This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

THE SUPERHILAC AND THE BERKELEY SUPERHEAVY ELEMENT PROGRAM^{*}

A. Ghiorso

Lawrence Berkeley Laboratory, University of California
Berkeley, California

Ladies and gentlemen, if you will remember, Dr. Zvara presented a slide this morning which gave an allegorical presentation of the search for superheavy elements supposedly hidden away on a magic island surrounded by a "sea of instability". Three vessels marked Xe, Kr, and Ge were shown embarked upon their individual missions, obviously those of the successful Dubna group; and one was shown being built, clearly the UNILAC, but nowhere was the SuperHILAC visible. At the Munich meeting last week I understand that it was said that it had been "thrown into the water". Well, that isn't exactly what has happened! We did launch our machine out almost immediately it encountered some hidden reefs and got stuck. Periodically, however there was an unusual high tide and we were able to float it off only to have it encounter new reefs further downstream. It seems that these were uncharted waters! By dint of a lot of effort and repair of the ravages of the hidden obstacles we have arrived finally downstream from these barriers and are about to set sail on the open sea to try and overtake our Dubna friends. In some respects our vessel should be better equipped to explore for the magic isle to look for hidden inlets although I must admit that the Dubna group under Prof. Flerov has done an outstanding job with their tandem cyclotron combination in their search for superheavy elements.

So much for the allegory, let us return to the real world. The SuperHILAC is a very complicated machine and it occurred to me that this audience might better appreciate a movie documentary, which our laboratory has just completed, more than a set of slides. This film was directed by James Halverson and intended for an intelligent lay audience rather than scientists. But I think that he has captured the essence and excitement of the construction of the new accelerator rather well so I decided that I would try the film out on this group. I think that it will go better than slides. (It did).

The 27 minute film "Building an Atomic Accelerator" was then shown.

(The film uses various analogies to explain some of the mysteries of heavy ion linear accelerators. The use of resonance devices is likened to the striking of a bell, for instance. Particularly effective is the beautiful use of a visible laser beam and various glass lenses to illustrate the action of strong-focussing forces which are so essential to the operation of the accelerator. The focus-defocus sequences are nicely shown by this technique.)

(The film shows the various processes involved in fabricating the machine. The bending of the copper-clad steel into 10 ft. diameter cylinders which are then assembled and welded together in final position, the winding and potting of the tape-wound quadrupole magnets, the installing of drift-tube structures, the aligning of the completed assemblies -- this is all shown to the accompaniment of

MASTER

^{*}Work performed under the auspices of the U. S. Atomic Energy Commission.

suitable musical sound effects. The high voltage injectors with their visually interesting parts are photographed effectively. Their action in initially accelerating the ionized atoms for injection into the first linear accelerator is illustrated by animation.)

(Finally, after the accelerator has been put together an attempt has been made to show some of the excitement engendered in the testing of a new machine. A sequence showing the testing of a new ion source was chosen and it is probably not too far from reality even though the narrator was a professional. It concludes with the first scientific experiment and it is reenacted fairly effectively by one of the scientists actually involved.) End of film.

I hope you enjoyed the film. Now let me add a little about the accelerator and bring you up-to-date on our progress toward stable operation. Fig. 1 shows the whole machine from high in the northwest corner of the building. The old HILAC was turned off for the last time in February, 1971 and within two weeks the building had been entirely cleared of everything. Only the shell of the building in the high bay area remained. By April, 1972 the new tanks, injectors, and ancillary equipment had been installed and we had obtained a $^{14}\text{N}^{3+}$ beam using the modified old injector. This was a dramatic accomplishment in such a short time and we knew that the basic design was going to be adequate.

We next turned our full attention to the new 3-MV injector. This shunt-fed voltage multiplier d.c. machine designed to accelerate ions with a charge-to-mass ratio as small as 0.045 had been meant for use with the ill-fated Omnitron. Its construction had been completed by the time the SuperHILAC had been well started but we did not have sufficient funds to finance the inevitable debugging operation in parallel with the completion of the linac work. Now we were to find that serious design limitations had been incorporated into this injector.

We seemed to have several problems at once and it was very difficult to solve one while plagued by others. We were not able to attain even moderate high potentials without blowing up parts of the delicate electronics needed to operate the terminal. The pressures in the terminal and in the column were sometimes unaccountably high causing large charge-exchange losses. The calibration of the meter which measured the potential on the terminal seemed to read too high by 15 - 25%. The 100 KHz RF power supply which furnished power for the shunt-fed Greinacher voltage multiplier circuit was erratic and seemed to burn out its components with the least provocation. It was quite a while until we could sort out the problems and arrange for their solution because we had a hopelessly inadequate diagnostic system and had to improvise methods of measuring what was going on.

Fortunately the linacs worked well with a minimum of problems. Since our old-but-modified 800 Kv injector was operating properly we were able to commence operations for experimenters with ions up to argon while the de-bugging of our 3-MV injector proceeded. We soon found that although the linacs worked well there were many things that we had to learn to get good beam performance. The SuperHILAC has turned out to be one of the most complicated accelerators in the world because of its built-in flexibility in being able to accelerate a wide variety of ions to different velocities.

CBB 722 - 751

Fig. 1 - Bird's eye photograph of the completed accelerator before the shielding was added.

After a few months of attempting to tune the accelerator by conventional methods we found that the old techniques were too clumsy, slow and inaccurate to allow rapid progress. We turned to the use of solid state particle detectors but soon found that the usual method of energy measurement of particles scattered by a thin foil also had severe limitations. This method is extremely sensitive to angle and energy and in the case of very short range particles can be very inaccurate, too.

Clearly a better method is to measure them by placing these detectors directly in the beam. Since there may be more than 10^{14} particles per second in a given beam it is necessary to attenuate by factors of 10^{10} or more to be able to make a measurement. At first we used sheets of mica in which tiny 2-micron holes had been etched normal to the surface after passage of ^{252}Cf fission fragments. The method worked but it was found that the mica was relatively delicate and we later supplanted it by using commercially available screen meshes each giving an attenuation factor as high as about 100. It was found to be important to separate the screens by two feet or more to prevent their geometrical regularity from causing problems. The attenuation factor is varied by inserting different combinations of screens and seems to be reasonably reproducible. The attenuators are inserted in the beam transfer lines between the injectors and the pre-stripper linac. Fig. 2 shows a plan view of the two injectors. Particles which happen to scatter from the edges of a hole in a screen are completely suppressed since they change enough in energy to be rejected by the linac. In practice we usually observe negligible amounts of low energy tailing in the particle energy spectra.

As Seaborg mentioned in his opening Plenary lecture we are in the process of connecting the SuperHILAC to the Bevatron by means of a beam transfer line to allow the acceleration of fully-stripped heavy ion beams to energies as high as 2700 Mev per nucleon. This combination we have labeled the Bevalac. Usually we will use relatively light ions from the 800 Kv injector and, to make it possible to deliver such beams at any given moment, we are also designing and constructing a time-share capability. By switching various magnets at crucial places in the beam lines every few seconds we will be able to direct a relatively short pulse (less than a millisecond long) into the Bevatron concurrently with using the other injector to supply a different beam of different energy to an experimenter at the SuperHILAC. When the Bevalac is not running we can use this dual beam capability for testing or for supplying another experimenter at the HILAC. Ultimately we will probably add a third injector to expand our research capacity even more.

Fig. 3 is a photograph showing the inside of the Pre-Stripper tank during construction and illustrates the typical drift-tube structures. Inside each drift tube is a tape-wound magnetic quadrupole which confines the beam. These quadrupoles were designed by Bob Main, who was in charge of building the SuperHILAC, and his design has been found to be excellent. We have never had a failure of a quadrupole even though their field strength is several times higher than that used by other accelerators.

Fig. 4 shows the interior of the completed Pre-Stripper with the 200K cryopumping line near the bottom of the tank. Our accelerator was the first to use a cryogenic pumping system; it allows the accelerator tanks to operate beautifully in the 10^{-7} torr region. We have found it to be inexpensive, clean, and very forgiving of errors in contrast to the old diffusion pump methods so that we plan to extend the technique to the experimental areas, too.

Fig. 5 is a plan view of the target area. It is obviously very crowded but we had no choice in the matter since we had no budget for expanding the old HILAC building. The big advantage of the SuperHILAC over the Dubna tandem cyclotrons is that our beam is automatically extracted whereas theirs is only usable as an internal beam. Our beams can be steered and focussed to any one of many experimental setups. Even

Plan View Injector Area

KBK 704 0177

Fig. 2 - Plan view of the injector area. The two injectors start their beams at different levels and converge at the entrance to the Pre-Stripper tank. Here a steering magnet directs either one along the linac axis.

CBB 739 - 5362

Fig. 3 - Interior of the Pre-Stripper tank during construction showing the drift-tube structures.

CBB 721 - 172

Fig. 4 - Interior of the Pre-Stripper tank after completion. Shows the 20°K cryogenic pumping line near the bottom of tank

SUPERHILAC TARGET AREA PLAN VIEW

ABL 721 5064

Fig. 5- Plan view of the SuperHILAC target area.

this many beam lines is not enough to take care of the demand and we are now in the process of expanding this number by more than two by adding other steering magnets further downstream in new areas along the axis of the machine. The experiments are becoming ever more complicated and we find it desirable to find almost permanent "homes" for a great many experimenters. About half of the available research time will be used by non-Berkeley user groups in the near future.

We have been able to make some interesting measurements of the absolute energy of the beam by using our solid state detectors in an unusual way. As well as measuring the energy of each particle that strikes a detector we measure its time of arrival relative to the 70MHz radio frequency that drives the cavities. We find that it is possible to do this with an accuracy of better than 0.1 ns and consequently we can study fine details of the phase distribution of the beam. We have also used the technique to calibrate our detectors on an absolute basis by measuring the time it takes for each group of particles to travel over a measured distance. This is done by tuning the machine to deliver a beam with a narrow phase distribution (one with a full-width at half-maximum of 0.5 ns is not unusual) at the Post-Stripper exit and then the centroid of this time distribution is measured again some 4 or 5 meters downstream. The absolute precision in velocity measurement and consequently energy measurement can be better than a few tenths of a percent. We have also been gratified to learn that the energy spread of the beam can be very small. Without any special effort at tuning we have measured $\Delta E/E$ as small as 0.2%; we expect that this can be bettered substantially by tuning procedures but have not yet had the time to do so.

Finally I would like to describe our special mass separator with which we will try to identify superheavy elements. This instrument which we call SASSY, an acronym for Small Aperture Separator System, has a half life sensitivity in the range from a microsecond to infinity. Referring to Fig. 6 one can see that the basic measurements that can be made with reaction recoils are velocity, energy, magnetic rigidity in a gas-filled magnetic field, rate of energy loss in solids and gases, characteristic X-rays, and subsequent radioactive decay after being brought to rest. Hopefully these quantities are redundant and together will identify a superheavy recoiling atom.

The first element in the separator is a Wien filter. This device uses crossed magnetic and electric fields to allow the bombarding projectiles to be bent out of the way while recoils in a desired velocity range traverse it regardless of charge state. At the end of this velocity separator there is a special multi-wire proportional counter (see Fig. 7) which we have developed for the purpose of determining (a) the spatial coordinates x and y of each recoil, (b) the time of arrival within a nanosecond or two, and (c) a rough value dE/dz in the counter gas. The counter operates at a pressure of about 0.5 torr of a gas such as pentane at a potential of some 300-400 volts. Very thin grid-supported windows ($7 \mu\text{gm-cm}^2$ formvar) confine the counter gas so that there is only a very small energy loss when a heavy recoil passes through the counter.

After each recoil is "tagged" by this first detector it is focussed by a triplet quadrupole through a following bending magnet. In order to obtain the greatest yield in this procedure it is performed in a low pressure of a light gas such as hydrogen, helium, or methane. This is done so that one can take advantage of the fact that each recoil of a given atomic number and velocity will have the same mean charge state and thus for a given mass will bend in the same way in a magnetic field. Each recoil iterates through the whole range of charge states continuously as it passes through the gas and thus experiences the same deflection to a first approximation.

SASSY

SMALL APERTURE SEPARATOR SYSTEM

CBB 739 - 5361

Fig. 6 - SASSY. An on-line mass separator using nuclear reaction recoils.

CBB 739 - 5363

Fig. 7 - SASSY multi-wire proportional counter for detection of heavy recoils. The counter has three planes of wires. The outer two are orthogonal and define the x and y coordinates of each particle. The center plane provides a fast timing signal (rise time < 10 ns) and an analog pulse for an approximate de/dz measurement. Amplifying transistor elements are mounted directly on the counter.

After passing through the quadrupole the recoil is detected a second time by another proportional counter to measure the same quantities as before. It then passes into a gas-filled magnetic field which bends the particle so that its magnetic rigidity can be determined. At the exit of this bending field a third proportional counter measures the pertinent quantities once more and then the recoil passes into a box for final detection.

In the final detector box the energy of the recoil (and thus its mass from the relationship $E = \frac{1}{2}mv^2$) will be determined by either solid state detectors or gaseous ionization chambers. Another possibility is the detection of the characteristic M x-rays to determine the atomic number of each recoil. After the recoil is stopped, such as by a solid state particle detector, any subsequent radioactive decays and their genetic relationship can be readily measured. In this way one can determine, for instance, a chain of alpha particle decays leading to termination by spontaneous fission. Alternate detectors can be nuclear emulsions or plastics for special cases.

As can be seen the system is highly redundant and it is possible to determine the same quantity in more than one way. We have tested individual parts of the instrument with spontaneous fission fragments from ^{252}Cf and are just about to calibrate SASSY with elastically scattered heavy atoms; for this purpose we will use low energy argon ions to bombard targets from the rare earths to californium.

SASSY is inherently a high efficiency device for recoils produced by projectiles heavier than about argon; it should be possible for us to explore for superheavy elements in a very definitive fashion since we are not dependent upon radioactive decay for detection. If a half life is greater than a fraction of a microsecond the atom will reach the last detector much of the time. We expect that our background should be essentially zero so that the lower limit on the production of superheavy recoils will be determined by the amount of accelerator time that can be devoted to a given experiment. Cross sections of less than 10^{-3}cm^2 should be attainable in a few days of running time.