**Energy spectra**

The energy spectrum of reaction products range from 0 to Q-value, the maximum energy released by the reaction. The reaction products of Gd neutron capture are prompt gamma, IC electrons, ACK electrons and X-rays. The excitation energy is distributed among these particles. 99% of the released energy is carried by prompt gamma-rays and 1.8% by IC electrons [?,?]. Since ACK electrons and X-rays are biproducts of an IC electron … (they get the energy from Ice)… gamma-rays cover everything between 0 and Q, while IC and its biproducts mostly give rise to discrete lines in the lower end of the spectrum.

The resulting energy spectrum is a superposition of a continuous component and a descrete component. It is the prompt gamma-rays that generate the continuous compoment and can on almost any value between 0 and Q. The descrete component is a result of descrete gamma-ray lines, IC electrons, ACK elecktrons and characteristic X-rays. These lines appear in the lower end of the spectrum, below 1MeV(?). In other words, prompt gamma-ray emission contributes to both descrete and continuous component, while the remainin reaction products contribute to the descrete spectrum. It is the descrete spectrum lines, we will later see, that plays an essential role in neutron detection. Characteristic peaks from IC electrons,/ promt gammas allos for comparison of references(?). A benchmark.

A screenshot of a cell phone

Description automatically generated A close up of a sign

Description automatically generated

The gamma-ray spectrum consist, as mentioned, of a descrete and continuous component. To understand why this occur its necessary to look at the nuclear structure of Gd and its excited energy states. Figure ? illustrates an arbitrary nuclueus and its excited energy states.

Energy level density increases with excitation energy. In lower energy regions states are easily seperable, they are descrete. As excitation energy increases energy states gradually become harder to distinguish and slowsly comes to represent a quasicontunuous domain of energy states.

The highest energy level represents, in our case, neutron capture state, i.e. Gd-156 or Gd-158 after neutron capture. The excitation energy of the top level (represented by the top bold line) is the Q-value of the reaction equation,++ for Gd156 and ++ for Gd158. The ground state of a nucleus is the lowest energy level (lowest bold line). To reach ground state an excited nucleus must release all its exitaiton energy in the form of radioactive decay(?).

In figure ? The continuous domain of energy states is represented by a gradient, where energy level density increases as the gradient darkens. The descrete is indicated with whole(?) lines. Dotted lines in the area of quasicontinuom represent energylevels within it. There is no clear boundary between the quasocontinuous and descrete domain, but rather a smooth transition between the two. For convenience, an energy level, up to which information of quantum states are known to a certain certainty, is defined for (why) convenience of modeling?[ref. from ] A transition from one level to another is indicated with and arrow.

A nucleus may transition once or several times before it reaches ground state.

Transisitons can occur between (1) states in the continuous domain, (2) states in the discrete domain and (3) everything between the two. It is the transitions with an initial state in the quasicontinuoum that give rise to the continuous energy spectrum. The domain has an endless number of states , thus giving the gamma endless possibilities of emission energies.

The continuous spectrum is a broad spectrum, ranging from low-medium to high energies. The distribution can be described by **Fermis Golden Rule** [ref?], which looks like this

[equation]

It is not of interest of this theisis to go into the details of the equation. There are two factors which are of interest, namely (1) and (2). (1) is (…) and describes (…), favors low energy. (2) is (…) and described (…), favors high energy. Since the distributuion probability relies on the two factors (1 and 2) and the factors favor energies at different ends of the spectrum, the result is a broad spectrum. (mean) (first gammas high energy, second generation decreases in energy?) [ref. ]

A typical decay of Gd-156/Gd-158 has an average of 4-step gamma cascade [ref. only know for one, find for the other], though cascades with up to 12(?) gamma-emissions are also possible (?ref. simulations) a cascade of an average of 4 gammas (4-step gamma cascade). Cascaded with up to 10(?) steps have also been observed [ref?]. In a multi-step cascade, most of the energy (how much%?) is carried by the first gamma and decreases with gamma generations. As the nucleus de-excites and approaches ground state it emits gammas from the discrete domain. There is a limited amount of discrete levels, so the number of possible gamma-emission energies are finite, in contrast to the continuum. This results in discrete peaks near the lowest part of the energy spectrum. For natural gadolinium these peaks occur around, , , , . The first pair from Gd-156 and the second pair from Gd158. It’s the gamma decay from the second excitation state with spin-parity 4+ to first secited state 2+ which give \_ and \_. And de-excitation from first state 2+ to ground state 0+ that give \_ and \_. [ref. ]

A representation of the complete prompt-gamma spectrum is illustrated in figure. Where discrete peaks are located in the lower energy range [from-to] and the continuous spectrum broadening over the remaining spectrum.

**Electron spectrum (and biproducts)**

IC emits an orbital electron. (Not to be confused with B-decay, whici is the emission of an electron from the nucleus)

IC competes with the emission of gamma-rays. The ration of internal conversion transition rate to gamma-ray transition rate is described by the internal conversion coefficient .

Each electron shell can be described by its own IC coefficient; and so on. The total IC coefficient can be expressed as a sum of shell coefficients:

*Ref to studies with IC coeff. For Gd? Why is this important for the explination of the spectrum?* ***Mention in summary?***

*Since IC becomes especially important for heavy nuclei, such as gadolinium (Z=64). [nuclear chemistry]*

Orbital electrons can be described by their wavefunction, which gives their probable position. Orbital electrons in lower shells, such as K,L and M, have wavfunctions that may… There is a slight probability of an orbital electron excisiting within the nucleus. The probability decreases the further a shell lies from the nucleus. IC of electrons from K shell is therefor more probable than from L shell, L shell than from K shell ,and so on. In other words, it depends heavily on the atomic electron density inside the nucleus. (studie of the probability of IC from shells [ref?], table?)

The closer an electron is the more probable it is to interact directly with the nucleus and receive transisiton energy (?). The available transition energy of a nucleus can be labeled as and the orbital electrons binding energy as . The IC electron is emitted with a kinetic energy

Energies of IC electrons are discrete, as the transitions take place in the discrete domain of energy levels. Depending on which shell an electron is emitted from it will have energy in the range 29-182 keV. Binding energies [ref. harms(?)].

In natural gadolinium, transitions from first state J = 2+ and to ground state (0+) and from second state (4+) to first state (2+) are the most probable. They are responsible for 96.7% of the energy carried by IC electrons after neutron capture in Gd157/Gd155. [ref.]

Something more here….

**X-rays and Auger electrons**

Following the expulsion of IC electrons are X-rays and Auger electrons. A vacancy is left behind by the IC electron and is subsequently filled by a higher-level electron to release atomic energy (?). This energy is dissipated either by an X-ray or an Auger electron. Both have discrete energies, in the 4-50 keV range, and contribute to the discrete component of the total energy spectrum from neutron capture. [Dumazert 2016]

The energy difference between the initial and final level correspond to the X-ray energy emitted during atomic relaxation. Most times the energy is released by a photon, but emission of yet another electron is also a possibility. This electron is called an Auger electron. The energy of an Auger electron is the

IC electrons leave a vacancy in its place and in turn (?) outer electrons of the atom cascade down and fill lower atomic levels. Atomic excitation energy is released by emission of characteristic X-rays with energy equal to the difference in electron binding energy between the atomic energy levels (?). (E.g. of typicla x-ray lines)

The x-ray may interact with another orbital electron and eject it. In this case the electron is called an Auger electron. (What are CK electrons? Don’t include this)

**Summary – take home message of section**

The complete spectrum resulting from reaction products and biproducts is superposition of a continuous spectrum and a discrete spectrum. The discrete lines appear in the lower end of the spectrum, while the continuum mid to high end of the spectrum. It is the discrete lines which play a prominent role in neutron detection.

**Comparison of yields. Which deposit energy in solid state detectors?**