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# Neutron Interactions with Matter

Neutrons are subatomic particles with zero net charge and a mass comparable to that of a proton. A single neutron is made up of three quarks, one up and two down. The composite quarks accolade to its lack of electric charge, the positive charge of one up quark (+2/3e) cancels the negative charge of two down quarks (2x-1/3e).

The four fundamental forces in physics are: the electromagnetic, the gravitational, the strong and the weak force. Neutrons are mainly affected by the latter two, the nuclear forces. Being neutral, they do not interact electromagnetically, and effects of gravity become insignificant in the shadow of nuclear interactions. The strong and weak force operate at a nuclear level and become effective only when the neutron is in close proximity of the other reacting particle; the strong force becomes effective at cm and the weak force closer still at cm. The former is responsible for holding quarks together (to form nucleons) as well as binding protons and neutrons (to form atomic nuclei), while the latter is liable for fusion reactions and atomic-radioactive decay.

The different types of interactions a neutron can have with matter are illustrated in figure ??

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## Elastic scattering (n,n)

A neutron has zero charge and does have to overcome any Coulomb barriers and low energy neutrons can scatter elastically from the nucleus. A neutron can scatter in one of two ways: resonance/compound elastic scattering and potential elastic scattering.

The first involves the incident neutron being absorbed in the nucleus and forming a compound nucleus. The resultant nucleus subsequently re-emits a neutron. *The energy of the neutron and the nucleus are conserved; after neutron emission the emitted neutron has the same kinetic energy as the incident neutron and the nucleus is in ground state.* Why the term "resonance" is used to describe the interaction will soon become apparent (hint: it has something to do with the cross-section dependency on neutron-energy and nuclear structure of the compound nucleus).

The second way is potential elastic scattering. The incident neutron is deflected off the surface of the target nucleus by the short-range nuclear force. The scattering processes are illustrated in figure ??.

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1. *Resonance elastic scattering: a neutron is absorbed and re-emitted. The neutron energy is conserved.*

*A picture containing electronics, device

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1. *Potential elastic scattering: a neutron scatters of the nuclear surface. The neutron energy is reduced.*

Neutrons with energies up to ~1MeV experience potential elastic scattering. The cross-section is nearly constant and can be expressed with the relation to the nuclear radius R

During the collision the neutron transfers a fraction of its energy to the nucleus and in the process, it gets deflected from its initial path. Initially at rest, the nucleus gains momentum from the energy transfer. After the collision the interacting neutron energy is reduced. The ration of the energy transferred to the incident neutron energy can be derived by applying the momentum and energy conservation laws of classical mechanics:

where is initial neutron energy, is the energy transferred and is the atomic mass number of the target nucleus. From equation ? It is apparent that the energy transfer depends on the number of nucleons inside the nucleus. Neutrons colliding with elements of low mass number lose a significant amount of energy. Inside materials of low atomic mass neutrons are effectively slowed down by elastic neutron-nuclei collision. This is why materials such as water and paraffin are often used to reduce the neutron speed (and energy).

## Inelastic scattering (n,n')

During inelastic scattering the target nucleus absorbs the incident neutron and is elevated to an excited nuclear state. The excited nucleus emits a neutron with energy lower than the initial neutron energy and continues to decay by gamma-ray emission until it reaches a stable state - in contrast to resonance elastic scattering where the nucleus is already in a stable state after neutron emission. Some of the initial neutron energy is absorbed by the nucleus and the emitted neutron energy is less than the initial neutron energy, hence the excited nuclear state after neutron emission.

Neutron capture depends on the initial neutron energy. The process requires the neutron energy to be of ample magnitude such that when the neutron is absorbed (and its energy transferred) the compound nucleus exists in one of its excited states. Because of this the inelastic scattering cross-section is zero up to a given threshold value. Lighter elements usually have higher values of nuclear excitation energies (WHY), while heavy elements have minimum excitation energies between 0.1 MeV to 1 MeV. High atomic mass nuclei are more prone to inelastic scattering and cover a larger region of energies with which the process can take place.

### Thermal Neutrons

Neutrons in matter either scatter, merge with nuclei or escape the material. In a material that does not absorb neutrons and under the assumption that alle neutrons are contained in the volume in question, the only interaction possible is scattering. Neutron-nuclei scattering causes slowing down of neutrons; a neutron experiences energy loss with each scatter event. Neutrons with kinetic energy less than the energy corresponding to the materials thermal motion may gain energy from the collision. When the probability of energy loss is the same as energy gain the neutrons are in thermal equilibrium. With scattering being the only neutron interaction (meaning neutron-capture and -escape do not occur) the interacting neutrons conform to the atoms thermal motion. In conformity with the theory of gases, the average kinetic energy of thermal motion of the atoms is:

where k is the Boltzmann constant and T the temperature. The atomic energy follows a Maxwellian-Boltzmann distribution (or just Maxwellian distribution). With it, one can express the most probable neutron velocity and kinetic energy as

At 20C (i.e. 293 K), from the above equations, the corresponding velocity and energy becomes 2200 m/s and 0.025 eV.

## Radiative capture (n, )

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Capture reactions start with the absorption of a neutron and (in the majority of the reactions) results in the emission of one or several gamma rays. The nuclear reaction is also referred to as neutron capture.

In neutron capture a nucleus merges with a neutron to form a compound nucleus. The resultant nucleus is in an elevated nuclear state. It rids itself of excess energy by radiating prompt gammas.

Unlike inelastic scattering, radiative capture can transpire for neutrons of all energies.

The cross-section is a function of the neutron energy and indicates three appropriately labeled energy regions, depicted in Figure ??. For low-energy neutrons, the probability of most capture reactions is inversely proportional to the square root of the neutron energy. Since the kinetic energy is a function of speed, this means that is proportional to . Neutrons have to be in close proximity in order to be absorbed by a nucleus and the more time they spend near the nucleus the more probable absorption becomes. Slow neutrons take more time to pass the nucleus and are thus more likely of being absorbed. Furthermore, the reaction probability can also be expressed in terms of the surrounding temperature , since energy can also be expressed in terms of temperature (see section ??). To summarize: . The low energy region (or **-region**) extends from 0 to 0.5 eV - also known as the *Cadmium cutoff*, because of Cadmium’s characteristic and sudden drop in cross-section at this value.

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The following region spans over neutron energies for which the cross-section experiences resonance. The **resonance region** starts where the low energy region ends (at 0.5 eV) and stretches up to 100 keV. The energies where resonance peaks occur are comparable to the energy levels of the compound nucleus.

In Figure ?? The correspondence between resonance cross-sections and nuclear level diagram of a compound nucleus.is shown The probability of forming a compound nucleus drastically increases if the incident neutron energy results in the compound nucleus being in one of its excited states.

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Resonance in the neutron cross-section correspond to the formation of excited states of the compound nucleus. (Total neutron cross-section and energy level diagram for O-17.) From [].

Most neutrons are created with a much larger energy (200 keV-20 MeV) and these are labeled as fast neutrons. Here the cross-section quickly and continuously drops to very small values. Moving into the fast neutron region, the likelihood of nuclear reactions lessens, and the probability of elastic scattering takes over.

## Particle emission

## Fission

## Neutron emission

### Gamma-Ray Decay

Gamma-ray decay occurs when an excited nucleus releases emission of electromagnetic radiation (a photon).

The nucleus can emit one or more gamma rays. The emitted photon can take on energies from few keVs to several MeVs, the upper limit being the starting nuclear excitation energy. If a single is emitted, all of the excess nuclear energy is transferred to the photon. If several gamma rays are released, the nucleus undergoes multiple gamma transitions before reaching ground state. The transition energy, , of an intermediate transition is equal to the energy difference in the final and initial nuclear energy state.

The energy diagram of a hypothetical nucleus and gamma transitions between its energy levels are illustrated in Figure??. Low-lying levels are easily distinguishable, each with a known spin and parity, they are discrete. As the excitation energy increases so does the nuclear level density. High lying levels eventually become indistinguishable from one another and resemble a continuum. Energy levels within the quasicontinuum are marked by dotted lines and the discrete domain with uninterrupted lines. There is no clear boundary between the continuous and discrete domain, but rather a smooth transition between the two. The highest energy level represents neutron capture state and the lowest level ground state, both are indicated by a bold uninterrupted line. A transition from one level to another is indicated by and arrow. A nucleus may transition once or several times before it reaches the ground state. Transitions can occur between (1) states in the continuous domain, (2) states in the discrete domain or (3) between the two.

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Each energy level features a distinct spin and parity and during the transition both must be conserved. Spin and parity are represented by the symbols [[1]](#footnote-1) and , respectively (NB: “1” indicates a footnote). The aforementioned properties are usually presented together as spin-parity denoted as . The parity of the radiated photon is the difference in parity of the initial and final transition states.

The total angular momentum of the initial and final energy state can be labeled as and and change in the spin as . The minimum angular momentum of a photon is one unit and thus the transitions where are forbidden. Possible values of the released lie in the range

What is my point…?

### Internal Conversion

Alternatively, the atom de-excite by means of internal conversion (IC), the direct emission of an orbital electron. IC and gamma emission are competing decay modes. The ratio of IC decay rate $\lambda\_{ICe^-}$ to gamma decay rate $\lambda\_{\gamma}$ can be described by the internal conversion coefficient (ICC) $\alpha$:

The coefficient becomes small in cases where gamma decay is preferred and large when IC is preferred. The probability of IC depends on the electron shell (K,L, M, …) and each shells therefore have respective coefficients (*αK, αL, αM*). Transition levels of lower energy favor internal conversion. Inner shell electrons, such as those from the K shell, are more likely to interact directly with the nucleus, since their wavefunction has finite probability of penetrating the nucleus. The probability of IC in a shell becomes less likely the further away it lies from the nucleus. In other words, IC depends heavily on the atomic electron density inside the nucleus. Consequently, odds of nuclear interaction with the K-shell is more likely than with the L-shell, than the M-shell and so on.

The total ICC is the ratio of total number of IC electrons to gamma-rays emitted by a nucleus and it can be expressed as a sum of the shell coefficients:

The energy of an IC electron is determined by the available transition energy and the binding energy of a shell.

### X-rays and Auger Electrons

When a conversion electron is expelled from subshell *m* a vacancy is left behind. Still in an excited state, the atom undergoes further de-excitation. An electron from a higher subshell (>) descends and fills the vacancy, releasing atomic excitation energy by either emission of x-rays or Auger electrons. X-ray emission occurs when the transition energy goes into electromagnetic radiation. Difference in binding energy makes up the x-ray energy.

On the other hand, the transition energy may go into freeing an electron of an intermediate subshell n where n lies between shell m and p. This is called Auger electron and has energy equal to the difference in transition energy and binding energy.

## Neutron-beam attenuation

A beam of N neutrons incident upon a target will exit the target with fewer neutrons. While traversing the target some of the neutrons are absorbed in the material. The number of neutrons N\_0 passing through the absorber is given by Lambert-Beers law, which states that

The absorption coefficient is characteristic of the material and neutron energy. It is inversely proportional to the mean free path . The chance of a neutron escaping the absorber is the ratio of escaped neutrons to incident neutrons () and the absorption probability can be expressed as

The probability of being absorbed increases for neutrons where the absorber thickness is relatively large to the mean free path.

# Electrons Interaction with Matter

**More elsewhere:** The detector under consideration is sensitive to charged particles. From radiative capture in gadolinium, conversion electrons are produced with energies from tens of keVs to hundreds of keVs. These electrons are the source term (of the signals registered by) in the detector.

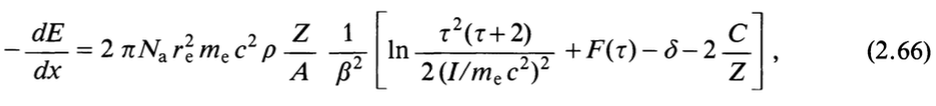
Electrons are charged particles and are affected by Coulomb forces. They interact with matter through elastic collisions (no energy loss) and inelastic collisions (energy loss). During a collision the electron loses energy and/or changes direction.

An incident electron can interact with atomic electrons and atomic nuclei of the material. Atomic electrons are negatively charged and repulse incident electrons. On the other hand, nuclei are positively charged and attract electrons. Elastic electron-nucleon collisions result in scattering of the electron without it losing any energy; its trajectory is merely altered, and its energy unaffected. The incident electron can also scatter from orbital electrons without losing energy.

The more interesting scenarios, however, are inelastic and involve electron energy loss *as such interactions leave a mark and can easily be observed by particle detectors*. Inelastic collisions with atomic electrons imply energy transfer from the incident electron to the atomic electron. With the nucleus, inelastic collisions of the incident electron result in bremsstrahlung (German for "break radiation"). In the nuclear electric field, the electron is attracted to the nucleus and deviates from its straight-line path. As a result of the acceleration (change in velocity vector) the electron radiates electromagnetic waves. The electromagnetic radiation comes at the expense of electron kinetic energy and the electron consequently slows down. The total energy loss of an interacting electron can thus be expressed as the sum of two energy loss terms: collisional loss and radiation loss.

## Collision loss and Bethe-Bloch

The Bethe Bloch formula models the average energy loss per unit length of charged particles. It is based on the assumption of heavy incident particles (e.g. protons and ions) and not light particles like electrons. Scattering of the incident particle can be ignored when its mass outweighs the target mass. The Bethe-Bloch is also applicable for electrons. H**owever**, some modifications must be made in order to correct for their small mass, scattering effects and the fact that collisions can occur between identical particles. The Bethe-Bloch corrected for electrons is:



Where:

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From the expression above one can derive the maximum possible energy loss for a single collision W\_max=T\_e/2 where T\_e/2 is the incident electron kinetic energy; in a single collision an electron can lose up to half of its energy. Two factors and their effect on energy loss are worth noting: electron speed and atomic number of the reacting material. In equation ?? the relationship between energy loss and incident kinetic energy becomes apparent; the linear energy loss is inversely proportional to electron speed (i.e. ). As its speed decreases the electron is more easily deprived of its energy. Moreover, high Z material slow down electrons more effectively than low Z material.

Radiation loss, a few sentences

Figure

As illustrated by figure ??, collision loss varies logarithmically and radiation loss linearly with energy. Electrons of energies less than 10 MeV predominantly lose energy through inelastic collisions with atomic electrons. As the electron energy steadily increases bremsstrahlung loss becomes the main loss term.

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## The CSDA range

The energy loss per unit path length, or stopping power, can be used to calculate the distance it takes to slow an electron down to a given energy. The calculation assumes continuous energy loss and the resultant range is appropriately named continuous slowing down approximation range, or CSDA range. [creditable reference?! [\*](https://xdb.lbl.gov/Section3/Sec_3-2.pdf)]

## Backscattering of low-energy electrons

Electrons not only experience inelastic collisions but also **elastic collisions from nuclei**. Since their mass is comparably insignificant to a nucleus it can be assumed that no energy transfer takes place and that the electron energy stays intact. Most of the collisions deflect the particle with a small angle. The particle zigzags its way through the material and the multiple scattering events build up to a net deflection from the initial particle trajectory, as illustrated in figure 1b.

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**Multiple Coulomb scattering** involve an average number of scattering events greater than 20 events. In such cases, one can apply statistical methods to the problem and acquired a probability distribution for the net angle of deflection as a function of the thickness of material traversed. (Most of which model small-angle scattering, angles of ~30, and are inapplicable for slow electrons, where <0.05, and electrons in large Z materials)

Electrons are especially exposed to large-angle deflections because of their small mass, so much so that the accumulated effect can be a 180 deg net deflection; the electron backscatters out of the material in the opposite direction as it entered (Fig??a). The effect is largely present for **low energy electrons** and continuously increases in **higher Z materials**. Figure ?? Illustrates the increased effect of backscattering in heavier materials. The **incident angle** also determines the probability of backscattering, where particles traveling parallel to the surface normal are less probable of turning around than those traveling at an angle to the normal.

Proposed by Tabat et al., the fraction of backscattered electrons to incident electrons as a function of energy takes on an S-shaped curve as shown in Fig??. The fraction is known as the backscattering coefficient and its relationship to may be expressed as in Eq??. Where are functions of , the atomic number of the material, and are constants independent of . [Tabat et al., 1971]

Al (<100keV): approx 13% backscattered

Air?

Backscattering can pose as a problem in detectors which rely on electron induced signals. Depending on detector material and geometry, a large fraction of incident electrons can be lost due to the effect and consequently reduce device efficiency drastically. [William R. Leo] 🡨 the whole electron section

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## Energy Straggling

Charged particles in matter mainly lose energy from inelastic collisions with atomic electrons

The mean linear energy loss (dE/dx) can be calculated with Bethe-Bloch.

While the model gives a good approximation to the average energy loss of a monoenergetic particle beam, it does not provide information on the various amounts of energy lost by individual particles of the beam.

Because particle scattering is a statistical phenomenon and follows a probability distribution, the number of collisions made by same-energy particles differ and so does the amount of energy lost by each particle. The small variation in energy loss is known as energy straggling.

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**Gauss**

A monoenergetic beam striking an absorber with a single energy exits the absorber with a shifted and spread-out energy distribution.

If each particle was to lose exactly dE/dx (beam average loss) the final beam energy would merely be shifted dE/dx lower than the initial.

In actuality, the exiting beam shows a spread out and shifted version of the discrete incident beam-energy. The exiting energy distribution is strictly related to the various energy loss of beam particles.

For heavy-charged particles (heavier than one atomic unit) in relatively thick (compared to the particle range) absorbers the energy loss takes on a Gaussian shape.

[Gaussian model Eq. And fig]?

A gaussian fit is applicable in cases where the number of collisions is large (which it is when the absorber is thick compared to particle range). This stems from the Central Limit Theorem in statistics which states that the sum of N random variables (e.g. particle collisions), subject to the same statistical probability, converges towards that of a gaussian-distributed variable as N approaches infinite (e.g. a very large number of collisions).

|  |  |
| --- | --- |
| A close up of text on a white background  Description automatically generatedFigure Energy loss distribution skewed right towards lower energies as particle energy and number of mean free paths (mfp) in the absorber increases. f) Slow particle: Gaussian spread, a) Fast particle: Landau spread. a -f: number of mfp in absorber. | A screenshot of a cell phone  Description automatically generated  Typical energy loss distribution of electrons. From [Dr. Leo R. William] |

**Landau**

As the absorber slims down and number of charged particle collisions decrease a Landau distribution becomes a more appropriate fit. In a slim absorber, traversing particles scatter less and the majority lose smaller energy portions than for the thick absorber case. Although slimmer, the probability of losing a large amount of energy in a single collision is still noticeable.

This causes an asymmetrical distribution where the most probable loss lies at low energies behind a tail of less probable higher-energy losses. The Landau-shaped spread appears as a left-skewed gaussian distribution with a trail to the right of the peak.

Different side of the same coin, the distribution shape depends on particle energy. Higher particle energies mean longer range and so the fixed-thickness absorber becomes relatively thinner. Traversing the same absorber, the energy loss of fast particles shows a Landau distribution while slower particles lean towards a gaussian distribution. With higher particle speed, low energy transfer events become trendier; the landau distribution shifts further left and grows a longer tail.

The energy loss situation of electrons is similar to that of heavy charged particles passing a thin absorber. Because of their small mass, electrons suffer from multiple scattering even in thin absorbers. They are also capable of significant energy loss in single collisions. The rare high loss events add a long tail to the distribution. The landau model works well for most materials and electron energies [Syed Naeem Ahmed]. [Dr. Leo R. William]

## Range

* CSDA range
* Path length

# Photon Interaction with Matter

In radiation detection the three most important photon interactions are photoelectric absorption, Compton scattering and pair production. These processes result in a photon being absorbed and/or scattered.

## Photoelectric absorption

The process of photoelectric absorption involves a photon and an atomic electron. Upon collision the photon is absorbed, and a photoelectron is emitted from the atom. The energy of the disappearing photon is transferred to the electron as kinetic energy and equals where is the binding energy of the photoelectrons original shell. Emission of inner shell electrons (e.g. K-shell) are the most probable. After electron emission, a vacancy appears in one of the atoms bound shells. This vacancy is then filled by free electrons or electrons from other atomic shells. Electron rearrangement in the atom results in x-ray emission. An electron descending from atomic shell m to n is mediated by an x-ray photon of energy

where represents original binding energy the descending electron.

As can be seen in fig??, photoelectric absorption probability decreases with increasing energy. It is the most likely interaction for photons with energy lower than 1 MeV. It also depends on atomic number and occurs more frequent in high Z-materials.

## Compton scattering

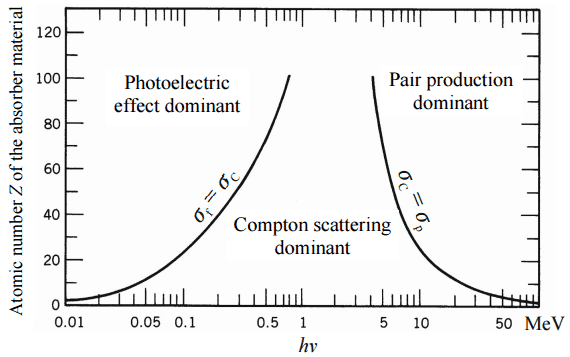
A photon can also interact is with free or loosely bound atomic electrons. This process is called **Compton scattering**. From the electrons frame of reference (i.e. the electron is at rest) the incoming photon has energy . Upon collision, energy is transferred from the photon to the electron and the electron gains momentum. Energy must be conserved; energy gained by the electron must equal energy lost by the photon. Final trajectories must conserve momentum. Assuming the photon travels along a horizontal line and the electron is at rest, the systems initial momentum is represented by the photons initial energy and direction. The net momentum vector, both before and after collision, is parallel to the horizon and has no vertical component. Thus, the scattered particles must travel vertically, with a certain angle to the horizontal, and in opposite directions, but in the same horizontal direction as the initial photon, in order to conserve momentum. Compton scatter occur in the energy range 10^2eV to 100GeV and is the most probable interaction for photons in proximity of 10^4eV.

## Pair production

Pair production requires considerably higher photon energies than the aforementioned interactions. The concept behind pair production is the creation of anti-particles. A highly energetic photon can decay into a particle pair in which the particles are the anti-particle of one another. The lowest energy required is 1.022 MeV. Decay of such a photon results in an electron-positron pair. The pair contributes to charge conservation (net charge is zero) as well as conservation of energy and momentum. Rest energy of electrons/positrons is 1.022 MeV/2. Hence a minimum of 1.022 MeV is required for the production. Excess energy beyond this value is gained by the particles as kinetic energy. For higher energies other anti-particle pairs may also be produced, such as muon-antimuon or proton-antiproton [wiki..].

The photon cross section energy dependence and Z dependence is illustrated in Figure1a) and b), respectively. The photoelectric effect is the dominating process for low energy photons and enhanced in high Z materials.

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## Gamma beam attenuation

The following scenario is illustrated in figure ??. A collimated photon beam of intensity I is directed at an absorbing target material. The beam consists of many individual photons travelling parallel to each other. Interacting photons are either deflected or absorbed. Absorbed photon disappears completely and deflected photons diverge from their original path, usually at a notable deflection angle. As the beam penetrates deeper into the target, constituent photons are removed and beam intensity decreases.

Like most radiation, gamma attenuation can be modeled by Beer-Lamberts law

where I is transmitted beam intensity after traversing an absorber of thickness t. It is also dependent on the attenuation coefficient of the target, which in turn depends on the target’s density.

# Bibliography

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| [1] | J. C. M. Z. a. J. C. M.J. Berger, "ESTAR, PSTAR, and ASTAR: Computer Programs for Calculating Stopping-Power and Range tables for Electrons, Protons, and Helium Ions (version 1.2.3), National Institute of Standards and Technology," Gaithersburg, MD U.S.A., 2005. |

1. Although often referred to as spin, whose actual symbol is , the symbol actually represents the total angular momentum (J=L+S) where denotes orbital angular momentum. [↑](#footnote-ref-1)