

Escola de Verão IF-2015
Espectroscopia gama

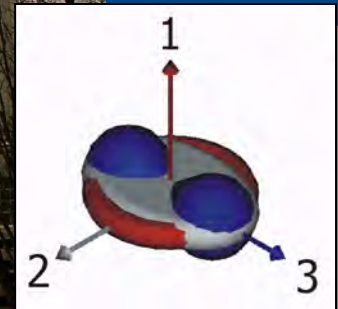
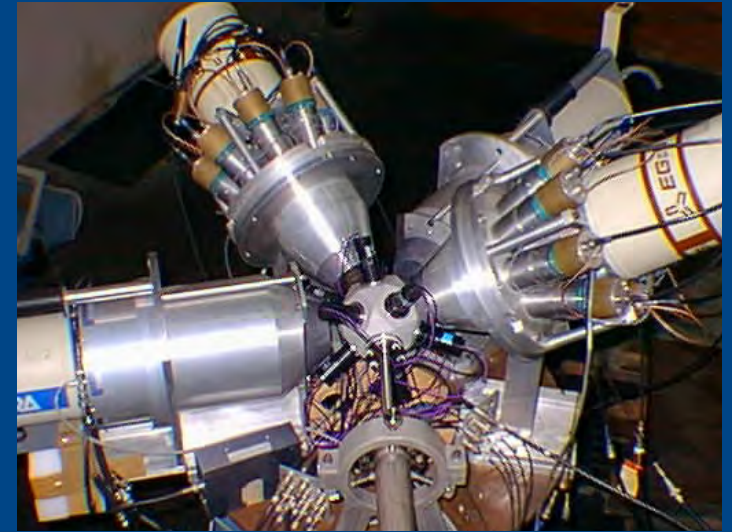
Prof. José Roberto Brandão de Oliveira
DFN-IFUSP

Aula 1: Introdução

- 1—Sobre meu grupo (γ) no LAFN/IFUSP (muito breve)
- 2—Contextualização:
 - Interações fundamentais e modelo padrão
 - Física nuclear e estrutura nuclear
 - Espectroscopia gama

Espectroscopia γ no IFUSP

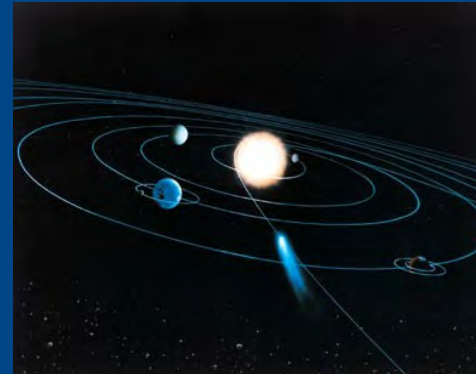
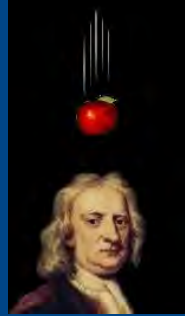
- *Pessoal: J.R.B.O., N.H.Medina, L. Gasques (profs); J. Alcántara-Núñez (Post-Doc); V. Zagatto, V. Aguiar, A. Souza, J. Duarte (pós graduação); ... Alunos de IC; Colaboradores: (IFUFF, IPEN, UNAL, LNS).*
- *Nosso espectrômetro γ (Saci Perere)*
- *Acelerador de partículas: Pelletron Tandem (8MV), LAFN – Laboratório Aberto de Física Nuclear*
- *Tópicos de pesquisa: Núcleos ímpar-ímpar: bandas quirais, isômeros, testes do LSSM, mecanismos de reação com núcleos fracamente ligados e arco-íris nuclear*



As interações fundamentais

(ou "as 4 forças da natureza")

- Gravitacional

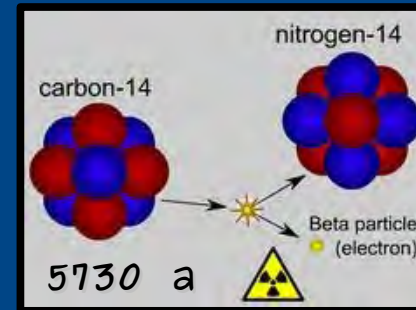


- Eletromagnética

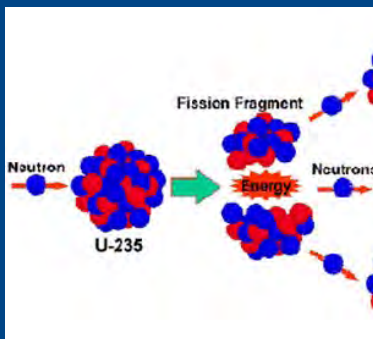


- Fraca

Decaimento β



- Forte, ou Nuclear



$$E = mc^2$$

Envolvidas na física do núcleo atômico

Interação eletromagnética

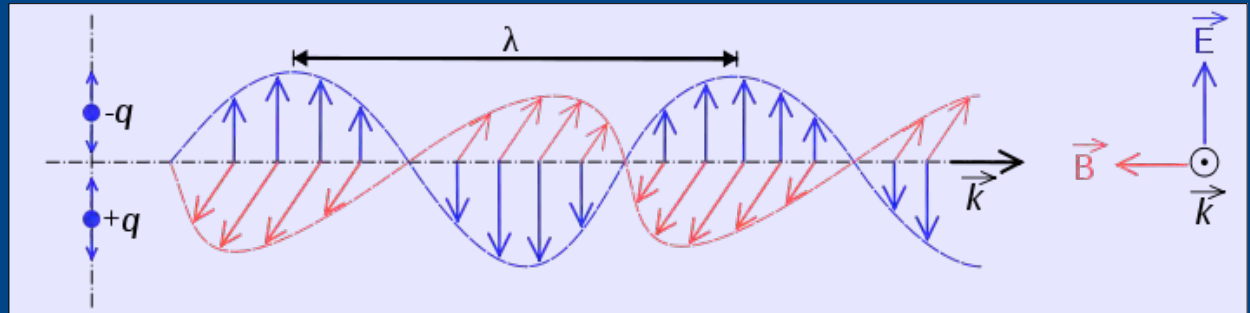
- Cargas elétricas (q) e campo eletromagnético (\vec{E} , \vec{B})
- Força de Lorentz $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
- Equações de Maxwell

Name	Differential form	Integral form
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$	$\oiint_{\partial V} \mathbf{E} \cdot d\mathbf{A} = \frac{Q(V)}{\epsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\oiint_{\partial V} \mathbf{B} \cdot d\mathbf{A} = 0$
Maxwell-Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_{\partial S} \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	$\oint_{\partial S} \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_S + \mu_0 \epsilon_0 \frac{\partial \Phi_{E,S}}{\partial t}$

Ondas eletromagnéticas

- Eq. de onda no vácuo: $\nabla^2 E - \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2} = 0$

- Solução tipo onda plana:

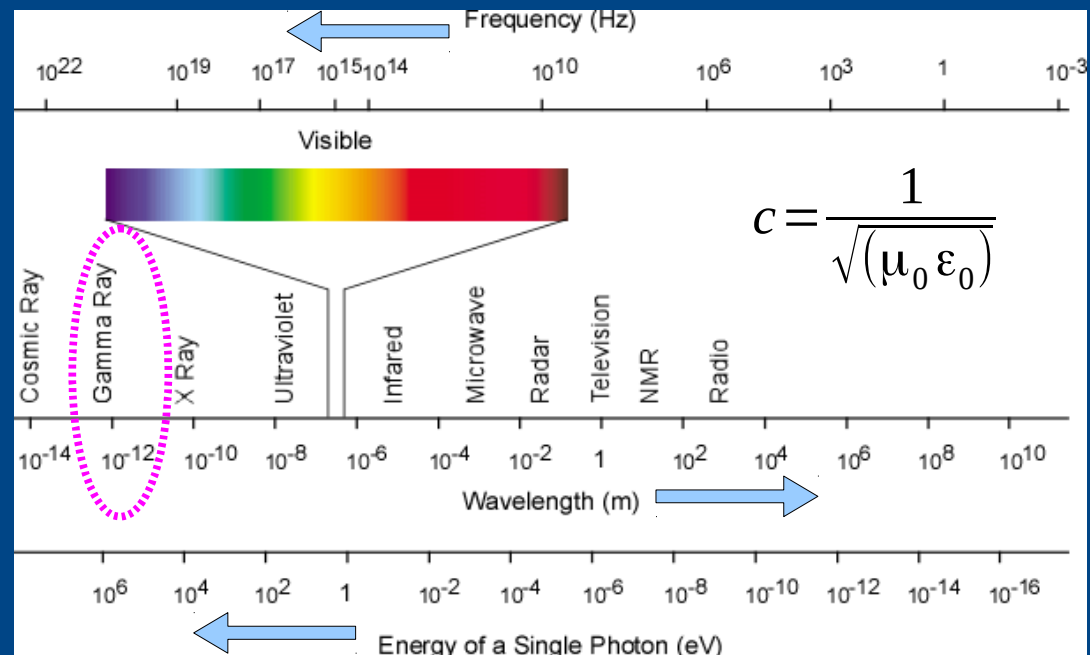


$$\vec{E} = E_0 \hat{e} \cos(\vec{k} \cdot \vec{r} - \omega t + \delta)$$

- Espectro

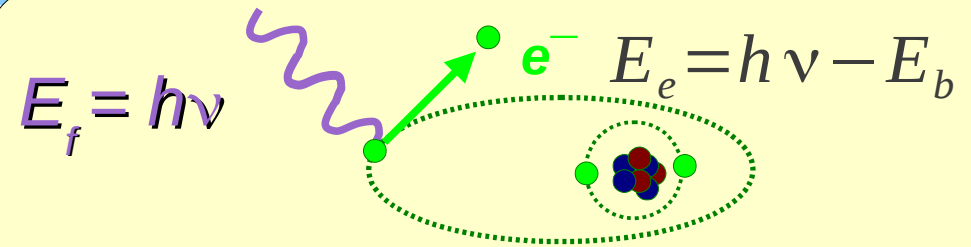
eletromagnético:

- Fóton: $E_f = hf = \frac{hc}{\lambda}$

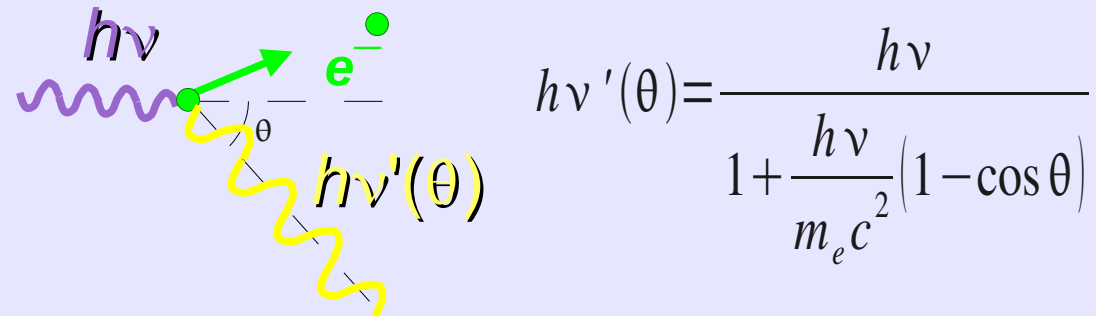


Fótons: quanta do campo E.M.

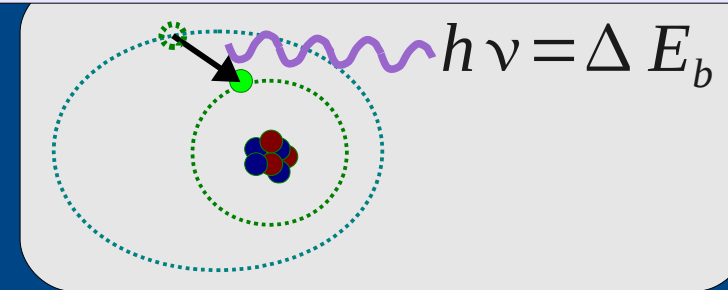
- Efeito fotoelétrico



- Efeito Compton



- Transições atômicas



- Espectro atômico



Hidrogênio



$\leftarrow h\nu, \lambda \rightarrow$

Níveis do Hidrogênio

$$E_n = -\frac{13.6}{n^2} [\text{eV}]$$

Eletrodinâmica quântica

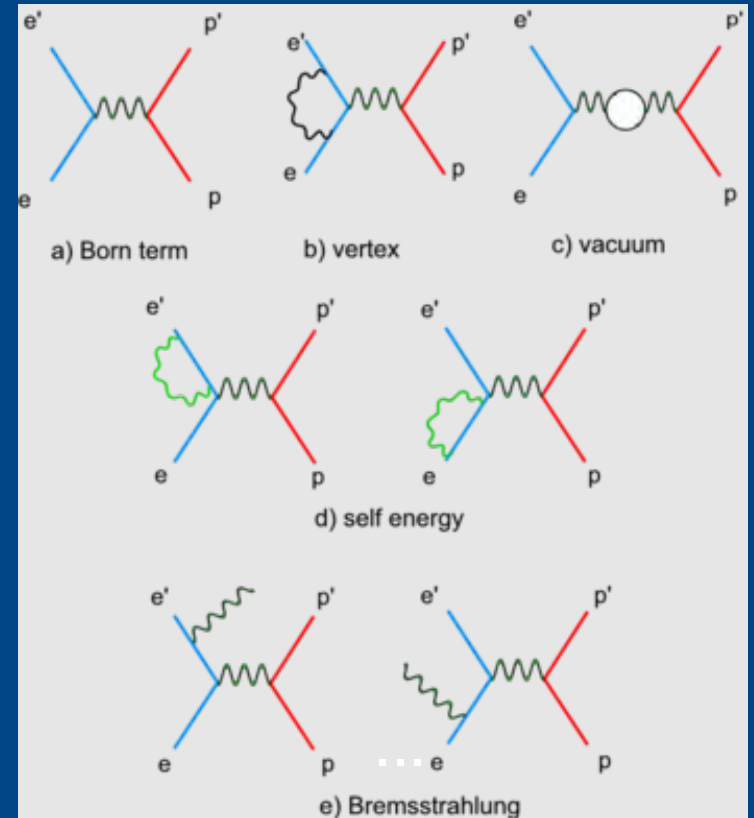


• Espalhamento p-e

- Auto energia
- Fator g do elétron

$$g_{exp}(e) = -2.002319304\ 36153(53)$$

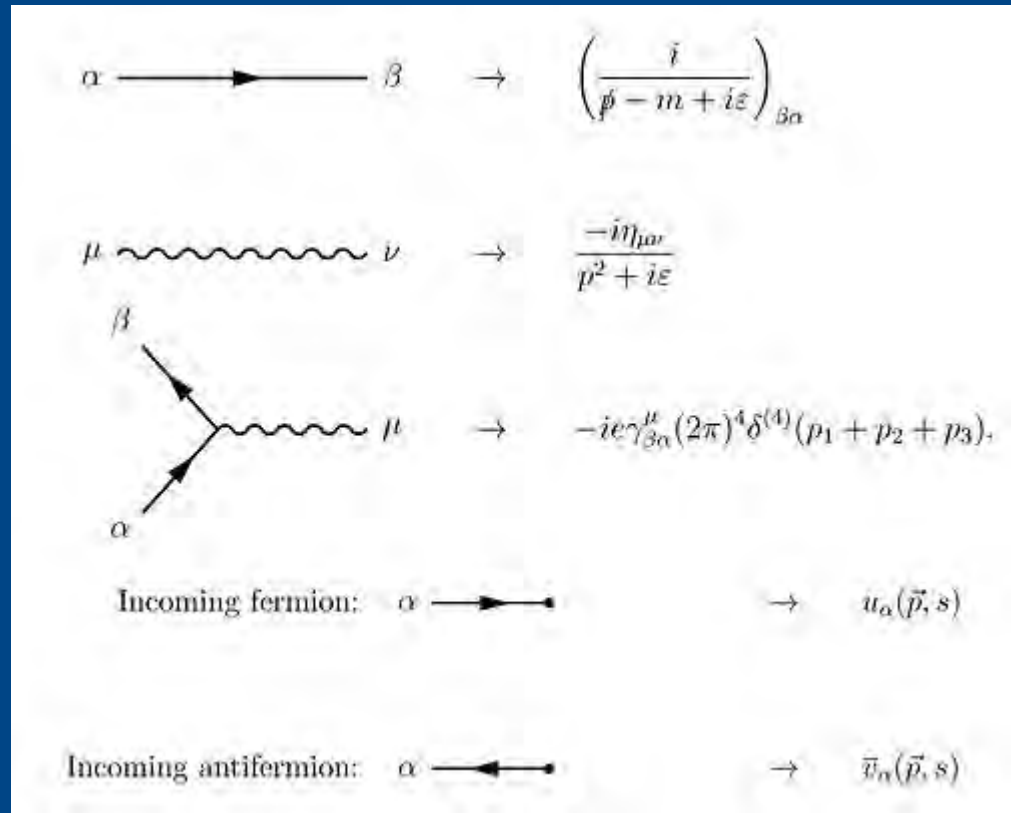
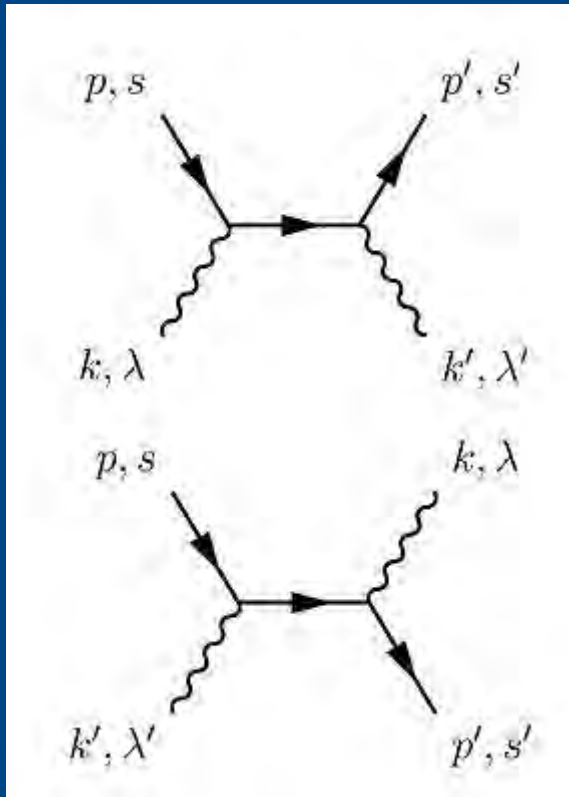
$$\frac{\mu}{s}$$



$$\alpha = \frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c} = \frac{1}{137} \quad \alpha^2 \ll \alpha$$

Ex. espalhamento Compton

Regras de Feynman (QED)



$$M_{fi} = (ie)^2 \bar{u}(\vec{p}', s') \not{\epsilon}'(\vec{k}', \lambda') \frac{\not{p} + \not{k} + m_e}{(p+k)^2 - m_e^2} \not{\epsilon}(\vec{k}, \lambda) u(\vec{p}, s) + (ie)^2 \bar{u}(\vec{p}', s') \not{\epsilon}(\vec{k}, \lambda) \frac{\not{p} - \not{k}' + m_e}{(p-k')^2 - m_e^2} \not{\epsilon}'(\vec{k}', \lambda') u(\vec{p}, s)$$

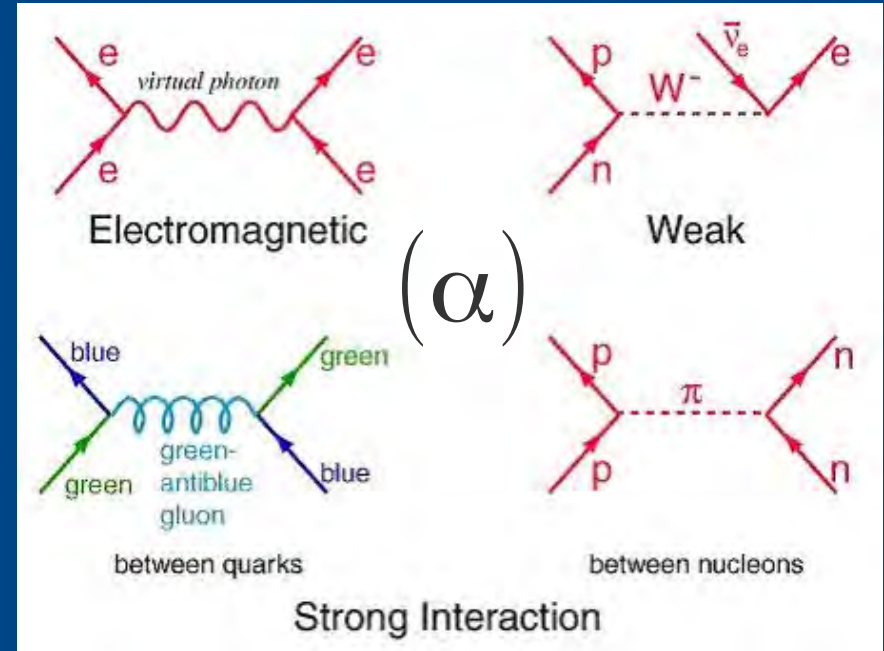
Modelo Padrão

Partículas elementares e interações

Three Generations of Matter (Fermions)				
	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
				Higgs *
Quarks				
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	d down	s strange	b bottom	g gluon
	< 2.2 eV	< 0.17 MeV	< 15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z weak force
Leptons				
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e electron	μ muon	τ tau	W[±] weak force

Color: **RGB** charges

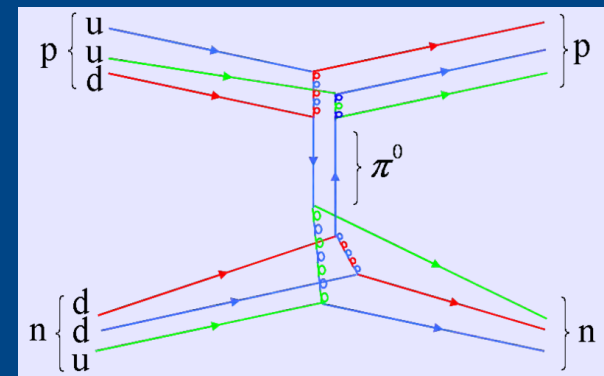
Bosons (Forces)



Hadrons – neutros em cor:

Mesons ($q\bar{q}$) – ex: π^+ ($u\bar{d}$);

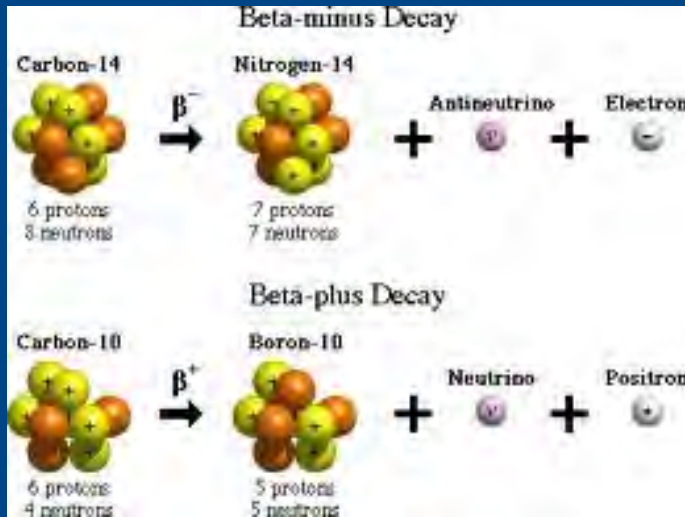
Bárions ($3q$) – ex.: núcleons $p(uud)$; $n(udd)$



Interação fraca

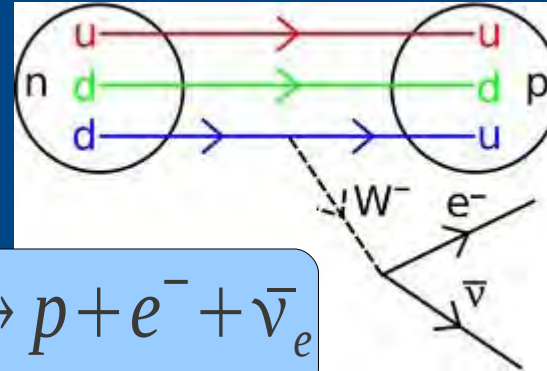
- Decaimento beta

β^-



β^+

Cons. do no. leptônico



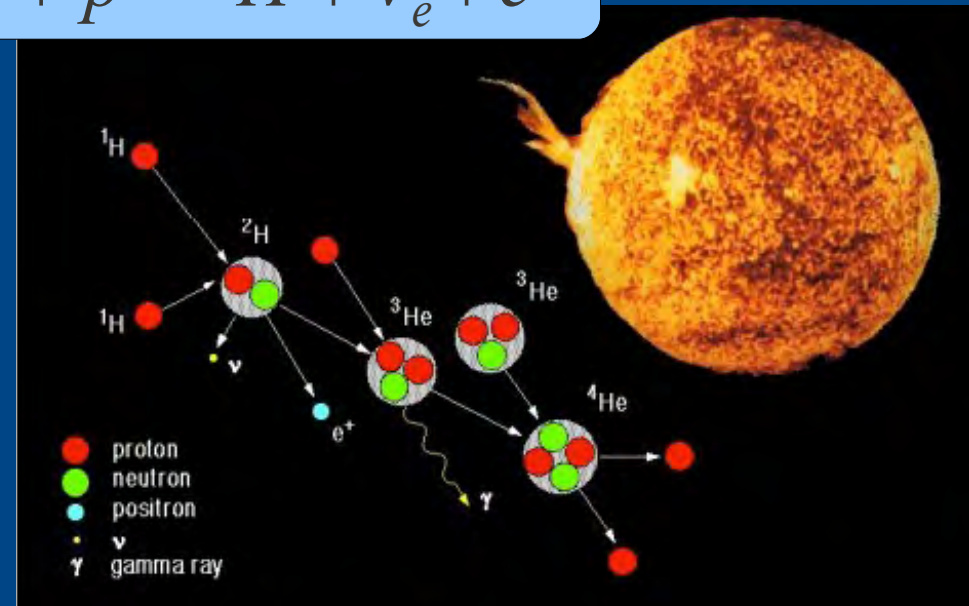
$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$p + p \rightarrow {}^2\text{H} + \nu_e + e^+$$

- Ciclo p-p

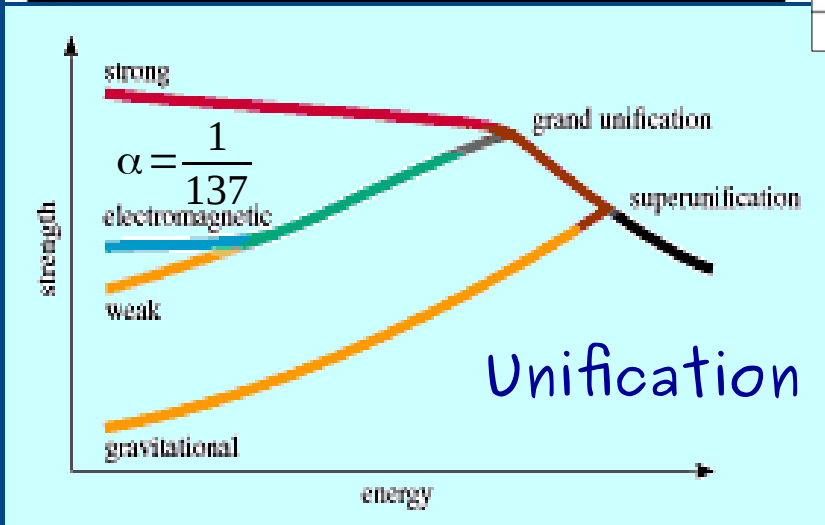
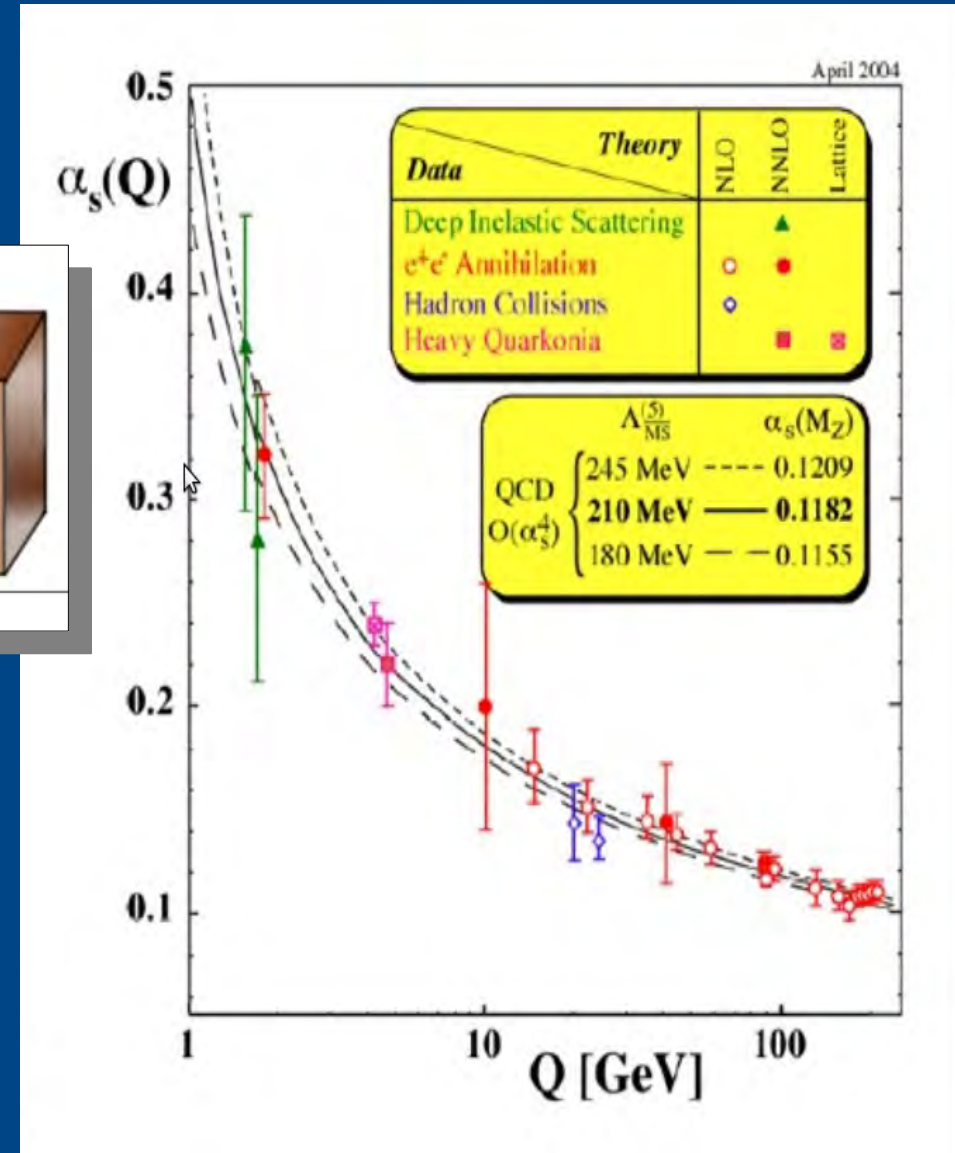
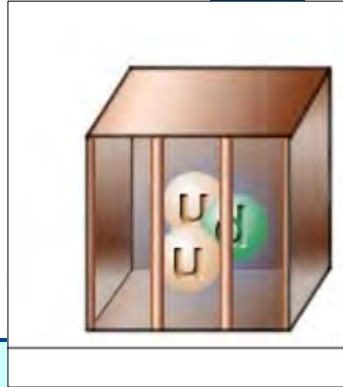
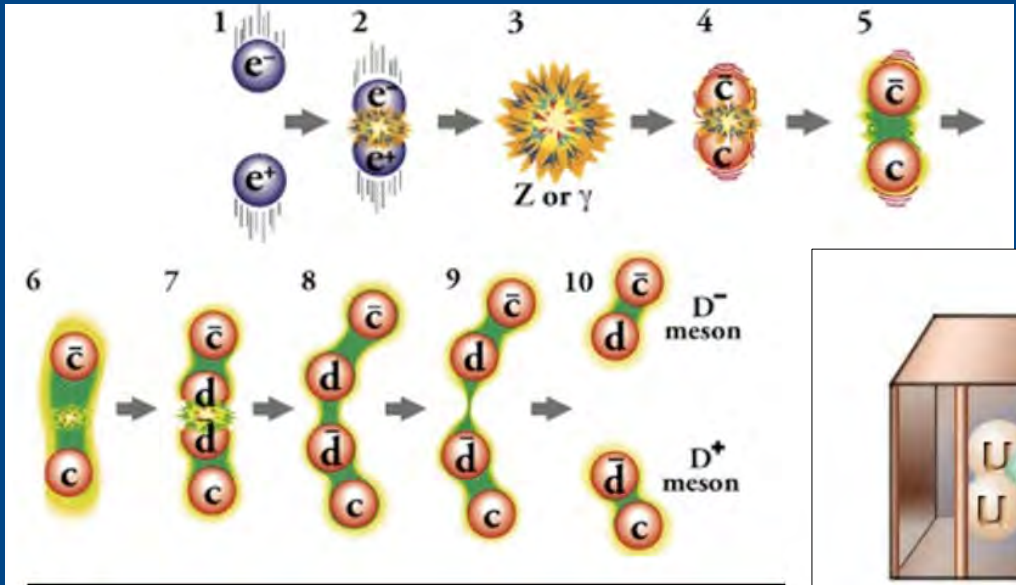
produção de energia (e neutrinos) no sol

PNS $\Delta m_\nu^2 \neq 0 (!)$ Oscilação de neutrinos

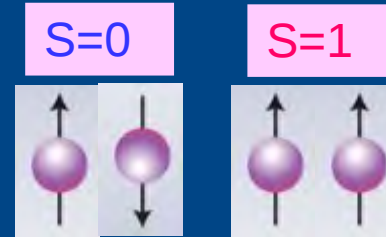
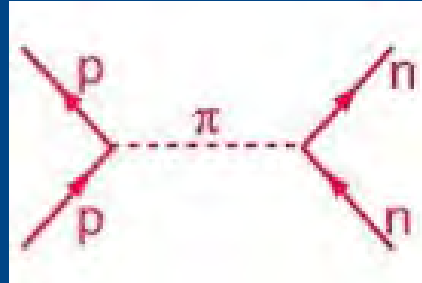


Interação forte, QCD

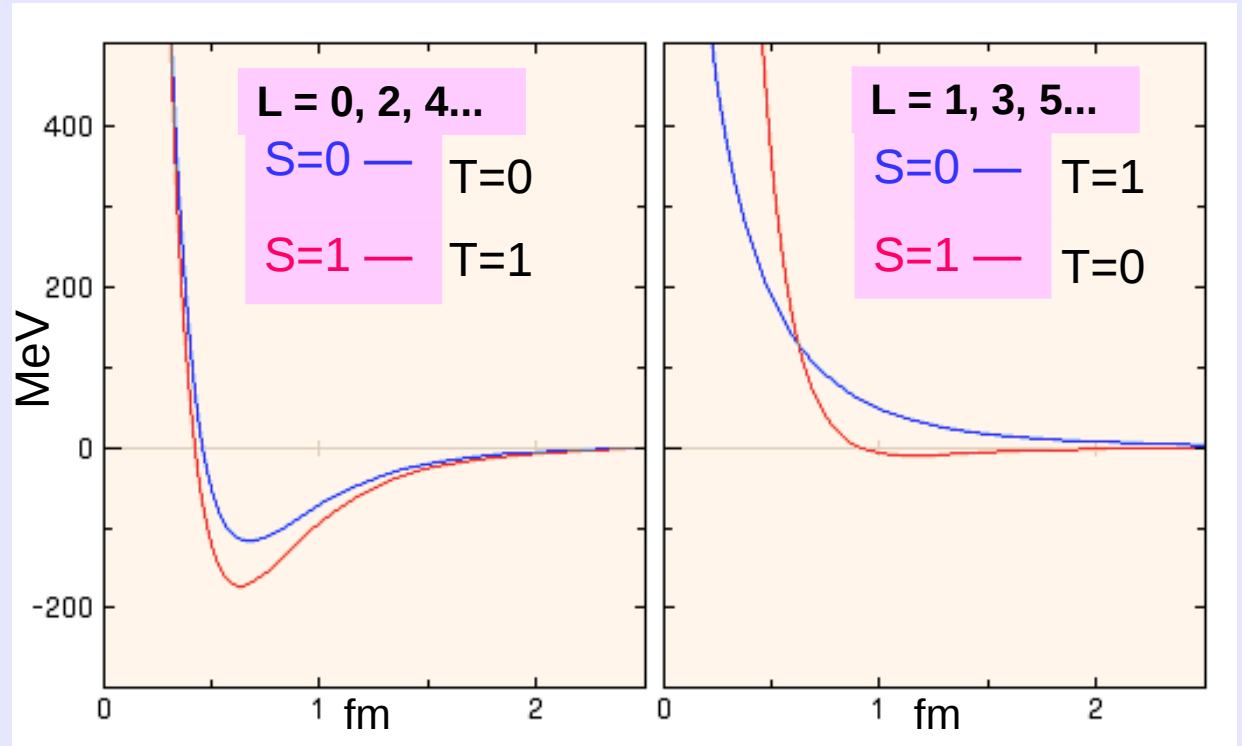
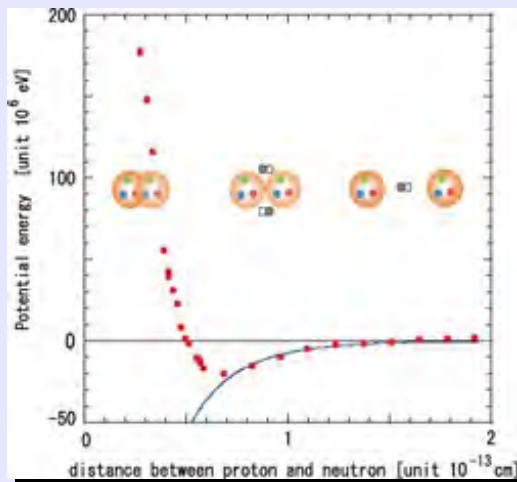
Confinamento x liberdade assintótica



A força N-N

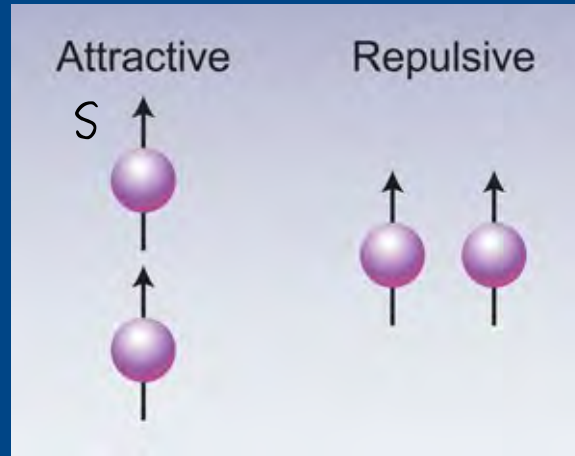


● Potencial de Paris
(parte central)



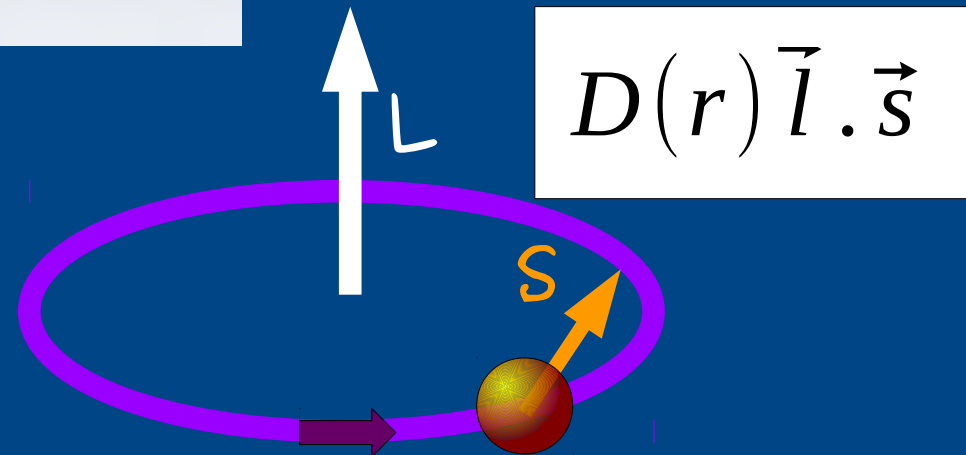
Outros termos da f.n.

- Tensorial



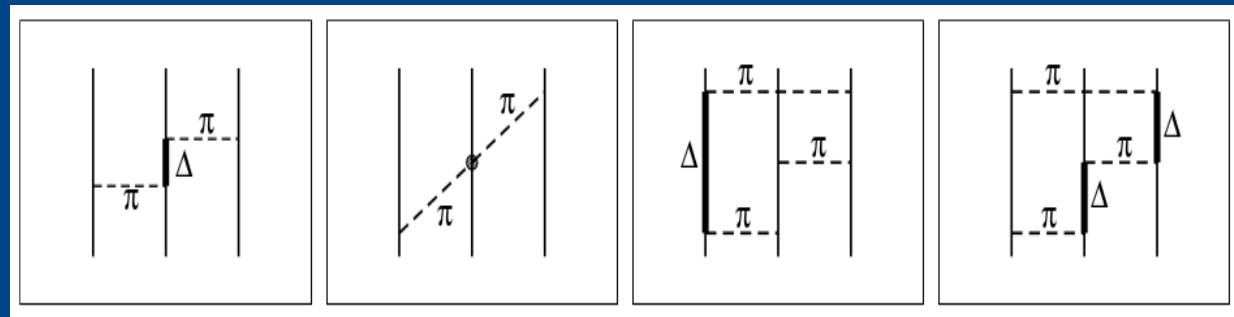
$$C(r) \left\{ \frac{3(\vec{s}_1 \cdot \vec{r})(\vec{s}_2 \cdot \vec{r})}{r^2} - \vec{s}_1 \cdot \vec{s}_2 \right\}$$

- Spin-órbita



$$D(r) \vec{l} \cdot \vec{s}$$

- 3 corpos

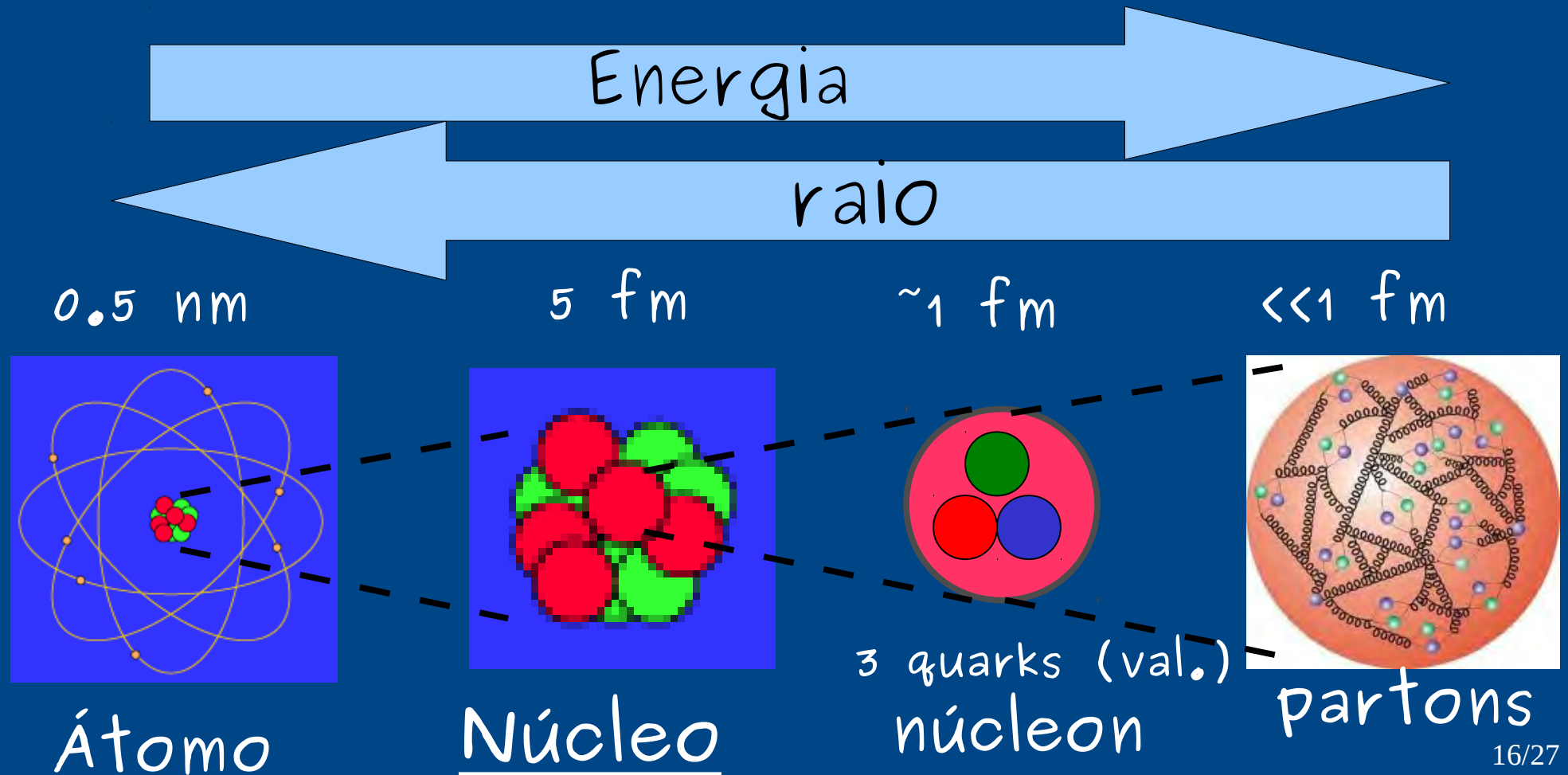


Física da Força Nuclear

- *F.N.: Menos compreendida das interações*
- *Peculiarmente forte - não é tratável perturbativamente, em nível fundamental, como a eletro-fracas (exceto a energias muito altas)*
- *É muito complexa e conseqüentemente muito rica, particularmente a baixas energias*

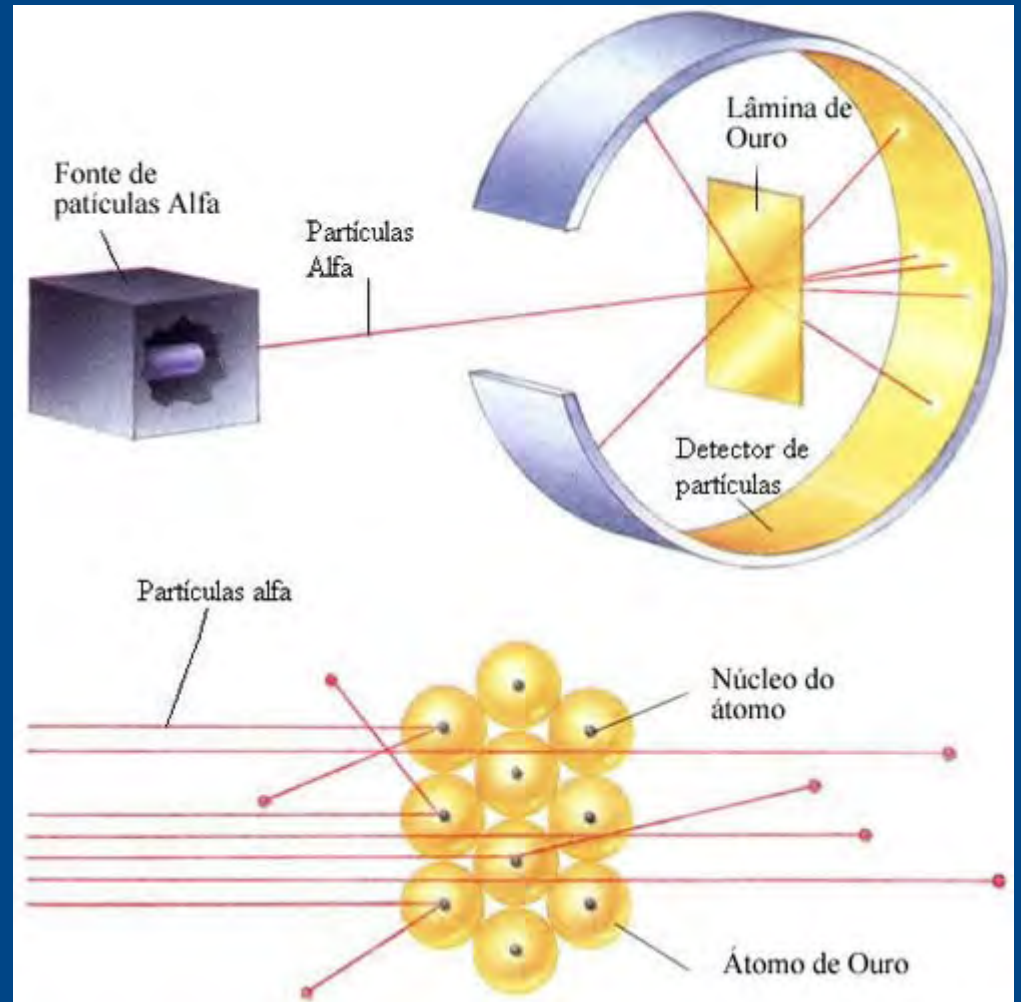
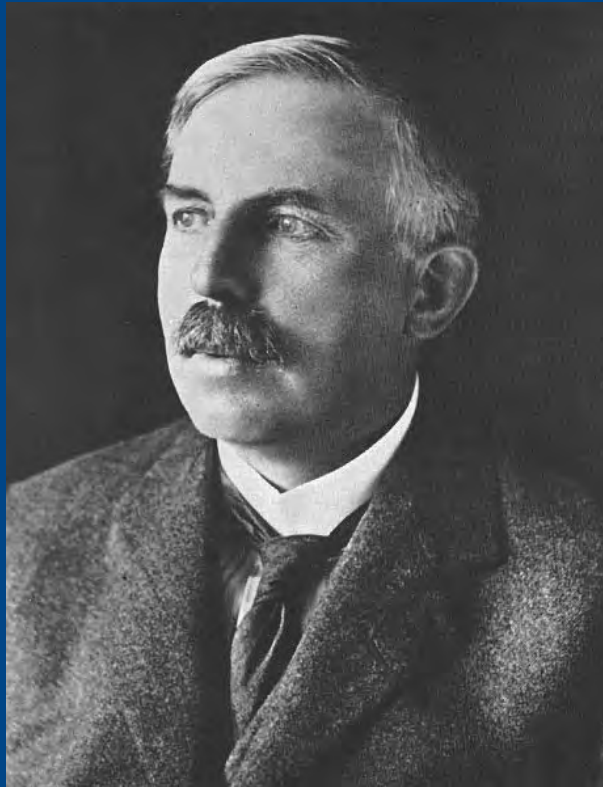
A escala do núcleo atômico

- Constituído de núcleons (N): p & n (os bárions mais leves)



Espalhamento Rutherford

- Descoberta do núcleo atômico
- Rutherford, 1911



O conceito de seção de choque

- σ : Área de um alvo na qual a partícula do feixe precisa incidir para acontecer "algo"



$$R = I n \sigma$$



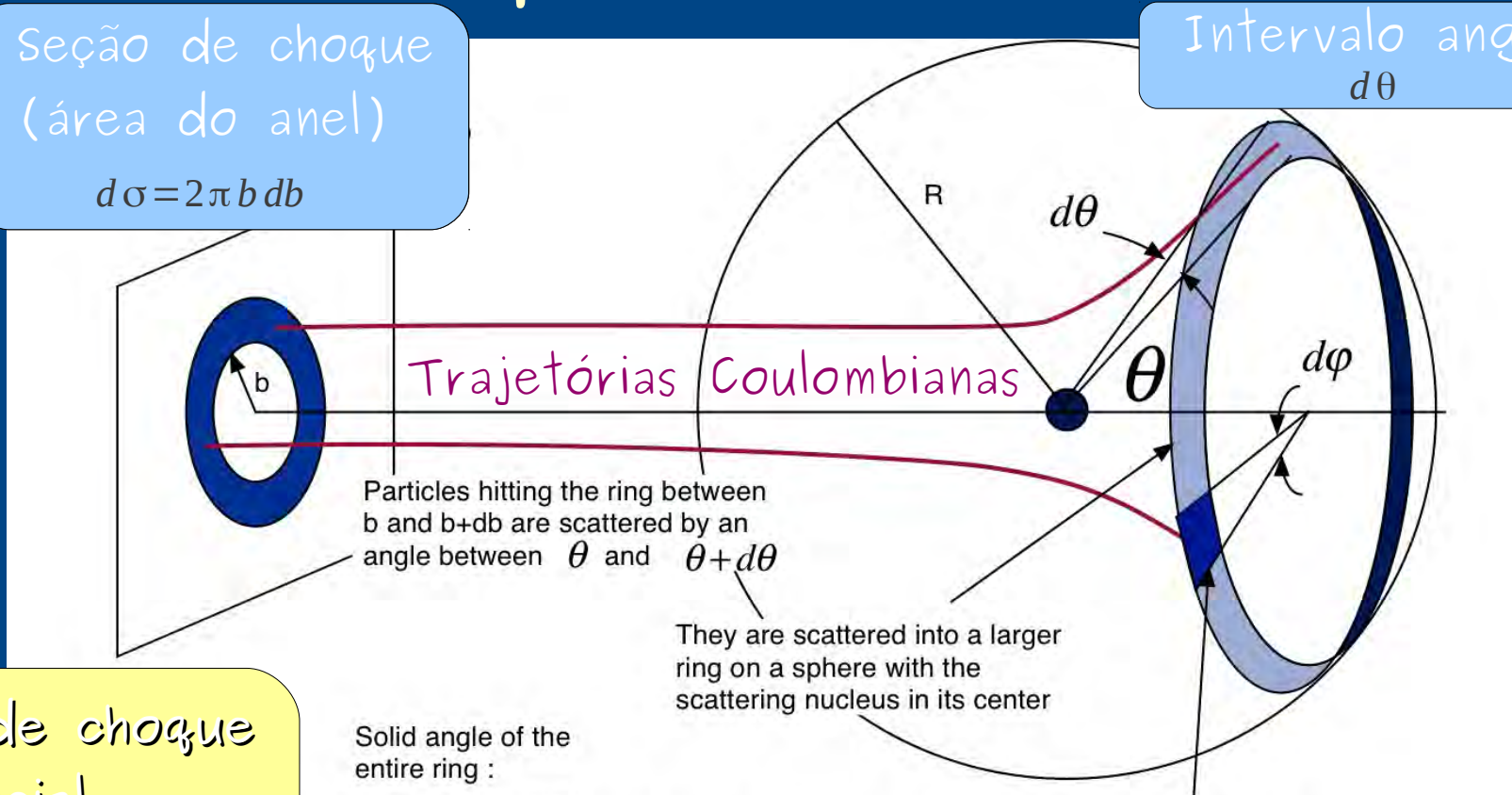
Seção de choque coulombiana

- Área correspondente a um ângulo sólido de espalhamento

Seção de choque (área do anel)

$$d\sigma = 2\pi b db$$

Intervalo angular $d\theta$



Solid angle of the entire ring :

$$d\Omega = \frac{2\pi R \sin(\theta) R d\theta}{R^2} = 2\pi \sin(\theta) d\theta$$

solid angle of small area:

$$d\Omega = \frac{d\phi R \sin(\theta) R d\theta}{R^2} = \sin(\theta) d\theta d\phi$$

Seção de choque diferencial

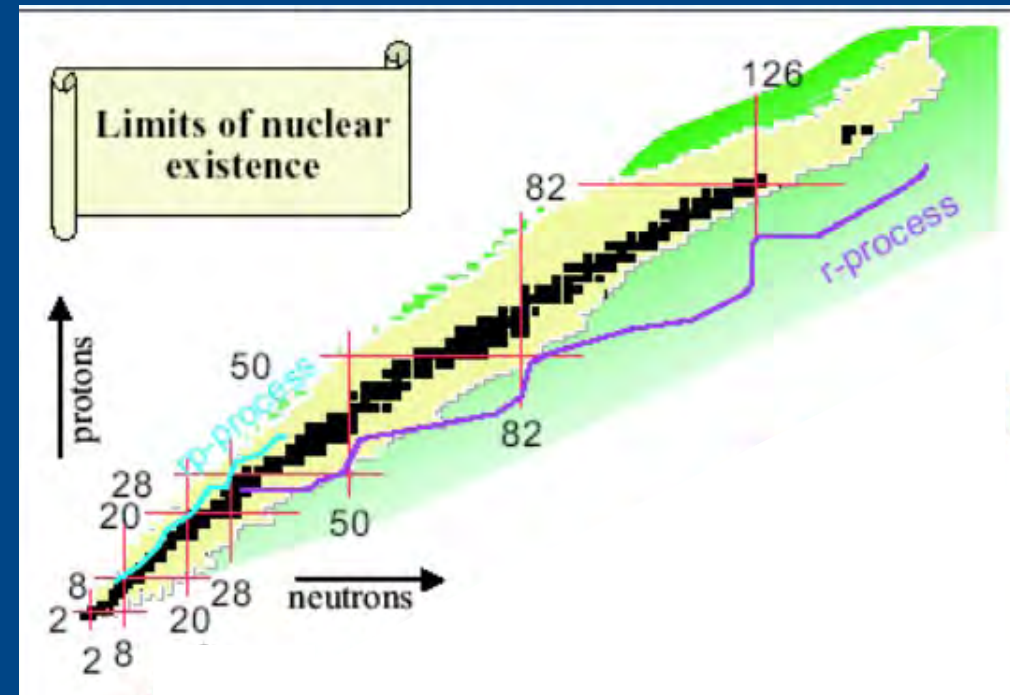
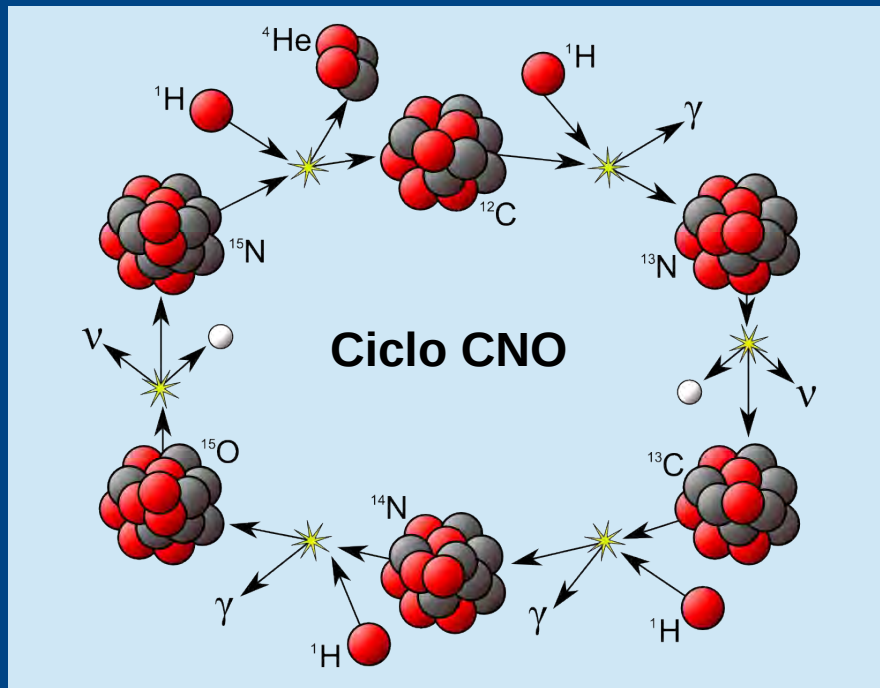
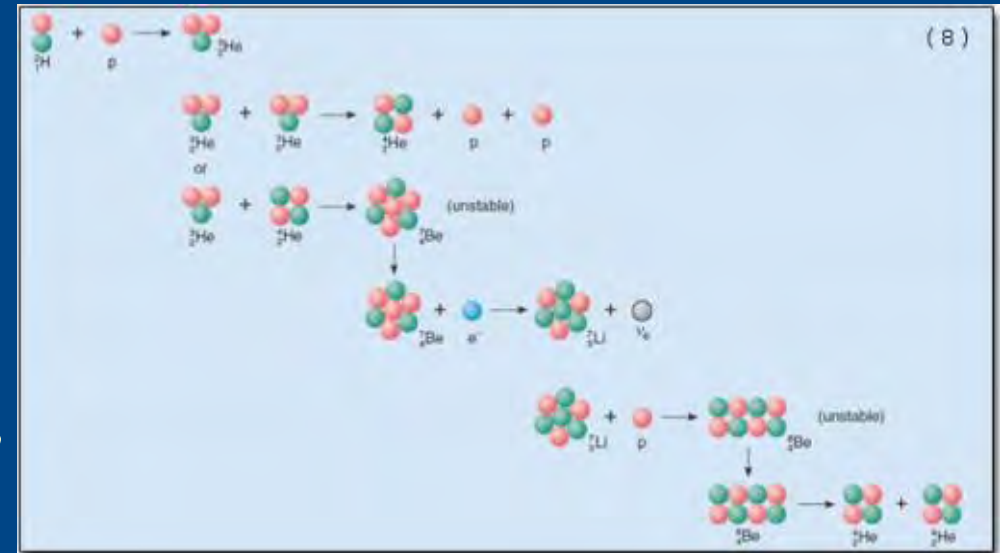
$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{4E} \right)^2 \frac{1}{\sin^4(\theta/2)}$$

Estrutura nuclear

- Peculiaridades interessantes (de baixa energia)
 - 1 - É um sistema de muitos corpos (mas não tantos... como em matéria condensada: $A < 300 \ll N_A = 6 \times 10^{23}$)
 - 2 - Aspectos coletivos e de partículas independentes
 - 3 - Envolve a força nuclear (!)
 - 4 - Envolve simetrias fundamentais e dinâmicas
 - 5 - Pode fornecer informações além do modelo padrão (decaimento duplo- β , por exemplo)
 - 6 - É fundamental para astrofísica nuclear

Astrofísica nuclear

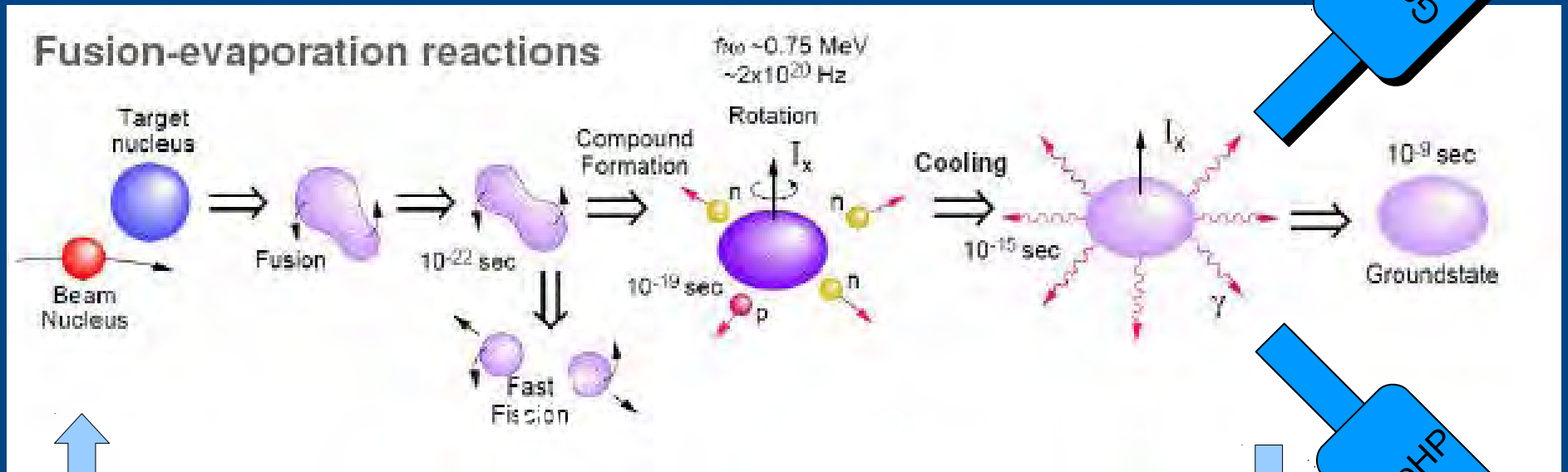
- *Nucleossíntese primordial*
- *Ciclo pp (Sol)*
- *Ciclo CNO*
- *Processos r (supernova) e rp*



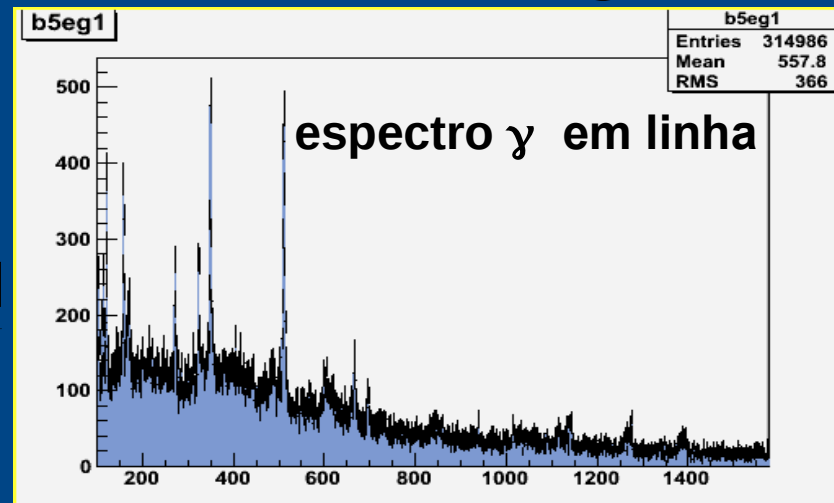
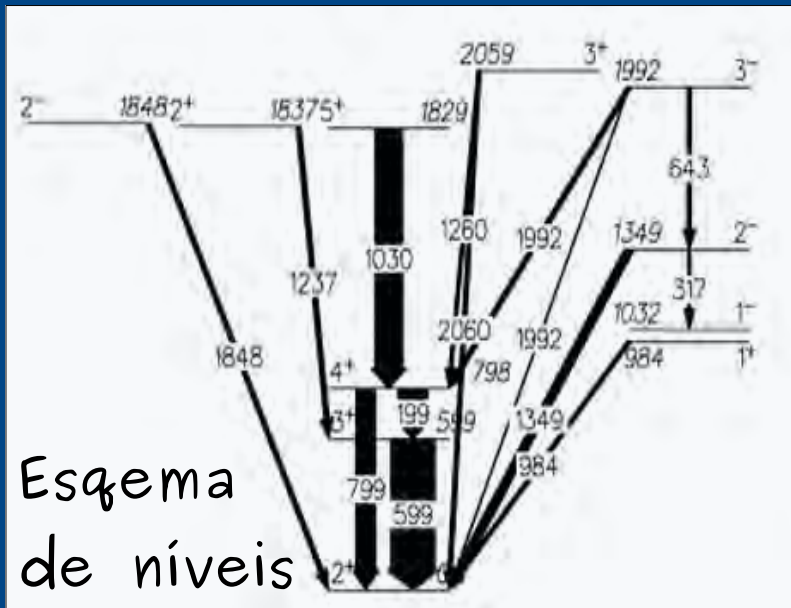
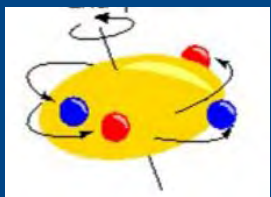
Espectroscopia γ

- O núcleo é muito pequeno para ser medido com instrumentos mecânicos ou elétricos
- A radiação gama é muito bem conhecida (QED)
- Permite acesso a propriedades dos estados e transições nucleares (esquema de níveis)

Experimento típico

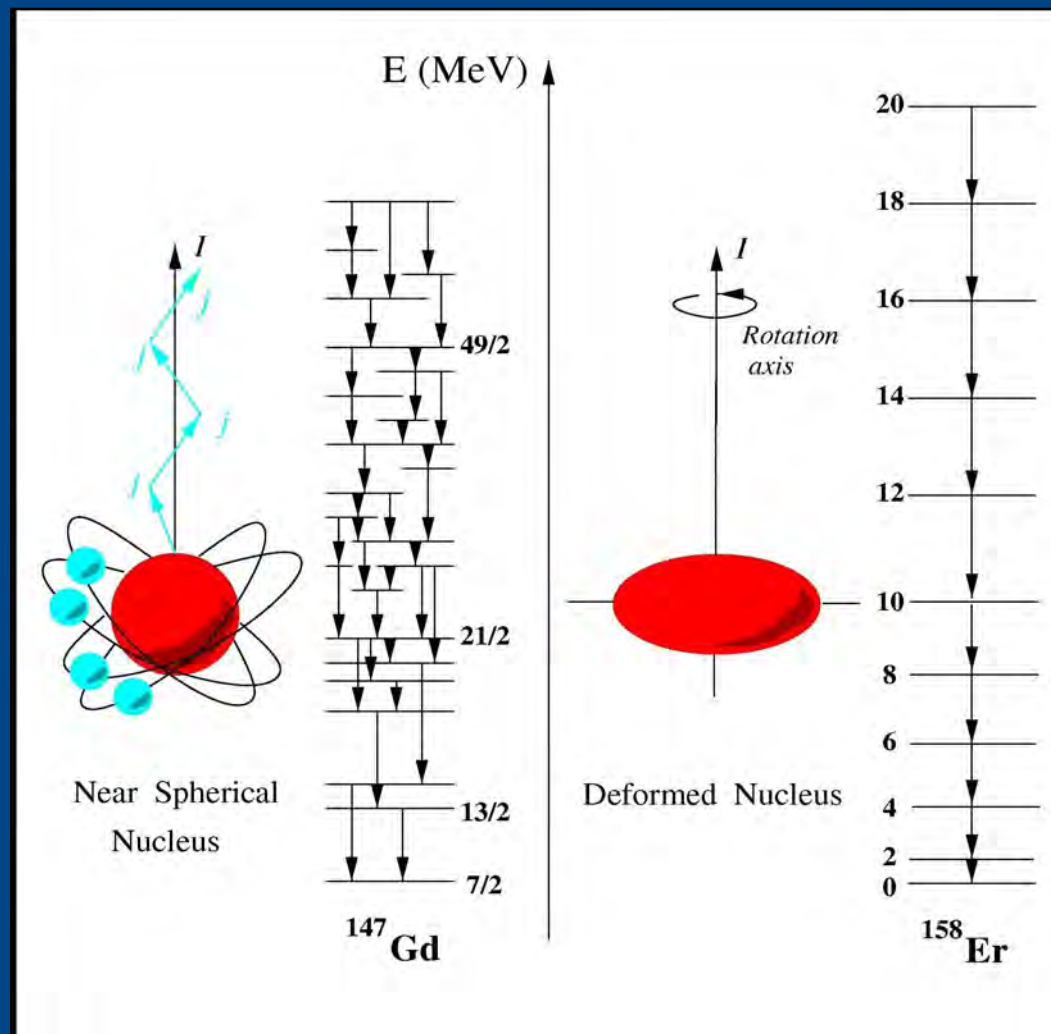


Modelo



Esquemas de níveis

- Manifestam a estrutura nuclear

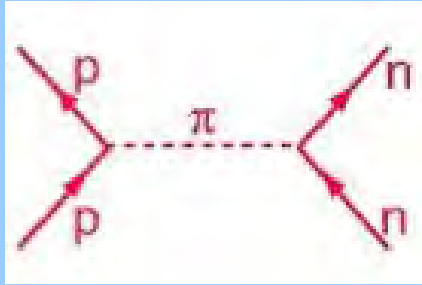


Próximas aulas

- Estrutura nuclear – modelos nucleares
- Espectroscopia gama – ferramentas
- Técnica de coincidências
- Perspectivas

Extras

A força N-N



Teoria mesônica
Yukawa, 1935
Pion, 1947

$$\Delta t \Delta E \approx \hbar$$

$$\Delta E = mc^2$$

$$c \Delta t mc^2 \approx \hbar c$$

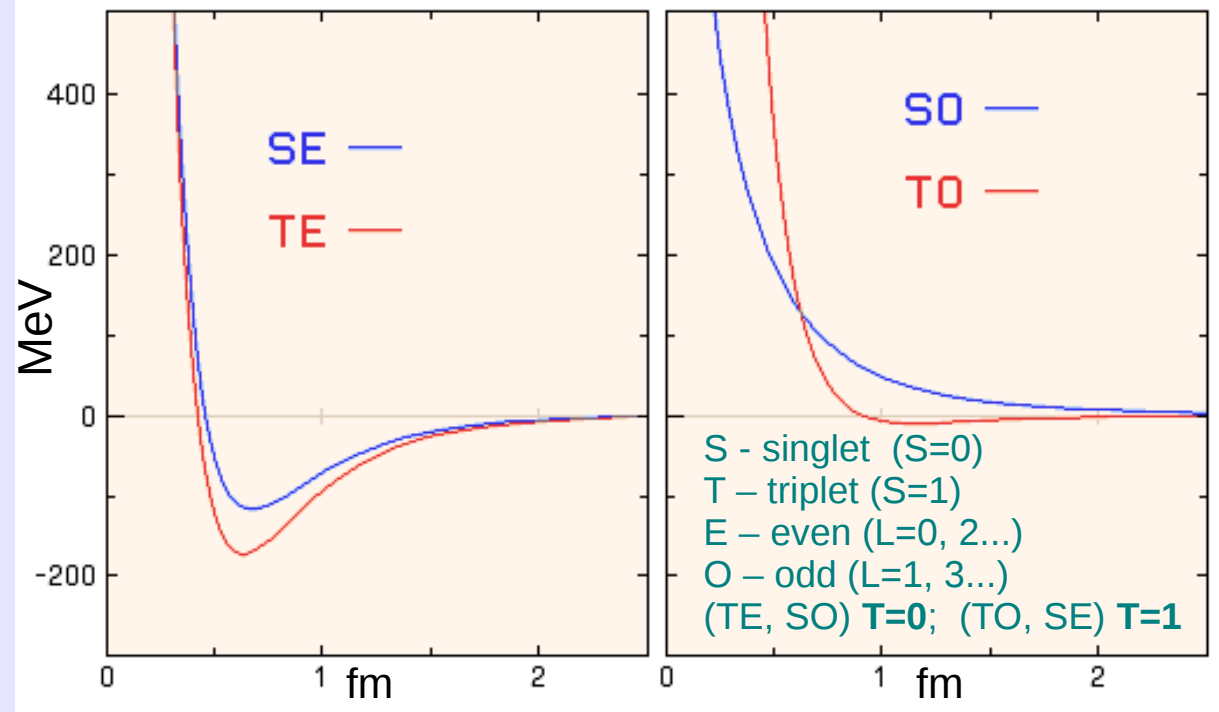
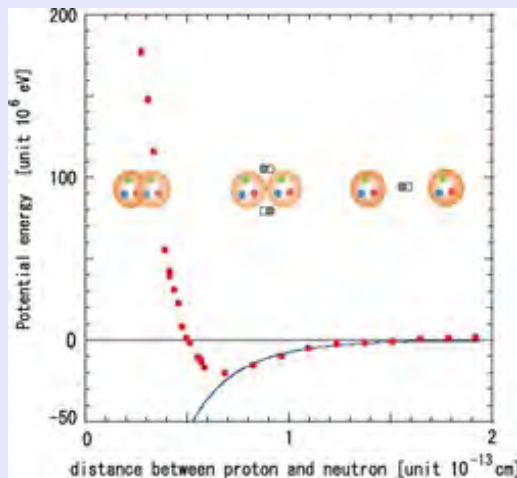
$$\Delta R = c \Delta t \approx \frac{\hbar c}{mc^2}$$

$$\hbar c \approx 200 \text{ MeV} \cdot \text{fm}$$

$$m_\pi c^2 \approx 140 \text{ MeV}$$

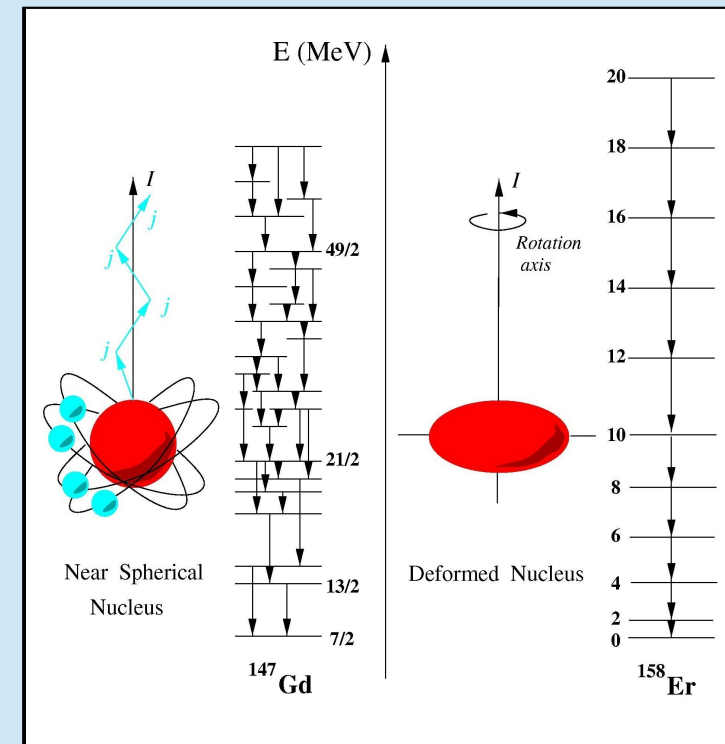
$$\Delta R \approx 1.4 \text{ fm}$$

● Potencial de Paris (parte central)



Aula 2 – Modelos Nucleares

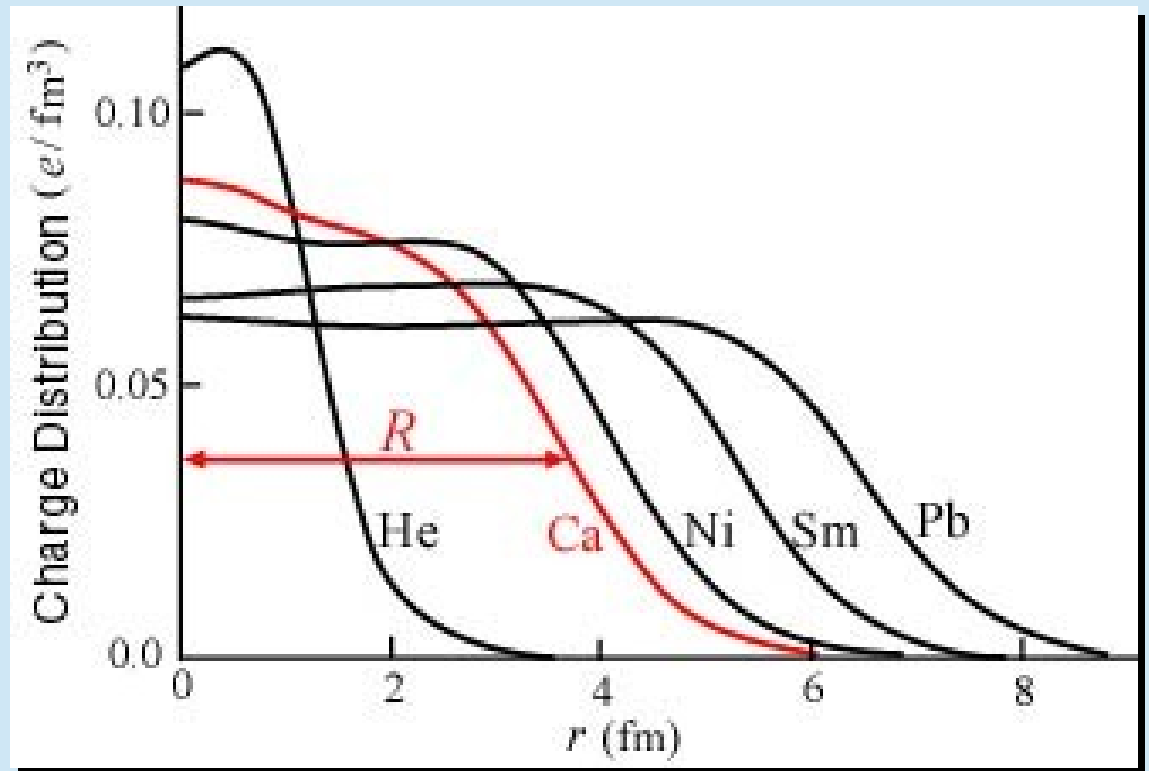
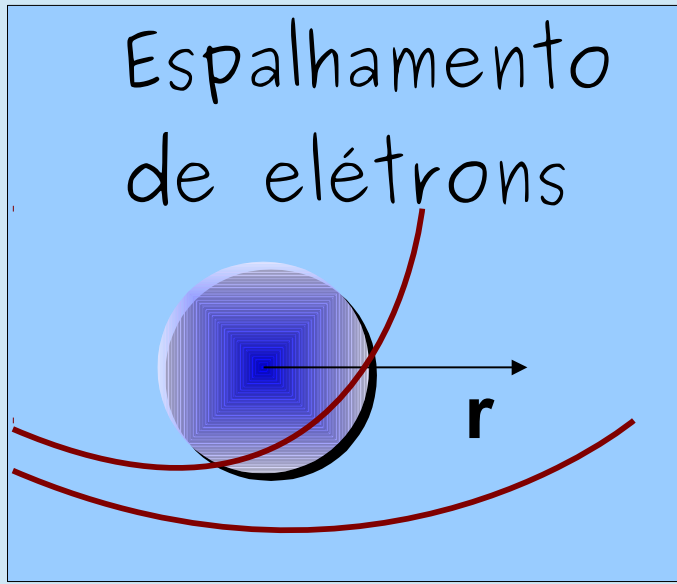
- Propriedades gerais de núcleos
- Modelo da gota líquida
- Mecânica quântica (em 1 slide!)
- Modelo de camadas
- Modelos coletivos
- Modelos de Nilsson e CSM
- Emparelhamento (senioridade)
- Altos spins – Backbending
- Bandas quirais



Propriedades gerais dos núcleos

- Raio, densidade de carga e de núcleons
- Energias de ligação
- Energias de separação de $2n$ e $2p$
(números mágicos)

A distribuição de carga e massa do núcleo

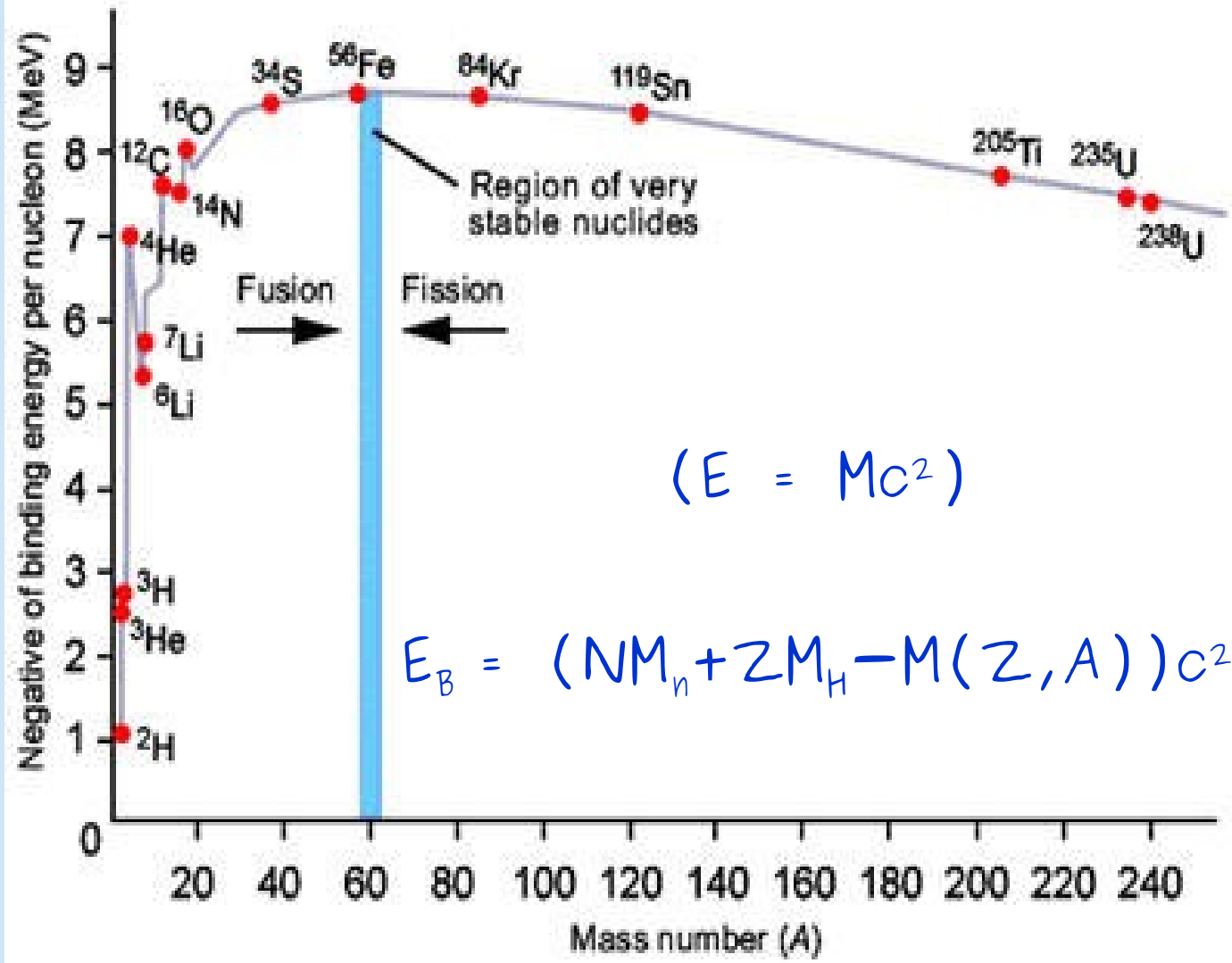


Na região do vale de estabilidade

- Densidade aprox. constante
- Raio nuclear: $R = R_0 A^{\frac{1}{3}}$ ($R_0 = 1.2 \text{ fm}$)

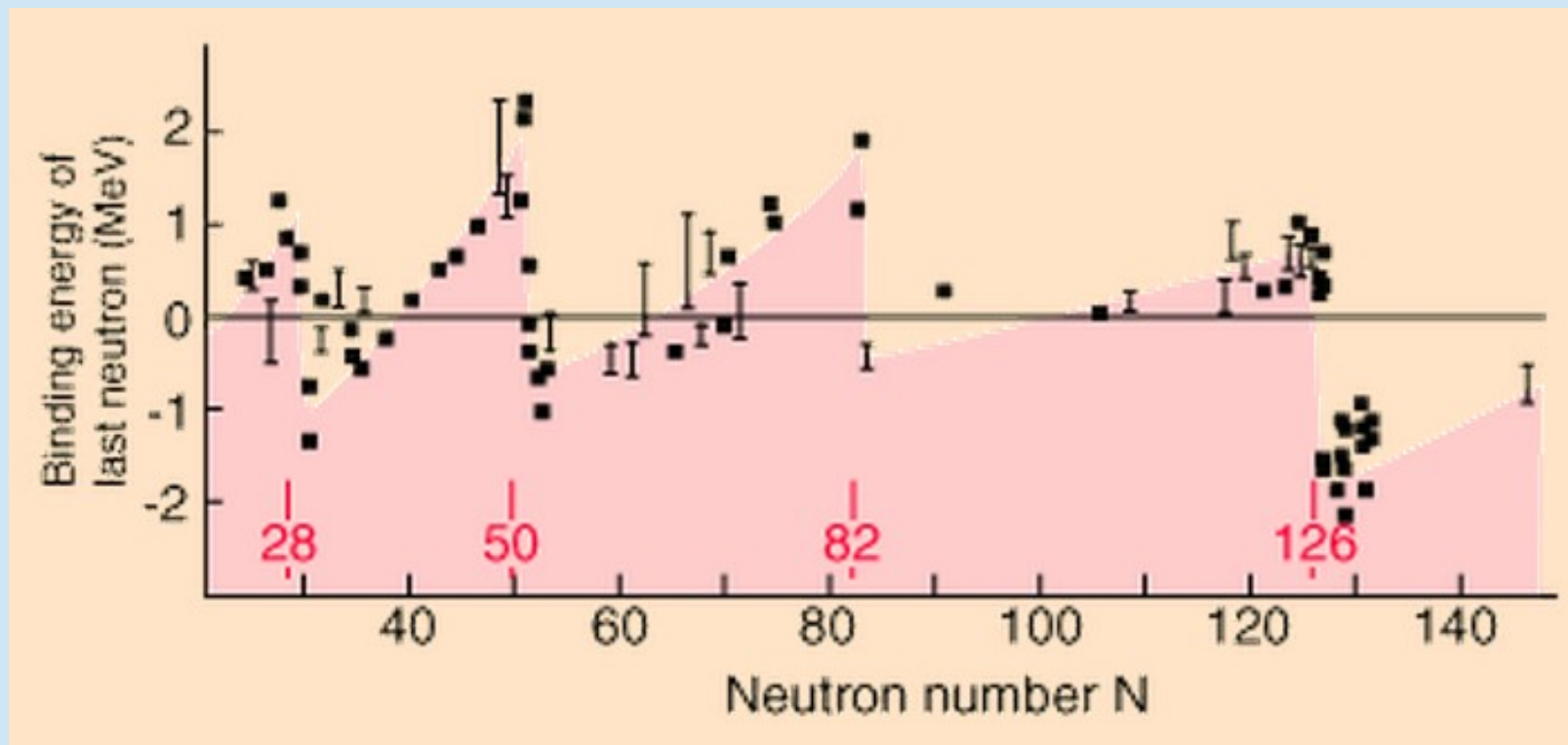
Energias de ligação

E_B/A



Números mágicos

N : 2, 8, 20, 28, 50, 82, 126



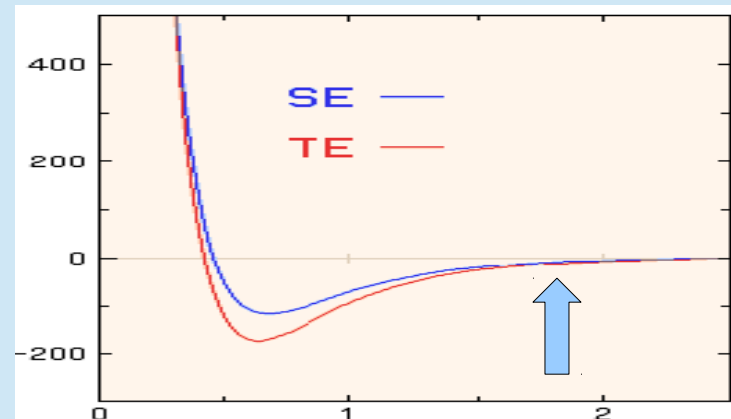
Obs.: ao menos na região do vale de estabilidade!

Modelo da gota líquida

- Raio nuclear: $R = R_0 A^{1/3}$ ($R_0 = 1.2 \text{ fm}$)

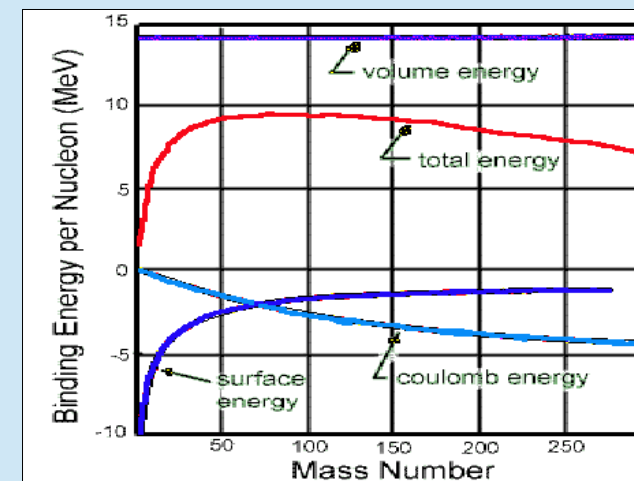
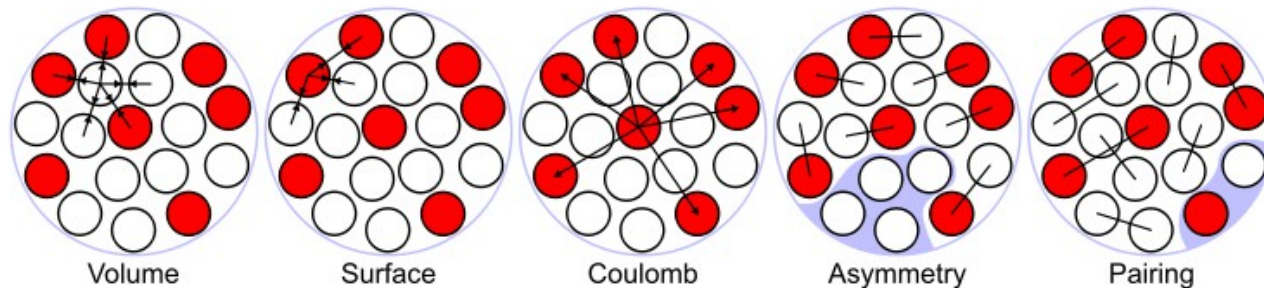
$$\rho_0 \approx 0.17 \text{ fm}^{-3}$$

$$\langle r_{NN} \rangle \approx 1/\sqrt[3]{\rho_0} = 1.8 \text{ fm}$$



- Fórmula semi-empírica de massa

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N - Z)^2}{A} - \delta(A, Z)$$



Mecânica quântica (em 1 slide!)

Função de onda
(em 1D): $\Psi(x, t)$

Operadores:

$$H = i\hbar \frac{\partial}{\partial t}$$

$$E_{cin} = \frac{p^2}{2m} = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2}$$

$$E_{pot} = V(x)$$

Energia mecânica:

$$H = E_{cin} + E_{pot}$$

$$P(x, t) = |\Psi(x, t)|^2$$

$$\text{Eq. Schrödinger } i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V(x)\Psi$$

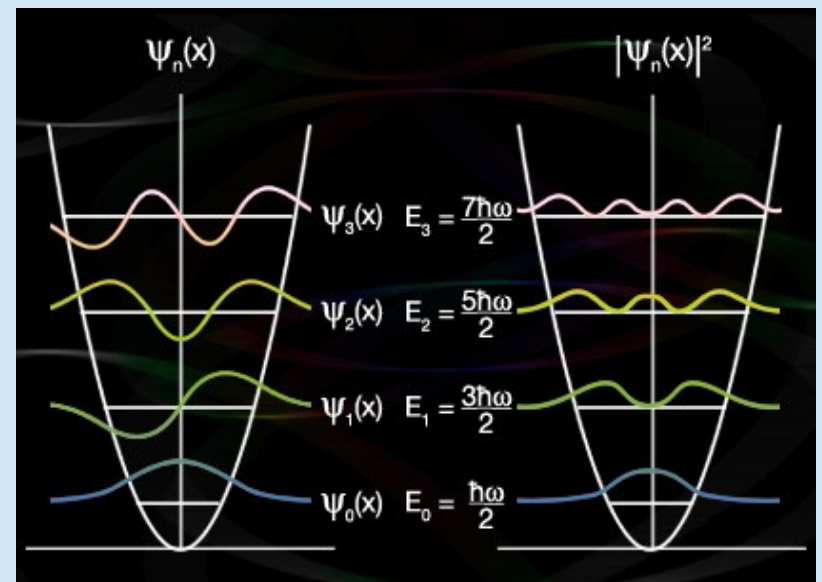
Autovalores de energia:

$$H\Psi_n = E_n\Psi_n$$

Ex. oscilador
harmônico:

$$V(x) = \frac{1}{2} m \omega^2 x^2$$

$$E_n = \left(n + \frac{1}{2}\right) \hbar \omega$$



Princípio da incerteza $\Delta p \Delta x \geq \hbar$

Ex.: Orbitais atômicos

$$(V \propto \frac{1}{r})$$

• Função de onda

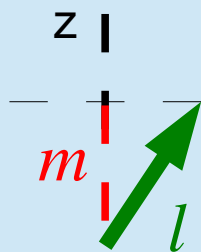
$$\Psi(r, \theta, \varphi) = R_n(r) Y_{lm}(\theta, \varphi)$$

Y_{lm} : Harmônicos esféricos

Estados de momento angular

m.a. orb.

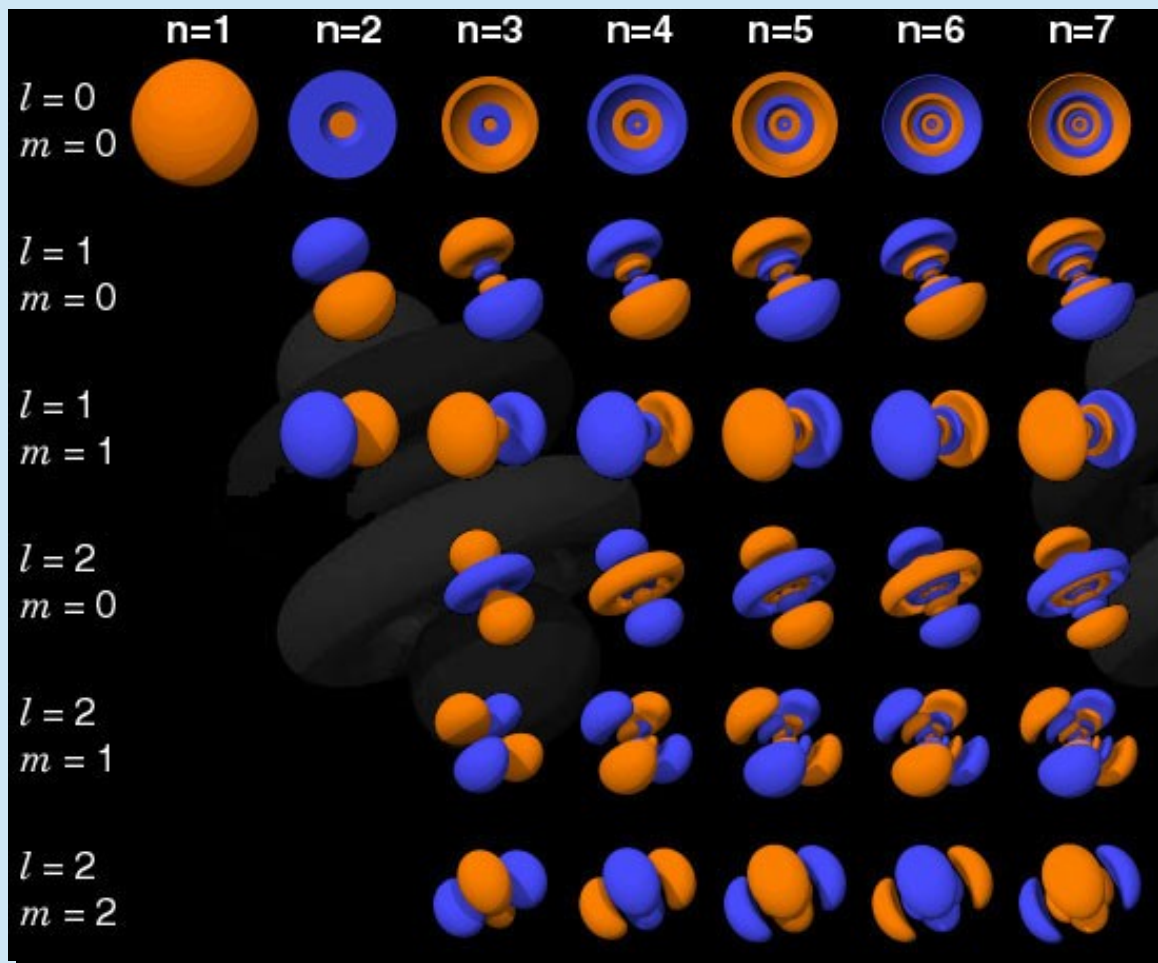
proj. z



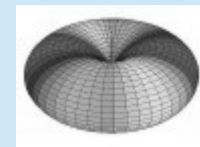
$$-l \leq m \leq l \quad 2l+1 \text{ estados}$$

ex.: $l=2: m=-2, -1, 0, 1, 2$

Re(Ψ): +, -



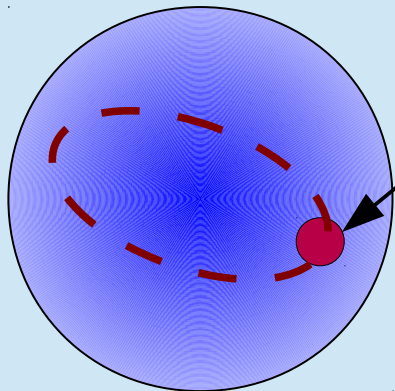
Distribuição de matéria $|\Psi_{2,2}|^2$



Modelo de Camadas

● Oscilador harmônico 3D $E^*(n) = (n + 3/2) \hbar \omega$

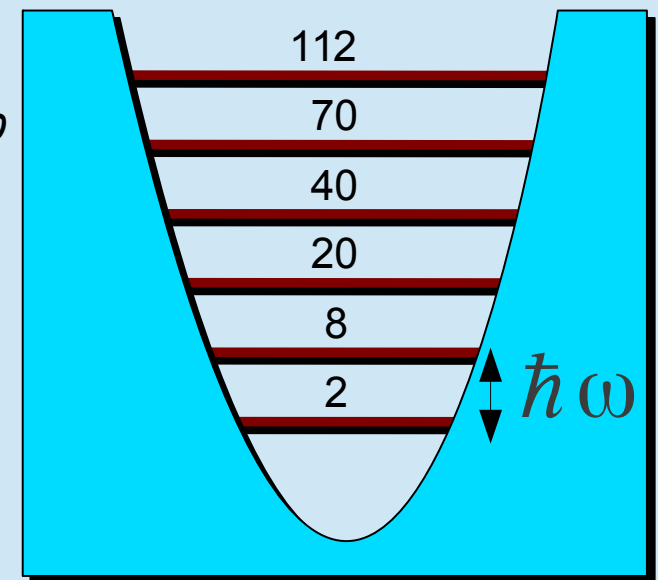
Campo médio



Partícula independente

Poço de potencial Parabólico

Ocupação



degen.

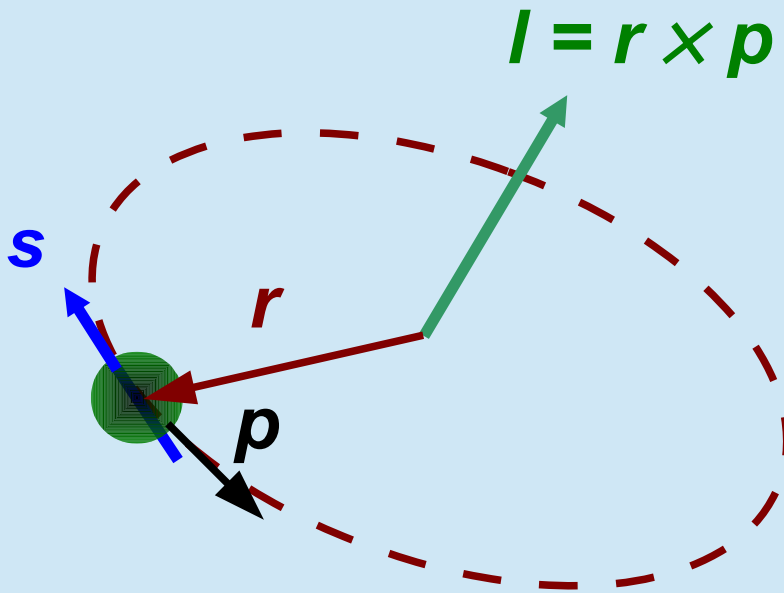
n	l	$(n+1)(n+2)$	N
0	0	2	2 ✓
1	1	6	8 ✓
2	0, 2	12	20 ✓
3	1, 3	20	40 ✓ ?
4	0, 2, 4	30	70 ✗
5	1, 3, 5	42	112 ✗

Números mágicos 4

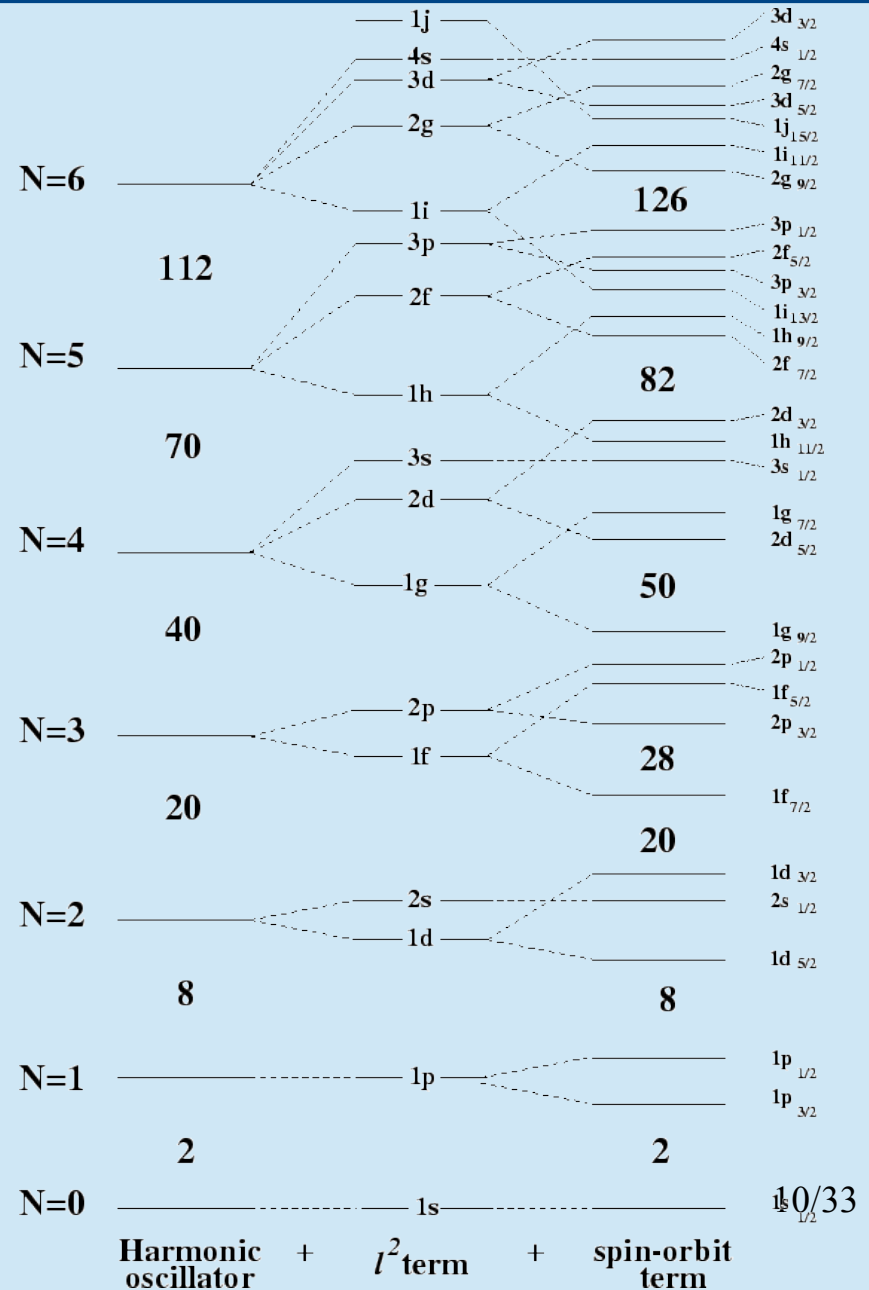
Modelo de Camadas

● Interação spin-órbita

$$H_{so} = k l \cdot s$$



● Números mágicos OK!



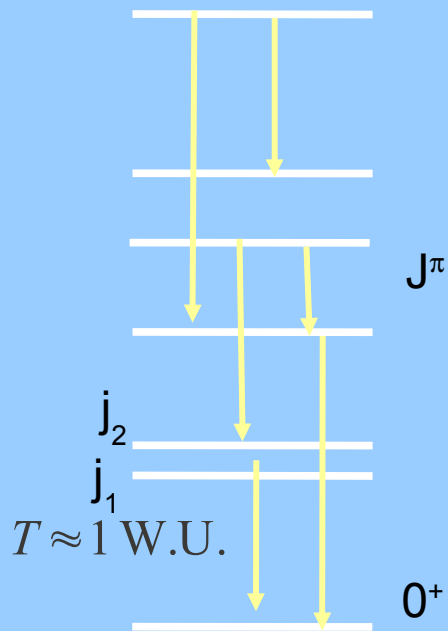
Modelo de camadas realístico

- Potenciais de Woods-Saxon, para n, e p + V(Coul.)

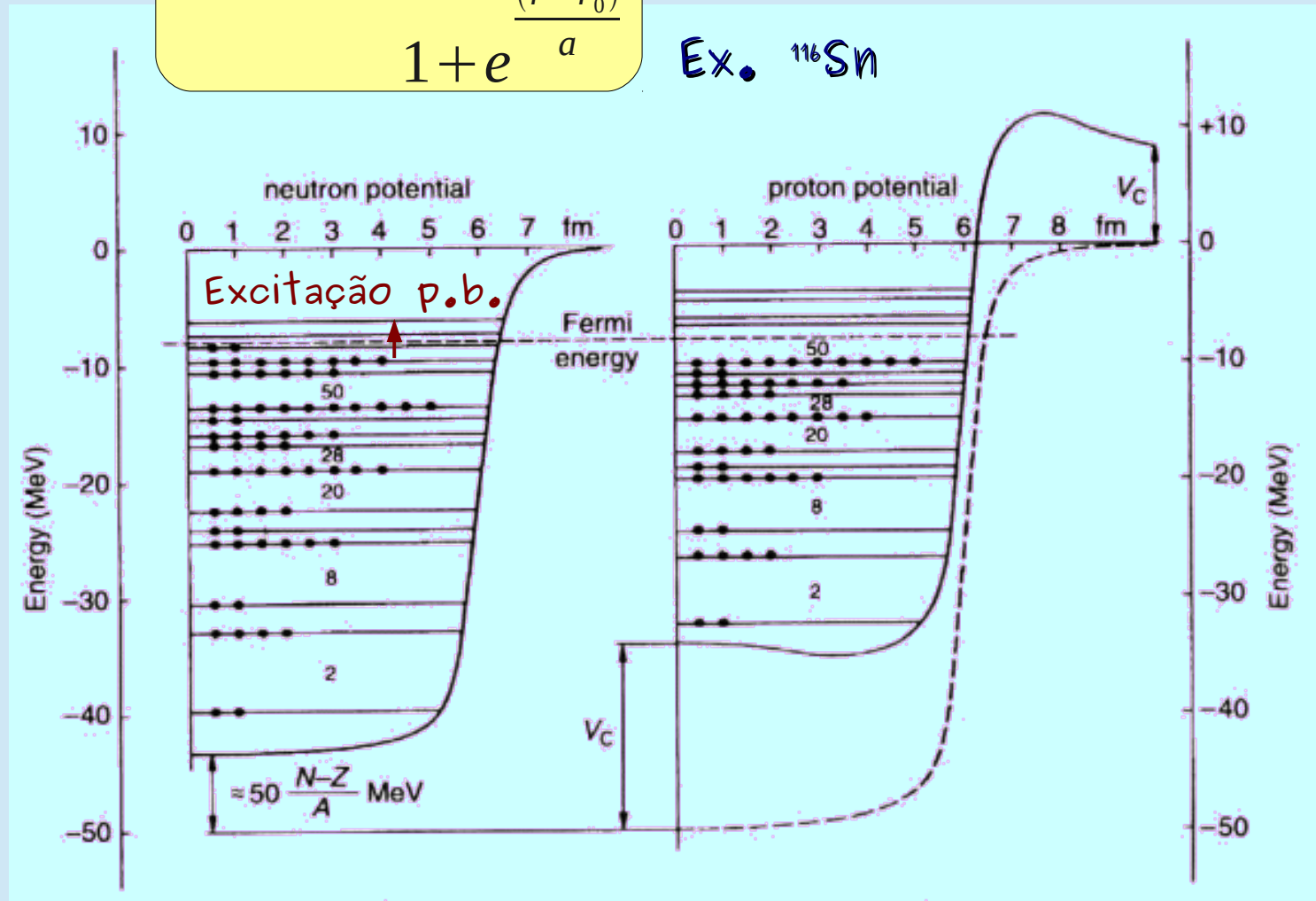
$$V_{WS}(r) = \frac{V_0}{1 + e^{\frac{r-r_0}{a}}}$$

Ex. ^{116}Sn

Esquema de níveis característico

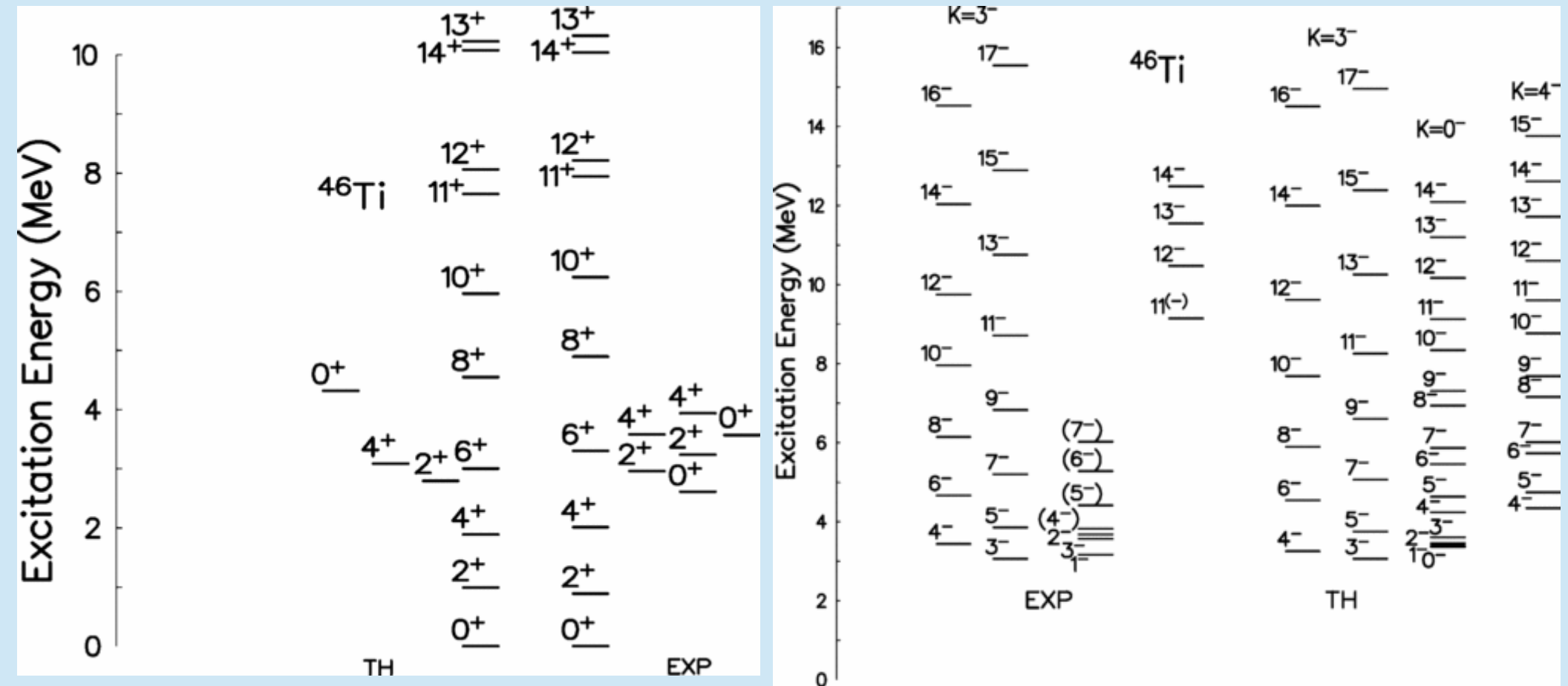


$$E = \sum E_i(p.b.)$$



Modelo de camadas de larga escala (LSSM)

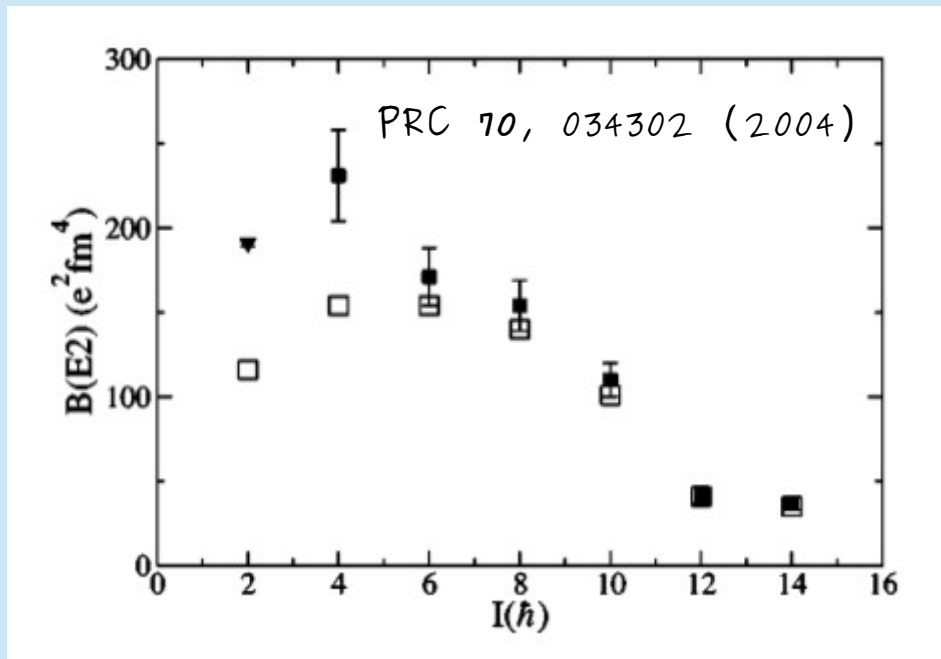
- M.C. com interação residual realística entre as partículas de valência (exs.: KB3, SDPF...)
- Ex. ^{46}Ti : Carço: ^{40}Ca ($N=Z=20$) PhysRevC70 034302



LSSM probabilidades de transição

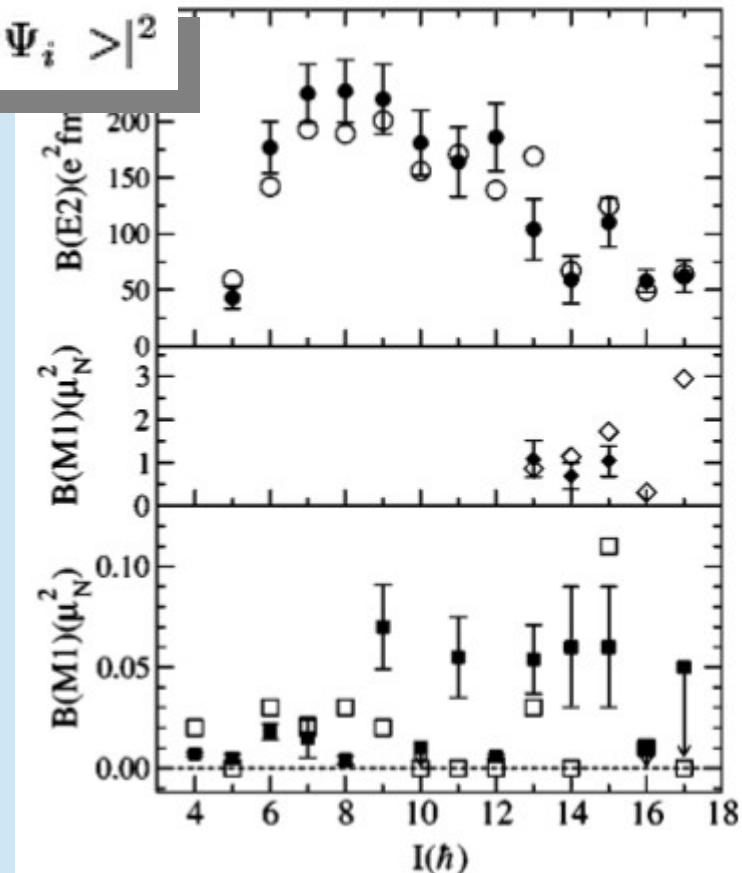
- Prob. de transição reduzida no ^{46}Ti

- $B\left(\frac{M}{E}\lambda; I_i \rightarrow I_f\right) = (2I_i + 1)^{-1} \left| \langle \Psi_f \parallel M\left(\frac{M}{E}\lambda\right) \parallel \Psi_i \rangle \right|^2$



Banda do estado fundamental

□○◇ - cálculos de LSSM



Banda de paridade negativa ($K^\pi = 3^-$)

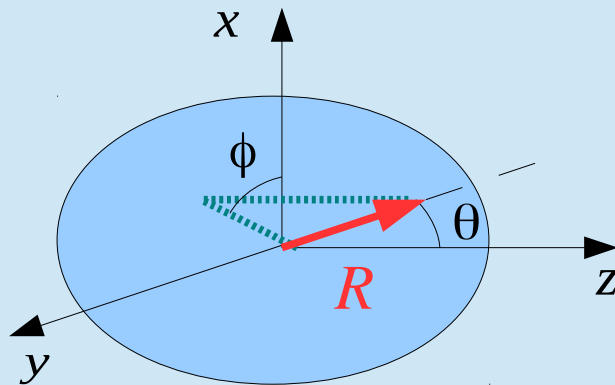
Modelos coletivos

- Parâmetros para descrição da forma nuclear

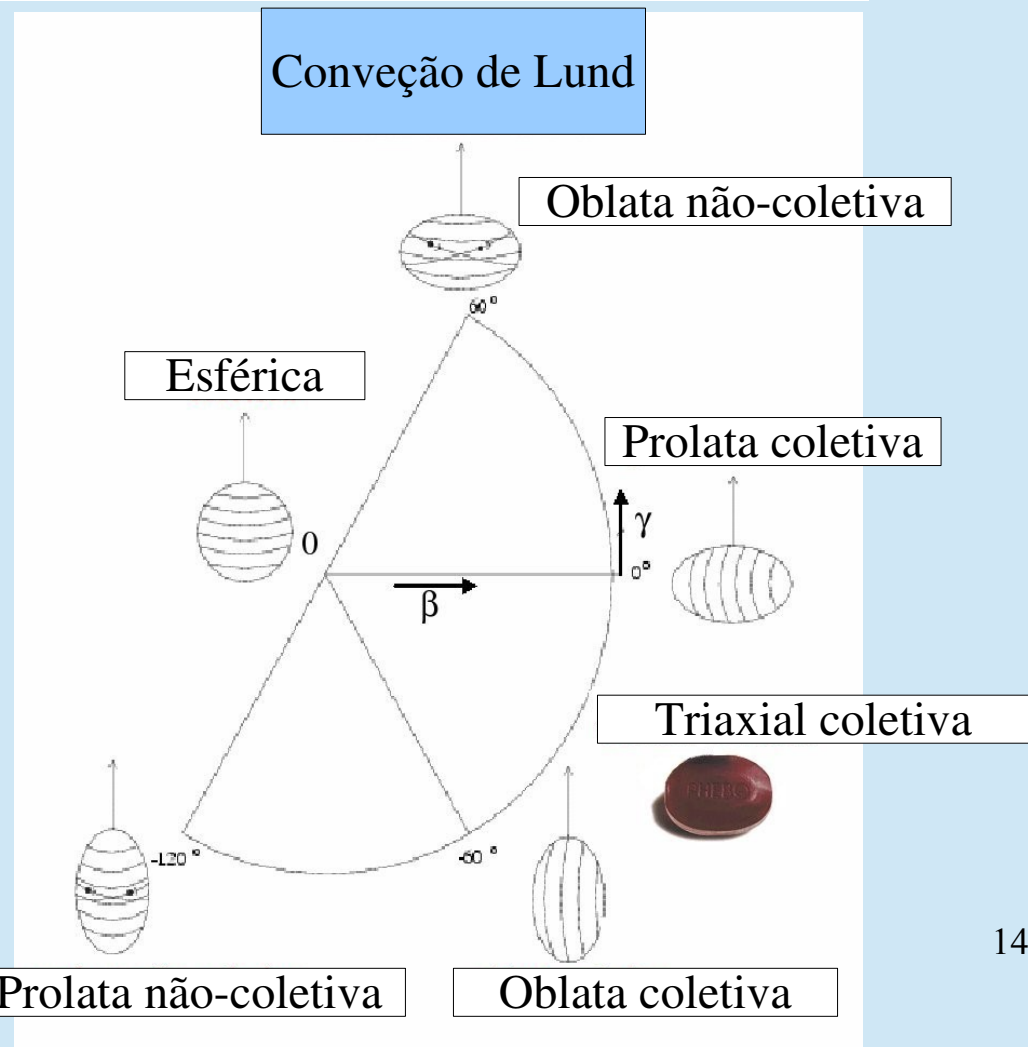
Hill-Wheeler

β, γ

$$R(\theta, \phi) = R_0 \left\{ 1 + \beta \sqrt{\frac{5}{16\pi}} \left(\cos \gamma (3 \cos^2 \theta - 1) + \sqrt{3} \sin \gamma \sin^2 \theta \cos 2\phi \right) \right\}$$

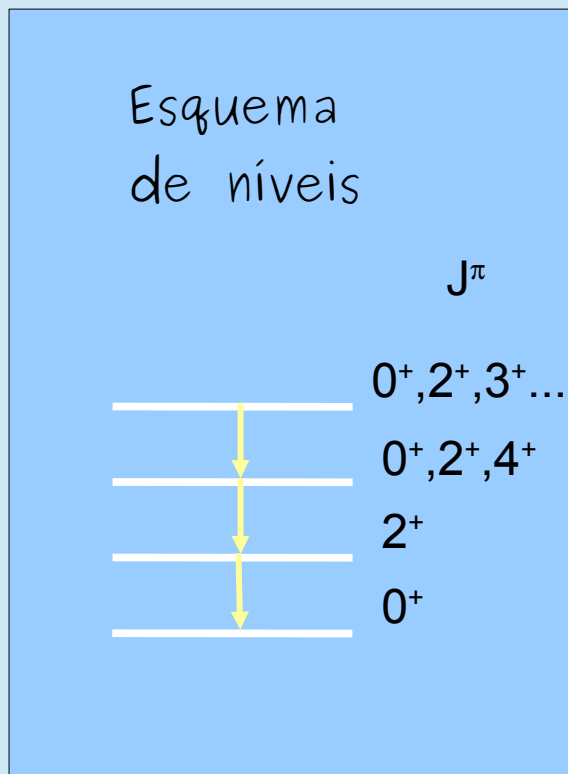


Deformações quadrupolares



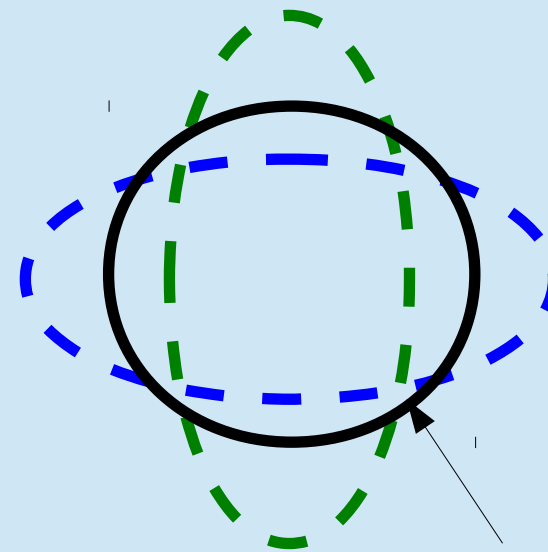
Modelo Vibracional

• Vibrações da superfície nuclear



$$E^*(n) = n \hbar \omega$$

Vibração harmônica quadrupolar $\beta = \beta(t)$



$$T \propto n \gg 1 \text{ W.U.}$$

Forma esférica de equilíbrio

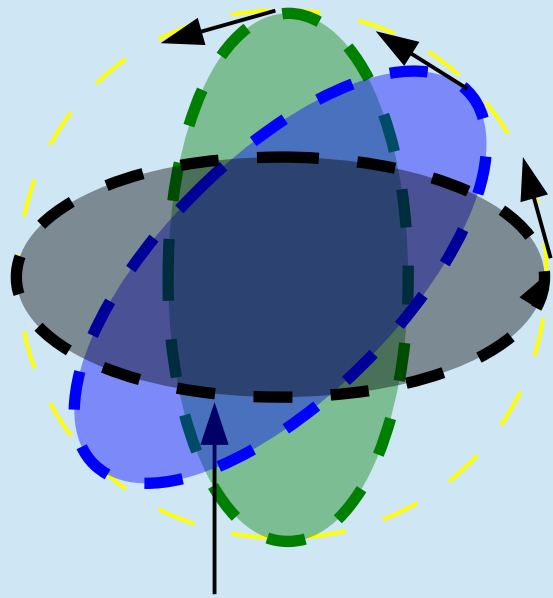
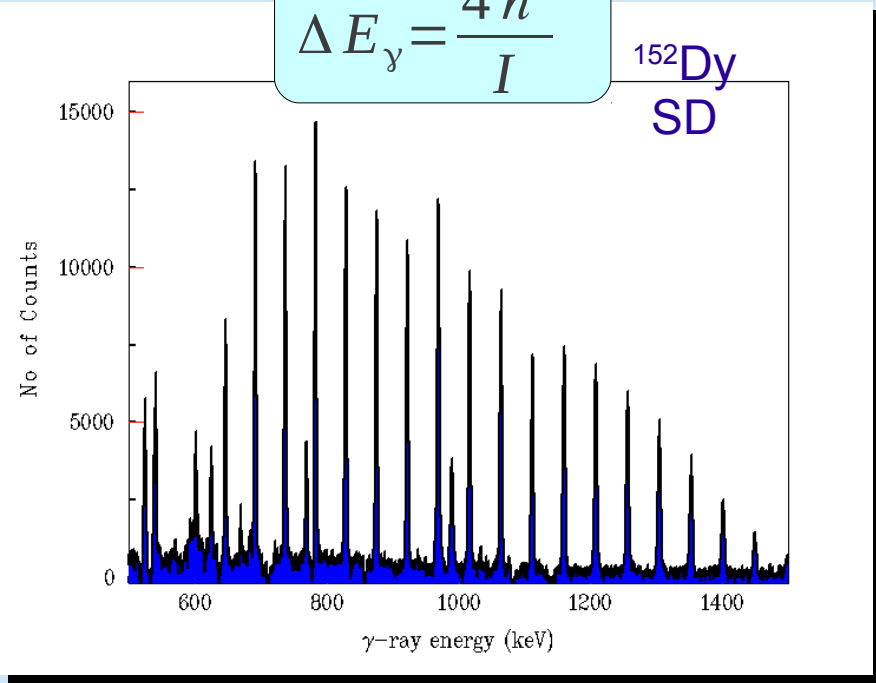
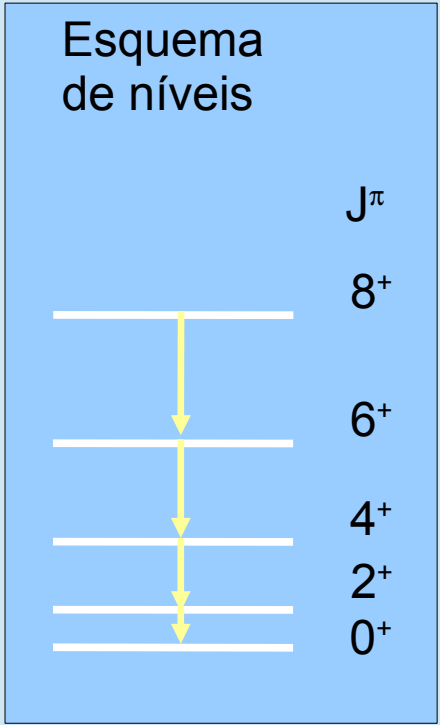
Modelo rotacional

- Rotação de núcleo quadrupolar por eixo perpendicular ao de simetria (coletiva)

$$E_{rot} = \frac{1}{2} I \omega^2 \quad L = I \omega \quad E_{rot} = \frac{L^2}{2I}$$

$$E_{rot} = \frac{\hbar^2 J(J+1)}{2I} \quad E_\gamma = \Delta E_{rot} (\Delta J = 2)$$

$$\Delta E_\gamma = \frac{4\hbar^2}{I}$$



Deformação β permanente

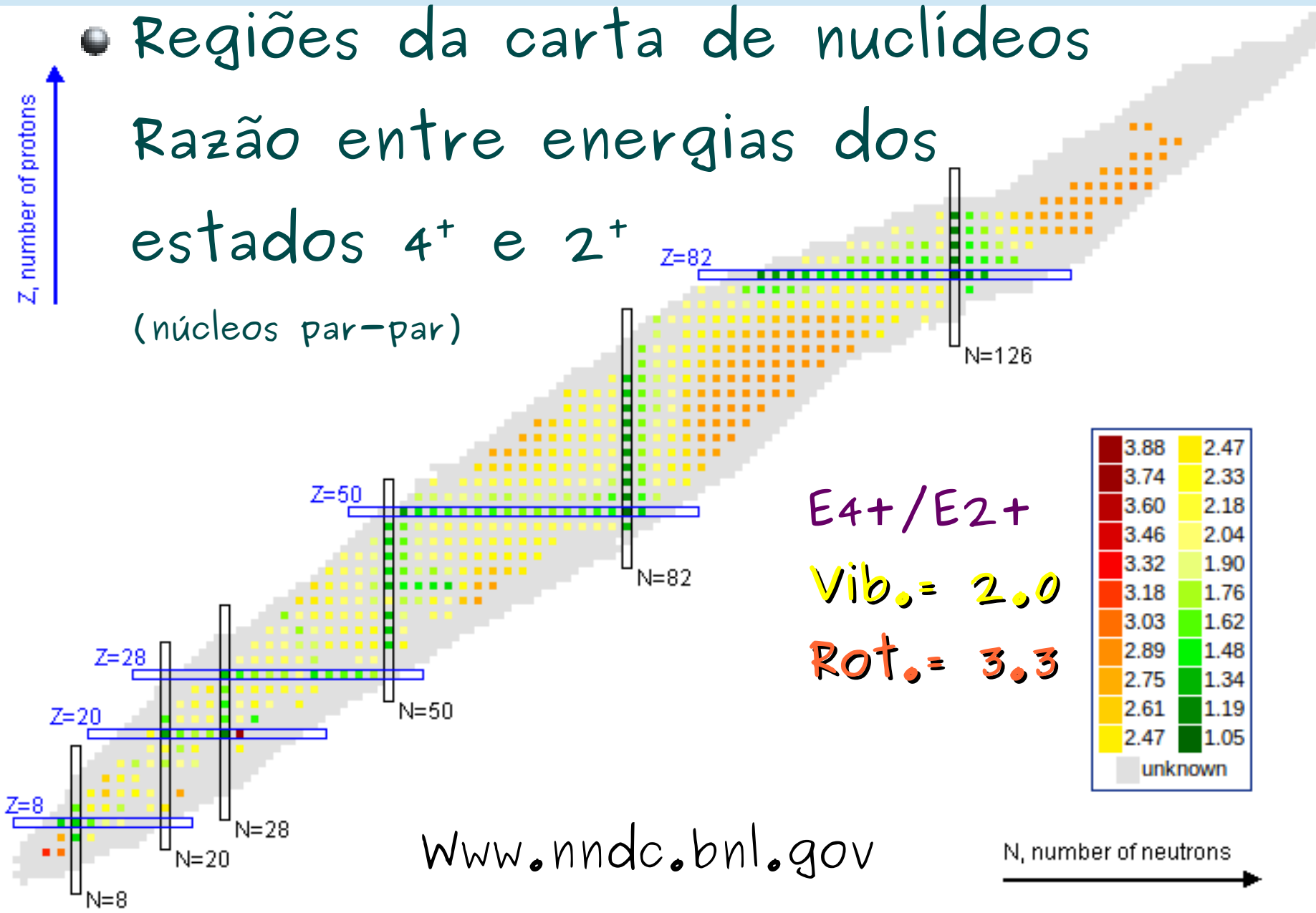
$T = T(J) \gg 1 \text{ W.U.}$

$$E_{rot} = \frac{\hbar^2 J(J+1)}{2I}$$

$$\hbar \omega = \frac{E_\gamma}{2} \quad 16/33$$

Rotacional ou vibracional?

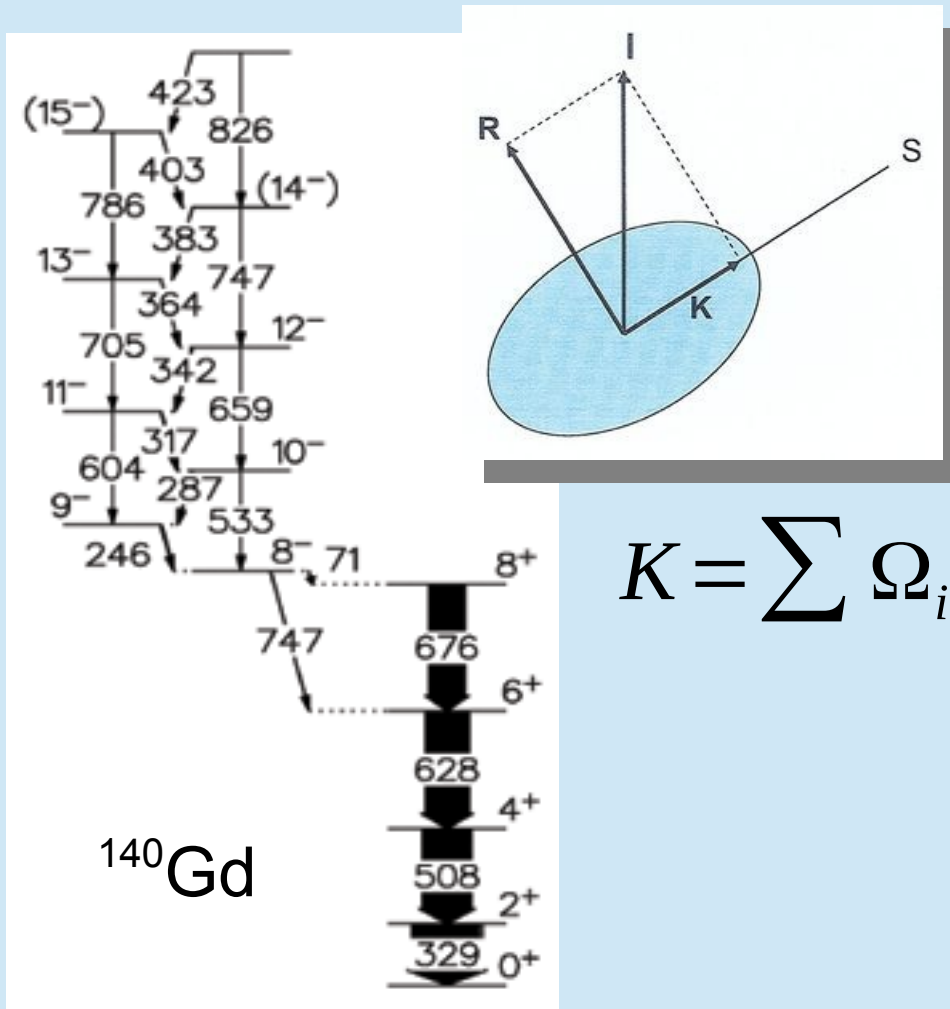
- Regiões da carta de nuclídeos
Razão entre energias dos
estados 4^+ e 2^+
(núcleos par-par)



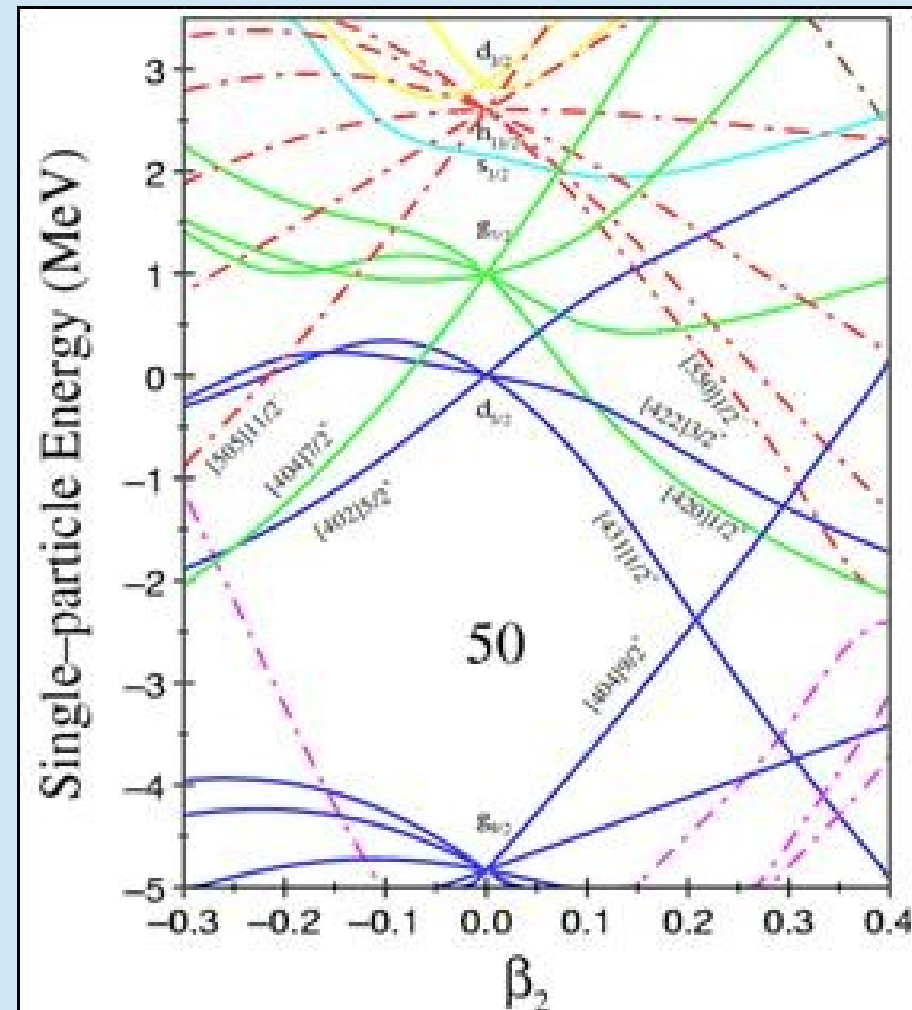
www.nndc.bnl.gov

Modelo de Nilsson

- Estados de partícula única em um potencial deformado

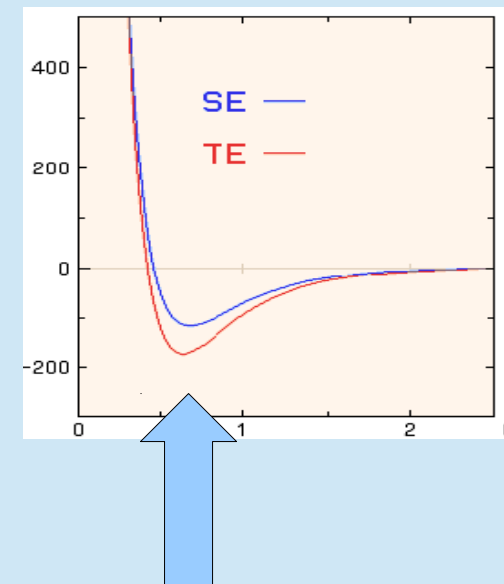
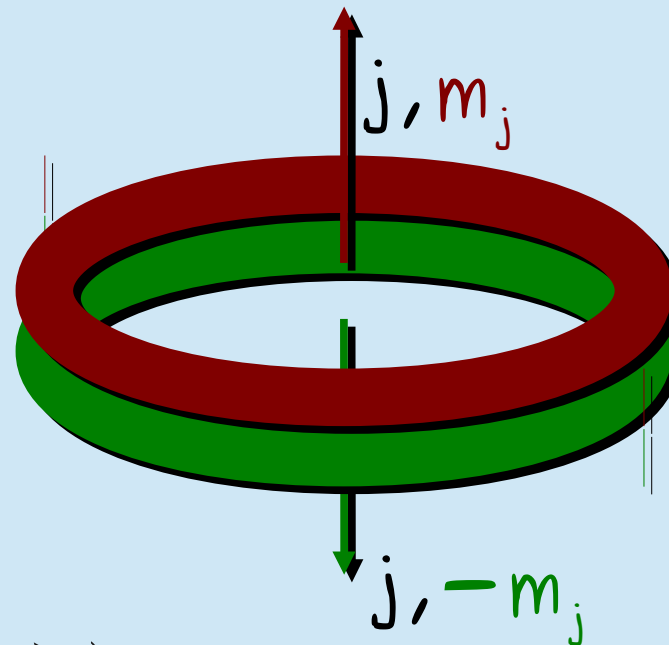
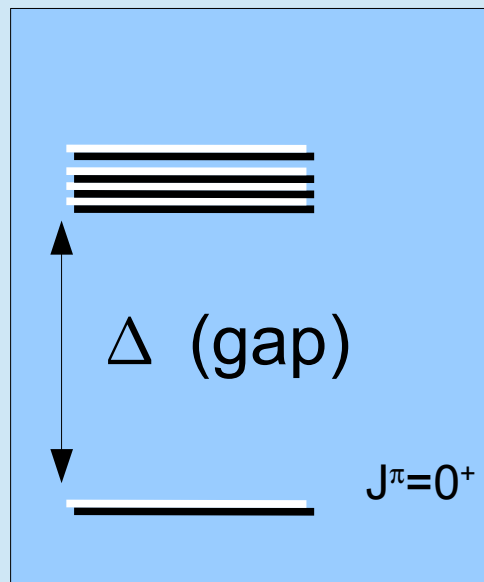


$$K = \sum \Omega_i$$



Emparelhamento

- Tendência ao acoplamento de órbitas com reversão temporal $\rightarrow J=0$



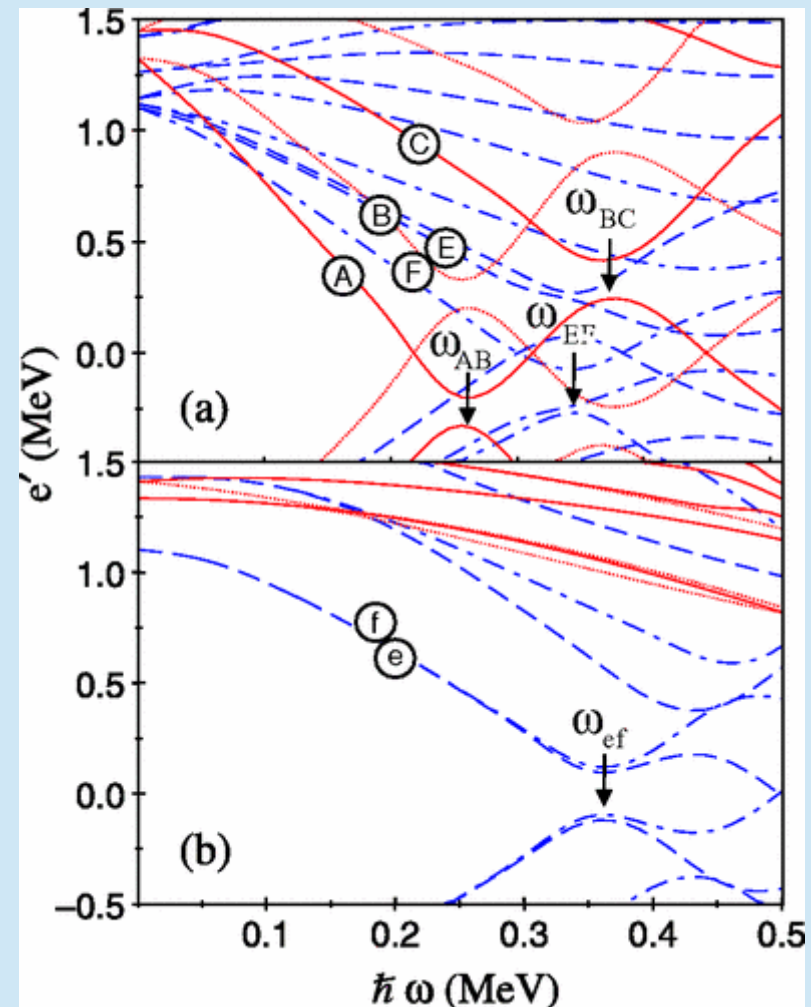
$$V(\vec{r} - \vec{r}') \approx \delta(\vec{r} - \vec{r}')$$

Correlações de emparelhamento (além do campo médio).
O núcleo é análogo a um supercondutor.

Modelo de "Cranking" (CSM)

- Mod. Nilsson + interação de Coriolis
- Routhiano $e' = e - \omega J_x$

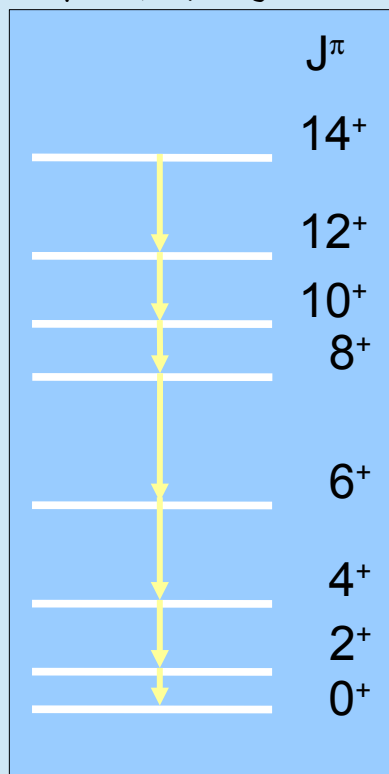
Energia no referencial
intrínseco (não inercial)
com velocidade angular
de rotação constante



Altos spins – “Backbending”

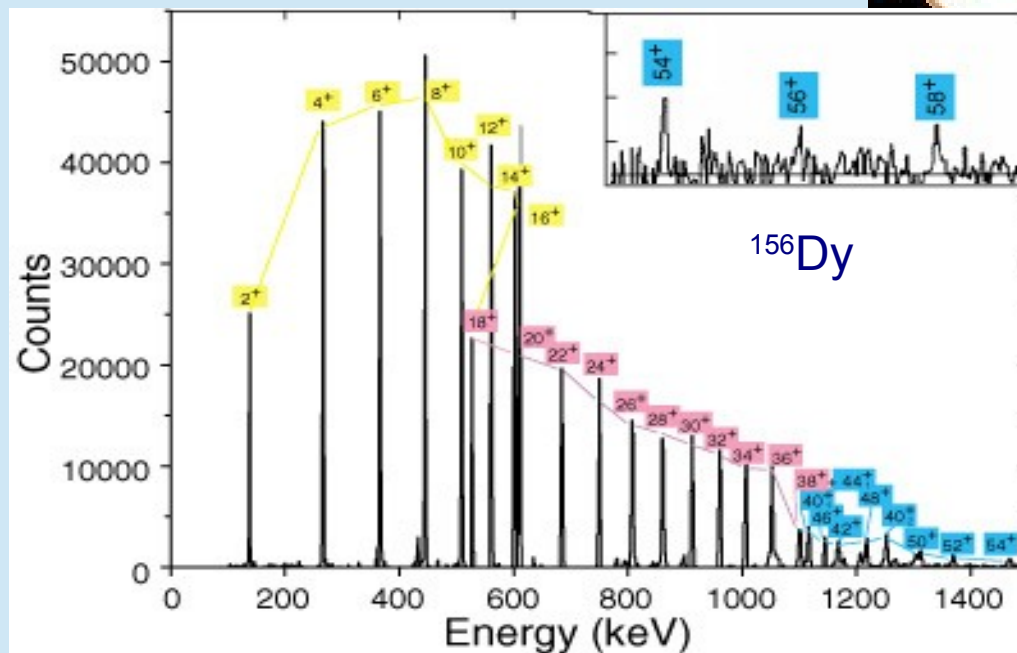
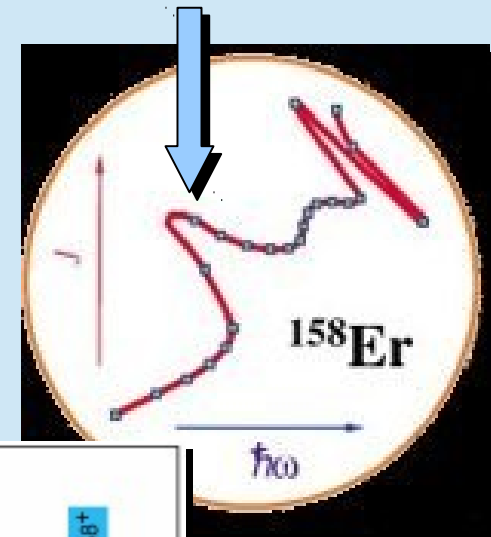
- Quebra de par induzida por Coriolis

Esquema de níveis



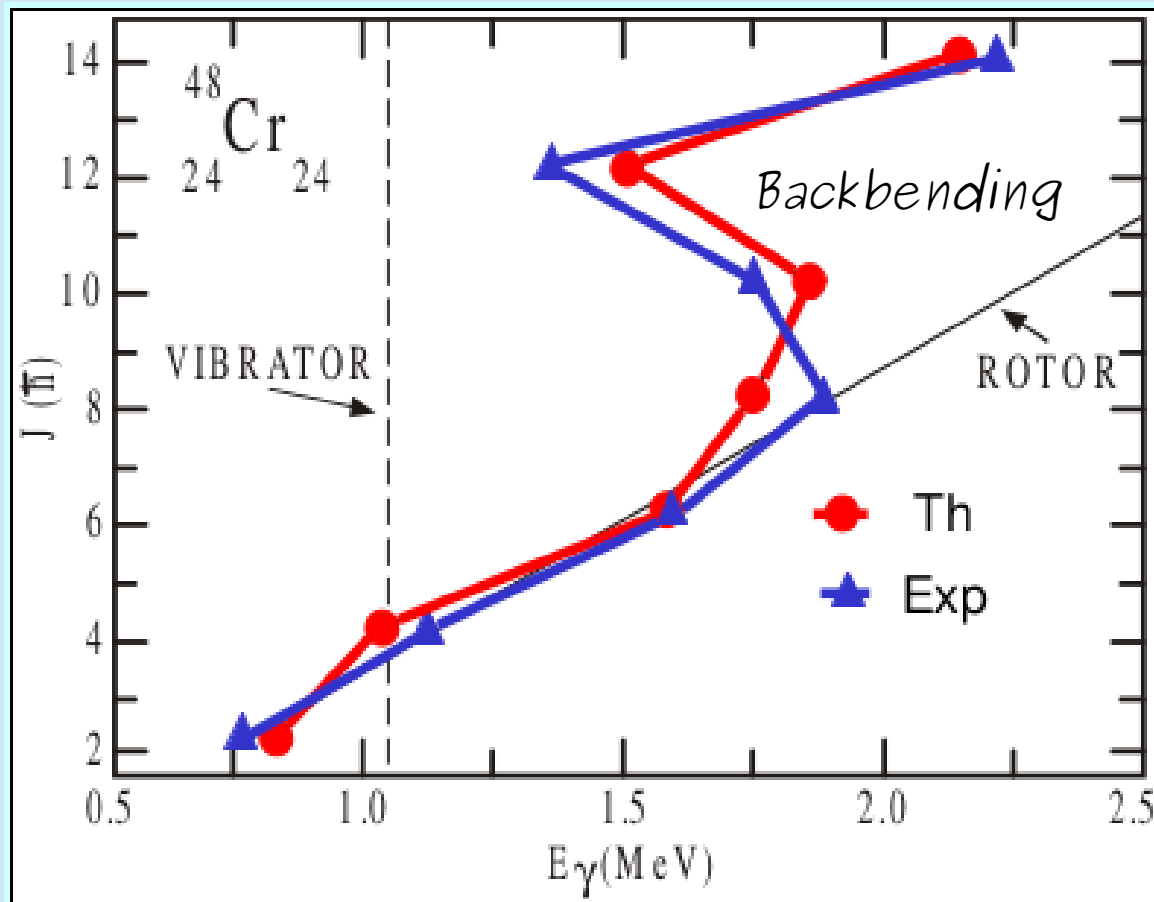
$$H_{\text{Coriolis}} = -\hbar \omega j_x$$

$$\hbar \omega = \frac{E_y}{2}$$



LSSM x Collective rotation

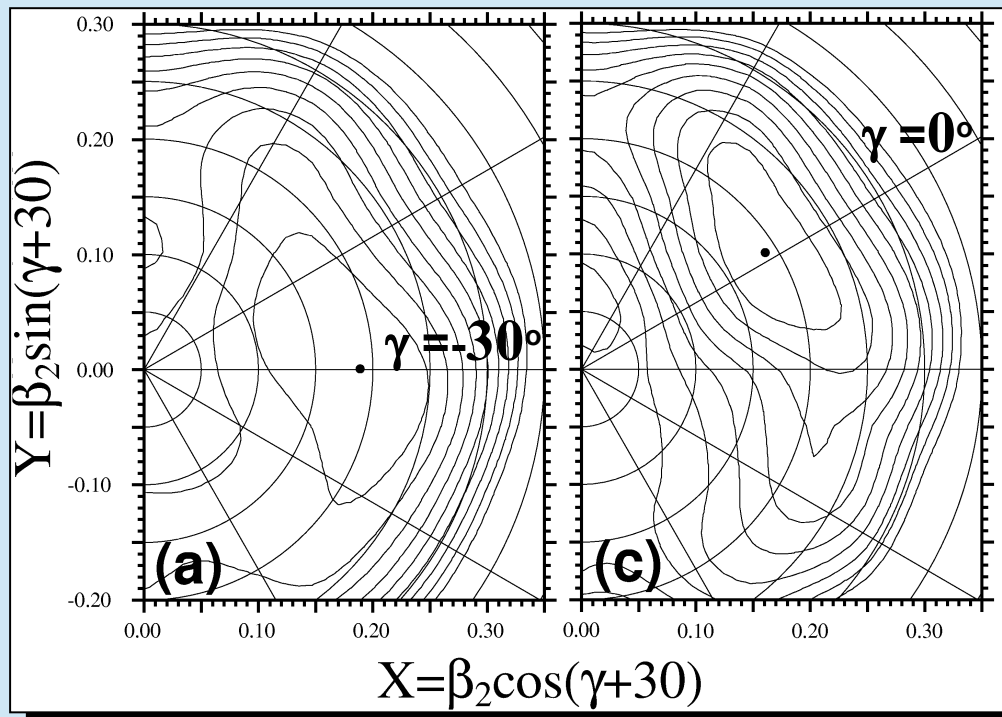
- Comportamento rotacional construído no MC com interações residuais



48Ni	49Ni	50Ni	51Ni	52Ni	53Ni	54Ni	55Ni	56Ni
47Co	48Co	49Co	50Co	51Co	52Co	53Co	54Co	55Co
46Fe	47Fe	48Fe	49Fe	50Fe	51Fe	52Fe	53Fe	54Fe
45Mn	46Mn	47Mn	48Mn	49Mn	50Mn	51Mn	52Mn	53Mn
44Cr	45Cr	46Cr	47Cr	48Cr	49Cr	50Cr	51Cr	52Cr
43V	44V	45V	46V	47V	48V	49V	50V	51V
42Ti	43Ti	44Ti	45Ti	46Ti	47Ti	48Ti	49Ti	50Ti
41Sc	42Sc	43Sc	44Sc	45Sc	46Sc	47Sc	48Sc	49Sc
40Ca	41Ca	42Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca
20	22	24	26	28				

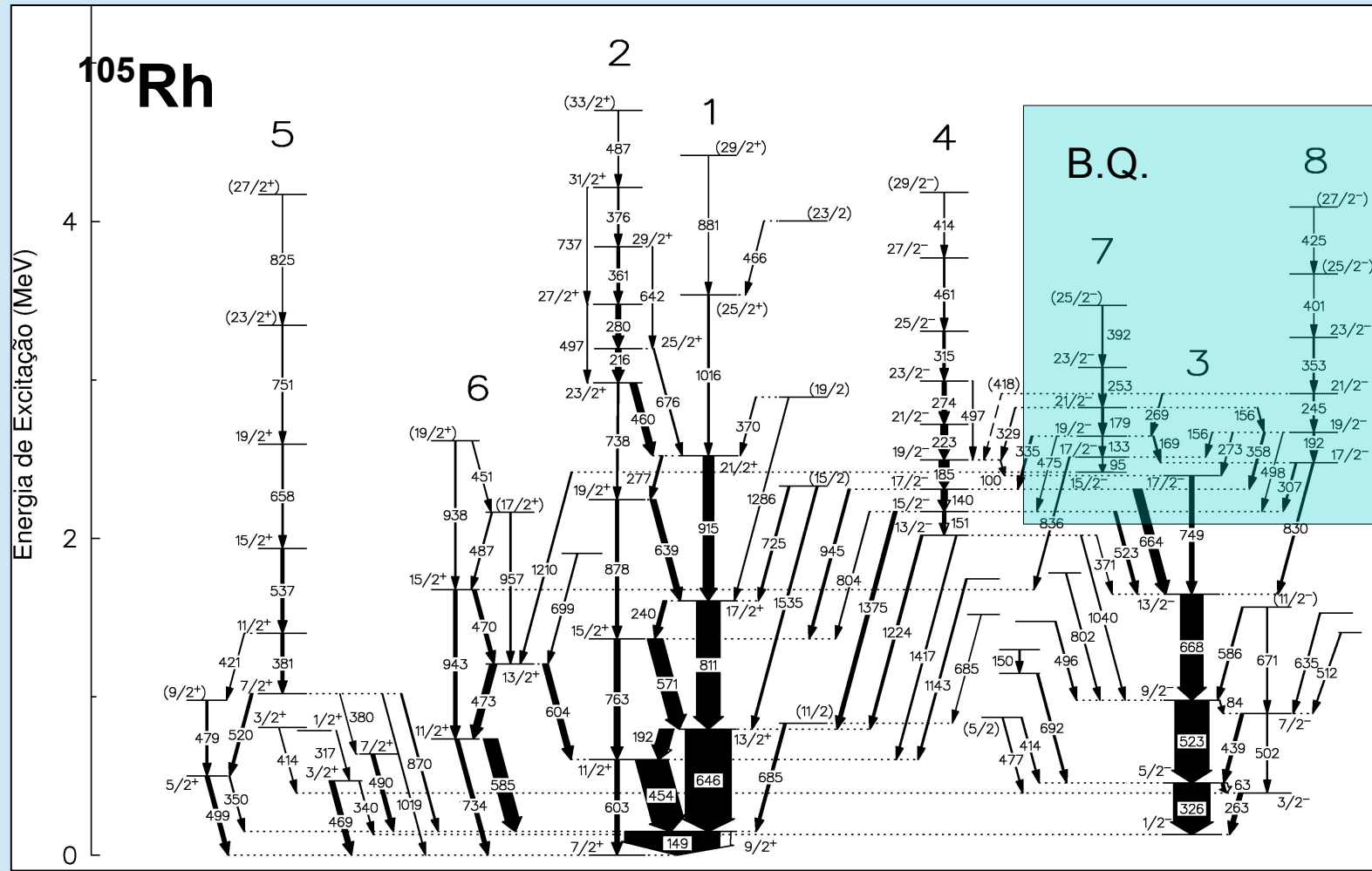
Modelo de Strutinsky

- Gota líquida + correções de camada
- TRS Total Routhian Surfaces



Exemplo de estudo no IF

- J.A. Alcántara-Núñez, Tese de Doutorado, IFUSP, 2003

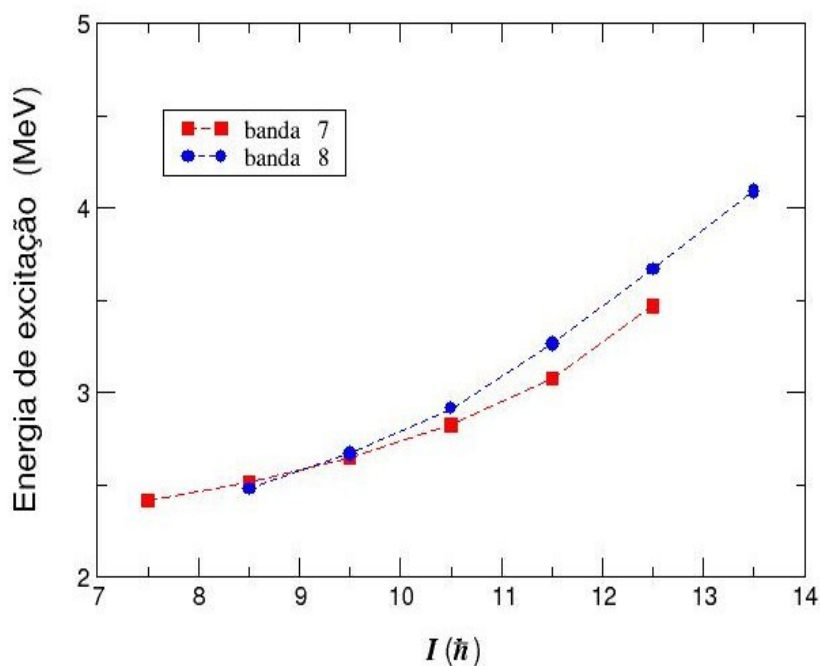


Quebra de simetria quiral

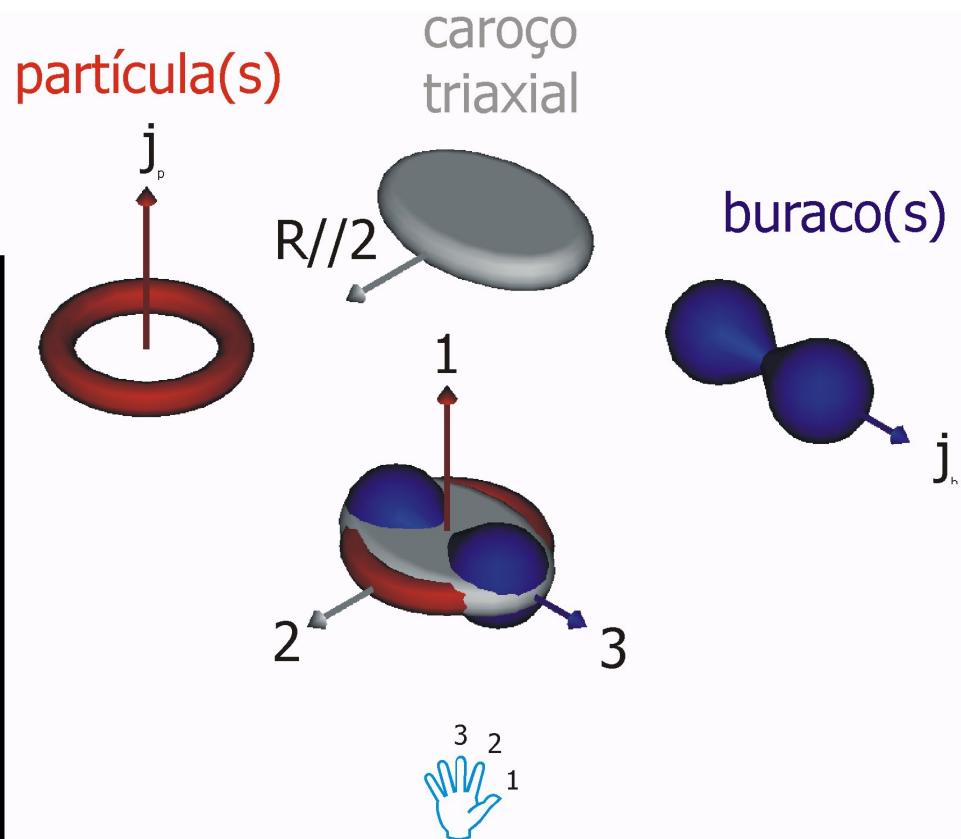
TAC

^{105}Rh

bandas quase degeneradas

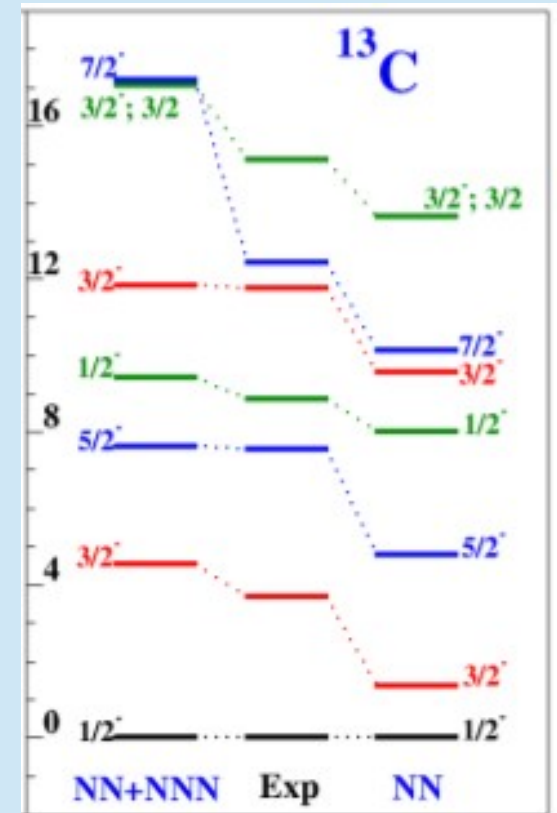


Quiralidade no sistema intrínseco



Ab Initio – NCSM

- NCSM – No Core Shell Model
- Teorias de campo efetivo (χ EFT)
- Uso de parâmetros da interação NN, NNN ajustados a dados de sistemas de poucos corpos

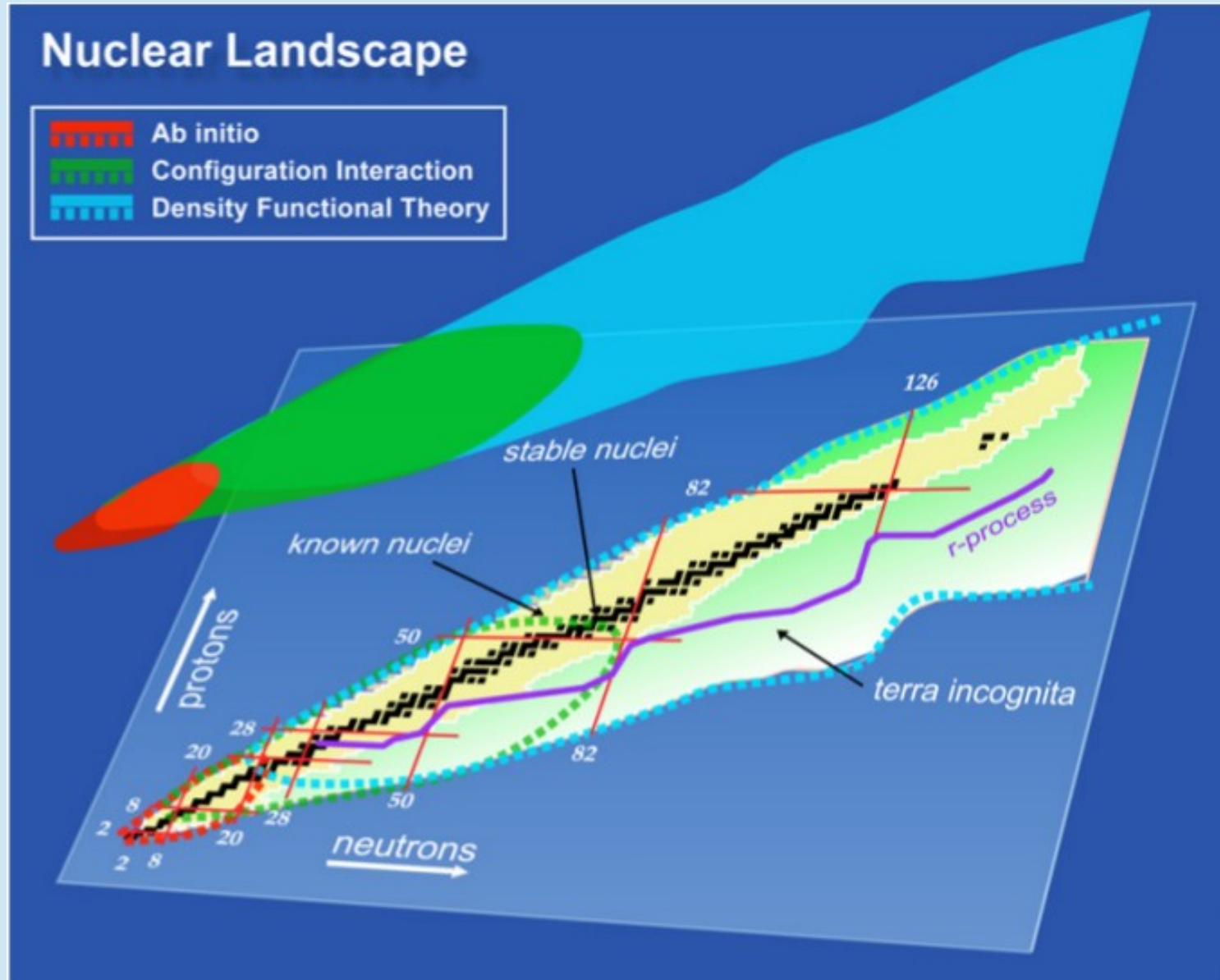


J.P. Vary

ntse-2014

(Nuclear Theory in the
Supercomputing Era), Russia

Cálculos teóricos de precisão



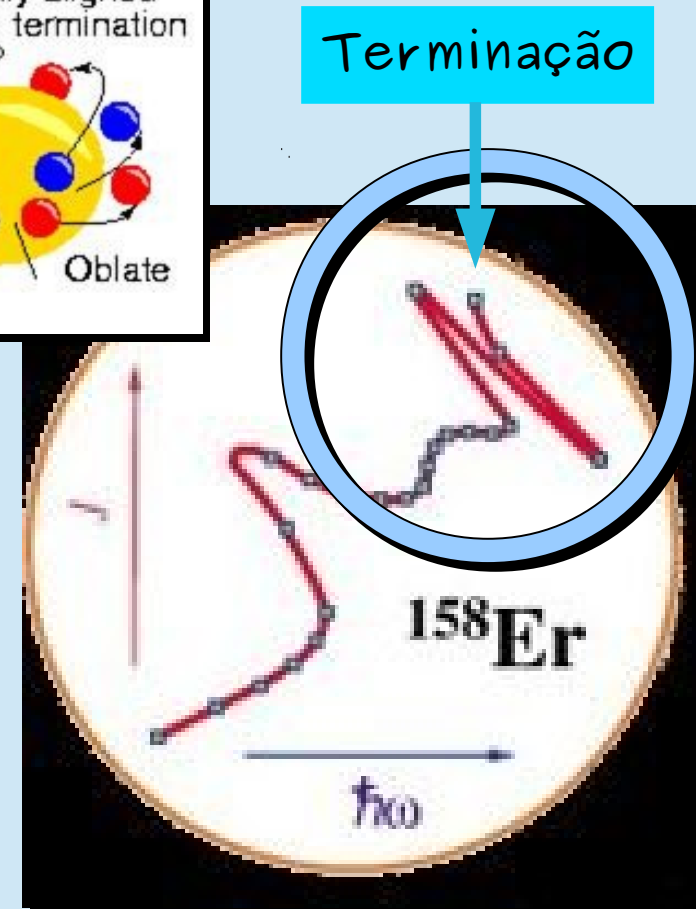
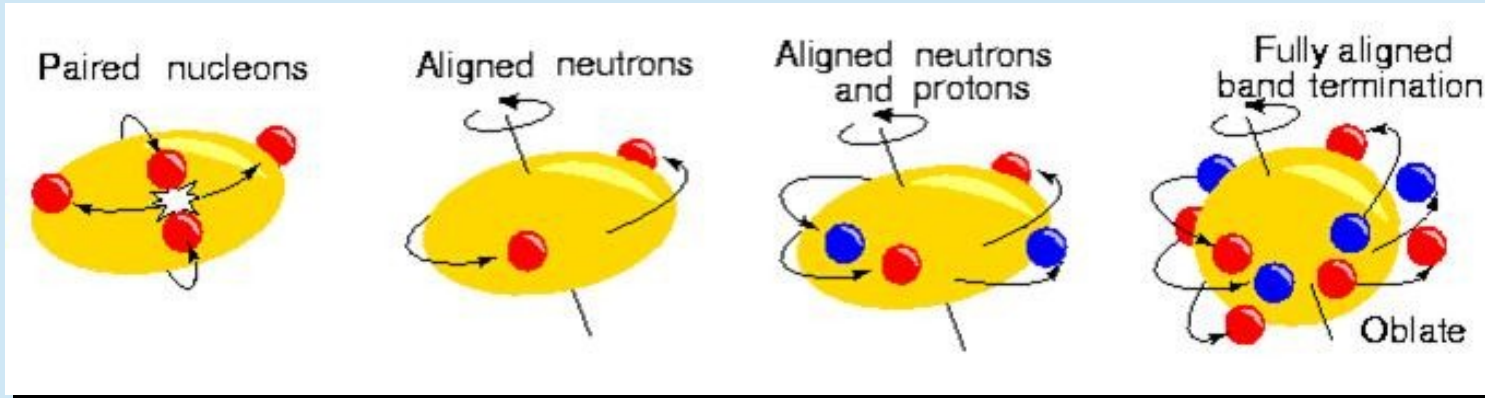
Próxima aula: Ferramentas de pesquisa

- Aceleradores de partículas
- Detectores de partículas
- Espectrômetros gama

Extras

Terminação de banda

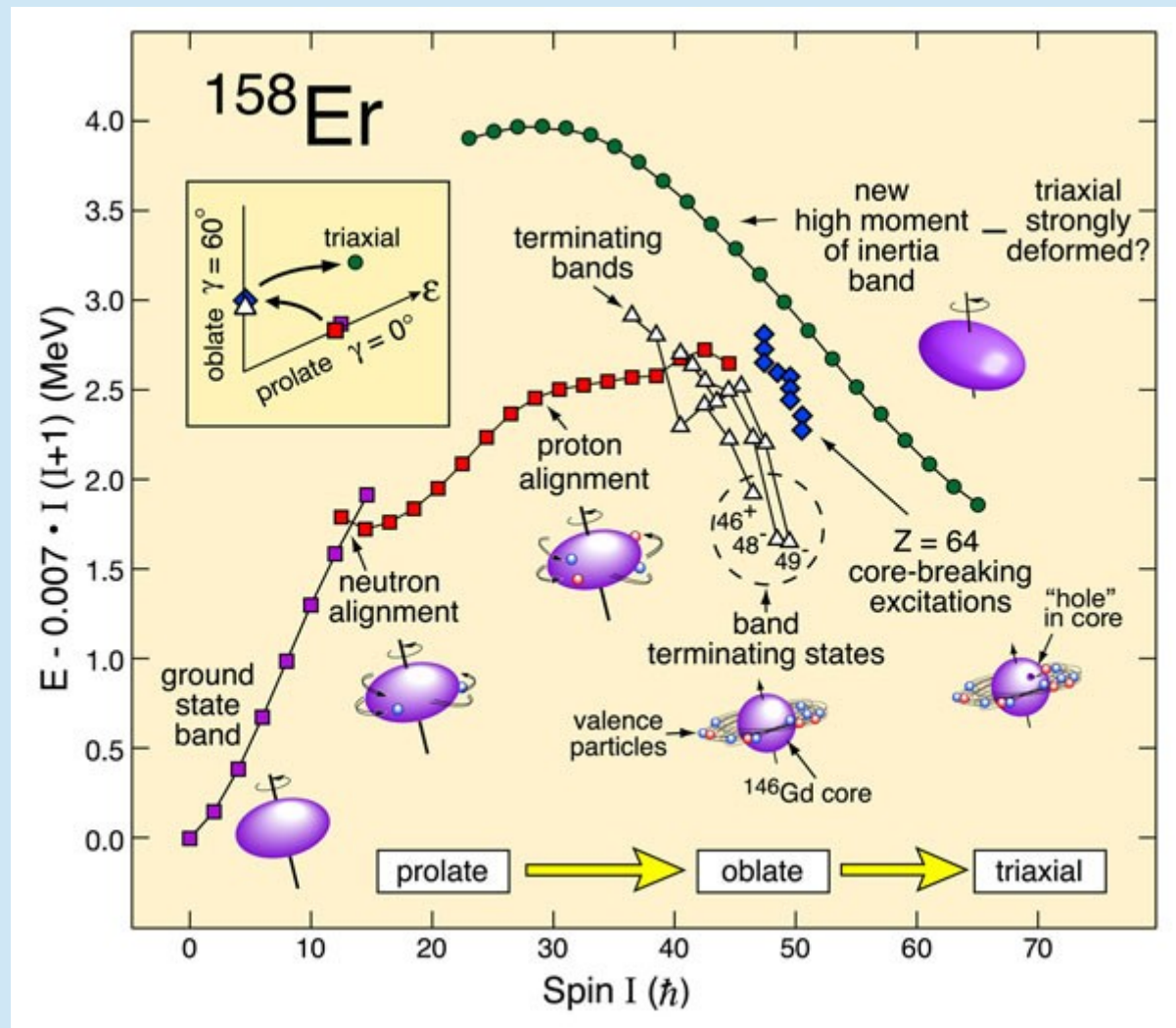
- Alinhamento de todas as partículas de valência



Coletividade além da terminação

Destaque PRL 2007

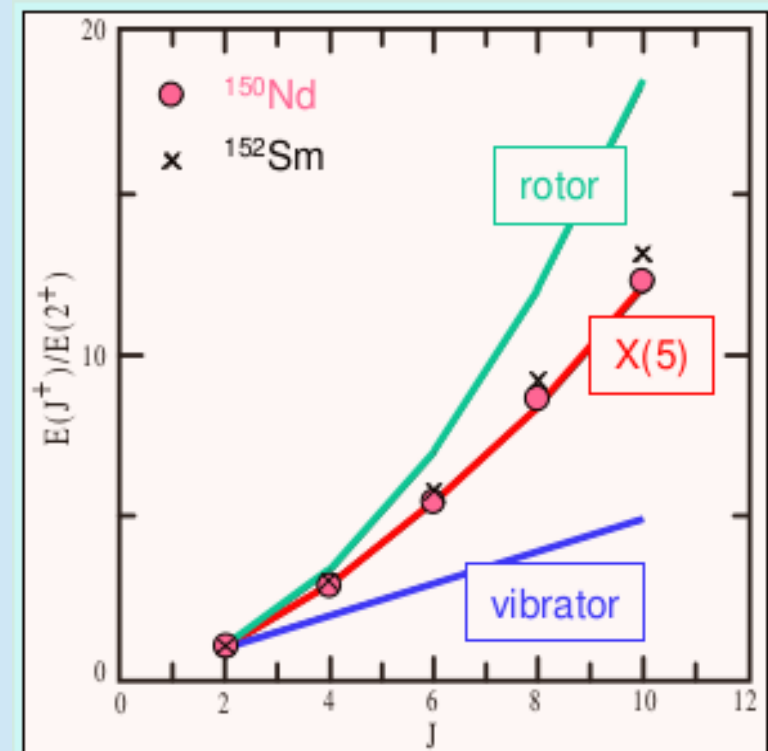
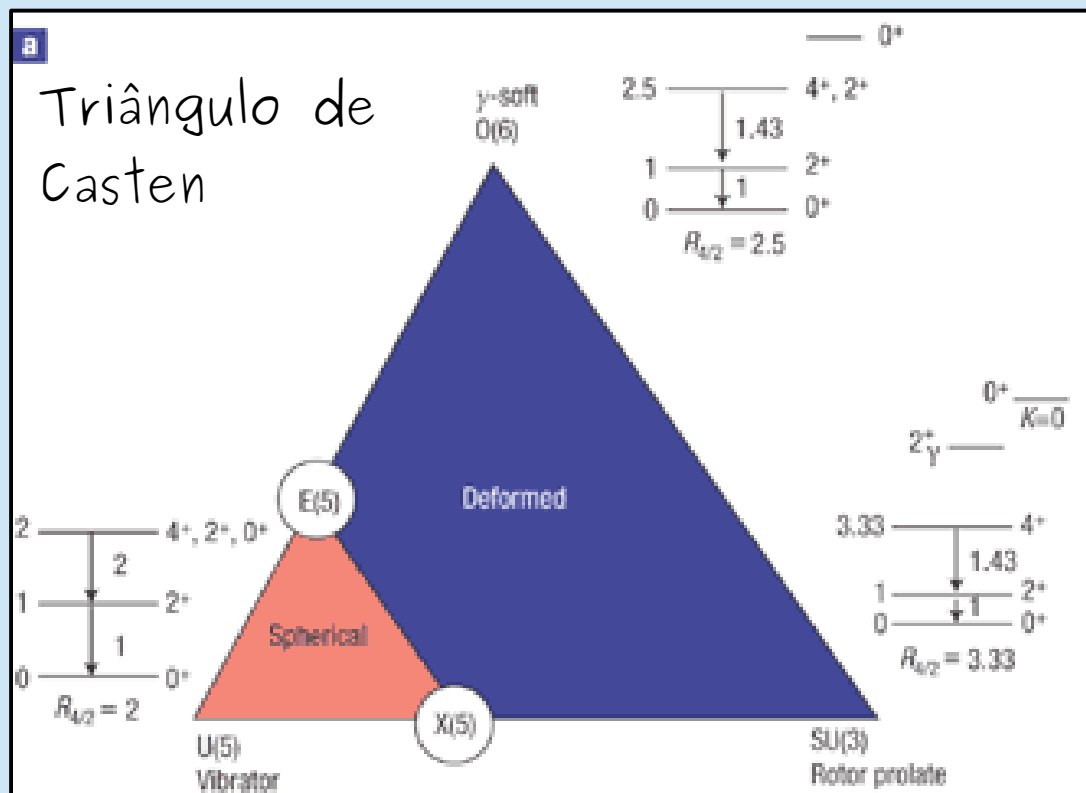
E.S. Paul et al.,
Phys. Rev. Lett.
98, 012501 (2007)



Simetria e transições de fase

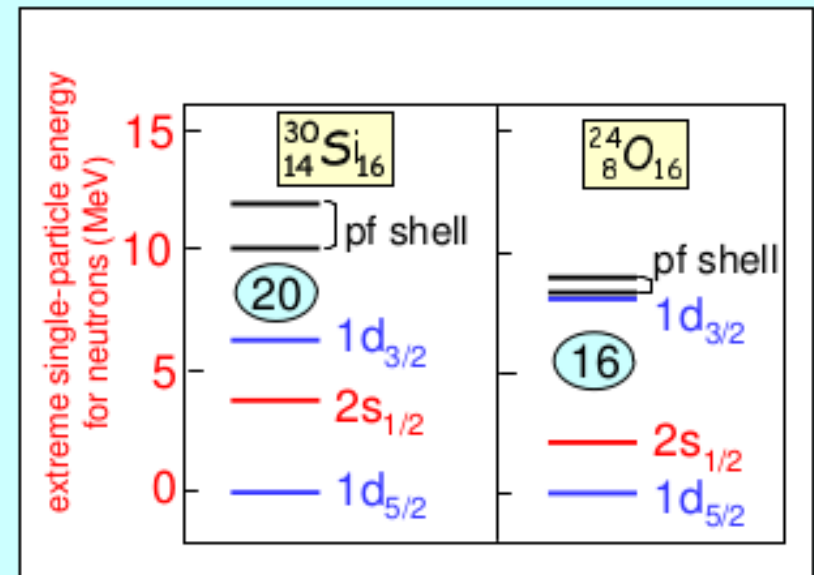
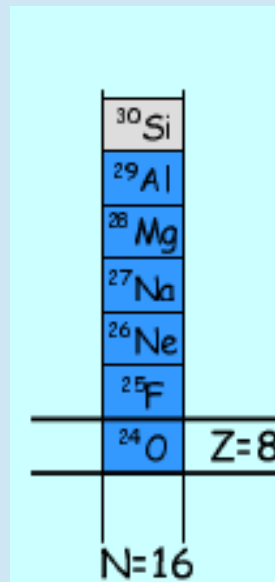
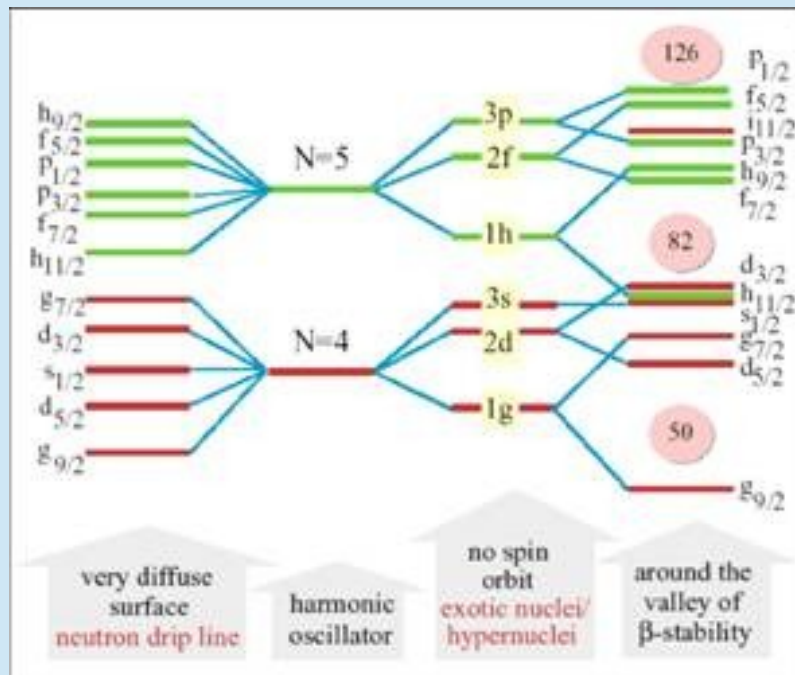
- IBM: s, d – bósons
simetrias dinâmicas

- Ex. X(5) ponto crítico da transição de fase rotor-vibrador



Novos números mágicos?

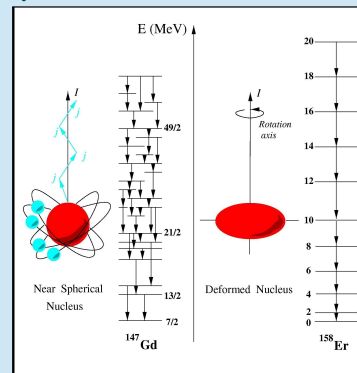
- Modificação das camadas longe do vale de estabilidade



Nupec LRP 2004

Aula 2 – Modelos Nucleares

- Propriedades gerais de núcleos
- Modelo da gota líquida
- Mecânica quântica (em 1 slide!)
- Modelo de camadas
- Modelos coletivos
- Modelos de Nilsson e CSM
- Emparelhamento (senioridade)
- Altos spins – Backbending
- Bandas quirais

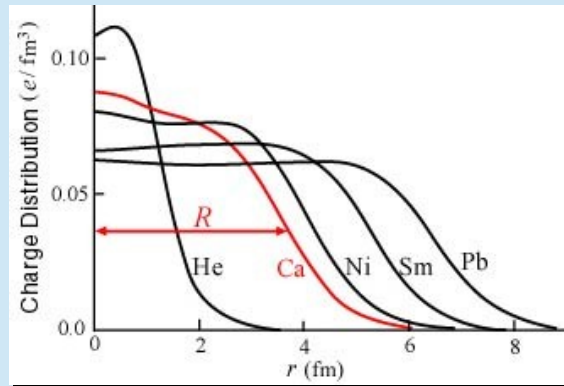
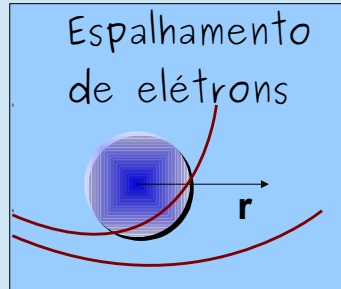


1/33
(29)

Propriedades gerais dos núcleos

- Raio, densidade de carga e de núcleons
- Energias de ligação
- Energias de separação de $2n$ e $2p$
(números mágicos)

A distribuição de carga e massa do núcleo

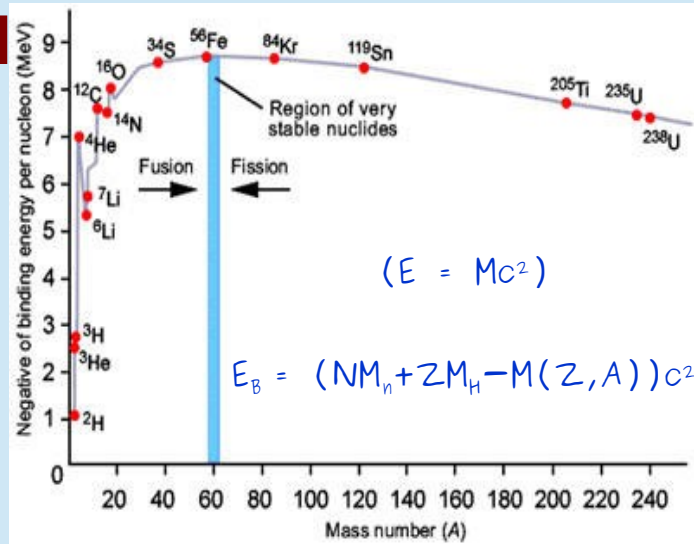


Na região do vale de estabilidade

- Densidade aprox. constante
- Raio nuclear: $R = R_0 A^{\frac{1}{3}}$ ($R_0 = 1.2 \text{ fm}$)

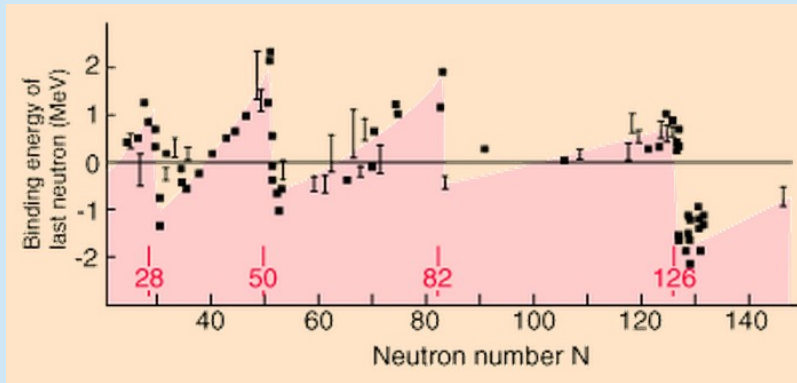
Energias de ligação

E_B/A



Números mágicos

N : 2, 8, 20, 28, 50, 82, 126



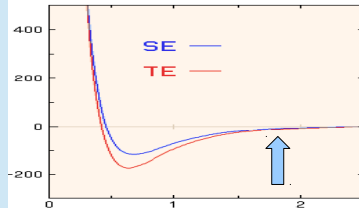
Obs.: ao menos na região do vale de estabilidade!

Modelo da gota líquida

- Raio nuclear: $R = R_0 A^{\frac{1}{3}}$ ($R_0 = 1.2 \text{ fm}$)

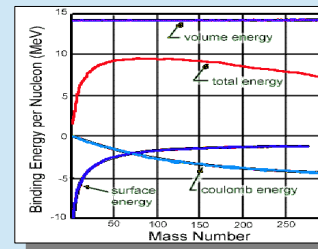
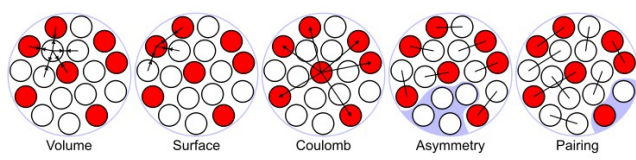
$$\rho_0 \approx 0.17 \text{ fm}^{-3}$$

$$\langle r_{NN} \rangle \approx 1/\sqrt[3]{\rho_0} = 1.8 \text{ fm}$$



- Fórmula semi-empírica de massa

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N - Z)^2}{A} - \delta(A, Z)$$



Mecânica quântica (em 1 slide!)

Função de onda
(em 1D): $\Psi(x, t)$

Operadores:

$$H = i\hbar \frac{\partial}{\partial t}$$

$$E_{cin} = \frac{p^2}{2m} = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2}$$

$$E_{pot} = V(x)$$

Energia mecânica:

$$H = E_{cin} + E_{pot}$$

$$P(x, t) = |\Psi(x, t)|^2$$

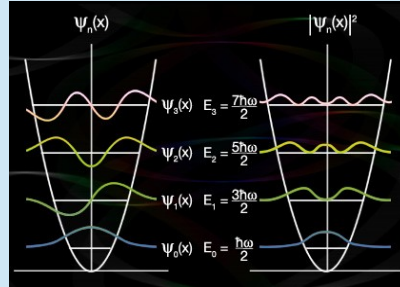
$$\text{Eq. Schrödinger } i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V(x)\Psi$$

$$\text{Autovalores de energia: } H\Psi_n = E_n\Psi_n$$

Ex. oscilador
harmônico:

$$V(x) = \frac{1}{2}m\omega^2 x^2$$

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega$$



Princípio da incerteza $\Delta p \Delta x \geq \hbar$

Ex.: Orbitais atômicas

$$(V \propto \frac{1}{r})$$

• Função de onda

$$\Psi(r, \theta, \varphi) = R_n(r) Y_{lm}(\theta, \varphi)$$

Y_{lm} : Harmônicos esféricos

Estados de momento angular

m.a. orb.

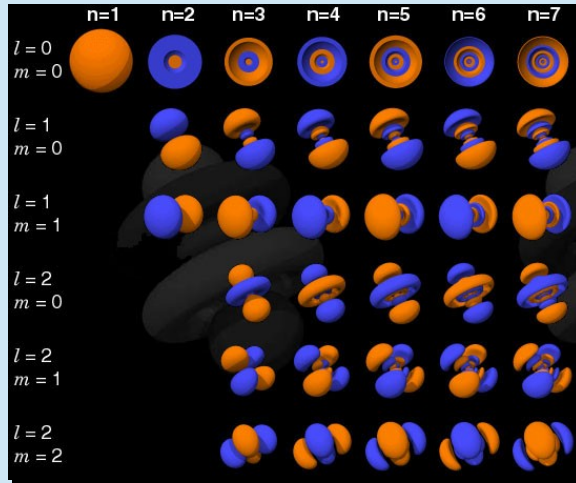
proj. z



$$-l \leq m \leq l \quad 2l+1 \text{ estados}$$

ex.: $l=2: m=-2, -1, 0, 1, 2$

Re(Ψ): +, -



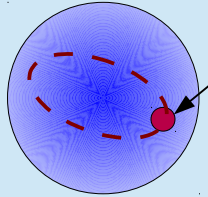
Distribuição de matéria | $\Psi_{2,2}|^2$



Modelo de Camadas

● Oscilador harmônico 3D $E^*(n) = (n + 3/2)\hbar\omega$

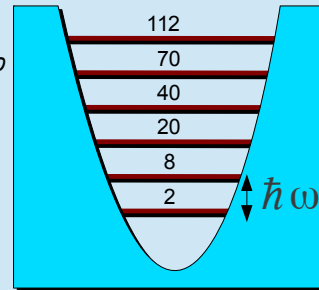
Campo médio



Partícula independente

Poço de potencial Parabólico

Ocupação



degen.

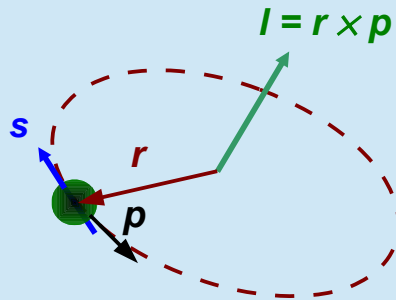
n	l	$(n+1)(n+2)$	N
0	0	2	2 ✓
1	1	6	8 ✓
2	0, 2	12	20 ✓
3	1, 3	20	40 ✓ ?
4	0, 2, 4	30	70 ✗
5	1, 3, 5	42	112 ✗

Números mágicos 4

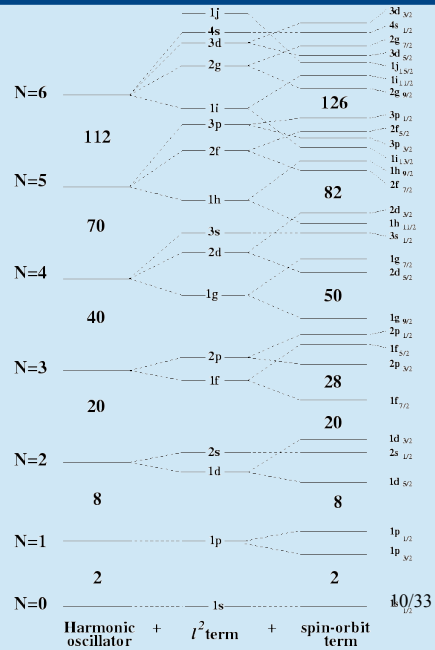
Modelo de Camadas

- Interação spin-órbita

$$H_{so} = k \mathbf{l} \cdot \mathbf{s}$$



- Números mágicos OK!

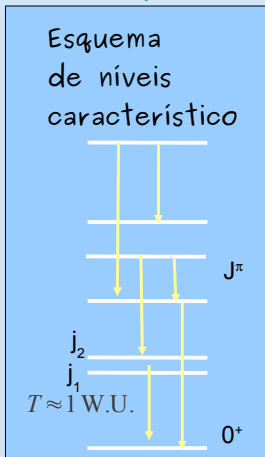


Modelo de camadas realístico

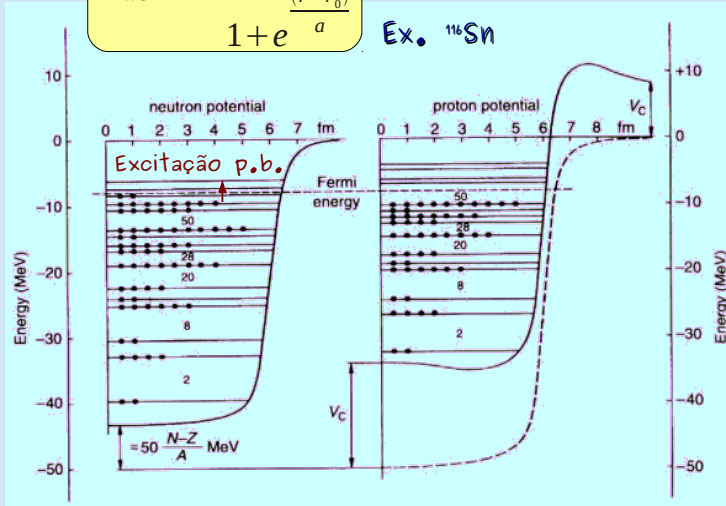
- Potenciais de Woods-Saxon, para n, e p + $V(\text{Coul.})$

$$V_{\text{WS}}(r) = \frac{V_0}{1 + e^{\frac{r-r_0}{a}}}$$

Ex. ^{116}Sn

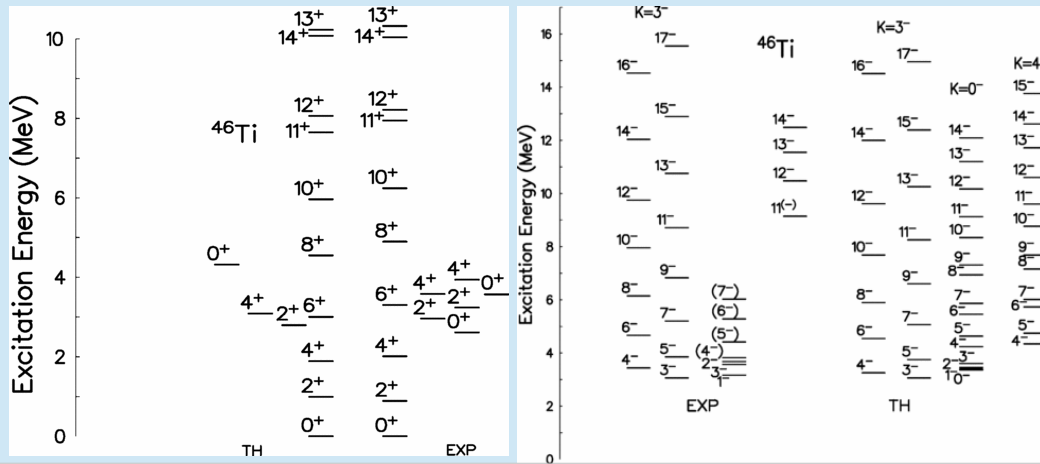


$$E = \sum E_i(p.b.)$$



Modelo de camadas de larga escala (LSSM)

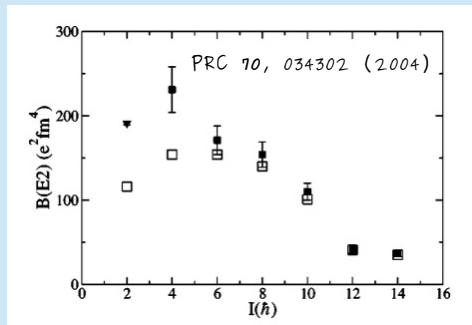
- M.C. com interação residual realística entre as partículas de valência (exs.: KB3, SDPF...)
- Ex. ^{46}Ti : Carroço: ^{40}Ca ($N=Z=20$) PhysRevC70 034302



LSSM probabilidades de transição

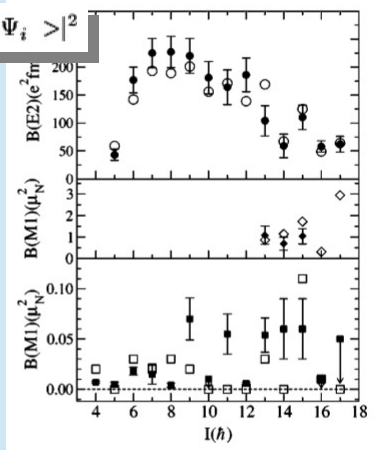
- Prob. de transição reduzida no ^{46}Ti

- $B\left(\frac{M}{E}\lambda; I_i \rightarrow I_f\right) = (2I_i + 1)^{-1} |\langle \Psi_f || M\left(\frac{M}{E}\lambda\right) || \Psi_i \rangle|^2$



Banda do estado fundamental

□◇ - cálculos de LSSM



Banda de paridade negativa ($K^* = 3^-$)

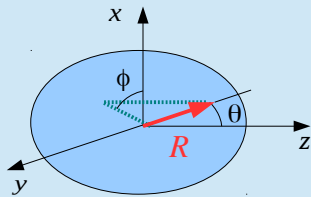
Modelos coletivos

● Parâmetros para descrição da forma nuclear

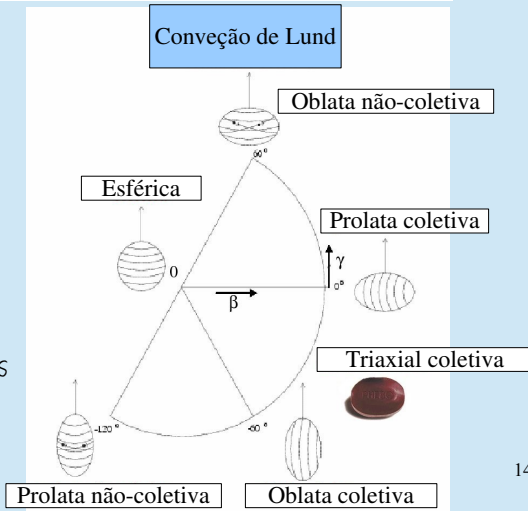
Hill-Wheeler

β, γ

$$R(\theta, \phi) = R_0 \left\{ 1 + \beta \sqrt{\frac{5}{16\pi}} \left(\cos \gamma (3 \cos^2 \theta - 1) + \sqrt{3} \sin \gamma \sin^2 \theta \cos 2\phi \right) \right\}$$

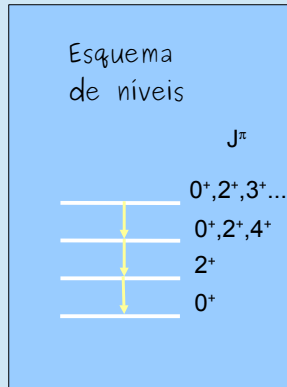


Deformações quadrupolares



Modelo Vibracional

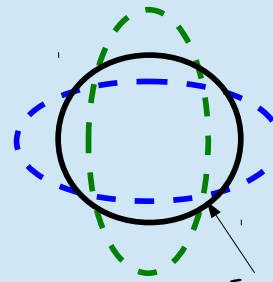
- Vibrações da superfície nuclear



$$E^*(n) = n \hbar \omega$$

Vibração harmônica quadrupolar $\beta = \beta(t)$

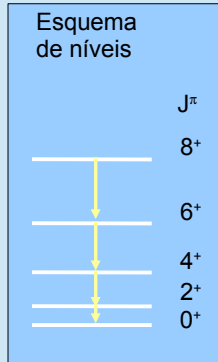
$T \propto n \gg 1$ W.U.



Forma esférica de equilíbrio

Modelo rotacional

- Rotação de núcleo quadrupolar por eixo perpendicular ao de simetria (coletiva)

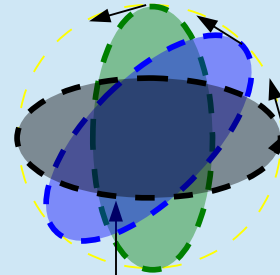
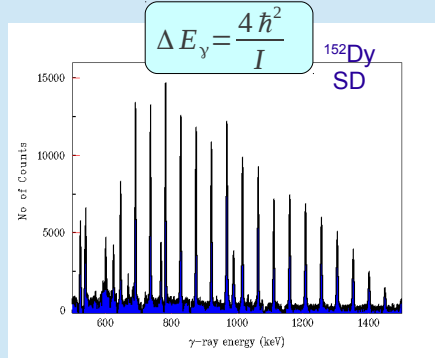


$T = T(J) \gg 1 \text{ W.U.}$

$$E_{\text{rot}} = \frac{\hbar^2 J(J+1)}{2I}$$

$$E_{\text{rot}} = \frac{1}{2} I \omega^2 \quad L = I \omega \quad E_{\text{rot}} = \frac{L^2}{2I}$$

$$E_{\text{rot}} = \frac{\hbar^2 J(J+1)}{2I} \quad E_\gamma = \Delta E_{\text{rot}} (\Delta J = 2)$$

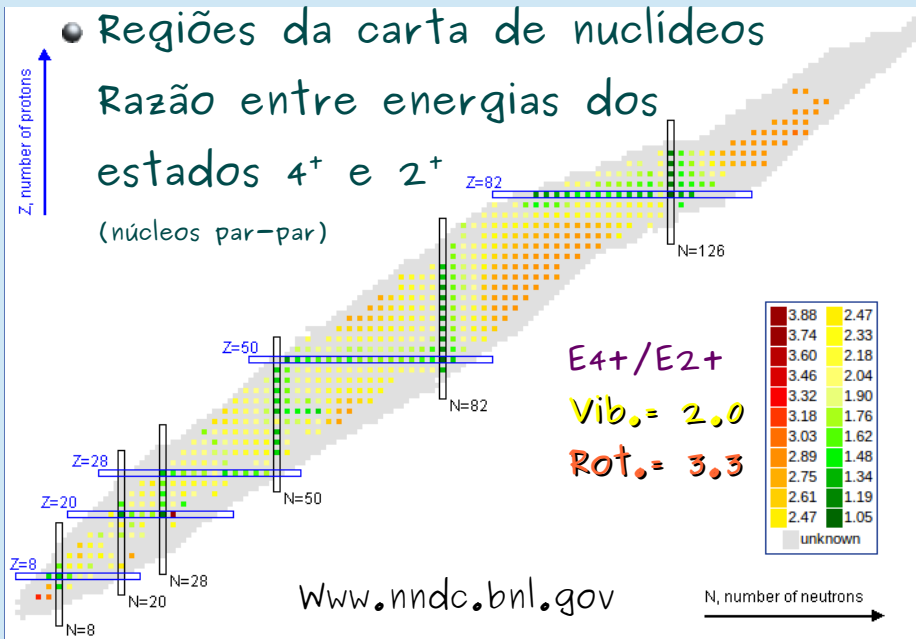


Deformação β permanente

$$\hbar \omega = \frac{E_\gamma}{2} \quad 16/33$$

Rotacional ou vibracional?

- Regiões da carta de nuclídeos
Razão entre energias dos
estados 4^+ e 2^+
(núcleos par-par)



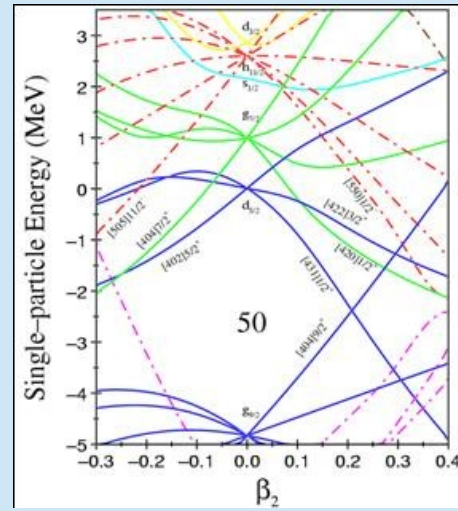
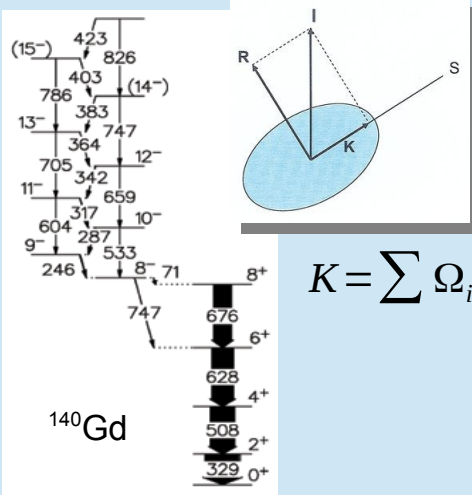
www.nndc.bnl.gov

N, number of neutrons

17/33

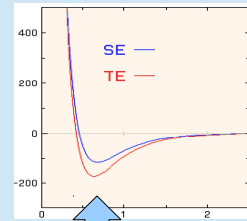
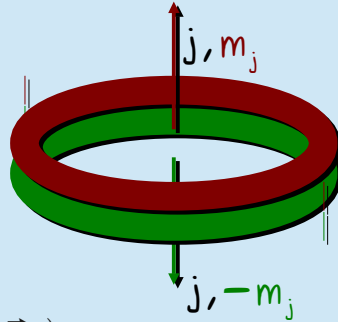
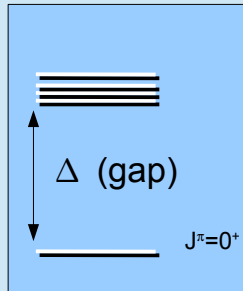
Modelo de Nilsson

- Estados de partícula única em um potencial deformado



Emparelhamento

- Tendência ao acoplamento de órbitas com reversão temporal $\rightarrow J=0$



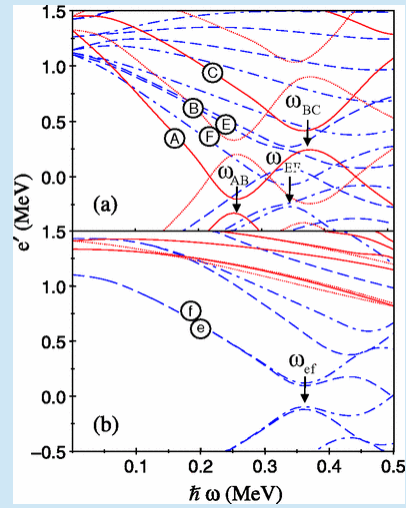
$$V(\vec{r}-\vec{r}') \approx \delta(\vec{r}-\vec{r}')$$

Correlações de emparelhamento (além do campo médio).
O núcleo é análogo a um supercondutor.

Modelo de "Cranking" (CSM)

- Mod. Nilsson + interação de Coriolis
- Routhiano $e' = e - \omega J_x$

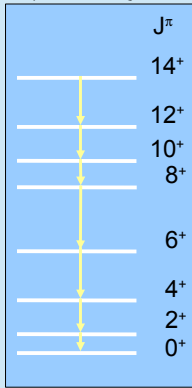
Energia no referencial
intrínseco (não inercial)
com velocidade angular
de rotação constante



Altos spins – “Backbending”

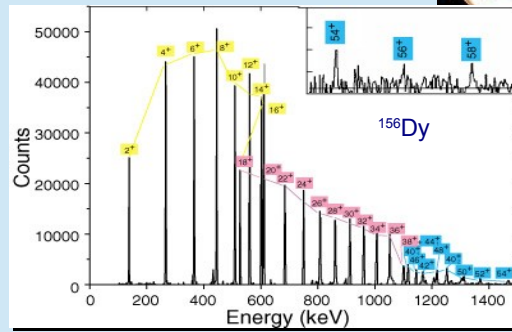
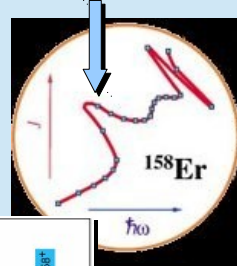
- Quebra de par induzida por Coriolis

Esquema de níveis



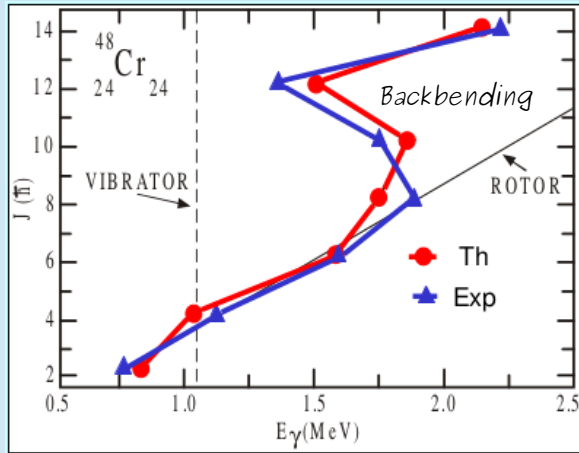
$$H_{\text{Coriolis}} = -\hbar \omega j_x$$

$$\hbar \omega = \frac{E_y}{2}$$



LSSM x Collective rotation

- Comportamento rotacional construído no MC com interações residuais



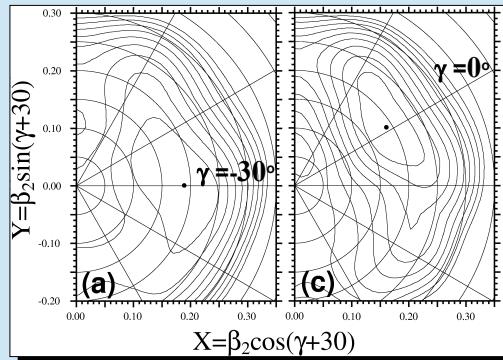
48Ni	49Ni	50Ni	51Ni	52Ni	53Ni	54Ni	55Ni	56Ni
47Co	48Co	49Co	50Co	51Co	52Co	53Co	54Co	55Co
46Fe	47Fe	48Fe	49Fe	50Fe	51Fe	52Fe	53Fe	54Fe
45Mn	46Mn	47Mn	48Mn	49Mn	50Mn	51Mn	52Mn	53Mn
44Cr	45Cr	46Cr	47Cr	48Cr	49Cr	50Cr	51Cr	52Cr
43V	44V	45V	46V	47V	48V	49V	50V	51V
42Ti	43Ti	44Ti	45Ti	46Ti	47Ti	48Ti	49Ti	50Ti
41Sc	42Sc	43Sc	44Sc	45Sc	46Sc	47Sc	48Sc	49Sc
40Ca	41Ca	42Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca
20	22	24	26	28				

$1f_{7/2}$

22/33

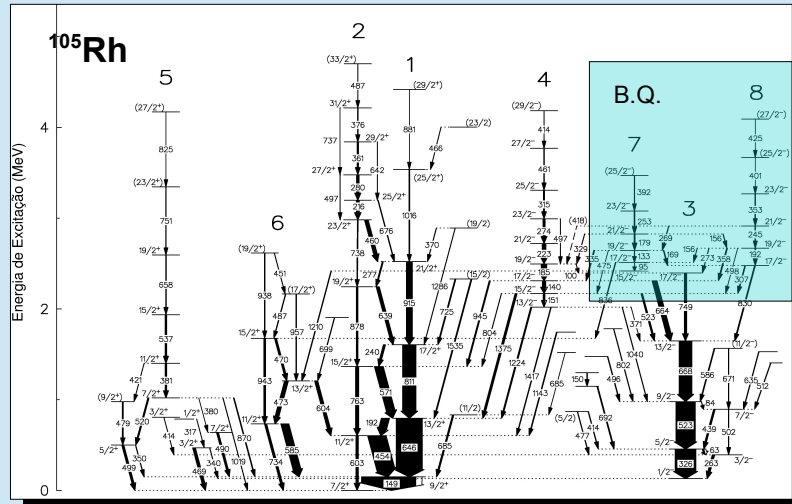
Modelo de Strutinsky

- Gota líquida + correções de camada
- TRS Total Routhian Surfaces



Exemplo de estudo no IF

- J.A.Alcántara-Núñez, Tese de Doutorado, IFUSP, 2003



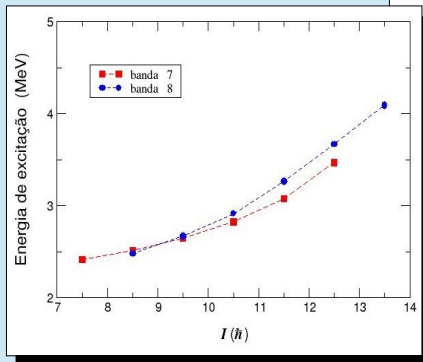
Espectrômetro Saci Perere - Acelerador Pelletron

Quebra de simetria quiral

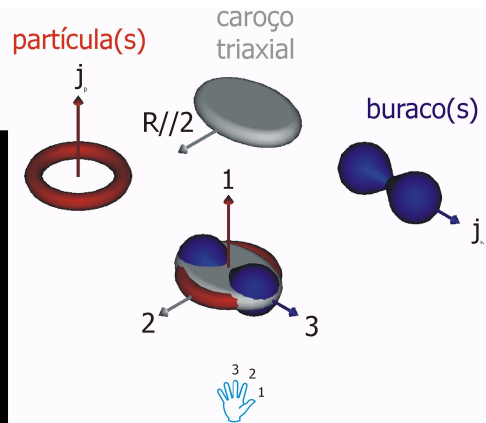
TAC

^{105}Rh

bandas quase degeneradas

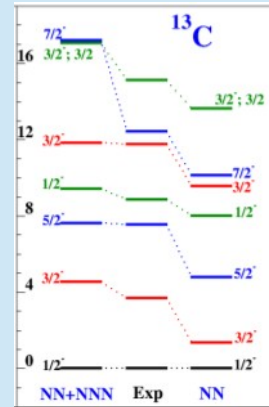


Quiralidade no sistema intrinseco



Ab Initio – NCSM

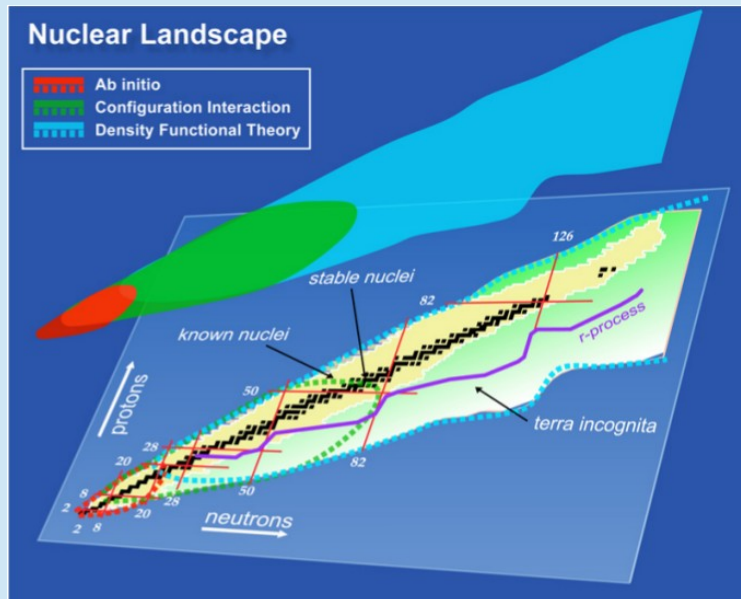
- NCSM – No Core Shell Model
- Teorias de campo efetivo (χEFT)
- Uso de parâmetros da interação NN, NNN ajustados a dados de sistemas de poucos corpos



J.P. Vary
ntse-2014

(Nuclear Theory in the
Supercomputing Era), Russia ^{26/33}

Cálculos teóricos de precisão



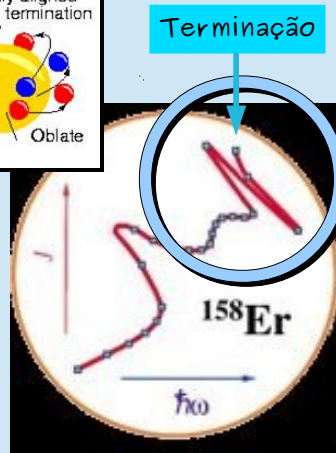
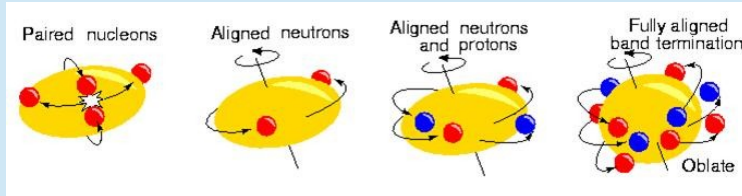
Próxima aula: Ferramentas de pesquisa

- Aceleradores de partículas
- Detectores de partículas
- Espectrômetros gama

Extras

Terminação de banda

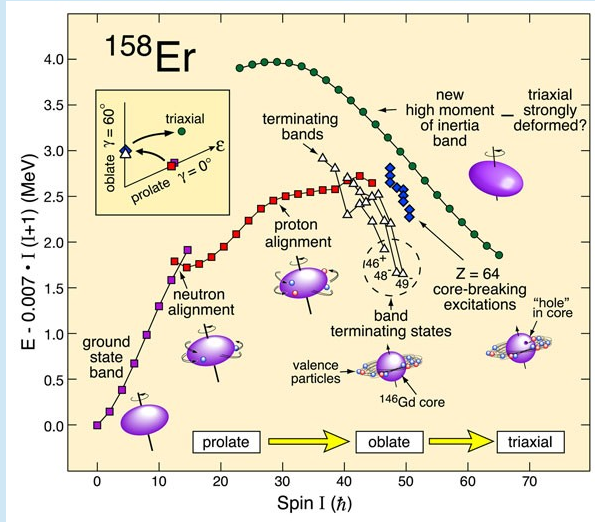
- Alinhamento de todas as partículas de valência



Coletividade além da terminação

- Destaque PRL 2007

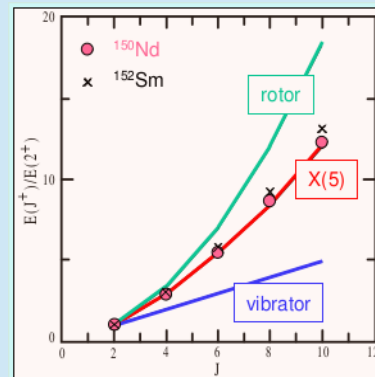
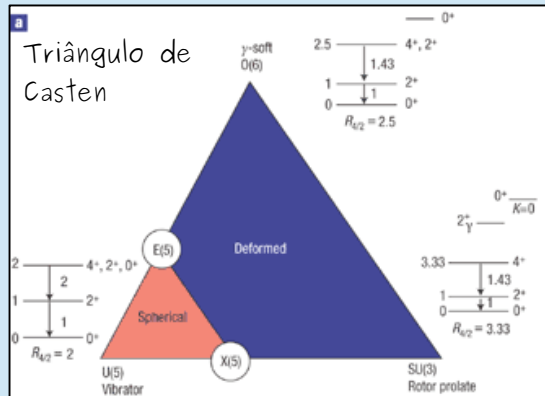
E.S. Paul et al.,
Phys. Rev. Lett.
98, 012501 (2007)



Simetria e transições de fase

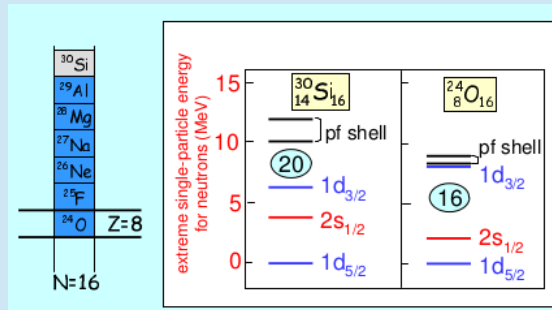
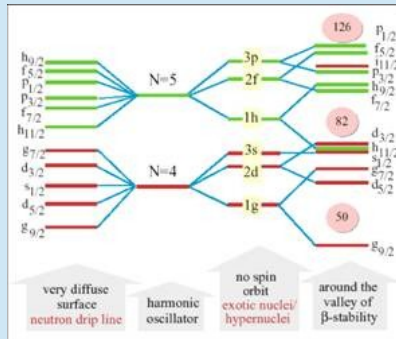
- IBM: s, d – bósons
Simetrias dinâmicas

- Ex. X(5) ponto crítico da transição de fase rotor-vibrador



Novos números mágicos?

- Modificação das camadas longe do vale de estabilidade



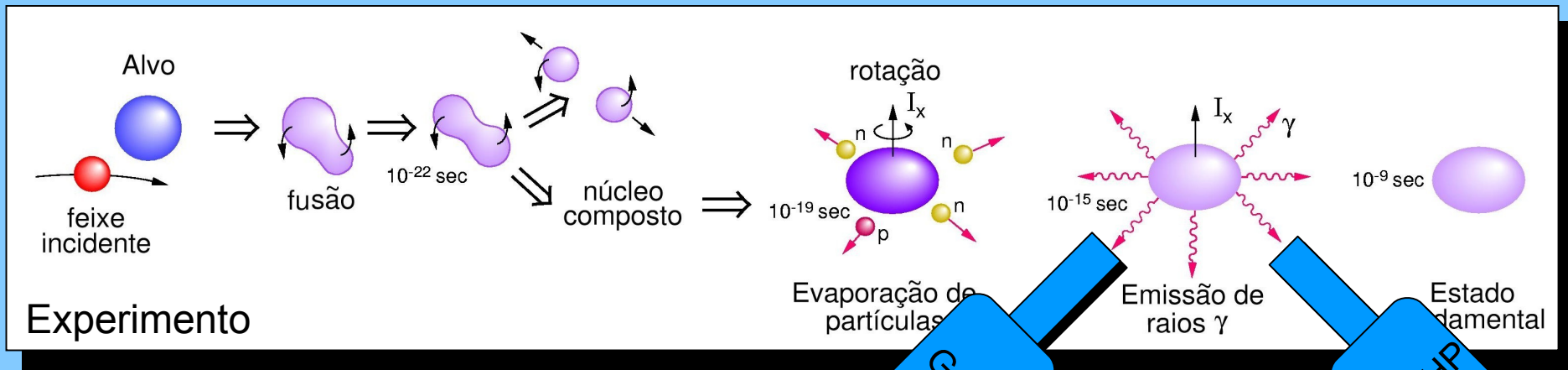
Nupec LRP 2004

Ferramentas de pesquisa

- Breve re-introdução
- Reações nucleares
- Aceleradores de Partículas
- Detectores de Radiação
- O Supressor Compton
- Eletrônica e aquisição de dados
- Sistema ancilar (Saci)
- Espectrômetros gama

Investigação da estrutura nuclear

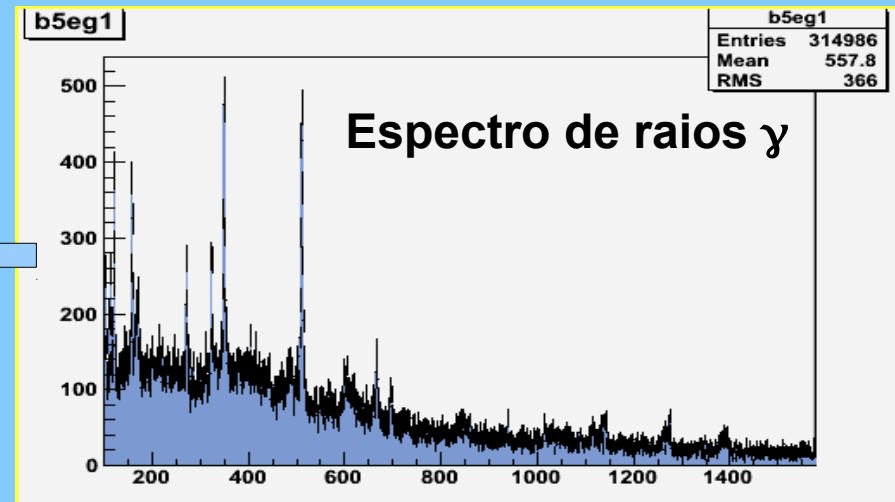
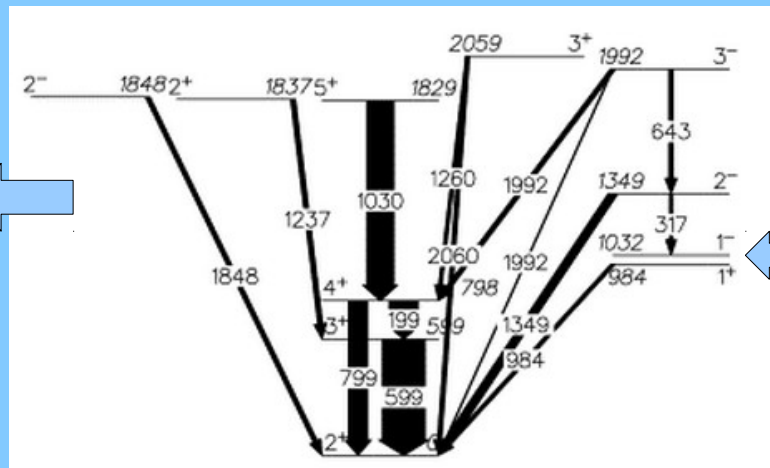
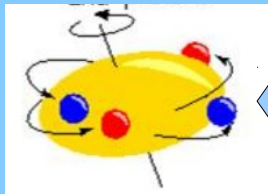
- Espectroscopia gama. Ex. reação de fusão-evaporação



Esquema de níveis

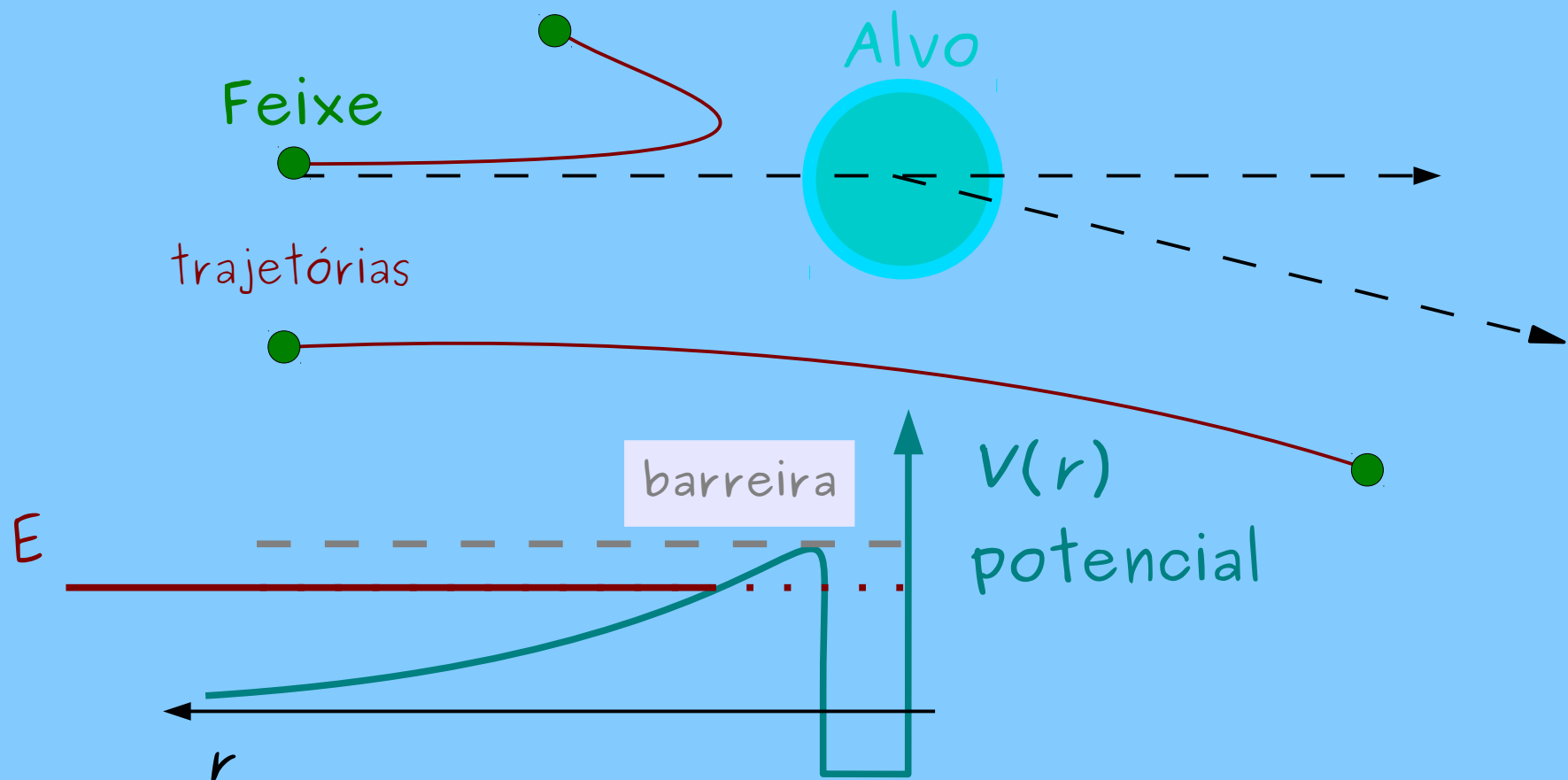
Detectores de alta resolução

Modelo



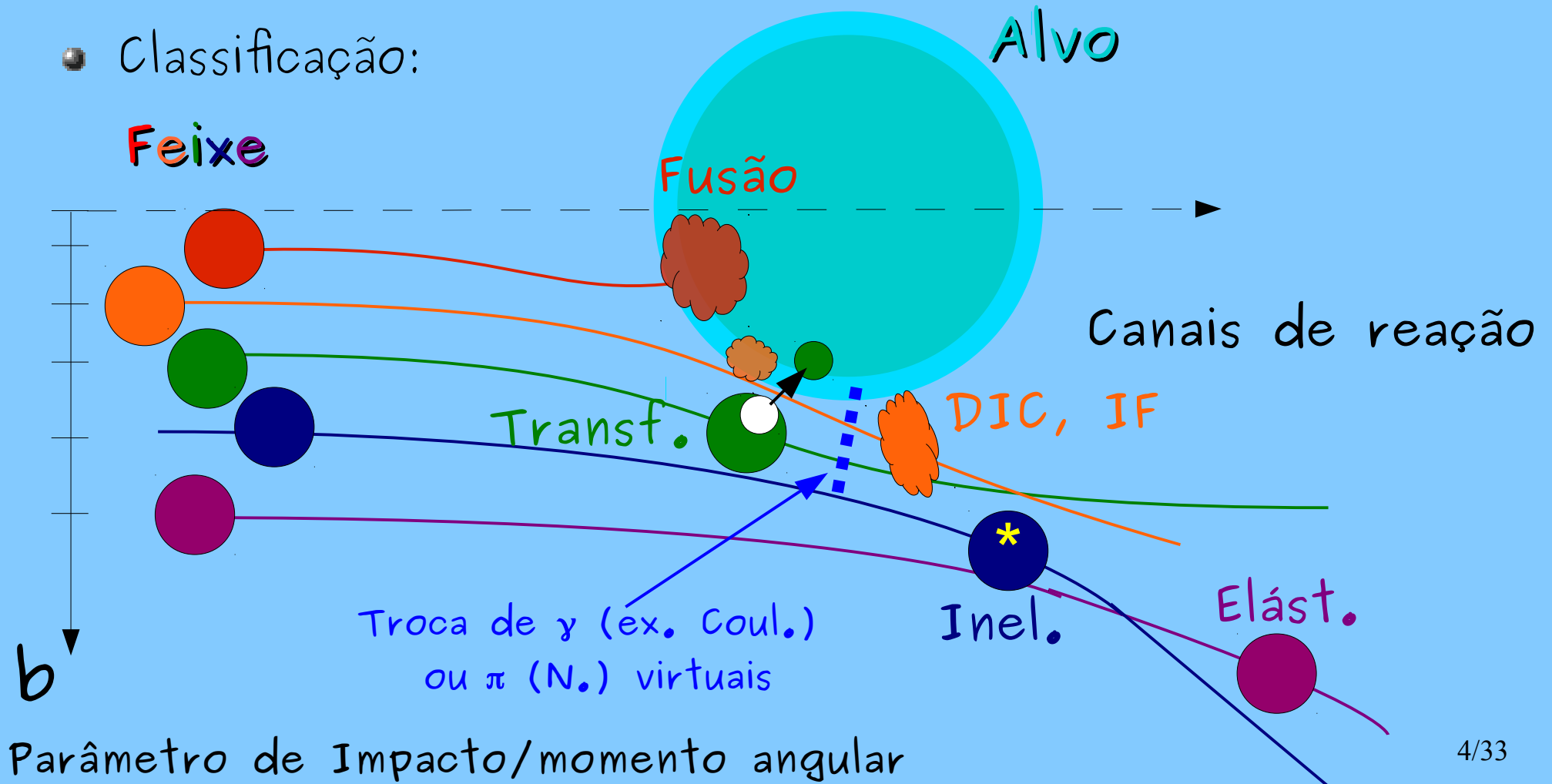
Colisões iônicas de baixa energia

- Bem abaixo da energia da barreira Coulombiana → somente espalhamento elástico (tipo Rutherford)
- Não há reação - não produz raios- γ



Reações Nucleares

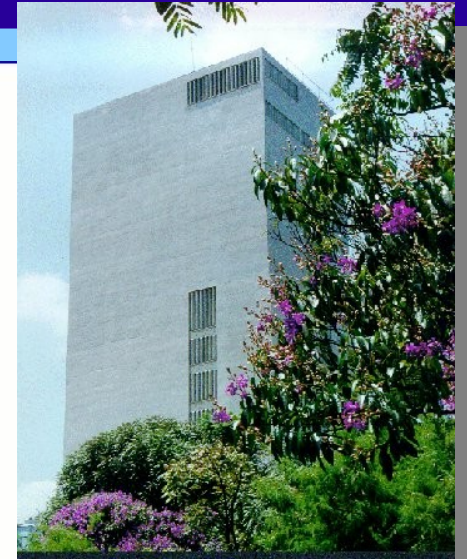
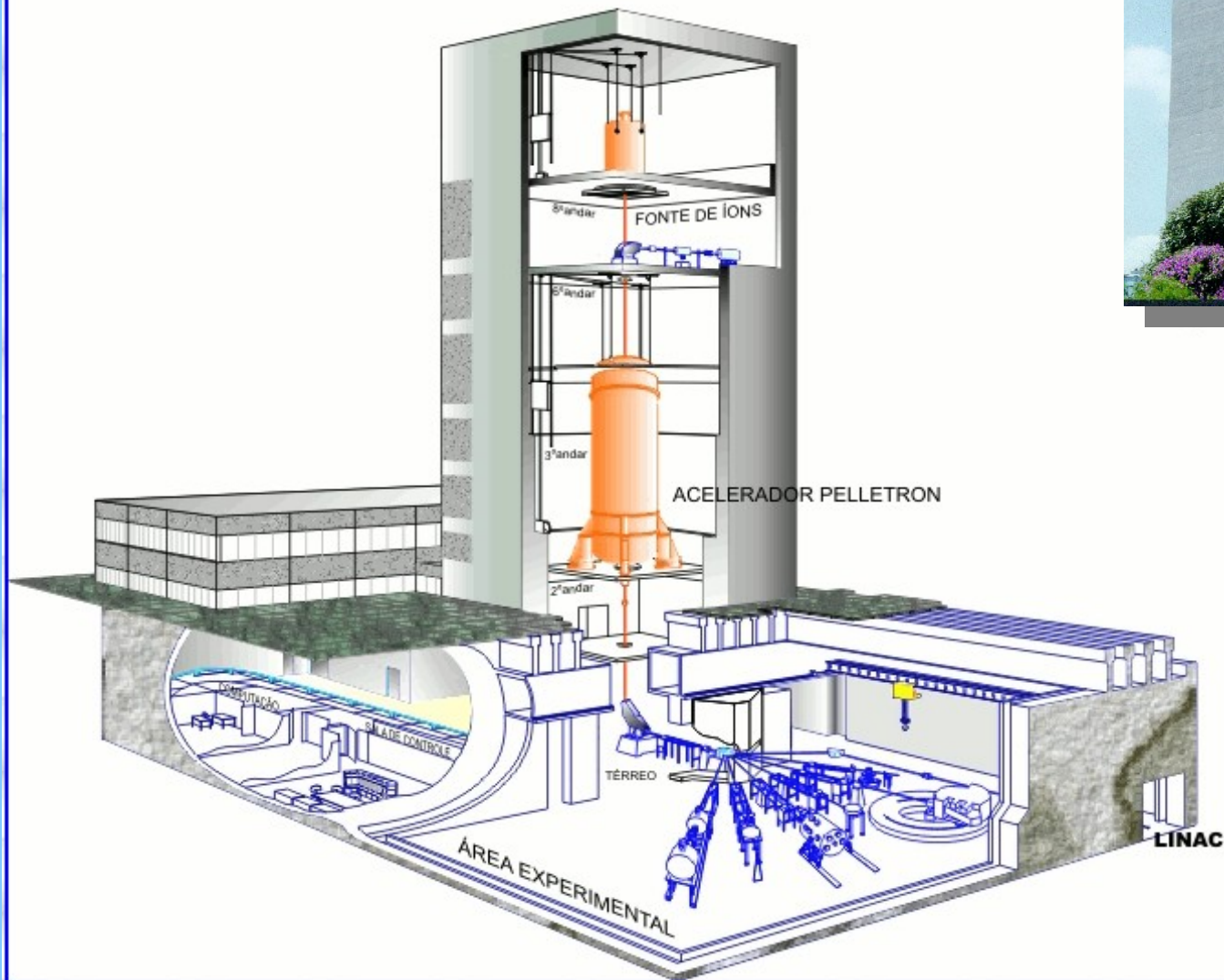
- Para energias acima da barreira (ou próximas, devido ao tunelamento) há envolvimento da força nuclear
- Classificação:



Acelerador Pelletron Tandem 8UD

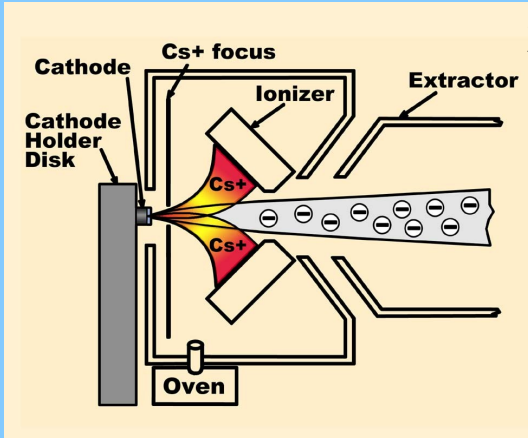
IFUSP

UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE FÍSICA
EDIFÍCIO "OSCAR SALA" - LAB. PELLETRON



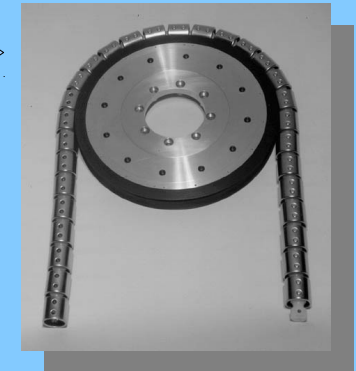
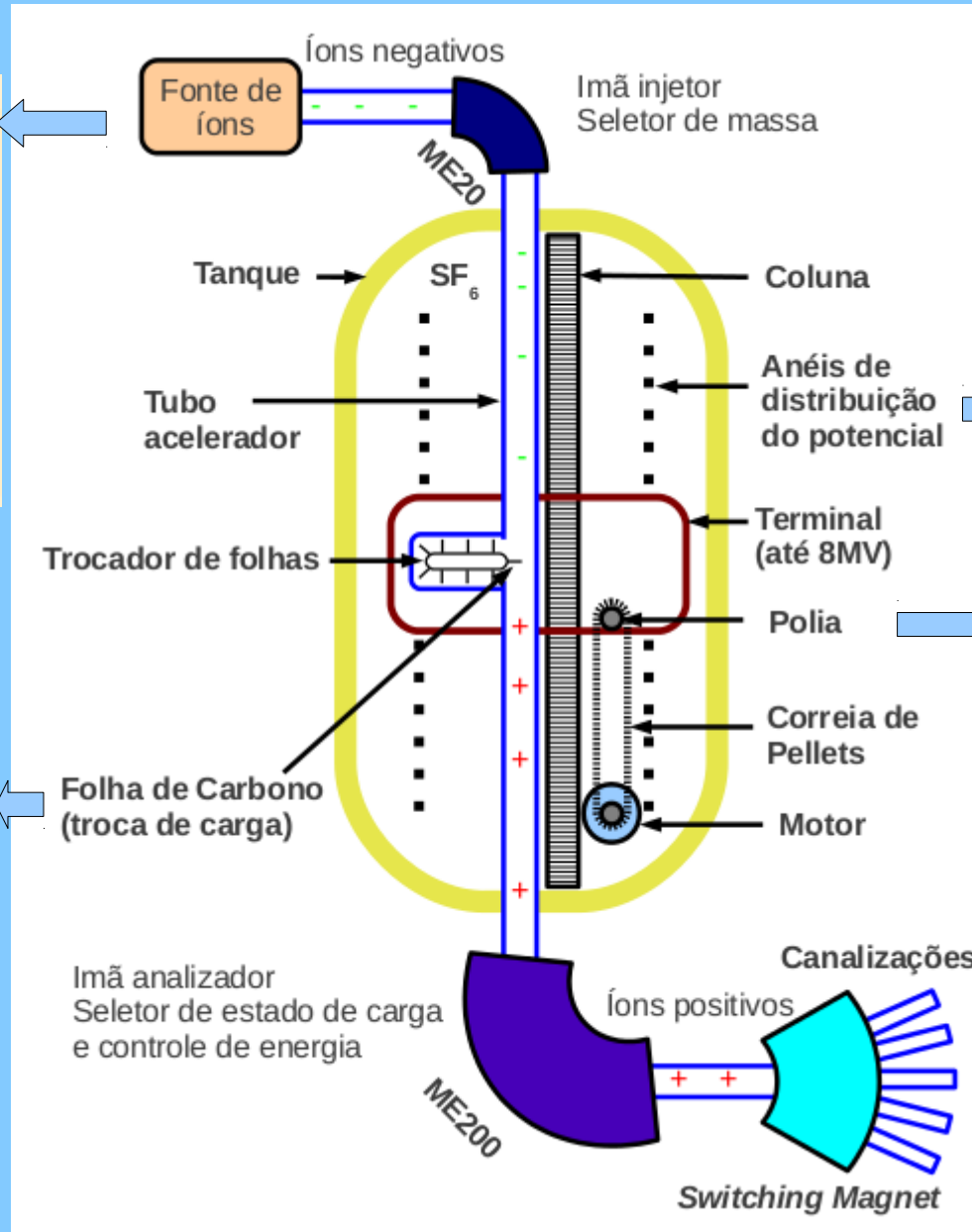
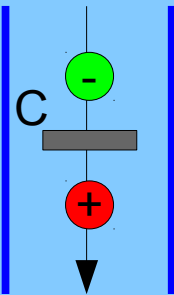
Esquema do acelerador Pelletron

Fonte SNICS

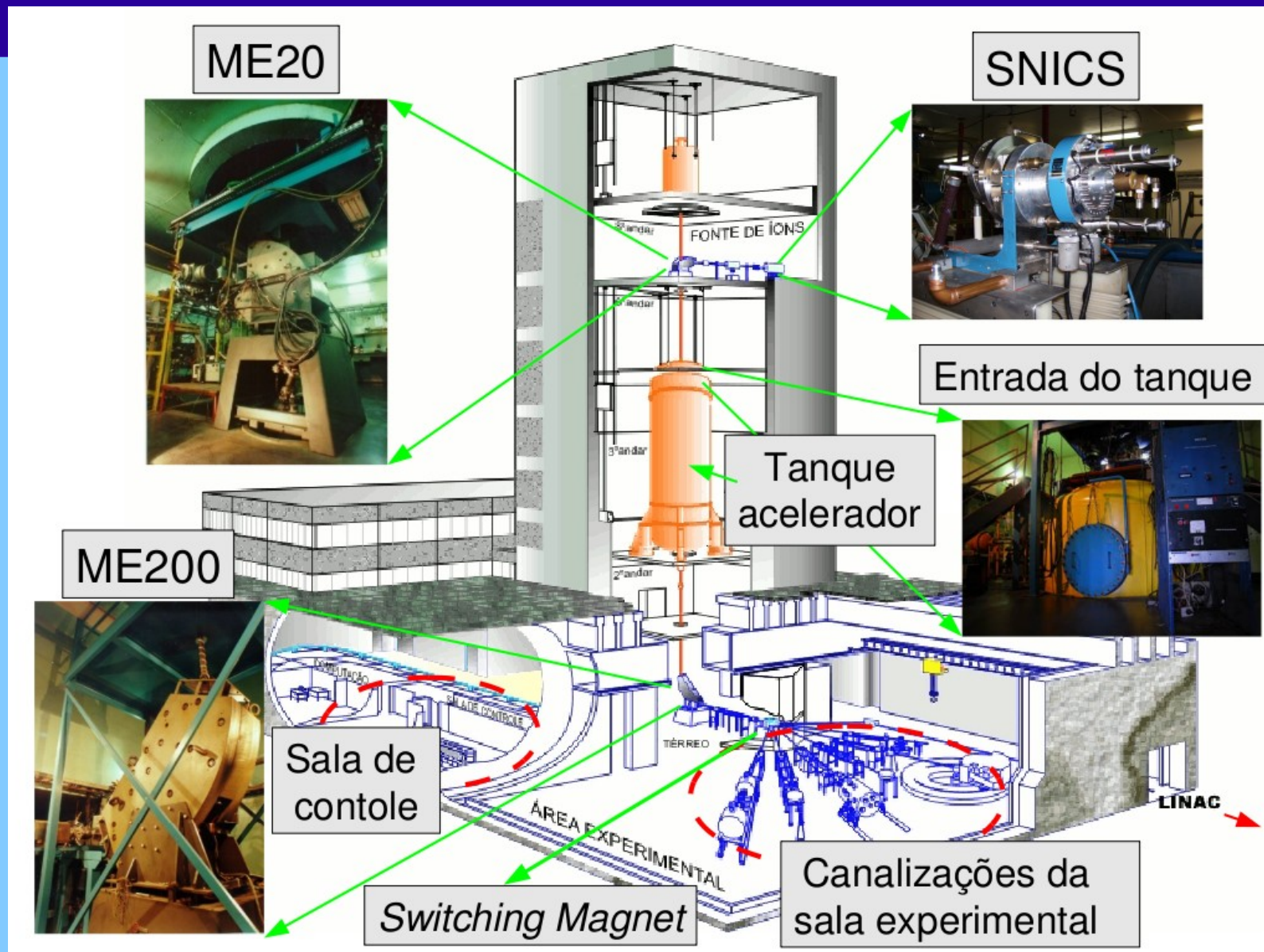


Estados de carga
-1

... +3; +4; ...+Z

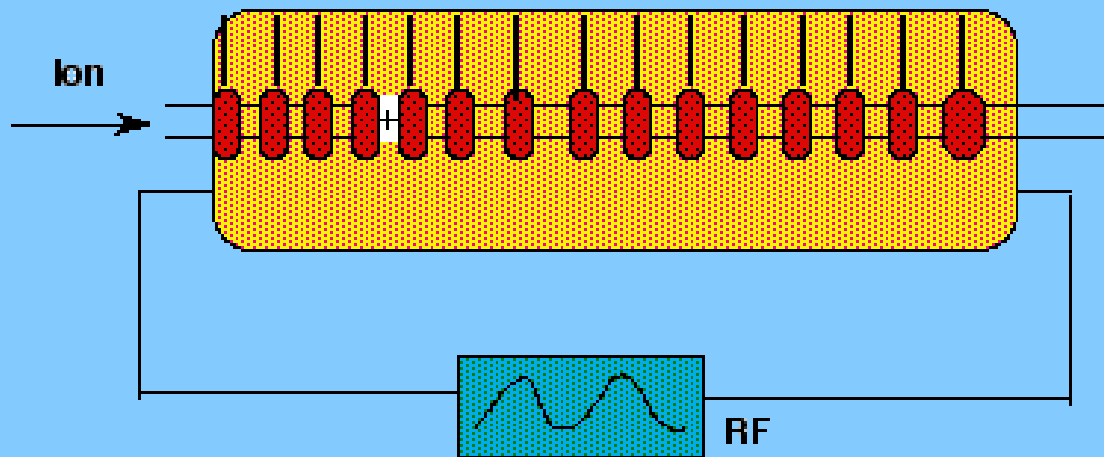


Partes do Acel. Pelletron

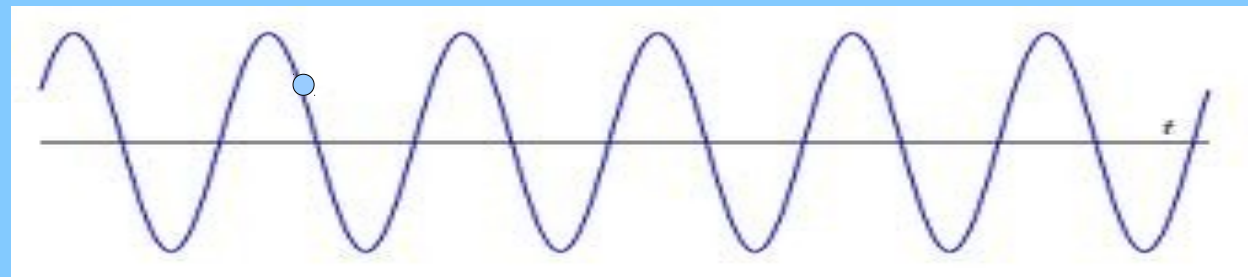


Acelerador linear

- LAFN IFUSP

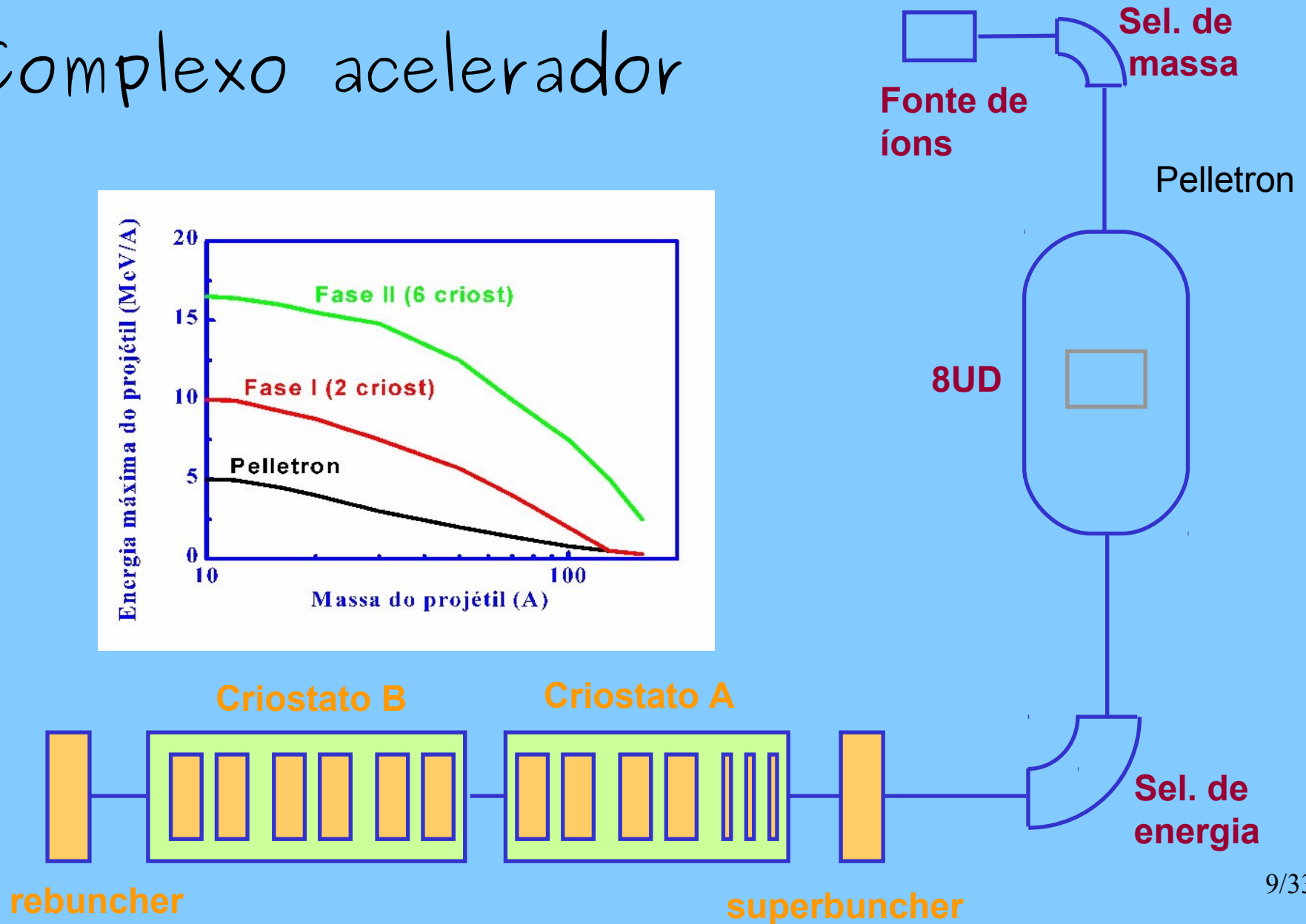
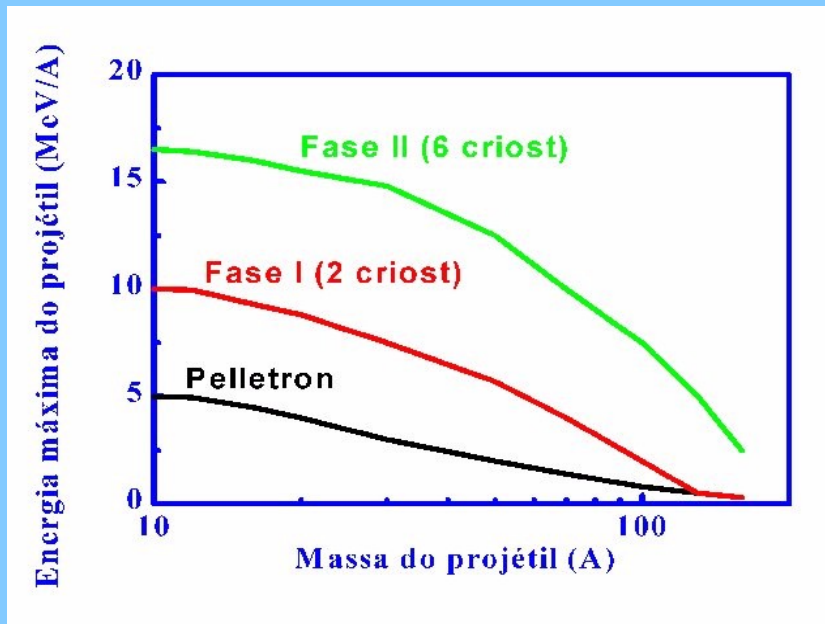


Ressoador



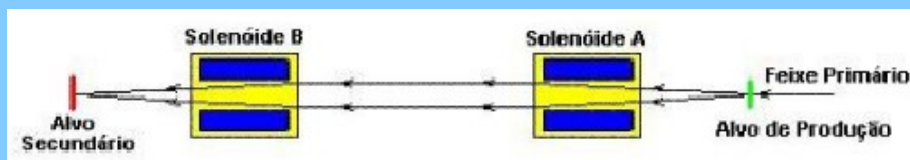
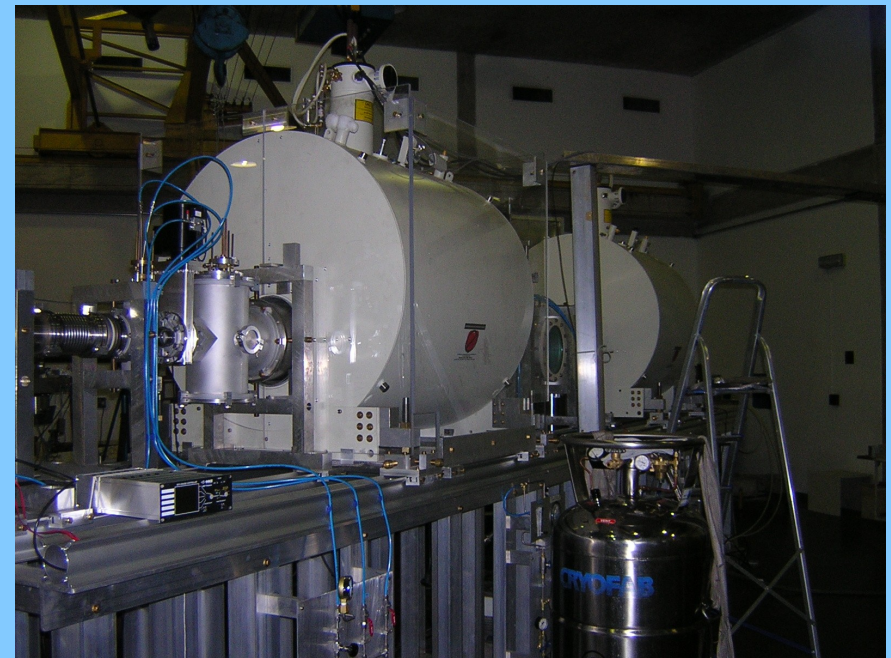
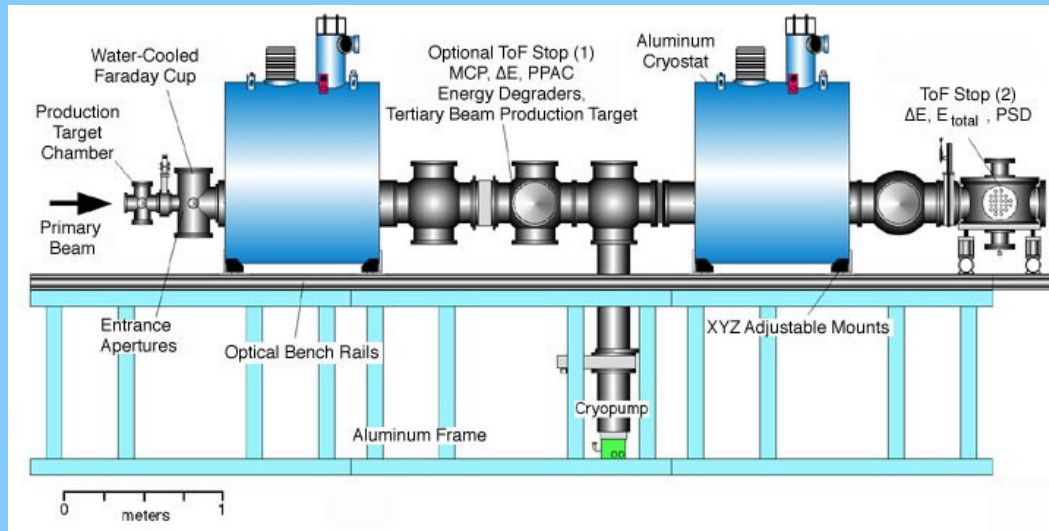
Pelletron-LINAC (LAFN-IFUSP)

- Complexo acelerador

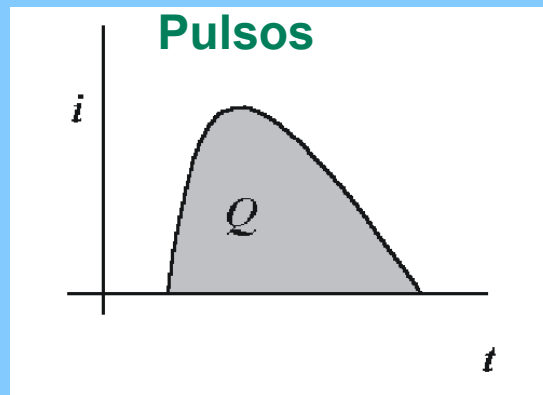
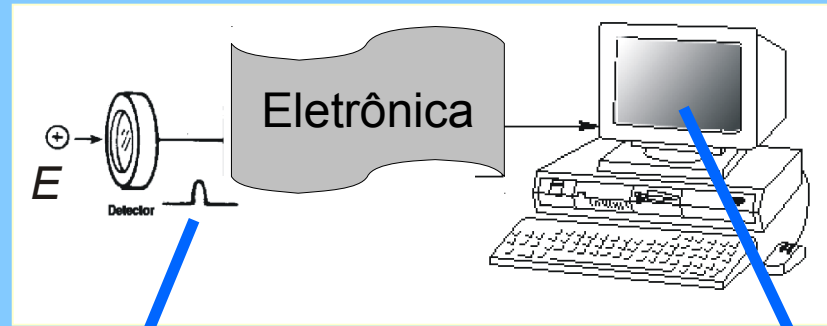


Produção de feixes radioativos

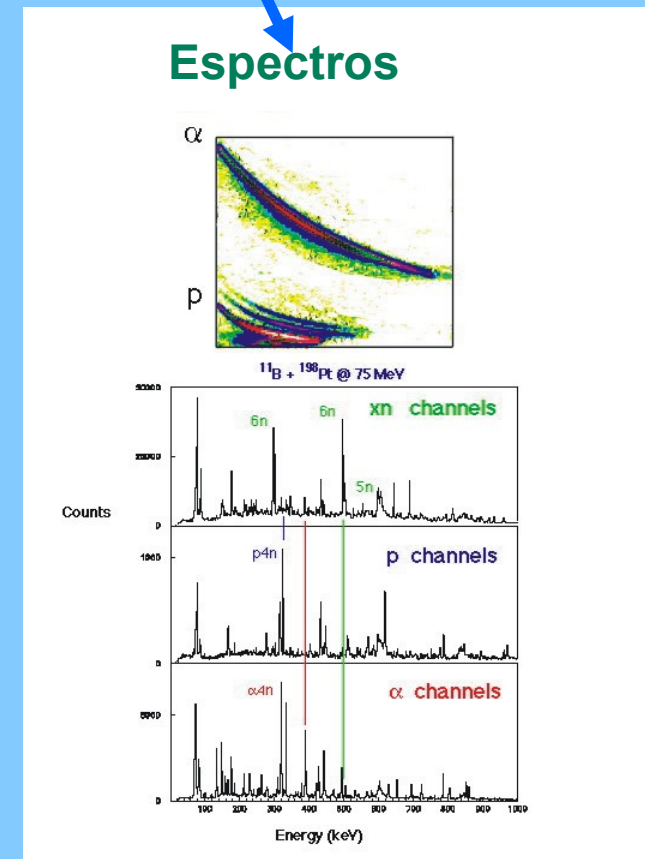
- Ribras - Pelletron (IFUSP)
- Solenóides supercondutores (6T)



Detectores e aquisição de dados

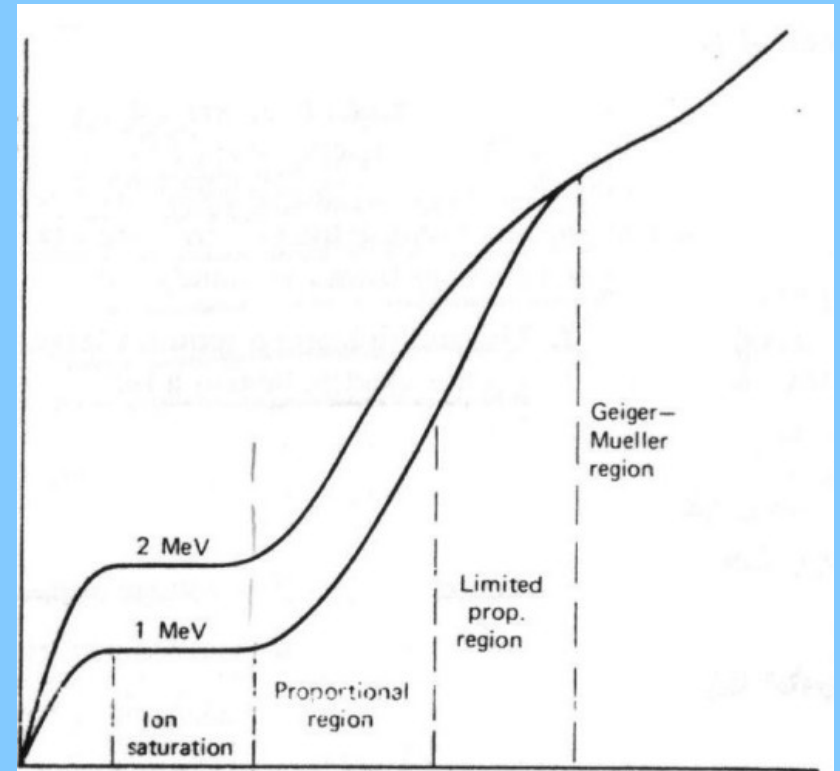
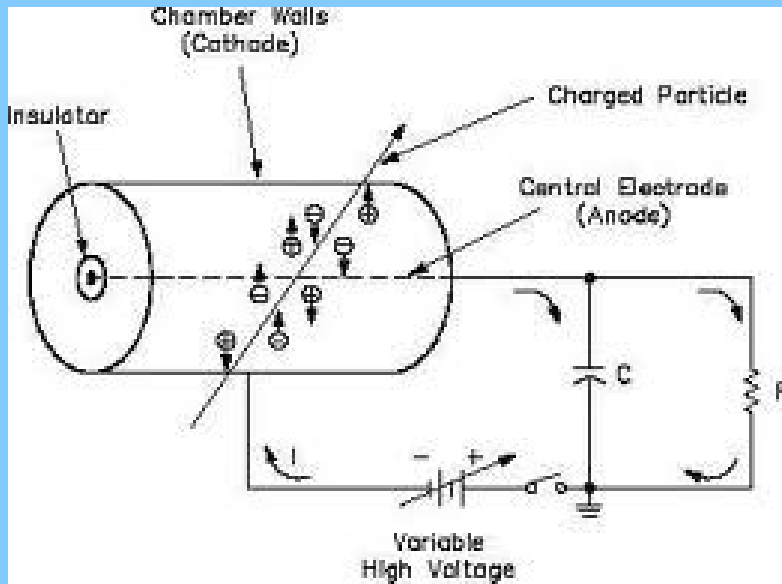


Energia (prop. Q),
Tempo de chegada
Forma: $Z, x \dots$

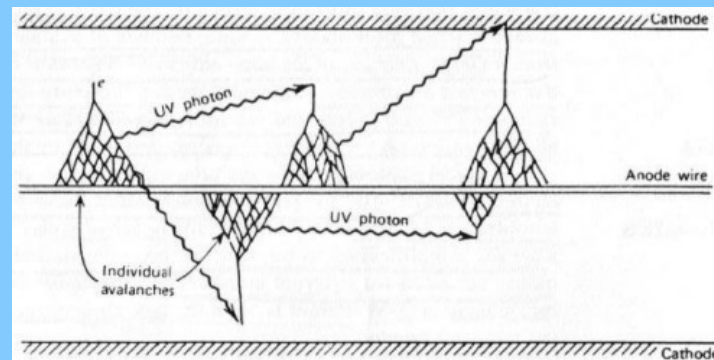


Detectores de radiação

- Detectores a gás Amplitude



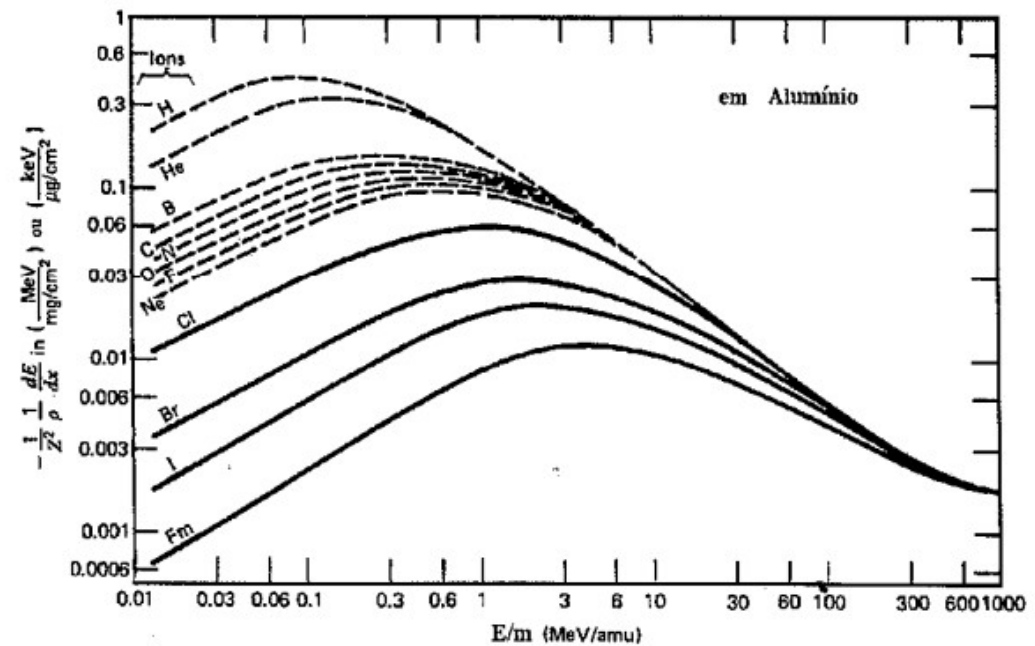
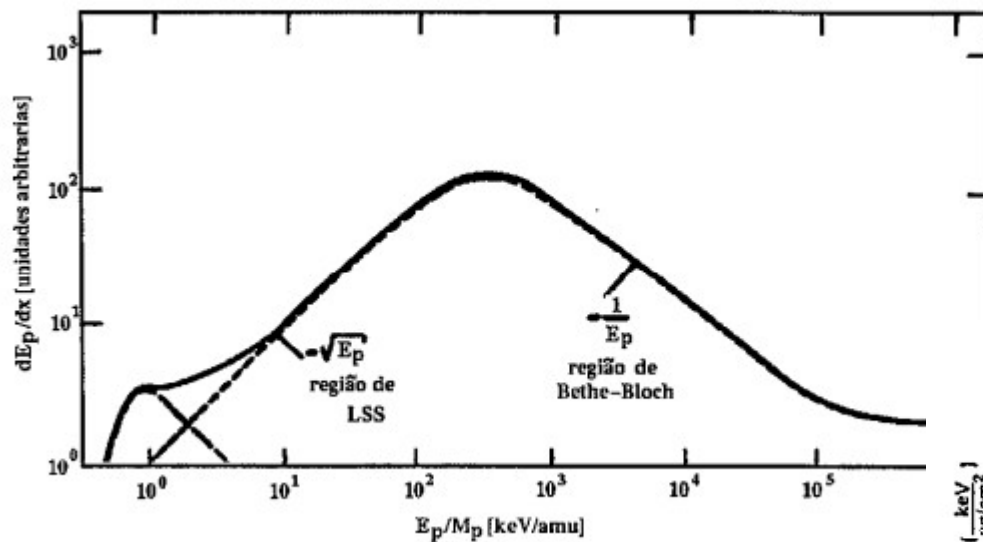
GM



Tensão

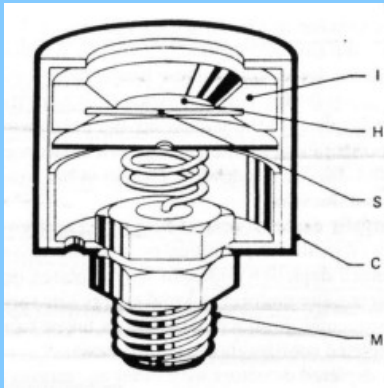
Freamento de íons em sólidos

- Curvas de perda de energia

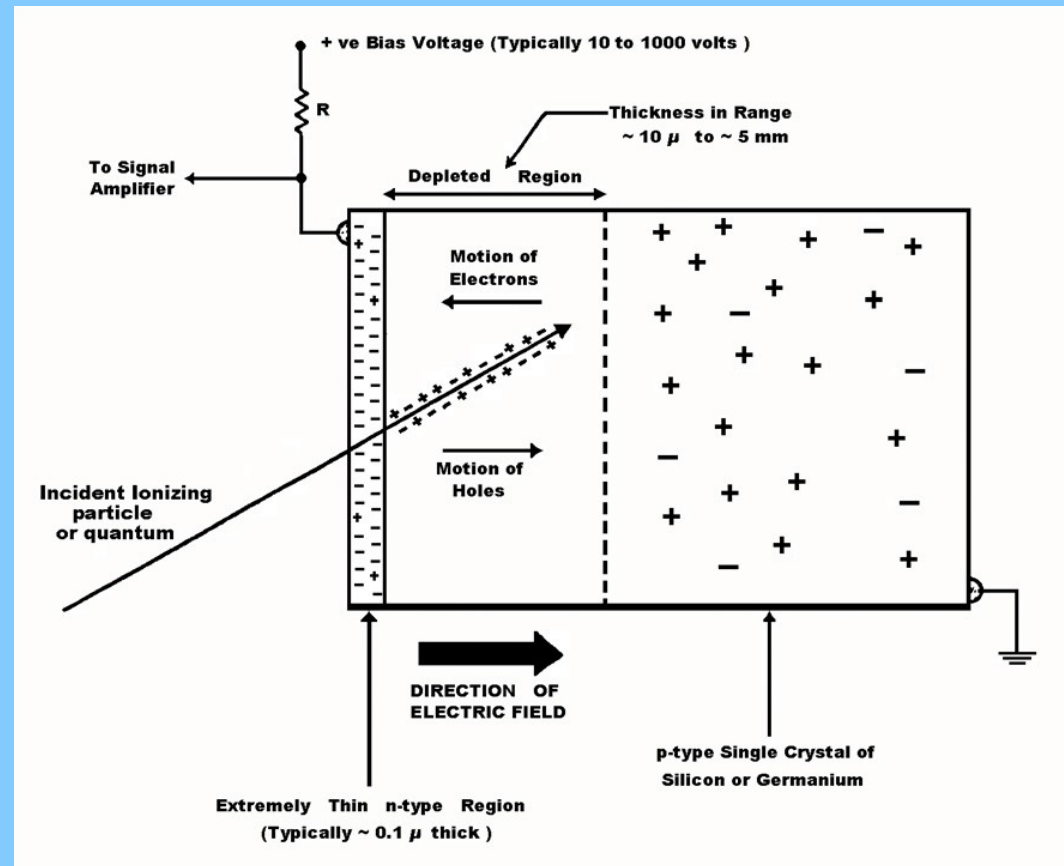
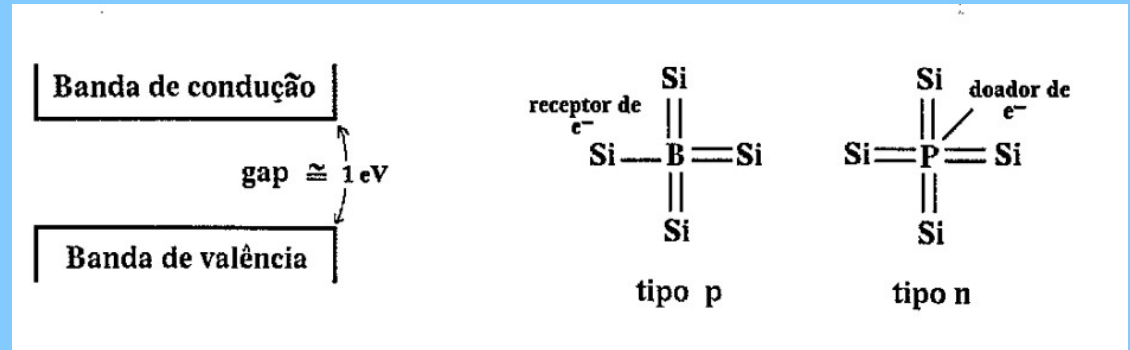


Detectores Semicondutores

- Detector de Si

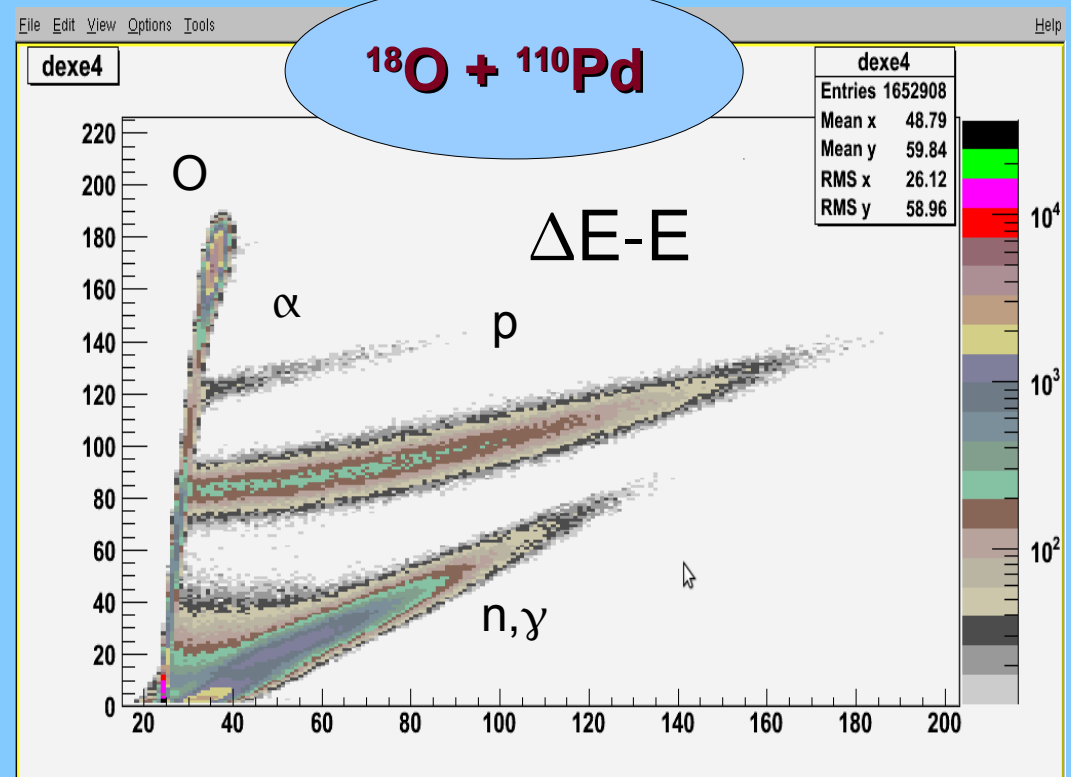
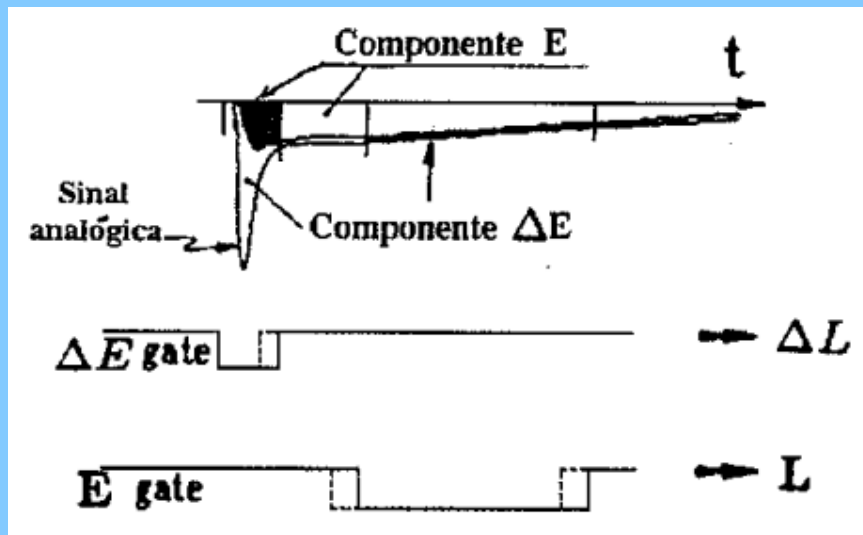
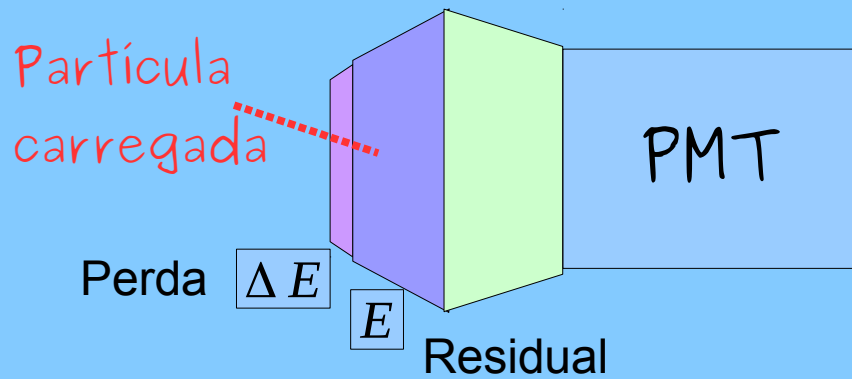


Diodo, sob polarização reversa



Cintiladores plásticos – Phoswich

- Dois tipos de plásticos cintiladores, com constantes de decaimento diferentes

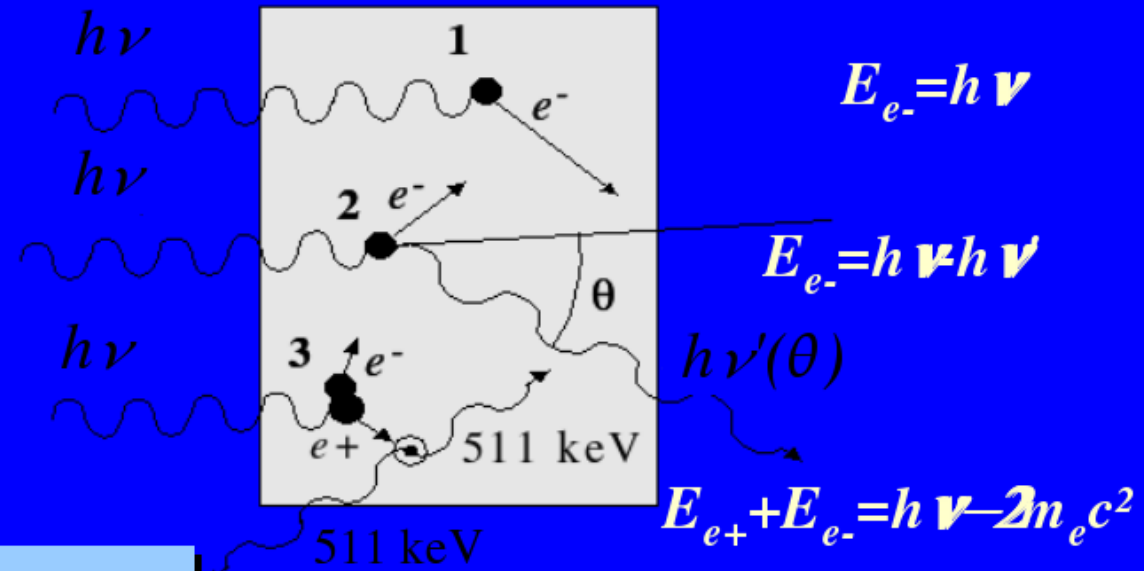


Interação da radiação γ com a matéria

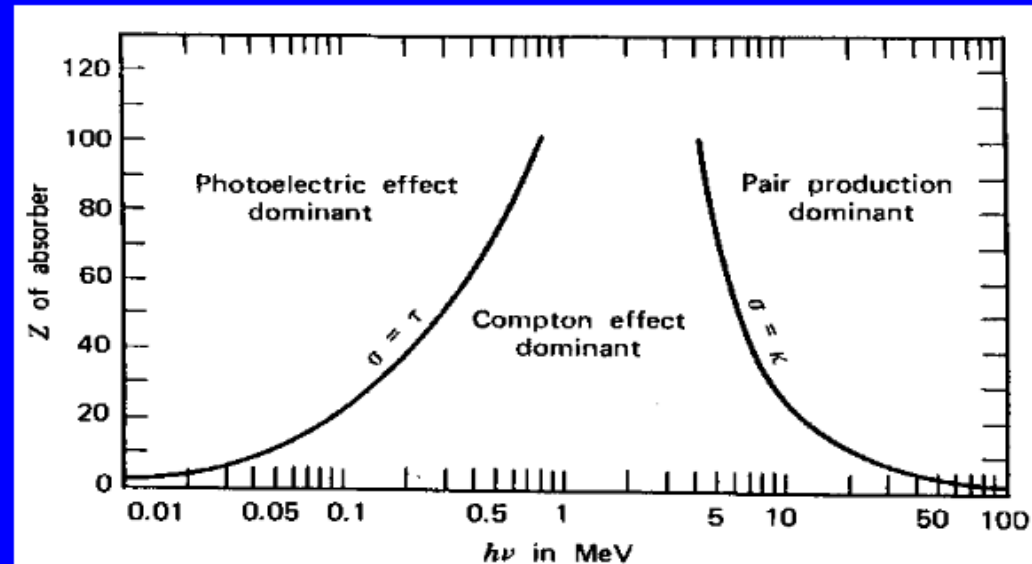
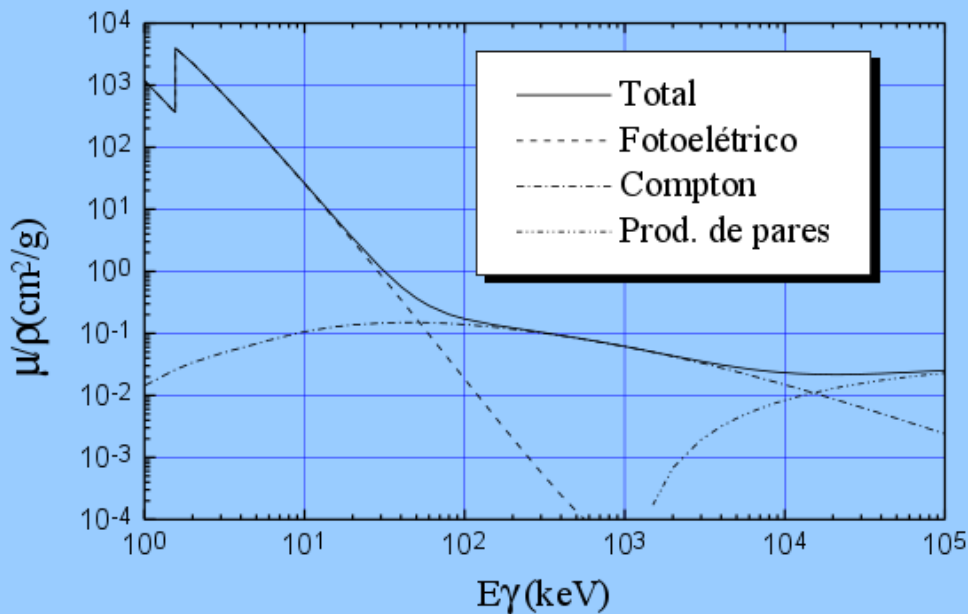
1 - Efeito fotoelétrico

2 - Efeito Compton

3 - Criação de pares

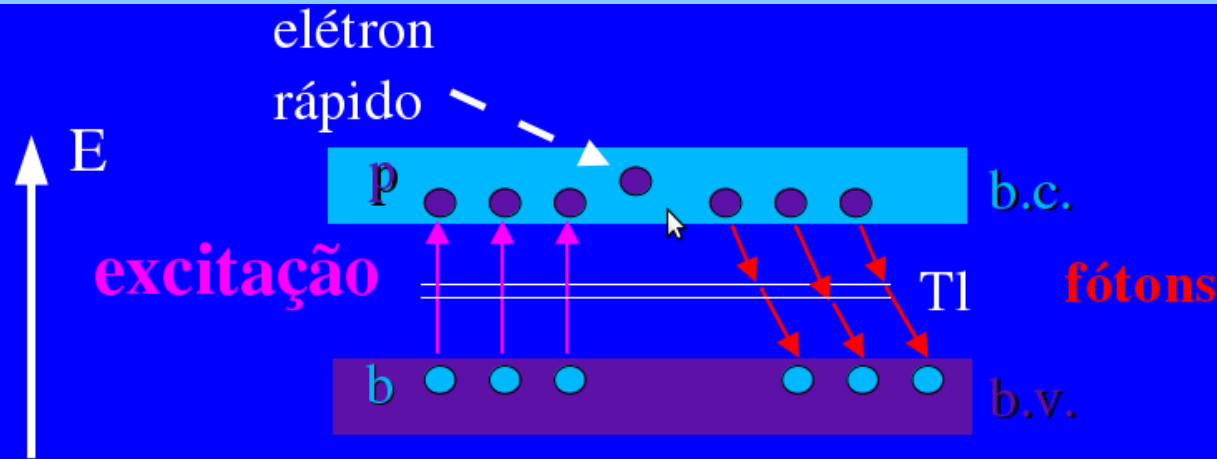


Coeficiente mássico de absorção para o Al



O cristal cintilador de NaI(Tl)

- Processo de detecção



NaI(Tl)

Iodeto de Sódio dopado com Tório

Gap: ≈ 7 eV

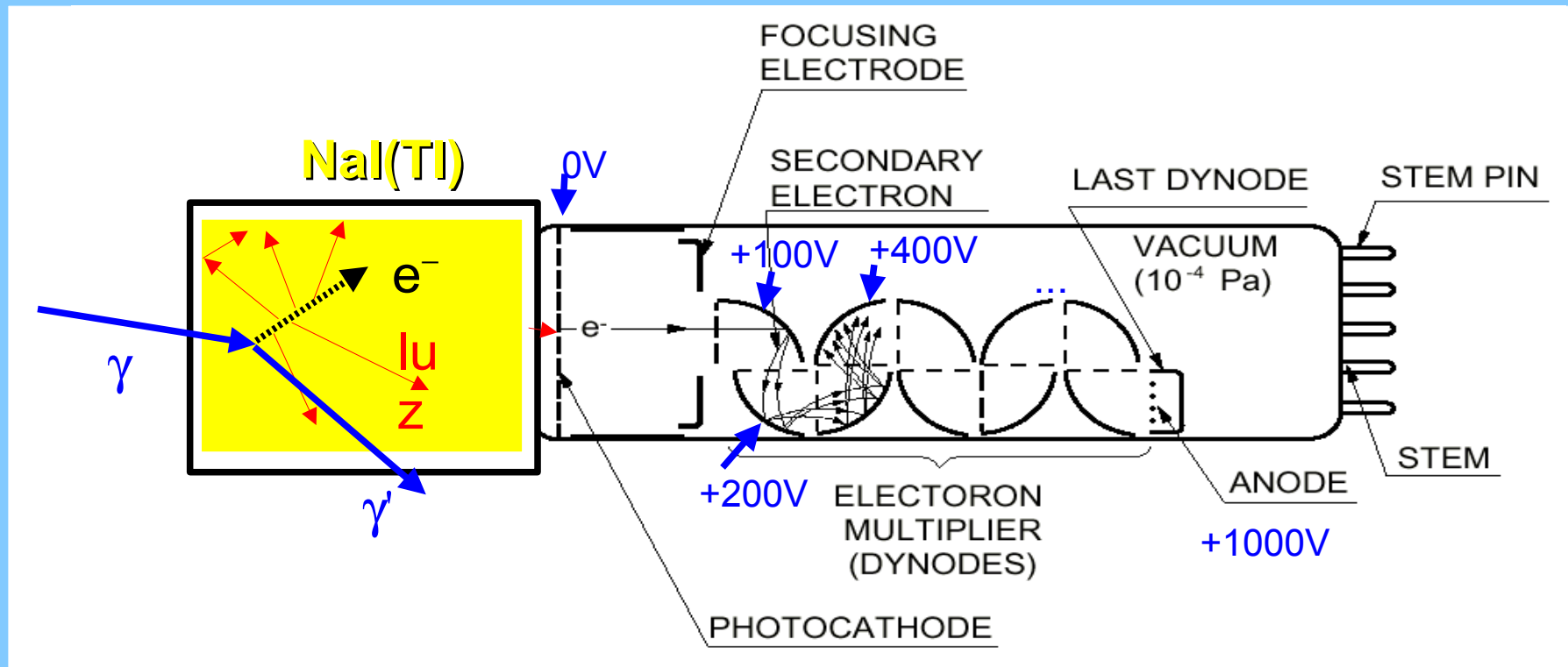
Energia média por fóton: 3 eV

Produção de luz: 38 fótons por keV (26 eV/fóton)

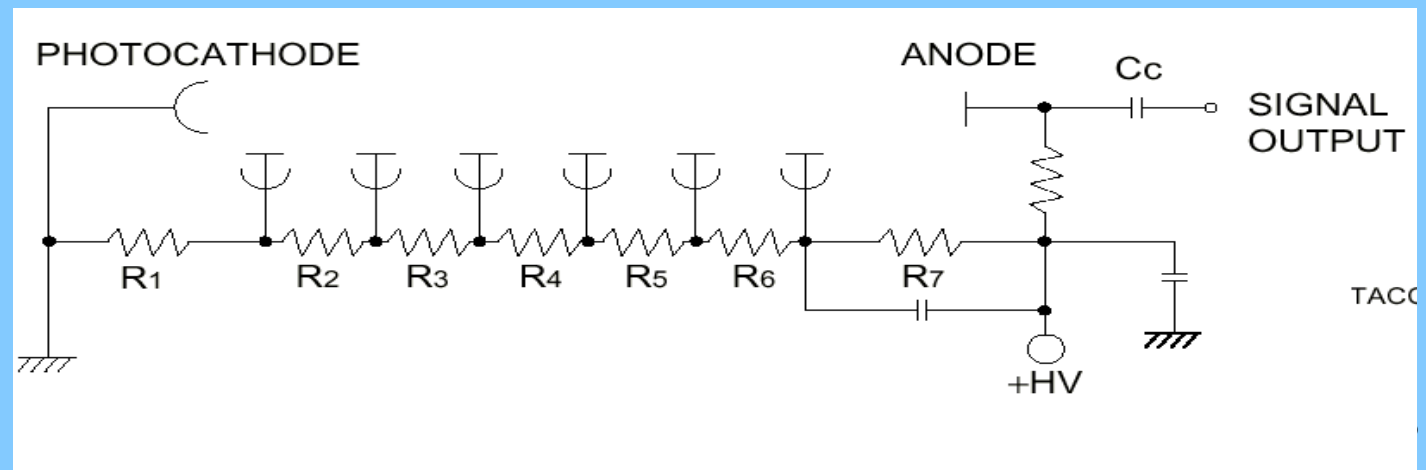
(Aprox. 1 fóton por par partícula-buraco)

Transparente para a própria cintilação

O tubo fotomultiplicador

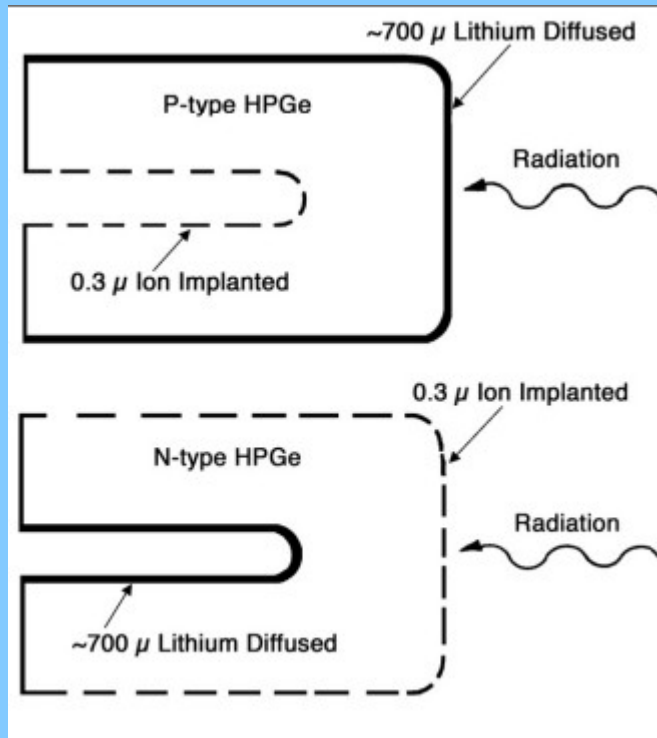


Base, para
alimentação
do tubo
fotomultiplicador:



Detector semicondutor de GeHP

- Cristais de Ge Hiperpuro



Botijão de N_2 Liq.

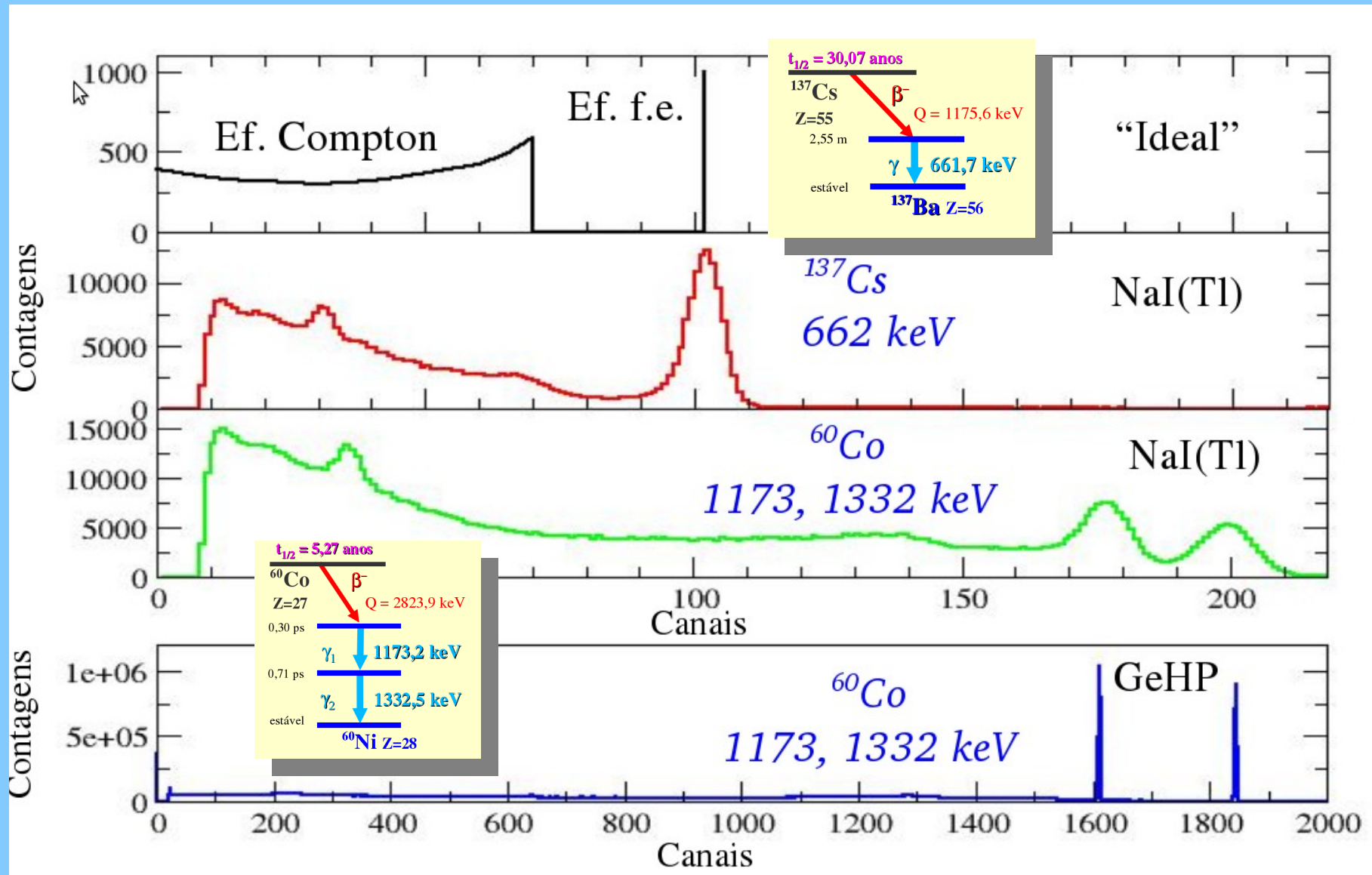
$T=77K$

Resolução em energia 2-3keV

Resolução em tempo ~ 20 ns

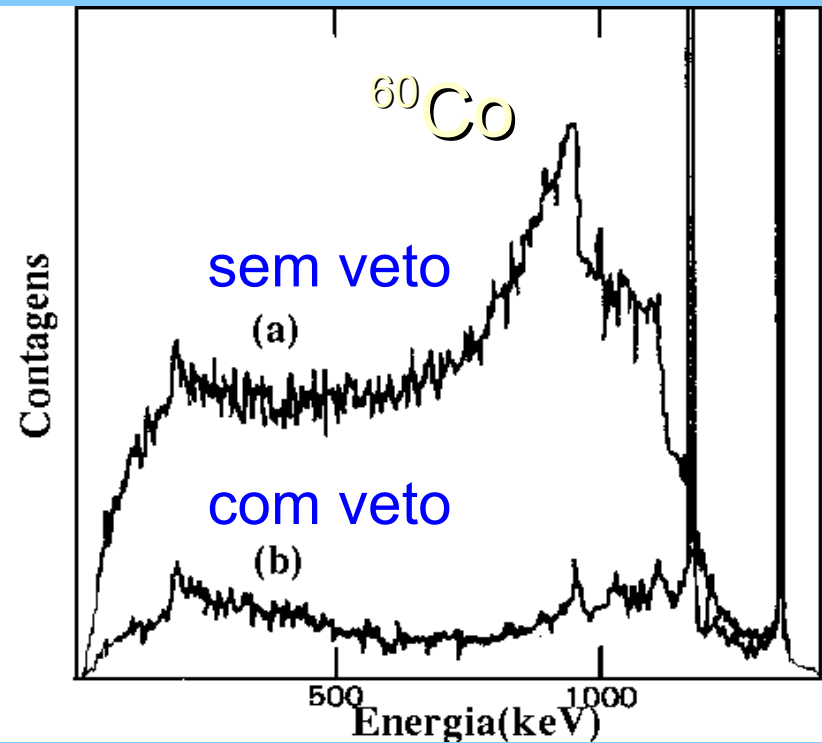
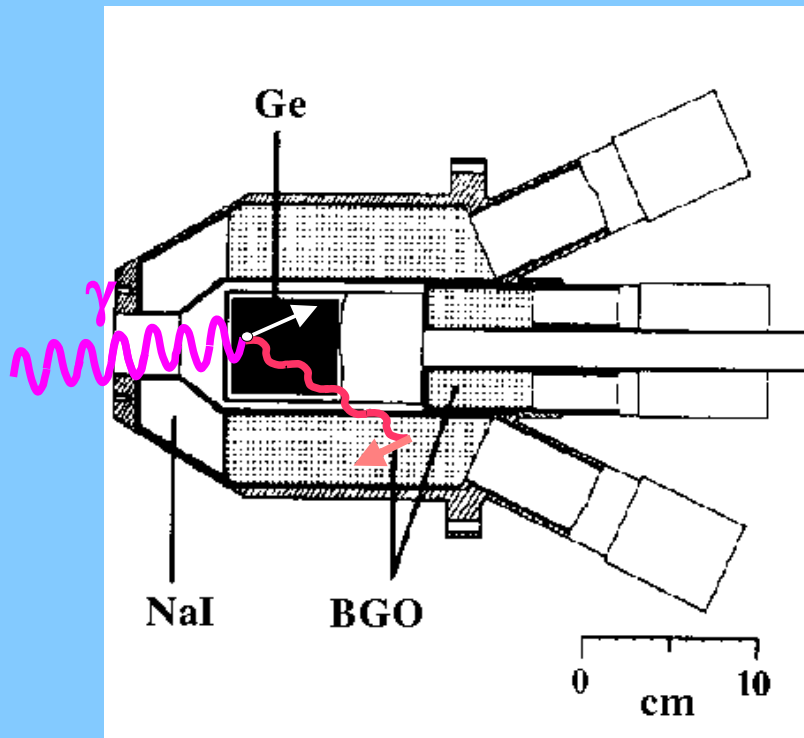
Alta tensão (2-5 kV)

Espectros gama



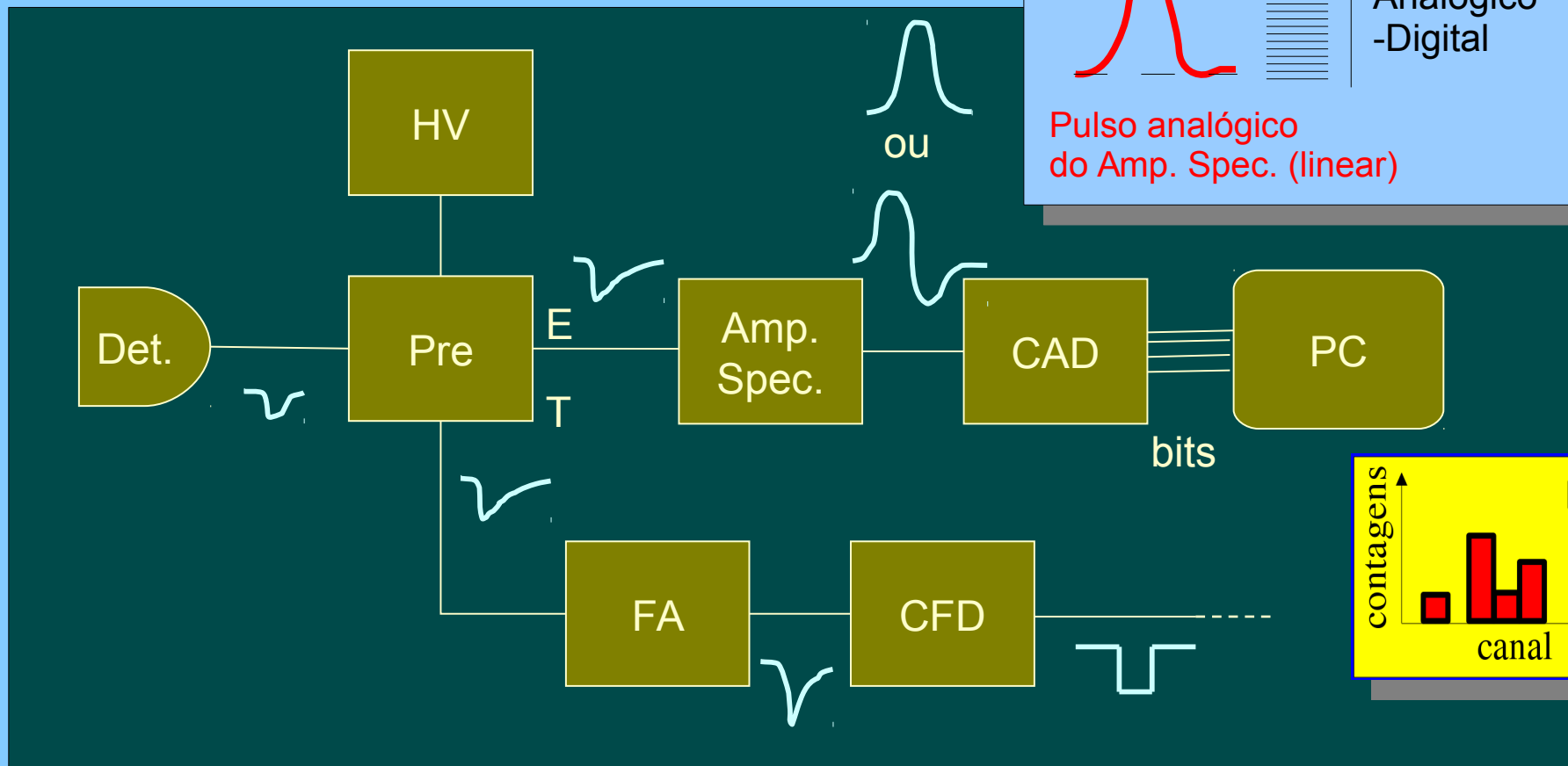
O Supressor Compton

- Veto de eventos que interagem com o filtro cintilador

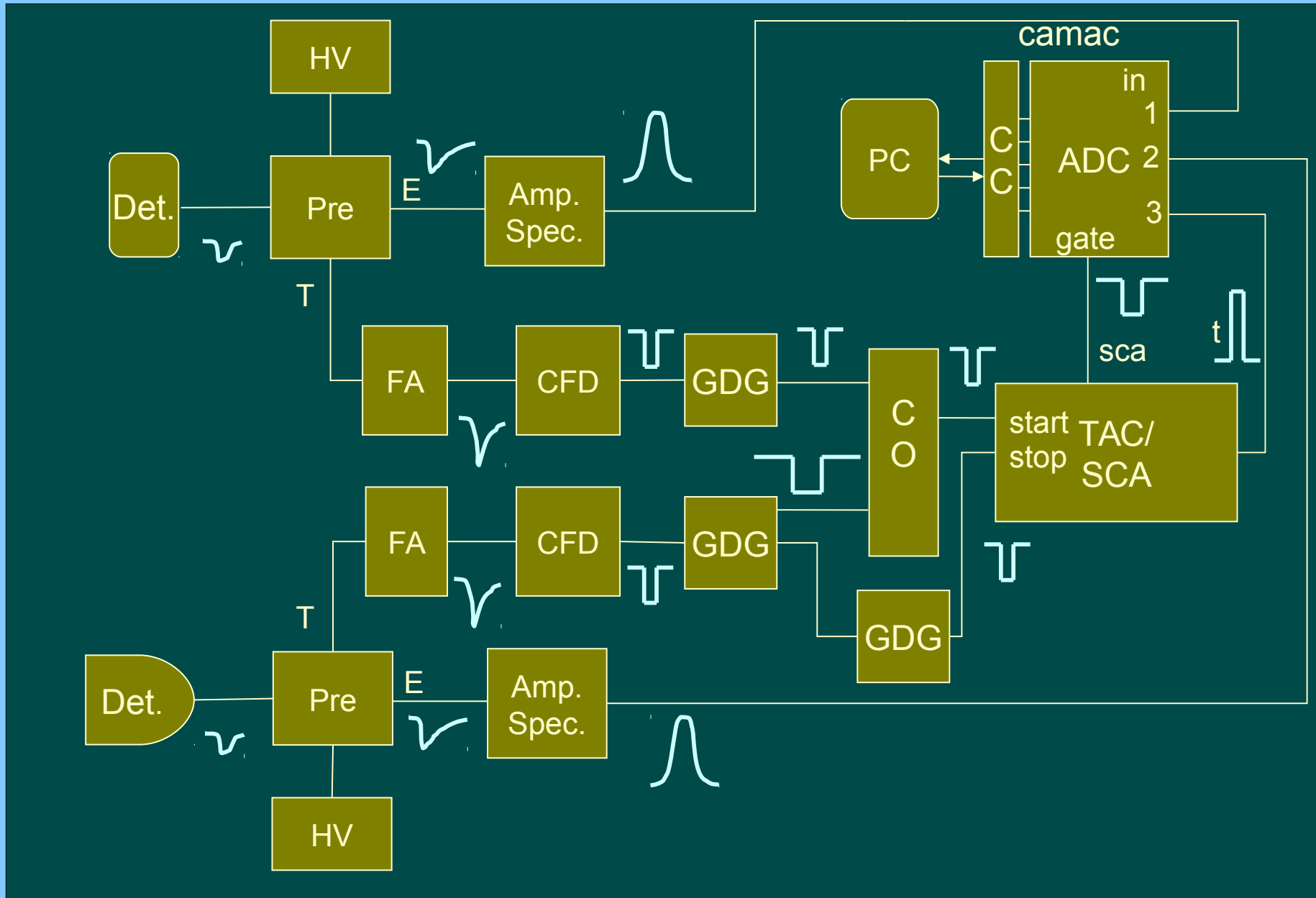


Eletrônica modular

- Espectro de energia

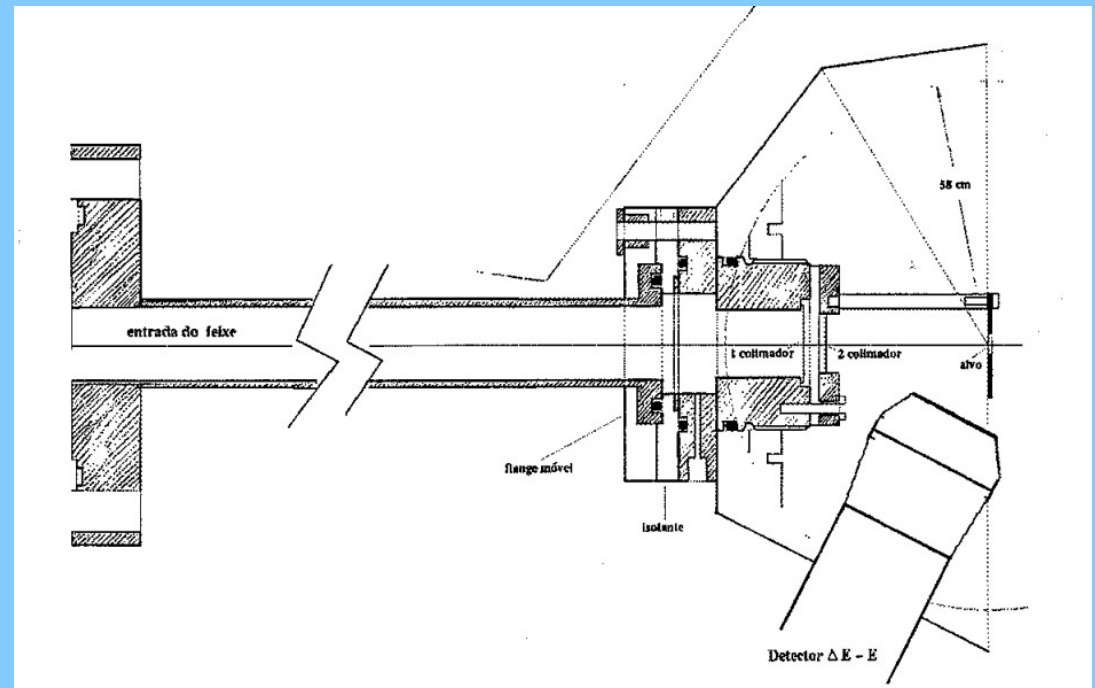
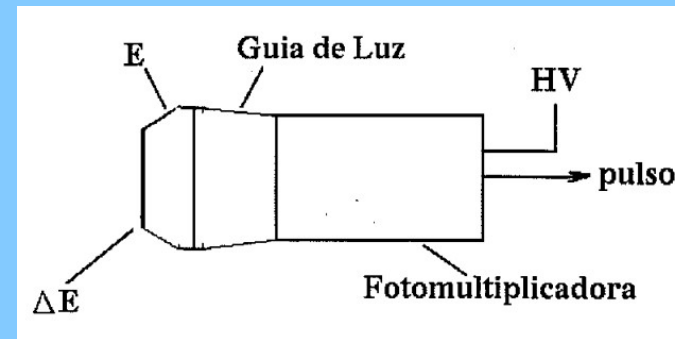
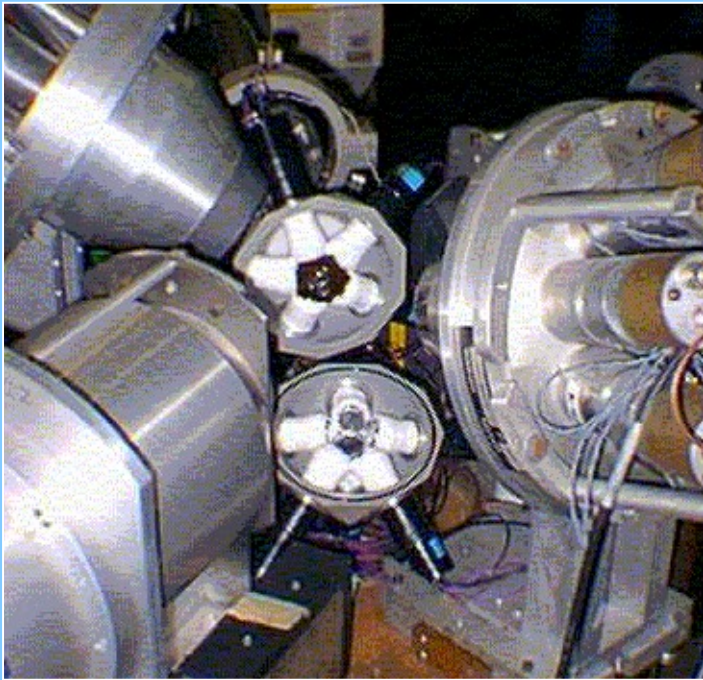


Eletrônica de coincidências



Sistema ancilar do espectrômetro

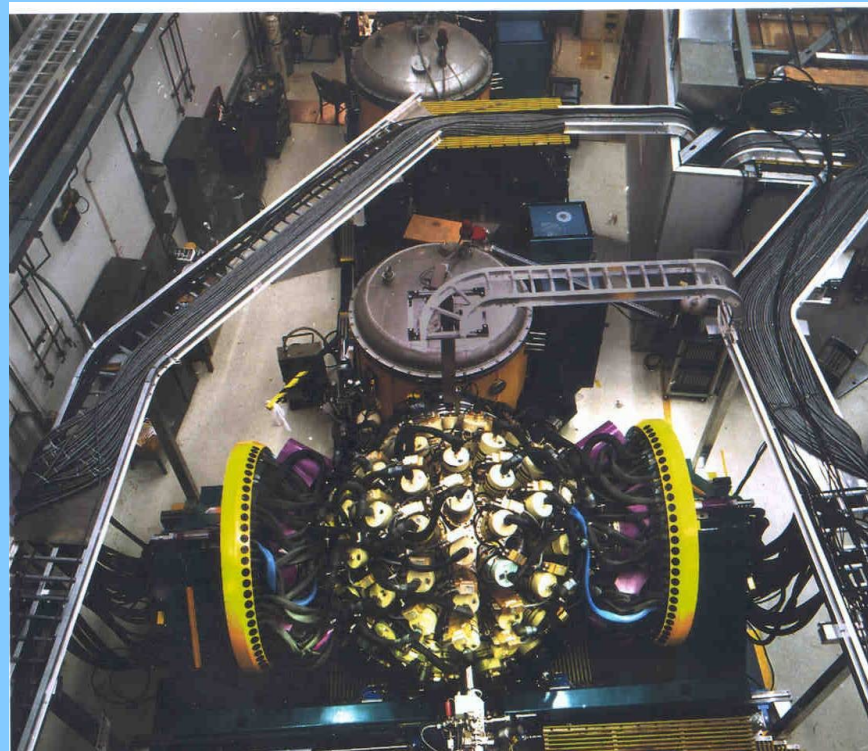
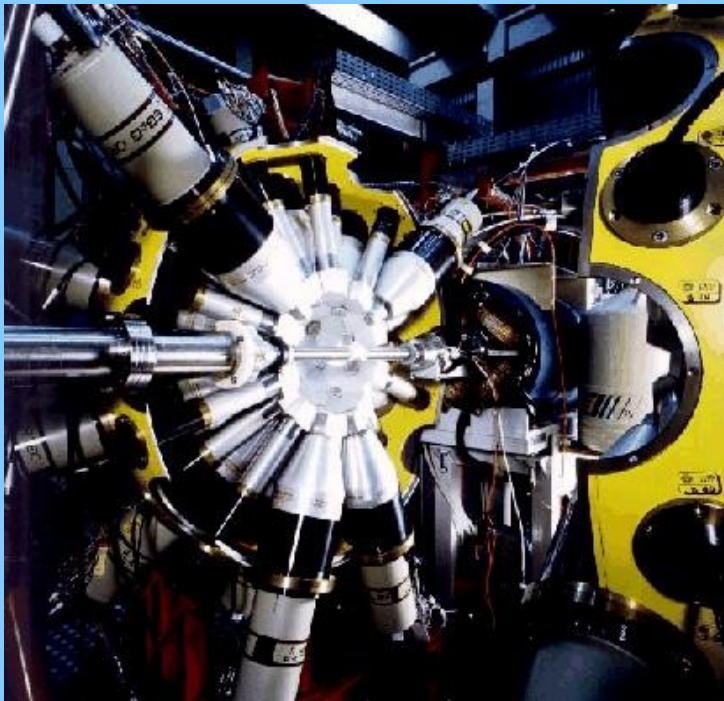
- sistema de detecção de partículas carregadas



SACI - sistema ancilar de cintiladores plásticos

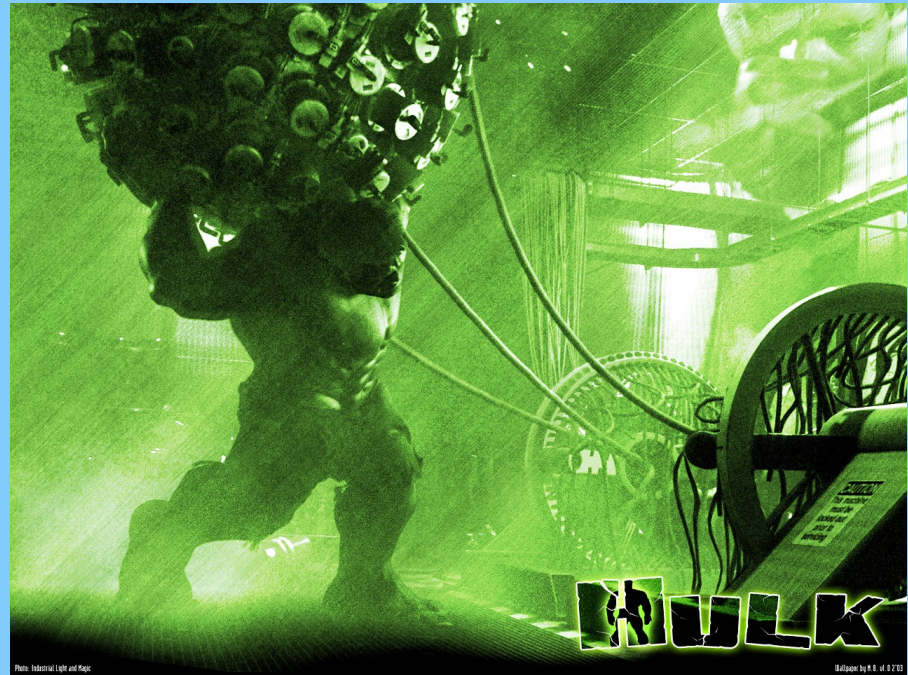
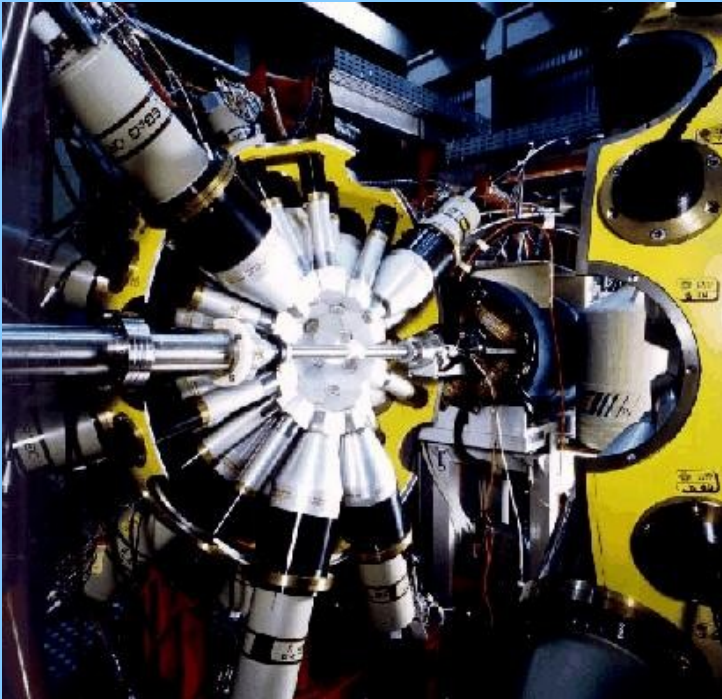
Espectrômetros

- sistemas multidetectores de GeHP/AC
 - GASP - LNL
 - 40 GeHP
 - GAMMASPHERE LBL/ANL
 - ~100 GeHP



Espectrômetros

- sistemas multidetectores de GeHP/AC
 - GASP - LNL
40 GeHP
 - GAMMASPHERE LBL/ANL
~100 GeHP



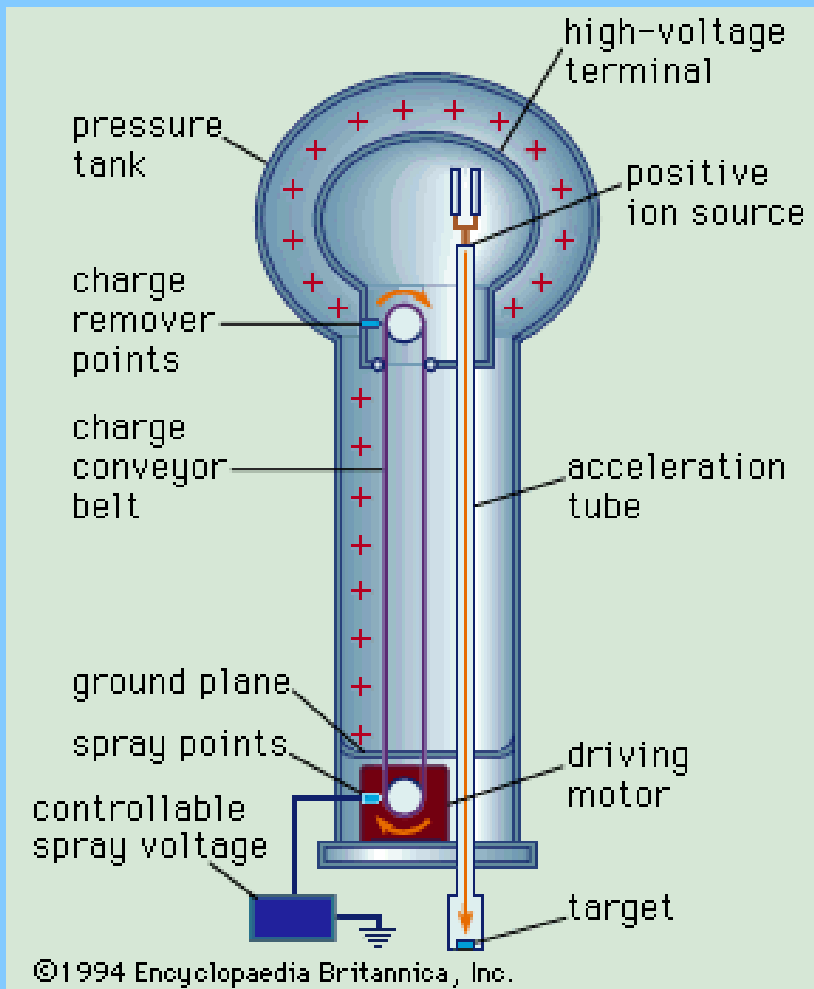
Próxima aula

- Técnica de coincidências
- Exemplos
- Técnica do Rastreamento (*Tracking*)
- Outras técnicas de medida de espectroscopia gama (vidas médias)

Extras

Aceleradores eletrostáticos

- Van de Graaf

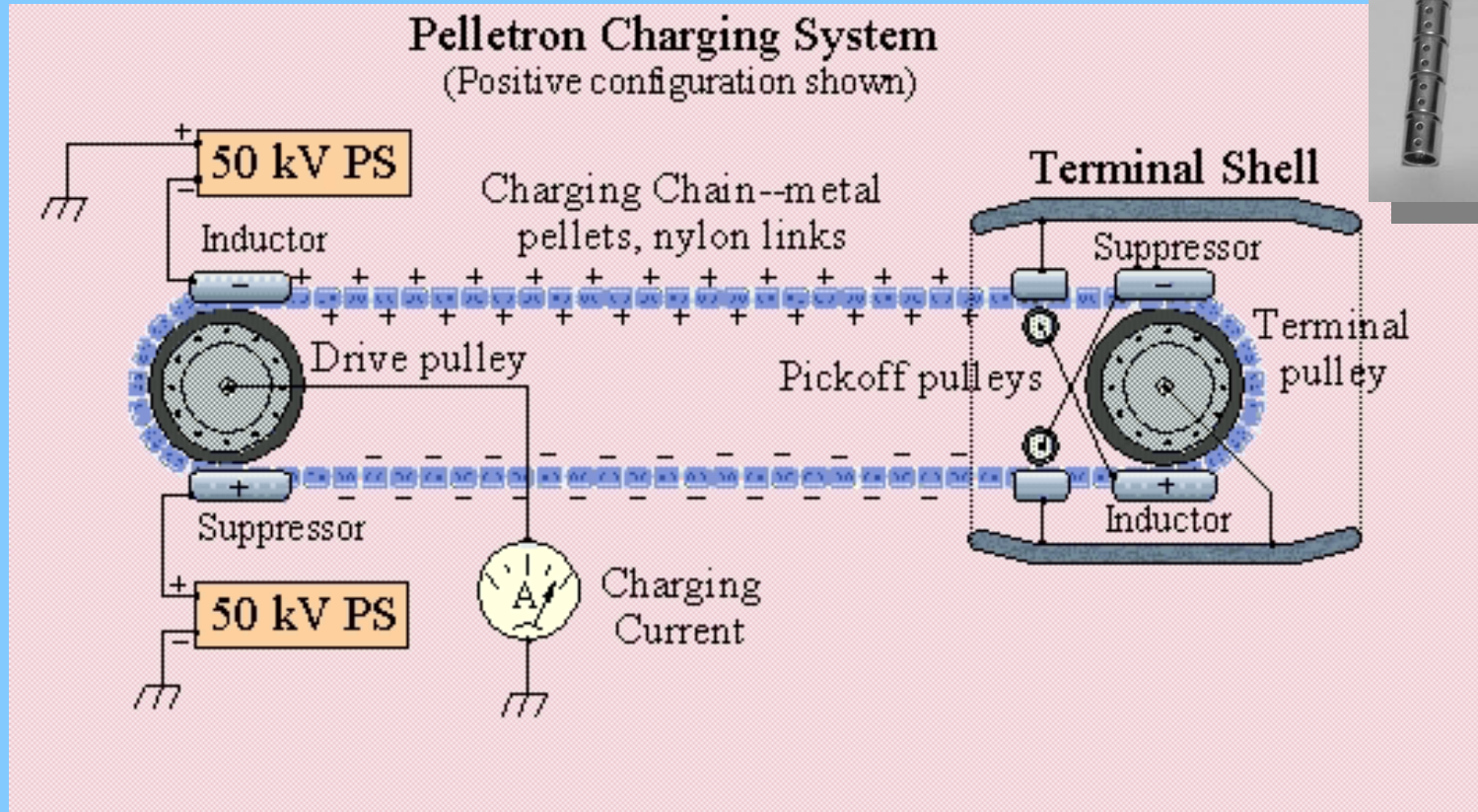
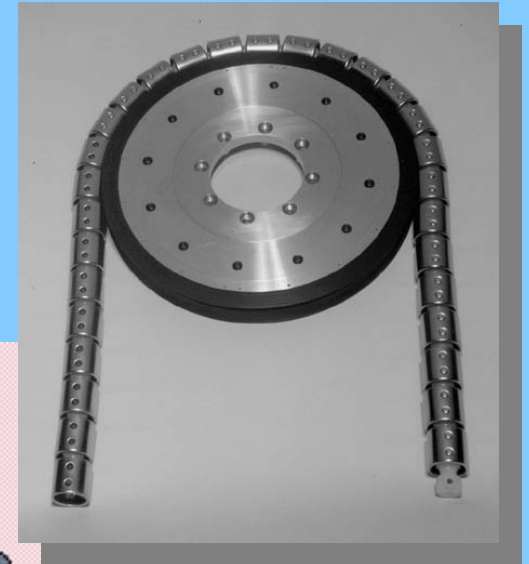


IFUSP anos 50



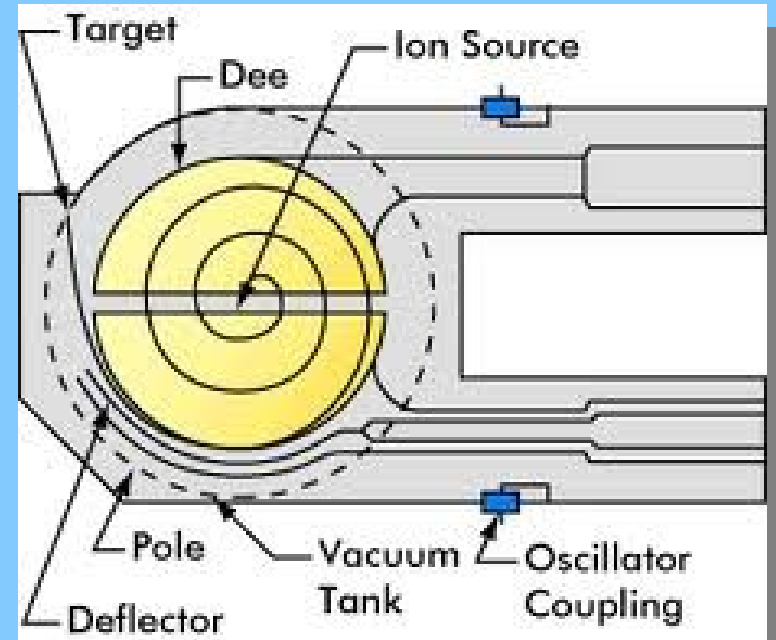
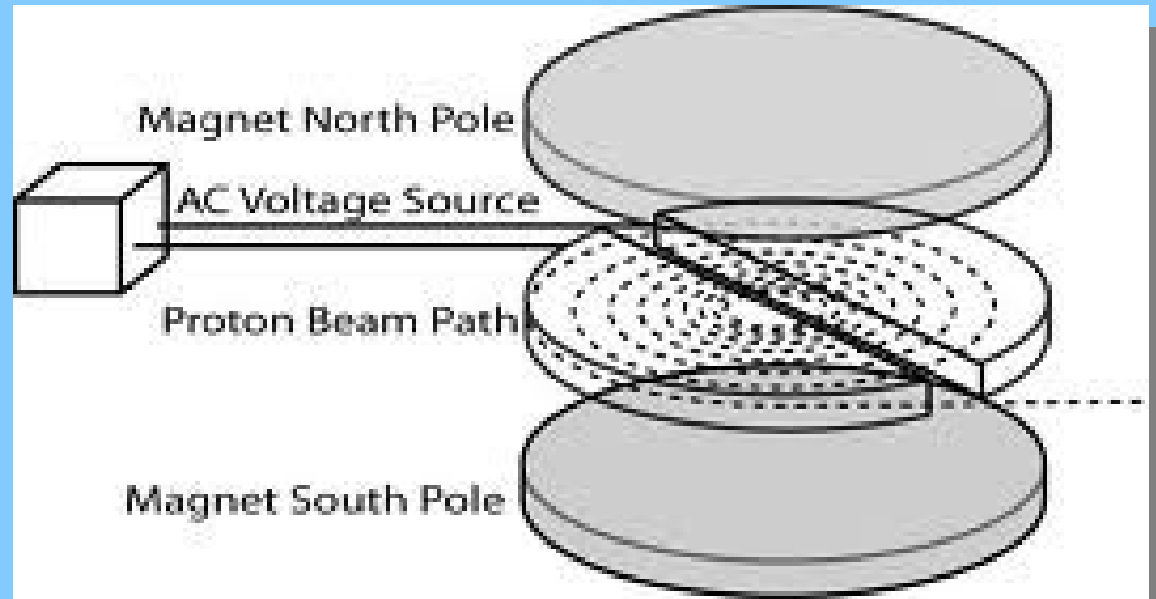
Sistema de carga

- Corrente de Pellets



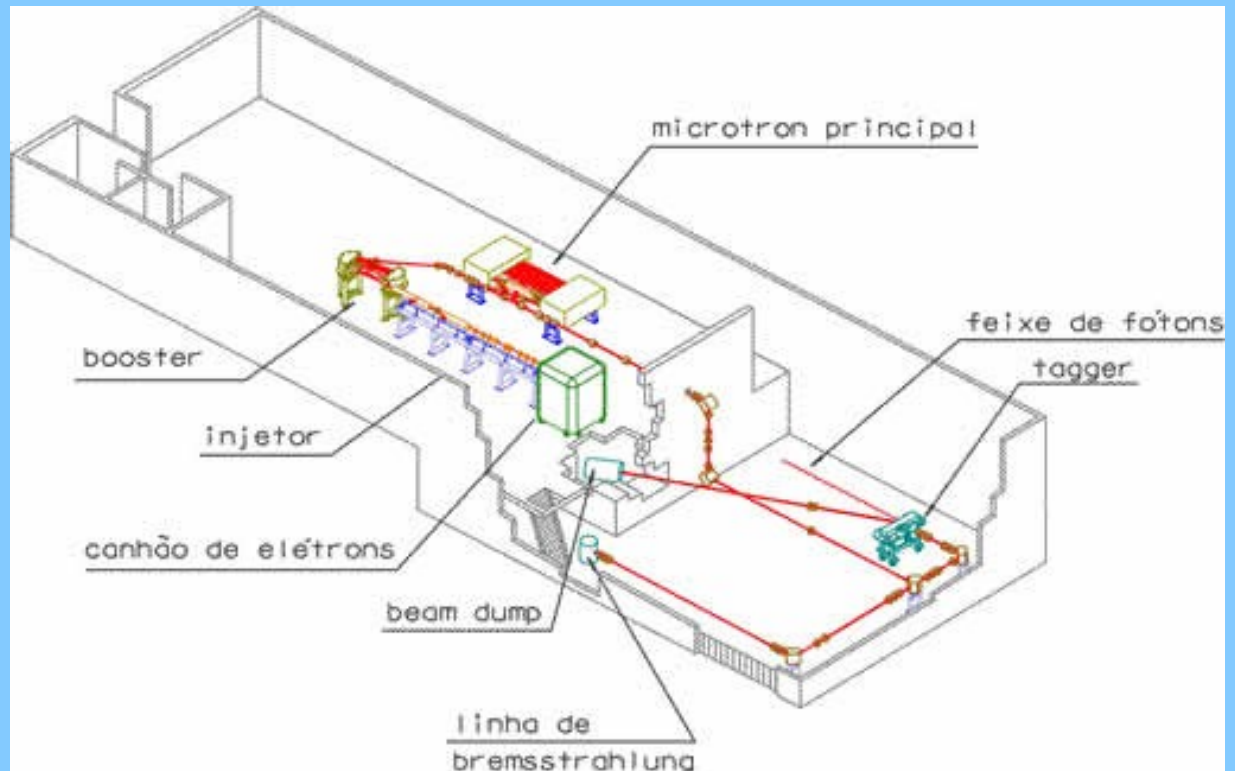
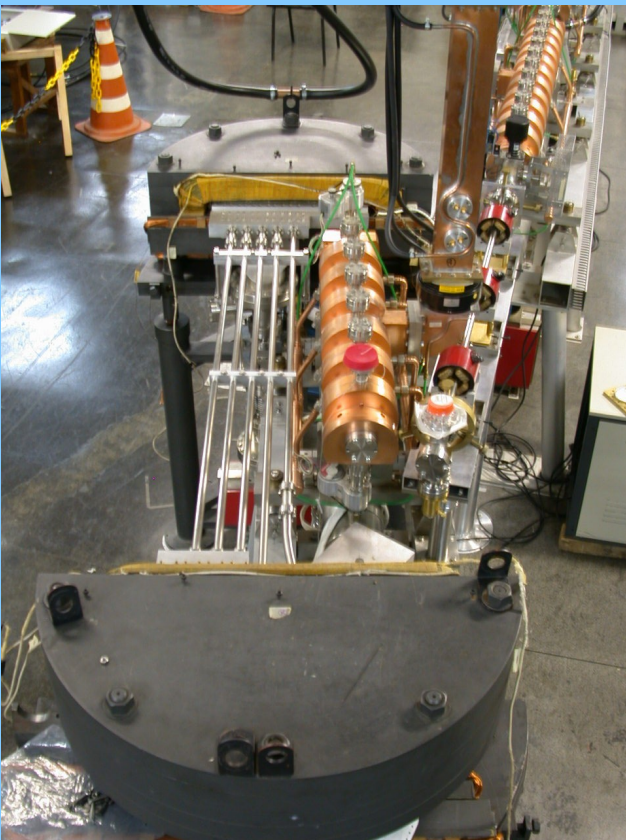
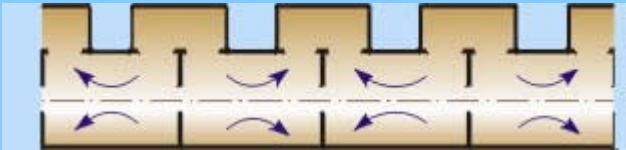
Ciclotron

- Ciclotron do IPEN
preparação de fontes radioativas



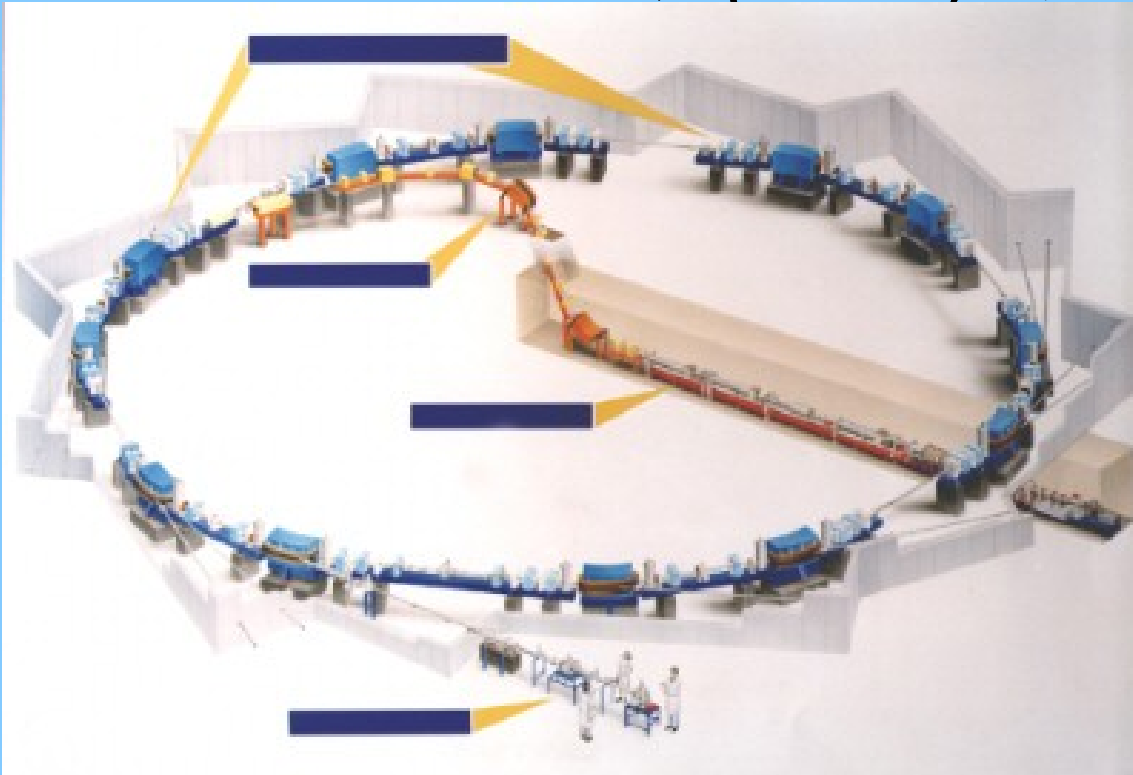
Microtron

- Acelerador de elétrons (2-32 MeV)



Síncrotron

- LNLS - Campinas, SP



LHC - CERN

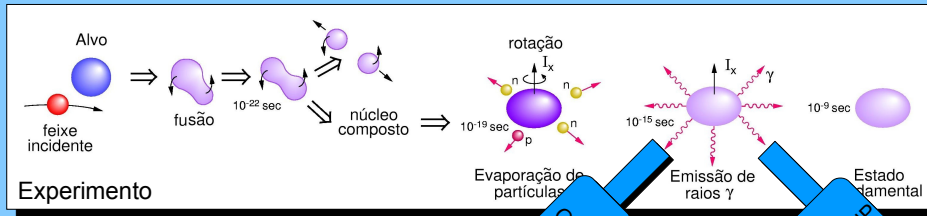


Ferramentas de pesquisa

- Breve re-introdução
- Reações nucleares
- Aceleradores de Partículas
- Detectores de Radiação
- O Supressor Compton
- Eletrônica e aquisição de dados
- Sistema ancilar (Saci)
- Espectrômetros gama

Investigação da estrutura nuclear

- Espectroscopia gama. Ex. reação de fusão-evaporação



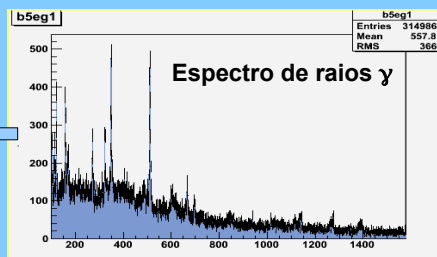
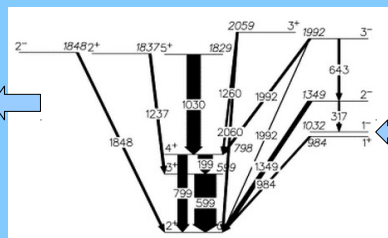
Experimento



Detecutores de alta resolução

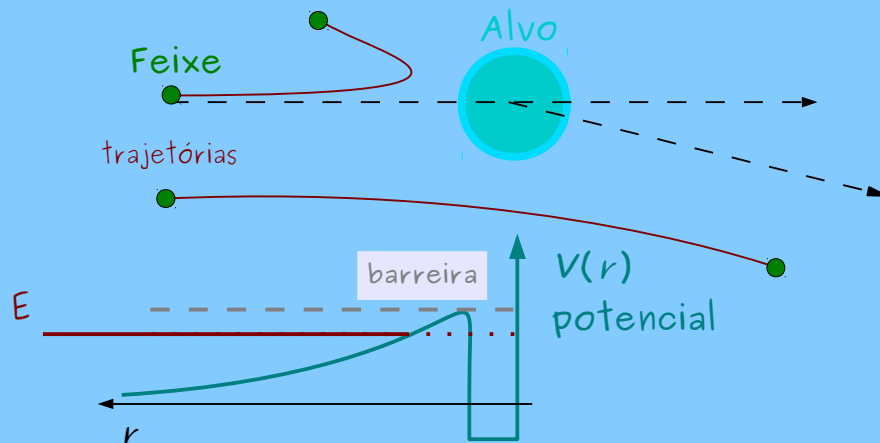
Esquema de níveis

Modelo



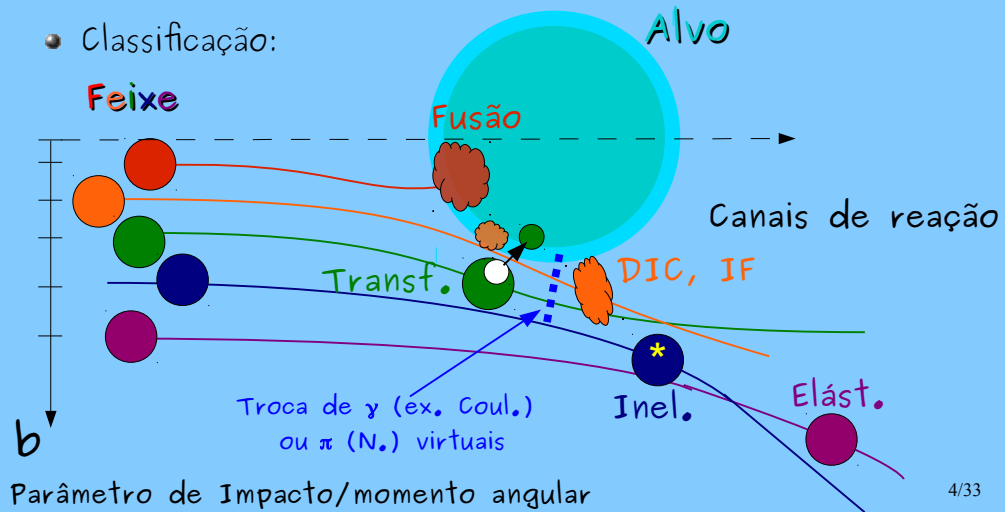
Colisões iônicas de baixa energia

- Bem abaixo da energia da barreira Coulombiana → somente espalhamento elástico (tipo Rutherford)
- Não há reação - não produz raios- γ



Reações Nucleares

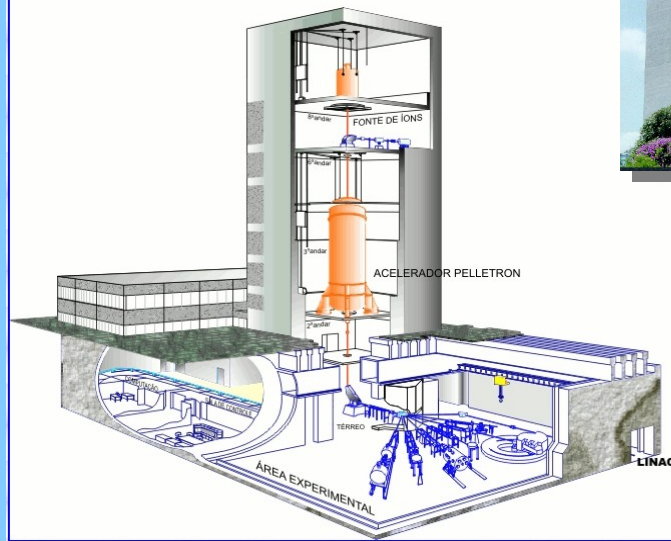
- Para energias acima da barreira (ou próximas, devido ao tunelamento) há envolvimento da força nuclear
- Classificação:



Acelerador Pelletron Tandem 8UD

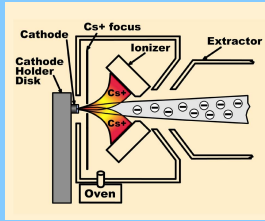
IFUSP

UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE FÍSICA
EDIFÍCIO "OSCAR SALA" - LAB. PELLETRON

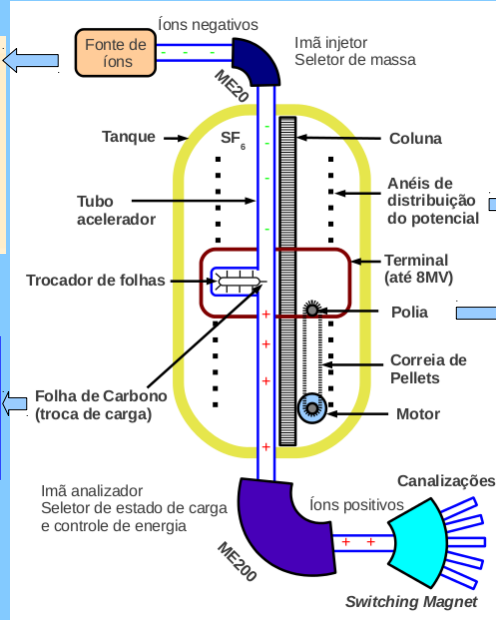
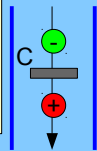


Esquema do acelerador Pelletron

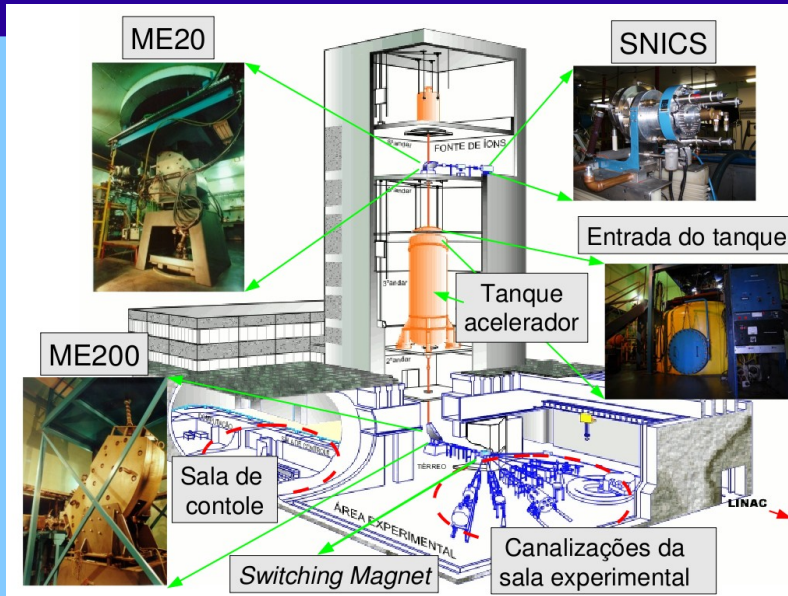
Fonte SNICS



Estados de carga
-1
... +3; +4; ...+Z

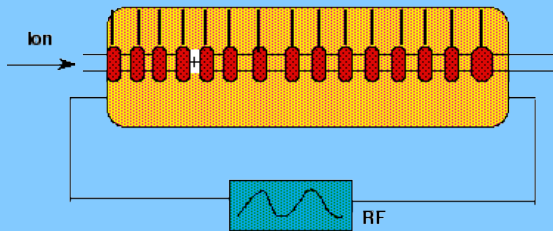


Partes do Acel. Pelletron

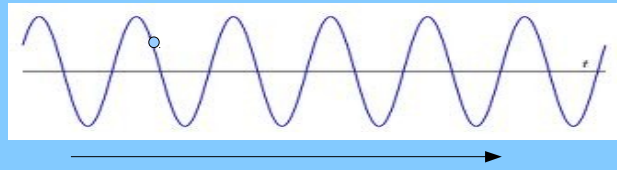
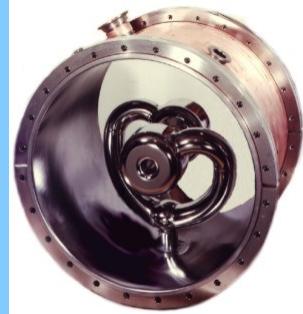


Acelerador linear

- LAFN IFUSP

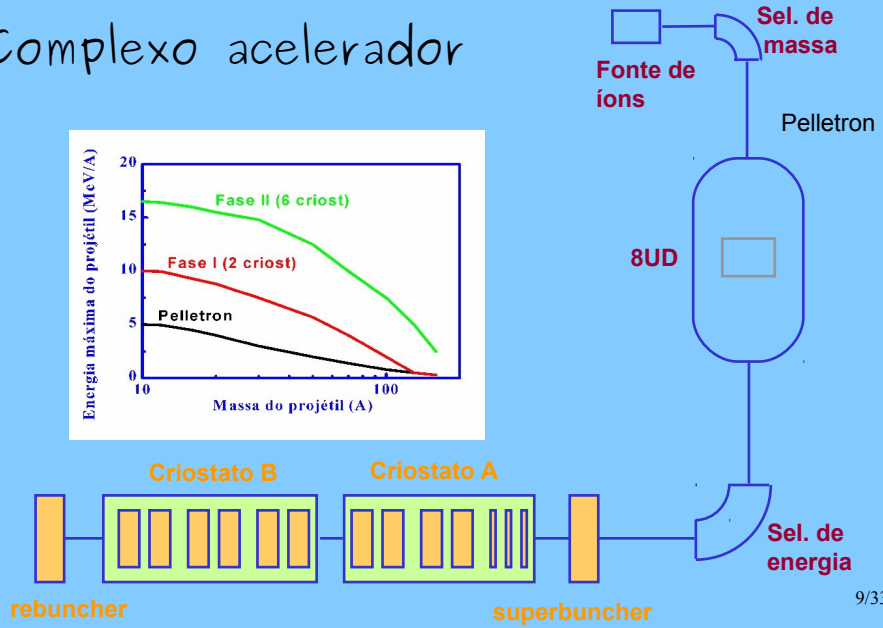
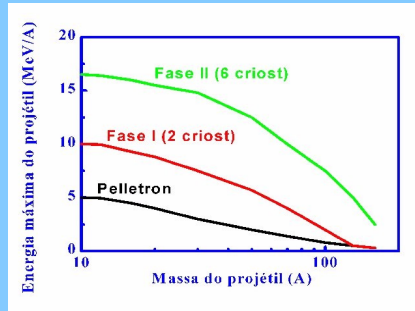


Ressoador



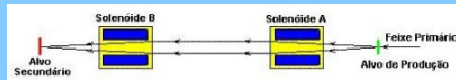
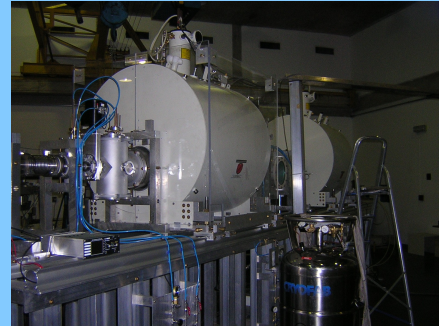
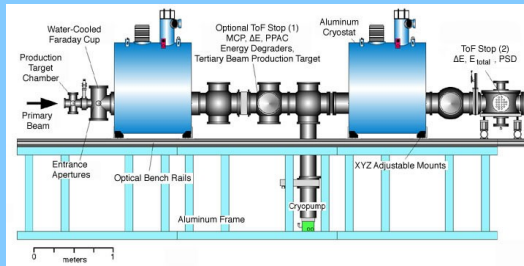
Pelletron-LINAC (LAFN-IFUSP)

- Complexo acelerador

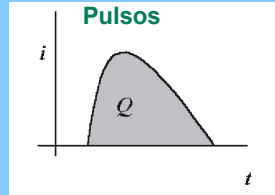
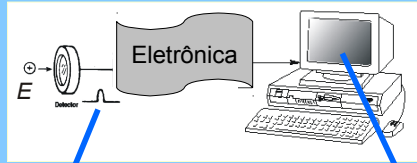


Produção de feixes radioativos

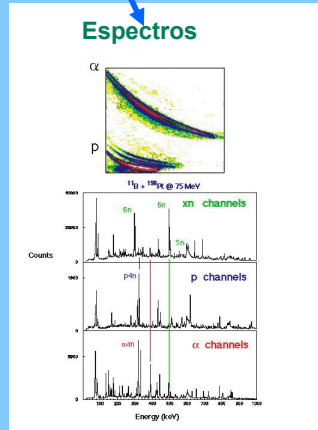
- Ribras - Pelletron (IFUSP)
- Solenóides supercondutores (6T)



Detectores e aquisição de dados

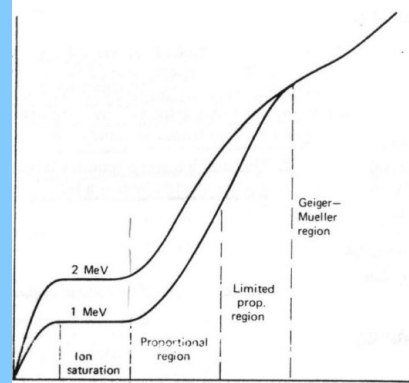
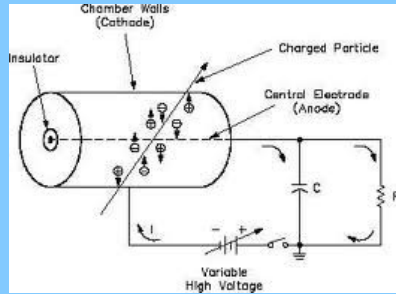


Energia (prop. Q),
Tempo de chegada
Forma: Z, x ...

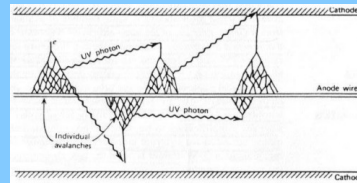


Detectores de radiação

• Detectores a gás Amplitude



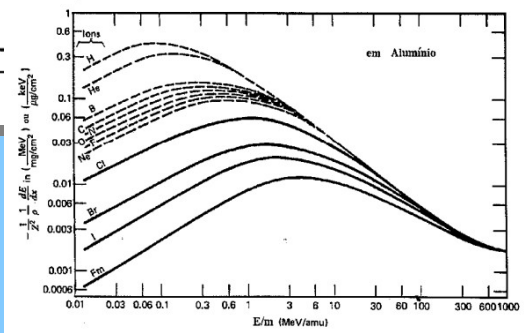
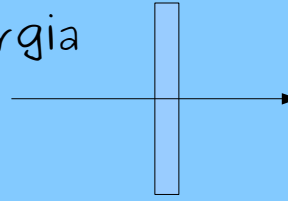
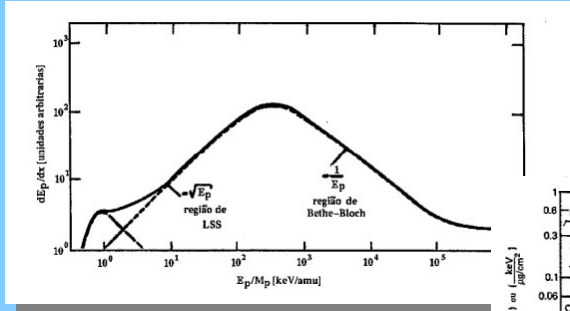
GM



Tensão

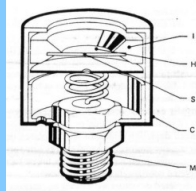
Freamento de íons em sólidos

- Curvas de perda de energia

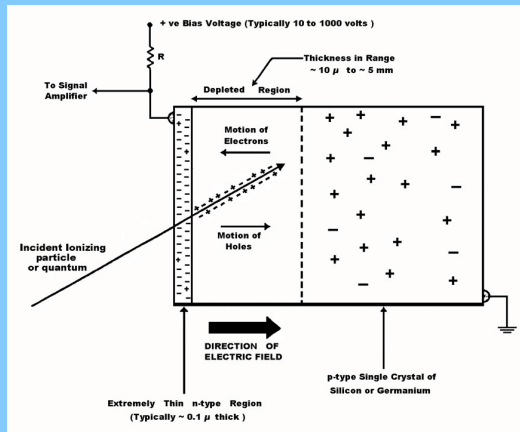
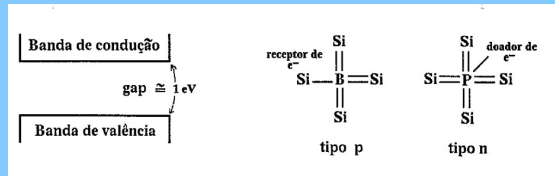


Detectores Semicondutores

• Detector de si

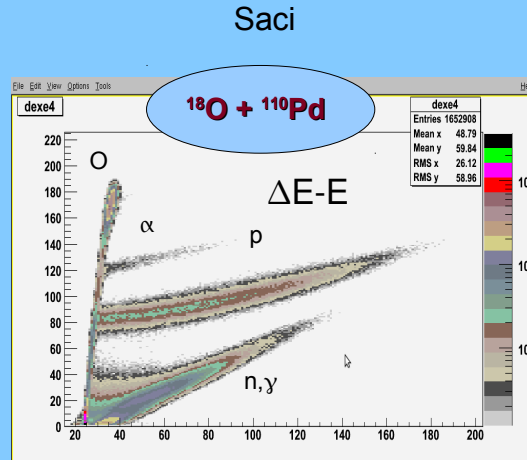
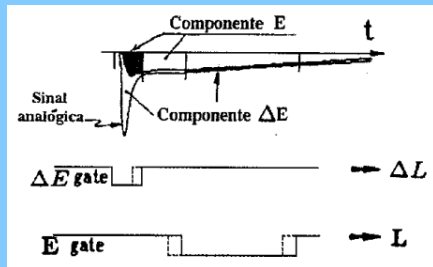
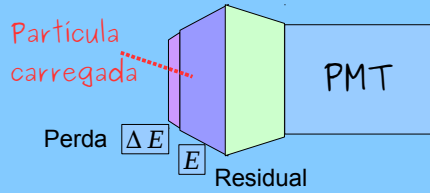


Diodo, sob polarização reversa



Cintiladores plásticos – Phoswich

- Dois tipos de plásticos cintiladores, com constantes de decaimento diferentes



Interação da radiação γ com a matéria

1 - Efeito fotoelétrico

$h\nu$

$$E_{e^-} = h\nu$$

2 - Efeito Compton

$h\nu$

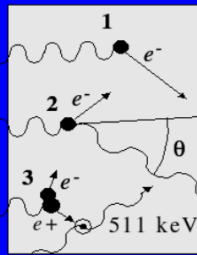
$$E_{e^-} = h\nu - h\nu'$$

3 - Criação de pares

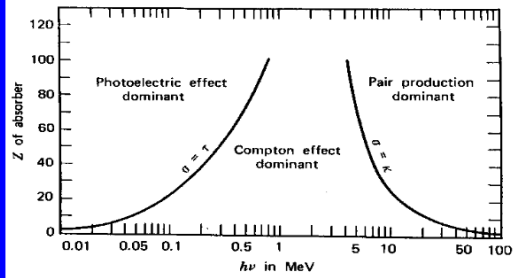
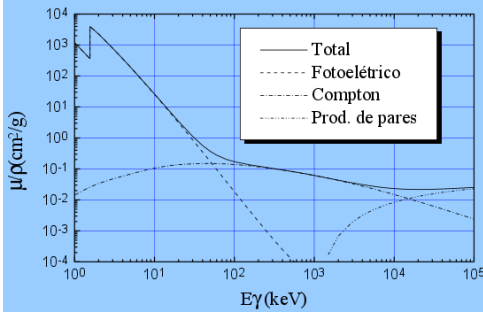
$h\nu$

$h\nu'(\theta)$

$$E_{e^+} + E_{e^-} = h\nu - 2m_e c^2$$

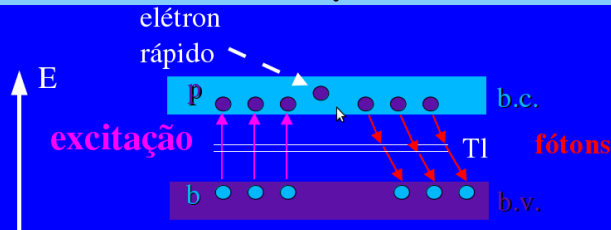


Coefficiente mássico de absorção para o Al



O cristal cintilador de NaI(Tl)

- Processo de detecção



NaI(Tl)

Iodeto de Sódio dopado com Tálcio

Gap: ≈ 7 eV

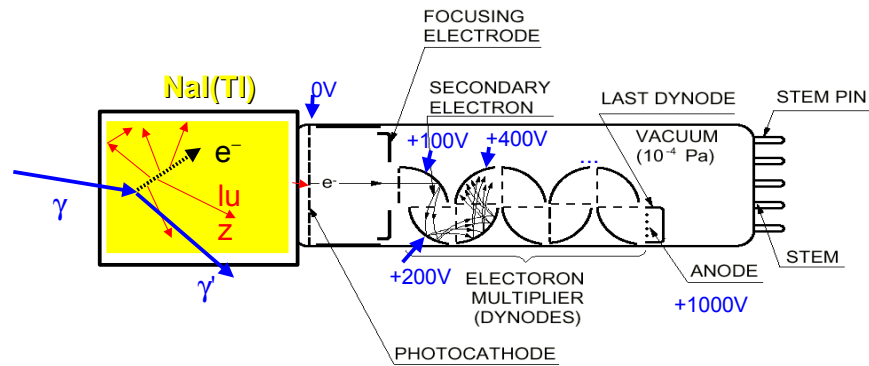
Energia média por fóton: 3 eV

Produção de luz: 38 fótons por keV (26 eV/fóton)

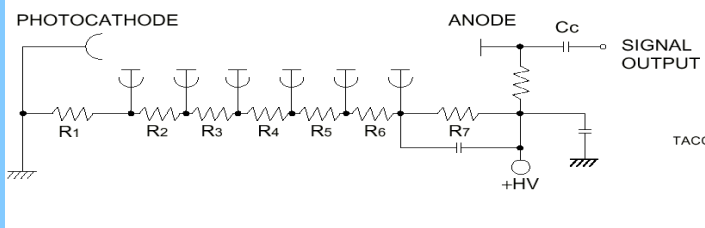
(Aprox. 1 fóton por par partícula-buraco)

Transparente para a própria cintilação

O tubo fotomultiplicador

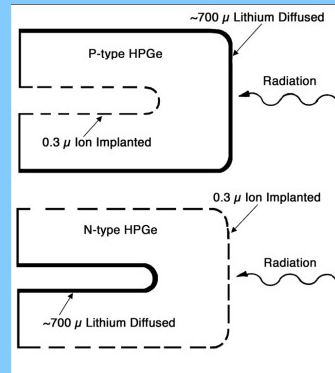


Base, para
alimentação
do tubo
fotomultiplicador:



Detector semiconductor de GeHP

- Cristais de Ge Hiperpuro

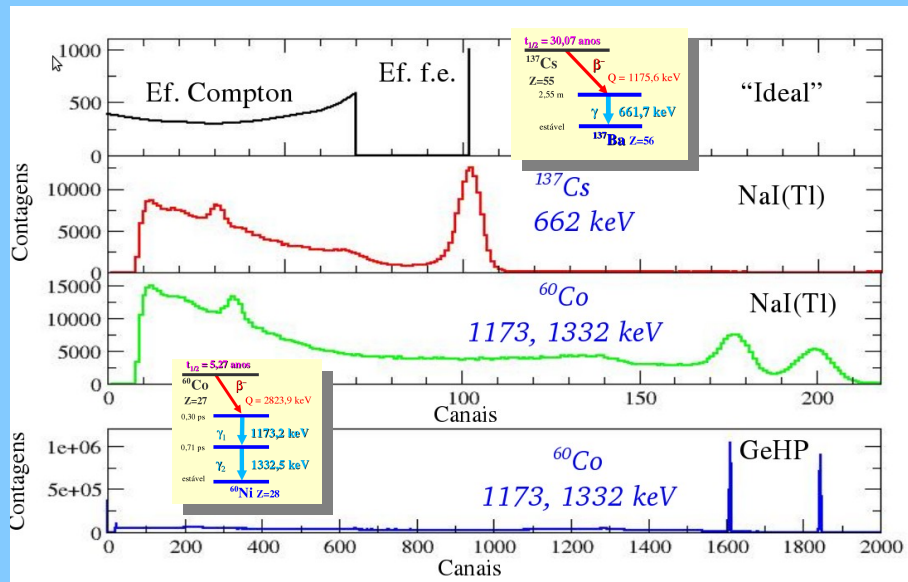


Botijão de N_2 Liq.
 $T=77K$

Alta tensão (2-5 kV)

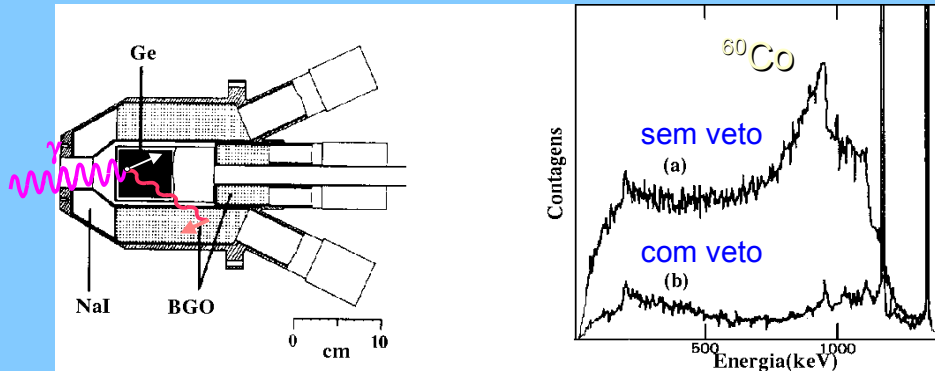
Resolução em energia 2-3keV
Resolução em tempo ~20 ns

Espectros gama



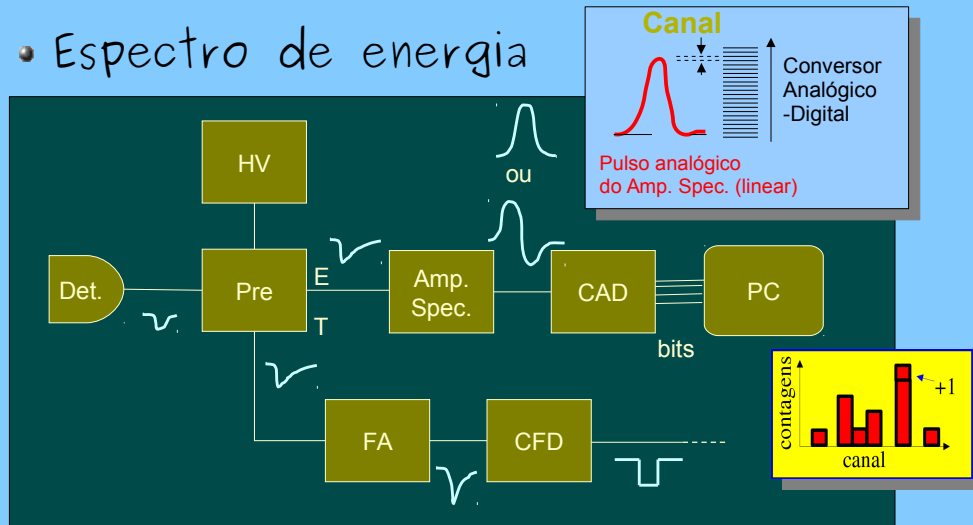
O Supressor Compton

- Veto de eventos que interagem com o filtro cintilador

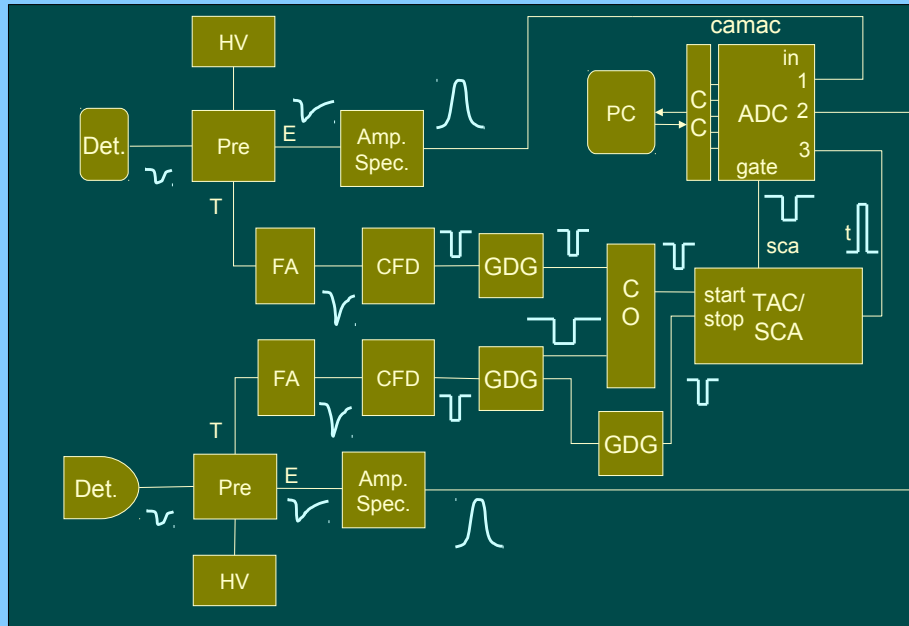


Eletrônica modular

- Espectro de energia

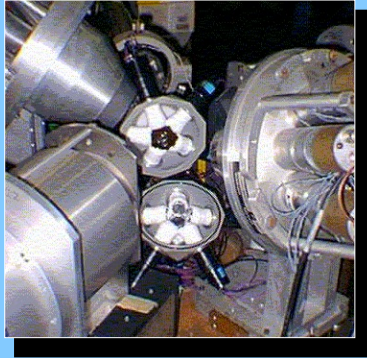


Eletrônica de coincidências

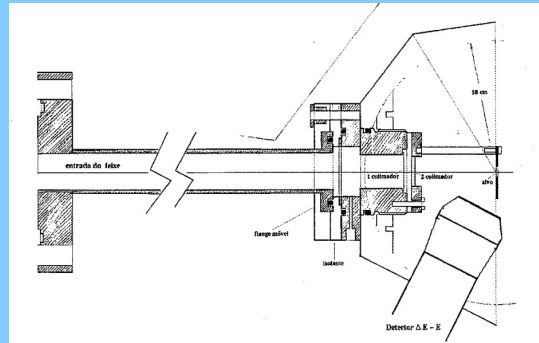
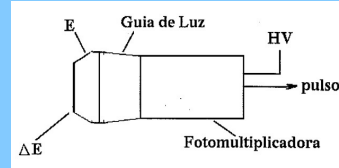


Sistema ancilar do espectrômetro

- sistema de detecção de partículas carregadas

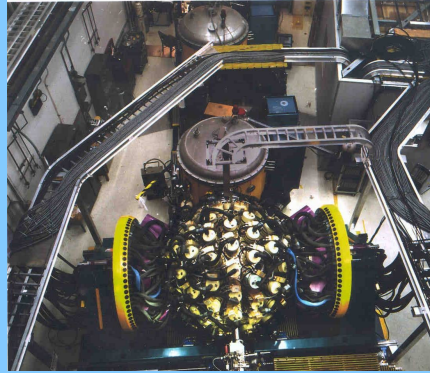
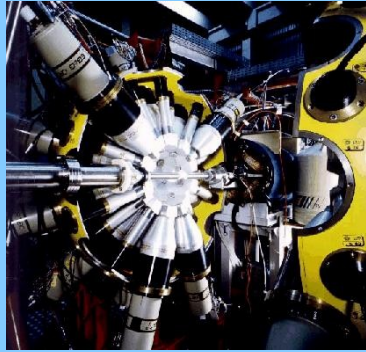


SACI - sistema ancilar de cintiladores plásticos



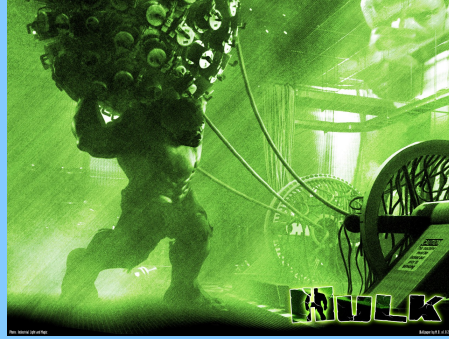
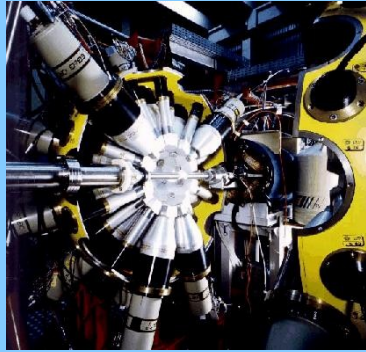
Espectrômetros

- Sistemas multidetectores de GeHP/AC
GASP - LNL
40 GeHP
GAMMASPHERE LBL/ANL
~100 GeHP



Espectrômetros

- Sistemas multidetectores de GeHP/AC
GASP - LNL
40 GeHP
GAMMASPHERE LBL/ANL
~100 GeHP



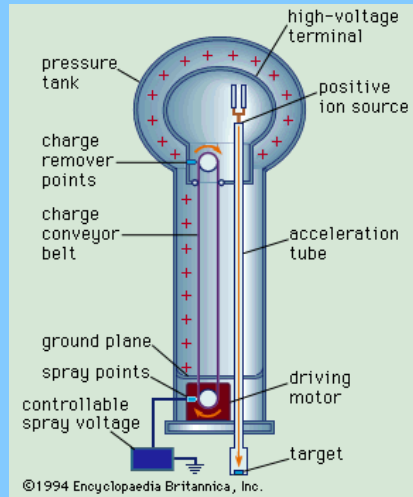
Próxima aula

- Técnica de coincidências
- Exemplos
- Técnica do Rastreamento (*Tracking*)
- Outras técnicas de medida de espectroscopia gama (vidas médias)

Extras

Aceleradores eletrostáticos

- Van de Graaf

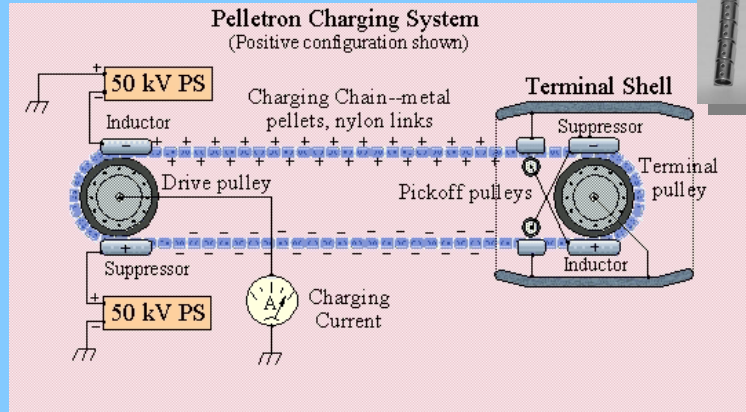
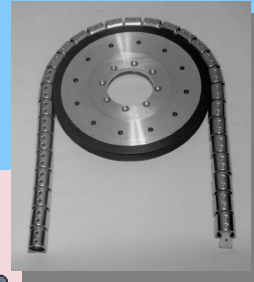


IFUSP anos 50



Sistema de carga

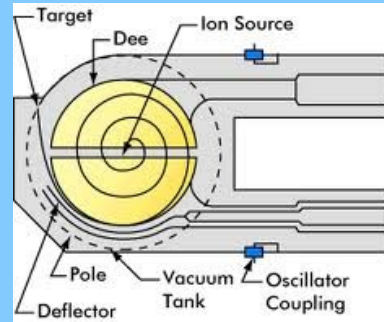
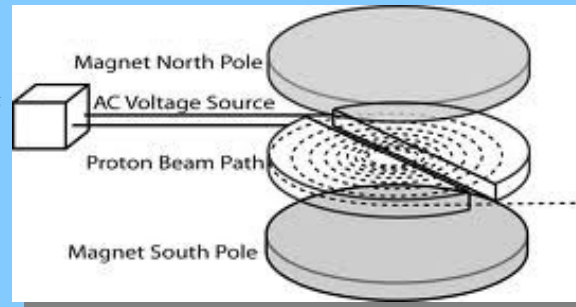
- Corrente de Pellets



Ciclotron

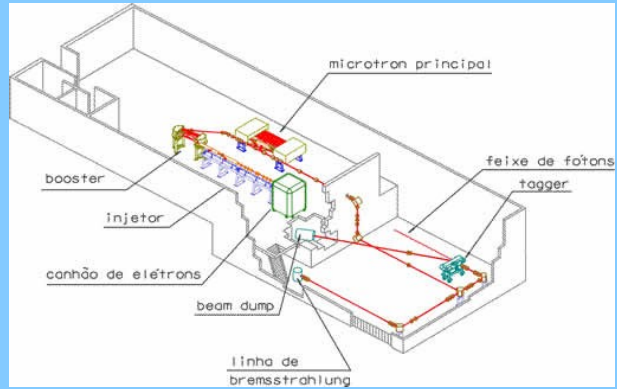
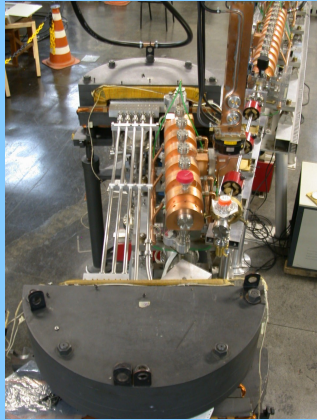
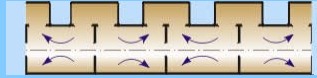
- Ciclotron do IPEN

preparação de fontes radioativas



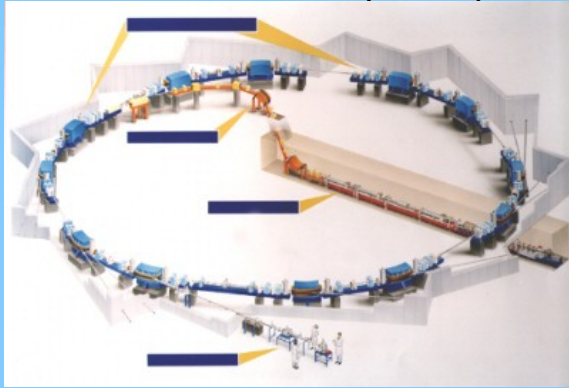
Microtron

- Acelerador de elétrons (2–32 MeV)



Síncrotron

- LNLS - Campinas, SP



LHC - CERN



Aula 4 – técnica de coincidências

- Utilidade do método
- Coincidências (γ - γ ; γ - p)
- γ - p – Medida de reações nucleares
- Rastreamento γ (*Tracking*)
- Outras técnicas de medida de espectroscopia γ (distr. Angulares, vidas médias,...)
- Poder de resolução dos espectrômetros

Taxa típica de reação (fusão)

- Cálculo da taxa de reações $R = I n \sigma$

- Valores típicos:

$$I = 1 \text{ pA} = 0.6 \times 10^{10} \text{ part./s}$$

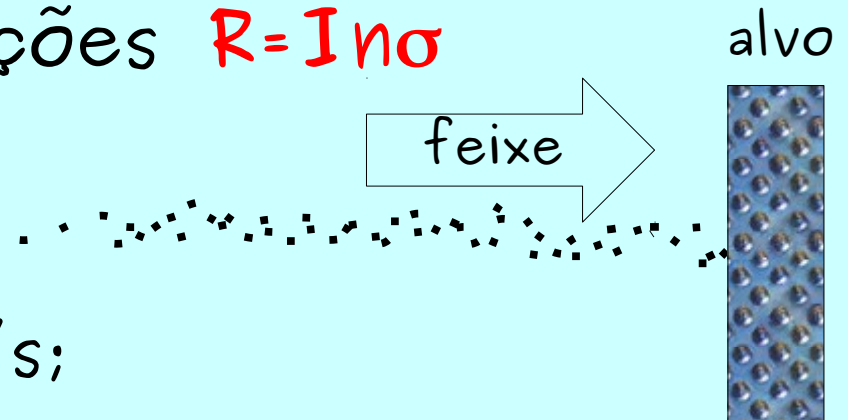
$$n = 6 \times 10^{18} \text{ átomos/cm}^2 \text{ (1mg/cm}^2, A=100)$$

$$\sigma = 1 \text{ b} = 10^{-28} \text{ cm}^2$$

$$\rightarrow R = 3.6 \times 10^5 \text{ reações/s}$$

- Intervalo médio $\langle t \rangle$ entre reações $1/R$:

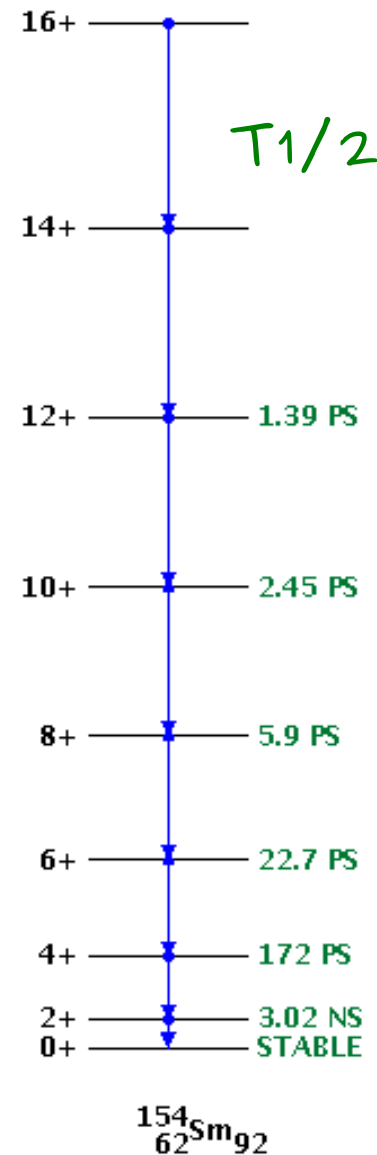
$$\langle t \rangle = 3 \times 10^{-6} \text{ s (3}\mu\text{s)} - \text{ como identificar de que reação veio um raio } \gamma?$$



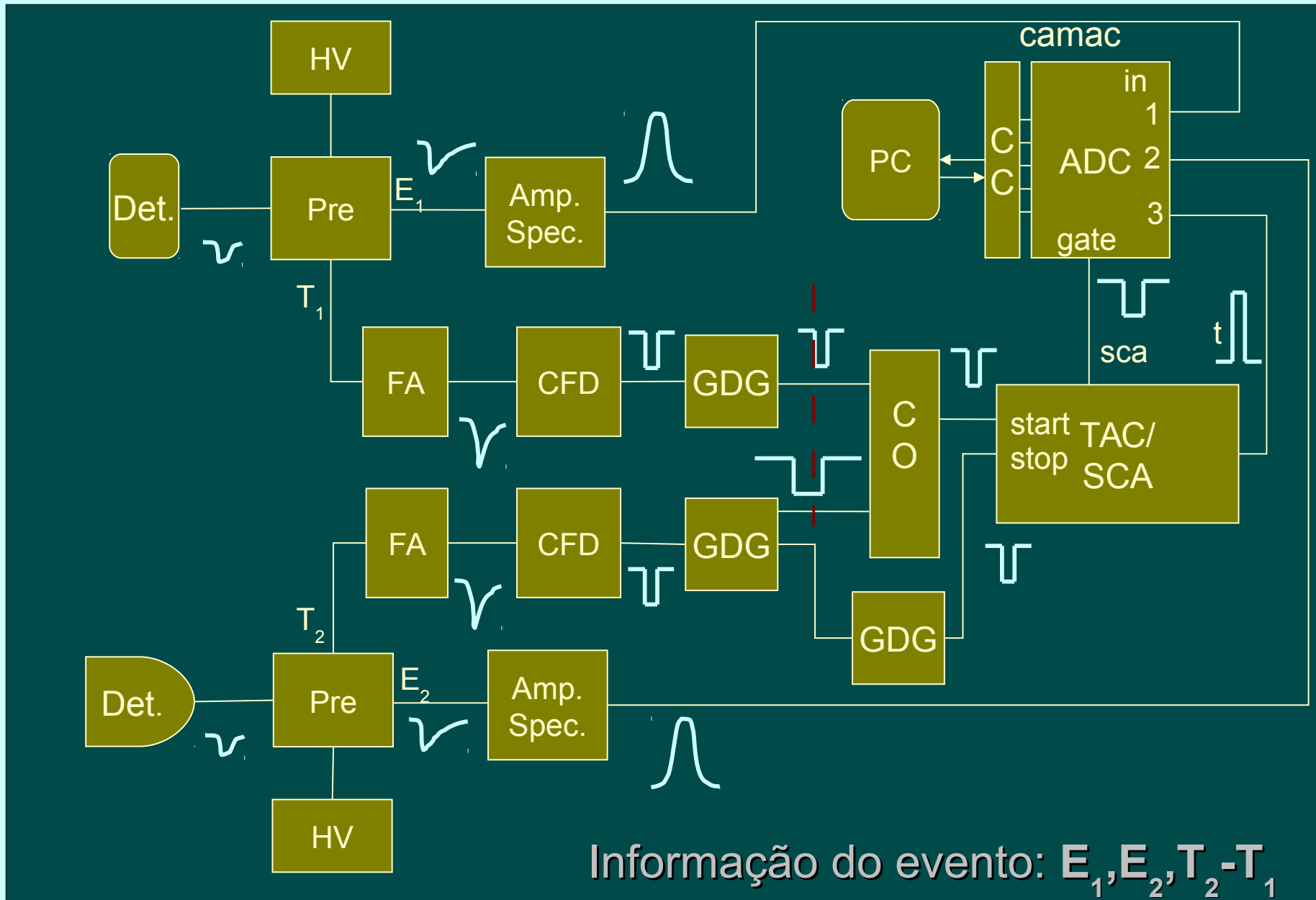
Correlação temporal

- Vidas médias de estados nucleares excitados em geral variam de 0.01 ps a 100 ns – muito menores que $3 \mu\text{s} = 3000 \text{ ns}$.
- Resolução temporal de detectores de Ge é cerca de 20 ns – nesta escala transições em cascata são praticamente simultâneas – “coincidentes”.
- Se dois raios γ são detectados dentro de $50\text{--}100 \text{ ns}$, provavelmente vem da mesma cascata.
- Processos nucleares são ainda mais rápidos, (ex. Evaporação de $p, n < 10^{-19} \text{ s}$)

Cascata γ

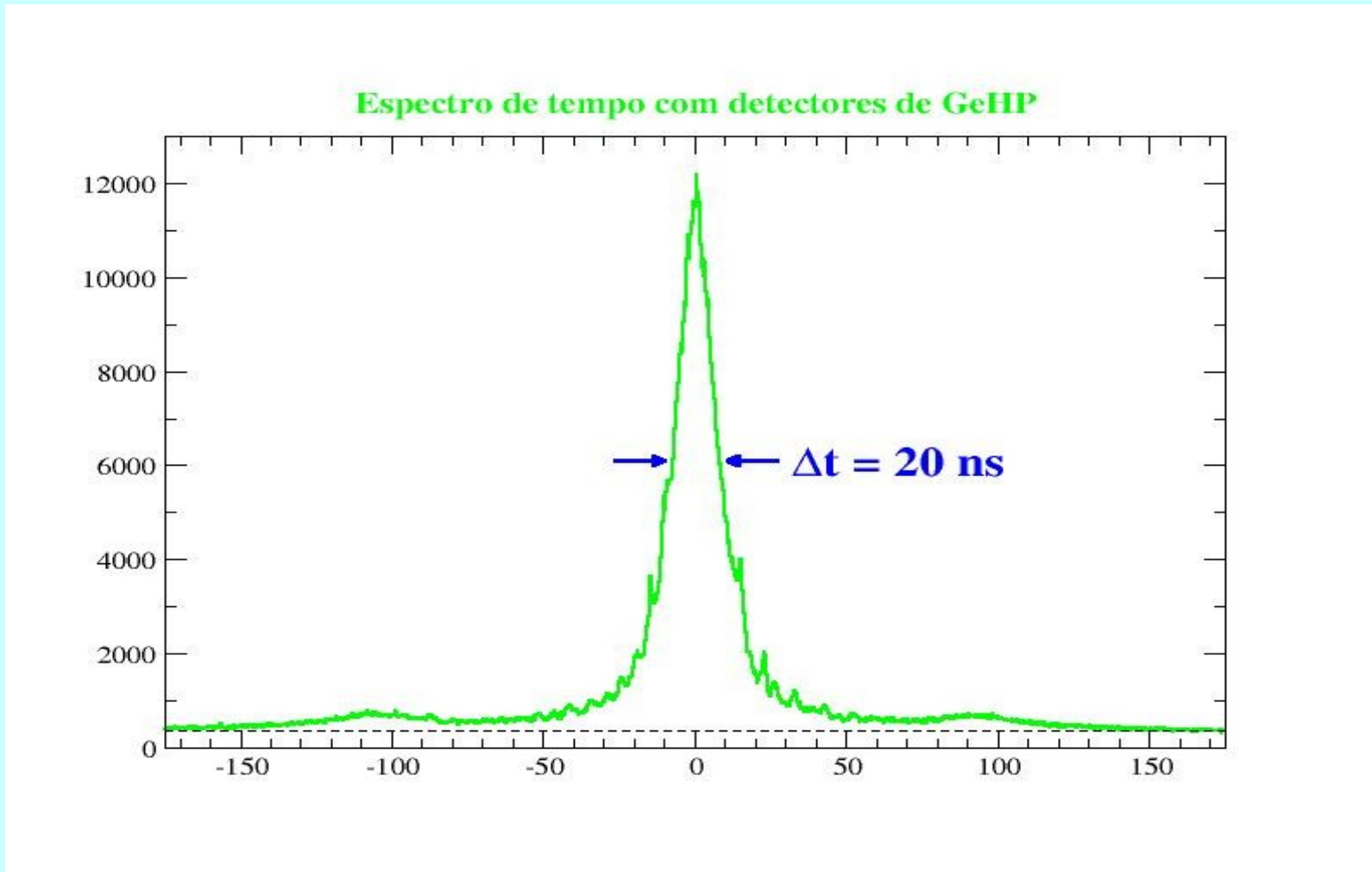


Circuito de coincidências



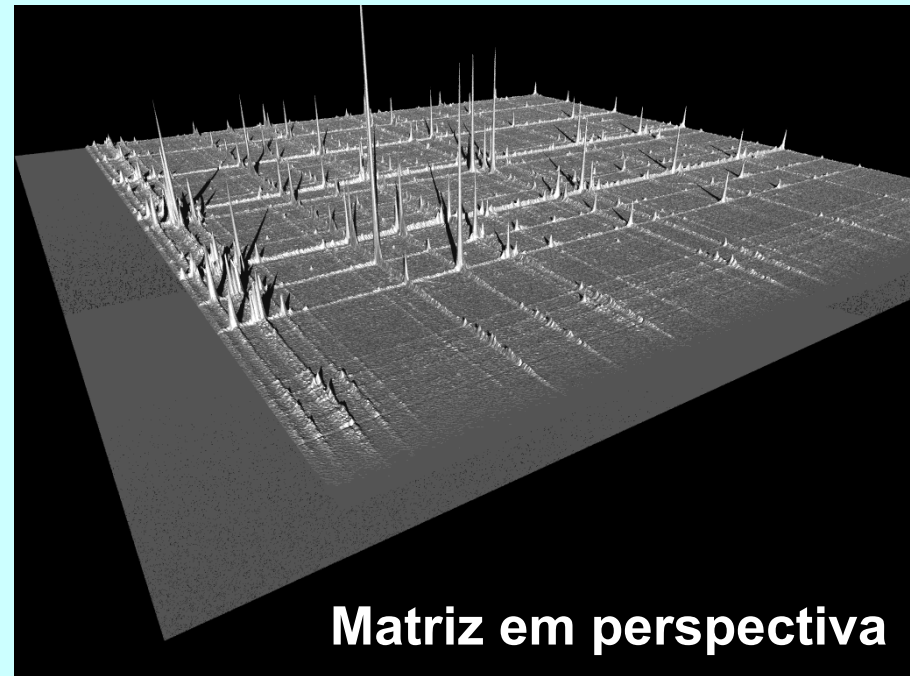
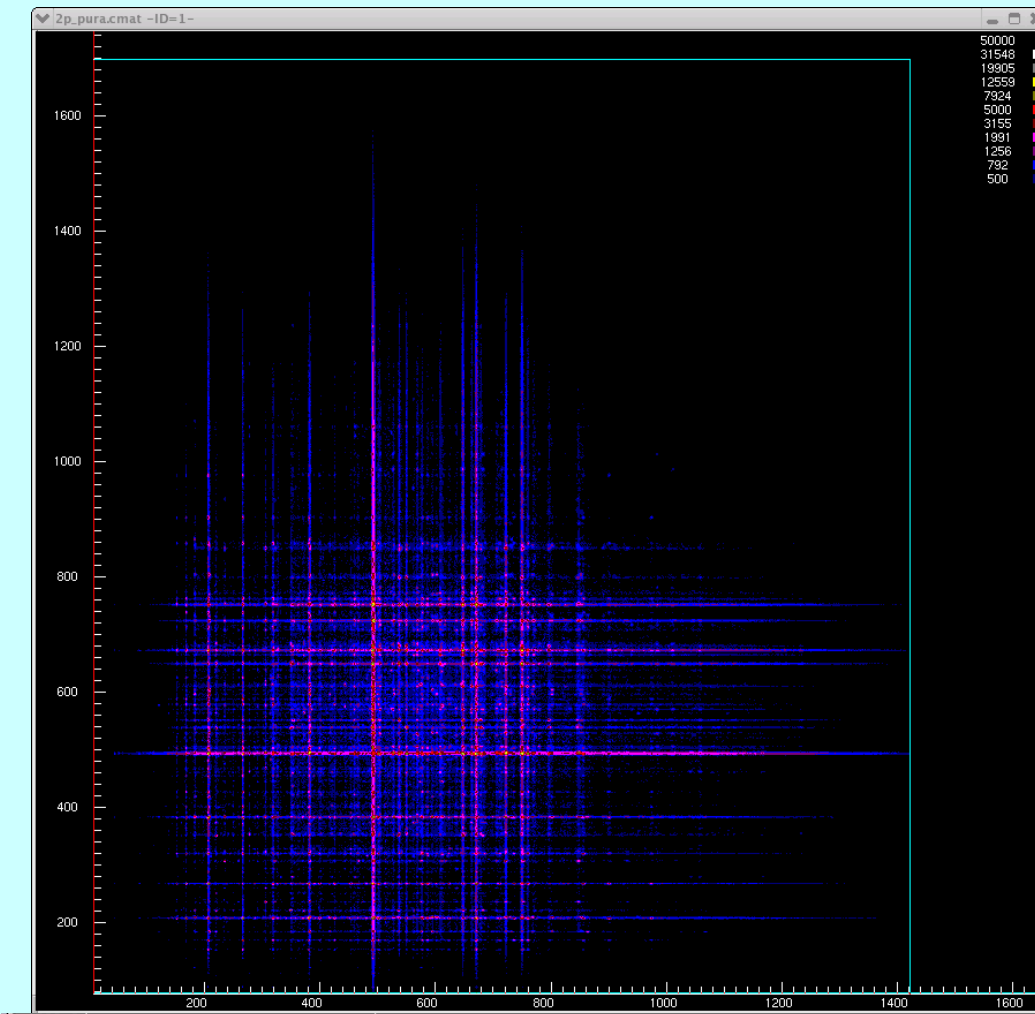
Espectro de tempo

- Diferença de tempo entre dois detectores



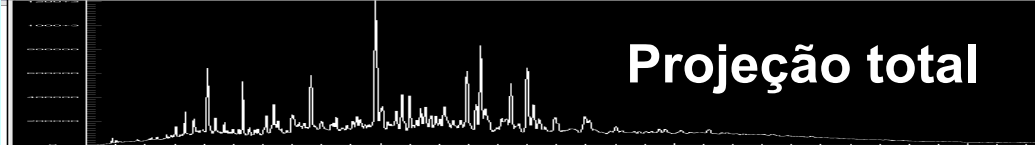
Matriz de coincidências γ - γ

- Espectro bi-paramétrico $E_1 \times E_2$

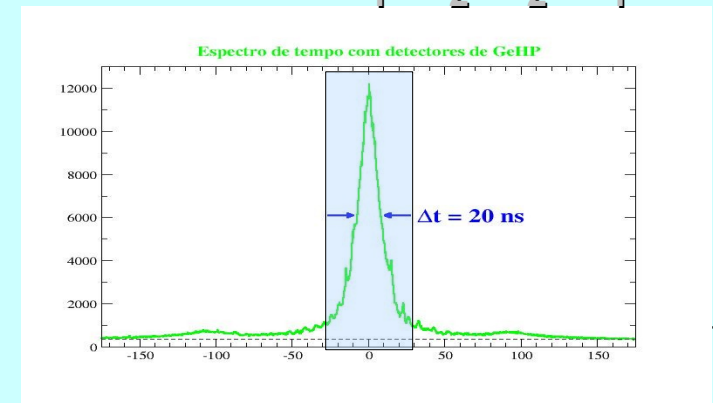


Matriz em perspectiva

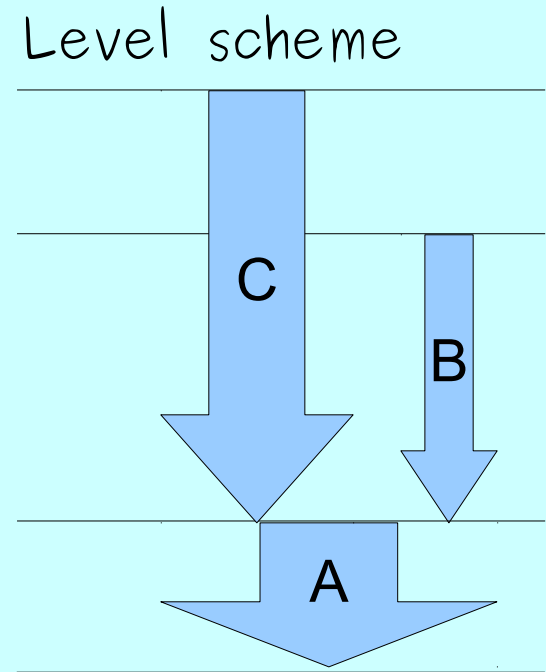
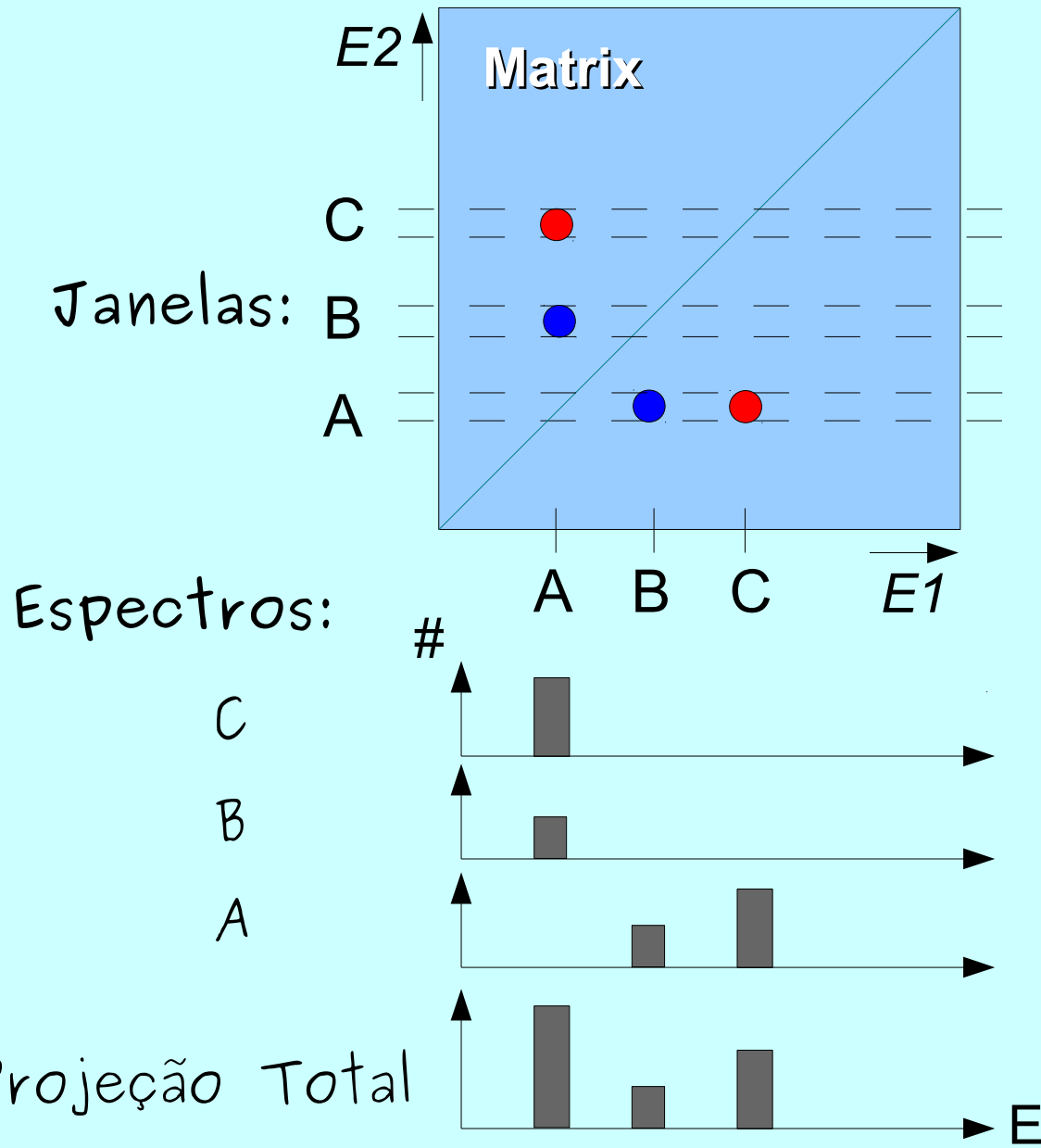
Evento: $E_1, E_2, T_2 - T_1$



Projeção total

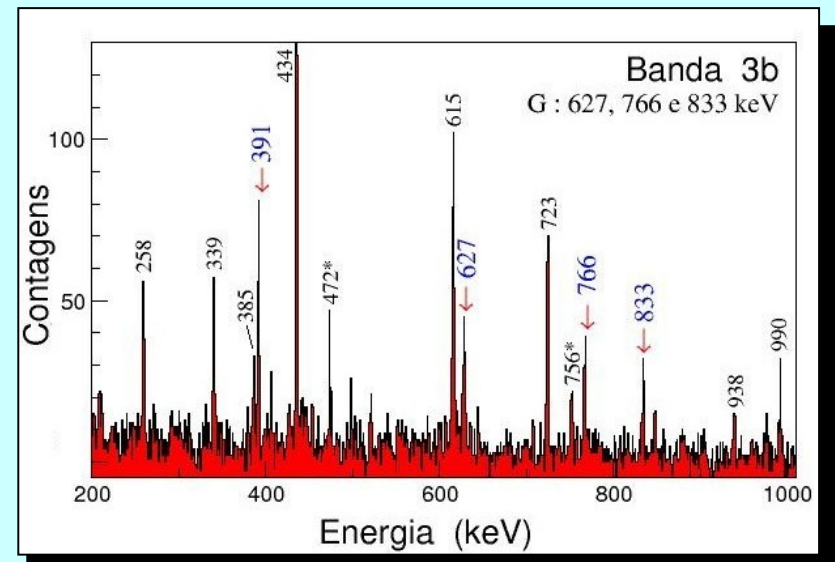
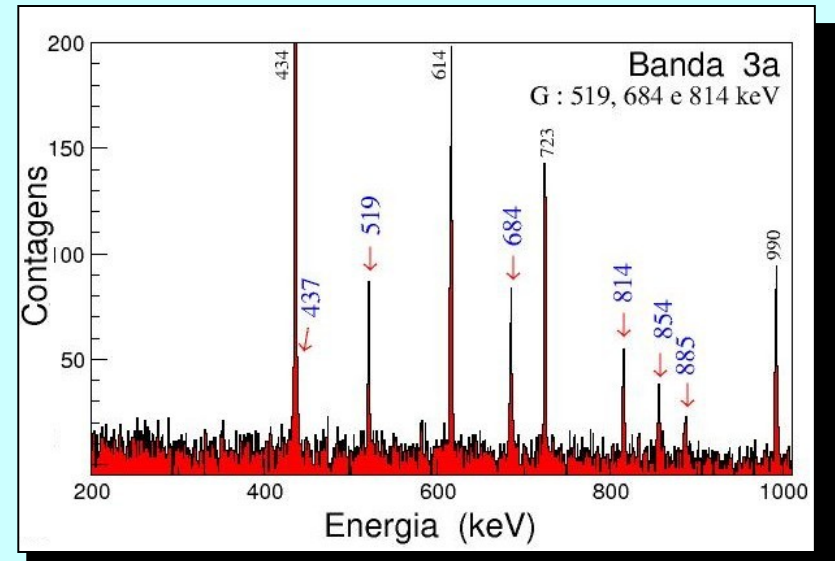
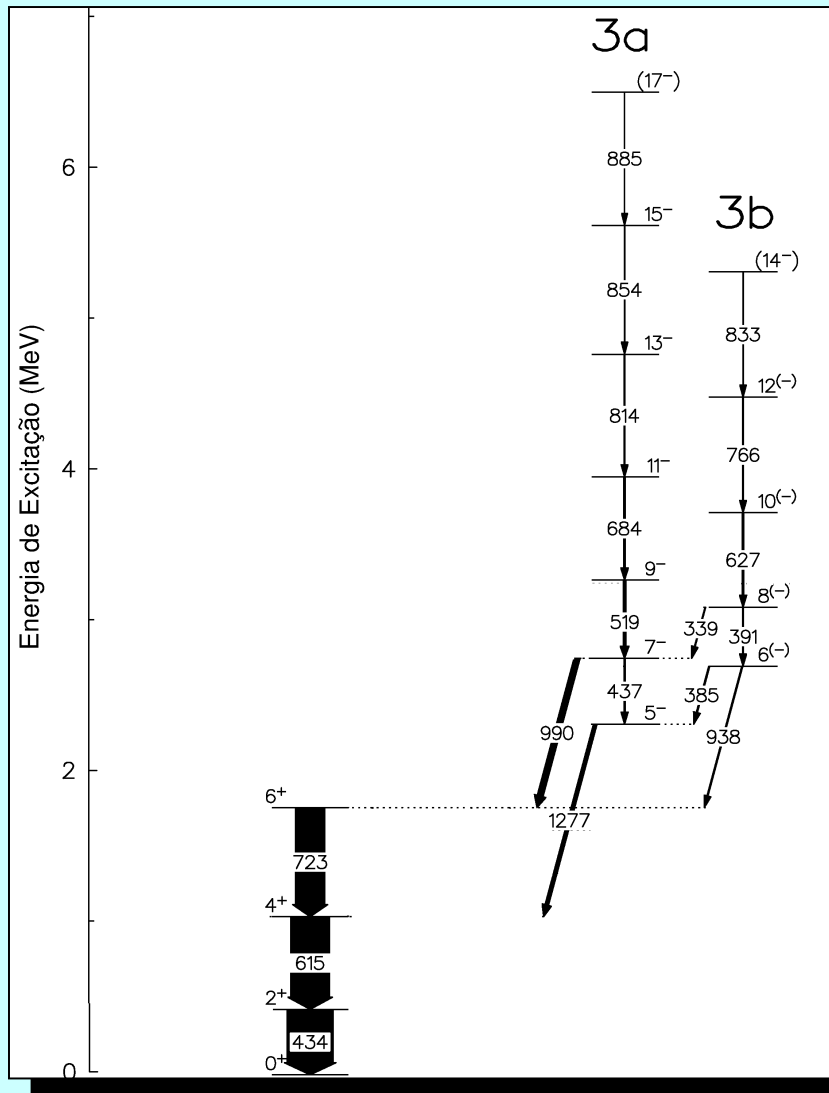


Janelas x Esquema de níveis



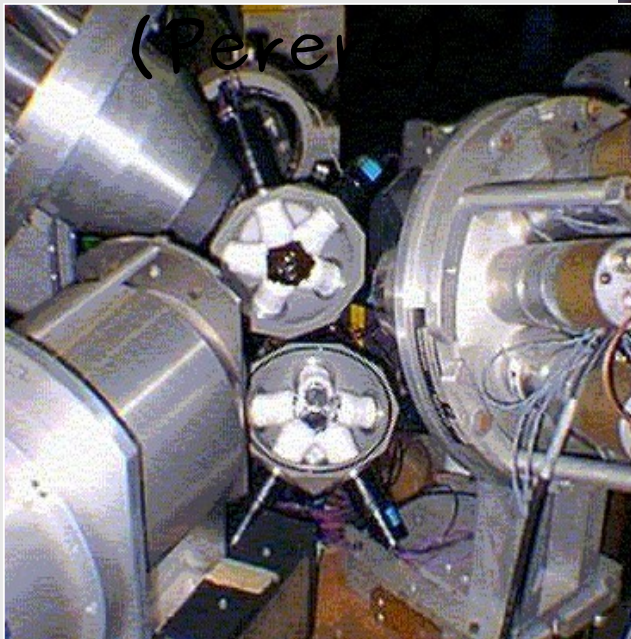
Exemplo- Janelas x Esquema de níveis

Dados ^{105}Rh



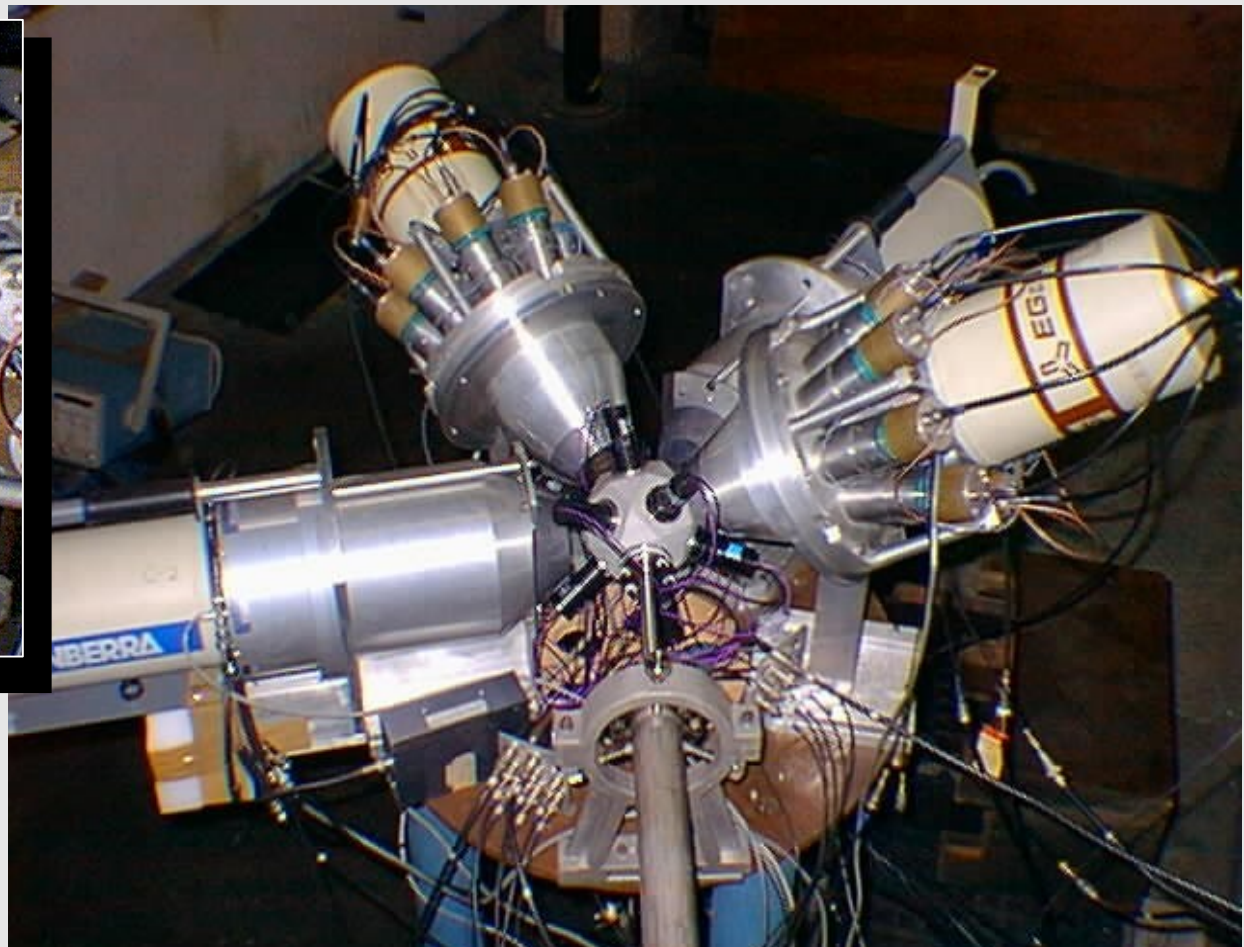
Nosso espectrômetro (IFUSP-DFN)

- Sistema Ancilar de Cintiladores (Saci)
- Pequeno Espectrômetro de Radiação Eletromagnética com Rejeição de Espalhamento

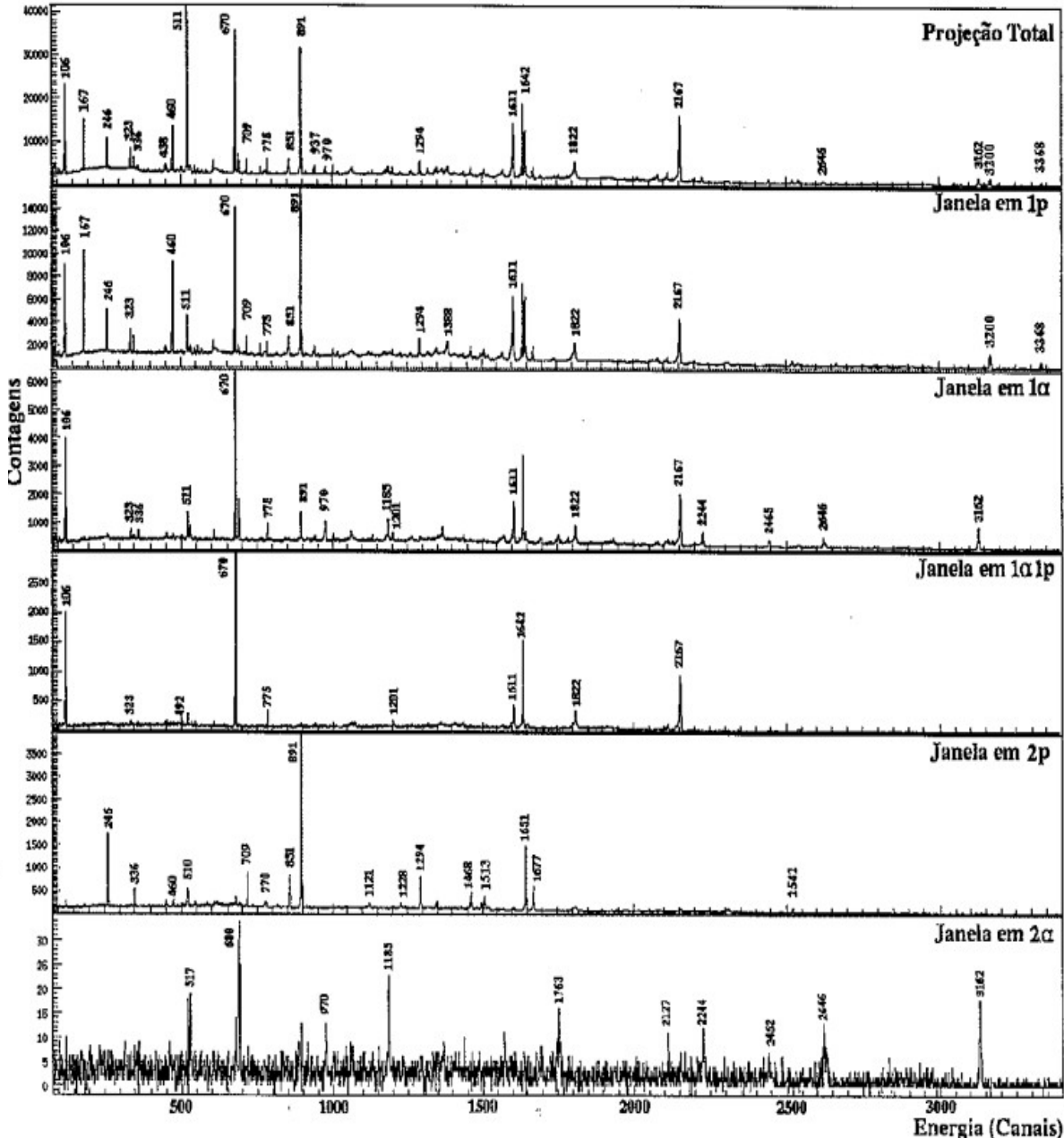
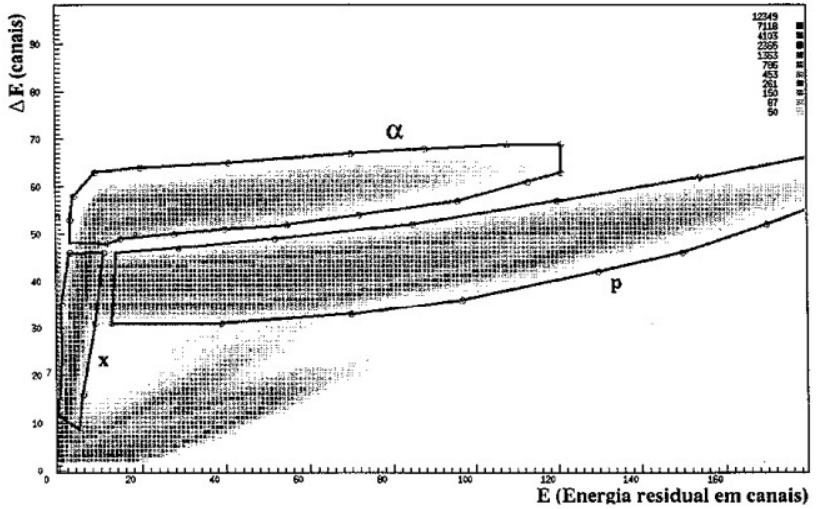


4 GeHP c/ AC

11 NaI (phoswich)

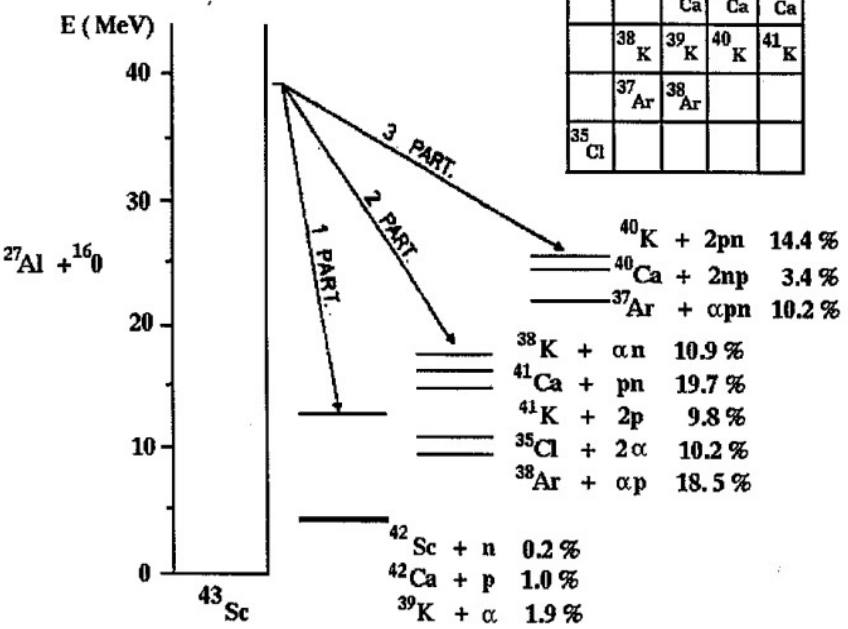


γ -p ($^{16}\text{O} + ^{27}\text{Al}$)



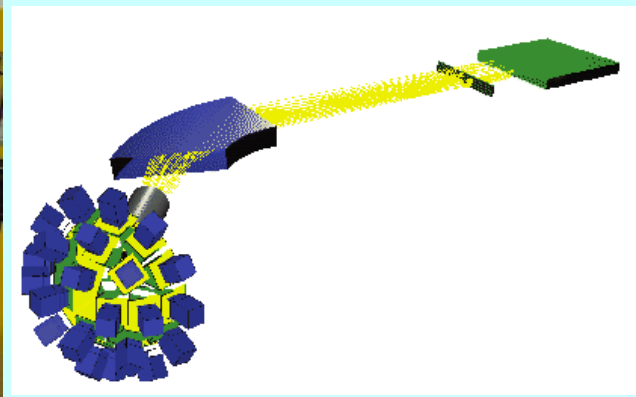
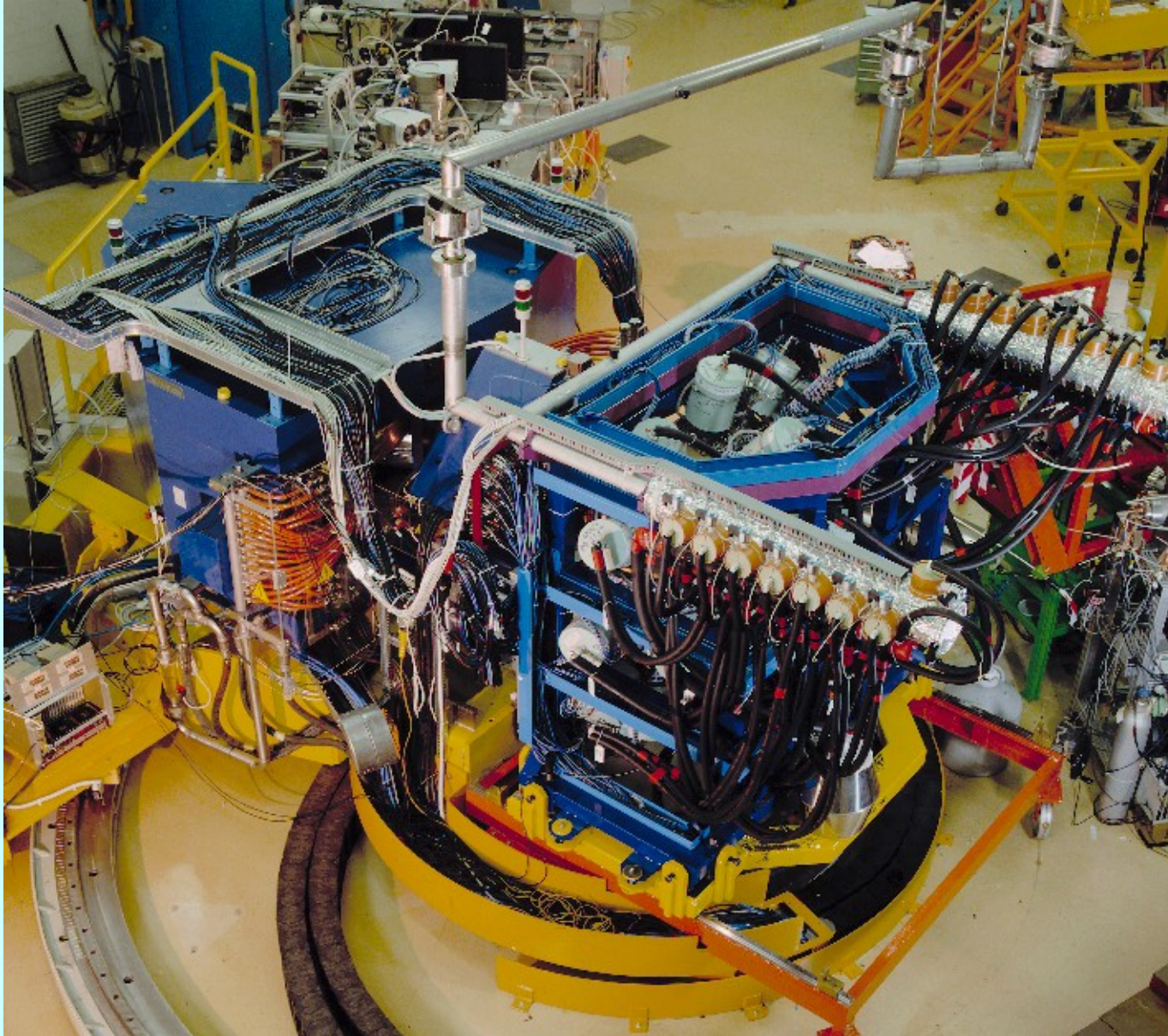
$^{27}\text{Al} + ^{16}\text{O}$ 40 Mev

			42 Se	43 Se
		40 Ca	41 Ca	42 Ca
	38 K	39 K	40 K	41 K
	37 Ar	38 Ar		
35 Cl				



Energia (Canais)

Espectrômetro y típico

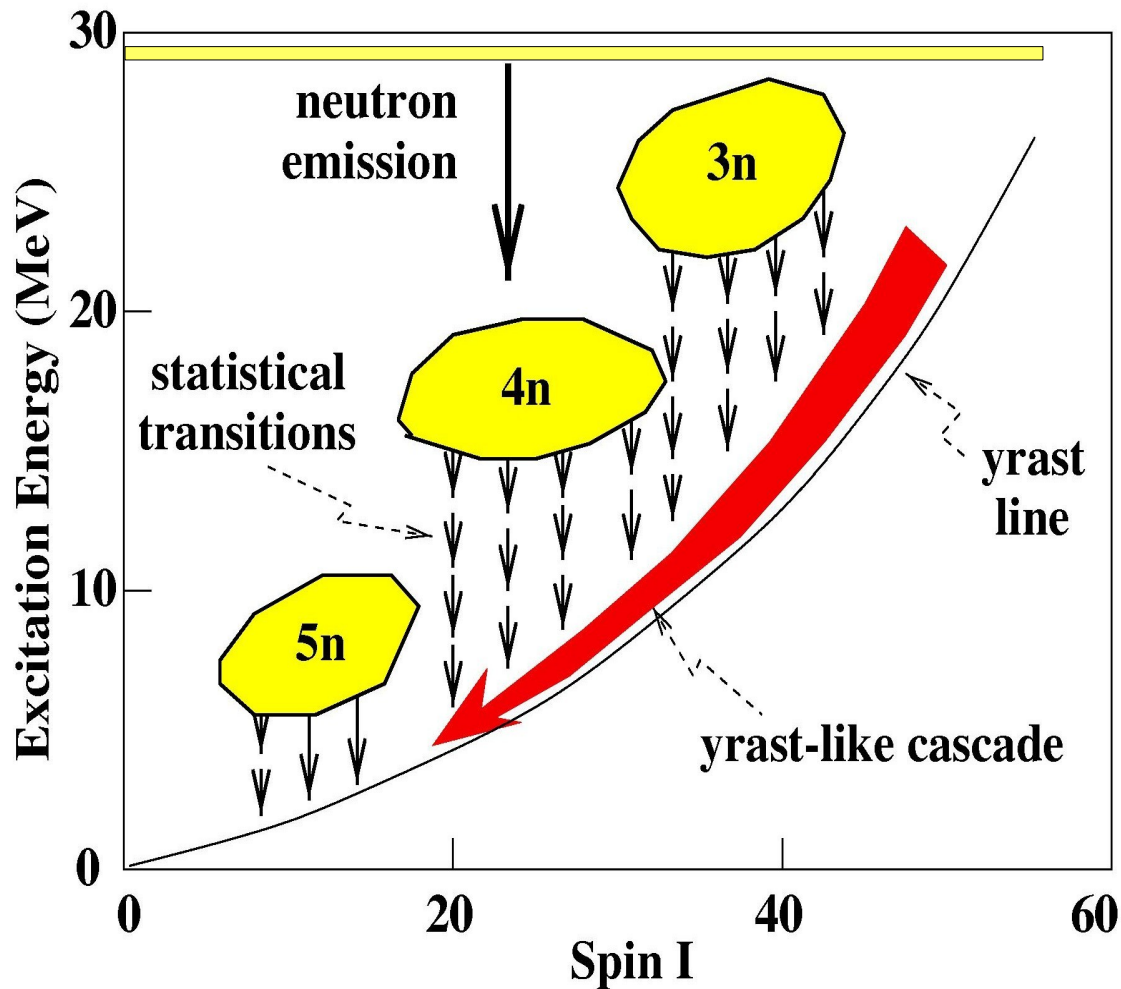


PRISMA-CLARA
LNL-INFN

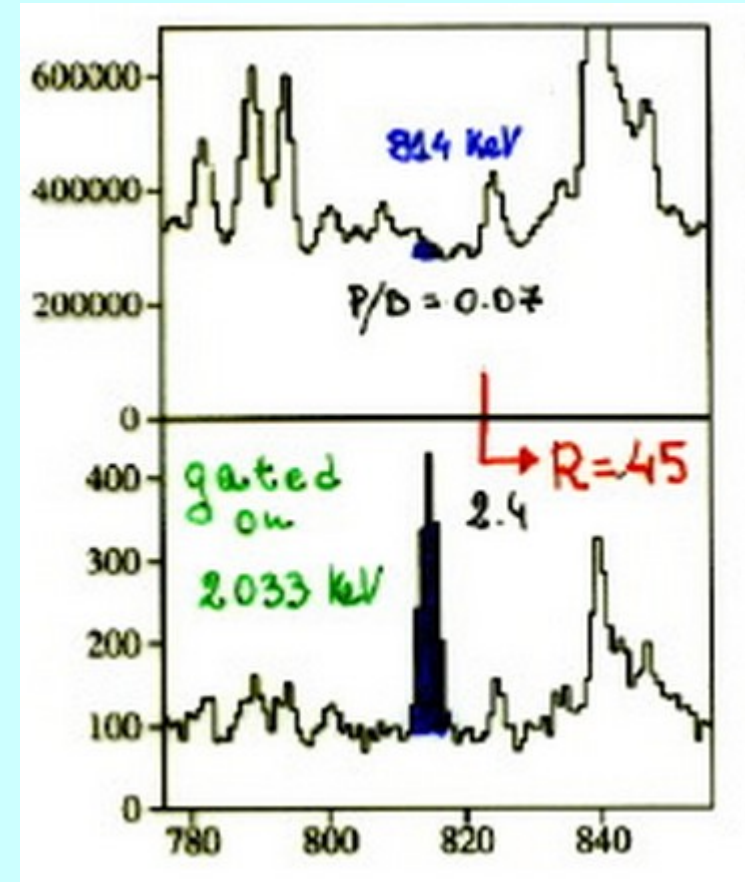
Por que tão
complexo?

Complexidade do espectro γ

Ex.: Reação de Fusão-evaporação



Singles spectrum



Coincidence spectrum

Compromise: efficiency \times resolving power (R)

O Conceito de poder de resolução

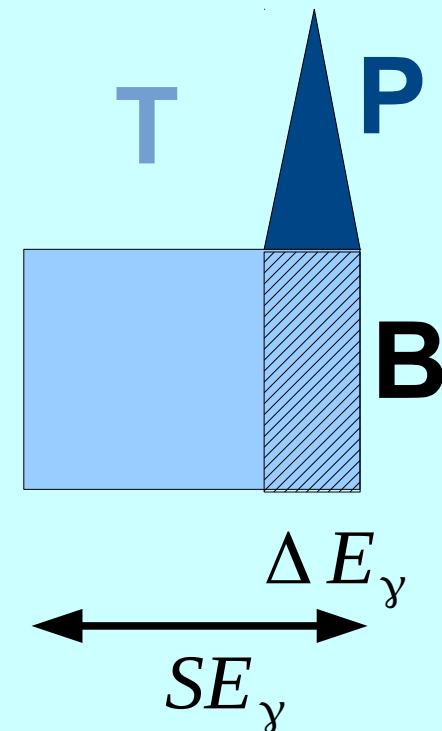
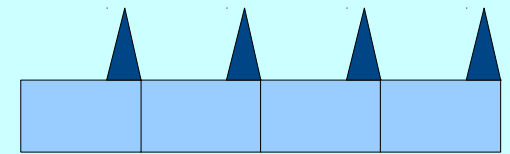
- A razão P/B melhora a cada seleção (janela) feita
- O fator de melhora é o poder de resolução

$$R = \frac{SE_{\gamma}}{\Delta E_{\gamma}} P/T$$

SE_{γ} É a separação média entre picos γ em uma cascata

ΔE_{γ} É a resolução em energia

P/T É a razão pico/total do detector



Multiple γ coincidences

• α : Limite observacional de um espectrômetro

R - Poder de resolução

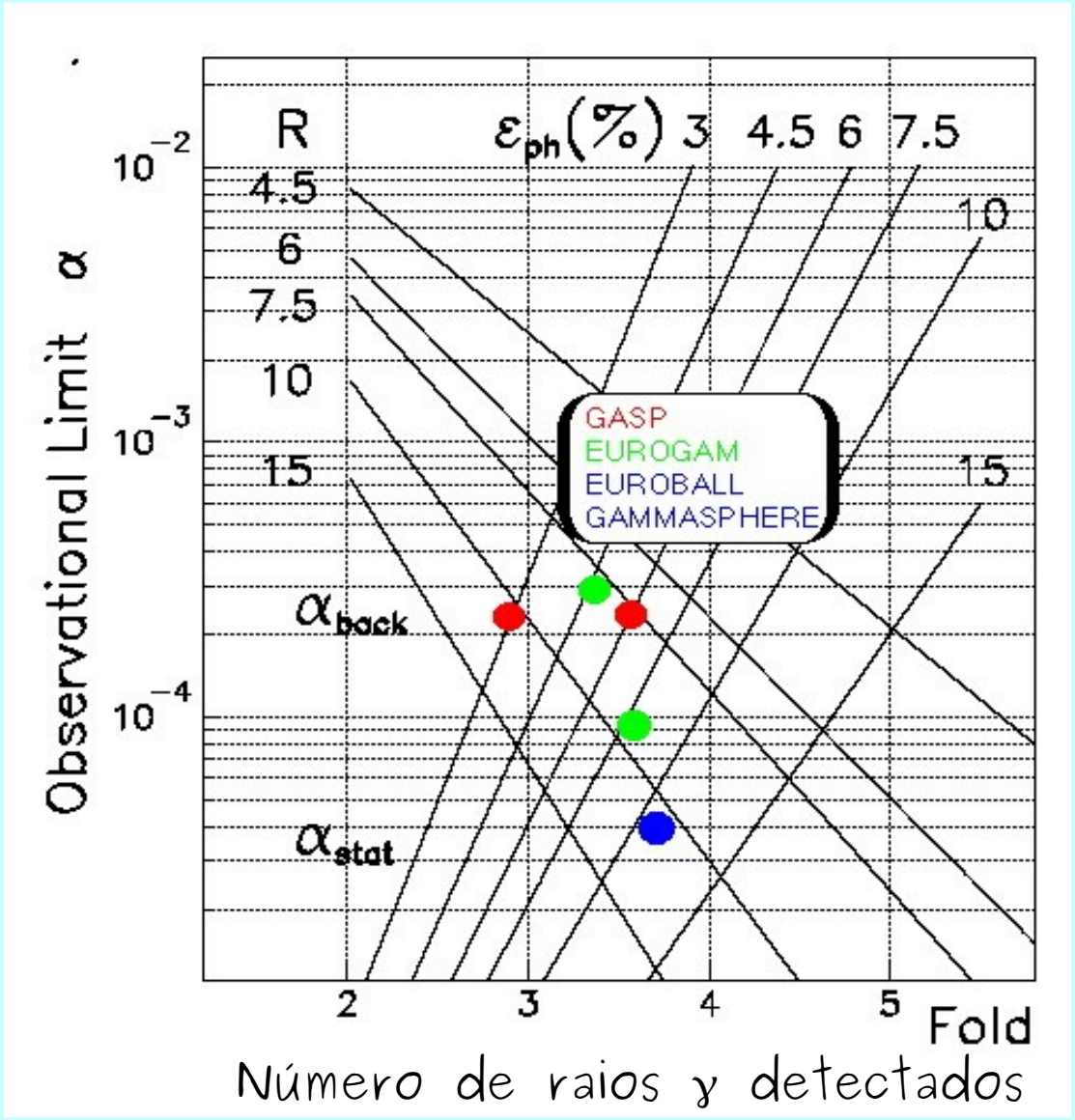
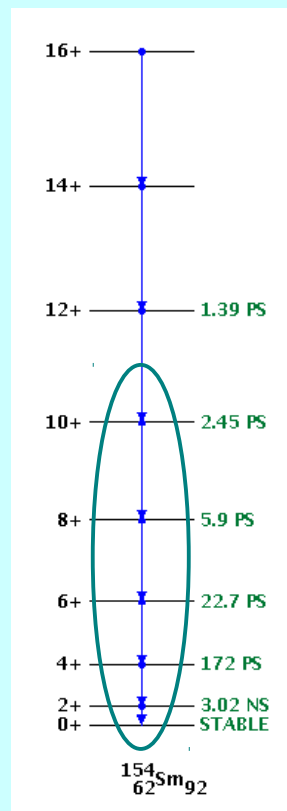
ϵ_{ph} - Eficiência de fotopico

$$R = \frac{SE_{\gamma}}{\Delta E_{\gamma}} P/T$$

$$\alpha_{back} = \frac{(P/B)_F}{R_0 (kR)^F}$$

$$\alpha_{stat} = \frac{N_F}{N \epsilon_0 (k \epsilon_{ph})^F}$$

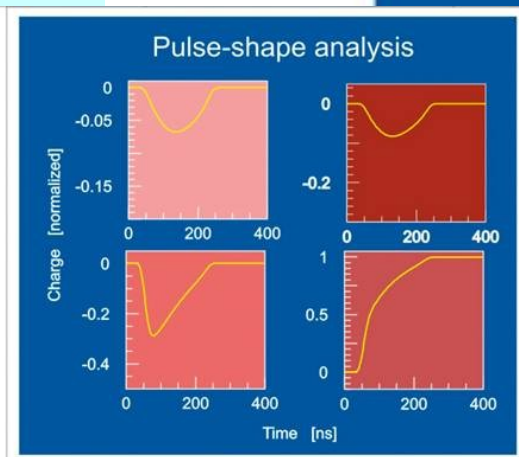
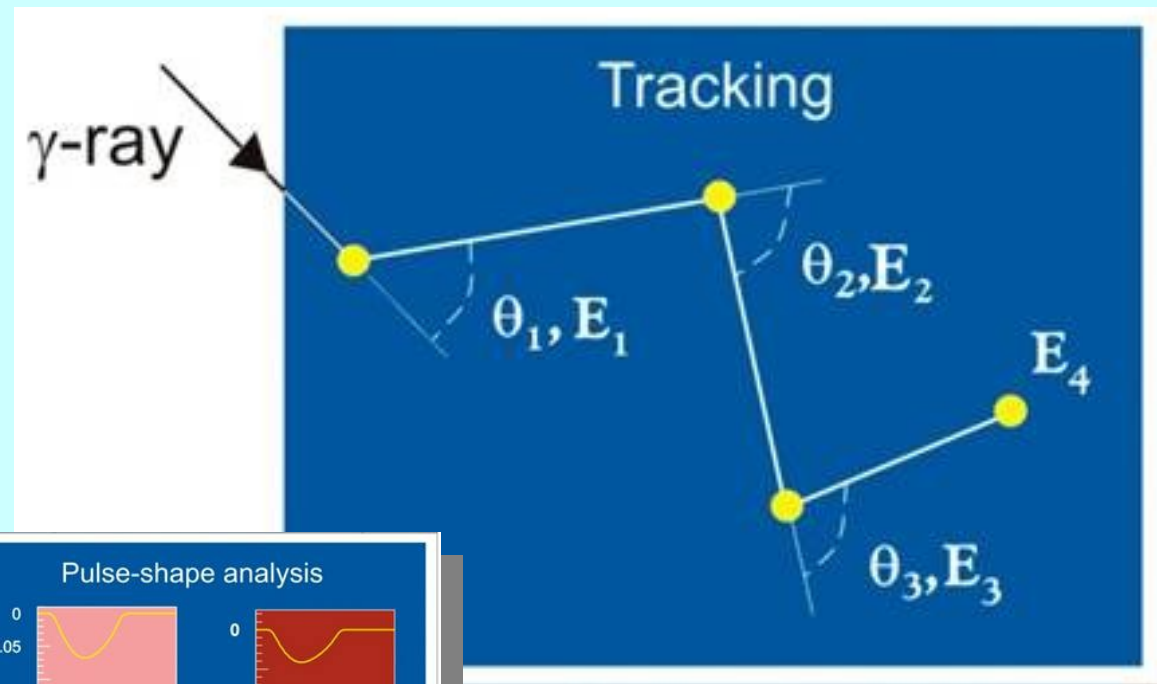
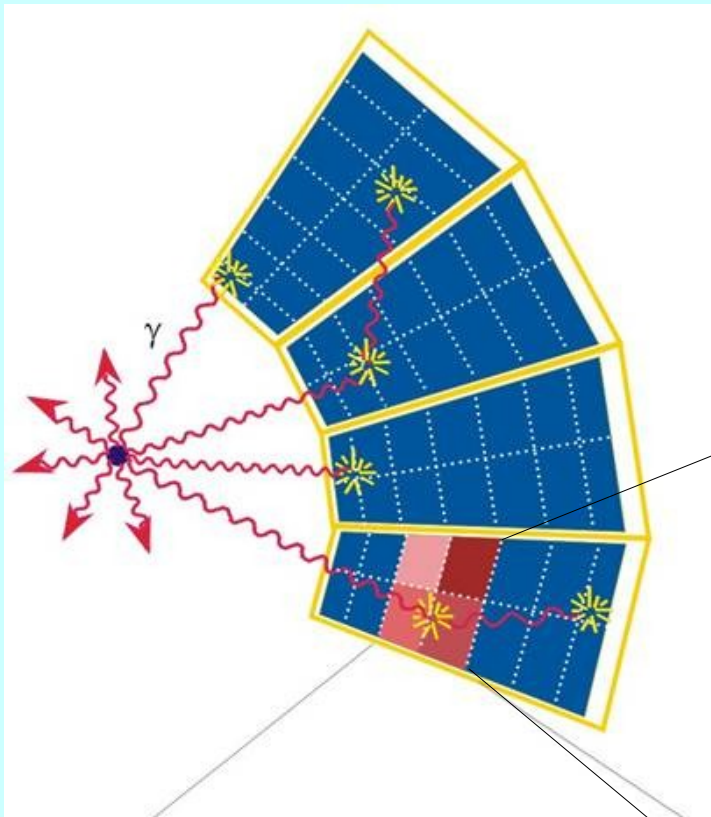
$N_F = 100; (P/B)_F = 0,2$



Ponto ótimo: $\alpha_{back} \approx \alpha_{stat}$

O Rastreamento γ (tracking)

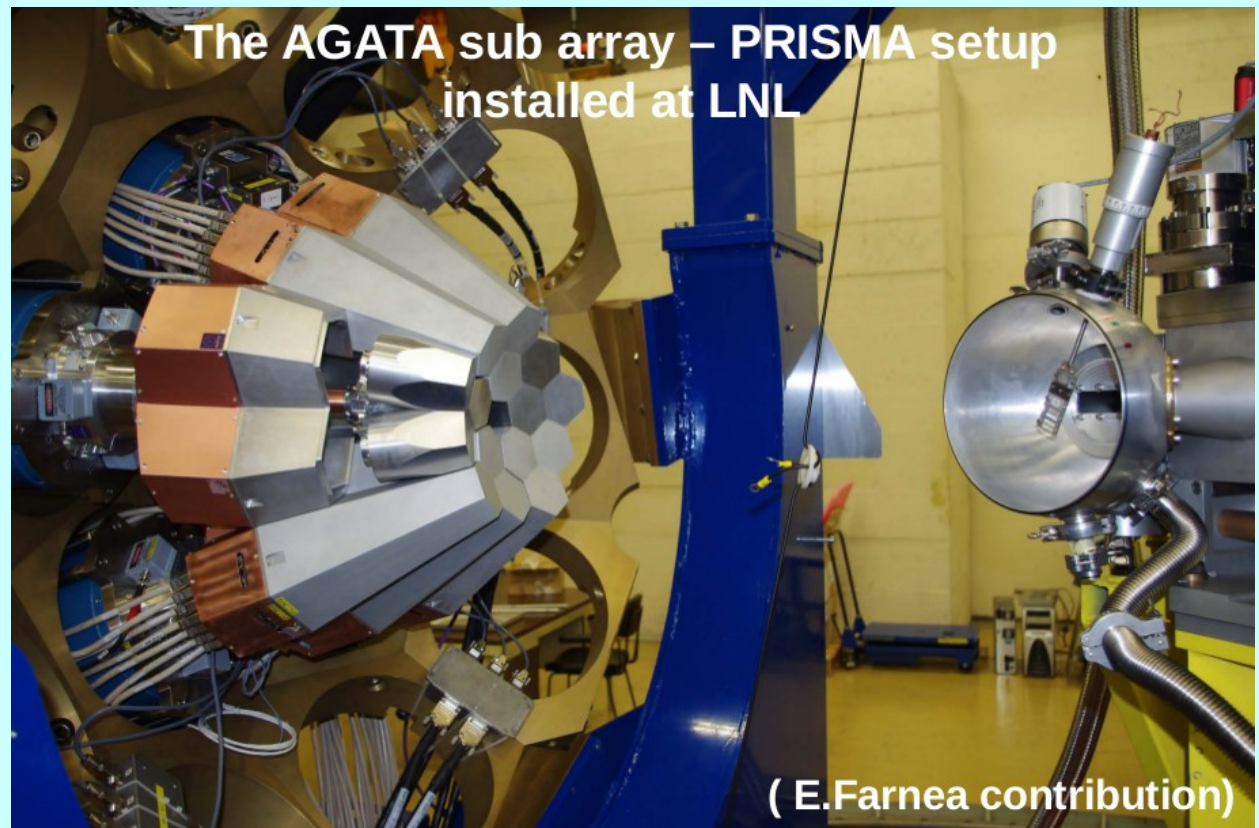
- Determinação da posição e da energia das interações γ em 3 dimensões
- Determinação seqüência de espalhamentos γ



Análise da forma de pulsos - DSP (FPGA)

Espectrômetros em construção

- Gretina (EUA); Agata (UE)



Eletrônica (GRETINA)

Digitizer module (LBNL)

14bit, 100 MHz
Energy
Pole/zero correction
Leading edge time
Constant fraction time
Pulse shape

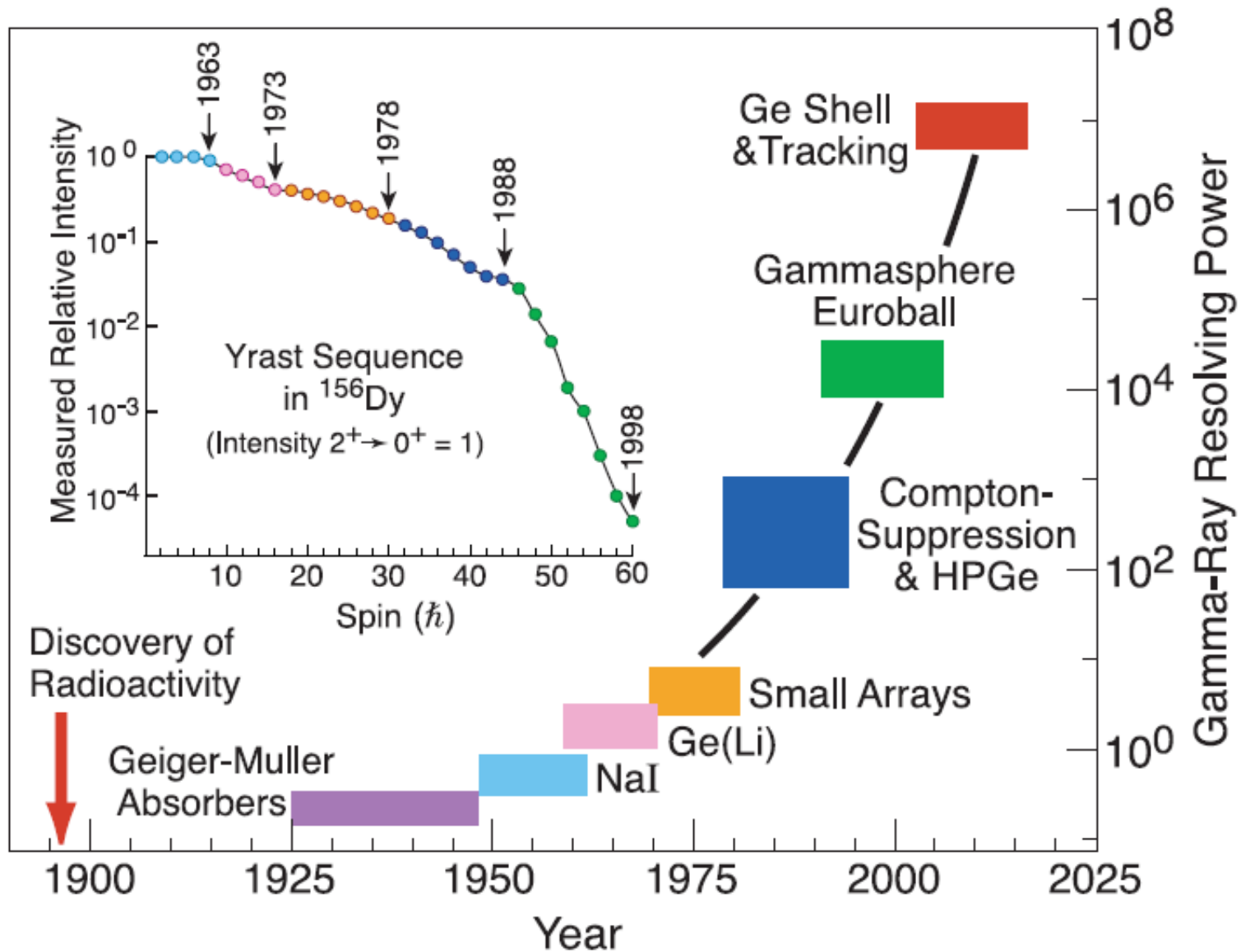


Trigger Timing & Control module (ANL)

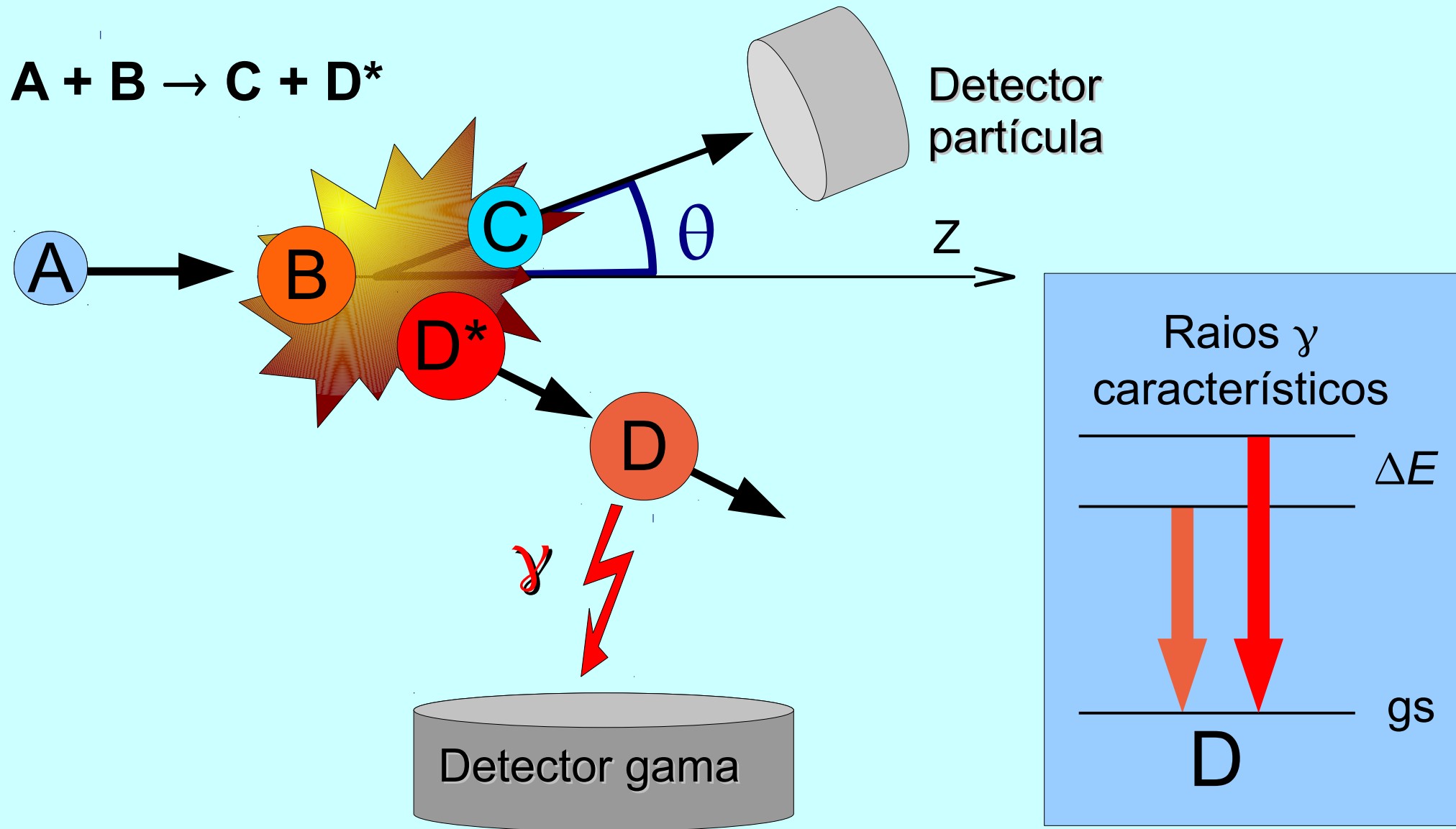
Fast trigger <250 nsec
Trigger decision time <20 μ sec
Trigger conditions
Multiplicity
Sum energy
Hit pattern



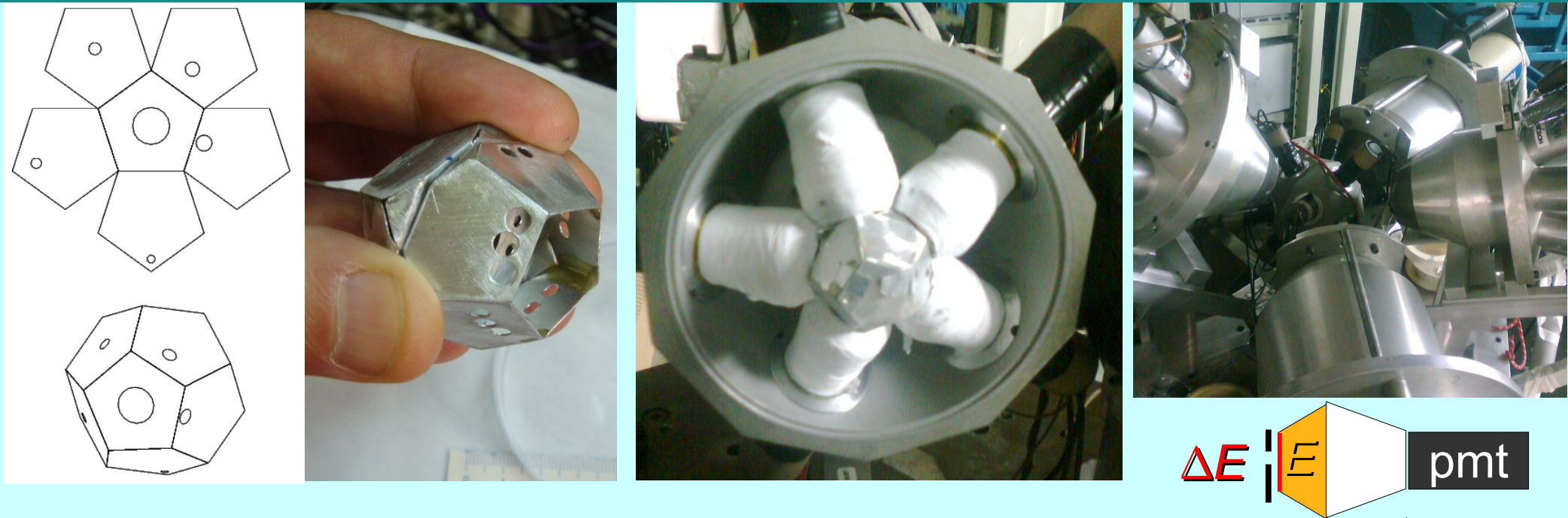
Evolução do poder de resolução



γ -p para medida de reação

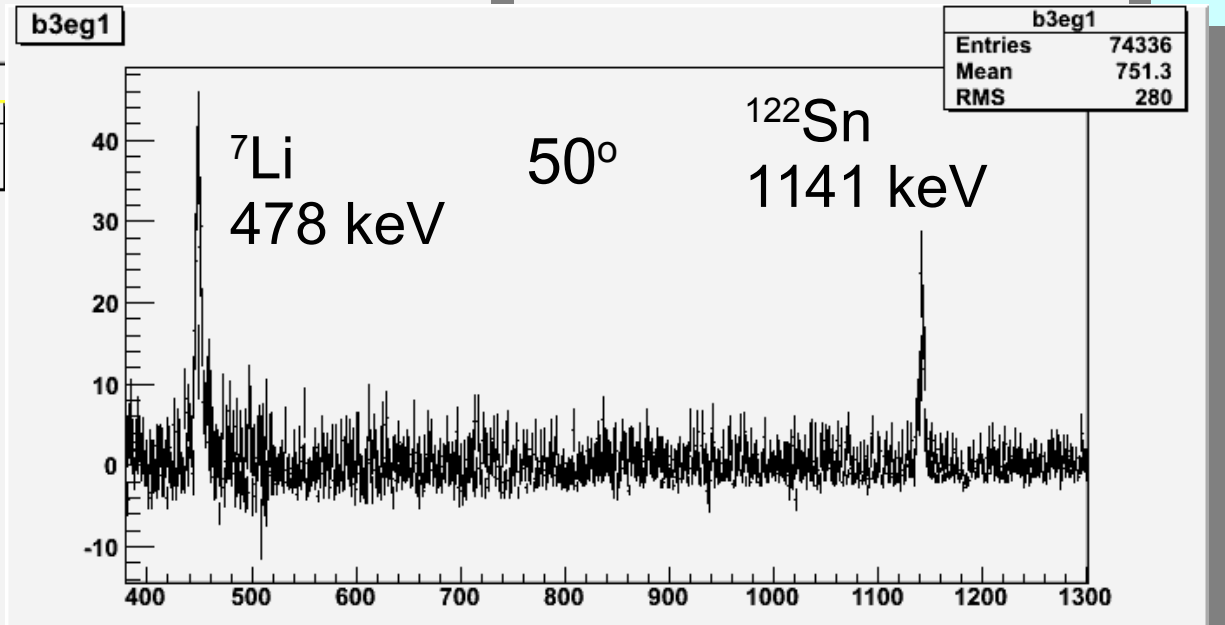
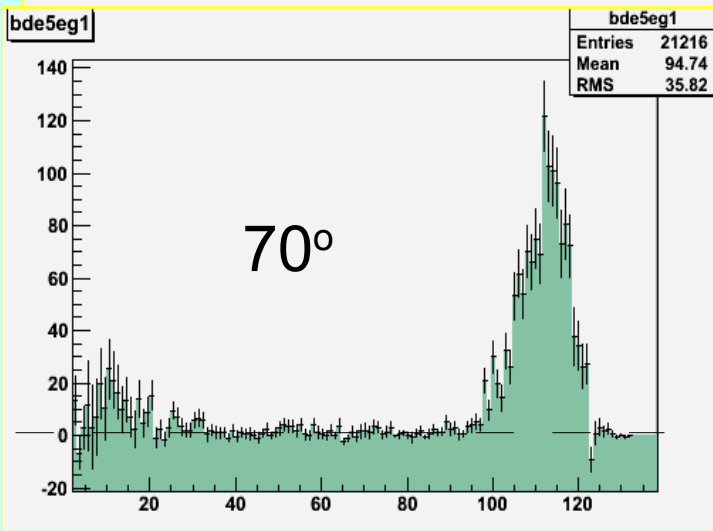
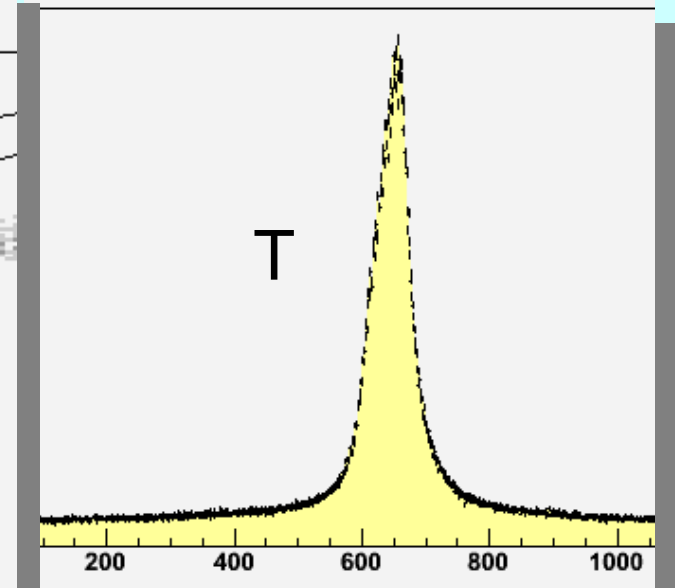
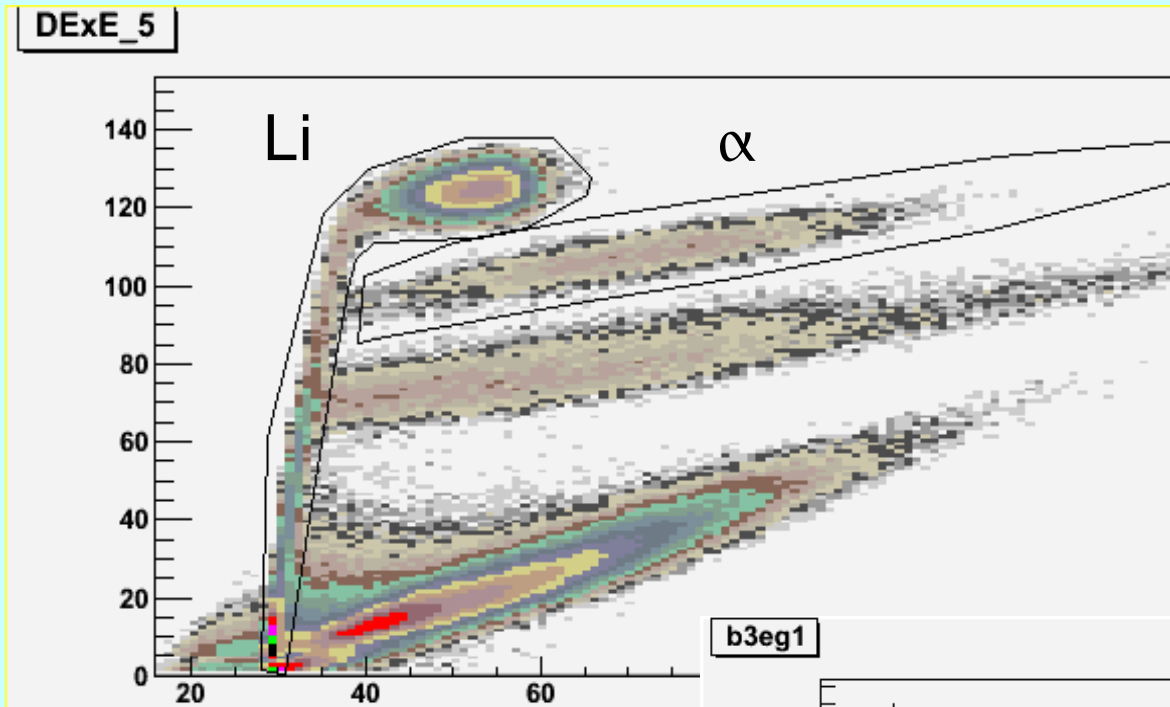


Adaptação do Saci para medidas de reações

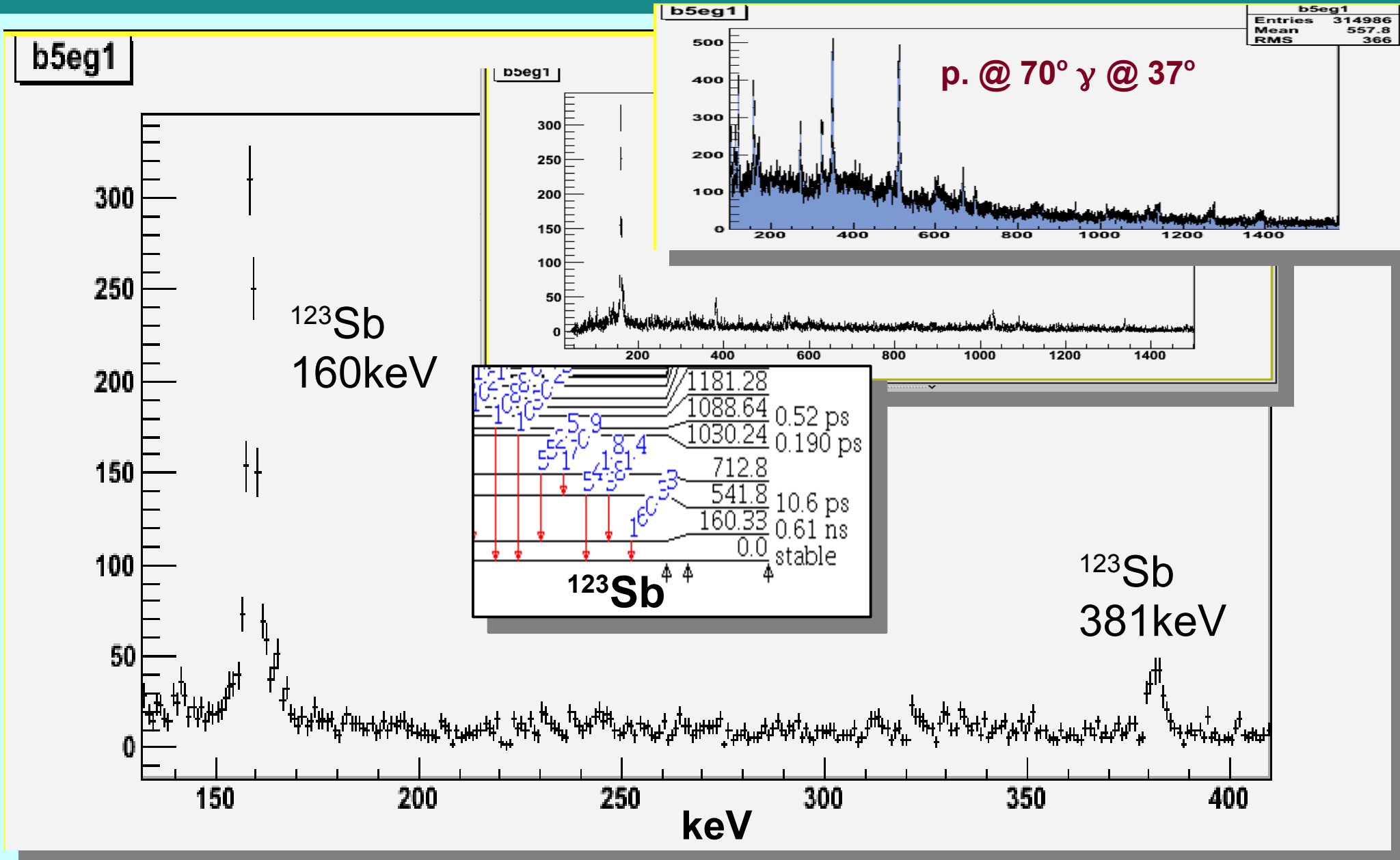


- **Colimadores** - $\Delta\Omega(\theta)$ ($\Delta\theta \leq 10^\circ$; limitação da taxa)
- Furos de 0.5-3.5 mm (placas de Al)
- 11 angulos (30, 40, 50, 60, 70, 80, 100, 120, 130, 140)
- Bases ativas nas PMT's (taxas até 100 kHz cada)

γ -p (${}^7\text{Li} + {}^{122}\text{Sn}$)



Banana de α 's

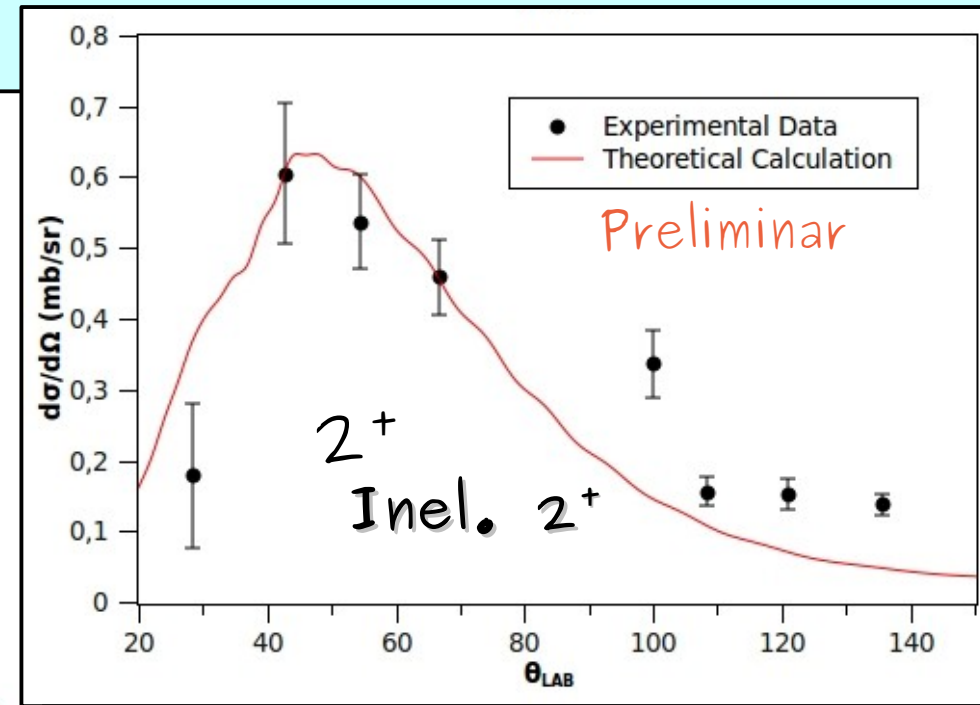
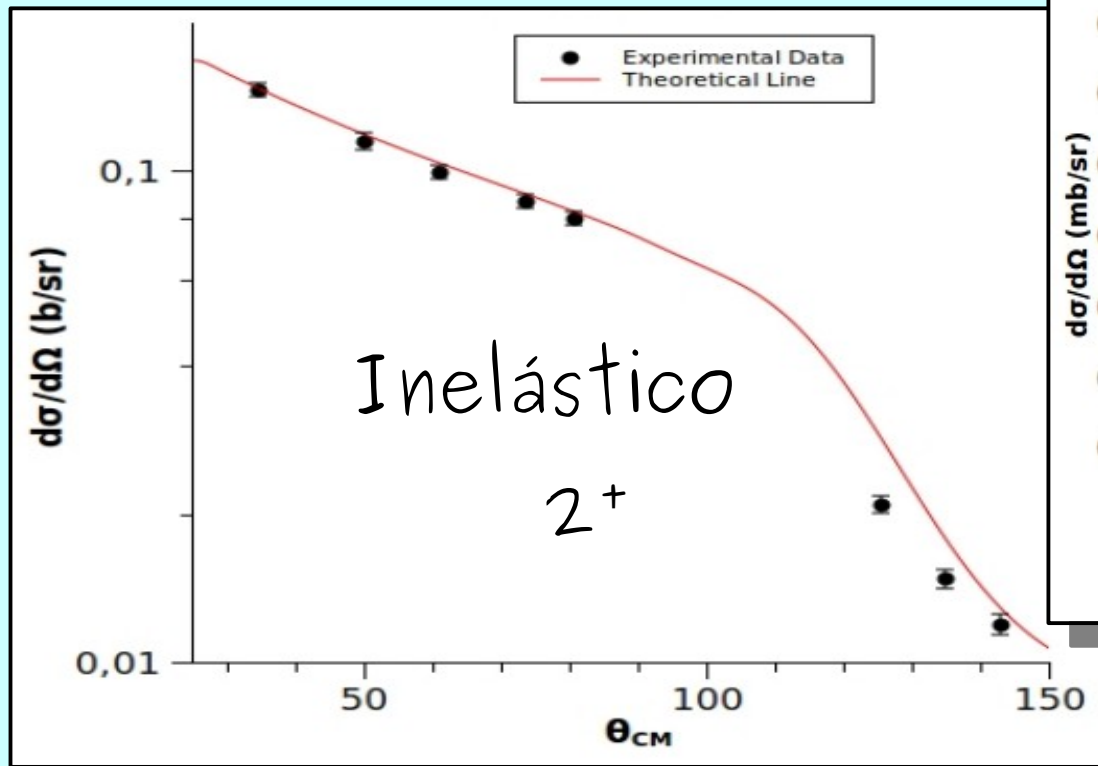


γ -p Resultados recientes

V.B. Zagatto (MS, IFUSP)
Nucl. Inst. Meth. A 749 (2014) 19

V.B. Zagatto (DR)
 ${}^7\text{Li}+{}^{120}\text{Sn}$ @ 24MeV

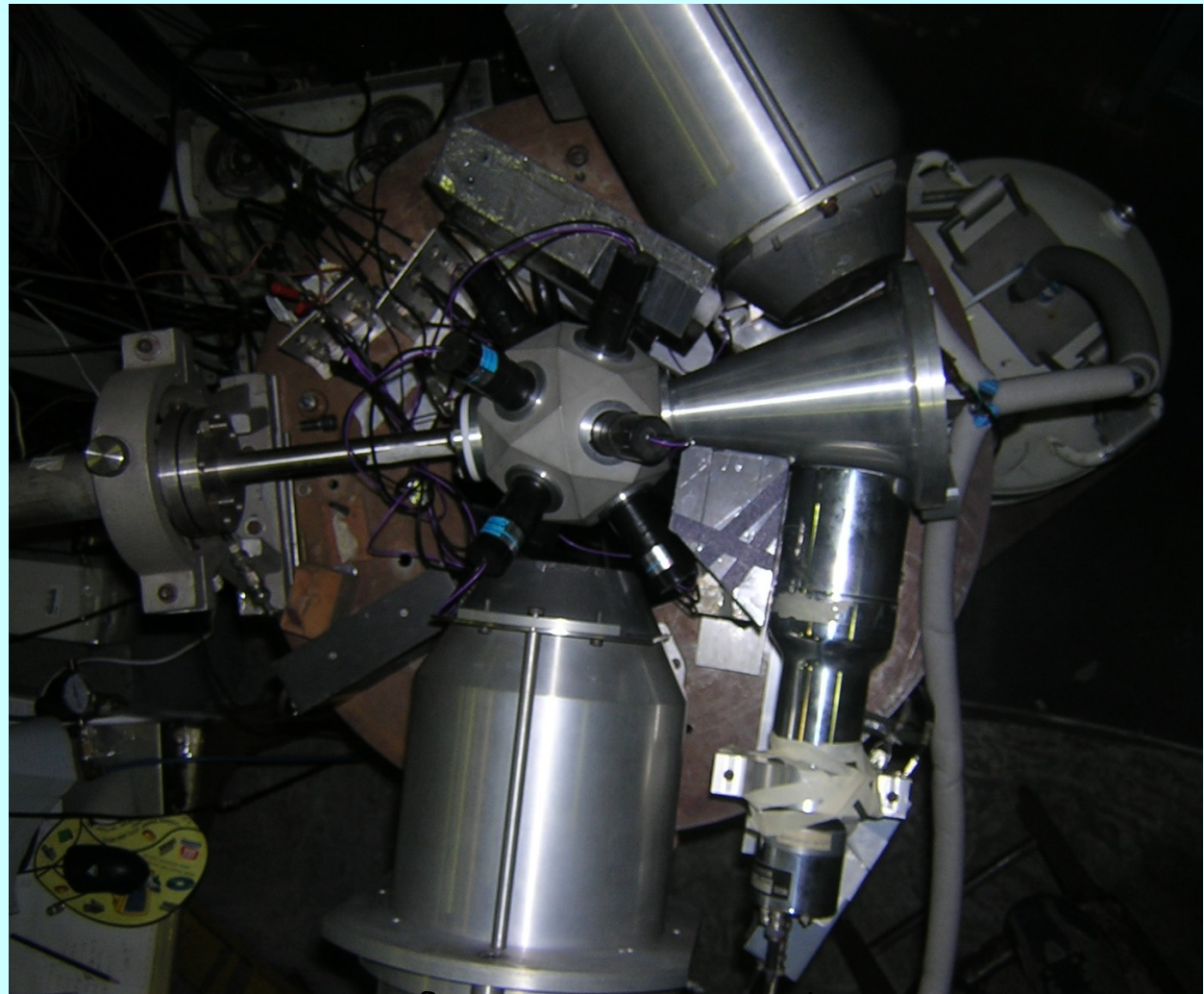
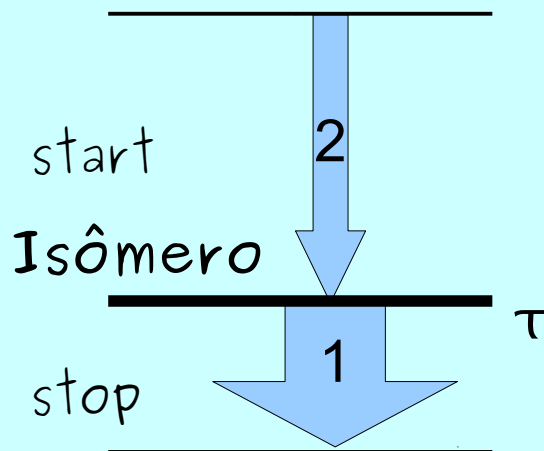
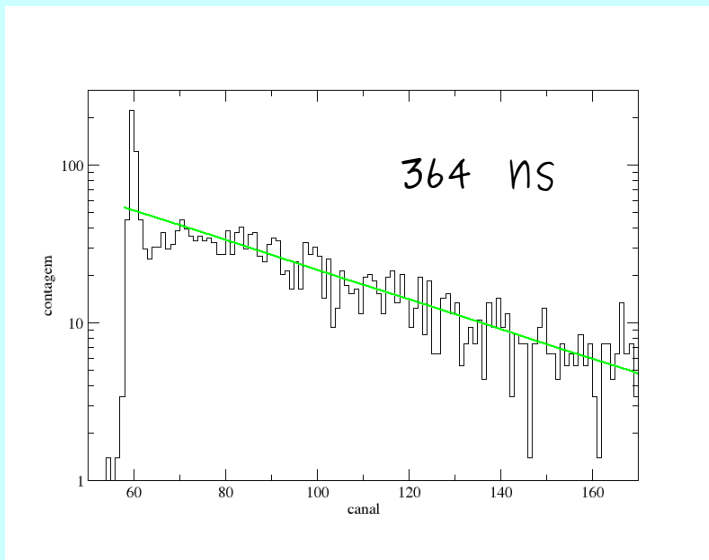
${}^{18}\text{O}+{}^{110}\text{Pd}$ @ 54MeV



FRESCO
SPP ← CDCC (bu)
23/40

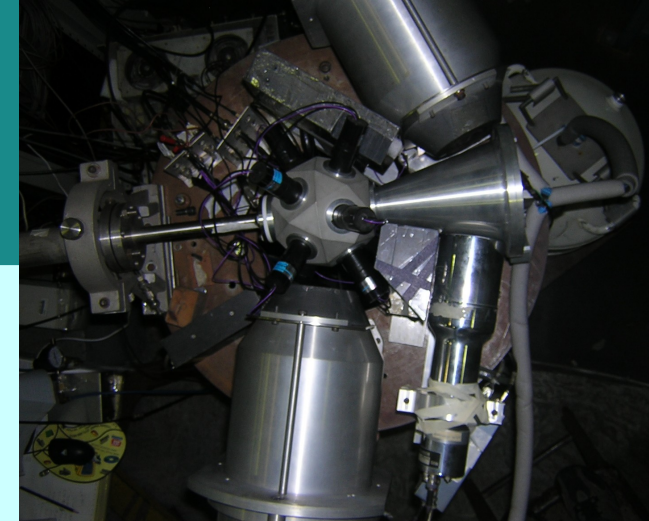
SISMEI

- Sistema de medidas de estados isoméricos

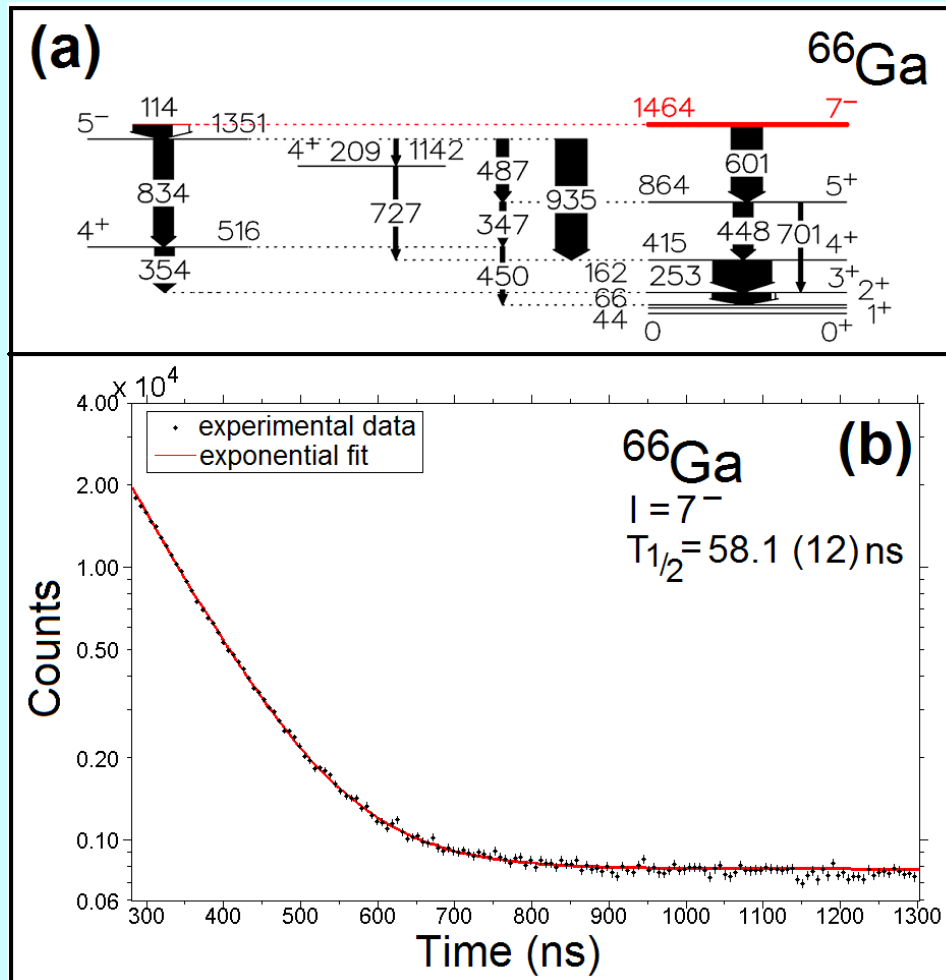


D.L. Toufen (Mestrado IFUSP)

SISMEI (Isomers)



Resolvendo inconsistências



$$T_{1/2} = 57.3 (14) \text{ ns}$$

A. Filevich et al., Nucl. Phys. A 295, 513, 1978.

or

~~$$T_{1/2} = 39 (2) \text{ ns}$$~~

T. Kouda et al., Ann. Rep. 1996, Radio-isotope Center, Tohoku University, Japan, p. 19, 1997.

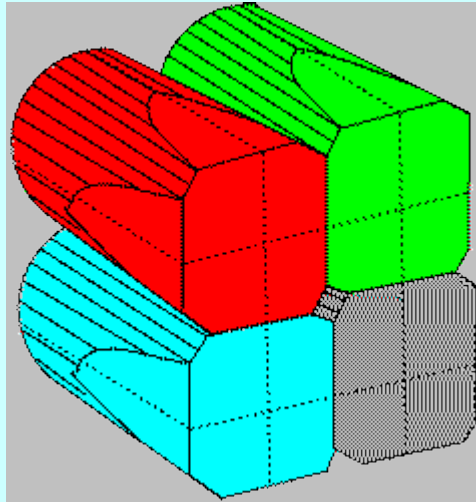
Próxima aula – Perspectivas

- No IFUSP
- Colaborações internacionais
- Núcleos exóticos (Feixes Radioativos)
- Momentos angulares extremos
- Superpesados
- Astrofísica nuclear (Baixa energia)
- Hipernúcleos

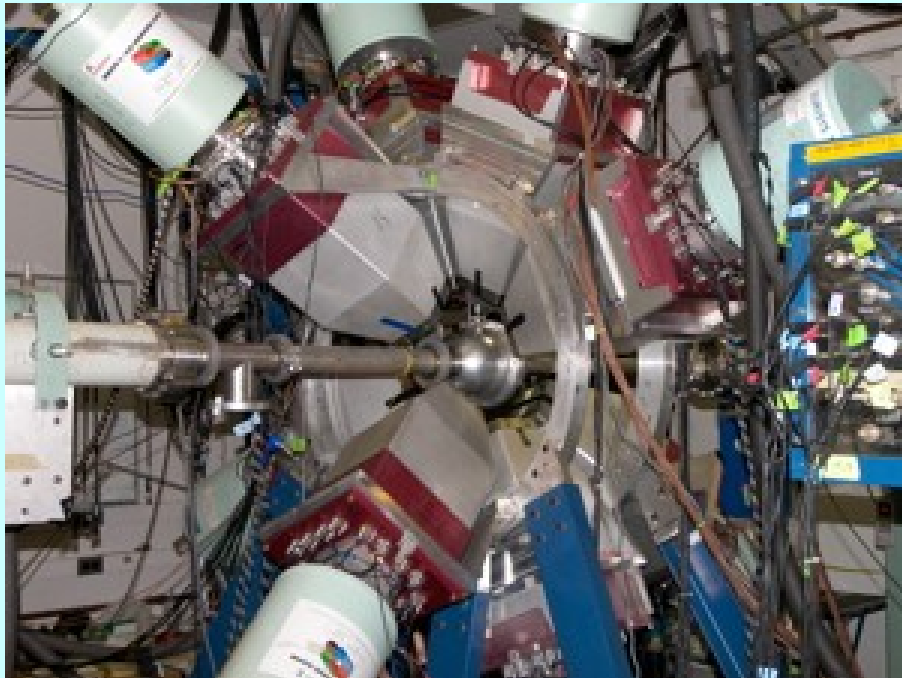
Extras

Detectores y segmentados

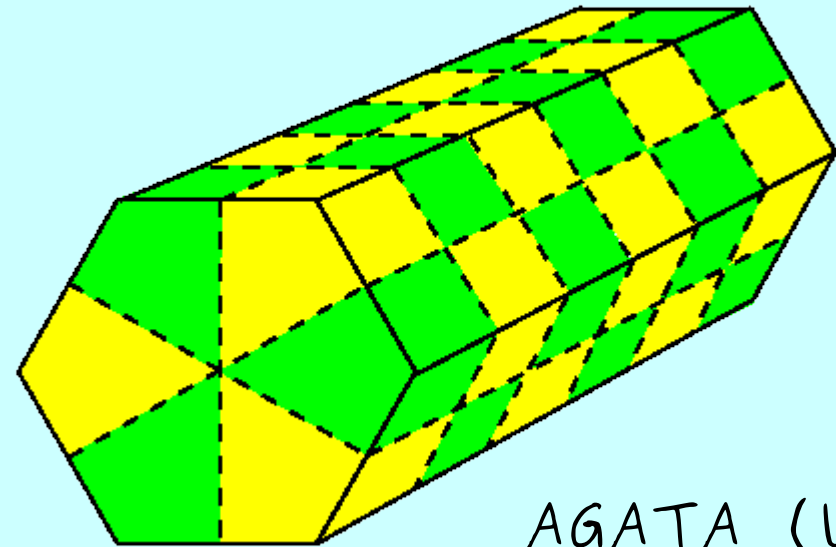
- Clover



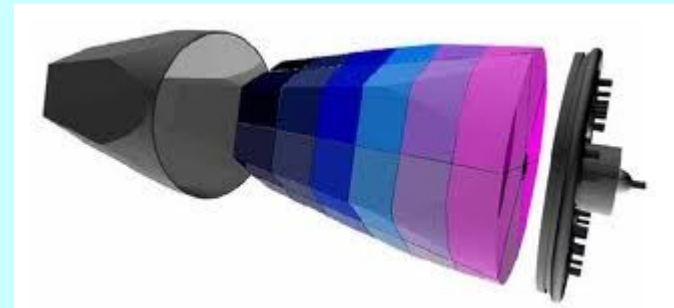
Yrast-Ball
(Yale)



- Multi-segmentado
(localização da interação)

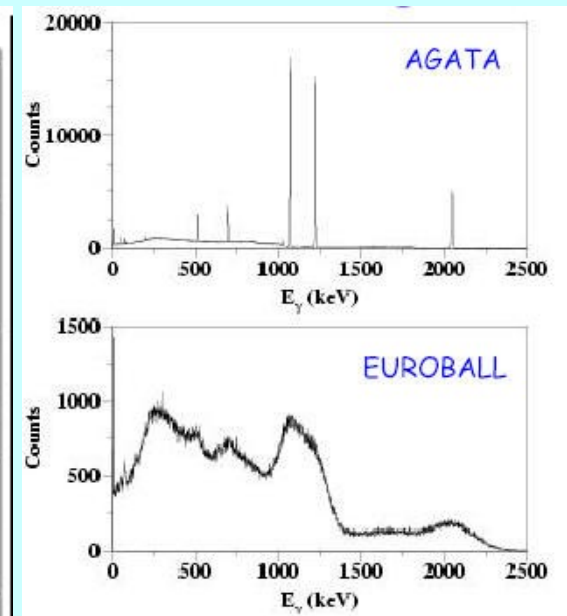
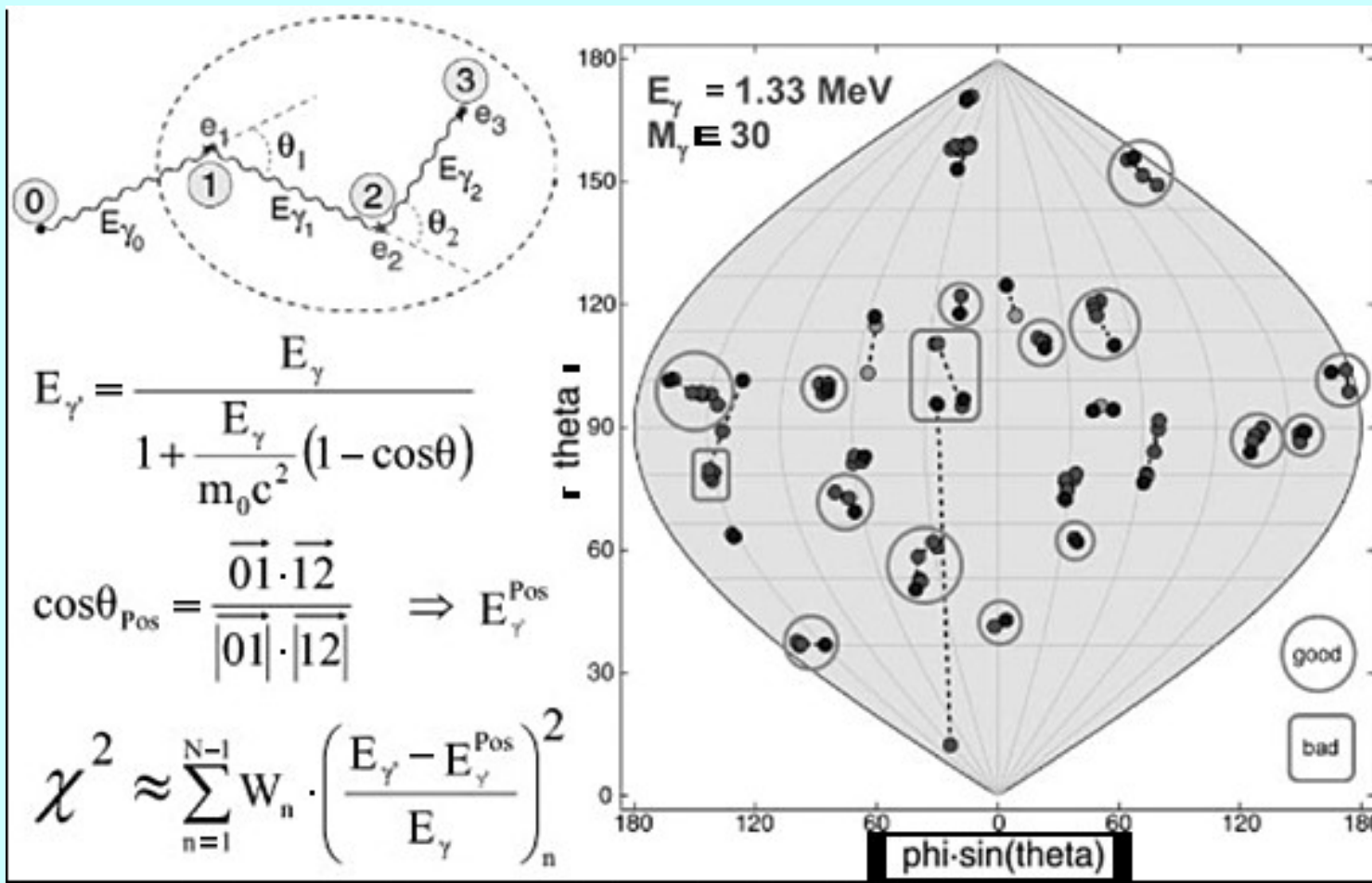


AGATA (UE)



γ -ray tracking

- "História" da detecção de um raio gama
- Identificação de eventos



Resolução 0.5%
 Eficiência 50%
 29/40

Espectrômetros de tracking

- Espectrômetros:

AGATA (UE);

GRETA (EUA)

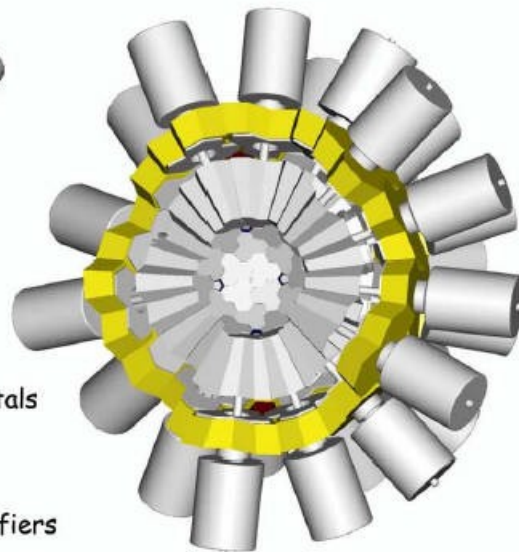
Detectors



Ge crystals:
Hexaconical shape
90-100 mm long
80 mm max diameter
36 segments
Al encapsulation:
0.6 mm spacing
0.8 mm thickness

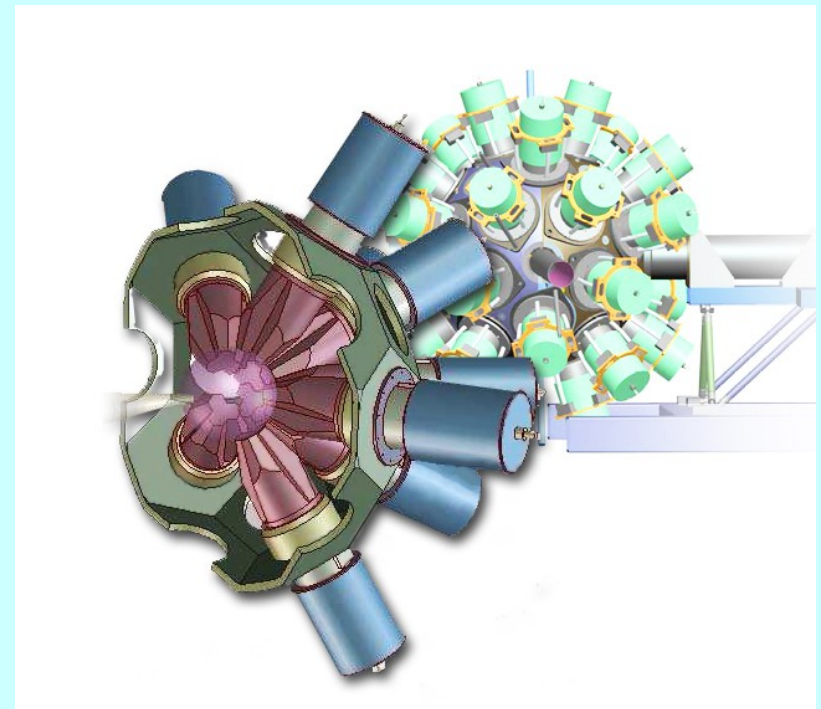


Triple clusters:
3 encapsulated crystals
Al end-cap:
1.5 mm spacing
1.5 mm thickness
111 cold FET preamplifiers



Distance between faces of crystals:
in same cluster ~3 mm
in adjacent clusters ~9 mm

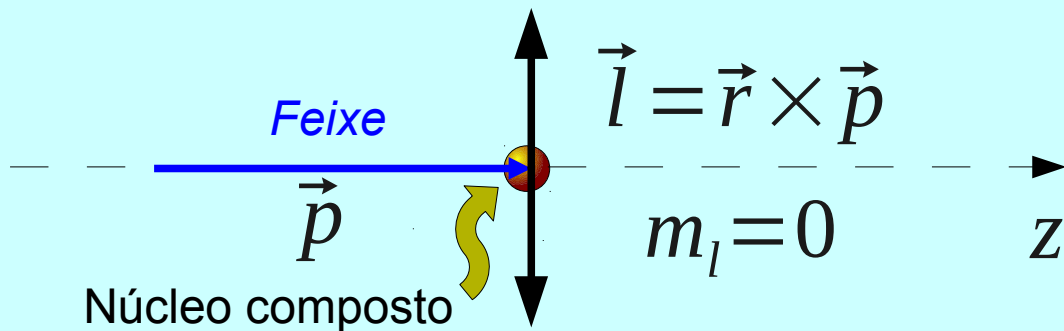
Total weight of the 60 clusters of the
AGATA-180 configuration ~2.5 tons
Mounted on a self-supporting structure



Outras técnicas de medidas de espectroscopia gama

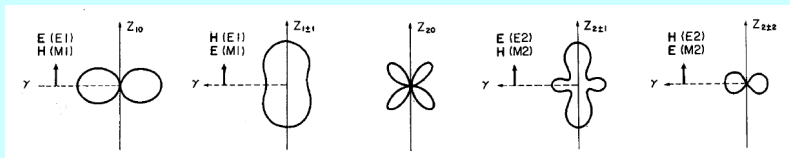
- Distribuições angulares (momento angular das transições)
- Vidas-médias (probabilidades de transição)
- Fatores giromagnéticos (configuração dos estados)
- Etc.

Distribuições angulares



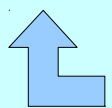
$$W(\theta) = \frac{1}{4\pi} \sum_k (2I+1)^{1/2} \rho_{k0} A_k(\delta) P_k(\theta)$$

Emissão de multipolos puros:

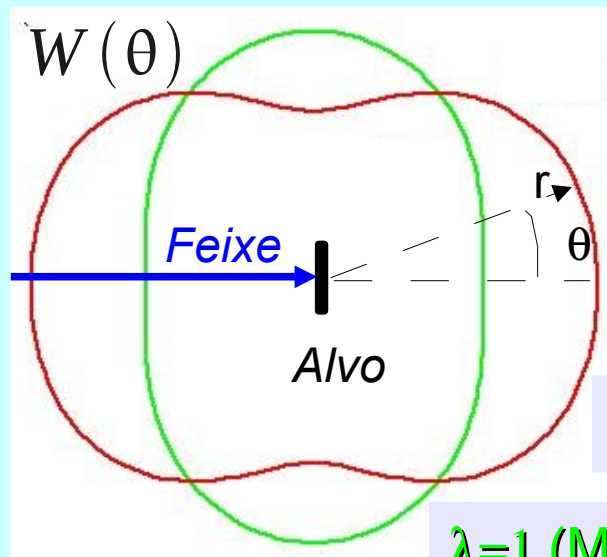
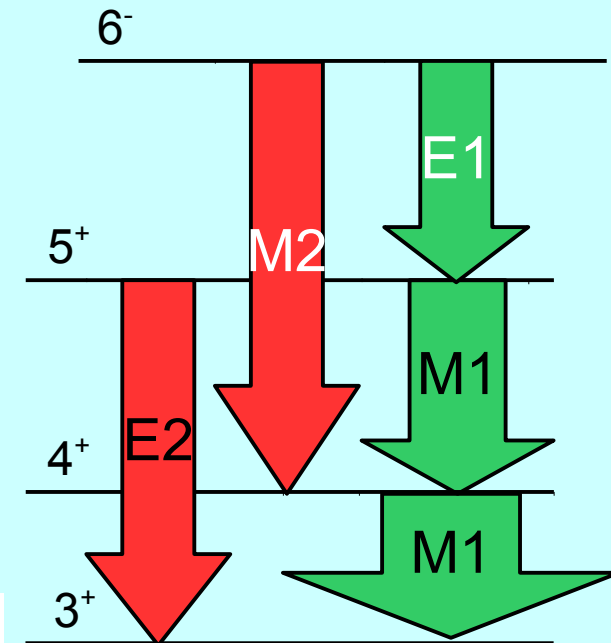


ρ_{kq} Tensor estatístico esférico

$\rho_{mm'}$ Matriz densidade



Amplitudes de população dos subestados magnéticos m

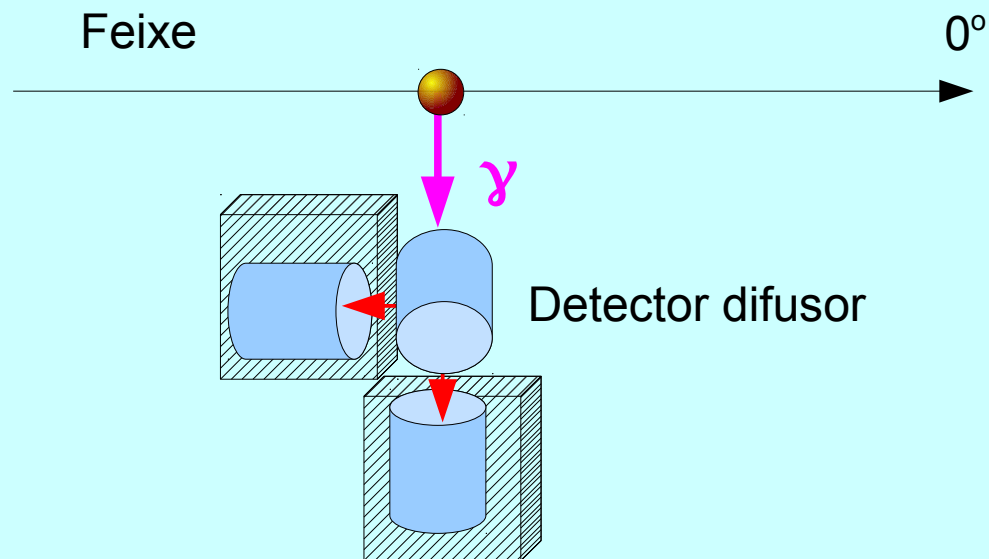


Det. 2

Det. 1

Polarização gama

- Medida do caráter magnético ou elétrico da transição



Medida de vidas médias

Técnicas mais utilizadas:

- Relógio ($> 1s$)
- TAC/TDC ($10ns - 1s$)
- Plunger ($1ps - 10ns$)
- DSAM ($10fs - 1ps$)

Curva de decaimento

- Decaimento de um estado de vida

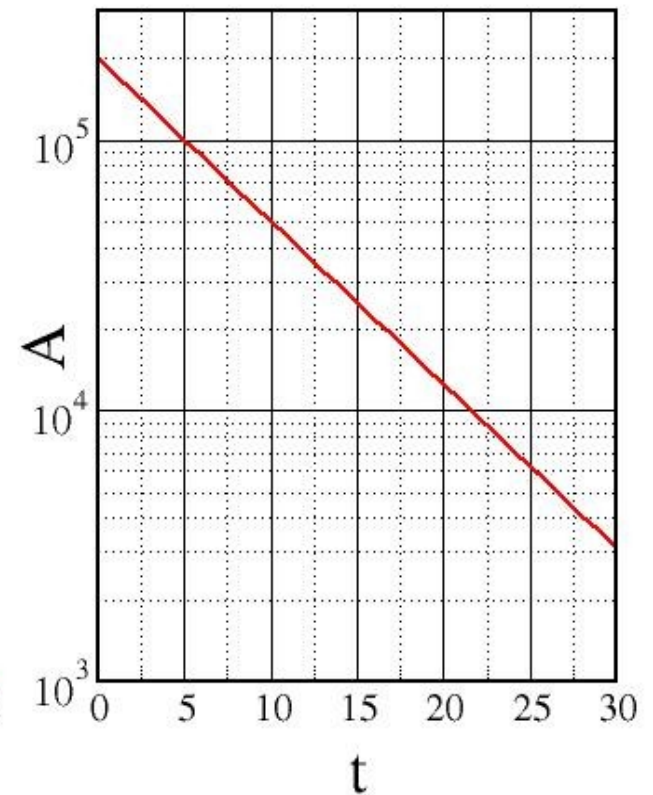
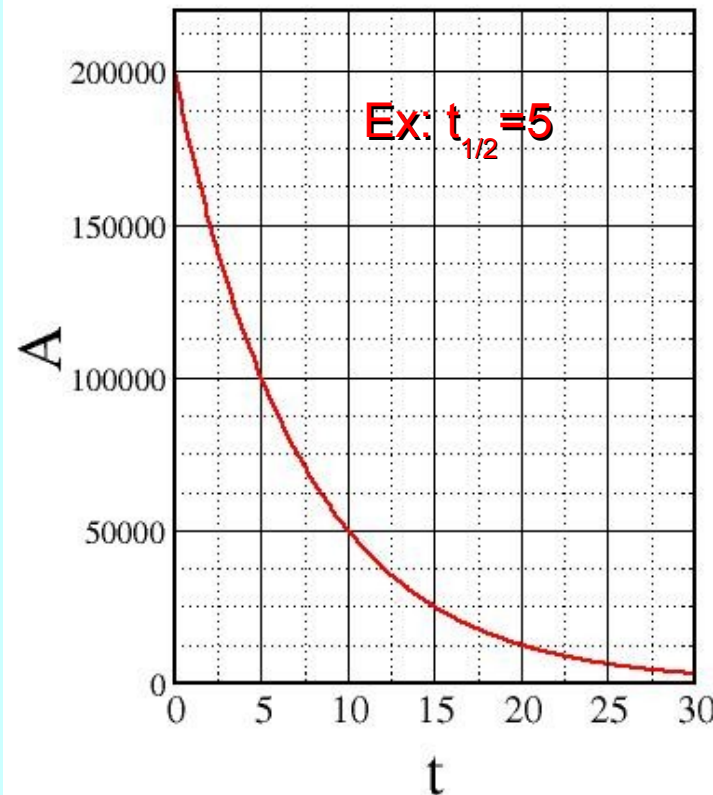
média $N = N_0 e^{-\frac{t}{\tau}}$

Atividade: $A = -\frac{dN}{dt} = \frac{N_0}{\tau} e^{-\frac{t}{\tau}} = A_0 e^{-\frac{t}{\tau}}$

Meia vida x vida média

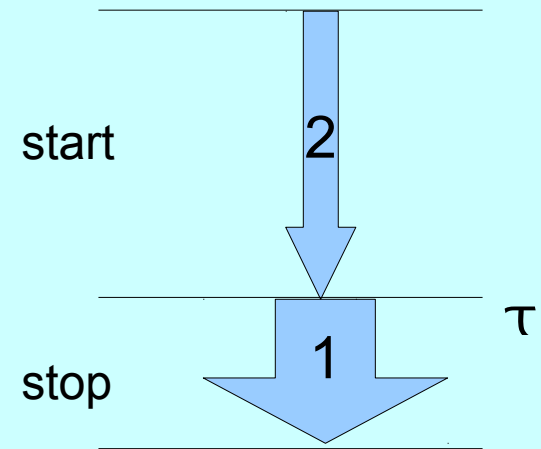
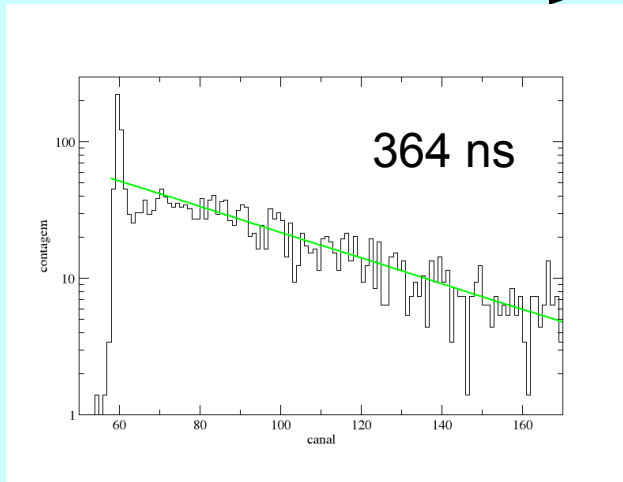
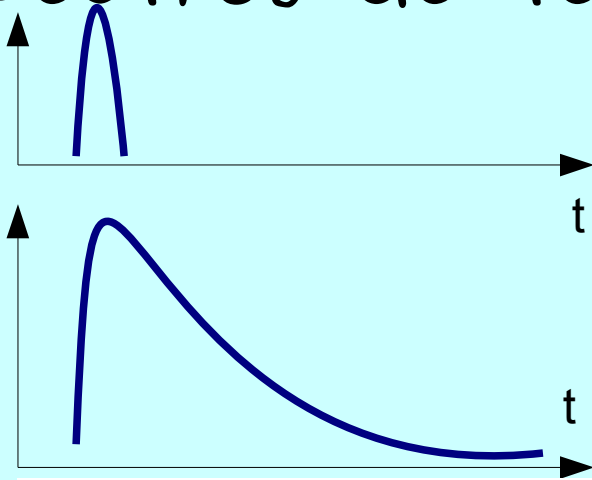
$$A = A_0 2^{-\frac{t}{t_{1/2}}}$$

$$t_{1/2} = \tau \ln 2$$

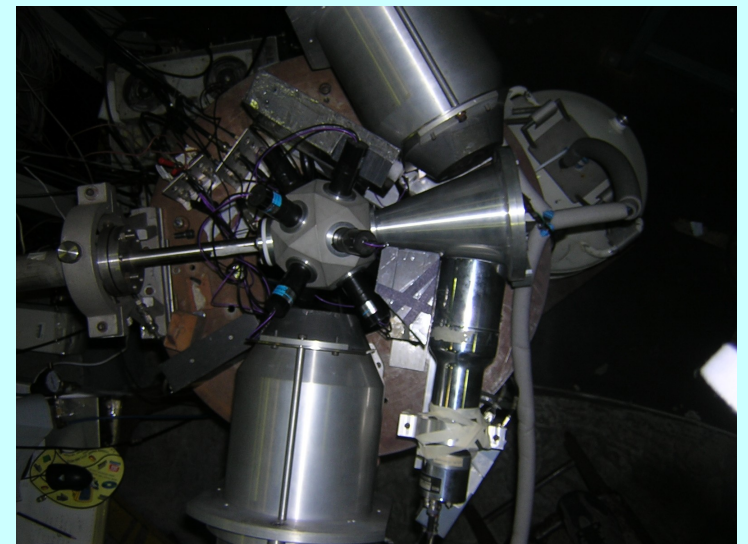


TAC/TDC

- Circuito de coincidências
- Espectros de tempo

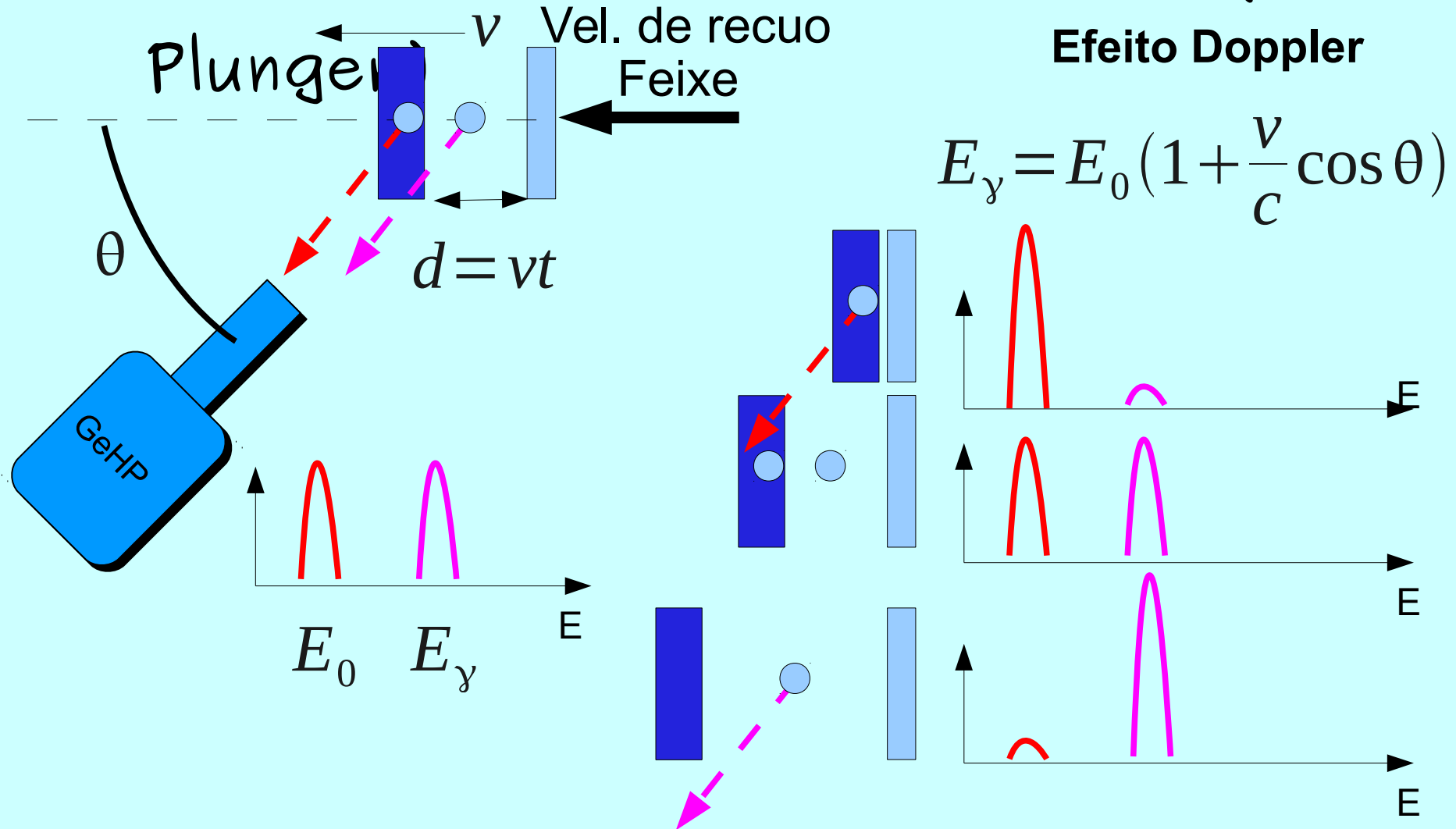


SISMEI (RSM)



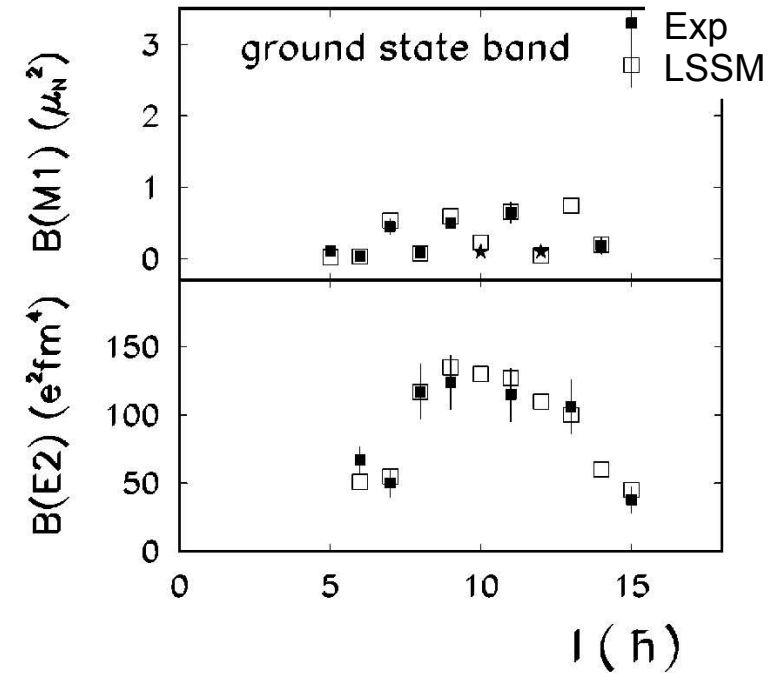
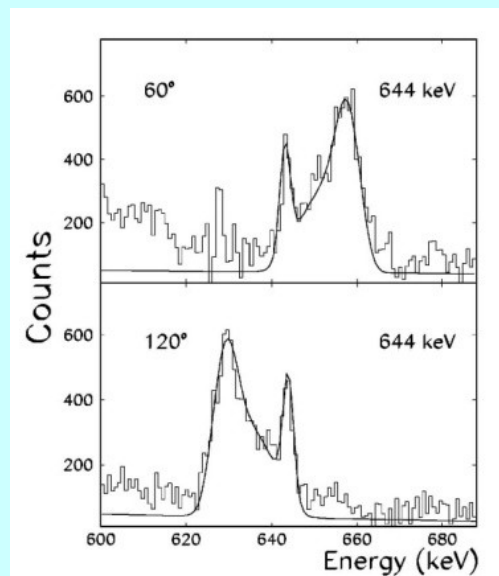
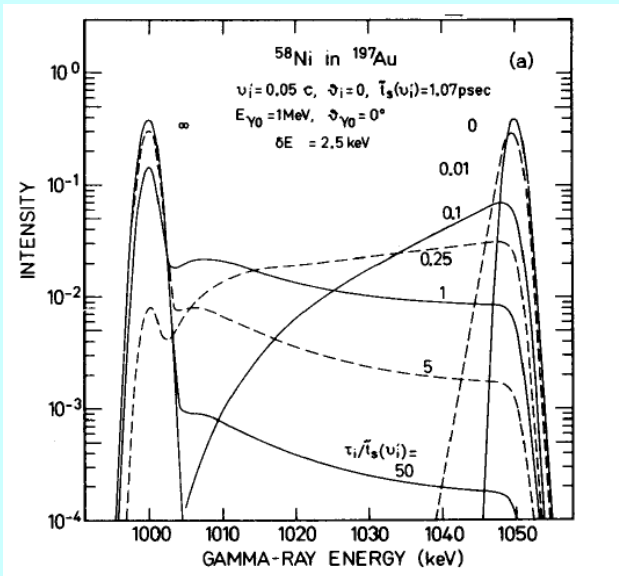
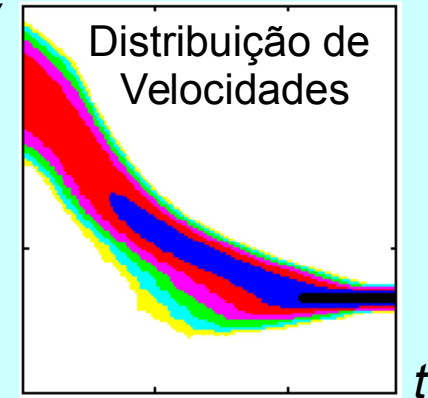
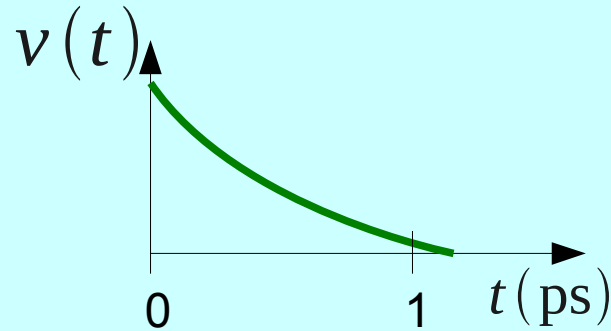
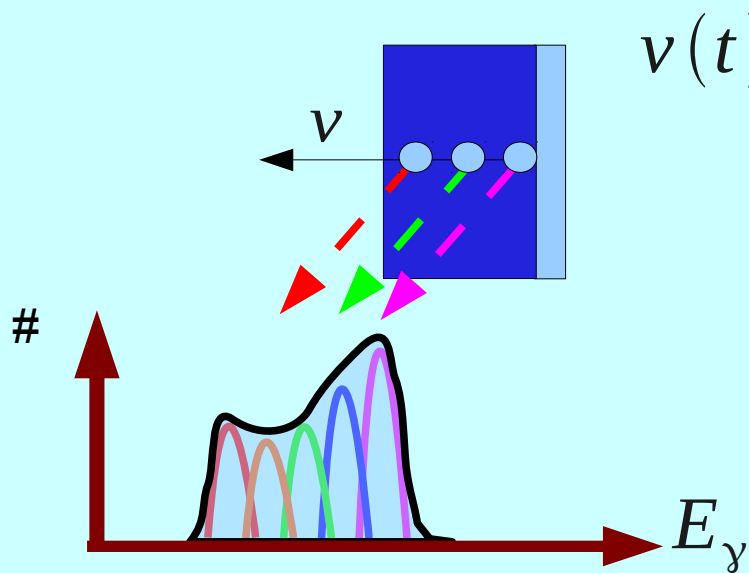
Plunger

- Método da distância de recuo (RDM -

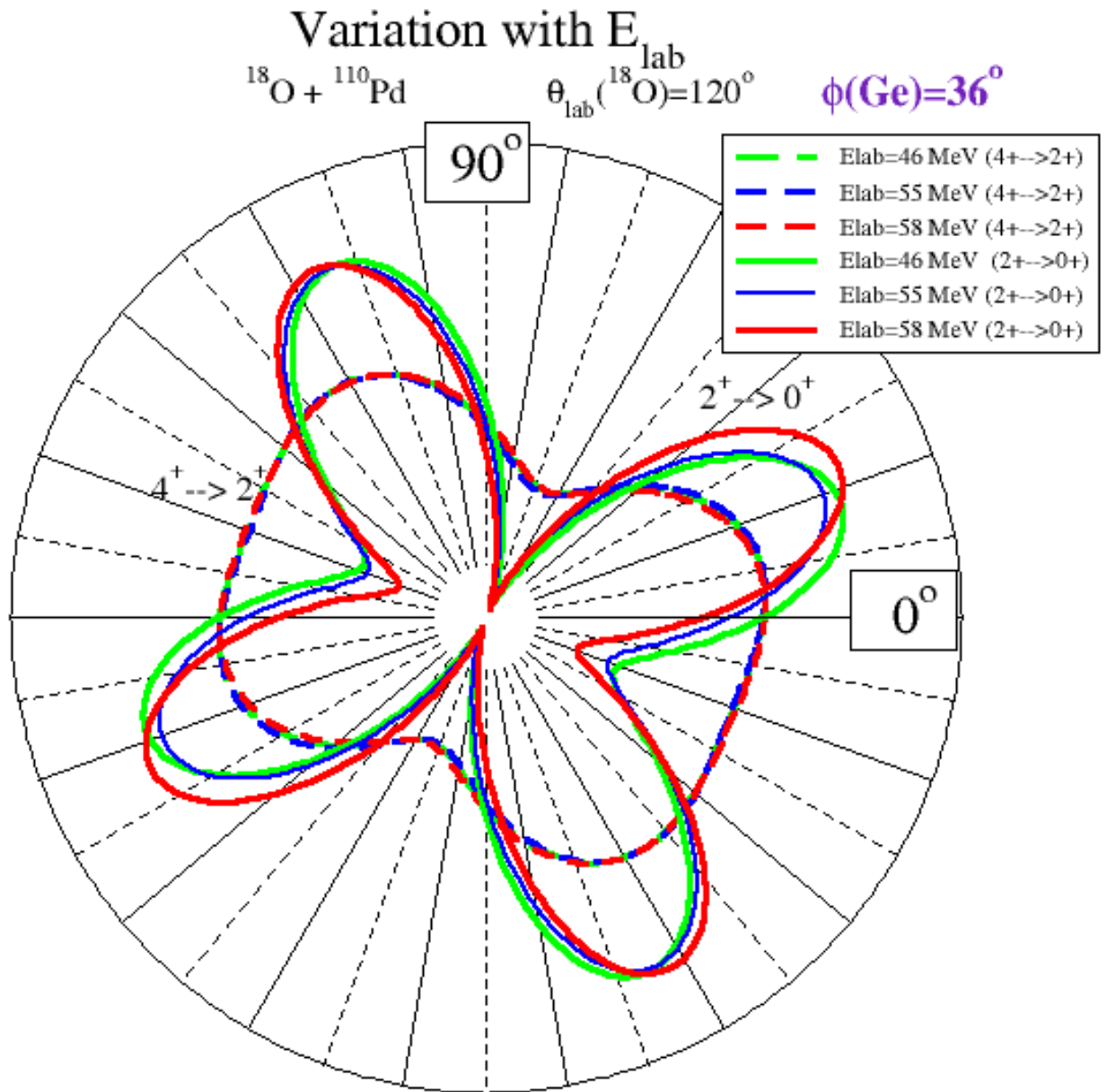


DSAM

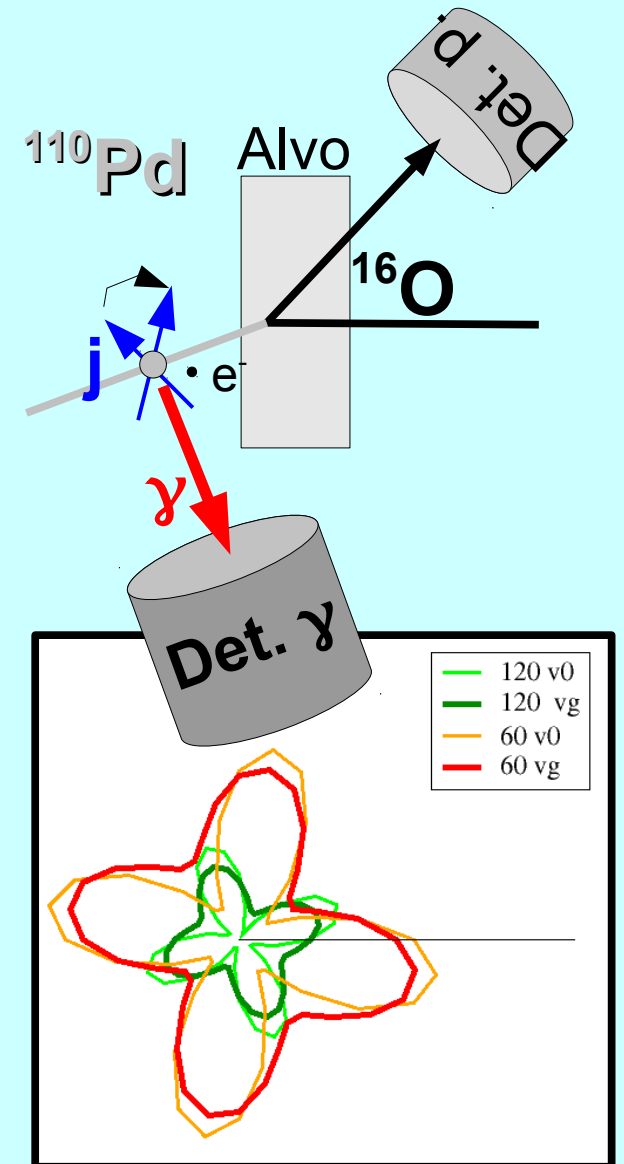
Atenuação do efeito Doppler



Correlação angular p- γ

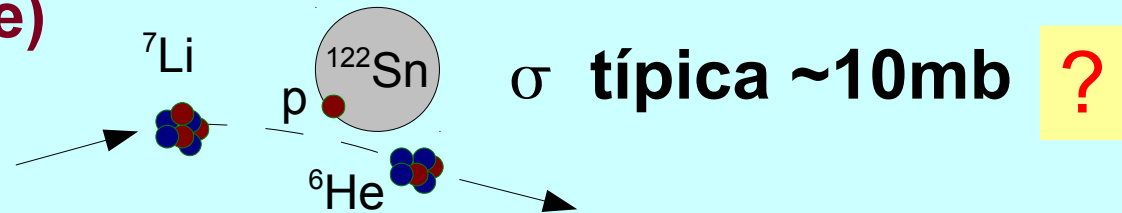


Desalinhamento em vácuo

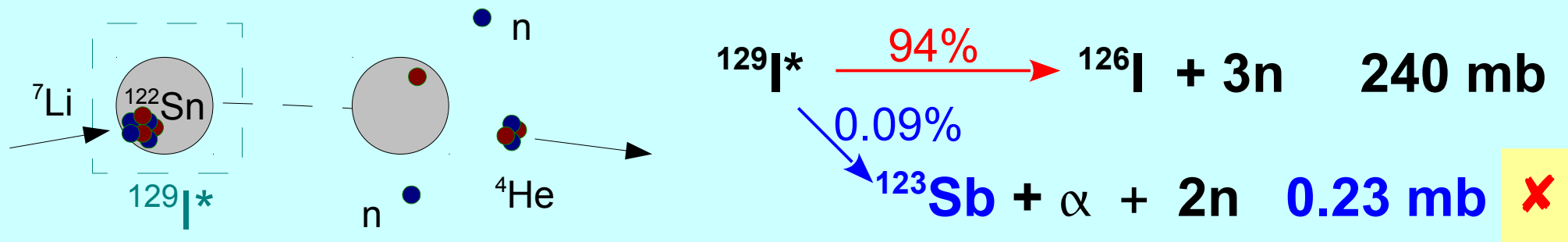


Como o ^{123}Sb ($= ^{122}\text{Sn}+1\text{p}$) é produzido?

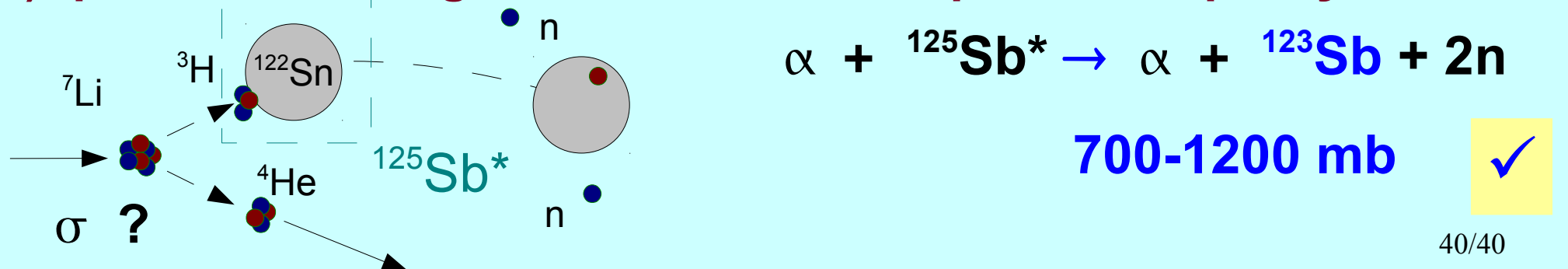
a) Transferência de 1p (sai ^6He)



b) Fusão completa seguida de evaporação de $1\alpha + 2n$



c) quebra do ^7Li seguida de fusão incompleta e evaporação de $2n$:



Aula 4 – técnica de coincidências

- Utilidade do método
- Coincidências (γ - γ ; γ -p)
- γ -p – Medida de reações nucleares
- Rastreamento γ (*Tracking*)
- Outras técnicas de medida de espectroscopia γ (distr. Angulares, vidas médias,...)
- Poder de resolução dos espectrômetros

Taxa típica de reação (fusão)

- Cálculo da taxa de reações $R = I n \sigma$

- Valores típicos:

$$I = 1 \text{ pA} = 0.6 \times 10^{10} \text{ part./s}$$

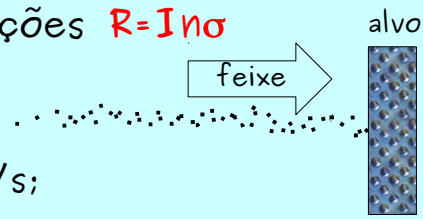
$$n = 6 \times 10^{18} \text{ átomos/cm}^2 \text{ (1mg/cm}^2, A=100)$$

$$\sigma = 1 \text{ b} = 10^{-23} \text{ cm}^2$$

$$\rightarrow R = 3.6 \times 10^5 \text{ reações/s}$$

- Intervalo médio $\langle t \rangle$ entre reações $1/R$:

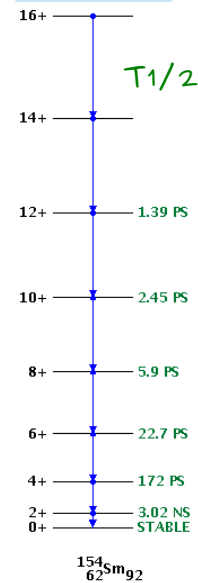
$$\langle t \rangle = 3 \times 10^{-6} \text{ s (3}\mu\text{s)} - \text{ como identificar de que reação veio um raio } \gamma?$$



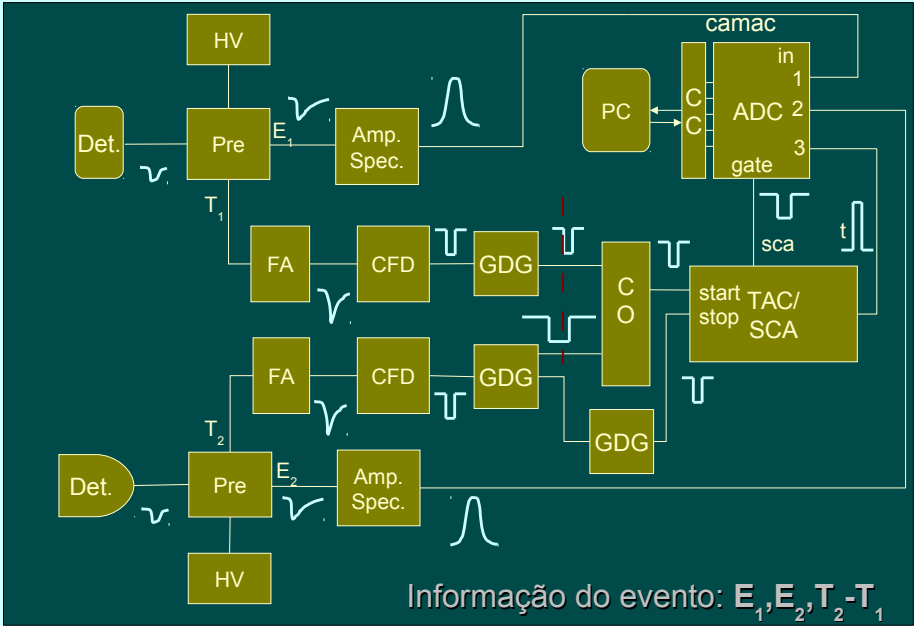
Correlação temporal

- Vidas médias de estados nucleares excitados em geral variam de 0.01 ps a 100 ns – muito menores que $3 \mu\text{s} = 3000 \text{ ns}$.
- Resolução temporal de detectores de Ge é cerca de 20 ns – nesta escala transições em cascata são praticamente simultâneas – ‘coincidentes’.
- Se dois raios γ são detectados dentro de $50\text{--}100 \text{ ns}$, provavelmente vem da mesma cascata.
- Processos nucleares são ainda mais rápidos, (ex. Evaporação de p , $n < 10^{-19} \text{ s}$)

Cascata γ

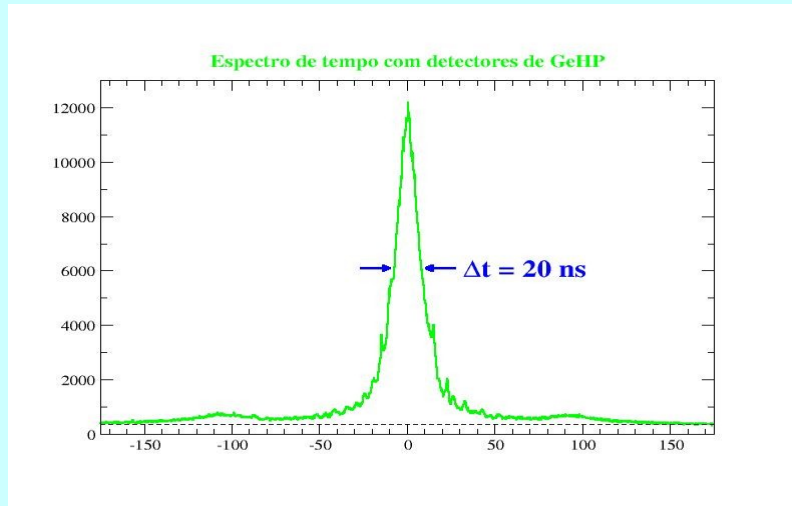


Circuito de coincidências



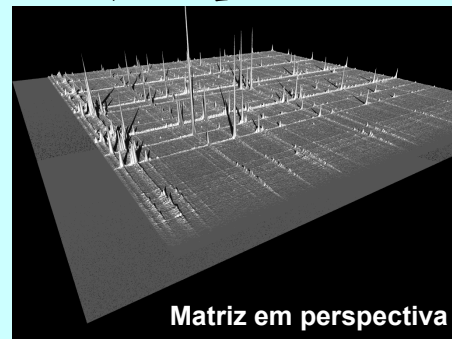
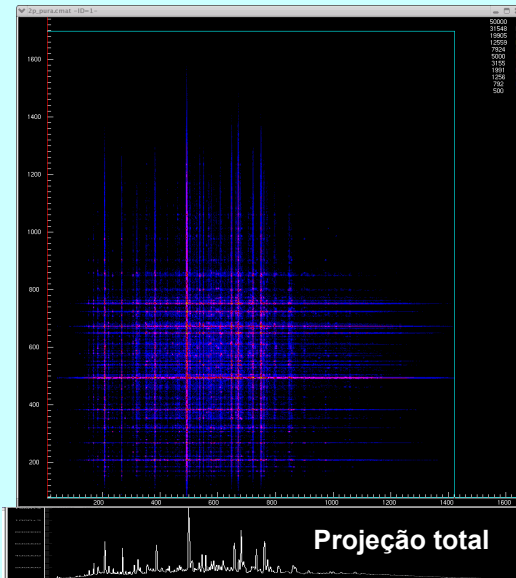
Espectro de tempo

- Diferença de tempo entre dois detectores



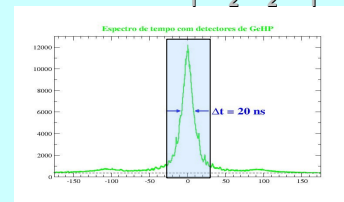
Matriz de coincidências γ - γ

- Espectro bi-paramétrico $E_1 \times E_2$

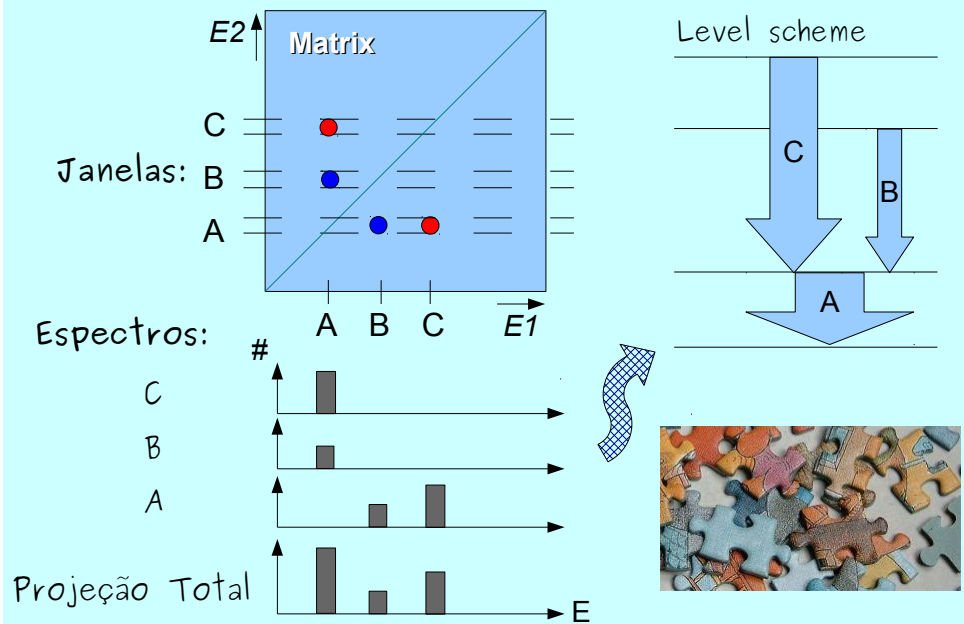


Matriz em perspectiva

Evento: $E_1, E_2, T_2 - T_1$

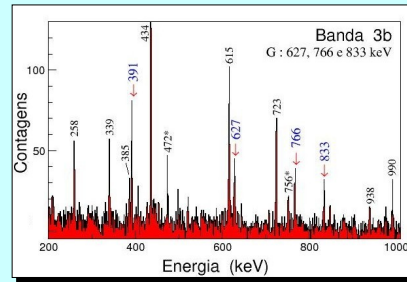
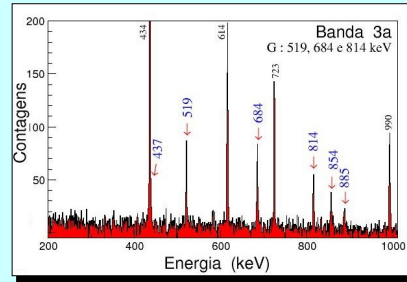
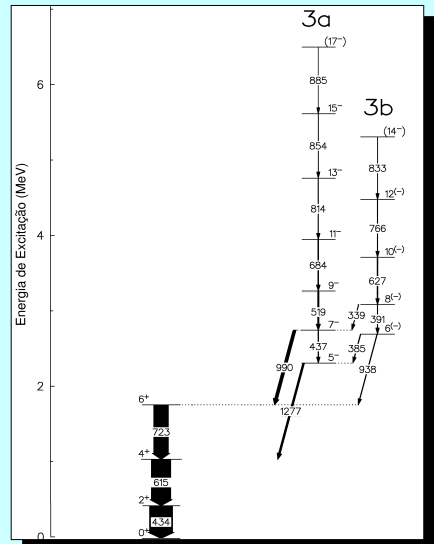


Janelas x Esquema de níveis



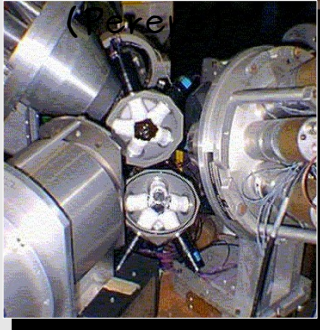
Exemplo- Janelas x Esquema de níveis

• Dados ^{105}Rh

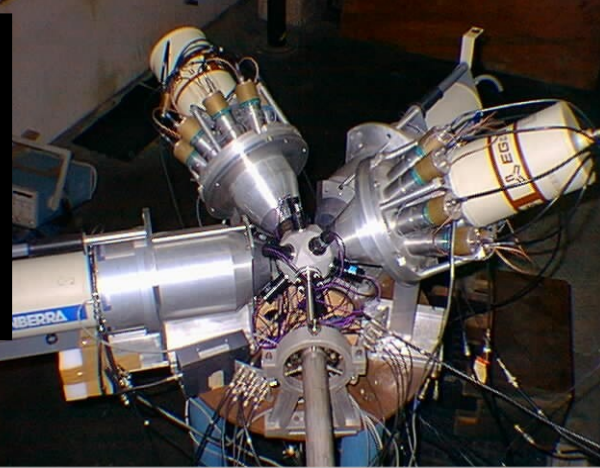


Nosso espectrômetro (IFUSP-DFN)

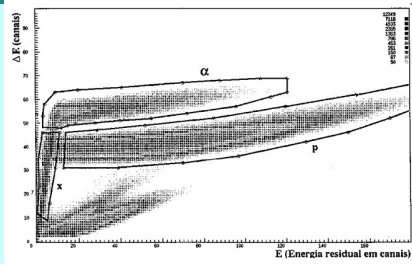
- Sistema Ancilar de Cintiladores (Saci)
- Pequeno Espectrômetro de Radiação Eletromagnética com Rejeição de Espalhamento



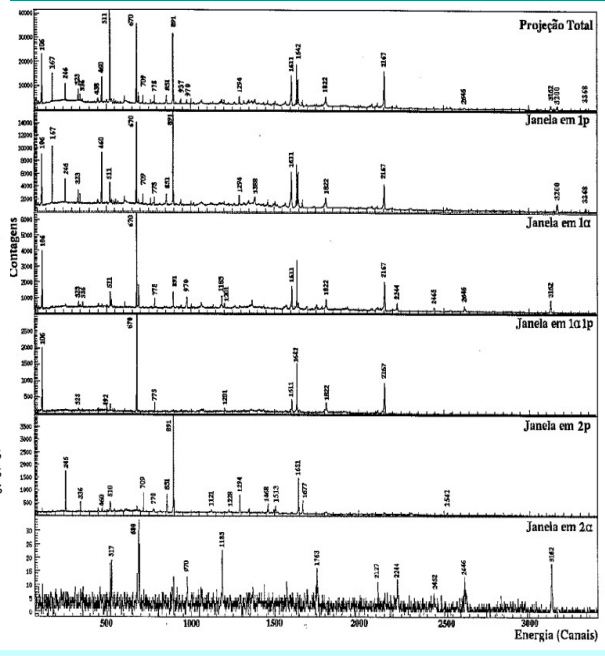
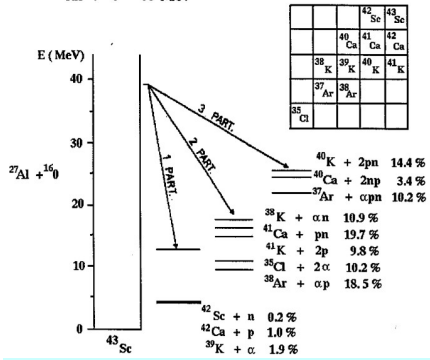
4 GeHP c/ AC
11 NaI (phoswich)



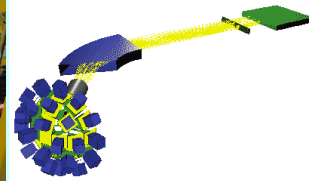
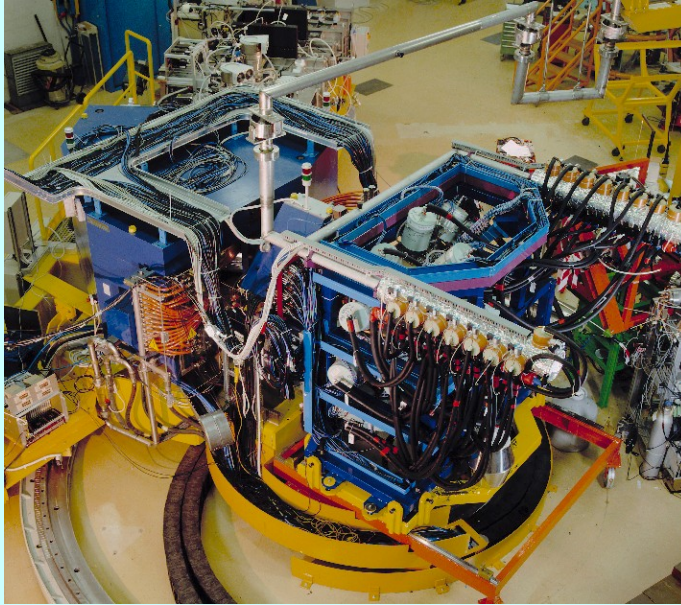
γ -p ($^{16}\text{O} + ^{27}\text{Al}$)



$^{27}\text{Al} + ^{16}\text{O}$ 40 Mev



Espectrômetro y típico

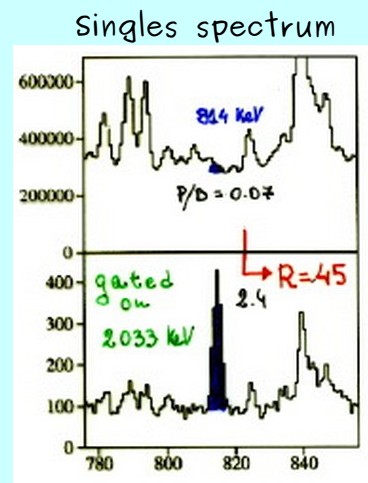
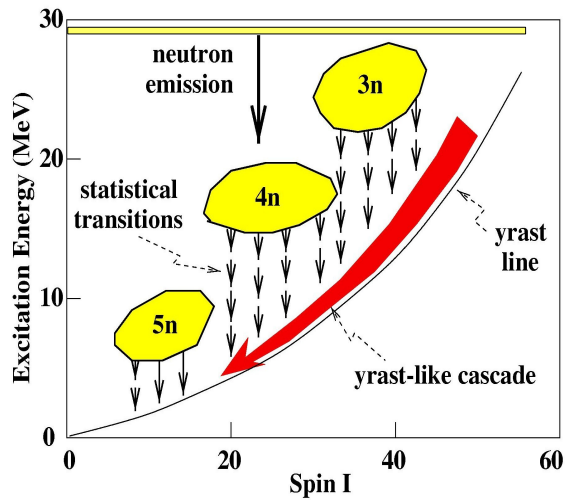


PRISMA-CLARA
LNL-INFN

Por que tão
complexo?

Complexidade do espectro γ

Ex.: Reação de Fusão-evaporação



Coincidence spectrum

Compromise: efficiency \times resolving power (R)

O Conceito de poder de resolução

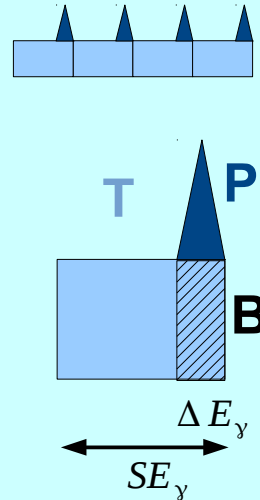
- A razão P/B melhora a cada seleção (janela) feita
- O fator de melhora é o poder de resolução

$$R = \frac{SE_y}{\Delta E_y} P/T$$

SE_y É a separação média entre picos γ em uma cascata

ΔE_y É a resolução em energia

P/T É a razão pico/total do detector



Multiple γ coincidences

- α : Limite observacional de um espectrômetro

R - Poder de resolução

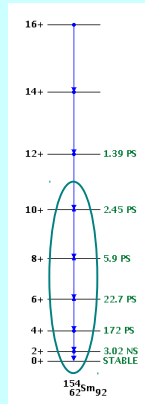
ϵ_{ph} - Eficiência de fotopico

$$R = \frac{SE_y P/T}{\Delta E_y}$$

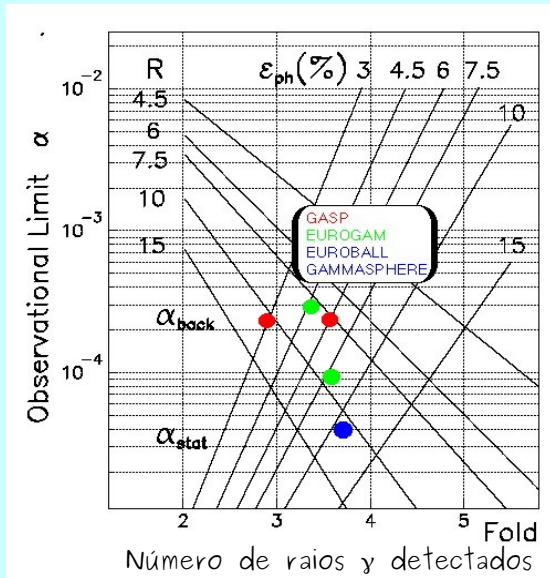
$$\alpha_{back} = \frac{(P/B)_F}{R_0 (kR)^F}$$

$$\alpha_{stat} = \frac{N_F}{N \epsilon_0 (k \epsilon_{ph})^F}$$

$$N_F = 100; (P/B)_F = 0,2$$

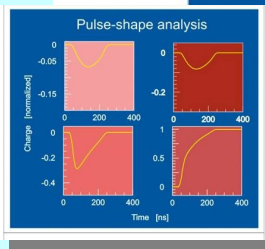
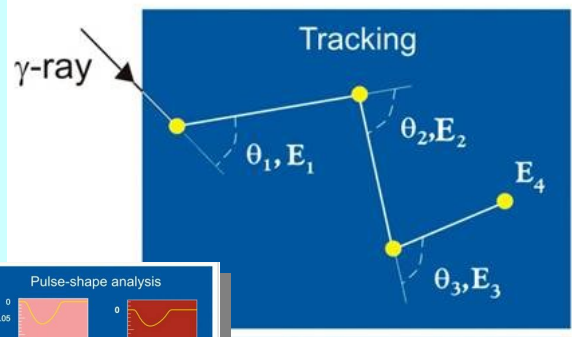
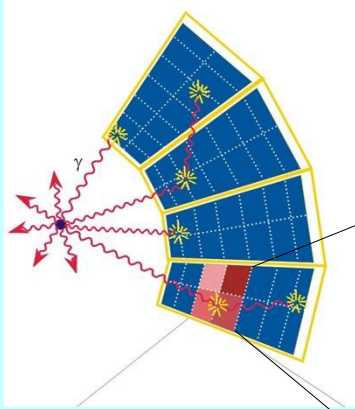


Ponto ótimo: $\alpha_{back} \approx \alpha_{stat}$



O Rastreamento γ (tracking)

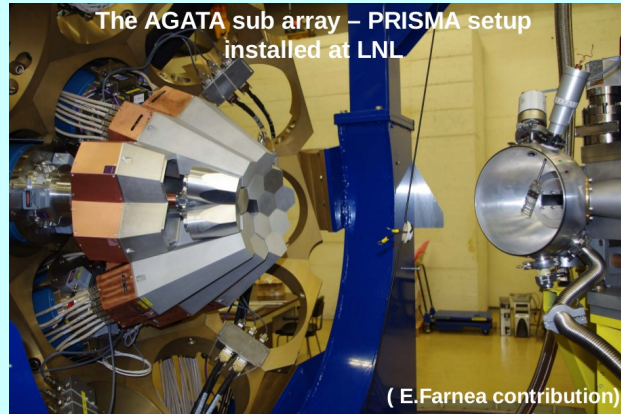
- Determinação da posição e da energia das interações γ em 3 dimensões
- Determinação seqüência de espalhamentos γ



Análise da forma de pulsos- DSP (FPGA)

Espectrômetros em construção

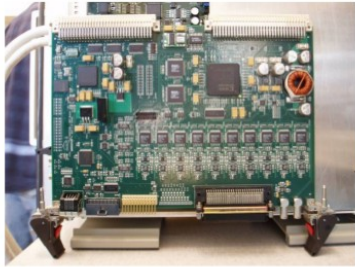
- Gretina (EUA); Agata (UE)



Eletrônica (GRETINA)

Digitizer module (LBNL)

14bit, 100 MHz
Energy
Pole/zero correction
Leading edge time
Constant fraction time
Pulse shape

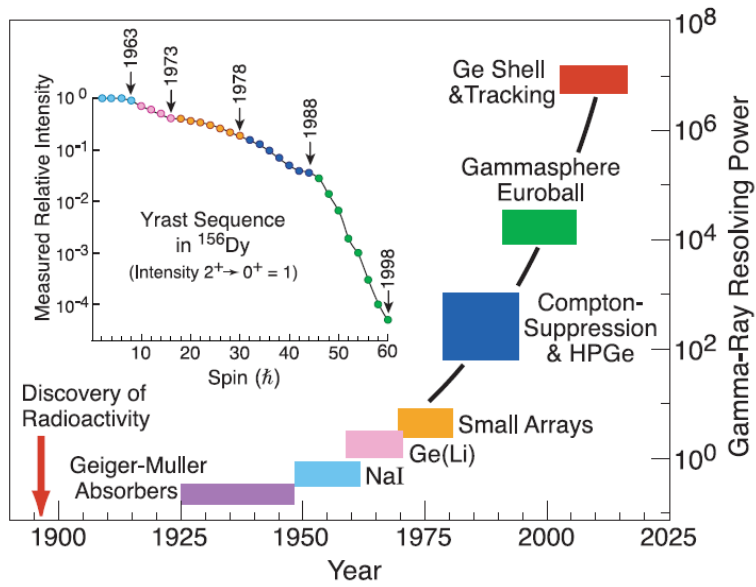


Trigger Timing & Control module (ANL)

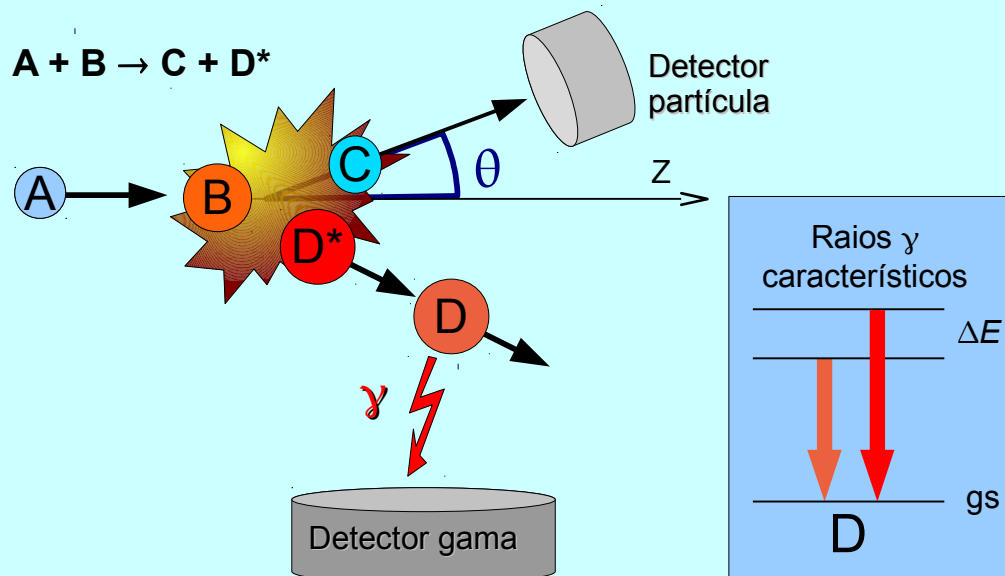
Fast trigger <250 nsec
Trigger decision time <20 μ sec
Trigger conditions
Multiplicity
Sum energy
Hit pattern



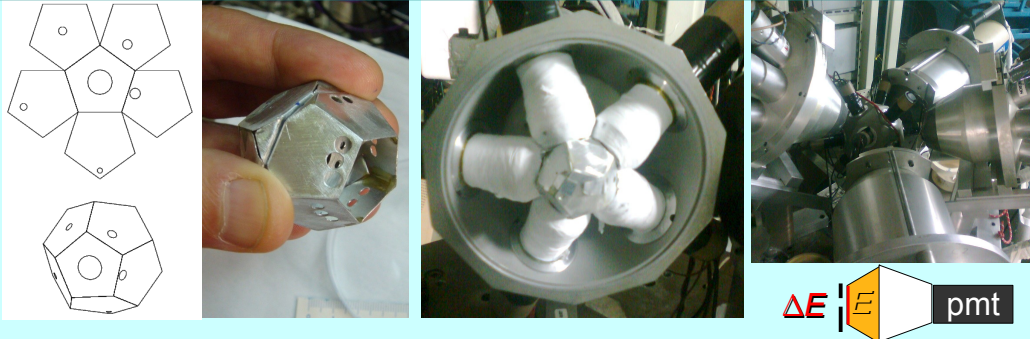
Evolução do poder de resolução



γ -p para medida de reação

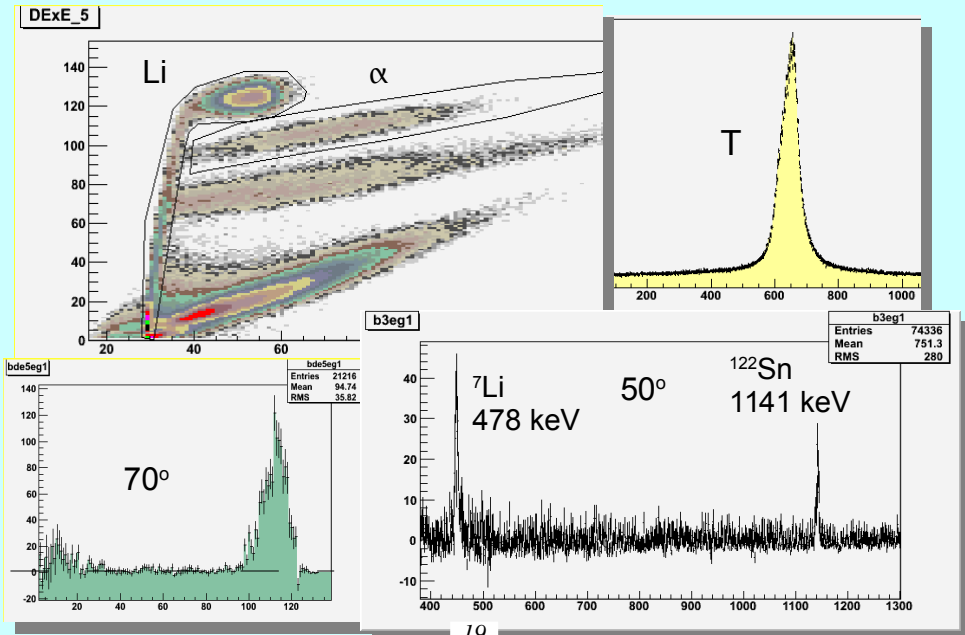


Adaptação do Saci para medidas de reações

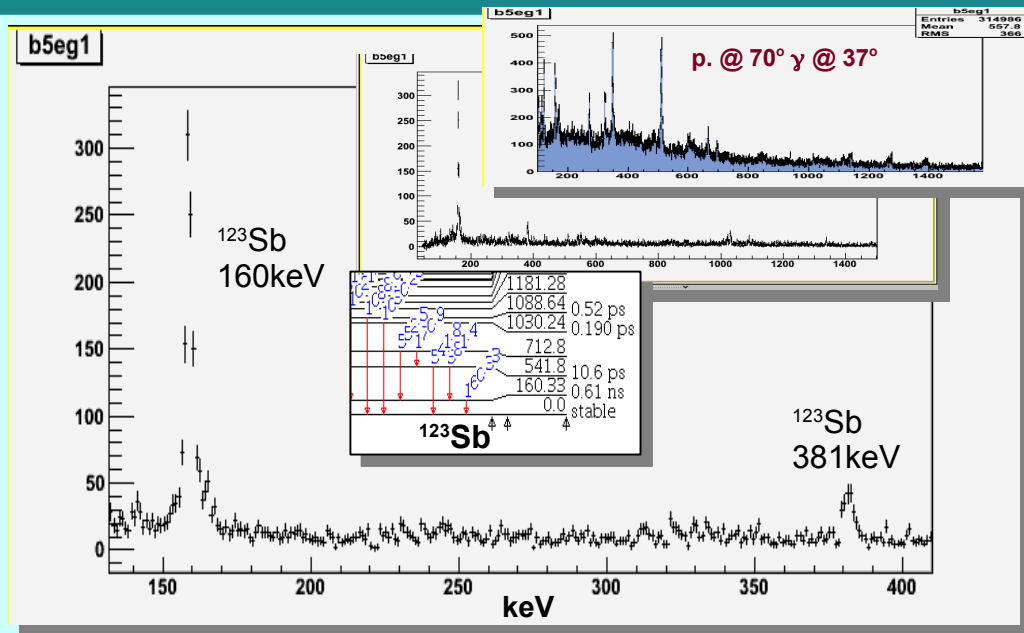


- **Colimadores** - $\Delta\Omega(\theta)$ ($\Delta\theta \leq 10^\circ$; limitação da taxa)
- Furos de 0.5-3.5 mm (placas de Al)
- 11 angulos (30, 40, 50, 60, 70, 80, 100, 120, 130, 140)
- Bases ativas nas PMT's (taxas até 100 kHz cada)

γ -p (${}^7\text{Li}+{}^{122}\text{Sn}$)



Banana de α 's

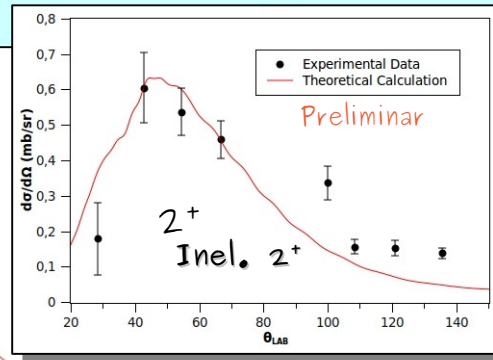
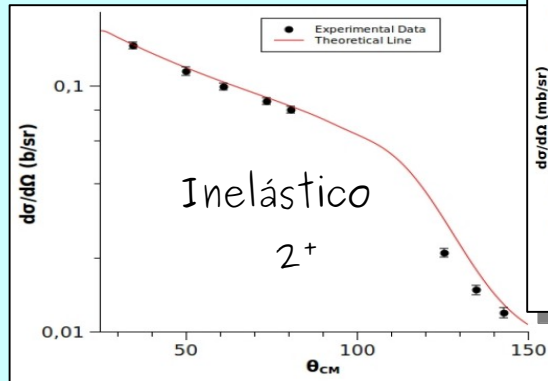


γ -p Resultados recientes

V.B. Zagatto (MS, IFUSP)
Nucl. Inst. Meth. A 749 (2014) 19

V.B. Zagatto (DR)
 ${}^7\text{Li}+{}^{120}\text{Sn}$ @ 24MeV

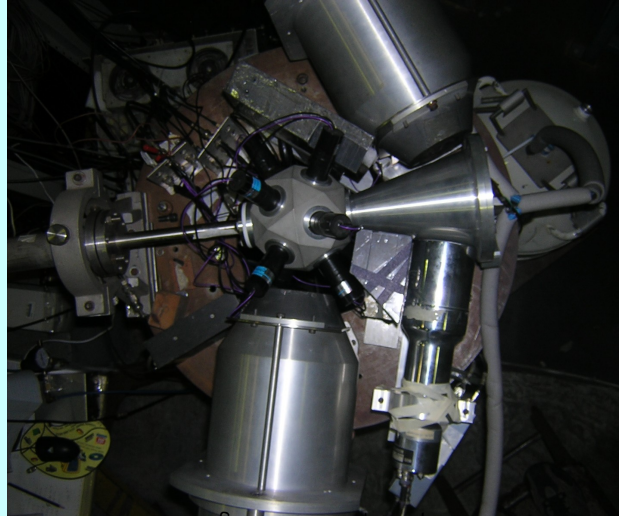
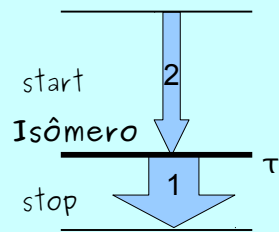
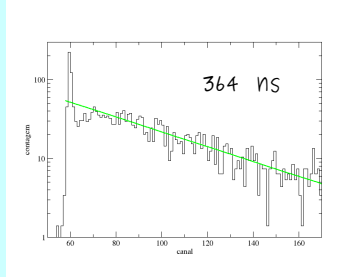
${}^{18}\text{O}+{}^{110}\text{Pd}$ @ 54MeV



FRESCO
SPP \leftarrow CDCC (bu)
23/40

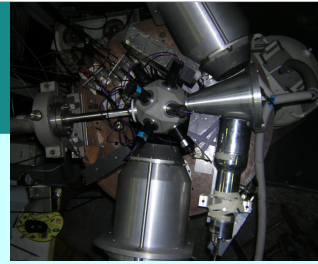
SISMEI

- sistema de medidas de estados isoméricos

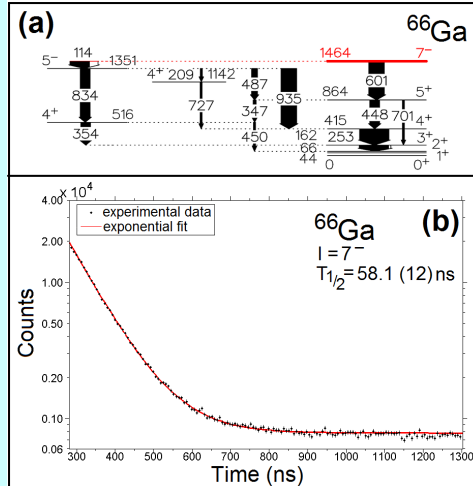


D.L. Toufen (Mestrado IFUSP)

SISMEI (Isomers)



- Resolvendo inconsistências



$T_{1/2} = 57.3 (14) \text{ ns}$

A. Filevich et al., Nucl. Phys. A 295, 513, 1978.

or

~~$T_{1/2} = 39 (2) \text{ ns}$~~

~~T. Kouda et al., Ann. Rep. 1996, Radio-isotope Center, Tohoku University, Japan, p. 19, 1997.~~

Paula R. P. Allegro, PhD IFUSP 2013

Próxima aula – Perspectivas

- No IFUSP
- Colaborações internacionais
- Núcleos exóticos (Feixes Radioativos)
- Momentos angulares extremos
- Superpesados
- Astrofísica nuclear (Baixa energia)
- Hipernúcleos

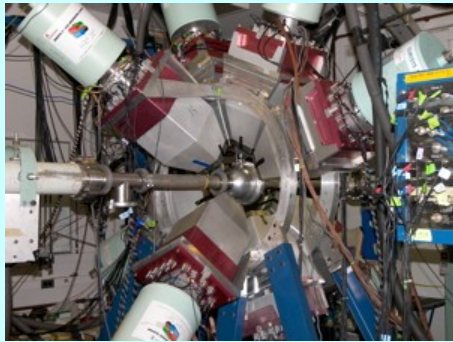
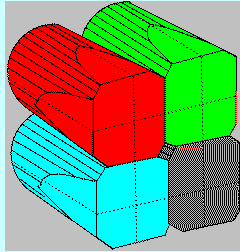
Extras

Detectores y segmentados

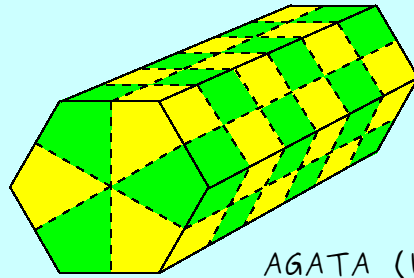
- Clover



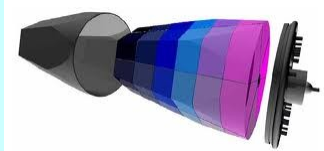
Yrast-Ball
(Yale)



- Multi-segmentado
(localização da interação)

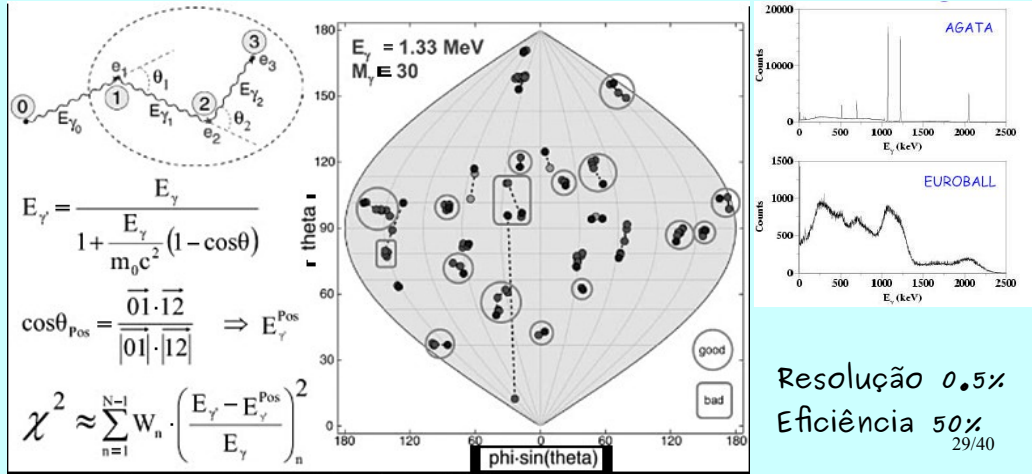


AGATA (UE)



γ -ray tracking

- "História" da detecção de um raio gama
- Identificação de eventos



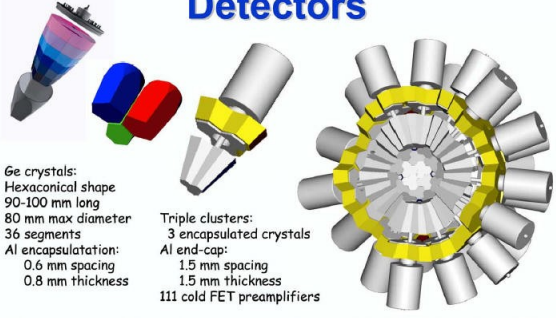
Espectrômetros de tracking

- Espectrômetros:

AGATA (UE);

GRETA (EUA)

Detectors



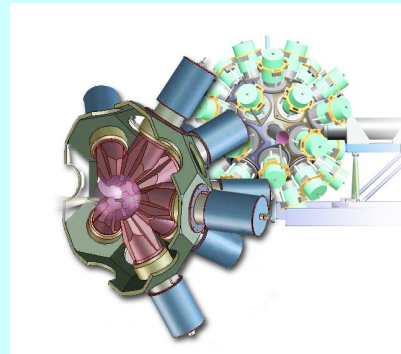
Ge crystals:
Hexaconical shape
90-100 mm long
80 mm max diameter
36 segments

Al encapsulation:
0.6 mm spacing
0.8 mm thickness

Triple clusters:
3 encapsulated crystals
Al end-cap:
1.5 mm spacing
1.5 mm thickness
111 cold FET preamplifiers

Distance between faces of crystals:
in same cluster ~3 mm
in adjacent clusters ~9 mm

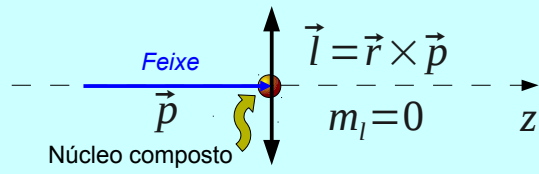
Total weight of the 60 clusters of the
AGATA-180 configuration ~2.5 tons
Mounted on a self-supporting structure



Outras técnicas de medidas de espectroscopia gama

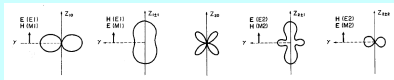
- Distribuições angulares (momento angular das transições)
- Vidas-médias (probabilidades de transição)
- Fatores giromagnéticos (configuração dos estados)
- Etc.

Distribuições angulares



$$W(\theta) = \frac{1}{4\pi} \sum_k (2I+1)^{1/2} \rho_{k0} A_k(\delta) P_k(\theta)$$

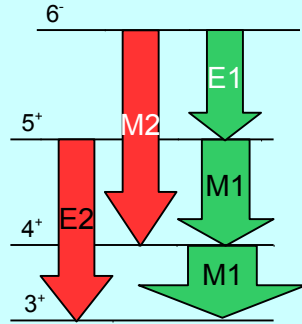
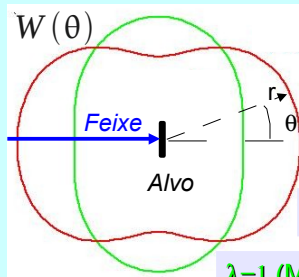
Emissão de multipolos puros:



ρ_{kq} Tensor estatístico esférico

$\rho_{mm'}$ Matriz densidade

Amplitudes de população dos subestados magnéticos m



Det. 2

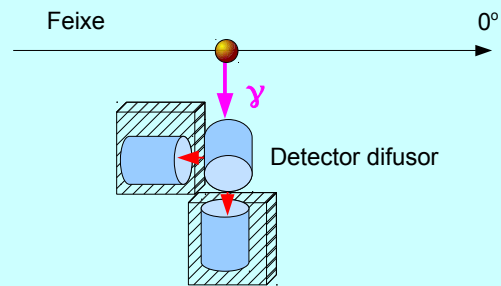
$\lambda=2$ (M2, E2)

$\lambda=1$ (M1, E1)

Det. 1

Polarização gama

- Medida do caráter magnético ou elétrico da transição



Medida de vidas médias

Técnicas mais utilizadas:

- Relógio ($> 1s$)
- TAC/TDC ($10ns - 1s$)
- Plunger ($1ps - 10ns$)
- DSAM ($10fs - 1ps$)

Curva de decaimento

- Decaimento de um estado de vida

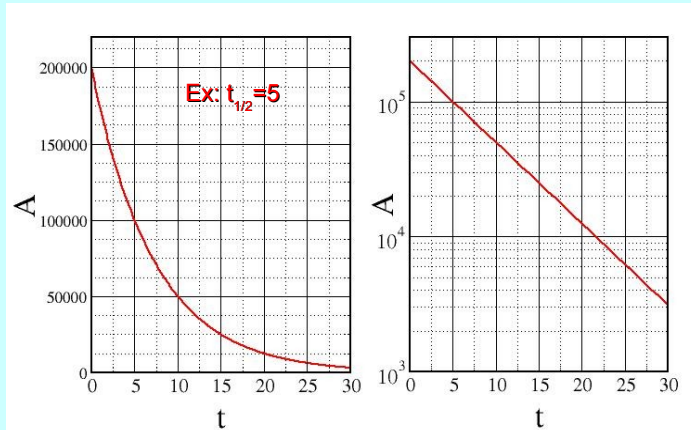
média $N = N_0 e^{-\frac{t}{\tau}}$

Atividade: $A = -\frac{dN}{dt} = \frac{N_0}{\tau} e^{-\frac{t}{\tau}} = A_0 e^{-\frac{t}{\tau}}$

Meia vida x vida média

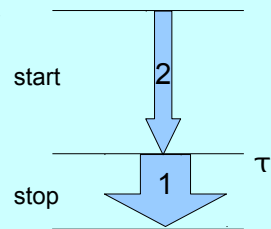
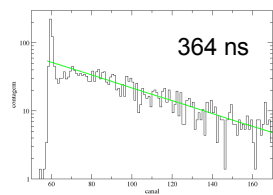
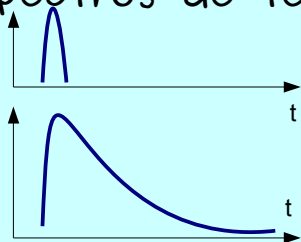
$$A = A_0 2^{-\frac{t}{t_{1/2}}}$$

$$t_{1/2} = \tau \ln 2$$

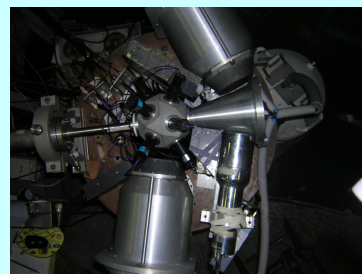


TAC/TDC

- Circuito de coincidências
- Espectros de tempo

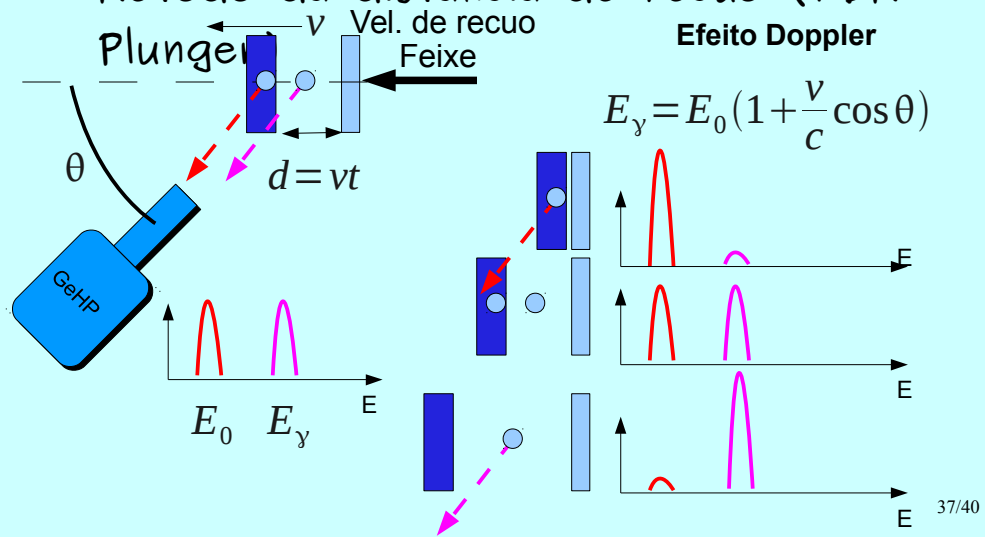


SISMEI (RSM)



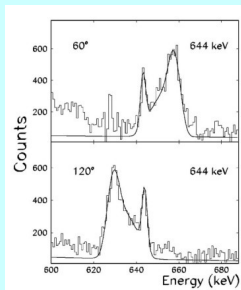
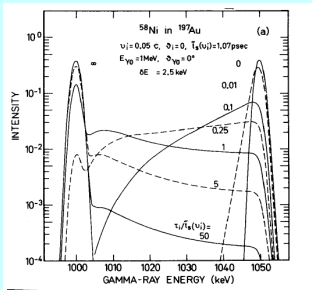
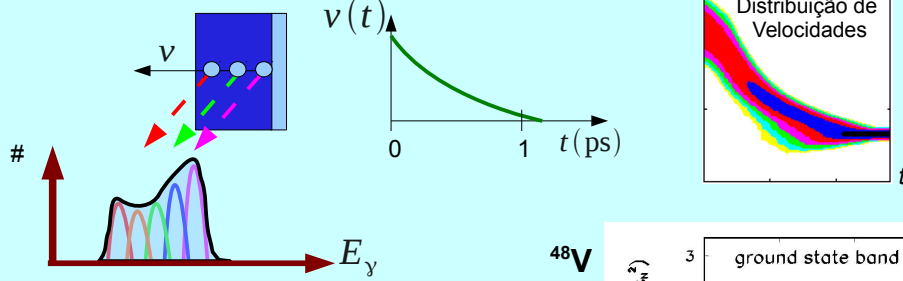
Plunger

- Método da distância de recuo (RDM -

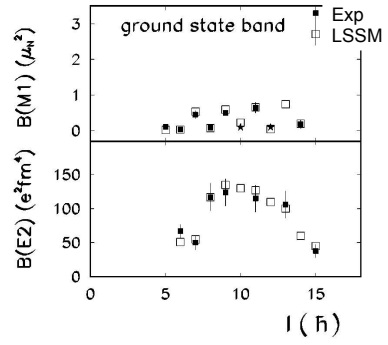


DSAM

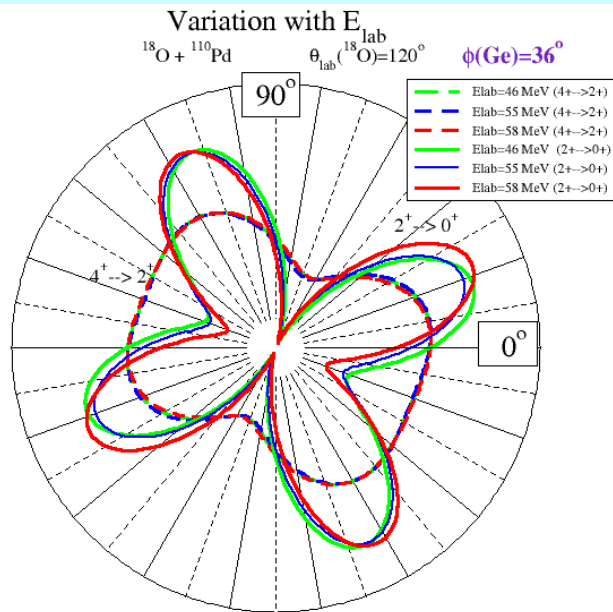
• Atenuação do efeito Doppler



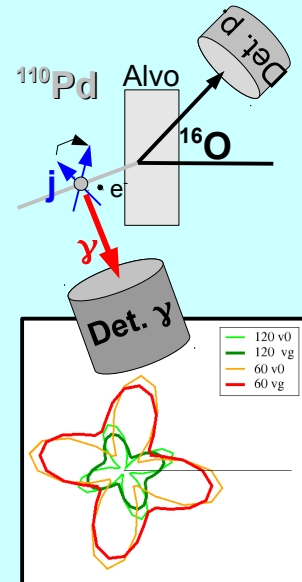
48V



Correlação angular p- γ

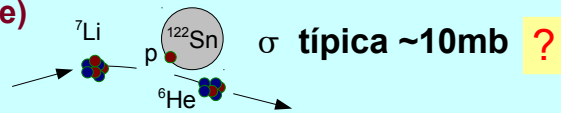


Desalinhamento em vácuo

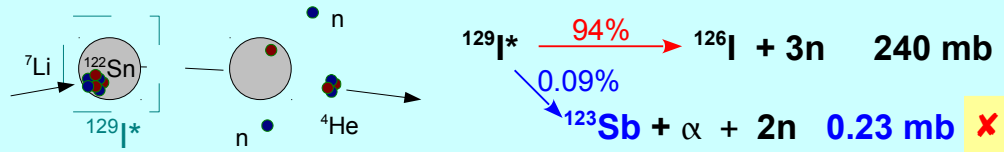


Como o ^{123}Sb ($= ^{122}\text{Sn}+1\text{p}$) é produzido?

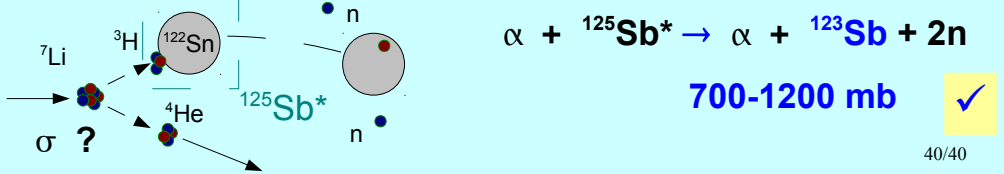
a) Transferência de 1p (sai ^6He)



b) Fusão completa seguida de evaporação de $1\alpha + 2n$



c) quebra do ^7Li seguida de fusão incompleta e evaporação de $2n$:

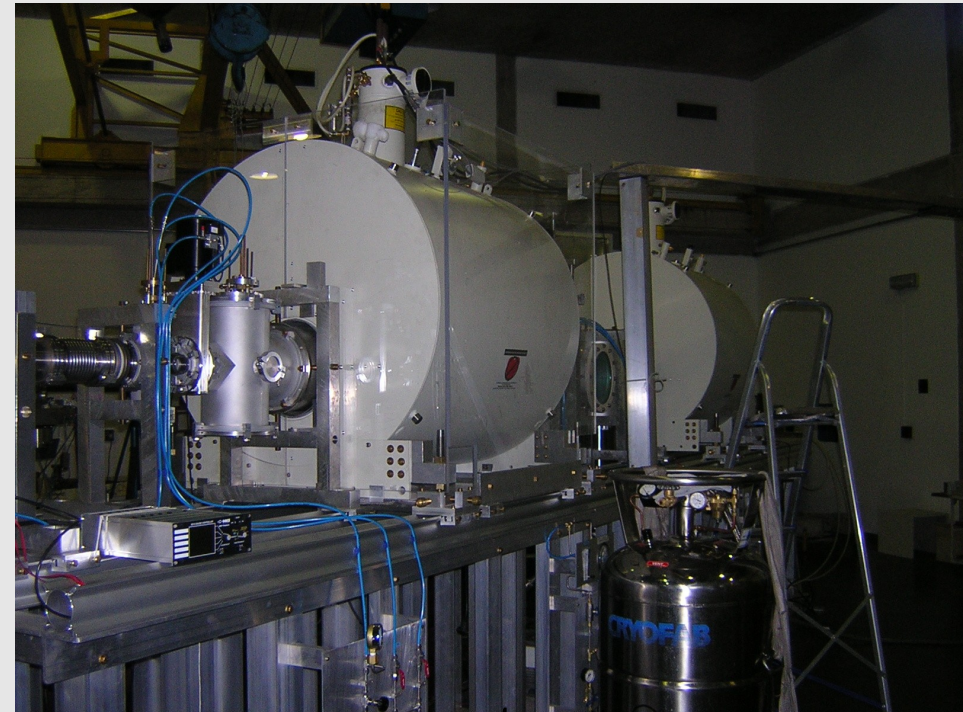
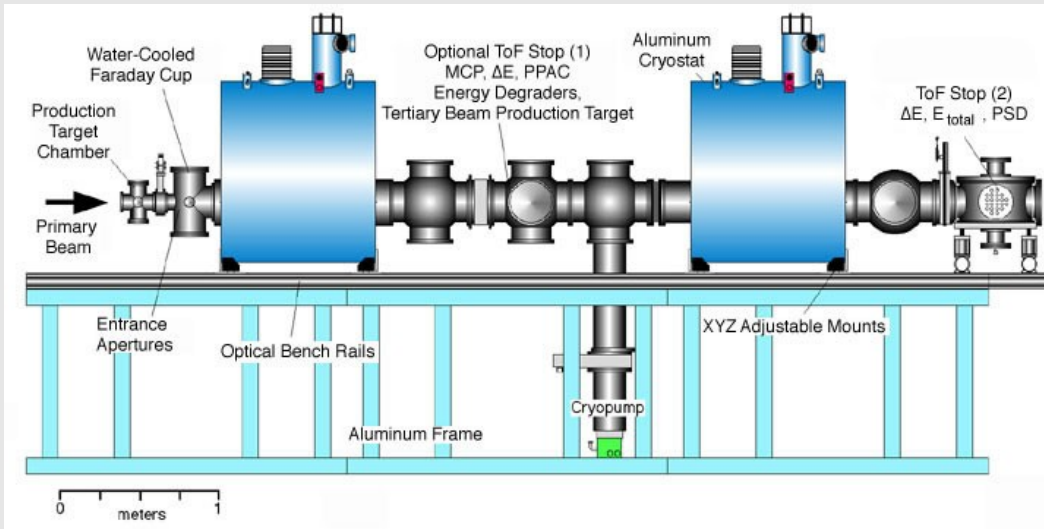


Aula 5 – Perspectivas

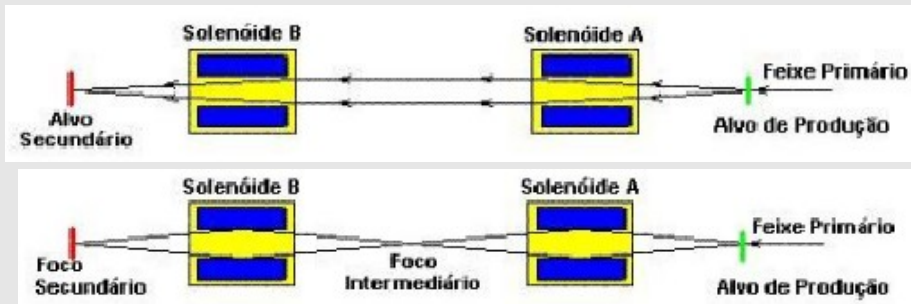
- No IFUSP
- Colaboração com LNS (arco-íris, NUMEN)
- Núcleos exóticos (Feixes Radioativos)
- Momentos angulares extremos
- Superpesados
- Astrofísica nuclear (Baixa energia)
- Hipernúcleos

RIBRAS (Pelletron-IFUSP)

• Solenóides supercondutores (6T)



Feixes radioativos

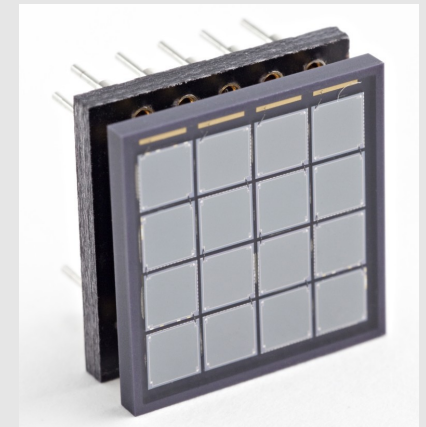


- Feixes fracamente ligados
- Espalhamento elástico
- Reações diretas

Reação	feixe secundário	(part/s)
${}^9\text{Be}({}^7\text{Li}, {}^8\text{Li})$	${}^8\text{Li}$	10^6
${}^9\text{Be}({}^7\text{Li}, {}^6\text{He})$	${}^6\text{He}$	10^4
${}^1\text{H}({}^{10}\text{B}, {}^7\text{Be})$	${}^7\text{Be}$	10^4
${}^{12}\text{C}({}^3\text{He}, {}^7\text{Be})$	${}^7\text{Be}$	10^4
${}^3\text{He}({}^6\text{Li}, n){}^8\text{B}$	${}^8\text{B}$	10^6
${}^{12}\text{C}({}^{17}\text{O}, {}^{18}\text{mF})$	${}^{18}\text{F}$	10^3

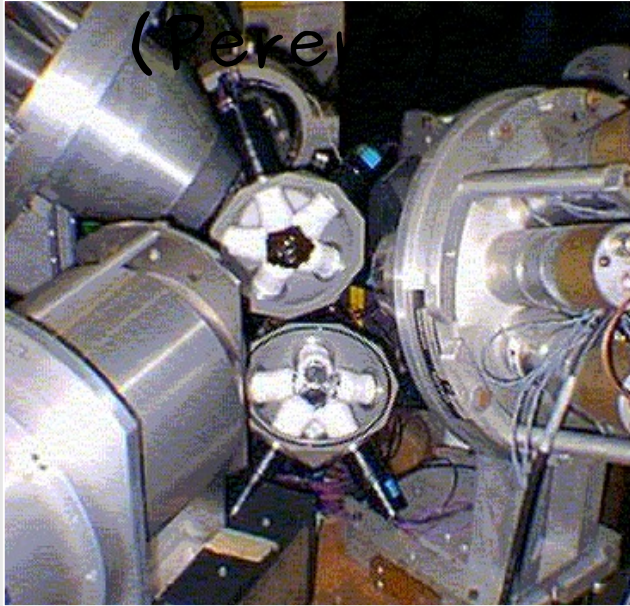
Uso do RIBRAS para espectroscopia γ

- Precisa blindagem de água borada para proteger GeHPs
- Substituir PMTs por SiPMs 4 x 4 Pixels
($3 \times 3 \text{ mm}^2 \sim 10^3 \text{ APDs/mm}^2$) devido ao campo magnético B (RIBRAS: $\sim 6 \text{ T}$)
- Testes planejados:
 ${}^6\text{He} + {}^{120}\text{Sn}$ (transferência de 2n)



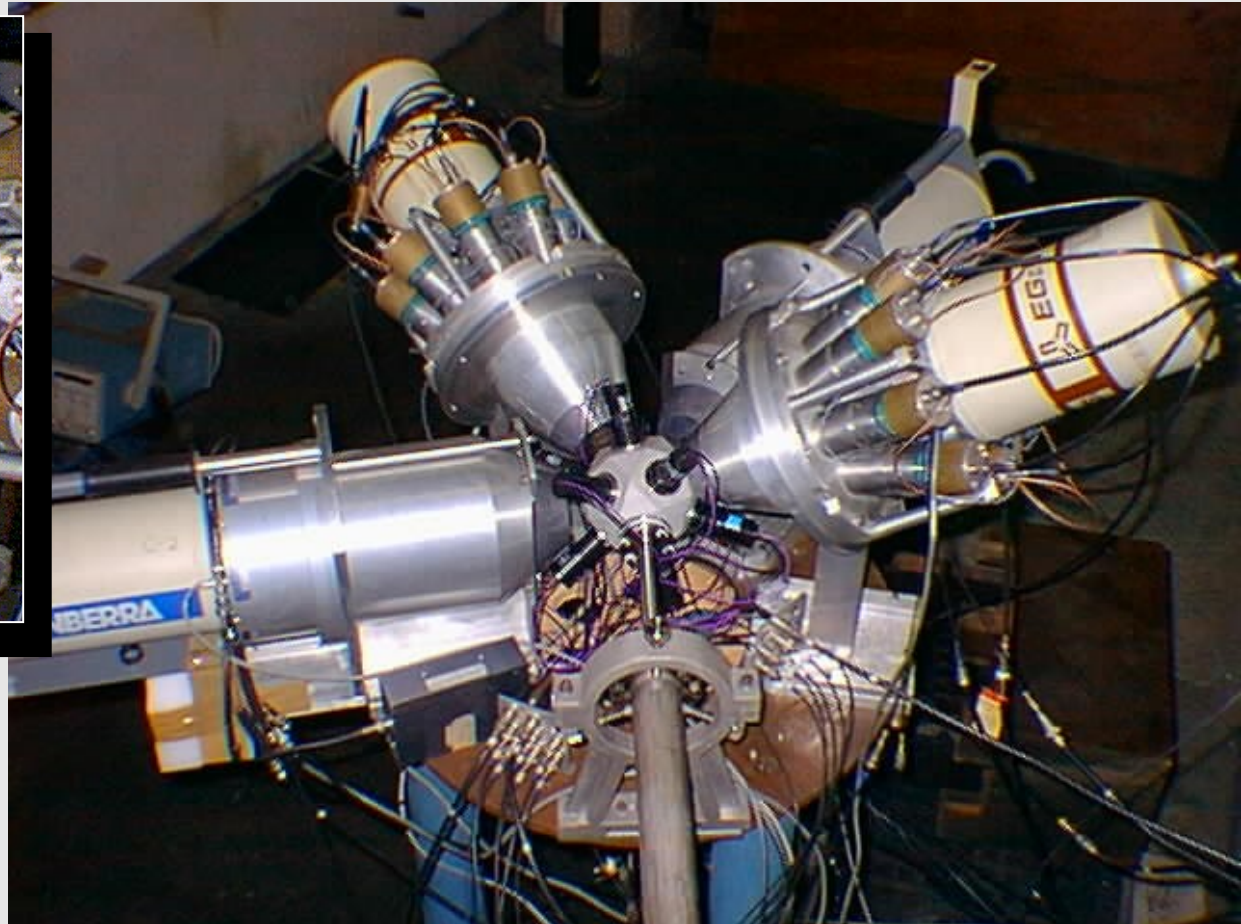
Nosso espectrômetro (IFUSP-DFN)

- Sistema Ancilar de Cintiladores (Saci)
- Pequeno Espectrômetro de Radiação Eletromagnética com Rejeição de Espalhamento



4 GeHP c/ AC

11 $\Delta E-E$ (phoswich)

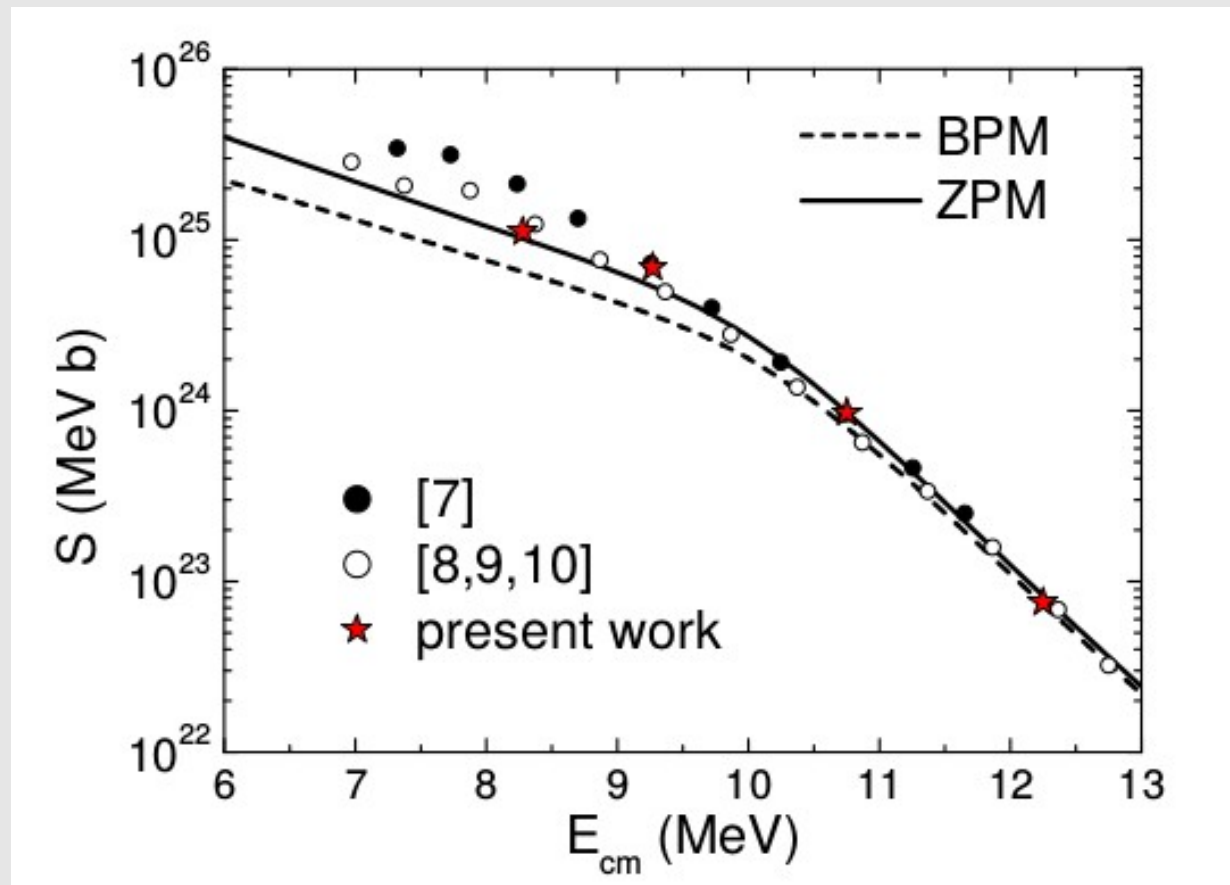


Reações de interesse a-f – IFUSP

- Medidas no acelerador Pelletron do IF

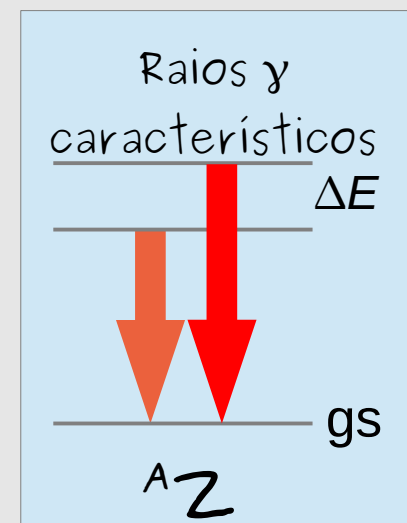
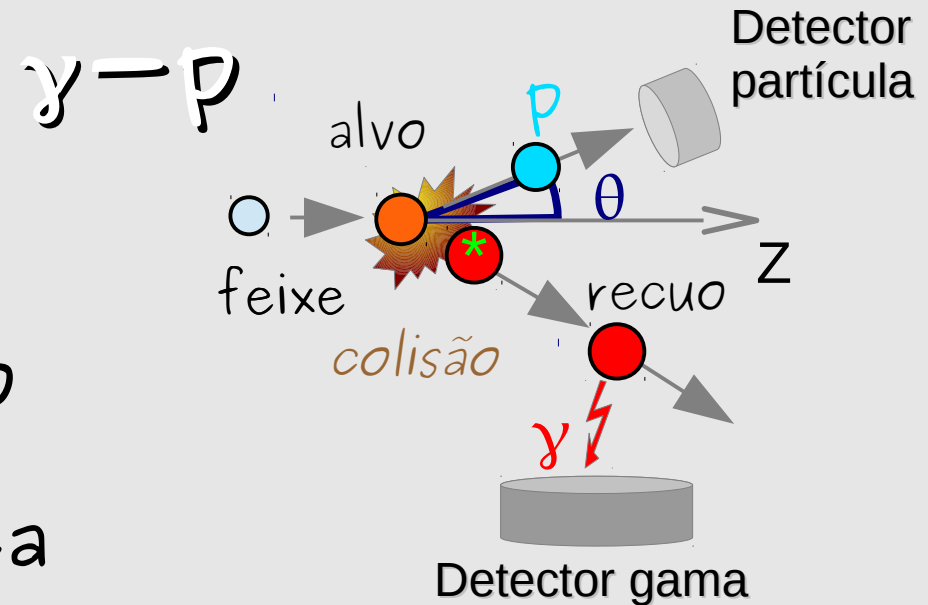
L. Gasques, J.R.B.O. – $^{16}\text{O} + ^{16}\text{O}$, esp. γ

Fator Astrofísico



Espectroscopia γ e mecanismos de reações

- Espalhamento inelástico
- Transferência inelástica
- Fusão completa e incompleta
- Transf. Múltiplas, DIC
- Quebra inelástica

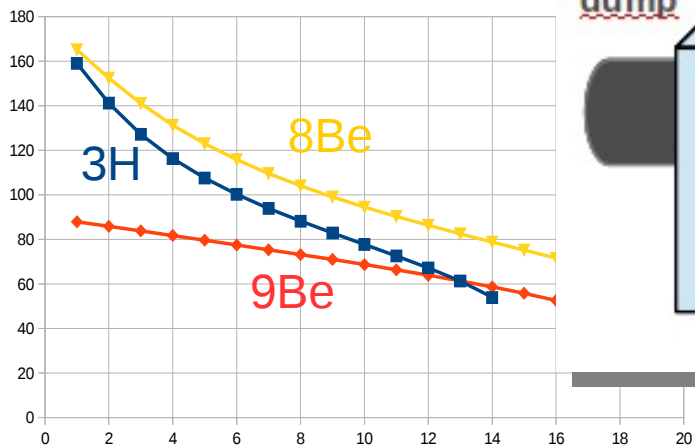
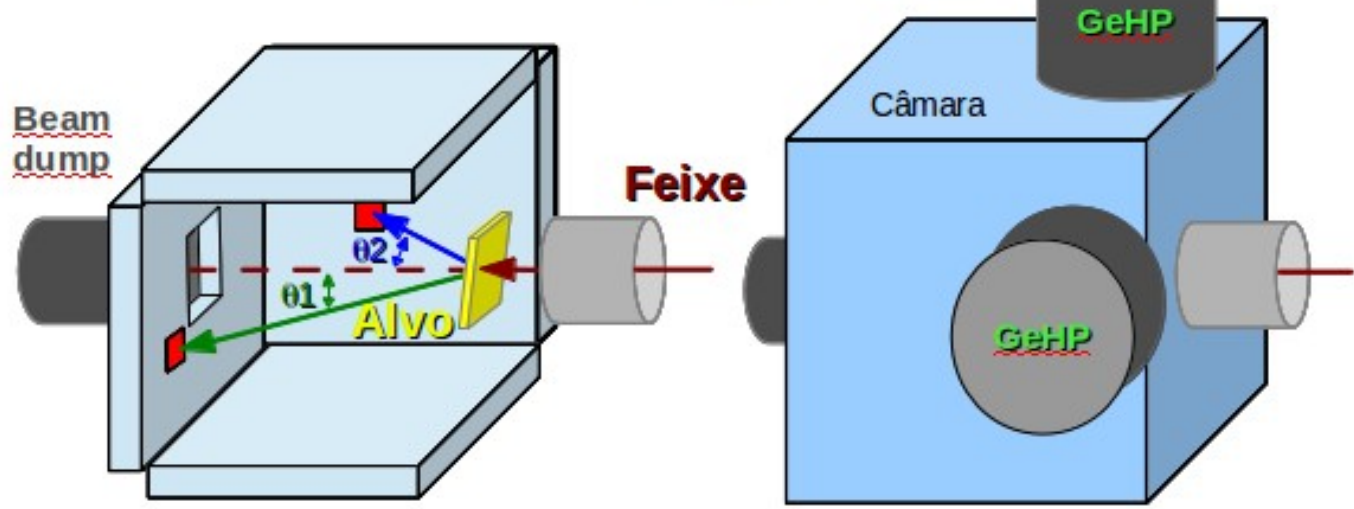
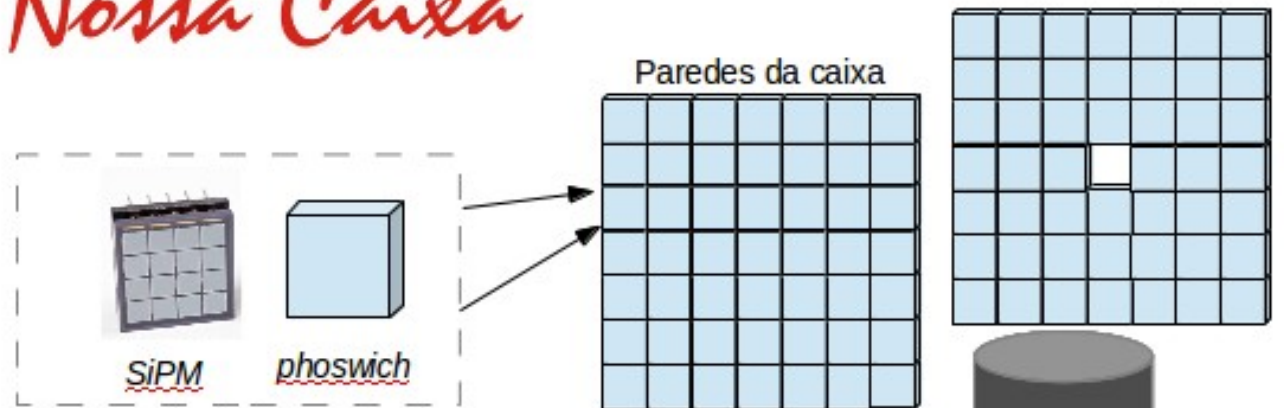


Futuro sistema 4π de partículas carregadas

- Alta granularidade para coincidências cinemáticas

Ideias preliminares:

Nossa Caixa

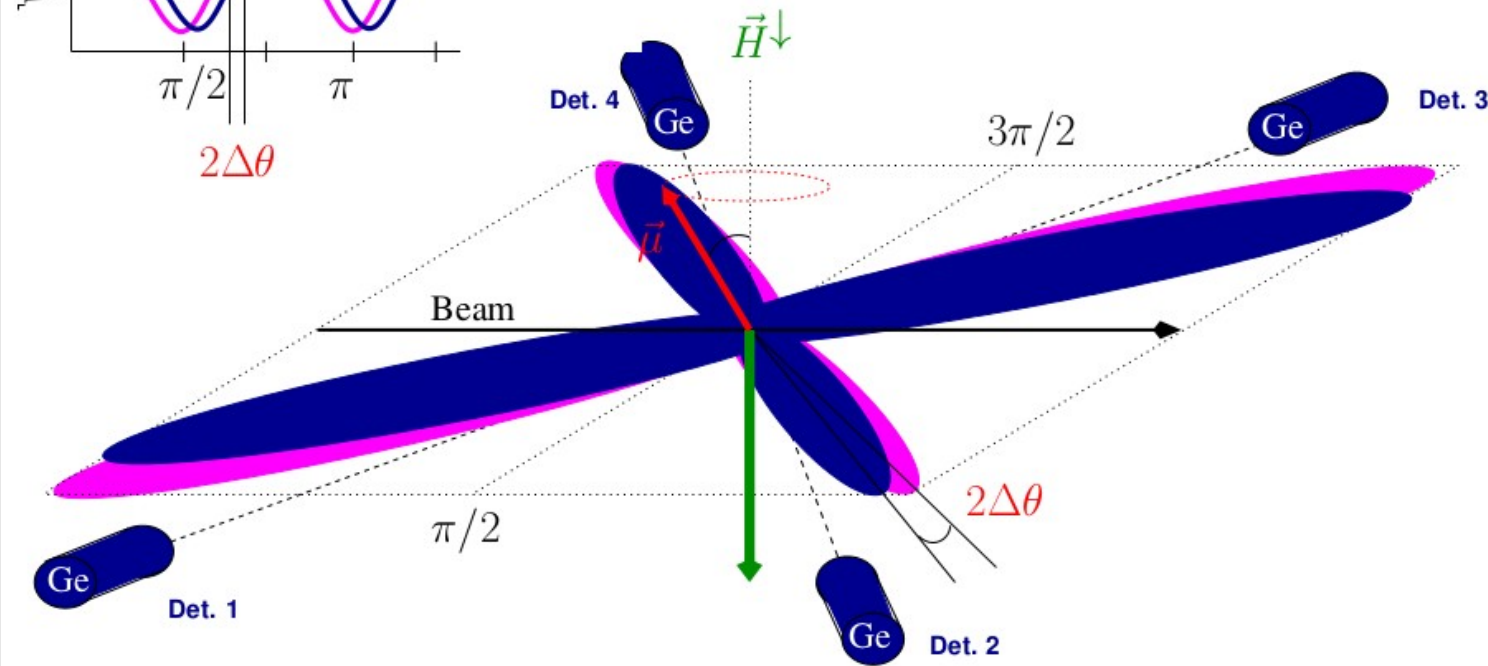
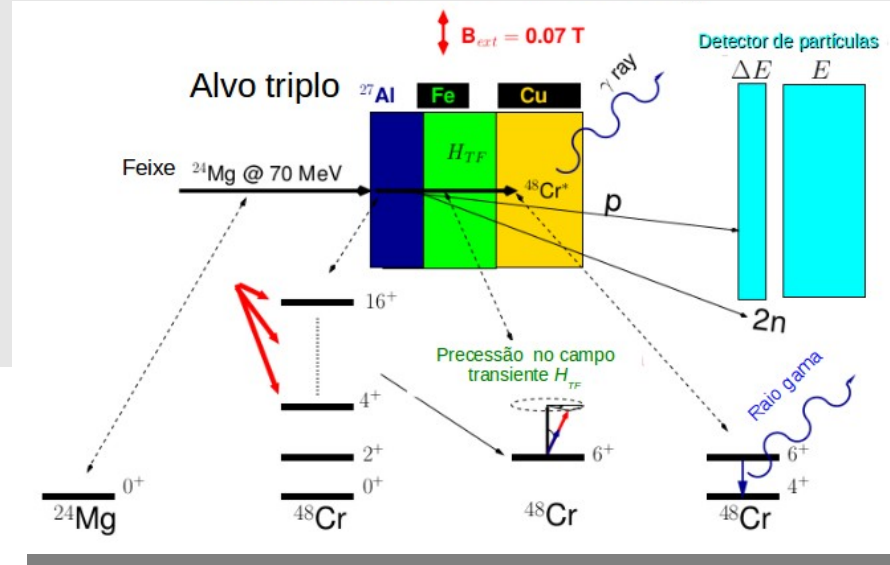
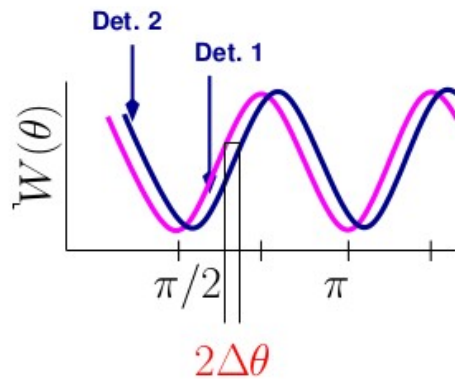


θ_1

Medida de fator g por CMT

- Técnica de medida

$H \uparrow \downarrow$



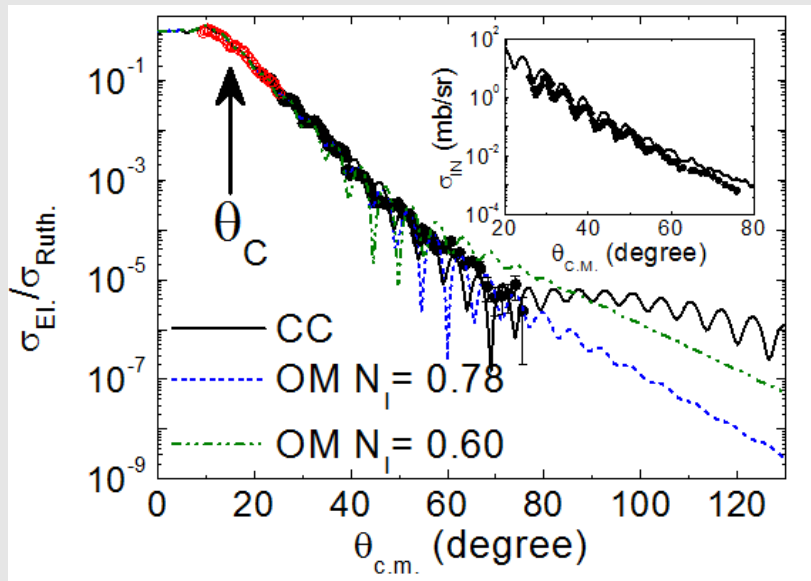
Proposta LAFN
Unal/USP

Colaborações com LNS/INFN

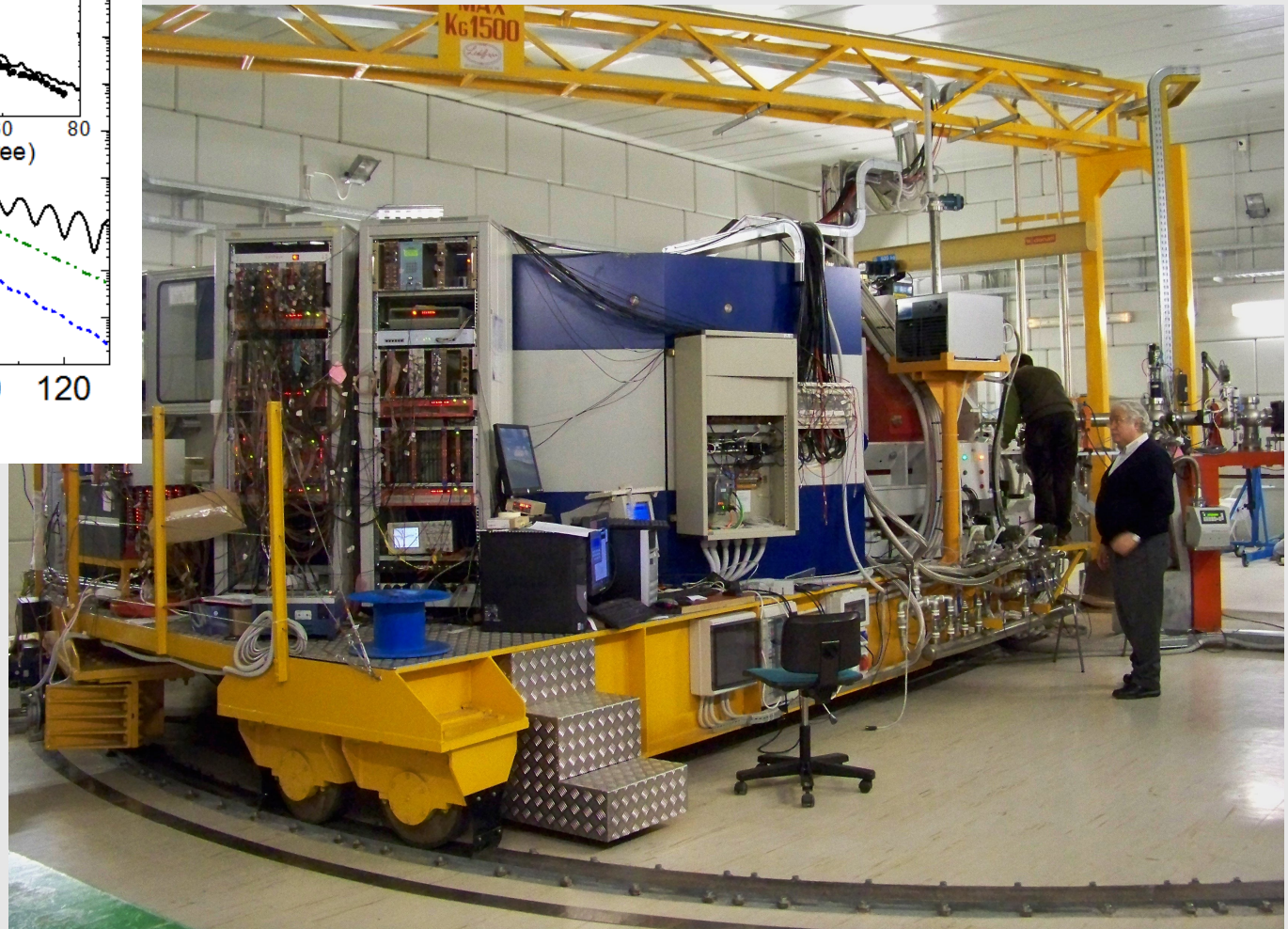
- Espectrômetro MAGNEX – Catania (Sicilia)
- Arco-íris nuclear
- NUMEN (duplo decaimento beta)
- Projeto de novo espectrômetro gama

Arco-iris nuclear – MAGNEX

- Proposta IFUSP – Experimento Catania LNS

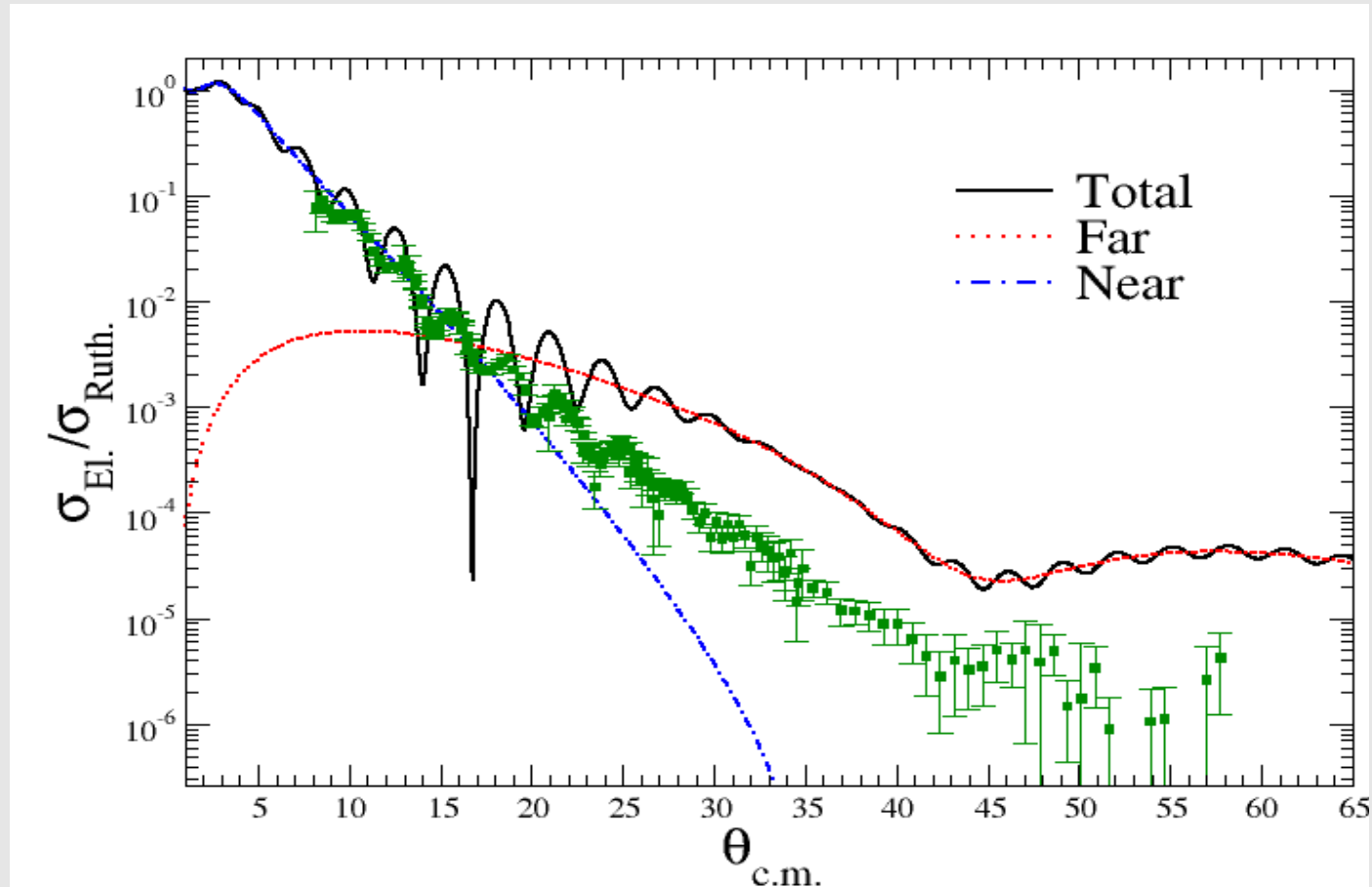


- D Pereira *et al.*
Phys. Lett. B 710 426
(2012)
- J R B Oliveira *et al.*
J. Phys. G 40
105101 (2013)



Arco-íris nuclear

$^{16}\text{O} + ^{27}\text{Al}$ @ 280 MeV CS+MAGNEX - LNS, Catania



OBS.: Dados Pelletron $^{10}\text{B} + ^{27}\text{Al}$ 22-42 MeV - aluno de mestrado 11/39

NUMEN

- Projeto em colaboração USP/UFF/LNS-INFN
- MAGNEX + espectrômetro gama
- Física do duplo decaimento beta
- Elementos de matriz de transição nuclear de dupla troca de carga

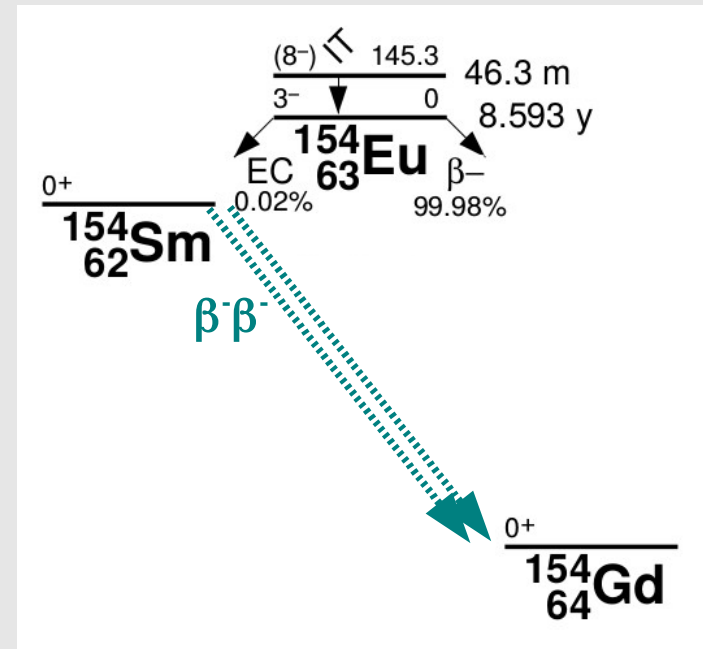
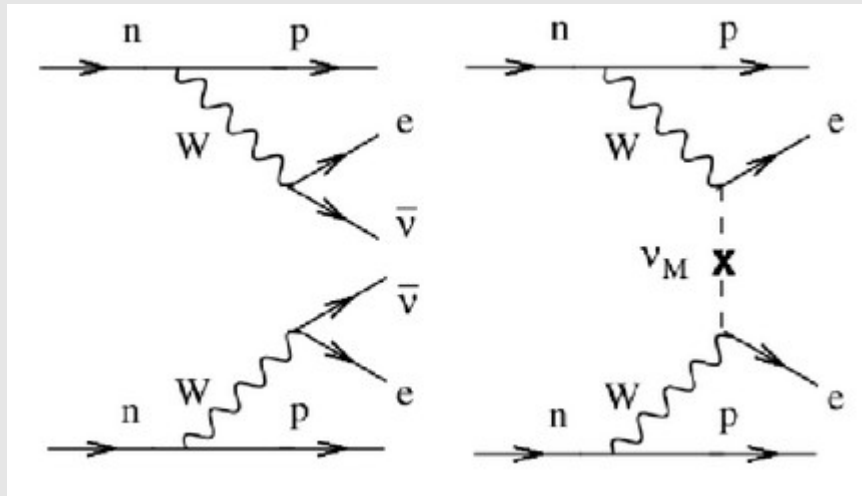
γ -Numen

Acoplamento de um espectrômetro γ ao MAGNEX



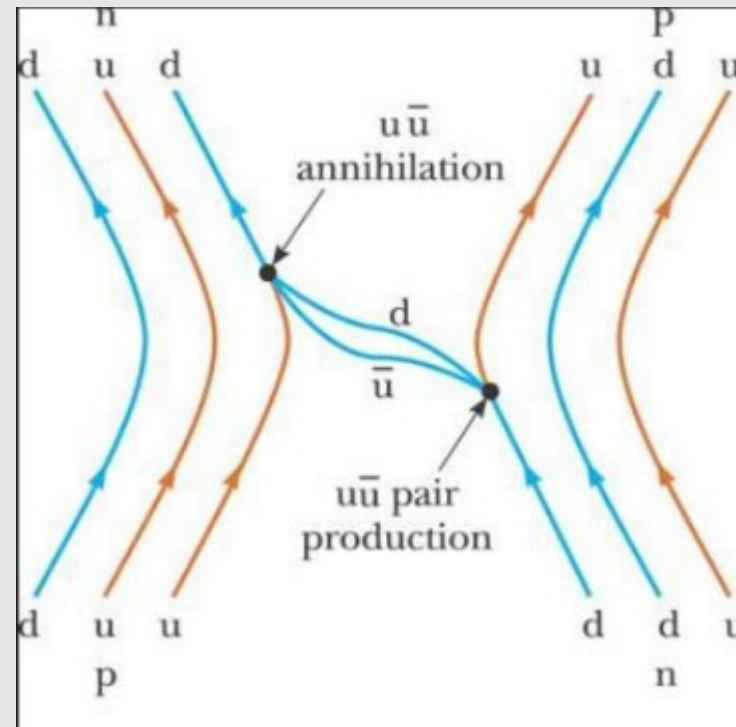
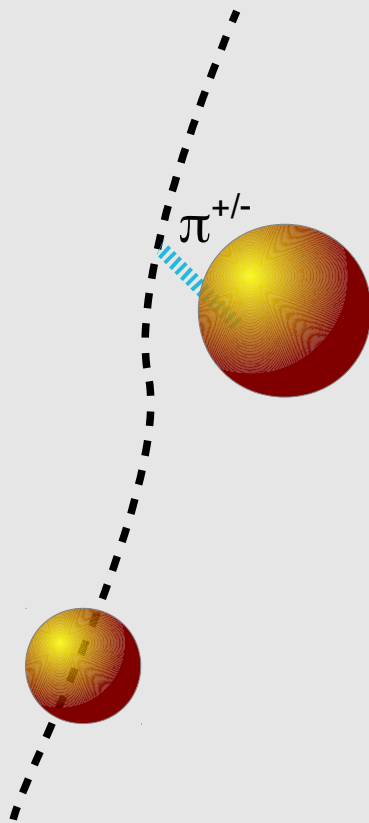
Duplo decaimento beta

- Decaimento muito raro $T_{1/2} = 10^{20} - 10^{24}$ anos
- Modelo Padrão: $\nu \neq \bar{\nu}$, $m_\nu = 0$ - decaimento duplo beta ocorre sempre com emissão de 2 neutrinos (no caso de $\beta^+\beta^+$) ou 2 anti-neutrinos (caso $\beta^-\beta^-$)
- Se $\nu = \bar{\nu}$ (neutrino de Majorana), duplo beta pode acontecer sem emissão de ν



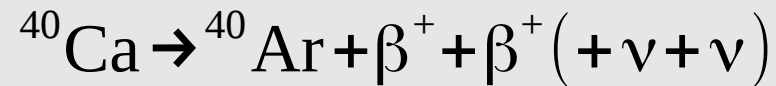
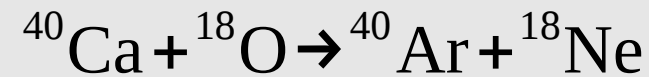
Reação de troca de carga SCE

- Troca de um pión ou outro méson carregado entre dois núcleos



Reação de dupla troca de carga DCE

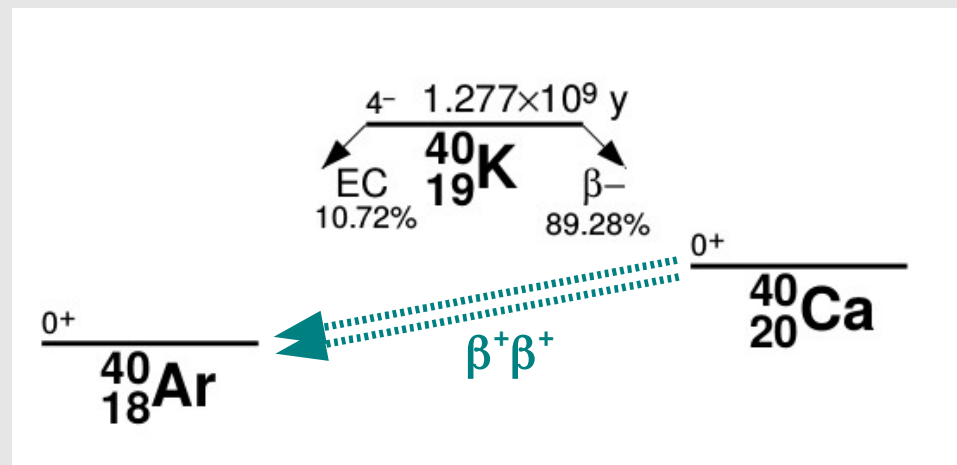
- Troca de dois mésons carregados entre os núcleos
- Semelhante ao duplo-decaimento beta sem ν
- Elementos de matriz M são proporcionais



$$\Gamma = G |M|^2 |m_{\beta\beta}|^2$$

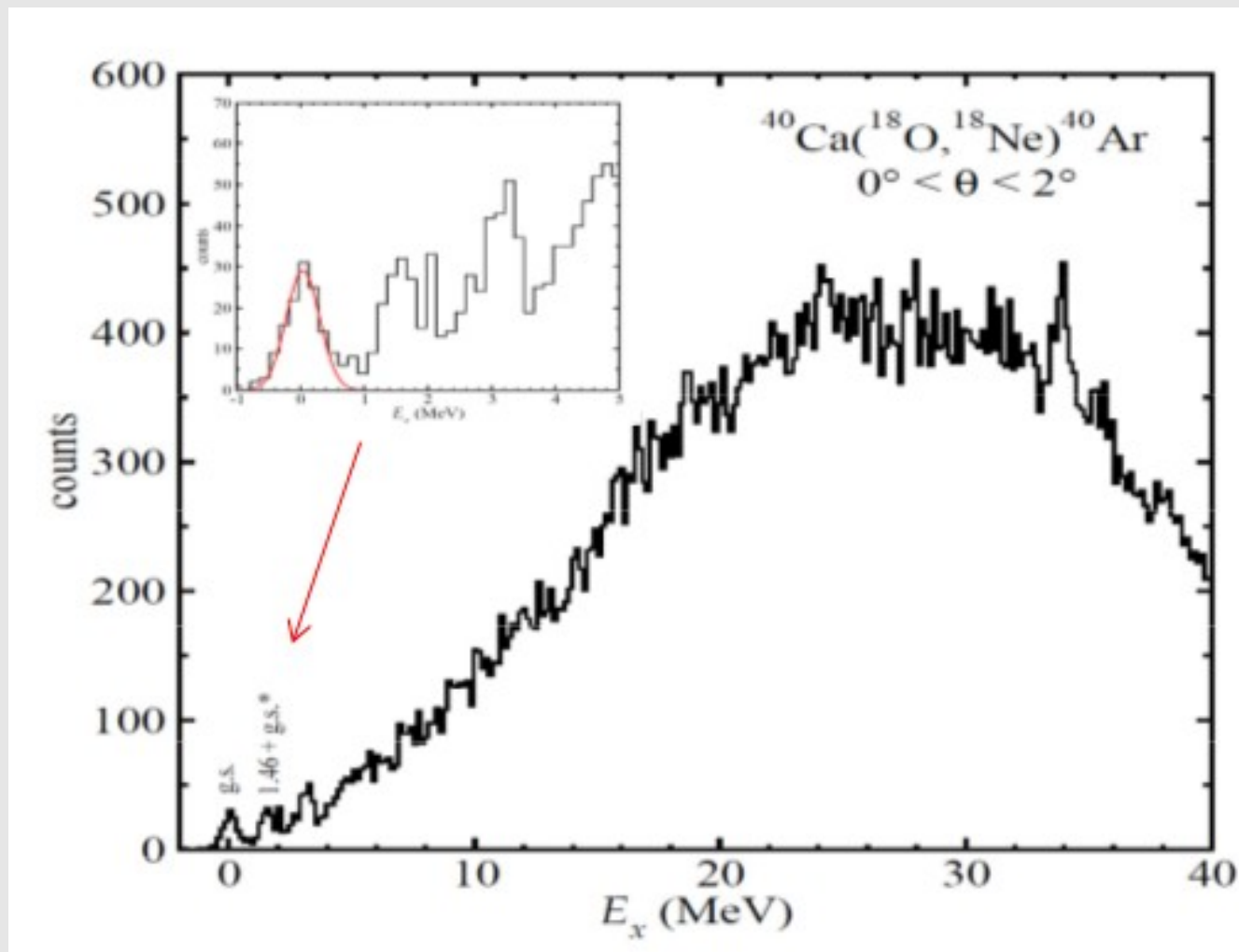
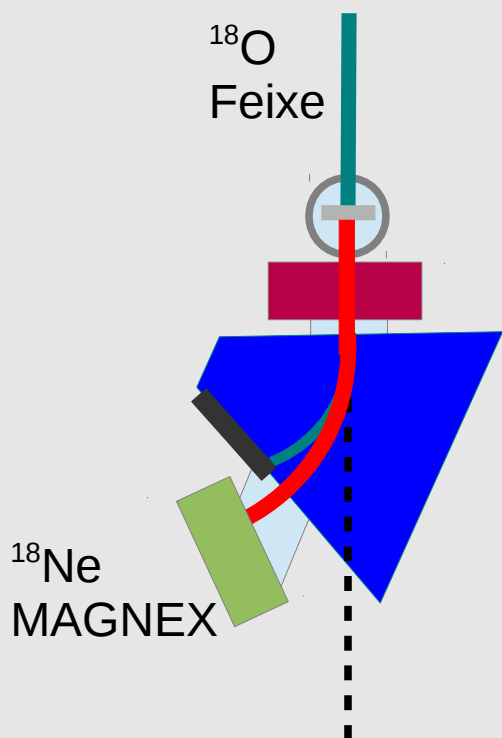
$$|m_{\beta\beta}|^2 = \sum_{i=1}^3 m_i U_{ei}^2$$

$$|M|^2 = |\langle \varphi_f | O^{\beta\beta} | \varphi_i \rangle|^2$$

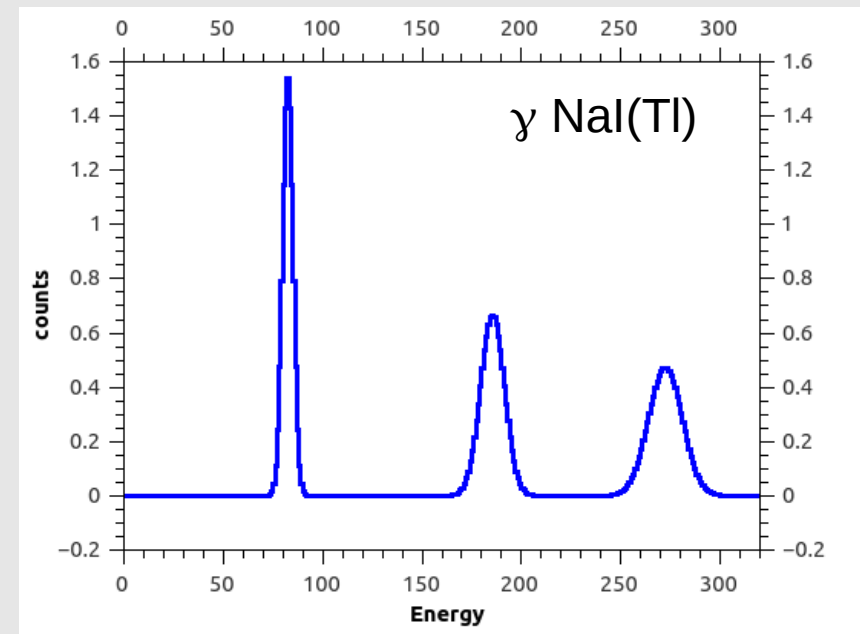
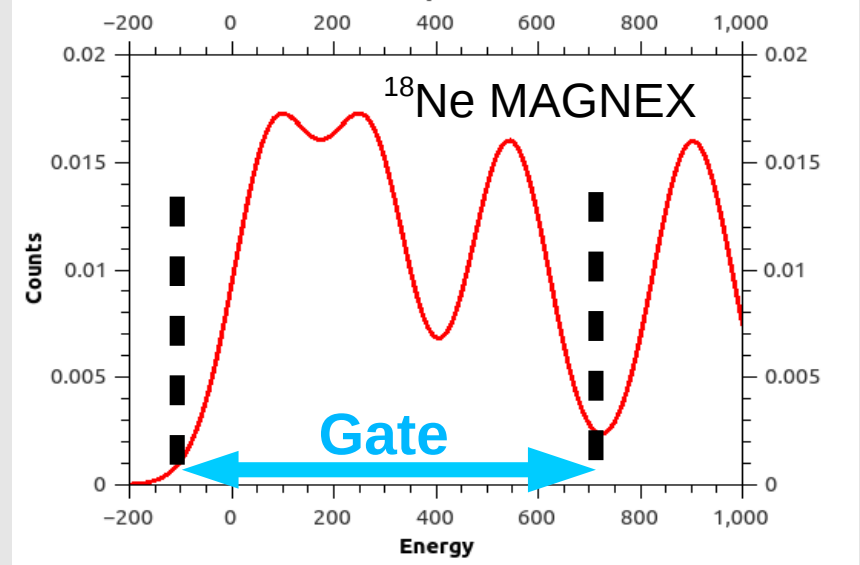
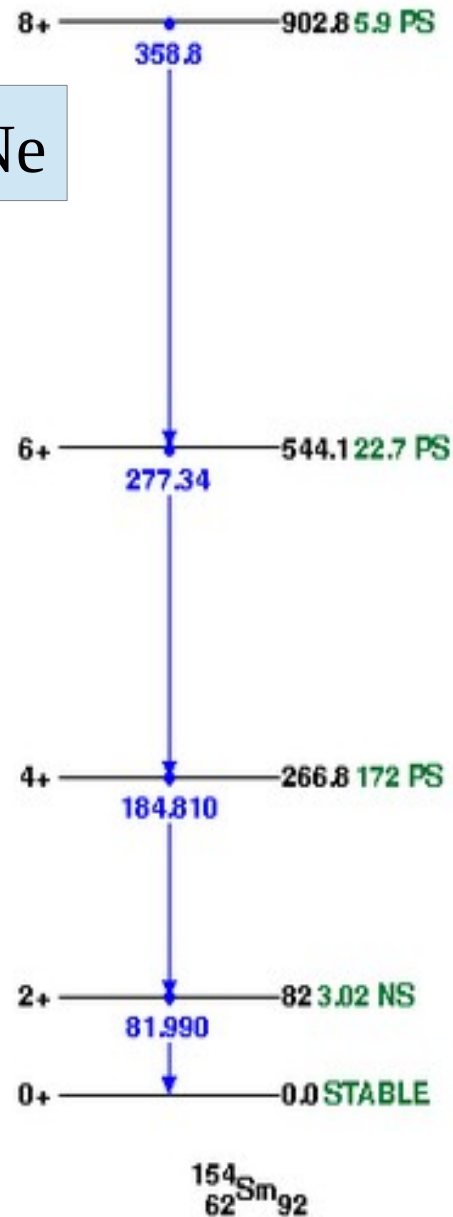
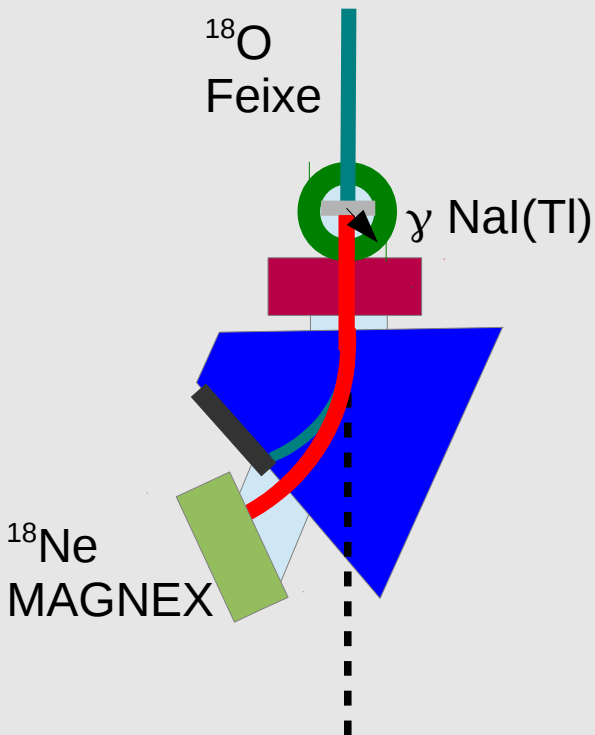
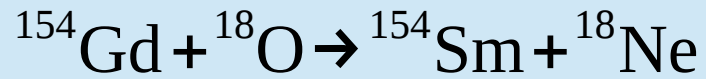


Espectro de energia de excitação

- ^{18}Ne detectado no MAGNEX ao redor de 0°



Espectros previstos para ^{154}Sm



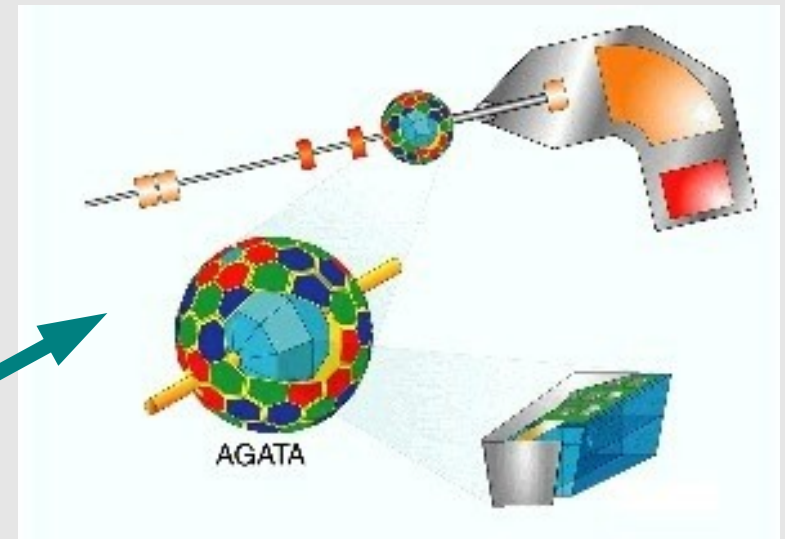
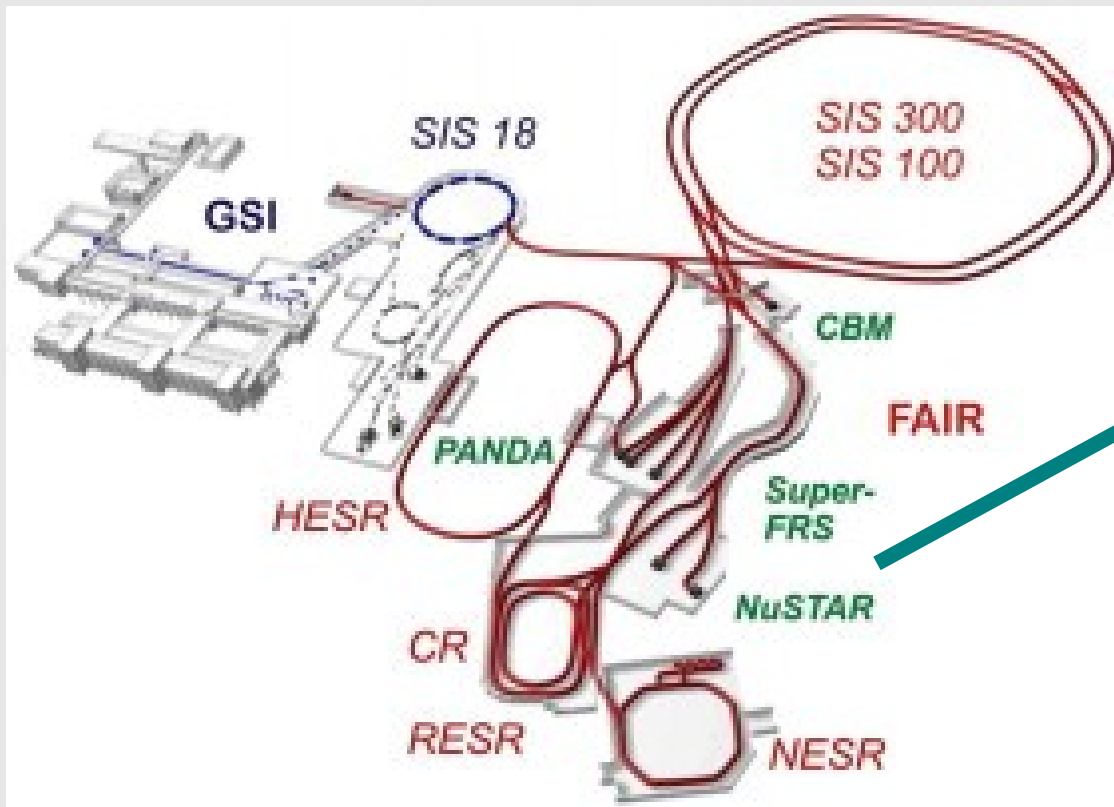
Perspectivas

1.- Fronteira extensiva:

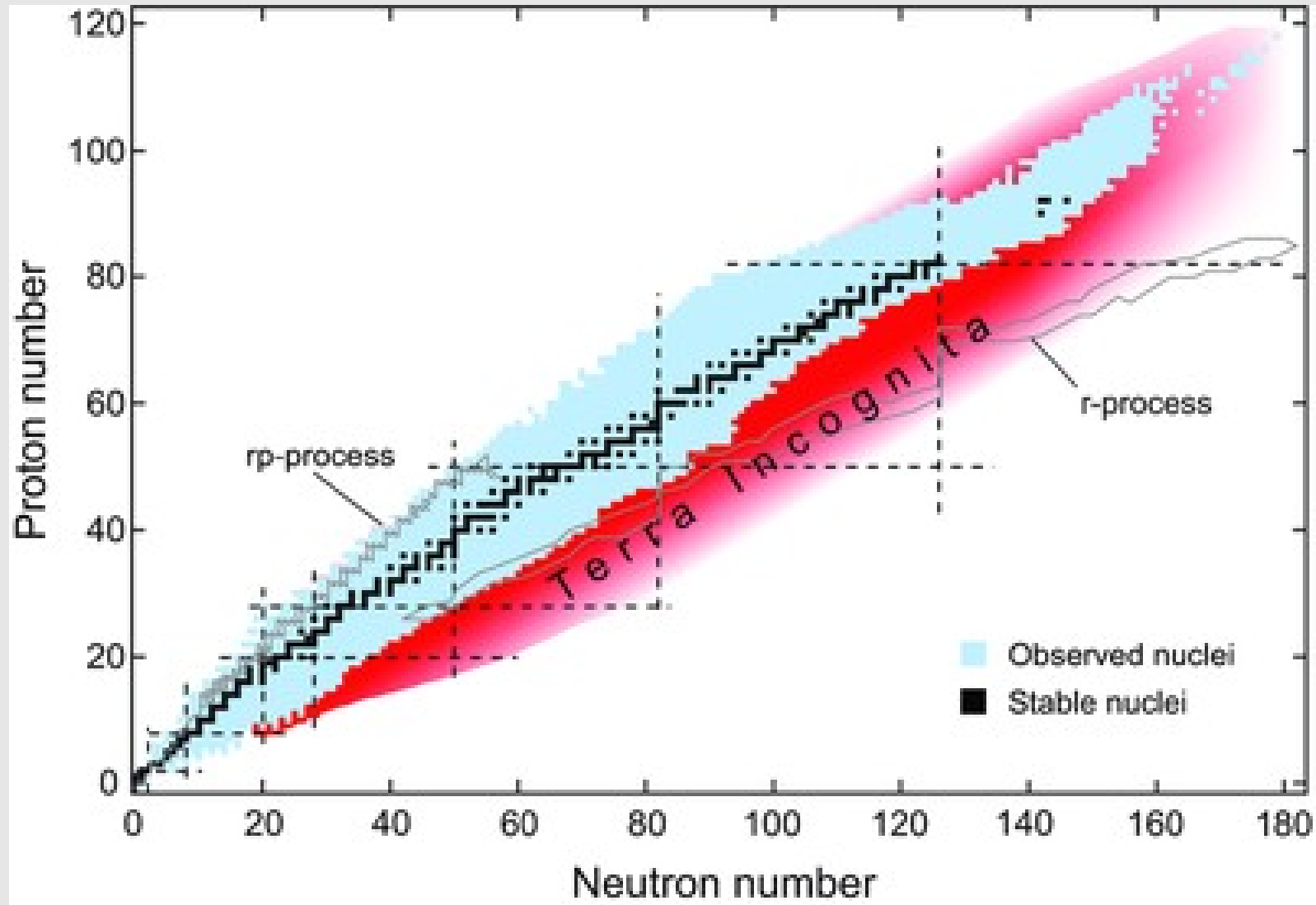
- Feixes radioativos de alta intensidade (SPES, FAIR, SPIRAL2...): razões N/Z extremas
- Baixíssimas energias (Astrofísica nuclear)
- Elementos superpesados (SHE): A extremo
- Hipernúcleos: Nova dimensão: S (Panda)
- Altos spins J (γ -tracking)

FAIR

- Facility for Antiproton and Ion Research
- Feixes Radioativos de alta intensidade
- HISPEC/DESPEC NuSTAR

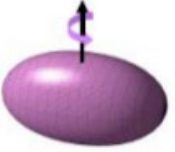


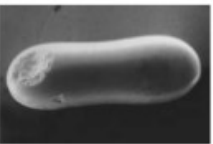
Terra Incognita




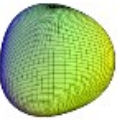
Momentos angulares extremos

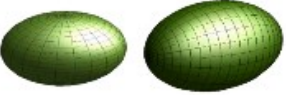
• Formas nucleares e fenômenos associados

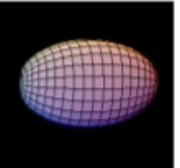
- 

Superdeformation
Hyperdeformation
- 

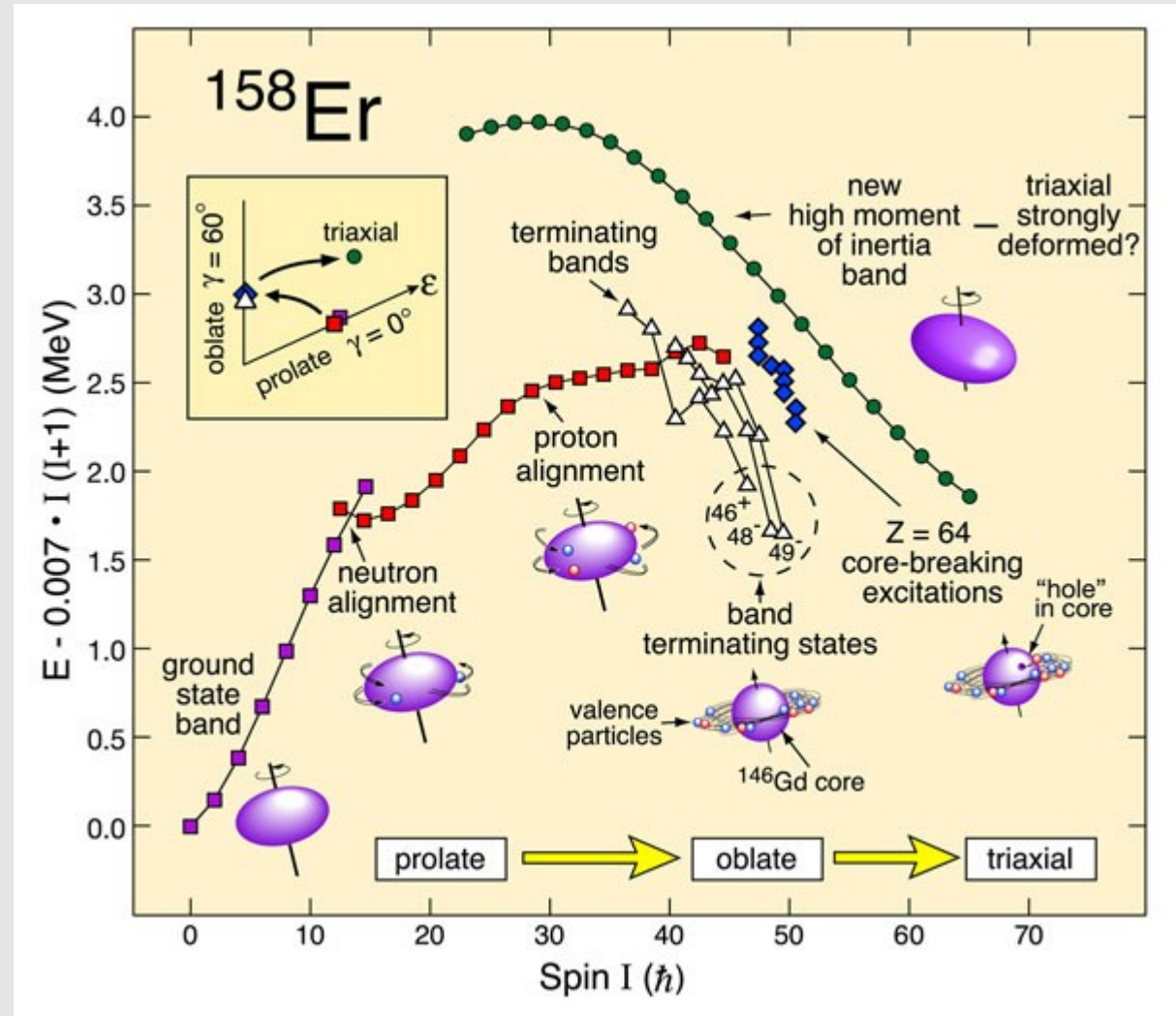
Jacobi shapes
- 

Triaxial shapes
3-dimensional rotation
- 

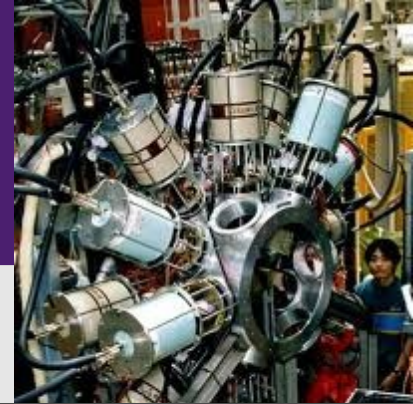
Higher-order shapes
(with high-rank symmetry):
tetrahedral, octahedral
- 

Shape coexistence
- 

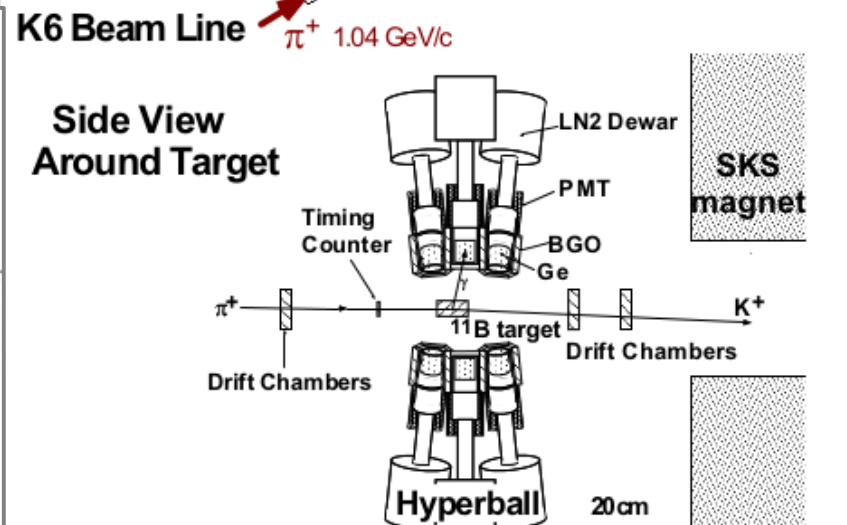
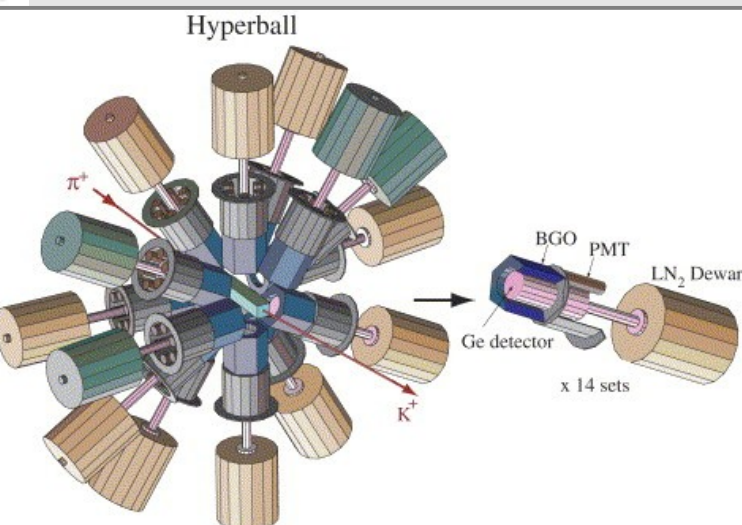
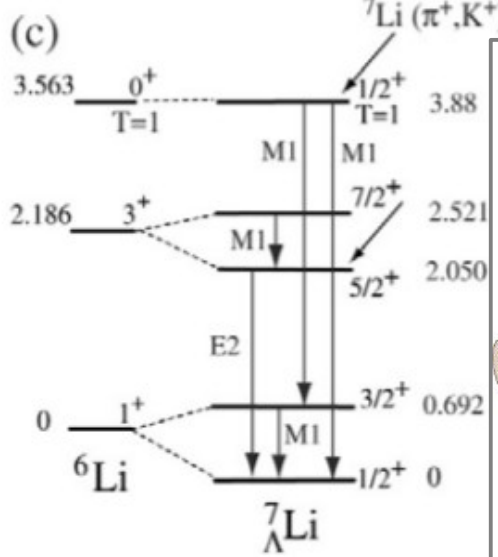
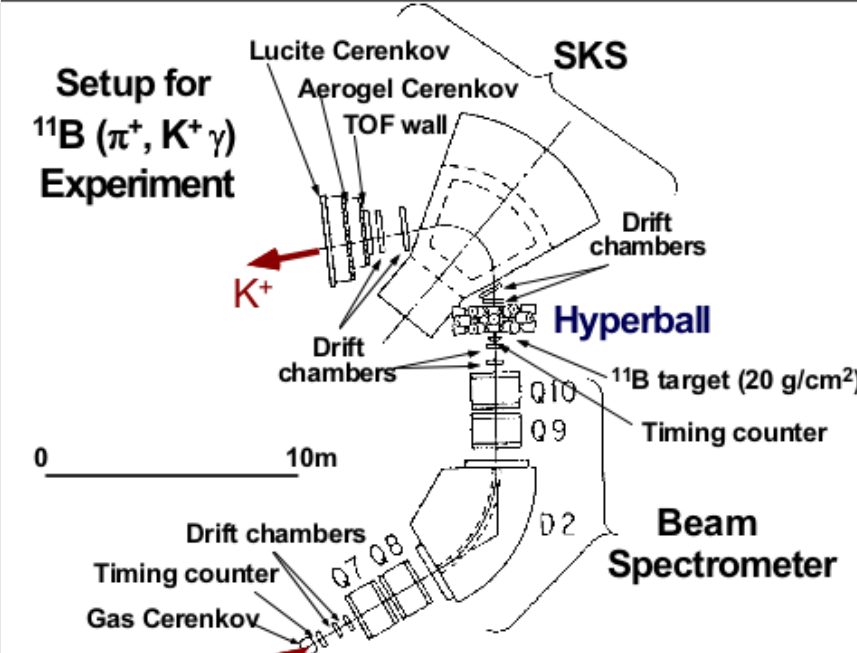
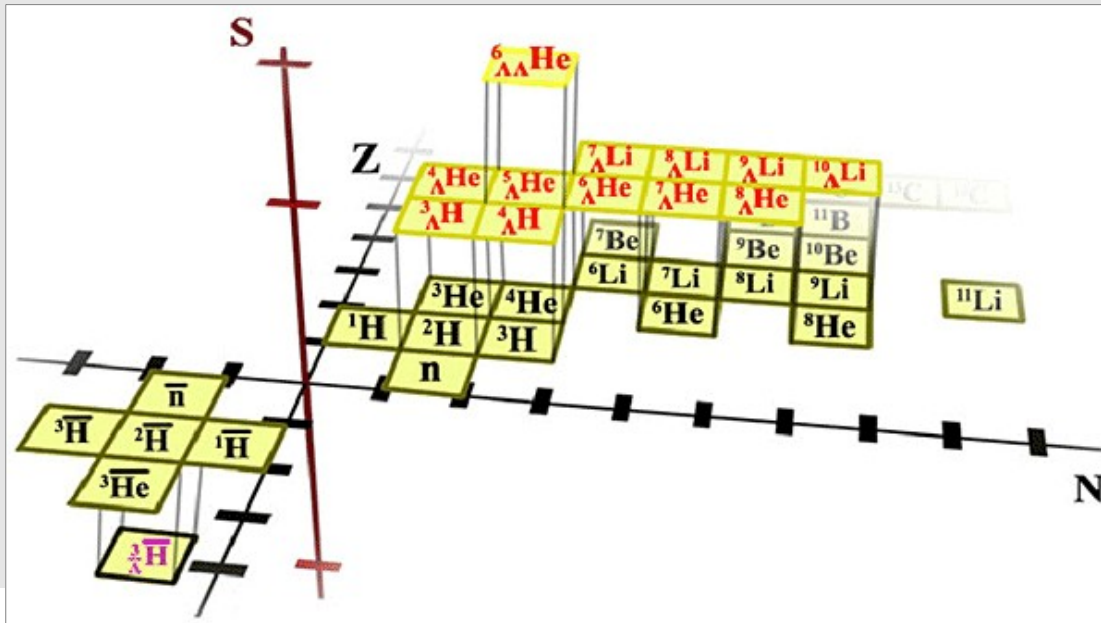
dynamic deformation
vibrations etc.



Hipernúcleos



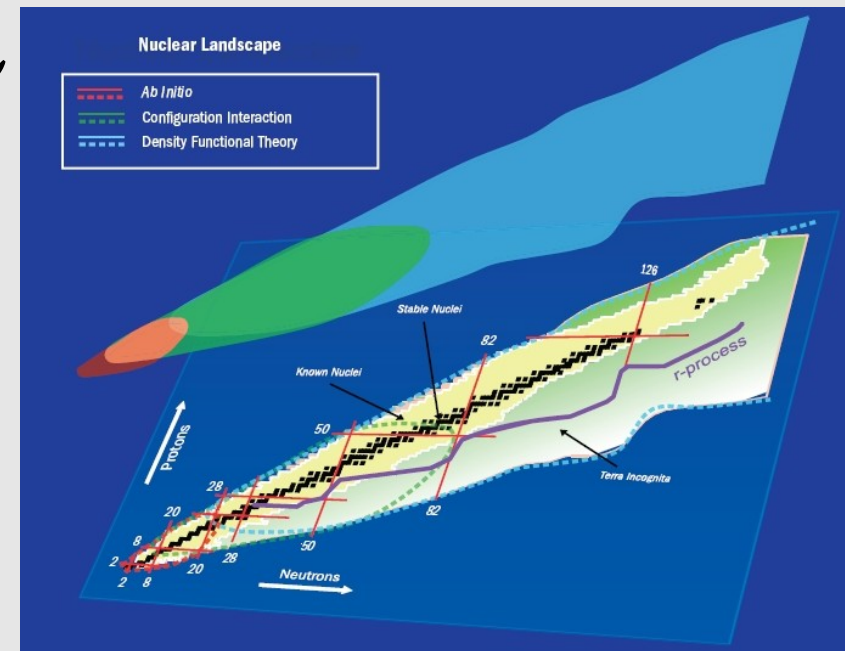
- Nova dimensão da carta de nuclídeos (s)



Perspectivas

2. Fronteira da precisão

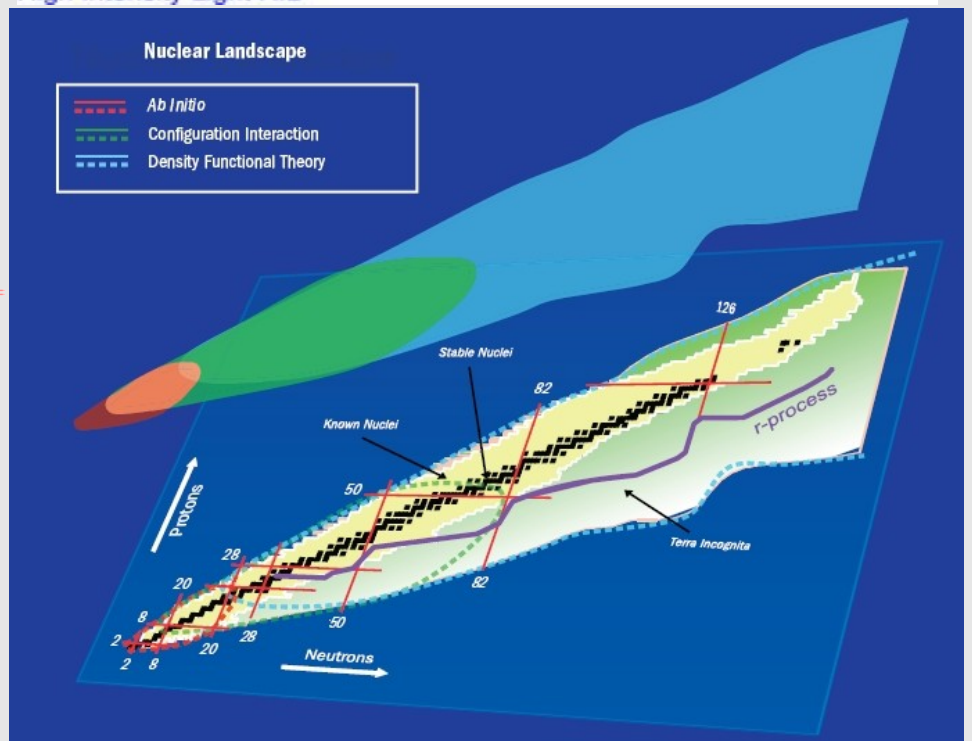
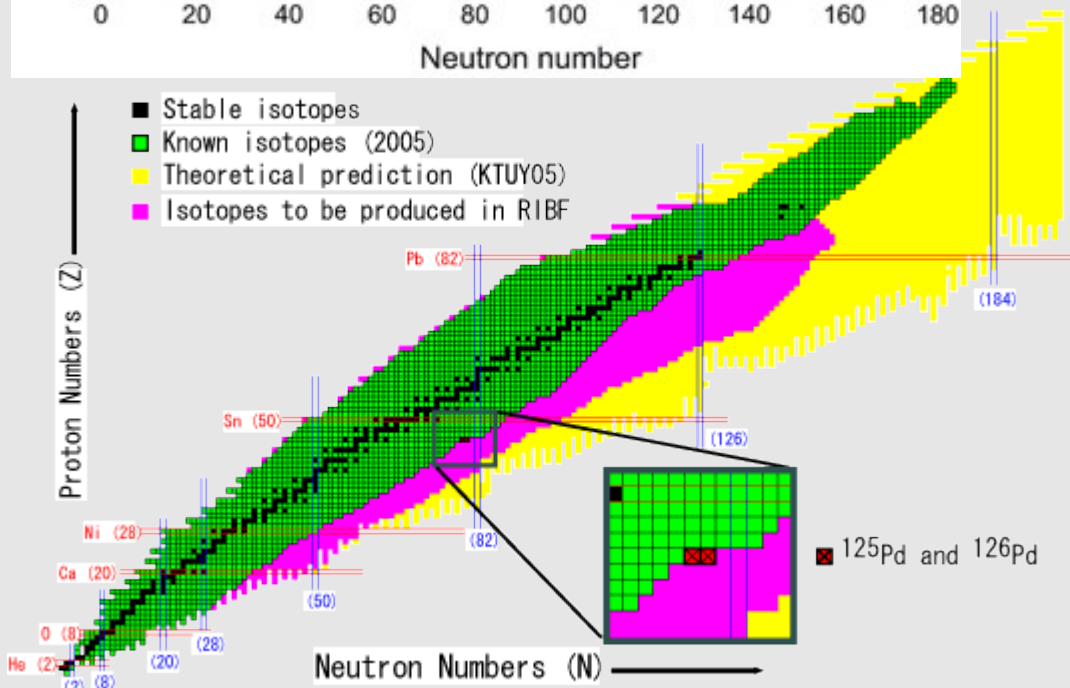
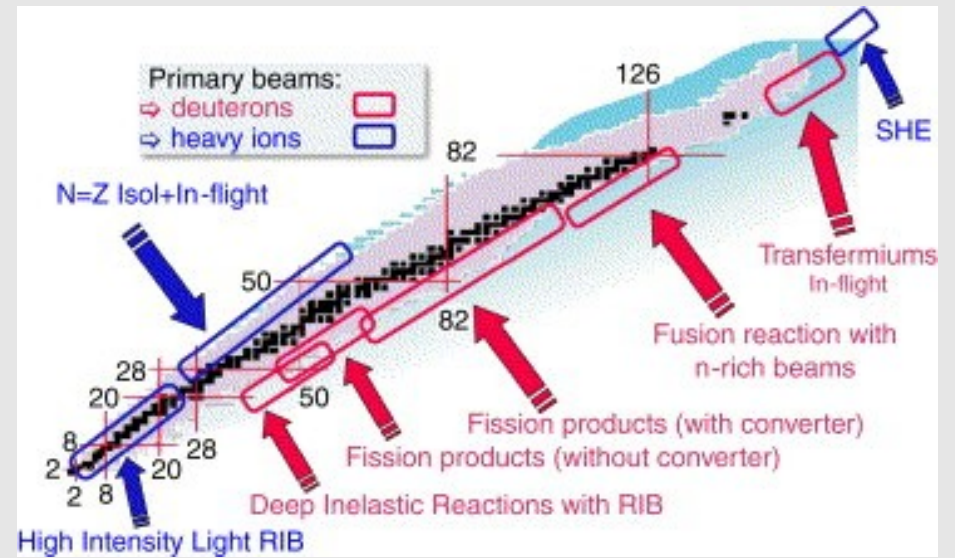
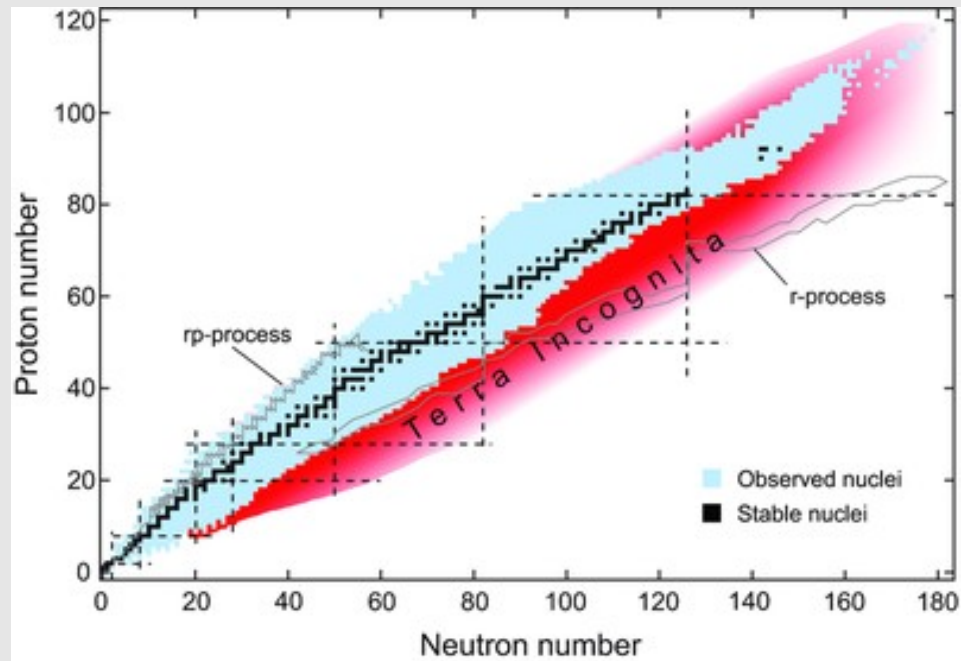
- Testes do "Ab Initio NCSM" e extensões (teoria)
- $\beta\beta$ -sensibilidade além do Modelo Padrão
- Medidas precisas de propriedades nucleares em casos críticos, e sistemáticas



Obrigado pela atenção!

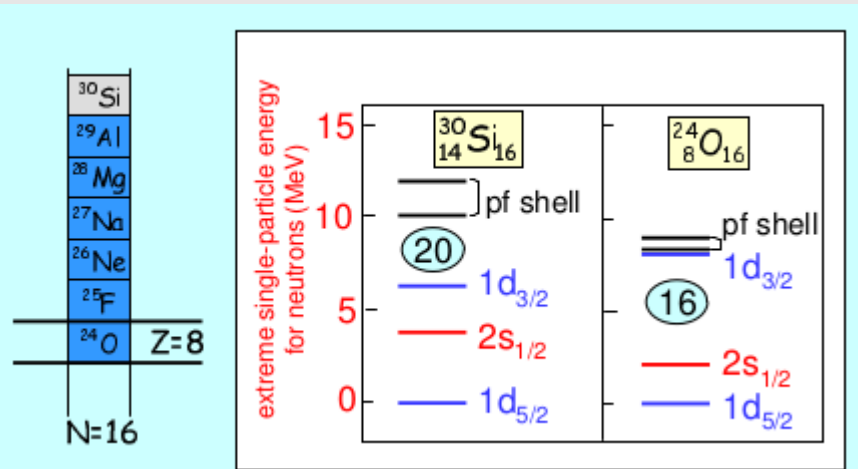
Extras

Terra Incognita

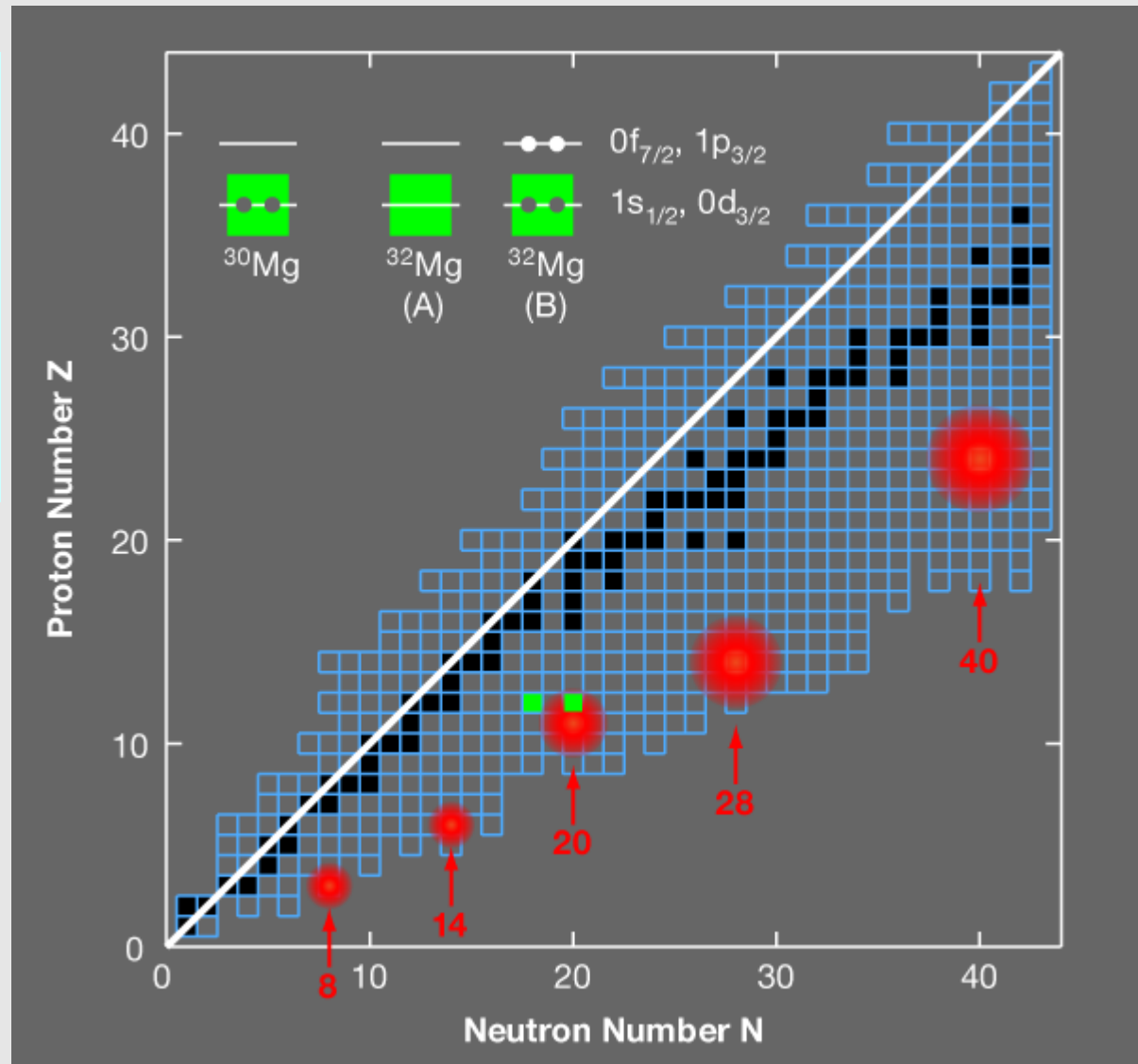


Evolução da estrutura de camadas

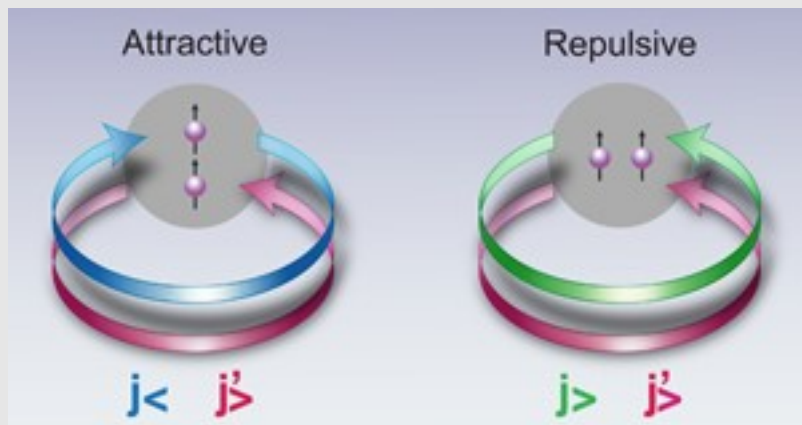
Novos n^os. mágicos



Previsões de "quebras" do MC

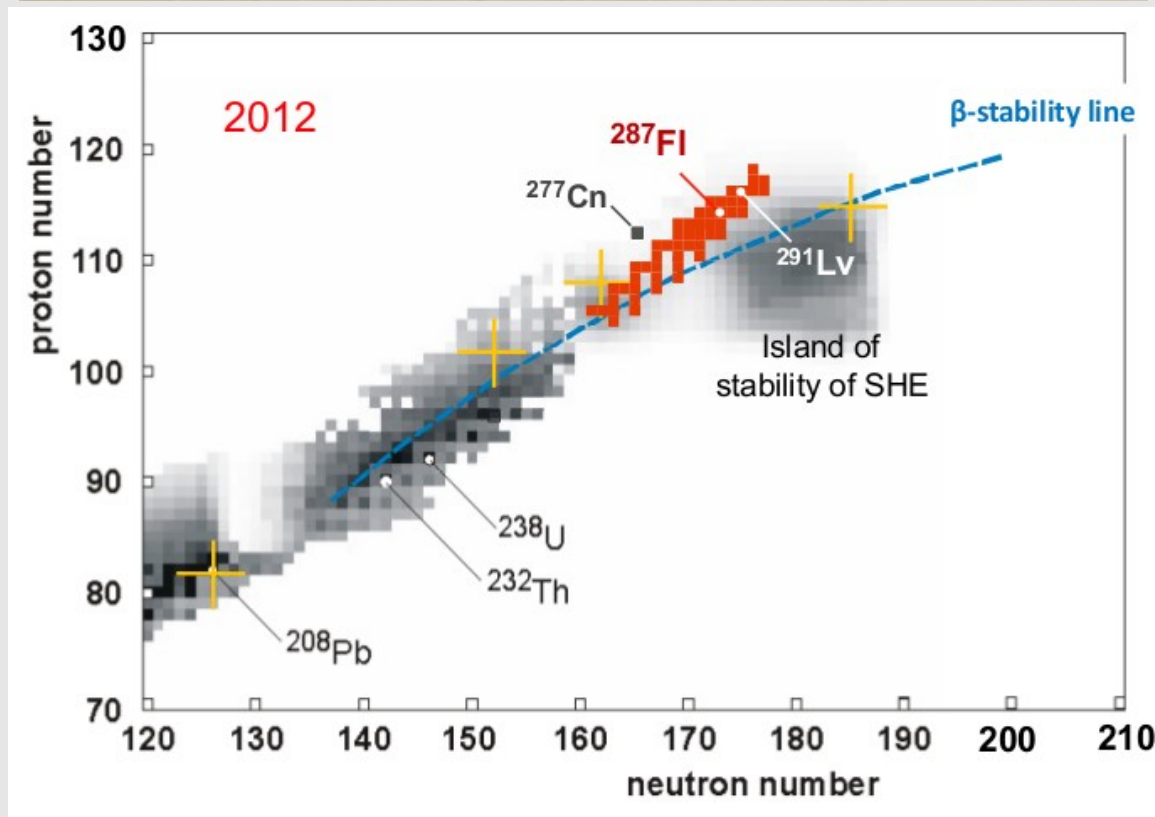
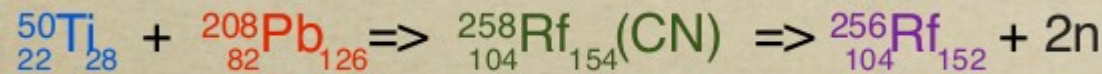


Força tensorial



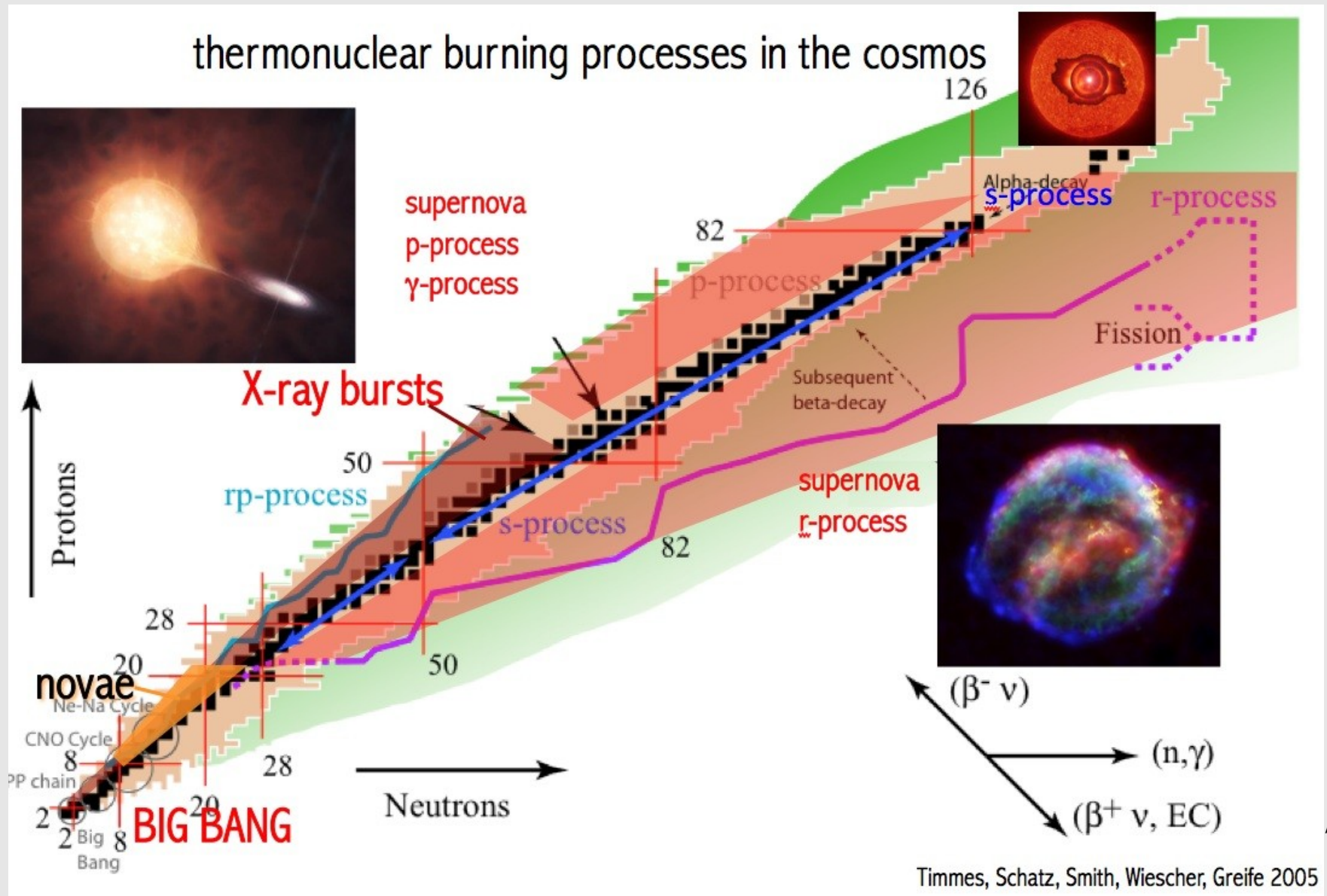
Elementos Superpesados (SHE)

- Primeira medida de espectroscopia gama de um SHE - J. Rubert et al. 2012 @ Jyvaskyla (~20 dias de experimento)

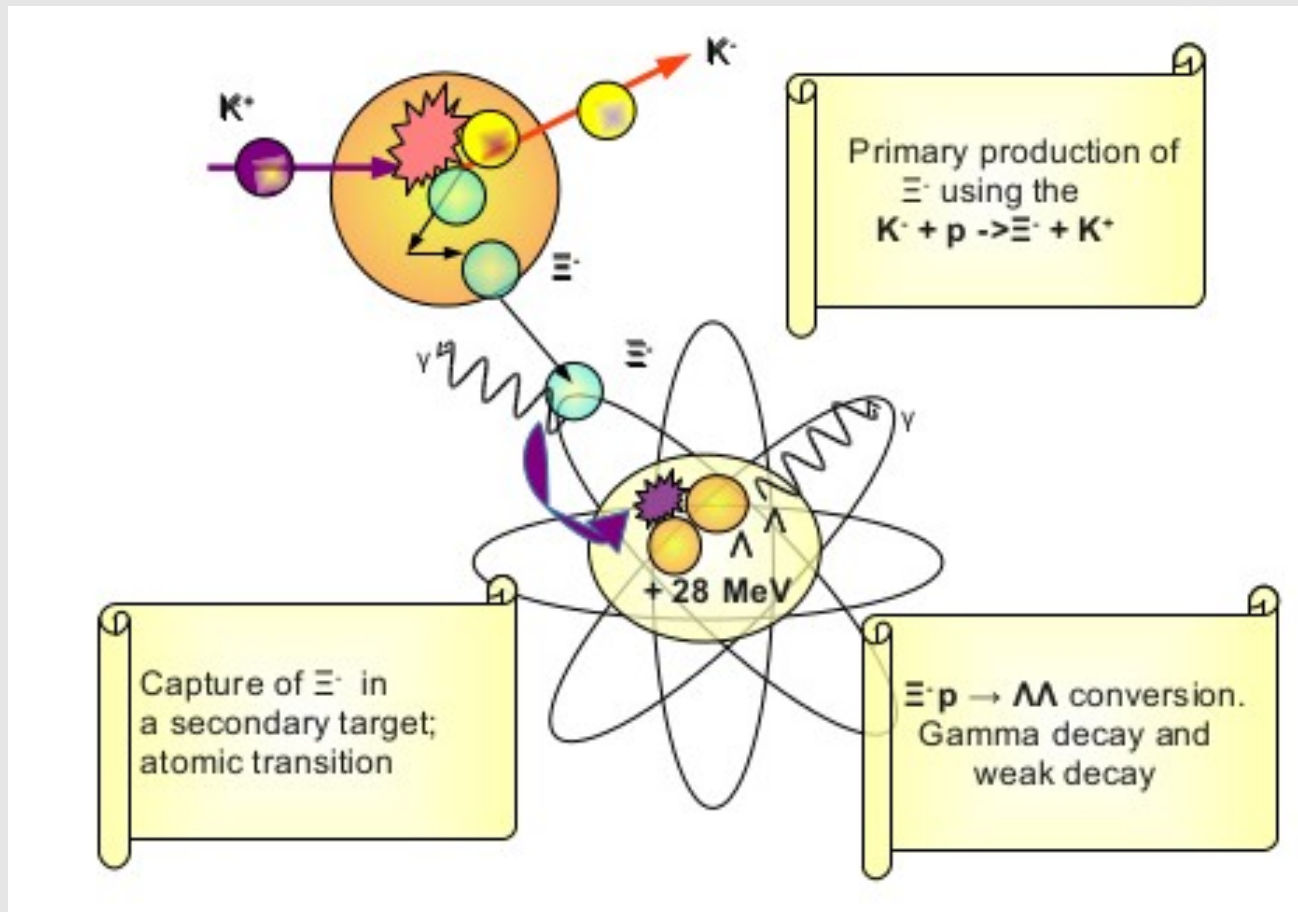


Astrofísica

- Reações a energias muito baixas



$\Lambda\Lambda$ - Produção



PANDA @ FAIR

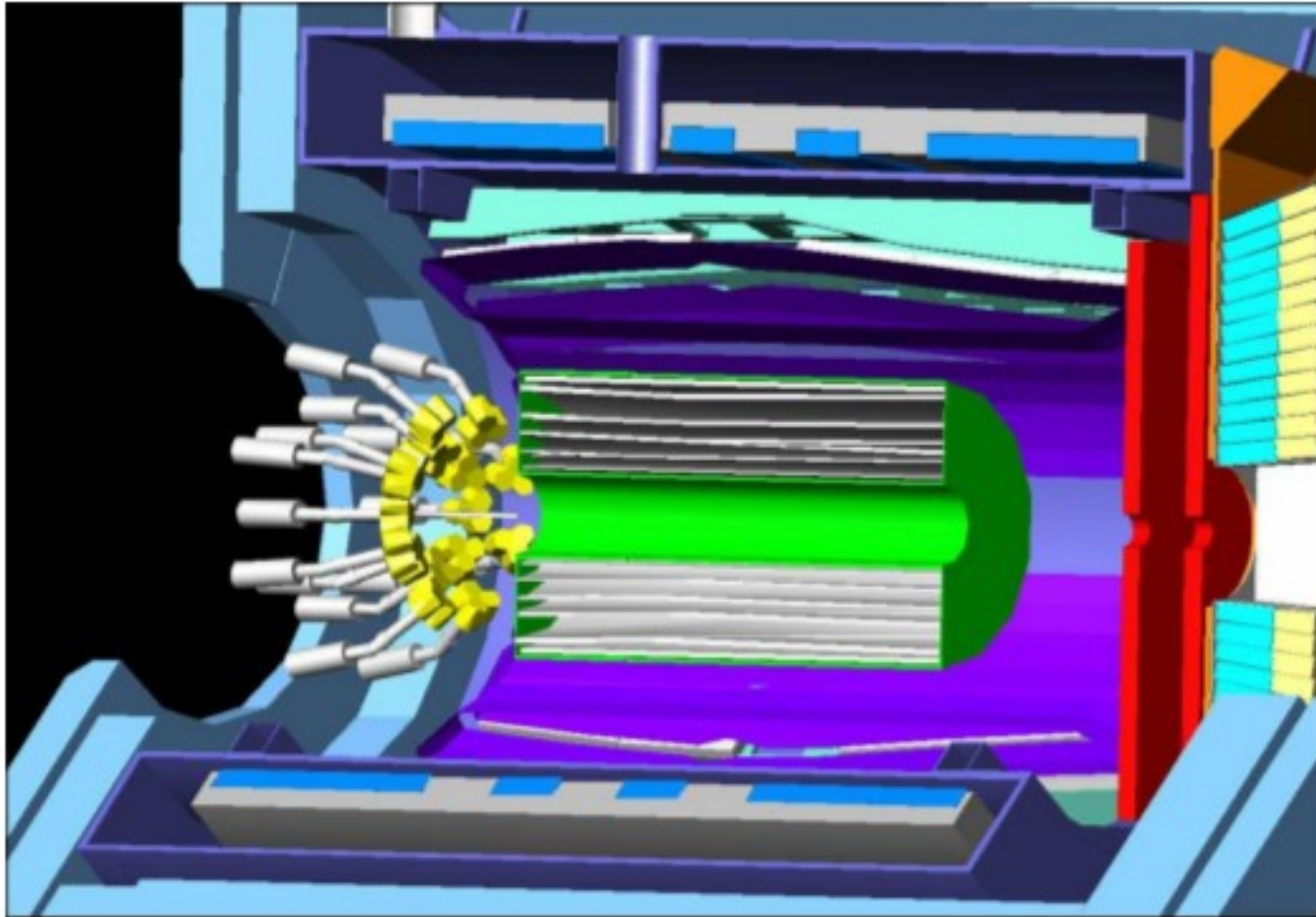
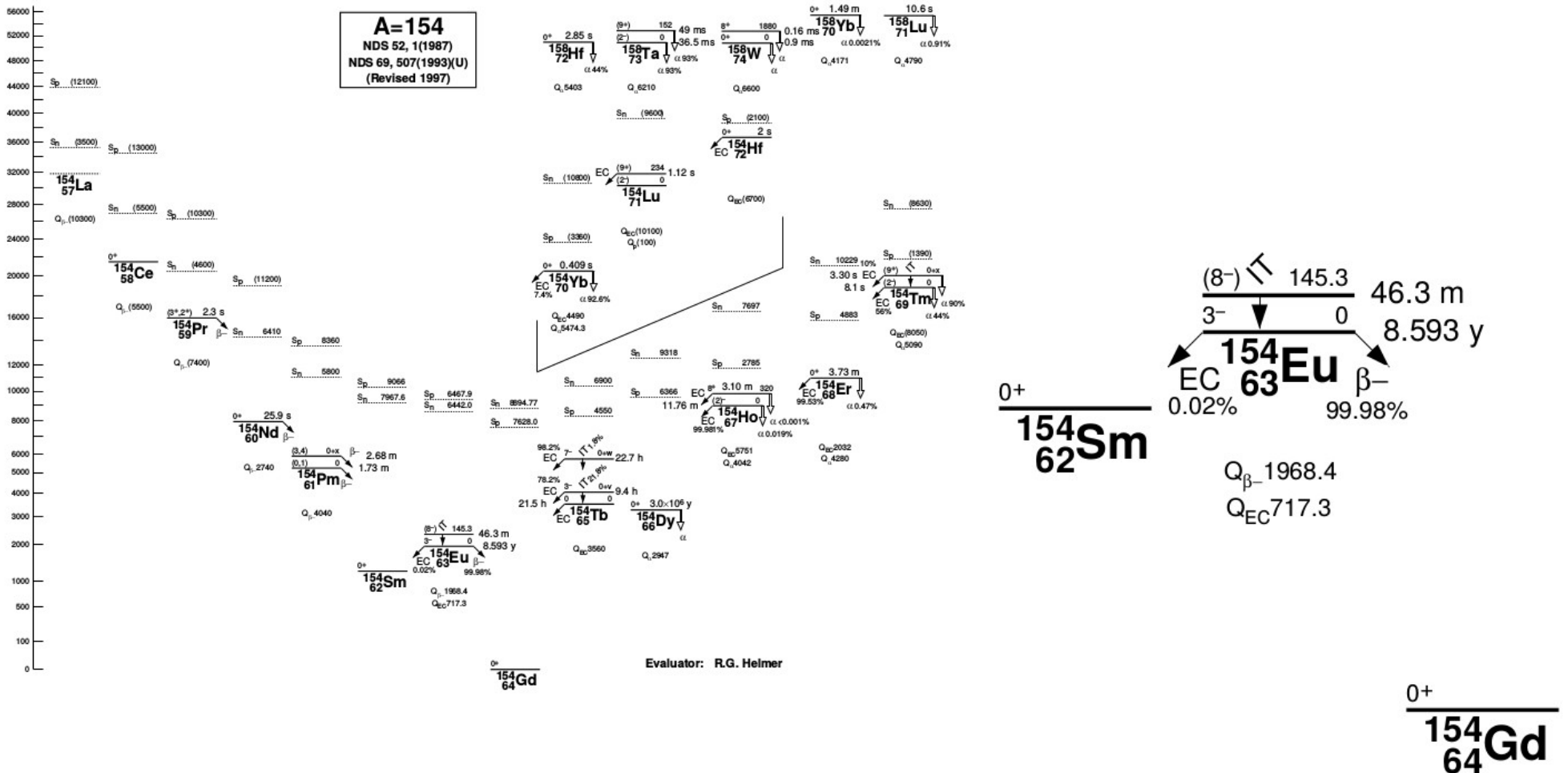


Figure 4.2: Integration of the secondary target and the germanium Cluster-array in the \bar{P} ANDA detector, with the beam entering from left.

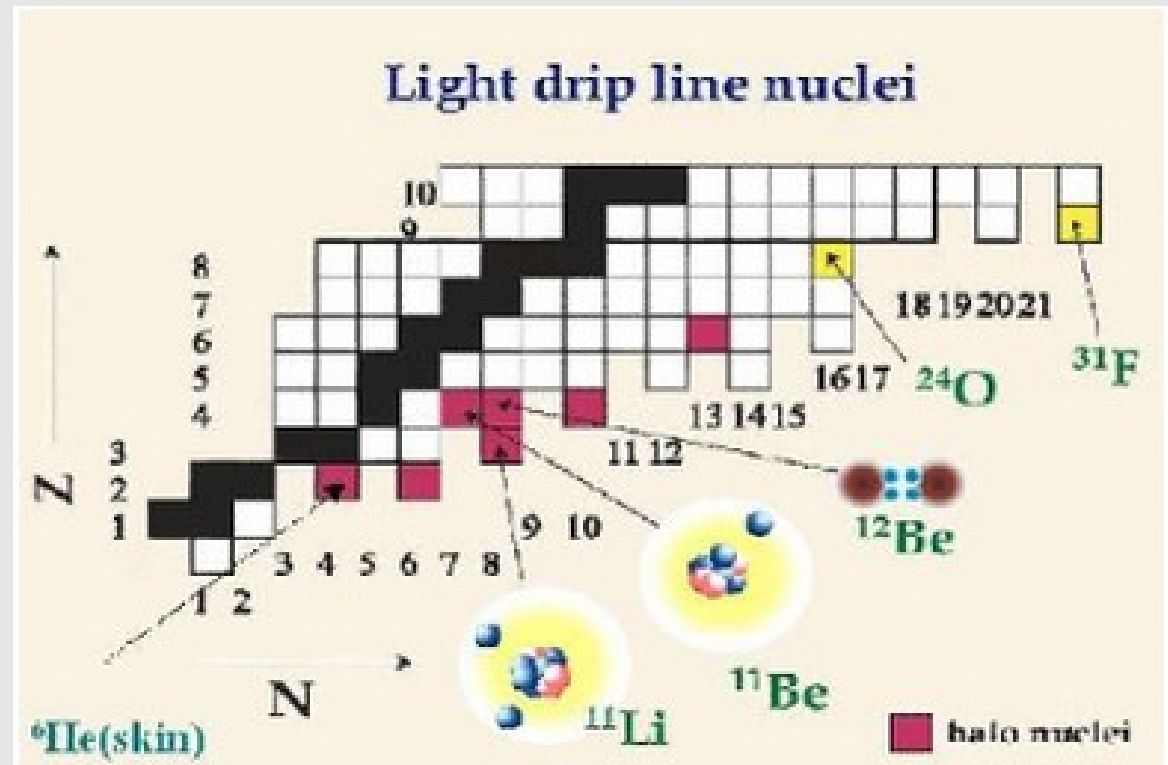
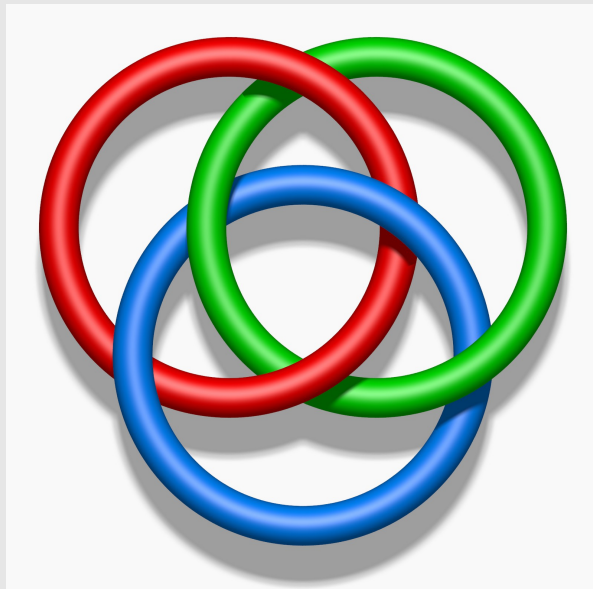
Introduction

- Double beta decay



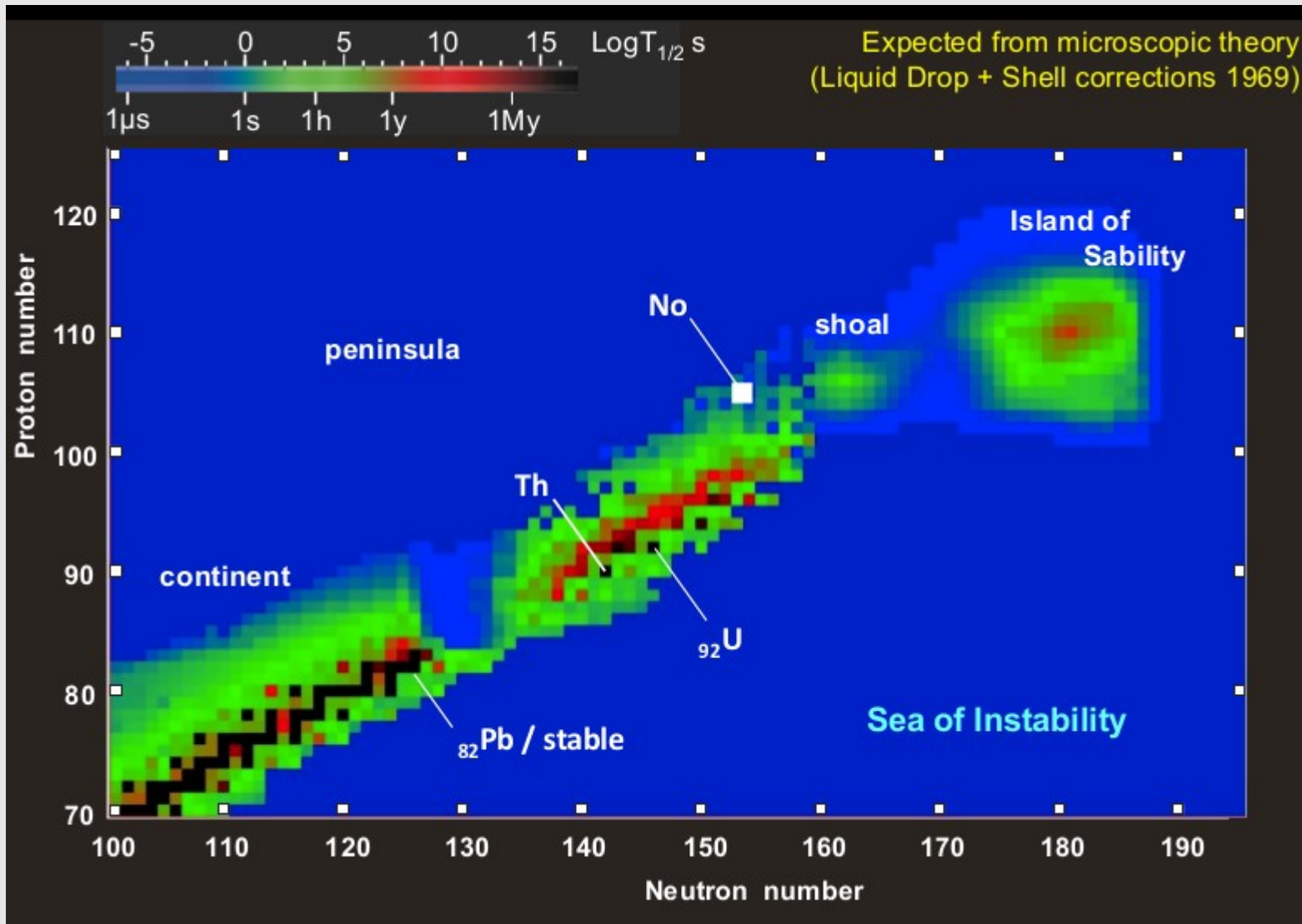
Núcleos halo

- Halos de nêutrons
- Superfície nuclear difusa
- Proximidade com o continuum (*drip line*)
- Borrromeanos

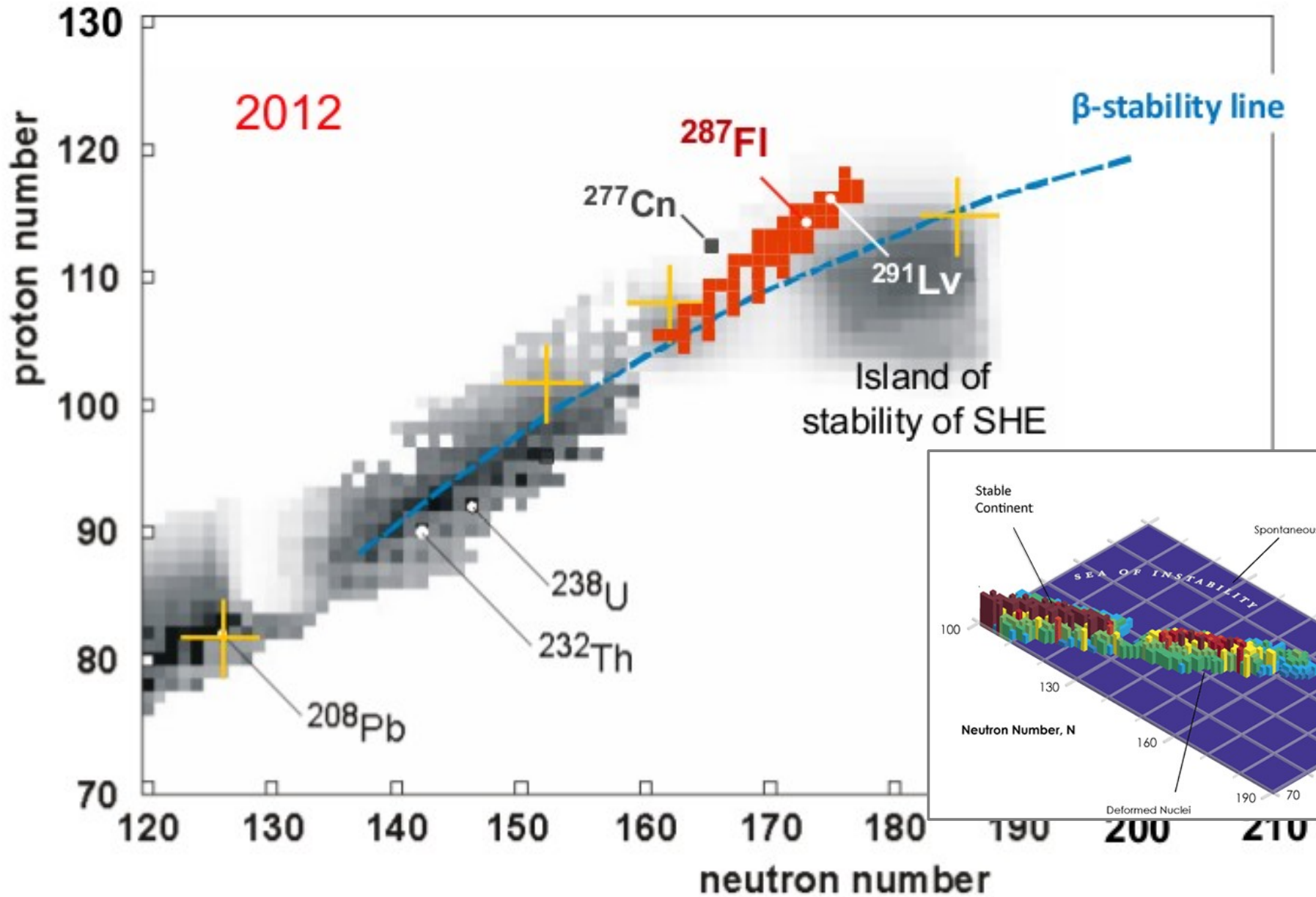


Núcleos Superpesados

- Previsão

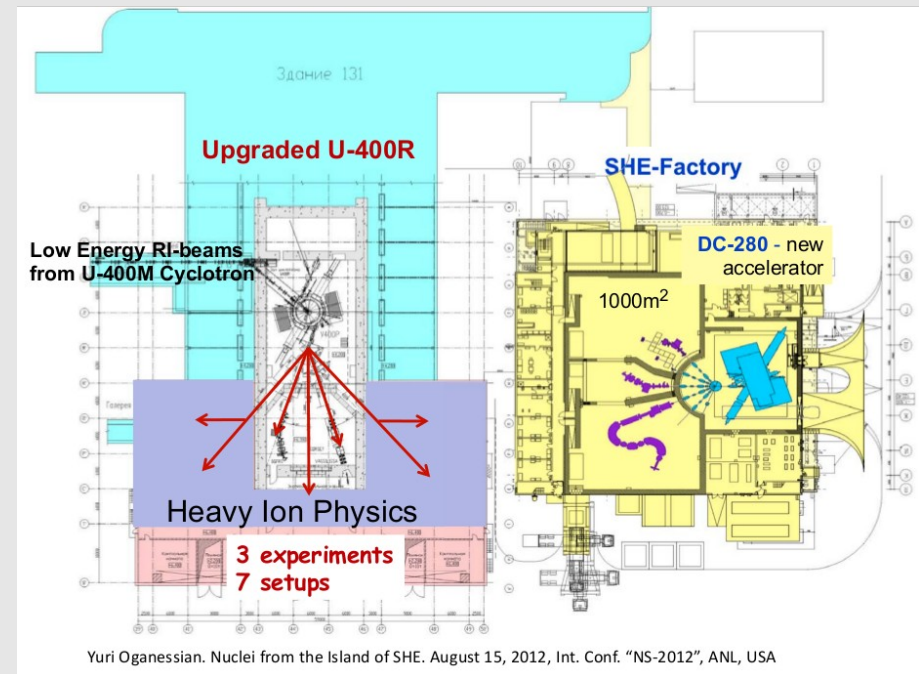
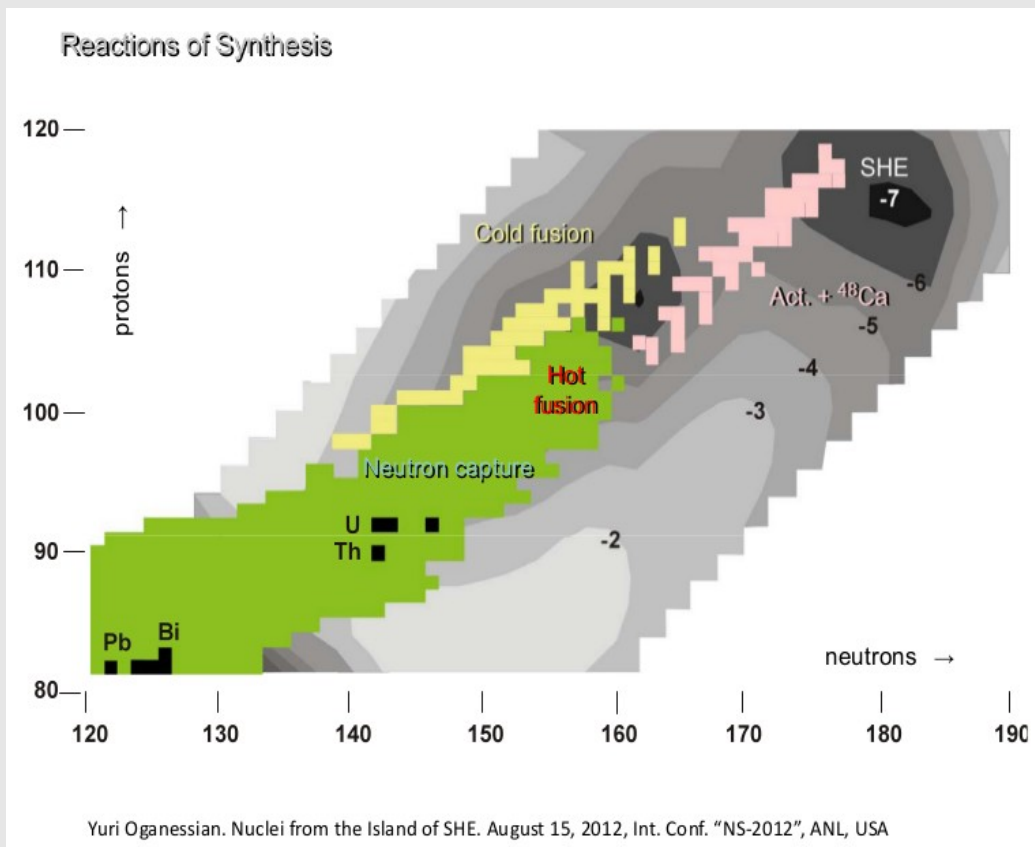


SHE (superpesados) produzidos



Produção dos SHE

- Fusão "fria" e "quente" ($^{48}\text{Ca} + ^{248}\text{Bk}$, $t_{1/2} = 320\text{d}$)
- Feixes Radioativos, novos aceleradores



Importância dos SHE

- F.Nuc. - Estrutura e propriedades de decaimento dos Superpesados; Novas camadas.
- Atrof. - SHE na natureza?
- Q. - Propriedades químicas
- F. At. - Estrutura eletrônica

${}^6\text{He} + {}^{120}\text{Sn}$ (RIBRAS)

● PHYSICAL REVIEW C 82, 034602 (2010)

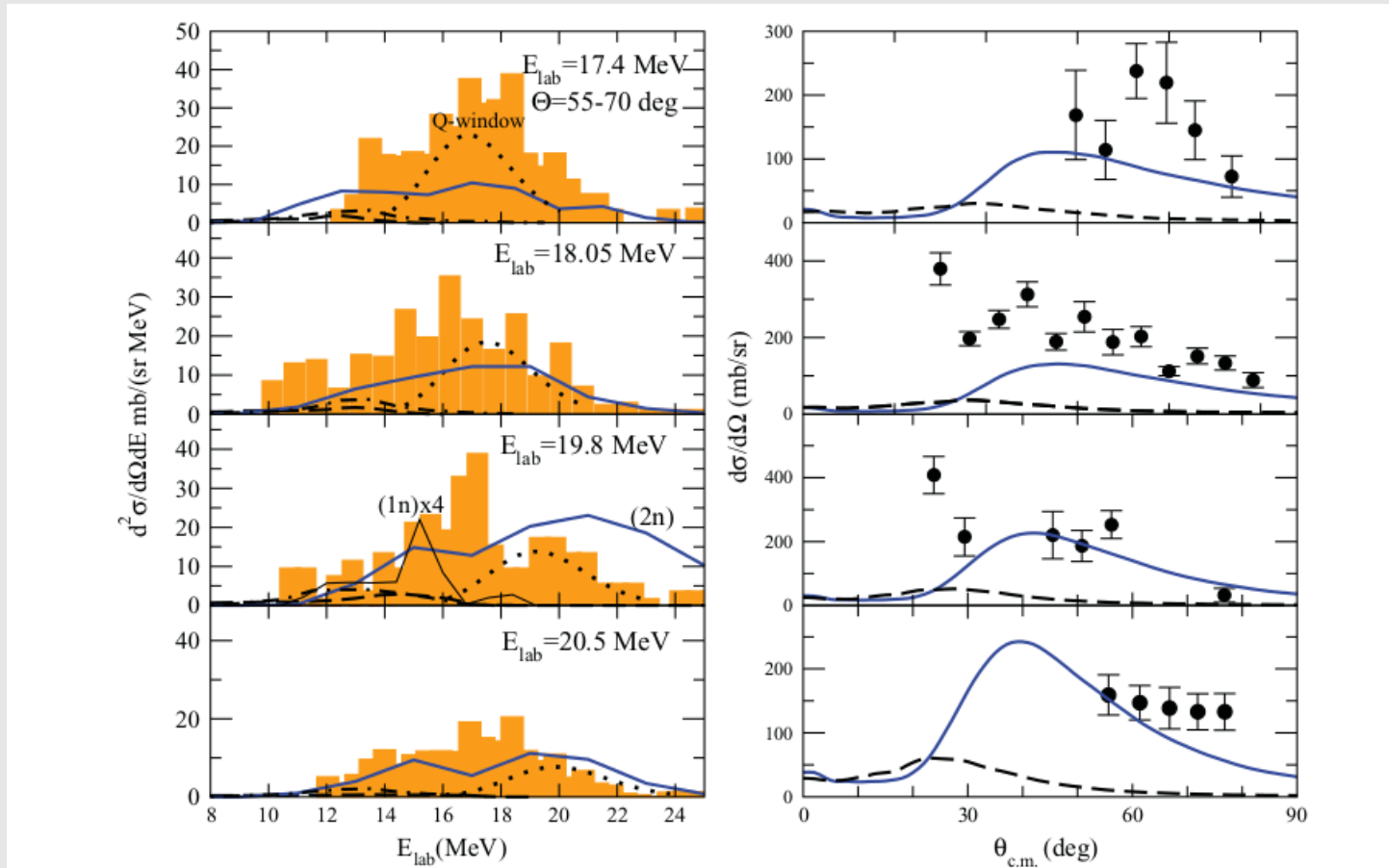


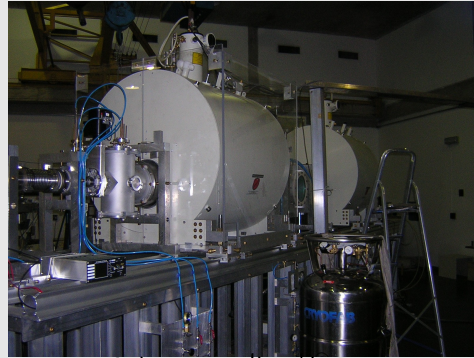
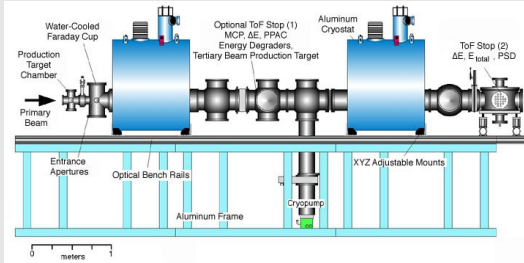
FIG. 2. (Color online) Energy spectra (left) and the corresponding angular distributions (right) of the α particles produced in the reaction ${}^6\text{He} + {}^{120}\text{Sn}$. The histogram (left) and the filled circles (right) are the experimental data. The dotted Gaussian stands for the Q window for the $2n$ transfer process, arbitrarily normalized. The solid line corresponds to the two-neutron distorted-wave Born approximation (DWBA) transfer calculation without any normalization. The dashed line corresponds to the breakup calculation without any normalization and the dot-dashed stands for the fusion-evaporation Projection Angular-momentum Coupled Evaporation (PACE) calculation arbitrarily normalized. The thin solid line plotted at $E = 19.8$ MeV (left) is the $1n$ DWBA calculation, multiplied by a factor of 4 to make the curve more visible.

Aula 5 – Perspectivas

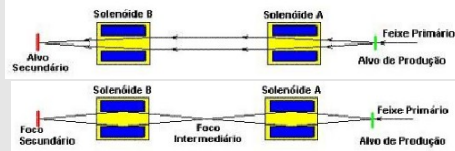
- No IFUSP
- Colaboração com LNS (arco-íris, NUMEN)
- Núcleos exóticos (Feixes Radioativos)
- Momentos angulares extremos
- Superpesados
- Astrofísica nuclear (Baixa energia)
- Hipernúcleos

RIBRAS (Pelletron-IFUSP)

- Solenóides supercondutores (6T)



Feixes radioativos

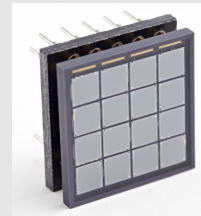


- Feixes fracamente ligados
- Espalhamento elástico
- Reações diretas

Reação	feixe secundário	(part/s)
${}^9\text{Be}({}^7\text{Li}, {}^8\text{Li})$	${}^8\text{Li}$	10^6
${}^9\text{Be}({}^7\text{Li}, {}^6\text{He})$	${}^6\text{He}$	10^4
${}^1\text{H}({}^{10}\text{B}, {}^7\text{Be})$	${}^7\text{Be}$	10^4
${}^{12}\text{C}({}^3\text{He}, {}^7\text{Be})$	${}^7\text{Be}$	10^4
${}^3\text{He}({}^6\text{Li}, n){}^8\text{B}$	${}^8\text{B}$	10^6
${}^{12}\text{C}({}^{17}\text{O}, {}^{18}\text{mF})$	${}^{18}\text{F}$	10^3

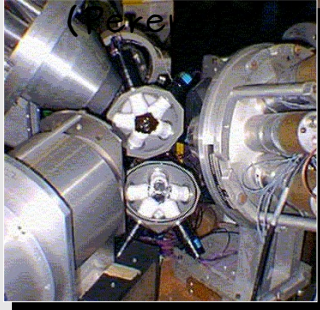
Uso do RIBRAS para espectroscopia γ

- Precisa blindagem de água borada para proteger GeHPs
- Substituir PMTs por SiPMs 4 x 4 Pixels ($3 \times 3 \text{ mm}^2 \sim 10^3 \text{ APDs/mm}^2$) devido ao campo magnético B (RIBRAS: $\sim 6 \text{ T}$)
- Testes planejados:
 ${}^6\text{He} + {}^{120}\text{Sn}$ (transferência de $2n$)

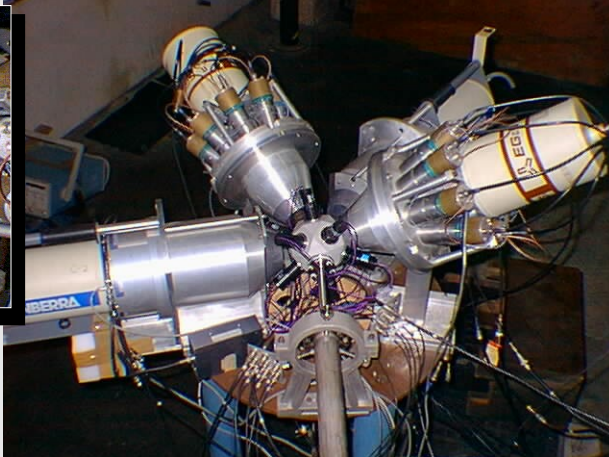


Nosso espectrômetro (IFUSP-DFN)

- Sistema Ancilar de Cintiladores (Saci)
- Pequeno Espectrômetro de Radiação Eletromagnética com Rejeição de Espalhamento



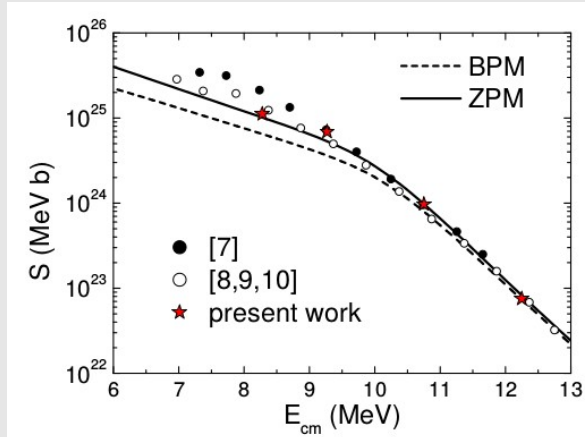
4 GeHP c/ AC
11 $\Delta E-E$ (phoswich)



Reações de interesse a-f - IFUSP

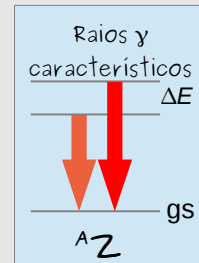
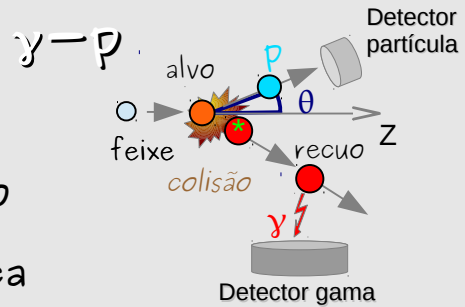
- Medidas no acelerador Pelletron do IF
L.Gasques, J.R.B.O. - $^{16}\text{O}+^{16}\text{O}$, esp. γ

Fator Astrofísico



Espectroscopia γ e mecanismos de reações

- Espalhamento inelástico
- Transferência inelástica
- Fusão completa e incompleta
- Transf. Múltiplas, DIC
- Quebra inelástica

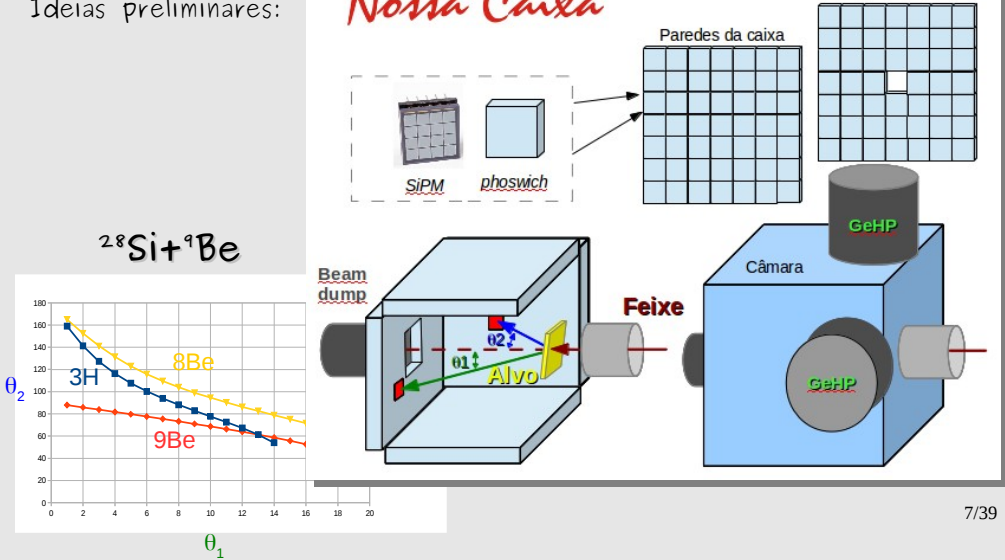


Futuro sistema 4π de partículas carregadas

- Alta granularidade para coincidências cinemáticas

Ideias preliminares:

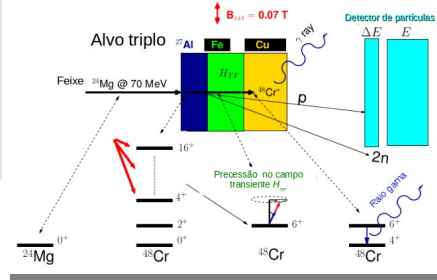
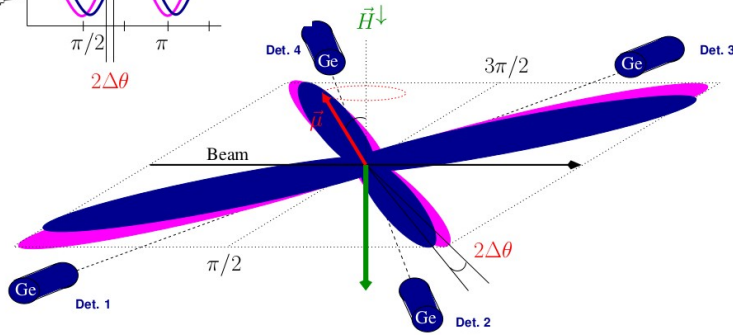
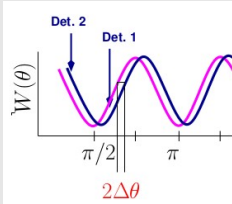
Nossa Caixa



Medida de fator g por CMT

- Técnica de medida

$H \uparrow \downarrow$



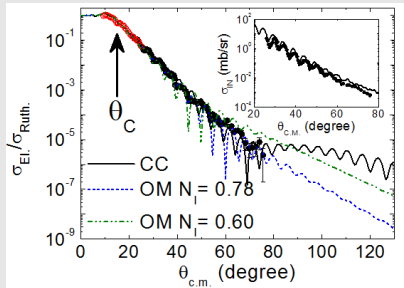
Proposta LAFN
Unal/USP

Colaborações com LNS/INFN

- Espectrômetro MAGNEX - Catania (Sicilia)
- Arco-íris nuclear
- NUMEN (duplo decaimento beta)
- Projeto de novo espectrômetro gama

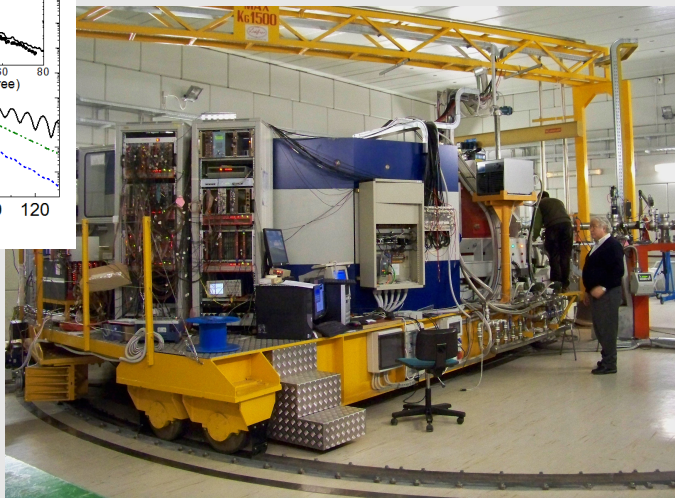
Arco-iris nuclear - MAGNEX

- Proposta IFUSP - Experimento Catania LNS



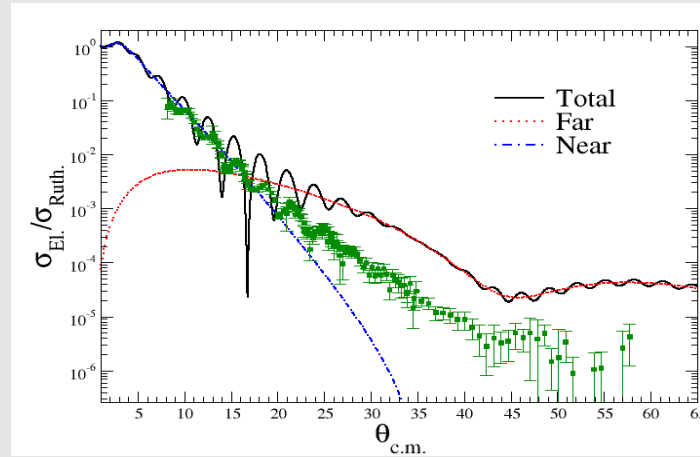
- D Pereira et al.
Phys. Lett. B 710 426
(2012)

- J R B Oliveira et
al. J. Phys. G 40
105101 (2013)



Arco-íris nuclear

$^{16}\text{O}+^{27}\text{Al}$ @ 280 MeV CS+MAGNEX - LNS, Catania



OBS.: Datos Pelletron $^{10}\text{B}+^{27}\text{Al}$ 22-42 MeV - alumno de maestrado 11/39

NUMEN

- Projeto em colaboração USP/UFF/LNS-INFN
- MAGNEX + espectrômetro gama
- Física do duplo decaimento beta
- Elementos de matriz de transição nuclear de dupla troca de carga

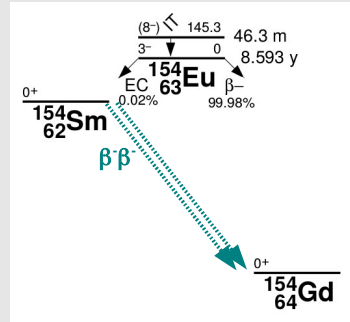
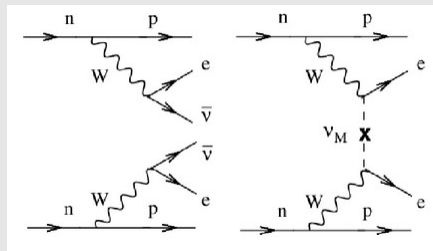
γ -Numen

Acoplamento de um espectrômetro γ ao MAGNEX



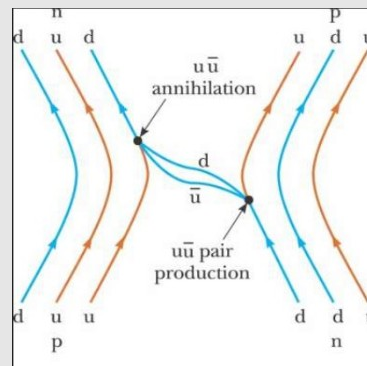
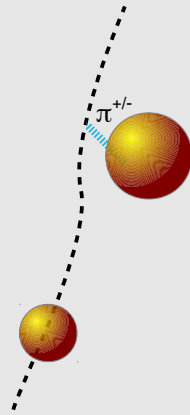
Duplo decaimento beta

- Decaimento muito raro $T_{1/2} = 10^{20} - 10^{24}$ anos
- Modelo Padrão: $\nu \neq \bar{\nu}$, $m_\nu = 0$ - decaimento duplo beta ocorre sempre com emissão de 2 neutrinos (no caso de $\beta^+\beta^+$) ou 2 anti-neutrinos (caso $\beta^-\beta^-$)
- Se $\nu = \bar{\nu}$ (neutrino de Majorana), duplo beta pode acontecer sem emissão de ν



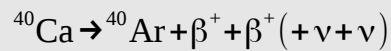
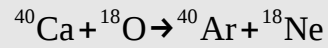
Reação de troca de carga SCE

- Troca de um pión ou outro méson carregado entre dois núcleos



Reação de dupla troca de carga DCE

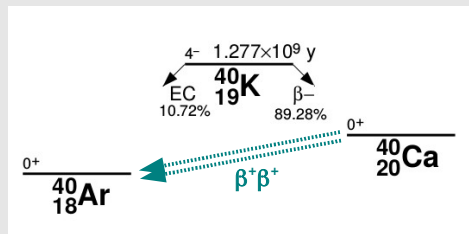
- Troca de dois mésons carregados entre os núcleos
- Semelhante ao duplo-decaimento beta sem ν
- Elementos de matriz M são proporcionais



$$\Gamma = G |M|^2 |m_{\beta\beta}|^2$$

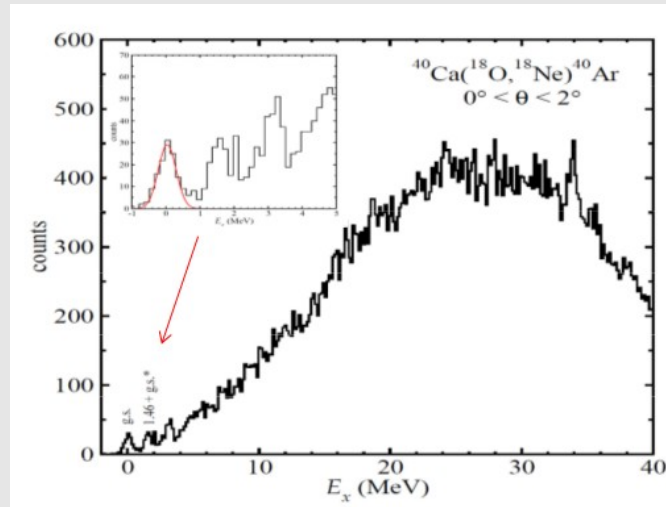
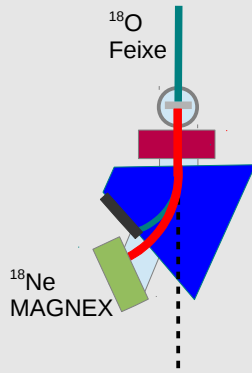
$$|m_{\beta\beta}|^2 = \sum_{i=1}^3 m_i U_{ei}^2$$

$$|M|^2 = |\langle \varphi_f | O^{\beta\beta} | \varphi_i \rangle|^2$$

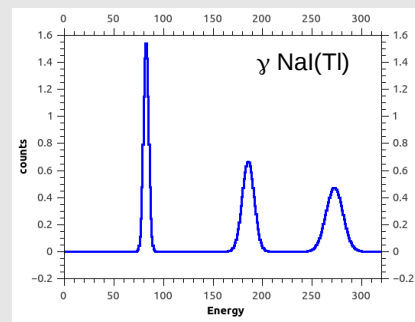
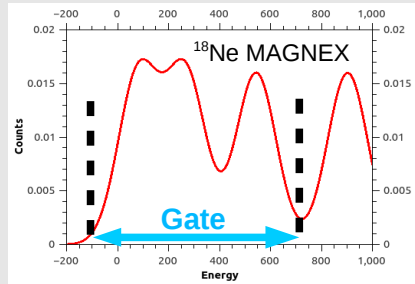
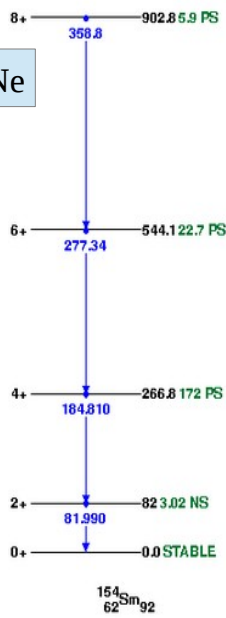
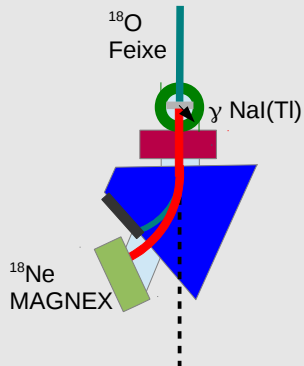
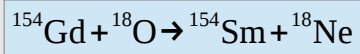


Espectro de energia de excitação

- ^{18}Ne detectado no MAGNEX ao redor de 0°



Espectros previstos para ^{154}Sm



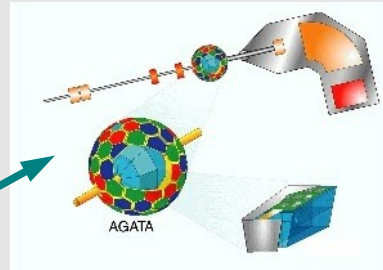
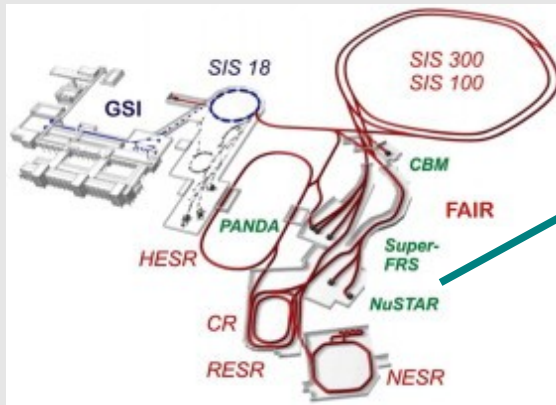
Perspectivas

1.- Fronteira extensiva:

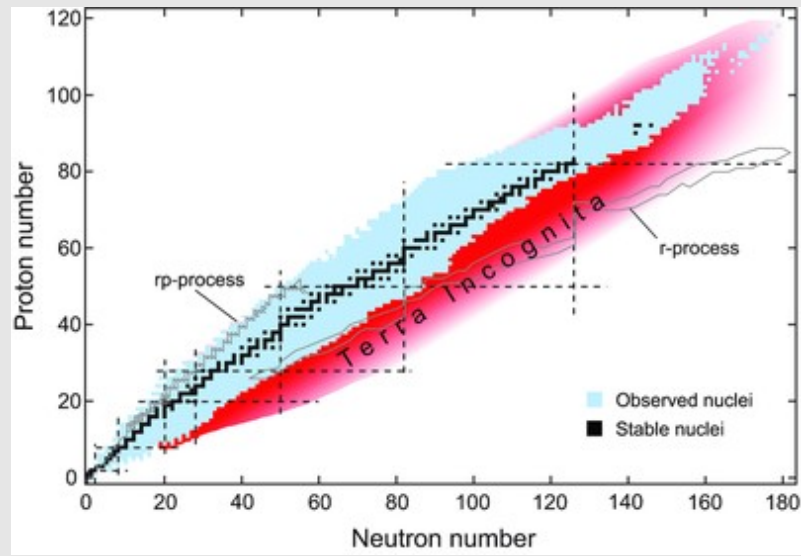
- Feixes radioativos de alta intensidade (SPES, FAIR, SPIRAL2...): razões N/Z extremas
- Baixíssimas energias (Astrofísica nuclear)
- Elementos superpesados (SHE): A extremo
- Hipernúcleos: Nova dimensão: S (Panda)
- Altos spins J (γ -tracking)

FAIR

- Facility for Antiproton and Ion Research
- Feixes Radioativos de alta intensidade
- HISPEC/DESPEC NuSTAR




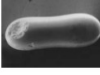
Terra Incognita




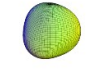
Momentos angulares extremos

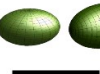
• Formas nucleares e fenômenos associados

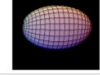
- 

Superdeformation
Hyperdeformation
- 

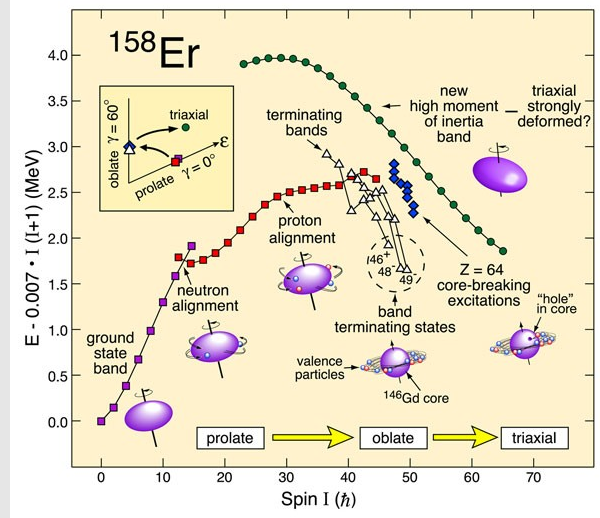
Jacobi shapes
- 

Triaxial shapes
3-dimensional rotation
- 

Higher-order shapes
(with high-rank symmetry):
tetrahedral, octahedral
- 

Shape coexistence
- 

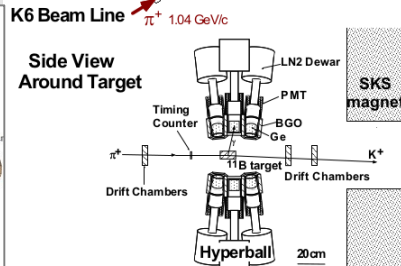
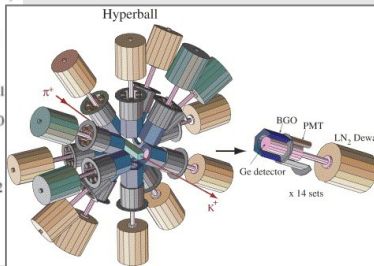
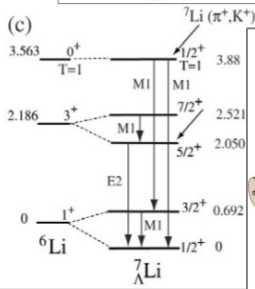
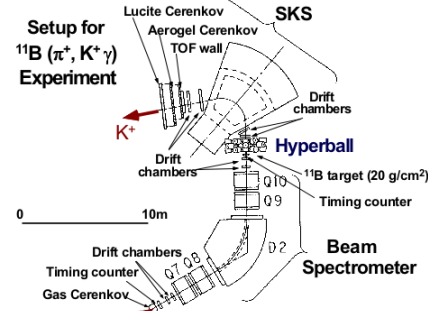
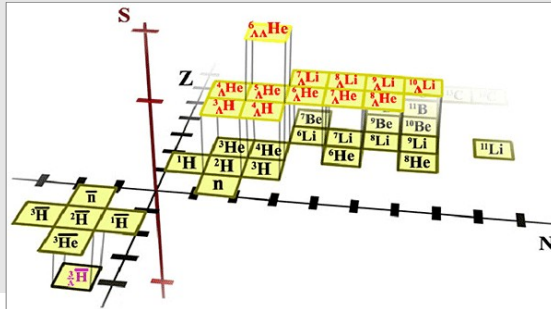
dynamic deformation
vibrations etc.



Hipernúcleos



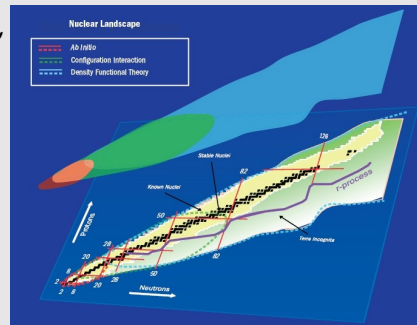
- Nova dimensão da carta de nuclídeos (s)



Perspectivas

2. Fronteira da precisão

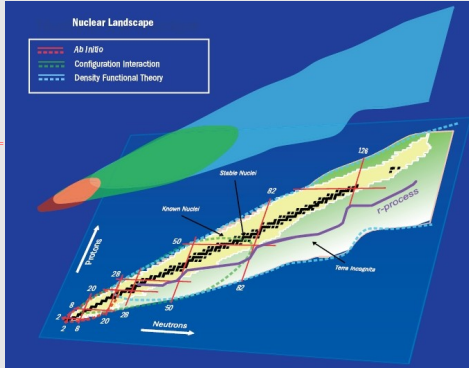
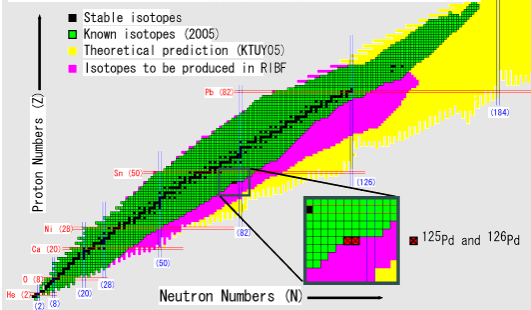
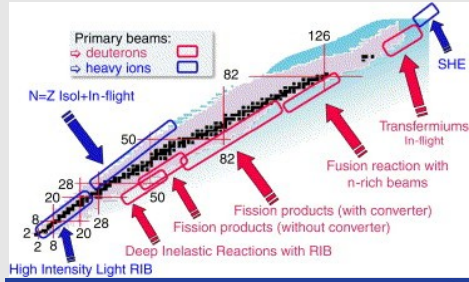
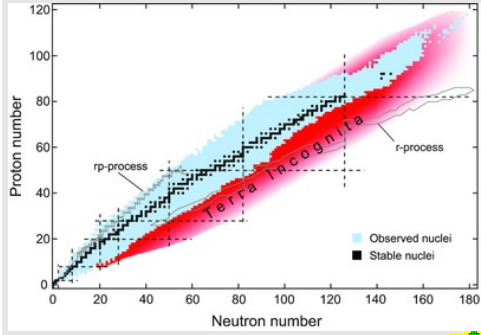
- Testes do "Ab Initio NCSM" e extensões (teoria)
- $\beta\beta$ - sensibilidade além do Modelo Padrão
- Medidas precisas de propriedades nucleares em casos críticos, e sistemáticas



Obrigado pela atenção!

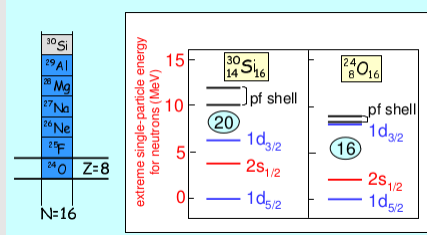
Extras

Terra Incognita

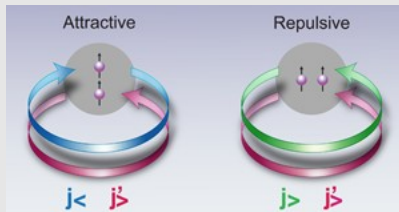


Evolução da estrutura de camadas

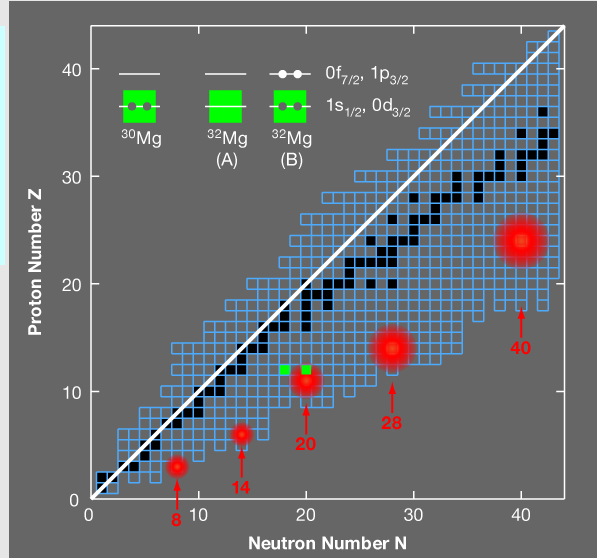
Novos n^{os}. mágicos



Força tensorial

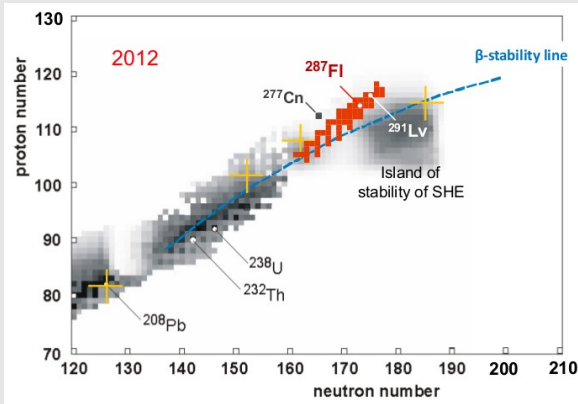
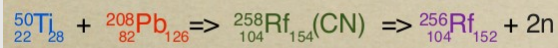


Previsões de "quebras" do MC



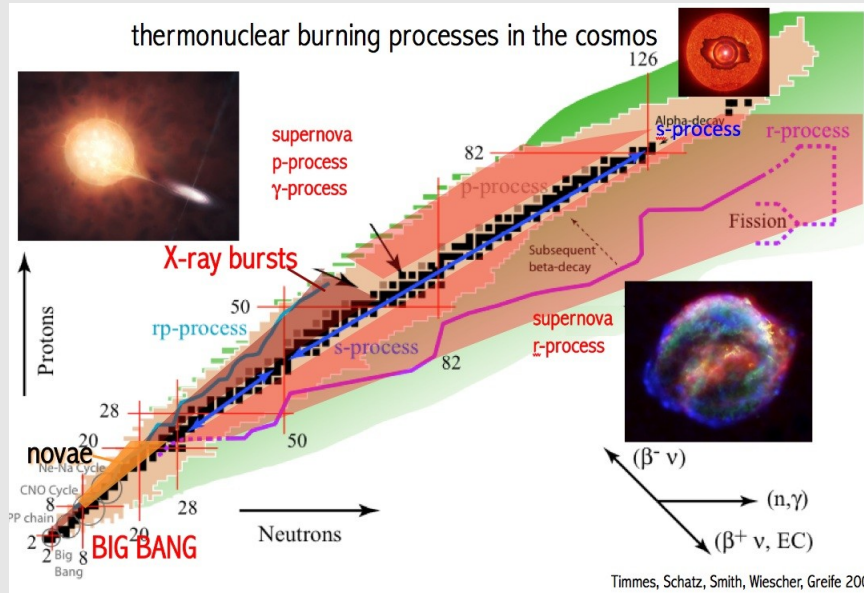
Elementos Superpesados (SHE)

- Primeira medida de espectroscopia gama de um SHE - J. Rubert et al. 2012 @ Jyvaskyla (~20 dias de experimento)

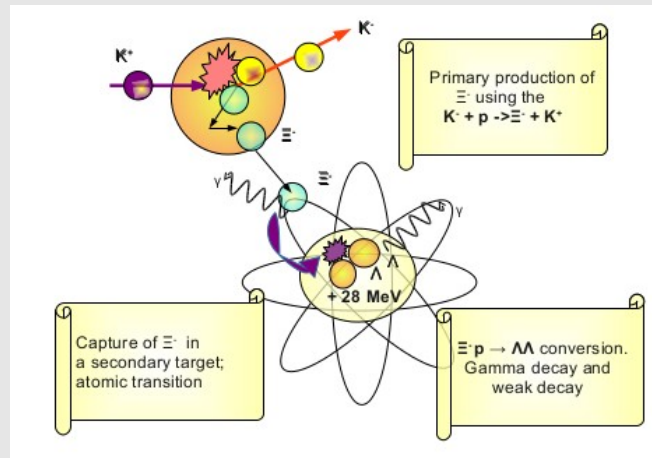


Astrofísica

- Reações a energias muito baixas



$\Lambda\Lambda$ - Produção



PANDA @ FAIR

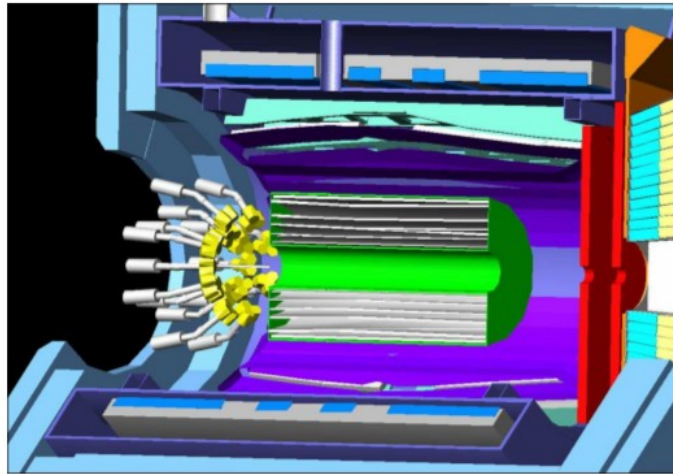
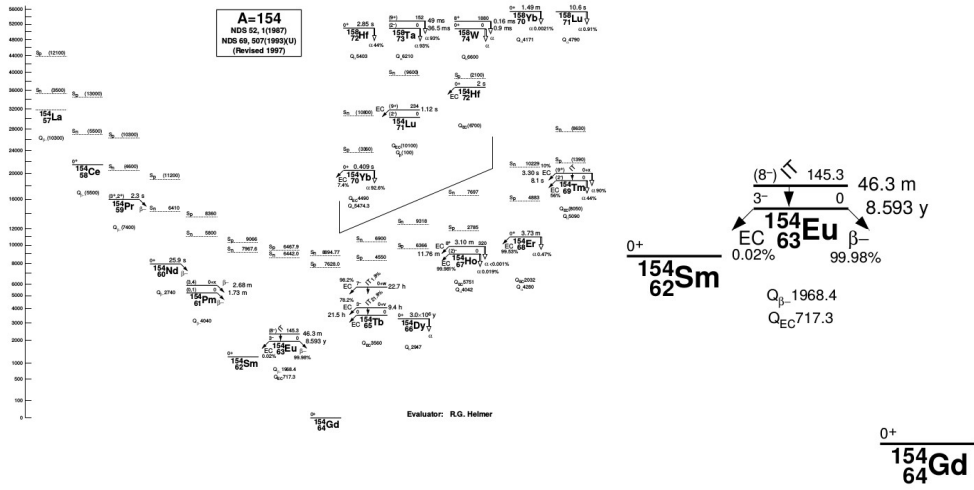


Figure 4.2: Integration of the secondary target and the germanium Cluster-array in the PANDA detector, with the beam entering from left.

52/39

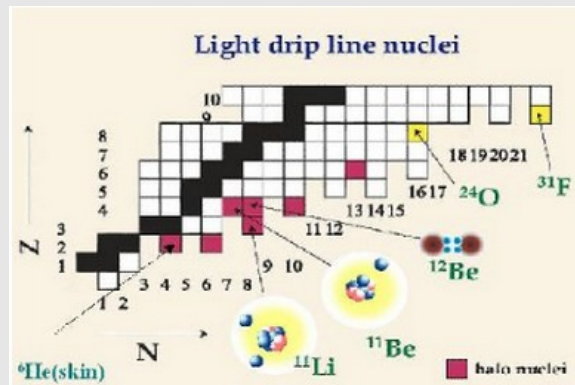
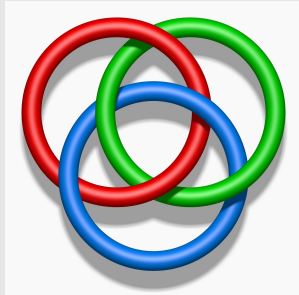
Introduction

- Double beta decay



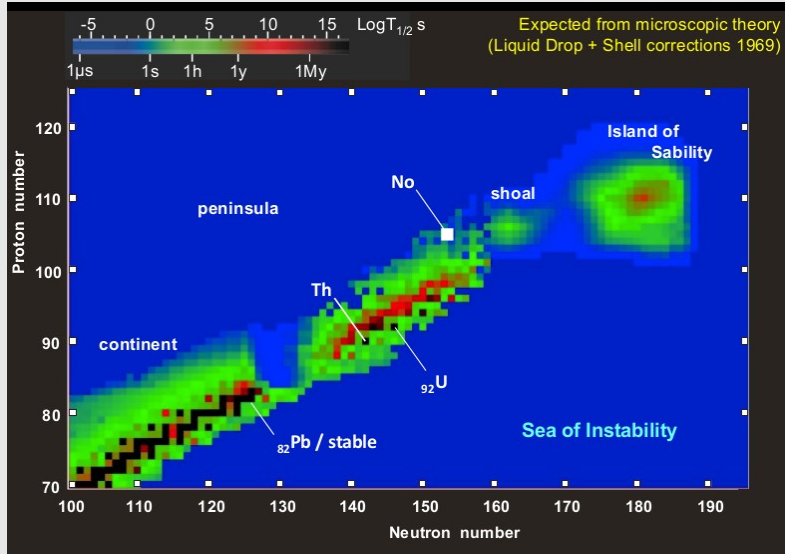
Núcleos halo

- Halos de nêutrons
- Superfície nuclear difusa
- Proximidade com o continuum (*drip line*)
- Borrromeanos

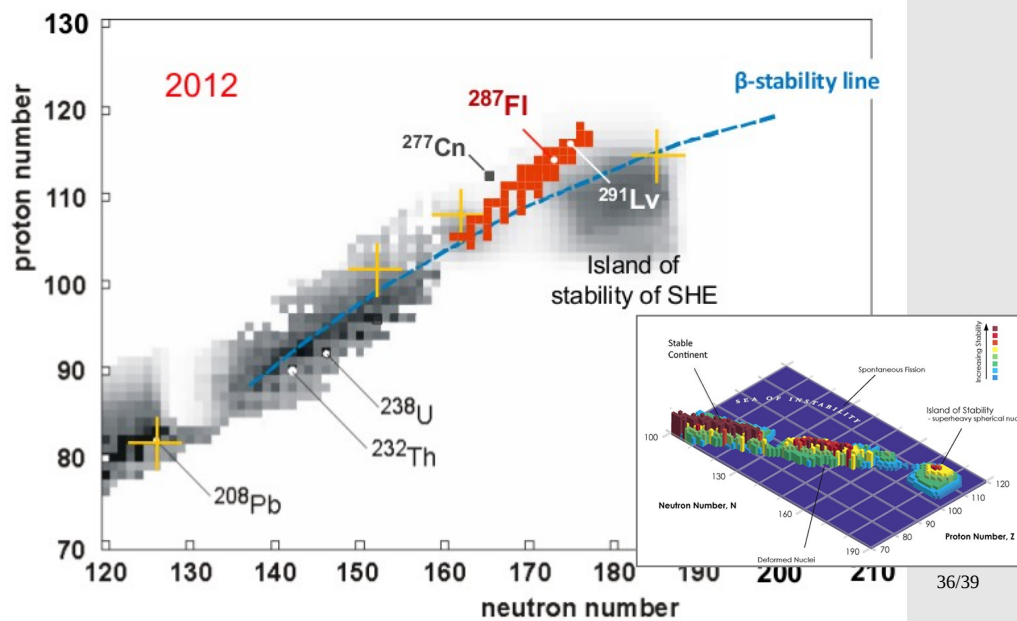


Núcleos Superpesados

- Previsão

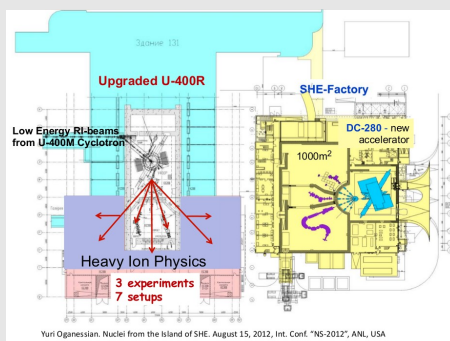
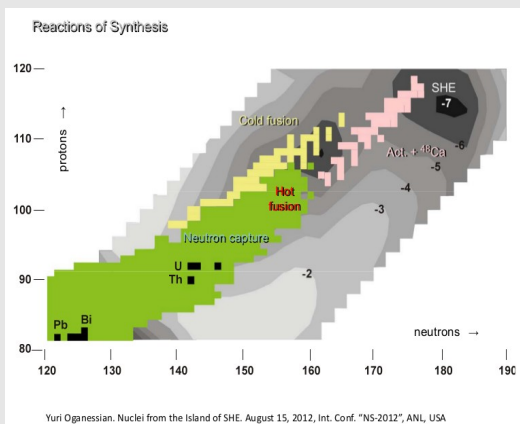


SHE (superpesados) produzidos



Produção dos SHE

- Fusão "fria" e "quente" ($^{48}\text{Ca} + ^{248}\text{Bk}$, $t_{1/2} = 320\text{d}$)
- Feixes Radioativos, novos aceleradores



Importância dos SHE

- F.Nuc. - Estrutura e propriedades de decaimento dos Superpesados; Novas camadas.
- Atrof. - SHE na natureza?
- Q. - Propriedades químicas
- F. At. - Estrutura eletrônica

${}^6\text{He} + {}^{120}\text{Sn}$ (RIBRAS)

PHYSICAL REVIEW C 82, 034602 (2010)

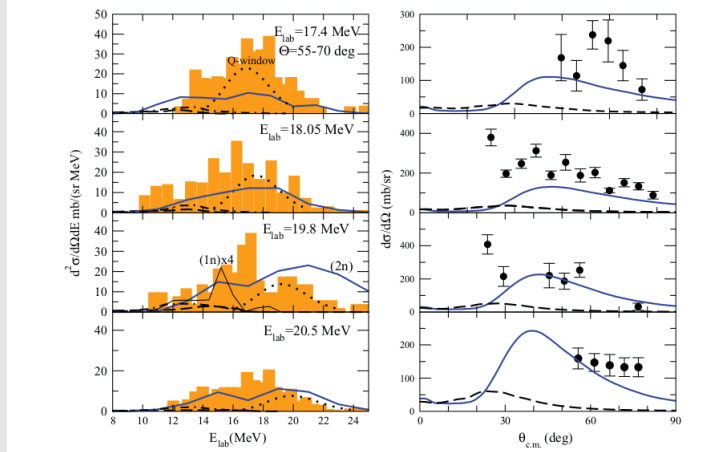


FIG. 2. (Color online) Energy spectra (left) and the corresponding angular distributions (right) of the α particles produced in the reaction ${}^6\text{He} + {}^{120}\text{Sn}$. The histogram (left) and the filled circles (right) are the experimental data. The dotted Gaussian stands for the Q window for the $2n$ transfer process, arbitrarily normalized. The solid line corresponds to the two-neutron distorted-wave Born approximation (DWBA) transfer calculation without any normalization. The dashed line corresponds to the breakup calculation without any normalization and the dot-dashed stands for the fusion-evaporation Projection Angular-momentum Coupled Evaporation (PACE) calculation arbitrarily normalized. The thin solid line plotted at $E = 19.8$ MeV (left) is the $1n$ DWBA calculation, multiplied by a factor of 4 to make the curve more visible.