

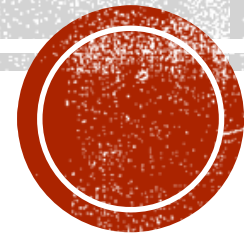
REAÇÕES NUCLEARES E A FÍSICA ALÉM DO MODELO PADRÃO

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<https://profs1.if.uff.br/rlinares>

Panoramas da física 2º/2018



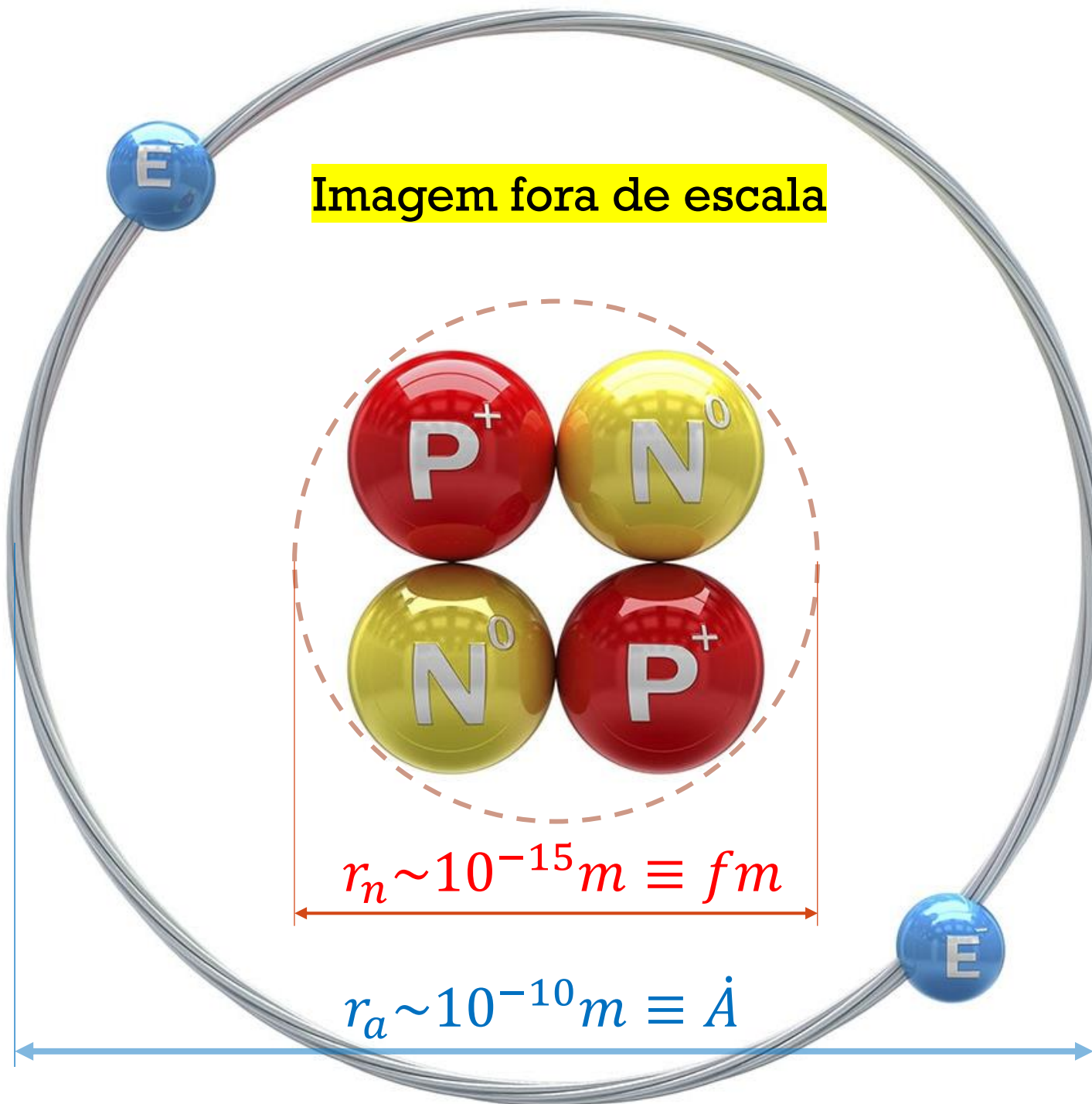
CONTEÚDO

- Núcleo atômico
- Decaimentos nucleares
 - Especificamente, decaimentos beta
- Noções do modelo padrão
 - Leis de conservação
 - What's next? Decaimento beta duplo sem a emissão de neutrino
- Reações nucleares
 - Transferência de partículas e troca de carga



NÚCLEO ATÔMICO

- Nêutrons
- Prótons



PROPRIEDADES DO NÊUTRON E PRÓTON

Próton

- Massa $\approx 938 \text{ MeV}/c^2 \cong 1,671 \times 10^{-27} \text{ kg}$
- Carga elétrica = $+e \equiv +1,60 \times 10^{-19} \text{ C}$
- Spin = $1/2$

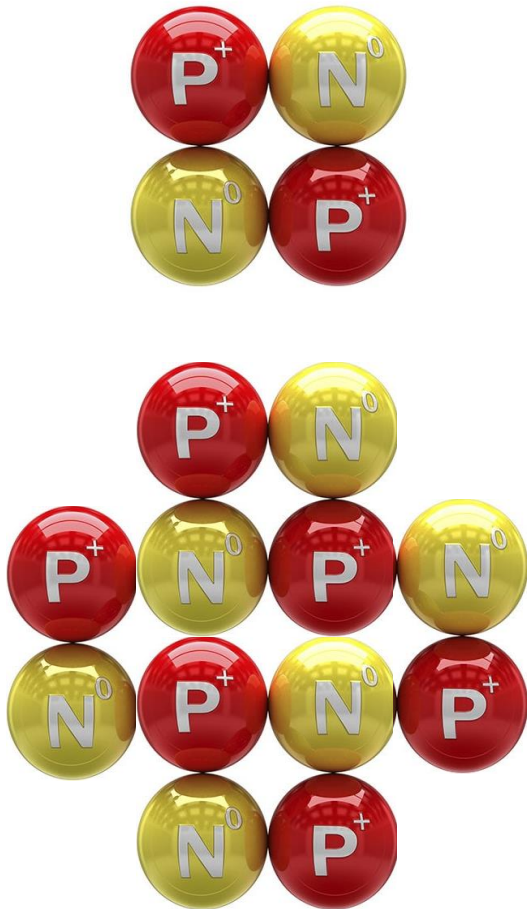
Nêutron

- Massa $\approx 939 \text{ MeV}/c^2 \cong 1,675 \times 10^{-27} \text{ kg}$
- Carga elétrica = 0
- Spin = $1/2$

Partículas de spin $1/2 \rightarrow$ férmions



NÚCLEOS



⁴He

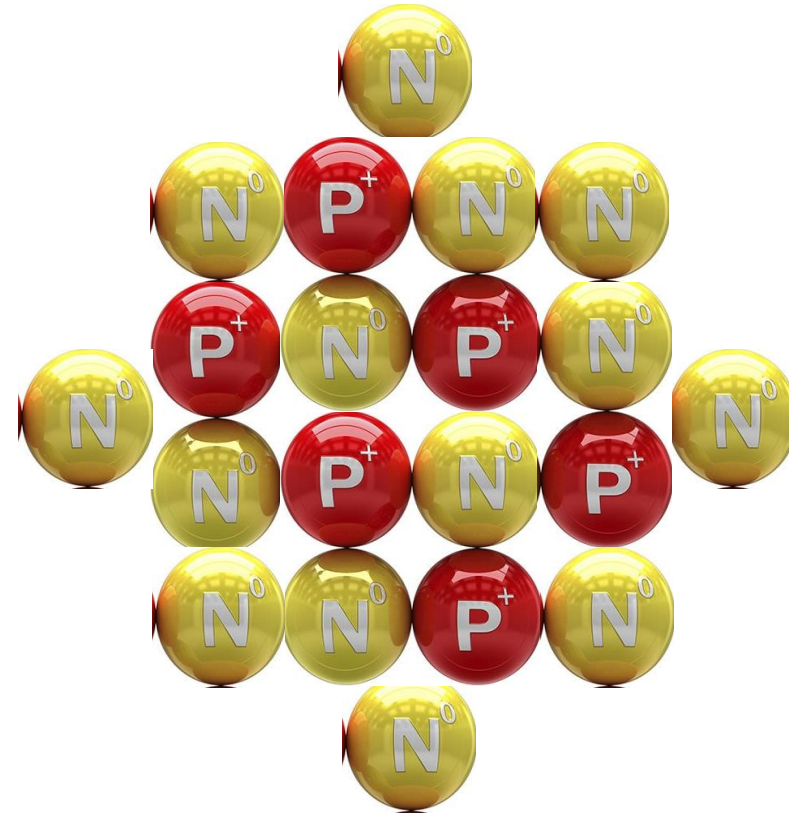
¹²C

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
Actinides		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	



ISÓTOPOS

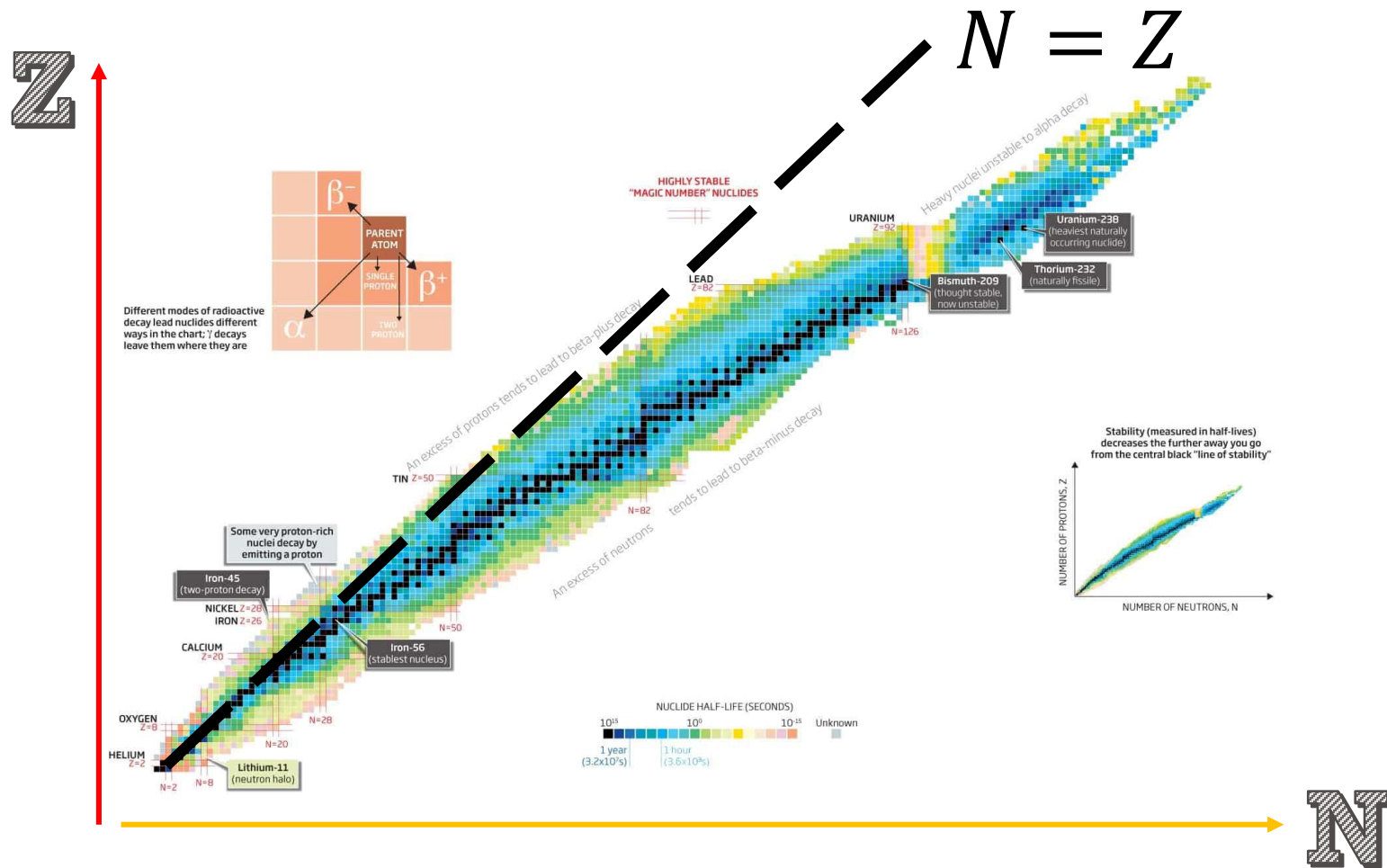
Núcleos atômicos com
mesmo número atômico
(mesmo número de prótons)



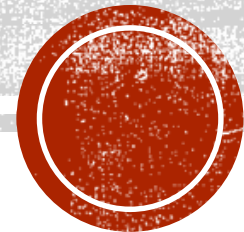
1
12
13
14
20



~300 núcleos estáveis e >3.000 núcleo instáveis



ESTABILIDADE NUCLEAR

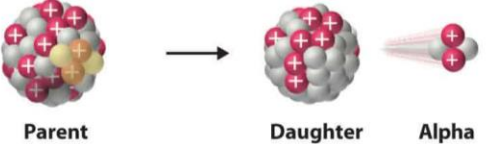

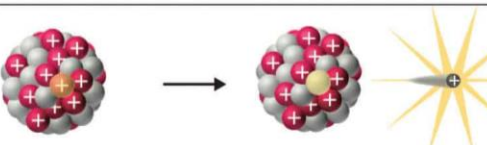


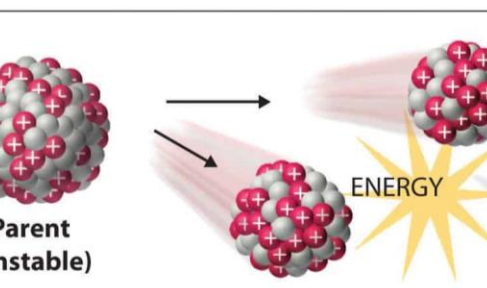


- Dada uma quantidade inicial de núcleos estáveis (N_i), após 1 meia-vida metade desses núcleos decaem.

Núcleo instável	Isótopos estáveis	Meia-vida
${}^6\text{He}$	${}^3\text{He}$, ${}^4\text{He}$	~0,81 s
${}^8\text{Li}$	${}^6\text{Li}$, ${}^7\text{Li}$	~0.84 s
${}^{14}\text{C}$	${}^{12}\text{C}$, ${}^{13}\text{C}$	~5.700 a
${}^{26}\text{Al}$	${}^{27}\text{Al}$	~0,72 Ma (milhão de ano)
${}^{210}\text{Bi}$	${}^{209}\text{Bi}$ (estável mais pesado)	~5,01 d (dias)
${}^{238}\text{U}$	não tem	~4,47 Ga (bilhões de anos)

NÚCLEOS INSTÁVEIS



Alpha decay	$\frac{4}{2}\alpha$	${}^A_ZX \longrightarrow {}^{A-4}_{Z-2}X' + \frac{4}{2}\alpha$	
Beta decay	${}^0_{-1}\beta$	${}^A_ZX \longrightarrow {}^{A}_{Z+1}X' + {}^0_{-1}\beta$	
Positron emission	${}^0_{+1}\beta$	${}^A_ZX \longrightarrow {}^{A}_{Z-1}X' + {}^0_{+1}\beta$	
Electron capture	X rays	${}^A_ZX + {}^0_{-1}e \longrightarrow {}^{A}_{Z-1}X' + \text{X ray}$	
Gamma emission	${}^0_0\gamma$	${}^A_ZX^* \xrightarrow{\text{Relaxation}} {}^A_ZX + {}^0_0\gamma$	
Spontaneous fission	Neutrons	${}^{A+B+C}_{Z+Y}X \longrightarrow {}^A_ZX' + {}^B_YX' + C{}_0^1n$	

DECAIMENTOS

- Decaimento beta não altera a massa atômica e, sim, as quantidades de prótons e nêutrons
- Póstron** é uma partícula com massa idêntica a do elétron mas carga elétrica oposta



39Ti 31 MS ε: 100.00% ε: 100.00%	40Ti 52.4 MS ε: 97.50% ε	41Ti 81.9 MS ε: 100.00% ε: 100.00%	42Ti 208.65 MS ε: 100.00%	43Ti 509 MS ε: 100.00%	44Ti 60.0 Y ε: 100.00%	45Ti 184.8 M ε: 100.00%
38Sc P	39Sc <300 NS P: 100.00%	40Sc 182.3 MS ε: 100.00% ε: 0.44%	41Sc 596.3 MS ε: 100.00%	42Sc 680.70 MS ε: 100.00%	43Sc 3.891 H ε: 100.00%	44Sc 3.97 H ε: 100.00%
37Ca 181.1 MS ε: 100.00% ε: 82.10%	38Ca 440 MS ε: 100.00%	39Ca 859.6 MS ε: 100.00%	40Ca >3.0E+21 Y 96.94% 2ε	41Ca 9.94E4 Y ε: 100.00%	42Ca STABLE 0.647%	43Ca STABLE 0.135%
36K 342 MS ε: 100.00% ε: 0.05%	37K 1.226 S ε: 100.00%	38K 7.636 M ε: 100.00%	39K STABLE 93.2581%	40K 1.248E+9 Y 0.0117% β-: 89.28% ε: 10.72%	41K STABLE 6.7302%	42K 12.355 H β-: 100.00%
35Ar 1.7756 S ε: 100.00%	36Ar STABLE 0.3336%	37Ar 35.04 D ε: 100.00%	38Ar STABLE 0.0629%	39Ar 269 Y β-: 100.00%	40Ar STABLE 99.6035%	41Ar 109.61 M β-: 100.00%
17	18	19	20	21	22	23

POR QUÊ NÚCLEOS ATÔMICOS DECAEM?

- Núcleos instáveis buscam o “vale da estabilidade”

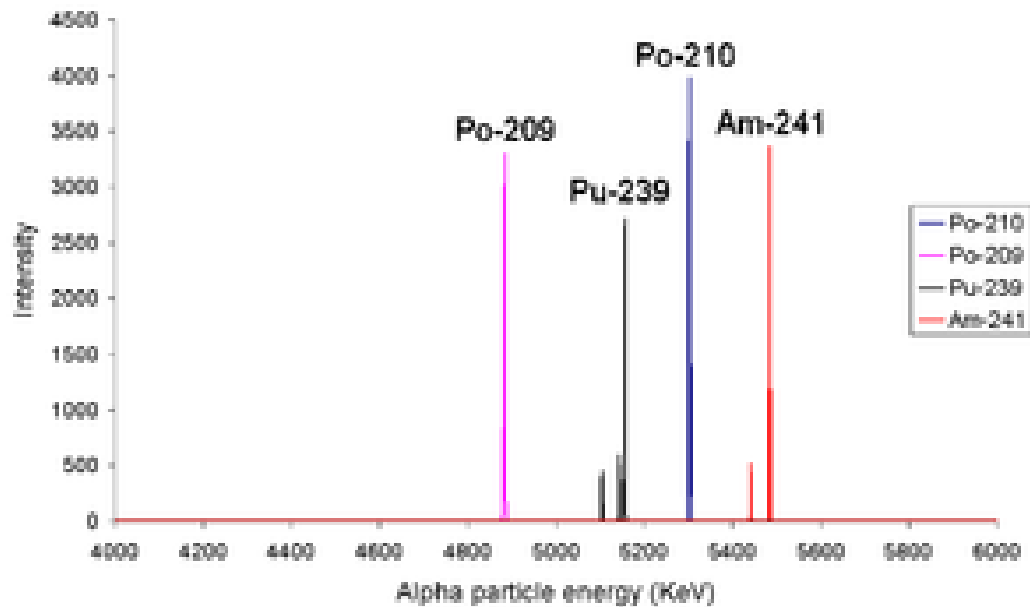
Ground and isomeric state information for $^{41}_{20}\text{Ca}$

E(level) (MeV)	J _n	Δ(MeV)	T _{1/2}	Decay Modes
0.0	7/2-	-35.137890625	9.94E4 y 15	ε : 100.00 %

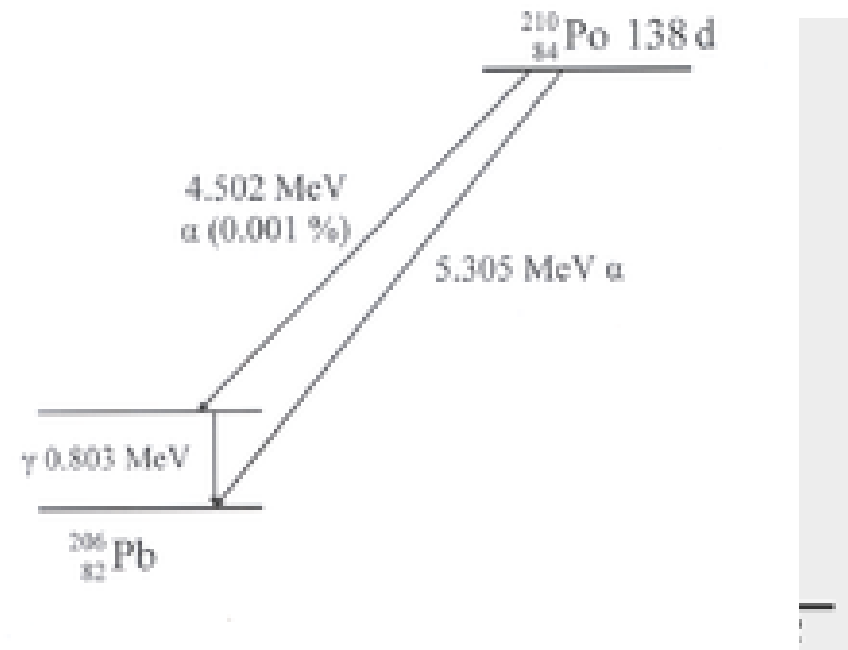


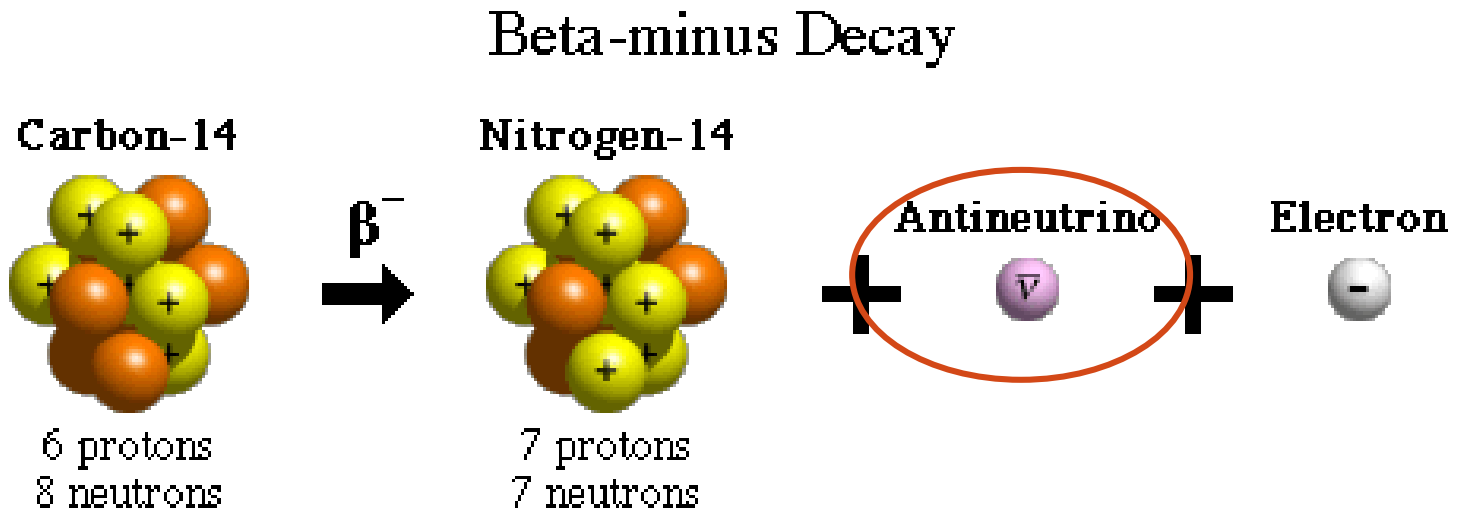
ESPECTROS DE EMISSÃO ALPHA E BETA

Decaimento alfa = discretizado



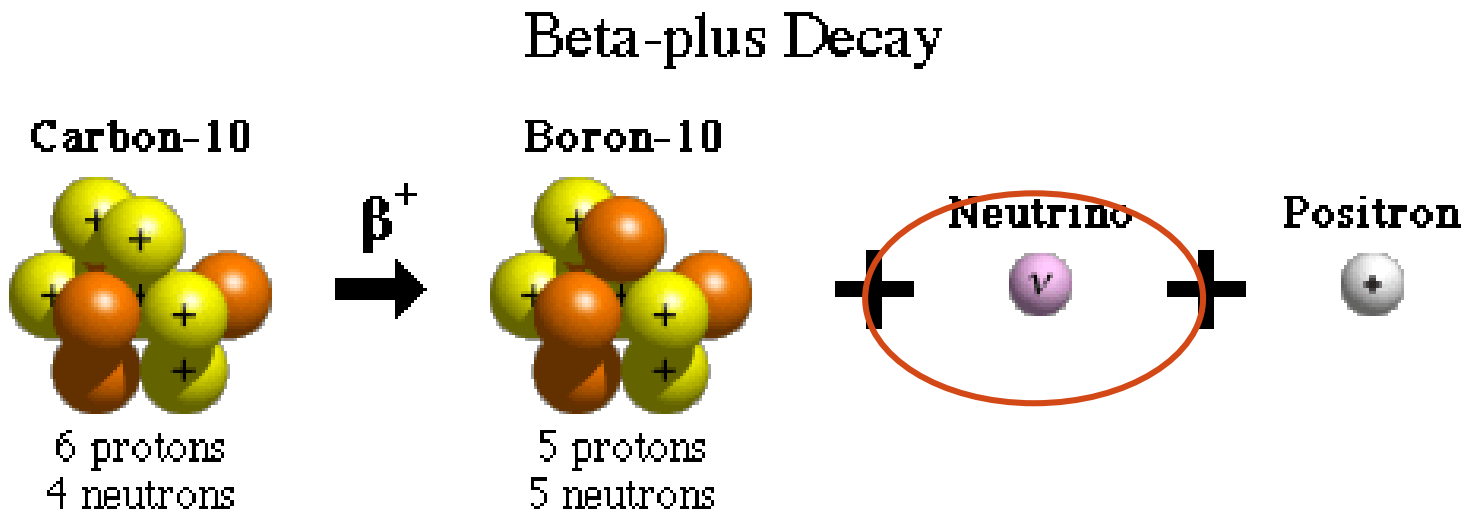
Decaimento beta = contínuo





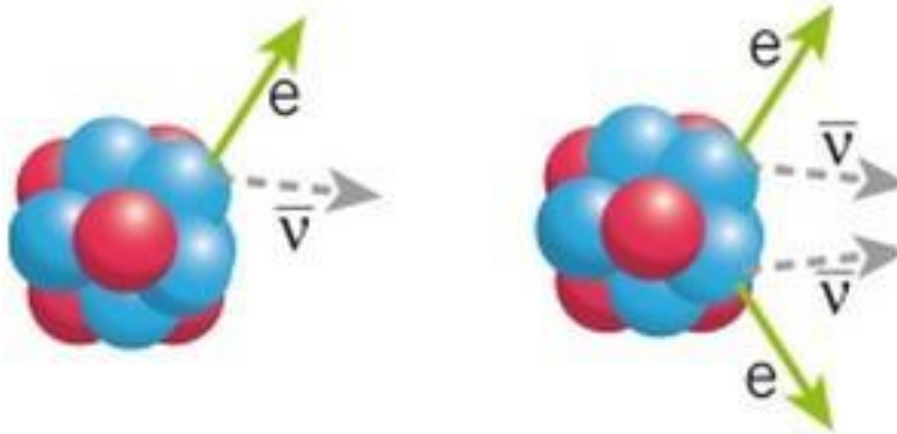
A HIPÓTESE DO NEUTRINO

- Uma partícula sem carga elétrica, leve e pouco interagente



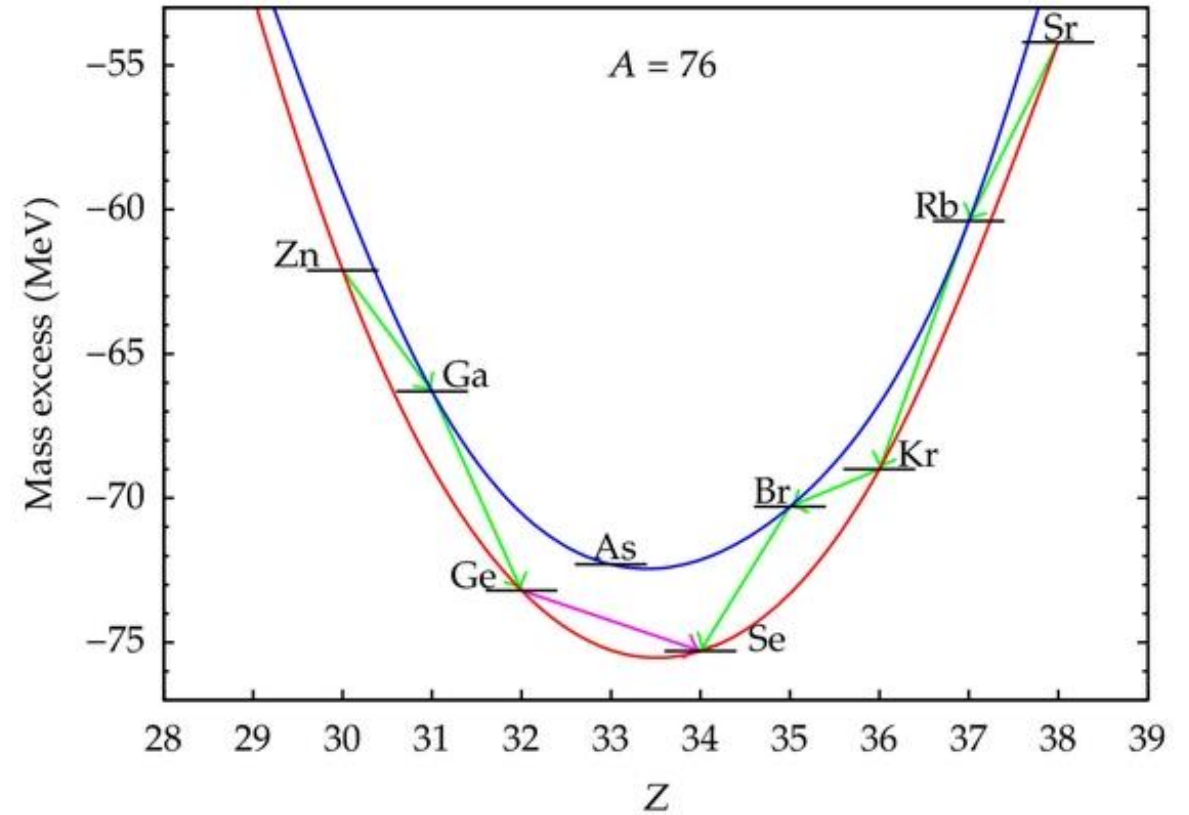
DECAIMENTO BETA SIMPLES E DUPLO

Emissão de anti-neutrino

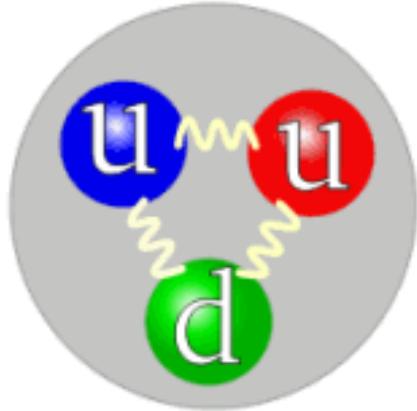


Standard β decay

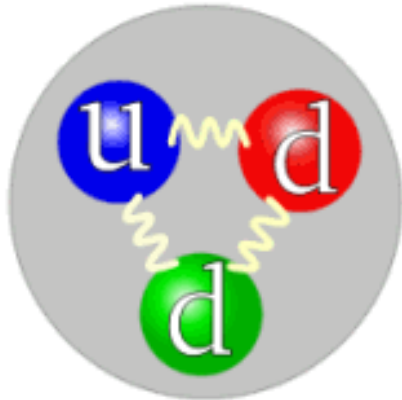
Double- β decay



PARTÍCULAS FUNDAMENTAIS



Proton



Neutron

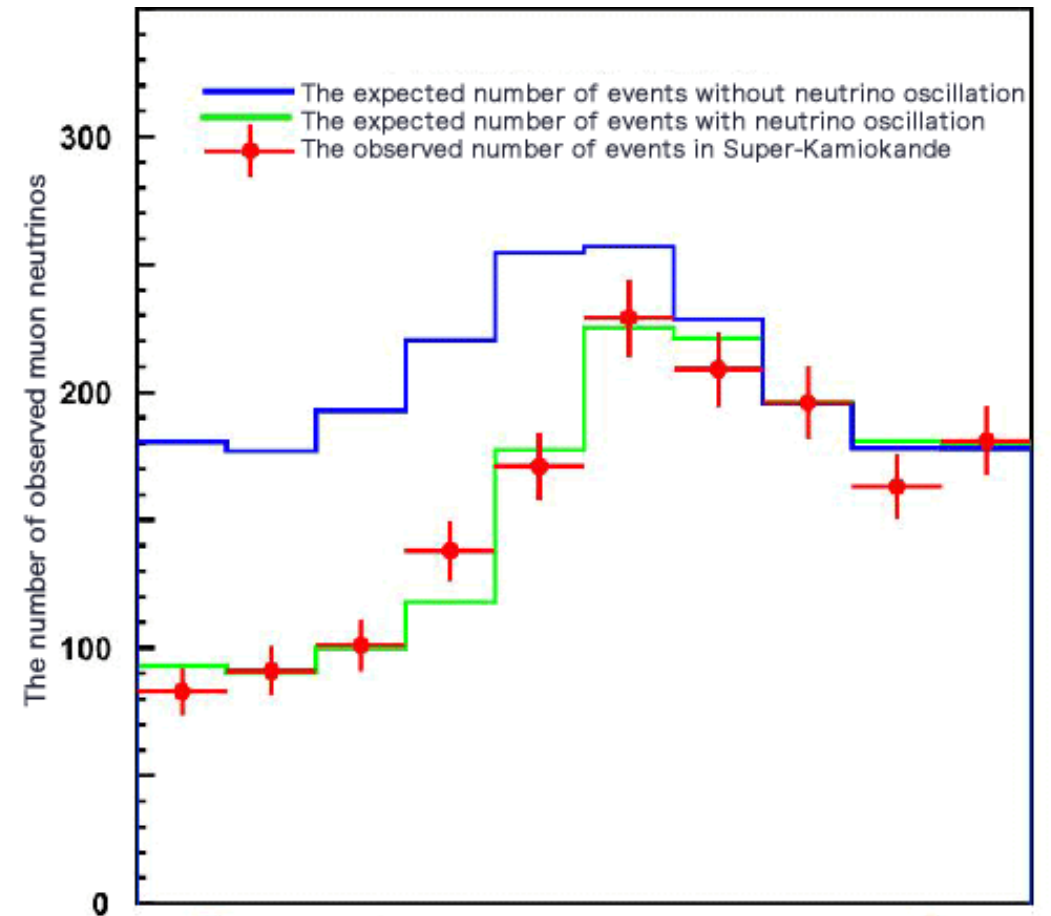
STANDARD MODEL OF ELEMENTARY PARTICLES

QUARKS			GAUGE BOSONS		
QUARKS	UP mass $2,3 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ 	CHARM mass $1,275 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ 	TOP mass $173,07 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ 	GLUON 0 0 1 	HIGGS BOSON mass $126 \text{ GeV}/c^2$ 0 0 0
	DOWN mass $4,8 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ 	STRANGE mass $95 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ 	BOTTOM mass $4,18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ 	PHOTON 0 0 1 	GAUGE BOSONS
	ELECTRON mass $0,511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ 	MUON mass $105,7 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ 	TAU mass $1,777 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ 	Z BOSON mass $91,2 \text{ GeV}/c^2$ 0 0 1 	
	ELECTRON NEUTRINO mass $<2,2 \text{ eV}/c^2$ 0 spin $\frac{1}{2}$ 	MUON NEUTRINO mass $<0,17 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ 	TAU NEUTRINO mass $<15,5 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ 	W BOSON mass $80,4 \text{ GeV}/c^2$ ±1 1 	



NEUTRINOS: PARTÍCULAS MUTANTES

- Neutrinos são partículas sem massa dentro do Modelo Padrão
- Extensões ao modelo permitem acomodar neutrinos massivos (também permitido dentro da teoria de Fermi-Dirac do decaimento beta)
- Oscilação de neutrinos confirmam que possuem massa



IDÉIAS GERAIS DO MODELO PADRÃO

- O Modelo Padrão também assume leis de conservação:

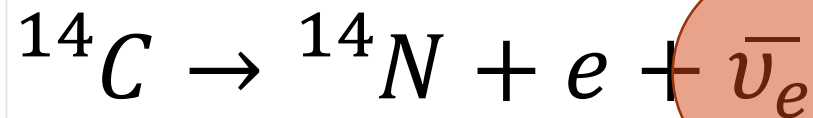
- Número Leptônico (L)

- Léptons $L = +1$

- Anti-léptons $L = -1$

- Número Bariônico (B)

- $B = \frac{1}{3}(n_q - n_{\bar{q}})$



Levam a simetria de matéria e anti-matéria no universo.



TEORIA DO DECAIMENTO BETA DUPLO COM A EMISSÃO DE NEUTRINOS

- Em 1935, paper de Maria Goeppert-Mayer

SEPTEMBER 15, 1935

PHYSICAL REVIEW

VOLUME 48

Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*

(Received May 20, 1935)

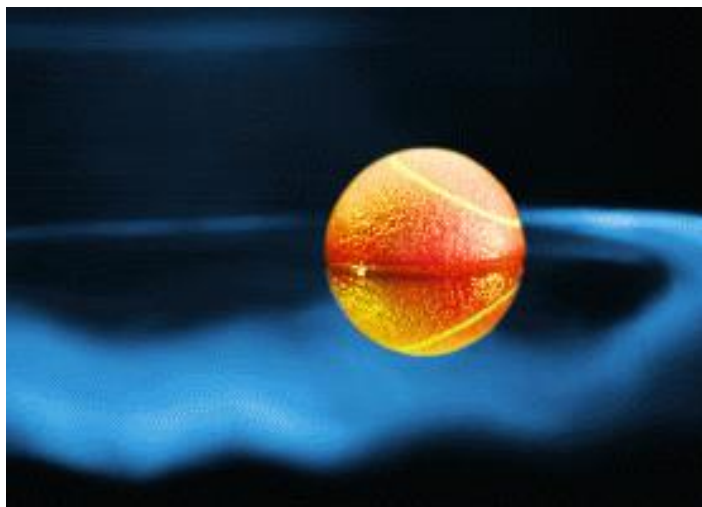
From the Fermi theory of β -disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

<https://doi.org/10.1103/PhysRev.48.512>



A symmetric theory of electrons and positrons(*)

ETTORE MAJORANA



Summary. — It is shown that it is possible to achieve complete formal symmetrization in the electron and proton quantum theory by means of a new quantization process. The meaning of DIRAC equations is somewhat modified and there is no longer any reason to speak of negative-energy states nor to assume, for any other types of particles, especially neutral ones, the existence of antiparticles, corresponding to the “holes” of negative energy.

INTRODUÇÃO

Em 1937, o paper de E. Majorana



PARTÍCULAS DE MAJORANA

- O que são partículas de Majorana?
 - Férmions (spin semi-inteiro)
 - Com massa
 - Idênticas às suas anti-partículas (conjugação de carga)
 - Sendo assim, devem ser eletricamente neutras
- Considerando partículas de spin $\frac{1}{2}$, apenas neutrinos são candidatos a serem partículas de Majorana



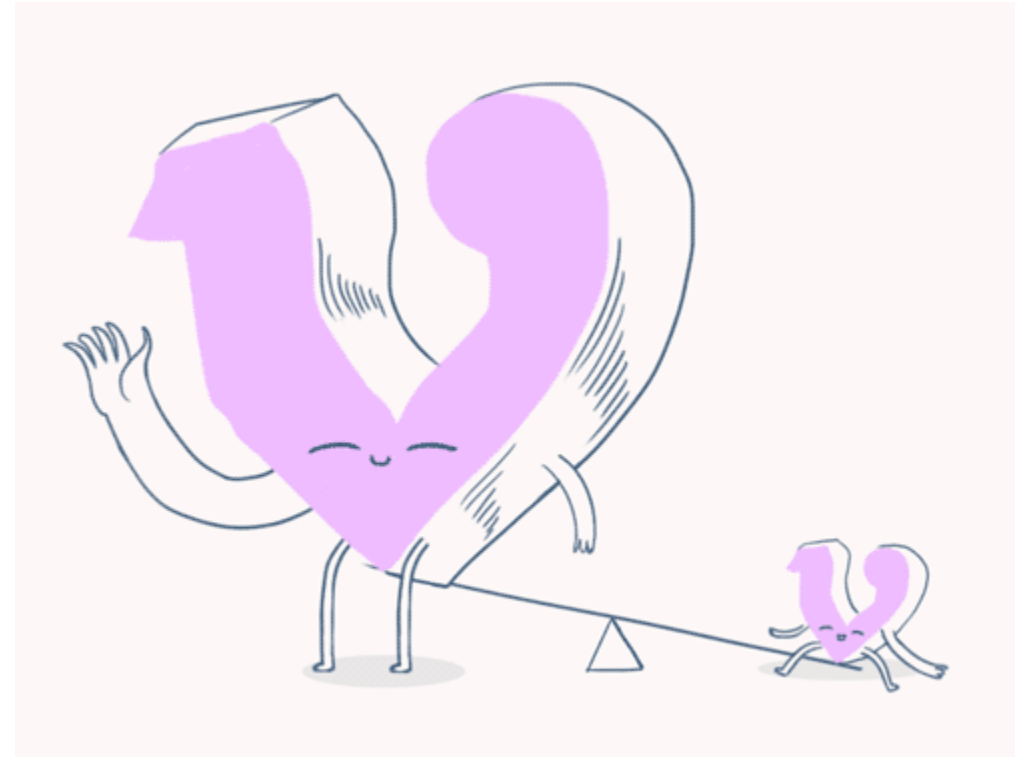


1. BARYON NUMBER VIOLATION
2. CP-SYMMETRY VIOLATION
3. INTERACTIONS OUT OF THERMAL EQUILIBRIUM



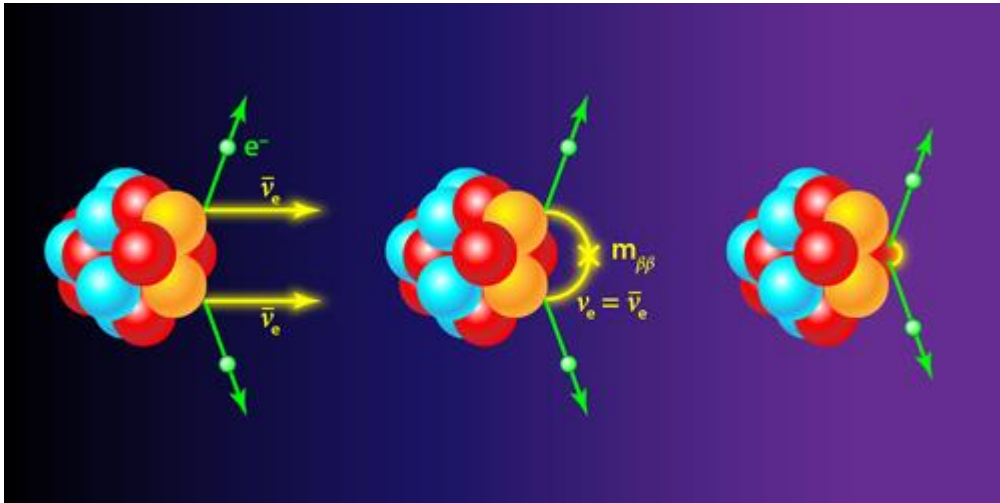
UMA FÍSICA ALÉM DO MODELO PADRÃO

- Se o decaimento $0\nu\beta\beta$ ocorre
 - Confirma o neutrino como uma fermion de Majorana elementar
 - Fornece uma explicação para a pequena massa do ν_e
 - Justifica a assimetria de matéria e anti-matéria no Universo



UMA FÍSICA ALÉM DO MODELO PADRÃO

- The Leptogenesis mechanism



"Do we all descend from neutrinos?"

1

- Partícula de Majorana (RH)

2

- Assimetria Leptônica

3

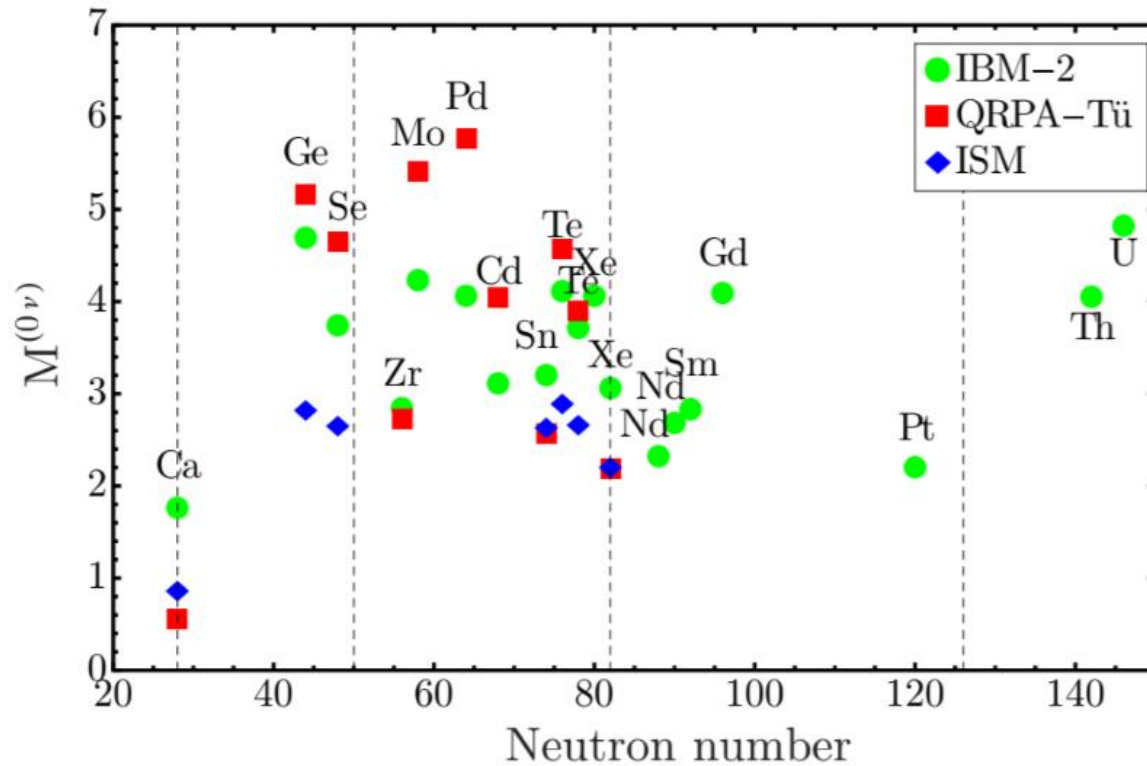
- Violação B + L

Assimetria bariônica

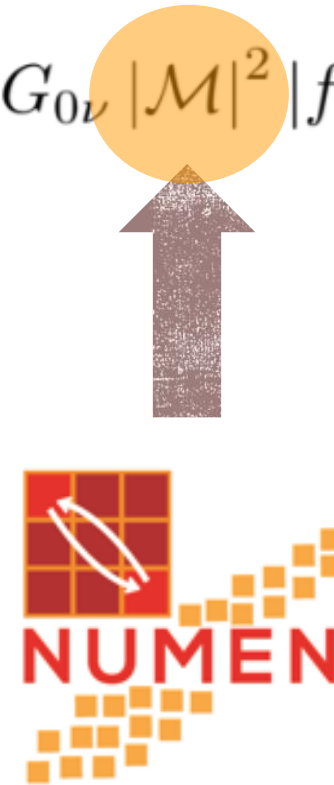


O PAPEL DA FÍSICA NUCLEAR

- A meia-vida do decaimento $0\nu\beta\beta$



$$[t^{1/2}]^{-1} = G_{0\nu} |\mathcal{M}|^2 |f(m_i, U_{ei})|^2$$



BUSCA EXPERIMENTAL DO $0\nu\beta\beta$

■ 4 Possíveis mecanismos

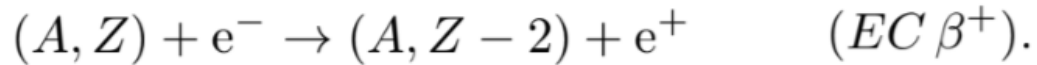
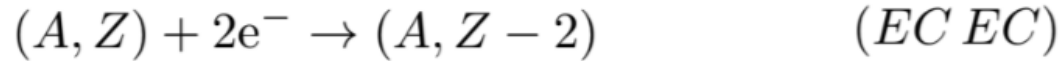
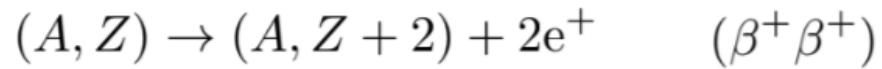
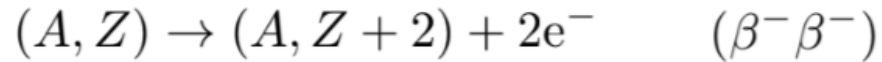


TABLE V. Isotopic abundance and Q-value for the known $2\nu\beta\beta$ emitters [175].

Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371



BUSCA EXPERIMENTAL DO $0\nu\beta\beta$

- Sensibilidade e alta resolução

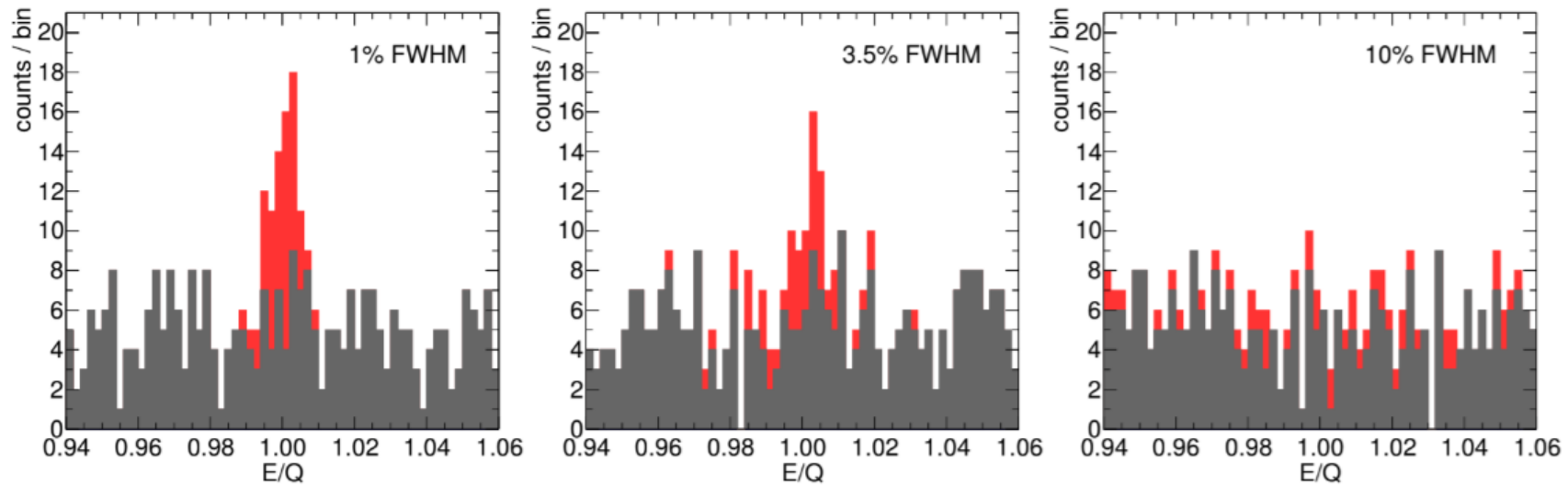


FIG. 15. Signal and background (red and grey stacked histograms, respectively) in the region of interest around $Q_{\beta\beta}$ for 3 Monte Carlo experiments with the same signal strength (50 counts) and background rate (1 count keV^{-1}), but different energy resolution: top: 1% FWHM, centre: 3.5% FWHM, bottom: 10% FWHM. The signal is distributed normally around $Q_{\beta\beta}$, while the background is assumed flat. Figure from Ref. [177].



GERDA EXPERIMENT

Editors' Suggestion

Featured in Physics

Improved Limit on Neutrinoless Double- β Decay of ^{76}Ge from GERDA Phase II

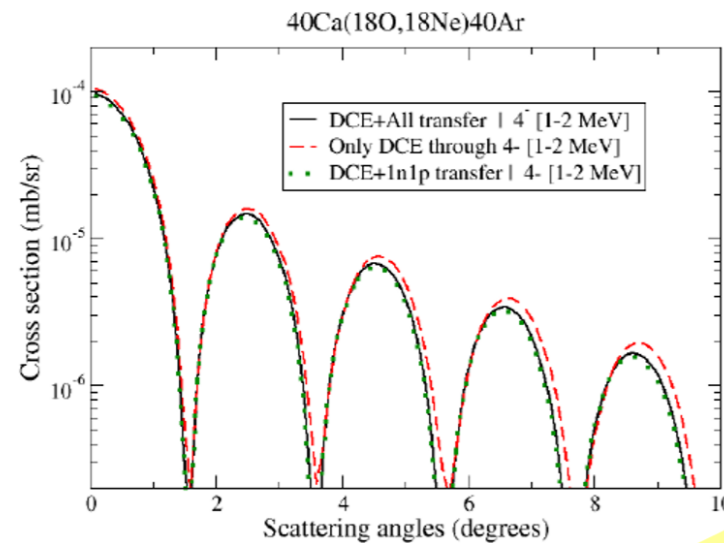
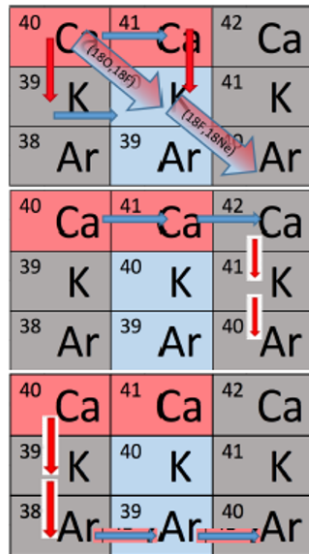
M. Agostini,^{1,b} A. M. Bakalyarov,¹⁴ M. Balata,¹ I. Barabanov,¹² L. Baudis,²⁰ C. Bauer,⁸ E. Bellotti,^{9,10} S. Belogurov,^{17,18} L. Bezrukov,¹² J. Biernat,⁴ T. Bode,¹⁶ D. Borowicz,^{6,d} V. Brudanin,⁶ R. Brugnera,^{17,18} A. Caldwell,

The GERDA experiment searches for the lepton-number-violating neutrinoless double- β decay of ^{76}Ge ($^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^-$) operating bare Ge diodes with an enriched ^{76}Ge fraction in liquid argon. The exposure for broad-energy germanium type (BEGe) detectors is increased threefold with respect to our previous data release. The BEGe detectors feature an excellent background suppression from the analysis of the time profile of the detector signals. In the analysis window a background level of $1.0^{+0.6}_{-0.4} \times 10^{-3}$ counts/(keV kg yr) has been achieved; if normalized to the energy resolution this is the lowest ever achieved in any $0\nu\beta\beta$ experiment. No signal is observed and a new 90% C.L. lower limit for the half-life of 8.0×10^{25} yr is placed when combining with our previous data. The expected median sensitivity assuming no signal is 5.8×10^{25} yr.



REAÇÕES NUCLEARES PARA A FÍSICA ALÉM DO MODELO PADRÃO

Preliminary results: DCE vs transfer



Preliminary results

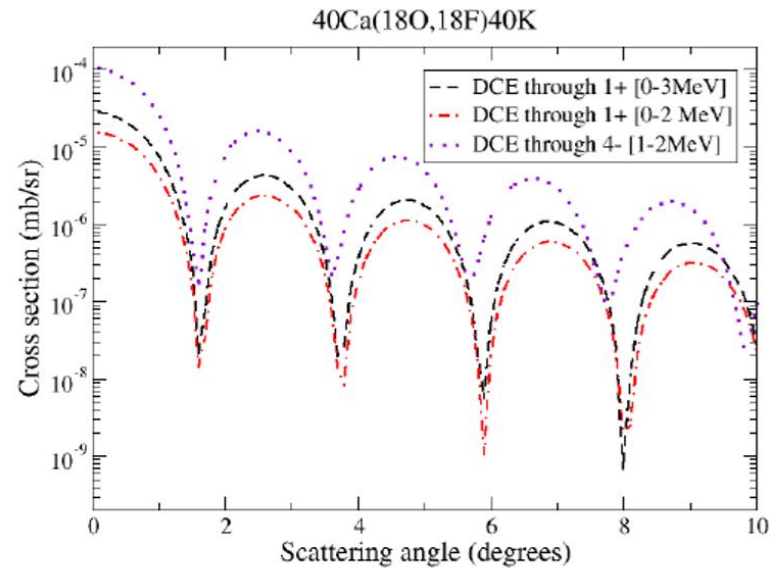
> Only ground states in 2n/2p transfers

FRESCO code: *J.A. Lay*



REAÇÕES NUCLEARES PARA A FÍSICA ALÉM DO MODELO PADRÃO

DCE cross section (DWBA): preliminary results



40 C	41 Ca	42 Ca
39 K	40 K	41 K
38 Ar	39 Ar	40 Ar

Arrows indicate transitions: (18O,18F) from C to K, and (18F,18Ne) from Ca to Ar.

FRESCO code:
Calculations by *J.A. Lay*
(LNS and Sevilla Univ.)

Preliminary results

