1) The nucleus

The model of the nucleus as a compact object with radius of order 1 fm = $10^{-15}$ m including positively charged particles with charge values that are multiples of the electric charge was understood from the results of Rutherford scattering and our understanding of atomic structure.

This picture left several mysteries.

a) Why did we observe the nuclear masses that we see? For instance, why was Helium four times more massive than hydrogen rather than twice?

b) How did you bind the positively charged particles together when they should have a strong electromagnetic repulsion?

c) How to explain other “radiation” emitted by the nucleus. Gamma rays (energetic photons above x-ray energies), beta particles (electrons and positrons), alpha particles (helium nuclei).

4) Nuclear composition.

Some simple possibilities to answer the mystery of the nuclear masses of the atoms were:

i) The nucleus was composed of positive particles with charge $\frac{1}{2} e$. This was discarded since the mass only approximately progressed as $2Z$. Especially some of the least and the most massive elements diverge. H Z=1 has an atomic mass of 1 not 2. Li, Z=3, has a mass of ~7 atomic units, not 6. Uranium Z=92 has a mass of 238.

ii) The nucleus included bound positive particles and electrons making and additional “neutral” particles. This was a popular idea because it was shown that the one type of particle emitted by the nucleus, beta particles, were electrons by analyzing their properties. Typical beta particles energies were on order a few MeV when emitted by the nucleus. This was energetic compared to typical atomic transition energies, which were up to keV. Quantum mechanics, rejected this idea since an electron bound in 1 fm area would have an energy on order 100MeV. Also there would have to be some new strong interaction to explain why the electron would be bound in a new very small orbital and no evidence for such an interaction has been seen.

This issue was mostly resolved with the discovery of the neutron. Bombarding light elements with alpha radiation produced a new type of radiation. A forth type of radiation that the nucleus can emit. These particles were neutral like the gamma rays. However, by analyzing their kinematic interactions with protons in hydrogen atoms it was found that they appeared to be massive with a mass similar to the proton.
The introduction of this new particle resolved the first mystery and the idea that the atoms were composed of \( A=N+Z \) particles where \( N \) is the number of neutrons was consistent with the data.

Also the neutron hypothesis was consistent with spin arguments. The proton, neutron and electron all have spin \( \frac{1}{2} \) and act as fermions. If you analyze the total spin of the Nitrogen nucleus you find that it is integer.

If for Nitrogen: \( N+Z=A: \) 7 + 7 = 12 spin \( \frac{1}{2} \) particles will give integer total spin.
If for Nitrogen: \( N+Z+\#e: \) 7 + 7 + 7 = 21 spin \( \frac{1}{2} \) particles will give half integer spin.
If you “pack” them in a box they would have different energies in the two hypotheses.

Aside: interestingly it is possible to “collapse” the electron into the proton forming a neutron in the presence of the strong compacting force. This is what happens to form a neutron star where the compacting force is the gravitational attraction.

Note that this explanation explains the mass and composition of the nucleus but not the other fundamental questions. In addition, it introduces the questions of what the neutron is why a neutral particle would bind in a nuclei.

2) Study of the nucleus

In this chapter we will concentrate on the composition, energy states and interactions of the nucleus. Note that the basic questions do have answers that we will study in detail later.

b) Protons (and neutrons) bind into nuclei due to a force called the strong force.

c) The emission of beta rays will be understood by studying a third force (strong and EM the first two and putting gravity last ordered by strength) known as the weak force. The emission of other types of radiation gamma, alpha, and neutrons will be understood by studying the structure and energy levels of the nucleus.

Study of the nuclear gamma ray spectrum indicated the presence of

a) Quantized energy states
b) Angular momentum (orbital and spin)
c) Magnetic moments (with energy splitting’s expected due to b and c)

All of this could be inferred from the spectrum that includes larger primary energy level separations and lesser splitting’s of those energy levels. The structure of the splitting’s was more complex, unsurprisingly due to presence of two types of nucleon.

Simple stuff
A number of nucleons, \( \sim \) mass number (same A isobars)
\( Z \) number of protons, atomic number (same \( Z \) isotopes)
\[ \frac{AX}{ZPN} = AX \]

3) Nuclear size

Nuclear size is a fundamental parameter for nuclear physics. The physics of the nuclear wave function should be determined by the potentials of the EM force and the strong force. The functional form and strength of those potentials will determine the primary characteristics of the nuclear wave function and thus the structure of the nuclear.

Another important factor is the spin of the nucleons, \( \frac{1}{2} \), making them fermions. The clearest observable feature of the nuclei is the radii. Since the structure of the nucleus and the form of the strong potential where unknown this type of information was used to understand the form of the potential.

The simplest methods of measuring the nuclear radii is Rutherford scattering using alpha particles or, later, electrons at high enough energy to reach the limit of the point like structure of the nucleus.

For alpha particles once you approach the nuclear size the alpha particles will start to interact via the strong force. The EM interaction predicted in the Rutherford equations is inversely proportional to the kinetic energy squared while the strong interaction falls more quickly. This information directly indicated that a second, different force/potential was involved. Note you can also study this with neutrons.
For scattering electron you do not observe effects due to the strong force since only the nucleons interact via this force. As we stated earlier there was no evidence for a strong force that bound protons and electrons together.

Once the wavelength of the probe becomes of order the nuclear radius you start to observe diffraction effects. At that energy you observe the simple diffraction pattern you expect from a circular hole (or object in this case)

The first minimum in the diffraction pattern is given by

\[ \sin \theta = 0.16 \lambda / R \]

At higher energies, high enough to be of order the separation distance between nucleons, you can observed diffraction effects due to the internal structure of nucleus.