UC-413
LBL-27947
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Journal of Radioanalytical and
Nuclear Chemistry

Man-Made Elements: Outlook for the Year 2039

K.E. Gregorich and G.T. Seaborg

October 1989

For Reference

Not to be taken from this room

LBL-27947
Copy 1
Bldg. 50 Library.

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal 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. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-27947

MAN-MADE ELEMENTS: OUTLOOK FOR THE YEAR 2039

K. E. Gregorich and G. T. Seaborg

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road
Berkeley, CA 94720

October 1989

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

MAN-MADE ELEMENTS: OUTLOOK FOR THE YEAR 2039

K. E. Gregorich and G. T. Seaborg

It has been 50 years since the discovery of nuclear fission. During those 50 years, we have seen the discovery and study of 19 man made elements. The present-day scope of the field of the study of the man-made elements, especially of the transuranium elements, surely could not have been foreseen by the discoverers of fission or other scientists of the time. Similarly, it is probably also true that the scope of this field in the year 2039 cannot be foreseen by present-day scientists. Nevertheless, we will try to take a look into the future, 50 years from now, and guess what the field of the man-made elements will be like on the 100th anniversary of the discovery of fission.

The technological advances of the last 50 years have been unprecedented. If one is to assume that the technology of the year 2039 will be as different from that of today as today's is from that of the time of the discovery of fission, the prediction of the state of almost any scientific field would seem a hopeless task. In this article, we have taken emerging technologies and assumed that they will mature within the next 50 years, and become commonplace. The prediction of technologies which have not yet appeared in any form, or 'second generation' technologies which grow out of those which are on the forefront of

science today has also been undertaken in a few cases.

Transuranium Research: Today and in the Past

There are, to date, 19 man-made elements which have been discovered and studied. A periodic table is presented in fig. 1, with the presently known man-made elements shaded. Of these, the 17 transuranium elements will be the main subjects of this work. The next few paragraphs contain a very brief summary of the work which has been done with the transuranium elements.

Nuclear Properties

In the 17 transuranium elements, there are about 184 known isotopes. There have been many reviews of the production of, and the study of the nuclear and chemical properties of these elements.[1-5] The measurement of the decay properties and masses of many of these isotopes has lent a great deal to the understanding of nuclear properties in general. Because of the instability of these nuclides against spontaneous fission, these studies are actually studies of the ultimate limits of nuclear stability. Important components of our understanding of nuclear properties which have been gained from the study of the transuranium elements include refinements to the liquid droplet model of the nucleus[6] and the understanding of the effect of deformed shells on the ground state masses.[7] The barrier against fission due to the macroscopic (liquid drop) properties of the nucleus decreases rapidly with increasing atomic number of the nucleus, to the point where, in the absence of shell effects, the heavy elements

would have extremely short spontaneous fission half-lives. In fact, the highest Z elements would be totally unstable with respect to fission. The shell effects are responsible for the relatively long spontaneous fission half lives of these elements. The study of the fission properties (mass and total kinetic energy distributions, neutron and gamma multiplicities, etc.) of those isotopes which undergo fission has been an especially rich field, which still defies precise theoretical understanding.[4,8,9]

Chemical Properties

Following the discovery of the 17 transuranium elements, has been the study of the chemical properties of 13 of them.[1,5,10-12] These studies of the chemical properties have defined the structure of the periodic table for the heavy elements. The position of the actinide elements (with the filling of the 5f atomic orbitals) has been well established. The chemical properties of the transactinide elements are just recently being studied, and seem to indicate that these elements are homologs of the 6d elements.[13-19] Relativistic effects on the atomic electrons have been predicted to play a very important role in determining the chemical properties of the heaviest elements.[20-23] These relativistic effects are being studied, and are adding a new twist to our understanding of periodic table properties. An example of how these relativistic effects could affect the chemical properties of the heaviest elements would be in the stabilization of electronic configurations which would otherwise be unobservable.

For example, the stabilization of the 7s electronic orbital would lead to stabilization of Lr^{1+}, 104^{2+}, and 105^{3+} with $[Rn]5f^{14}7s^{2}$ electronic configurations, rather than the Lr^{3+}, 104^{4+}, and 105^{5+} ions with the classically expected $[Rn]5f^{14}$ electronic configuration.

A Comparison of 1939 Techniques with Present-Day Techniques

While researchers in the time shortly after the discovery of fission struggled to produce and identify small numbers of atoms of the first few transuranium elements, over the years, the production methods and separation techniques progressed until, in turn, the chemical properties became well understood, the first production of weighable (and visible) quantities were produced, and finally, the mass production of milligram to kilogram quantities were routinely produced.[2,3] Today, the research being done with the heaviest elements (with atomic numbers greater than 100) is similar to that which was being done on the first few transuranium elements just after the time of the discovery of fission. Researchers are working with small numbers of atoms, and learning about the nuclear and chemical properties of these elements. The prospect of making large quantities of isotopes of these transfermium elements is remote at best, but in fifty years, production methods for (presently undiscovered) isotopes with sufficiently long half-lives may become available.

What Will the Future Bring?

New Nuclides

By the year 2039, it can be expected that the isotopes of the heavy elements (especially in the lower-Z transuranium elements) will have been discovered for all isotopes out to the proton drip-line, adding a few hundred more isotopes (for which masses will be known) to the set of data used for the understanding of macroscopic and microscopic nuclear properties. In these neutron-deficient nuclei, the relative rates of fission and proton emission (or delayed fission and delayed proton emission) will be interesting. Techniques will be developed for the production and detection of these isotopes at levels some orders of magnitude below present-day capabilities. The production of extremely neutron-rich isotopes will also become a possibility, possibly through the multiple fast neutron capture technique, which is presently only possible in supernovae and in the detonation of nuclear devices. Aside from learning of the detailed nuclear properties of these isotopes, much will be learned about the astrophysical r-process for the production of the heavy elements.

New Elements

We can expect the discovery of a number of new elements in the next 50 years. Todays technology may be capable of identifying isotopes of elements 110 and 111 at an atom-per-day to atom-per-month production rate. To go beyond these elements

would require the use of much higher beam intensities with specially designed targets. The stability of superheavy nuclei with atomic number near 114 and neutron number near 184 is expected as a result of generally accepted theory,[24] but the production of these nuclei has proved impossible so far.[25,26] The future production of superheavy elements remains a possibility, and further searches (with far greater sensitivity) will surely be carried out. A schematic picture of the limits of nuclear stability is presented in figure 2.

The study of the chemical properties of the heaviest elements will continue. The detailed chemical properties will be worked out for the elements through 106. Chemical procedures which can be performed on a millisecond or microsecond time scales will become available, making the basic chemical studies of even the short-lived isotopes of the elements through 109 (or even higher) possible.

Theoretical Studies

It can be assumed that computing power for theoretical treatments will become nearly unbounded, both in speed and capacity. This will allow the solution of many of the self-consistent many-body problems which apply to the nucleus. It can be hoped that the calculation of fission properties such as half-lives, mass distributions and total kinetic energy distributions will improve to the point where there will be a quantitative agreement between theory and experiment.

The increase in computing power should also make the exact calculation of the chemical properties of multi-atom complexes possible. Perhaps calculations could even be performed for the larger ensembles which will be necessary to predict the aqueous phase behavior of mixtures of complex ions.

FUTURE PRODUCTION OF NEW ELEMENTS AND HEAVY ELEMENT ISOTOPES

Nuclear Reactions for the Production of Heavy Element Isotopes

The Isotopes of the transuranium elements are unstable with respect to radioactive decay, and, in general, do not exist in nature. They must be produced in nuclear reactions of some sort. A brief explanation of the types of nuclear reactions, their merits and their limitations for the production of heavy element isotopes will be presented here. It should be noted here that because of the instability of the heavy element nuclei toward fission, the production of heavy element isotopes is extraordinarily difficult. Present research in the heavy element region has come very near to the high-Z limit of nuclear stability. As the number of protons confined to the nucleus increases, the stability of the nucleus decreases. In fact, for nuclei with atomic number greater than 100, the liquid drop fission barrier is much too small to stabilize these nuclei against spontaneous fission. These nuclei are stabilized against fission by the existence of a shell effect fission barrier. These shell-effect fission barriers are quite narrow and not stable with increased excitation energy. The nuclear reactions used to produce the heaviest elements leave the resulting nucleus in a state of high excitation energy. The de-excitation of these reaction products generally proceeds by the evaporation of neutrons. There is a strong competition with fission at each of the neutron evaporation steps, resulting in a severe depletion of the desired reaction products by fission during their de-excitation. In some

extreme cases, only one out of 10^{10} of the compound nuclei survive the deexcitation process without fissioning.

Production by "Hot Fusion"

Most of the transuranium elements were first synthesized by the "hot fusion" method where the nucleus of a light ion beam (such as ^{4}He, or ^{18}O, accelerated by a cyclotron or a linear accelerator) is used to bombard actinide nuclei in a stationary target. When a nucleus in the beam has a central collision with the nucleus of a target atom, they can fuse to form a compound nucleus. The yield of compound nuclei is quite high, but the minimum excitation possible in the compound nucleus is generally about 40 MeV, making the depletion of the compound nucleus products by fission during de-excitation especially severe. A review of the hot fusion technique, including the successful modeling of the production rates of actinide and transactinide isotopes has been undertaken by Alonso[27] (see also Sikkeland et al.[28]).

Atoms of elements through 106 have been produced by the hot fusion method.[29] With present technologies, atoms of elements 104 and 105 can be produced at a rate of about one atom per minute (where the target is being bombarded by well over 10^{12} ions per second),[17] and atoms of element 106 can be produced at a rate of a few atoms per hour. The yields of atoms with higher atomic numbers by the hot fusion method is expected to be much lower, making other reaction methods favorable for their production.[30] In the future, much higher beam intensities and the

necessary new target technologies to handle these higher beam currents will increase the sensitivity for these reactions by a few orders of magnitude, making the production of atoms with atomic numbers as high as 108 or 110 possible by hot fusion even with presently available target and projectile combinations.

One of the main drawbacks of the hot fusion technique is the limitation on the number of neutrons in the final products of de-excitation. Since the excited compound nuclei de-excite by emission of neutrons (in competition with fission), it is difficult to produce the neutron-rich products which are expected to have longer half-lives toward fission, alpha decay, and electron capture.

Production by "Cold Fusion"

In recent years, the heaviest elements have been produced by the "cold fusion" technique.[30,31] This is also a compound nucleus mechanism, but the target materials used have mass and atomic numbers near those for the doubly magic ^{208}Pb. The projectiles used are therefore much heavier than those used for hot fusion, often being in the region of the iron isotopes. The extra stability in the target nucleus manifests itself in a lower excitation energy in the compound nucleus. This lower excitation energy, as low as 10-15 MeV, results in the evaporation of only one or two neutrons during the deexcitation process, greatly decreasing the depletion of the compound nucleus product by fission.

This increased de-excitation survivability compared to the hot fusion method is partially offset by the fact that the probability for the compound nucleus formation is significantly lower for these cold fusion methods.[32,33] The access to neutron-rich nuclides is more severely limited than in the case of the hot fusion reactions because of the possible choices of target-projectile pairs. Isotopes of elements 107-109 have been produced by this method at production rates of an atom per day to an atom per week. As the production rates decrease further for the heavier elements, new technologies must become available for the detection of elements beyond 110 or 111.

Production by "Warm Fusion"

Very recently, there have been attempts to produce heavy element nuclei by the warm fusion technique,[34] which is intermediate between the cold fusion and hot fusion techniques. In the warm fusion technique, light actinide targets are used with projectiles in the range of Ar to Ca. There are target-projectile combinations which will reach moderately neutron-rich products. The excitation energy of the compound nuclei is as low as about 25 MeV, assuring a good de-excitation survival rate, but the compound nucleus formation rate is intermediate between that for the hot fusion and cold fusion methods.

Production by Binary Transfer Reactions

Binary transfer reactions have been used to produce a number of heavy element isotopes. In this mechanism, the projectile

nucleus comes into contact with the target nucleus for a small time during which the two nuclei exchange nucleons, energy, and angular momentum. The products resulting immediately after the target- and projectile-like particles separate after interacting can have broad ranges of proton- and neutron-numbers, excitation energy and angular momentum. These broad product distributions allows the production of exotic heavy element nuclei at low excitation energy. This type of reaction has been used, for example, in the production of 32-d ^{260}Md and 4.5-h ^{262}Lr from transfer reactions between ^{22}Ne projectiles and ^{254}Es targets.[8,35]

Neutron Irradiations

Neutron irradiations have been used for the production of many transuranium isotopes.[2,3] In these neutron irradiations, heavier elements are produced by a series of neutron captures and beta decays on actinide target material. Weighable quantities of elements with atomic number as high as 99 have been produced from material which was originally ^{238}U. Picogram quantities of ^{257}Fm are also produced. The series of neutron-captures and beta-decays leading to the production of heavy actinides, beginning with ^{239}Pu, is illustrated in figure 3. The yearly production of some key isotopes is also indicated in figure 3. There are two main limitations for this production technique. First, a neutron capture reaction in the actinide region results in a product nucleus with an excitation energy of about 6 MeV which may undergo before it can de-excite. This limits the yields of the

heavy elements. Second, many transuranium isotopes cannot be produced because there is no series of neutron-captures and beta-decays which end up at these isotopes. It seems unlikely that the production of heavier isotopes in reactors will become possible, because the heavier Fm isotopes which would be produced by neutron capture on ^{257}Fm are short-lived fission activities, and, therefore, would not beta-decay to mendelevium.

New Target Material Capabilities

The production of heavy element isotopes by the cold-, warm-, and hot- fusion methods and by transfer reactions could be greatly enhanced by the introduction of new, more exotic target materials. There are many nuclides which, in the future, may become available in the milligram quantities necessary for use as targets which would allow access to measurable amounts of new heavy element nuclides by nuclear reactions at particle accelerators. Also, remote handling techniques will become available which will allow the use of many isotopes, which are presently available, but are too radioactive for routine use as target materials.

Reactor Actinide Production

The production of target materials for hot-fusion reactions or transfer reactions has, to a large extent been performed by reactor irradiations. The limit on the amount of material of a given isotope which can be produced is limited by the amount of

material which can be irradiated in the reactor. At the Oak Ridge National Laboratory's High Flux Isotope Reactor, the material which is irradiated to produce $^{253-255}Es$ and ^{257}Fm consists of about 2 grams of ^{252}Cf which is irradiated for many days. The loss of yield due to fission during the various neutron capture steps limits the production of these isotopes. The yearly output for ^{254}Es is 5μg and for ^{257}Fm it is 1 pg. New techniques which involve the removal of thermal neutrons with a cadmium filter should allow the production of these isotopes in a yield which is about ten times larger.[36] It should become physically (but possibly not economically) possible to produce, irradiate, and recover heavy actinides from much larger amounts of ^{252}Cf. In 50 years it should be possible to use as much as 2 kg of ^{252}Cf in a specially designed (and much larger) reactor. Vastly improved remote handling and reprocessing techniques will be developed for the recovery of the heavy element isotopes. It should be noted that the production of the 2 kg of ^{252}Cf is another multifaceted technological problem which must be overcome. The next few paragraphs will describe some of the possibilities for heavy element research using amounts of target materials which would become available in yields which are 1000 times what they are today.

^{254}Cf will be produced in quantities as large as hundreds of micrograms. Use of this as a target would allow access to very neutron-rich heavy element isotopes which will be stable toward electron-capture decay. These isotopes will also have relatively long alpha decay half-lives, and it is expected that their

spontaneous fission half-lives may also be significantly longer than those of the more neutron-deficient isotopes. Compound nucleus reactions could lead to several interesting isotopes. ^{271}108 and ^{271}108 could be produced by the (^{22}Ne,5n) and (^{22}Ne,4n) reactions. These isotopes should have half-lives much longer than those for the known 108 isotopes, and the measurements of the spontaneous fission properties and ground-state shell effects should be interesting. ^{267}106 could be produced by the (^{18}O,5n) and (^{17}O,4n) reactions. This isotope should be quite long-lived and should allow detailed studies of the chemical properties of element 106. The same can be said for ^{263}Rf produced by the ^{254}Cf(^{13}C,4n) reaction. The use of transfer reactions with neutron-rich projectiles and a ^{254}Cf target could produce the special isotope ^{264}Fm, whose spontaneous fission properties should be very interesting because it can fission into two doubly magic ^{132}Sn nuclei.

Reactor irradiations will also produce larger quantities of other actinide isotopes. Many of them would make other experiments, similar to those outlined in the preceding paragraph, possible. It will be possible to produce milligram quantities of ^{254}Es which will allow the programs outlined in the Large Einsteinium Activation Program[36] (LEAP) proposal to be carried out with even more sensitivity than described there. More interestingly, quantities of hundreds of micrograms of ^{255}Es will become available, giving access to even more neutron-rich actinides and transactinides than are obtainable with a ^{254}Es target. It may also be possible to produce a target of 1 ng of ^{257}Fm. While this is a small amount of target material, it will still be

possible to perform new physics with such a target.

Production with a Monoenergetic Neutron Source

When producing the heavy actinides in a reactor, there are severe losses due to neutron-capture followed by de-excitation by fission, (n,f), reactions in competition with the desired de-excitation by gamma-ray emission, (n,gamma). These losses could be decreased dramatically when a high intensity monoenergetic neutron source, with adjustable neutron energy is made. With such a neutron source, the neutron energy for bombardment of a given actinide target could be adjusted to a (n,gamma) resonance to produce the desired activity with very little competition from fission. This procedure could be repeated several times (on each of the intermediate products). The production of milligram quantities of ^{257}Fm may be possible by this method.

Production in Nuclear Explosions

The production of heavy actinides in the detonation of nuclear devices has been shown to be a viable process for the production of relatively large amounts of exotic target materials. Lougheed et al. were able to separate $3x10^{12}$ atoms of ^{250}Cm from 10 kg of rock from the site of an underground detonation of a nuclear device.[37]

If a nuclear device were specifically designed for the production of heavy elements, the yield of these heavy elements

can be quite high. Assuming the amount of debris which contains a high heavy element concentration is several orders of magnitude larger than the 10 kg used in the previous study, it may be possible to recover weighable quantities of ^{250}Cm. The heavy actinides would presumably be recovered from the debris in a dedicated reprocessing plant. This target material would be especially valuable for the production of neutron-rich actinide isotopes of the elements from uranium through 106. It should also be possible to study the beta-delayed fission of the neutron-rich Bk, Am, and Np isotopes. This production method may also be the best for the production of ^{254}Cf. It should also be possible to produce miligram quantities of ^{257}Fm.[38]

Production in Light Ion Bombardments

Within the next fifty years, it will become possible to have high intensity light ion accelerators dedicated to the production of heavy element target materials. For example, microgram quantities of ^{230}U could be produced in a 10^6-s irradiation of a molten 1 g/cm^2 ^{232}Th target with a 250-mA proton beam. This could be used as a target material for the production of very neutron deficient actinides in secondary bombardments. Similarly, microgram quantities of ^{236}Pu and ^{235}Np could be produced in $^{235}U(d,n)$ and $^{235}U(d,2n)$ reactions, respectively. More of these nuclides could be produced, because their longer half-lives allow longer times for their production. These neutron-deficient target materials will be used for the study of

even more neutron-deficient electron-capture-delayed-fission activities, and in studies of nuclear properties of the actinide elements out toward the proton-drip-line.

The production of even more exotic target materials is also possible if some of the nuclides which are considered extremely exotic by todays standards are used as a target material. For example, It may be possible to produce weighable quantities of the 58-d ^{258}Md. A target of ^{255}Es (produced, presumably, by the methods mentioned earlier) could be bombarded with a high intensity alpha beam to produce the ^{258}Md by the (alpha,n) reaction. A ^{258}Md target would be an incredible asset in the study of the chemical and nuclear properties of the heaviest elements, which could be produced by hot fusion reactions and by binary transfer reactions.

The Use of Other Short-Lived Nuclides

It will also become possible to safely use several short-lived nuclides as target materials. For example, ^{210}Pb , which can be separated from uranium (which had been separated from lead some years before) could be used as a new neutron-rich target material for cold-fusion reactions. ^{228}Ra, which can be separated from ^{232}Th, could be used as a target material for warm-fusion reactions, to reach new neutron-rich isotopes.

New Accelerator and Beam Capabilities

Accelerator technology will surely continue to advance. It is difficult to predict to what point these advances will lead in fifty years, but the new accelerator ideas presently being conceived present interesting possibilities for future transuranium research, especially when combined with the future capabilities in target materials discussed above.

Higher Beam Intensities

Improvements in accelerator technology will significantly increase the beam intensities available for production of heavy element isotopes. Accelerator ion sources and pre-accelerators will become much more efficient at producing large intensities of highly charged beams for acceleration. The beams available from these sources will be sufficient to exceed the phase space limitation of present-day accelerators, so newer accelerators will have to be designed with increased capabilities. These accelerators will have to be equipped with elaborate control systems, because the high beam intensities will be capable of melting any accelerator or beamline parts on which the beam is inadvertently focussed. It will probably also be necessary to perform almost all maintenance on the accelerator remotely, because of the increased levels of induced activities in the accelerator parts. Beam intensities of tens to hundreds of particle microamperes of elements from all parts of the periodic table can be expected.

New types of accelerators will be introduced which will decrease the difficulty of running the accelerators reliably, an example of such a new accelerator technology which may be developed to the point of being practical is the Ion Front Accelerator,[40] which accelerates positively charged ions in a moving electric potential well created by an electron beam pulse.

Target and Beam Handling Capabilities

These higher beam intensities present severe problems for the experiments. The increased beam intensities bring with them an increased amount of heat created in the target materials as the beam passes through. The heat from the beams of the intensities discussed above are sufficient to melt or vaporize almost any target which they pass through.

The thicknesses of targets used for these accelerator bombardments are limited by the energy loss of the beam as it passes through the target material. This limit is imposed in two ways. First, the useful energy of the beam in the target is determined by the excitation function of the product of interest. In other words, since there is usually a narrow energy range at which the desired nuclear reaction will occur at a reasonable rate, the total effective thickness of target material cannot be more than that which is sufficient to degrade the beam energy completely through this effective energy range. The second, and more severe limitation is that of the heat created in the target as the beam looses energy in passing through the target.

The use of very thin metallic targets will be developed. By using a series of targets with thicknesses of only a few $\mu g/cm^2$, the total target thickness can be kept relatively large (near the useful range of energies due to the energy loss of the beam as it passes through the targets). The beam's heat loss in any one of the targets will be quite small, because of its small thickness. This can be sufficiently small to allow gas cooling or cooling by blackbody emission of the heat.

Molten and gas-phase targets will also be developed to an extent which will make them more versatile than they are at present.[41] These will be capable of running at very high temperatures, allowing the efficient removal of the heat.

Radioactive Nuclear Beams (RNBs)

A particularly interesting development which will greatly enhance our capabilities to produce exotic transuranium nuclides will be the availability of Radioactive Nuclear Beams (RNB). A first-generation RNB machine, as presently conceived,[42] would consist of a high intensity proton accelerator which would bombard a molten target. Large amounts of some radioactive isotopes would be produced by spallation reactions. One isotope of these radioactive products could be extracted from the molten target, mass separated, and accelerated to Coulomb-barrier energies (or even higher) in a secondary accelerator. By this method, relatively high intensities of beams of ions which are more neutron-rich or neutron-deficient than presently available beams could be provided. The neutron-rich beams would be useful for the produc-

tion of new neutron-rich isotopes of the heavy elements by compound-nucleus reactions or by binary transfer reactions. The neutron-deficient beams could be used in compound nucleus reactions for the production of heavy element isotopes approaching the proton-drip line. The first machines would be capable of producing RNB's with intensities of a few particle nanoamperes. Future machines are expected to have much higher beam intensities.

A good example of the types of experiments which will be possible with these RNB's is a search for superheavy elements near Z=114 and N=184. If the ^{250}Cm target discussed above were available, it could be bombarded by a beam of ^{50}Ca, yielding a compound nucleus with 116 protons and 184 neutrons, very near the predicted most stable superheavy element isotopes.

Second generation RNB machines are also possible. For example, it may become possible to produce and use a radioactive target material as the molten target in the first stage of the RNB machine. If ^{44}Ti were available (produced in light ion bombardments) and used as the first stage target material, it would be possible to produce and accelerate a beam of ^{42}Ti. When combined with neutron-deficient target materials (such as ^{202}Pb, also produced in light ion bombardments), extremely neutron-deficient nuclides will be accessible. In this case, extremely neutron-deficient isotopes of element 104 would be produced, whose fission properties should prove to be very interesting.

Using the most neutron-rich RNBs in transfer reactions with neutron-rich targets (or in colliding RNB experiments), will make the production of extremely neutron-rich nuclides possible. The

nuclides available for study will be much nearer to the neutron-drip-line, making direct studies of the decay properties of important r-process nuclides possible. With neutron-deficient RNBs, the production of extremely neutron-deficient nuclides is possible. It should be possible to study the decay properties of nuclides all the way out to near the proton-drip-line. In the transuranium region, this would make possible, in theory, to produce about 400 new nuclides with half-lives long enough to measure.

New Tools for the Study of the Man Made Elements

Limitations on the Study of the Man Made-Elements

Production Rates Are Small

The study of the chemical and physical properties of the man-made elements is particularly difficult. As stated in the section on the production of the transuranium elements, the production rates of transuranium nuclei can be extremely low. These low production rates often leave the experimenters with the task of detecting the presence of single atoms of the desired products by their radioactive decay.

Detection of Small Numbers of Atoms

At present, the best method for the detection of a small number of atoms is that of the detection of the radiations from the decay of radioactive isotopes. These radiations are generally emitted with a half-life and energy which are characteristic of the decaying isotope. Some types of radioactive decay, such as alpha-particle emission, allow the identification of a nuclear species by the detection of the decay of a single atom. The discrete nature of the alpha particle energy spectrum from any given isotope, along with its half-life, can provide a fairly unique identification of the presence of that isotope. In the special case where the daughter nucleus resulting from an alpha decay is also unstable with respect to emission of an alpha

particle, the detection of both parent and daughter alpha particles, and the lifetimes of the parent and daughter, provides a more unambiguous identification.[29,43,44] The detection of gamma rays of a given energy can also provide good identification. There are other problems associated with identification by a small number of gamma-rays, such as the relatively low efficiency for many gamma-ray detectors and the unavoidable background in gamma-ray energy spectra. Identification by the emission of beta particles and by spontaneous fission are difficult because of the non-discrete nature of the beta-particle and fission fragment mass and energy distributions.

Interfering Activities

The identification of the existence of a nuclide by the detection of the radiations from the decay of a small number of atoms is often limited by the presence of interfering activities from other nuclides which are present in much higher yields. These interfering activities may be produced by Prompt fission of excited products of nuclear reactions, or by transfer reactions with the various materials in and around the target. Almost any nuclear reaction used to produce the heavy elements produces, simultaneously, vastly greater numbers of unwanted activities, so that separation from these interfering activities is necessary for an unambiguous identification. These separations cam be made by physical methods, such as mass separation, or by the use of chemical separations. The use of chemical separations on a small number of atoms presents a separate set of constraints which may

not apply to chemical procedures used for larger amounts of material.[45]

Future Techniques for the Study of Nuclear Properties

Large Gamma-Ray Detector Arrays

The development of large gamma-ray detector arrays will develop far beyond that envisioned today in the proposed GAMMA-SPHERE.[46] Arrays will be built in which the high resolution detectors cover all of the space around a target (or source) area. All of the individual elements will be very small with very little inactive material. In this way, almost all gamma-rays would register full energy in the detector array: if a gamma-ray is scattered out of one crystal, the residual energy will be detected in an adjacent crystal.

With such an array, and the data processing power that must come with it, it would be possible to construct detailed level schemes from the observation of the decay of a relatively small number of atoms. With this detector array in conjunction with charged particle detectors, the level structures fed in the decay of the heavy elements could be efficiently explored. This would also be an ideal detector for the identification of electron-capture and beta-decay activities based on single events. It would also make some very difficult spectroscopy relatively easy, such as the study of the level structure inside the second potential wells of fission shape isomers. It may also be possible to

identify the Z and A of a single fissioning nucleus by measuring the prompt gamma-rays and x-rays emitted by the fission products as they de-excite. It could also be used as a calorimeter, to accurately determine the Q value associated with a decay on the basis of a small number of events.

Alpha and Fission Spectrometry

Improvements will be made in the detection of alpha particles and fission fragments. The efficiencies and resolutions of devices for detecting these radiatins will improve greatly.

It may become possible to identify a fissioning species by identifying the Z and A of both of the fission fragments. Some gas filled detector modules are presently being developed which will significantly improve the Z and A resolution obtainable in the detection of fission fragments.[36,47,48] Another possibility would be the use of a multilayered silicon charged particle detector as a Bragg curve spectrometer. In such a device, several energy-sensitive layers, each a few μm thick would be produced on the top of a silicon chip. Each layer would have a well defined thickness and the energy signal from each layer would be processed separately. This device would allow the determination of the total energy, the range, and the energy loss as a function of the distance traveled through the silicon.

Improvements will be made in the efficiency and resolution of alpha-particle detectors. Presently, the detection of charged particles in solid-state detectors is limited by the solid angle

the detector subtends relative to the source. By deeply implanting the atom to be studied into the detector, the alpha particles can be measured with a 100% efficiency. The appropriate high efficiency implantation techniques will be developed. Advances will also be made in the field of liquid scintillation for alpha and fission spectroscopy. Systems will be developed in which the resolution rivals that of present-day solid-state detectors. Techniques will be developed for the detection of alpha particles and fission fragments with extremely high energy resolution. An example of such a charged particle detector which may have this capability is the super-cooled bolometer[49] which measures alpha particle energy by the temperature increase in a supercooled crystal. If these devices were operated at very near $0^{o}K$, the energy resolution could be better than 1 keV.

Mass separators, Velocity Filters, etc.

The machines and techniques used for physical separations of heavy element products will improve. Recoil spectrometers will be built with the capabilities of separating products in a narrow range of Z, A, and recoil energy. These products will then be available for further physical analysis, such as a high resolution mass spectrometer, or sent to a low-background counting area. The recoil spectrometers will have very high angular and energy acceptance, making it possible to use them with the broad angular and recoil energy distributions typical of the binary transfer reaction mechanism. The separation time in such a spectrometer is on the order of a few microseconds, allowing the

detection and study of extremely short-lived heavy element activities.

High resolution mass spectrometers will be developed which can be used with amounts of source material as small as a single atom. One such machine could consist of an accelerator storage ring, where the time of flight could be measured over several well defined orbits. The mass resolution on such a machine would be sufficient for accurate determination of the mass defects, allowing the determination of the nuclear binding energy by this physical technique, alone. With this high resolution, the mass separator would be capable of Z separation as well as mass separation.

Future Techniques for the Study of Chemical Properties

The study of the chemical properties of the man-made elements is important because man made elments comprise 16% of the elements for which the chemical properties have been studied. This fraction can only increase, as the number of man-made elements for which the chemical properties have been studied increases. Without the man-made elements, important periodic table structures, such as that of the actinide series may remain undiscovered. The study of how the relativistic motions of the electrons about the heaviest elements affects the chemical properties of these elements is a way of studying relativity in a test tube.

Study of Macroscopic Chemical Properties

It will become possible to study the macroscopic (or bulk) properties of Fm and Md, which at present can only be produced in picogram quantities or less. By making use of the techniques mentioned in the preceeding section, larger quantities of these elements will be produced. With microgram quantities, It will be possible to produce crystals of the elements to study their crystal structure, metallic properties and spectroscopic properties. It should also become possible to study these bulk properties in microcrystals containing just a few hundred atoms. This should make the study of the macroscopic properties of Lr possible by making use of microcrystals of 4-h ^{262}Lr. ^{265}Rf, and ^{266}Ha are presently undiscovered isotopes whose half-lives should be long enough to make this type of study possible with elements 104 and 105.

Study of Tracer Scale Chemical Properties

In most cases, the study of the chemical properties of the heaviest elements involves determining the chemical behavior of a small number of atoms. The fact that only a small number of atoms are produced precludes the study of the bulk properties, because the interaction of these heavy element atoms with like atoms is extremely unlikely. Chemical procedures which are applicable to small numbers of atoms, or even single atoms must be chosen. One of the main problems in the study of the chemical properties of the transuranium elements comes about because of

the short half-lives of many of the isotopes, especially those of with the highest Z. The chemical procedures used must be fast enough so that all of the atoms of interest are not lost due to decay during the chemical separations.

Computer Controlled Chemical Separations

There is presently much progress being made in the field of performing rapid chemical separations with the aid of computer controlled separations devices. The computer control, along with increasing the speed of the separations, also increases their reliability and reproducibility. There are several computer-controlled liquid chromatography systems[50,51,52] and some automated extraction devices.[53,54] The miniaturization of these devices allows the volumes of liquids being used to be small and the speed of the separations to increase. In work with the transuranium elements, minimization of the volumes is extremely important, because the detection of the presence of a small number of short-lived atoms is usually accomplished by alpha particle spectroscopy. In order to produce a source suitable for alpha particle spectroscopy, it is usually necessary to evaporate a final liquid fraction. With larger volumes, this can be a time-consuming step.

Presently, computer controlled chromatographic separations are possible on a one-minute time-scale, allowing the study of the chemical properties of 34-s ^{262}Ha. Automated extractions are possible on a one-second time scale[54] which will allow chemical studies of element 106, making use of the 0.9-s isotope with mass

number 263. Further improvements and miniaturizations in the next fifty years should allow the processes to become faster, possibly to the point where the separations are limited by reaction kinetics.

High Temperature Separations

When the separation times reach limitations imposed by reaction kinetics, it will become necessary to increase the speed at which the reactions proceed. This can most easily be accomplished by performing the separations at high temperatures. In fifty years, with liquid phase chemical separations being performed on millisecond time scales, it may be necessary to use temperatures as high as several hundred ^{o}C to increase the reaction speeds.

Source Preparation

As was mentioned above, the preparation of sources for alpha -particle spectroscopy can be a time consuming process, making the detection of the radiations from the many short-lived activities in the heaviest elements impossible. New techniques will be developed for faster source preparation. These may include fast electroplating techniques, or flash evaporation techniques to produce sources suitable for use with standard semiconductor charged-particle detectors. High resolution liquid scintillation techniques may be developed, eliminating the need for the evaporation of the final fraction. It may also become possible to suspend the activities of interest in a gas phase and use a gas

ionization chamber for the detection of alpha and fission activities. Methods are being developed for performing alpha particle spectroscopy with a semiconductor detector through a thin film of liquid,[55] eliminating the need for source preparation by evaporation of electroplating.

Gas Phase Separations

Gas-phase chemical separation techniques used for the study of the chemical properties of the short-lived transuranium elements are still in their infancy. The simplest of thermochromatographic and isothermochromatographic separations have been performed.[13,18,56-58] These are single step separations in which the volatility of the elements of compounds of the elements are measured. These gas-phase separation techniques can be expected to improve vastly over the next 50 years. It will be possible to perform many-step separations, resulting in samples which have a much higher degree of chemical purity. The theoretical understanding of these gas phase thermochemical processes will be improved, allowing more accuate prediction and interpretation of thermochromatographic properties. There will also be non-thermochromatographic gas-phase separations methods. The speed of these gas phase separations can be much greater than that for aqueous phase separations, especially at high temperatures, and the production of sources suitable for the detection of α and SF activities is greatly simplified. It should be possible to perform some gas phase separations on a millisecond time scale.

Stern Gerlach Experiments on Single Atoms

An interesting proposal has been put forth by Hulet et al.[59] in which the ground state electronic configuration of single atoms of the heaviest elements could be determined by a Stern-Gerlach type of experiment. This would be accomplished by forming a well collimated "molecular beam" of these atoms by allowing the gas mixture in a recoil chamber to expand into a vacuum through an orifice. This beam (consisting of single atoms or molecules of the element to be studied) would then be passed through an inhomogeneous magnetic field, allowing the separation of the different projections of the electronic angular momentum. This technique will be developed and become commonplace, allowing the determination of the electronic configurations of the heaviest elements

Laser Spectroscopy on Single Atoms in Ion Traps

It should become possible, to perform spectroscopic studies at infrared through x-ray frequencies on single atoms of the short-lived transuranium elements. This could be accomplished by holding the newly produced atoms in an electromagnetic ion trap, and exciting electronic transitions with a powerful laser. With a detector of sufficient selectivity and sensitivity, the photons emitted in the deexcitation of these excited electronic states could be observed.

Exact Calculations of Electronic Configurations

The increase in computing power expected in the next 50 years, along with improvements in methods for the exact calculations of self-consistent solutions of many-body problems, may make it possible to perform exact calculations of the electronic configurations of the elements. Taking this one step further, it will then be possible to model the behavior of molecules and the interactions between molecules. In the final extreme, it would be possible to model the behavior of the large number of molecules necessary for a treatment of, for example, aqueous solution chemistry.

Conclusions

Some of what are presently our "wildest dreams" are contained in the preceeding pages. In the next fifty years, the field of the study of the man-made elements will surely exceed some of these wildest dreams, or proceed in new directions not envisioned here.

We have the potential to discover at least six new elements and at least 400 new nuclides. We will be able to produce nuclides which can not be produced presently in quantities sufficient for their study by reaction methods that are unavaialble to us today. Those nuclides which can presently be produced will be available in quantities (or at production rates) orders of magnitude greater than are available today. The study of the nuclear properties of these nuclides will increase our understanding of the nuclear shell structure responsible for the stability of these elements. The fission of heavy elements, which determines the ultimate limits to nuclear stability, may finally be understood in detail. The determination of the tracer scale chemical properties of all of these elements may be possible (especially for the odd-Z elements which will be more stable toward fission and alpha-decay). We will study the bulk properties of the elements through at least Lr. The determination of the chemical properties of these heaviest elements will define the structure of the upper end of the periodic table and the study of relativistic effects in chemical properties will cause us to re-evaluate the chemical properties of the lighter elements in the light of these relativistic effects.

One subject which has not been thoroughly addressed is that of the possible applications of this heavy element research in ways which can have a direct impact on our lives. Advances in these technologies will accompany the advances mentioned in this work. Improvements in things such as todays imaging devices (for both medical and industrial uses) which use radiations emitted from man-made elements will be made. The use of radioactive species for medical diagnosis and treatment will become possible with even smaller overall radiation doses and with sources in chemical forms which are specifically targeted for the organ(s) to be diagnosed or treated. As always, the technologies developed for basic scientific studies will be adaptable for other practical applications which may have little to do with the study or use of the man-made elements.

As a final thought, we would like to present a scenario for a future experiment, which by todays standards, may be considered an ultimate man-made element experiment (of course, in fifty years, our conception of the "ultimate experiment" will surely shift further toward what is unimaginable today). This would be an experiment to produce and study the chemical and nuclear properties of the superheavy elements with atomic numbers near 114 and neutron numbers near 184. The reaction used in this example is the bombardment of a ^{250}Cm target with a ^{52}Ca beam. The even-even nucleus ^{300}116, with a closed shell at N=184 would be produced by the ^{250}Cm(^{52}Ca,2n) reaction. Possibly more importantly, the ^{250}Cm(^{52}Ca,α2n) reaction would produce ^{297}114. Z=114 has been predicted to be especially stable against spontaneous

fission. The neutron number 183 is very near the closed shell at N=184, and the odd neutron number will lend some additional stability against spontaneous fission and alpha-particle decay.

In this experiment, a high intensity radioactive nuclear beam of ^{52}Ca would be produced by proton spallation of ^{60}Fe, or other heavier targets. The 10^5-year ^{60}Fe would, itself, have been produced in a dedicated nuclear reactor by multiple neutron capture on lighter iron isotopes. This ^{52}Ca would then be accelerated to coulomb barrier energies by a secondary accelerator, and used to bombard a series of very thin secondary targets of ^{250}Cm. The ^{250}Cm would have been produced in underground nuclear explosions, and separated from many tons of rock in a dedicated chemical processing plant. The superheavy element products recoiling from the targets would be analyzed by a mass separation technique, which has sufficient resolution to separate different elements among the same mass chain by utilization of their different mass defects. These mass and Z separated atoms would then be subjected to rapid chemical separations procedures, and finally the nuclear properties would be studied by observing the decay of these elements with 100% efficient particle and photon detection systems. A schematic of all involved in this experiment is presented in figre 4. Of course, the economic feasibility of such an experiment is not addressed here.

ACKNOWLEDGMENT

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

REFERENCES

1) G.T. Seaborg, *Encyclopedia of Chemical Technology*, Vol. 1, 3rd ed., p. 456, John Wiley & Sons, Inc., New York, (1978).

2) O.L. Keller, D.C. Hoffman, R.A. Penneman, G.R. Choppin, Physics Today, March 1984, 35 (1984).

3) D.C. Hoffman, Nucl. Instr. Meth. *A249*, 13 (1986).

4) D.C. Hoffman, L.P. Somerville, Lawrence Berkeley Lab. Rept. LBL-23475, (1987), also published as a chapter in *Charged Particle Emission from Nuclei*, Vol. III, pg. 1, CRC Press, Inc., Boca Raton, FL.

5) G.T. Seaborg, J. Nucl. Materials *166*, 22 (1989).

6) P. Möller, W.D. Meyers, W.J. Swiatecki, J. Treiner,

7) P. Möller, G.A. Leander, J.R. Nix, Z. Phys. *A323*, 41 (1986).

8) E.K. Hulet, J.F. Wild, R.J. Dougan, R.W. Lougheed, J.H. Landrum, A.D. Dougan, M. Schädel, R.L. Hahn, P.A. Baisden, C.M. Henderson, R.J. Dupzyk, K. Sümmerer, G.R. Bethune, Phys. Rev. Lett. *56*, 313 (1986).

9) P. Möller, J.R. Nix, W.J. Swiatecki, Los Alamos Nat. Lab. Rept. LA-UR-86-3182 (1986).

10) O.L. Keller, G.T. Seaborg, Ann. Rev. Nucl. Sci. *27*, 139 (1977).

11) E.K. Hulet, Radiochim. Acta *32*, 7 (1983).

12) O.L. Keller, Radiochim. Acta *37*, 169 (1984).

13) I. Zvara, Yu.T. Chuburkov, R. Tsaletka, M.R. Shalaevskii, Sov. Radiochem. *11*, 161 (1969).

14) R.J. Silva, J. Harris, M. Nurmia, K. Eskola, A. Ghiorso, J. Inorg. Nucl. Chem. *6*, 871 (1970).

15) I. Zvara, V. Z. Belov, V. P. Domanov, M. R. Shalaevskii, Sov. Radiochem. *18*, 328 (1970).

16) E.K. Hulet, R.W. Lougheed, J.F. Wild, J.H. Landrum, J.M. Nitschke, A. Ghiorso, J. Inorg. Nucl. Chem. *42*, 79 (1980).

17) K.E. Gregorich, R.A. Henderson, D.M. Lee, M.J. Nurmia, R.M. Chasteler, H.L. Hall, D.A. Bennett, C.M. Gannett, R.A. Chadwick, J.D. Leyba, D.C. Hoffman, G. Herrmann, Radiochim. Acta *43*, 223 (1988).

18) B.L. Zhuikov, Yu.T. Chuburkov, S.N. Timokhin, Kim U Jin, I. Zvara, Radiochim. Acta *46*, 113 (1989).

19) J.V. Kratz, H.P. Zimmermann, U.W. Scherrer, M. Schädel, W. Brüchle, K.E. Gregorich, C.M. Gannett, H.L. Hall, R.A. Henderson, D.M. Lee, J.D. Leyba, M.J. Leyba, D.C. Hoffman, H. Gäggeler, D. Jost, U. Baltensperger, Ya Nai-Qi, A. Türler, Ch. Lienert, GSI Rept. GSI-89-37 (1989) (in press, Radiochim. Acta).

20) K.S. Pitzer, Acc. Chem. Res. *12*, 271 (1979).

21) P.A. Christiansen, W.C. Ermler, K.S. Pitzer, Ann. Rev. Phys. Chem. *36*, 407 (1985).

22) P. Pyykkö, J.P. Desclaux, Acc. Chem. Res. *12*, 276 (1979).

23) P. Pyykkö, Chem. Rev. *88*, 563 (1988).

24) G.T. Seaborg, W. Loveland, Contemp. Phys. *28*, 33 (1987).

25) P. Armbruster, Y.K. Agarwal, W. Brüchle, J.P. Dufour, H. Gäggeler, F.P. Hessberger, S. Hofmann, P. Lemmertz, G. Münzenberg, K. Poppenseiker, W. Reisdorf, M. Schädel, K.-H. Schmidt, J.H.R. Schneider, W.F.W. Schneider, K. Sümmerer, D. Vermeulen, G. Wirth, A. Ghiorso, K.E. Gergorich, D. Lee, M. Leino, K.J. Moody, G.T. Seaborg, R.B. Welch, P. Wilmarth, S. Yashita, C. Frink, N. Greulich, G. Herrmann, U. Hickmann, N. Hildenbrand, J.V. Kratz, n. Trautmann, M.M. Fowler, D.C. Hoffman, W.R. Daniels, H.R. von Gunten, H. Dornhöfer, Phys Rev. Lett. *54*, 406 (1985).

26) R.W. Lougheed, J.H. LAndrum, E.K.Hulet, J.F. Wild, R.J. Dougan, H. Gäggeler, M. Schädel, K.J. Moody, K.E. Gregorich, G.T. Seaborg, Phys. Rev. C, *32*, 1760 (1985).

27) Alonso, Gmelin Handbuch der Anoranischen Chemie Verlag Chemie, GmbH Weinheim/Bergstrasse) Band 7b Part A1 p.28 (1973).

28) T. Sikkeland, A. Ghiorso, M. Nurmia, Phys. Rev. *172*, 1232 (1968).

29) A. Ghiorso, J.M. Nitschke, J.R. Alonso, M. Nurmia, G.T. Seaborg, E.K. Hulet, R.W. Lougheed, Phys. Rev. Lett. *33*, 1490 (1974).

30) P. Armbruster,Ann. Rev. Nucl. Part. Sci *35*, 135 (1985).

31) Yu.Ts. Oganessian, M. Hussonnois, A.G. Demin, Yu.P. Kharitonov, H. Bruchertseifer, O. Constantinescu, Yu.S. Korotkin, S.P. Tretyakova, V.K. Utyonkov, I.V. Shirokovsky, J. Estevez, Paper presented at the International Conference on Nuclear and Radiochemistry, Lindau, October 8-12, 1984.

32) M. Schädel, GSI Scientific Rept. 1988, p. 19, GSI-89-1, ISSN 0714-0814, March, 1989.

33) W. Reisdorf, GSI Scientific Rept. 1988, p. 20, GSI-89-1, ISSN 0714-0814, March, 1989.

34) Yu.Ts. Oganessian, Yu.V. Lobanov, M. Hussonnois, Yu.P Kharitonov, B. Gorski, O. Constantinescu, A.G. Popeko, H. Bruchertseifer, R.N. Sagaidak, S.P. Tretyakova, G.V.Buklanov, A.V. Rykhlyuk, G.G. Gulbekyan, A.A. Pleve, G.N. Ivanov, V.M. Plotko, Paper presented at the International School on Physics "Enrico Fermi", Varenna, Italy, June 23-July 3, 1987, (JINR Rept. D7-87-392) (1987).

35) R.W. Lougheed, K.J. Moody, R.J. Dougan, J.F. Wild, E.K. Hulet, R.J. Dupzyk, C.M. Henderson, C.M. Gannett, R.A. Henderson, D.C. Hoffman, D.M. Lee, K. Sümmerer, R.L. Hahn, Nucl. Chem. Div. FY87 Annual Rept., Lawrence Livermore National Lab., UCAR 10062/87, p. 2 (1987).

36) A. Ghiorso, D.C. Hoffman, E.K. Hulet, O.L. Keller, G.T. Seaborg, *LEAP (Large Einsteinium Accelerator Program) A Proposal to Investigate the Inorganic and Nuclear Chemistry of Elements in the Transfermium Region Including a Search for Superheavy Elements*, Lawrence Berkeley Laboratory Publication No. Pub-5118, (1984).

37) D.C. Hoffman, Proc. of the Lysekil Symp. on Nuclides Far Off the Stability Line, Arkiv För Fysik, Band 36 nr 61, 533 (1967).

38) R.W. Hoff, Proc. of Symp. Commemorating the 25th Anniversary of Elements 99 and 100, Lawrence Berkeley Lab., Jan. 1978, Lawrence Berkeley Lab. Rept. LBL-7701, pg. 39 (1979).

39) R.W. Lougheed, J.F. Wild, E.K. Hulet, R.W. Hoff, J.H. Landrum, J. Inorg. Nucl. Chem. *40*, 1865 (1978).

40) C.L. Olson, *Collective Ion Acceleration Springer Tracts in Modern Physics*, Springer-Verlag, Heidelberg (1979).

41) H.L. Ravn, L.C. Carraz, J. Denimal, E. Kugler, M. Skarestad, S. Sundell, L. Westgaard, Nucl. Instr. Meth. A *139*, 267 (1976).

42) Radioactive Nuclear Beams Machine has been discussed at length at several meetings in 1989 preliminary to the Nuclear Science Advisory Committee's formation of a Long Range Plan.

43) G. Münzenberg, P. Armbruster, F.P. Heβberger, S. Hoffman, K. Poppensieker, W. Reisdorf, J.H.R. Schneider, W.F.W. Schneider, K.-H. Schmidt, C.-C. Sahm, D. Vermeulen, Z. Phys. A *309*, 89 (1982).

44) G. Münzenberg, S. Hoffman, F.P. Heßberger, W. Reisdorf, K.H. Schmidt, J.H.R. Schneider, P. Armbuster, C.C. Sahm, B. Thuma, Z. Phys. A *300*, 107 (1981).

45) R. Guillammont, J.P. Aldorf, A. Peneloux, Radiochim. Acta *46*, 169 (1989).

46) M.-A. Delaplanque, R. M. Diamond, *GAMMASPHERE - A proposal for a National Gamma Ray Facility*, Lawrence Berkeley Publication No. PUB-5202 (1988).

47) J.B. Wilhelmy, Los Alamos Nat. Lab. Rept., LA-UR-85-2937 (1985).

48) J.G. Boissevain, M.M. Fowler, A.I. Gavron, D.C. Hoffman, P. Lysaght, J.B. Wilhelmy, Los Alamos National Lab. Rept., LA-10366-PR, pg. 147 (1985).

49) N. Coron, G. Dambier, G.J. Focker, P.G. Hansen, G. Jegoudez, B. Johnson, J. Leblanc, J.P. Moalic, H.L. Ravn, H.H. Stroke, O. Testard, Nature *314*, 75 (1985).

50) M. Schädel, W. Brüchle, B. Haefner, Nucl. Instr. Meth. *A264*, 308 (1988).

51) M. Schädel, W. Brüchle, E. Jäger, E. Schimpf, J.V. Kratz, U.W. Scherer, H.P. Zimmermann, GSI Rept., GSI-89-38 (1989) (in press, Radiochim. Acta).

52) C.E.A. Palmer, H.L. Hall, P.A. Baisden, D.C. Hoffman, D.M. Lee, Lawrence Livermore Nat. Lab. Nucl. Chem. Div. Ann. Rept., UCAR 10062-88, pg. 126 (1988).

53) G. Skarnemark, P.O. Aronsson, K. Bróden, J. Rydberg, T. Björnstad, N. Kaffrell, E. Stender, N. Trautmann, Nucl. Instr. Meth. *171*, 323 (1980).

54) H. Persson, G. Skarnemark, M, Skålberg, J. Alstad, J.O. Liljenzin, G. Bauer, F. Haberberger, N. Kaffrell, J. Rogowski, N. Trautmann, (in press Radiochim. Acta (1989)).

55) N. Trautmann, private communication (1989).

56) D.T. Jost, H.W. Gäggeler, Ch. Vogel, M. Schädel, E. Jäger, B. Eichler, K.E. Gregorich, D.C. Hoffman, Inorganica Chimica Acta *146*, 255 (1988).

57) Ya Nai-Qi, D.T. Jost, U. Baltensperger, H.W. Gäggeler, Radiochim. Acta *47*, 1 (1989).

58) N. Greulich, U. Hickmann, N. Trautmann, G. Herrmann, Fresenius Z. Anal. Chem. *323*, 839 (1986).

59) E.K. Hulet, Private communication, Information is contained in the LEAP proposal (reference 36) and the associated addenda.

FIGURE CAPTIONS

1. A present-day periodic table with the presently known man-made elements shaded. The elements which are presently unknown have dotted borders and atomic numbers in italics.

2. A schematic drawing of the limits of nuclear stability.

3. The series of neutron captures and beta decays which produce the heavy element isotopes in a reactor irradiation. The yearly production capacity at the HFIR-TPP facility, using a 2-g ^{252}Cf target, for some key isotopes are listed.

4. A schematic of a future experiment to study the chemical and nuclear properties of superheavy elements which makes use of many of the concepts presented here.

PERIODIC TABLE OF THE ELEMENTS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	*	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	**	Rf 104	Ha 105	106	107	108	109	*110*	*111*	*112*	*113*	*114*	*115*	*116*	*117*	*118*

*	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
* *	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

Fig. 1

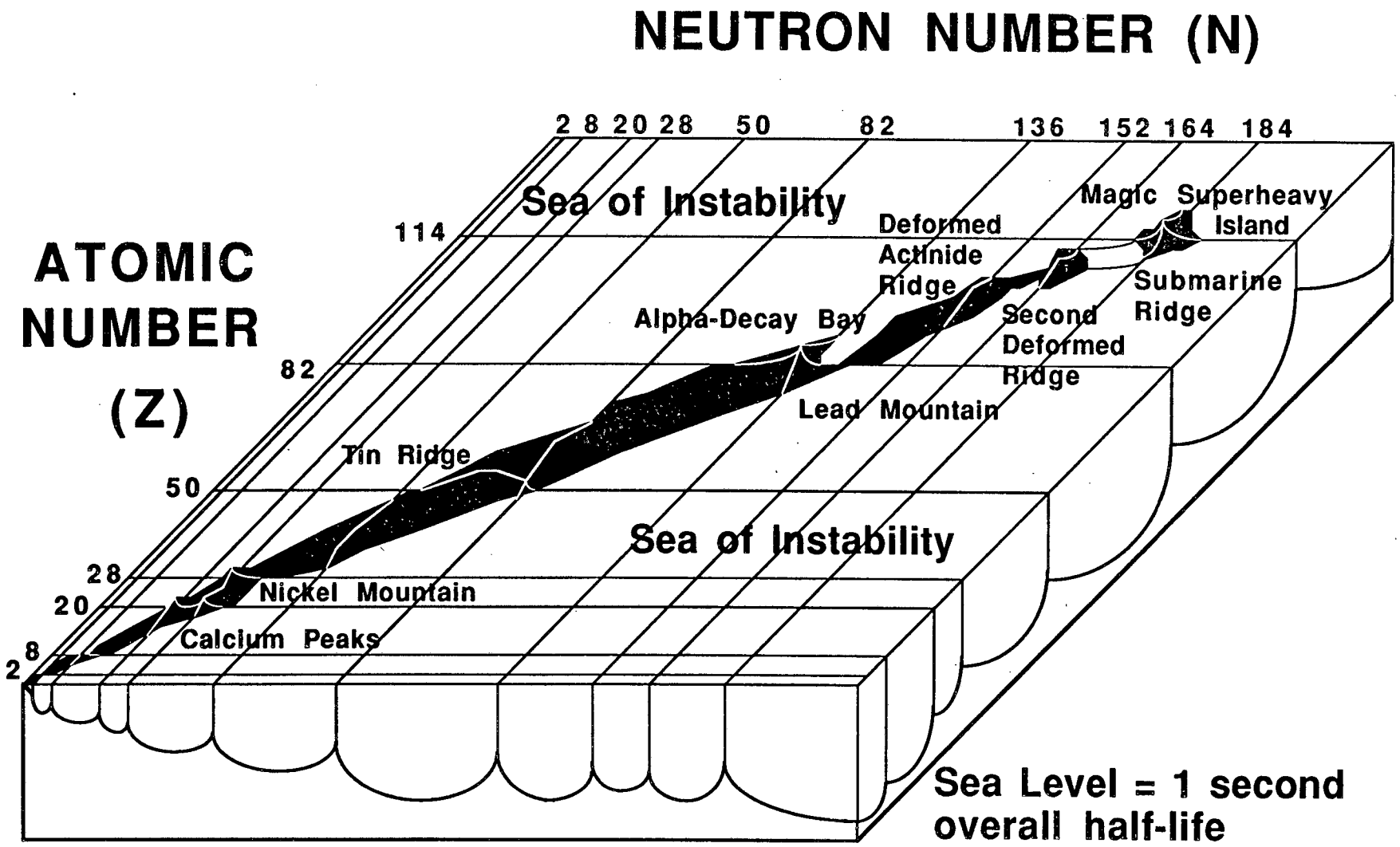
NEUTRON NUMBER (N)
2 8 20 28 50 82 136 152 164 184
ATOMIC NUMBER (Z)
114
82
50
28
20
8
2
Sea of Instability
Sea of Instability
Deformed Actinide Ridge
Magic Superheavy Island
Submarine Ridge
Second Deformed Ridge
Alpha-Decay Bay
Lead Mountain
Tin Ridge
Nickel Mountain
Calcium Peaks
Sea Level = 1 second overall half-life

Fig. 2

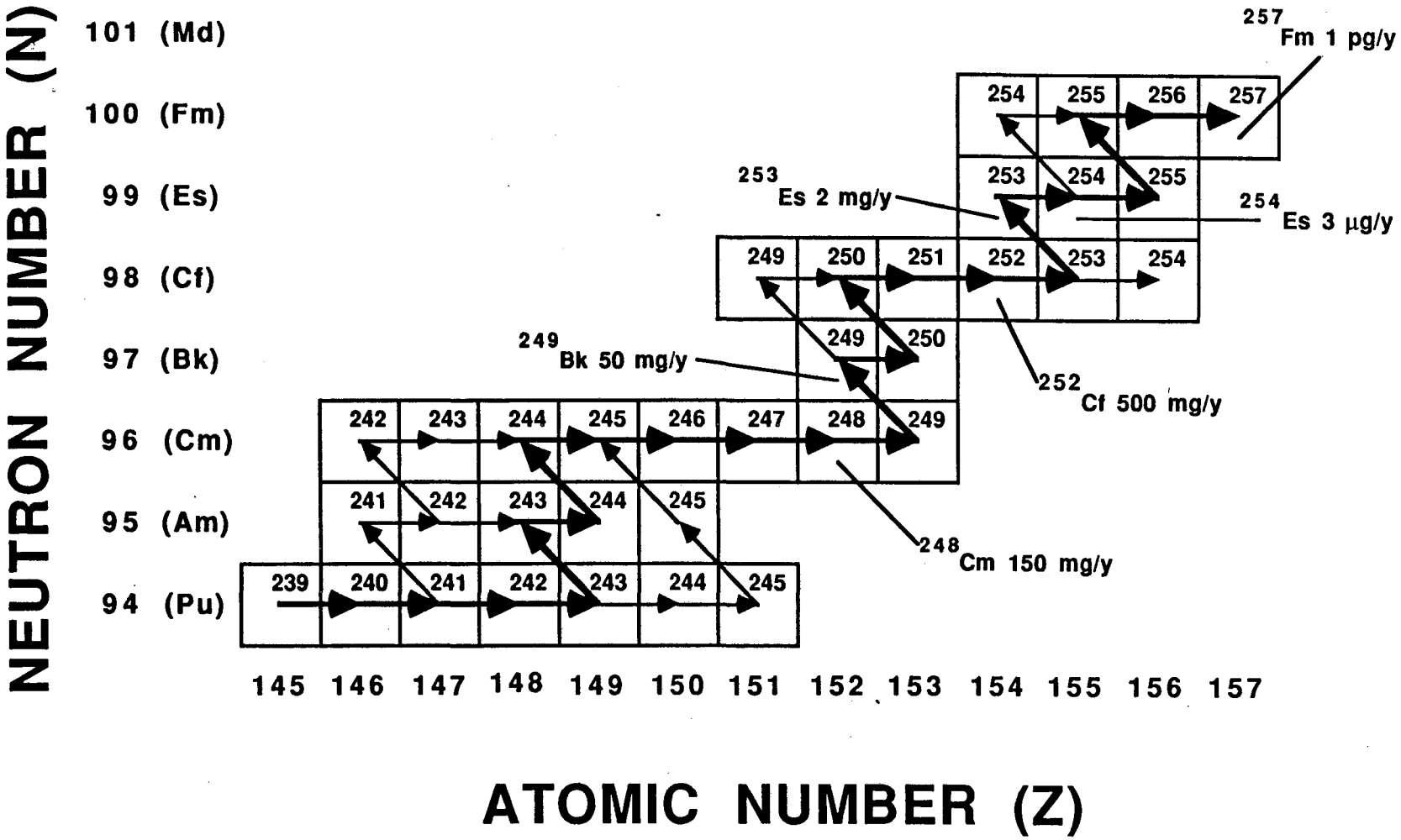
NEUTRON NUMBER (N)
101 (Md)
100 (Fm)
99 (Es)
98 (Cf)
97 (Bk)
96 (Cm)
95 (Am)
94 (Pu)
239 240 241 242 243 244 245
241 242 243 244 245
242 243 244 245 246 247 248 249
249 250
249 250 251 252 253 254
253 254 255
254 255 256 257
257 Fm 1 pg/y
253 Es 2 mg/y
254 Es 3 μg/y
249 Bk 50 mg/y
252 Cf 500 mg/y
248 Cm 150 mg/y
145 146 147 148 149 150 151 152 153 154 155 156 157
ATOMIC NUMBER (Z)

Fig. 3

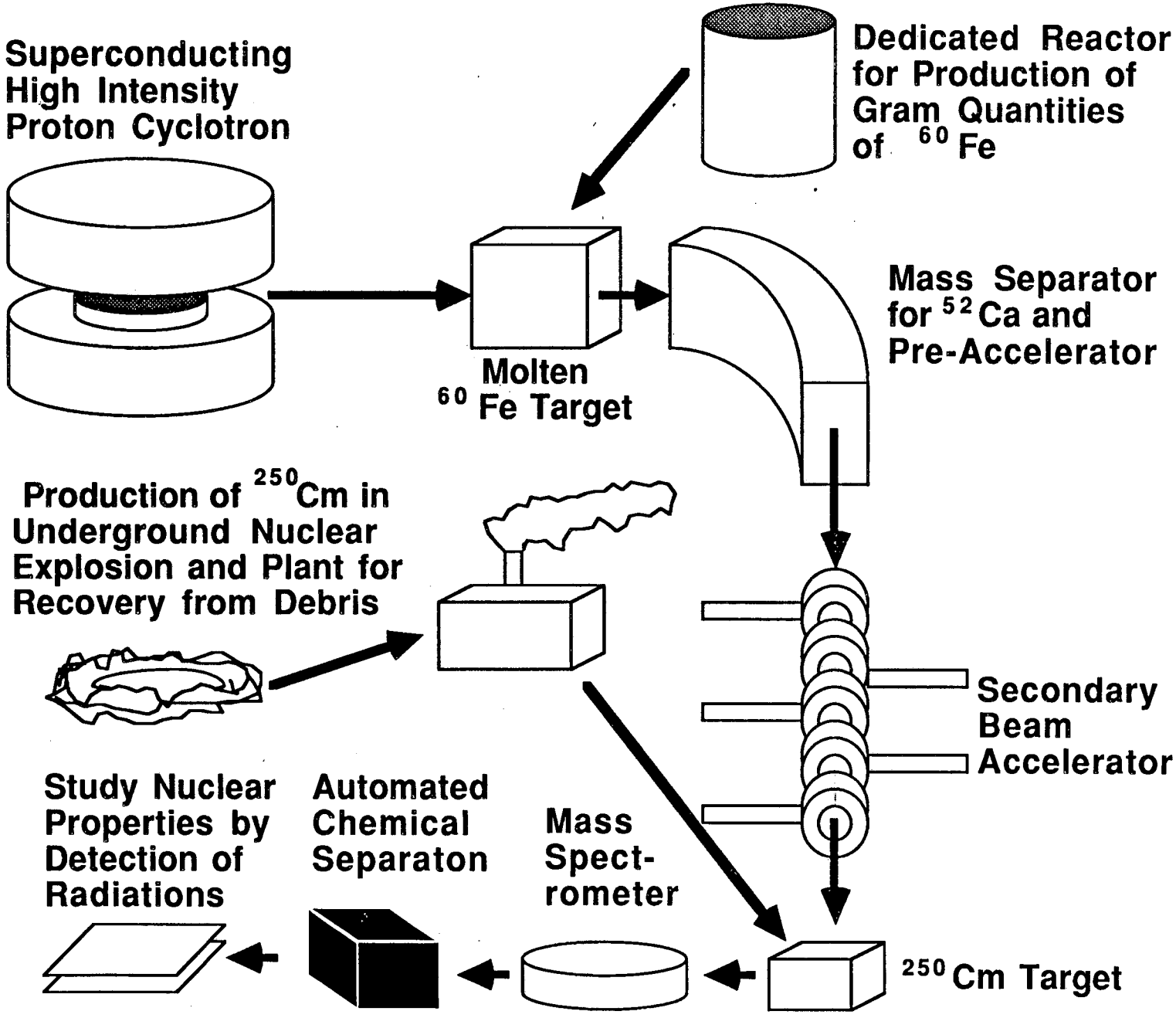
Superconducting High Intensity Proton Cyclotron
Dedicated Reactor for Production of Gram Quantities of ^{60}Fe
Molten ^{60}Fe Target
Mass Separator for ^{52}Ca and Pre-Accelerator
Production of ^{250}Cm in Underground Nuclear Explosion and Plant for Recovery from Debris
Secondary Beam Accelerator
Study Nuclear Properties by Detection of Radiations
Automated Chemical Separaton
Mass Spect-rometer
^{250}Cm Target

Fig. 4

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720