**Energy spectra**

(reaction equations)

* Complete specrum (?)
  + Descrete and continuous
  + RP: gamma, ICE, ACK and X-rays
  + Cont.: gamma (99.2%)
  + Descrete: gamma, ICE (0.8%), ACK and X-rays
* Nulcear structure, excited states
  + Figure of nuclear structure
  + Write last
* Gamma
  + Overview
  + Continuous
  + Descrete
  + Most common peaks? (ref. Dumarezt(?))
  + Previous studies?
* Electron
  + Descrete spectrum
  + Theoretical energy
  + Observed energies, (slowed down)
  + Energy peaks
    - Binding energy ref.: A.A.Harms&G.McCormack\_1974.pdf

**Continuous component (?)**

Gamma spectrum

* Transitions can occur between (se figure)
  + Quasicontinuoum lvls
  + Descrete levels
  + And between lvls from each cont and descrete
* Continuous (and broad)
  + Multi-step de-excitation 🡪 continuous
  + Carries most of the Q-value
  + Distribution described by Fermis Golden Rule
    - Provide equation, briefly describe only the most important factors.
      * A more in-depth explanation of Fermis Golden rule in APPENDIX Might have misunderstood. Read more
    - Two competing factors
      * Nuclear density level, favors low E\_gamma
      * Transmission coeff., favors large E\_gamma
      * Both are factors of the distrubtion prob, and they favor energies from opposite ends of the spectrum. 🡪 Broad peak
* Descrete
  + Low energy transitions in discrete domain.
    - From first excited state 2+ to ground state
    - From second excited state 4+ to 2+(first excited state?)
  + Distribution dominated by
    - Gd155: 88.967keV and 199.213keV
    - Gd157: 79.51keV and 181.931 keV
    - Ref.: Dumazert [41,42]

**Discrete component (?)**

(Gamma spectrum)

Electron spectrum

* Transitions occur between low lying states where electron wave functions have higher probability of being located inside the nucleus. Direct contact between electron and nucleons.
* Compete with gamma-decay between low lying energy levels, as mentioned above
* *Internal conversion coeff.*
* Energy of ICE: E\_ICE = ∆E -E\_b
* Energy distribution; most prominent peaks
* De-excitation between 4+->2+ and 2+->0+ responsible for 96.7% of the energy carried by ICE.
  + Ref.: Dumazert [44,45]
  + Energy corresponding to these transitions, ref. to study about the peaks?

ACK and X-rays

* Biproducts of ICE
* ICE leaves a vacancy
* Vanacy Is filled by electromn in higher subshell
* Emits characteristic X-ray w/ energy ∆E = E\_f-E-\_i
* Alternatively, ACK emitted from shell between f and I (read more about this)

**Energy spectrum**

The energy spectrum consists of a descrete and cont

Gamma

* Cont
* desc

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 promt 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 mosty give rise to descrete 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.

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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. ]

Gd-156/Gd-158 takes an average of 4 gamma decays [ref. only know for one, find for the other], 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 descrete domain. There are limited descrete states, restricting possible gamma-emission energies. This results in descrete 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 promt-gamma spectrum is illustrated en figure. Where descrete 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?*

*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 descrete, as the transitions take place in the descrete 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….

ACK and X-rays