Chapter 8 Cosmic Rays

Crouch, 1952-1987 · Reines, 1959-1966 · Frye, 1960-1993 · Jenkins, 1960-1995
Woods, 1964 -1970 · Wang , 1966 -1970 · Albats, 1973 -1978 · Koga 1974 -1980

In the 1930's and 40's, discoveries in cosmic rays were opening a brand new area of physics: "high energy" or "particle" physics. While there were already accelerators which reached energies of millions of electron volts, high enough to probe nuclei, the particles incoming from space had energies of billions of electron volts. The equivalent accelerators would not be built until the 1950's. In the intervening slice of time, it was the people doing cosmic rays who were making all the exciting discoveries. Flying in balloons and climbing to mountain tops, this athletic group of researchers set up their detectors - Geiger counters, cloud chambers, nuclear emulsion stacks - to catch glimpses of a whole new zoo of particles.

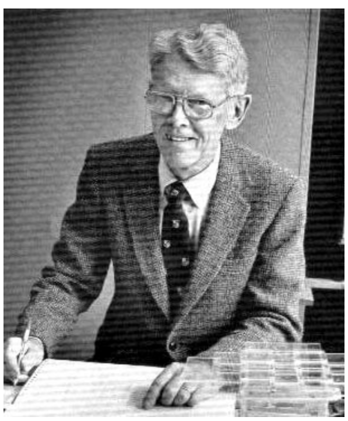

Fig. 8-1. Marshall Crouch.

Crouch: cosmic rays and neutrons

Marshall F. Crouch did his BS at the University of Michigan, put in a three-year stint in the army, and completed his PhD in 1950 at Washington University St. Louis under advisor Robert D. Sard. He did post-docs at Michigan and Harvard before becoming assistant professor at Case in 1952. A photo taken in the 1980's is shown in **Fig. 8-1**.

Among the particles discovered in cosmic rays were the new mesotrons (now called mesons), charged particles with masses between those of the electron and the proton. These were produced by collisions of high energy primary cosmic rays with the atoms of our atmosphere. At Washington U., Crouch *et al*. published two papers on the observation of secondary neutrons caused by incoming cosmic ray mesons. (*Phys. Rev*. **74** 97 1948, and **76** 1134 1949) The setup is shown in **Fig. 8-2**. The experiment made use of new developments in fast electronics which allowed one to count events in which two or more Geiger counters were hit within a well defined time interval. (These were called "coincidence" counters. Earlier versions were used by Shankland in the 1930's, with mixed results as described in Chapter 6.) In this case, the incoming particle must traverse 8 cm of lead (that is, it must be a penetrating μ meson), give a count in both the A and B trays of Geiger counters and plough into a second layer of lead. In addition, *no* hits must be observed in

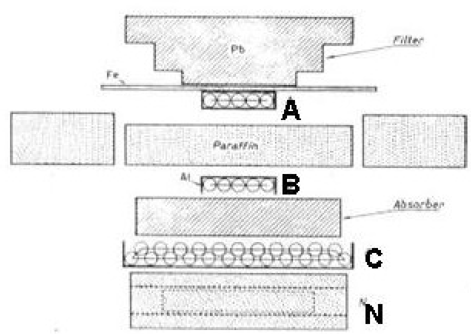

Fig. 8-2. Cosmic muon telescope.

the C tray, indicating that the incident meson stopped in the lead. There it is captured by a positive Pb nucleus, which soon breaks up. Among the fragments are neutrons. The neutrons are detected after they enter a block of paraffin encased special neutron counters (N). The paraffin, which contains many hydrogen atoms, acts as a moderator slowing down the neutrons. The slow neutrons are then absorbed by ^{10}Boron nuclei coated on the counters. These nuclei then fission, giving a characteristic signal in the counter. With the fancy fast electronics, the experimenters could ask for A yes, B yes, C no, N yes.

Cosmic muons as probes of nuclei

Crouch continued this work after he arrived at Case in 1950, with two major improvements. To minimize background counts, part of the running was done in the sub-basement of the St. Louis phone company (and later in a deeper location under a local brewery); and the neutron detectors were replaced by boron-fluoride counters which were twice as sensitive as the earlier counters. The emphasis of this work was the "neutron multiplicity", *i.e.* how many neutrons were emitted when a μ meson breaks up a Pb nucleus. There were theoretical models for this process, one based on a charge exchange with a single proton, the other based on a general explosion of the nucleus. They predicted respectively roughly 1 and 6 neutrons per capture, and, as so often happens, the experimental result fell right in between: 2.16 ± 0.15. (Grad student **Arthur H. Benade**, who would later join Crouch on the Case faculty, is thanked for calibrating some of the counters.) (*Nuovo Cim*. **VIII** 1 1951) and "Distributions of Multiplicities of Neutrons Produced by Cosmic-ray mu-mesons Captured in Lead" (*Phys. Rev*. **85** 120 1952).

Crouch and Washington U. collaborator, Sard, put together a fifty-page review article on the subject of "Nuclear Interactions of Stopped μ-Mesons". It was published in the 1954 issue of *Progress in Cosmic Ray Physics*. (Vol. II. North Holland Publishing, Amsterdam 1954) This paper provided an important summary of work-to-date, with over 100 references, experimental and theoretical. In the first part they report results from experiments similar to their earlier work. As in those experiments, cosmic ray muons are identified by traveling through a slab of lead (only muons could make it through) and then brought to rest in a sample of the material being studied. The neutrons which are then expelled from the affected nuclei are detected, and the delay between the muon time of arrival in the sample and the time of the neutron detection is recorded. From these data, the muon capture rate can be determined. Some examples: the survival time τ for a muon in beryllium (Z=4) is 2.05 ± 0.06 μs, for copper (Z=29) 0.116 ± 0.009 μs, and for lead (Z=82) 0.076 ± 0.004 μs. The data are well fitted by $1/\tau \sim Z^4$, that is, the large positive nuclei snap up the negative muons very quickly.

In the second part of their paper, Crouch and Sard review the data taken from nuclear emulsion and cloud chamber experiments, in which one may observe directly the charged particles emitted by nuclei which have captured a muon. They mention that beams of muons are just becoming available at the new accelerators (which would soon take over muon research from cosmic rays). An interesting feature of their discussion is the hypothesis of the existence of a neutral particle produced in the reaction $\mu^- p \rightarrow n \mu^o$. A few years later, the μ^o would be identified with the μ-type neutrino, ν_μ. In their conclusions: "…the strength of the coupling between μ-mesons and nucleons is the same order of magnitude as that between electrons and nucleons (β-decay) and that between μ-mesons and electrons (μ → e decay). This agreement is suggestive of some deep relationship that will emerge in a future theory of the fundamental particles." And so indeed it has! This was an early indication of what is known today as the "weak interaction".

Crouch spent the summer of 1956 at Argonne National Laboratory where he participated in a very different type of experiment. It concerned, somewhat indirectly, the interaction between the electron and the neutron, specifically one beyond the expected interaction between the electron's charge and the neutron's magnetic dipole moment. Other experimenters had reported observing such a new interaction. In 1951, Les Foldy (who will be introduced in Chapter 9 as the first theoretical physicist at Case Institute) had published a short note on this subject. (*Phys. Rev.* **83** 688 1951) Foldy pointed out that, in addition to effects which may be caused by the neutron's transformation to virtual π^- - proton states, one could also show "that an electron-neutron interaction of the desired character and magnitude can also be obtained as a direct consequence of attributing to a neutron an anomalous magnetic moment in the manner suggested by Pauli without any further assumption." The determination of the strength of the experimentally observed interaction depended on knowledge of the coherent scattering amplitudes for neutrons on krypton and xenon. It was these quantities which were measured at Argonne by Crouch and his collaborators. Their experiment involved scattering thermal neutrons from the surface of liquid Kr and Xe, both monatomic entities with lots of electrons. Their results, when combined with earlier measurements, showed that the electron-neutron interaction was compatible with that calculated by Foldy. "Coherent Neutron Scattering Amplitudes of Krypton and Xenon, and the Electron-neutron Interaction" (*Phys. Rev.* **102** 1321 1956)

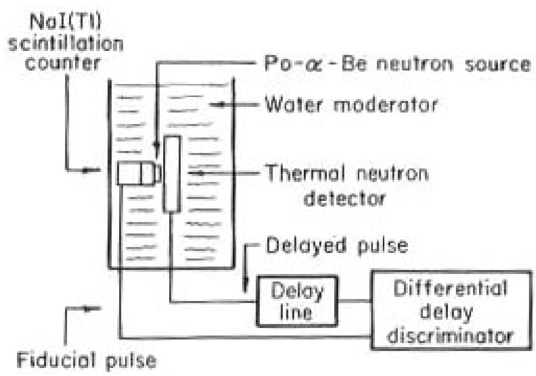

Fig. 8-3. Slowing neutrons in water.

Crouch and his student, Robert Stooksberry, turned their attention to the question of how quickly energetic neutrons would be slowed down in water – a question of particular interest to designers of nuclear reactors. The sketch in **Fig. 8-3** shows the experimental setup. In the "Po-α-Be" neutron source, a polonium nucleus spontaneously emits an alpha, the alpha fissions a beryllium nucleus from which a neutron and simultaneous 4.4 MeV γ are emitted. The γ is detected first, indicating the time of the birth of the free neutron. The neutron bounces around in the water, losing energy until it is traveling slowly enough to interact in the boron fluoride detector. The delay time then is a measure of the time it takes for the neutron to slow down in water. In this experiment, two large, water-filled coaxial cylinders are used to facilitate the corrections needed for neutrons escaping from the sensitive volume. They found that the mean lifetime for neutrons in water is 206.3±5.0 μs, corresponding to a neutron proton capture cross section of

0.330±0.008 10^{-24} cm^2. (*Nucl. Sci. and Engr.* **2** 626 and 631 1957, ibid. **6** 545 1959); "Neutron-Proton Capture Cross Section" (*Phys. Rev.* **114** 1561 1959).

Reines takes over: neutrino physics

Fig. 8-4. Chairman Fred Reines

In 1959, Shankland decided to step down after 15 years as department head, and a committee made up of Erwin Shrader, Martin Klein and Les Foldy was selected to conduct the search for a new chairman. An outside candidate, 41-year-old **Frederick Reines** was selected. (PhD New York University, 1944) He was an experimental particle physicist at Los Alamos National Laboratory. **Fig. 8-4**.

Reines had just published a paper with Clyde L. Cowan on their observation of neutrino induced reactions at a nuclear reactor. (*Phys. Rev.* **113** 273 and 280 1959) *The chargeless, possibly massless, neutrino ("little neutral one") had been hypothesized two decades earlier as the missing player in the decay of the neutron ($n \rightarrow p\ e^-\ \nu$), but the neutrino had never been directly observed.* Reines and Cowan devised a way to see the related inverse reaction (νbar p $\rightarrow$ n e^+) initiated by an antineutrino from the high flux Savannah River nuclear reactor (*νbar* is the antineutrino). They named their search for the elusive neutrino "Project Poltergeist". The key to the experiment was the observation of both outgoing particles, the neutron and the positron. They detected both γ's from the positron annihilation ($e^+ e^- \rightarrow 2\gamma$) and subsequently a third γ coming from an excited cadmium nucleus which had captured the neutron. (The neutron was slowed in a water bath, and the cadmium was in the $CdCl_2$ dissolved in the water.) **Fig. 8-5** shows a schematic of the process. Their result for the cross section for antineutrinos interacting with protons is $\sigma = 11 \pm 2.6\ 10^{-44}$ cm^2 . *This is about 10^{18} times smaller than the cross-sectional area of a proton. With such a small probability for interaction, the antineutrino (and neutrino) can easily fly through the earth, or even through the sun, without interacting.*

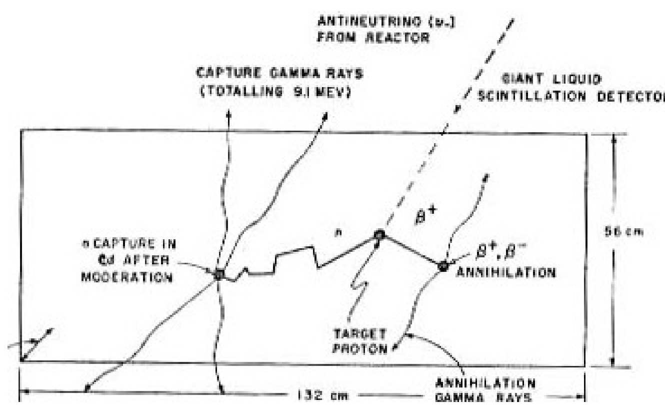

Fig. 8-5. Detecting reactor neutrinos.

A later paper (*Phys. Rev.* **117** 159 1960) reported a refinement of the experiment, including better shielding and comparisons of rates with the reactor turned on and off.

Reines was a great catch for Case, though at the time, who knew that his neutrino work would lead to a Nobel Prize 35 years later? He was to continue his chase after the obscure neutrino while at Case, and for many years afterward. As a, perhaps **the**, recognized expert on experimental neutrino physics, Reines published a review of the field. (*Ann. Rev. of Nucl. Sci.* **10** 1 1960) In it, he describes his earlier results, his plans for an experiment to measure neutrino scattering by electrons, the work by Ray Davis at Brookhaven National Laboratory which showed that the neutrino and antineutrino are two different species, and even some proposals to use nuclear explosions as one-shot "pulsed" neutrino sources. He then discusses what might be done at the new high-energy accelerators, correctly predicting the construction of intense neutrino beams. Neutrinos from space and from interactions of cosmic rays are also proposed as a suitable area for study, something which Reines and his Case colleagues would soon be undertaking. In his discussion of solar neutrinos, he even mentions reactions on the deuteron (currently being exploited at the Sudbury underground neutrino detector in Ontario). In effect, the paper provided a roadmap for the accelerator and cosmic ray neutrino work which would be tackled worldwide over the following forty years.

Reines and proton decay

Reines' interest in hard-to-detect reactions was not limited to those involving neutrinos. As early as 1954 he had participated in an experiment with Maurice Goldhaber in a search for evidence of proton decay. By looking for counts in large detectors placed far underground, shielded from cosmic rays, they were able to set a limit on the lifetime of the proton of greater than 10^{22} years. The idea is that if a proton decays, its positive charge must be carried off by a positron or some other light positive particle, and that this would give a signal in a detector. Therefore, in 1961 at Case, Reines and his first graduate student, Charles C. Giamati, set up a detector 585 meters underground at the Morton Salt Mine under Lake Erie about 30 miles east of Cleveland. (Subsequent similar "low-background" experiments, many involving Reines, would take place at this site for the next thirty-five years.) The 1961 experiment featured a 200-liter liquid scintillation counter inside an iron housing surrounded by a large cylindrical water Čerenkov anti-coincidence counter to eliminate the residual incoming cosmic rays. (A hit in an anti-coincidence counter vetoes the coincidence signal.) A schematic of the setup is shown in **Fig. 8-6.** Knowing the number of protons in the tank, the length of time the detectors were activated, the efficiency of the detectors, and the rate of background counts, they could place a limit on how often one of their protons decays. The new lower limit on proton decay, 10^{26} years, was ten thousand times longer than that reported in the earlier work. (*Phys. Rev*. **137B** 740 1965)

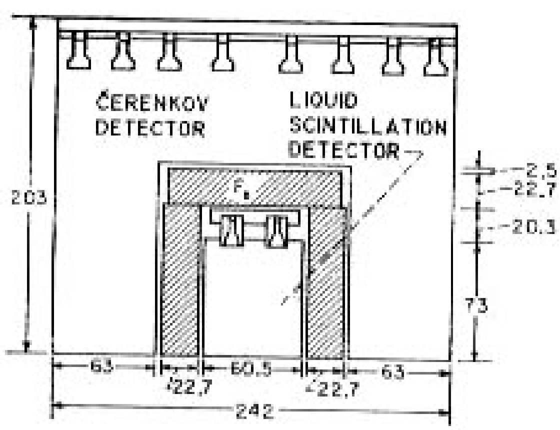

Fig. 8-6. Deep mine proton decay experiment.

Expanding the "rare event" program: Jenkins joins Reines

A year after the arrival of Fred Reines, two new experimental physicists were added to the department. Along with Reines and Crouch, they made up a respectable "particle physics" group. **Thomas L. Jenkins** completed his PhD at Cornell in 1956. He would begin at Case by joining Reines in the study of neutrinos. Jenkins' work will be described both in this chapter and in the chapter on accelerator physics. There is a photo of Tom in **Fig. 16-1**. The second new person was **Glenn M. Frye** whom we shall introduce later in this chapter.

As a graduate student at Cornell, Jenkins worked at the 300 MeV electron synchrotron, writing his dissertation on electron-positron pair production. Subsequently he spent five years at Lawrence Livermore Laboratory working on application of shock hydrodynamics to nuclear weapons design. At Case, in 1960, he soon began work with Reines on a new neutrino experiment at the Savannah River reactor. This time, they were looking at the interaction of neutrinos with the deuteron. While the inverse beta decay reaction $\nu_e\ p \rightarrow n\ e^+$ had been studied previously (by Reines and Cowan), $\nu_e\ d \rightarrow n\ n\ e^+$ had not. Although both of these reactions turn protons into neutrons, the second has two neutrons in the final state. The Pauli principle requires that these must have opposite spins. Thus the e^+ retains the angular momentum of the incoming ν_e. The proton reaction can involve either of the two orientations of the neutrino angular momentum and so is a mixture of Fermi (e^+ and ν_e spins opposite) and Gamow-Teller (e^+ and ν_e spins parallel) interactions, while the deuteron reaction is pure Gamow-Teller. The reaction was observed in a 97 liter deuterated organic scintillator mixed with a gadolinium compound for the neutron capture. The calculation of the rates was quite complicated as it had to include the efficiencies for picking up photons from the capture of *both* neutrons and from the annihilation of the positron. The resulting cross-section ($3.0 \pm 1.5\ 10^{-45}$ cm^2/fission antineutrino) agreed reasonably well with the predictions of theory. (*Phys. Rev.* **185** 1599 1969)

Back to the saltmine: underground in Ohio

Back at Case, Jenkins and Reines designed and tested a new liquid scintillator anti-coincidence guard. The plan was to use this setup in a new neutrino experiment at the Ohio salt mine. Neutrino induced events are extremely rare relative to spurious background events, even deep underground. A prototype setup was placed in a hole in the floor of the basement of the physics building under 88 cm of concrete and a two-meter stack of iron ore. **Fig. 8-7** shows the location and the amount of covering material. In the test setup, the main detector consisted of 50 liters of scintillator and two photomultipliers. The anti-coincidence guard which was eventually installed in the mine had

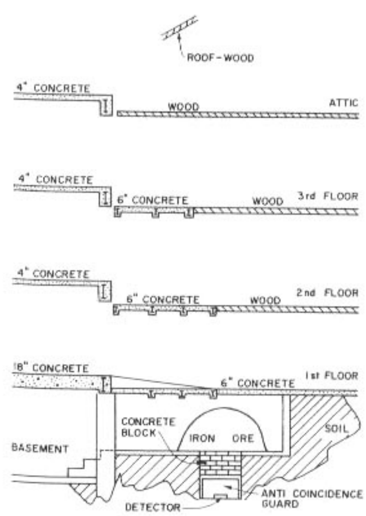

Fig. 8-7. Anticoincidence test setup on campus.

16 photomultipliers looking at 1500 liters of liquid scintillator. **Fig. 8-8** shows engineer Gus Hrushka with the containment tank. The number of counts in the main detector is reduced by a factor of ten thousand when the anti-coincidence guard is switched on. (*Rev. Sci. Instr*. **35** 370 1964)

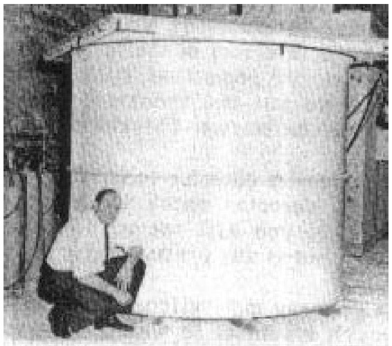

Fig. 8-8. Engineer Gus Hrushka and containment vessel.

The low-level background available at the nearby Morton salt mine invited a different type of experiment: the search for "double beta decay". The nuclear decay in which two neutrons simultaneously emit electrons, ${}^{Z}A \rightarrow {}^{Z+2}A + 2e^{-}$, had been sought by many experimenters. It had been proposed that if the neutrino were its own anti-particle, then this neutrinoless process may very well proceed. In double beta decay, two electrons would be created without any accompanying neutrinos.

Reines had published a paper at Los Alamos in 1956 on an unsuccessful attempt to detect the double beta decay of neodymium, ${}^{150}Nd^{60} \rightarrow {}^{150}Sm^{62}$. At Case, he suggested to Tom Jenkins that he give it a try, this time in the low-background environment of the salt mine. Graduate student Larry V. East assembled his experiment with an anti-coincidence guard similar to the one tested at Case. Because the two electrons in a neutrinoless decay carry away all the kinetic energy, their total energy would be a fixed amount. East used three sets of large scintillators and recorded the pulse-heights associated with two-electron coincidences. He was able to report a lower limit for the lifetime against neutrinoless decay of 5 10^{18} years. (*Phys. Rev*. **149** 913 1966.) In Chapter 10 we'll see that Rolf Winter at WRU had also searched for double beta decay, ten years earlier. Even in 2005, the search goes on in many laboratories.

A second of Jenkins' students, Gary R. Smith improved upon the double β decay experiment. He built a two-arm magnetic spectrometer **(Fig. 8-9)** to direct the electrons from the neodymium source to the detectors, thus eliminating most of the background counts. However, once again only a lower limit could be determined, essentially the same as that reported by East. (*Phys. Rev*. **C4** 1344 1971.) Even in the low-background salt mine, natural radioactivity of the surroundings and the equipment itself place a limit on how small a rate can be observed.

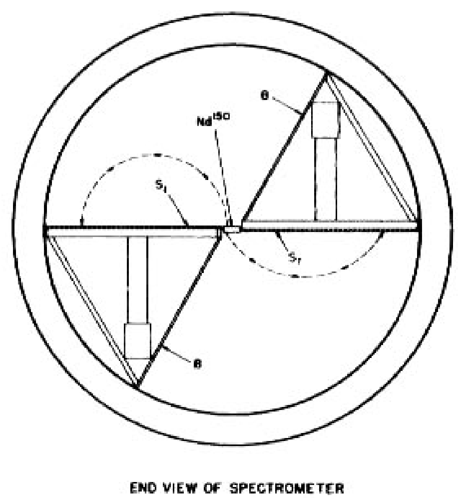

Fig. 8-9. Double beta decay spectrometer.

Neutrinos from the sun

Jenkins, with his students, Fred Dix and Larry Levit, set up another experiment in the saltmine: a search for solar *neutrino* interactions on the deuteron. This was quite different from the earlier experiment at Savannah River where *antineutrinos* from the reactor caused inverse beta decay of the proton in the deuteron. Here, the search was for *neutrinos* from the sun causing inverse beta decay of the neutron in the deuteron: $\nu\ n \rightarrow p\ e^-$. They installed a 2000 liter heavy-water (D_2O) Čerenkov counter with 55 5-inch photomultiplier tubes, surrounded by a foot-thick anti-coincidence shield. This effort, too, was limited by background in the mine. Nevertheless, the idea of sorting out neutrinos and antineutrinos by using a deuteron target is at the heart of today's Sudbury Neutrino Observatory's program, where they are able to sort out the three flavors of neutrinos in the search for neutrino oscillations.

With the arrival in 1966 of **Bill Frisken**, Jenkins returned to accelerator physics, where the beam is a bit more predictable and the backgrounds much more manageable than in double-beta decay or neutrino experiments. We'll describe their accelerator-based work in Chapter 16. Subsequently, in the 1980's, Jenkins teamed up with Glenn Frye in his work on balloon-borne gamma-ray detectors

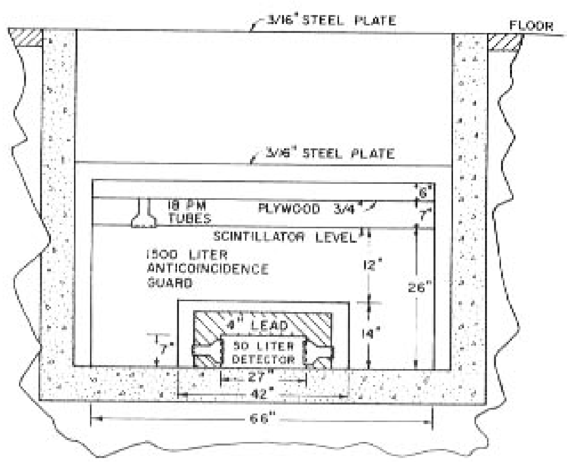

Fig. 8-10. Solar neutrino experiment in Ohio saltmine.

The anti-coincidence shield idea was again put to use in a search for neutrino interactions at the Morton salt-mine site. (*Phys. Rev. Lett.* **12** 457 1964) Reines and Bill Kropp put together a detector which was "surrounded by a large Čerenkov anti-coincidence detector and located 2000 feet underground". **Fig. 8-10.** The goal was to observe recoil electrons from elastic scattering of solar neutrinos. The rate would depend on two quantities, the rate of production of neutrinos in the sun, and the cross-section for scattering in the detector, $\nu\ e^- \rightarrow \nu\ e^-$. The nuclear processes in the sun had long been studied by theorists like Bethe, Bahcall and Fowler, and there were predictions on the rates and energies of the neutrinos produced in them. Reines *et al.* were looking for the 9 to 15 MeV neutrinos in the high energy tail of the distribution from the decay of ^8B. They could set their electronics to select recoil electron signals in this energy range, at the same time requiring no signal in the "shield". "In a counting time of 4500 hours only three events were observed in the energy range 9 to 15 MeV." The rather modest result of this run was "the elastic scattering cross section is ... <35 times the expected value" (assuming the theoretical neutrino production and interaction rates). This experiment marks the beginning of forty years of experiments to detect neutrinos from the sun at underground sites all over the world. The neutrino will turn out to be not only elusive, but to suffer from multiple personalities. In his 1964 letter, Reines turns quickly to a discussion of how large a detector would be required to detect the solar ^8B neutrinos. He estimated 25 m^3 at 2000 feet underground.

"There always remains the possibility of going deeper underground." Reines is looking for a "better hole".

In a paper following-up on the run at the salt-mine (*Phys. Rev.* **137** B740 1965), Reines summarizes his findings, relative to both the solar neutrino flux and the proton decay rate. From the abstract:, "Depending on the assumed decay modes, nucleon lifetime limits in the range 0.6 to 4 times 10^{28} yr were obtained. The upper limits on the neutrino cross-section flux products are <8.5 10^{-38} neutrino per second and <3.2 10^{-38} antineutrino per second." (These numbers represent the product of the neutrino flux and the cross section for neutrino interaction – and thus have the simple units of s^{-1}.) The experiment pushes the baryon lifetime upward another factor of 100. The paper includes extremely detailed analyses of the backgrounds and efficiencies.

In the meantime, Reines looks into the possibility of using inverse beta decay to see solar neutrinos. The plan is to use large slabs of lithium or boron, sandwiched between layers of liquid scintillator, to detect the reactions $\nu\ {}^{11}B \rightarrow e^-\ {}^{11}C$ or $\nu\ {}^{7}Li \rightarrow e^-\ {}^{7}Be$. As an example of the expected rates, for one ton of one-inch thick lithium slabs placed in the salt-mine and scintillators sensitive to 5 MeV electrons, Reines and a new addition to the department, R. M. Woods, calculated a rate of about 180 events per *year*. (*Phys. Rev. Lett.* **14** 20 1965).

Robert M. Woods, Jr. had completed his doctorate at the University of Michigan in 1963. He worked in beta spectroscopy with M. L. Wiedenbeck and had considerable experience in electronic detectors and in the new art of computerized data reduction. Consequently, when he applied to Reines for a position at Case, he was quickly offered an assistant professorship and the opportunity to join in Reines' research. He would work principally on the salt mine experiments until Reines' departure. Finding himself without a research program, and with the post-federation reduction in the department's size, Woods took advantage of an offer of a position with the High Energy Physics Program with the US AEC in Washington.

Reines thought of another use for the low-background environment in the salt mine laboratory: electron decay with charge non-conservation. What if an electron in an inner shell of an atom decides to decay into, say, a neutrino and a photon – thus violating charge conservation? Perhaps one could detect the decay photon in conjunction with a series of x-ray photons coming from the atom as it refills the inner shell. With grad student Michael K. Moe, Reines set up a pair of photomultiplier tubes and a sodium iodide detector in the mine. Result: the lifetime of an electron against such a decay is greater than 2 times 10^{22} years. (*Phys. Rev*. **140** B992 1965)

A later letter, authored by Reines, Kropp and Woods, reported a reexamination of the Fairport Harbor saltmine data. The object was to search for signals coming from muon decays. The idea was to determine whether most or all the observed counts could be attributed to muons. A predictable fraction of the muons would decay in the apparatus, and the resulting decay electron would be detected within a few microseconds. The observed time distribution of such events was compatible with the conclusion that all incoming particles were muons: another disappointing indication of the absence of neutrino signals. (*Phys. Rev. Lett.* **20** 1451 1968)

Cosmic Ray conference at Case - 1965

Having established himself as a world-class experimenter, Reines teamed up with Aihud Pevsner of Johns Hopkins and Larry Jones of Univ. of Michigan to organize a "Conference on the Interaction Between Cosmic Rays & High Energy Physics". It was held at Case in September of 1965. Papers were presented by future Nobelists Reines, Luis Alvarez, and Mel Schwartz, as well as by Jones, Yash Pal of MIT, S. Neddermeyer of Wisconsin, R. W. Thompson of Indiana and theorist J. D. Jackson of Illinois. The conferees had an interesting discussion after the final session, including remarks by representatives of the major funding agencies, NASA and NSF. It had largely to do with identifying those areas of research for which cosmic rays are more suited than accelerator beams. An intriguing remark on funding was made by Reines: "If we weren't meeting here today, then each of us would probably continue trying to push his proposal into various agencies and try to proceed just as in the past. The question we're exploring is, is there any way in which we can combine our effort to make some kind of sensible, all-over program; so increasing the support each one of us receives?" It is not clear that he found an affirmative answer to that question.

In his remarks at the 1978 "Reinesfest" at Irvine, celebrating Reines' 60th birthday, Marshall Crouch described the impressive list of colloquium speakers who visited during the Reines years at Case. "The department had grown a bit when Fred came to Case, and he inaugurated a program of colloquia in which if someone was doing interesting work in physics, that person was jolly-well invited to come to Cleveland and tell us about it himself. In the space of a few years we were inspired by colloquia given by at least a dozen Nobel laureates or laureates-to-be. Names like Luis Alvarez, John Bardeen, Hans Bethe, Owen Chamberlain, Leo Esaki, Richard Feynman, William Fowler, Donald Glaser, Robert Hofstader, Polycarp Kusch, I.I. Rabi, Emilio Segré, William Shockley and Eugene Wigner." Reines' colloquium program seems to have been generously supported by the Case administration.

"Natural" neutrinos

The "better hole" that Reines was seeking turned out to be one reaching 10,500 feet below the earth's surface in a gold mine in South Africa. Reines, Crouch and Jenkins, along with *factotum* technician Gus Hrushka, recent PhD graduate William Kropp, and graduate student Henry Gurr, packed up and crossed the Atlantic with tons of detector equipment. The Case team was joined by collaborators from the University of Witwatersrand in Johannesburg. They set up their detectors in the East Rand Proprietary Mine in Boksburg, east of Johannesburg. The goal was to detect muons produced in the rock surrounding the mine tunnel by high energy neutrinos which were in turn produced in the atmosphere by incoming cosmic rays. To maximize the material through which the neutrinos must pass, the detectors were arranged to catch muons traveling sideways, *i.e.* within 45^{o} of the horizontal.

The two sketches **(Fig. 8-11 and 8-12)** are from a Scientific American article by Reines and the South African physicist J. Friedel Sellschop. (*Sci. Am.* **214** 2 40 1966) They show how the alignment of the two rows of large scintillators would pick up these "daughter" muons, but not the "sister" muons which are produced in the atmosphere. The trick is that the "horizontal" daughter muons must have been formed in the earth, because they could not have made it through the long horizontal trip in the rock. They could only have been produced in the rock by the penetrating neutrinos. The detector consisted of 36 rectangular boxes of scintillator liquid, each roughly 5 m long, 0.5 m high and 12 cm thick. They were arranged in two parallel walls containing 6 "bays" of three elements each. Each element had two photomultipliers at each end. The most convincing evidence of a horizontal muon's passage was a signal in all eight photomultiplier tubes on two slabs of a given bay, one in each "wall". The photomultiplier signals were displayed on oscilloscopes and photographed for later scanning. In their letter (*Phys. Rev. Lett.* **15** 429 1965) the authors reported seven such events over the course of about five months of running, the first event being recorded on 23 February 1965. This was the first observation of neutrino induced interactions occurring in nature (as contrasted with Reines' earlier observation of neutrinos from a nuclear reactor.) The experiment heralded a new generation of deep underground neutrino observatories.

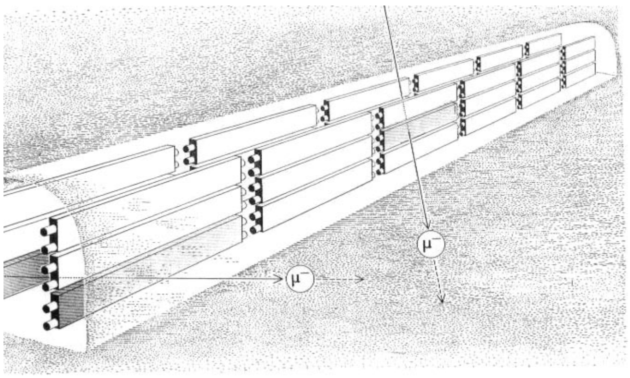

Fig. 8-11. Detecting neutrino induced muons in South African experiment.

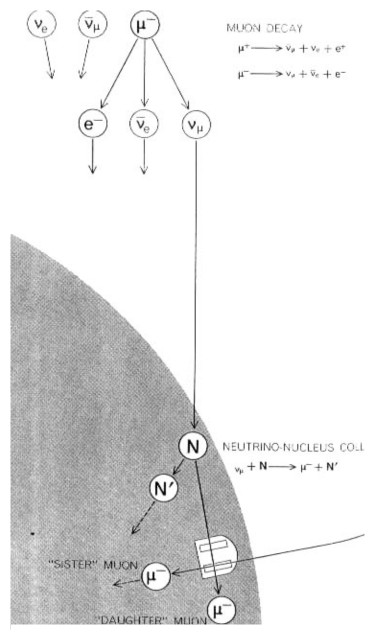

Fig. 8-12. Cosmic neutrinos produce muons deep underground.

Marshall Crouch and Bill Kropp have written an account of the setting up of the experiment and its principal results. Here are several excerpts:

"The logistics of moving the many tons of equipment by land, sea, and air, from the US to South Africa was elaborate and complex, and was tangled by both US and South African custom procedures, by maritime strikes, and lost, stolen, and misdirected shipping crates. But these difficulties paled in comparison to the problems associated with transporting the equipment through the labyrinth of the mine to the laboratory site. We will long remember the work chants of the black native miners in Zulu or Xhosa or Basuto as they manhandled the crates in their tortuous route to our crosscut…. The environmental conditions were extremely hostile, the rock temperature was about 135 deg. F, while the air temperature

with the help of the mine's massive air conditioning plant was a cool 95 deg. The humidity was always near saturation. Our engineer, Gus (Hrushka) lost nearly 30 pounds during the six month construction stage……In all, 35 neutrino events were recorded during the first phase of the experiment, with an additional 132 events, with much improved angular resolution, observed with the upgraded array. In addition, new limits were placed on the fluxes of extraterrestrial neutrinos, and on the lifetime of the proton for many possible decay modes. Finally the muon depth-intensity curve was extended many decades, reaching for the first time slant depths so great that only the constant flux of neutrino induced muons is observed." (W. Kropp, M. Crouch, in a memoir dated 7 September 1989)

Of course, a new lower limit on the baryon lifetime was set with the equipment in the South African deep mine laboratory: 2 times 10^{28} years, a hundred times longer than the 1961 Ohio salt mine number. (*Phys. Rev.* **158** 1321 1967)

Even with all the work and excitement associated with the deep-mine neutrino experiments, Reines decided in 1965 to direct a Case grad student, Frank Nezrick, in an improved version of the reactor experiment done seven years earlier. Returning to the Savannah River reactor with large sodium iodide detectors (29 cm diameter 7.6 cm thick cylinders from Harshaw Chemical), the two men studied the inverse beta decay reaction νbar p $\rightarrow e^+$ n taking place in a liquid-scintillator target. The signal from the positron was quickly followed by signals from the positron annihilation ($e^+ e^- \rightarrow 2\gamma$). Within the following 50 μs the neutron is captured by a gadolinium nucleus which subsequently emits other γ's. As mentioned before, one advantage of looking for reactor-produced neutrinos as opposed to solar neutrinos is that one can turn the reactor on and off. They observed 549 events in 2484 hours (0.22 per hour) with reactor ON and 12 events in 357 hours (.03 per hour) with reactor OFF. In contrast to the 1958 Reines-Cowan effort, this experiment measured the *energy* of the positron, and thus determined the energy spectrum of the antineutrinos coming from the reactor. (*Phys. Rev.* **142** 852 1966)

CWRU comes; Reines goes

By 1966, it was clear that Case and Western Reserve would join to form a new institution, Case Western Reserve University. (Still today, almost 40 years later, people are trying to think of a more manageable name. With a significant number of loyal Case and Reserve alumni still fine-tuning their wills, it may take a few more years for this to happen.) *(Flash: the 2003 administration has adopted "CASE" as the name by which the world should know the institution, having determined that "CWRU" can be pronounced only in Welsh.)* Whether the impending union of the two physics departments had anything to do with Reines' decision to leave, or whether it was the attractiveness of the position he was offered at University of California Irvine, would be interesting to learn. In any event, in 1966 Reines became the founding Dean of the School of Physical Sciences at UCIrvine, where he was to remain for the rest of his career. He took his young colleagues Henry Gurr and Bill Kropp, and the multi-talented Gus Hrushka with him to California. His neutrino and baryon decay work would continue for many years, including new experiments at the Ohio salt mine and the Johannesburg gold mine. He returned to Case on several occasions, including a visit to give a talk at the October 1987 Michelson-Morley Centennial celebration. It just happened, the previous February, on Valentine's Day, that the proton-decay detector in the Ohio salt mine had seen a burst of neutrinos from Supernova 1987A – rather nice timing considering that the expanding shell of neutrinos had traveled 175,000 years to get to Fairport Harbor just in time for the centennial celebration. The signal consisted of seven neutrino events in ten seconds, while the usual background rate was one or two events per *day*!

Reines' colleagues, friends and family were very pleased that he was awarded the Nobel Prize in physics in 1995 while he was still well enough to enjoy it. He died three years later.

In 1966, the theoretical physicist and historian **Martin Klein** (Chapter 9) was appointed interim head of the Case department. **B. S. Chandrasekhar,** whom we shall meet in Chapter 15, was the chairman of the Reserve department, and the two of them became co-chairs of the new, greatly inflated CWRU department. There had been 22 members of the WRU department and 31 in the CIT department. The total number was clearly much too large. It would be reduced by half over the following ten years, roughly where it remains in 2005. (Other departments did not suffer the same fate because they did not have large numbers on both sides.)

Glenn Frye

Glenn M. Frye completed his doctorate at the University of Michigan in 1950. Before his arrival at Case in 1960, he had spent seven years at the Los Alamos Scientific Laboratory where he studied charged particles coming from neutron induced nuclear reactions in light nuclei. The neutron beam was produced in collisions of deuterons with tritium nuclei. (The deuterons were accelerated in the Los Alamos Cockcroft-Walton 250 keV machine.) The outgoing charged particles - protons, deuterons, and tritons - were identified in nuclear emulsions.

In one of these experiments, Frye looked at neutrons scattered from ^{6}Li and ^{7}Li nuclei, identifying those scattered elastically (i.e. the neutron just bounces off the nucleus without exciting it or breaking it up), and those in which the nucleus is left in a well-defined excited state. The differences associated with the extra neutron in the ^{7}Li nucleus cast light on the structure of these two isotopes. (*Phys. Rev*. **93** 1086 1954 and *Nucl. Phys*. **52** 505 1964) I recently asked Frye why there was a ten-year delay in publication of the second paper on the lithium work. He said that it had been classified for a long while. The government wanted to keep to itself any information on the production of tritium, a key component in thermonuclear devices.

Frye then moved on to experiments at the newly operating Bevatron at Berkeley. This 6 GeV proton accelerator was built largely to search for the antiproton, having just enough energy to reach the threshold for p p → p p p pbar. The discovery was made promptly, and Frye was among those who hurried to study these new examples of antimatter. He and his collaborator, Alice Armstrong, exposed a stack of nuclear emulsions to a magnetically analyzed 700 MeV/c negative beam coming from a Cu target in the machine. Among the many, mostly π^--induced, collisions were sixteen antiproton induced events. These were measured and the charge and momenta of the annihilation products, all pions, were determined. (*Phys. Rev.* **110** 170 1958, *Nuovo Cim.* **13** 77 1959) There is a photo of Glenn Frye later in this chapter. **Fig. 8-23.**

Physics by balloon, cosmic gammas and electrons

While his colleagues, Reines, Crouch and Jenkins, were putting their detectors as far below the earth's surface as possible, Frye was doing just the opposite. In two papers published in the same week, Frye and his grad student, Lawrence H. Smith, describe data taken with spark chambers flown at an "altitude" of 3.5 millibar pressure on balloons launched from the National Center for Atmospheric Research in Palestine, Texas. (*Phys. Rev. Lett.* **17** 733 1966 and *Phys. Rev.* **149** 1013 1966) *(The atmospheric pressure drops off logarithmically as the altitude increases, so 3.5 millibars is about 40 Km.)* The first was an attempt to observe high energy gamma rays from discrete astronomical sources. The second measured the high energy electron flux.

There had been proposals that powerful discrete radio sources might be fueled by antimatter annihilations, producing copious neutral π mesons, which in turn would decay into energetic γ's (in the hundreds of MeV range). The flying spark chamber was triggered when there was no incoming charged particle, but there were two outgoing charged particles, presumably an electron-positron pair coming from the materialization of an energetic γ. The spark chambers were photographed, along with digitized information on the orientation of the detector, so that the direction of the incoming γ could be determined. (The cameras had to be recovered after the balloon returned to earth, sometimes after a wild chase across Texas.) Special effort was made to look toward such objects as the Crab nebula and Cygnus A, but only upper limits (order of 10^{-4} γ per square cm per sec) could be set.

The work done by Frye did not go unnoticed. The following is a paragraph from a letter in Bob Shankland's files (in the departmental archives). It is from Luis Alvarez to Shankland, dated March 1965.

"Jan and I spent the week end with friends in Palm Springs, and Edward Teller was also there. Edward told me that he had figured out where the quasars found their tremendous energies. He said he felt sure that they must be collisions between galaxies and anti-galaxies. He had calculated the number of gamma rays that would be incident on the top of the atmosphere, and he felt sure that the experiments to look for them would be very difficult, but he hoped that somebody might undertake them in the future. I told him of Glenn Frye's beautiful spark chamber experiments, and from then on Edward was disconnected from the rest of the guests. He sat and thought, and didn't pay a speck of attention to anyone else at the party. Finally he disappeared from the room, and after quite some time, he came back with a big smile on his face, and said he had just been talking with Glenn Frye on the phone. He said his theory was on the ropes and probably wouldn't survive, but at least he was very happy to have heard the experimental results when he did."

Frye's next paper described the flights of a lead-plate spark chamber in which energetic *electrons* would produce recognizable showers. Two separate flights were made from the Texas launch facility so that the electron flux could be measured at two very different altitudes. The object was to determine the increase in the number of electrons as one looks deeper in the atmosphere. The altitude was given in g/cm^2 of residual pressure. At the higher level (2.16 g/cm^2) the flux was 4.8 ± 5.4 electrons/steradian m^2 sec and at the lower level (4.35 g/cm^2) it was found to be 16.3 ± 5.3 electrons/steradian m^2 sec. The conclusion was that no more than 5 electrons/steradian m^2 sec arrive vertically at the top of the atmosphere; this is less than one percent of the primary *proton* cosmic ray flux. The higher flight was made with a 6-million cubic foot ½ mil polyethylene balloon; it flew for 8 hours and ended up near Montgomery, Alabama.

In 1966, Frye was joined in the balloon work by a newly appointed associate professor, **Chia Ping Wang**. Wang had done his doctorate at the University of Singapore in 1953 and had held faculty positions in Chinese and Hong Kong universities, followed by two years at Catholic University in Washington. At CWRU, in addition to his work with Frye, Wang published a study of particle multiplicities in high energy collisions. He compiled pion-nucleon and nucleon-nucleon data from over fifty accelerator experiments, with energies up to 27 GeV. He proposed a model for the sub-structure of the target nucleon which appeared to follow from the observed multiplicities. (*Phys. Rev.* **180** 1463 1969.) This work was extended to 60 GeV data on pion-nucleon and antiproton-nucleon from the Serpukhov accelerator in the USSR. (*Phys. Lett. B* **30** 115 1969.) Wang left the CWRU department in 1970. He continued to publish on this approach to nucleonic structure while associated with several university departments, including MIT and Cambridge.

Frye and Wang returned to the search for high energy γ's from discrete astronomical sources, but again came up empty handed. After a group at Rochester reported a signal from somewhere in the constellation Cygnus, the Case group mounted three balloon flights with the electron-positron-pair-detecting spark chambers. Their maximum flux turned out to be ten times *less* than what had been reported by the Rochester group. (*Phys. Rev. Lett.* **18** 132 1967 and *Canadian Jour. Phys.* **46** S448 1968)

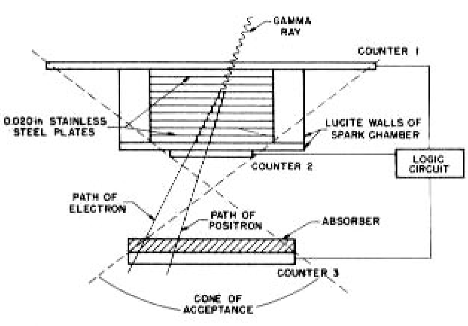

Fig. 8-13. Balloon borne γ-ray telescope.

An even more elaborate balloon-flight experiment was undertaken in 1967, again from the Palestine, Texas launch facility. The object was to make a more detailed measurement of the electron component of the primary cosmic rays. To better separate the electrons from protons and other heavier particles, a gas Čerenkov counter was placed above four aluminum and fifteen lead plates in the spark chambers. To reduce the power requirements, glass sheets were placed over all the metal plates to reduce the amount of charge in each spark. One must appreciate the experimental challenges of designing self-contained detectors like these, along with the necessary power supplies and data recording systems. Two flights were made, one at 5.30 g/cm^2 residual atmosphere took data for 5 hours and ended up in Arkansas, the other at 2.72 g/cm^2 for 2 hours on its way to Louisiana. It was determined that the electron flux more energetic than 3 GeV (4.3 ± 0.97 electrons/sterad m^2 s) was independent of altitude and may be attributed to primary cosmic rays. (*J. of Geophys. Research* **74** 53 1969)

Data on cosmic gamma rays from a flight in August 1968 out of the Texas launch site were published several years later. The object was to see if the flux at 10 MeV were consistent with power-law extrapolations from lower energies. The data consisted of 149 electron pairs which satisfied all the selection criteria. The use of the spark-chamber telescope allowed the determination of the direction and the energy of the incident gamma. The telescope package is sketched in **Fig. 8-13**. The authors conclude that "the measured value is an order of magnitude *above* the extrapolation of the power-law which holds below 1 MeV." They propose that the observed excess is due to a diffuse gamma flux of cosmic origin, superimposed on gammas which are secondary atmospheric radiation. "The Cosmic Diffuse Gamma-ray Flux at 10 MeV" (*Astrophys. J.* **182** L51 1973.)

Discovering discrete cosmic gamma sources

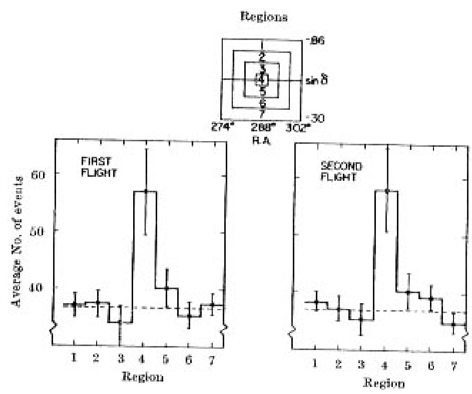

Fig. 8-14. Search for discrete gamma sources.

In February 1969, Frye and his grad students Alan Zych and Jon Staib teamed up with a group from the University of Melbourne on two balloon flights from New South Wales. This time, they identified a point source of high energy gammas. Using two different sets of spark-chamber and Čerenkov detectors and two different gondolas, the collaboration found a remarkable excess of events above 50 MeV in a particular 4^o half angle cone in the direction of Sagittarius. (*Nature* **223** 1320 1969) **Fig. 8-14**. (The little square shows the seven regions on the sky which are plotted beneath.) A follow-up paper detailed the results of the two February flights, and a third flight in November of 1969. Data from the three flights were combined, and three gamma-ray sources were observed. The measured intensity for each of the three sources was about 1.5 10^{-5} γ cm^{-2} s^{-1}. (*Nature* **231** 372 1971) The third flight ultimately yielded a fourth gamma source. **Fig. 8-15** shows the regions on the sky which were searched by each of the three flights, and the positions of the four γ-ray sources observed. "New Point γ-source Lib γ-1: Evidence for Time Variation and Possible Identification with PKS 1514-24" (*Nature* **233** 466 1971).

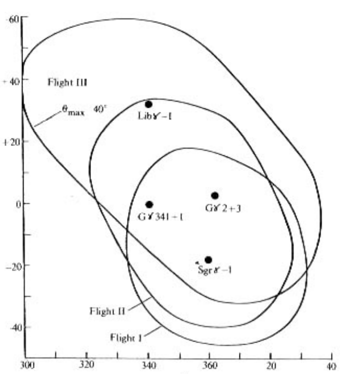

Fig. 8-15. Four γ-ray sources discovered.

Returning to the northern hemisphere later in 1969, Frye and Wang completed four flights with a 30-plate spark chamber with angular resolution 2.6^{o}. They did an extensive survey of the northern sky and found no gamma point sources. They were able, however, to set limits on the γ's coming from a variety of candidates (31 in number), e.g. the crab nebula, Cygnus A, the sun, 3C 273, etc. In so doing, the authors were able to test several proposed theories for energy generation in these systems. (*Astrophys. J.* **158** 925 1969) **Fig. 8-16** shows one of the four "equal solid angle" plots, There are three integers in each solid angle bin: respectively >100MeV events, <100MeV events, and events with single tracks. It's a nice way to look for hot spots in the sky.

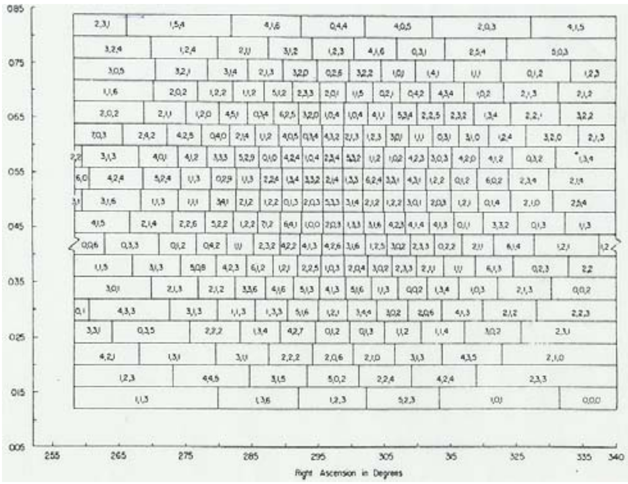

Fig. 8-16. "Equal solid angle" plot showing three categories of γ-ray counts.

Another Texas balloon launch was carried out in the summer of 1969, this time to measure the flux of cosmic ray *neutrons* as a function of altitude. The neutron detector included polyethylene absorbers in which neutrons could hit protons. The recoil protons were observed in spark chambers and the tracks recorded photographically. The balloon was slowly deflated to allow sampling at a series of altitudes. A total of 45,000 pictures was taken. The proton recoil angle and range helped identify the neutron events and their incident directions. The experimenters had considerable difficulty subtracting the large background of electrons produced by γ's. "Altitude Variation of High Energy Neutrons Near the Top of the Atmosphere" (*Acta Phys. Acad. Scien. Hungarica* **29** 709 1970.)

Fig. 8-17. Paul Albats

In 1969, Frye hired 27-year-old **Paul Albats** as a research associate. Latvian-born Albats had completed his BS at the University of Chicago and his PhD research at Cornell. **Fig. 8-17.** In 1973 he was appointed assistant professor. In addition to his work on high altitude balloon-borne experiments, he was instrumental in creating a digital electronics laboratory for the physics-majors.

Frye, Albats and Zych teamed up once again with the Melbourne group for another balloon flight from Palestine Texas. This time, the spark chamber system was designed to detect gamma rays in the 10 to 30 MeV range. The goal was to look for gammas coming from the Crab Nebula Pulsar, NP 0532. This object had been observed to emit electromagnetic radiation from 0.1 to 10 MeV, in pulses with period of about one thirtieth of a second. Frye *et al.* wanted to extend the measurements to higher energies.

The thirty million cubic foot balloon remained for nine hours at an altitude of 46.7 km (the highest flight to that date, according to their paper). An essential component of the apparatus was an onboard digital clock which recorded the time of the events to within a millisecond, and which was synchronized once each second with a ground based clock. Because the pulse from the pulsar had a width of less than 3 ms, a signal from NP 0532 must appear as an excess of events in the same absolute-time 3 ms bin as the lower energy radio frequency, visible, and X-ray signals. **Fig. 8-18** shows the number of events in one millisecond bins during a four hour exposure to the sky within 15^o of the Crab. A more than 5 standard deviation peak appears at the correct time. That this was indeed associated with NP 0532 was based on several arguments: the time and the width of the signal were correct; the peak disappeared when a slightly different period was used or when neighboring areas of the sky were observed. The resulting observed energy flux fit rather well with lower energy data on the $E^{-1.2}$ exponential curve.

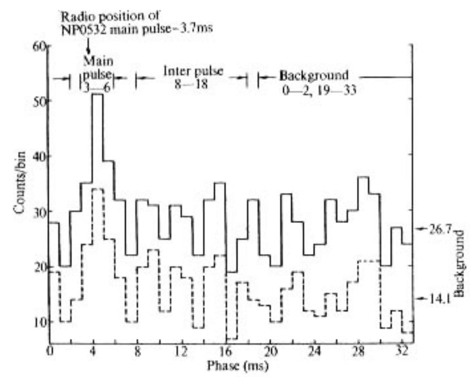

Fig. 8-18. Signal from the Crab Nebula 3.7 msec pulsar.

Fig. 8-19 "Two New Sources of High Energy Cosmic Gamma Rays" *Nature* **231** 372 1971. "New Point Gamma Ray Source Lib γ-1: Evidence for Time Variation and Possible Identification with PKS 1514-24" *Nature* **233** 466 1971. "Detection of 10-100 MeV γ-rays from the Crab Nebula Pulsar NP 0532" *Nature* **240** 221 1972.

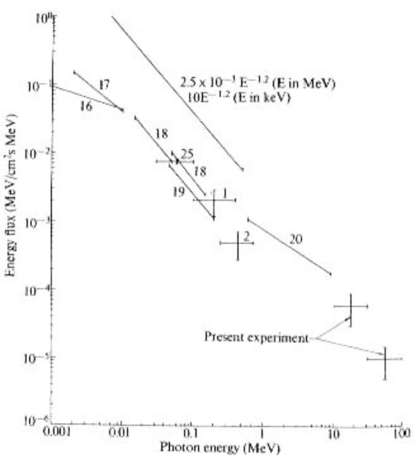

Fig. 8-19. Exponential drop-off of γ-ray flux with energy.

The whole detection apparatus of the preceding experiment was then transported to Australia for a look at another pulsar, the one in Vela: PSR 0833-45. The result, based on 21 events where the background is 8 events, was quite convincing. An interesting feature of the paper is a brief discussion of the relation between intrinsic luminosity and period which, in a certain theoretical model, was predicted to be $L \propto T^{-4.25}$. Given the observed periods and the known distances to the two pulsars, the ratio of Crab to Vela intensities should be 68, compared to the experimental 64 ± 32 – not very conclusive, but indicative of the type of measurement which may be made. "Pulsed 10-30 MeV Gamma Rays from PSR0833-45" *Nature* **251** 400 1974.

Frye and Zych combined data from two balloon flights (one in Panama and one in Australia) and a ground-based run (on the CWRU campus) to determine the flux of γ's produced in the atmosphere by incoming cosmic rays. They used the same spark chamber arrangement which was used in the search for discrete γ sources. **Figs. 8-20 and 8-21** show the measured high-altitude γ intensity as a function of energy (50 MeV to 1 GeV) and the angular distribution of the γ's relative to the zenith. The intensity is given in γ's per (sec g sterad MeV). (*J. Geophys. Res.* **79** 929 1974.)

Back to cosmic neutrons

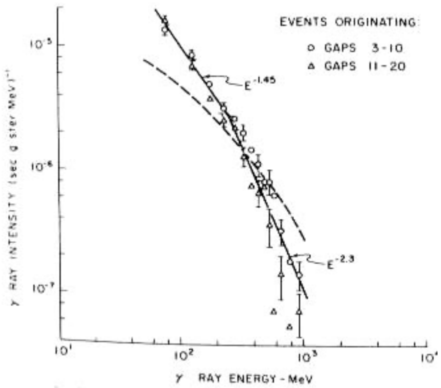

Fig. 8-20. Energy distribution of γ-rays produced in the atmosphere.

Throughout the 1970's Frye, Zych, Albats and their students continued the development of particle detectors which would give detailed information on incident cosmic ray particles and at the same time be self-contained enough to operate while hanging from a balloon dozens of kilometers above the earth. The abstract of a paper in 1977 begins with a compact description of their latest efforts: "A new detection method for 15 to 150 MeV neutrons from an extended source utilizes a spark chamber, time-of-flight technique. Both secondary particles in an n-p scatter are measured – the recoil proton in a spark chamber and the scattered neutron in a time-of-flight hodoscope, enabling the direction and energy of the incident neutron to be determined uniquely. … The detection efficiency is 10^{-4} at 70 MeV, the acceptance cone 40°, the angular resolution 3.0° and the energy resolution 10%. The detector has been used on high altitude balloon flights to measure the flux of atmospheric neutrons and to search for solar neutrons."

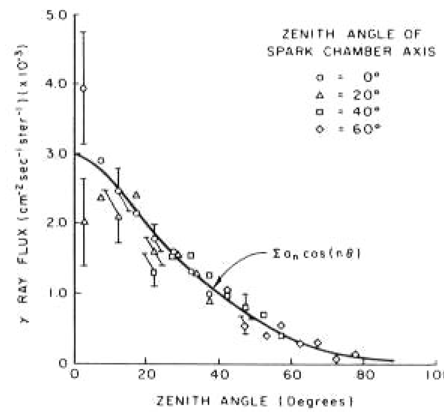

Fig. 8-21. Direction of atmospheric γ-rays.

Figs. 8-22 shows a schematic of this detector. An incoming neutron coming from the upper-left hits a proton in the polyethylene stack and the outgoing proton travels downward. The proton first passes through two planes of scintillator and the time interval between the two signals is recorded. The proton then enters a sandwich of spark chambers where the path of the particle is recorded on film; in addition the distance it travels through the chambers is recorded. Meanwhile, the scattered neutron travels off at 90° to the proton, hopefully entering one of the elements of the neutron detecting hodoscope (the 18 cylinders in the schematic). The time interval between the hit in the first proton scintillator and the arrival of the neutron in the hodoscope gives the speed of the neutron. The position of the struck hodoscope element gives a rough measure of the neutron's detection. All the recorded information appears on the spark-chamber photographs in the form of little images of lights. With all these required signals, one can see why the efficiency for this device in detecting a neutron is only one in ten-thousand – but

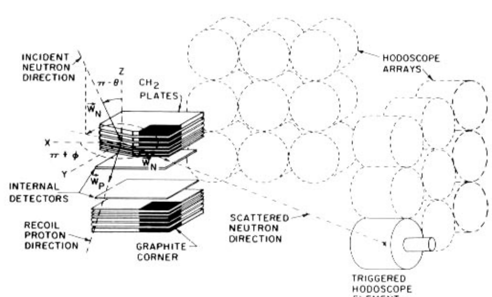

Fig. 8-22. Schematic of balloon-borne neutron detector.

there are a lot of neutrons out there. (*Nucl. Instr. and Methods* **144** 183 1977.) A photo of Glenn Frye, taken in the 1960's, appears in **Fig. 8-23.**

In the spring of 1978, the department voted to promote Albats to associate professor, but this was turned down by the administration. He subsequently accepted a position with the international Schlumberger organization, where he would work on neutron and γ-ray instruments for oil well logging. His departure dealt a serious blow to CWRU's cosmic-ray research program. Nevertheless, Frye would be joined by Jenkins in a continuation of balloon-borne experiments.

Fig. 8-23. Glenn Frye.

In the 1980's, Frye and post-doc Rokutaro (Rocky) Koga built a large multi-wire gamma-ray telescope with arc-minute resolution for flights launched from Australia. In 1987, Frye, Jenkins, Koga and Albats collaborated with groups from Imperial College, Frascati and New South Wales in a stratospheric balloon flight in search of 50 to 500 MeV γ-rays emitted by Supernova 1987A. (*AIP Conference Proceedings* **170** 80 1988).

Under Tom Jenkins' supervision, grad student Ken DelSignore completed his doctoral research by participating in the study of gammas and neutrons emitted in an unusually powerful solar flare in June 1991. The data were collected by the Oriented Scintillation Spectrometer Experiment (OSSE) which was aboard the Compton Gamma-ray Observatory Satellite. The balloon era was ending, and the exciting new satellite-based cosmic ray experiments would soon take over. According to DelSignore's dissertation, this was the most intense gamma ray flare observed to that date.

Glenn Frye retired to emeritus status in 1993, and Tom Jenkins did likewise two years later. Jenkins, a long-time member of the Sierra Club, continues to be active in the environmental protection movement.

Mining more results from the South African experiment

Marshall Crouch participated with the Reines UC Irvine group in a further analysis of the South African gold-mine data, this time to extract the *intensity* of surviving cosmic ray muons as a function of depth in the rock. The same large scintillator hodoscope described above (page 98) was used. The incident muon flux was determined as a function of angle relative to the vertical, thus allowing the experimenters to select different thicknesses of rock overlay. The resulting muon flux could then be parameterized $I_\mu(h) = a_\mu e^{-h/\lambda}$ where $a_\mu = 1.04\ 10^{-6}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}$ and $\lambda = 8.04\ 10^{4}\ \mathrm{g\ cm}^{-2}$ and h is the depth in g cm^{-2}. (The uncertainties are about 15% in a_μ and about 5% in λ.) These results could then be compared with the measured energy distribution of muons at sea level combined with the measured rate of energy loss and interaction cross sections for muons.

“Cosmic-Ray Muon Intensity Deep Underground versus Depth” (*Phys. Rev.* **D1** 2229 1970)

Since the neutrino data from the South African experiment included the *time* of arrival of muon neutrinos, the Reines group decided to look to see if there were any coincidences between the arrival of neutrinos and of the *gravitational* wave signals reported by Joseph Weber of the University of Maryland. Weber provided the authors with the times of his signals during the first nine months of 1970, the period during which the neutrino experiment was running. There were two events in which the Weber pulse and the neutrino hit were within two minutes of one another. “we assume that the observed coincidences are consistent with accidentals and take the upper limit on neutrino pulses associated with Weber waves to be 2 yr^{-1}.” “Upper Limit on High-Energy Neutrinos from Weber Pulses” (*Phys. Rev. Lett.* **26** 1451 1971.) *(While it is unlikely that Weber had really detected gravitational radiation, the search continues today with some very sophisticated and expensive long-baseline interferometry experiments. Reines was always on the look-out for opportunities to exploit the gold-mine of data from the gold-mine experiment.)*

The “definitive paper” on the South African neutrino experiment was published in two parts, “Experiment” and “Analysis”, in the *Physical Review* in 1971. Crouch was included as an author of the first part, along with members of the Irvine and Witwatersrand groups. The emphasis was on the events in which a neutrino coming laterally through a large thickness of rock produced a muon. Much of the material had appeared in the earlier papers, but this longer format allowed the inclusion of a table giving the details for each neutrino event “Muons Produced by Atmospheric Neutrinos: Experiment (and Analysis)” (*Phys. Rev.* **D4** 80 and 99 1971.)

In a two-author letter published three years later, Crouch and Reines present a new analysis of their search for baryon decay in the South Africa mine. At question were baryon decay modes which resulted in $\mu \rightarrow e$ decays. Their new result pushed up the lower limit of the baryon lifetime by a factor of three. Their earlier paper had described a search for muon signals which were in excess of those expected from cosmic neutrinos. In this paper, that search was refined, in that the measured delay between the detection of the muon and of its electron decay-product is included in the selection process. As often seen in Reines’ papers, the authors discuss briefly how one might improve the experiment, including increasing the size of the detector from 20 to 100 tons. "Baryon-Conservation Limit" (*Phys. Rev. Lett.* **32** 493 1974.)

Four years later, in 1978, one more paper based on the 1967-1971 gold-mine data was published by Reines and his group at Irvine, along with their Witwatersrand partners and CWRU's Marshall Crouch. “Our basic motivation for this study is to investigate the weak interaction in the high-energy region. Measurement of the muon flux deep underground provides a test of the correctness of the theory of the ν_μ + νbar_μ processes producing muons (*i.e.,* charge-changing ν_μ interactions) which occur in the rock. In addition, the atmospheric neutrino flux represents an important component of the cosmic radiation which should be studied to complete our understanding of cosmic rays as an observed geophysical phenomenon." Recall that the experiment observes muons and the direction in which they move through the underground detector. At large angles, the effective thickness of rock is so great that the muons must be those created when *neutrinos* interact in the rock. As the authors put it: "The depth and array configuration were chosen to permit measurement of the transition from the angular region where penetrating muons produced in the earth's atmosphere predominate (zenith angle < 45^o), to the region where the entire muon flux is neutrino-induced."

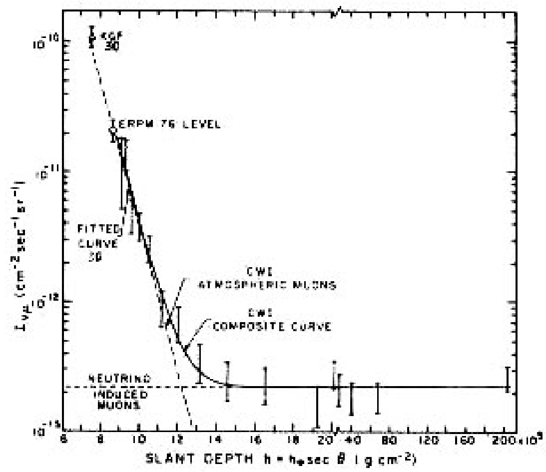

Fig. 8-24. Muon intensity vs. "slant depth" showing neutrino induced μ's.

The measured vertical muon intensity as a function of vertical depth, h, was best fitted by the sum of an exponential drop-off plus a constant term: $I_{\nu\mu}(h) = A \exp(-h/\lambda) + B_{\nu\mu}$, with $A = (2.26 \pm 0.16)\ 10^{-6}$ cm^{-2} s^{-1} sr^{-1}, $\lambda = (7.58 \pm 0.09)\ 10^4$ g cm^{-2}, and $B = (2.23 \pm 0.20)\ 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The value of the attenuation length λ measures the absorption of atmospheric muons in the rock and it can be compared to what one might expect from the strength of the weak and electromagnetic interactions. The value of the depth (and angle) independent term, B, measures the number of muons produced by neutrinos in the rock. **Fig. 8-24** shows the muon intensity as a function of "slant depth", clearly illustrating the exponential drop-off and the constant term. This figure, coming from a 1990 review paper by Marshall Crouch, was supplied by him for inclusion here. It shows the muon intensity as a function of slant-depth below the top of the atmosphere, from the measurements by Millikan in 1925 to those by those made in the South African gold mine. "Cosmic-ray muon fluxes deep underground: Intensity vs depth, and the neutrino-induced component" (*Phys. Rev.* **D18** 2239 1978).

Crouch goes after quarks (and tachyons)

The success of the quark model in categorizing a large number of sub-nuclear particles and in explaining their properties prompted many groups to search for evidence of fractionally charged *free* quarks. Candidates were sought in everything from meteor fragments to oyster shells. Crouch decided to build a new detector to search for quark signals in the cosmic rays. **Fig. 8-25** shows a sketch of the counter telescope. It consisted of five layers of 135 x 57 x 12 cm scintillator slabs, interspersed with 1000 flash tubes. The required signal was energy deposition in each layer of from 30 to 80% of E_o where E_o is the amount deposited by a single through-going fast singly-charged muon. The energy expected from a fast particle with a charge of only 2/3 e would be 4/9 E_o. The trajectory of the particle through the telescope was determined by the hits in the many layers of flashtubes. Background signals from electron showers are eliminated by single-track discrimination in the flash-tube array. In 1157 hours of running, there were 963 quark candidates. This number was reduced to 115 events with a clear single track and the required energy deposition. These are shown in **Fig. 8-26**, where all events except one pile up at the high end of the energy window. This single event, at 0.57 E_o, is somewhat above the 0.44 E_o expected for a charge 2/3 e particle. The resulting upper limit for 2/3 e quarks is given as 2.2 10^{-6} m^{-2} s^{-1} sr^{-1}. "Search for Relativistic Charge 2/3 e Quarks in the Cosmic Radiation" (*Phys. Rev.* **D5** 2667 1972).

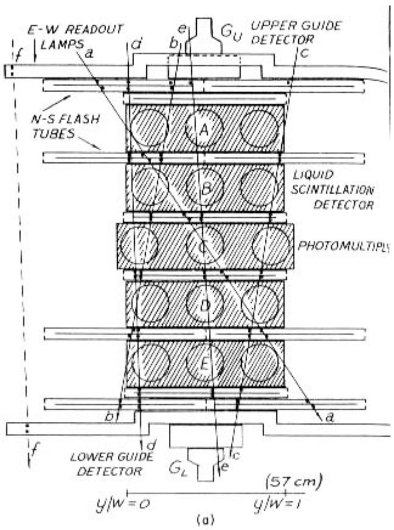

Fig. 8-25. Quark search telescope.

Crouch spent 1974 on sabbatical leave in Japan at the University of Tokyo. In a paper written there with G. Tanahashi, the authors explain: "We have carried out an experiment to search for tachyons produced in interactions of high energy cosmic ray particles which generate extensive air showers, the signature for faster-than-light particles being signals observed in advance of the shower front of relativistic particles." Some earlier experimenters had presented preliminary evidence for tachyons (i.e particles which can travel *only* at speeds greater than the speed of light). The Crouch - Tanahashi experiment was done at the Air Shower Array (ASA) of the Japanese Institute for Nuclear Study. This facility had been in operation for a dozen years; it featured a very large array of detectors for the study of extensive air showers, typically with energies in excess of 10^{15} eV. A trio of one-m^2 scintillation detectors was arranged in a triangle at the center of the ASA. The signals from these three detectors were fed into an electronic delay line where they languished for 96 μs. When a signal of eight or more hits in the ASA was detected, the delay line was read out, providing data of what was happening *before* the shower. The resulting data were compared with similar streams of data taken at randomly selected times. As you may have guessed, tachyons were not discovered in this experiment.

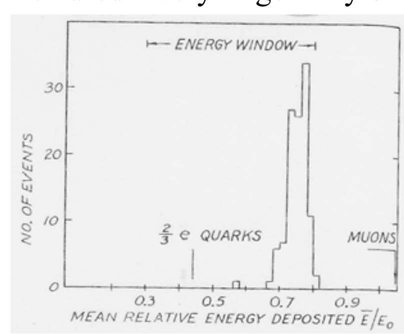

Fig. 8-26. Search for fractionally charged particles.

Marshall Crouch retired in 1987. He lives with his wife in nearby Willoughby, Ohio, and occasionally attends university and department events.