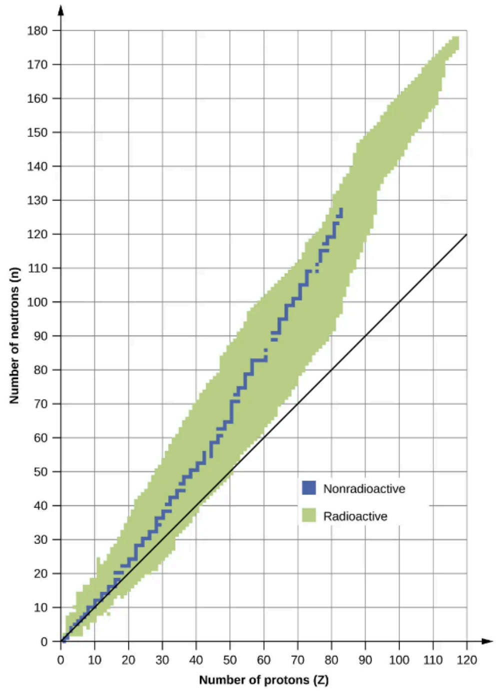
Nuclear Structure and Stability

This worksheet will cover the structure of atoms, highlighting their nucleus composed of protons and neutrons called nucleons. It will discuss two primary classifications of nuclides: **stable isotopes**, maintaining a balanced proton-neutron ratio for long-term stability, and **radioisotopes**, which, due to an imbalance in this ratio, undergo radioactive decay, emitting radiation to achieve a more stable state. As you progress through the worksheet, you'll develop the skills to differentiate between stable and radioactive (unstable) isotopes.

1. Write the following isotopes in hyphen notation
    a. ${}^{24}_{11}Na$
    b. ${}^{29}_{13}Al$
    c. ${}^{73}_{36}Kr$
    d. ${}^{194}_{77}Ir$

2. Write the following isotopes in nuclide notation
    a. Carbon-14
    b. Oxygen-14
    c. Copper-70
    d. Francium-217
    e. Plutonium-244

3. Which of the following lie within the band of stability (graph shown below)?
    a. Carbon-14
    b. ^{204}Bi
    c. ^{122}Ba
    d. ^{222}Rn
    e. Oxygen-16
    f. Chlorine-37
    g. ^{206}Pb
    h. ^{211}Pb



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4. Classify each nuclide as stable or radioactive
   a. $^{30}_{15}P$
   b. $^{98}_{43}Tc$
   c. $^{15}_{8}O$
   d. $^{232}_{90}Th$
   e. $Tin - 118$

5. What are the two principal differences between nuclear reactions and ordinary chemical changes?

ANSWER KEY:

1. Write the following isotopes in hyphen notation
   a. $^{24}_{11}Na$
   b. $^{29}_{13}Al$
   c. $^{73}_{36}Kr$
   d. $^{194}_{77}Ir$

Solution:

Strategy – hyphen notation is the name of the element preceding the total mass number of the element. In this case, the problem gives us the nuclide notation which contains the atomic symbol, mass number (shown in superscript) and proton number (shown in subscript).

a. Sodium-24
b. Aluminum-29
c. Krypton-73
d. Iridium-194

2. Write the following isotopes in nuclide notation
   a. Carbon-14
   b. Oxygen-14
   c. Copper-70
   d. Francium-217
   e. Plutonium-244

Solution:

Strategy – hyphen notation of an element provides the name of the element and the total mass number of the element. Thus, to convert the hyphen notation to nuclide notation, all one needs is the atomic symbol, mass number (given), and proton number. Remember, the proton number never changes for an element but the mass number can (which is why we have isotopes).To convert the above to nuclide notation, the superscript is the mass number, the subscript is the proton number, and following that is the atomic symbol of the corresponding element. **NOTE:** The proton number of any element can be found on the Periodic Table.

a. $^{14}_{6}C$
b. $^{14}_{8}O$
c. $^{70}_{29}Cu$
d. $^{217}_{87}Fr$
e. $^{244}_{94}Pu$

3. Which of the following lie within the band of stability (graph shown below)?
    a. Carbon-14
    b. ^{204}Bi
    c. ^{122}Ba
    d. ^{222}Rn
    e. Oxygen-16
    f. Chlorine-37
    g. ^{206}Pb
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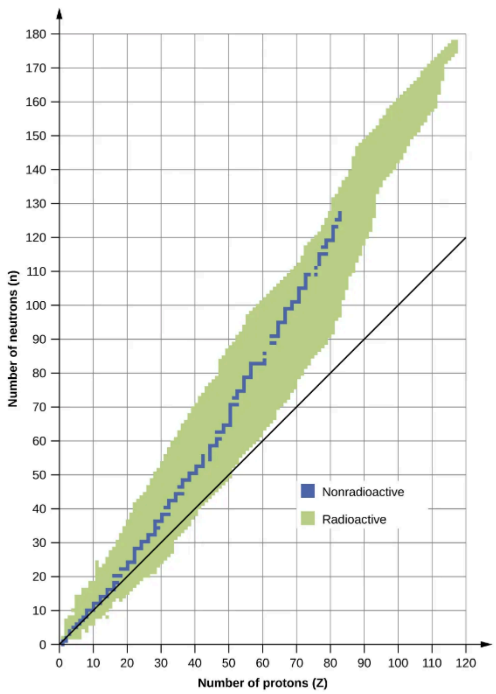

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Solution:

Brief introduction on the Band of Stability: The concept of the "band of stability" refers to a region on a graph that illustrates the relationship between the number of neutrons and protons in stable nuclei. Nuclei within this band are considered to be stable and are commonly found in nature. This band is roughly diagonal on a plot of neutron number (N) against proton number (Z). The neutron-proton (N/P) ratio plays a pivotal role in determining the stability of a nucleus. As the atomic number increases, the repulsive forces between protons become stronger. Neutrons act as a buffer against these repulsive forces, preventing the nucleus from disintegrating due to electrostatic repulsion. Therefore, nuclei with higher N/P ratios are generally more stable because the presence of extra neutrons counteracts the electrostatic forces between protons. Thus, a general rule of thumb is that small, stable atoms have a N/P ratio of 1:1 and bigger, stable atoms have an N/P ratio of 1.5:1. **Note:** the diagonal black line in the graph above illustrates the 1:1 ratio line.

Strategy – This question is similar to question 3 where an element that is within the band of stability is considered a stable isotope (from the graph above this is the blue region). In contrast, the isotopes that lie on the edge of the region are unstable (radioactive – this is the green region in the graph above). To check if an isotope lies within the band of stability, one can eyeball it as the x-axis is the number of protons and the y-axis is the number of neutrons. But we can also check the result numerically by calculating the ratio of the number of neutrons and number of protons. For elements with an atomic number **less** than 20, the ratio N/P should be 1:1 to be stable. For elements with an atomic number greater than 20 and less than 83, the ratio should be 1.5:1 for the nuclei to be stable.

a. Carbon-14 has 8 neutrons and 6 protons. The ratio is 1.33 but since the atomic number of carbon is 6, the ratio indicates that carbon-14 is unstable and thus does not lie within the band of stability
b. Bismuth-204 has 121 neutrons and 83 protons. The ratio is 1.45 but since the atomic number of bismuth is 83, it is automatically considered unstable and does not lie within the band of stability. Even though the ratio is close to 1.5:1. If you eyeball where bismuth is on the band of stability, it is in the green region, which confirms the conclusion.
c. Barium-122 has 66 neutrons and 56 protons thus the ratio is 66/56 = 1.17. Since the atomic number is 56 and is greater than 20, the ratio should be 1.5 but is closer to 1. Thus, Barium-122 does not lie within the band of stability
d. Radon-222 has 136 neutrons and 86 protons. With an atomic number of 86, it is unstable and thus it also does not lie within the band of stability
e. Oxygen-16 has 8 neutrons and 8 protons with a ratio of 1:1. Thus, it lies within the band of stability
f. Chlorine-37 has 20 neutrons and 13 protons with a ratio approximately 1.5:1 which is in line with the trend and so thus chlorine lies within the band of stability
g. Lead-206 has 124 neutrons and 82 protons with a ratio of 1.5:1. Since its atomic number is also below 83, Lead-206 lies within the band of stability
h. Lead-211 has 129 neutrons and 82 protons with a ratio of 1.6:1 so lead-211 does not lie within the band of stability

4. Classify each nuclide as either stable or radioactive.
   a. $^{30}_{15}P$
   b. $^{98}_{43}Tc$
   c. $^{15}_{8}O$
   d. $^{232}_{90}Th$
   e. $Tin - 118$

Solution:

Strategy – The question is asking to predict nuclear stability. To do so, use the protons, neutron-to-proton, and the presence of odd or even numbers of neutrons and protons to predict radioactivity or stability of each nuclide. The general rule for this is indicated in the table below regarding the trend of stability of odd vs even neutron and protons:

Protons	**Neutrons**	**Number of Stable Isotopes**	**Stability**
Odd	Odd	5	Least Stable
Odd	Even	50	More stable
Even	Odd	53	Even more stable
Even	Even	175	Most Stable

Another important rule is that an element with a proton count equal to or above 83 are automatically unstable isotopes.

a. This isotope of phosphorus has 15 neutrons and 15 protons which gives a N/P ratio of 1:1. Additionally, the isotope has an odd number of both protons and neutrons thus it is unstable and thus is a **radioactive (unstable) isotope**. Moreover, another justification that can be used is that even though phosphorus-15 is a small atom with a 1:1 ratio, when referring to the “band of stability” the ratio should be greater than 1:1 in this case.
b. This isotope of technetium has 55 neutrons and 43 protons, giving a neutron-to-proton ratio of 1.28. This places technetium-98 near the edge of the “band of stability” which suggests that this is a stable isotope. However, both protons and neutrons are odd numbers and thus are predicted as **radioactive**.
c. Oxygen-15 has 7 neutrons and 8 protons. Since oxygen is a small atom, the ratio for a stable isotope for small atoms is 1:1 however, because the neutrons do not match the proton for this small atom, it is thus an unstable and **radioactive isotope** of oxygen.
d. Thorium-232 has an atomic number of 90. Because nuclei with a proton count or atomic number above 83 is considered radioactive, this makes Thorium-232 a **radioactive isotope.**
e. Tin-118 has 68 neutrons and 50 protons. The N/P ratio is 1.36 and lies within the “band of stability” as well as the proton count being below 83. Additionally, both neutron and proton count in Tin-118 are even so it is sufficient to say that Tin-118 is a **stable isotope**.

5. What are the two principal differences between nuclear reactions and ordinary chemical changes?

Solution:

1. Nuclear reactions usually change one type of nucleus into another; chemical changes rearrange atoms.
2. Nuclear reactions involve much larger energies than chemical reactions and have measurable mass changes.