Nuclear Physics - Summary - Nuclear Properties

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This summary is based on the book Chapter 3.1-3.3 from Krane, Kenneth: Introductory Nuclear Physics.

1 Nuclear Radius

The nuclear radius is measured in two different ways:
- **mean radius**: where the density falls to half its central value. $R = R_0 A^{1/3}$
- **skin thickness**: the region where the density falls from 90% to 10%

There are two main ways to measure the nuclear radius. The **radius based on the charge distribution**, probed trough the electromagnetic (or Coulomb) force.
- **low energy scattering experiments:** the radius can be calculated from the distribution of the scattering angle
- **K X-ray energy differences (also called isotope shift)**: comparing the energy differences between isotopes, when the electrons shift from the L shell to the K shell.
- **muonic X-rays**: similar to the regular isotope shift, but with captured muons (μ^-) instead of electrons. This is more accurate since the higher mass of the μ compared to the e^- means a larger energy difference between the energy levels.
- **direct measurements of the Coulomb energy differences** between nuclei with **mirror nuclei**. Mirror nuclei have the same number of protons as the number of neutrons in the pair and the same number of neutrons as the number of protons in the other nucleus. Examples: ${}^3_1H_2$ and ${}^3_2He_1$; ${}^{13}_7N_6$ and ${}^{13}_6C_7$; ${}^{39}_{20}Ca_{19}$ and ${}^{39}_{19}K_{20}$. The energy difference is the measure of the Coulomb energy of the extra proton compared to the extra neutron in the mirror nuclei. This can be measured with
  - nuclear β decay where one of the protons changes to a neutron and emits a positron. The max energy of the e^+ is the energy difference.
  - nuclear reactions: if an element is bombarded with protons occasionally the proton gets captured and knocks out a neutron from the nucleus. The minimum p^+ energy needed for this is the energy difference.

Measuring the **nuclear density distribution**, trough the strong force.
- **high energy scattering experiments**. To probe the nuclear force, we need to overcome the Coulomb force first, we need higher energies for the scattering experiment.
- **radioactive decay**: the α decay probability depends on the radius of the nucleon.
- **π mesonic X-rays**: in this case π mesons get captured like and electron by the nucleus. First the π cascades down the "electron" shells to the lowest energy state. During this photons get emitted. Then the π can get absorbed into the nucleus and this disappearance rate can be used to measure the radius.

All methods to measure the nuclear radius give consistent results.

2 Nuclear Mass:

Ways to **measure the nuclear mass**:
- **mass spectrometer:** has the following components: ion beam, velocity selector (with E and B field), momentum selector (with B field). This is a relative measurement also called the **mass doublet method**. Suitable for most isotopes, except fast decaying radioactive materials.
- **nuclear reactions:** Suitable for fast decaying radioactive isotopes. Example: nuclear fission (x + X $\to y + Y$) By measuring the kinetic energy of the reacting particles, we can calculate the mass ratio of the particles, which can be used to measure the mass of one of the particles.

Nuclear abundances: All natural materials are composed of a certain mixture of isotopes.

Isotopes can be separated with the following methods:
- mass spectrometer
- laser isotope separation: works with two lasers. Laser 1 excites the target isotope, laser 2 ionises the target isotope. The ionised isotopes can be deflected with a B field and collected.

Nuclear binding energy: the difference in mass energy between ${}^{A}_{Z}X_N$ and its constituents Zp^{+} and Nn^{0}. This can also be expressed as the **mass defect** $\Delta = (m - A)c^2$

Neutron separation energy: the amount of energy that needs to be supplied to a nucleus to remove a neutron. This is the difference in binding energies between ${}^{A}_{Z}X_N$ and ${}^{A-1}_{Z}X_{N-1}$. Indicates shell structure of the nucleus.

Proton separation energy: the amount of energy that needs to be supplied to a nucleus to remove a proton. This is the difference in binding energies between ${}^{A}_{Z}X_N$ and ${}^{A-1}_{Z-1}X_N$.