ACCESS Science
The Science Authority

Proton and neutron drip lines

Article by:

Thoennessen, Michael National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan.

Baumann, Thomas National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan.

Last updated: 2016

DOI: https://doi.org/10.1036/1097-8542.551325 (https://doi.org/10.1036/1097-8542.551325)

Content

Lines on the chart of nuclides that delineate the limits of how many protons and neutrons can be bound within the atomic nucleus. The large variety of atomic nuclei, built up of protons and neutrons, can be classified into three groups: stable nuclei, bound but unstable (that is, radioactive) nuclei, and unbound nuclei. Any combination of protons and neutrons will fall into one of the three groups. Expressed in simple terms, the drip lines delineate the boundary between bound and unbound nuclei.

The distinction between bound and unbound nuclei is based on the particle separation energy, which is the amount of energy that is needed to remove a nucleon from the nucleus. If the separation energy is negative, the nucleon will not bind to the rest of the nucleus. Such a configuration is also called particle unstable, because the nucleus will decay by proton or neutron emission. Therefore the location of the drip line is determined by the separation energy crossing zero.

Neutron drip line

Isotopes have a constant number of protons but a varying number of neutrons. For the neutron-rich isotopes of each element, the limit at which any additional neutron will not be bound is called the neutron drip line. The one- or two-neutron separation energy becomes negative as the neutron drip line is crossed. This means that a nucleus beyond the neutron drip line gains a more stable configuration by emitting one or two neutrons directly. The location of the neutron drip line coincides with the limit of existence of the nucleus, meaning that nuclei beyond the neutron drip line decay with time scales of the order of 10^{-22} s (the time scale of a direct nuclear reaction).

Staggering of drip lines

The difference in binding energy between an odd number and an even number of protons or neutrons results in the characteristic staggering of the drip lines. An even number of neutrons or protons results in a larger binding energy. For neutron-rich isotopes, this means that those with an even number of neutrons tend to be more bound than the odd-neutron-numbered neighbor (**Fig. 1**). So, as one approaches the neutron drip line, for most elements the first unbound isotope will be one with an odd number of neutrons, while the next heavier isotope with an even number of neutrons is oftentimes bound again. In the same way, the odd–even effect for protons creates a staggered proton drip line, with lines of elements with even proton numbers extending to lighter isotopes.

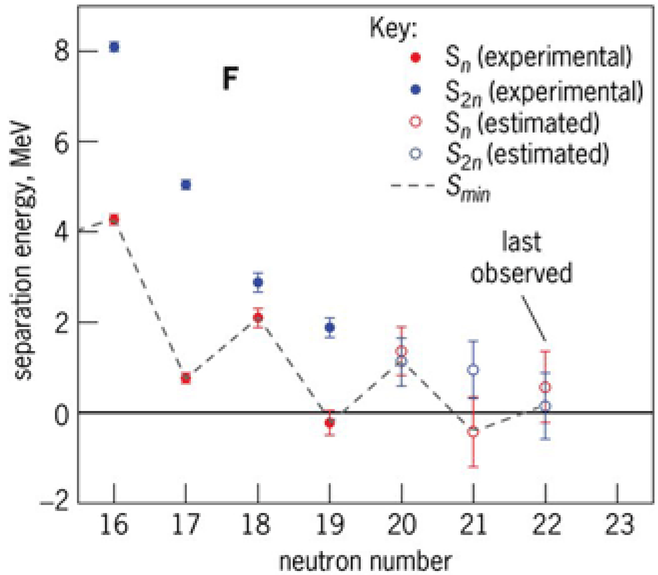

Fig. 1 One- and two-neutron separation energies (S_n, S_{2n}) for the neutron-rich fluorine (atomic number Z = 9) isotopes. Separation energies are calculated from the atomic mass evaluation mass table. Open circles indicate separation energies that are based on estimated masses. The broken line follows $S_{\min}$, the smaller of the two values of S_n and S_{2n}. The fluorine isotopes showcase nicely the odd–even staggering of the neutron separation energy, which results in the odd-neutron-number isotopes ^{28}F and ^{30}F (neutron numbers N = 19 and 21) being unbound.

Therefore the neutron drip line is best outlined by locating the lightest bound element for a set of isotones. (Isotones have a varying number of protons but a constant number of neutrons.) In the same way, the location of the proton drip line will be defined by the lightest bound isotope for a given element.

Figure 2 shows the one- and two-neutron separation energies for isotones with 18 neutrons at the neutron drip line. The neutron drip line is reached at fluorine-27 (^{27}F), with 9 protons. The isotone with one less proton, oxygen-26 (^{26}O), is barely unbound with regard to two-neutron emission and decays into the heaviest bound oxygen isotope, ^{24}O.

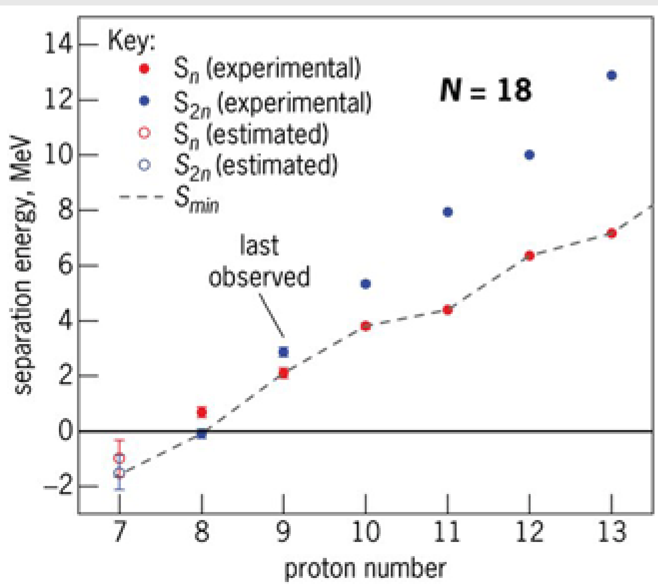

Fig. 2 One- and two-neutron separation energies for the N = 18 isotones. Separation energies are calculated from the atomic mass evaluation mass table. Values based on estimated masses are indicated by open circles. The lightest bound N = 18 isotone is ^{27}F; the next lighter isotone, ^{26}O, is unbound by a very small amount with regard to two-neutron emission.

Proton drip line

The proton drip line is not as easily found as the neutron drip line. Using an equivalent definition as for the neutron drip line, the proton drip line is located where the proton separation energy (or two-proton separation energy) crosses zero. Nuclei beyond the proton drip line are technically unbound and can therefore decay by proton emission. However, many nuclei, especially for elements of medium mass and above, do exist beyond the proton drip line as a result of the proton's charge. For the unbound proton (or protons) to be emitted, they have to tunnel through the Coulomb barrier, which is holding protons in the nucleus, leading to half-lives of the order of milliseconds up to seconds.

Figure 3 shows the evolution of one- and two-proton separation energies for the lightest holmium (atomic number Z = 67) isotopes. While the drip line is located at holmium-146 (^{146}Ho, neutron number N = 79), because the next lighter holmium isotope is unbound with regard to one-proton emission, holmium isotopes with neutron numbers below 79 have considerable half-lives, ranging from 4.1 ms to 2.4 s. Proton emission has been detected only for the two lightest observed isotopes, ^{140}Ho and ^{141}Ho, due to the small Q-values (energy released) for proton emission of the other proton-unbound holmium isotopes. The small Q-value results in a smaller tunneling probability through the Coulomb barrier for the proton, so that beta positron decay (β^+) becomes more likely.

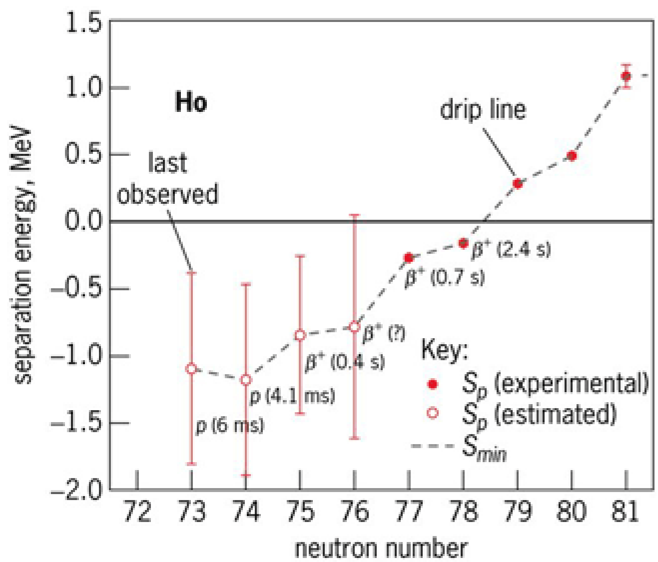

Fig. 3 Proton separation energies (S_p) for the lightest holmium (Z = 67) isotopes plotted against neutron number N. Separation energies are calculated from the atomic mass evaluation. Values based on estimated masses are indicated by open circles. The drip line is located at ^{146}Ho (N = 79), because ^{145}Ho has a negative one-proton separation energy. The two lightest observed holmium isotopes (^{140}Ho and ^{141}Ho) are proton emitters with half-lives of milliseconds. Half-lives and predominant decay modes are indicated for the unbound holmium isotopes.

Charts of nuclides

A chart of nuclides plots all possible combinations of protons and neutrons. The chart of nuclides in **Fig. 4** shows every bound nuclide and every nuclide with a half-life of 1 ns or more, based on experimental values and theoretical calculations. A color scale ranging from blue to white indicates the minimum separation energy for each bound nuclide, with white representing a value of zero at the proton and neutron drip lines. This part of the plot clearly shows the odd–even staggering, and also reveals the location of magic numbers, numbers of protons and neutrons that result in stronger binding. On a red-to-yellow scale, the lifetimes of nuclides beyond the proton drip line are plotted, down to 1 ns. These are the unbound nuclei that exist due to the effect of the Coulomb barrier.

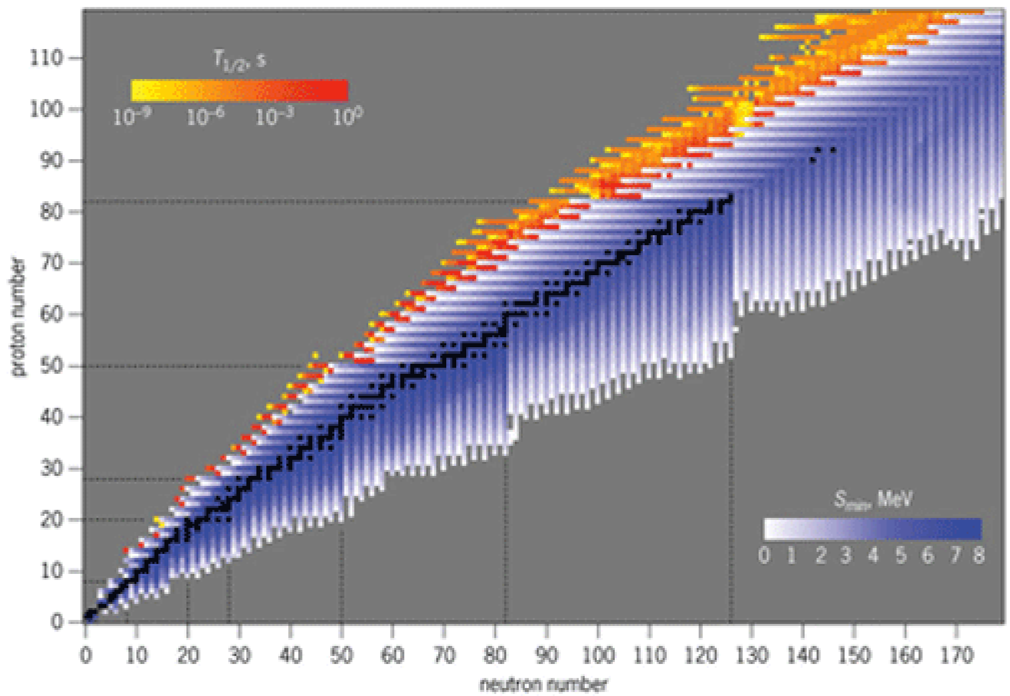

Fig. 4 This chart of nuclides displays the minimum, S_{min}, of neutron and proton separation energies, from blue to white, based on the atomic mass evaluation mass table and a theoretical model (the KTUY mass model of H. Koura, T. Tachibana, M. Uno, and M. Yamada) for every bound nuclide. Black squares indicate stable and primordial nuclides. (Primordial nuclides have half-lives comparable to the age of the universe.) Indicated in red to yellow are half-lives, $T_{1/2}$, of nuclides beyond the proton drip line that exist mainly due to the Coulomb barrier.

The chart of nuclides in **Fig. 5** shows about 300 stable and primordial nuclides (primordial nuclides have half-lives comparable to the age of the universe) and, additionally, about 2800 nuclides that have been identified in experiments. However, these nuclides are probably only about half of all the nuclei that are predicted to exist based on theoretical calculations. The large number of nuclides that have not been observed means that the drip lines are not known very well.

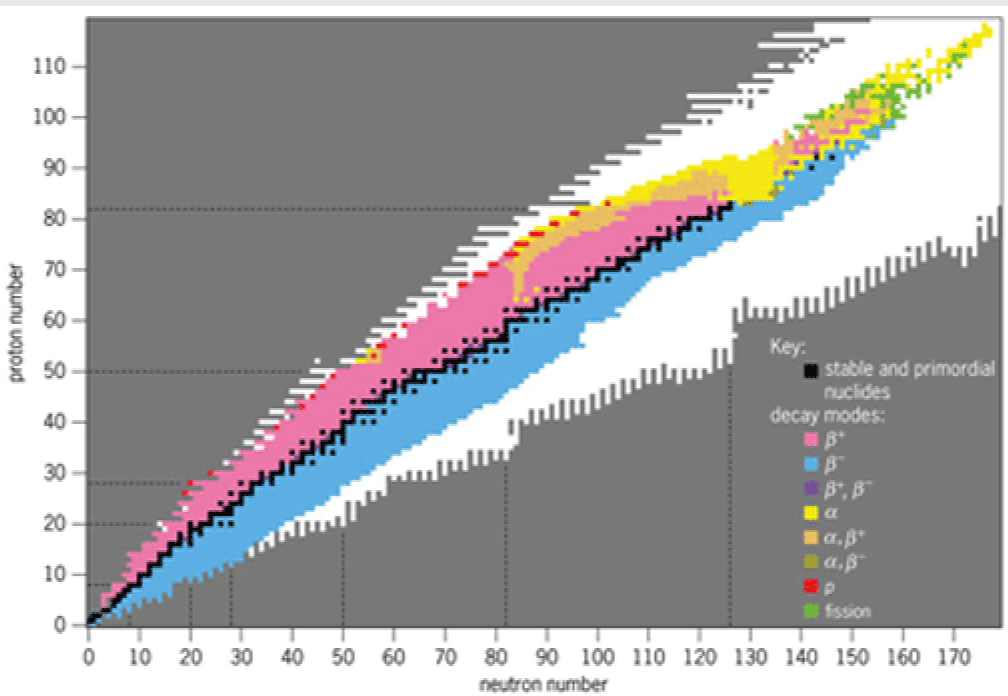

Fig. 5 In this chart of nuclides, known nuclides are marked by colors indicating their predominant decay modes. The white space denotes nuclides that are thought to exist with half-lives of more than 1 ns, but that have not yet been observed. This plot shows that most of the unknown nuclides are neutron-rich.

Knowledge of drip lines

The neutron drip line is confirmed experimentally only up to fluorine (*Z* = 9). The heaviest discovered isotope is ^{31}F (*N* = 22, **Fig. 1**), and ^{32}F as well as ^{33}F have been shown to be unbound.

The proton drip line has been reached and crossed experimentally up to bismuth (*Z* = 83) by the observation of proton emission. Because the proton drip line does not coincide with the limit of existence, it is more difficult to verify experimentally. The exact location of the proton drip line for odd- and even-*Z* elements is known only up to aluminum (*Z* = 13).

Study of exotic nuclei

The study of radioactive nuclei that are close to the drip line is of great interest because of the unusual nuclear structure effects that some of these nuclides exhibit, such as neutron halos, new magic numbers, and the role that these exotic nuclei play in the formation of the elements in stellar explosions.

Thomas Baumann
Michael Thoennessen

Links to Primary Literature

M. Arnould, S. Goriely, and K. Takahashi, The r-process of stellar nucleosynthesis: Astrophysics and nuclear physics achievements and mysteries, *Phys. Rep.*, 450:97–213, 2007

G. Audi et al., The AME2012 atomic mass evaluation (I). Evaluation of input data, adjustment procedures, *Chin. Phys. C*, 36:1287–1602, 2012

P. D. Cottle and K. W. Kemper, Viewpoint: A walk along the dripline, *Physics*, 5:49 (3 pp.), 2012

J. Erler et al., The limits of the nuclear landscape, *Nature*, 486:509–512, 2012

P. G. Hansen and J. A. Tostevin, Direct reactions with exotic nuclei, *Annu. Rev. Nucl. Part. Sci.*, 53:219–261, 2003

A. C. Mueller and B. M. Sherrill, Nuclei at the limits of particle stability, *Annu. Rev. Nucl. Part. Sci.*, 43:529–583, 1993

M. Thoennessen, Current status and future potential of nuclide discoveries, *Rep. Progr. Phys.*, 76:056301 (35 pp.), 2013

M. Thoennessen and B. Sherrill, From isotopes to the stars, *Nature*, 473:25–26, 2011

Additional Readings

Facility for Rare Isotope Beams, Michigan State University: Mass Explorer (http://massexplorer.frib.msu.edu)

Michael Thoennessen: Discovery of Nuclides Project (https://people.nscl.msu.edu/~thoennes/isotopes)

National Nuclear Data Center, Brookhaven National Laboratory: Chart of Nuclides (http://www.nndc.bnl.gov/chart)

National Superconducting Cyclotron Laboratory, Michigan State University: LISE++ Exotic Beam Production with Fragment Separators (http://lise.nscl.msu.edu/lise.html)