

**The Early History of Accelerator Radiological Protection
or A Limey in Wonderland
(With apologies to Lewis Carroll)**

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1. Prehistory: The Birth of Health Physics

The First Health Physicist? Have you ever wondered who the first health physicist was? My own tongue-in-cheek instinct is that it was Wilhelm Roentgen who, in Würzburg, accidentally discovered x-rays in 1895 with the aid of a primitive electron accelerator. Why? Because of all the photographs I have seen none were of Roentgen putting his hand in the radiation field, but rather those of his wife's hand wearing a ring or the hands of his technician or colleagues. Perhaps he knew a thing or two?

Moving on seventy years this reminds me of a similar view expressed by a nurse who was a member of the class on radiation safety at Harbor-UCLA Medical Center in Torrance, California. We were discussing the early radiologists (circa the twenties and earlier) who were observed to have shorter life-spans when compared with physicists not exposed to ionizing radiations. In the thirties radiation protection standards were established and subsequent studies suggested a steady return, with time, to "normal" of the lifespan of radiologists. The accepted inference was that the protection standards gradually introduced in the first three decades of the twentieth century were effective. One of my students had other views. A nurse remarked, *"I don't think it was the standards, it was because the radiologists just handed on the task of taking X-rays to technicians. You never see a radiologist taking an X-ray now!"*

It is worth mentioning that, although not published until 1897, a year preceding the discovery of radium by Marie and Pierre Curie, J. J. Thomson's work on cathode rays and consequent discovery of the electron preceded Roentgen's discovery of x-rays.

One point that history buffs should not miss is that the work of Roentgen in 1895 sowed the seed of the Profession of Health Physics and its first concern was protection from radiation produced by an accelerator.

2. 1932 The Annus Mirabilis: “We’ve Split the Atom!”

There were three great events in physics during 1932 for which it is remembered by the title of *annus mirabilis*. Chadwick announced the discovery of the neutron; Cockcroft and Walton in Cambridge and Lawrence and Livingston in Berkeley announced their seminal experiments with the new particle accelerators. Of less significance, except to me, is that it was in the November of this “year of miracles” that I was born and the neutron and particle accelerators were eventually to have a great influence on my life in Wonderland.

“We’ve Split the Atom!”



Figure 1. Photograph of the Cockcroft-Walton Accelerator. John Cockcroft is in the cabin observing nuclear disintegrations.

It is reported that, following their great discovery, John Cockcroft and Ernest Walton danced down the streets of Cambridge happily singing “we’ve split the atom” to the bemusement of all the passers-by. My first “big boss” was indeed Sir John Cockcroft. He was knighted in 1948 the year I started work at the Atomic Energy Research Establishment [AERE] at Harwell and was the first Nobel laureate that I ever spoke to. It was a brief conversation: I was leaving his office complex one day and opened the swing-door. Looking behind me I saw that Sir John was following me. Being

polite and certainly not wishing him to be hit by the door I held it open. “*Thank you,*” he said. “*Don’t mention it,*” I replied.

Those early years at AERE were a wonderful prelude to the “wonderland” I had entered. Indeed, one of my treasured memories is when, as a timid youth of seventeen, Otto Frisch, the co-discoverer of nuclear fission, met with our group at Harwell to review its work. Even though by far the youngest member, I was given the privilege of listening in. When the conversation lulled for a moment I used my initiative and offered that great English panacea: “*Professor Frisch,*” I said, “*would you care for a cup of tea?*” The great man beamed at me and accepted, my group leader beamed at me and that evening I could have walked on air!

Meanwhile in Berkeley Lawrence and Livingston developed the cyclotron, capable of accelerating charged ions to energies of 1 MeV. For those that have seen it, 10 cm in diameter, small enough to be held in the human hand, this tiny accelerator seems to affirm the meaning of the old adage “*Good things come in small packages.*”

It was quickly realised that Lawrence and Livingston’s cyclotron was readily adaptable and that it was possible to achieve much higher energies than the 1 MeV achieved by that first cyclotron. Quickly cyclotrons achieved the ability to produce energetic charged particles whose interaction with materials generated those newly discovered neutrons.

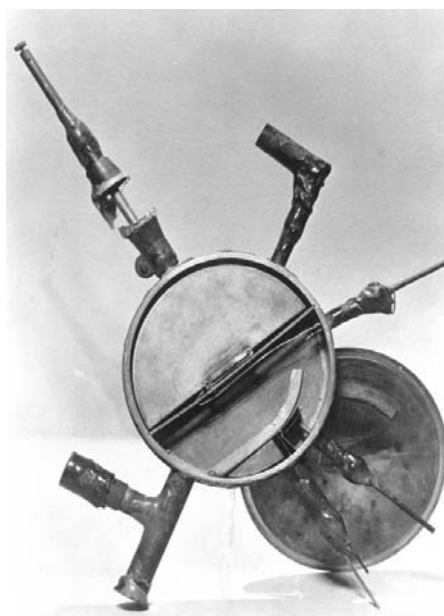


Figure 2. The first cyclotron, 4 inches in diameter and capable of accelerating ions to energies above 1 MeV. (Courtesy of Lawrence Berkeley National Laboratory)

3. The Thirties: From Miracles to the Second World War

Immediately following their discovery, X-rays were rapidly and extensively applied to medical diagnosis. In the thirties the preponderant interests of radiological protection were largely determined by the needs of the medical profession and therefore concerned with protection against excessive exposure of both staff and patients to low-LET radiations (photons and electrons). However, the invention of the cyclotron added other types of (high-LET) ionising radiations that needed to be studied and understood.

Cyclotrons quickly achieved the ability to produce energetic charged particles whose interaction with materials generated neutrons. At universities around the United States, and indeed around the world, there was a keen competition to increase both energy and current. At Berkeley, for example, in the years from 1934 to 1940 no less than three cyclotrons were constructed: the “27 inch,” the “37 inch” and the “60 inch.” Deuterons were often the particles of choice for acceleration because of the copious supply of neutrons. In this time the accelerated energy rose from 2.6 MeV to 16 MeV and the deuteron current available rose by two orders of magnitude from about 1 micro-amp to 100 micro-amperes. Thus, there were new radiations to explore, uncertain hazards to define and staff to protect from them. Berkeley was fortunate that there were a handful of talented people capable of exploring these issues and it is not unlikely that John Lawrence, who had trained as a physician, had his brother Ernest's ear.

Indeed, in the very few years before the beginning of the Second World War it is amazing just how much new information was obtained by “pure” research scientists long before what we would now recognise as “professional accelerator health physicists” had appeared on the scene. Some of the significant work done at Berkeley and elsewhere is listed:

- 1933 •** Fermi *et al.* and Joliot-Curie discovered neutron produced “artificial radioactivity”
- 1935 •** John Lawrence and his colleagues established a value of 10 for the neutron RBE (alas we haven't made much progress since those early days!)
- 1935 •** A limit of 0.01 R/day for neutron exposure limit was established at Berkeley by Ernest Lawrence
- 1935 •** Hamilton and his colleagues took the first tentative steps in establishing “Nuclear Medicine” by exploring the human metabolism of radio-sodium and radio-phosphorus
- 1936 •** Stone and his colleagues attempted the first use of neutrons for radiotherapy
- 1938 •** Louis Alvarez established that of the pair ^3H and ^3He it was tritium (^3H) that was radioactive
- 1940–42 •** McMillan and Seaborg discovered the transuranic elements neptunium and plutonium



Figure 3. McMillan recreating the search for neptunium at the time of the announcement of the discovery, June 8, 1940. (Courtesy of the Oakland Tribune and the Lawrence Berkeley National Laboratory)

Although considerable data were gathered describing the characteristics of the new radiations in the thirties and during World War II, it was to take another fifteen years or so before, with the resumption of purely scientific research after the end of the Second World War that, as will be discussed in Section 4, what we would now recognise as “professional accelerator health physicists” appeared on the scene.

4. The Fifties: Post War at the Berkeley Rad Lab

Throughout the thirties and the Manhattan Project years much practical information on the operation of and radiation hazards produced by particle accelerators had been obtained. As the physics departments of the great universities redirected their attention from “war-work” back to fundamental research there were soon plans on the drawing board for new accelerators with much greater energies and intensities than hitherto and therefore they would need staff who understood the elements of radiological protection. Now there was “artificial radioactivity” and those neutrons to deal with. It was this need to develop adequate protection standards for both low- and high-LET radiations that continues to differentiate accelerator health physics (and associated interests such as air travel, space travel) from the interests of the discipline as a whole.

Once the mechanisms of the induction of radioactivity had been identified, radioactive materials could be produced in large quantities at accelerators and were rapidly put to use. The Lawrence brothers vigorously promoted the application of radioactive materials to research in many disciplines on the Berkeley campus and to other research institutions. Because of John Lawrence’s medical

training it was not surprising that the following decade saw the birth of nuclear medicine and the first application of ion accelerators to therapy. For a summary of this era, the interested reader is referred to the excellent history by Heilbron and Seidel (*Lawrence and His Laboratory*, University of California Press, 1989).

Panofsky has given shrewd analysis of the development of the accelerator health physics profession from the end of the Second World War until the late fifties: “*During those days the principal calculations relating to accelerator radiological protection were more than likely done by the responsible physicists rather than separate specialists. For instance, Norman Ramsey at Harvard University personally did many of the shielding calculations for the Harvard cyclotron, and I had the privilege to calculate electromagnetic shower propagation and the resultant track-length for photonuclear processes in shielding for the proposal to construct the Stanford two-mile linear accelerator. But the burden of accelerator radiological protection became sufficiently heavy that specialists were needed; in consequence, they were grown from within the accelerator and particle physics communities after the war.*”

Rad Lab Personalities. Of the group of outstanding scientists shown in Figure 4 three are well known to members of the Northern California and Sierra Nevada Chapters of the Health Physics Society. There are Health Physics Society awards named in honour of Burt Moyer and Wade Patterson. Both Wade and Lloyd served terms as presidents of the Northern California Chapter of the HPS.

Moyer was one those described in Panofsky’s analysis and thus it was in 1947 at Berkeley that Ernest Lawrence, no doubt spurred on by his brother John, asked Burton Moyer to establish a health physics group at Berkeley. Moyer was already heavily committed with his research and teaching obligations and so quickly created an independent health physics group to support him in this endeavour and with which accelerator designers could consult on matters of radiation safety. By doing so, Moyer set a pattern followed by accelerator laboratories around the world.



Figure 4. Personalities (from left to right): Burton Moyer, Joe McCaslin, Lloyd Stephens, Wade Patterson, and Al Smith. (Courtesy of Lawrence Berkeley National Laboratory)

The Bevatron and Its Early Radiation Difficulties. In its early years the Bevatron was the most powerful proton accelerator in operation. Some would say (and others deny) that the Bevatron was built with just one purpose in mind—to discover the antiproton—but that it certainly did. I remember full well in 1954 my own professor at University College London doubting the existence of the antiproton but in fact Segrè, Chamberlain and their colleagues proved him wrong in October 1955! Four years later the significance of this work was recognised by the award of the Nobel Prize.

The Bevatron was the third first-generation weak-focussing proton synchrotron to be constructed during the first decade following the end of the Second World War. It was designed to accelerate protons to a kinetic energy of 6.2 GeV with an initial beam intensity of 10^9 protons per pulse, at a repetition rate of 10 pulses per minute but within a few months of its first operation in 1954 the design intensity of $\sim 10^9$ protons per pulse was achieved. Within a year an intensity of $\sim 10^{10}$ protons per pulse was attained. By 1962 the beam intensity had exceeded 10^{11} protons per pulse, at which intensity operations were severely restricted. There were three problems: Radiation levels on the working areas were becoming uncomfortably high; the background radiation levels were swamping the experimental detectors; and, due to the phenomenon of “skyshine,” radiation levels at the site boundaries were approaching unacceptable levels (see the section on skyshine). Furthermore operational experience now suggested that the Bevatron was capable of increasing its output by at least a hundred. This was of course most desirable for the experimenters. So plans for appropriate changes to the accelerator had to be made and the radiation problems solved.

Burton Moyer and Accelerator Health Physics. Moyer took aboard the resolution of the shielding and skyshine issues. For the former he developed a simple model (the “Moyer Model”), in which he combined the exponential attenuation of the radiation within the shield with its dilution by

the inverse square law. With the selection of appropriate values for the model's parameters Moyer designed the complex shield shown in the next figure. In the case of "skyshine" experimental data were supported by simple theory. It was during this period, by his finding solutions to the Bevatron's early radiation problems, that Moyer made his most significant contributions to Accelerator Health Physics.



Figure 5. The installation of Moyer's roof shielding above the Bevatron in progress. The interlocking roof-blocks are keyed together with one another and to the supporting cylindrical shield wall so as to ensure seismic stability. Bending magnets of the synchrotron are clearly visible (1963). (Courtesy of Lawrence Berkeley National Laboratory)

Skyshine. The success of Moyer's shielding design and skyshine studies is best seen by a comparison between the total number of protons accelerated each year and the integrated radiation levels in the same year at the Lab boundary. Figure 6 gives an overview of the laboratory and indicates the locations at which radiation routine measurements were made. These locations were determined by studying the results of radiation measurement at the site perimeter and the presence of nearby houses.

It was understood by Moyer that the reported site boundary doses included a comfortable cushion to compensate for lack of complete information at that time. It is also important to say that despite this conservatism at no time did site boundary doses ever exceed recommended (legal) dose limits.

In 2001, with the increased understanding of neutron spectra and of fluence-to-dose conversion coefficients, it was thought worthwhile to reassess the data and determine the magnitude of the intrinsic "comfortable cushion" in the early reporting. The study showed the maximum dose equivalents reported at the site boundary were overestimated by more than a factor of five.

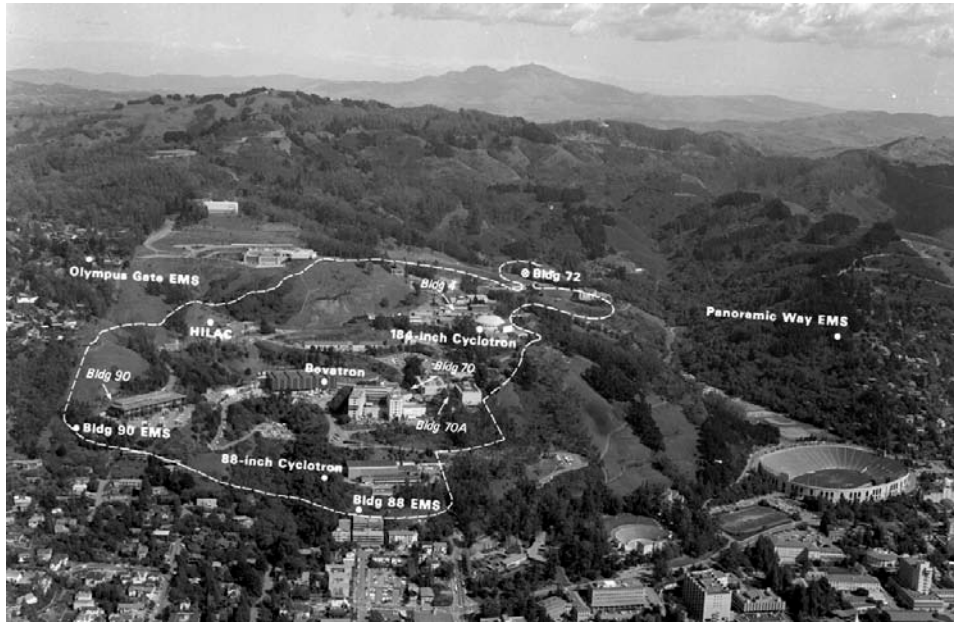


Figure 6. Overhead view of the LBNL site and its immediate neighbours. (Courtesy of Lawrence Berkeley National Laboratory)

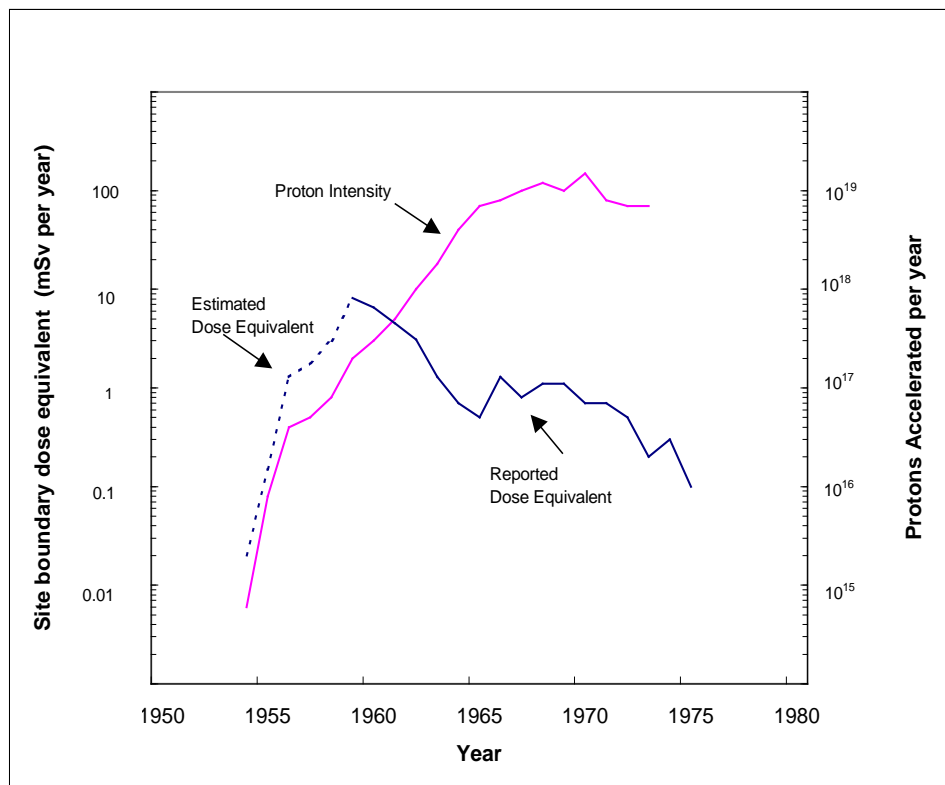


Figure 7. A comparison between the number of protons accelerated per year by the Bevatron and the annual radiation dose reported at the Olympus Gate monitoring station for the years 1959–1973. (Courtesy of Lawrence Berkeley National Laboratory)

5. The Sixties: Shielding Experiments

Despite the success of the Moyer shielding design for the specific case of the Bevatron a more comprehensive understanding of the physical processes of high-energy radiation transport was needed to facilitate the design of efficient and economic accelerator shielding for a variety of new accelerators under construction or being planned. It was necessary to improve the basic data required for the universal economic and efficient shield design. The data needed were obtained by performing several “shielding experiments” throughout the sixties and continuing into the seventies. These experiments were costly and required collaborative efforts. Various groups from BNL, CERN, DESY, Berkeley Lab, Daresbury Laboratory, Oak Ridge National Laboratory, Rutherford High Energy Laboratory, and Stanford Linear Accelerator Center (SLAC) collaborated to make measurements at the Alternating Gradient Synchrotron, Bevatron, CERN Proton Synchrotron, Nimrod, Nina, and SLAC.

Many such shielding experiments were performed to determine the data needed to design economic accelerator shielding with practicable shielding materials (earth, concrete and steel). These were usually collaborative efforts by several high-energy laboratories and were treated in an identical fashion as other nuclear physics or high-energy physics experiments when competing fiercely for the principal use of the accelerator time. It is a tribute to the accelerator community that these opportunities were afforded radiation physicists, particularly at the front-rank accelerators at the “cutting edge” of particle physics.

The design of efficient and economic accelerator shielding demanded an understanding of the physical processes of high-energy radiation transport. Two geometries were used: either in the line of, or transverse to, the high-energy proton beam, known colloquially as “beamstop” or “overhead shielding.” Measurements were made with a wide variety of radiation detectors in concrete, earth, or steel and with incident proton energies ranging from 2–30 GeV.

Such experiments, the increased understanding of the basic physics and, most importantly, the great strides in computer technology have greatly facilitated the accurate calculations necessary for shield design in particular and radiation problems in general. The need to replicate the heroic experimental measurements similar to those of the sixties is now thus very unlikely.



Figure 8. Concrete assembly for a 6 GeV proton shielding experiment at the Lawrence Radiation Laboratory. Michael Pick is seen inserting radiation detectors into the experiment. (1964)

6. The Early Seventies: Apollo 13 and Eye Flash Experiments

As early as the fifties Cornelius Tobias of the Donner Laboratory had speculated that “eye flashes” might be observed by space travellers caused by the interaction in the retina of the high-LET particles that are present in the cosmic radiation. Indeed in 1969 Edwin Aldrin and other crew members of the Apollo Lunar Missions 11 and 12 privately reported observing “eye flashes” during flight. For fairly obvious reasons there was reluctance by the astronauts to report these observations to their medical staff but subsequently the experiences aboard Apollo 13 forced their hand.

On its return to Earth the module lost power and all members of the crew were actually “in the dark” and became very well dark-adapted. There was no doubt in the minds of all three crew members that these eye flashes were not hallucinations but real events.

When these observations became generally known many physicists, as an alternative to Tobias’ hypothesis, attributed them to Čerenkov radiation but in the summer of 1970 Tobias confidently set out to test his hypothesis. The most immediately accessible source of high-LET particles at Berkeley was from the neutron beam of the 184-inch synchrocyclotron.



Figure 9. The first of a series of Apollo 13 eye flash experiments: Cornelius Tobias (under the black hood for dark-adaptation) positions his head in the neutron beam of the Rad Lab 184-inch cyclotron to observe eye flashes induced in the laboratory (Magnet, December 1970).

At separate times two dark-adapted subjects placed their eyes in the neutron beam. Tobias *et al.* estimated the dose equivalent rate to be ~ 1.2 millirem s^{-1} ($12 \mu\text{Sv } s^{-1}$) which would probably stand up to scrutiny today. At unannounced random intervals, the beam was switched on for a few seconds and the response of the subjects recorded. *“When the beam was ‘on’, both subjects experienced clusters of star-like flashes over their entire visual field. The subjects had never previously experienced this phenomenon . . . it disappeared promptly, in a fraction of a second, when the beam was turned off.”*

The promising results of the 184-inch cyclotron experiment encouraged further studies. Soon afterwards the Bevatron was modified to accelerate nitrogen ions to 36 GeV. Tobias was quick to take advantage of this new circumstance to absolutely confirm his hypothesis. Now much more elaborate and sophisticated experiments were possible. Most importantly the exact location of the head in relation to the ion beam could be precisely controlled and determined. This made it possible to irradiate precise sites in the brain and eye with pencil beams. Wick has reported the reports of these later and more conclusive experiments. *“Three scientifically trained observers—LBL director and Nobel laureate E. M. McMillan, scientist-astronaut Philip Chapman, and Cornelius Tobias—placed their heads in the beam of nitrogen ions and saw bright streaks when the ions penetrated the posterior part of their retinas . . . they concluded that the accelerated ions produce bright streaks*

and flashes if they interact with the retina and if they are near the end of their range where the ionization is greatest.” Thus, after a gestation of 18 years Toby’s hypothesis was confirmed and throughout the course of these experiments it was again my exciting and rather pleasant duty to act as health physicist during the exposures of scientists that I respected and admired.

In assisting with these experiments I felt for the first time in my life that I had earned my salary. For the most part my salary always seemed like a gift. Our profession, of course, springs from the concern to protect people from any harmful effects from the uses of ionizing radiations. However, when the safety of one’s own friends and colleagues is at stake the words “being protected” assume a whole new meaning and with it a sense of urgency.

7. The Eighties: Early Days of Waxahachie and the Large Hadron Collider

A tacit assumption of the Moyer model was that the number of neutrons would increase linearly with proton energy and this was the assumption usually made in accelerator shield design until the eighties. However, as accelerators increased in size, we were in a new energy realm and hence uncertainty. It was also important to improve shield design for economic reasons. The new research accelerators are very large; for example the Large Hadron Collider was designed to achieve a proton beam energy of 7 TeV and has a circumference of about 17 miles. At the early stages of the planned 20 TeV collider (the Superconducting Super Collider to have been constructed at Waxahachie, Texas) would have had a circumference of 54 miles (large enough to surround the District of Columbia)! Such accelerators are placed underground, rather like an urban subway system. It was clearly necessary to be able to determine the minimum depth below the surface which would result in no significant radiation environments at surface level.

It was assumed that the neutron production would be a power function of energy E_p^m where E_p is the proton energy. (The smaller the value of m the thinner the shield will be compared with the Moyer Model). A search of the literature, with one exception, showed that hypothetical values of m were all over the map, ranging from 0.25 to 1.

At the time only limited experimental data were immediately available in the energy range from 6–30 GeV and the extrapolation to the TeV region was decidedly uncertain (see Fig. 9.) Fortunately some time later Cossairt *et al.* at Fermi Lab published measurements at 350 GeV. Although not of great accuracy in themselves these measurements made possible an improved estimate of $m = 0.80 \pm 0.10$ over the energy range $5 \text{ GeV} \leq E_p \leq 500 \text{ GeV}$.

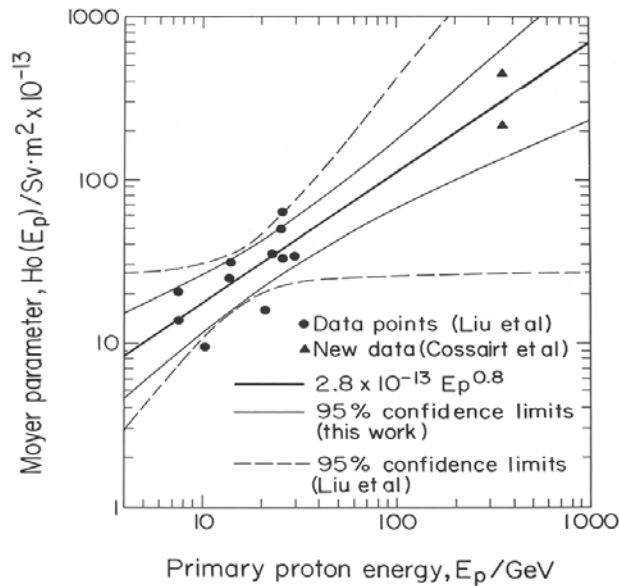


Figure 10. Neutron yield as a function of primary proton energy, E_p . The dashed lines show the 95% confidence bands for the limited data analysed by Liu *et al.* while the solid lines show the improvement in this band when the measurements of Cossairt *et al.* are included (Thomas and Thomas 1984).

8. The People at the Rad Lab

(A personal diversion. The author asks for the reader's indulgence to end with a personal diversion attempting to describe why working in accelerator radiological protection for fifty years was indeed living in a "Wonderland.")

Working at the Rad Lab was a joy not only because of the exciting and interesting nature of the work, where one felt near to the "frontier of physics" but perhaps more because of the camaraderie that existed between all those that participated. So many bright people from whom one could learn and, of course all the Nobel Laureates wandering about, at first making one catch one's breath until one got used to it. What is the collective noun, I wonder, for Nobel Laureates? A Litter? A Nobility? or, perhaps best of all, an Illumination of Nobel Laureates?

So I want to end this talk just to show how great working with such luminaries really was by relating an anecdote about my own family's interaction with just one of them, Edwin McMillan.

One day late in April 1972 my office telephone rang. The following is my memory, thirty-nine years later, of the ensuing conversation:

R.T.: Hello!

E.M.: "This is Ed McMillan here. There is something that has to be done immediately!"

R.T. (Thinks): Wow—the Director calling. Urgent! What have I not done? Am I in trouble?

E.M. (Clears his throat): "You have a daughter Susie and she wants to visit the Bevatron!"

R.T.: (Thinks): Oh blimey—a six year old at the Bevatron - I'm in real trouble!

R.T.: (Aside): Not known to me Susie had written to the Director saying that it was her seventh birthday on the 9th of May and Mavis and I had suggested going to the San Francisco Zoo for her treat—but she insisted that she wanted to go to the Bevatron because it was much more interesting. My mind raced with all the bureaucracy that such an adventure might unleash. But no! I was greatly mistaken.

E.M.: “Of course *Susie may go to see the Bevatron. You will keep her safe I'm sure.*”

A couple of days later Susie received a letter. It read:

Berkeley

2 May 1972

Dear Susie,

I will be very happy to have you visit the Bevatron on your birthday, and I am glad that you like it better than the zoo. Your comparison of the Bevatron with the zoo is very good, because the Bevatron is used to discover new particles, and the new particles are so many and so remarkable that they have been compared to animals in a zoo. Some people have used the expression “the Nuclear Zoo” for these particles.

Have a good time on your birthday visit!

With best regards,

Edwin M. McMillan

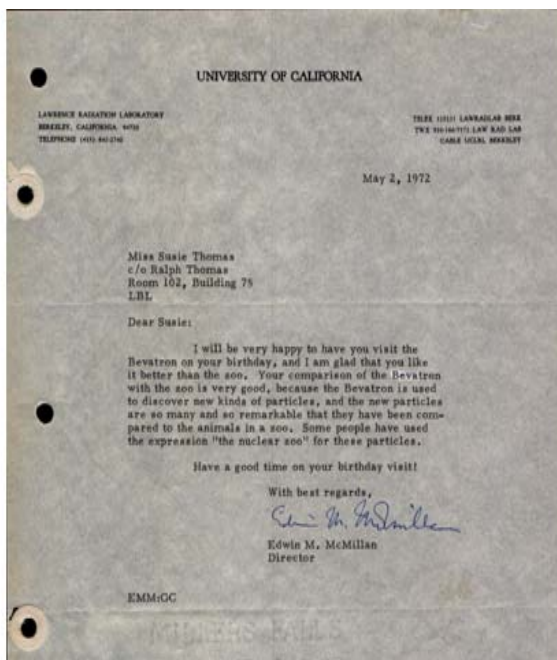


Figure 11. The “Nuclear Zoo” letter.

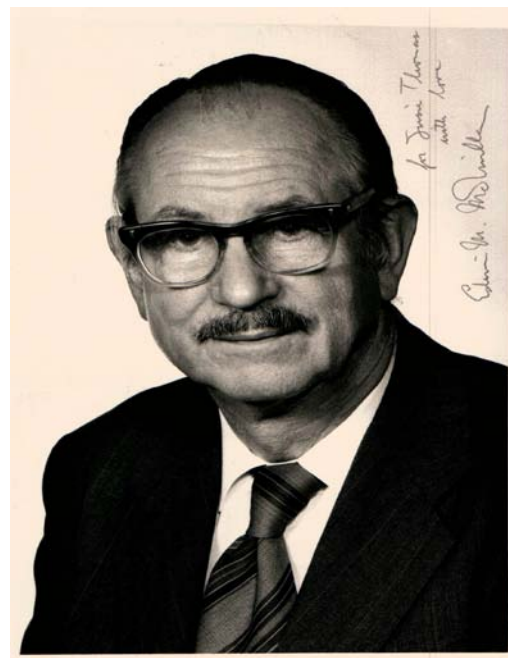


Figure 12. Edwin Mattison McMillan (circa 1972).

9. References

This paper is based upon many previous lectures given by the author. A list of references is not given here but suggested sources are the following;

1. “Radiological Protection Guidelines for Particle Accelerator Facilities.” Report 144, National Council for Radiation Protection and Measurements, Bethesda, Maryland (2003).
2. Morgan Lecture, “Accelerator Radiological Protection—A Personal and Privileged Odyssey,” www.hps.org/iarpe/thomas (September 2003).
3. Thomas R.H. and Stevenson G.R. “Radiological Safety Aspects of the Operation of Proton Accelerators,” Technical Report No. 283, International Atomic Energy Agency, Vienna (1988).

10. Acknowledgements

It was a particularly great honour and privilege to be invited to speak at this seminar in honour of Newell Stannard. He was a man greatly admired, who made great contributions to our profession but was always modest and kind. He was indeed a true scholar and gentleman.

Thanks to my friends and colleagues from the Accelerator Section, the Northern California and Sierra Chapters of the Health Physics Society for inviting me back, after eighteen years of what is best described as “a very partial retirement” to speak today. Your support and encouragement have reinforced my fellow countryman Dr. Johnson’s admonition: “*Don't think of retiring from the world until the world will be sorry that you retire.*”

Many of the photographs shown were obtained courtesy of the Lawrence Berkeley National Laboratory, University of California.

Finally, my great thanks to Marcia Hartman of the UC Davis Medical Center, Sacramento, and Linnea Wahl of the Lawrence Berkeley National Laboratory for their support help in preparing the PowerPoint presentation, reading the several drafts of this talk and making many helpful and pertinent suggestions.