

**Neutron Activation,  
Alpha & Beta Decay**  
as  
***TRANSMUTATION***  
of the  
***ELEMENTS***

***Jess H. Brewer***

# Neutron Decay



A *free* neutron will  $\beta$ -decay into a proton, an electron and an electron antineutrino in an average of **15 minutes**.  
When *bound in a nucleus*, neutrons are usually *stable*; but if they are only *weakly* bound, they still may  $\beta$ -decay, leaving behind a nucleus with one extra proton — *i.e.* *transmuted* into a **different element!**

# The Periodic Table of the Elements

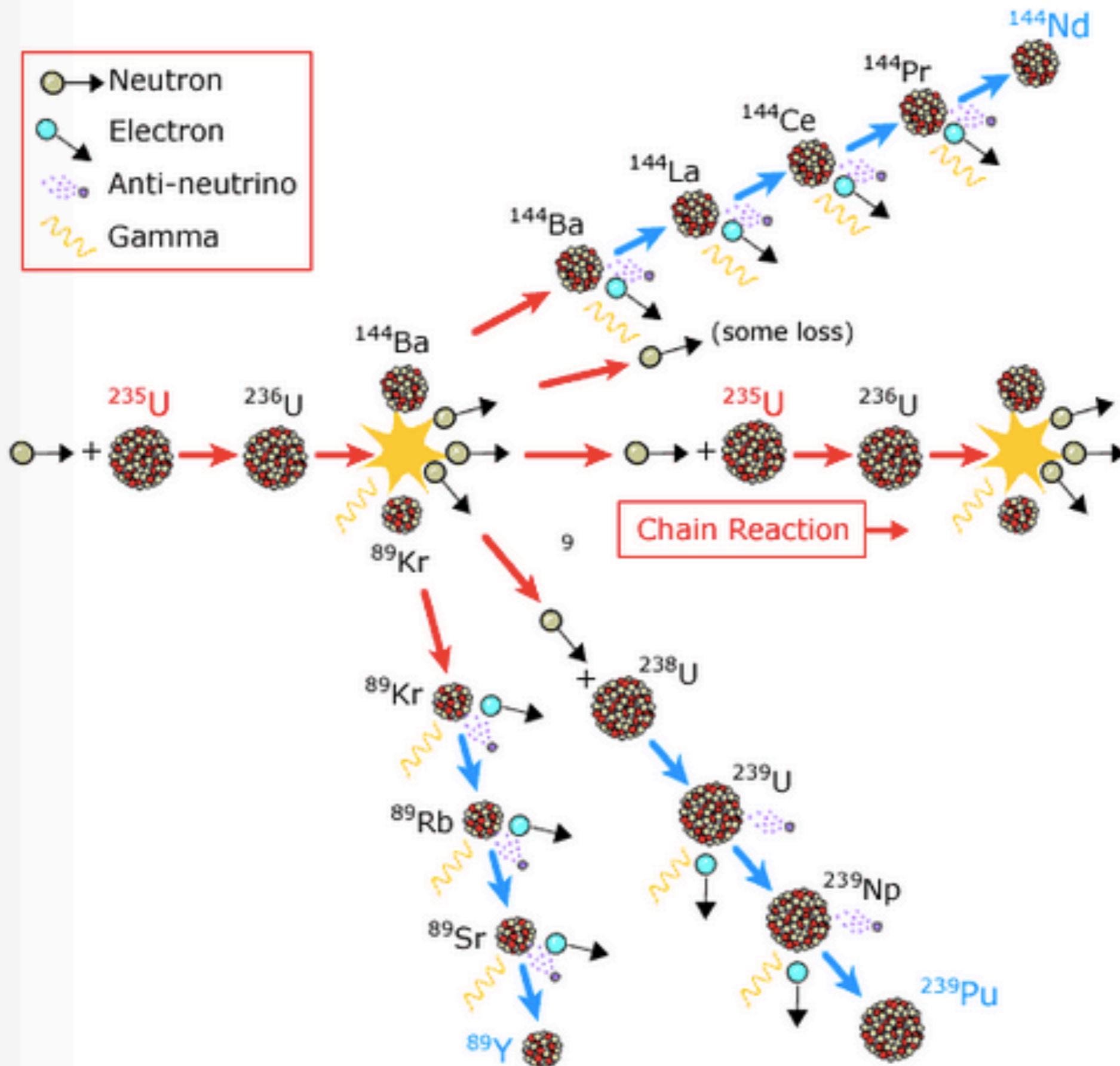
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18											
												Pnictogens		Chalcogens		Halogens														
1	<b>H</b> Hydrogen 1.008	<table border="1"> <tr> <td colspan="2">Metals</td> <td colspan="2">Metalloids</td> <td colspan="2">Nonmetals</td> </tr> <tr> <td>Alkali metals</td> <td>Alkaline earth metals</td> <td>Lanthanoids</td> <td>Transition metals</td> <td>Post-transition metals</td> <td>Reactive nonmetals</td> </tr> <tr> <td></td> <td></td> <td>Actinoids</td> <td></td> <td></td> <td>Noble gases</td> </tr> </table>										Metals		Metalloids		Nonmetals		Alkali metals	Alkaline earth metals	Lanthanoids	Transition metals	Post-transition metals	Reactive nonmetals			Actinoids			Noble gases	<b>He</b> Helium 4.0026
Metals		Metalloids		Nonmetals																										
Alkali metals	Alkaline earth metals	Lanthanoids	Transition metals	Post-transition metals	Reactive nonmetals																									
		Actinoids			Noble gases																									
2	<b>Li</b> Lithium 6.94	<b>Be</b> Beryllium 9.0122											<b>B</b> Boron 10.81	<b>C</b> Carbon 12.011	<b>N</b> Nitrogen 14.007	<b>O</b> Oxygen 15.999	<b>F</b> Fluorine 18.998	<b>Ne</b> Neon 20.180												
3	<b>Na</b> Sodium 22.990	<b>Mg</b> Magnesium 24.305											<b>Al</b> Aluminium 26.982	<b>Si</b> Silicon 28.085	<b>P</b> Phosphorus 30.974	<b>S</b> Sulfur 32.06	<b>Cl</b> Chlorine 35.45	<b>Ar</b> Argon 39.948												
4	<b>K</b> Potassium 39.098	<b>Ca</b> Calcium 40.078	<b>Sc</b> Scandium 44.956	<b>Ti</b> Titanium 47.867	<b>V</b> Vanadium 50.942	<b>Cr</b> Chromium 51.996	<b>Mn</b> Manganese 54.938	<b>Fe</b> Iron 55.845	<b>Co</b> Cobalt 58.933	<b>Ni</b> Nickel 58.693	<b>Cu</b> Copper 63.546	<b>Zn</b> Zinc 65.38	<b>Ga</b> Gallium 69.723	<b>Ge</b> Germanium 72.630	<b>As</b> Arsenic 74.922	<b>Se</b> Selenium 78.971	<b>Br</b> Bromine 79.904	<b>Kr</b> Krypton 83.798												
5	<b>Rb</b> Rubidium 85.468	<b>Sr</b> Strontium 87.62	<b>Y</b> Yttrium 88.906	<b>Zr</b> Zirconium 91.224	<b>Nb</b> Niobium 92.906	<b>Mo</b> Molybdenum 95.95	<b>Tc</b> Technetium (98)	<b>Ru</b> Ruthenium 101.07	<b>Rh</b> Rhodium 102.91	<b>Pd</b> Palladium 106.42	<b>Ag</b> Silver 107.87	<b>Cd</b> Cadmium 112.41	<b>In</b> Indium 114.82	<b>Sn</b> Tin 118.71	<b>Sb</b> Antimony 121.76	<b>Te</b> Tellurium 127.60	<b>I</b> Iodine 126.90	<b>Xe</b> Xenon 131.29												
6	<b>Cs</b> Caesium 132.91	<b>Ba</b> Barium 137.33	57-71	<b>Hf</b> Hafnium 178.49	<b>Ta</b> Tantalum 180.95	<b>W</b> Tungsten 183.84	<b>Re</b> Rhenium 186.21	<b>Os</b> Osmium 190.23	<b>Ir</b> Iridium 192.22	<b>Pt</b> Platinum 195.08	<b>Au</b> Gold 196.97	<b>Hg</b> Mercury 200.59	<b>Tl</b> Thallium 204.38	<b>Pb</b> Lead 207.2	<b>Bi</b> Bismuth 208.98	<b>Po</b> Polonium (209)	<b>At</b> Astatine (210)	<b>Rn</b> Radon (222)												
7	<b>Fr</b> Francium (223)	<b>Ra</b> Radium (226)	89-103	<b>Rf</b> Rutherfordium (267)	<b>Db</b> Dubnium (268)	<b>Sg</b> Seaborgium (269)	<b>Bh</b> Bohrium (270)	<b>Hs</b> Hassium (277)	<b>Mt</b> Meitnerium (278)	<b>Ds</b> Darmstadtium (281)	<b>Rg</b> Roentgenium (282)	<b>Cn</b> Copernicium (285)	<b>Nh</b> Nihonium (286)	<b>Fl</b> Flerovium (289)	<b>Mc</b> Moscovium (290)	<b>Lv</b> Livermorium (293)	<b>Ts</b> Tennessine (294)	<b>Og</b> Oganesson (294)												
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		6		<b>La</b> Lanthanum 138.91	<b>Ce</b> Cerium 140.12	<b>Pr</b> Praseodymium 140.91	<b>Nd</b> Neodymium 144.24	<b>Pm</b> Promethium (145)	<b>Sm</b> Samarium 150.36	<b>Eu</b> Europium 151.96	<b>Gd</b> Gadolinium 157.25	<b>Tb</b> Terbium 158.93	<b>Dy</b> Dysprosium 162.50	<b>Ho</b> Holmium 164.93	<b>Er</b> Erbium 167.26	<b>Tm</b> Thulium 168.93	<b>Yb</b> Ytterbium 173.05	<b>Lu</b> Lutetium 174.97												
		7		<b>Ac</b> Actinium (227)	<b>Th</b> Thorium 232.04	<b>Pa</b> Protactinium 231.04	<b>U</b> Uranium 238.03	<b>Np</b> Neptunium (237)	<b>Pu</b> Plutonium (244)	<b>Am</b> Americium (243)	<b>Cm</b> Curium (247)	<b>Bk</b> Berkelium (247)	<b>Cf</b> Californium (251)	<b>Es</b> Einsteinium (252)	<b>Fm</b> Fermium (257)	<b>Md</b> Mendelevium (258)	<b>No</b> Nobelium (259)	<b>Lr</b> Lawrencium (266)												

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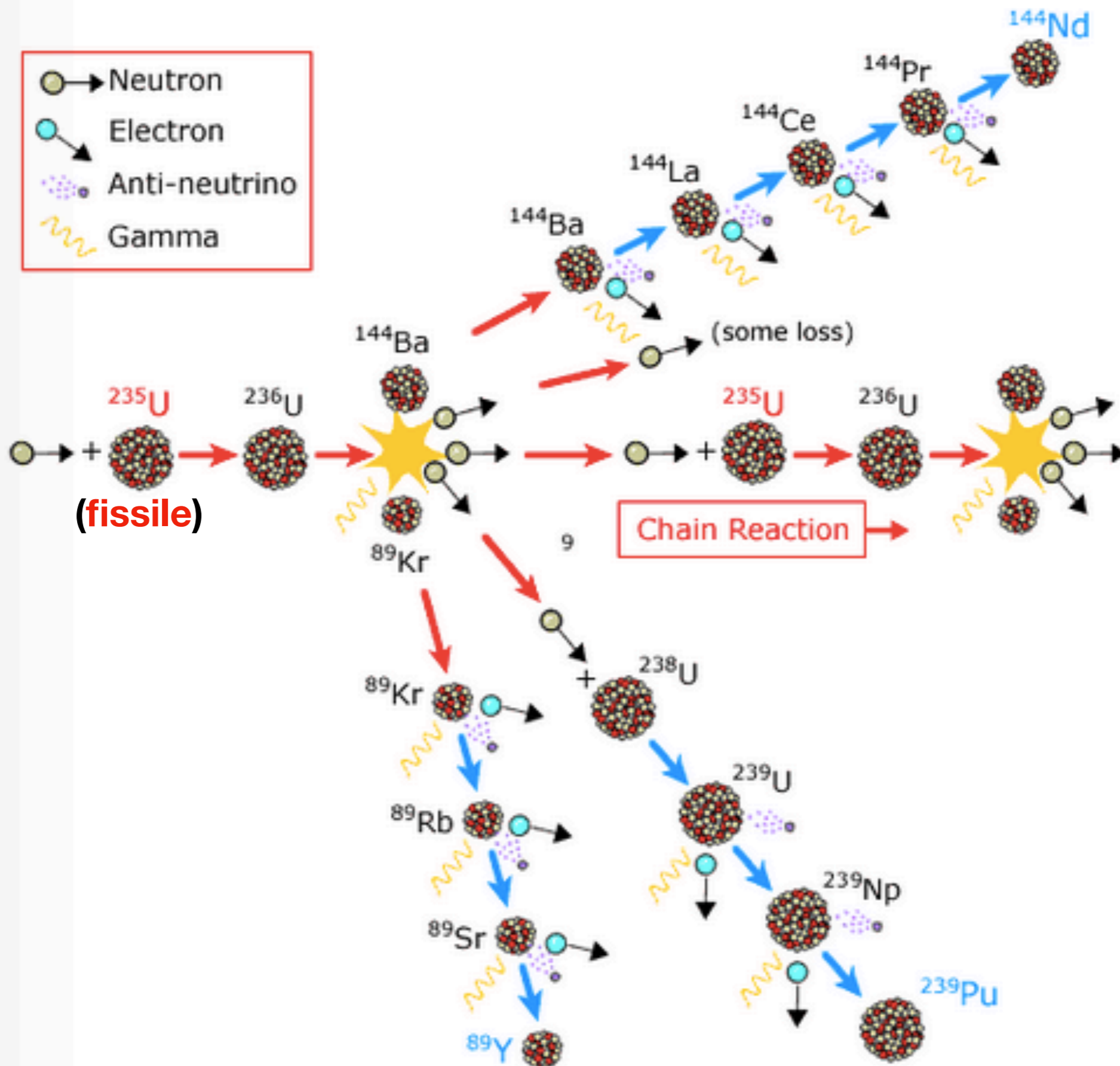
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4	<b>19</b> <b>K</b> Potassium 39.098	<b>20</b> <b>Ca</b> Calcium 40.078	<b>21</b> <b>Sc</b> Scandium 44.956	<b>22</b> <b>Ti</b> Titanium 47.867	<b>23</b> <b>V</b> Vanadium 50.942	<b>24</b> <b>Cr</b> Chromium 51.996	<b>25</b> <b>Mn</b> Manganese 54.938	<b>26</b> <b>Fe</b> Iron 55.845	<b>27</b> <b>Co</b> Cobalt 58.933	<b>28</b> <b>Ni</b> Nickel 58.693	<b>29</b> <b>Cu</b> Copper 63.546	<b>30</b> <b>Zn</b> Zinc 65.38	<b>31</b> <b>Ga</b> Gallium 69.723	<b>32</b> <b>Ge</b> Germanium 72.630	<b>33</b> <b>As</b> Arsenic 74.922	<b>34</b> <b>Se</b> Selenium 78.971	<b>35</b> <b>Br</b> Bromine 79.904	<b>36</b> <b>Kr</b> Krypton 83.798		
5	<b>37</b> <b>Rb</b> Rubidium 85.468	<b>38</b> <b>Sr</b> Strontium 87.62	<b>39</b> <b>Y</b> Yttrium 88.906	<b>40</b> <b>Zr</b> Zirconium 91.224	<b>41</b> <b>Nb</b> Niobium 92.906	<b>42</b> <b>Mo</b> Molybdenum 95.95	<b>43</b> <b>Tc</b> Technetium (98)	<b>44</b> <b>Ru</b> Ruthenium 101.07	<b>45</b> <b>Rh</b> Rhodium 102.91	<b>46</b> <b>Pd</b> Palladium 106.42	<b>47</b> <b>Ag</b> Silver 107.87	<b>48</b> <b>Cd</b> Cadmium 112.41	<b>49</b> <b>In</b> Indium 114.82	<b>50</b> <b>Sn</b> Tin 118.71	<b>51</b> <b>Sb</b> Antimony 121.76	<b>52</b> <b>Te</b> Tellurium 127.60	<b>53</b> <b>I</b> Iodine 126.90	<b>54</b> <b>Xe</b> Xenon 131.29		
6	<b>55</b> <b>Cs</b> Caesium 132.91	<b>56</b> <b>Ba</b> Barium 137.33	57-71	<b>72</b> <b>Hf</b> Hafnium 178.49	<b>73</b> <b>Ta</b> Tantalum 180.95	<b>74</b> <b>W</b> Tungsten 183.84	<b>75</b> <b>Re</b> Rhenium 186.21	<b>76</b> <b>Os</b> Osmium 190.23	<b>77</b> <b>Ir</b> Iridium 192.22	<b>78</b> <b>Pt</b> Platinum 195.08	<b>79</b> <b>Au</b> Gold 196.97	<b>80</b> <b>Hg</b> Mercury 200.59	<b>81</b> <b>Tl</b> Thallium 204.38	<b>82</b> <b>Pb</b> Lead 207.2	<b>83</b> <b>Bi</b> Bismuth 208.98	<b>84</b> <b>Po</b> Polonium (209)	<b>85</b> <b>At</b> Astatine (210)	<b>86</b> <b>Rn</b> Radon (222)		
7	<b>87</b> <b>Fr</b> Francium (223)	<b>88</b> <b>Ra</b> Radium (226)	89-103	<b>104</b> <b>Rf</b> Rutherfordium (267)	<b>105</b> <b>Db</b> Dubnium (268)	<b>106</b> <b>Sg</b> Seaborgium (269)	<b>107</b> <b>Bh</b> Bohrium (270)	<b>108</b> <b>Hs</b> Hassium (277)	<b>109</b> <b>Mt</b> Meitnerium (278)	<b>110</b> <b>Ds</b> Darmstadtium (281)	<b>111</b> <b>Rg</b> Roentgenium (282)	<b>112</b> <b>Cn</b> Copernicium (285)	<b>113</b> <b>Nh</b> Nihonium (286)	<b>114</b> <b>Fl</b> Flerovium (289)	<b>115</b> <b>Mc</b> Moscovium (290)	<b>116</b> <b>Lv</b> Livermorium (293)	<b>117</b> <b>Ts</b> Tennessine (294)	<b>118</b> <b>Og</b> Oganesson (294)		
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	<b>57</b> <b>La</b> Lanthanum 138.91	<b>58</b> <b>Ce</b> Cerium 140.12	<b>59</b> <b>Pr</b> Praseodymium 140.91	<b>60</b> <b>Nd</b> Neodymium 144.24	<b>61</b> <b>Pm</b> Promethium (145)	<b>62</b> <b>Sm</b> Samarium 150.36	<b>63</b> <b>Eu</b> Europium 151.96	<b>64</b> <b>Gd</b> Gadolinium 157.25	<b>65</b> <b>Tb</b> Terbium 158.93	<b>66</b> <b>Dy</b> Dysprosium 162.50	<b>67</b> <b>Ho</b> Holmium 164.93	<b>68</b> <b>Er</b> Erbium 167.26	<b>69</b> <b>Tm</b> Thulium 168.93	<b>70</b> <b>Yb</b> Ytterbium 173.05	<b>71</b> <b>Lu</b> Lutetium 174.97					
	<b>89</b> <b>Ac</b> Actinium (227)	<b>90</b> <b>Th</b> Thorium 232.04	<b>91</b> <b>Pa</b> Protactinium 231.04	<b>92</b> <b>U</b> Uranium 238.03	<b>93</b> <b>Np</b> Neptunium (237)	<b>94</b> <b>Pu</b> Plutonium (244)	<b>95</b> <b>Am</b> Americium (243)	<b>96</b> <b>Cm</b> Curium (247)	<b>97</b> <b>Bk</b> Berkelium (247)	<b>98</b> <b>Cf</b> Californium (251)	<b>99</b> <b>Es</b> Einsteinium (252)	<b>100</b> <b>Fm</b> Fermium (257)	<b>101</b> <b>Md</b> Mendelevium (258)	<b>102</b> <b>No</b> Nobelium (259)	<b>103</b> <b>Lr</b> Lawrencium (266)					

the Actinides

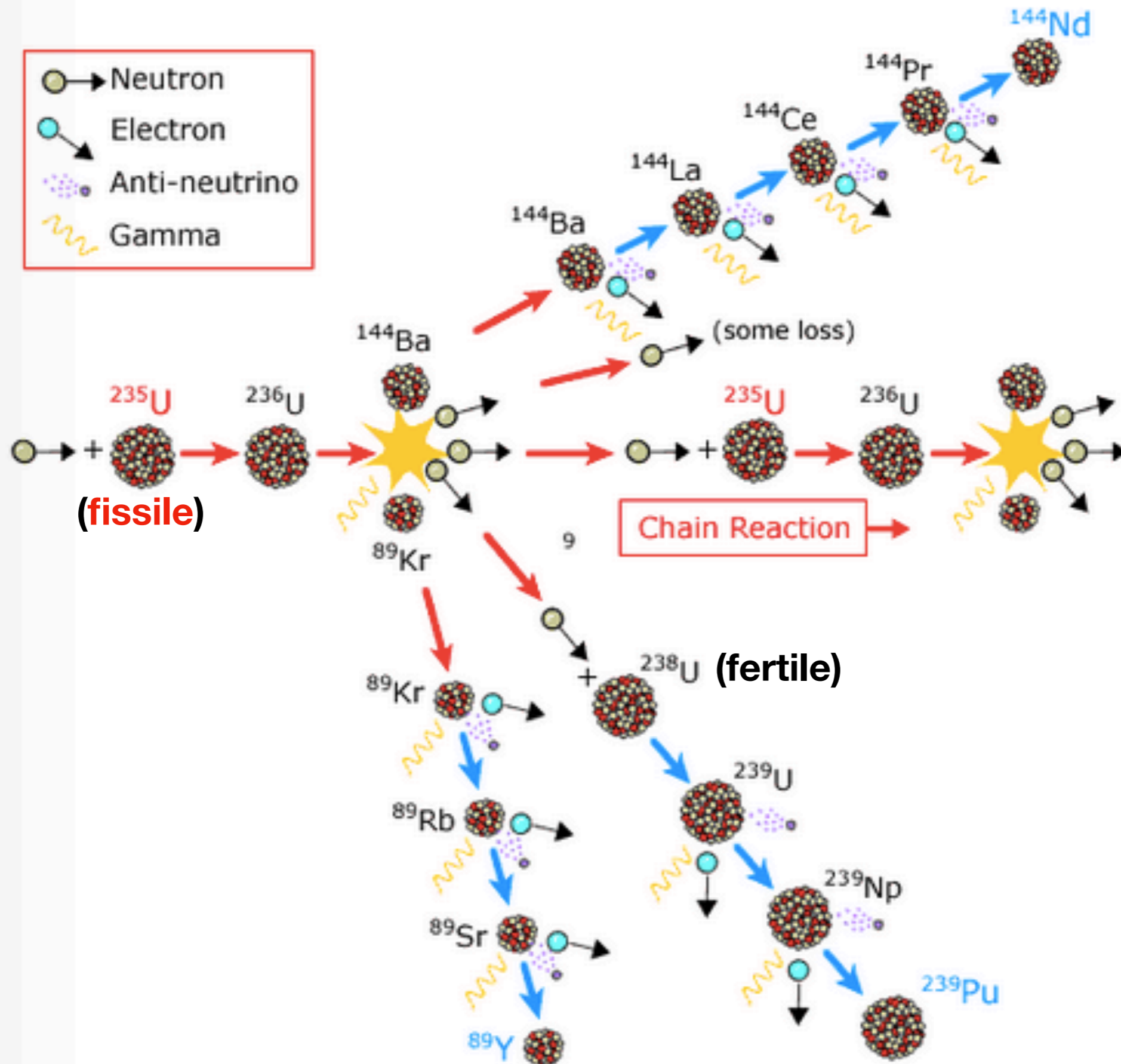
# Transmutation tricks with Neutrons:



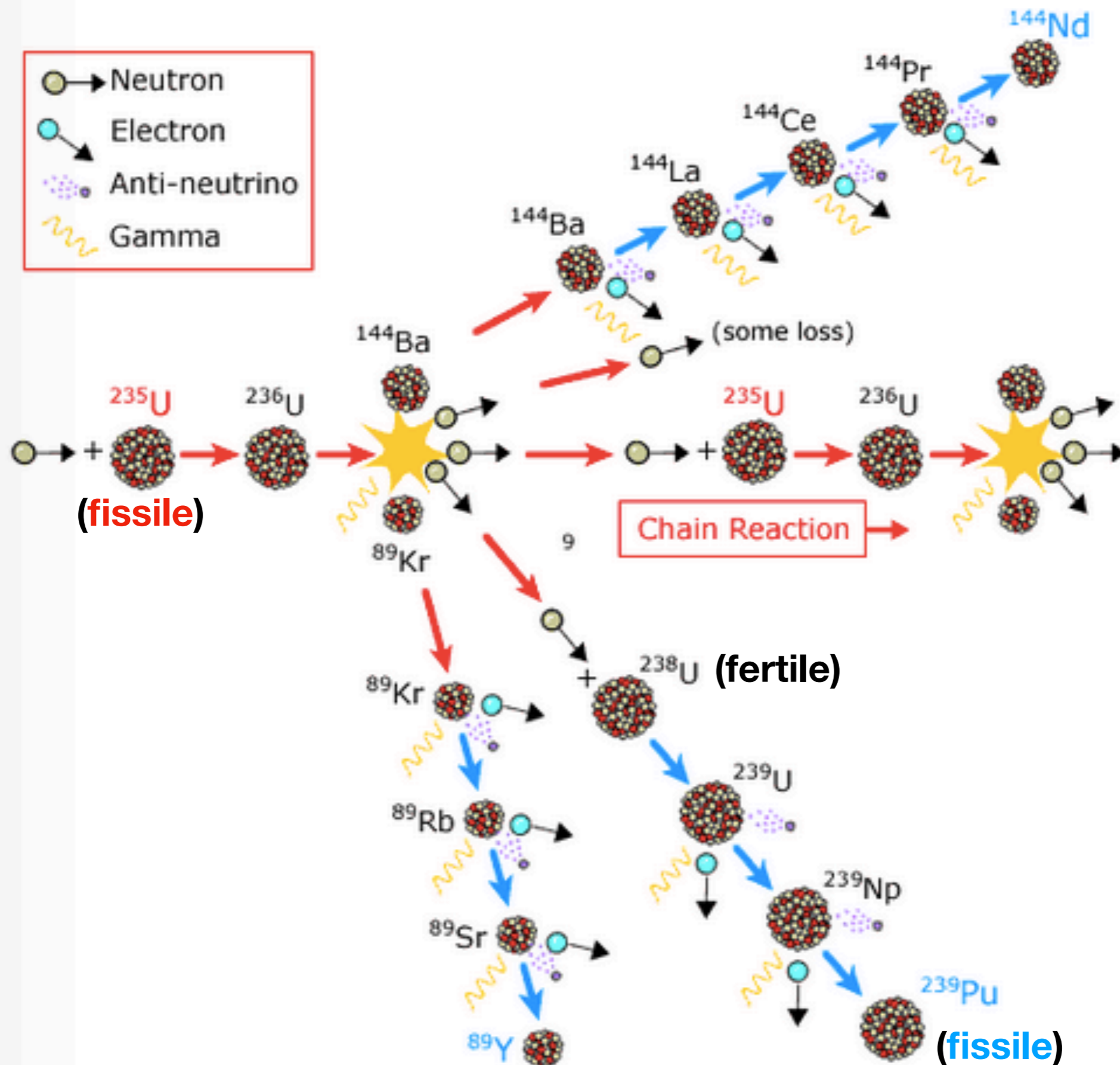
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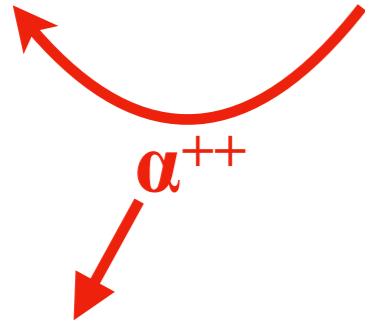


# Spontaneous Transmutation among the Actinides

89 <b>Ac</b> Actinium (227)	90 <b>Th</b> Thorium 232.04	91 <b>Pa</b> Protactinium 231.04	92 <b>U</b> Uranium 238.03	93 <b>Np</b> Neptunium (237)	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (266)
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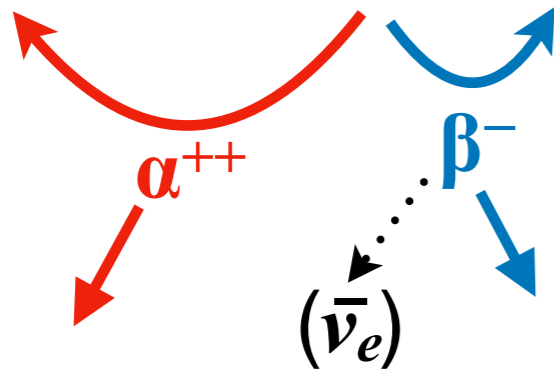
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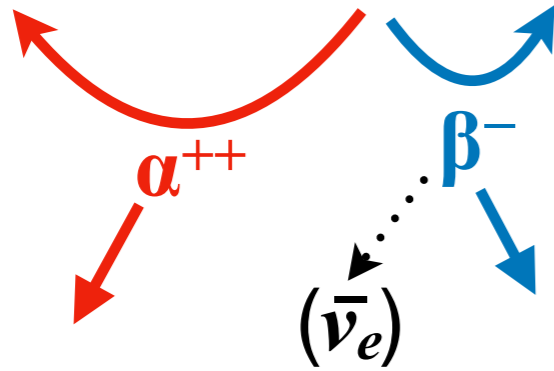
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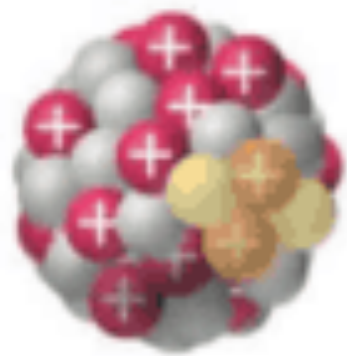
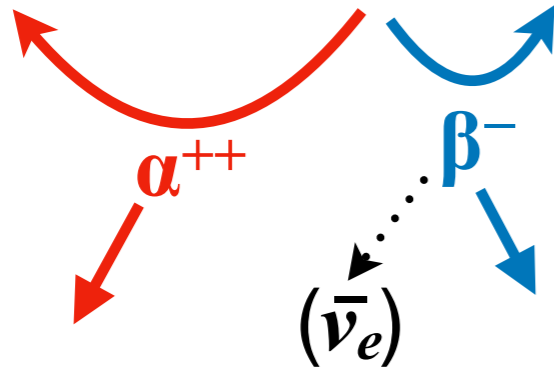
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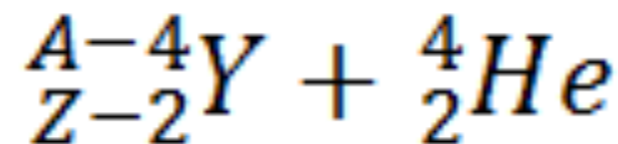
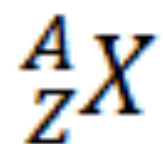
Parent



Daughter



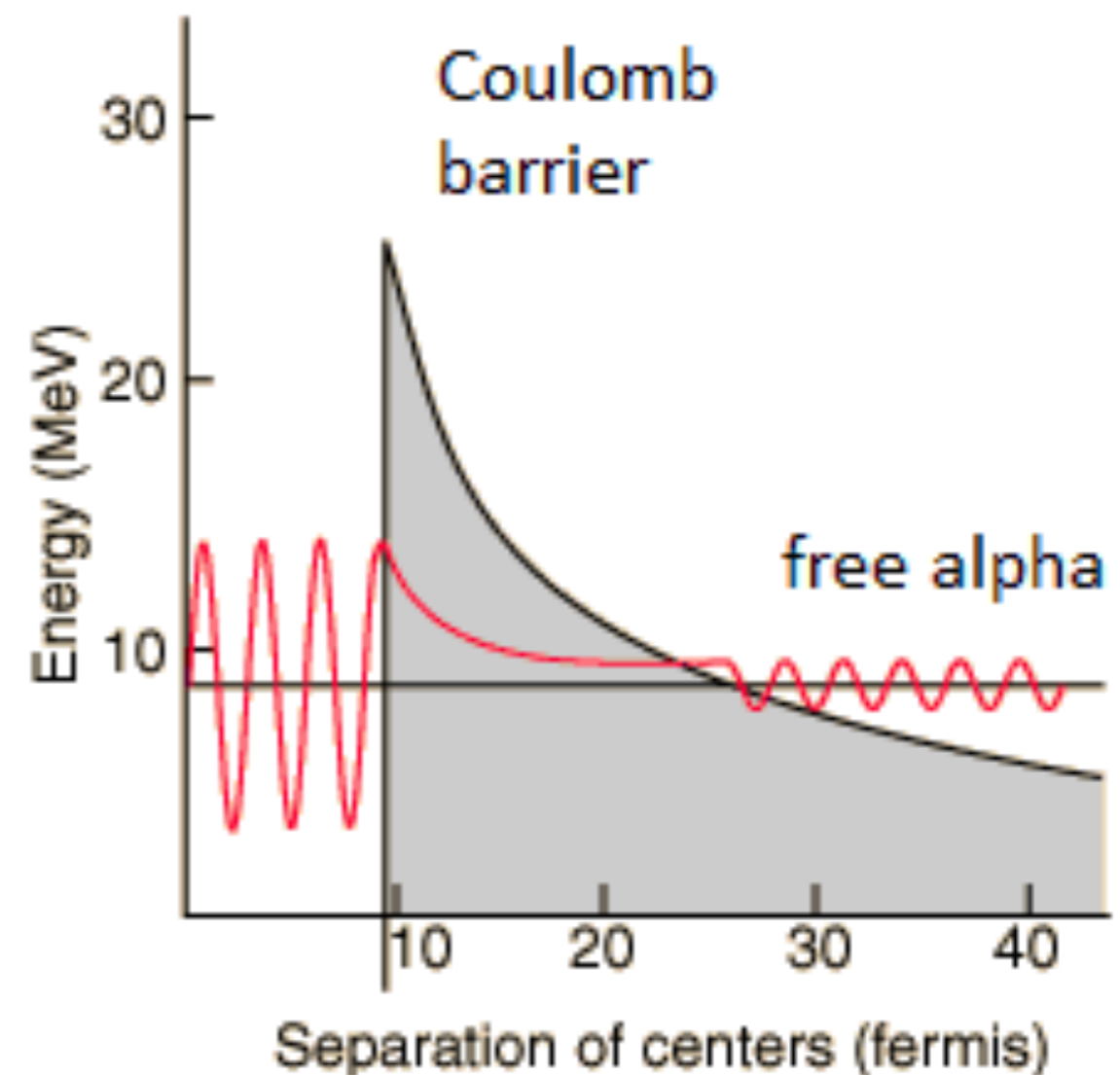
Alpha Particle



# Alpha Decay as Quantum Tunneling



The alpha particle (a helium nucleus, consisting of two protons and two neutrons strongly bound together) is rattling around inside the  $X$  nucleus without enough energy to get over the “Coulomb barrier”... unless it **tunnels through** the narrow barrier, leaving behind the  $Y$  nucleus.



Beta Decay as  $n \rightarrow p^+ + e^- + \bar{\nu}_e$



Beta Decay as  $n \rightarrow p^+ + e^- + \bar{\nu}_e$

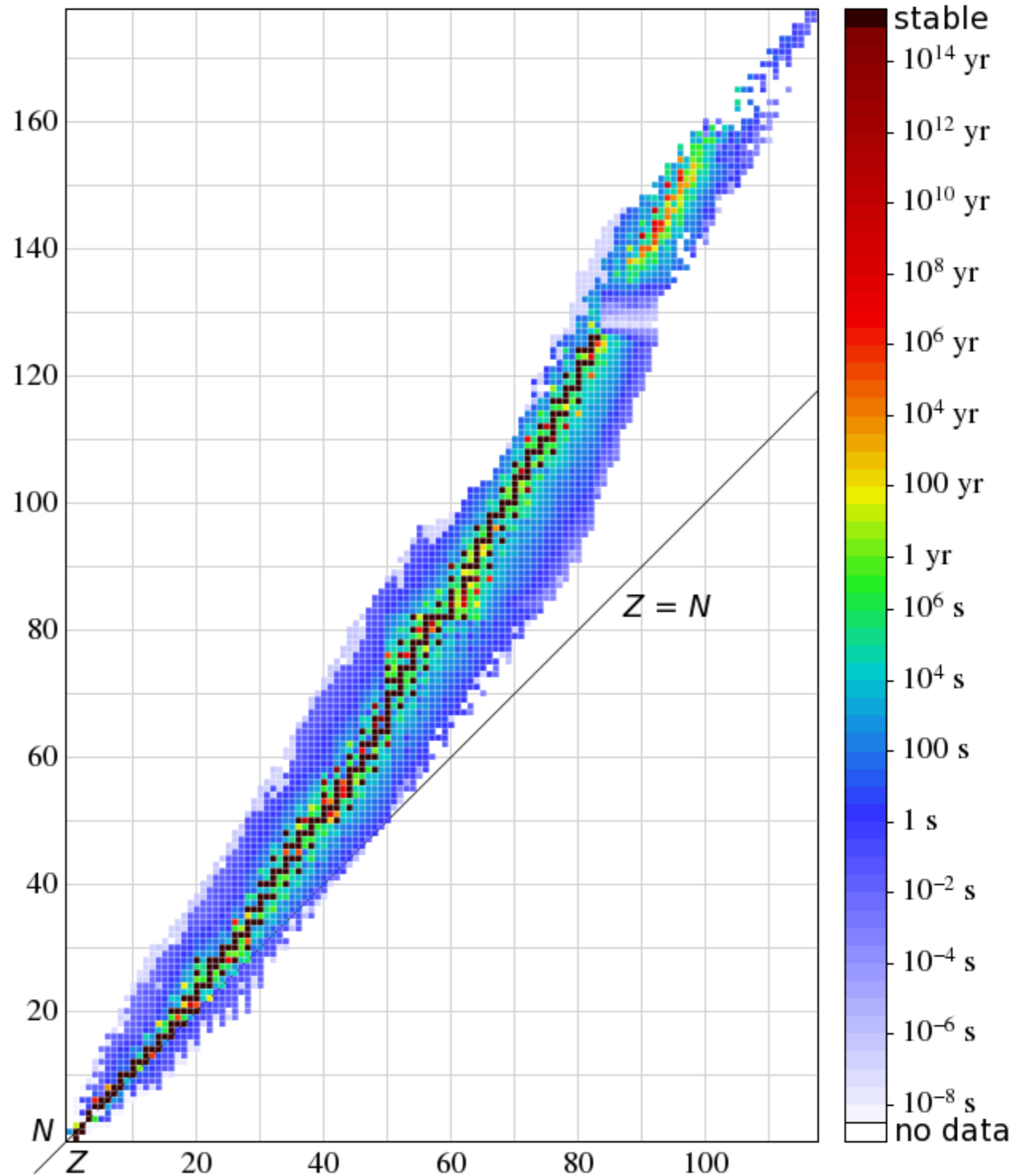




# ISOTOPES and their (color-coded) Half-Lives

**$Z$  = # of protons**

**$N$  = # of neutrons**



# Decay of Fission Products

Wikipedia: “The radioactivity in the fission product mixture is [initially] mostly *short-lived* isotopes such as  $^{131}\text{I}$  and  $^{140}\text{Ba}$ ; after about four months  $^{141}\text{Ce}$ ,  $^{95}\text{Zr}/^{95}\text{Nb}$  and  $^{89}\text{Sr}$  take the largest share, while after about two or three years the largest share is taken by  $^{144}\text{Ce}/^{144}\text{Pr}$ ,  $^{106}\text{Ru}/^{106}\text{Rh}$  and  $^{147}\text{Pm}$ .”

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## Medium-lived Daughters

Prop:	$t_{1/2}$	Yield	Q *	$\beta\gamma$ *
Unit:	(a)	(%)	(keV)	
$^{155}\text{Eu}$	4.76	0.0803	252	$\beta\gamma$
$^{85}\text{Kr}$	10.76	0.2180	687	$\beta\gamma$
$^{113\text{m}}\text{Cd}$	14.1	0.0008	316	$\beta$
$^{90}\text{Sr}$	28.9	4.505	2826	$\beta$
$^{137}\text{Cs}$	30.23	6.337	1176	$\beta\gamma$
$^{121\text{m}}\text{Sn}$	43.9	0.00005	390	$\beta\gamma$
$^{151}\text{Sm}$	88.8	0.5314	77	$\beta$

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$^{155}\text{Eu}$	4.76	0.0803	252	$\beta\gamma$
$^{85}\text{Kr}$	10.76	0.2180	687	$\beta\gamma$
$^{113\text{m}}\text{Cd}$	14.1	0.0008	316	$\beta$
$^{90}\text{Sr}$	28.9	4.505	2826	$\beta$
$^{137}\text{Cs}$	30.23	6.337	1176	$\beta\gamma$
$^{121\text{m}}\text{Sn}$	43.9	0.00005	390	$\beta\gamma$
$^{151}\text{Sm}$	88.8	0.5314	77	$\beta$

## Long-lived Daughters

Nuclide	$t_{1/2}$	Yield	Decay energy <sup>[a 1]</sup>	Decay mode
	(Ma)	(%) <sup>[a 2]</sup>	(keV)	
$^{99}\text{Tc}$	0.211	6.1385	294	$\beta$
$^{126}\text{Sn}$	0.230	0.1084	4050 <sup>[a 3]</sup>	$\beta\gamma$
$^{79}\text{Se}$	0.327	0.0447	151	$\beta$
$^{93}\text{Zr}$	1.53	5.4575	91	$\beta\gamma$
$^{135}\text{Cs}$	2.3	6.9110 <sup>[a 4]</sup>	269	$\beta$
$^{107}\text{Pd}$	6.5	1.2499	33	$\beta$
$^{129}\text{I}$	15.7	0.8410	194	$\beta\gamma$

# Health Concerns

Isotope	Radiation	Half-life	GI absorption	Notes
Strontium-90/yttrium-90	$\beta$	28 years	30%	
Caesium-137	$\beta, \gamma$	30 years	100%	
Promethium-147	$\beta$	2.6 years	0.01%	
Cerium-144	$\beta, \gamma$	285 days	0.01%	
Ruthenium-106/rhodium-106	$\beta, \gamma$	1.0 years	0.03%	
Zirconium-95	$\beta, \gamma$	65 days	0.01%	
Strontium-89	$\beta$	51 days	30%	
Ruthenium-103	$\beta, \gamma$	39.7 days	0.03%	
Niobium-95	$\beta, \gamma$	35 days	0.01%	
Cerium-141	$\beta, \gamma$	33 days	0.01%	
Barium-140/lanthanum-140	$\beta, \gamma$	12.8 days	5%	
Iodine-131	$\beta, \gamma$	8.05 days	100%	
Tritium	$\beta$	12.3 years	100%	[a]