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THE CHALLENGE OF HIGH ENERGY RADIATION DOSIMETRY AND PROTECTION*

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Introduction

Health physics as a profession is devoted to the protection of man and his environment from unwarranted radiation exposure. Over the last 30 years great progress has been made in this field by scientists from many disciplines. If I may expand on the list given in the text by Morgan and Turner,[1] health physicists have come from the fields of chemistry, physics, biology, medicine, mathematics, geology, hydrology, ecology, meteorology, computer science, and many other scientific and engineering fields. The purpose of this lecture is to demonstrate how the accelerator health physicist can and should use these diverse talents to best advantage in an accelerator environment.

Before continuing, let me describe briefly the traditional role of the accelerator health physicist. His responsibilities might include (from the text by Patterson and Thomas[2]):

1. Familiarity with the immediate program of accelerator operation.
2. Periodic surveys of all radiation produced.
3. Studies of induced radioactivity.
4. Evaluation of shielding.
5. Proper use, calibration, and interpretation of radiation monitoring equipment, including personnel monitors.
6. Radiation safety training.
7. Knowledge of rules and regulations regarding personnel exposure.
8. Public relations.

The more traditional role of the health physicist is performing operational tasks like these, and possibly including some work-related research into his activities. As a result of this limited scope of activities, a large number of his accelerator and particle physics colleagues approach him only when they want specific health physics information, such as exposure records, dose rates, etc.

A more challenging role, however, which I wish to examine, is one whereby the accelerator health physicist is actively involved in performing and publishing research of a broad, not directly work-related, nature using the latest techniques and equipment. In doing this, he will become more involved with his accelerator colleagues, both at the accelerator facility and outside. I can think of three good reasons why this is important. First, he will be much better prepared for new problems that might arise—problems that are out of the ordinary. Second, he will be able to establish better relationships with the people he is protecting if he not only understands, but is involved in, their problems. And third, he will find his job more challenging and exciting—and therefore much more enjoyable.

Basically, I believe it a maxim that the more accelerator health physics, as a profession, spreads its interests, the better prepared it will be in doing its job. There are certainly other viewpoints, for there are as many different health physics programs as there are accelerator installations, and each is shaped by many factors. We, at any given accelerator, should not be bound by the view that our way is the only way, but should welcome diverse approaches to operating a health physics group. At SLAC, we suggest being as inclusive and broad as possible simply because it has worked extremely well during the last dozen or so years.

The challenge of health physics is not only in performing the routine tasks of radiation safety, but in expanding its interests and expertise into those fields it is protecting.

The remainder of this lecture will be devoted to giving many diverse examples that illustrate the broader role that an accelerator health physicist can assume in

1. performing research for applied, as well as academic, purposes;
2. participating with accelerator physicists in machine design;
3. providing support to the particle physicist in many areas; and
4. making contributions to environmental and medical sciences.

The majority of the examples that will be presented illustrate work performed at the Stanford Linear Accelerator Center by members of the Health Physics group. In no way should this imply that we have a monopoly on these types of efforts. The lecture has been written from this viewpoint because it is a convenient way for me to demonstrate a philosophy, and because I know that we will have the opportunity to continue the discussion with others at one of the roundtable sessions.

Examples of Health Physics Participation

Various examples can be given to illustrate the broader scope of health physics. These might include creating computer codes, doing high energy physics research, studying high energy dosimetry, working with biologists or physicians to study radio-biophysical phenomena, etc.

I would like to begin by discussing a computer code that has been developed at SLAC in recent years. The program is called EGS, an acronym for electron-gamma shower, which simulates the development and transport of electromagnetic cascade showers by the Monte Carlo technique. The original code was written by H. Nagel[3] in 1965. Over the years, the SLAC Health Physics group has spent considerable effort and time in order to make it more versatile and complete. The Nagel version of the code, which is generally referred to as SHOWER, was limited to cascades initiated in lead cylinders by electrons or photons having energies less than or equal to 1 GeV. EGS is presently capable of simulating cascades in any element, compound, or mixture for any geometry, initiated by particles having energies up to and including 1000 GeV. Whereas SHOWER had a photon cut-off energy of 0.25 MeV, we have successfully run EGS as low as 1 keV. These, and many other features that I won't go into here, make EGS very useful as a tool for health physicists, but more important in the context of this paper, EGS has become invaluable to our accelerator colleagues. Let me demonstrate this by first describing how it has become useful to the accelerator design engineers.

In Fig. 1 we see one of the devices (the wand) used at SLAC to create positrons. The electron beam strikes the lower inside portion of the wand, bremsstrahlung is produced, some of the photon energy materializes into electron-positron pairs, and solenoid magnets and pulsing techniques select out the positrons into a given phase space for further acceleration down the remaining two-thirds of the two-mile accelerator. Physical damage has occurred to the device, most likely due to some heat transfer difficulty. We used the EGS code to simulate the heat deposition in copper, and in particular to give the radial spread of the energy per unit volume in very small histogram bins (0.01 radiation lengths). The exact mechanism that resulted in the damage shown is not known as yet.

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Fig. 1. Photograph of the SLAC positron target known as the wand.

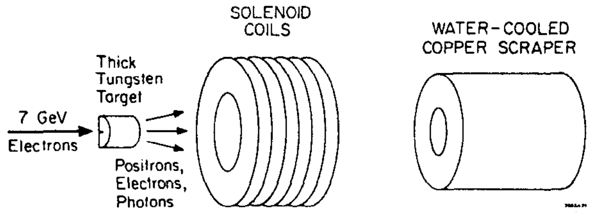


Fig. 2. Drawing that depicts another SLAC positron target with associated solenoid magnet and beam scraper.

Another type of positron source that is used at SLAC is depicted in Fig. 2 along with a beam scraper and a solenoid magnet. EGS has recently been used by the accelerator engineering department to redesign this new target for maximum positron yield and to understand the various heating problems. The program can also aid in the design of shielding to prevent coil windings from failing due to radiation damage.

A much larger version of the SLAC storage ring, SPEAR, is in the design stages as a collaboration between the Lawrence Berkeley Laboratory and SLAC. Figure 3 is a drawing of a cross section of the vacuum chamber in which the positrons and electrons will circulate in the new storage ring, called PEP. Also shown are the magnets that keep the particles in a circular path. Needless to say, the particles will emit a large amount of synchrotron radiation due to this bending action. As the photon radiation emanates from the trajectory it strikes the aluminum vacuum chamber walls where it either passes through or interacts. Preliminary calculations indicated that a large number of Compton-scattered photons could reach the coil windings and cause radiation damage. In addition to coil winding damage, there was some worry about the production of nitric acid and ozone in the air path that could eventually result in corrosive problems. By using the EGS code and the known synchrotron spectrum, we were able to show that the coil windings would suffer rather severe radiation damage after only one year of PEP operation under typical conditions.[4] The solution to the problem was simple; three or four millimeters of lead have been added to the design in certain regions of the chamber. The photoelectric absorption by the lead will attenuate out a large portion of the photons. It was also determined that nitric acid and ozone production would not pose any problems. To make EGS useful in this application, we had to extend the photon energy range down to 1 keV.

Sometimes these codes can be extended to situations not directly concerned with high energy laboratories, and such was the case with EGS. We have recently used the EGS code to see if we could simulate the bremsstrahlung that is produced by the higher energy medical accelerators (e.g., Varian Clinac 35). Two reasons motivated us to make this comparison. First, we wanted to check our program with

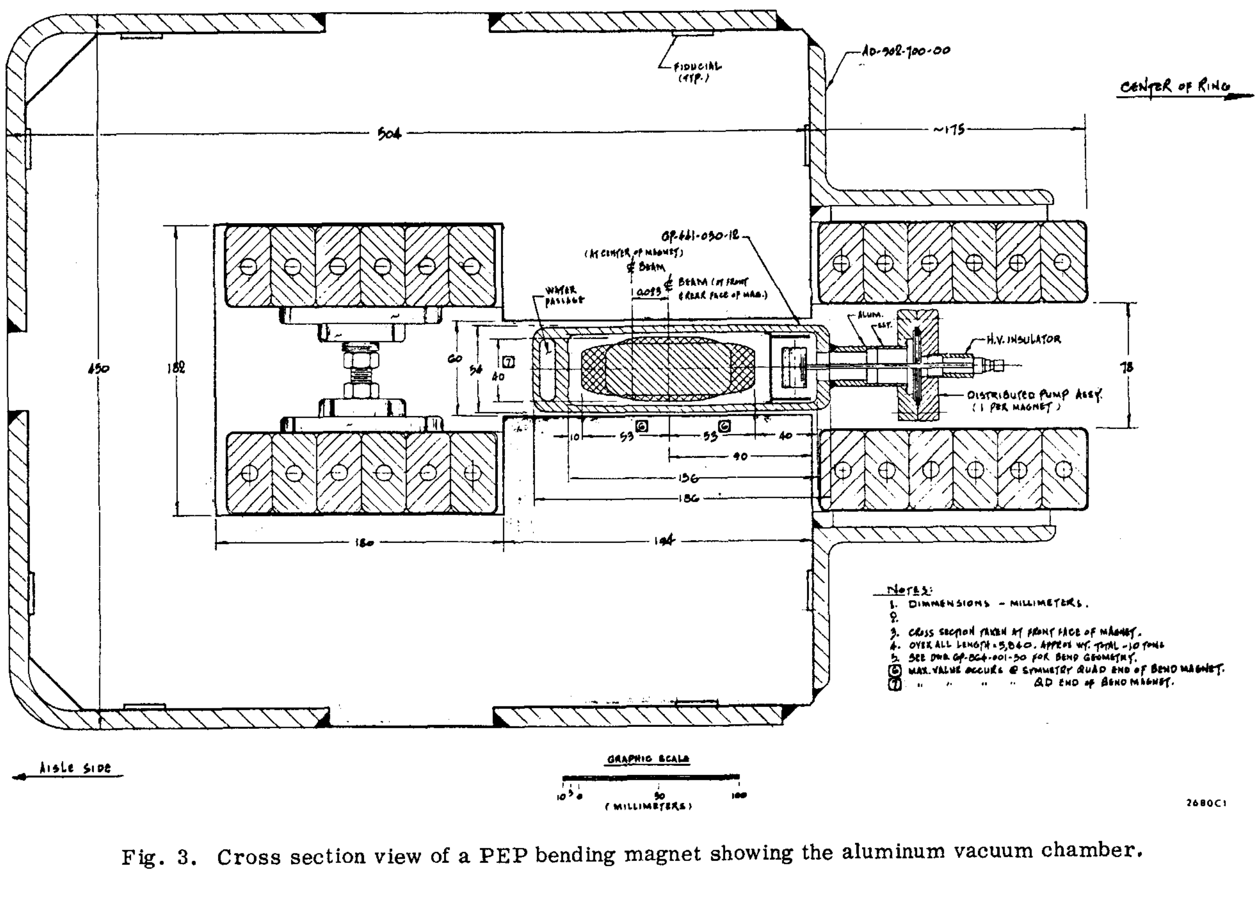


Fig. 3. Cross section view of a PEP bending magnet showing the aluminum vacuum chamber.

existing experimental data at these lower energies. But equally important, in our viewpoint, was the fact that our colleagues who work in the medical fields might profit from our efforts. In Fig. 4 we have the geometry that was used for the comparison. In Fig. 5 we have plotted the dose as a function of depth in water downstream from the bremsstrahlung target-flattener.[5]

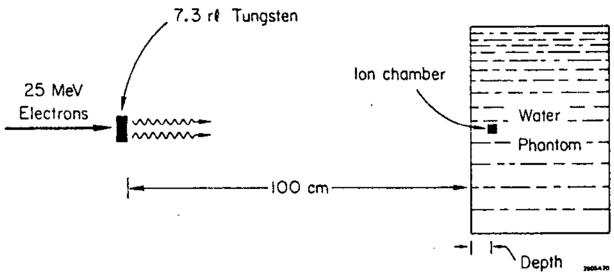


Fig. 4. Geometry used in the EGS calculation for the production of a 25-MeV bremsstrahlung and the re-showering in a water phantom.

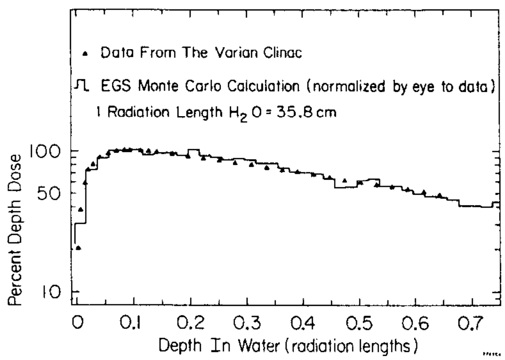


Fig. 5. Depth-dose results using the EGS Monte Carlo code compared with experimental data.

EGS has been used by high energy particle physicists mostly to design shower counters and to understand background and other effects in a number of experiments. An example of this is the design of the SPEAR detector system known as Crystal Ball.[6] In Fig. 6 we have an artist's conception of the detector showing a side view and a front view. The positron and electron beams intersect at the center. The Crystal Ball has a solid angle acceptance very close to 4π (~97%), and it emphasizes the complete detection and precise energy measurement of photons in e^+e^- annihilation events, particularly those associated with π^0 and η^0 decay. The system has four components. The first component is a set of cylindrical multiwire proportional chambers that are located around the beam pipe to define charged-particle trajectories. The second component consists of an almost spherical array of compact and greatly segmented NaI(Tℓ) detectors—630 individual prisms in all, each about 35 - 40 cm long and each with a photomultiplier tube and associated electronics. The third component is referred to as the tagger and closes the solid angle around the beam pipe. Each of the two end caps consists of 20 hexagonal modules of NaI(Tℓ) that are 50 cm long. The fourth component not shown in the figure is a forward luminosity monitor capable of measuring to an accuracy of ± 2%. The estimated cost of the Crystal Ball detector system is upwards of $800,000 and should take about 1.5 years to construct. The EGS computer code was used to re-design various components and provided detailed information such as the optimum size, the amount of NaI, angular resolution, and energy resolution. For hadronic cascades which are also of interest, use was made of the Oak Ridge National Laboratory code called HETC.[7]

Let us now look at some of the instrumental and experimental techniques that are a product of high energy accelerator health physics groups. Multiwire spark chambers are tools commonly used in particle physics for locating the tracks of ionizing particles. Some of the possible applications in health physics and medicine have been explored by Rindi.[8] The use of wire spark chambers with magnetostrictive readout for the location of gamma emitters is illustrated in Fig. 7 and involved

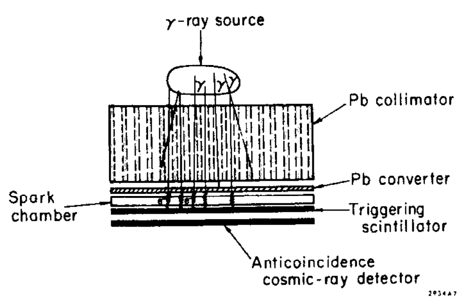
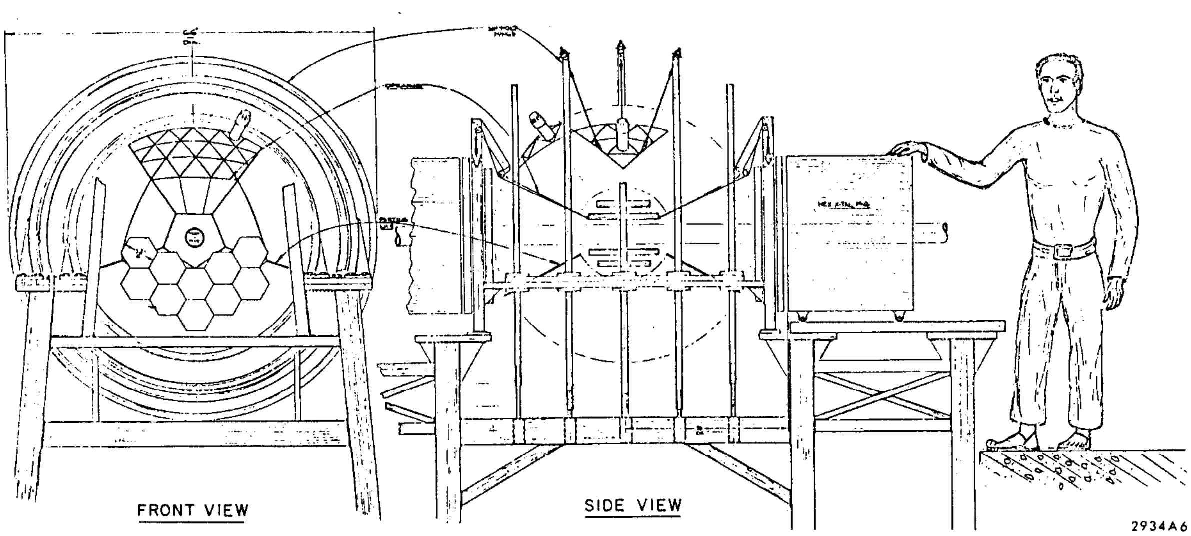


Fig. 7. Magnetostrictive (medical) wire chamber for locating γ-emitting isotopes.



the use of a lead collimator for the gamma rays and a lead converter in front of the chamber.[9] The resolution of the system is dictated by the resolution of the collimator. Fig. 8 shows a computer picture obtained from a 62-mm by 0.5-mm wire of ^{60}Co.

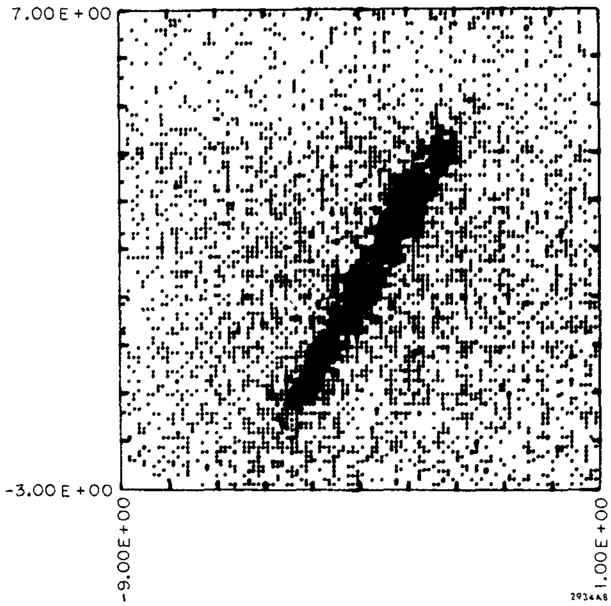


Fig. 8. Example of resolution of medical multiwire chamber. Computer plot of ^{60}Co wire-source (62 mm by 0.5 mm diameter).

Optical spark chambers have already been used for neutron spectrometry by a group from the Princeton-Pennsylvania Accelerator and the Health and Safety Laboratory in New York.[10] The LBL group has been working on a filmless multiwire spark chamber with magnetostrictive readout,[11,12] and a schematic view of the apparatus is shown in Fig. 9. The sensitive part of the spectrometer consists of

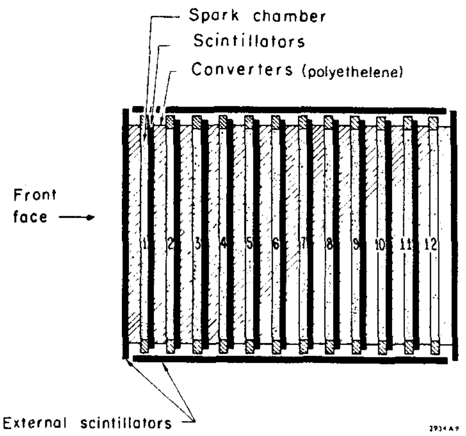


Fig. 9. Drawing of multiwire spark chamber system used at the Lawrence Berkeley Laboratory as a neutron (proton) spectrometer.

a stack of 12 multiwire chambers, 13 sheets of hydrogenous material, and 15 scintillators. The hydrogenous material has the dual purpose of generating recoil protons and of slowing them down. The scintillators are used for simultaneously triggering the high voltage on the chambers. Recent advances in multiwire proportional chambers eliminate the necessity of triggering-scintillators, and plans are apparently underway by the LBL group to replace the present design with self-triggered chambers. Such an apparatus has a broad range of applications. It can be used as a high-sensitivity spectrometer for 30 to 300 MeV neutrons with a known spatial distribution, or a much less efficient neutron spectrometer in the energy range 30 to 150 MeV in a field of unknown spatial distribution where it also detects the direction. It can also be used as a proton spectrometer with capability of determining angular distributions.

Increasingly the health physicist may be found working in the field of environmental protection. A number of years ago at SLAC, we were asked to measure the concentration of ozone in various parts of the accelerator housing and target areas. The result was the development of an instrument known as the Portable Ethylene Chemiluminescence Ozone Monitor.[13] A drawing of the mixing chamber and the photomultiplier tube assembly is shown in Fig. 10. Air containing ozone is pulled in through the top tube and ethylene gas

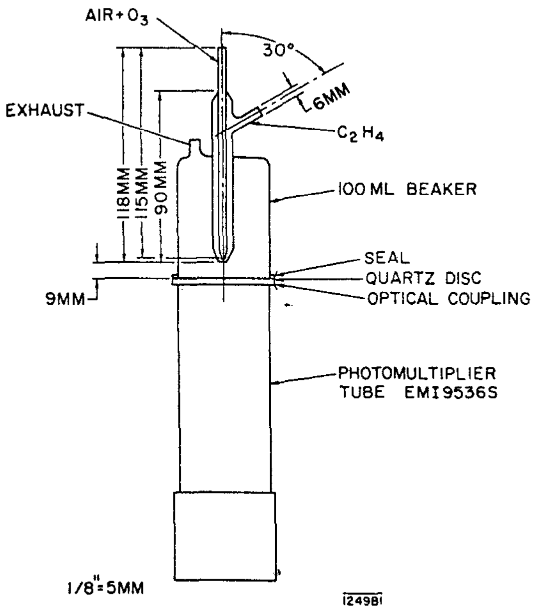


Fig. 10. Drawing of the mixing chamber and photomultiplier tube assembly used in the ozone monitor.

comes in through the side tube. The chemiluminescence that results due to the mixing of the ozone and ethylene is measured by means of the photomultiplier tube and a nanoammeter. A signal that is proportional to the ozone concentration results. The instrument is quite portable and can be used for industrial hygiene survey work. We have received a large amount of interest in this instrument from the Environmental Protection Agency in the United States and other agencies throughout the world.

There are many examples of health physics work done in the field of radiobiology. I shall give an example of work done in the field of nuclear medicine. The proximity of SLAC to the Division of Nuclear Medicine in the Stanford Medical School has recently allowed the development of methods to use the ^{11}C isotope to study alcohol addiction, and results of preliminary tests that were done on cats with ^{11}C-tagged ethanol have been reported.[14] The ^{11}C is produced by photospallation of oxygen and appears in the form of carbon dioxide whenever high energy beams dissipate their energy in water targets or beam dumps. Yields of 100 - 500 mCi of ^{11}C are easily retrieved because the total inventory of ^{11}C at saturation in the water target from electron or positron beams is of the order of 1 Ci/kW, and

SLAC quite often runs in the 100 to 500 kW range.

The radioisotope is injected by means of a catheter in the cat's femoral vein while it is anesthetized, and a pinhole-collimated gamma camera is used in order to map the localization of the activity in the animal. Some results are shown in Fig. 11 where the distribution of radioactivity is shown as a fraction of the total activity present in the animal.

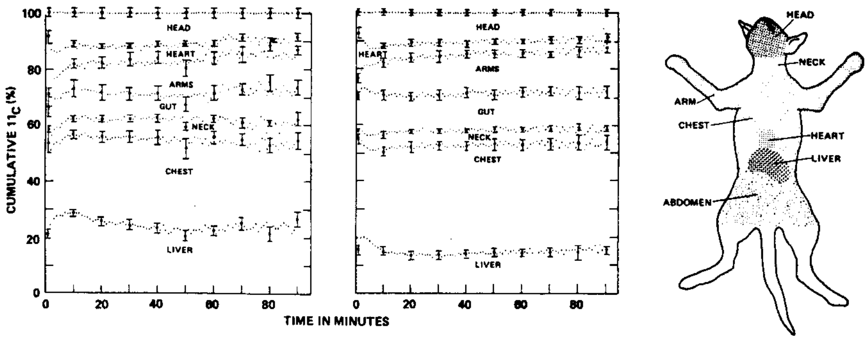


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Fig. 11. Distribution of ^{11}C activity in a cat injected with ^{11}C-labeled ethanol. Right-hand chart is for cats that had been preloaded with ethanol before injection of the labeled ethanol. Left-hand chart is for normal ^{11}C-ethanol injection.

The chart on the left is for cats that were injected with the ^{11}C-ethanol. That on the right is for cats that were preloaded with ethanol (i.e., drunk) and then injected with the tagged ethanol. We see that over 50% of the activity is present in the liver and the chest (lungs). The reduction in the liver activity for cats that were given an ethanol load is quite apparent (almost a factor of two decrease). This particular study demonstrated that it is possible to use ^{11}C-labeled compounds to obtain useful in vivo information by gamma scintigraphy. It is interesting to note that the collaboration was done between a physician, a biochemist, and a physicist at the Stanford Medical School, and a health physicist and a mechanical engineer at SLAC. Also, the fact that use was made of a SLAC by-product that would have otherwise gone to waste should be kept in mind in case similar situations exist elsewhere.

Activation detectors have been around for a long time as a tool for measuring radiation environments. One high energy reaction that is particularly interesting is the production of ^{149}Tb from gold irradiated by protons having energies greater than 600 MeV.[15] Unfortunately, very thin gold foils must be used in order to detect the alpha particles that are emitted by the ^{149}Tb and the technique is too insensitive for most accelerator radiation fields. McCaslin and Stephens[16] observed that ^{149}Tb, when produced by spallation in mercury, slowly diffuses to the top surface of the liquid mercury. The process can be accelerated by centrifuging the mercury sample. The ^{149}Tb floating on the surface may then be removed by adhesive tape and counted in a gas flow proportional counter. McCaslin and Stephens found that 60% of the ^{149}Tb could be extracted from a 500-g sample of mercury within an hour time period and that this results in a factor of 10^4 increase in the sensitivity over the gold-foil technique. We have successfully used this procedure at SLAC to measure the high energy component of hadrons emitted from a thick target bombarded with a 10-GeV electron beam.[17] Chemical separation of ^{149}Tb from mercury has also been reported by Shaw at the Rutherford High Energy Laboratory.[18]

In recent years J. Routti has developed a technique whereby the angular distribution of momentum-integrated secondary particle fluxes around high energy accelerator targets can be determined using a single activation detector system. This is done by direct gamma-ray spectrometry of a large number of spallation reactions induced in a single medium-heavy target, such as copper. The small cross sections of some of the reactions and the low detection efficiency of some of the products limit the technique to regions of high flux density. Nonetheless, the method is very interesting and is particularly useful in providing various checks on computer codes. The technique is best illustrated from a recent experiment published by Routti.[19] Copper foils were placed around a target at various angles ranging from 15 to 165 degrees. The 22-GeV/c beam at the CERN Proton Synchrotron was used. A Ge(Li) detector was used to measure the activities induced in the copper foils and computerized data analysis methods were used along with semi-empirical cross section formulae to obtain particle fluxes above different threshold energies. Good agreement between Monte Carlo calculation[20] and measurement was found and the value of this technique has been demonstrated.

This work by Routti can serve to illustrate several interesting points. To analyze the gamma ray data a code called SAMPO[21] was used. To obtain the integrated flux an unfolding technique[22] was needed. Finally, hadron cascade calculations[20] were necessary for a comparison to be made. Now, if we look at the associated references, we see that the various contributing studies were published in journals for the fields of nuclear engineering, accelerator machine design, nuclear instrumentation, and computational physics. In other words, the various aspects of this research are of interest to a wide range of scientists.

The second point to be made is that spallation reactions by high energy hadrons were only of academic interest a number of years back. Here we see a definite emerging use for this type of research. Similar photospallation studies have been done recently involving accelerator health physicists.[23,24] One of our challenges is in being able to foresee radiation protection applications of applied research as Routti has shown in the example.

Recently, Smith, Stephens, and Thomas[25] have used activation dosimeters in the heavy ion beam of the Bevalac at the Lawrence Berkeley Laboratory. Suitable reactions provide a means of checking the reproducibility and linearity of other detectors such as TLD's, ion chambers, and secondary-emission chambers. They may also be used to give information on the incident heavy ion beam composition, or the beam purity. This example, however, leads us to another point that should be stressed: Namely, that the health physicist should be aware of new facilities as they are developed at accelerator installations. Considerable multidisciplinary interest in research using heavy ions at relatively high energies has been pointed out by Thomas,[26] and it seems rather appropriate that the LBL health physics group should conduct dosimetry research using the Bevalac.[27,28]

In a very similar manner, Svensson took advantage of the laser beam facility at SLAC in order to measure the photofission cross sections of thorium at high energies. The research was part of an attempt to demonstrate the feasibility of the use of solid state track detectors for neutron dosimetry at SLAC.[29] A brief description of the overall problem is probably in order here. A common technique nowadays makes use of the fact that fission fragments, with their high stopping power, are capable of causing damage in insulators like plastic, and minerals like mica. The damage can be enlarged by suitable etching techniques and then counted. A thorium foil placed against a piece of lexan plastic can be used in this manner to measure neutron fluence. Unfortunately, a major component of a radiation field at an electron accelerator consists of photons, and photofission can be a competing process in such measurements. There was a need therefore to know the (γ, f) cross section at high energies. Svensson made measurements in ^{232}Th and ^{238}U which are shown in Fig. 12. The measurements were made using a bremsstrahlung beam produced by

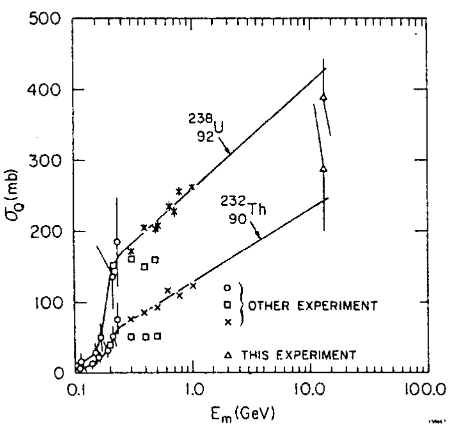

Fig. 12. Photofission cross section (per equivalent quantum) as a function of the maximum bremsstrahlung energy.

13-GeV electrons so that the cross section was determined per equivalent quantum using a quantameter. A more appropriate and useful measurement would have been to use a monoenergetic photon beam, and the laser beam facility that was in operation just about this time period provided exactly that. Monoenergetic photons were produced at SLAC[30] by colliding high energy electrons with low energy photons provided by a high power laser device. The photons were Compton-scattered back in the direction of the primary electron beam where ingenious methods allowed for extraction of a clean, monoenergetic, high energy photon source. The photofission cross section was absolutely determined once the photon intensity was known. This was obtainable by counting the electron-positron pairs produced in the 82-inch hydrogen bubble chamber downstream. The results of this experiment have not been made available yet, but the fact that a very unique tool at SLAC, as in the case of the Bevalac facility at LBL, was used by a radiation protection group to make measurements is important to note in the context of this lecture.

My last two examples really demonstrate the extremes that an accelerator radiation protection physicist encounters. At one end of the range we have the high energy muon shielding studies that were performed at SLAC and recently applied to the design of particle physics experiments by others. At the other end, we have the contributions made to experiments that are on-going at the Stanford Synchrotron Radiation Project (SSRP). The muon work[31] was initiated by the SLAC health physics group in order to experimentally verify calculations that we had made[32] and were planning to use in future accelerator designs. After discovery of the psi resonances at SPEAR and elsewhere, a number of experiments were proposed that were associated with the $\mu^+\mu^-$ decay channel. To make such measurements feasible, information about the photo-muon background was needed, and our measurements provided exactly that.

At the other extreme, we have the SSRP facility at SLAC that uses the synchrotron light emitted by the storage ring, SPEAR. Aside from the various operational health physics tasks that we have encountered, we have also been asked to consult with these experimenters on problems within our domain of expertise. For example, we have in Fig. 13 an artist's drawing of the focusing optics used in low-angle X-ray diffraction experiments by the chemistry department of the California Institute of Technology. The synchrotron light leaves the SPEAR trajectory and enters from the right side of the picture. Both the elliptically curved glass mirror

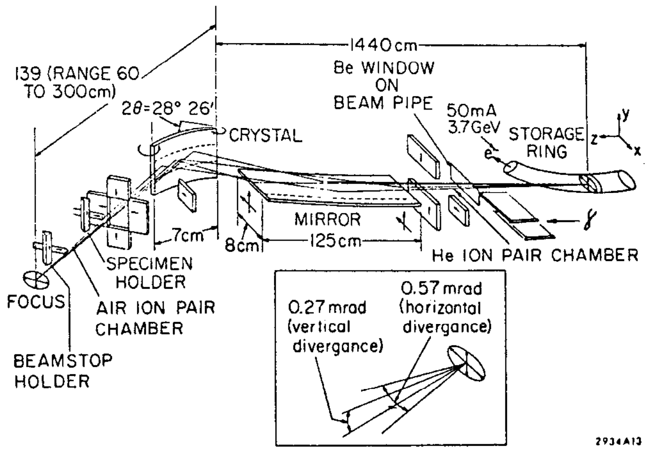

Fig. 13. Drawing of the Cal Tech focusing optics used in low-angle diffraction experiments at SSRP.

and the logarithmically spiraled silicon crystal provide variable focus and monochromatization from 0.5 to 3 Angstroms (25 keV to 4 keV). In order to determine the efficiency of this system, ion chambers were designed by our group and procedures suggested to calculate the flux from ion chamber measurements. The equipment is to be used to study classical low-angle diffraction of biomolecules in vitro and subcellular components in vivo. We also provided this group with a computer code that enabled them to calculate the synchrotron spectrum produced by SPEAR. This turned out to be rather easy for us because we had already solved a synchrotron radiation problem in the PEP work described earlier.

Summary

What I hope I have demonstrated by these many examples is that an accelerator health physicist can make contributions in many fields of science. He can, in addition to the various operational tasks that he is charged with, support others in his laboratory. He can do this by designing shielding for new accelerators and storage rings, by consulting with experimenters on background radiation problems that they may encounter, by helping the high energy physicist select appropriate radiation sources for checking out his equipment, by providing him with low energy atomic and nuclear physics calculations, and many other ways. Most of all, he can perform and publish research using the many tools and techniques that are at his disposal at a high-energy accelerator laboratory. This he should do.

I would like to end this lecture by quoting from a paper presented by Rindi at the Second International Conference on Accelerator Dosimetry and Experience that was held at Stanford University in 1969[8]:

"The health physicist working around high-energy accelerators has the advantage over identical professionals working in more conventional centers of being associated with the most advanced techniques in many scientific fields, particularly those connected with particle detection. Many of the peculiar problems they are bound to solve require the use of some of these sophisticated new techniques. Moreover, it is my opinion that it is also one of their duties to provide a linkage between the physics and the correlated technical activities that they are involved in (or look upon). This applies especially to the fields of biology and medicine, to which, as health physicists they are necessarily (though perhaps indirectly) related. This liaison has benefits for all."

Acknowledgments

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