NUCLEAR PROPERTIES

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NUCLEAR PROPERTIES

A nucleus can describe by *static* properties;

- Electric charge
- Radius
- Mass
- Binding energy
- Angular momentum
- Parity
- Magnetic dipole and electric quadrupole moments
- Energies of excited states

Dynamic properties;

- including decay and reaction probabilities

The Force Between Nucleons

- At short distances it is stronger than the Coulomb force; the nuclear force can overcome the Coulomb repulsion of protons in the nucleus.
- At long distances, of the order of atomic sizes, the nuclear force is negligibly feeble; the interactions among nuclei in a molecule can be understood based only on the Coulomb force.
- Some particles are immune from the nuclear force; there is no evidence from atomic structure, for example, that electrons feel the nuclear force at all
- The nucleon-nucleon force seems to be nearly independent of whether the nucleons are neutrons or protons. This property is called *charge independence.*

The Force Between Nucleons

- The nucleon-nucleon force depends on whether the spins of the nucleons are parallel or antiparallel.
- The nucleon-nucleon force includes a repulsive term, which keeps the nucleons at a certain average separation.
- The nucleon-nucleon force has a noncentral or *tensor* component. This part of the force does not conserve orbital angular momentum, which is a constant of the motion under central forces.
- The nucleon-nucleon force is charge *symmetric*.

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The density of nucleons and the nuclear potential have a similar spatial dependence-relatively constant over short distances beyond which they drop rapidly to zero.

It is therefore relatively natural to characterize the nuclear shape with two parameters: the mean radius, where the density is half its central value, and the “skin thickness,” over which the density drops from near its maximum to near its minimum.

The radius that we measure depends on the kind of experiment we are doing to measure the nuclear shape. These experiments can be divided into two main classes:

A) The nuclear methods

B) The electromagnetic methods

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The radius of the nucleus obtained by the first method is called the nuclear force radius and is defined as the distance from the center of the nucleus at which an incoming particle comes under the influence of the nuclear force.

The radius of the nucleus obtained by the electromagnetic method is called the charge radius. The charge density is uniform from the center of the nucleus up to a certain distance, beyond which the charge density, instead of falling sharply to zero, trails off as shown in Figure 6.1 (Fundamentals of Nuclear Physics by Atam P. Arya.)

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In some experiments, such as high-energy electron scattering, muonic X rays, optical and X-ray isotope shifts, and energy differences of mirror nuclei, we measure the Coulomb interaction of a charged particle with the nucleus. These experiments would then determine the *distribution* of *nuclear charge.*

In other experiments, such as Rutherford scattering, α decay, and pionic X rays, we measure the strong nuclear interaction of nuclear particles, and we would determine the distribution of nucleons, called the *distribution* of *nuclear matter.*

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The density of nuclear material can be calculated if we know the mass and the volume of the nucleus. We assume that the nucleus is spherical in shape, and that the protons and the neutrons are arranged in such a way as to give a uniform spherical mass-distribution. The name given to the model is the *liquid-drop* model of the nucleus because the picture of the nucleus is similar to that of a drop of liquid.

The volume of the nucleus V is given by,

$$V = \frac{4\pi R^3}{3}$$

where R is the radius of the nucleus.

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The central nuclear charge density is nearly the same for all nuclei. Nucleons do not seem to congregate near the center of the nucleus, but instead have a fairly constant distribution out to the surface

Thus the number of nucleons per unit volume is roughly constant:

$$\frac{A}{\frac{4\pi}{3}R^3} \sim constant$$

The analysis of all the existing experimental data has resulted in the following expression for the nuclear radius.

$$R = r_0 A^{1/3}$$

where r_0 is a constant, and A is the mass number.

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The value of r_0 depends on the experimental technique used for evaluating the nuclear radius and varies from 1.2×10^{-13} cm to 1.48×10^{-13} cm.

From electron scattering measurements, it is concluded that $r_0 \cong 1.2$ fm. The density of the nuclear material

$$\rho = \frac{M}{V} = \frac{M}{\frac{4\pi}{3} R^3} = \frac{M}{\frac{4\pi}{3} r_0^{\,3} A}$$

where M is the mass of the nucleus.

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Even though we must analyze the energy balance in nuclear reactions and decays using nuclear masses, it is conventional to tabulate the masses of neutral atoms. It may therefore be necessary to correct for the mass and binding energy of the electrons.

The measurement of nuclear masses occupies an extremely important place in the development of nuclear physics. Mass spectrometry was the first technique of high precision available to the experimenter in separating isotopes with slight differences in their atomic masses.

To determine the nuclear masses and relative abundances in a sample of ordinary matter, which even for a pure element may be a mixture of different isotopes, we must have a way to separate the isotopes from one another by their masses.

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To measure masses to precisions of order 10^{-6} requires instruments known as *mass spectroscopes*.

The separated masses may be focused to make an image on a photographic plate, in which case the instrument is called a *spectrograph;* or the masses may pass through a detecting slit and be recorded electronically (as a current, for instance), in which case we would have a *spectrometer.*

(See Fig 3.13 in Introductory Nuclear Physics by Kenneth S. Krane for a schematic diagram of a typical mass spectrograph)

All mass spectroscopes begin with an *ion source*, which produces a beam of ionized atoms or molecules. The next element is a *velocity selector*, consisting of perpendicular electric and magnetic fields.

NUCLEAR MASSES

The ***E*** field would exert a force qE that would tend to divert the ions upward (See Figure 3.13 in Introductory Nuclear Physics by Kenneth S. Krane); the ***B*** field would exert a downward force qvB. Ions pass through undeflected if the forces cancel, for which

$$qE = q\upsilon B \qquad , \qquad \upsilon = \frac{E}{B}$$

The final element is a momentum selector, which is essentially a uniform magnetic field that bends the beam into a circular path with radius r determined by the momentum:

$$m\upsilon = qBr \qquad , \qquad r = \frac{m\upsilon}{qB}$$

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Since *q*, *B*, and *v* are uniquely determined, each different mass m appears at a particular *r*. Often the magnetic fields of the velocity and momentum selectors are common, in which case

$$m = \frac{qrB^2}{E}$$

In practice we could calibrate for one particular mass, and then determine all masses by relative measurements. The fixed point on the atomic mass scale is ^{12}C, which is taken to be exactly 12.000000 u. It would be preferable to measure the smaller difference between two nearly equal masses.

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For example, let us set the apparatus for mass 128 and measure the difference between the molecular masses of C_9H_{20} (nonane) and $C_{10}H_8$ (naphthalene). This difference is measured to be **Δ=** 0.09390032 ± 0.00000012 u. Neglecting corrections for the difference in the molecular binding energies of the two molecules (which is of the order of 10^{-9} u), we can write

$$\Delta = m\left(C_9H_{20}\right) - m\left(C_{10}H_8\right) = 12m\left({}^1H\right) - m\left({}^{12}C\right)$$

Thus

$$m\left({}^1H\right) = \frac{1}{12}\left[m\left({}^{12}C\right) + \Delta\right] = 1.00000000 + \frac{1}{12}\Delta = 1.00782503 \pm 0.0000001u$$

NUCLEAR MASSES

Given this accurate value we could then set the apparatus for mass 28 and determine the difference between C_2H_4 and N_2:

$$\Delta = m\left(C_2H_4\right) - m\left(N_2\right) = 2m\left({}^{12}C\right) + 4m\left({}^{1}H\right) - 2m\left({}^{14}N\right)$$

$$= 0.025152196 \pm 0.000000030u$$

from which we find:

$$m\left({}^{14}N\right) = m\left({}^{12}C\right) + 2m\left({}^{1}H\right) - \frac{1}{2}\Delta = 14.00307396 \pm 0.00000002u$$

This system of measuring small differences between close-lying masses is known as the *mass doublet* method, and you can see how it gives extremely precise mass values.

It is also possible to determine mass differences by measuring the energies of particles in nuclear reactions.

Measurement of Masses From Nuclear Disintegration Data

Consider the nuclear reaction x + X → y + Y, in which a projectile x is incident on a stationary target X. By measuring the kinetic energies of the reacting particles, we can determine the difference in masses, which is known as the Q value of the reaction:

$$Q = \left[\left(M_X + m_x \right) - \left(M_Y + m_y \right) \right] c^2$$

For example, consider the reaction $^{1}H + {}^{14}N \rightarrow {}^{12}N + {}^{3}H$. From mass doublet measurements we know that m(^{1}H) = 1.007825 u, m(^{14}N) = 14.003074 u, and m(^{3}H) = 3.016049 u.

The measured Q value is -22.1355 ± 0.0010 MeV. We thus deduce

$$m\left({}^{12}N\right) = m\left({}^{1}H\right) + m\left({}^{14}N\right) - m\left({}^{3}H\right) - \frac{Q}{c^2} = 12.018613 \pm 0.000001 u$$

REFERENCES

1. Introductory Nuclear Physics. Kenneth S. Krane

2. Fundamentals of Nuclear Physics. Atam. P. Arya