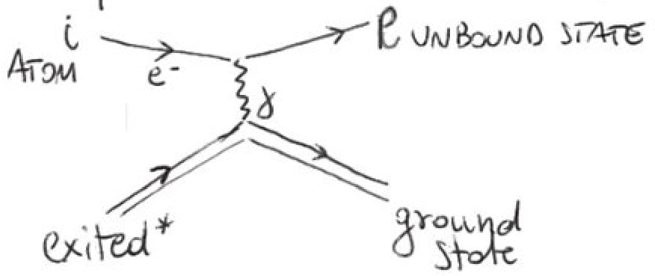
INTERNAL CONVERSION

$0^+ \to 0^+$ transitions can not occur via e.m. γ transition. This is because the e.m. operator does not have an $l=0$ component, since photon's intrinsic spin is $S=1$

However there is an e.m. process that can cause $0^+ \to 0^+$ transition, a process called INTERNAL CONVERSION

The classical visualization is that an electron (from k-shell) enters the nucleus, feels the e.m. force from a nucleon in an exited states, or a collection of nucleons in an exited states, and acquires enought energy to liberate the e^- from the nucleus to transition to lower energy level. A nucleus as a whole, recoils to conserve energy.

The quantum mechanical picture is similar:



Wheter we adopt quantum electro-dynamics or Fermi Golden Rule approach, the most important part, which is also the less known part, is the transition element $M^{i\text{-}f}$

For internal conversion this is

$$M_{ic}^{i\to f} = \langle \psi_N^{f} \psi_e^{free} | \vartheta_{em} | \psi_e^{band} \psi_N^{i} \rangle$$

which has to be compared with that of γ conversion

$$M_{\gamma}^{i\to f} = \langle \psi_N^{f} \psi_\gamma^{tree} | \vartheta_{em} | \psi_N^{i} \rangle$$

hey look similar. they contain many physical similarity, that are ccompanied by mathematical similarity.

n fact, every γ decay is in COMPETITION with internal conversion. he only one that stands alone is $0^+ \to 0^+$ internal conversion, that has not ounterpart.

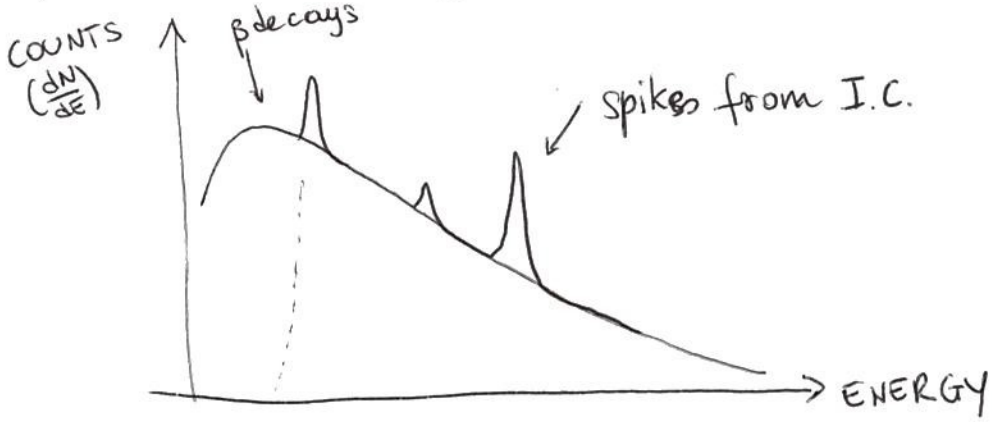
When a nucleus decay, it does so via α, β, γ decay. Often a decay can proceed via more than one decay channel, and the daugher can decay as well.

A particular interesting case is when β decay and internal conversion happen in close temporal proximity. For example:

$$^{203}_{80}\mathrm{Hg}_{123} \longrightarrow {}^{203}_{81}\mathrm{Tl}^{*}_{122} + e^- + \bar{\nu}_e \longrightarrow {}^{203}_{81}\mathrm{Tl}_{122} + e^- \; (\mathrm{I.C})$$

⇒ A measurement of the electrons being emitted from $^{203}\mathrm{Hg}$ sees both β decay electrons and IC electrons.

However, the signature of both these processes are very distinct. The β e^- gives a CONTINUOS energy spectrum, while I.C. e^- are seen as sharp lines of the energy of nuclear transition (minus recoil)



The kinetic energies of electrons is given by:

$$T_e = \frac{Q-B}{1+\frac{m_e}{M_{x'}}}\underbrace{\left[\frac{1+\frac{Q-B}{2m_x c^2}}{1+\frac{Q-B}{(M_{x'}+m_e)c^2}}\right]}_{\longrightarrow\ \simeq 1\ \rightarrow\ \text{If "corrections" are ignored}} \simeq Q-B$$

$$\downarrow$$

$$\frac{m_e}{M_{x'}} \propto \frac{0{,}0005}{A} \rightarrow \simeq 0$$

The correction may be needed for lighter elements with large Q.

One of the worse case is observed for $^{16}\mathrm{O}$ decay $0^+ \rightarrow 0^+$ which is a clear I.C.: in this case the correction is ≃ 0,5% in corrections are ignored.

B = binging energy of converted electron; this cannot be ignored and depends upon the atomic shell from which the electron was converted.

Specific example:

$$^{203}_{80}Hg_{123} \longrightarrow {}^{203}_{81}Te_{122} + e^- \, (I.C.)$$

$Q = 279{,}910$ KeV

X-ray NOTATION	Spectroscopic notation	B_e (keV)	T_e (keV
K	$1S_{1/2}$	85,5	193,7
L_1	$2S_{1/2}$	15,4	263,8
L_2	$2P_{1/2}$	14,7	264,5
L_3	$2P_{3/2}$	12,7	266,5
M_1	$3S_{1/2}$	3,7	275,5

Internal conversion contribution to decay rate

ince γ e IC both contribute to e.m. decay rate, the total decay ate can be written as:

$$\lambda_{em} = \lambda_\gamma + \lambda_e \qquad \lambda_\gamma\left(1+\frac{\lambda_e}{\lambda_\gamma}\right)$$

$$\alpha \equiv \lambda_e / \lambda_\gamma \quad \Rightarrow \quad \lambda_{em} = \lambda_\gamma (1+\alpha)$$

$$\lambda_{em} = \lambda_\gamma + \lambda_{e_K} + \lambda_{e_{L_i}} + \lambda_{e_M} + \dots$$

$$\text{or} \quad \lambda_\gamma (1 + \alpha_K + \alpha_L + \alpha_M + \dots)$$

sing hydrogenic wave function it is possible to estimate:

$$\alpha(E\ell) \simeq \frac{Z^3}{n^3}\left(\frac{\ell}{\ell+1}\right)\alpha^4\left(\frac{2m_ec^2}{E_\gamma}\right)^{\ell+5/2}$$

$$\alpha(M\ell) \simeq \frac{Z^3}{n^3}\alpha^4\left(\frac{2m_ec^2}{E_\gamma}\right)^{\ell+3/2}$$

= Atomic number of daugher nucleus

The expressions are approximate but a number of features of I.C. can be illustrated:

1) They increase as Z^3 $\Rightarrow$ I.C. is more important for heavy nuclei.

E.g.: ${}^{22}_{10}Ne \rightarrow \alpha_K = 6{,}8 \cdot 10^{-6}$ 1,27 MeV E2 transition

${}^{182}_{74}W \rightarrow \alpha_K = 2{,}5 \cdot 10^{-3}$ 1,22 MeV E_2 transition

ratio is $\simeq (10/74)^3$ as expected while $\frac{6{,}8 \cdot 10^{-6}}{2{,}5 \cdot 10^{-3}} = 2{,}47 \cdot 10^{-3}$

$\hookrightarrow 2{,}5 \cdot 10^{-3}$

2) The conversion coefficient decrease rapidly with increasing transition energy (In contrast with γ)

E.g. ${}^{56}Co \rightarrow M_1$ with energies: 158 keV, 270 keV, 847 keV

$\alpha_K = 0{,}011$, $\alpha_K = 0{,}0034$, $\alpha_K = 0{,}00025$

these decrease $\propto E^{-2{,}5}$

3) The conversion coefficient increase rapidly as multipole order increases: for high L conversion may be far more probable than γ emission.

E.g. ${}^{99}Tc$

M1 141 keV $\alpha_K = 0{,}10$

M4 143 keV $\alpha_K = 30$

Expected value of ratio: $\frac{\alpha_K(143)}{\alpha_K(141)} \simeq \left(\frac{2\, m_e c^2}{E}\right)^3 \simeq 370$

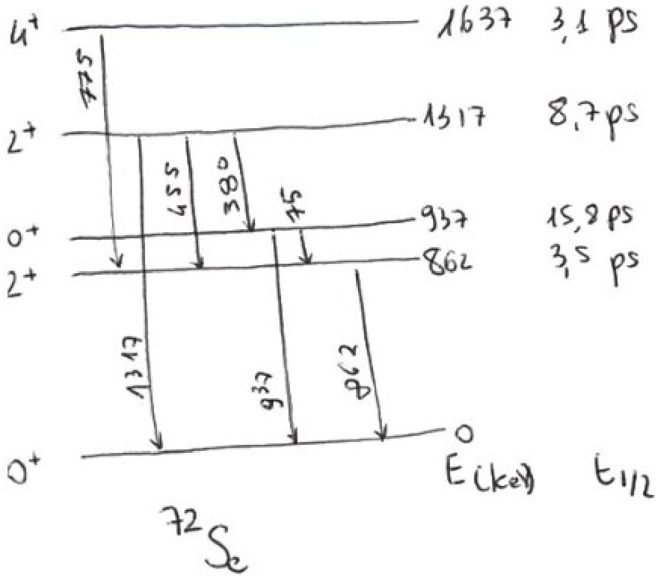
Measured " : $\simeq 300$

4) The atomic conversion coefficient for higher atomic shells ($n>1$) decrease like $1/n^3$. Roughly we would expect $\alpha_K / \alpha_L \simeq 8$. Using the correct e^- w.f. the ratio varies within 3–6 $\Rightarrow$ The estimate is rather good.

While the estimates gives reasonable qualitative values, for quantitative results the detailed computations of conversion coefficient are needed. $\Rightarrow$ It will be possible to get insight of the different matrix elements $\Rightarrow$ Informations of the nucleon structure.

LIFETIME FOR γ EMISSION

Let's consider this example:



The $t_{1/2}$ of 1317 keV level has been measured to be 8,7 ps

$$\lambda_t = \frac{\ln 2}{t_{1/2}} = 8 \cdot 10^{10}\ s^{-1}$$

The decay rate which is measured is the sum of the 3 transitions that de-populate the state:

$$\lambda_t = \lambda_{t,1317} + \lambda_{t,455} + \lambda_{t,380}$$

$$= \lambda_{\gamma,1317}(1+\alpha_{1317}) + \lambda_{\gamma,455}(1+\alpha_{455}) + \lambda_\gamma(1+\alpha_{380})$$

$$\alpha_{xxx} \ll 1 \Rightarrow \quad \lambda_t = \lambda_{\gamma,1317} + \lambda_{\gamma,455} + \lambda_{\gamma,380}$$

The relative intensities can be measured $\Rightarrow$

$$\lambda_{\gamma,1317} : \lambda_{\gamma,455} : \lambda_{\gamma,380} = 51 : 39 : 10$$

$\Rightarrow$

$$\lambda_{\gamma,1317} = 0{,}51 \times (8 \cdot 10^{10}\,s^{-1}) = 4{,}1 \times 10^{10}\,s^{-1}$$

$$\lambda_{\gamma,455} = 0{,}39 \times (8 \cdot 10^{10}\,s^{-1}) = 3{,}1 \times 10^{10}\,s^{-1}$$

$$\lambda_{\gamma,380} = 0{,}10 \times (8 \cdot 10^{10}\,s^{-1}) = 0{,}8 \times 10^{10}\,s^{-1}$$

These partial rates for γ emission can be compared with calculated

Values, eg. Weisskopf estimates:

For E_2 transitions:

$$\lambda_{E_2,1317} = 8,7 \cdot 10^{10}\ s^{-1}$$

$$\lambda_{E_2,453} = 4,3 \cdot 10^{8}\ s^{-1}$$

$$\lambda_{E_2,380} = 1,7 \cdot 10^{8}\ s^{-1}$$

Doing the same passages done for measurement for data and model one gets results which are similar, but not identical. Why? Because this is a strong evidence of collective aspect of nuclear structure, as discussed previously.

The Weisskopf estimates are based on the assumption that the transition arises from a single nucleon motion, and infact the "model coefficients" are smaller than the measurement! This means that there must be many nucleons that takes part to the transitions.

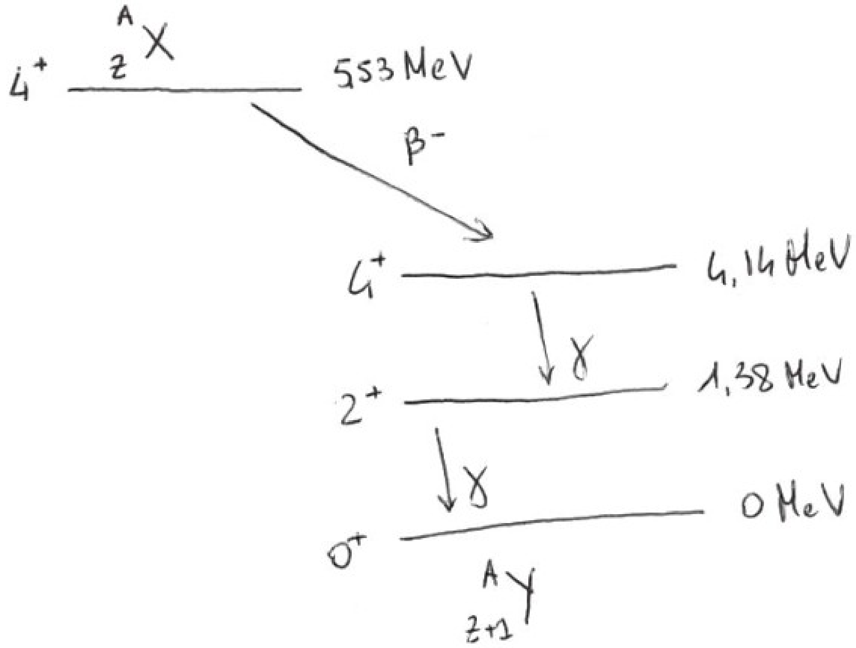
EXERCISE

Radioactive nucleus $^{A}_{Z}X$ is known to undergo β^- decay to $^{A}_{Z+1}Y$.
In a measurement one finds a distribution of electrons, but in addition two groups of positrons with discrete end-point energies are observed.

a) What could be the process giving rise to the positrons?

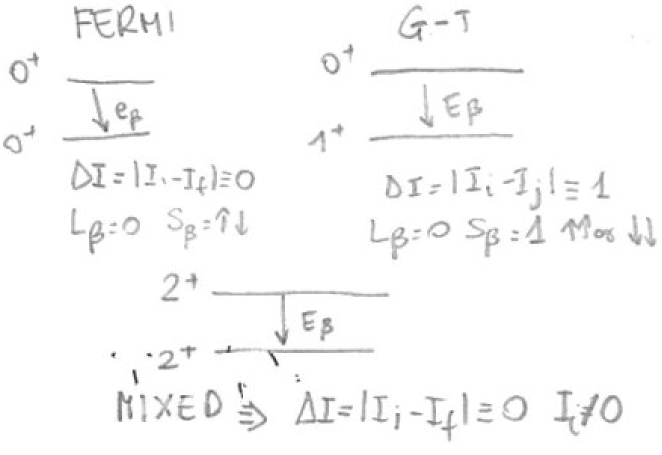
b) What are the expected end-point energies of the 2 positron groups?

c) What are the decay modes for the indicated transitions?



a). Two possible explanations:

1) Pair production from γ
2) Internal conversion ←



b) End-point energies:

$E(g_1) = (4,14 - 1,38) = 2,76$ MeV

$E(g_2) = 1,38$ MeV

$\Delta \ell = 0 \Rightarrow \Delta J = 0$

c) Decay modes: β^- $4^+ \rightarrow 4^+$ allowed, F and GT

γ_1 $4^+ \rightarrow 2^+$ E_2 $\Delta\pi = NO$ $2 \leq J \leq 6$

γ_2 $2^+ \rightarrow 0^+$ E2 , $\Delta\pi = 0$, J=2

NUCLEAR REACTIONS

If energetic particles from a reactor or accelerator (or even radioactive Source) are allowed to fall upon bulk matter, there is the possibility of nuclear reactions taking place.

The first nuclear reactions were done by Rutherford: in the first experiment the α ptc merely rebounded elastically: the phenomenon known as "Rutherford scattering" gave the first evidence for the exitence of atomic nuclei. In other experiments Rutherford was able to observe a change or "transmutation" of nuclear species, e.g:

$$\alpha + {}^{14}N \longrightarrow {}^{17}O + p$$

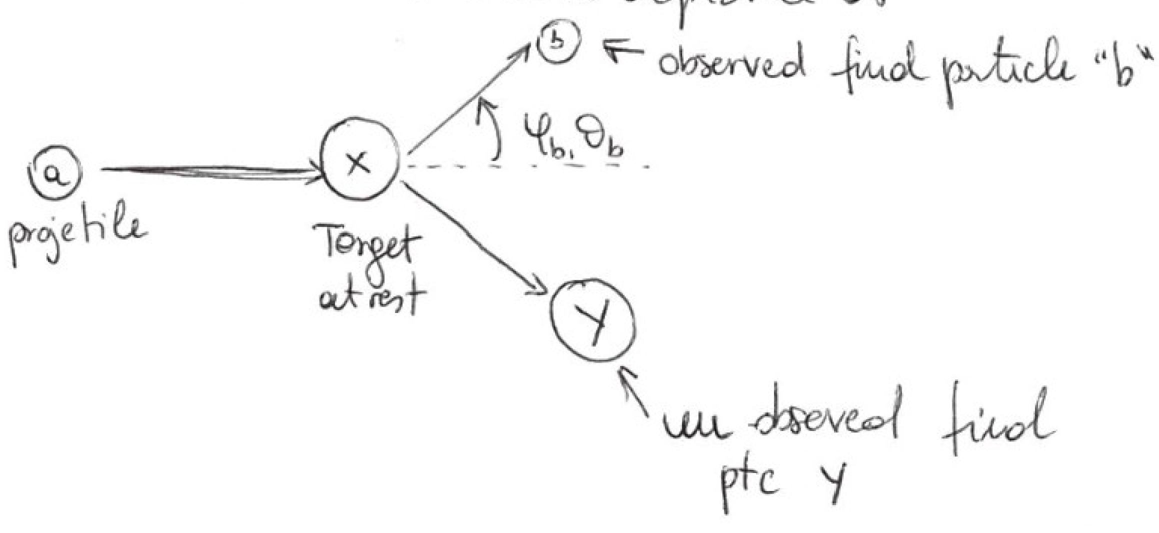
The first particle accelerator capable ~~of~~ introducing nuclear reactions was built in '30 and observed the reaction

$$p + {}^{7}Li \rightarrow {}^{4}He + \alpha$$

This is a "Nuclear reaction".

In most cases the "projectile" is a light nucleus ($A \leq 4$) incident on heavy target. The energy of the reaction can be "low" if $E \lesssim 10$ MeV, Medium" for a range 10 MeV ÷ 1 GeV (meson production => exchange of and n) or "High" energy. It the latter all sort of exotic particles an be produced.

A typical nuclear reaction can be depicted as



The symbolic shorthand of the reaction is

$$a + X \rightarrow Y + b$$

An alternative and compact way of indicating the same reaction is: $X(a, b)Y$

The reactions can be classified in many ways: If the incident particle is the same as the outgoing one, the process is a "scattering", elastic if Y e b are in the ground state and inelastic if Y or b are an excited state (from which it generally decay quickly by γ emission).

Sometimes, a and b are the same particle, but the reaction causes an other nucleus to be ejected separately. This is called knockout reaction. In transfer reactions, one or two nucleons are transferred between projetile and target.

Reactions can also be classified by the mechanism that govern the reaction. Direct reactions are reactions where only a few nucleons take part in the reaction and the remaining nuclei are called "spectators

Such reactions might insert or remove a single nucleons from a shell state, and therefore might be used to study nuclear structure

The other extreme is compound nucleus mechanism, in which the incoming and target nuclei merge briefly.

Between the two mechanisms, there is the resonance reaction in which the incoming ptc form a "quasi bound" state before the outgoing particle is ejected.

EXAMPLE OF NUCLEAR REACTIONS

$X(a,\gamma)Y$	radiative capture
$X(\gamma, b)Y$	nuclear photoeffect
$X(a, a)Y$	nuclear elastic scattering
$X(a, a)Y^*$	" inelastic "

DIRECT REACTIONS : Short time ~~of~~ w.r.t. the time needed tram frgance to transit the target ($\sim 10^{-22}$ s)

- KNOCK-OUT REACTIONS
- STRIPPING "
- PICK-UP "

INDIRECT REACTIONS: COMPAUND REACTIONS (Formations of a compound state) After a certain time the intermediate state decays and produces final ptc.

- ELASTIC CHANNEL : $a + A \to C^* \to a + A$
- INELASTIC " : $a + A^* \to C^* \to a + A^*$
- NEAREACTION : $a + A \to C^* \to b + B + \dots$
- RADIATIVE CAPTURE: $a + A \to C^* \to \gamma + C$

in general indirect reactions have reaction time $> 10^{-6}$ s