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Nuclear Physics Basics and Terms

September 9, 2019

A primary goal of nuclear reactor analysis and design is the reliable prediction of neutron population production and loss rates. In order to fully describe neutron transport through media, we need to describe neutron motion and neutron interactions with matter.

To begin determining probabilities of neutron-nuclear reactions, we will first review the aspects of nuclear physics that are relevant for fission chain reactions.

Nuclear Physics of Chain Reactions

Notation reminder: ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}$ indicates that chemical element X has Z protons (atomic number) and A total nucleons (protons + neutrons; mass number). This leaves N neutrons.

Excited states are written as ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}^*$, and metastable/isomeric as ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}^m$.

There are two types of **basic nuclear transformations**:

1. spontaneous disintegration: The spontaneous decay of unstable nuclei, with emission of particles or radiation

$$X \rightarrow Y + y + Q$$

   These are probabilistic events that depend only on the type of nucleus.

2. induced by collision: An event in which, because of interaction with a particle or radiation (a projectile), a nucleus (target) is changed in mass, charge or energy state, and particles or radiation is emitted.

$$x + X \rightarrow Y + y + Q$$

Here, y and x are typically α, β, or γ and Q is energy.

<u>Examples</u> of common reactions:

- Potential elastic scattering (n, n): ${}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}$
- Resonance elastic scattering (n, n): ${}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \rightarrow ({}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}^{*}) \rightarrow {}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}$
- Inelastic scattering (n, n'): ${}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \rightarrow ({}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}^{*}) \rightarrow {}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} + \gamma$
- Radiative capture (absorption) (n, γ): ${}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \rightarrow ({}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}^{*}) \rightarrow {}^{\mathrm{A+1}}_{\mathrm{Z}}\mathrm{X} + \gamma$
- Fission (absorption) (n, f): ${}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \rightarrow {}^{\mathrm{A1}}_{\mathrm{Z1}}\mathrm{X} + {}^{\mathrm{A2}}_{\mathrm{Z2}}\mathrm{X} + (\text{a few}){}^{1}_{0}\mathrm{n}$
- Charged-Particle Reactions (absorption): (n, α) ${}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \rightarrow {}^{\mathrm{A-3}}_{\mathrm{Z-2}}\mathrm{Y} + {}^{4}_{2}\mathrm{He}$;
  (n, p) ${}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \rightarrow {}_{\mathrm{Z-1}}{}^{\mathrm{A}}\mathrm{Y} + {}^{1}_{1}\mathrm{p}$
- Neutron-Producing Reactions (absorption): $(n, 2n)$${}^{1}_{0}\mathrm{n} + {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \rightarrow {}^{\mathrm{A-1}}_{\mathrm{Z}}\mathrm{X} + 2{}^{1}_{0}\mathrm{n}$

Which reaction happens depends on the type of nucleus, the energy of the incoming neutron, and statistics. We can, fortunately, draw general categories for many types of reactions:

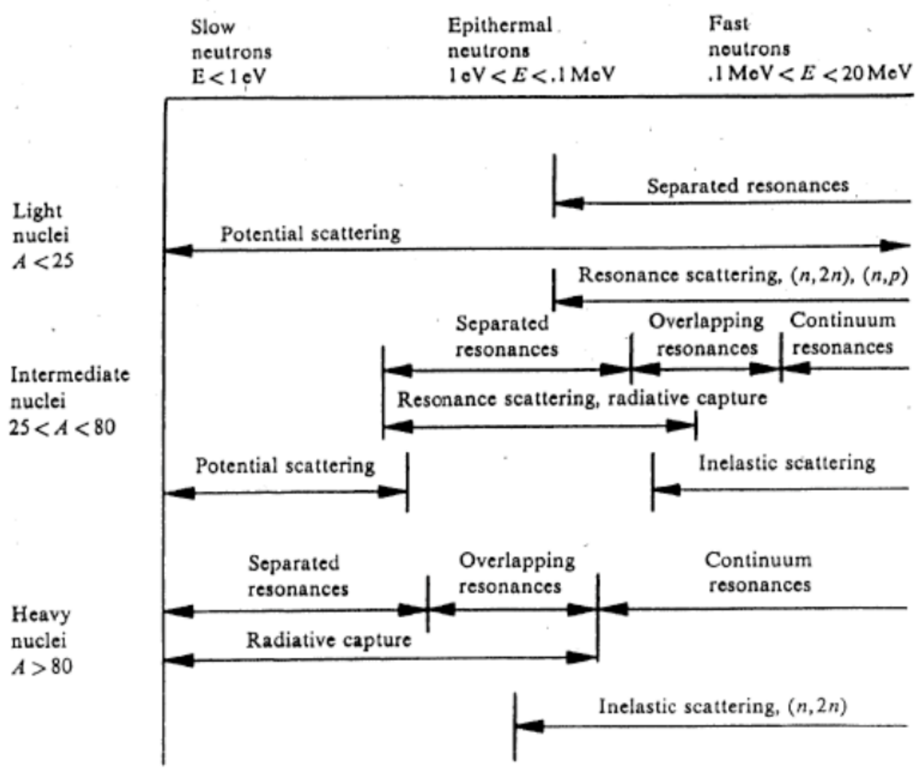

Figure 1: Neutron Interactions by Energy and Atomic Number

Nuclear reactions have to obey a set of **Conservation Laws**, which govern what actually happens in the transformations.

- Conservation of mass/energy: The total energy of the system before nuclear transformation must be equal to the total energy of the system after the transformation.
- Conservation of Linear Momentum: Total linear momentum of the system (a vector) before nuclear transformation must be equal to the total linear momentum of the system (a vector) after the transformation.
- Conservation of charge: Total charge of the system before nuclear transformation must be equal to the total charge of the system after the transformation.
- Conservation of nucleons: Total number of nucleons (protons and neutrons) of the system before nuclear transformation must be equal to the total number of nucleons (protons and neutrons) of the system after the transformation.

The conservation laws govern what reactions can happen. What reactions actually happen govern the neutron population in a reactor.

What we'll cover next are the definitions and terms we will use to describe neutrons in six-dimensional phase space: $(x, y, z, \hat{\Omega}, E)$.

Definitions

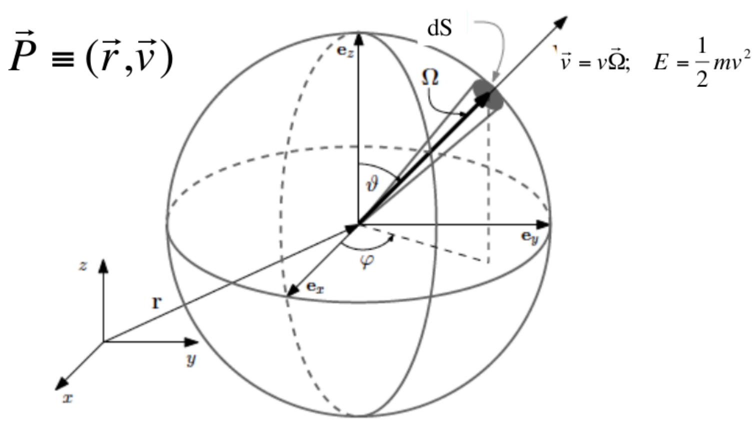

Figure 2: Schematic of Phase Space

Spatial logistics

- $d\vec{r} = d^3r$ = ordinary volume = $r^2 \sin(\theta) d\theta d\varphi dr$
- v = speed (scalar)

- $\vec{v}$ = $v\hat{\Omega}$ = velocity (vector)
- $d\vec{v} = d^3v$ = velocity volume = $v^2\sin(\theta)d\theta d\varphi dr$
- $v = \sqrt{(2E)/m}$ where m is the rest mass of the particle. Thus, we can relate energy and speed.
- $\hat{\Omega}$: unit directional vector in velocity space, $\vec{v} = v\hat{\Omega}$
- $d\hat{\Omega} = \sin(\theta)d\theta d\varphi = d^2\Omega$

These are the possible reactions we're generally going to worry about:

total (t): all interactions. We can break total into:

- scattering (s): a neutron interacts with an atom and bounces off either elastically or inelastically.
- absorption (a): a neutron is absorbed by a nucleus.
- fission (f): cause the nucleus to split into two pieces, releasing more neutrons.

Physics terms we will use:

1. **microscopic x-sec** (σ, [cm^2]): measure of the probability that an incident neutron will collide with a specific nucleus; σ_j indicates a specific reaction, e.g. $j = f$ is fission.
2. **macroscopic x-sec** (Σ [cm^{-1}]): measure of the probability per unit path length that an incident neutron will collide with a target

   $$\Sigma_j = \sigma_j N \ ,$$

   where N is the atomic density of the target. The total cross section is simply the sum of all possible reaction types, j.

   If a material is made of multiple isotopes, the material macroscopic cross section is also the sum over all materials, i:

   $$\Sigma_i(\vec{r}, E, t) = \sum_{j=1}^{J} N_j(\vec{r}, t)\sigma_{i,j}(E) \qquad \Sigma_t(\vec{r}, E, t) = \sum_{j=1}^{J}\sum_{i=1}^{I} N_j(\vec{r}, t)\sigma_{i,j}(E)$$