Bevalac Operations

1989

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7.

BEVALAC OPERATIONS

*... record uranium-beam
intensity ... over 24 hours,
the average was 5×10^7
particles per pulse ...*

SEPARATELY AND TOGETHER, THE BEVATRON and the neighboring SuperHILAC have enabled decades of fruitful research. The Bevalac (Figure 7-1) effectively established two new scientific disciplines: relativistic heavy-ion physics and heavy-ion biomedical research and treatment. The system's capabilities are still unique, and beamtime remains in great demand for the physical and life sciences.

As a national user facility, the Bevalac is available to qualified researchers from around the world; about half of the available beamtime is used by scientists from outside LBL. Over the last five years, researchers representing more than 40 U.S. institutions, as well as another 40 international ones, participated in Bevalac experiments. Education, too, is served by the facility; some 80 students have based their doctoral dissertations on Bevalac-related research, and nearly 50 graduate students are currently taking part in experiments there. The focal point of support for this user community is the

Bevalac

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BEVALAC OPERATIONS

Figure 7-1. The Bevatron, a synchrotron, accelerates beams from either its local injector or the SuperHILAC heavy-ion linear accelerator. The dotted lines in the picture show the beam path from the SuperHILAC through the Bevatron. The SuperHILAC, which has three complementary ion sources, is used when higher energies and heavier ions are needed, i.e., in most of the nuclear-physics programs. The beams are delivered to a variety of users in the External Particle Beam hall. The faint dashed lines in the drawing correspond to the circular and rectangular buildings shown in the photograph. The various experimental areas are separated by a "maze" of shielding blocks.

XBB 766-4673A

XBL 909-5927

Accelerator Research Coordination Office at the Bevalac; it handles all stages of interaction between users and LBL, from proposal submittal through experimental runs.

Program Advisory Committees (Table 7-1) meet annually to review proposals from prospective users and to apportion beamtime accordingly. In addition, several Users' Associations, whose executive-committee members are listed in Table 7-2, recommend operational and procedural improvements and facilitate the exchange of information.

Funding limitations have ended operation of the SuperHILAC as a stand-alone user facility with extensive programs and technical support for experimenters.

These panels of experts recommend beamtime allocations. The LBL scientific director of each program may allocate about 10% of the beamtime on a discretionary basis. The SuperHILAC committees are now inactive because of the curtailment of the user program there.

Table 7-1. Bevalac Program Advisory Committees for 1989.

Bevalac Nuclear Science PAC

R. Madey, Kent State University (users' representative)
 S. Datz, Oak Ridge National Laboratory
 B. Feinberg, LBL (acting operations manager)
 C. Gelbke, Michigan State University
 F. Goldhaber, State University of New York at Stony Brook
 W. Henning, GSI, Darmstadt, FRG
 G. Krebs, LBL (research coordinator)
 F. Lothrop, LBL (scheduling coordinator)
 P. McMahan, LBL (executive secretary)
 F. Plasil, Oak Ridge National Laboratory
 L. Schroeder, LBL (scientific director)
 V. Viola, Indiana University (chair)

Bevalac Biomedical PAC

S.J. Adelstein, Harvard University (chair)
 E.A. Blakely, LBL
 J.D. Chapman, Cross Cancer Institute
 E.R. Epp, Memorial General Hospital
 B. Feinberg, LBL (acting operations manager)
 R.J.M. Fry, Oak Ridge National Laboratory
 F. Hutchinson, Yale University
 G. Krebs, LBL (research coordinator)
 F. Lothrop, LBL (scheduling coordinator)
 R.E. Krisch, University of Pennsylvania
 W. Schimmerling, LBL (executive secretary)
 R.C. Urtasun, University of Alberta

SuperHILAC PAC (disbanded after 1989)

P. Armbruster, GSI, Darmstadt, FRG
 H. Britt, Lawrence Livermore National Laboratory
 T. Khoo, Argonne National Laboratory (chair)
 W. Meyerhof, Stanford University
 R. Nix, Los Alamos National Laboratory

Table 7-2. Bevalac Nuclear Science Users' Association Executive Committees for 1989.

W. Benenson, Michigan State University
 P. Brady, University of California at Davis
 J. Carroll, University of California at Los Angeles (chair-elect)
 S.Y. Fung, University of California at Riverside
 R. Madey, Kent State University (chairman)
 M. McMahan, LBL (executive secretary)
 L. Schroeder, LBL (scientific director)
 K. Toth, Oak Ridge National Laboratory
 H. Wieman, LBL

BEVALAC OPERATIONS

A steady program of technology upgrades, combined with long experience at efficient scheduling and with continual fine tuning of operating procedures, has helped the Bevalac staff overcome several years of decreasing budgets and inflationary erosion. Nineteen eighty-nine saw the third consecutive record for experimental beamtime at the Bevalac: 4161 hours, up slightly from last year's 4034 hours.

Accelerator Technology and Operations Summary

Many factors affect beam delivery, including scheduled and unscheduled shutdowns for maintenance, usage for machine studies and tuning, and seasonal fluctuations in the cost and availability of electricity (traditionally, the facility shuts down during part of the summer). Despite these variations, there have been steady improvements.

The physical sciences—mostly nuclear physics—continued to use about two-thirds of the experimental beamtime at the Bevalac. The life sciences, comprising radiotherapy research and basic radiobiology and radiation biophysics studies, accounted for the rest. Table 7-3 summarizes the year's operating statistics and compares them to figures for past years and projections for the future.

1989 Performance Statistics

Fast Switching

Ion pulses can be injected into the Bevatron from either the SuperHILAC, which supplies the intense beams of heavy ions that are typically required for nuclear science, or the Local Injector, which can deliver beams of lighter ions for radiotherapy. Switching between the two inputs once required a substantial fraction of an hour for retuning of the Bevatron. Today, a fairly drastic switch—from neon at 500 MeV/nucleon to niobium at 1200 MeV/nucleon, for instance—can be performed in two minutes or less. Fast switching is especially advantageous in a mixed-use facility like the Bevalac, because a radiotherapy or radiosurgery treatment lasts about half an hour but involves only a few minutes of actual beamtime.

The Bevalac has an ongoing program of technology upgrades designed to increase efficiency, improve user service, and ensure safety. Among them were a comprehensive project aimed at a fivefold increase in the intensity of very-heavy-ion beams from the SuperHILAC, with smaller intensity increases for lighter ions; continued control-room modernization; and a magnet upgrade that is saving nearly 750 MW-hours of electricity per year.

Other significant upgrades included a new electronically controlled beam-spill control system. Progress was also made in two ongoing projects: various electronics upgrades for beamline-tune monitoring systems and a study of possible power-supply modernizations for the main guide-field magnet that would result in much-improved performance during low-field operation.

To complement a recently completed intensity upgrade at the SuperHILAC, the latest generation of the LBL-developed metal-vapor vacuum arc (MEVVA) ion source was installed. In 1989, commissioning of the MEVVA IV source (Figure 7-2) continued for elements ranging from Ti to La. In early tests, we found that the new source delivers 7.5 mA of Ti^{++} to the entrance of the first linac tank while running at about half the maximum arc current and extraction voltage, whereas the older Penning Ion Gauge (PIG) source could provide only 3 mA.

The accelerator improvement program has been vital in keeping the venerable Bevalac useful for today's research, in which the survey experiments have largely been completed and in-depth, high-statistics investigations are becoming the norm. An example of direct user benefit is a new record for uranium-beam intensity, set in late 1989. Over a 24-hour period, the average intensity was 5×10^7 particles per pulse, with a peak intensity of

Accelerator Improvement Projects

Table 7-3. Operating summary, fiscal 1988 and 1989, and projections, fiscal 1990-1991.

Bevalac Operation (hours)	1988	1989	1990	1991
Research	4023	4161	3600	3100
Machine Studies	197	282	250	200
Tuning	706	709	900	600
Total Operation	4926	5350	4750	3900
Unscheduled maintenance	706	707	581	550
Scheduled shutdowns	2837	2703	3429	4310
Total Downtime	3543	3410	4010	4860
Beam Use for Research (hours)*				
Nuclear Science	2727	2712	2400	2067
Life Sciences	1307	1450	1200	1033
SuperHILAC	1749	897	500	0
Total	5783	5059	4100	3100
Number of Bevalac nuclear-science and SuperHILAC experiments receiving beam	49	33	21	15
Number of participating scientists	189	163	145	145
Institutions represented				
Universities	26	19	15	15
National laboratories	5	5	5	5
Other**	15	13	12	8
Total	46	37	32	28
Use of Beamtime (%)				
In-house staff	50	50	50	50
Universities	35	35	35	35
DOE national laboratories	5	5	5	5
Other institutions	10	10	10	10

* This figure includes the SuperHILAC parasitic program and therefore may exceed the research beamtime reported under Bevalac Operation.

** Includes foreign institutions, NASA, some medical institutions, and industrial/commercial investigators.

Figure 7-2. The latest generation of the LBL-developed metal-vapor vacuum arc (MEVVA) ion source, installed at the SuperHILAC as part of the intensity-upgrade project, continued to progress through commissioning in 1989. The ring of protruding cylinders is the multiple-cathode array, which can be rotated to bring different kinds of cathodes into the source one at a time—to provide a variety of ion species for different experiments, for example. In early tests, it provided 7.5 mA of Ti^{++} while running at about half the maximum arc current and extraction voltage, whereas the older Penning Ion Gauge (PIG) source could provide only 3 mA. A variety of MEVVA-related technology-transfer possibilities are also being explored, as metal-ion beams can be used to fabricate and modify various materials.

CBB 860-9309A

9×10^7 ; the extraction efficiency averaged 25%. According to preliminary results, these sustained intense beams enabled experimenters to measure the Lamb shift in three-electron uranium to a precision of about 0.1%—an improvement of two orders of magnitude over previous measurements with two-electron uranium. The work has inspired quantum-electrodynamics theorists to refine their calculations, and it is serving as a benchmark for planned experiments at GSI in Darmstadt, West Germany.

Control-System Updates. One of the major accelerator improvement projects of recent years has been installation of a modern control system throughout the Bevalac complex. The goals are better beam control, including truly reproducible restoration of best tunes; automatic fault diagnosis; uniformity of user interfaces and operating procedures; improved connections with the nuclear-science and biomedical research areas; easier maintenance; and increased safety.

The full complement of 14 control consoles based on Sun workstations has been installed. Subsidiary control rooms for the motor-generators and local injector are now equipped with these consoles, and the SuperHILAC and Bevatron main control rooms now have consoles dedicated to safety alarms. Operators have become adept at producing or modifying the screen templates, whereas any changes to the previous system required the assistance of professional programmers. There have been many enhancements to the user interface, not only through this custom tailoring of screens but also through an increase in the extent to which the accelerator is controlled

through the computers, with a correspondingly lower dependence on physical knobs and buttons.

The next goal is installation of VME-bus systems, interfaced to the control consoles, to control accelerator devices. This plan would bypass the 15- to 20-year-old Modcomp central computers that now hold the accelerator data. This scheme will be tested first in the rf system for the local injector, where it is expected to aid the radiotherapy program by improving the speed and flexibility of fast switching. Other early sites for the new system will include the Experimental Particle Beam (EPB) hall, where it will control collimators and magnet power supplies, and the motor-generator room. Hardware has been ordered, and software is being designed and written.

Future Improvement Projects. The general theme of the accelerator improvement projects now underway is improvement of user service in the EPB hall, a program that goes hand in hand with the control-system update. Modernized controls for the power supplies in the EPB hall will save time by making beamline tunes more easily reproducible. A variety of previously independent systems, including both experimental beam-delivery equipment and safety devices, will be integrated with the central control system.

A 1991 project will modify the power supply for the main guide-field magnet to support a higher duty cycle for many experiments—as much as 80%, as opposed to 25% at present. This will allow the Bevalac to provide better service in light of today's emphasis on high-statistics investigations rather than survey experiments.

Beam quality enhancements are also planned for 1991 and 1992. Delivering intense, high-quality beams at the experimenters' targets can greatly increase the effectiveness of experiments. (For Bevalac purposes, beam quality may be broadly defined as sharp focus at the experimenter's target, combined with pulse shapes that come up to full intensity quickly, carry on evenly with relatively little structure, and then terminate cleanly.) Intensity and quality are affected to some extent by operating techniques, but are intimately linked with technological characteristics such as the "ripple" in magnet power supply voltage. Particularly important among the beam-quality enhancements will be a variety of measures to minimize and strip away beam "halo" and reduce beam emittance, thus cutting the rate of unwanted background events.

Technology Transfer Implications. The technologies developed and deployed through the years have also had ramifications beyond the Bevalac. An example is the rf quadrupole linac (RFQ), which accelerates ions to a few hundred keV.* RFQs may prove to be useful not only in research accelerators like the Bevalac (which has an RFQ in the local injector), but also in commercial and industrial applications.

Airport security is an example. We recently developed an integrally formed RFQ (Figure 7-3) that, unlike previous models, can be manufactured and commissioned in a few relatively simple steps. Because it combines the inherent compactness of an RFQ with unprecedented affordability, it might lend itself to use in a safer explosives-detection system. Instead of using a radioactive source in a public area, a thermal neutron analyzer could use ions from an RFQ to bombard a neutron-production target.

* RFQs, based upon a 1960s Soviet idea and first constructed at Los Alamos National Laboratory in the mid-1970s, have been built and used at many laboratories. The LBL innovation is the integral construction, which gives an order-of-magnitude reduction in assembly time and greatly reduces the need for painstaking alignment by highly skilled technicians.

CBB 882-1567

Figure 7-3. This LBL-designed radio-frequency quadrupole (RFQ) accelerator, shown here with the top vane removed, can be manufactured with conventional, numerically controlled machine tools. The parts align themselves at assembly, without adjustment, to the required vane-tip positional accuracy of ± 0.03 mm. Previous RFQs had been constructed from a number of separate parts that made up the resonator cavity and the vanes inside; these parts had to be painstakingly aligned. This unit can be fabricated and assembled for about one-third the cost of an old-style RFQ; assembly time alone has been reduced from 300 to 30 hours, largely because of the self-aligning nature of the design. Potential uses include particle accelerators for physical research and medical treatment, airport security monitors, industrial ion implanters, and defense systems.

Nearly 60 years after Chadwick's discovery of the neutron ushered in the modern era of nuclear physics, a great many questions remain about the nature and behavior of the nucleus. With its ability to provide beams of heavy ions in the MeV- and GeV-per-nucleon range (Figure 7-4), the Bevalac lends itself to the study of many aspects of nuclear matter. The Bevalac nuclear-science program focuses upon extreme conditions of temperature and pressure, but many widely diverse investigations have been built upon that common theme. They include studies of

- the equation of state (EOS), which is of interest both in nuclear science and in particle astrophysics
- reaction dynamics
- properties of exotic nuclei
- subthreshold production of pions, kaons and antiprotons

These studies are carried out by numerous U.S. and international researchers, with AFRD's technical support and scientific collaboration.

Some of the effects of nuclear collisions are rather exotic, as are the means of observation. However, many of the effects are analogous, in considerable detail, to phenomena that one might expect to see in everyday, macroscopic matter. (An example of such behavior is collective flow, which was first observed in the Plastic Ball and Streamer Chamber detectors at the Bevalac.) Depending on temperature and pressure, nuclear matter can be thought of as a solid, liquid, gas, or plasma. The EOS mathematically describes the balance among these phases and the borderlines of the phase transitions.

Nuclear Science

Nuclear Physics and EOS Studies

Figure 7-4. In its ability to provide relativistic beams of all ions up to and including uranium, the Bevalac complements other heavy-ion accelerator facilities now running or being built in the U.S., such as the Alternating Gradient Synchrotron and the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, as well as lower-energy accelerators like the one at Michigan State University.

XBL 875-2271B

Knowledge of the EOS is of great fundamental importance to nuclear scientists. It is also useful to astrophysicists, because certain hypotheses about mechanisms within supernovae and neutron stars are based on assumptions related to the EOS. The hypotheses are especially sensitive to the value of nuclear incompressibility.

Probing the EOS under conditions far removed from the equilibrium state of nuclear matter requires considerable disturbance of the entire volume of interacting matter. This calls for head-on impacts from beams of heavy ions. The greater the mass of the target nucleus and the projectile, the greater the disturbance and the greater the number of participating nucleons. Therefore an ongoing highlight of Bevalac research is exploration of the EOS, as shown in Figure 7-5, at high temperatures (typically 50–100 MeV of thermal energy) and high densities (two to four times normal). The Bevalac energy range is especially appropriate because regions of the EOS far from

XBL 881-8818

Figure 7-5. A schematic phase diagram for nuclear matter, showing some of the states and transformations predicted by various theories. The normal state of nuclear matter can be characterized as a liquid. It may undergo phase transitions to a hadron gas at relatively low densities or, at higher densities, to some condensed phase such as a pion condensate or a superdense nucleus containing thousands of nucleons. Under extreme conditions, the hadrons themselves are expected to break down into "deconfined" quarks and gluons; such conditions are thought to have existed in the first few fractions of a second after the Big Bang, and are thought to exist today in neutron stars and supernovae. Such extreme conditions can be re-created at a laboratory scale through central collisions between nuclei at extreme relativistic energies.

equilibrium can be reached, yet the phenomena are still strongly influenced by the nuclear mean field. In other words, the nucleus still behaves as a unit in the collision, whereas at much-higher energies one enters a regime of "hadrons flying in formation" in which the effects resemble those of elementary particles striking each other.

Time Projection Chamber. Experimenters have found that the heavier reaction fragments appear to fly away from the reaction at an azimuthal angle closer to the reaction plane than do lighter fragments. Furthermore, the in-plane flow momenta of heavier fragments are significantly larger. However, the effective compressibility of nuclear matter remains uncertain to within a factor of 2, so clearly a consensus on the form of the EOS has not been reached. Further research will be aided by a new time projection chamber (TPC), an electronic 4π detector that will fit inside the Heavy Ion Superconducting Spectrometer (HISS) magnet as shown in Figure 7-6.

The TPC is designed for full-solid-angle coverage, hence the term " 4π ." It will be able to identify and analyze the momenta of most of the 200 or so mid-rapidity charged particles (mostly protons, deuterium and tritium nuclei, ^3He and ^4He nuclei, and pi mesons) that are produced when heavy nuclei such as gold collide at Bevalac energies. The TPC is being placed in the HISS dipole because its functions will be complemented there by a variety of existing detectors. In 1988 a scale-model TPC was successfully tested with beams of ^{197}Au (which is highly ionizing and therefore useful as a test of dynamic range) and ^4He (which produces "clean" tracks so performance can be compared with simulation results). The full-scale TPC should come on line in spring 1991.

Dilepton Spectrometer. Another important detector is designed to provide an especially clear view of certain reactions. The Dilepton Spec-

Figure 7-6. The HISS TPC will be a full-solid-angle detector able to identify and analyze the momenta of most of the 200 or so mid-rapidity charged particles (mostly protons, deuterium and tritium nuclei, ^3He and ^4He nuclei, and pi mesons) that are produced when heavy nuclei such as gold collide at Bevalac energies. A prototype was tested in 1988, and the full-scale TPC should come online in summer 1991.

CBB 899-8246

trometer (DLS), a unique detector installed at the Bevalac in 1986, offers special insights into reaction dynamics by watching for a rare event: emission of an electron and positron correlated in their paths and their time and place of origin.

This is thought to provide an especially undistorted view of nucleus-nucleus, proton-nucleus, and proton-proton collisions because leptons interact with other forms of matter through the weak nuclear force and the electromagnetic force. Thus there is only a small probability of scattering or reabsorption on their way out of the reaction area, and reliable data can be obtained on deep and early phenomena of the collision. In particular, dilepton spectrometry might provide insights into one of the key theoretical unknowns of nuclear collisions: the behavior of pions and other mesons. (It is also thought that dilepton production might signify the formation of a quark-gluon plasma in the higher-energy heavy-ion colliders of the future.)

In 1987 the DLS collaboration established that dilepton emission does indeed occur at Bevalac energies. Subsequent work further defined the role of dilepton spectrometry in studying the EOS and other behavioral aspects of hot, compressed nuclear matter. In 2.1- and 4.9-GeV/nucleon $p+^9\text{Be}$ collisions, and to some extent in 1.95-GeV/n $^{40}\text{Ca} + ^{40}\text{Ca}$ collisions, the mass spectra have a sharp peak around 300 MeV, which is twice the rest mass of a pion. A great many models have been proposed to explain the early DLS data; in one of them, the peak might be interpreted as the matter-antimatter annihilation spectrum of pion pairs (π^+/π^-).

To verify this preliminary finding, the dilepton spectrum will be measured for a proton beam and a liquid-hydrogen target. In this collision,

which involves elementary nucleons rather than nuclei with their collective "mean field," the sharp peak is expected to disappear. This would be a dramatic confirmation that dilepton spectra directly reflect the properties and behavior of pions in hot, compressed nuclear collisions. This ability to visualize the early stages of a collision would be a key addition to current techniques, which often cause an interpretational stalemate because they primarily provide data on flow and other phenomena from late in the reaction process.

However, in order to take advantage of this capability, special detection techniques are needed to find the rare correlated leptons amid the hail of other reaction products. Typically these experiments average about one dilepton pair per hour, out of a total of 20 000 or so events. In previous upgrades to the four-year-old DLS, extra drift chamber planes were added, allowing measurements of a great many charged particles. In spring 1989, the system was further enhanced with a conical 96-segment multiplicity array surrounding the DLS scattering chamber. (Both central and peripheral collisions occur in any experiment. Multiplicity arrays allow the centrality of each collision to be determined.) Figure 7-7 shows some examples of significant DLS data taken recently: the response of the multiplicity array to a 2.1-GeV Ca + Ca collision, along with the mass cross section per nucleon for Ca + Ca at 2.0 GeV/n.

Subthreshold Production. A particle that a nucleon-nucleon collision could produce only above a certain threshold energy can be produced by a nucleus-nucleus collision at a considerably lower energy. The implication is that in addition to the internal Fermi energy of the nucleus—kinetic energy from the vibrations of the nucleons—there are "collective" phenomena, occurring in nucleus but not nucleon collisions, that help make up the deficit. Subthreshold production of particles is a prominent area of Bevalac study because it provides insights into collective phenomena. Fittingly enough,

Figure 7-7. Left: DLS data show how a recently added multiplicity detector—a 96-element hodoscope configured as a cone surrounding the target chamber—responds to a 2.1-GeV Ca + Ca collision. The hodoscope detects charged particles and gives information about the centrality of the event. The figure shows the hit distribution on a plane transverse to the beam axis. The elements that show the most hits are oriented at the smaller angles. Right: The mass cross section per nucleon for the reaction $\text{Ca} + \text{Ca} \rightarrow e^+ e^-$ at 2.0 GeV/n was measured with the DLS. The dashed line shows the estimated Dalitz-decay contribution, which cannot account for the true-pair signal for masses above 200 MeV.

XBL 907-2521

XBL 894-1306

the antiproton is the subject of subthreshold-production study at the accelerator where it was first observed in 1955. Subthreshold production of π and K mesons (pions and kaons) is also studied.

A 1989 Bevalac experiment involving $^{28}\text{Si} + ^{28}\text{Si}$ at 2.1 GeV/n (Figure 7-8) resulted in the first observations of subthreshold antiproton production in a nucleus-nucleus collision. The antiproton yield was more than three orders of magnitude larger than was expected based on calculations that took into account the internal nuclear momentum of the projectile and target nuclei. However, the results from the same set of calculations agreed with experimental data for $p + \text{Cu}$ collisions in the range of 2.9–6 GeV. Research continues at LBL and elsewhere in search of collective phenomena that may account for the discrepancy.

Pion Studies. Pions, the most abundant particles created at Bevalac energies, have long been the subject of experimental scrutiny, especially for studying the effects of central collisions. Pion yields provide unique insights into compressional effects, the π^+/π^- ratio in various regions of phase space can be used to study the role of the Coulomb force in nuclear collisions, and pion interferometry based on the Hanbury-Brown and Twiss effect is used to measure the magnitude of the emission in space and time.

Figure 7-8. A 1989 Bevalac experiment involving $^{28}\text{Si} + ^{28}\text{Si}$ at 2.1 GeV/n yielded these time-of-flight spectra for subthreshold particle production. The topmost illustration is for negative particles prior to vetoing by the aerogel Cerenkov counters. The π^- and K^- peaks are distinct from one another and a small $\bar{p}$ peak is visible. The middle plot is for those negative particles that survived vetoes by both aerogel and liquid Cerenkov counters: 50 antiprotons survived the veto, although only two pions did so. The bottom plot, with the beamline tuned for positively charged particles in the same momentum range, shows π^+ , K^+ , and $\bar{p}$ peaks at the same positions as their π^- , K^- , and $\bar{p}$ counterparts.

XBL 907-2520

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In 1989, a Streamer Chamber experiment to study multipion production in Au + Au collisions at 0.8 and 1.2 GeV/n indicated a nonthermal component for pions emitted in the center of mass and at 90° to the direction of the collision fragments (Figure 7-9). This may indicate that pion data can reveal occurrences in the hot participant zone of a collision. Plans for 1990 include a new Streamer Chamber experiment designed to substantially increase the number of very-high-multiplicity ("supercentral") events; in the subsequent data interpretation, experimenters will, for the first time, search for correlations between pion emission and nuclear flow.

Other ongoing pion studies include high-statistics HISS correlations of two- and three-pion emission, as well as systematic pion interferometry using the JANUS spectrometer. The JANUS experiment, which involves La + La collisions, also includes a multiplicity array to distinguish between central and peripheral collisions. As mentioned earlier, subthreshold pion production is also examined as a probe of collective phenomena in heavy-ion collisions.

Substantial interest has developed in exploiting the Bevalac's unique ability to provide beams of the heaviest ions at 20–200 MeV/n. The goal of the program is to produce thermally "hot" nuclei and study their modes of decay. In particular, multifragmentation processes are being studied to explore the "liquid-gas" phase transition. Recent studies in the lower part of that energy range have shown that asymmetric heavy-ion collisions below about 50 MeV/n are dominated by incomplete fusion reactions. These reactions form very hot compound nuclei, which emit light particles and numerous complex fragments ($Z > 2$) as they decay. The angular distributions of the fragments are isotropic. In the range of 80–100 MeV/n, though, the

Intermediate-Energy Program

CBB 898-7314

Figure 7-9. A Streamer Chamber picture shows an Au + Au collision. Analysis of Streamer Chamber data from experiment to study multipion production in Au + Au collisions at 0.8 and 1.2 GeV/n indicated a nonthermal component for pions emitted in the center of mass and at 90° to the direction of the collision fragments. This may indicate that pion data can reveal occurrences in the hot participant zone of a collision.

angular isotropy disappears, the mass distribution is completely different in character, and many multifragment events are observed. A possible explanation is that incomplete fusion gives way to the "fireball" regime in this energy range.

To obtain a relatively undistorted view of the early stages of intermediate-energy reactions, an important Bevalac program uses an array of 18 neutron counters and a charged-particle time-of-flight wall in the HISS facility. The goal is to examine the early, high-density stage of a heavy-ion collision. Neutrons are relatively unaffected by final-stage phenomena—in particular, being neutral, they do not undergo Coulomb interaction. The neutron detectors, covering polar angles of about 3° to 90° , determine the energy of the neutrons as a particle-inclusive experiment. The time-of-flight wall (Figure 7-10) covers about 28° , sampling about half the particles that an ideal 4π detector would see, and determines the azimuthal angle of each neutron relative to the plane of the reaction. With these data, absolute triple-differential neutron cross sections can be determined, along with some of the most detailed information ever obtained on collective flow in nuclear collisions.

Figure 7-10. This charged-particle time-of-flight wall in the HISS facility complements an array of neutron detectors. The goal is to examine the early, high-density stage of a heavy-ion collision. Neutron detection is a challenging task, but is considered worthwhile for this purpose because neutrons are relatively unaffected by phenomena from later stages in the reaction—Coulomb effects in particular. The experiment searches for correlations characteristic of fluid-like collective behavior, or "flow," in nuclear collisions. Such correlations signal the release of compressional energy and provide a relative measure of the peak nuclear pressure achieved in the collision. The time-of-flight wall resolves time to ± 100 ps or closer and indicates the charge of a fragment. Work is now underway on tracking methods that will improve the overall time resolution and diminish the extent to which time resolution depends on position.

CBB 887-7209

BEVALAC OPERATIONS

Studies of symmetric systems in the range of 50–100 MeV/n are also underway to examine the transition from sequential decay of composite systems at low energies to multifragmentation at higher energies. The goal is to build a comprehensive database regarding the competition among various reaction mechanisms in composite systems ranging from several hundred MeV to several GeV. IMED, a new Intermediate Energy Detector, is being planned so that the energy range of 50–150 MeV/n can be mapped over the next few years.

As indicated earlier, head-on or “central” collisions are not the only area of interest. A significant program involves peripheral or “grazing” collisions at low and intermediate energies. Such collisions can produce large temperatures at lower densities, permitting exploration of another region of the EOS and addressing an important question—the amount of energy that a nucleus can hold without breaking up. Nuclei are “heated” until their excitation energy exceeds their binding energy; the decay modes and products are then studied.

Grazing collisions tend to produce exotic reaction fragments, some of which have extreme numbers of protons and neutrons. Thus they provide an opportunity to map the proton and neutron “driplines”: the stability boundaries defining the stable region of the chart of the nuclides. The decay of these exotic products is also of interest because it provides information on nuclear structure.

Considerable progress has been made in using projectile fragmentation to produce secondary beams of radioactive nuclei for study. These experiments have shed light upon new features of nuclear structure. The program recently yielded the first interaction radii for ${}^6\text{He}$, ${}^8\text{He}$, and ${}^{11}\text{Li}$. The radius of ${}^{11}\text{Li}$ was found to be much larger than was expected for nuclei in this mass region, and evidence for a diffuse neutron skin was found. The technique has since been extended to unstable *sd*-shell nuclei such as O, F, and Ne by fragmenting ${}^{40}\text{Ar}$ from intense beams. These results will have to be accounted for in theoretical models of low-mass, neutron-rich nuclei. Other recent experiments with radioactive beams have explored

- Energy dependence of the interaction cross sections of unstable nuclei
- Total electromagnetic-dissociation (EMD) cross sections of exotic nuclei
- Energy dependence of fragmentation of very weakly bound systems
- Isospin symmetry in fragmentation of an exotic mirror pair
- Giant resonance in a radioactive nucleus (measured through EMD)

This program of using projectile fragmentation to study the ground-state properties of exotic nuclei is a pioneering effort developed at the Bevalac and well suited to its capabilities.

Another significant collaborative study uses a variety of nuclear-magnetic-resonance (NMR) and polarization-flipping techniques to determine the magnetic moments of short-lived, beta-emitting fragments. Early success with ${}^{43}\text{Ti}$ produced from primary beams of ${}^{46}\text{Ti}$ indicated that this method is effective for studies of nuclear structure in the $f_{7/2}$ nuclear shell and for examination of weak interaction in beta decay. The techniques, now being refined and extended to several other fragments such as ${}^{39}\text{Ca}$, ${}^{37}\text{K}$, and ${}^{55}\text{Ni}$, can be used to help characterize reaction mechanisms at 100–200 MeV/n.

Peripheral Collisions and Fragmentation Studies

Atomic Physics and NASA Instrument Calibration

Fragmentation experiments have been enhanced with the successful operation, using Au beams, of a new tracking detector for HISS. The new detector, named MUSIC II, is the second generation of the Multiple Sampling Ionization Chamber. By combining concepts from traditional ionization chambers and from time projection chambers, it provides charge identification and precise determination of track position and angle for up to 10 particles. MUSIC II is optimized for fragments of intermediate and higher mass (carbon and above), so it complements the existing HISS drift-chamber system. The Au experiments produced a variety of events, ranging from very peripheral binary-fission events with a sum charge near 79 to multifragment events involving as many as 10 charged fragments.

Although the Bevalac is used primarily for studies of the nucleus, a variety of other experiments can be performed there. Atomic physicists use the Bevalac's ability to provide "hydrogen-like" and "helium-like" uranium ions (that is, ions stripped down to one or two electrons). Because uranium has 92 protons, these ions represent an extreme condition of the atom. On their small scale, they have the strongest electric fields found in nature, enabling scientists to address phenomena in quantum electrodynamics, including the Lamb shift.

The experiments with highly stripped uranium may also lead to new experimental techniques for higher-energy machines, such as the Relativistic Heavy Ion Collider (RHIC) being built at Brookhaven National Laboratory. Recent theoretical calculations indicate that the high-Z environment associated with colliding nuclei may be a source of electron-positron pairs; further, the produced electron is thought to be captured by the outgoing nucleus. Measurements scheduled for 1990 at the Bevalac can be used to test the theoretical models.

Bevalac beams are also used for instrument calibration by researchers from the National Aeronautics and Space Administration (NASA) and by other cosmic-ray scientists. They use the beams to calibrate detectors that will be used on balloon, rocket, and satellite flights. The 1990 plans include recalibration of heavy-ion instrumentation aboard the Long Duration Exposure Facility, a satellite that was recovered by the space shuttle in January 1990.

Biomedical Research

The word "radiation" has ominous connotations to many, but radiation can be a lifesaver. One of its therapeutic applications is charged-particle radiotherapy/radiosurgery, in which accelerated ions are delivered very precisely so that a tumor or arteriovenous malformation (AVM) is treated with minimum harm to healthy tissues nearby. Because particles deposit most of their energy abruptly near the end of their travel, the deposition being characterized by a sharp curve known as the Bragg peak, they can be used as a kind of "magic scalpel" to reach places that are surgically inaccessible. (Tumors within the eye and very close to the spinal column are classic examples.) Bragg-peak treatments conducted here over the last several years have resulted in impressive rates of remission for several kinds of tumors. The radiotherapy research continues, focusing on three primary areas:

- *development of technologies and techniques for dose localization*
- *determination of optimal treatment protocols*
- *tracking of patients already treated*

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Other life sciences research at the Bevalac, accounting for about 25% of biomedical beamtime, includes basic studies of the effects of radiation on both normal and abnormal cells and tissues. In vivo and in vitro experiments examine such subjects as damage and repair of DNA, cell and tissue kinetics, and radiation tumorigenesis.

These studies and treatment programs are carried out primarily by LBL's Research Medicine and Radiation Biophysics Division and Cellular and Molecular Biology Division, with technical support from AFRD. Scientists from other institutions, including the University of California at San Francisco, the Department of Radiation Medicine of the Massachusetts General Hospital, and the Harvard Cyclotron Laboratory, are also involved through collaborative programs.

As multiyear clinical studies affirmed the effectiveness of ion-beam therapy, a number of medical centers became interested in medical accelerators for treatment and research. In the course of research and treatment at the 184-Inch Synchrocyclotron and the Bevalac, LBL established itself as a leading center for developing and transferring advanced beam-delivery, dosimetry, and patient-positioning technologies. The Laboratory's scientists and engineers, including many from AFRD, have been heavily involved in the planning of medical accelerators at Loma Linda University Medical Center, NIRS (the National Institute for Radiosurgery at Chiba, Japan) and EULIMA (the proposed European Light Ion Medical Accelerator).

Much of the recent R&D activity has focused on beam delivery. To provide radiation fields of the desired diameter and range, a versatile, computer-controlled single-scatterer system (Figure 7-11) was developed. As the beam enters the treatment room, it is spread laterally by a combination of metal scattering foils and a variable-thickness water absorber. All the scattering material is placed as far upstream as possible in order to produce a sharp lateral field edge. In addition to scattering, the water absorber shortens the range of the beam; thus it can be used to "stack" the Bragg peak in 3- or 4-mm steps so that the target volume is covered in depth. The number of particles delivered at each step is set by a computerized dose-minimization procedure. These technologies and techniques result in isosurvival—equal biological effects upon all parts of the target—while minimizing damage to adjacent healthy tissues.

Scattering techniques are best suited to small tumor volumes. For large tumors, their shortcomings include diminished range, lowered intensity of the delivered beam, and nuclear fragmentation caused by the scattering foils. Electromagnetic beam steering avoids these difficulties but is quite difficult to implement because of the "rigidity" of the beam. An innovation currently being developed is the raster-scanner beam delivery system, a step beyond the "wobbler" system now in use (which itself won an R&D 100 award from *Research and Development Magazine* in 1986). The raster scanner moves the beam back and forth somewhat as the electron beam is moved in a television picture tube. This technique offers sharper-edged radiation fields with greater uniformity. In 1989 we continued development of the raster scanner and its control software and performed dosimetry to define the beam characteristics needed for its use.

Other innovations are aimed at quality assurance and safety in biomedical treatments. An example is the LBL-developed dosimetry system shown

Treatment Systems

XBL 896-6557

Figure 7-11. The Bragg peak (right) gives charged particles an advantage over electromagnetic radiation (such as x-rays) for radiosurgery. Electromagnetic radiation grows weaker exponentially as it is absorbed, so delivering an effective dose to a deep tumor means considerable damage to healthy tissues in front of and behind the tumor. Particles, by contrast, lose most of their energy in a relatively narrow part of their range; the location of this "Bragg peak" can be accurately predicted and precisely controlled. In the radiosurgical instrument arrangement diagrammed above, an energy-absorbing wax or Lucite bolus matches the depth of the Bragg peak to the thickness of the tumor, while collimators control the cross section of the beam. Not shown is an upstream "binary filter," or absorber, which draws the beam back in sequential layers. By changing these variables, researchers can fit the treatment area to the tumor across three dimensions.

XBL 737-969

in Figure 7-12, which measures the two-dimensional dose distribution of the radiation field delivered to a patient. This ionization-chamber system has 144 elements, each about 0.2 cm^2 in area, so its resolution is comparable to that of the computerized tomography systems that are often used when diagnosing a tumor and planning its treatment. Its size allows it to be placed very close to the patient, and its water-equivalent thickness, only 0.2 mm, means there is relatively little interference with the radiation beam. Radiation-sensitive films possess similar characteristics, but they provide results only after the fact, whereas the new system shows the radiation dose as it is delivered. This unique combination of features allows physicians to use it not only for treatment planning but also for "real-time" monitoring to ensure that the patient receives the proper dose of radiation in the correct places.

Refinement of systems related to the wobbler continued; the results included improved calibration data and procedures and better plexiglass "propellers" to spread out the Bragg curves. With Ne as well as He now being used in Cave I, computer monitoring of the positions of critical devices on the beam-optics bench has been added. Procedural safety has also been enhanced through the use, in all treatments, of Ne^{9+} , which has a unique charge-to-mass ratio, instead of Ne^{10+} .

CBB 864-2666

Figure 7-12. This LBL-developed dosimetry system gives real-time feedback on the two-dimensional dose distribution of the radiation field delivered to a patient. Its resolution is comparable to that of the computerized tomography systems that are often used when diagnosing a tumor and planning its treatment; its size allows it to be placed very close to the patient; and its water-equivalent thickness, only 0.2 mm, means relatively little interference with the radiation beam.

Clinical research medicine at the Bevalac focuses primarily on stereotactic Bragg-peak radiation treatment. Two general types of treatments are carried out: radiosurgery of intracranial AVMs and radiotherapy of tumors.

Treatment Development and Analysis. The stereotactic radiosurgery clinical research program is currently investigating how life-threatening intracranial AVMs respond to focal irradiation. Another area of effort is development of safe, reliable, and reproducible treatment strategies that can be reproduced at hospital accelerators. The program comprises development of the optimal relationships among dose, treatment volume, ion type, beam delivery, and fractionation of treatment. During the past year, researchers have continued to treat patients under a dose de-escalation protocol and have also analyzed the clinical and neuroradiologic outcomes of treatment.

The ideal outcome, of course, is obliteration of the AVM or tumor with a minimum of complications and without relapse. According to a study of 65 patients, irradiation of the entire arterial phase of the AVM with 90% of the maximum target dose resulted in complete cure. Continued optimization of dose-localization techniques has been performed during the past year through improvements in treatment planning, delivery, and verification. Developing a protocol to optimize the dose and its distribution is important;

Heavy-Ion Radiotherapy and Radiosurgery

the goal is to provide effective treatment while minimizing side effects, including potential delayed radiation injury to critical brain structures nearby.

Heavy-Ion Radiotherapy of Tumors. Previously, a Phase I-II trial of neon-ion irradiation of locally advanced tumors of different anatomical regions delivered promising initial results on glioma of the brain; selected head/neck tumors; tumors of the esophagus, pancreas, stomach, lung, and prostate; and sarcoma of soft tissue, bone, and other sites. Local control rates from 50% to 90% were achieved in lung, locally advanced paranasal sinus and nasopharynx tumors, salivary gland tumors, and sarcoma of bone or soft tissue. Randomized Phase III studies have been established for most of these. In addition, plans are being made for further trials involving other types of tumors at various sites, including "radioresistant" histologies such as melanoma and renal carcinoma.

A new Phase III trial has been started to compare the effects of neon ions, which have high linear energy transfer (LET), against those of the more-familiar, low-LET helium ions. The high-LET ions are thought to offer advantages in effectiveness and dose localization. However, accelerators and related systems for heavier ions are more costly and complex, so it is important to determine whether those characteristics are needed for effective treatment, and, if so, under what conditions. The trial will involve sarcoma in the thoracic and lumbar paraspinal regions and sinus/nasopharynx tumors invading the base of the skull. Another new trial will compare results from the combination of neon ions and chemotherapy against a well-characterized low-LET database for the combination of x-rays and chemotherapy.

Uveal Melanoma Treatment Follow-up Studies. One of the most successful uses of ion therapy has been control of uveal melanoma, an eye tumor that formerly had to be treated by "enucleation," or surgical removal of the eye. Treatment using helium ions began several years ago at the 184-Inch Synchrocyclotron and is being continued at the Bevalac. A local control rate of 97% has been observed over study periods ranging from 3 to 139 months (with a median of 62 months). Tumor control was excellent at all dose levels studied. Overall, 83% of the patients retained the affected eye, and about 40% have regained vision of 20/400 or better. The actuarial survival rate is 80% at 5 years.

Radiobiology and Radiation Biophysics

It was recognized rather early in the study of radiation that different kinds have different degrees of impact on living tissue. More-detailed examinations have shown that this subject has additional layers of subtlety. Not only do ions have different effects than electromagnetic radiation such as gamma rays (corresponding to different mechanisms of energy deposition), but the effectiveness of a given dose depends upon the mass of the ion in ways contrary to previous expectations. Yet another factor that can be examined is the exact effect upon the cell, e.g., damage to DNA, carcinogenesis, and so forth. Because of these issues, the Bevalac is the host of a diverse program in radiation biophysics.

Current research in this area includes the physical characteristics and biological effects of heavy-ion irradiation in the central nervous system and other tissues. Animal models and *in vitro* studies are of primary importance in this research. Considerable progress has been made in understanding the complex interactions among dose-distribution patterns, damage and repair

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of DNA, tissue kinetics, and delayed radiation injury. Also studied are the basic physical and biological characteristics of heavy-charged-particle beams. Some recent highlights are discussed below.

Cancer-Causing Effects of High-LET Ions. One of the ongoing radiation biology programs at the Bevalac examines the likelihood of tumor induction in the Harderian glands* of mice. This model system is used to examine the physical parameters (dose, LET, and fluence) and the biological parameters (cell survival and transformation, hormonal influence, and repair capacity) that affect charged-particle tumor induction. Figure 7-13 shows some preliminary results for tumor prevalence as a function of dose after irradiation with various ions that had LETs ranging from 1.6 to 650 keV/ μm .

Extrapolating from previous knowledge of normal tissue and transformation responses, one would expect the curve of relative biological effectiveness (RBE) versus LET to peak around 190 keV/ μm (i.e., iron at 600 MeV) and then drop off nearly as fast as it had risen. However, it appears from current Bevalac research that there is only a slight dropoff above 190 keV/ μm ; very heavy ions, with their very high linear energy transfer, remain quite carcinogenic, with RBEs between 20 and 30. Note the comparison of the tumor-induction potential of heavy ions to that of low-LET radiation such as the gamma rays given off by cobalt-60. Bevalac experiments using protons will provide RBE data that can be compared on a particle-per-particle basis.

Genetic Damage and Mutagenic Effects. The effectiveness of high-energy ionized particles in the induction of three types of genetic lesions were studied using the nematode *C. elegans*. These gene locations were used to measure dose and fluence response curves. Inactivation cross sections were derived as functions of LET; however, LET alone was not sufficient to account for the observed kinetics.

In other studies, mutational yield was found to be qualitatively different for two human genes: one autosomal gene and one X-linked gene. LET differences in hyperthermic radiosensitization correlated with protein synthesis were seen, but no dose dependence was observed in the oxygen effect in synchronized mammalian cells. (This refutes previously published work and affects theoretical concepts of low-dose radiation responses.) Finally, measurements were made of therapeutic gain for local tumor control and of inhibition of the metastatic spread of tumor by combining cisplatin with high-LET radiation.

Carcinogenic and mutagenic effects of heavy ions were studied for NASA. The effect of energetic protons on cell transformation and mutation were studied to determine the effect of shielding on the energetic iron particles in inducing neoplastic transformation. Methods and techniques for studying radiogenic transformation of human epidermal cells in culture were undertaken. Studies were made of the effects of x rays on cell inactivation and neoplastic transformation, along with molecular mechanisms of neoplastic cell transformation with restriction enzymes.

* The Harderian gland, present in most animals, is found adjacent to the eyeball and is composed of epithelial cells that secrete lipids for lubrication of the eye. To maximize the expression of radiation-induced Harderian tumors, pituitaries from isogenic donors are implanted into irradiated mice; this also reduces the latency period of tumor appearance.

Figure 7-13. These tumor-incidence measurements, made 16 months after irradiation, are among the early results of a Bevalac-based study of heavy-ion carcinogenesis. The study uses an animal model: the Harderian glands of white mice made more susceptible to tumors by pituitary implants. The baseline tumor incidence for the control group is 2.5%; note that the effects of all the heavy ions we studied were at least 100% over baseline at the lowest doses we used. Other radiation-biophysics programs at the Bevalac include studies of genetic damage and mutation.

XBL 905-5509

Further Applications of Radiation Biophysics Findings

The knowledge gained through radiation biophysics studies is important both as basic science and as background information for those who use radiation as a medical tool. However, it is useful in other fields. One application of particular topical interest is the safety of prolonged space flight, especially beyond the protective influence of the earth's magnetic field.

It has been postulated that, during a three-year interplanetary mission such as a voyage to Mars, up to 30% of the cells in an astronaut's body might be penetrated by highly damaging heavy cosmic rays.* Iron, which is abundant among cosmic rays, might be especially troublesome. For example, its effects stood out in the carcinogenesis studies described above. Further, it is well known that the carcinogenic and mutagenic effects of chronic low-level exposure to radiation are quite different from the effects of acute high-level exposure. The situation is further complicated by the difficulty and expense of carrying shielding material on a space flight. Obviously the biophysical effects of energetic particles ought to be understood more thoroughly before such a mission is undertaken.

* Cosmic rays comprise electrons and a broad mixture of naturally occurring nuclei, some of them quite energetic. In addition to the always-present background level of cosmic rays, an extended manned mission might encounter solar-flare radiation. The bursts of radiation from solar flares are relatively short-lived (several days) but intense.

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Accelerator Technology and Operations

- S. Abbott, R. Caylor, R. Gough, D. Howard, R. MacGill, and J.W. Staples, "Design of an integrally formed RFQ," in *Proceedings of the IEEE Particle Accelerator Conference* (Chicago, IL, 1989), Bull. Am. Phys. Soc. **34** (1989); abstract published as Lawrence Berkeley Laboratory report LBL-25890a (1989).
- J.G. Alessi, F.M. Brennan, J. Brodowski, H.N. Brown, R.A. Gough, A. Kponou, V. LoDestro, P. Montemurro, K. Prele, J.W. Staples, and R. Witkov, "Performance of the new AGS RFQ preinjector," in *Proceedings of the IEEE Particle Accelerator Conference* (Chicago, IL, 1989), Bull. Am. Phys. Soc. **34** (1989).
- J.R. Alonso, "Particle accelerators: from research tools to workhorses for mankind," presented at AAAS Science Encounters (San Francisco, CA, 1989).
- J.R. Alonso, "Intermediate energy heavy ions," University of California at Irvine Medical Physics Department, Colloquium (Irvine, CA, 1989).
- J.R. Alonso, M. Prior, D. Dietrich, and D. Schneider, editors, *Proceedings of the Workshop on Highly Charged Ions, New Physics and Applications* (Berkeley, CA, 1989), Nucl. Instrum. Meth. B **43** (1989).
- J.R. Alonso, "Magnetically scanned ion beams for radiation therapy," invited paper in *Proceedings of the Tenth Conference on the Application of Accelerators in Research and Industry* (Denton, TX, 1988), Nucl. Instrum. Meth. B **40/41** (1989).
- J.R. Alonso, "Intermediate energy heavy ions: an emerging multidisciplinary research tool," invited paper in *Proceedings of the Tenth Conference on the Application of Accelerators in Research and Industry* (Denton, TX, 1988), Nucl. Instrum. Meth. B **40/41** (1989).
- J.R. Alonso, B. Feinberg, J.G. Kalnins, G.F. Krebs, M.A. McMahan, and I. Tanihata, "Radioactive beam production at the Bevalac," in *Proceedings of the First International Conference on Radioactive Beams*

(Berkeley, CA, 1989), World Press (in press); also published as Lawrence Berkeley Laboratory report LBL-27441 (1989).

D. Howard, R. Caylor, R. Gough, J. Lax, R. MacGill, R. Richter, R. Ridgeway, and J.W. Staples, "Optimizing the high power input to the LBL 400 MHz proton RFQ," in *Proceedings of the IEEE Particle Accelerator Conference* (Chicago, IL, 1989), Bull. Am. Phys. Soc. **34** (1989); abstract published as Lawrence Berkeley Laboratory report LBL-25948a (1989).

R.J. McDonald, J.R. Alonso, G.F. Krebs, collaborative works, "Research opportunities at the Bevalac," Lawrence Berkeley Laboratory report PUB-660 (1989).

M.A. McMahan, R.F. Lebed, and B. Feinberg, "Charge state distributions for heavy ions in carbon stripper foils," in *Proceedings of the IEEE Particle Accelerator Conference* (Chicago, IL, 1989), Bull. Am. Phys. Soc. **34**; also published as Lawrence Berkeley Laboratory report LBL-25930 (1989).

M.A. McMahan, S.A. Meaney, D. Hubbard, and B. Feinberg, "Stripping with a Fomblin supersonic jet at 112.5 keV/nucleon," *Proceedings of the IEEE Linear Accelerator Conference* (Newport News, VA, 1988); Continuous Electron Beam Accelerator Facility report CEBAF-Report-89-001 (1989).

J. Staples, "Heavy ion RFQ's," invited paper, *Proceedings of the International Symposium on Electron Beam Ion Sources and their Applications* (Brookhaven National Laboratory, Upton, NY, 1989), AIP Conference Proceedings (Particles and Fields Series **38**, no. 188 (1989).

J. Staples, "RFQ for an EBIS-Based RHIC Injector," invited paper, *Proceedings of the International Symposium on Electron Beam Ion Sources and their Applications* (Brookhaven National Laboratory, Upton, NY, 1989), AIP Conference Proceedings Series **38**, no. 188 (Particles and Fields).

J. Staples, "RFQ's," invited paper, *Proceedings of the 1989 Brookhaven Accelerator Summer School* (Brookhaven National Laboratory, Upton, NY, 1989), AIP Conference Proceedings Series (in press).

Publications and Presentations

Nuclear Science: Collaborative Research by Bevalac Staff and Other Users

H. Berg, R. Dörner, C. Kelbch, S. Kelbch, J. Ullrich, S. Hagmann, P. Richard, H. Schmidt-Böcking, A.S. Schlachter, M. Prior, H.J. Crawford, J. Engelage, I. Flores, D.H. Lloyd, J. Pedersen, and R.E. Olson, "Multiple ionization of rare gases by high-energy uranium ions," *J. Phys. B* **21** (1988).

J. Carroll, G.F. Krebs, and DLS Collaboration, "Measurements of e^+e^- pair production at the Bevalac," *Nucl. Phys. A* **495** (1989).

R.J. Charity, K.X. Jing, D.R. Bowman, M.A. McMahan, G.J. Wozniak, L.G. Moretto, N. Colonna, G. Guarino, A. Pantaleo, L. Fiore, A. Gobbi, and K.D. Hildenbrand, "Sources of complex fragment emission in lanthanum-induced reactions at $E/A = 14.7$ and 18.0 MeV," *Nucl. Phys. A* **511**, 59 (1990); Lawrence Berkeley Laboratory report LBL-26859 (1989).

Nelson Claytor, B. Feinberg, Harvey Gould, Curtis E. Bemis, Jr., Jorge Gomez del Campo, Carl A. Ludemann, and Charles R. Vane, "Electron impact ionization of U^{88+} - U^{91+} ," *Phys. Rev. Lett.* **61** (1988); also published as Lawrence Berkeley Laboratory report LBL-25534 (1988).

G. Claesson, G.F. Krebs, J. Miller, G. Roche, L.S. Schroeder, W. Benenson, J. van der Plicht, J.S. Winfield, G. Landaud, J.F. Gilot, and H. Stocker, "Observation of a 90 degree enhancement in proton production from multiplicity-selected, central La+La collisions at $E/A=246$ MeV," presented at the fall meeting of the American Physical Society (1989).

A.J. Cole, H.J. Crawford, B.G. Harvey, and P.J. Lindstrom, "Peripheral reactions induced by a 2.1 GeV/n ^{12}C beam on a carbon target using a simple combinatoric model," *Phys. Rev. C* **3** (1989).

N. Colonna, R.J. Charity, D.R. Bowman, M.A. McMahan, G.J. Wozniak, and L.G. Moretto, "Incomplete fusion and complex-fragment emission: a continuum of isotropic sources," *Phys. Rev. Lett.* **62**, 1833 (1989).

H.J. Crawford and E802 Collaboration, "Results from the BNL E802 spectrometer for 14.5 GeV/C per nucleon silicon beams," *Nucl. Phys. A* **498**, 67c (1989).

J. Crawford, J. Engelage, P. Ferrando, G. Guzik, F.C. Jones, P.J. Lindstrom, J.W. Mitchell, A. Soutoul, C.J. Waddington, W.R. Webber, and J.P. Wefel, "A database of fragmentation cross section measurements applicable to cosmic ray propagation calculations," in *Proceedings of the Twenty-first International Cosmic Ray Conference* (Adelaide, Australia, 1989), OG **8.3** (1990).

H.J. Crawford, J. Engelage, T.G. Guzik, J. Isbert, P.J. Lindstrom, J.W. Mitchell, J.J. Pitts, W. Schimmerling, M. Simon, and J.P. Wefel, "The fragmentation of ^{28}Si ," in *Proceedings of the Twenty-first International Cosmic Ray Conference* (Adelaide, Australia, 1989), OG **8.3** (1990).

R.J. Charity, D.R. Bowman, R.J. McDonald, M.A. McMahan, G.J. Wozniak, L.G. Moretto, W.L. Kehoe, S. Bradley, A.C. Mignerey, and M.N. Namboodiri, "Emission of complex fragments from highly excited systems produced in $^{93}Nb + ^9Be$ and ^{27}Al reactions at $E/A=25$ and 30 MeV," *Nucl. Phys. A* **476**, 5516 (1988).

K. Danzmann, W.E. Meyerhof, E.C. Montenegro, E. Dillard, H.P. Hülskotter, N. Guardala, D. Spooner, D. Kotlinski, D. Cline, A. Kavka, C. Beausang, J. Burde, M. A. Deleplanque, R.M. Diamond, R.J. McDonald, A.O. Macchiavelli, B.S. Rude, F.S. Stephens, and J.D. Molitoris, "Narrow sum-energy lines in the two-photon spectrum from Coulomb excitation of high spin states in ^{232}U ," *Phys. Rev. Lett.* **62**, 2353-56 (1989).

J. Engelage, M.E. Baumgartner, E. Beale, B.L. Berman, F. Bieser, F.P. Brady, M. Bronson, J.B. Carroll, H.J. Crawford, I. Flores, D.E. Greiner, L. Greiner, O. Hashimoto, G. Igo, S. Kadota, P.N. Kirk, P.J. Lindstrom, C. McParland, S. Nagamiya, D.L. Olson, J. Porter, J.L. Romero, C.L. Ruiz, T.J.M. Symons, I. Tanihata, R. Wada, M.L. Webb, J. Yamada, and H. Yee, "Design of the Bevalac heavy ion spectrometer system and its performance in studying ^{12}C fragmentation," *Nucl. Instrum. Meth. A* **277** (1989).

BEVALAC OPERATIONS

- J.W. Harris, G.F. Krebs, J. Miller, H.G. Pugh, P.R. Entein, G. Roche, L.S. Schroeder, R.N. Treuhaft, P.N. Kirk, R. Brockmann, and K.L. Wolf, "Midrapidity π^-/π^+ ratios in 1.05 GeV/nucleon $^{40}\text{Ca} + ^{40}\text{Ca}$ collisions," Lawrence Berkeley Laboratory report LBL-27105 (1989).
- T.F. Hoang and H.J. Crawford, "Characteristics of π^- , $\bar{p}$, and antinuclei from pp collisions," *Zeitschrift für Physik C* **43** (1989).
- J. Isbert, H.J. Crawford, T.G. Guzik, M. Hof, K.D. Mathis, J.W. Mitchell, J. Neuhaus, M. Simon, and J.P. Wefel, "A drift chamber for high Z particles," in *Proceedings of the Twenty-first International Cosmic Ray Conference* (Adelaide, Australia, 1989), OG 10.5-18 (1990).
- T. Kobayashi, S. Shimoura, I. Tanihata, K. Katori, K. Matsuta, T. Minamisono, K. Sugimoto, W. Muller, D.L. Olson, T.J.M. Symons, H. Wieman, "Electromagnetic dissociation and soft giant dipole resonance of the neutron-dripline nucleus ^{11}Li ," *Phys. Lett. B* **232**, 51 (1989).
- A. Letessier-Selvon, J. Bystricky, J. Carroll, J. Gordon, T. Hallman, G. Igo, P. Kirk, G.F. Krebs, E. Lallier, G. Landaud, L. Madansky, H.S. Matis, D. Miller, C. Naudet, G. Roche, L.S. Schroeder, P.A. Seidl, Z.F. Wang, R. Welsh, and A. Yegneswaran (DLS collaboration), "Mass and transverse momentum dependence of the dielectron yield in p-Be collisions at 4.9 GeV," *Phys. Rev. C* **40**, 3 (1989); also published as Lawrence Berkeley Laboratory report LBL-27080 (1989).
- C. Naudet and G.F. Krebs, "Electron pair production in p+Be and Ca+Ca collisions at the Bevalac," in *Proceedings of the International Nuclear Physics Conference* (Sao Paulo, Brazil, 1989).
- C. Naudet, J. Bystricky, J. Carroll, J. Gordon, T. Hallman, G. Igo, P. Kirk, G.F. Krebs, E. Lallier, G. Landaud, A. Letessier-Selvon, L. Madansky, H.S. Matis, D. Miller, G. Roche, L. Schroeder, P.A. Seidl, Z.F. Wang, R. Welsh, and A. Yegneswaran (DLS collaboration), "Threshold behavior of electron pair production in p-Be collisions," *Phys. Rev. Lett.* **62**, 23 (1989).
- V.P. Pereygin, S.G. Stetsenko, H.J. Crawford, and T.J.M. Symons, "Analysis of the results of calibrating meteoritic olivine crystals with ^{238}U nuclei at the Bevalac accelerator," in *XXI ICRC* **3**, 65 (Adelaide, Australia, 1990).
- R. Planeta, K. Kwiatkowski, S.H. Zhou, V.E. Viola, H. Breuer, M.A. McMahan, W.L. Kehoe, and A.C. Mignerey, "Nucleon exchange properties of the $E/A = 8.5$ MeV $^{74}\text{Ge} + ^{165}\text{Ho}$ reaction," *Phys. Rev. C* (in press); Indiana University report INC-40007-63 (1989).
- R. Planeta, K. Kwiatkowski, S.H. Zhou, V.E. Viola, H. Breuer, M.A. McMahan, J. Randrup, and A.C. Mignerey, "Nucleon exchange and heat partition in damped collisions," *Phys. Rev. C* **39**, 1197 (1989).
- G. Rai, F. Bieser, H.S. Matis, C. McParland, G. Odyniec, D.L. Olson, H.G. Pugh, H.G. Ritter, T.J.M. Symons, and H. Wieman, "Status of the HISS TPC," in *Proceedings of the NATO Advanced Study Institute on the Nuclear Equation of State* (Peñíscola, Spain, 1989).
- G. Roche, J. Bystricky, J. Carroll, J. Gordon, T. Hallman, G. Igo, P. Kirk, G.F. Krebs, G. Landaud, A. Letessier-Selvon, L. Madansky, H.S. Matis, D. Miller, D. Miller, C. Naudet, L.S. Schroeder, P.A. Seidl, Z.F. Wang, R. Welsh, and A. Yegneswaran, "Dielectron production in Ca+Ca collisions at 1.0 and 2.0 GeV," *Phys. Lett. B* **226**, 3-4 (1989); also published as Lawrence Berkeley Laboratory report LBL-27050 (1990).
- D.G. Sarantites, D.R. Bowman, G.J. Wozniak, R.J. Charity, Z.H. Liu, R. McDonald, M.A. McMahan, and L.G. Moretto, "Complex fragments from excited actinide nuclei: a new test of the finite range model," *Phys. Lett. B* **218**, 427 (1989).
- J. Schambach, R. Madey, W.M. Zhang, M. Elaasar, D. Keane, B.D. Anderson, A.R. Baldwin, J. Watson, G.D. Westfall, G.F. Krebs, and H. Wieman, "Collective flow of charged fragments and neutrons from Bevalac experiment 848H," submitted to *The Nuclear Equation of State*, edited by W. Greiner, Plenum, London (Proc. of NATO Advanced Study Institute, Peñíscola, Spain, 1989).
- J. Shor, G.F. Krebs, M.A. McMahan, E.F. Barash, J.B. Carroll, T. Hallman, G. Igo, G. Kalnins, P. Kirk, P. Lindstrom, F.J. Urban, and Z.F. Wang, "Subthreshold antiproton, K^- , K^+ , and energetic-pion production in relativistic nucleus-nucleus collisions," *Phys. Rev. Lett.* **63** (20) (1989); Lawrence Berkeley Laboratory report LBL-27477 (1989).

**Biomedical Research and Treatment:
Collaborative Research by Bevalac
Staff and Other Users**

J. R. Alonso, J. Bercovitz, W. T. Chu, B. A. Ludewigt, M. Nyman, R. P. Singh, F. Stradtner, R. Tafelski, and R. Waltori, "Relocation of the Helium Radiotherapy Program from the 184"Synchrocyclotron to the Bevalac," in *Proceedings of the IEEE Particle Accelerator Conference* (Chicago, IL, 1989), Bull. Am. Phys. Soc. **34** (1989).

W.T. Chu, J.R. Alonso, J.B. Halliwell, B.A. Ludewigt, M.A. Nyman, T.R. Renner, R.P. Singh, G.D. Stover, and R. Stradtner, "Toward perfecting dynamic beam delivery methods," in *Proceedings of the International Heavy Particle Therapy Workshop* (Paul Scheerer Institute, Villigen, Switzerland, 1989), in press.

W.T. Chu, B. Ludewigt, M. Nyman, T.R. Renner, R.P. Singh, and R. Stradtner, "Preliminary results of a raster scanning beam delivery system for light ions," in *Proceedings of the IEEE Particle Accelerator Conference* (Chicago, IL, 1989), Bull. Am. Phys. Soc. **34**, 214 (1989).

W.T. Chu, T.R. Renner, and B.A. Ludewigt, "Dynamic beam delivery for three-dimensional conformal therapy," in *Proceedings of the EULIMA Workshop on the Potential Value of Light Ion Beam Therapy*, P. Chauvel and A. Wambersie, editors, EUR 12165 EN, 295-328 (Nice, France, 1989).

B. Ludewigt, W. Chu, M. Nyman, T.R. Renner, R.P. Singh, and R. Stradtner, "A raster scanning beam delivery system for light ions," in *Proceedings of the IEEE Particle Accelerator Conference* (Chicago, IL, 1989), Bull. Am. Phys. Soc. **34**, 1174 (1989).

T.R. Renner, W. T. Chu, B. Ludewigt, M. Nyman, and R. Stradtner, "Multi-segmented ionization chamber dosimetry system for light-ion beams," Nucl. Instrum. Meth. A **281**, 640 (1989).

R.P. Singh, W.T. Chu, B.A. Ludewigt, K.M. Marks, M.A. Nyman, T.R. Renner, and R. Stradtner, "Software quality assurance and software in the biomed control system," Lawrence Berkeley Laboratory report LBL-27948 (1989).

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