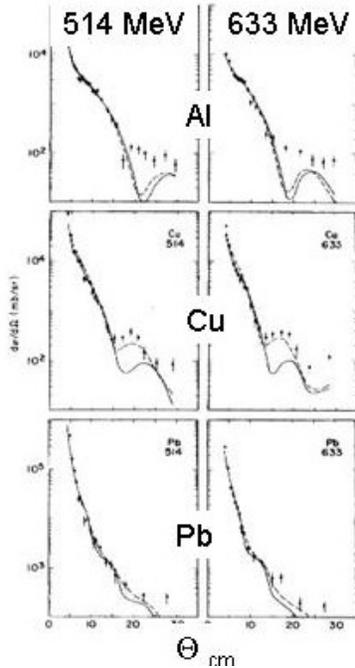
The third experiment was a “quicky” measurement of the scattering of 514 and 633 MeV/c  $\bar{p}$ bars by *nuclei*: Al, Cu and Pb. Strips of metal were mounted in place of the hydrogen target. The measured differential cross sections (**Fig. 16-25**) were fitted to an optical potential which had terms describing both elastic scattering and absorption (analogous to what happens when a beam of light passes through a cloudy crystal ball). It was useful to compare these data with those for *proton-nucleus* scattering,



**Fig. 16-24.** Search for S(1938) meson. Left: elastic channel; right: annihilation channels.

since in *antiproton*-nucleus scattering, annihilation channels would make additional contributions to the absorption of the antiprotons (i.e. to the “cloudiness” of the crystal ball.) “Low energy antiproton-nucleus elastic scattering” *Phys. Rev.* **C30** 1080 1984.

### Antiproton annihilations in deuterium

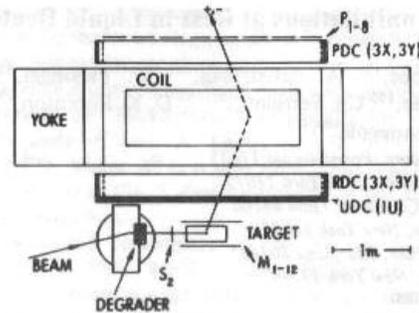


**Fig. 16-25.** Antiproton scattering from nuclei.

ject  $X^0$  along with a  $\pi^-$ , there should be a bump in the  $\pi^-$  momentum spectrum:  $p\bar{a}d \rightarrow \pi^- X^0 p_s$ , where  $p_s$ , the spectator proton, is assumed to have negligible momentum. Here is the tricky part: to extract the signal from neutron annihilations, one subtracts the observed  $\pi^+$  momentum distribution from the observed  $\pi^-$  distribution: making a so-called “difference spectrum”. **Fig. 16-27** shows the result, where the large mountain is ascribed to an  $X^0$  with mass 1485 MeV. If this “bump” were significantly narrower, comparable to the experimental resolution, it would be much more credible as evidence for a new particle. “Evidence for a New State Produced in Antiproton Annihilations at Rest in Liquid Deuterium” *Phys. Rev. Lett.* **56** 211 1986 and *Phys. Lett.* **B180** 313 1986.

Ted Kalogeropoulos of the University of Syracuse headed a group which planned an experiment in the same beam at the AGS. Fickinger and Robinson and grad student Ramiro Debbe joined the collaboration. It was another “bump-hunting expedition”, this one looking for neutral multipionic resonances. The technique was rather interesting: antiprotons were brought to rest in liquid deuterium, where they annihilated either with the proton or the neutron. Alongside the deuterium was a large bending magnet, with some scintillators and wire chamber planes before and after it. Charged particles from the annihilations passed through the magnet. The trajectory gave the momentum of the particle, and the time of flight gave its velocity, so that  $\pi^+$ ,  $\pi^-$  and protons could be tagged. **Fig. 16-26** shows the setup.

Pions produced in  $p\bar{a}$  annihilations on a proton must have identical  $\pi^+$  and  $\pi^-$  momentum distributions, but those produced in annihilations on a neutron can produce different  $\pi^+$  and  $\pi^-$  spectra. In particular, if  $p\bar{a}$  annihilation at rest with a neutron produces a neutral mesonic ob-

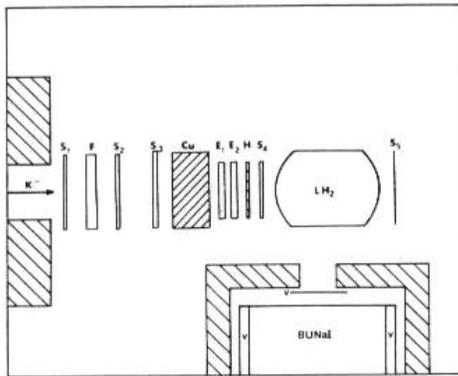


**Fig. 16-26.** Antiproton annihilations on deuterons.

## Hyperon radiative decays

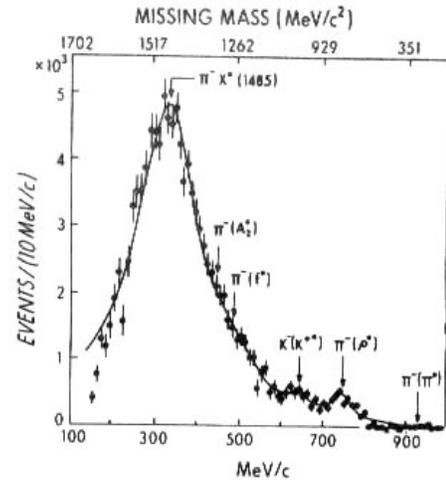
Having several years experience working with the Brookhaven and Syracuse groups at the AGS LESB, Fickinger and Robinson signed on in 1987 to a new and very different series of experiments in the same beam. This time, it was with a multi-university collaboration headed by Lee Roberts of Boston University. It involved the detection of photons from rare reactions and decays. A proposal was submitted by the CWRU group to the NSF for the support of their participation in these experiments. However, the group lacked the critical size needed to compete for funding, and the NSF declined to renew its support. Fickinger and Robinson nevertheless each spent about two months per year for three years at Brookhaven installing and operating major components of the data acquisition system. The CWRU PDP 11/45 and the Los Alamos data acquisition software were at the center of the series of runs.

The first phase of the experiment was built around three large sodium iodide crystal detectors which were large enough and sensitive enough to detect and identify rare events. The first run involved stopping  $K^-$  mesons in a liquid hydrogen target where they would be captured by a proton. Most of the time, the resulting product is a  $\Lambda$  or  $\Sigma$  hyperon along with a  $\pi$  meson. About once in a thousand captures, the hyperon is accompanied by a *photon* rather than a pion. Determination of the rates for these “radiative captures” is of theoretical interest in that the final states involve only the weak and electromagnetic interactions, free from the strong interaction complications associated with the pions. The key to the measurement is the ability to extract a tiny signal from the many other processes in which photons are produced, mostly from  $\pi^0$  or  $\Sigma^0$  decays.

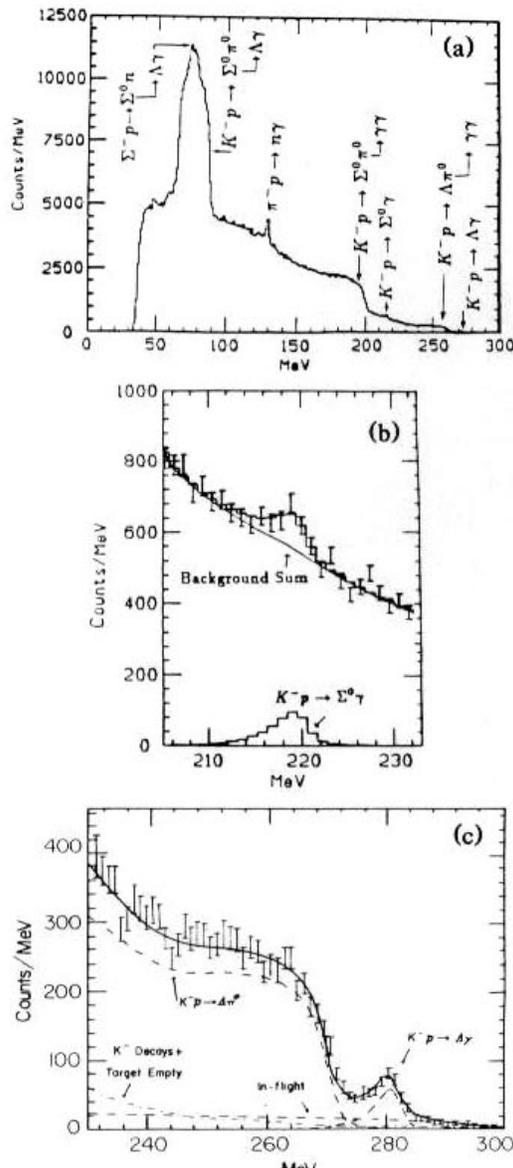


**Fig. 16-28.** Radiative capture experiment.

The BUNaI (Boston University sodium iodide) detector was a very large cylindrical single crystal (56 cm long, 50 cm diameter) surrounded by veto scintillators, enclosed in a lead and steel box. It was used in the second phase of the run. **Fig. 16-28** shows the setup, with the incident  $K^-$  coming from the left, the copper degrader in the middle, and the liquid hydrogen target sitting opposite the window to BUNaI. **Fig. 16-29** shows the total photon spectrum at the top, where the bumps of interest at 220 and 280 MeV can hardly be seen. Below are blown-up portions



**Fig. 16-27.** Search for new neutral meson states.



**Fig. 16-29.** Observation of radiative capture of K mesons. (a) total photon spectrum (b)  $\Sigma \gamma$  signal (c)  $\Lambda \gamma$  signal.

49'er out in back. The resulting  $\Sigma^+$  radiative decay sample of 408 events was twice the previous world total. The radiative rate was  $(1.45 \pm 0.26) 10^{-3}$  times the total decay rate. "A Measurement of the Branching Ratio for the  $\Sigma \rightarrow p \gamma$  Decay" *Zeit. Phys.* **C42** 175 1989.

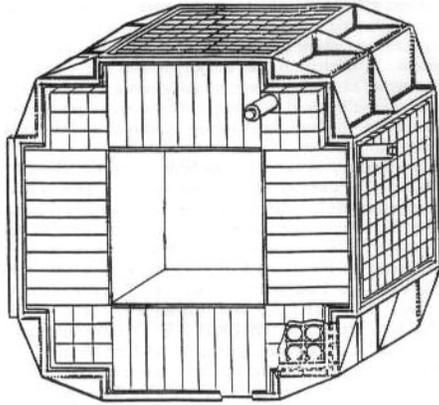
BUNaI and the 49'er served well as detectors of photons from stopping K's, but when the opportunity arose to borrow the "Crystal Box" from LAMPF, the group soon put it to work at Brookhaven. This detector consisted of 396 optically isolated NaI crystals. It covered about half of the total solid angle around the target, a great improvement

of the spectrum showing several hundred events in each of the two radiative capture peaks. "Radiative Kaon Capture at Rest in Hydrogen" *Phys. Rev. Lett.* **63** 1352 1989.

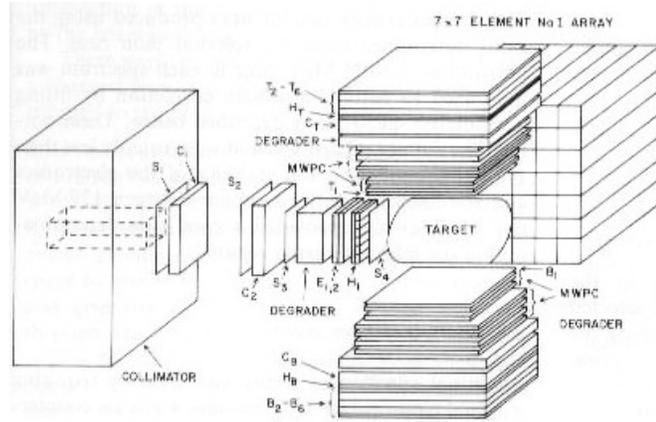
Stopping kaons and BUNaI were used once again, this time with liquid deuterium in the target. The goal was to detect the radiative process  $K^- d \rightarrow \Lambda n \gamma$ . This reaction can provide information on two interesting quantities: the radiative capture rate and the  $\Lambda n$  scattering length. The former was determined directly from the size of a bump at the high end of the photon spectrum. The  $\Lambda n$  scattering was of interest to theoretical groups who were studying low energy baryon-baryon scattering. The predictions of the Nijmegen Model relative to the shape of the high-end tail of the photon spectrum were found to compare favorably with the data. "Radiative Kaon Capture on Deuterium and the  $\Lambda n$  Scattering Lengths" *Phys. Rev.* **C42** R475 1990.

The next phase of this experiment looked at the  $\Sigma^+$  hyperons produced by stopping kaons:  $K^- p \rightarrow \Sigma^+ \pi^-$ . A very small fraction of these  $\Sigma^+$  decay by the emission of a photon,  $\Sigma^+ \rightarrow p \gamma$ . The trick in this experiment was the detection of the monoenergetic  $\pi^-$  to signal the creation of the  $\Sigma^+$ , along with the determination of the direction and energy of the photon. This latter measurement required a *segmented* photon detector, so BUNaI was retired and replaced by a 49-element rectangular array of NaI crystals: the "49'er". **Fig. 16-30** shows the setup, with the big pion detectors above and below the hydrogen target and the

over the earlier detectors. A sketch of the detector is shown in **Fig. 16-31**. The ability to catch 3, 4, or even 5  $\gamma$ 's in the Crystal Box opened up several interesting reactions. The 3  $\gamma$  events included a signal for  $K^-p \rightarrow \Lambda \pi^0$  followed by  $\Lambda \rightarrow n \gamma$  and  $\pi^0 \rightarrow \gamma\gamma$ ; some of the 4  $\gamma$  events are from  $K^-p \rightarrow \Sigma^0 \pi^0$  followed by  $\Sigma^0 \rightarrow \Lambda \gamma$  and  $\Lambda \rightarrow n \gamma$ . More than 1800  $\Lambda$  radiative decays were found among the 3 and 4  $\gamma$  samples, giving a branching ratio of  $(1.75 \pm 0.15) 10^{-3}$ . "The Weak Radiative Decay  $\Lambda \rightarrow n \gamma$  and the Radiative Capture  $K^-p \rightarrow \Sigma(1385) \gamma$ " *Phys. Rev.* **D47** 799 1993.



**Fig. 16-31.** The LAMPF Crystal Box detector with 396 NaI crystals.



**Fig. 16-30.** Catching gammas from  $K^-p$  interactions in the BU 7x7 detector.

This series of counter-based Brookhaven runs were the last experiments in which Fickinger and Robinson participated. Fickinger became director of undergraduate studies under chairman Lawrence Krauss who joined the department in 1993. Robinson took on the job as director of the introductory laboratories. Fickinger retired at the end of 1999 and Robinson in 2002. Experimental accelerator-based particle physics would resume at CWRU when, in the mid-1990's, theorist Cyrus Taylor put together a new team to work at Fermilab and CERN, work which continues to the present time. (Chapter 18)