

worked up by a team of chemists. When purified, it resulted in the first plutonium to be seen without the benefit of a microscope. The cyclotron at Washington University in St. Louis also contributed to the early production of microscopic quantities of plutonium.

### **1.3. Transplutonium Elements**

While the Seaborg group was still in Chicago they started their first efforts to make transplutonium elements by sending targets of  $^{239}\text{Pu}$  to Berkeley for bombardment with  $^4\text{He}$  ions in the 60-Inch Cyclotron. This resulted in the discovery of element 96 in the form of  $^{242}\text{96}$ , identified in 1944 by a distinctive alpha energy and half-life (see Chapter 4). When the bombardment was repeated months later they were puzzled when they observed a different isotope,  $^{240}\text{96}$ , with a higher alpha energy and a shorter half-life. The mystery was solved when they found that the cyclotron energy had been increased substantially by another modification in between the two bombardments; they deduced that the excitation functions must be much narrower in width than they had expected. By interposing energy absorbing foils over the target they were able to take advantage of this new tool to fractionate the isotopes and this became a routine procedure in future research. The long distance bombardments continued until the group transferred to Berkeley in 1945–1946.

Now the shorter half-lives became available for investigation, and after the protracted period that it took for the group to set up in its new quarters, elements 97 and 98 were discovered in 1949–1950, as discussed in Chapter 5. The chief reason for the delay was that there were great hazards in dealing safely with the very radioactive americium and curium targets before, during, and after the bombardments and this demanded a lot of special attention. A new one-story laboratory, Bldg. 5, was built for this purpose and there the famed Berkeley glove boxes were developed by Nels Garden and his group. In addition, new methods of detecting  $\alpha$ - and X-radiation had to be worked out to detect the meager amount of activity after

it had been separated from the target. All of this preparation was put to good use in 1952 in the work done on the Mike bomb debris (see Chapter 6).

By 1955, the group had progressed to the point where it was ready for what might be called the *tour de force* of all the research on transuranium elements. For the first time, the discovery of a new element was made one atom at a time by means of a new technique. This was element 101, mendelevium, and its discovery is described in detail in Chapter 7. To make the experiment feasible it was necessary to increase the beam density in the 60-Inch Cyclotron by an order of magnitude over its normal value. Bernard Rossi, the cyclotron supervisor, worked hard at this and succeeded by taking advantage of the fringe magnetic field, but it meant that a special probe had to be designed for the experiment. This was the first recoil experiment to be performed for this type of nuclear chemistry/physics and its success led to its use for all of the following discovery experiments.

The Berkeley group had gotten this far by using neutron capture reactions in nuclear reactors or from helium ion ( $\alpha$ -particle) bombardments in the Cyclotron. To go higher in atomic number with the target materials that were then available, it was clear that ions heavier than helium were needed. A decade earlier, Alvarez had demonstrated that fully stripped carbon ions could be accelerated in the big cyclotron but at intensities many orders of magnitude lower than would be needed, so Ghiorso and Rossi undertook a regular program at the 60-Inch Cyclotron to try to improve the output. After some months of research, they discovered that the  $C^{6+}$  ions were not produced at the ion source; they were produced by a two-step process. They theorized that carbon ions with two electrons missing were produced at the ion source and accelerated at one third the normal velocity with a good intensity. These ions occasionally would collide with gas molecules and be fully stripped and then be accelerated in the normal way. This third harmonic type of operation was observed for other heavy particles also. It led to a poor energy

distribution but it was better than nothing, and the group was able to do some important preliminary experiments and point up the need for a dedicated heavy ion accelerator. Alvarez, fresh from his success with his proton linear accelerator that had just been completed at Berkeley, proposed that a linear accelerator be used for the heavy ions with the difference that each drift tube would contain a magnetic strong focusing element. A joint study/design group was set up with the Yale Physics Department for such a machine and after many months they came up with a Heavy Ion Linear Accelerator (HILAC) along the lines that Alvarez had suggested.

At this stage an amusing incident caused by Lawrence himself occurred that could have changed the history of heavy ion acceleration at Berkeley. On a Sunday in 1955 the Lab had its first Open House celebration and during the event Lawrence sought out Ghiorso, who happened to be there. He asked how the HILAC design was going and when told that it had been finalized and construction was about to begin, he said that he had been thinking that maybe the possibility of building a cyclotron instead of a linac should be reconsidered! He suggested that a meeting of all of the Lab experts should be convened the next day to make sure that the correct decision had been made. One didn't easily dissuade Lawrence in those days, so the meeting was held and in a small group Ernest could be a dominating personality. He had a lot of good points to make, but his suggestion at that time would have delayed the project several more years, because to build a machine equivalent to the HILAC would have meant a very large cyclotron. Ghiorso knew this and searched for the powerful counterargument that would save the linac. He found it when he pointed out that extraction of the beam was a problem for cyclotrons at that time, a figure of 10% being optimistic, whereas extraction from a linac was automatically 100%. That argument, reiterated over and over, finally carried the day. In retrospect, that was a very important decision, because the inventions of the Omnitron and the BevaLAC that followed the HILAC would not have occurred and this in turn would have meant that RHIC would not have been built.

The AEC authorized the construction of the twin accelerators at Berkeley and Yale and they were promptly built. The HILAC consisted of a 750 kV Cockcroft–Walton injector that produced ions with a low charge state for injection into a 30-foot-long, grid-focussed prestripper linac to accelerate the heavy ions up to 1.0 MeV/A. These ions were then passed through a cloud of mercury vapor to strip more electrons from each ion to raise it to a higher charge state and thus minimize the necessary length of the second tank. The second tank was a 90-foot-long linac with magnetically strong focussed drift tubes that took the ions up to 10 MeV/A. The final energy was fixed and the pulse rate was only 2 Hz. The tanks were 10 feet in diameter, so there was a lot of internal surface area to be outgassed. It turned out that the low duty cycle (a pulse rate of 2 Hz with a pulse width of only 2 ms) meant that it was difficult to inject enough power to break through the various “ion locks” very quickly, and as a consequence it was many months before the vacuum was good enough to allow high RF voltage gradients to be established so that acceleration experiments could begin.

#### **1.4. Current Status**

The first real transuranium element (neptunium, 93) was identified in 1940. Since then, we have seen the synthesis and identification, i.e., the discoveries, of 20 elements with atomic numbers greater than that of uranium (element 92) — the transuranium elements. These discoveries have added more than 20% to our list of chemical elements and the study of these elements has added much to our understanding of nuclear and atomic structure, the periodic table, nuclear fission and the limits to nuclear stability, and nuclear reaction mechanisms.

The current periodic table, as of April 1998, is shown in Fig. 1.6. The elements through 112 are now known. The names and symbols we shall use throughout this book are those approved by The International Union of Pure and Applied Chemistry (IUPAC) in August 1997 or earlier, except for element 105, for which we shall