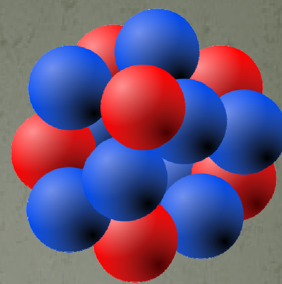
Neutron Scattering

Atomic nucleus



The **nucleus** is the very dense region consisting of protons and neutrons at the center of an atom. A model of the atomic nucleus showing it as a compact bundle of the two types of nucleons: protons (red) and neutrons (blue).

Basic properties of the neutron

The neutron is a nuclear particle with a mass rather close to that of the proton

$$m_n = 1.675 \quad 10^{-27} \text{ kg.}$$

The neutron does not exist naturally in free form, but decays into a proton, an electron, and an anti-neutrino. The neutron lifetime, $\tau = 886$ s , is much longer than the time of a neutron within a scattering experiment, where each neutron spends merely a fraction of a second. The neutron is electrically neutral but still possess a magnetic moment

$$\mu = \gamma\mu N,$$

where $\gamma = -1.913$ is the neutron magnetogyric ratio and the nuclear magneton is given by

$$\mu N = e\hbar/m_p$$

The neutron interacts with nuclei via the strong nuclear force and with magnetic moments via the electromagnetic force.

Particle-wave duality

In neutron scattering experiments, neutrons behave as particles when they are created, as waves when they scatter, and again as particles when they are detected. To be more specific, a particle moving with constant velocity, v, can be ascribed a corresponding (de-Broglie) wavelength, given by

$$\lambda = 2\pi\hbar/mv$$

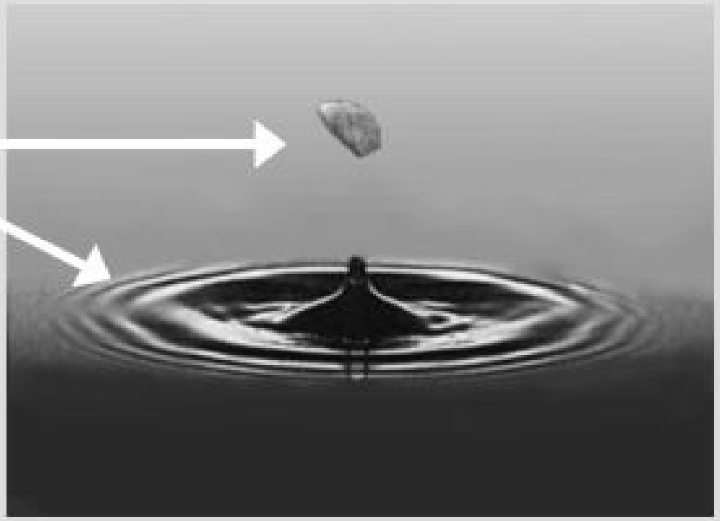
where the Planck constant is $\hbar = 1.034 * 10{-}34$ Js. In neutron scattering, the wave nature is often referred to in terms of the neutron wave number,

$$k = 2\pi / \lambda,$$

or the wave vector of length k and with same direction as the velocity:

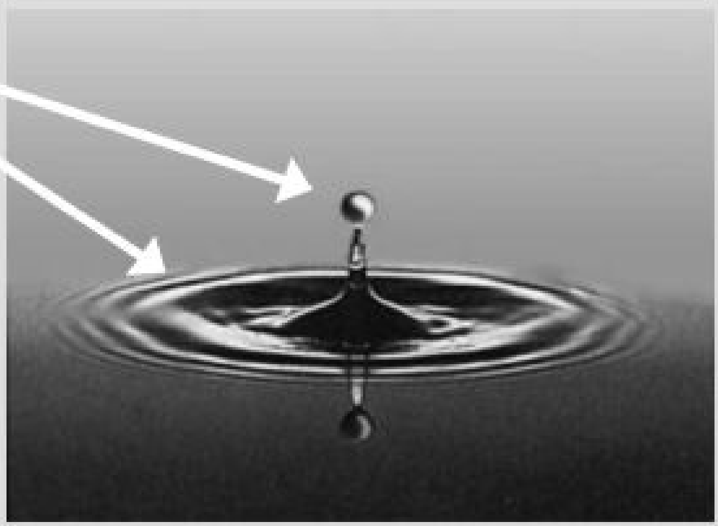
$$k = mv/\hbar$$

Example 1:
A stone
and a water wave
are of different matter.



In that case, the wave-particle duality can't be explained.
It is an enigma.

Example 2:
A drop of water (corpuscle)
and a water wave
are of identical matter.
Water has either a corpuscle behavior or a wave behavior.



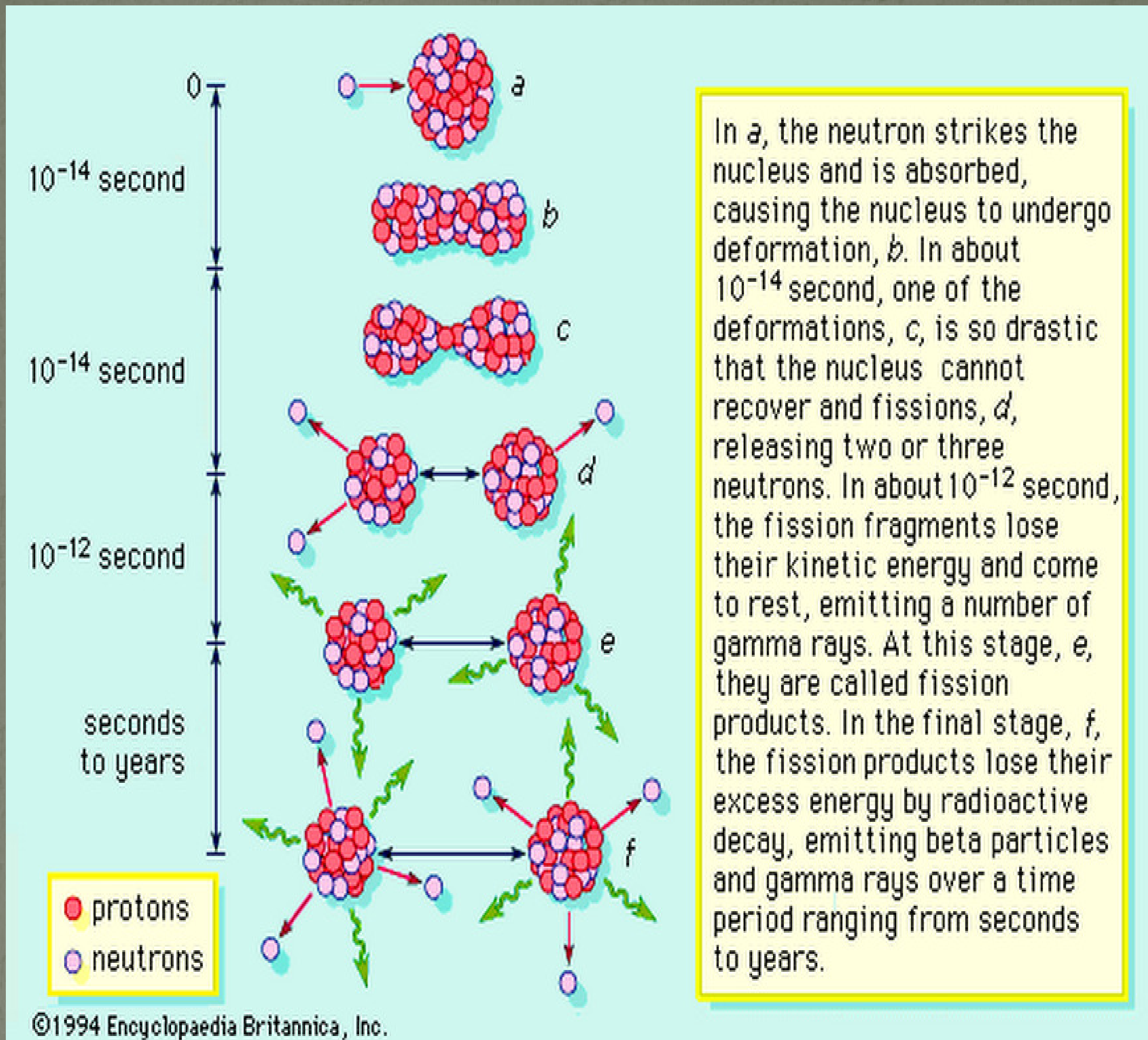
In this particular situation, wave-particle duality is explained with logic and consistency.

Introduction to neutron scattering

Neutron scattering, the scattering of free neutrons by matter, can refer to either the physical process or the experimental technique which uses this process for the investigation of materials. Neutron scattering as a physical process is of primordial importance in nuclear engineering. Neutron scattering as an experimental technique is used in crystallography, physics, physical chemistry, biophysics, and materials research.

Neutron scattering is one of the most powerful and versatile experimental methods to study the structure and dynamics of materials on the nanometer scale.

Neutron scattering is the technique of choice for condensed matter investigations in general because thermal/cold neutrons are a non-invasive probe; they do not change the investigated sample since they do not deposit energy into it.


0
10^{-14} second
10^{-14} second
10^{-12} second
seconds to years
a
b
c
d
e
f
protons
neutrons
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In *a*, the neutron strikes the nucleus and is absorbed, causing the nucleus to undergo deformation, *b*. In about 10^{-14} second, one of the deformations, *c*, is so drastic that the nucleus cannot recover and fissions, *d*, releasing two or three neutrons. In about 10^{-12} second, the fission fragments lose their kinetic energy and come to rest, emitting a number of gamma rays. At this stage, *e*, they are called fission products. In the final stage, *f*, the fission products lose their excess energy by radioactive decay, emitting beta particles and gamma rays over a time period ranging from seconds to years.

Basic idea of neutron scattering experiment:

Neutron sources

Research reactor

$^{235}U + n \rightarrow A + B + 2.3n$ *(A, B: fission fragments)*

→ chain reaction, keeps going by itself until "fuel" (uranium enriched by ^{235}U) *is exhausted → source of both* ***energy (nuclear power reactors) and neutrons (research reactors)***

Neutron detectors

Since neutrons are electrically neutral, they are difficult to detect directly. One therefore converts them into charged particles via a nuclear reaction such as:

$n + 3He \rightarrow 3H + p$

The protons are collected by a high electric field and converted into electric current.

Another type of neutron detector is based on a gas of

$^{10}BF3$. ^{10}B *has a high neutron capture cross section via the nuclear reaction*

$n + {}^{10}B \rightarrow {}^{7}Li + {}^{4}H$

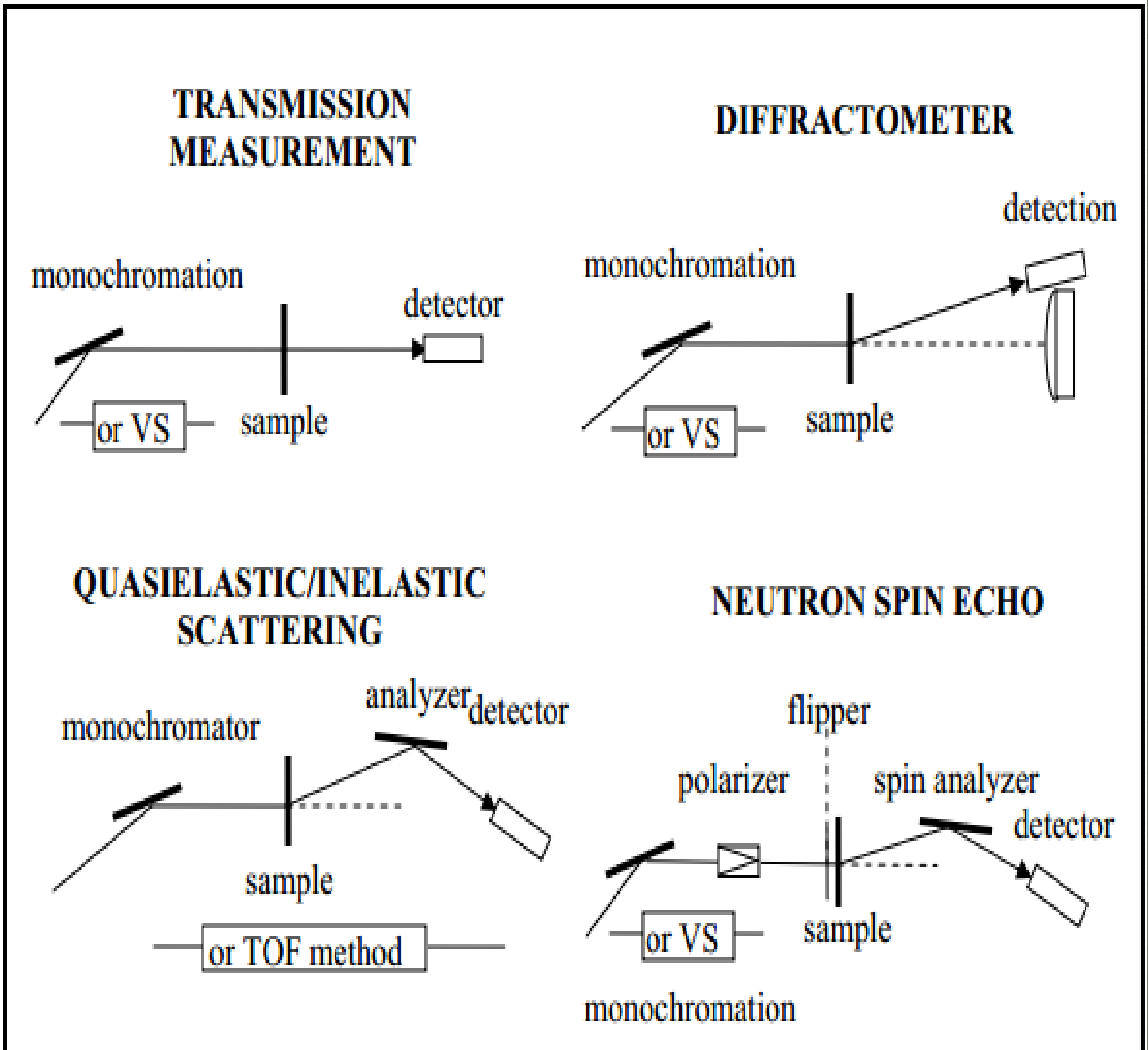
The energetic nuclei produced in this reaction ionize gas molecules, which are again collected by a high electric field.

TYPES OF NEUTRON SCATTERING

There are four main types of neutron scattering.

(1) **The simplest type** consists in a measurement of the sample transmission. This measurement requires a monochromatic beam (or the time-of-flight method), some collimation and a simple neutron detector (end-window counter). Transmission measurements contain information about the sample content and the relative fractions of the various elements. For example, the relative ratio of carbon to hydrogen in crude oils (the so-called cracking ratio) could be measured accurately.

(2) **Elastic neutron scattering** consists in measuring the scattered intensity with varying scattering angle. This is a way of resolving the scattering variable $Q = (4\pi/\lambda) \sin(\theta/2)$ where λ is the neutron wavelength and θ is the scattering angle. This is performed by either step-scanning or using a position-sensitive detector. The main types of elastic scattering instruments are diffractometers (either for single-crystal, powder diffraction or for diffuse scattering from amorphous materials), reflectometers and SANS instruments. Diffractometers probe the high Q range ($Q > 0.5$ Å^{-1}) whereas reflectometers and SANS instrument cover the low-Q range ($Q < 0.5$ Å^{-1}). They all investigate sample structures either in crystalline of amorphous systems.


TRANSMISSION MEASUREMENT
monochromation
detector
or VS
sample
DIFFRACTOMETER
detection
monochromation
or VS
sample
QUASIELASTIC/INELASTIC SCATTERING
monochromator
analyzer
detector
sample
or TOF method
NEUTRON SPIN ECHO
flipper
polarizer
spin analyzer
detector
or VS
sample
monochromation

(3) **Quasielastic/inelastic neutron scattering** consists in monochromation, collimation, scattering from a sample, analysis of the neutron energies then detection. The extra step uses a crystal analyzer (or the time-of flight method) in order to resolve the energy transfer during scattering. Quasielastic scattering corresponds to energy transfers around zero, whereas inelastic scattering corresponds to finite energy transfers. The main types of quasielastic/inelastic spectrometers are the triple axis, the time-of-flight, and the backscattering spectrometers. These instruments cover the μeV to meV energy range. They investigate sample dynamics and structure. Inelastic instruments are used to investigate phonon, optic and other types of normal modes. Quasielastic instruments are used to investigate diffusive modes mostly.

(4) **The spin-echo instrument** is another type of quasielastic spectrometer. It is singled out here because it measures correlations in the time (not energy) domain. It uses polarized neutrons that are made to precess in the pre-sample flight path, get quasielastically scattered from the sample, then are made to precess again but in the other direction in the post-sample flight path. A neutron spin analyzer keeps track of the number of spin precessions. The difference in the number of spin precessions before and after the sample is proportional to the neutron velocity change during scattering and therefore to the energy transfer. Scanned Q ranges are between (0.01 $Å^{-1}$ and 0.5 $Å^{-1}$) and probed times are in the nanoseconds range. This instrument is useful for investigating diffusive motions in soft materials.

Inelastic neutron scattering is an experimental technique commonly used in condensed matter research to study atomic and molecular motion as well as magnetic and crystal field excitations. It distinguishes itself from other neutron scattering techniques by resolving the change in kinetic energy that occurs when the collision between neutrons and the sample is an inelastic one. Inelastic scattering experiments normally require a mono chromatization of the incident or outgoing beam and an energy analysis of the scattered neutrons. This can be done either through time-of-flight techniques (neutron time-of-flight scattering) or through Braggs reflection from single crystals (neutron triple-axis spectroscopy, neutron back scattering).