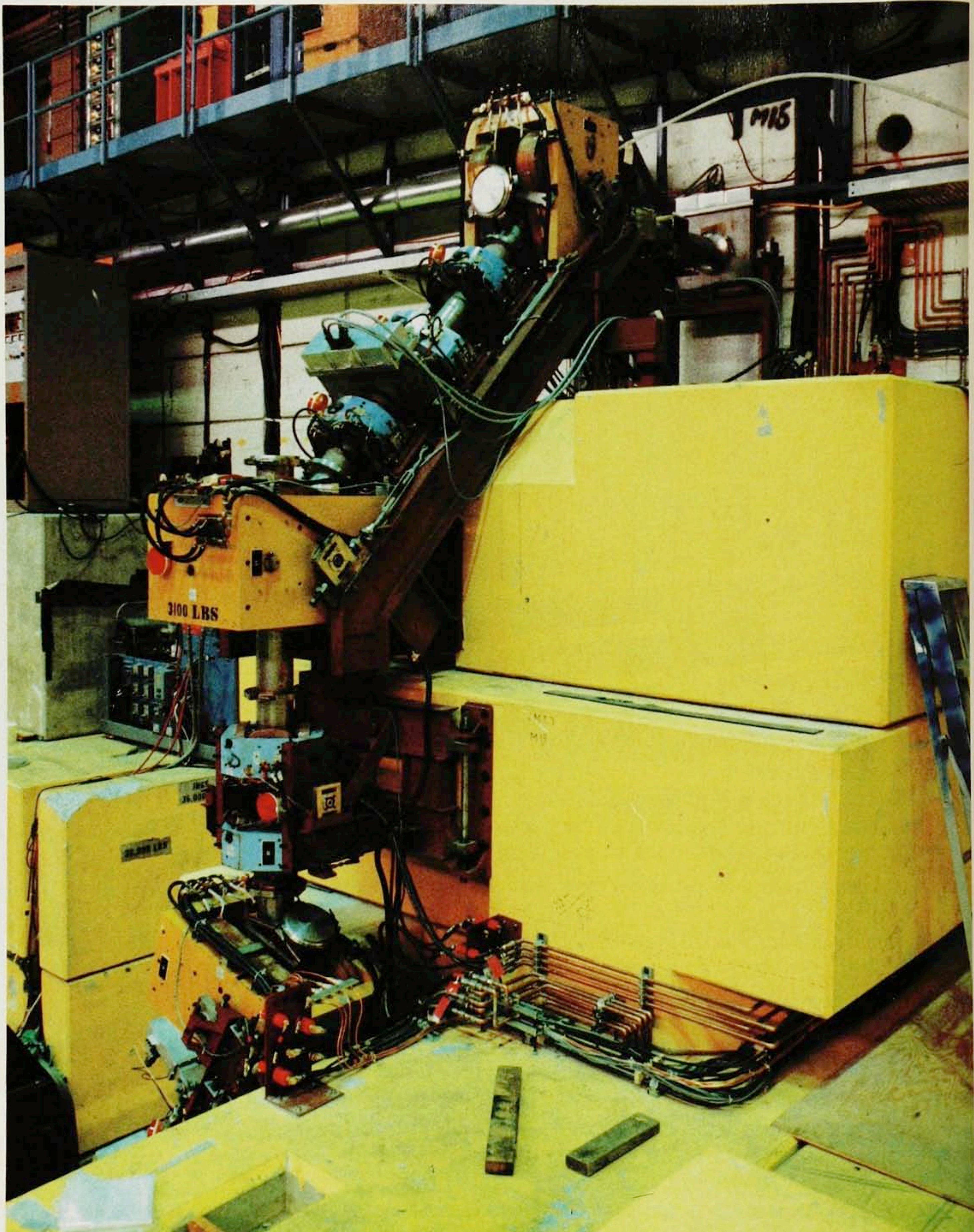

New beam line at TRIUMF dedicated to the production of surface muons. The beam elements transport the surface muons from a target in the main external proton beam, below the shielding blocks, upward and out of the experimental hall and into a separate building for muon spin rotation and muon decay experiments. Jaap Doorbos designed the beam line. Figure 1

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The surface muon beam

One of the inventors of an intense, completely polarized muon beam that every 'meson factory' now provides discusses the bittersweet history of the invention and some of the recent experiments that it made possible.

Theodore Bowen

Genius, in truth, means little more than the faculty of perceiving in an unhabitual way.
William James
The Principles of Psychology (1890).

Long ago, shortly before World War II, when I was but 13 years of age, I was excited by an article in *Popular Mechanics* magazine that described Ernest O. Lawrence's project to construct the world's greatest atom smasher, a 184-inch cyclotron, on a hill overlooking the Berkeley campus of the University of California. From that point on, my career goal was to become a physicist. While the 184-inch-cyclotron project has always symbolized to me the beauty and excitement of unlocking the mysteries of nature, I never suspected, even for many years into my career as a high-energy and cosmic-ray physicist, that I would have a rendezvous with destiny involving the 184-inch cyclotron: using it in its waning years to make my most significant contribution to the progress of science.

By 1969, when this story begins, I was the leader of a small high-energy-physics group at the University of Arizona. We had carried out a series of spark-chamber and counter experiments at the Lawrence Berkeley Laboratory Bevatron, as well as several cosmic-ray searches for fractionally charged free quarks. The group included three permanent faculty members and a young assistant professor, Alburt E. ("Burt") Pifer, with whom I enjoyed especially close rapport in discussing ideas for new experimental techniques.

The search for discoveries in experimental physics is not only an effort to find and interpret interesting experimental facts, but is also a creative intellectual effort to invent new experimental techniques that extend the frontiers of experimental feasibility (see figure 1). Often we physicists, while carrying out straightforward experiments, are at the same time contemplating ideas that might permit us to carry out interesting experiments that were thought to be impossible. Thus, during the intervals between our group's visits to Berkeley to set up or carry out Bevatron experiments, we engaged in frequent intense discussions of other possible experiments.

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The challenge

A difficult experiment discussed frequently in the group, especially by Pifer and me, was one that Gerald Feinberg and Steven Weinberg suggested[1] in 1961, to search for the muonium-to-antimuonium conversion

$$\mu^+ + e^- \rightarrow \mu^- + e^+$$

Muonium is a hydrogen-like atom, and antimuonium has exactly the same rest energy. If the difference between muons and electrons were not an additive quantum number, analogous to strangeness but a multiplicative quantum number such as parity, then the conversion from μ^+e^- to μ^-e^+ *might* be possible. The most serious experimental difficulties are associated with the muon's finite lifetime—2.2 microsec—and the fact that μ^+e^- and μ^-e^+ remain degenerate in energy only if they are in a vacuum and free from atomic collisions. The latter requirement poses a dilemma as muons arise at energies of many MeV from pion decay and must be slowed down in matter.

We embarked on serious calculations with the help of a new graduate student in the group, Ken Kendall. We eventually abandoned our original solution to the matter-vs-vacuum dilemma: It involved introducing large electric fields in a huge vacuum chamber to slow the muons to low velocities. Then we hit on the idea of stopping the muons in a thin foil that is at high temperature, and allowing thermal diffusion to carry the muons to the surface, where, we reasoned, they would evaporate into the vacuum region as neutral muonium atoms. A 0.001-inch-thick platinum foil heated to incandescence appeared promising, so we became intensely interested in obtaining relatively high intensities of positive muons, which stop in a thickness on the order of 50 mg/cm^2.

The conventional method for obtaining a muon beam requires first using a proton beam to produce an intense pion beam, then allowing the pions to coast through a decay region, and finally collecting a small fraction of the decay muons into a muon beam. The pion decay is

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

A typical momentum for the resulting muons is 100 MeV/c; a 50-mg/cm^2 target stops only a few percent of muons with this momentum. Also, the polarization of the beam muons depends upon the decay kinematics, and typically might be only 70%.

The idea. In our conversations in search of a better technique, our thoughts would revolve around the fact that π–μ decay has a two-body final state. Hence, when π–μ decays were first discovered in nuclear emulsions, the pion decaying at rest always produced a muon with a range of 0.6 mm. If only we could take advantage of this effect in a beam! Such muons have a kinetic energy of 4.1 MeV and a momentum of 30 MeV/c, which are very low compared to the values for typical beams in accelerator laboratories.

With our thinking geared to low energies and momenta, I suggested to Kendall an arrangement where one focuses π^+ mesons onto a very thin stopping target so that all the decay muons leaving the target would have nearly their initial 30 MeV/c momentum. One could then refocus a portion of these 30 MeV/c muons on the final target, which might contain a slowing-down section followed by the thin foil. This would be better than the conventional method because muon intensity is normally diminished by two effects: the randomness of the decay's direction and the randomness of its laboratory-frame momentum. When the pions stop and decay from rest, only the decay direction is random.

Pifer recalls returning to Arizona from one of his frequent trips to Berkeley and having Kendall and me excitedly explain to him our latest ideas. He recollects our explaining to him the concept that the density of μ^+ stops from π–μ decays at rest is simply equal to the density of the parent π^+ stops times the fraction of the solid angle subtended by the muon-beam transport system.

Pifer pointed out that the π^+ beam section was superfluous, because there would be an even higher density of stopping pions if the intermediate target were simply the surface of the π^+ production target—the target bombarded by the primary accelerator beam. It was obvious to the three of us after a few more minutes of discussion, looking at the proposed scheme from many points of view, that the intensity of μ^+ stops in thin targets would be improved enormously. The intensity gain turns out to be a factor of almost 100, as figure 2 indicates. Another advantage for some experiments soon was obvious: Our beam would be 100% longitudinally polarized because the polarization must be aligned along the direction of the associated neutrino, which is emitted 180° to the muon direction when the pion decays at rest. Our scheme eventually became known as a "surface muon beam," because it uses π–μ decays that occur just below the surface of the accelerator beam target. Because LBL designated us the "Arizona group," our beam usually was called the "Arizona beam" in the early years.

Why had this unusual μ^+ intensity enhancement not been discovered by accident during almost 20 years of experiments with laboratory-produced mesons? Seemingly the only requirement was to retune the bending and focusing magnets of a conventional beam line down to 30 MeV/c momentum. There are, however, three special requirements:

▶ The production target must be outside regions of high magnetic field

▶ The beam path must be in a vacuum so the low-energy muons can go many meters without significant loss of energy through ionization

▶ The scintillation counters through which the beam is expected to pass must be very thin.

The early meson-producing cyclotrons required the production target to be inside the region of high magnetic field because the protons could not be extracted; this prevented the escape of low-momentum positive secondaries. By the early 1960s, most meson-producing cyclotrons could provide external proton beams. Because no one had thought it necessary to design meson-laboratory beam-lines for 4-MeV particles in 1970, all low-energy pion beams were designed to operate in air or helium! Ironically, at higher momenta, vacuum beam paths were in wide use for electrostatically separated $K^{\pm}$ beams, where finely focused images are required to separate kaons and pions. The new generation of "meson factories," such as LAMPF, SIN and TRIUMF, then being designed or built, did contemplate vacuum beam lines to reduce spurious scattering, but these lines usually featured fairly thick entrance and exit windows. Designing sufficiently thin (0.5 mm) scintillation counters was not a serious technical problem because slow particles have a high specific ionization; in fact, the surface muons were later observed even with a single scintillator acting as the stopping target inside the vacuum chamber.

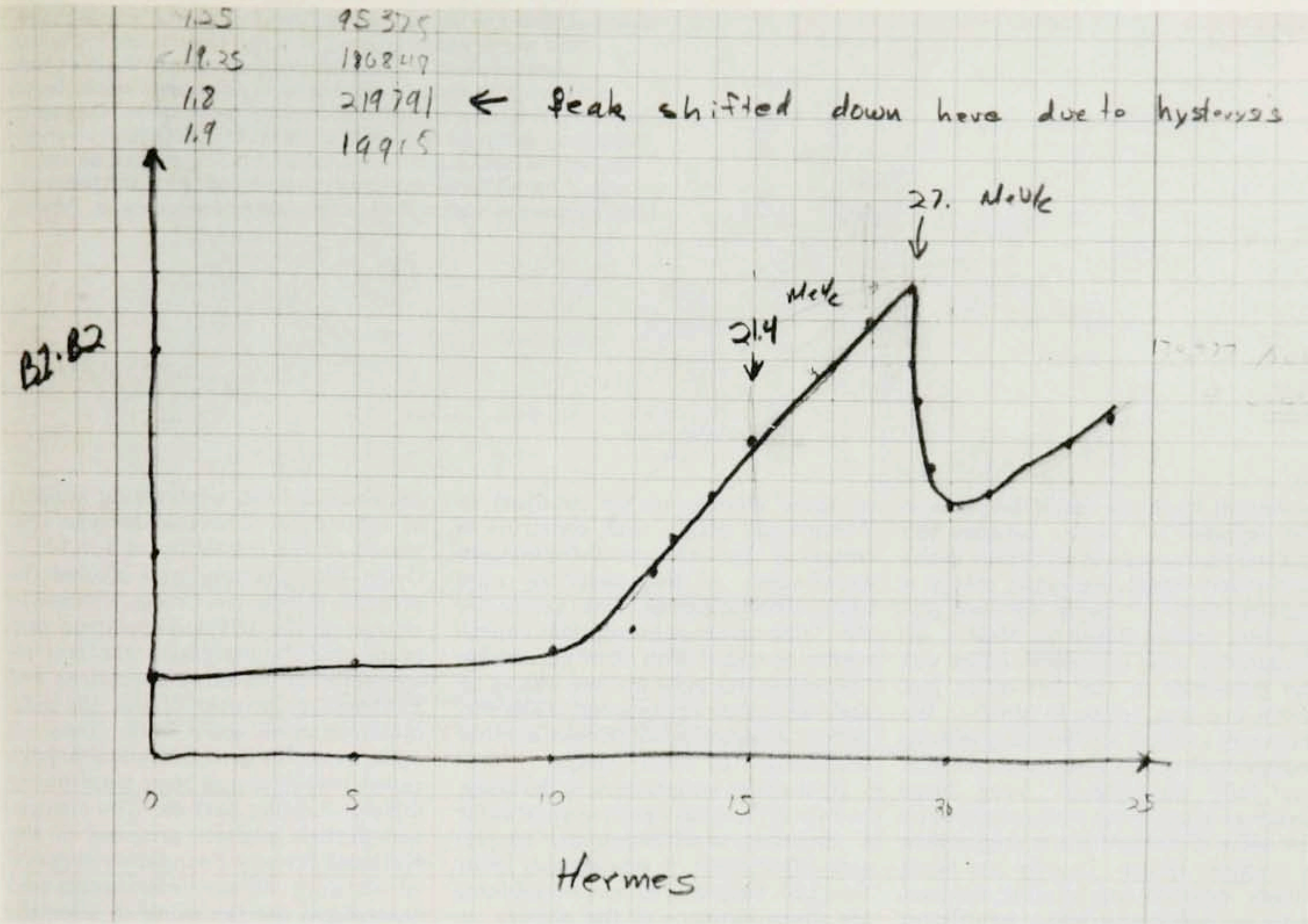
The experimental verification

Because we were already doing experiments at the LBL Bevatron, we naturally turned to the 184-inch cyclotron in considering the actual construction of a beam and a muonium-to-antimuonium experiment. We soon found in presenting our proposal, in May 1970, that no one believed that the new beam concept could work. Before LBL would consider construction of a new beam with a costly vacuum chamber in the bending magnet gap and another vacuum chamber surrounding the production target, they wanted us to carry out a Monte Carlo simulation. Pifer and Kendall did the simulation, and it confirmed our original rough estimates. Another uncertainty was the production cross section for low-energy pions by 740-MeV protons. The Arizona group, by chance, was doing a pion-scattering experiment at that time in a Bevatron secondary beam line that could be tuned to 740-MeV protons. A 24-hour experiment to observe the rate of pion-to-muon decays in a thin scintillator at the surface of a tungsten target bombarded by the protons gave favorable numbers for our proposed surface-muon-beam design.

Only partially convinced by our calculations and experimental π^+ production rates, the program committee for the 184-inch cyclotron imposed one final condition for approval: The new beam line must be designed also to provide a high-intensity stopping $\pi^{\pm}$ beam for an unrelated experiment by another group. This requirement necessitated a very short beam line because many low-energy pions would decay in flight, whereas the muon-decay loss at 30 MeV/c is insignificant. Pifer suggested and designed a sector-focused beam that satisfied everyone, and we spent many long days and late evenings making magnetic measurements and installing steel shim blocks on four bending magnets, named for Greek gods, to meet the sector-focusing specifications. (See figure 3.) This duality of purpose persists to this day, as many facilities provide both surface-muon and low-energy-pion beams.

Beam tuning began in March 1971. We soon found that too many "junk" particles were coming down the beam channel. The cure was to fill every superfluous void with shielding material, including a half ton of brass in magnetic-field regions inside the beam vacuum tank. In April we retuned all counters and magnets. On our first attempt to observe a μ^+ peak just below 30 MeV/c, only a slight shoulder in the intensity-vs-momentum curve was visible. Then we raised the beam counter discriminator thresholds to reduce the number of pulses due to positrons; a sharp edge appeared at a magnet current corresponding to 27 MeV/c momentum, as figure 2 shows. Our log book contains no triumphant comments at this point and indicates that we immediately went on to tuning other counters needed for our experiments. We did not appreciate at that time that we had just experimentally demonstrated our most significant contribution to science!

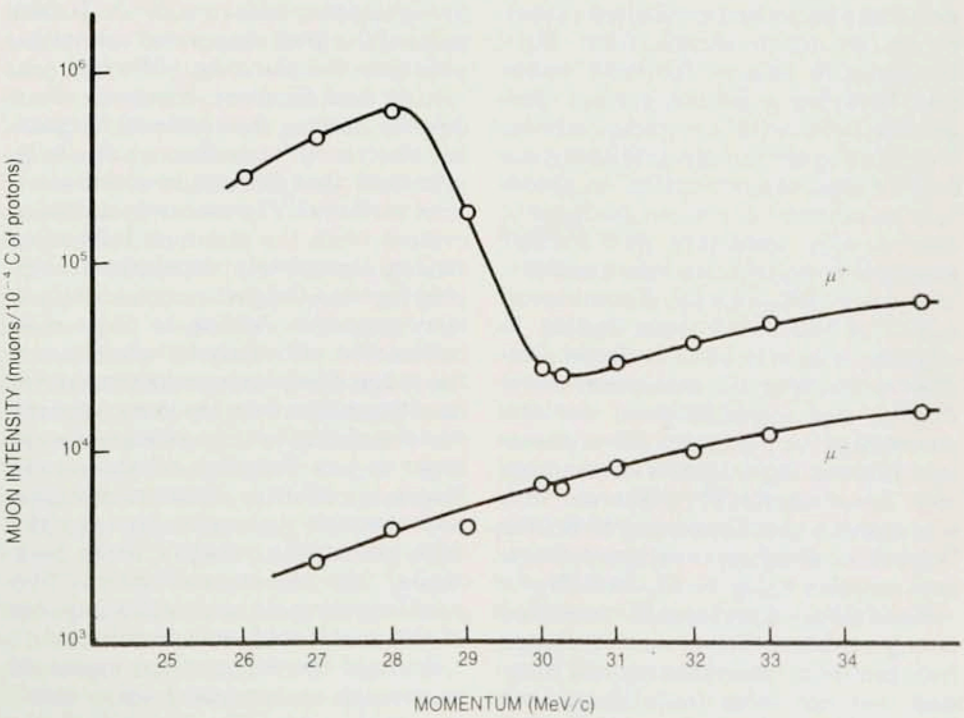
As we gained experience with our



a

Muon intensity peak. Plotted in **a** is the second set of data points taken at the 184-inch cyclotron in April 1971, in search of the μ^+ intensity peak expected from π^+ decays at rest in a tungsten production target. In the first run, not shown, the discriminator thresholds on the scintillation counter were too low, resulting in the counting of too many positron-produced accidental coincidences. For the second run, experimenters raised the discriminator thresholds significantly. The plot in **b** shows μ^+ and μ^- intensities as a function of momentum from a beryllium target at SIN (reference 3). The surface muon peak is evident in the top curve for momenta less than 30 MeV/c. There is no corresponding peak for μ^- because π^- particles are captured by nuclei. These curves are typical of those obtained at any 600–1000 MeV proton accelerator. Figure 2

b



Beam scheme and ray tracings. **a:** Layout for the first sector-focused low-energy beam designed for surface muons and low-energy negative pions. A three-fold coincidence from the thin plastic scintillation counters B1, B2 and B3 registers each muon. **b:** Ray tracings of first-order horizontal and vertical beam optics. Counter B1 has plastic-scintillator and beryllium-foil covers, which form an energy degrader at magnet 3, the intermediate focusing magnet, so that μ^+ and e^+ have different momenta in the second half of the beam line. Most surface muon beam lines use this separation technique. Figure 3

new beam, we found that it did produce the expected μ^+ rates. Because the stopped pions decay at all depths in the production target, we could obtain a high-intensity μ^+ beam for any momentum setting below 30 MeV/*c*, although the most impressive effect was the difference in the intensities just above and just below 30 MeV/*c*. We narrowly avoided a potentially serious background whose magnitude we had not fully anticipated: Very large numbers of positrons with momenta on the order of 30 MeV/*c* also originate in a tungsten target. Luckily our beam design included two bending sections, with an energy-degrading scintillator between them; the momentum loss in the scintillator was negligible for positrons, and several MeV/*c* for muons, so they were separated in the second section. Modern surface-muon-beam systems sometimes include an electrostatic field to further separate the positrons.

The next challenge

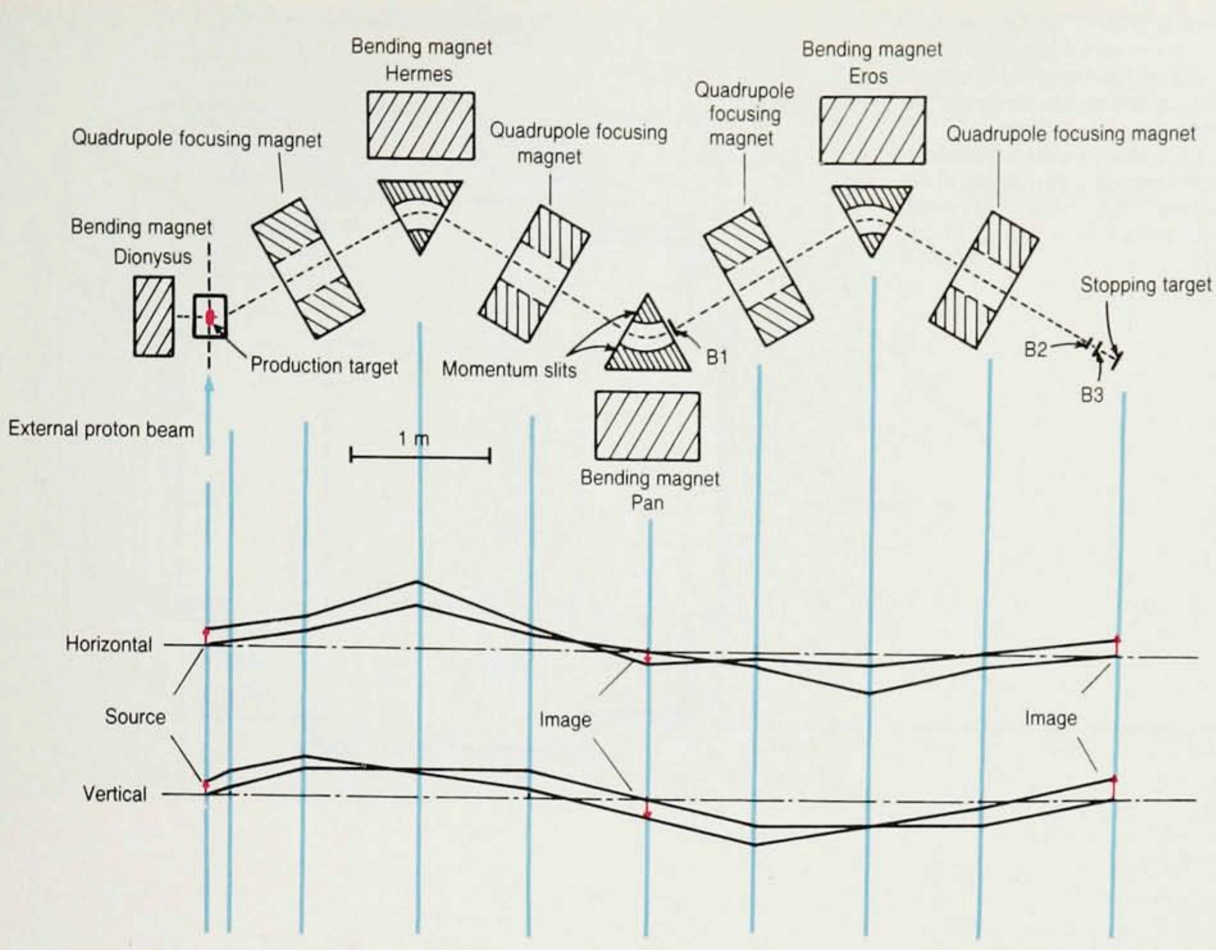
As our graduate student Kendall tuned the beam and conducted experiments on muon escape from high-temperature foils, a frequent visitor was Berkeley graduate student Jess Brewer, who with his thesis adviser Ken Crowe was rapidly developing the field of muon-spin rotation or muon-spin relaxation—the muon analogue to electron-spin resonance and nuclear magnetic resonance (see PHYSICS TODAY, December 1984, page 38). Their experiments at that time were limited to stopping muons in solid or liquid samples on the order of a centimeter thick. Brewer was quick to point out the potential of our beam to perform muon-spin rotation experiments on gas samples. Later we would collaborate with him and his new University of British Columbia colleagues to measure muonium reaction rates in Cl_2 and Br_2.

Kendall's experiments provided strong evidence that muons do escape from platinum, molybdenum and tungsten, but not from tantalum, as we expected from the hydrogen affinities of these metals, so we returned to Arizona to design and construct a complete muonium-to-antimuonium experiment. At that time, we could never have imagined that, except for the later muon-spin-rotation experiments on gases with Brewer and his colleagues, our good fortune was at an end—all future exploitation of the surface muon beam would be done at other accelerators by other groups.

By the time we returned to Berkeley, in July 1973, to set up the apparatus for a muonium-to-antimuonium conversion experiment, it was already clear that LBL budget problems would force the discontinuance of the physics research program at the 184-inch cyclotron by July 1975. (Regular operation for experimental medical radiotherapy with α particles has continued.) We thought that enough time would remain to test our apparatus, and afterwards we could transfer it to a more intense μ^+ beam at LAMPF. However, with only a few months remaining, we found a serious problem with our method of indirectly heating the platinum muon-stopping foils to 1000 °C: Hotter parts of the oven evaporated contaminants onto the platinum. (We had previously had frequent burnouts when directly heating the platinum by passing electric currents through the foils, a method that did ensure clean platinum surfaces.) The contamination was evident when the platinum foils, after cooling, completely depolarized stopping muons—the platinum had become ferromagnetic! Adding to these difficulties, the university by whose name the muon beam became known took a faculty position from the group, and my two remaining faculty colleagues were eager to join Fermilab collaborations. Hence our effort to study muonium-to-antimuonium conversion, having yielded a potentially valuable beam technique,[2] but also representing a five-year-long struggle against the demands of the real world, was terminated.

Some of the support that sustained us through an important achievement is notable. At LBL, we enjoyed the enthusiastic and unwavering support of individuals who had become convinced of the feasibility of our beam: Owen Chamberlain, who headed the program committee; Crowe, who was in charge of the 184-inch-cyclotron program; and Jimmy Vale, who was responsible for cyclotron operations and had been a member of the 184-inch-cyclotron crew since 1942. They all made available to us considerable laboratory resources and beam time during difficult funding periods. The elementary-particle physics program of the National Science Foundation supported our work without interruption and encouraged the flexibility in scientific objectives that made our effort possible.

The Arizona beam travels. The Arizona beam gradually became known through personal contacts to a few scientists interested in experiments with stopping muons at other accelerator laboratories. In 1975, Brewer joined the University of British Columbia and TRIUMF, and surface muons were first observed at TRIUMF in March 1976. At TRIUMF he found a beam designer, Jaap Doornbos, who was enthusiastically receptive to the surface-beam concept and who began a long-term effort to improve the performance of surface beams. An East Coast collaboration, led by Chung-Yun Chang and Philip H. Steinberg of the University of Maryland, was also developing a muonium-to-antimuonium experiment, but based upon stopped muons escaping from gold foils at room temperature. Due to requests from them and from a group at Yale led by Vernon Hughes, in 1976 we shipped the entire Arizona beam—magnets, vacuum chamber, target and counters—to the Space Radiation Effects Laboratory in Newport News, Virginia, where Chang and Steinberg's group began to operate the equipment in January 1977. It is ironic that because budget limitations forced the Space Radiation Effects Laboratory to close in July 1978, this group's muonium-to-antimuonium experiment, which had been our chief rival, was the only experiment that had



a chance to use our apparatus. The closure terminated the experiment before it reached a definitive result.

Scientists at LAMPF knew of the Arizona beam through their many personal contacts with LBL. According to the official list of LAMPF "milestones," surface muon beams were first obtained in the LAMPF Stopped Muon Channel in July 1977, and later that year Chris Tschalär, on leave from the Swiss Institute for Nuclear Research in Zurich, began extensive calculations that showed how to optimize surface muon beams at any meson factory. Subsequently, LAMPF tuned its low-energy-pion and pion-particle-physics beam lines to surface muons. SIN produced its first surface muon beam in August 1979 in its πE3 beam line by removing two 1-mm-thick aluminum windows that had previously separated individual vacuum regions.[3]

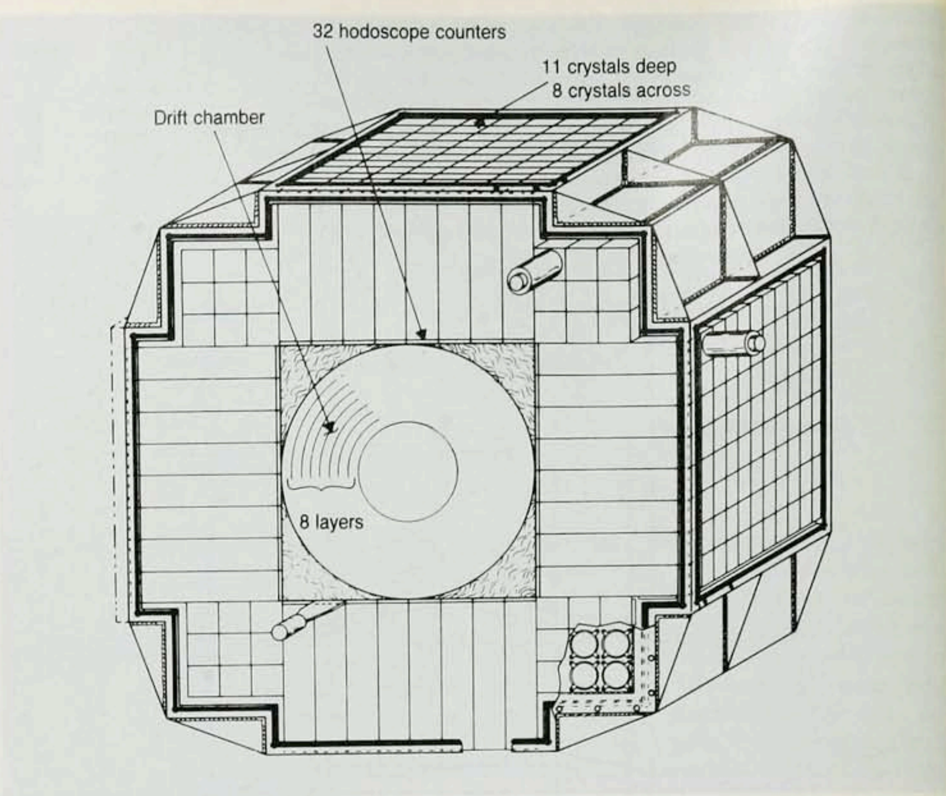
The Booster Meson Facility at the KEK injector in Tsukuba, Japan, uses 50-ns pulses of 500-MeV protons at a rate of 20 pulses/second to produce low-energy pion and muon beams. A port for surface muons went into operation in 1981, and an electrostatic separator was added in 1983. A pulsed surface muon beam is under construction at the 800-MeV Spallation Neutron Source at Rutherford–Appleton Laboratory in Chilton, England. These pulsed beams are well suited to muon-spin-rotation experiments where one needs good statistical accuracy on the numbers of decay electrons from precessing muons as a function of time; because all the muons must enter the sample at the same time, the number of muons employed is limited only by accelerator and beam design, and the counting equipment need only detect the decay electrons. Pulsed beams are also ideal for resonance experiments in microwave cavities or laser beams, because these experiments require only a short, high-intensity pulse of electromagnetic field.

Comparisons of the μ^+ stopping densities for conventional decay-in-flight beams and surface beams are only approximate because the optimum number and arrangement of magnets is quite different. Also, the yield of surface muons is sensitive to the profile of the incident proton beam; the yield appears best if the protons form a thin "ribbon" beam passing through the target slightly below the surface. Olin van Dyck and his coworkers at LAMPF have given[4] an interesting comparison of beam intensities relative to available phase space $p^2 dp d\Omega$. When compared in this manner, the surface muons are more intense than the pions in the same beam! Van Dyck's group estimates that the surface muons are 20 to 30 times more intense than the unpolarized cloud muons just above 30 MeV/c; at TRIUMF, Brewer estimated a factor of 80. Cloud muons originate from pion decays outside, but near, the pion production target; surface muons, on the other hand, originate from π^+ decays inside, but near the surface of, the production target. For experiments that require a beam with high polarization, one should compare the surface beam with the "conventional" beam, and here the factor exceeds 100.

Applications

While each accelerator laboratory has carried out many types of stopping μ^+ experiments made possible by the surface muon technique, I will mention only a sampling of experiments that illustrate the technique's advantages, namely, its high muon-stopping or phase-space density, 100% polarization and low cost. Experiments on the parameters involved in the weak-interaction decay of the μ^+ have especially benefited. At LAMPF, in the Crystal Box experiment,[5] depicted in figure 4, drift chambers and NaI scintillators surround stopping muons to search for hypothetical rare muon-decay modes, down to branching ratios as small as

Crystal Box at LAMPF. The experiment based on the detector depicted in this conceptual drawing is designed to search for hypothetical rare decay modes of the muon at branching ratios down to 10^{-12}. The crystals are sodium iodide scintillators. Surface muons stop in a thin target at the center of the "box," which has overall dimensions 113 × 113 × 71 cm. (Reference 5.) Figure 4



10^{-12}. Examples of these modes are:

$$\mu^+ \to e^+ + e^+ + e^-$$
$$\mu^+ \to e^+ + e^+ + e^- + \nu + \bar{\nu}$$
$$\mu^+ \to e^+ + \gamma$$
$$\mu^+ \to e^+ + \gamma + \gamma$$

A large number of muons must stop and decay at rest in a very thin target to minimize the effect of spurious background events.

Another LAMPF experiment[6] seeks to measure more accurately the muon-decay spectrum's Michel parameters, which summarize all the experimentally observable effects of this weak interaction. This experiment uses a time-projection chamber to observe the stopping point of the incoming muon and the radius of curvature of the outgoing decay positron. The muon stopping target is *very* thin—it is the time-projection-chamber gas itself.

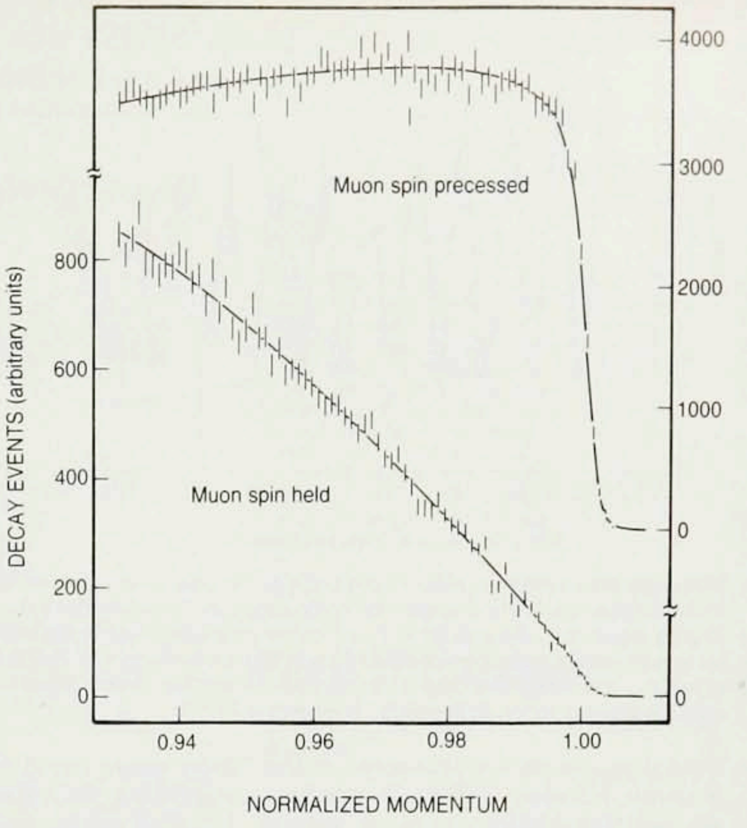
At SIN, the SINDRUM experiment[7] uses a very thin target in a surface muon beam to search for the decay $\mu^+ \to e^+ + e^+ + e^-$, down to a branching ratio of 10^{-12}. The 100% beam duty cycle at SIN allows the highest possible rate of observation of individual μ–e decays.

A clever TRIUMF experiment[8] by an LBL–Northwestern–TRIUMF collaboration led by Mark Strovink exploited the unique 100% polarization of the surface muon beam to search for right-handed currents in μ^+ decay. The intensity of decay positrons at the end point of the spectrum depends strongly on the direction of the positron relative to the direction of the muon spin; in the spin direction the intensity should extrapolate to zero according to the standard $V-A$ model of weak interactions. Thus a 100%-polarized beam permits a null experiment to test the exactness of the standard theory. Figure 5 shows the number of decay electrons as a function of momentum, both for a randomly oriented muon spin (upper curve) and for 100% polarization (lower curve). With complete polarization, the rate extrapolates to zero at maximum momentum, consistent with the $V-A$ theory.

An ever-increasing number of stopping μ^+ experiments involve atomic, molecular and condensed-matter physics and chemistry. The muon at rest often captures an electron to form the hydrogen-like muonium atom. The muonium atom is of great interest for precise tests of quantum electrodynamics because neither the muon nor the electron participates in strong interactions. Hence purely electromagnetic interactions should dominate their behavior to high order. One of the quantities of great interest in testing quantum electrodynamics is the muonium hyperfine structure interval $\Delta\nu$. This is the same transition that gives rise to the famous 21-cm line in atomic hydrogen, but for muonium the wavelength is approximately 6.7 cm. An experiment[9] at LAMPF by a Yale–Heidelberg–Darmstadt–Bern collaboration led by Hughes improved significantly the precision of our knowledge of the splitting $\Delta\nu$ because the surface-muon technique permitted lower-pressure stopping gas inside the microwave cavity. The result agrees well with quantum electrodynamics theory, but with the theoretical error an order of magnitude larger than the experimental error. Subsequently, experimenters at both LAMPF and TRIUMF used surface muon beams to make an initial measurement[10] of the Lamb shift between the 2s and 2p levels of muonium; this is considered a fundamental test of quantum electrodynamics.

At the molecular level of research, I did enjoy the privilege in 1974–75 of participating in pioneering experiments in muonium-gas chemistry, in which we measured[11] the rates at which muonium reacts with Cl_2 and Br_2 to form MuCl and MuBr, the analogues of HCl and HBr. We stopped the Arizona beam from the 184-inch cyclotron in atmospheric-pressure argon gas

Momentum spectrum of positrons from μ^+ decay, near the end point of the spectrum. The maximum positron momentum is defined as 1.00. The upper curve represents data for muons whose spins were allowed to precess to a random orientation before decay. The spins of muons represented by the lower curve were held antiparallel to the beam direction. If the muon polarization is 100% and $V-A$ theory is exact (no right-handed currents), then the lower curve should go to zero at maximum momentum. (Reference 8.) Figure 5



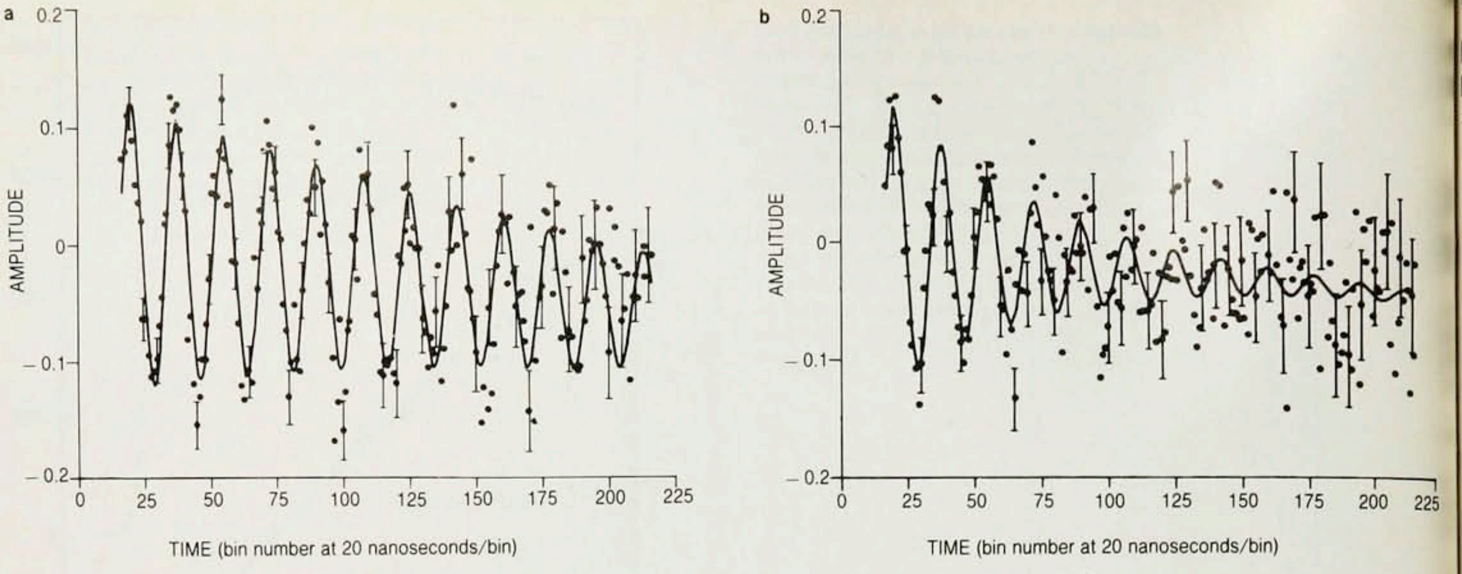
into which we had introduced various concentrations of bromine or chlorine. We monitored the presence of muonium by measuring the decay rate of the rapidly precessing muonium atom, whose frequency is 103 times that of a free muon. Chemical reactions shorten the lifetime of muonium, as figure 6 indicates. By measuring this effect as a function of the partial pressure of the reactant gas, we determined the reaction rates. Ironically, this reaction-rate measurement is more straightforward for muonium than it is for the more common isotopes, hydrogen and deuterium! We found the rate to be higher than that for hydrogen by more than the expected factor of $(m_H/m_\mu)^{1/2}$ that accounts for the relative thermal velocities of muonium and hydrogen. Such results with widely varying isotopic mass may allow one to study the relative importance of quantum-mechanical tunneling and zero-point energy in various reactions.

The most rapidly expanding application of surface muon beams is muon-spin rotation, where muons or muonium probe the almost unlimited variety of states of condensed matter: liquids, solids and surfaces.[12] In these applications, the surface muon beam offers the advantages of high stopping rates in very small samples, a high degree of polarization and low cost of construction and operation. The low cost is due to the low beam momentum of less than 30 MeV/c, for which the bending and focusing magnets must be designed; this translates into small magnets and low operating power. Most meson accelerator laboratories have set up surface muon beams dedicated to muon-spin-rotation experiments, which receive the beam automatically whenever the accelerator is running. A muon-spin-rotation facility ideally includes cooling equipment, enabling one to study samples at cryogenic temperatures, as well as a permanent arrangement of precession-magnetic-field and counting equipment. Because a typical muon-spin-rotation experiment requires only a few hours of beam time, one facility can accommodate a large number of independent researchers, each of whom need only make brief visits to the measurement area.

Muon-spin rotation allows one to explore microscopic magnetic fields and their changes with time as muons diffuse to different sites, in analogy with nmr and esr. In metals, for example, only the bare muon state appears, and one can monitor its precession to determine the metal's internal magnetic fields and the muon's rate of diffusion at various temperatures. In copper at low temperature and no external magnetic field, the polarization of injected muons decreases rapidly to zero and then returns to one-third its original value if the local nuclear dipole fields are random but static. If the fields are not static because of muon diffusion, the relaxation as a function of time changes shape.[13]

In insulators and semiconductors, all or a significant fraction of the muons form muonium. In the diamond-type lattice typical of semiconductors such as germanium, silicon and diamond itself, an anomalous state of muonium also forms. This state is characterized by a precession frequency that depends upon the orientation of the external magnetic field with respect to the crystal axes.[14]

The radioactive decay of the muon into a positron permits another novel application to solid-state physics, because the positron may be channeled, or blocked, depending upon the lattice site occupied by the muon before decay. B. D. Patterson and his coworkers at the Physics Institute of the University of Zurich demonstrated[15] this effect at SIN, using a surface muon beam to concentrate the μ^+ stops at an optimum depth in a silicon single crystal that was slightly bent to focus all the



Muonium precession signal. These plots of the difference between decay positron counts into left and right counters vs time show amplitude change due to relaxation of muon polarization. **a:** Experiment measuring background relaxation in pure argon at 1 atm and 23 °C in a 2-gauss magnetic field. **b:** Experiment with about 10 ppm Cl_2 added to the Ar. The increased rate of relaxation of the muonium precession signal is due to the removal of free muonium atoms by chemical reaction. The plots have been corrected for the amplitude decay due to the 2.2-microsec muon lifetime. The curves are least-square fits to the data points. (Reference 11.) Figure 6

crystal planes on a single point at the positron detector. Figure 7 compares the positron blocking pattern with a conventional Laue x-ray photograph.

Future prospects

Figure 1 shows what is probably the world's most sophisticated surface-muon beam line. Doornbos designed this line, drawing on his experience designing many surface muon beams at TRIUMF. Muons go up and out of the main experimental hall into a separate building exclusively for stopping-muon experiments. The beam line includes two electrostatic separators, which serve the dual purpose of separating beam positrons and rotating the spin either transverse or longitudinal to the beam direction. This beam was initially tuned in October 1984, and is now serving experiments. The muon experimental area will be equipped with a low-temperature cryostat and other apparatus to allow muon-spin-rotation studies by a diverse group of users.

There are ideas for even further improvements of surface muon beams. Doornbos estimates that it might be possible to obtain an additional factor-of-ten increase in the density of muon stops in targets with projected areas under 1 cm^2 by designing a beam system that is achromatic to higher order, that is, a system that gives more equal treatment to particles of differing momenta. Another idea would partially overcome the limitation on the instantaneous rate, which is less than 10^5 muons/sec because one must wait for each μ^+–e^+ decay, with the muon's 2.2-microsec mean lifetime, before sending another muon into the experiment. If a much more intense muon beam could be gated on and off in times less than about 0.5 microsec, then each muon could be individually admitted into the experiment immediately following the decay of the previous muon. Alternatively, a gated beam might provide short bursts containing many muons, repeating the bursts at 10–20 microsec intervals.

Why have I never mentioned μ^-, the negative muon? Alas, while the decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$ can occur at rest, stopped π^- mesons near any atom are captured into Bohr orbits around the nucleus, followed by capture and annihilation at a rate many orders of magnitude greater than the decay rate. Are there any exceptions? There is experimental and theoretical evidence[16] that in room-temperature H_2 gas at atmospheric pressure, approximately 6% of stopped negative pions undergo π^-–μ^- decay. If this does indeed occur, the fraction decaying should vary inversely with the product of the density and the square root of the absolute temperature. Practical designs using hydrogen gas for the "surface" appear to require gas densities such that the fraction of negative pions decaying at rest is very small. Another possibility might lie in the fact that when π^- mesons are stopped—that is, slowed to a velocity below about 0.01c—in a liquid-helium bubble chamber, 1.2% undergo π–μ decay.[17] For comparison, only 0.01% decay in a liquid-hydrogen bubble chamber.[18] The anomalously low capture probability in liquid helium is not well understood and might be connected with the π^- being "trapped" in a π^-He^+ energy level characterized by quantum numbers n and l of 16 and 13, respectively.[19] I suggest an alternative explanation in which a π^-He^+ atom forms, but with its electron highly excited. Such an atom would form a localized bubble state in liquid helium in which the $\pi^-\alpha$ core would be isolated from atomic collisions.[20] A study of the capture rate as a function of temperature and pressure in liquid and dense gaseous helium might reveal conditions for even lower capture rates.

Now, with ten years of disappointments in efforts to search for muonium-to-antimuonium conversion,[20] would a sensitive search be easier to carry out, and would it settle any theoretical controversy?

In answer to the first part, most of the ingredients are now in place to do a sensitive experiment: Meson factories with intense well-designed surface muon beams exist, and physicists at TRIUMF have developed[21] a time-projection chamber in a magnetic field in an arrangement ideally suited to detecting the decay electron from μ^- decay, which would signal the presence of antimuonium atoms μ^-e^+. A sensitive radiochemical detection scheme has also been proposed in which μ^- capture in barium produces cesium-136 with a 13-day half-life.[21] However, there appears to be a need for more work to find a more efficient and convenient source of slowly moving muonium atoms in a vacuum, a source based on methods better than those that use thin, hot Pt foils, thin Au foils, thin layers of SiO_2 powder, or low-momentum surface muon beams through degrader foils.[22]

As for the theoretical signficance, the standard model of electroweak interactions with three generations of quark–lepton families does not suggest any simple mechanisms for muonium-to-antimuonium conversion. When only the two leptons $e^\pm$ and $\mu^\pm$ were known, there was the possibility that they differed by a lepton parity, where one was positive and the other nega-

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Proceedings of the 5th International Summer School on Crystal Growth and Materials Research, Davos, Switzerland, September 3–10, 1983

edited by E. KALDIS

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tive, which might have permitted the transformation

$$\mu^+ + e^- \rightarrow e^+ + \mu^-$$

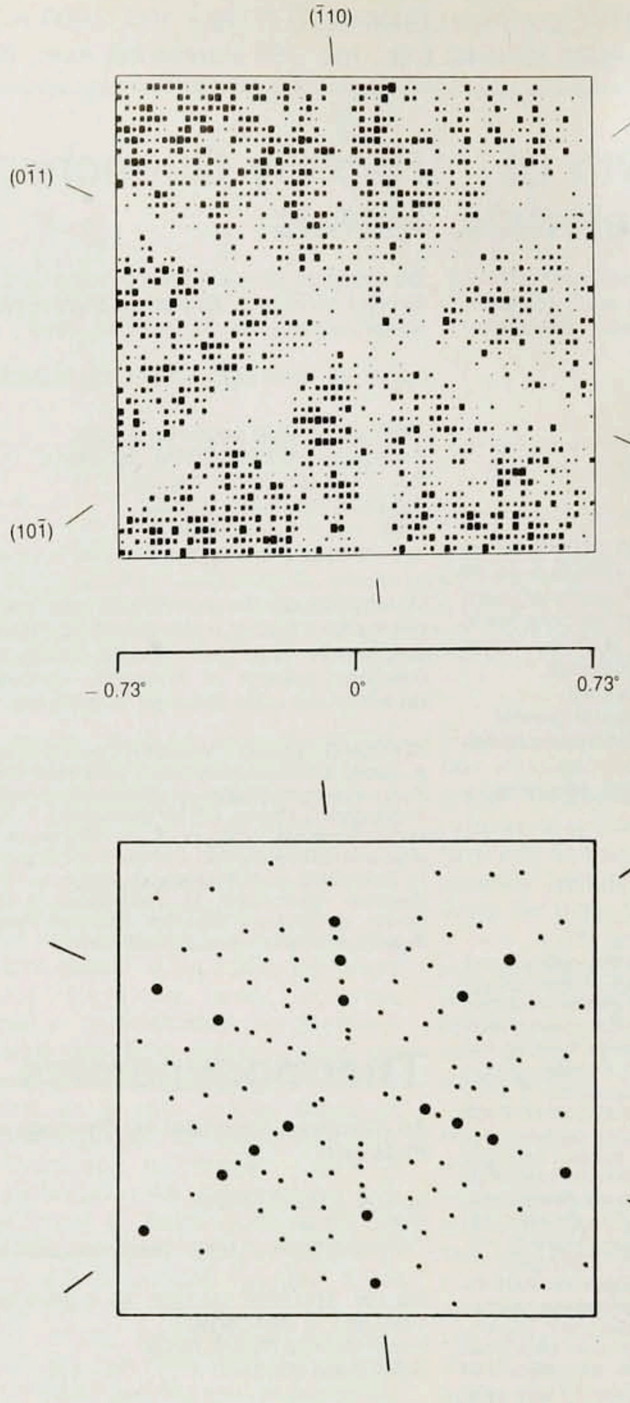
However, with three known leptons, $e^{\pm}$, $\mu^{\pm}$ and $\tau^{\pm}$, this idea is no longer so attractive.[23] Just as for the muon itself, which evoked many comments in the early years following its discovery ("Who ordered it?" Isidor I. Rabi is said to have asked), no one has any need in present-day models for muonium-to-antimuonium conversion. Perhaps this is all the more reason to perform the experiment, as it is often the surprise discoveries that promote major scientific advances.

Epilogue

Like other inventions and discoveries, undoubtedly many other physicists developed a partial or complete understanding of the surface-muon-beam concept, but circumstances suppressed their ideas. Perhaps some came close to discovering the effect accidentally. Hughes recalls one earlier consideration of the concept: In a discussion in the early 1960s about experiments that might be done with an electron linac at Stanford, Wolfgang Panofsky suggested that intense pulses of low-energy muons could be obtained from the pions decaying at rest in the target bombarded by the electron beam. Panofsky, a physicist who will be long remembered for generously sharing many good ideas with his colleagues and supporting their efforts to exploit them, wrote me:

> I do not have any pride of authorship in this matter.... You ask whether I find it surprising that this type of idea has been dormant for so long; I am indeed surprised, although I am even more surprised that your more detailed calculations indicate that the potential gains are as large [as they are].

With the beginning of the era of the meson factory, was an accidental discovery of the μ^+ peak below 30 MeV/c imminent? These accelerator designs had production targets and beam lines in vacuum, but usually with metal windows to isolate vacuum regions and to form the beam exit. The windows were too thick to be penetrated by 30-MeV muons. Though an accidental discovery of surface muons was only one or two windows away at some accelerators, chance removal of these windows was not likely. Tschalär recalls that when he returned in 1977 to SIN, where he was in charge of the beam facilities, just after making calculations at Los Alamos on surface and cloud muon beams, it was not he but others who were eager to remove or reduce the thickness of vacuum windows. If there had been a vacuum failure in any part of the modified system, the entire accelerator program would have been shut down, and repairs would have been time-consuming and costly because many components were highly radioactive.



Positron blocking pattern (top) and conventional Laue x-ray photograph (bottom) for a silicon crystal. Physicists at SIN used a multiwire proportional chamber to measure the angular distribution of positrons from μ^+ decays in the crystal's [111] surface at room temperature. (From reference 15.) Figure 7

Finally, what has become of the principals of this drama? The LBL 184-inch cyclotron stands as a proud survivor, running 20 hrs/week to provide an α-particle beam for experimental cancer therapy. Graduate student Kendall received his PhD and continued another year with our group as a postdoc. He later left the scientific establishment in Canada to earn his living for eight years as skipper of his own ship, trolling for salmon off the coast of British Columbia, but recently returned to TRIUMF to help design beam-line equipment. Pifer continues his collaboration as an adjunct associate research professor at the University of Arizona. Along the way he became chief engineer and part owner of a small company that arose from a

lightning-locating instrument invented by one of my former graduate students, Phil Krider.

As for me, in my work as professor of physics and radiology at the University of Arizona I continue my explorations in the hills and valleys of cosmic-ray, high-energy particle, medium-energy nuclear, and medical physics, attempting to develop new scientific techniques, believing this is my forté. I am assisted by enthusiastic graduate students and postdoctoral associates, and I am still supported by the National Science Foundation, and indirectly by my understanding and anonymous colleagues who advise it. My journey is not unlike that of a nomadic prospector in search of another valuable gemstone—wondering if I will recognize it if I find it, happily making many lesser finds along the way.

* * *

I thank Gerald Dugan of the Fermi National Accelerator Laboratory for bringing to my attention evidence for the decay of π^- particles at rest in hydrogen gas. I also had useful discussions with Richard Young, now at Bell Communications Research Inc, concerning conditions for stable bubbles in liquid helium. I appreciate the assistance of many of those mentioned in this article for sharing their recollections and for providing me with information on the latest applications of surface muon beams.

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