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Superheavy Elements

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Since the days of Mendelyeev's periodic table of atomic elements, chemists and physicists have been interested in the discovery or synthesis of new elements to fill the gaps in the periodic table and to extend it. They have been able to fill all the gaps and to extend the periodic table up to atomic number $Z \sim 100$, where the atomic number, Z, gives the number of protons in the nucleus. At this point, it becomes increasingly difficult to make elements with a larger number of protons. In fact, elements beyond plutonium ($Z = 94$) are not found in nature, and half-lives for heavier elements become less and less; that is, they only exist for a short time before decaying into lighter elements by various radiative mechanisms. The newest element, synthesized this year, $Z = 106$, exists for less than one second.

Thus great excitement was generated when the possibility of the occurrence of a small group of elements around $Z \sim 114$ with relatively long half-lives (of the order of years or longer) was predicted by theoreticians a few years ago. These are usually referred to as superheavy elements. The existence and properties of these elements have important bearings not only in the fields of chemistry and physics, but also in the studies of supernovae, cosmic rays, meteorites, and natural abundances of known elements.

Before we go on, it is well to understand the basic reason for the limited number of elements. Why are there now 106 elements rather than 2 or 3, or 2000 or 3000? The underlying physics responsible for the limited extent of the periodic table is the competition between attractive "nuclear forces" among the nucleons (i. e. protons and neutrons) and the repulsive electrostatic forces among all the positively charged protons. The limit of the periodic table at Z ~106 is then set by the process of nuclear fission, which takes place when the disruptive effect of electrostatic forces overcomes the cohesive effect of the nuclear forces.

The picture began to change when, in 1964, a clearer understanding was reached by Myers and Swiatecki on the relation between fission half-lives and a well-known property of the nucleus called the magic numbers. It has been known for some time that if the number of protons (or neutrons) in a nucleus is equal to the proton magic number (or neutron magic number) then such a nucleus displays some special features; one example is that it is spherical in shape. The work of Myers and Swiatecki showed that such a nucleus also displays an extra stability against fission. This means that this nucleus will have a longer half-life than would be expected otherwise. Thus the next important question is what are the proton (or neutron) magic numbers? From experiments it has been deduced that the proton magic numbers are 8, 14, 28, 50, and 82. Many people have tried to predict the next magic number. It is now believed by many workers in this field that the next proton magic number is probably 114. The above discussions may be illustrated schematically in Fig. 1 where we look at various nuclei with different numbers of protons. The vertical axis indicates the fission half-lives. The extra stability due to magic numbers shows up as extra long half-lives localized at these numbers, while their general trend dips at Z ~106 into a region of such short half-lives that detection of such nuclei becomes almost impossible. Perhaps one cannot even claim that such nuclei can be made at all. Thus this region which is shaded in the figure may be called the "sea of instability". However, because of the magic number 114, a small group of elements around 114 may stick out of the sea and appear as an "island of stability" with extra long half-lives. These are what are now known as the super-heavy elements which have caused much excitement and activity in the last few years.

To make the picture more complete, one should also consider the number of neutrons in the nucleus with its set of magic numbers. It turns out that the neutron and proton magic numbers are the same at lower numbers but deviate from each other at larger numbers. The neutron magic numbers are 8, 14, 28, 50, 82 and 126, with the next predicted number at 184. A similar figure as Fig. 1 may be drawn with neutrons on the x axis in which the dip into the Sea of instability occurs at N ~158. Including both proton and neutron numbers in the same picture gives Fig. 2. In this figure the known nuclei are illustrated by a peninsula surrounded by the sea of instability. Mountains and ridges on the peninsula occur at the proton or neutron magic numbers representing regions of extra stability against fission. It is to be noted in this figure that nuclei exist with a certain ratio of protons and neutrons. If a nucleus has too many protons or too many neutrons, it will decay by emitting a positron or an electron. The superheavy elements occur in this picture as an island of stability a little distance beyond the known peninsula with the center of the island at the proton magic number 114 and the neutron magic number 184.

At about the same time as Myers and Swiatecki's work, Strutinsky developed a method, which has come to be known by his name, by which a quantitative estimate can be made of the stability of such superheavy nuclei. This method combines two well-known approaches in nuclear physics: the liquid drop model and the shell model of the nucleus. The first systematic calculation of the half-lives of both the known heavy nuclei and the predicted superheavy nuclei was made by Nilsson and coworkers in 1969, using the Strutinsky method. Several more refined calculations were made during the period up to 1973, the latest and most complete version being perhaps that by Nix and coworkers. To a large extent, they agreed with each other in their main conclusions.

One of the surprising results that came out of the work of Nilsson and coworkers is that these superheavy elements may live as long as the age of the solar system! After considering all the major decay mechanisms they predicted that several of these elements, in particular the element with Z = 110, have half-lives about 10^8 years. Thus an interesting possibility arises that if these elements were made in nature along with the other known elements during the formation of the earth, then small fractions could have survived the period of time ($\sim 4.5 \times 10^9$ years) since the earth was formed. This suggestion is illustrated in Fig. 1 by showing the extra long-lived 114 peak touching a broken line representing a half-life long enough for the element to be found in nature.

It was realized by workers in the field that great uncertainities were involved in these predictions. If the prediction of 10^8 years is off by two or three orders of magnitude downwards, which is well possible in the present state of art in theory, then no naturally occurring superheavy elements are expected to be found. Also it is an open question whether such elements would have been made at the formation of the solar system. Nevertheless extensive efforts were spent looking for these elements in nature. It is like a person making a bet. Even though he knows that the chance is very much against him, the great prize, if he did win, prompts him to put down his bet.

A search for new elements on the earth depends on suitable choices of the most promising minerals and ores containing known elements having chemcial properties most resembling those of the elements being sought. Using the time-honored method of Mendelyeev, it is seen (Fig. 3) that superheavy elements 110, 111, 112, 113, 114, and 115 should have chemical properties similar to those of Pt, Au, Hg, Tl, Pb, and Bi respectively. Calculations using much more sophisticated methods developed in recent years have also been performed for these elements giving detailed predictions of their chemcial properties.

Over the last five years or so, Thompson's group at Berkeley, Flerov's group at Dubna (USSR), Herrmann's group at Mainz (Germany) and others have looked at a variety of ores and minerals, including natural platinum ores, old lead glasses, moon rocks, and manganese nodules collected from the ocean which are found to be particularly rich in metallic minerals. Typically one tries to detect fission events or accompanying neutron emission, characteristic of these superheavy elements. However, in some cases, alpha decay detection is also made since it has been predicted that alpha emission energies of these elements are exceptionally larger than those of known elements. In the case that fission may have occurred many years ago, experiments were also done to find the tracks caused by fission fragments in, for instance, lead glasses and moon rocks. In all these experiments, no traces of superheavy elements have conclusively been found. In many of the experiments the limit of the possible existence of these elements is less than 10^{-11} gram per gram of ore; in other words, if superheavy elements with a half-life of 10^{8} years are present in the ore to the extent of only 10^{-11} gram in one gram of ore, the experiment should have detected them. Other experiments gave an even lower limit of 10^{-17} gram per gram of the mineral ore.

A number of other searches for superheavy elements in nature have been made, including a search in cosmic rays which may include elements produced in explosions in distant stars or supernovae. None, so far, has given conclusive evidence of their presence. Although the results up to now do not definitely rule out the presence of these elements in nature, the weight of evidence is such as to suggest that they do not exist on earth. Their absence may be due to one or both of two reasons. First, their half-lives may be a few orders lower than predicted, and they would have disappeared by radioactive decay during the 4.5×10^{9} years since the earth was formed. Secondly, recent calculations indicate that, at the formation of the earth when most of the elements were synthesized, these superheavy elements were prevented from being produced. Very roughly, the reason is that to build up heavy nuclei from light elements during the formation of the solar system, the gap of very short fission half-lives that exists between the island of superheavy elements and the lighter nuclei has stopped Nature short of reaching the island.

Perhaps it is expecting too much to hope that these superheavy elements have such long half-lives. Superheavy elements with half lives of one year, one day or even one minute can be studied with present day techniques, if we can synthesize them. Obviously in this case we have to make a big jump over the sea of instability to the island. In other words we have to take a target such as U, Pu or Cm and bombard it with a heavy ion such as Ar, Ca, or Kr and make them fuse together to form a superheavy nucleus. Some suggestions are:

$${}^{48}_{20}\mathrm{Ca}_{28} \quad + \quad {}^{248}_{96}\mathrm{Cm}_{152} \quad = \quad {}^{292}116_{176} \quad + 4n$$

$${}^{76}_{32}\mathrm{Ge}_{44} \quad + \quad {}^{232}_{90}\mathrm{Th}_{142} \quad = \quad {}^{304}122_{182} + 4n$$

In a discussion of heavy ion reactions such as the ones shown above, it is necessary to recognize the need to accelerate heavy ions to a sufficiently high energy. Why not just mix two elements together and extract a product of much higher atomic number? The electrostatic energy, which, as we have seen before, becomes increasingly important at the end of the present periodic table, prevents fusion. The very large positive charges in the target and projectile nuclei prevent them from coming within the very small distances required to make them touch and fuse together. This fusion distance is about 10^{-12} centimeter, the radius of a heavy nucleus being about 6×10^{-13} cm. In order to make even a relatively light ion, such as argon, fuse with uranium, the argon must have its energy raised to about 200 MeV, which corresponds to a velocity of about 10^9 cm/sec. It is rather difficult to achieve such high energies. Until recently only projectiles up to ^{40}Ar were available with sufficient energies to fuse with heavy targets, and it is not possible to bring about a jump close to the center of the island with the use of ^{40}Ar. But with the newer heavy ion accelerators at Dubna (USSR), and Orsay (France), heavier projectiles are available. Even more intense beams of heavy ions have recently become available at Berkeley, and a new heavy ion accelerator is currently under construction at Darmstadt (Germany), hopefully to be completed early next year. Thus the stage is set for a major effort in synthesizing superheavy elements. Already extensive experiments have been made at both Dubna and Orsay, but the results so far are negative. Berkeley, with its more intense beam, will also attempt to produce these elements soon.

Numerous problems may hinder the fusing of two nuclei into a superheavy nucleus. We shall mention here some major ones.

(1) To make a superheavy nucleus, we have to fuse two existing nuclei with appropriate proton numbers such that they add up to about 114. However, it turns out that the corresponding neutron numbers do not add up to 184, usually less by quite a few units. Hence it is impossible to make a jump to the center of the island.

(2) When the projectile and target nuclei collide, the process is fairly "violent," and the system has a high excitation energy. It usually cools down by emitting several neutrons, typically four which is assumed for the above reaction equations. But there is the question whether before such cooling can take place, a superheavy nucleus can survive the violent "shaking" without breaking up.

(3) In most of the collisions, the two nuclei collide off center and will start to rotate around each other. The disruptive centrifugal effect associated with the rotation turns out to be quite important.

(4) The largest uncertainty of all has to do with the probability for the projectile and target to fuse together. It is not sufficient for the projectile and the target nuclei to merely come in contact with each other: an extra push is necessary to force them to fuse together. The probability that they can be made to fuse together into a final spherical superheavy nucleus involves not only the inertia, which acts against the push, but also the viscosity of the flow of nuclear matter, which is a dissipative effect converting the pushing energy into useless excitation energy. Good estimates of nuclear inertias and viscosities have not been made so far; these are important gaps in our knowledge of nuclear properties.

All of these problems are currently under intensive theoretical and experimental study. A better understanding has been achieved in some of these items, and this will affect the conditions under which one would attempt to produce superheavy elements.

I hope I have given you a flavor of the exciting field of superheavy elements. If they were synthesized, not only would they have practical implications in geology and astrophysics, but they would also provide a completely new testing ground for our understanding of the chemistry of the elements and the physics of the nuclus: they would point at gaps in our knowledge and new directions in research. Already in the spin-off new areas of research are opened which are significant in their own right, such as the physics of collision of two heavy nuclei, possibility of forming very deformed nuclei, and atomic physics of an element with as many as 170 protons.

Some review articles for further studies:

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Acknowledgment

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FIGURE CAPTIONS

Fig. 1. Schematic picture of the effect of extra stability due to magic numbers on the half-lives of elements. The dark line indicates the decrease of half-lives as the proton number, Z, increases, if the magic numbers were not present. The magic numbers modify the curve locally, shown in the figure as small peaks, increasing the half-lives of elements around these numbers. The shaded region represents the sea of instability, and the broken line indicates the value of the half-life above which the nuclei live long enough such that they would exist in nature if they had been made during the formation of our solar system.

Fig. 2. Nuclear stability is illustrated in a scheme that shows a peninsula of known elements and an island of predicted stability (nuclei around proton number 114 and neutron number 184) in a "sea of instability." Grid lines show magic numbers of protons and neutrons giving rise to exceptional stability. Magic regions on the mainland peninsula are represented by mountains or ridges.

Fig. 3. Conventional form of the periodic table showing predicted locations of new elements. The number in a square where no chemical symbol is shown gives the atomic number of the new element.

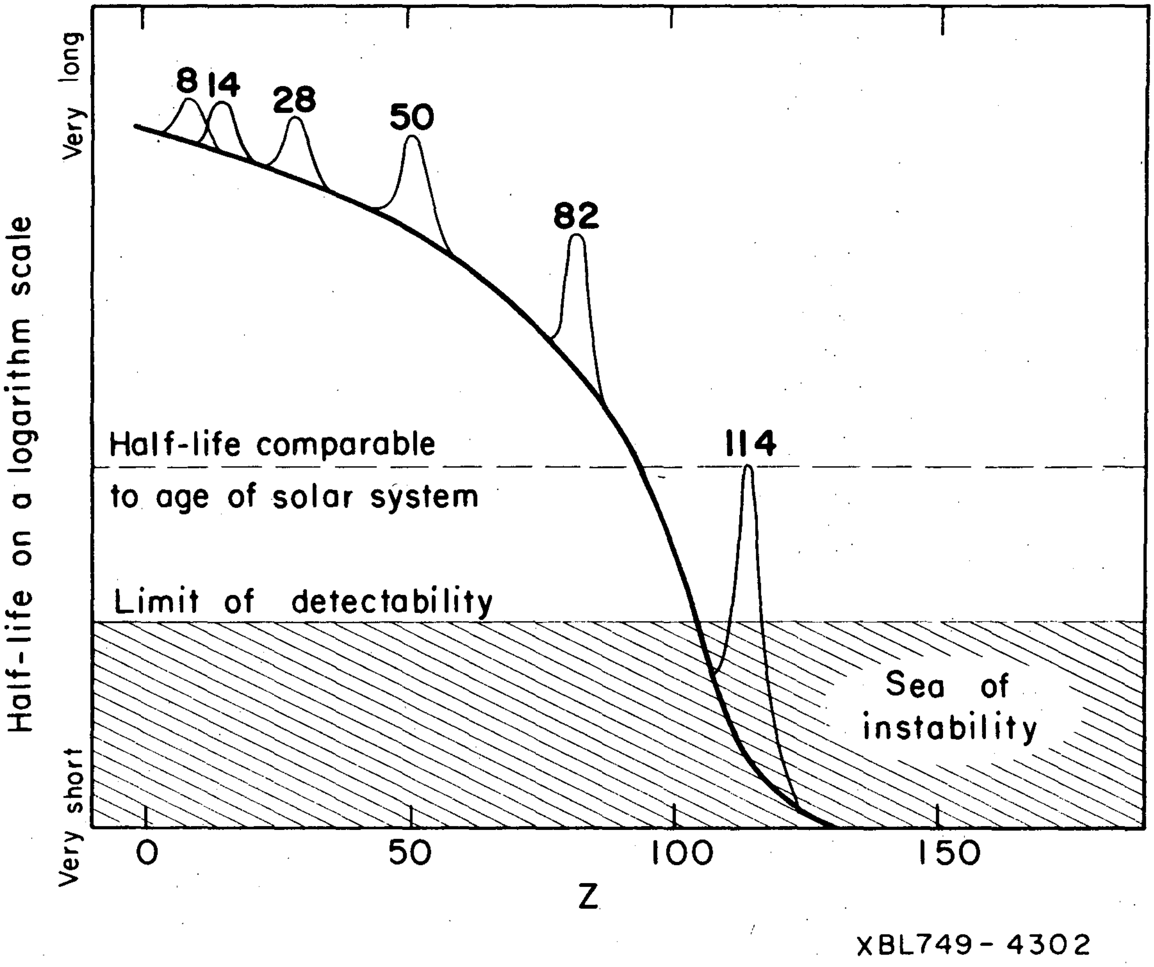
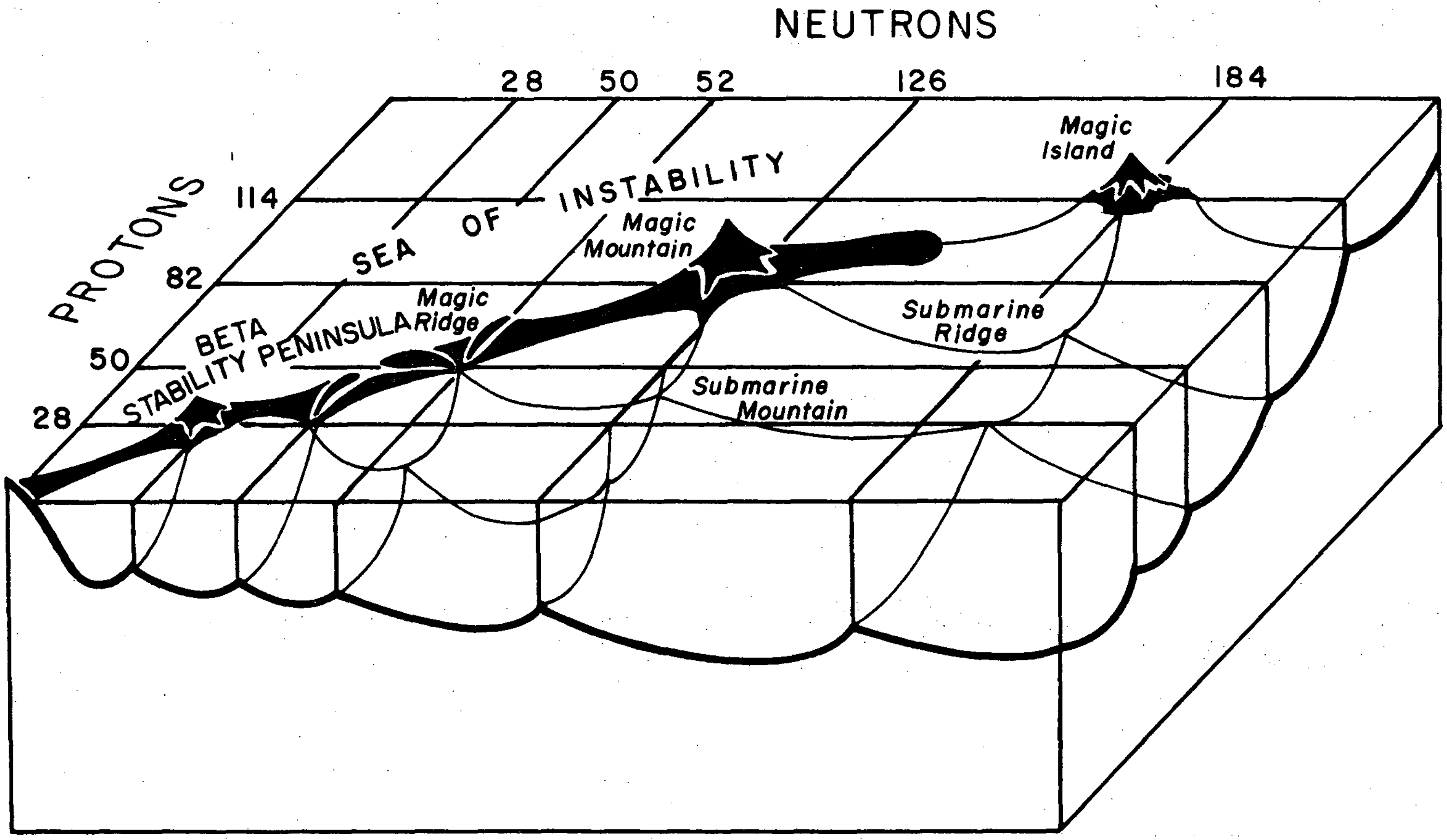
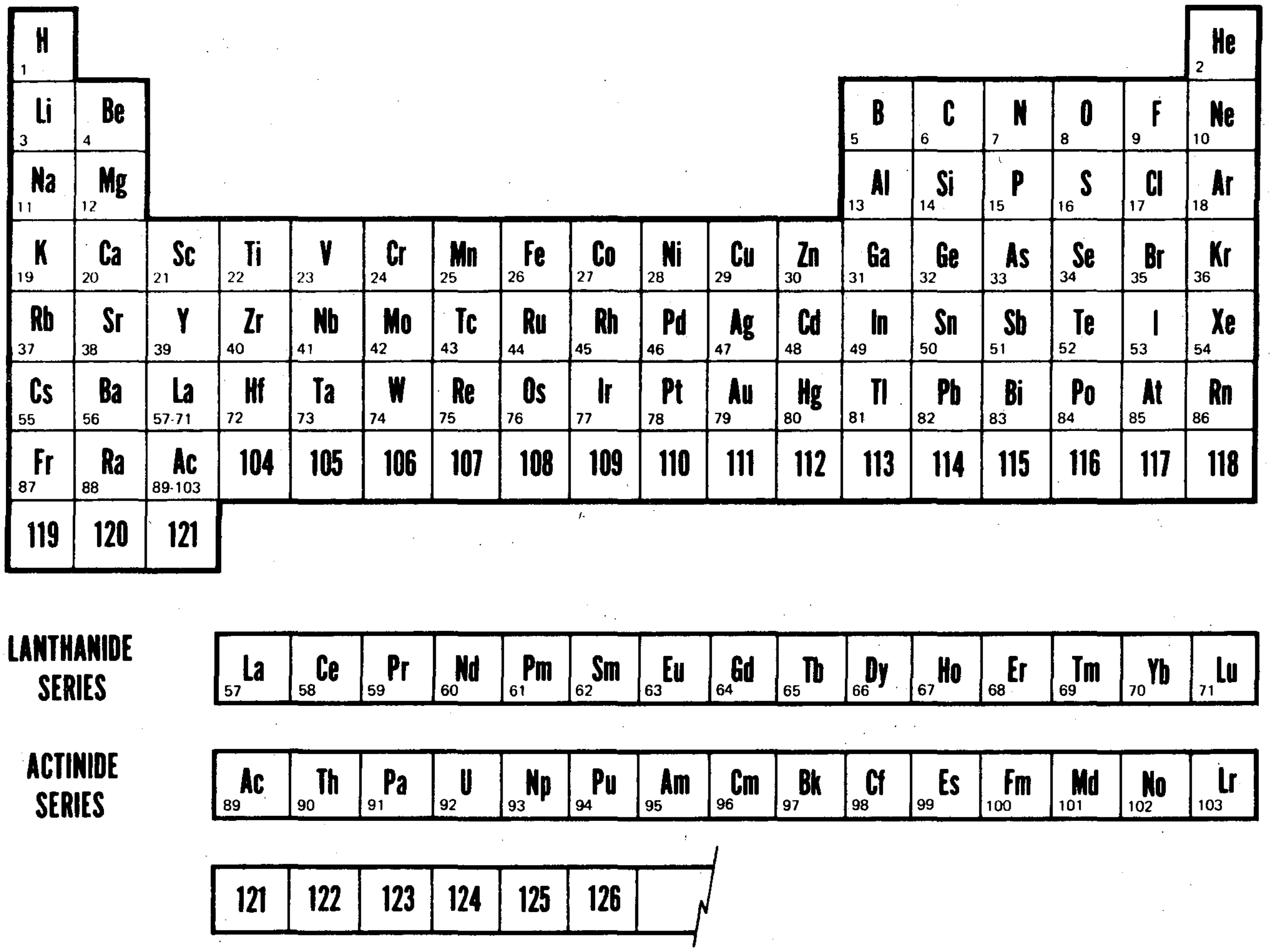

Half-life on a logarithm scale
Very long
Very short
8
14
28
50
82
114
Half-life comparable to age of solar system
Limit of detectability
Sea of instability
0
50
100
150
Z
XBL749-4302

Fig. 1



CBB 725-2592

Fig. 2



XBL 691-1654

Fig. 3

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