# Gadolinium as a converter foil

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**Introduction to Gd**

Gadolinium (Gd) is a chemical element with atomic number 64. It is a metal and appears as a solid under standard pressure and room temperature. In nature Gd occurs as a composition of seven isotopes; the most abundant being Gd-158 (24.84%), followed by Gd-160 (21.86%), Gd-156 (20.47%), Gd-157 (15.67%) and Gd-157 (14.80%).

**Gd Cross section and its use**

Gd has many favorable characteristics allowing an eclectic range of use; for instance in alloys to make magnets, electronics and data storage disks( [\*](https://www.rsc.org/periodic-table/element/64/gadolinium)); and as a contrast agent in MRI, to diagnose cancerous tumors([\*](https://www.chemicool.com/elements/gadolinium.html)).

Of particular interest is its high *neutron absorption cross section*, high probability of neutron capture. Of all known natural occurring nuclei, Gd-157 has the highest neutron absorption cross section having resonance at thermal-neutron energies ([\*](https://ebookcentral-proquest-com.pva.uib.no/lib/bergen-ebooks/reader.action?docID=404842&ppg=536)). As efficient neutron absorbers, Gd plays an important role in neutron shielding alloys for nuclear reactor safety and storage ([\*](https://digital.library.unt.edu/ark:/67531/metadc898814/)). An additional use of great Gd neutron capture is as Gd-based neutron poison, for instance Gd(III) nitrate in moderator systems for regulating power generation and shut-down of Heavy Water Nuclear Reactors ([\*](https://web.archive.org/web/20080423194722/http:/www.hss.energy.gov/NuclearSafety/techstds/standard/hdbk1019/h1019v2.pdf) page 31).

Not limited to the field of nuclear physics, Gd neutron absorption capability also benefit(s?) neutron capture therapy for cancer treatment and **neutron detection**, due to reaction products following neutron capture. *In gadolinium neutron capture therapy (GdNCT) a cancer patient is injected with Gd endused tracer followed by exposure to a neutron beam. Neutron absorbed by the Gd tracer produce secondary particles such as photons and electrons. While traversing tissue, the particles deposits dose and The particles travels the tissue exposed to a neutron beam, once Gd absorbs neutrons, decays and release product particles the particles is injected to the cancer patient product particles deposits dose locally to*

Introduction to neutron detection???

**Neutron capture in gadolinium**

Neutron capture cross section of natural Gd is given by the weighted sum of isotopic cross sections. Relative abundance of Gd isotopes in natural Gd and their neutron capture cross section are listed in table 1. Isotopes Gd-157 and Gd-155 collectively contribute 99.99% of the cross section, resulting in . Natural Gd interaction with thermal neutrons may therefore be simplified as a *“two-absorbing isotope system*” consisting of the isotopes Gd155 and Gd157 [Dumazert, 2018].

**Nuclear reaction equation**

Since natural Gd interaction with neutrons can be ascribed to isotopes Gd-157 and Gd-155, it is worth studying their corresponding nuclear reaction equation.

Once a Gd nuclei has absorbed a neutron it exists in an excited energy state from which it decays by *gamma-transition, resulting primarily in (*means of) gamma-ray () emission and internal conversion (IC) electrons. Byproducts of the decay are ACK electrons and X-rays, prompted by vacancies left by the IC electrons, *for further explanation of gamma-transition see section ??. The Q-value () is defines as the difference in mass before and after a nuclear reaction and the net energy released during the decay. This energy is distributed as kinetic energy among product particles. Due to the Gd nuclei’s large mass, compared to a photon (massless) and an electron, the recoil energy is neglectable ( Modern Nuclear Chemistry, page 219*[*\**](https://ebookcentral-proquest-com.pva.uib.no/lib/bergen-ebooks/reader.action?docID=4830611&ppg=238)*). I.e. most of the Q-value is distributed among gamma-rays and IC electrons.*

*Second draft, OVERVIEW*

*Gadolinium – general information (descriptive)*

*Wide Field of use (?)*

*Neutron detection*

**Natural Gadolinium and its cross section**

Natural Gd is a composite of six isotopes (isotope abundance in natural Gd in parentheses) ; (%) …. . Its cross section is the weighted sum of its isotopic constituent’s cross-section, each weight determined by its corresponding isotopes abundance. Neutron absorption cross-section and abundance of isotopes in natural Gd are tabulated in Tabel #.

Though Gd-155 and Gd-157 are not the most abundant, their great ability to capture neutrons triumph the other isotopes. Gd-157 has an absorption probability of … barns, the larges thermal neutron absorption cross section known of any stable element, and Gd-155 … barns (a close second place?). Together they ascribe to 99% of natural Gds total cross section, .. barns. e

Because of Gd-155 and Gd-157 large contributions to natural Gd interaction with neutrons it is **worth studying** their corresponding nuclear reaction equation:

The equations, (1) and (2), highlight three stages of neutron capture in Gd. First, a stable Gd, pre-absorption atomic nucleus lies in the path of an incoming neutron.

In the second stage, nuclear absorption of the neutron takes place, causing a structural rearrangement in the nucleus. Its atomic number increases by one nucleon. Gd-155 transforms to Gd-156, and similarly Gd-157 to Gd-158. Once the capture has occurred the daughter nucleus is in an exited/elevated energy state (neutron capture state), denoted by an asterisk . The neutron capture state of Gd-156 and Gd-158 has an excitation energy of 8.5 MeV and 7.9 MeV, respectively. **(Something about s-wave resonance state?)** The excitation energy has the same value as each reaction equations Q-value (), the measure of total energy released by a nuclear reaction.

De-excitation is the third, and last, stage of the reaction process. The excited nucleus emits decay products as it **transitions** from neutron capture state to ground state. ~~Ground state of Gd-156 and Gd-158 is~~ **~~(reference about ground states).~~**Primary products of the decay are prompt gamma-rays and internal conversion (IC) electrons. Biproducts of IC electron emission are Auger and Coster-Kroning (ACK) electrons and X-rays.

**Transition**: A transition is a process in which an atomic nucleus undergoes a transformation

by disintegration or de-excitation.

*(Something about the total spectrum? Energies from 0 to Q value? Sum equal Q -value?)*

Something about quantum mechanic states?

By nature, an unstable nucleus **decays by means** of radiation. Gd-156\* and Gd-158\* return to lower energy levels by gamma-transition. Gamma-transition **(def. ?)** includes three electromagnetic processes: gamma-ray emission, internal conversion and internal pair production. A process’ propriety is determined by the initial and final quantum mechanical (QM) state of the nucleus.

A nucleus in a QM state can be described by a set of distinct quantum numbers. These quantum numbers *describe* conservative properties of the nucleus, such as the energy, parity **(?)** and angular momentum.

**Gamma-emission**

During gamma-emission a nucleus de-excites from one state to another by emitting a high energy photon. The process must conserve energy, parity and angular momentum of the system. The emitted photon must therefor be connect to the initial and final state of the nucleus, by conservation of these quantities.

*Assuming the daughter nucleus is stationary after neutron capture, the only contribution to angular momentum is its intrinsic angular momentum, also known as its spin.* The change in intrinsic nuclear angular momentum of the initial and final state can be written as:

Where and represent the initial and final angular momentum of the nucleus, respectively, and is the unit of angular momentum.

Photon properties

* **parity**
* spin

For angular momentum to be conserved, the emitted photon must carry a spin equal to . In 1931 it was experimentally proven by C.V Raman and S. Bhagavanta. [[\*](http://dspace.rri.res.in/bitstream/2289/2123/1/1931%20IJP%20V6%20p353.pdf)] that the photon possesses an intrinsic spin equal to one unit of angular momentum (. In other words, if decay by gamma emission is to occur transitions where are prohibited. This restriction gives rise to the selection rules of gamma-emission. which state possible transitions of gamma-decay.

Something about 0+\* to 0+ 🡪 IC and pair production

**Energy spectrum**

* **gamma**
* **IC**
* **(Pair)**

**Quantum mechanics and *Energy levels***

A nucleus in a QM state can be described by a set of distinct quantum numbers. These quantum numbers *describe* conservative properties of the nucleus, such as the energy, parity **(?)** and angular momentum. Angular momentum is the sum of spin angular momentum (also know as intrinsic angular momentum) and orbital momentum.

During a nucleus decay energy is released and the nucleus sinks to a lower energy state. All states of the nucleus are characterized by a definite parity and angular momentum. sIn gamma-transition a nucleus transitions from an initial state to a final state. Both states are characterized by a definite parity and angular momentum.

Assuming the nucleus is stationary after neutron capture, the only contribution to angular momentum is its intrinsic angular momentum, or spin. During the process, parity and spin of the system must be conserved.

After the nucleus absorbs a neutron it is in a neutron capture state. It is from this state it transitions and eventually reaches ground state, the lowest energy level. This may happen in one or several transitions. (something on the probability of transition multiplicity?) No matter the multiplicity, a transition occurs between two states of definite quantum state, with distinct parity and angular momentum. Assuming

***Energy levels***

The density of nuclear levels increases with increasing excitation energy from the discrete domain of separable levels to a continuum of indistinguishable states. In figure ? descrete levels are represented by solid lines and the continuum by a gradient area transitioning from light to dark. There is no clear boundary separating the two regions. They are connected seamlessly, but for the convenience of modeling an arbitrary level is commonly defined, up to which point complete information of states are presumably available.

**Excited Gadolinium**

*From an excited state the nucleus may transition once, or several times, before reaching ground state, its lowest energy level.*

After neutron absorption, Gd-158 is in an neutron capture state with excitation energy **(energy)**.

**NB!**The same applies for Gd-156, save energy values.

*As illustrated by Fig (?), the density of energy levels increase with increasing excitation energy. Density of energy states is exponentially proportional with excitation energy. The density drastically increases with energy making it near impossible to distinguish ine energy state from another. The range of energy states may therefor be sectioned into a continuous domain and a discrete domain.*

**Describe figure**

Fig ? illustrates the distribution of energy states of a hypothetical nucleus. Solid lines represent descrete levels, while dashed lines indicate … . The gradient area is analogous to continuous distribution of energy levels.

**Describe allowed transitions?**

A screenshot of a cell phone

Description automatically generated

levels of the nucleus can be split into a continuous and desdcete … (?). Descrete energy levels (?) are…. And are located…. As excitation energy increates the There is no clear boundary between the two domains, but for

Each transition occurs between states of definite parity and angular momentum. *Illustration of energy levels in fig.…*

If a nucleus is in an excited it If excited, a nucleus exist in a state elevated above its ground state, the lowest energy level.

By definition an excited nucleus exists in an energy state elevated above the ground state. By transitioning to a lower state it gradually makes it’s way to gound state, **(def of ground?)**from one state to a lower state it

A nucleus may have several different states, each corresponding to a different. Each state characterized by (dynamical properties) can be described by can be desc

Quantum numbers, from the theory of QM, can be used to describe quantities of a physical system. These quantities are usually discrete and conserved, such as energy, parity **(?)** and angular momentum. For instance, a stationary nucleus

There are two types of angular momentum, spin angular momentum (also known as intrinsic angular momentum) and orbital angular momentum.

In the case of gamma-transition, the physical properies angular momentum and spin of a nucleus but of special interest for the understanding of gamma-transitions is angular momentum. Angular momentum is composit of

A nucleus (the physical system) has a determined QM state, described by

For instance, a nuclues (the physical system) and its that characterize a state of a physical system. Quantum numbers refer to descrete

are descreteFor instance, a nucleus and it’s energy states. Each QM state of a nucleus must have a distinct set of QM numbers, which describe quantites . a nucleus A nucleus’ dynamic properties can be described by its quantum machenical (QM) numbers. Each quamtum

Quantum states of nucleus.

* Descrete
* Continuous
* Allowed transitions

“Conservation of angular momentum plays a controlling role in the gamma-ray process”.

Which gamma-transition process takes place is heavily related to the conservation of angular momentum. An excited nucleus transitions and emits a photon. The initial and final quantum mechanical state of the nucleus has a fixed angular momentum and parity. The angular momentum and parity must be conserved by the emitted photon. Following these constraints are selection rules, which *allow only certain quantum state transitions to emit a photon.*

*The change in the neucleus intrinsic angular momentum is the difference between* the angular momentum of its final and initial angularmomentum, and , respectively. It *can be written as:*

The angular momentum carried by the photon , pronounced “ell”, must carry at least one unit (?). In other words, the transition is prohibited.

* Definite Quantum mechanical state, with known angular momentum and parity, of initial and final nucleus
* A photon is emitted, must conserve angular momentum and parity
  + Carries exact integer of angular momentum units
  + Cannot be 0
* Neutron capture state
  + : the energy needed to remove one [nucleon](https://en.wikipedia.org/wiki/Nucleon) compound nucleus from A+1
  + Gd-155
    - Resonance energy: 26.8meV
    - Spin-parity: 2- (?)
    - : 8.5 MeV
  + Gd-157
    - Resonance energy: 31.4meV
    - Spin-parity: 2- (?)
    - : 7.9 MeV
* Ground state
  + Gd-156
    - Spin-parity: 0+
  + Gd-158
    - Spin-parity: 0+
* Angular momentum determines decay process
* Nucleus decays from one definite quantum mechanical state to another and emits a photon
* Photon must conserve parity and angular momentum
  + Parity?
* Change in intrinsic angular momenta
* A photon must carry at least one unit of angular momenta (to connect the two nuclear states?)
  + gamma transition forbidden

(?)

Each Gd isotope has a resonance energy, listed in table 1, of neutron capture. Gd-155 and Gd-157 show a peaking capture ability at thermal neutron energies (25meV). Resonance energy for neutron capture of Gd isotopes are listed in table 1.

Decay by gamma emission is most likely to happen when the nucleus transitions between energy levels relatively far apart, resulting in a high energy gamma.

* **Something about branching ration.**
* **References?**
* % **of gammas to conversion electrons?**
* **Internal conversion coefficient?**

**Internal pair production**

In internal pair production, de-excitation energy is directly transformed into an electron-positron pair. For it to take place the energy must equal or surpass the joined mass of an electron and a positron (1.02 MeV). Something about the probability/branching ration of pair production in Gd. Come back to later… (what are Dieters opinion on this?) e+ annihilate, e- stop? **The probability of pair?**

**Prompt (?) Gamma-ray emission**

(transition into gamma rays. process of which the nucleus releases most of its energy?)

The excited Gd nucleus

**Internal conversion**