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# Curso de capacitación 2020

# Aplicaciones

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## **Contenido Módulo 2:**

Preguntas que se hace la Física Nuclear. Sobre la Tecnología Nuclear. Generalidades de los núcleos atómicos. Estado actual de los límites de la Tabla Periódica. Límite de existencia de los núcleos atómicos. Sobre las aplicaciones de los radioisótopos Tecnecio y Boro. Principio de funcionamiento del resonador magnético nuclear.

## **Lecturas recomendadas:**

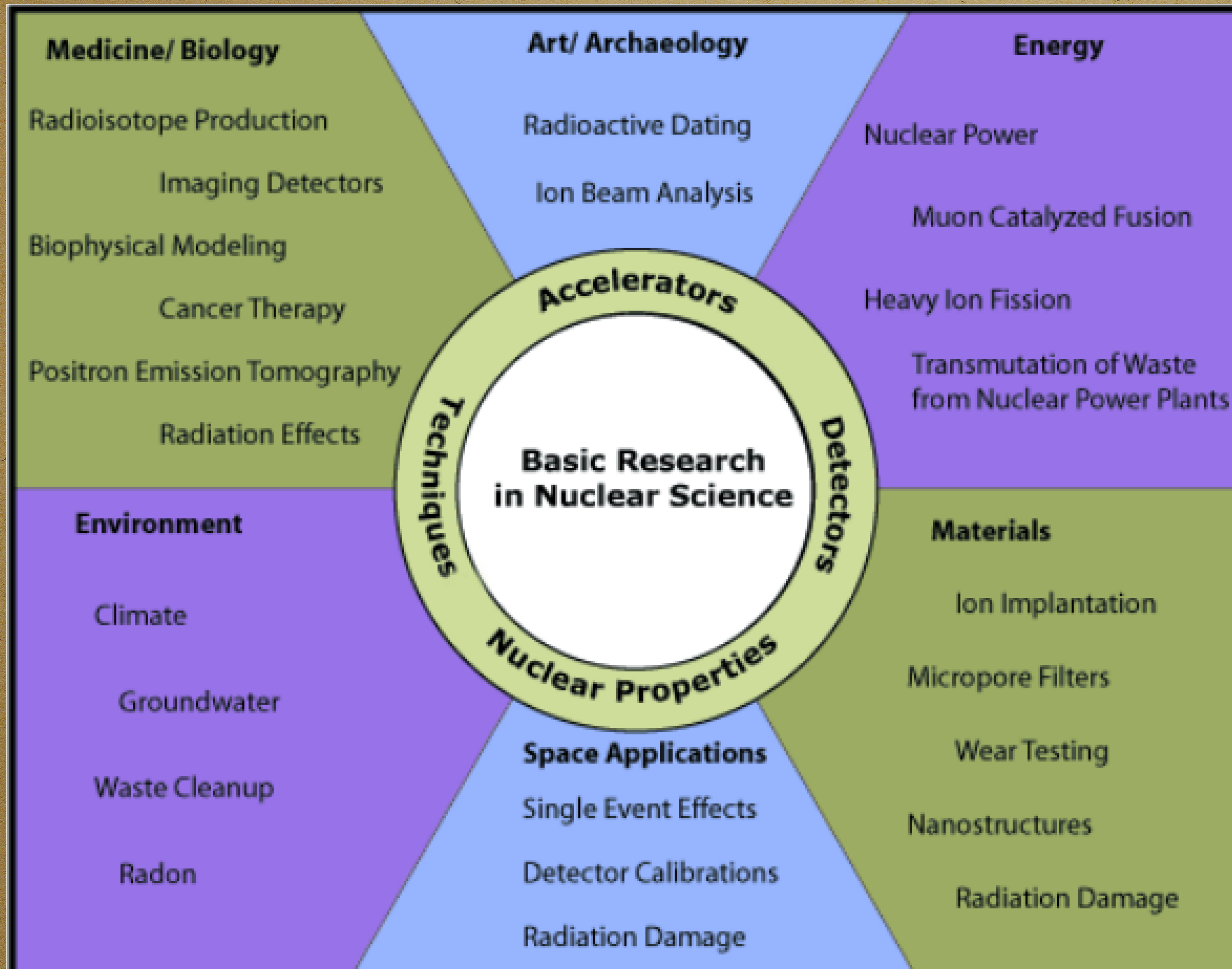
- Nuclear Physics: Exploring the Heart of Matter. The National Academies Press (2013).
  - NuPecc Long Range Plan 2017. Perspectives in Nuclear Physics. European Science Foundation (2017).
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# **Aplicaciones de la Física Nuclear**



# Tecnología Nuclear





# **Aplicaciones de los radionucleidos**



# Aplicaciones de radionucleidos

- Producción de energía: 435 plantas nucleares en el mundo (17%), 3 en Argentina (7%).
- Entender el origen y la evolución del Universo.
- Datación de materia orgánica con núcleos de carbono 14 ( $T_{1/2} = 5730$  años).
- Determinación de rocas/meteoritos ( $10^9$  años).  
Radiometría por Estroncio
- Detectores de humo (obsoleto).
- Metalurgia: medir espesores o fallas en metales con rayos gamma
- Medicina nuclear para diagnóstico y cura (1/3 de los internados se tratan con medicina nuclear en USA).



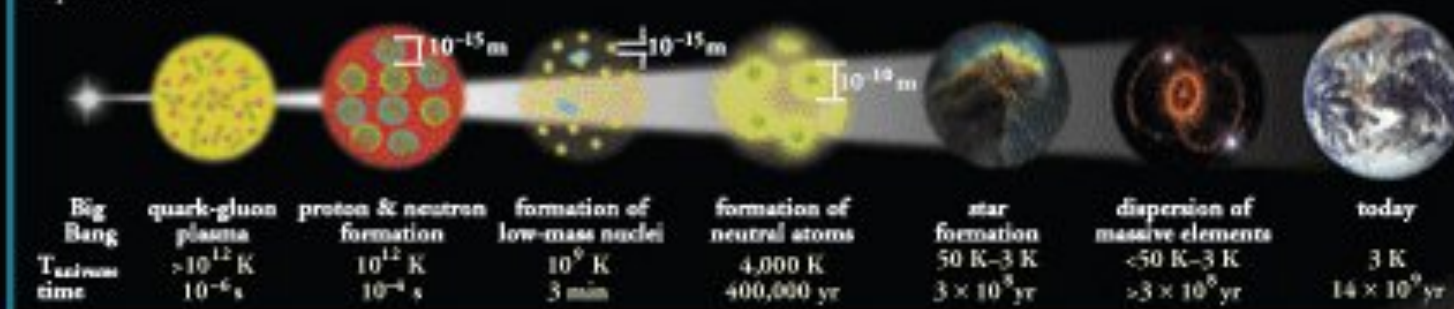
# Otras aplicaciones

[www.CPEPweb.org](http://www.CPEPweb.org)

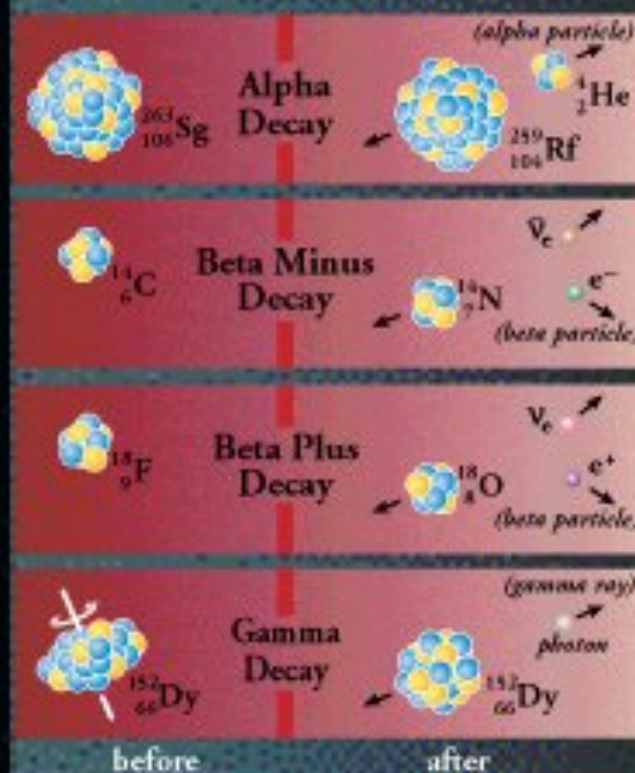
## Nuclear Science

### Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about  $10^{-6}$  second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe,  $T_{univ}$ , cooled to about  $10^{12}$  K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.



### Radioactivity



Radioactive decay transforms a nucleus by emitting different particles. In alpha decay, the nucleus releases a  ${}^4_2\text{He}$  nucleus—an alpha particle. In beta decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of anti-particles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In gamma decay, the nucleus lowers its internal energy by emitting a photon—a gamma ray. This decay does not modify the chemical properties of the atom.

### Chart of the Nuclides

The Chart of the Nuclides presents in graphic form all known nuclei with atomic number,  $Z$ , and neutron number,  $N$ . Each nuclide is represented by a box colored according to its predominant decay mode. Magic numbers ( $N$  or  $Z = 2, 8, 20, 28, 50, 82$  and 126) are indicated by a rectangle on the chart. They correspond to major closed shells and show regions of greater nuclear binding energy.



#### Color Key

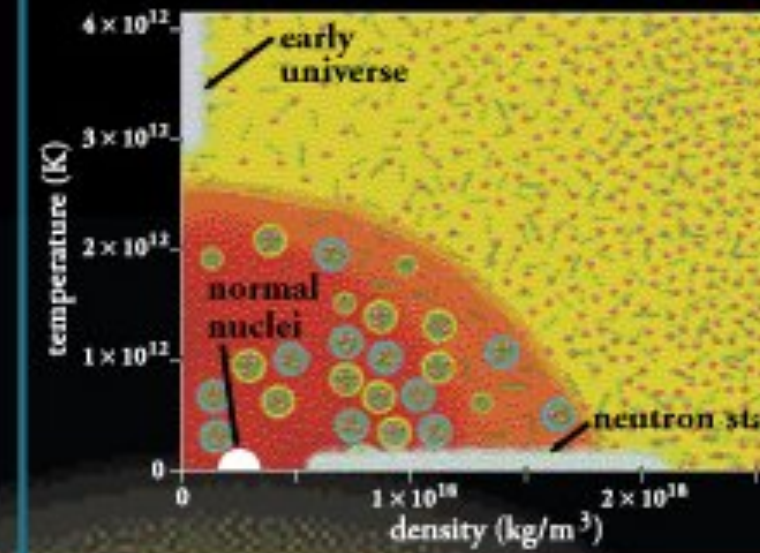
- Stable
- Spontaneous fission
- Alpha particle emission
- Beta minus emission
- Beta plus emission or electron capture

[www.CPEPweb.org](http://www.CPEPweb.org)

Nuclear Science is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as Why do nucleons stay in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed or rapidly rotated? What is the origin of the nuclei found on Earth?

Legend: electron ( $e^-$ ), proton, neutron, quark, gluon field, photon ( $\gamma$ ), neutrino ( $\nu$ ), antineutrino ( $\bar{\nu}$ ), positron ( $e^+$ ), gluon, photon ( $\gamma$ ), neutrino ( $\nu$ ), antineutrino ( $\bar{\nu}$ ). Atomic number  $Z$ , mass number  $A$ , neutron number  $N$ .  $N_{neutron} = A - Z$ .

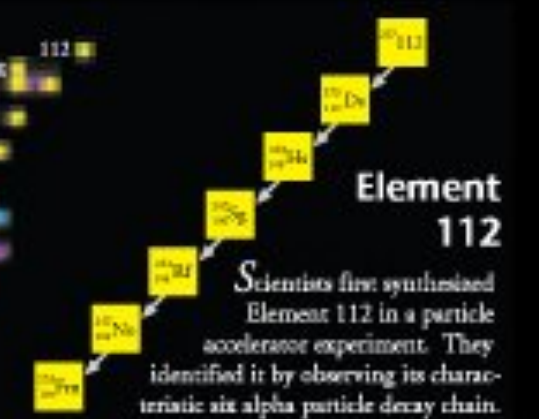
### Phases of Nuclear Matter



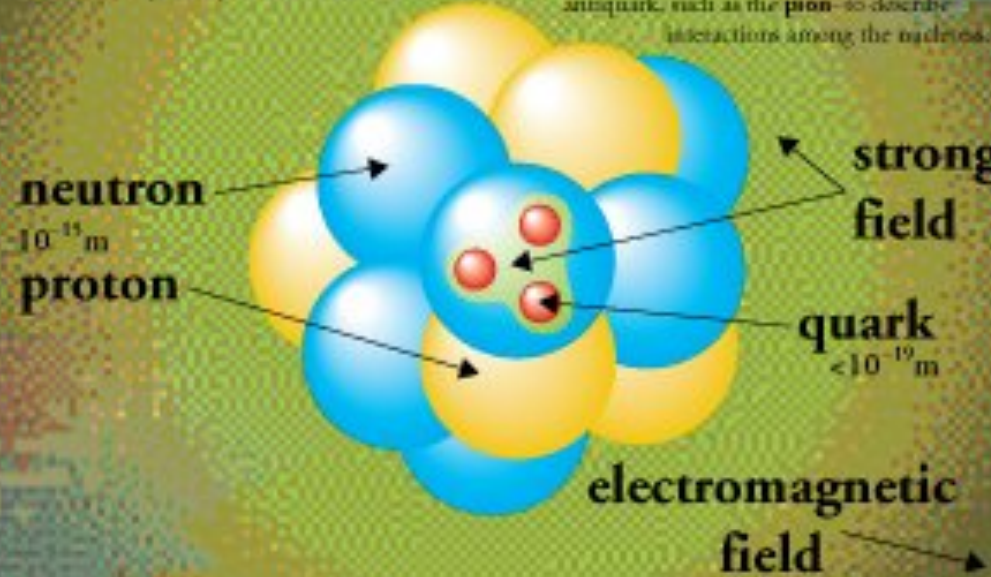
Nuclear matter can exist in several phases. When collisions excite nuclei, individual protons and neutrons may evaporate from the nuclear fluid. At sufficiently high temperature or density, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.

### Unstable Nuclei

Stable nuclides form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decays, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nuclides. Nuclear theory predicts that there are at least 4000 more to be discovered with  $Z \leq 112$ .

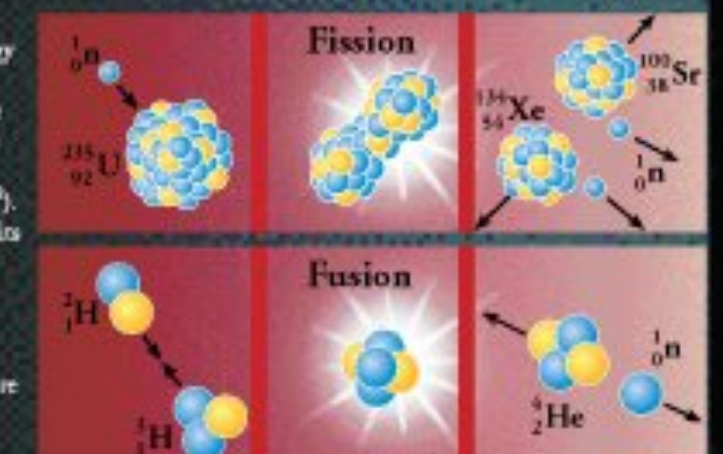


### The Nucleus



In an atom, electrons range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were drawn to scale, this chart would cover a small room.

### Nuclear Energy



In the early stages of stellar evolution of our sun and other stars, hydrogen fuses to form helium, releasing energy in the form of photons (light) and neutrinos. During the later stages of stellar evolution, more massive nuclei up to and beyond uranium are synthesized by fusion. By measuring the number of neutrinos that come from the Sun, scientists recently have demonstrated that neutrinos must have a mass greater than zero.

### Applications



#### Radioactive Dating

Naturally occurring radioactive isotopes such as  ${}^{14}\text{C}$  are used to date objects that were once living, such as wood. For example, from a study of artifacts found at the site, scientists determined that Stonehenge was built nearly 4,000 years ago.



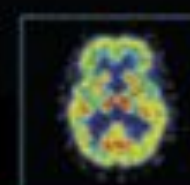
#### Smoke Detectors

Many smoke detectors use a small amount of the alpha emitter  ${}^{241}\text{Am}$  to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.



#### Space Exploration

Scanners used alpha particles to identify chemical elements present in Martian rocks. On Earth, nuclear reactions are used in many areas from criminal investigations to art authentication.



#### Nuclear Medicine

Radioactive isotopes, such as  ${}^{99\text{m}}\text{Tc}$ ,  ${}^{67}\text{Ga}$ , and  ${}^{18}\text{F}$ , are commonly used in the diagnosis and treatment of disease. Positron emission tomography (PET) is used to generate images of brain activity.



#### Nuclear Reactors

Nuclear reactors use the fission of  ${}^{235}\text{U}$  or  ${}^{239}\text{Pu}$  nuclei to produce electric power. Reactors and most other nuclear applications generate radioactive waste; disposal of this waste is a subject of current research.



#### Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) makes use of atomic transitions involving the magnetic field of a nucleus to study the local chemical environment. This technique accurately maps the density of hydrogen to produce three-dimensional images of the human body.

Astrophysical pictures courtesy NASA/JPL/Caltech and AURA/STScI.

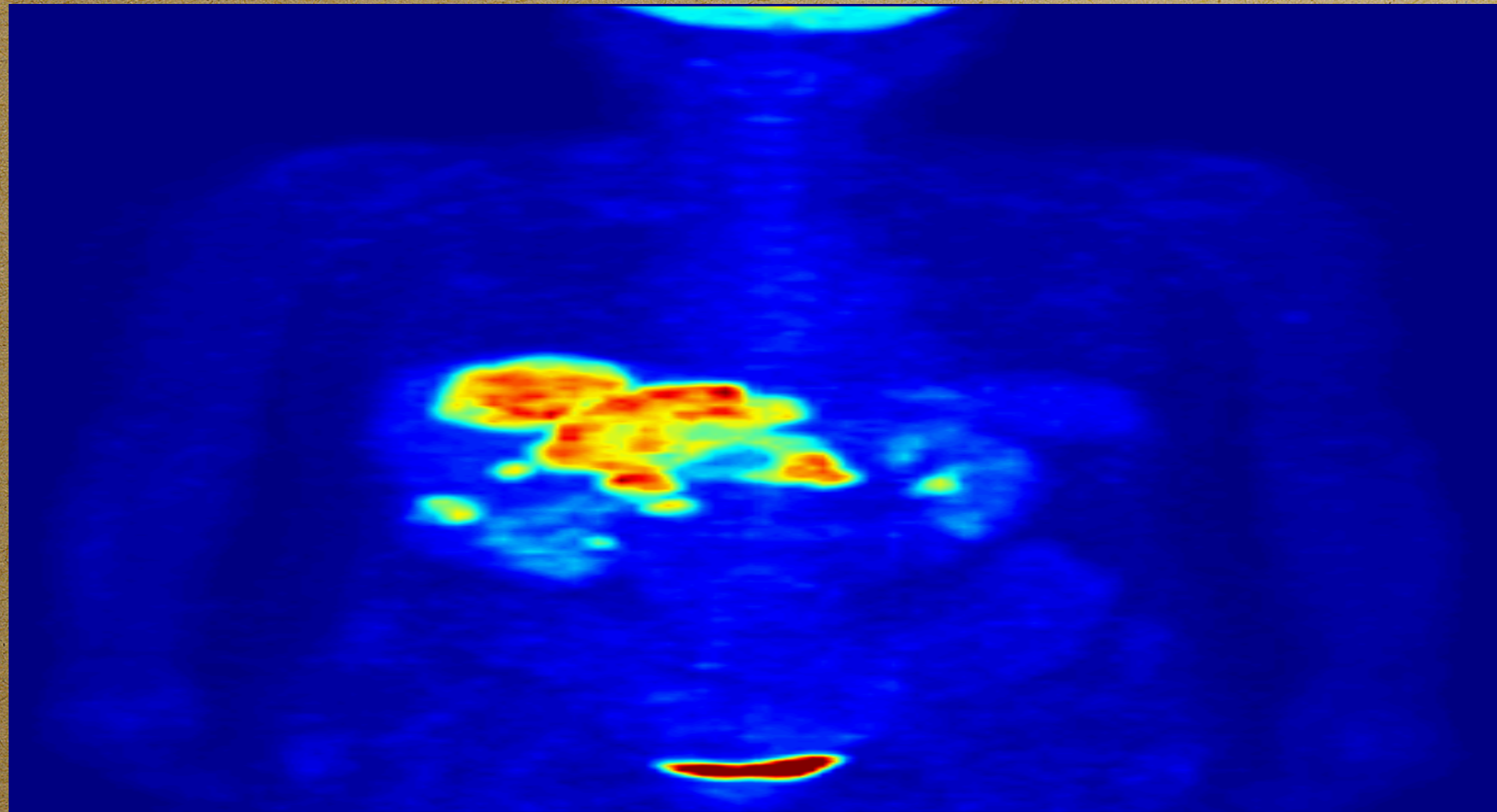


# **Generalidad sobre aplicación de radionucleidos en medicina**

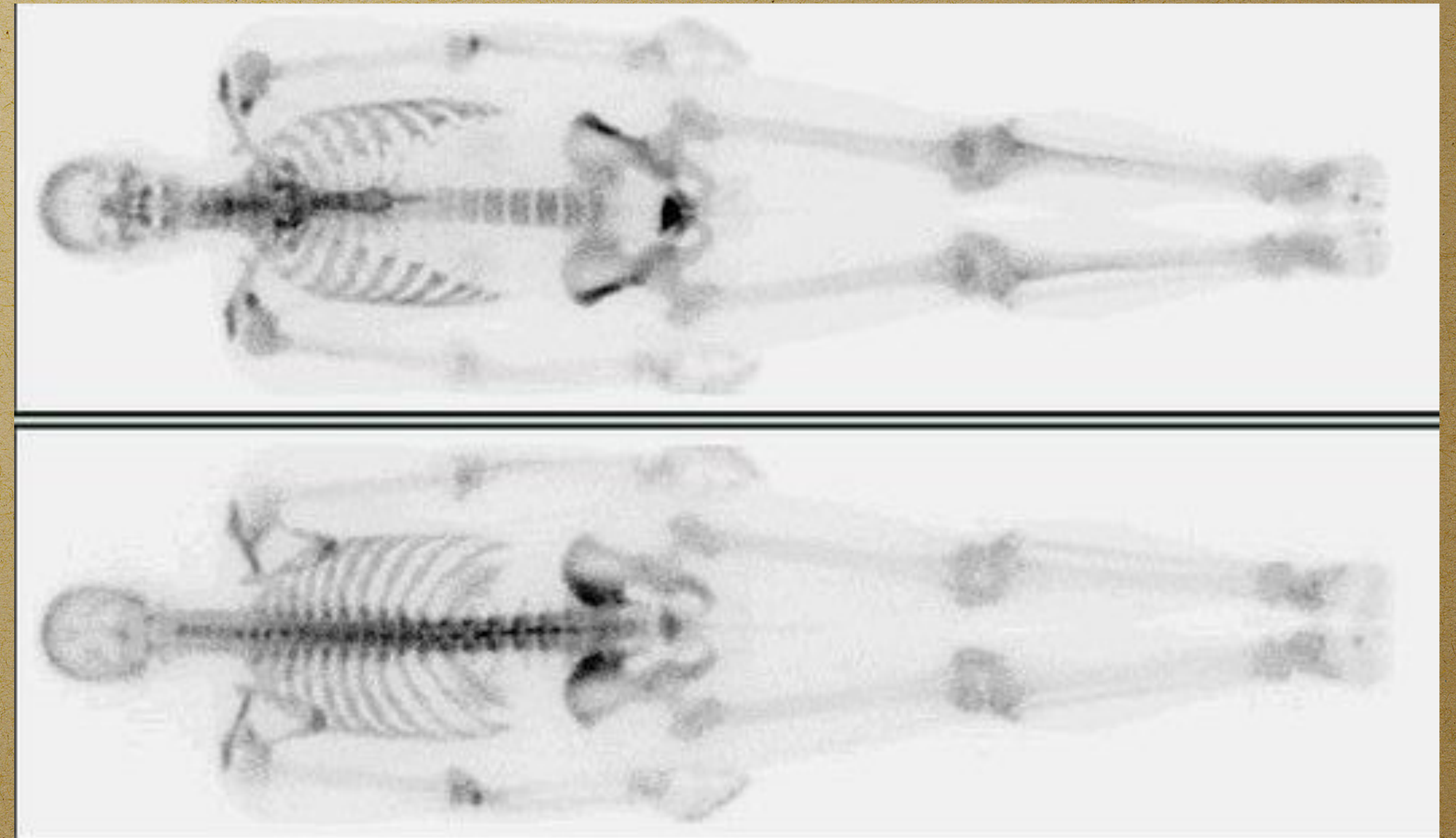


# Diagnóstico con núcleos radiactivos

Consiste en generar imágenes de los organismos para estudiar daños o funcionamiento incorrectamente.



Toografía de positrones(beta+)



Crédito: [wikipedia.org](https://www.wikipedia.org)

Se inyecta núcleos radioactivos como agua, oxígeno o azúcar para que se deposite mayormente en el organismo de interés.

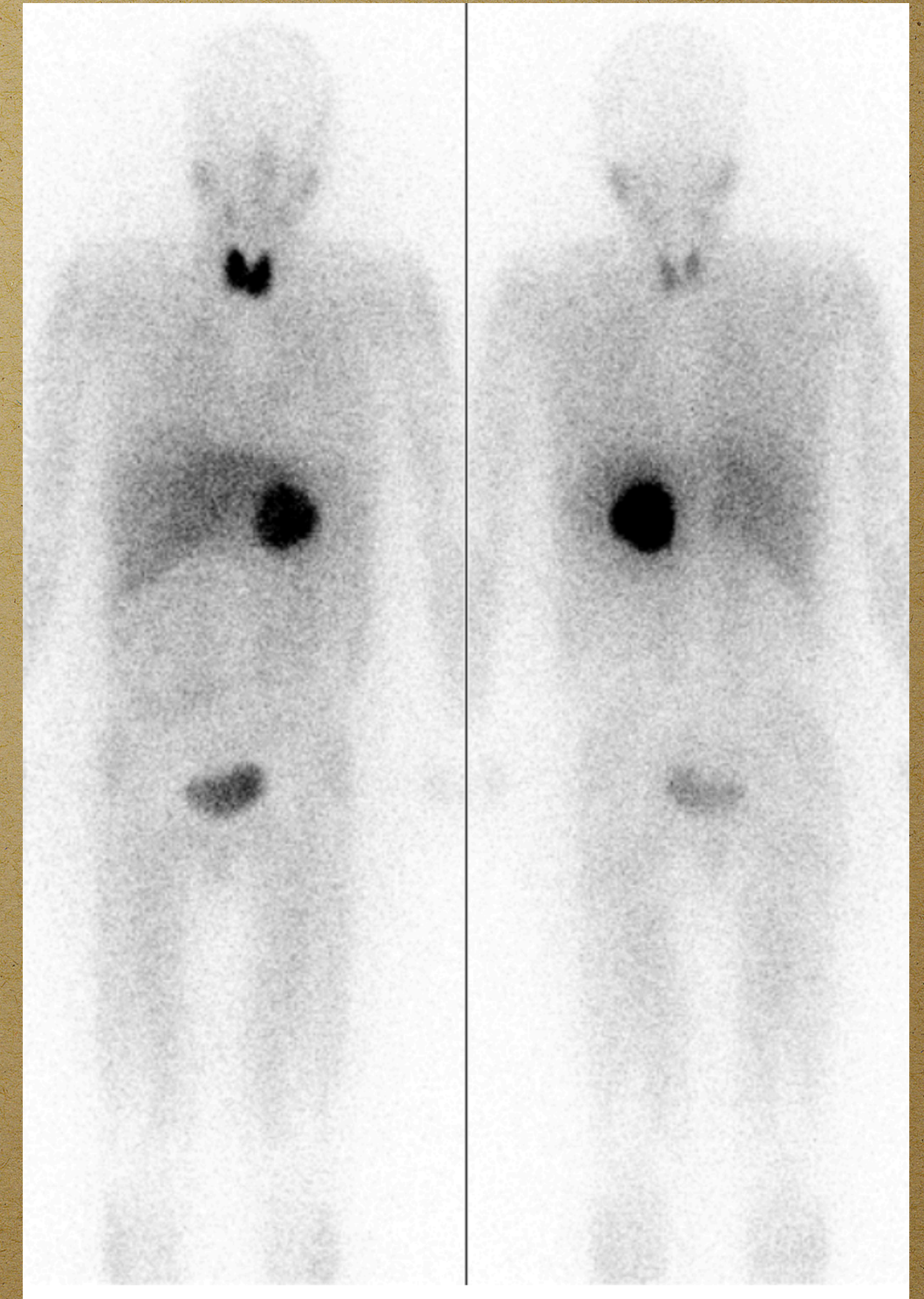


# Diagnóstico con núcleos radiactivos

Diagnóstico por Yodo:  $^{123}\text{I}$  –  $^{125}\text{I}$



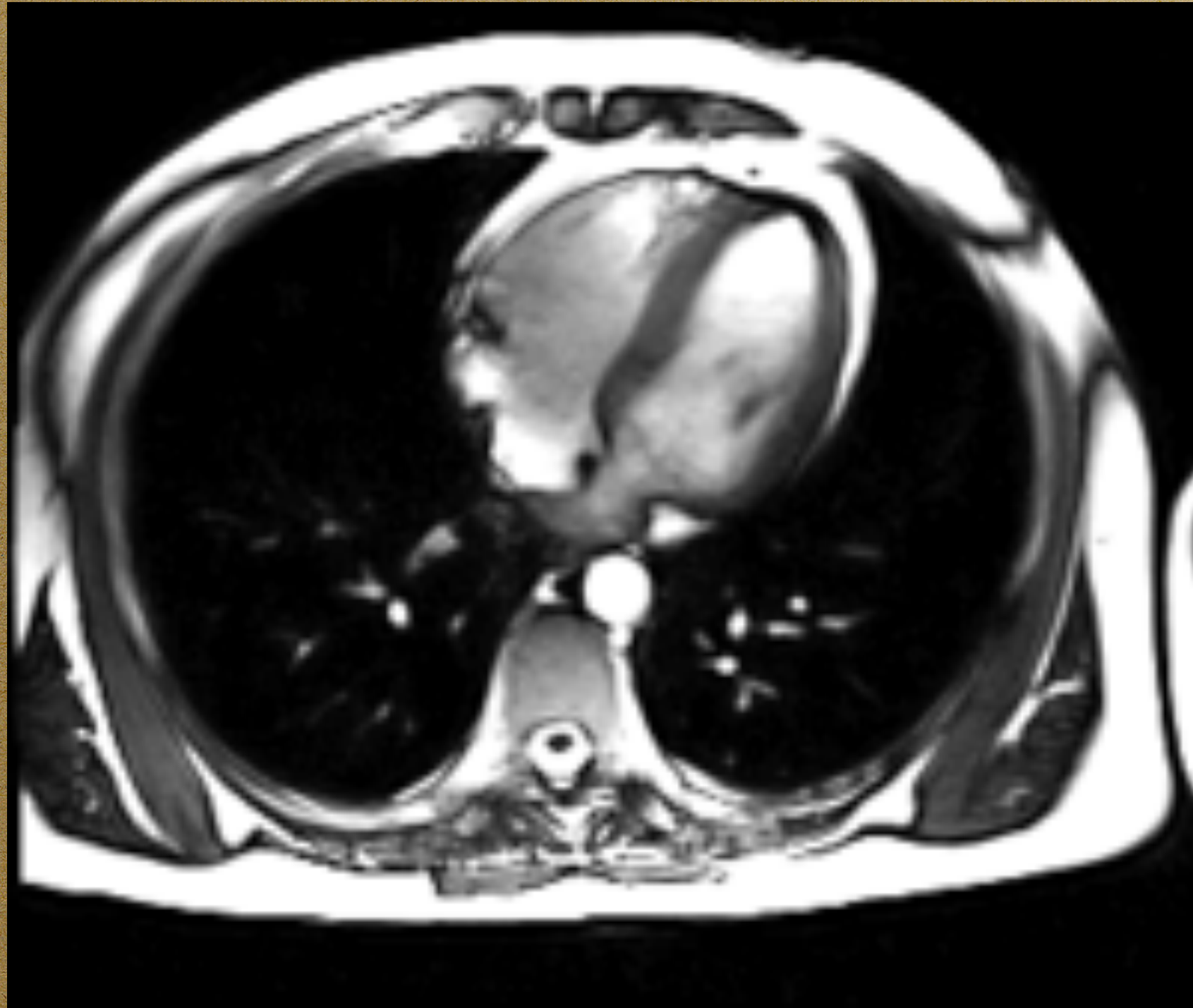
Crédito: [mineralin.com.co](http://mineralin.com.co)



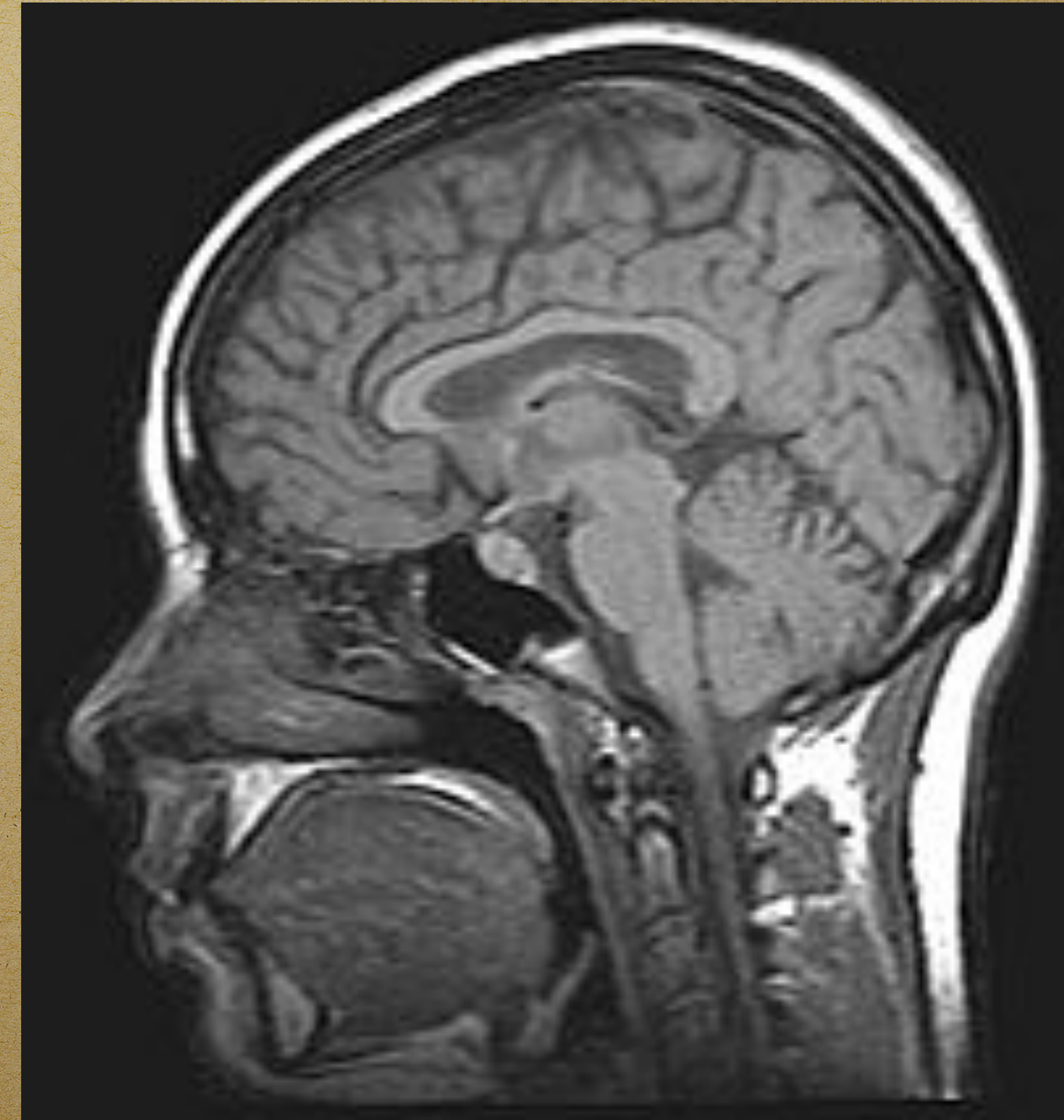
Crédito: wikipedia



# Diagnóstico por resonancia nuclear



Corazón



Cerebro



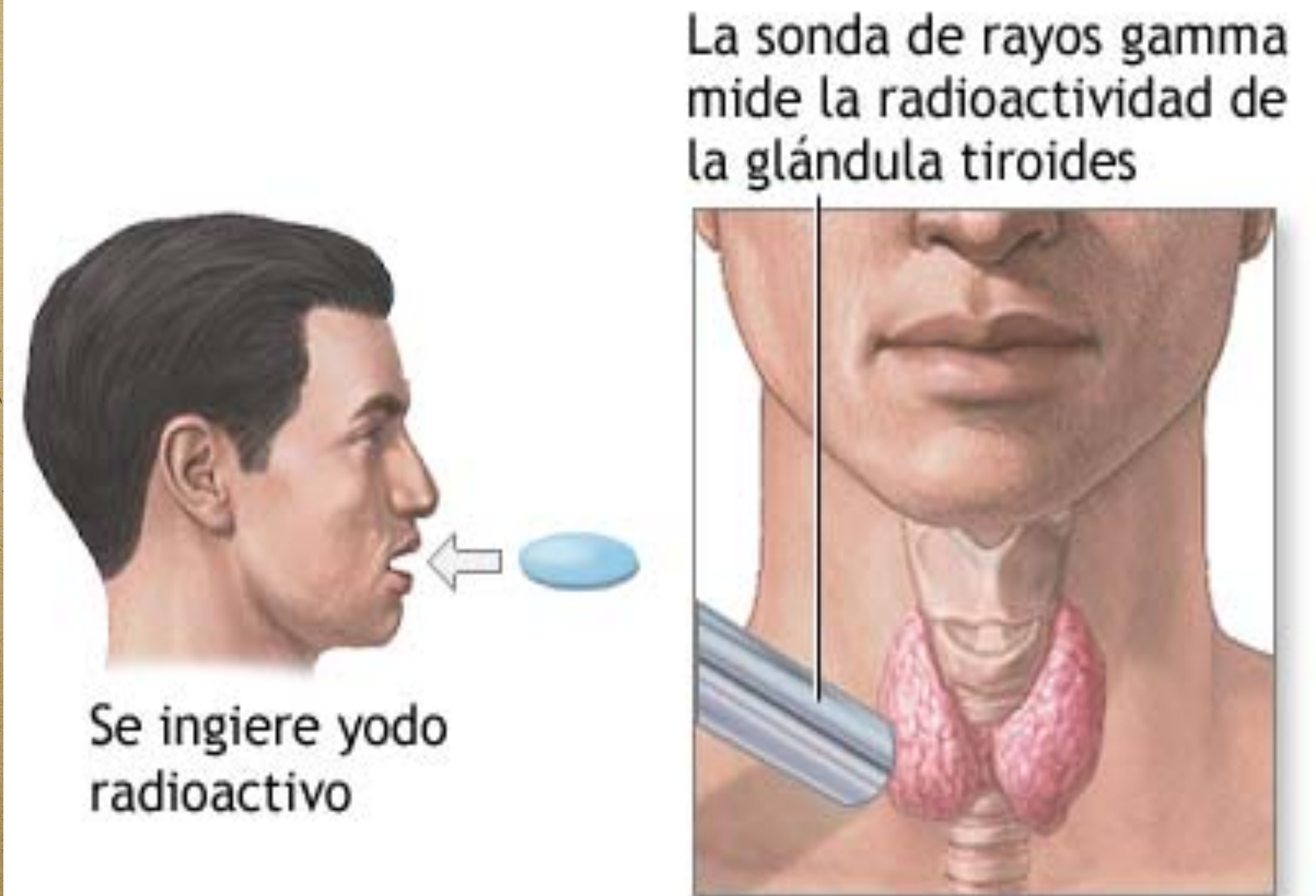
# Terapia con núcleos radiactivos

Consiste en el uso de radiación para destruir las células cancerígenas.

Se inyecta núcleos radioactivos más energéticos que destruyen las células dañadas

Se inyecta núcleos estable que luego se activan (Ej. Boro)

Radio terapia por Yodo:  $^{131}\text{I}$   
Rango 0.6-2 mm



ADAM.

Crédito: [umm.edu](http://umm.edu)



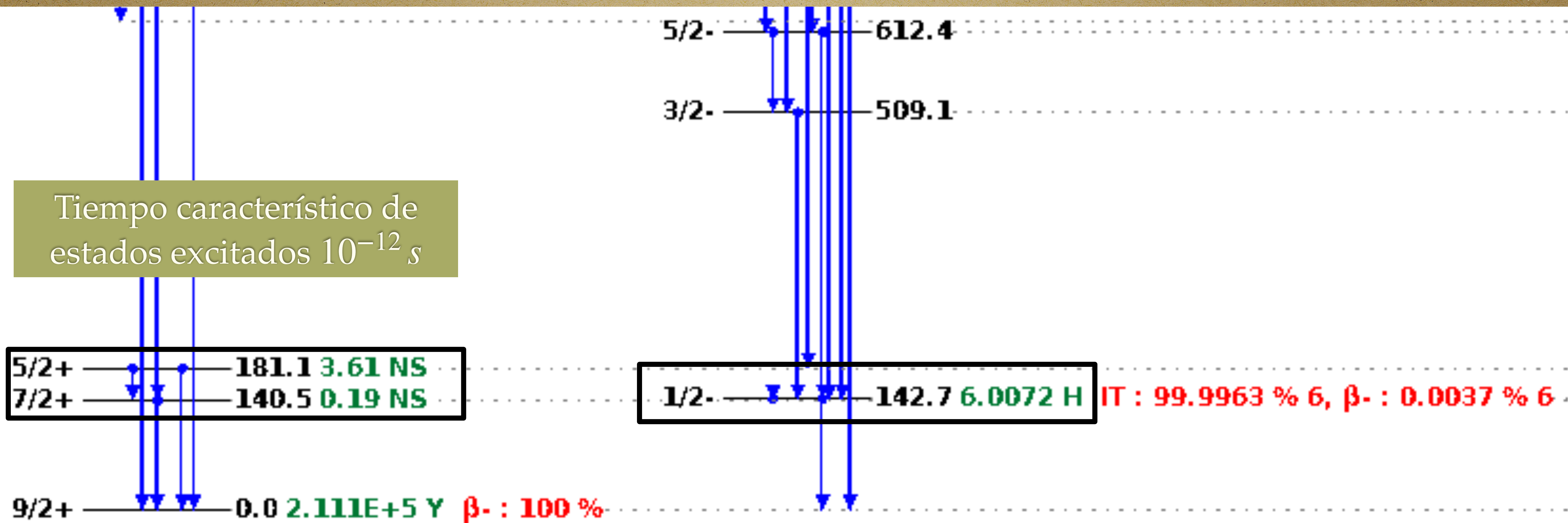
# **Uso de núcleos isómeros para diagnóstico**



# Núcleos isómeros

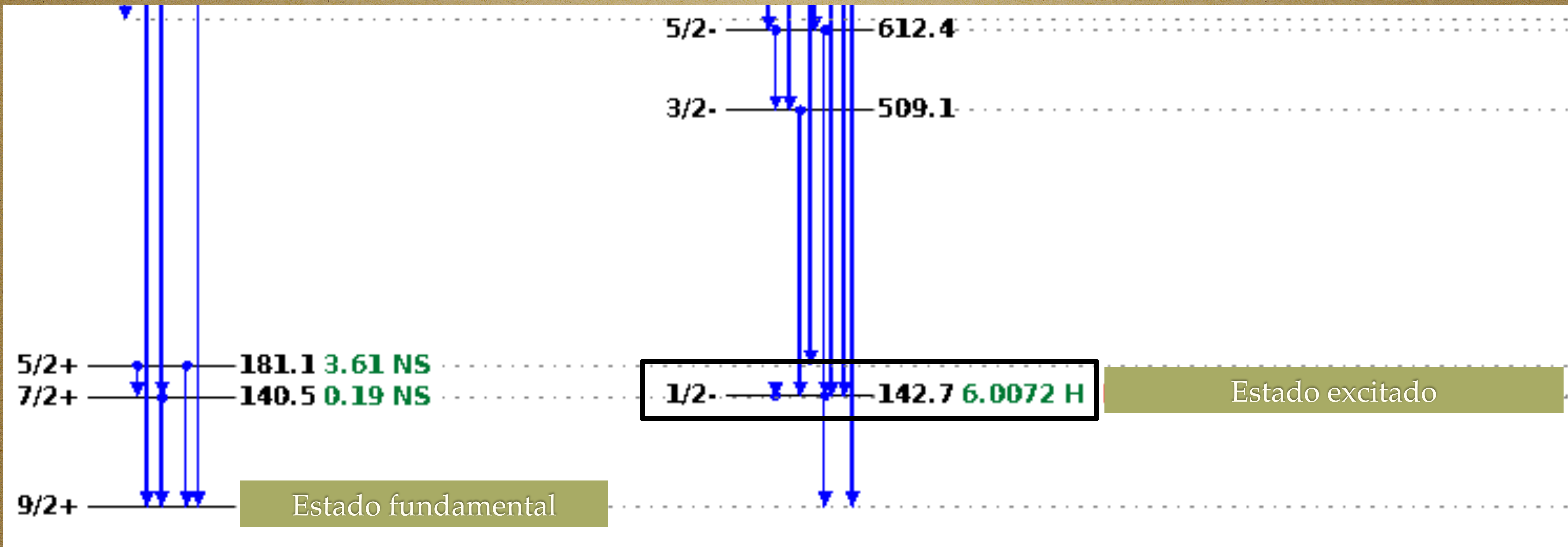
Tiempo característico de isómeros  
 $> 10^{-9} s$

Tiempo característico de estados excitados  $10^{-12} s$





# Núcleos isómeros



→

$$T_{1/2} = 6 \text{ hs}$$



# Sobre el Tecnecio

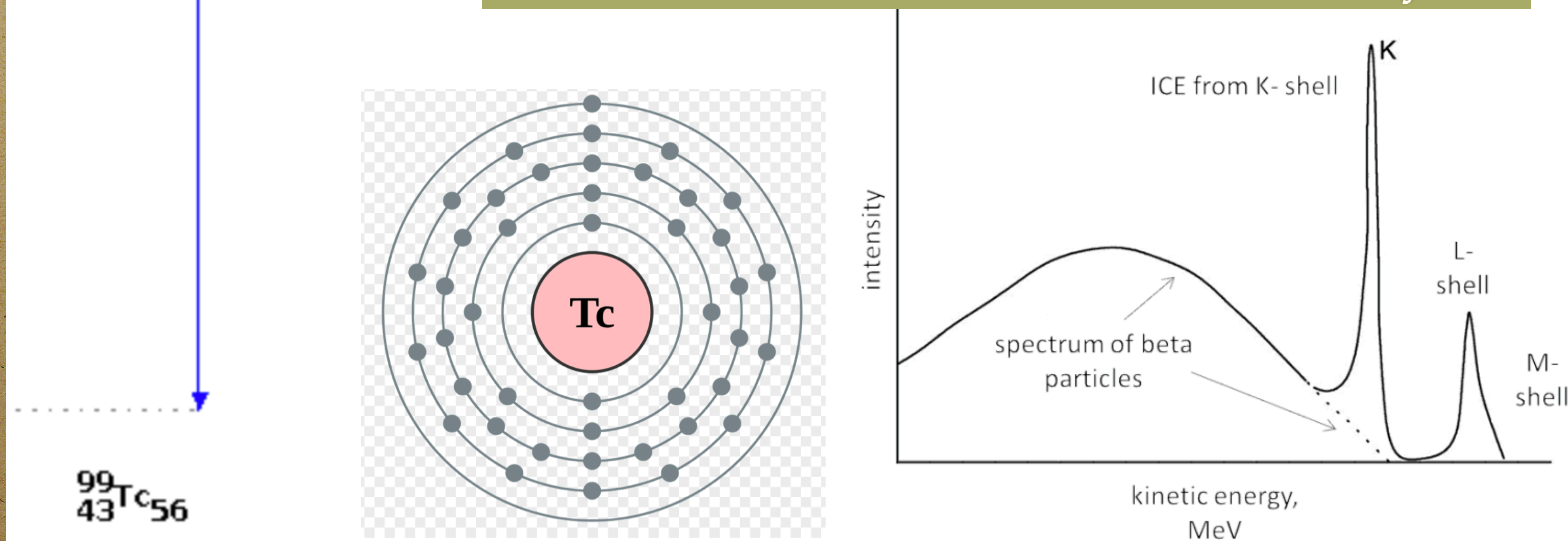


Energía de decaimiento:  
140 keV

Modo de decaimiento:  
internal conversion

1/2- 142.7 6.0072 H IT : 99.9963 % 6,  $\beta^-$  : 0.0037 % 6

Internal conversion versus beta decay





# Sobre el Tecnecio

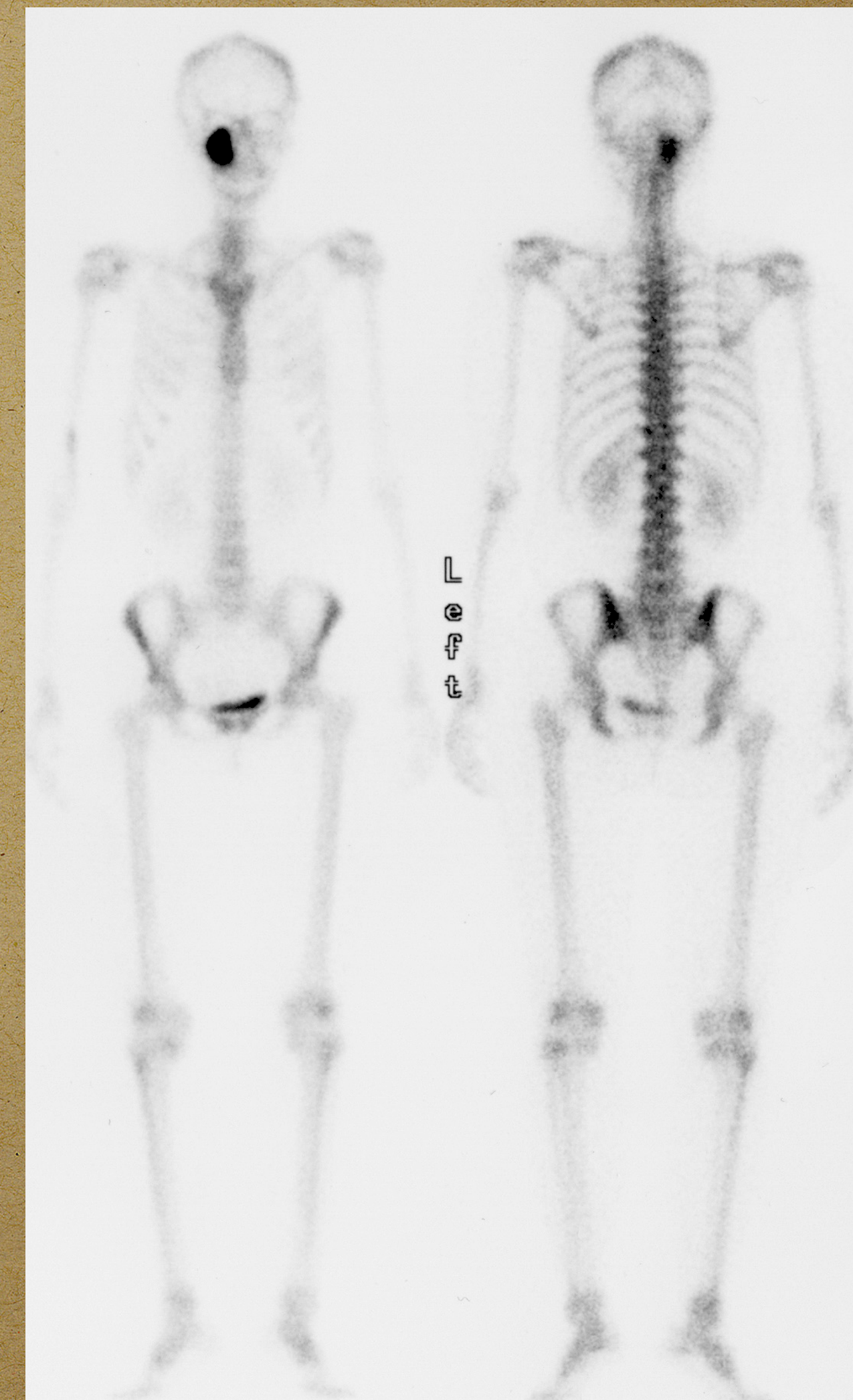
Energía de decaimiento:  
140 keV

Modo de decaimiento:  
internal conversion

Tiempo de vida media:  
 ${}^{99}_{49}\text{Tc}^{\text{m}} \rightarrow T_{1/2} = 6 \text{ hs}$

- El 80% de los diagnósticos por imagen usan Tecnecio
- Existen alrededor de 31 radiofármacos que pueden combinarse con el Tecnecio para aplicarse al organismo

- Permite el estudio:
  - Cerebro
  - Miocardio
  - Glándula tiroidea
  - Pulmones
  - Hígado
  - Vesícula biliar
  - Riñones
  - Esqueleto
  - Sangre
  - Tumores



Crédito: Raziell~commonswiki  
<https://commons.wikimedia.org/w/index.php?curid=616971>



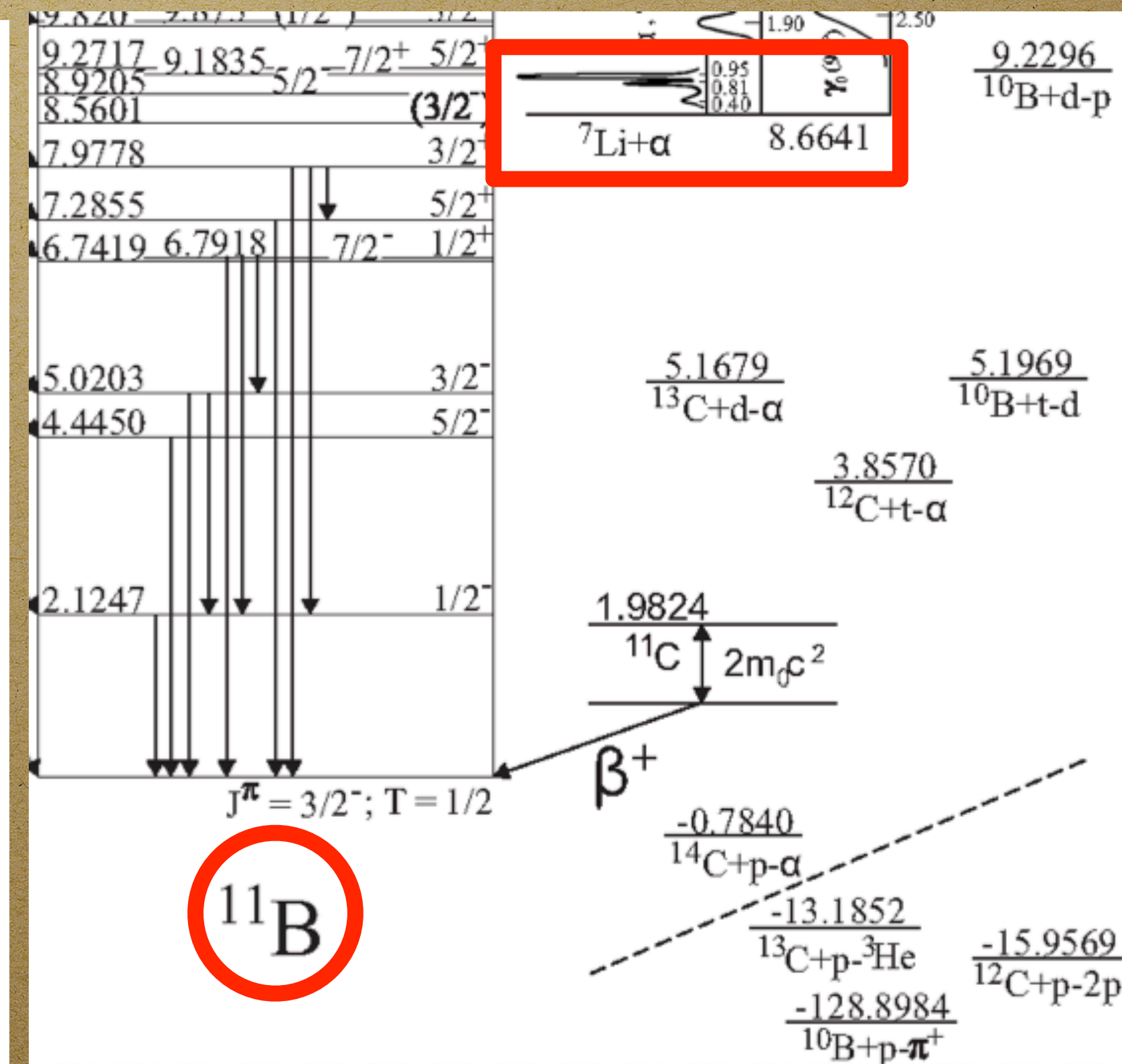
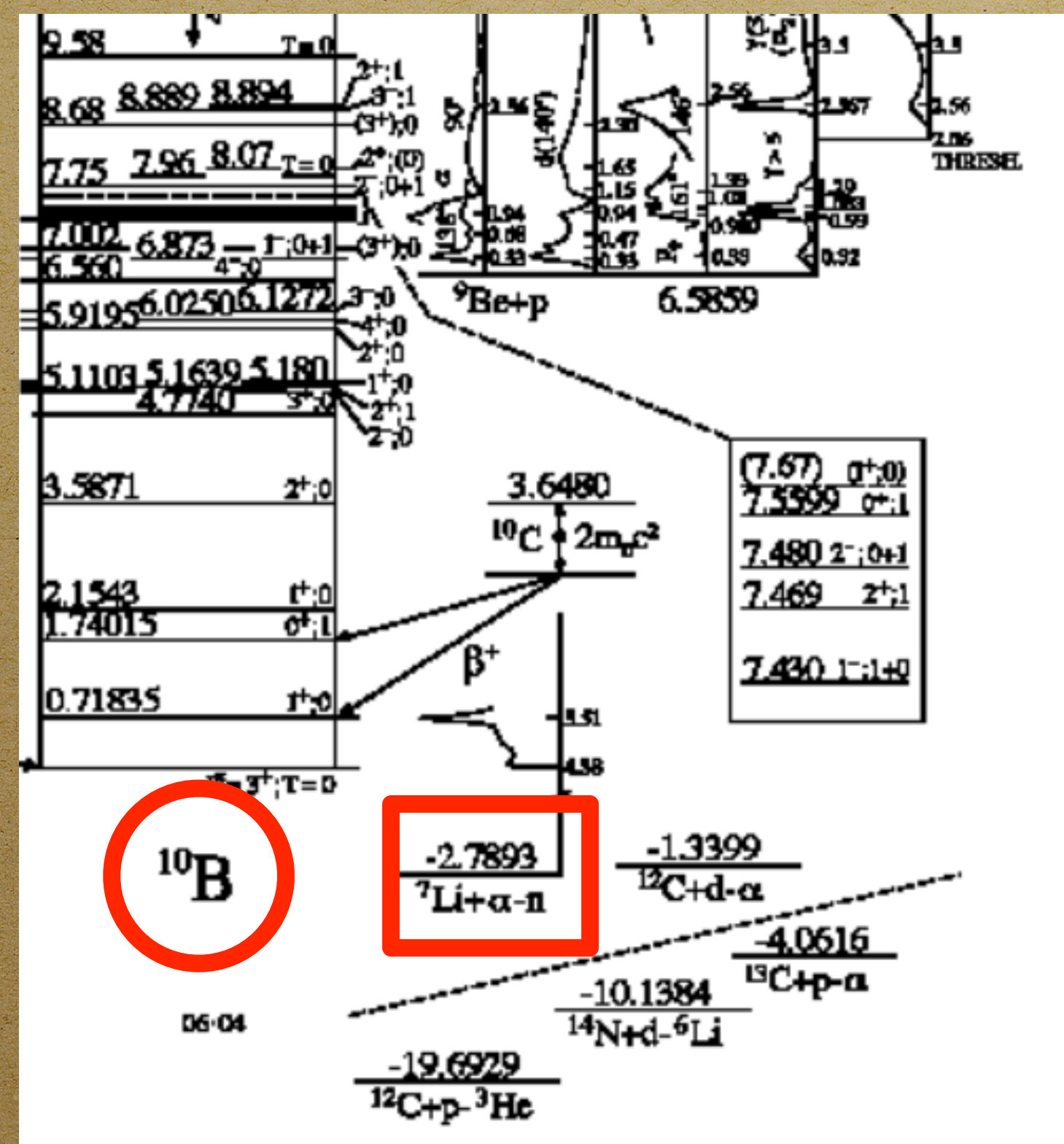
# **Uso del Boro para terapia**



# Sobre la estabilidad del núcleo de Boro

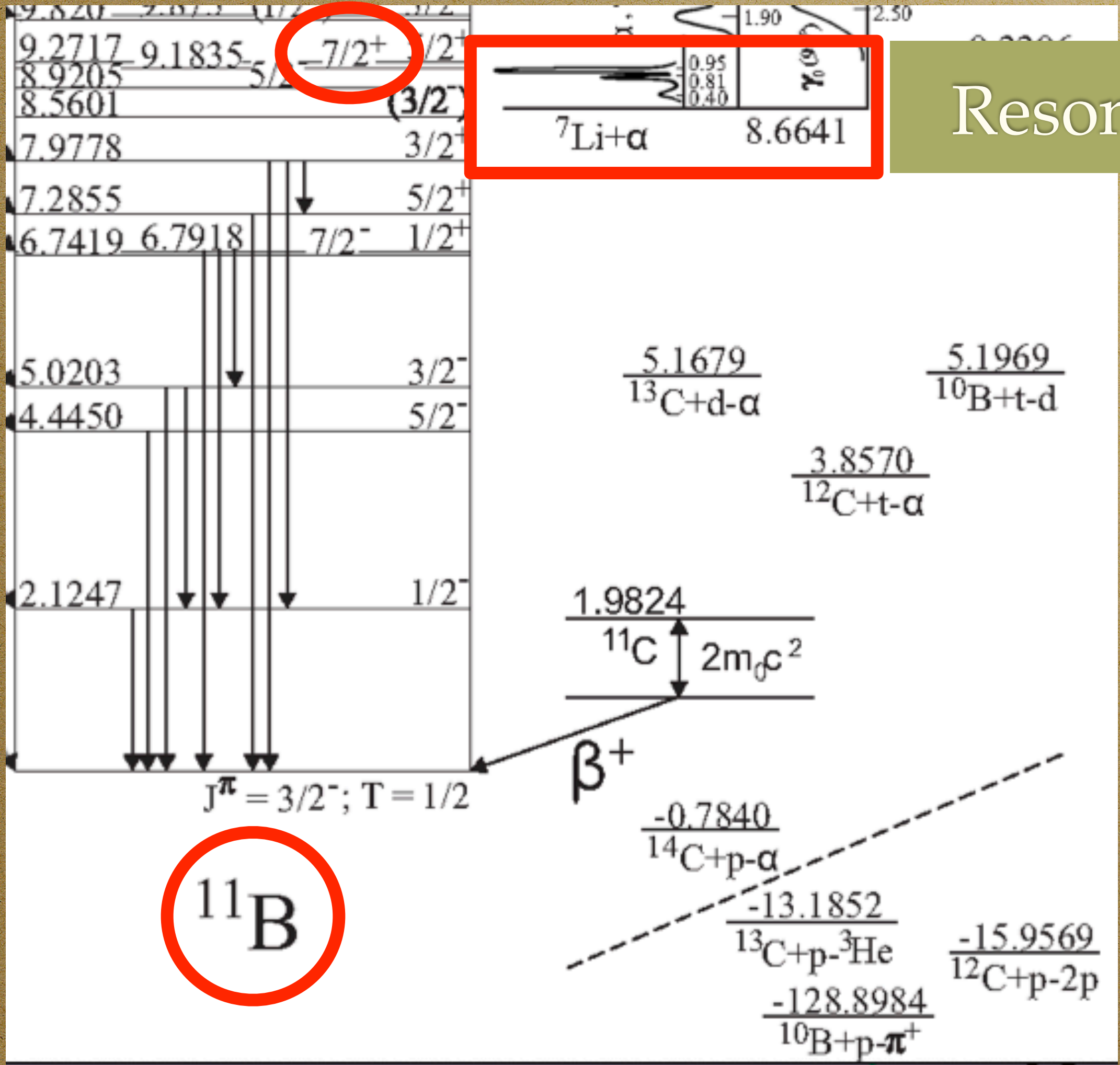
Z=5

9B	10B	11B	12B
0.54 KeV	STABLE	STABLE	20.20 MS
2 $\alpha$ : 100.00%	19.9%	80.1%	$\beta^-$ : 100.00%
P: 100.00%			B3A: 1.58%
8.43E-19	1.00E+24	1.00E+24	2.02E-2

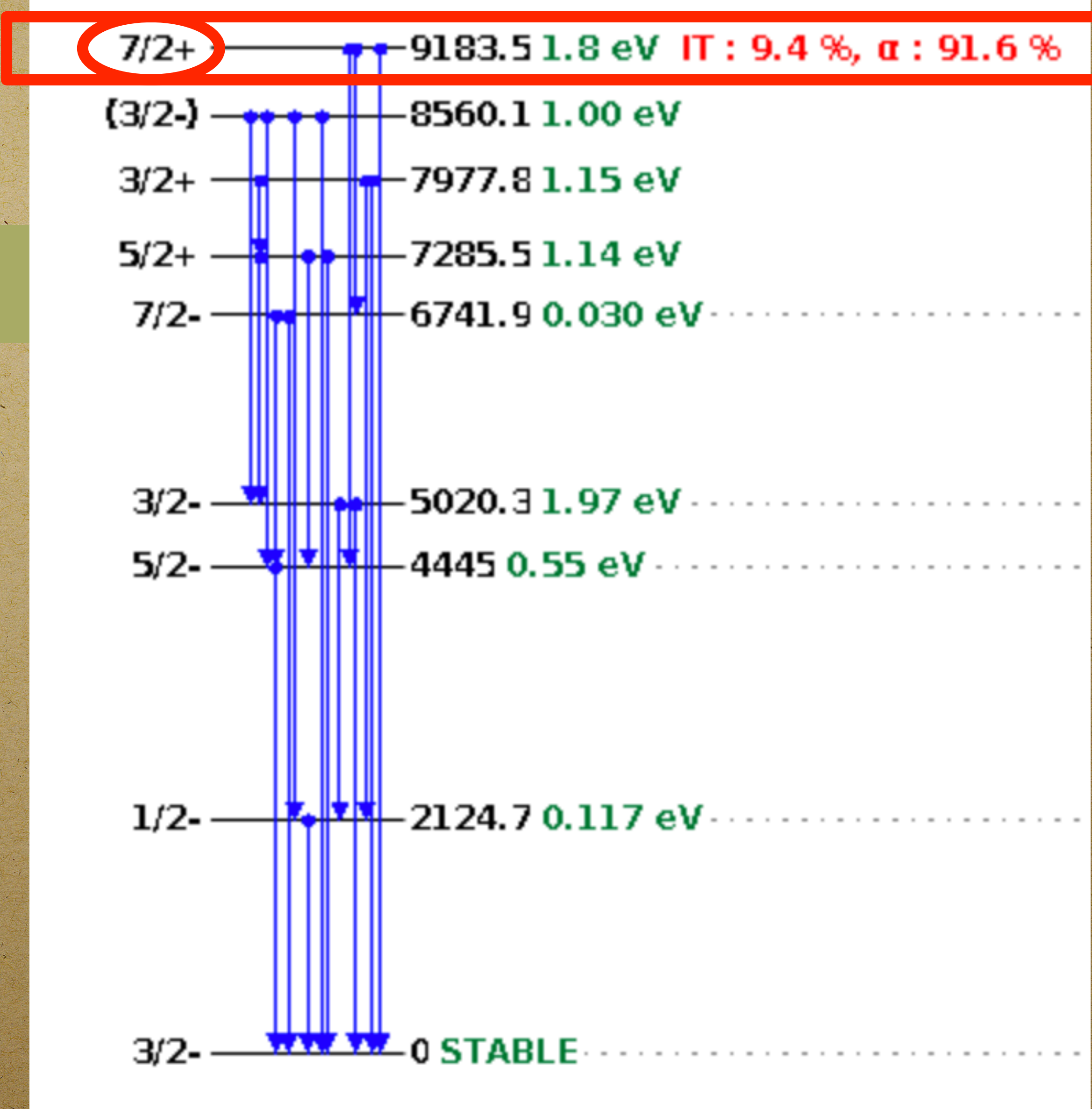




# Resonancia en el núcleo de Boro



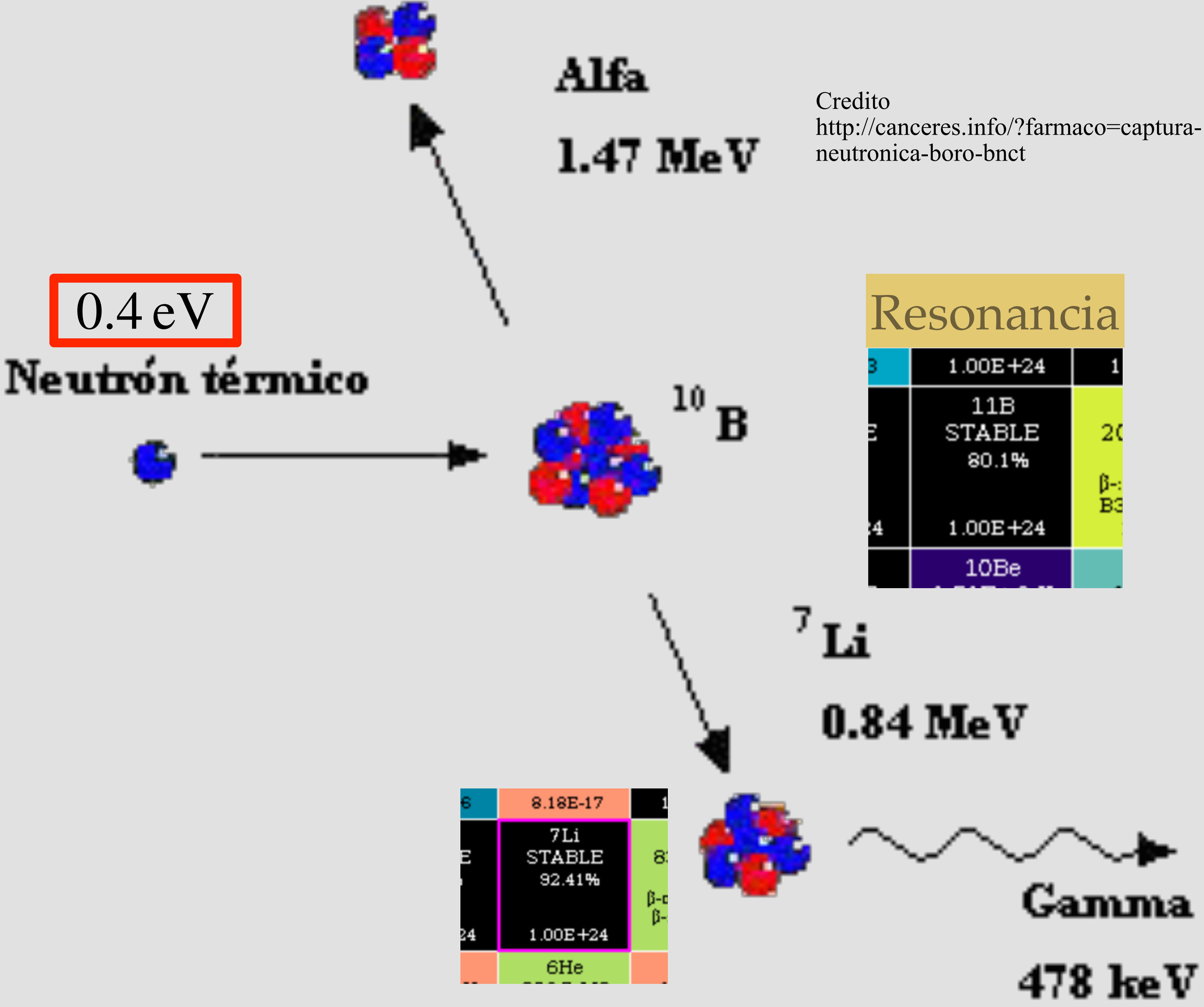
Resonancias





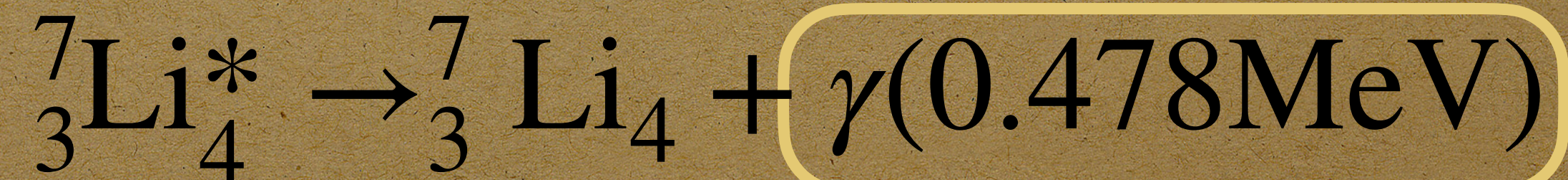
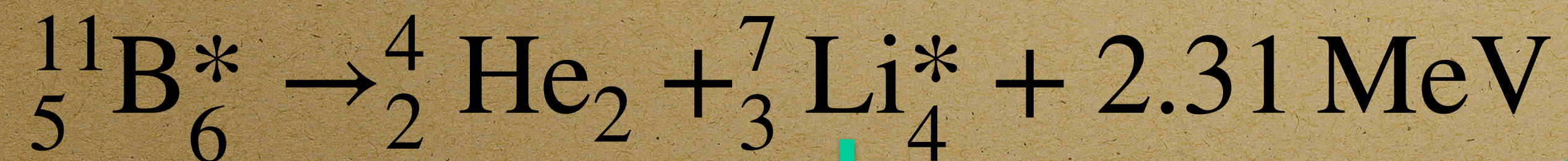
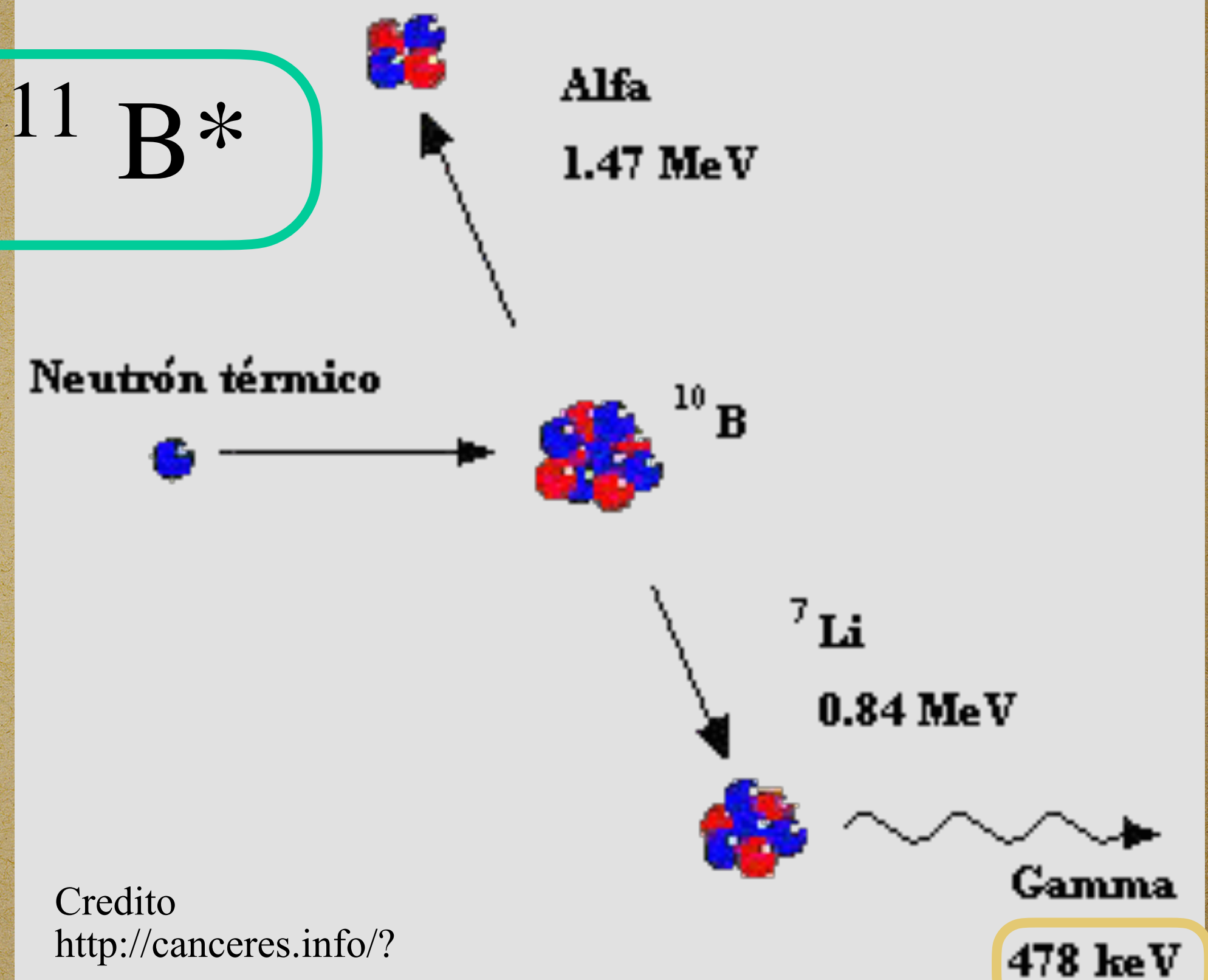
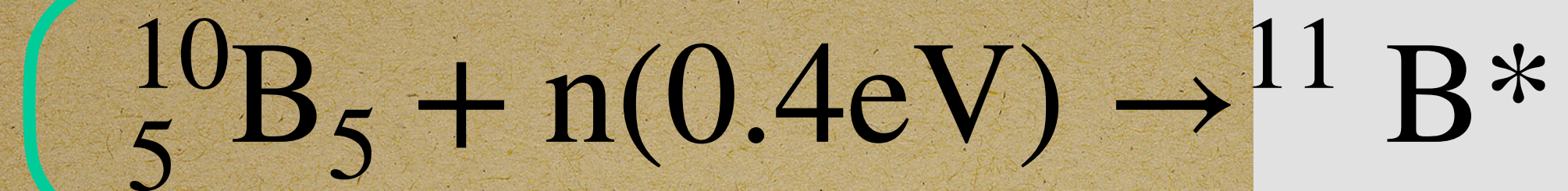
# Ruptura del $^{11}\text{B}$

100.00%	P: 100.00%	$\epsilon$ : 100.00%	$\epsilon$ : 100.00%	99.63%
9C 6.5 MS	10C 19.308 S	11C 20.364 M	12C STABLE 98.93%	13C STABLE 1.07%
100.00% 81.60%	$\epsilon$ : 100.00%	$\epsilon$ : 100.00%		
8B 70 MS	9B 0.54 KeV	10B STABLE 19.9%	11B STABLE 80.1%	12B 20.20 MS
100.00% 100.00%	P: 100.00% 2 $\alpha$ : 100.00%			$\beta^-$ : 100.00% B3A: 1.58%
7Be 3.22 D	8Be 5.57 eV	9Be STABLE 100.0%	10Be 1.51E+6 Y	11Be 13.76 S
100.00%	$\alpha$ : 100.00%		$\beta^-$ : 100.00%	$\beta^-$ : 100.00% $\beta$ - $\alpha$ : 3.10%
6Li TABLE 7.59%	7Li STABLE 92.41%	8Li 839.9 MS	9Li 178.3 MS	10Li
		$\beta$ - $\alpha$ : 100.00% $\beta^-$ : 100.00%	$\beta^-$ : 100.00%	N: 100.00%
3	4	5	6	7



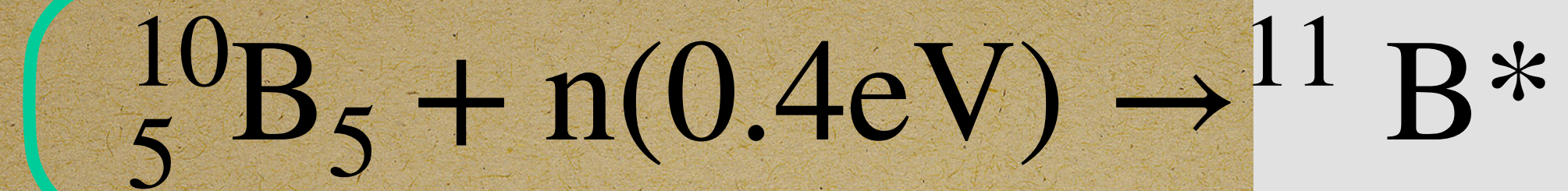


# Reacción

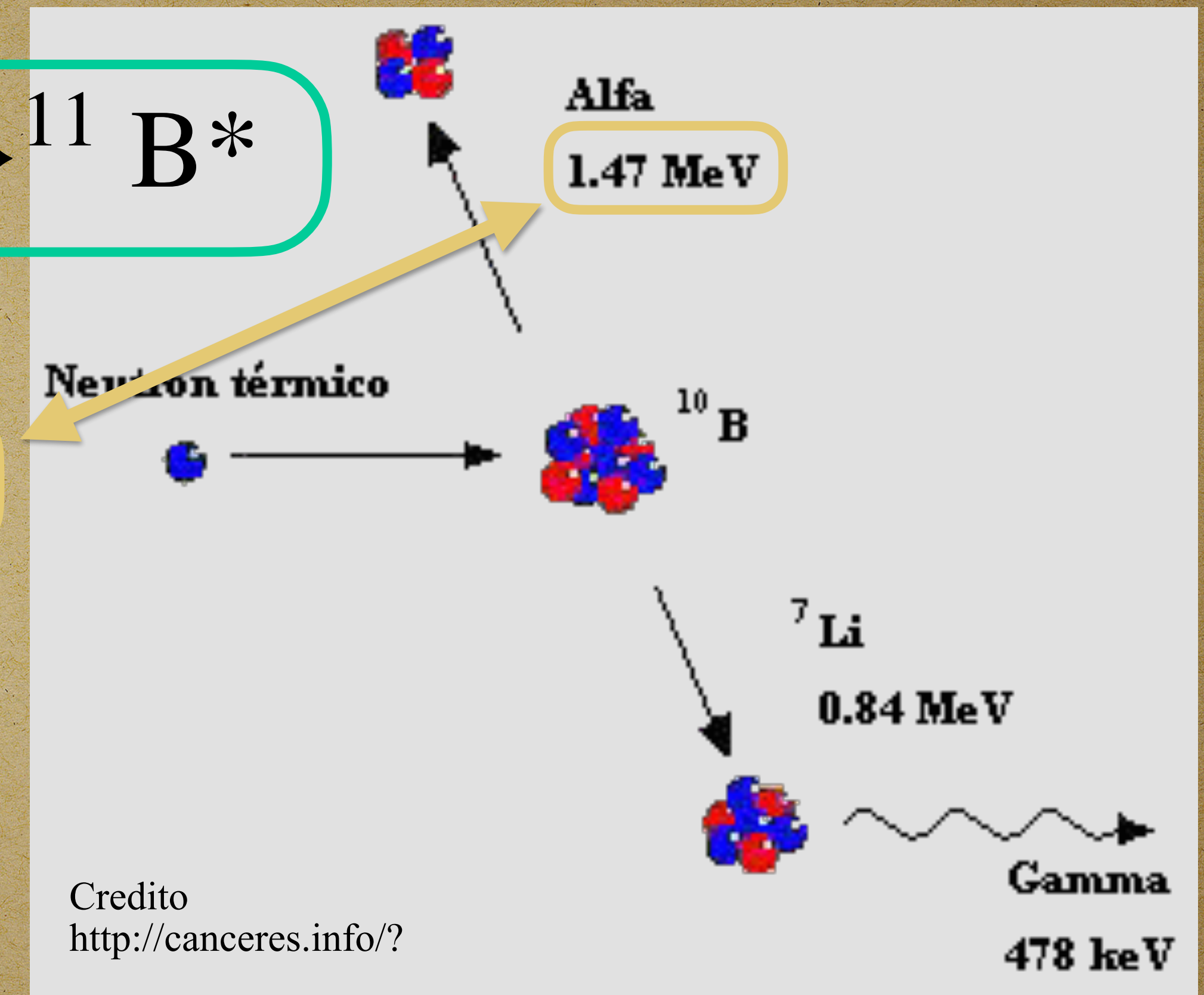
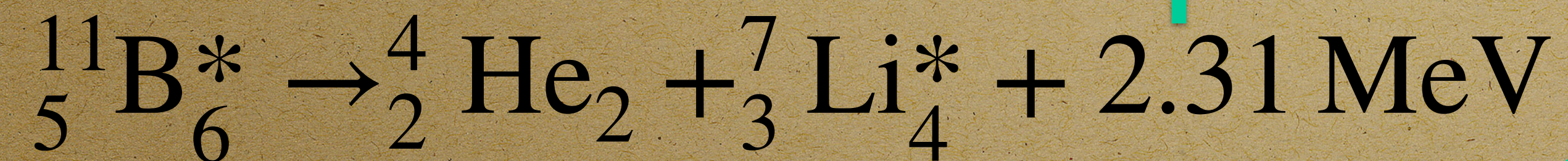




# Reacción

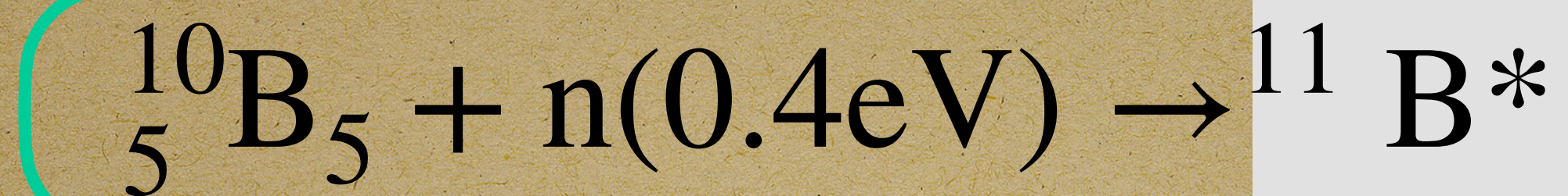


$$0.840\text{ MeV}(\text{Li}) + 1.47\text{ MeV}(\alpha)$$

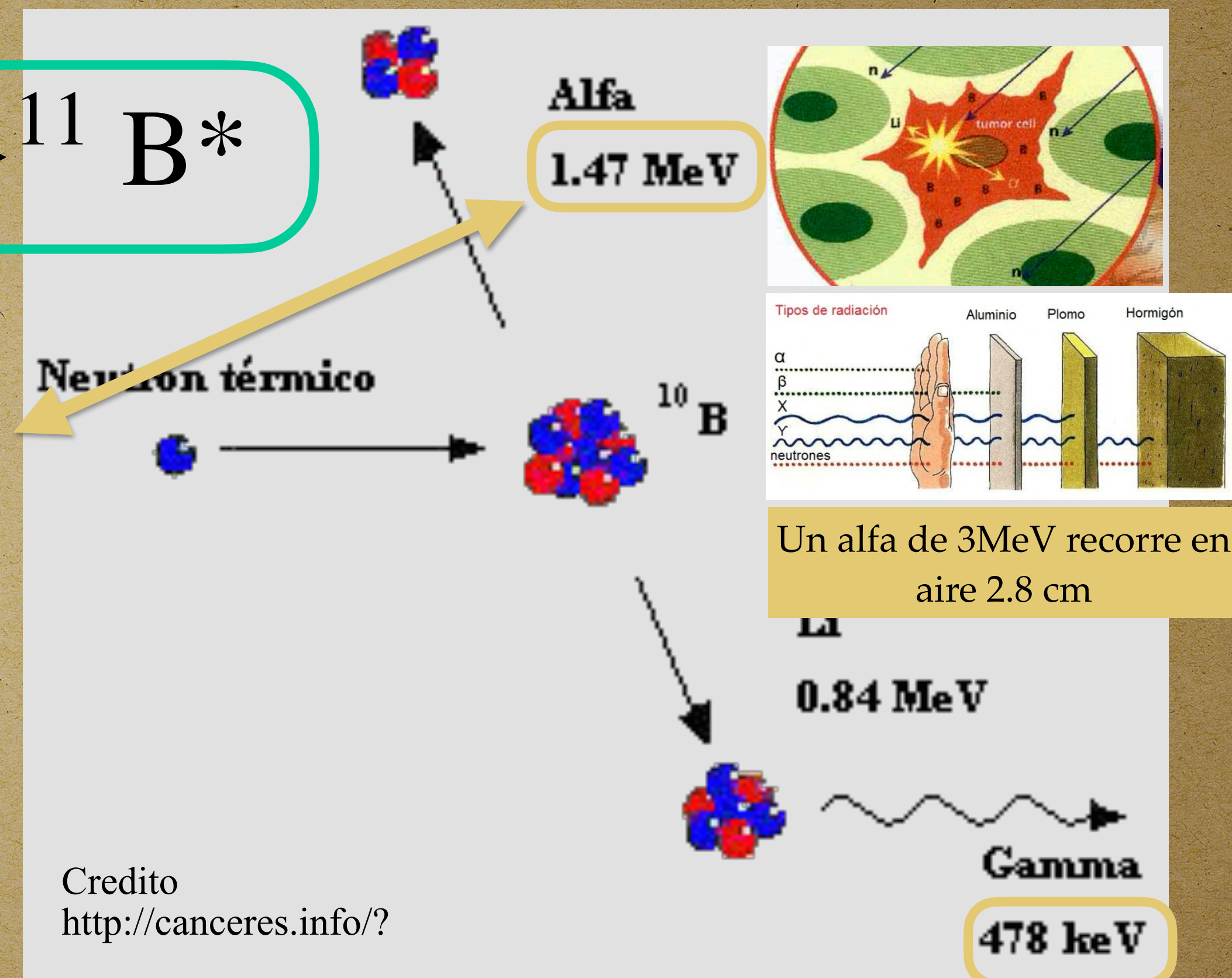
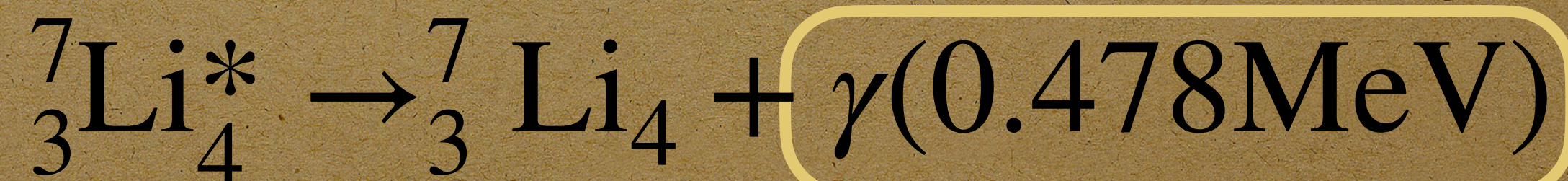
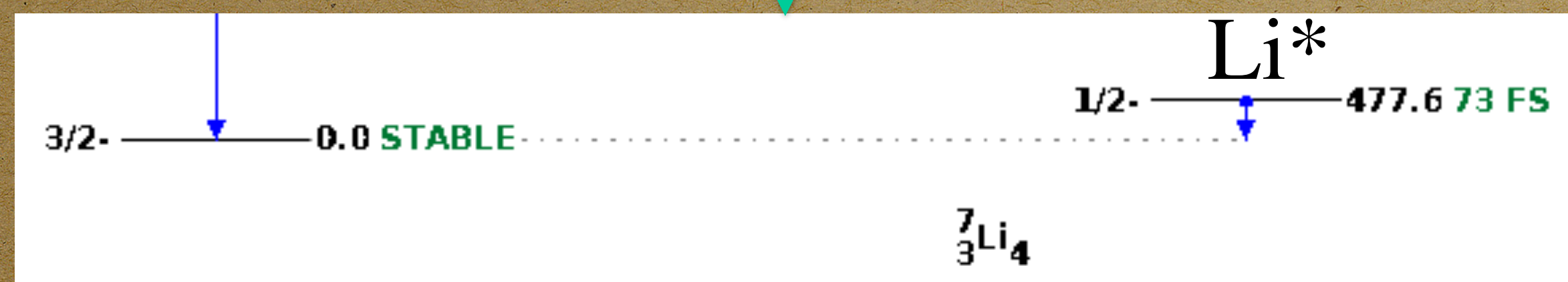




# Destrucción celular



$$0.840\text{ MeV}(\text{Li}) + 1.47\text{ MeV}(\alpha)$$

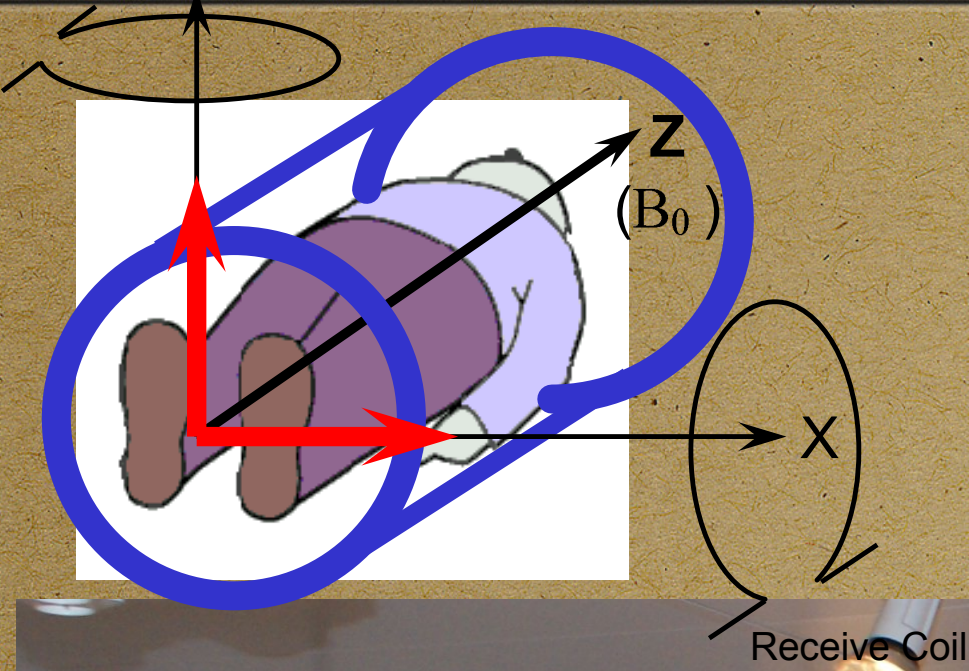




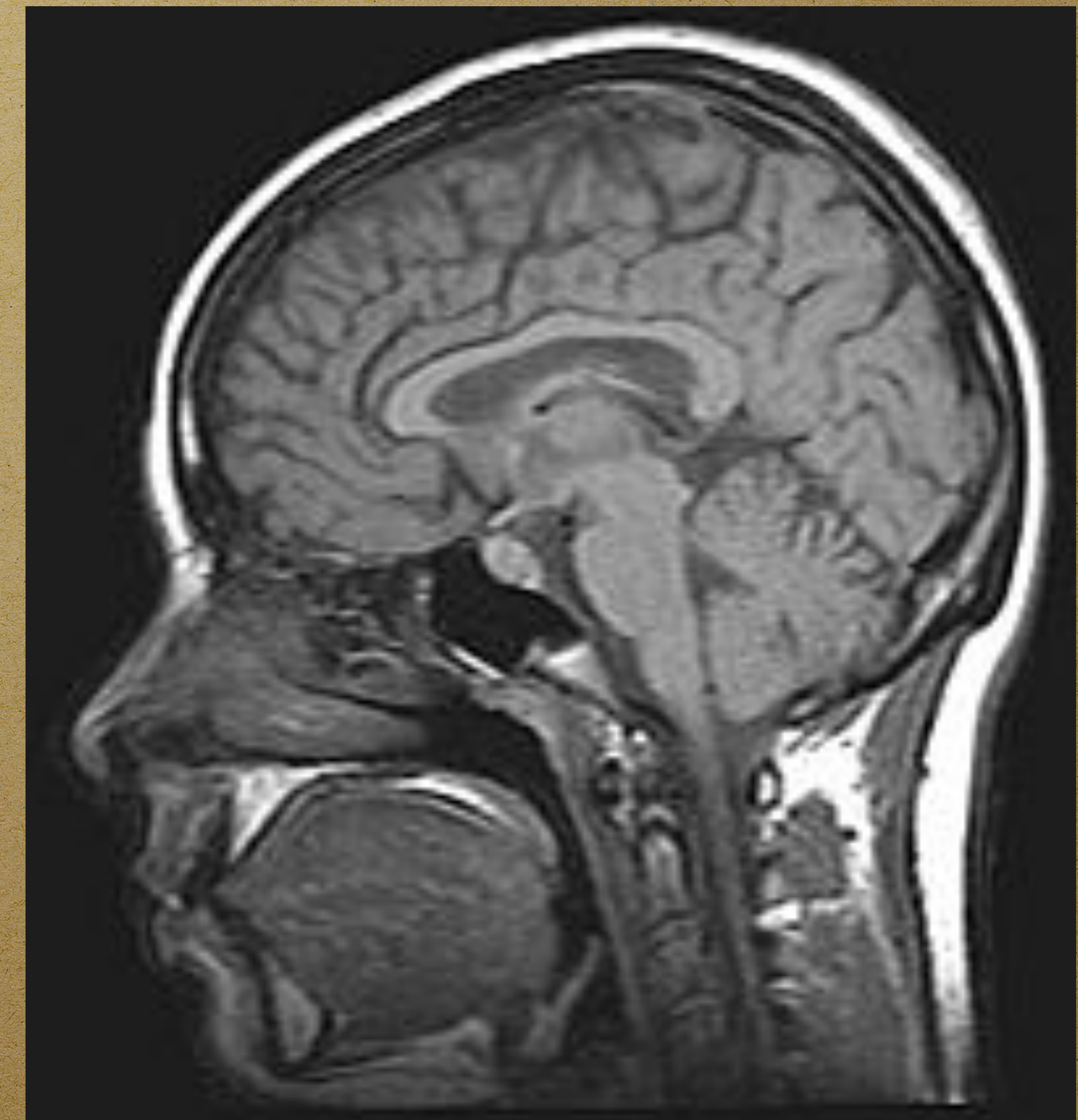
# **Resonancia magnética nuclear**



# Diagnóstico por resonancia nuclear



Crédito: Evert J. Blink



Crédito: Wikipedia



# Momento magnético

## Momento magnético

$$\mu = \frac{g}{2mc}qs$$

## Campo magnético

$$B = B_0 \hat{k}$$

## Interacción

$$H = -\mu \cdot B$$

$$H = \omega_0 s_z$$

$$\omega_0 = -\frac{g}{2mc}qB_0$$

Frecuencia de Lamor

## Solución Hamiltoniano

$$H|\pm\rangle = E_{\pm}|\pm\rangle$$

$$E_{\pm} = \pm \frac{\omega_0 \hbar}{2}$$



# Momento magnético con campo estático

## Momento magnético

$$\mu = \frac{g}{2mc}qs$$

## Campo magnético

$$B = B_0 \hat{k}$$

## Interacción

$$H = -\mu \cdot B$$

$$H = \omega_0 s_z$$

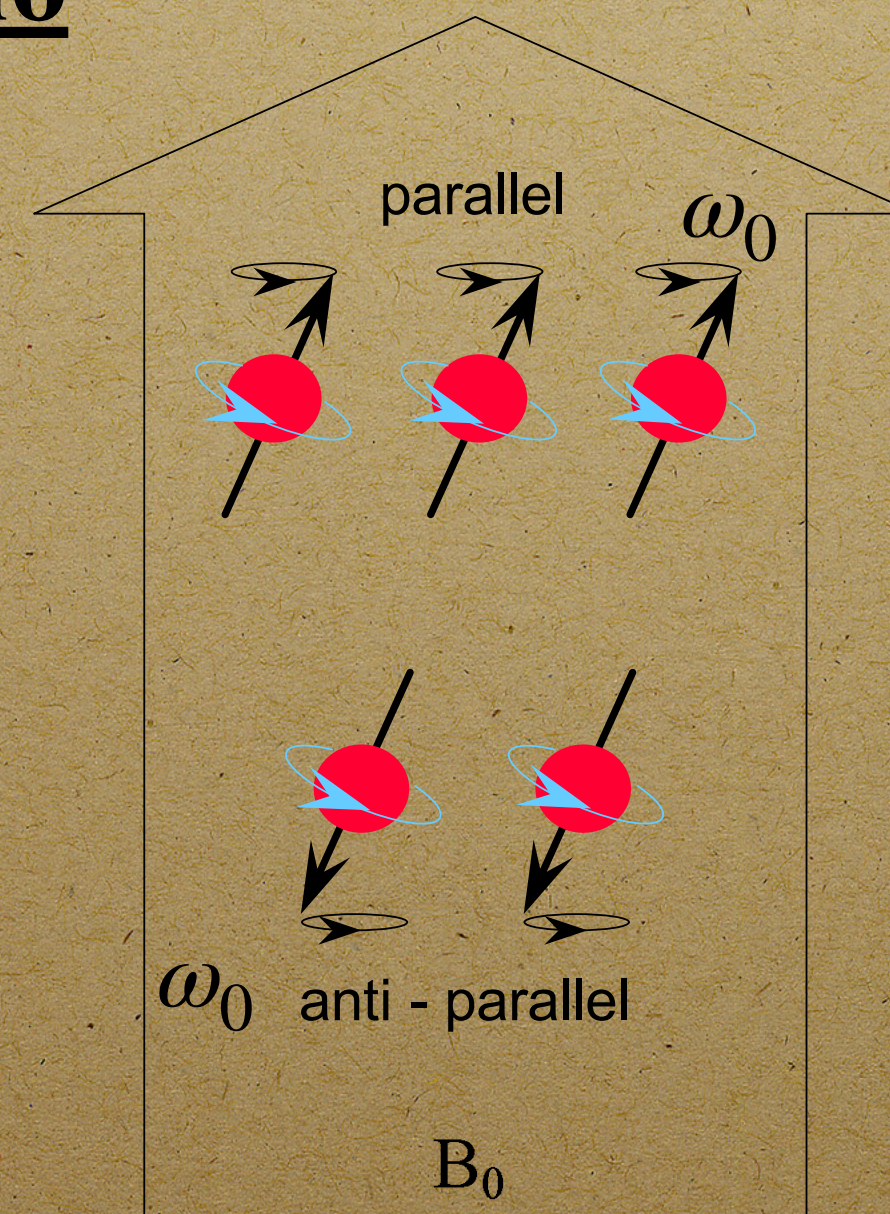
$$\omega_0 = -\frac{g}{2mc}qB_0$$

Frecuencia de Lamor

## Solución Hamiltoniano

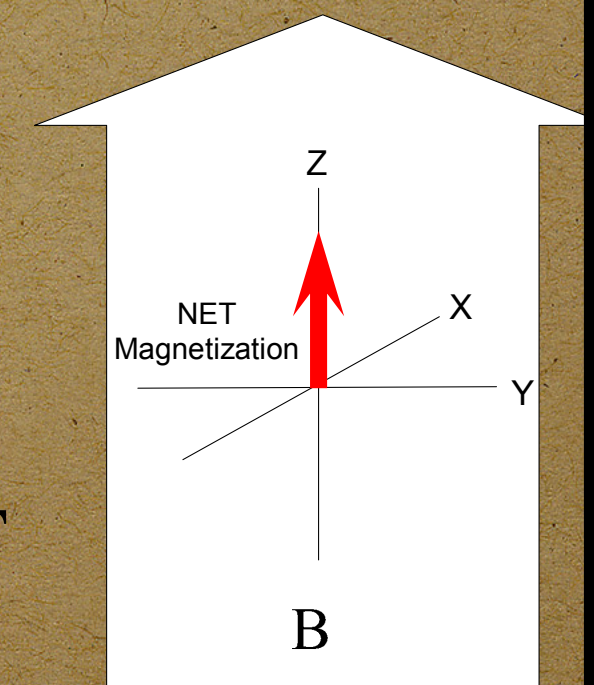
$$H|\pm\rangle = E_{\pm}|\pm\rangle$$

$$E_{\pm} = \pm \frac{\omega_0 \hbar}{2}$$



## Efecto neto

$$\frac{|-\rangle - |+\rangle}{|-\rangle} \sim \frac{6}{10^6} \Big|_{B_0=1T}$$



## Para referencia:

$$B_0(\text{Tierra}) \sim 30 - 70 \mu\text{T}$$

Crédito: Evert J. Blink



# Campo magnético dependiente del tiempo

## Resonancia = Palanca

### Campo magnético

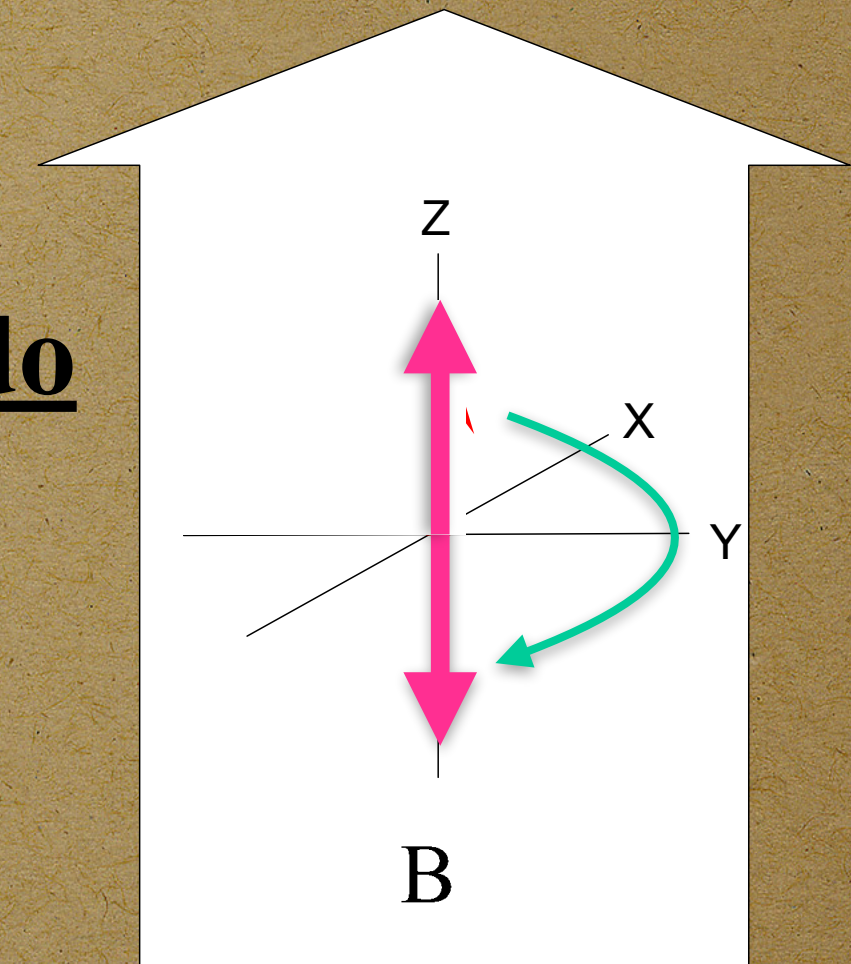
$$B = B_1 \cos \omega t \hat{i}$$

$$B_1 \ll B_0$$

### Transición Resonante

$$\omega \rightarrow (E_- \rightarrow E_+)$$

### Cambio de estado excitado al fundamental



### Interacción dependiente del tiempo

$$H = \omega_0 s_z - \frac{gqB_1}{2mc} \cos \omega t s_x$$

$$H = \frac{\hbar}{2} \begin{pmatrix} \omega_0 & \omega_1 \cos \omega t \\ \omega_1 \cos \omega t & -\omega_0 \end{pmatrix}$$

Emisión de energía

$$\omega_1 = -\frac{g}{2mc} qB_1 \quad |\omega_1| \ll |\omega_0|$$

Condición sobre el campo dependiente del tiempo



# Campo magnético dependiente del tiempo: solución

## Hamiltoniano

$$H\Psi(t) = i\hbar \frac{d\Psi(t)}{dt}$$

$$H = \frac{\hbar}{2} \begin{pmatrix} \omega_0 & \omega_1 \cos \omega t \\ \omega_1 \cos \omega t & -\omega_0 \end{pmatrix}$$

## Ansatz

$$\Psi(t) = e^{-i\frac{\omega_0}{2}t} a(t) |+\rangle + e^{i\frac{\omega_0}{2}t} b(t) |-\rangle$$

$$\frac{d^2 b}{dt^2} + i(\omega_0 - \omega) \frac{db}{dt} + \left( \frac{\omega_1}{4} \right)^2 b = 0$$



# Campo magnético dependiente del tiempo: solución

Condición contorno

Solución

$$a(t=0) = 1; \quad b(t=0) = 0$$

$$\Psi(t) = e^{-i\frac{\omega_0}{2}t} a(t) |+\rangle + e^{i\frac{\omega_0}{2}t} b(t) |-\rangle$$

$$|a(t)|^2 + |b(t)|^2 = 1$$

$$a(t) = 2A \frac{\omega_0 - \omega_1}{\omega_1} e^{i\frac{(\omega_0 - \omega)}{2}t} \left( -\sin \Omega t - i \sqrt{1 + \frac{\omega_1^2}{4(\omega_0 - \omega)^2}} \cos \Omega t \right)$$

$$b(t) = A e^{-i\frac{(\omega_0 - \omega)}{2}t} \sin \Omega t$$

$$\Omega = \frac{1}{2} \sqrt{(\omega_0 - \omega)^2 + \frac{\omega_1^2}{4}}$$

Breit-Weigner

$$|A|^2 = \frac{(\omega_1/2)^2}{(\omega_0 - \omega)^2 + (\omega_1/2)^2}$$



# Probabilidad transición de un nucleón en un campo

## Evolución temporal

$$\Psi(t) = e^{-i\frac{\omega_0}{2}t} a(t) | + \rangle + e^{i\frac{\omega_0}{2}t} b(t) | - \rangle$$

## Condición inicial

$$a(t = 0) = 1; \quad b(t = 0) = 0$$

## Probabilidad transición

$$|b(t)|^2 = \frac{(\Gamma_1/2)^2}{(E_0 - E)^2 + (\Gamma_1/2)^2} \sin^2 \Omega t$$

$$E = \hbar\omega; \quad \Gamma_1 = \hbar\omega_1$$

$$\Omega = \frac{1}{2} \sqrt{(E_0 - E)^2 + \frac{\Gamma_1^2}{4}}$$



# Tiempo de relajación al quitar la perturbación

## Evolución temporal

$$\Psi(t) = e^{-i\frac{\omega_0}{2}t} a(t) | + \rangle + e^{i\frac{\omega_0}{2}t} b(t) | - \rangle$$

## Condición inicial

$$a(t = 0) = 1; \quad b(t = 0) = 0$$

## Resonancia

$$|b(t)|^2 = \frac{(\Gamma_1/2)^2}{(E_0 - E)^2 + (\Gamma_1/2)^2} \sin^2 \Omega t$$

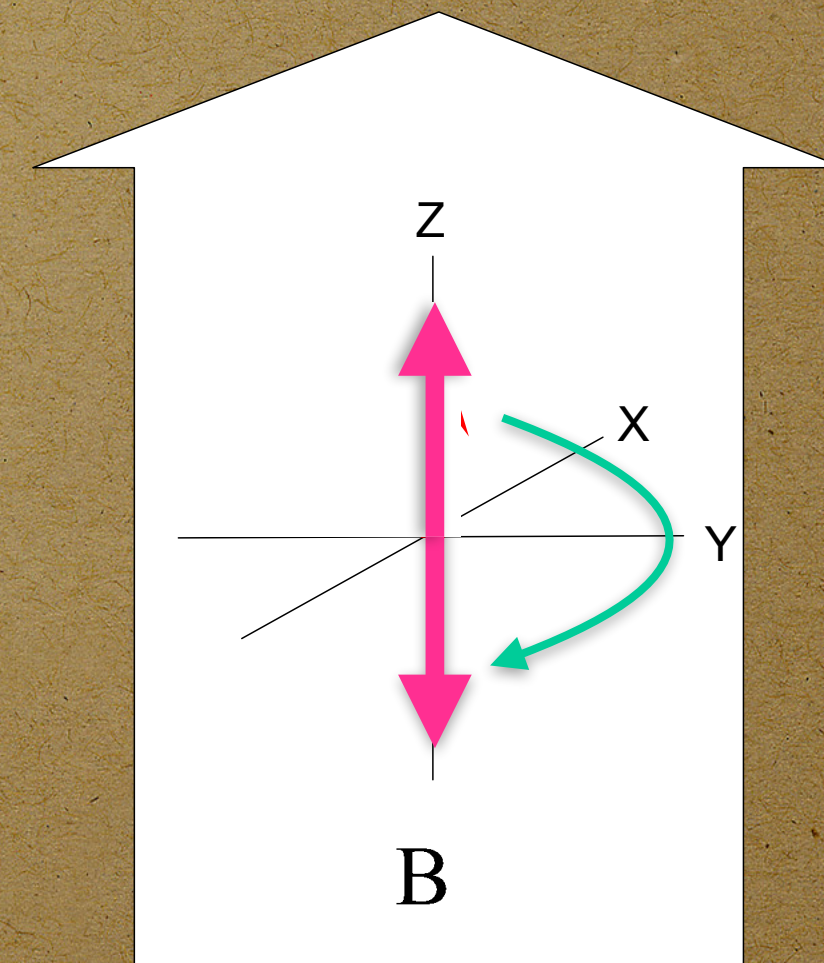
## Resonancia

$$\omega \rightarrow (E_- \rightarrow E_+)$$

## Tiempo de relajación

$$| + \rangle \rightarrow | - \rangle$$

$$T = \frac{\hbar}{\Gamma_1} = |\omega_1| = \frac{2mc}{g|q|B_1}$$



Cada sustancia emite un fotón con energía característica

$$E_{\pm} = \pm \frac{\omega_0 \hbar}{2}$$



# Funcionamiento

- El campo  $B_0$  alinea mayormente los momentos magnéticos de los protones

$$\mathbf{B} = B_0 \hat{k}$$

- El campo débil  $B_1$  excita algunos protones mediante un proceso resonante

$$\mathbf{B} = B_1 \cos \omega t \hat{i}$$

$$\omega \rightarrow (E_- \rightarrow E_+)$$

- Al quitar el campo débil  $B_1$  la resonancia decae con un tiempo de relajación

$$|b(t)|^2 = \frac{(\Gamma_1/2)^2}{(E_0 - E)^2 + (\Gamma_1/2)^2} \sin^2 \Omega t$$

$$T = \frac{2mc}{g |q| B_1}$$

- La energía del fotón en la transición depende del tejido donde se encuentre el protón

$$h\nu = E_+ - E_-$$

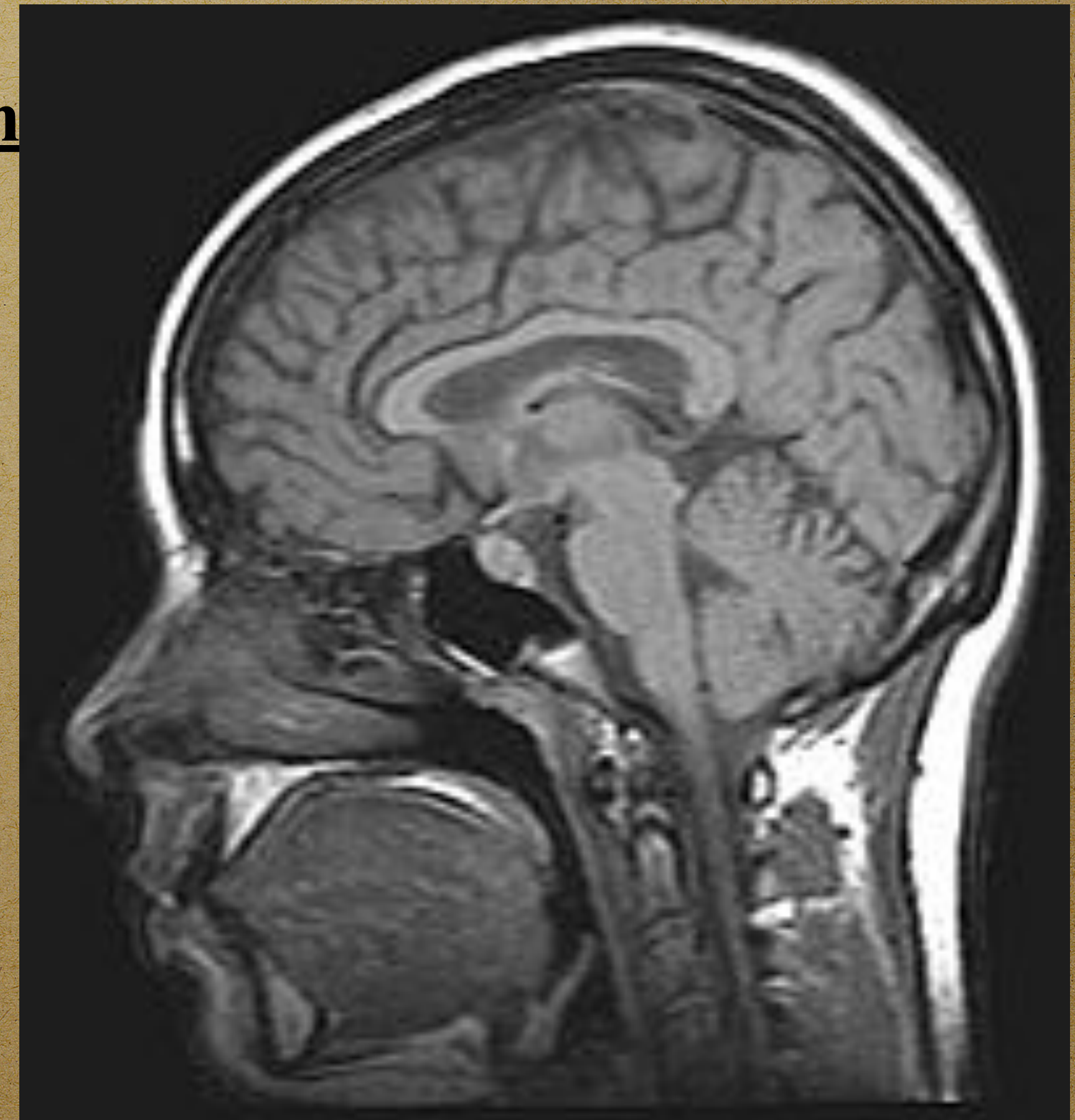


# Funcionamiento

- El campo  $B_0$  alinea mayormente los momentos magnéticos de los protones
- El campo débil  $B_1$  excita algunos protones mediante un proceso resonante
- Al quitar el campo débil  $B_1$  la resonancia decae con un tiempo de relajación
- La energía del fotón en la transición depende del tejido donde se encuentre el protón
- ...+ ELECTRÓNICA + IMAGEN...

$$\mathbf{B} = B_0 \hat{k}$$

$$|b(t)|^2$$





**Preguntas  
+  
Fin**



- **Sobre el TP**
- **Sobre la próxima Clase (7/12)**
- **Sobre el examen (14/12)**